



CERN-THESIS-2018-181
29/05/2018



ZACHODNIOPOMORSKI UNIWERSYTET TECHNOLOGICZNY W SZCZECINIE

WYDZIAŁ INŻYNIERII MECHANICZNEJ I MECHATRONIKI

mgr inż. Dariusz Pulikowski

Praca doktorska

**Badania doświadczalne i numeryczne uzwajania cewek nadprzewodnikowych
wykonanych z przewodu wielożyłowego Nb₃Sn typu Rutherford**

Promotor

dr hab. inż. Mirosław Pajor, prof. ZUT

Praca doktorska została wykonana w ramach programu CERN Doctoral Student oraz badań
Future Circular Collider

Szczecin, 2018



WEST POMERANIAN UNIVERSITY OF TECHNOLOGY IN SZCZECIN

FACULTY OF MECHANICAL ENGINEERING AND MECHATRONICS

M.Sc. Eng. Dariusz Pulikowski

Doctoral thesis

**Experimental and numerical investigation of the winding process of
superconducting coils made of multi-strand Rutherford-type Nb₃Sn cable**

Supervisor

dr hab. inż. Mirosław Pajor, prof. ZUT

This doctoral thesis has been carried out and supported by the CERN Doctoral Student
Program in the framework of Future Circular Collider study

Szczecin, 2018

STRESZCZENIE

Projekt High Luminosity-LHC (HL-LHC) oraz badania Future Circular Collider (FCC) wymagają osiągnięcia wyższego pola magnetycznego niż to generowane przez magnesy aktualnie zainstalowane w Wielkim Zderzaczu Hadronów (ang. Large Hadron Collider, LHC). Aby spełnić te założenia nowe dwu- oraz czterobiegunowe magnesy zostały zaprojektowane z wykorzystaniem związku międzymetalicznego niobu z cyną. Ze względu na kruchość związku Nb_3Sn , nawinięcie cewki z wykorzystaniem tego nadprzewodnika wymaga złożonej technologii cieplno-mechanicznej, zwanej wind-and-react. Technika ta polega na uzwajaniu cewki przy użyciu plastycznego przewodu zawierającego substraty chemiczne (niob oraz cynę) w stabilizującej macierzy miedzianej. Następnie cewka jest poddawana obróbce cieplnej w celu uzyskania nadprzewodnika.

Przewód wykorzystywany w produkcji wspomnianych cewek składa się z 40 żył o średnicy do 1 mm. Przewód typu Rutherford, o przekroju poprzecznym w kształcie trapezu, został zoptymalizowany w celu uzyskania spójnego przekroju cewki typu $\cos-\theta$. Z tego powodu uzwajany przewód jest poddawany gięciu o małym promieniu w szczególności na krańcach cewki, co prowadzi do niestabilności (deformacji) poszczególnych żył. Te niechciane deformacje wpływają na jakość wynikowej geometrii cewki oraz jej wydajność elektromagnetyczną. Podczas gdy manualna korekcja przewodu może być akceptowalna w fazie prototypowania czy produkcji jednostkowej, w przypadku produkcji wielkoseryjnej (dla przykładu w projekcie FCC) jest to niedopuszczalne.

Głównym celem rozprawy jest opracowanie procedury ilościowej oceny zdolności przewodu typu Rutherford do nawijania cewek nadprzewodnikowych. Aby uniknąć ingerencji w trwający proces produkcji cewek, badania eksperymentalne wymagają zaprojektowania specjalnych narzędzi umożliwiających uzwajanie reprezentatywnych próbek. Dzięki stanowisku testowemu złożona kinematyka maszyny do uzwajania została uproszczona. Uzwojone próbki cechują się jednakowym rodzajem deformacji jak te zaobserwowane podczas produkcji. W celu przeprowadzenia ilościowej oceny deformacji kluczowe było zdefiniowanie adekwatnej metody pomiarowej. W tym celu zaprojektowane zostało optyczne urządzenie pomiarowe pozwalające na dokonanie inspekcji próbki uzwojenia.

Równolegle do przeprowadzanych eksperymentów, zrealizowana została numeryczna symulacja procesu uzwajania przy użyciu Metody Elementów Skończonych (MES) oraz analiza geometrii przewodu z wykorzystaniem absorpcji rentgenowskiej. Definicja danych materiałowych została poprzedzona badaniami wytrzymałościowymi żył Nb_3Sn . Pomimo uproszczeń geometrycznych, przeprowadzona symulacja umożliwia wygenerowanie funkcji odkształcenia przewodu porównywalnych z tymi zaobserwowanymi w badaniach eksperymentalnych.

Dwie warstwy izolacji przewodu Nb_3Sn , złożone z włókna szklanego typu S-2 oraz miki, utrudniają bezpośrednią obserwację zachowania żył podczas uzwajania. Dlatego też

przeprowadzono badanie z wykorzystaniem techniki aktywnej termografii, aby zdefiniować pozycję poszczególnych żył bez usuwania warstw zewnętrznych.

Należy podkreślić, iż analiza deformacji opisana w tej pracy ma na celu zdefiniowanie podstaw umożliwiających polepszenie jakości oraz powtarzalności geometrii produkowanych cewek nadprzewodnikowych. Zaproponowano potencjalne ulepszenia procesu, takie jak rozszerzona kontrola jakości geometrii podczas uzwajania oraz utwardzania czy rozbudowa kinematyki maszyny do uzwajania.

Praca doktorska składa się z dziewięciu rozdziałów. Rozdział 1 zawiera wprowadzenie oraz dzieli się na dwie części. Część pierwsza opisuje infrastrukturę badawczą Europejskiej Organizacji Badań Jądrowych oraz trwające projekty i badania. Część druga definiuje elementy złożenia magnesu dwu- oraz czterobiegunowego, przedstawia zjawisko nadprzewodnictwa oraz wykorzystywany przewód typu Rutherford. Opisany został również proces projektowania oraz parametry geometrii cewki z wykorzystaniem oprogramowania ROXIE.

Rozdział 2 zawiera opis procesu uzwajania cewek nadprzewodnikowych na podstawie procedur oraz doświadczeń pochodzących z Large Magnet Facility w CERN. Pierwsze trzy podrozdziały opisują kinematykę maszyny do uzwajania z wykorzystaniem notacji Denavita-Hartenberga, przeprowadzane operacje oraz manualną korektę położenia przewodu. Czwarty podrozdział przedstawia deformację przewodu zaobserwowaną podczas uzwajania prototypu cewki. Natomiast kategoryzacja deformacji charakterystycznych dla przewodu typu Rutherford na podstawie momentu gnącego jest przedstawiona w podrozdziale piątym.

Rozdział 3 opisuje główne cele pracy, przedstawia jej hipotezę oraz zakres.

Rozdział 4 prezentuje wyniki modelowania przy użyciu MES. Pierwszy podrozdział skupia się na zasymulowaniu rozkładu naprężenia uzwojonego przewodu wywołanego siłą naciągu. Model zawiera znacznie uproszczoną geometrię przewodu (jednorodny materiał o przekroju prostokątnym), natomiast podstawą jest krańcowy element złożenia bieguna cewki 11 T. Drugi podrozdział opisuje symulację uzwajania zawierającą przewód typu Rutherford o dziesięciu żyłach. Dane wykorzystane do zdefiniowania deformacji plastycznej pochodzą z badań wytrzymałościowych żyły Nb_3Sn . Geometria przewodu została przebadana z wykorzystaniem tomografii komputerowej. Funkcje deformacji, wygenerowane na podstawie dedykowanego algorytmu, zostały przedstawione w trzecim podrozdziale.

Rozdział 5 opisuje trzy przenalizowane techniki digitalizacji powierzchni badanej próbki. Pierwszy podrozdział opisuje badanie mające na celu zlokalizowanie poszczególnych żył przewodu Nb_3Sn typu Rutherford pod dwiema warstwami izolacji (włókno szklane i mika) z wykorzystaniem aktywnej termografii. Drugi podrozdział zawiera analizę porównawczą rozdzielczości przestrzennej skanów próbki uzyskanych technikami laserowej triangulacji oraz skanowania światłem strukturalnym. Urządzenie o najlepszej rozdzielczości zostało wykorzystane do zweryfikowania wyników uzyskanych zaprojektowanym skanerem.

Rozdział 6 jest podzielony na cztery podrozdziały oraz definiuje metodykę eksperymentalnej analizy uzwajania. Pierwszy podrozdział opisuje stanowisko do uzwajania próbek oraz dostosowywane parametry. Drugi podrozdział zawiera opis skanera który umożliwia uzyskanie skanu próbki o wysokiej rozdzielczości przy użyciu trzech stopni swobody oraz laserowej głowicy pomiarowej. Otrzymany skan jest analizowany na podstawie algorytmu przedstawionego w trzecim podrozdziale. Obliczone wyznaczniki umożliwiają ilościowy opis trzech rodzajów deformacji. Czwarty podrozdział prezentuje metodę mającą na celu oszacowanie odkształcenia plastycznego próbki przewodu.

Rozdział 7 dzieli się na trzy podrozdziały opisujące badania eksperymentalne przeprowadzone na podstawie metod przedstawionych w rozdziale 6. Pierwszy podrozdział opisuje badanie deformacji uzwojenia uzyskanej dla różnych wartości naciągu (5, 20 oraz 30 kg) oraz kierunku uzwajania. Uzyskane wyniki umożliwiają dobór zalecanych parametrów uzwajania w celu zminimalizowania określonego typu deformacji dla danego kryterium. Drugi podrozdział bada wpływ skrócenia wstępnego przewodu na wynikową deformację. Przedstawione wyniki udowadniają iż kontrolowanie dodatkowego stopnia swobody jest korzystne dla jakości oraz powtarzalności uzwajania. Dodatkowe badania przeprowadzone z wykorzystaniem zaprojektowanej metody są zawarte w podrozdziale trzecim. Przebadano deformację względną przewodu poddanego obróbce cieplnej, oraz zdefiniowano sposób digitalizacji objętości przewodu z wykorzystaniem tomografii neutronowej.

Rozdział 8 przedstawia zaproponowane dodatkowe pomiary geometryczne przeprowadzone podczas uzwajania oraz utwardzania cewki czterobiegunowej MQXFB CR107. Do standardowej procedury zawierającej pomiar pozycji dolnej krawędzi przewodu dodane zostały pomiary pozycji krawędzi górnej oraz dystansu przewodu od podstawy cylindrycznej. Wykonane pomiary umożliwiają dokładną analizę deformacji poszczególnych warstw uzwojeń cewki nadprzewodnikowej w kolejnych etapach produkcji. Dodatkowo zdefiniowane metody pomiarowe mogą zostać zaadaptowane do procesu obróbki termicznej jak i impregnacji, co umożliwiłoby zwiększenie kontroli nad powtarzalnością produkcji.

Szczegółowe podsumowanie rozprawy doktorskiej jest zawarte w rozdziale 9. Zaprezentowane są uzyskane cele pracy oraz zalecenia dotyczące kontynuacji badań mających na celu automatyzację procedury uzwajania.

ABSTRACT

The High Luminosity-LHC (HL-LHC) project and the Future Circular Collider study (FCC) require higher magnetic fields than provided by the magnets presently installed in the Large Hadron Collider (LHC). In order to fulfill this requirement new dipole and quadrupole magnets are designed based on Nb₃Sn superconductor. Due to the brittleness of Nb₃Sn compound, the cable is wound into a coil in its pristine state. Subsequently, after the coil winding process a heat treatment cycle is carried out in order to form the superconducting intermetallic phases. This production sequence is also called wind-and-react technique.

The cable used to produce these coils consists of 40-strands with a diameter of up to 1 mm. This Rutherford cable with its trapezoidal cross section was optimized to allow a tight azimuthal compaction in a cos- θ coil type. Due to the compact coil design the cable is subjected to a small bending radius in the coil-end regions, which can lead to mechanical instabilities (deformations) of the individual strands. These unwanted strand deformations can impact overall geometrical quality and electromagnetic performance of the coil. Manual corrections of such deformations might be acceptable for prototyping phases or small series production. However it is crucial to develop methods to minimize these phenomena especially in view of large series productions like foreseen for the production of the FCC magnet system.

This thesis is therefore aiming to develop methods to define, quantify and compensate the observed strand deformations based on numerical computations and experimental campaigns. The experimental campaigns will require to develop a special testing machine and winding specimens, since one requirement is not to interfere ongoing series production. The ongoing winding process for prototype and series coil production was mainly of scientific input regarding the observed mechanical instabilities. It will be shown that the complex winding kinematics can be in a first iteration reduced to single Degree Of Freedom (DOF) on a small winding setup, which will allow to reproduce the observed cable deformation. This setup is used to carry out test campaigns with different Rutherford cables, which allow good comparison of winding performance of various cable designs. In order to quantify the observed deformation it is crucial to define an adequate measurement routine. This is addressed by the development of an optical scanning device, which allows to perform the metrological inspection of the winding samples.

In parallel to these experimental campaigns numerical computations and X-ray absorption tomograms are carried out aiming to support the theoretical input in understanding the winding deformations. Mechanical tests improve the material definition for the numerical model will be carried out. The multi-body model will allow to generate deformation functions similar to the ones observed on the full-size winding machine and 1 DOF winding specimen.

In addition, it is shown that the Nb₃Sn cable insulation layers deteriorate the direct observation of the strand deformation. Therefore a non-destructive inspection method will be examined aiming to determine the strand location underneath those layers.

It is important to underline that the analysis and contribution described in this thesis intends to provide the basis allowing to improve the quality and repeatability of obtained coil geometry. A potential further development is suggested that includes an enhanced monitoring of the coil geometry and development of winding machine kinematics, which can be applied for a future winding process.

The doctoral thesis is composed of nine chapters. Chapter 1 is introductory and is subdivided in two parts. Part 1 describes CERN particle accelerator infrastructure and introduces the ongoing projects and studies. Part 2 describes the dipole and quadrupole superconducting magnet constituents, introduces the superconductivity phenomenon and utilized Rutherford-type cables. In addition, the dipole coil optimization performed at CERN with ROXIE software is introduced along with the main design parameters.

Chapter 2 describes the winding process of superconducting coils based on the procedures and experience gathered at CERN Large Magnet Facility. First three subchapters describe the winding machine kinematics following the Denavit-Hartenberg notation, operations performed during the process and required manual manipulation. Afterwards, fourth subchapter includes the cable deformations observed during the prototype coil winding, i.e. the strand pop-out and protrusion. The Rutherford cable deformation is categorized based on the applied bending momentum in fifth subchapter.

Chapter 3 determines main goals of presented thesis and states the hypothesis. Additionally, it includes the scope of a conducted research.

Chapter 4 deals with the modelling with use of Finite Element Method. First subchapter investigates the stress distribution of the wound cable due to the tensioning force. The model includes a simplified cable geometry (i.e. rectangular cross-section stripe of homogeneous material), and the 11 T end-key is used as a support. Second subchapter describes the winding simulation of 10-strand Rutherford cable, and includes the plastic material property (i.e. the multilinear isotropic hardening). The material definition is derived from the performed tensile test. The Rutherford cable geometry is investigated based on the Computed Tomography of the cable specimen. The cable deformation functions are extracted using a developed algorithm, and the discussion is given in third subchapter.

Chapter 5 introduces three tested techniques allowing digitizing the inspected specimen. First subchapter aims to locate the individual strands underneath the S-2 Glass and Mica insulation layers by use of the Active Thermography method. Second subchapter evaluates the spatial resolution of obtained scans by use of laser triangulation and structural light surface scanning techniques. Afterwards, the highest quality scans are used to validate a developed in-house scanner.

Chapter 6 is subdivided on four parts and focuses on defining the winding experiment methodology. First part describes the winding frame used to wind specimens in controllable environment. Second part shows a developed specimen scanning device. The Winding Scanner allows obtaining high accuracy scan of specimen's outer surface with use of three motorized DOF and laser measurement head. The obtained scan is analyzed following the method shown in third subchapter. The computed deformation indicators allow quantifying

three observed deformation types, i.e. the envelope, the strand pop-out, and the protrusion. Fourth part shows the method used to measure the cable springback angle in order to estimate the amount of elastic deformation of a wound cable.

Chapter 7 is divided into three subchapters and define the winding test campaigns conducted following the methodology described in chapter 6. First subchapter investigates cable deformation obtained by various winding tension and direction. Shown results include recommended parameters allowing obtaining the lowest amount of cable deformation for given criteria. Second subchapter investigates the influence of cable pre-torsion on the winding deformation. The presented results indicate that the additional Degree Of Freedom of the winding machine is beneficial for performance and repeatability of winding process. The additional tests performed with use of developed method are shown in third subchapter. These include the investigation of wound cable deformation due to the Reaction Heat Treatment in up to 650°C, as well as the wound cable volume digitization with use of the neutron tomography.

Chapter 8 concentrates on the additional geometrical measurements performed during winding and curing of MQXFB CR107 quadrupole coil. In addition to the standard procedure of measuring the cable bottom position, the top position of the cable as well as the cable protrusion were measured. Proposed investigation contribute to understanding the geometry variations between consecutive coil production steps (i.e. winding and curing). In addition, the improved Quality Control (QC) procedure is applicable to the reaction and impregnation procedures, and may allow to control the repeatability of obtained coil geometry.

Comprehensive summary is given in chapter 9. This includes the description of obtained objectives and a recommended outline of future studies aiming for automated superconducting coil winding.

ACKNOWLEDGEMENTS

I would like to thank Dr. Friedrich Lackner who during the last three years have never accepted nothing less from me than excellence. I am truly grateful for his time spent on cultivating creativity and all the discussions and comments that allowed me learn.

I want to thank Professor Mirosław Pajor for the continuous academic guidance, numerous discussions and support in overcoming obstacles I have been facing throughout my studies.

I appreciate the contribution of my colleagues at the Faculty of Mechanical Engineering and Mechatronics on West Pomeranian University of Technology, for their availability and help with carrying out measurements.

In addition, I would like to acknowledge the members of Large Magnet Facility and Magnet Design and Technology sections at European Organization for Nuclear Research who provided with valuable remarks.

I am glad to be able to contribute to the Future Circular Collider study, therefore I am especially grateful to Davide Tommasini who found the results valuable to be presented to the community.

Last but not least, I would like to thank my wonderful girlfriend Kasia, and my family: my father, my mother, my sister and my niece, who always support, motivate and inspire me. I would not be able to do it without you.

LIST OF ABBREVIATIONS

AMS	Alpha Magnetic Spectrometer
APDL	Ansys Parametric Design Language
AT	Active Thermography
AWAKE	Advanced Wakefield Experiment
BAM	Federal Institute for Materials Research and Testing
CAD	Computer Aided Design
CERN	European Organization for Nuclear Research
CLIC	Compact Linear Collider
CLOUD	Cosmics Leaving OUtdoor Droplets
CT	Computed Tomography
DOF	Degree Of Freedom
DS	Dispersion Suppressor
FCC	Future Circular Collider
FEA	Finite Element Analysis
FEM	Finite Element Method
HiLumi	High Luminosity Large Hadron Collider
HL-LHC	High Luminosity Large Hadron Collider
HTS	High Temperature Superconductor
IR	InfraRed
ISOLDE	Isotope Mass Separator On-Line Facility
ISS	International Space Station
LCD	Liquid-Crystal Display
LHC	Large Hadron Collider
LINAC	LINEar ACcelerator
LMF	Large Magnet Facility

LTS	Low Temperature Superconductor
MAGLEV	MAGnetic LEVitation
MDT	Magnet Design and Technology
MRI	Magnetic Resonance Imaging
OST	Oxford Superconducting Technology
PIT	Powder In Tube
PS	Proton Synchrotron
PSB	Proton-Synchrotron Booster
PTFE	PolyTetraFluoroEthylene
QPS	Quench Protection System
R2R	Radiation to Electronics
RF	Radio Frequency
RHT	Reaction Heat Treatment
RRP	Restacked Rod Processing
SLS	Selective Laser Sintering
SPS	Super Proton Synchrotron
SRF	Superconducting Radio Frequency
WF	Winding Frame
WM	Winding Machine
WS	Winding Scanner
ZUT	West Pomeranian University of Technology in Szczecin

TABLE OF CONTENTS

Streszczenie	i
Abstract	iv
Acknowledgements	vii
List of abbreviations.....	viii
Table of contents.....	x
1. Introduction	1
1.1. CERN	1
1.1.1. Particle accelerators and LHC infrastructure	2
1.1.2. High Luminosity-LHC	4
1.1.3. Future Circular Collider	9
1.1.4. Superconducting magnet facilities at CERN.....	10
1.2. Superconducting magnets.....	11
1.2.1. Superconductivity.....	13
1.2.2. Rutherford cable	17
1.2.3. Coil geometry	21
2. Superconducting coil winding.....	24
2.1. Winding machine kinematics	25
2.2. Operations during winding	35
2.3. Manual cable correction	38
2.4. Observed winding defects	40
2.5. Qualification of the Rutherford cable deformation	41
3. Research questions and scope of work.....	43
4. Numerical modelling of the winding process.....	45
4.1. Stress distribution of the wound cable.....	45
4.1.1. Setup definition	46
4.1.2. Results	47
4.2. Simulation of the winding process	48
4.2.1. Winding simulation setup.....	49
4.2.2. X-ray absorption tomography of 40-strand Rutherford cable	50
4.2.3. Geometry definition	52
4.2.4. Result analysis	59

4.2.5. Guide curve interpretation.....	61
4.3. Conclusion and further development.....	66
5. Surface digitization methods.....	67
5.1. Active thermography.....	67
5.1.1. Experimental setup.....	68
5.1.2. Obtained results.....	68
5.1.3. Conclusion.....	72
5.2. Surface scanning devices.....	72
5.2.1. Evaluation.....	74
5.2.2. Conclusion.....	77
6. Development of the winding test equipment.....	78
6.1. Winding Frame.....	78
6.1.1. Specimen preparation.....	79
6.1.2. Adjustable parameters.....	82
6.2. Winding Scanner.....	85
6.2.1. Operation principle.....	88
6.2.2. Measurement validation.....	90
6.2.3. Laser head research and repeatability computation.....	94
6.3. Deformation analysis methodology.....	97
6.3.1. Cartesian transformation.....	98
6.3.2. Data separation.....	99
6.3.3. Virtual unwinding and normalization.....	100
6.3.4. Deformation functions.....	101
6.3.5. Indicator computation.....	102
6.3.6. Winding matrix aggregation.....	105
6.3.7. Analysis example.....	106
6.4. Springback measurement.....	108
7. Winding campaigns.....	110
7.1. Winding tension and direction.....	111
7.1.1. Obtained results.....	113
7.1.2. Discussion and conclusion.....	119
7.2. Cable pre-torsion.....	124
7.2.1. Obtained results.....	127
7.2.2. Discussion and conclusion.....	130
7.3. Complementary experiments using the winding specimen.....	131
7.3.1. Deformation due to reaction heat treatment.....	131
7.3.2. Cable volume digitization with computed tomography.....	135

8. Supplementary geometrical measurement during the coil fabrication.....	140
8.1.1. Measurement results.....	145
8.1.2. Discussion	149
9. Comprehensive summary	151
Bibliography.....	154
List of Figures	159
List of Tables.....	168

1. INTRODUCTION

The presented research is carried out in the European Organization for Nuclear Research within the scope of High Luminosity-LHC project and Future Circular Collider study. The chapter 1.1 provides a concise description of the LHC infrastructure and introduces the assumptions of those projects. The introduction to superconducting magnet constituents, the superconductivity, the description of the Rutherford superconducting cable, and the design of a coil geometry is given in chapter 1.2. The work focuses on studying the initial stage of the superconducting magnet production. The study of the Rutherford cable mechanical instabilities, their description as well as their quantification is presented in this thesis.

1.1. CERN

Presently, the European Organization for Nuclear Research (CERN) is the largest particle accelerator laboratory in the world. Founded in 1954, hosts over 12000 visiting physicists and engineers, and over 2500 staff members. It is located at the Franco-Swiss border close to Geneva, and joins 22 member states in an unprecedented endeavor of understanding the early universe.

Beside the Large Hadron Collider (LHC) experiments, discussed further in the following chapter, the CERN hosts multiple extraordinary experiments, among others:

- The Compact Linear Collider (CLIC) – a concept for a machine to collide electrons and positrons head-on at energies up to several Teraelectronvolts (TeV) in two linear accelerators facing each other [1];
- The Advanced Wakefield Experiment (AWAKE) – a proof-of-principle experiment investigating the use of wave generated by the protons travelling through a plasma to accelerate charged particles [2];
- The Cosmics Leaving Outdoor Droplets (CLOUD) – a cloud chamber to study the possible link between galactic cosmic rays and cloud formation [3];
- The Isotope Mass Separator On-Line Facility (ISOLDE) – a facility located at the Proton-Synchrotron Booster (PSB), dedicated to the production of a large variety of radioactive ion beams for experiments in the fields of nuclear and atomic physics, solid-state physics as well as materials science and life sciences [4];
- The Alpha Magnetic Spectrometer (AMS) – a particle-physics detector that looks for dark matter, antimatter and missing matter from a module attached to the outside of the International Space Station (ISS) [5].

Such a scientific diversity combined with a multinational and multidisciplinary environment allows CERN to give a major contribution in many scientific disciplines remaining at the forefront of the engineering, information technology and physics.

1.1.1. PARTICLE ACCELERATORS AND LHC INFRASTRUCTURE

The particle accelerators are designed to accelerate charged particles close to the speed of light, where relativistic effects becomes dominant. The particles, called also a beam or a bunch, are accelerated by the RadioFrequency (RF) cavities, which are specially formed to exert a propelling force on the particles by resonating electromagnetic waves. One can distinguish the linear accelerators – where the particles are displaced in a straight line (see LINAC 3 and LINAC 2 in Figure 1.1), and the circular accelerators – where the particles follow a circular orbit (e.g. LHC, SPS and PS in Figure 1.1).

The particle trajectory is given by the magnetic lattice, often referred as an accelerator optics. Its main objective is to focus the beam, and in case of a circular accelerator to bend the particle trajectory towards the center. In order to prevent the beam from diverging, the quadrupole magnets are used. The particles are bent due to the seen linear dipole field which keeps the beam on its circular trajectory.

One can visualize the magnetic lattice of an accelerator with the analogy to the optics, by imagining the particle beam as the beam of light, the quadrupole magnet as the focusing (converging) lens and the dipole magnet as the reflective mirror.

The most powerful synchrotron-type particle accelerator today is the 27-km-circumference Large Hadron Collider (LHC) designed and built at CERN, where bunches of particles are accelerated in opposite directions in two adjacent beams. The beam intersection occurs in so-called interaction points, where some of the particles collide. The kinetic energy during the collision is transformed into a shower of particles, following the mass-energy equivalence $E = mc^2$.

The LHC beam starts in a 50-MeV LINAC2 linear accelerator, afterwards is passed to a multi-ring booster synchrotron where is accelerated to 1.4 GeV. Next reaches the Proton Synchrotron (PS), a 628-m-circumference machine providing 26 GeV, and the 7-km-circumference Super Proton Synchrotron (SPS) where the bunch is accelerated to 450 GeV. At this point, the beam is ready for the final transfer to the LHC. The injected beam has a total kinetic energy of more than 2 MJ after a cycle which roughly takes 20 s. Such energy can already damage the LHC equipment, thus fast kicker magnets are involved to abruptly change the trajectory of the beam and guide it through the 3 km transfer line. Finally, the particle bunch reaches 7 TeV in the LHC tunnel. The LHC performance allows for roughly 30 million proton-proton collisions per second with center-of-mass energy of 13 TeV [6].

Beside the energy, equally important is the luminosity of an accelerator. Each discovery needs to be supported by a very high amount of events, in agreement with a tested theory. The luminosity is the quantity that measures the ability of a particle accelerator to produce the required number of interactions. As expressed in the equation (1.1), it is the

proportionality factor between the number of events per second (dR/dt) and the cross section σ_p . Therefore the unit of the luminosity L is $cm^{-2}s^{-1}$ [7].

$$\frac{dR}{dt} = L * \sigma_p \quad (1.1)$$

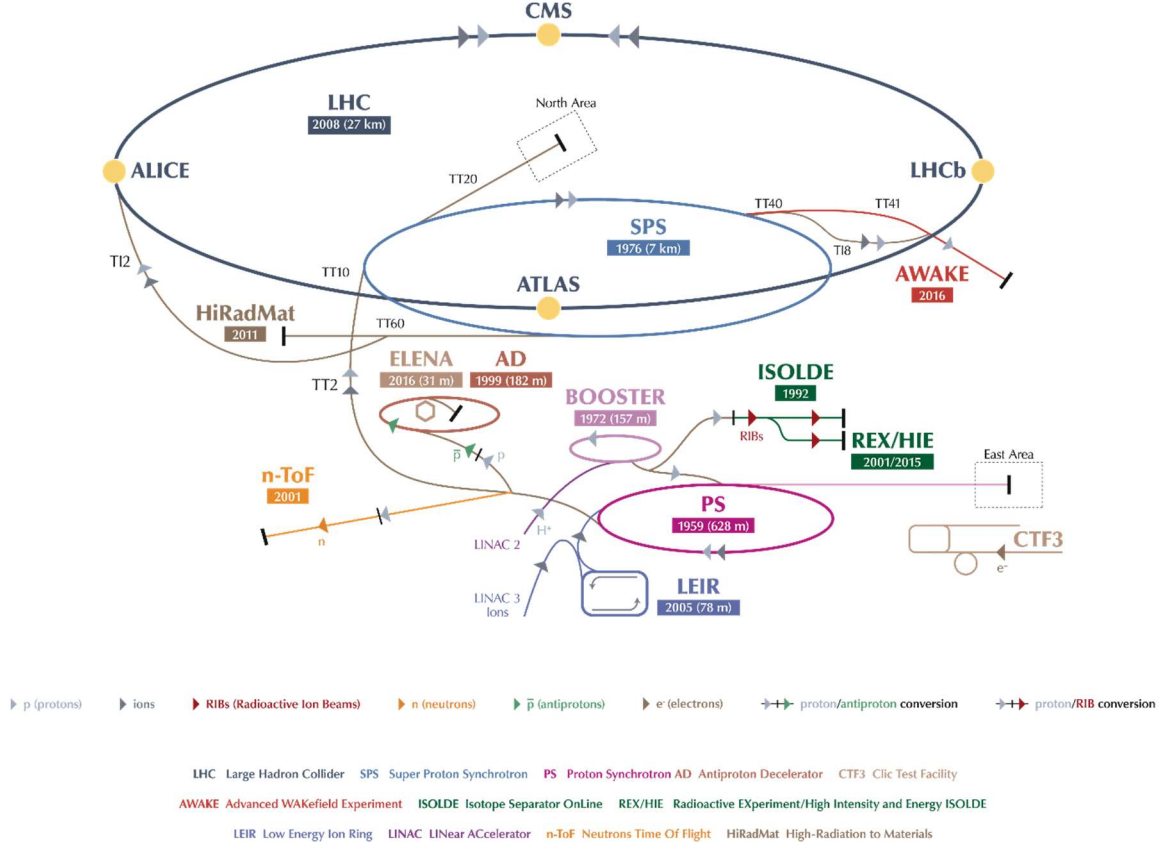


Figure 1.1 The CERN accelerator complex. Source: CERN Document Server.

The collision is probed by the specialized detectors, which allows recording the trajectory, momentum and energy of the resulting particles. There are four detectors in the LHC ring, positioned in four interaction points (marked by a yellow circles in Figure 1.1). The ATLAS detector is the largest volume particle detector ever built. It consists of four major components: the Inner Detector – measuring the direction, momentum, and charge of electrically charged particles, the Calorimeter – measuring the energy a particle loses as it passes through, the Muon Spectrometer – identifying and measuring the momenta of muons and the Magnet System – bending the trajectory of particles. One can see the aerial view of the LHC and the four major experiments in the Figure 1.2.

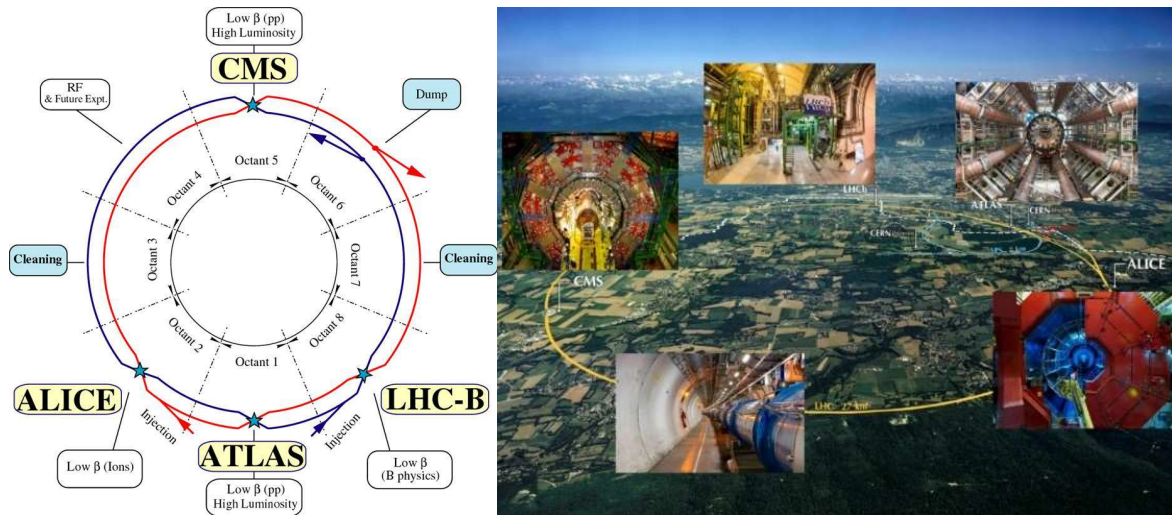


Figure 1.2 Overview of the four major experiments of the LHC. Left: the schematic view of the LHC with its octants and insertion regions (blue stars). Right: Aerial view of the Geneva area with the placement of LHC and four major experiments. Source: CERN Document Server.

The collision energy has a direct impact on a detail of the particle discovery. In order to reach even further levels of energy than the LHC, physicists and engineers have already started to explore so-called post-LHC era. This broad term includes all research activities aiming to provide higher luminosity and sustain beam of higher energies than the LHC. One can distinguish two most prominent projects:

- High Luminosity LHC (HL-LHC or HiLumi) [8] – the LHC upgrade with a target of increasing the peak luminosity, described in chapter 1.1.2;
- Future Circular Collider (FCC) [9] – a new circular collider which uses LHC ring and its infrastructure as an injector chain, aiming at proton-proton collision energy of 100 TeV, described in chapter 1.1.3.

1.1.2. HIGH LUMINOSITY-LHC

The HL-LHC project aims to extend a discovery potential of LHC by increasing its luminosity by a factor of ten – up to 3000 fb^{-1} . This upgrade will enable physicists to go beyond the Standard Model and Higgs boson, in search for the dark matter and supersymmetry. This decade-long project aims to develop the key technologies, such as the development of state-of-the-art 11 T dipoles with Nb_3Sn superconductor, compact radio-frequency cavities and 100-m-long high-power superconducting links.

The commissioning of the LHC for a 7 TeV centre-of-mass proton-proton collisions was finished in 2010 [10]. The consecutive upgrades allowed to nearly doubling the energy, up to present 13 TeV centre-of-mass proton-proton collisions from 2015. Undoubtedly, the most

remarkable discovery enabled by the LHC was the discovery of the Higgs boson in 2012 [11]. Beyond this, the unprecedented energy has the potential to help with understanding the supersymmetry theory, the nature of dark matter or the existence of extra dimensions [12].

For at least the next two decades, the LHC will remain the most powerful accelerator in the world, allowing the Europe to maintain at the forefront of the high energy physics. The full exploitation of the machine is the highest priority of the European Strategy for particle physics, with the baseline shown in Figure 1.3. A major upgrade is planned in the 2020s in order to increase its peak luminosity to $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and integrated luminosity of 250 fb^{-1} per year. The ultimate objective is to obtain the 3000 fb^{-1} of integrated luminosity in about 12 years following the upgrade (see Figure 1.4) [13].

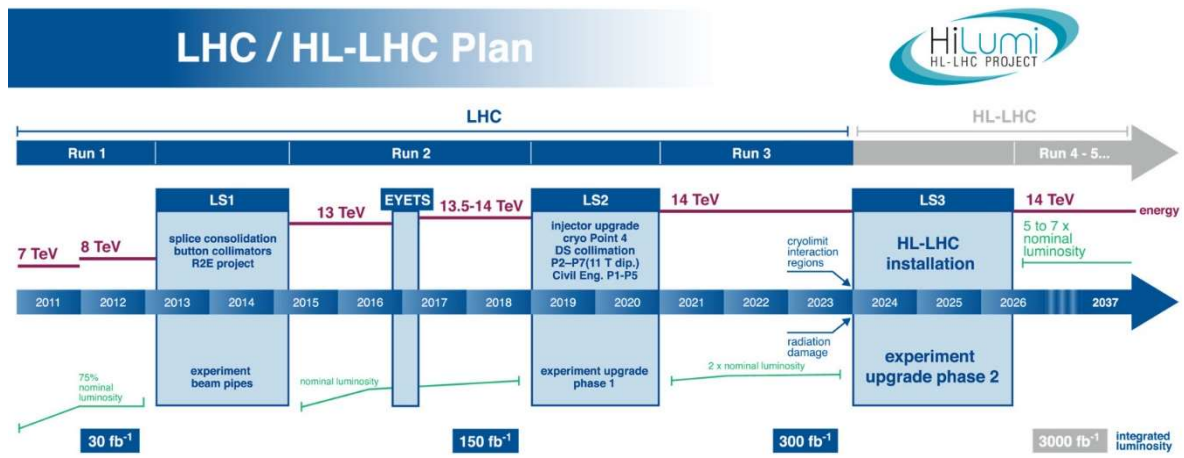


Figure 1.3 The LHC baseline showing the progression of the collision energy (red line) and luminosity (green line). The High Luminosity transition is shown after the Run 3 [14].

The HL-LHC relies on a number of key technologies: cutting-edge Nb_3Sn high-field superconducting magnets; compact superconducting cavities for beam rotation with ultra-precise phase control; new technology for beam collimation; and high-power superconducting links with negligible energy dissipation [14]. The LHC and HL-LHC baseline scheme is shown in Figure 1.3, and the nominal progression of the peak and integrated luminosity is depicted in Figure 1.4.

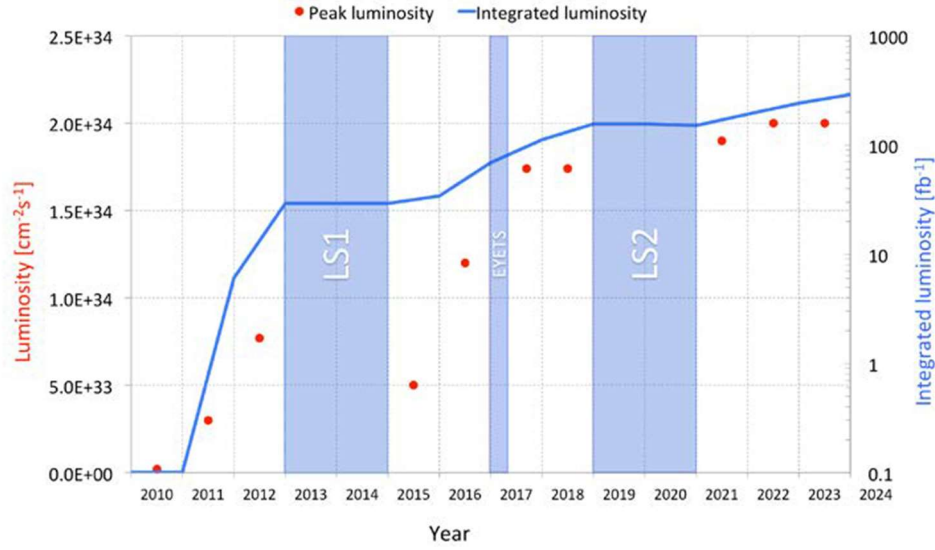


Figure 1.4 LHC luminosity plan up to third Long Shutdown (LS3). Peak luminosity shown with red dots; integrated luminosity shown with blue solid line [14].

Several systems need to be improved in order to avoid a breakdown and limit the accelerator aging, due to the higher operational radiation:

- Dispersion Suppressor (DS) regions – anticipating a possible LHC performance limitation due to the off-momentum particle leakage in to the superconducting magnets. In order to cope with the issue additional collimators could be installed, which require additional space. The solution is to replace the existing bending LHC dipole with two shorter magnets of equal integrated bending strength. The new high-field 11 m-long 11 T dipoles [15] will provide the bending strength of $\sim 120 \text{ Tm}$, substituting the 14.2 m 8.3 T LHC dipole. The three meters of gained space will be sufficient for the collimation system;
- Inner triplet magnets – the possible radiation damage of nested corrector magnets are anticipated, that could result in severe failure necessitating a long repair. Therefore, the replacement of the low- β triplet is foreseen with a new magnet types called MQXF, which are 4.2 m- and 7.15 m-long [16];
- Cryogenics – segmentation of the cooling systems of the Superconducting Radio Frequency (SRF) cavities [17], the arc magnets, and inner triplets. This is in order to improve the intervention flexibility and availability of the collider;
- Collimation – material and design improvements taking into account the lower impedance of the increased beam intensities [18];
- Radiation to electronics (R2R) and superconducting links for the remote powering of cold circuits;
- Quench Protection System (QPS) of the superconducting magnets;
- Machine protection against a beam mis-injection, breakdown of a kicker and asynchronous beam dump;

- Improved remote manipulation allowing for a faster repair or replacement of key elements of the collider.

This thesis is related to the DS and inner triplet upgrade and focuses on the analysis of a winding process of the 11 T [15] and MQXF [16] magnets.

The 11 T dipole full assembly consists of two cold masses (LMBHA and LMBHB) with the collimator installed in the middle (LEN), see Figure 1.5. The design of the cold mass consists of two apertures in a common yoke and shell assembly, so called two-in-one configuration.

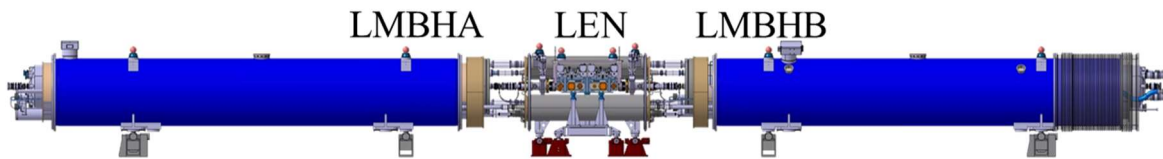


Figure 1.5 11 T dipole full assembly, including two dipole magnets (LMBHA and LMBHB) and a collimator (LEN). Source: CERN Document Server.

One can see the collared coil on the left side of Figure 1.6. The coils feature two layers and six blocks of Nb₃Sn Rutherford cable. The inner layer of the coil consists of 22 turns, and the outer layer 34 turns. Both layers are wound from the same continuous length of cable, with no interconnection in the layer-jump. In order to balance the electromagnetic forces, the cold mass assembly contains of austenitic steel collars for each aperture, vertically split iron yoke and a welded stainless steel shrinking cylinder (see right side of Figure 1.6).

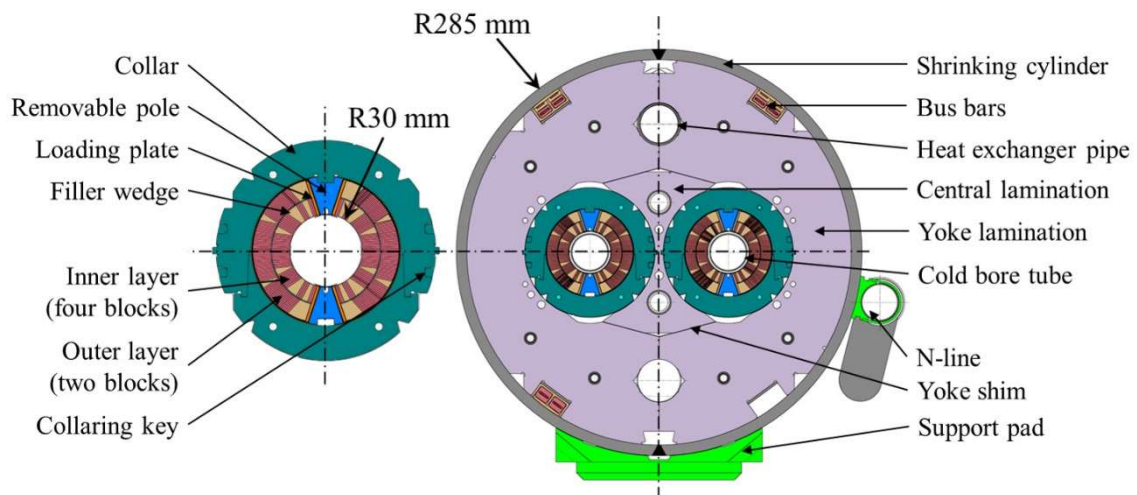


Figure 1.6 11 T dipole cross section. Left: collared coil. Right: Cold mass assembly. Source: CERN Document Server.

The 11 T magnet is designed with use of the Nb₃Sn superconductor technology. The cable and insulation details are shown in the Table 1.1. The electrical insulation is completed during vacuum impregnation with the Epoxy resin CTD-101K[®].

Table 1.1 Features of the 11 T superconducting cable.

Superconductor	Nb ₃ Sn
No. strands	40
Strand diameter (mm)	0.7
Manufacturing method	RRP [®] and PIT
Keystone angle (°)	0.79 for RRP 0.50 for PIT
Insulation	C-shaped Mica tape braided S2-Glass sleeve

In contrary to the 11 T magnet the MQXF magnet (aperture 150 mm), also shell-based structure, uses the so-called bladder and key assembly technique [19]. The stress levels of the magnet are precisely fine-tuned in room temperature with use of the water-pressurized bladders and locking keys. The main mechanical pre-stress comes from the aluminum shell that is the outermost layer of the magnet. During the cool-down the shell contracts, providing the additional force counteracting the Lorentz force. One can see the cross section of the MQXF triplet magnet in Figure 1.7.

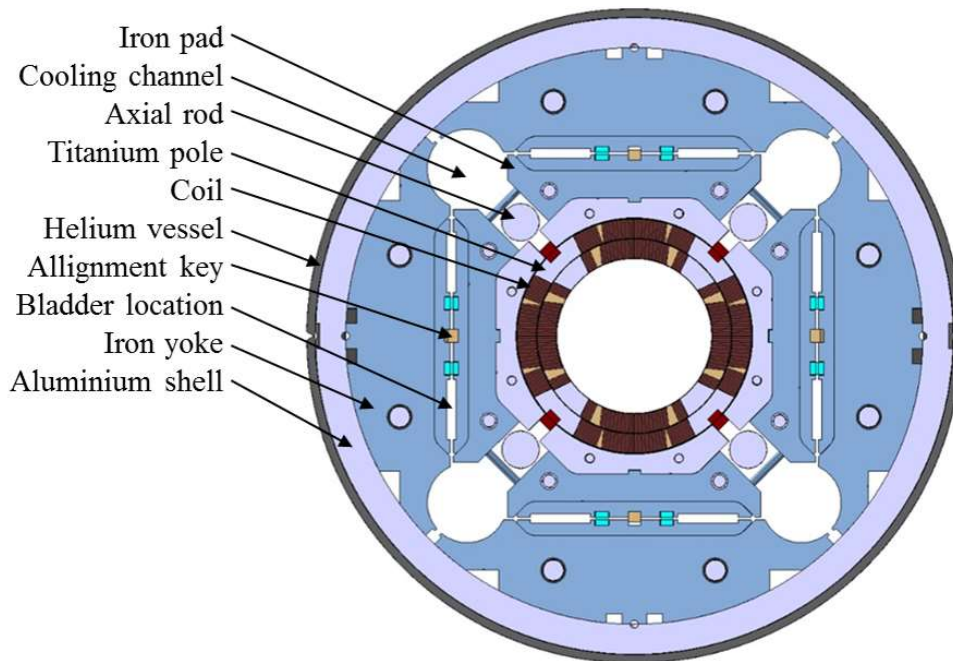


Figure 1.7 MQXF triplet magnet cross section [20].

The MQXF magnet is also designed with use of the Nb₃Sn superconductor. The Rutherford type cable and insulation details are shown in the Table 1.2. Alike the 11 T design, the electrical insulation is completed during vacuum impregnation with an epoxy resin.

Table 1.2 Features of the MQXF superconducting cable.

Superconductor	Nb ₃ Sn
No. strands	40
Non-Cu I_c (A/mm²)	1280 @ 15 T and 4.2 K
Cu/non-Cu ratio	1.2
Strand diameter (mm)	0.85
Manufacturing method	RRP®
Keystone angle (°)	0.40
Insulation	S2-Glass braided sleeve (145 µm @ 5 MPa)

1.1.3. FUTURE CIRCULAR COLLIDER

CERN's long-term future in the field of high energy physics could be given by the construction of a new accelerator like the Future Circular Collider. The magnitudes within the FCC study are enormous, see Figure 1.8. One can distinguish two parameters driving the collision energy: circumference and dipole magnetic field. In order to reach the assumed 100 TeV with use of 8.33 T LHC main dipoles, the ring would have to be 250 km-long. On the other hand, if the LHC 27-km-long ring would be used to achieve such energy, the dipoles would have to provide 70 T magnetic field. The FCC study alters both parameters, providing an optimal solution. Currently the design foresees a circumference of 80 to 100 km (see Figure 1.8) with a main bending dipole magnetic field of 16 to 20 T [9]. Such a magnetic field can be achieved with the existing technology of Nb₃Sn superconductor. The higher magnetic field with comparison to the LHC dipole imposes higher tolerances on every component and re-evaluation of possible magnet designs, like Cosine-Theta [21], Canted-Cosine-Theta [22] or Common Coil [23].

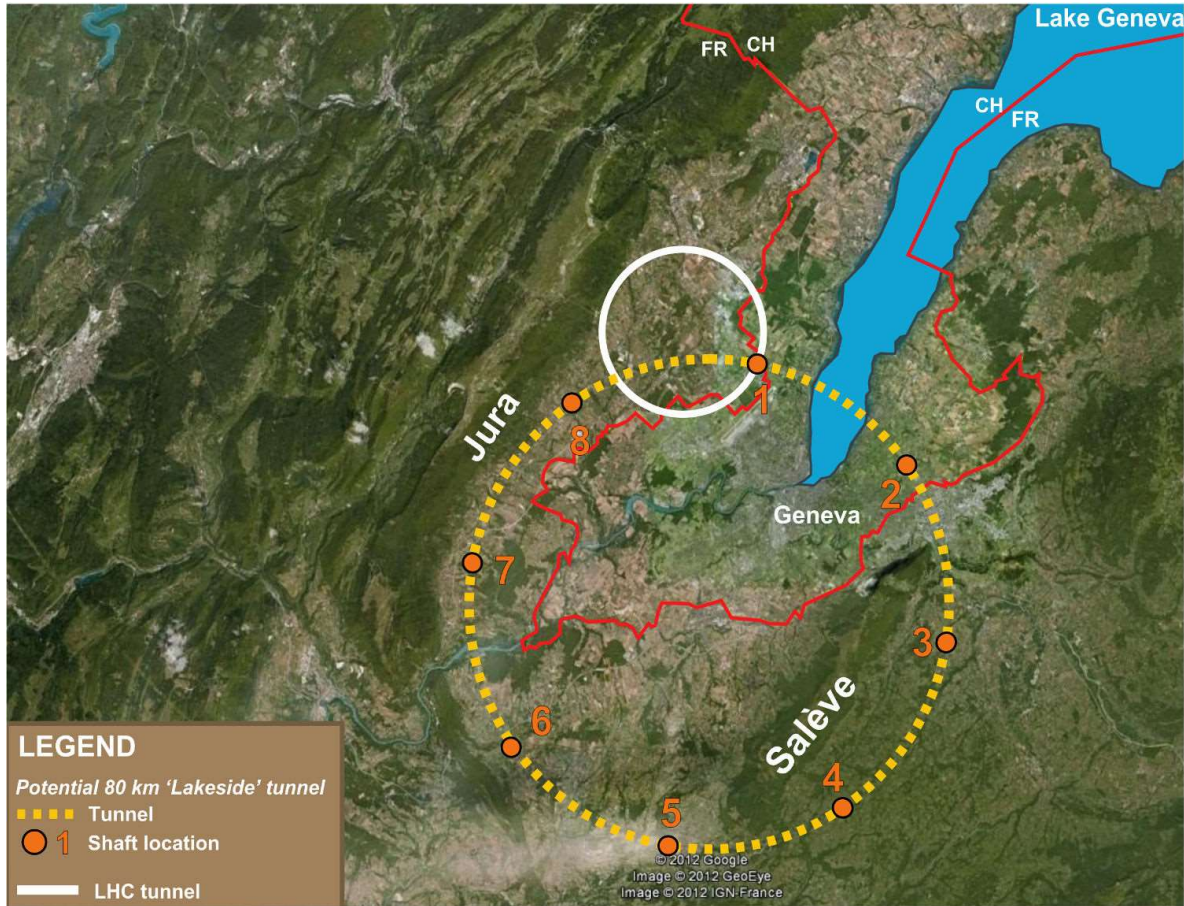


Figure 1.8 Schematic of 80 km tunnel for a Future Circular Collider at CERN. Source: CERN Document Server.

1.1.4. SUPERCONDUCTING MAGNET FACILITIES AT CERN

There are two sections at CERN standing behind the development of the superconducting magnet technology: the Magnet Design and Technology (MDT) with a mandate of developing short model magnets (e.g. 2.5 m 11 T dipole), and the Large Magnet Facility (LMF) with a mandate of manufacturing full-length magnet prototypes (e.g. 5 m-long 11 T dipole). Both laboratories are responsible for the wide range of activities aiming to support the engineering, tooling development, procurement, manufacturing, and maintenance of the superconducting magnets. The workshops are equipped with specialized instruments, e.g. Kapton cable insulating machine, winding machines, curing press, collaring press, welding press, geometrical alignment systems, pressure and leak testing as well as electrical testing equipment. In addition, certain research activities are conducted, e.g. material mechanical tests, development of the numerical model of the magnet cross-section, critical current degradation study, winding process analysis and development. The LMF laboratory is shown in Figure 1.9.

The experience acquired by the MDT and LMF sections allows determining the manufacturing procedures and requirements for the Nb₃Sn magnet production. The following thesis and investigation of the coil winding process is based on the documentation and experience of the variety of teams working in both facilities.



Figure 1.9 The Large Magnet Facility at CERN in 2017.

1.2. SUPERCONDUCTING MAGNETS

The LHC is not a perfect circle. In fact, it consists of eight 2.45-km-long arcs and eight 545-m-long straight sections (also called insertions). The straight section layout is differing based on the functional requirements, it is either beam collision, injection, beam dump or beam cleaning. The arc lattice however is composed of standard segments containing a sequence of magnets shown in the Figure 1.10.

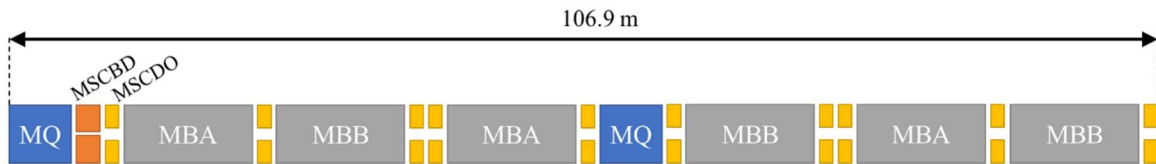


Figure 1.10 The LHC arc lattice, consisting a quadrupole (MQ), dipoles (MBA, MBB) and other multipole correction magnets.

In total, the LHC chain contains of 1232 main dipole magnets, each deflecting the beam by $\frac{2\pi}{1232} = 5.1 \text{ mrad}$ in order to keep it in a circular orbit. The focusing is provided by 396 quadrupole magnets installed in the arcs. When the LHC is operating with the maximal

collision energy of 13 TeV, the dipole field reaches 8.33 T. The draft of a transversal cross section of the LHC dipole is shown in the Figure 1.11. This so-called twin-aperture design allows enclosing two high-vacuum beam pipes and coil windings in close proximity and provides sufficient mechanical strength. The assembly needs to withstand high stresses resulting from the high magnetic field and the large temperature gradient of 270 K [24].

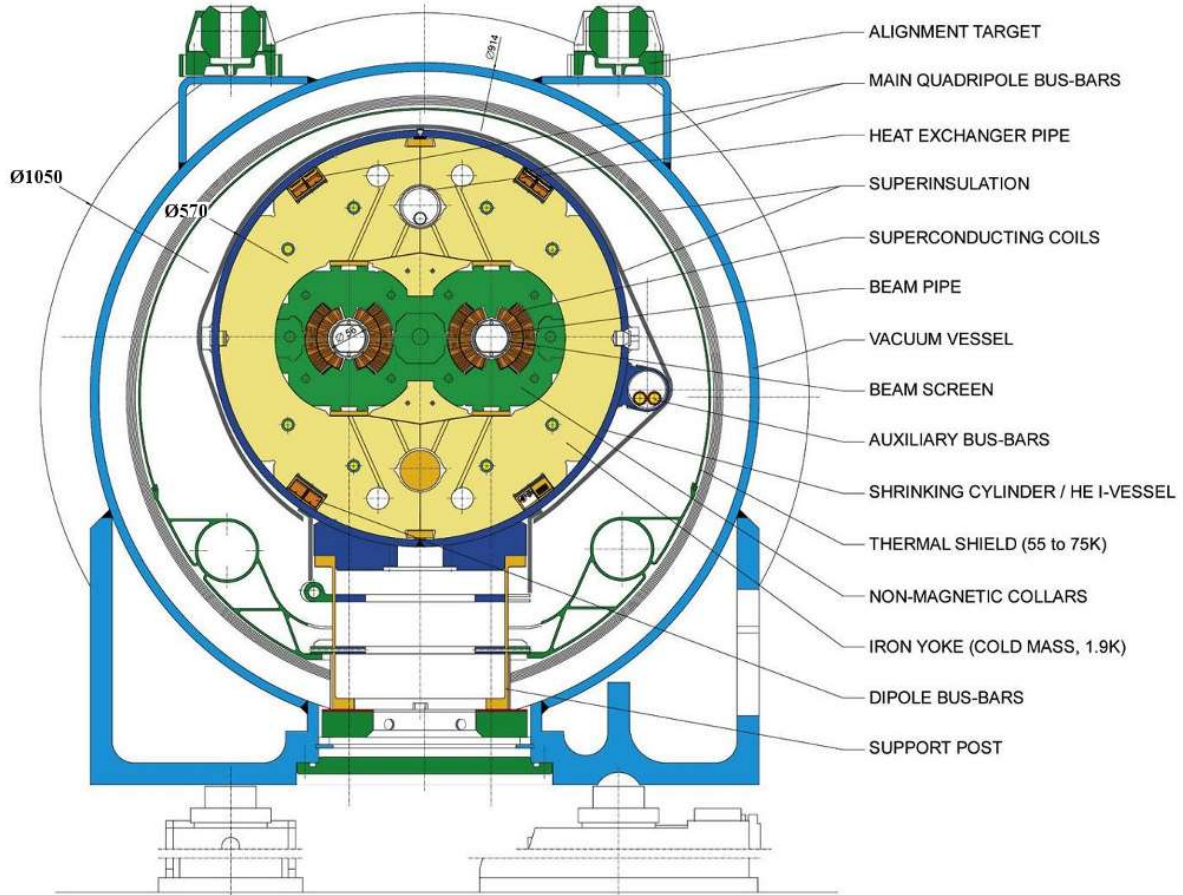


Figure 1.11 Diagram showing the cross-section of an LHC dipole magnet with cold mass and vacuum chamber. Source: CERN Document Server.

The collision energy in a circular accelerator is directly proportional to the magnetic field strength of the main dipole and the diameter of the ring. The energy of one beam can be calculated with the equation [24]:

$$E_{beam} \cong 0.3BR \quad (1.2)$$

Where energy E is expressed in TeV, the dipole magnetic field B is expressed in tesla, and R is the radius of curvature expressed in kilometers. Not the entire circumference of an accelerator contributes to bending of the beam, which is represented by the 0.3 coefficient shown in the equation.

1.2.1. SUPERCONDUCTIVITY

Discovered in 1911 [25], superconductivity is a phenomenon occurring in certain materials which causes the electrical resistance reducing to zero when cooling below the critical temperature T_c . Negligible resistivity allows transporting a high-density current, resulting with a much higher magnetic field in comparison to conventional magnets. Commonly used electromagnets with copper windings and iron yoke are limited to 2 T. Superconducting materials can be separated on two groups: type-I typically containing elements, e.g. mercury [25], lead or aluminum; and type-II including compounds and alloys such as Nb-Ti [26], [27], Nb₃Sn [28] or ReBCO [29].

Type-I superconductors, also called soft superconductors, are losing superconductivity abruptly when placed in an external magnetic field. One can see in the Figure 1.12 left, that when exposed to the magnetic field higher than critical B_c , the type-I superconductor transfer to normal conductive state. While in superconducting state, type-I superconductor generates current on the surface and fully shields the magnetic field, this phenomenon is called the Meissner-Ochsenfeld effect [30]. Above critical magnetic field the surface does not shield the magnetic field, thus the material loses its superconductivity. As one can see on the right side of Figure 1.12, type-II superconductors lose their superconductivity gradually when placed in the external magnetic field. This is explained with the Abrikosov effect [31], when beyond the first critical field B_{c1} the magnetic field starts penetrating so called vortices in a superconductor volume. The vortices comprise of a circulating electrical shielding current allowing the normal state to exist at their center. The transition to normal state occurs after exceeding over upper critical magnetic field B_{c2} . Such a mixed state is stable and allows achieving high magnetic fields. Therefore, type-II superconductors are used for every practical application.

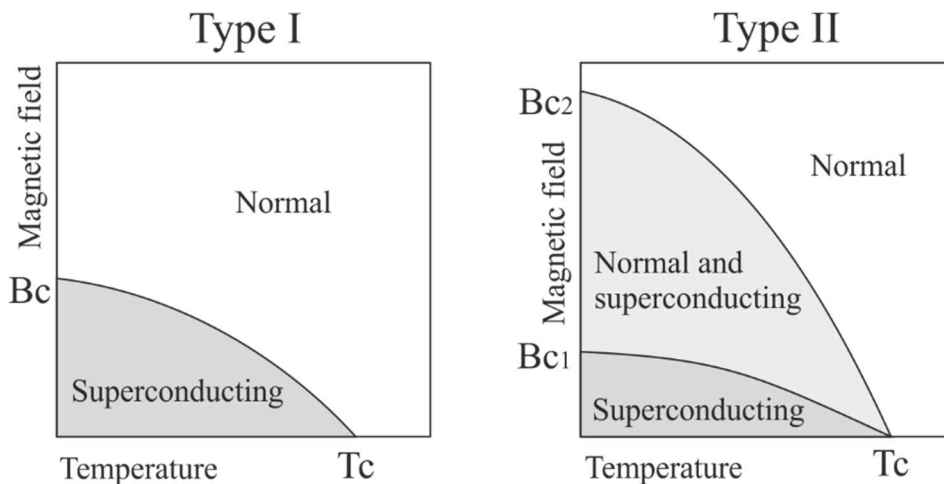


Figure 1.12 Magnetization in function of temperature of type-I (on the left) and type-II (on the right) superconductors.

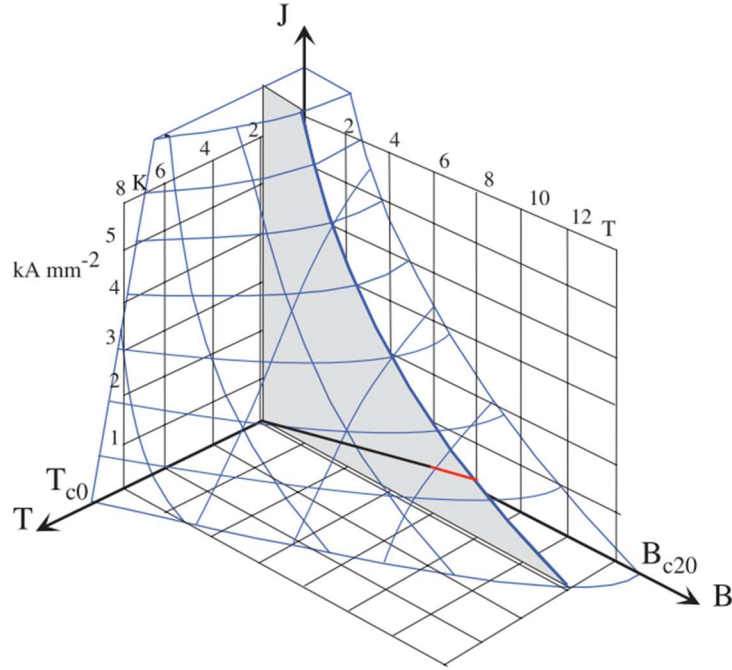


Figure 1.13 Critical surface of Nb-Ti LHC superconductor [32].

The superconducting current density is limited by the critical value J_c . This limit is implied by the Lorentz force acting on the vortices causing the detachment of vortex from its pinning center. When this so-called pinning force is smaller than the force induced by the magnetic field, the vortices start to move causing the energy dissipation and eventual increase in resistivity. Consequently, the superconductivity is dependent on both the magnetic field and the temperature, and can occur below the so-called critical surface. One can see the critical surface of Nb-Ti superconductor in Figure 1.13. The type-II superconductors are further subdivided on two categories based on their critical temperature. Low Temperature Superconductors (LTS) feature the critical temperature below the boiling point of liquid nitrogen (about 77 K), whereas High Temperature Superconductors (HTS) – above.

Nowadays, the most applied LTS superconductor is the niobium-titanium (Nb-Ti) alloy. This conductor is used in most of the practical applications, like Magnetic Resonance Imaging (MRI) scanners, MAGnetic LEVitation trains (MAGLEV) or particle accelerators. This unique alloy is the only ductile type-II superconductor currently available in long lengths of wire. The next LTS superconductor, regarded as the Nb-Ti successor, is the triniobium-tin (Nb_3Sn). The Nb-Ti at zero flux density has the critical temperature T_c of 9.2 K, and Nb_3Sn of 18.1 K. In order to operate the superconducting magnet, the temperature must be maintained below the critical temperature of a superconductor. A technical coolant of the LHC magnets is the helium at its superfluid state, discovered by Allen, Misener and Kapitza [33], [34] in 1938. The operating temperature of the LHC magnet is 1.9 K, which is below the λ point of helium (2.17 K). The superfluid's negligible viscosity allows permeating the

cold mass voids and the cable insulation, effectively buffering the thermal transient effects. Additionally, close to the λ point the helium features a high volumetric specific heat allowing for an efficient heat leveling. In order to benefit from those characteristics, the electrical insulation of the cable must have sufficient porosity while maintaining the dielectric strength and mechanical resistance [35].

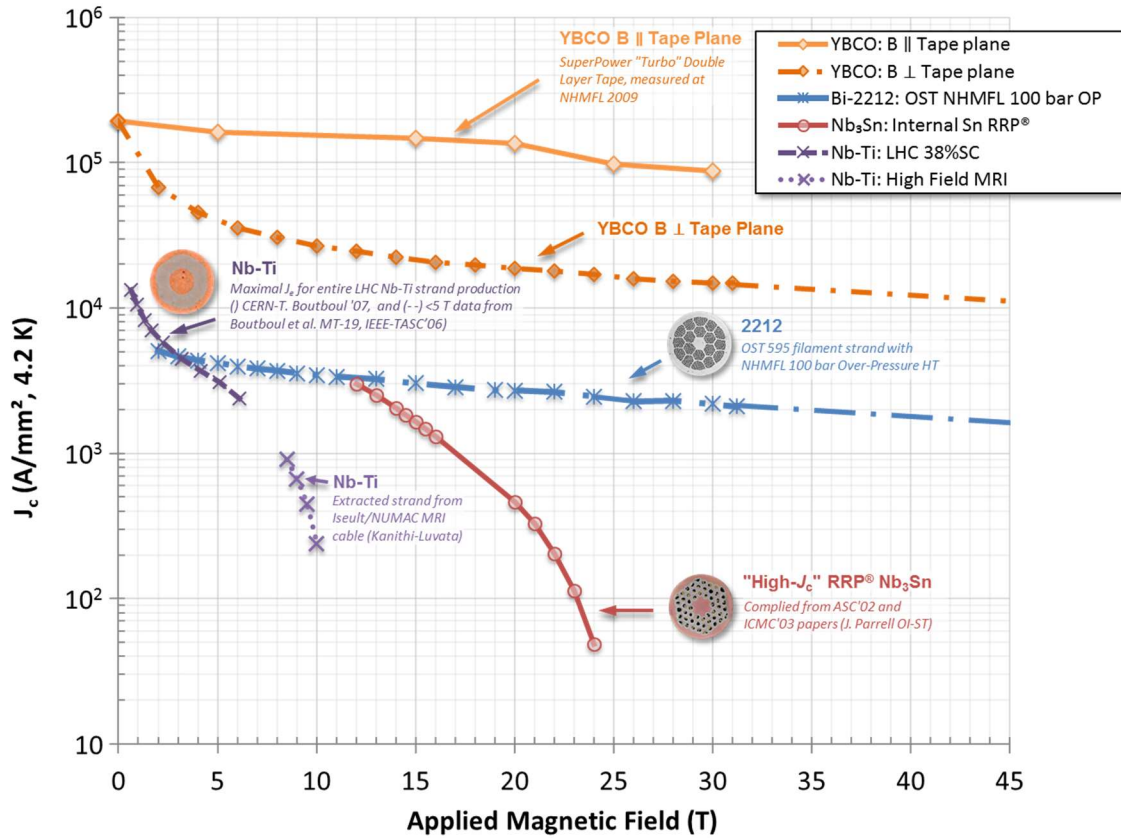


Figure 1.14 Engineering critical current density of most common type-II superconductors versus magnetic field. Measured in 4.2 K unless otherwise stated [36].

The practical magnetic field limit of a coil wound with Nb-Ti superconductor is 8 T [24]. In order to surpass this limit the Nb₃Sn [28] superconductor is used, offering the peak field in operational conditions of 15 T [8]. One can see in Figure 1.14 the engineering critical current density of the Nb-Ti (in purple) and Nb₃Sn (in red) in the function of the applied magnetic field. The Nb₃Sn wire allows roughly doubling the magnetic field limit of the Nb-Ti. Unlike the Nb-Ti, the A15 phase Nb₃Sn is a brittle compound, making it practically impossible to form a cable or wind a coil without damaging the filaments. One can see the high strain sensitivity of the Nb₃Sn compound on a critical current degradation shown in the Figure 1.15. This issue is addressed by the wind-and-react technique. The coil is first wound with a ductile cable containing strands with the Nb₃Sn substrates and a Cu stabilizer, and is afterwards

subjected to the heat treatment at up to 650°C [37], in order to form the superconducting Nb₃Sn.

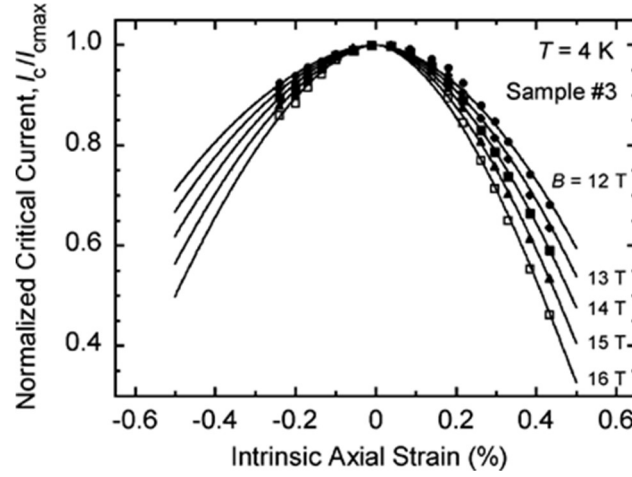


Figure 1.15 Normalized critical current I_c/I_{cmax} at 4 K of reacted Nb₃Sn ITER strand as a function of intrinsic axial strain for magnetic fields from 12 T to 16 T [38].

The magnet cannot be built from wires made of pure superconductor, because the normal resistivity of superconductors above the critical temperature T_c is several orders of magnitude higher than the resistivity of Cu. When the temperature in a superconductor carrying high current density exceeds the critical temperature T_c , the resistivity increases strongly and Joule heating melts the superconductor. In order to prevent the superconductor from overheating at $T > T_c$, superconducting filaments are incorporated in a normal metal with low electrical resistivity. This so-called stabilizing matrix is usually made of Cu. In addition, pure and large superconductors are vulnerable to heat generation caused by flux jumps. The flux jumps are reduced with the use of thin filaments in the order of a few μm [39], [40].

The strand's volume consists of filaments in a stabilizing matrix. The filaments formed in stacks contain the substrates of the Nb₃Sn compound, which can be seen in Figure 1.16 right. The material and the geometrical arrangement of the filaments varies depending on the type of superconductor. The strand production is dominated by the Restacked-Rod-Processing method (RRP®), which involves extrusion, rolling, drawing, stacking and re-stacking processes in order to obtain a required strand geometry [41]. One can see in the left of Figure 1.16 the transversal cross section of 1 mm diameter LHC Type 01 main dipole Nb-Ti superconducting cable. The Nb₃Sn strands developed with RRP® and PIT (Powder In Tube) methods with different number and arrangement of filaments are shown in the Figure 1.17 with a description below each cross section. In the description of RRP® wire, the first number represents the number of superconductive sub-elements, and the second number corresponds to the total number of restacks in the core. Whereas, in the description of PIT wires, the number corresponds to the amount of superconducting filaments in the cross section.

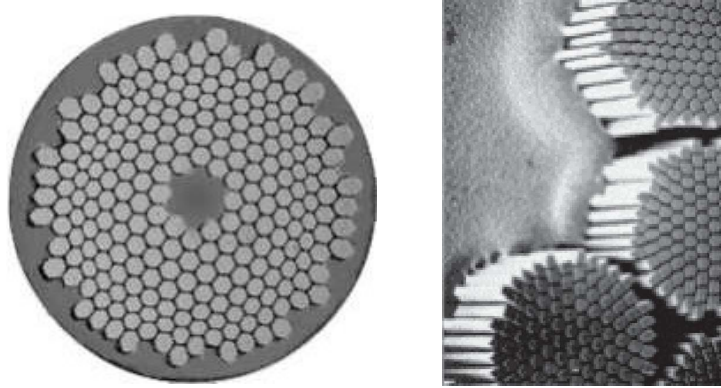


Figure 1.16 Transversal cross section of 1 mm diameter Nb-Ti strand. Enlarged section on the right side shows 8800 filament bundles in a hexagonal structure – called stack [42].

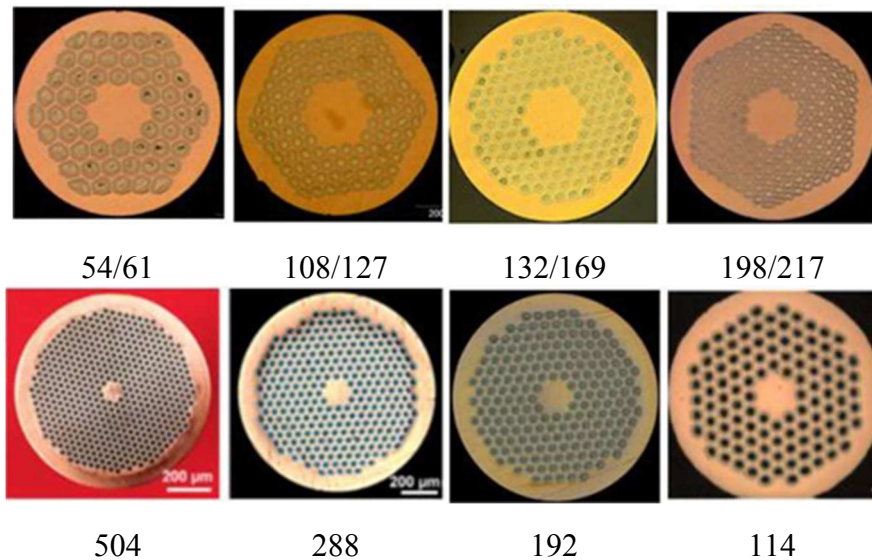


Figure 1.17 Overview on various types of developed RRP and PIT wires. Top row: cross section of RRP strands, courtesy of OST. Bottom row: cross section of PIT wires, courtesy of SMI and Bruker EAS [42].

1.2.2. RUTHERFORD CABLE

The superconducting coils are wound with the cable consisting of several wires, in order to reduce the skin effect and the proximity effect [32]. The accelerator coils, e.g. the LHC dipole and quadrupole, are wound from so-called Rutherford cables of trapezoidal cross-section, see the 40-Strand cable scheme in Figure 1.18. The name was given after the Rutherford Appleton Laboratory in the United Kingdom, where it was shown in 1973 that the cable could be produced without damaging the filament [43]. Two layers of fully transposed strands limit

non-uniformities in the current distribution within the cable caused by the cable's self-field and flux linkage between the strands. The Rutherford scheme allows for the cable compaction of 88-94% without strand damage with a good geometrical accuracy of approximately 0.01 mm. One can see the Rutherford cable geometry presented in Figure 1.19.

Due to the radial positioning of the windings, which can be seen in the Figure 1.11, it is favourable for the cable to feature a keystone. The keystone angle, shown in the Figure 1.18, allows a better compaction of the windings. The individual strands in the cable are not insulated, which forms the adjacent and transverse electrical contact resistances between the strands. These resistances are forming closed loops in which coupling currents can be induced during the magnet operation. In order to minimize this effect, the stainless steel core is introduced in the middle of the cable.

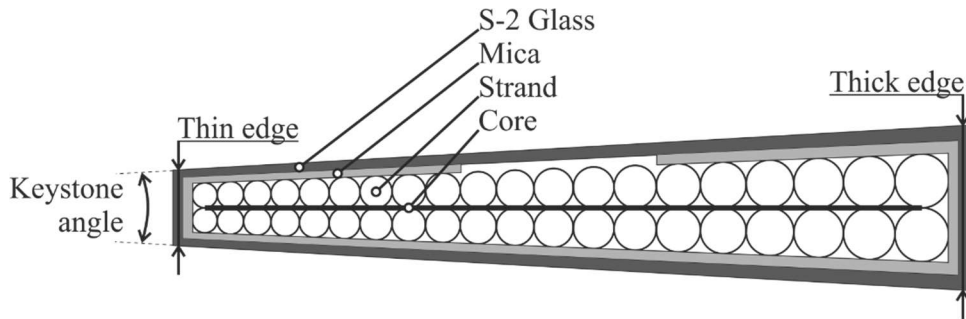


Figure 1.18 Sketch of 40-Strand Rutherford Nb_3Sn cable cross-section with S-2 Glass and Mica insulation. Not to scale to visualize the keystone angle.

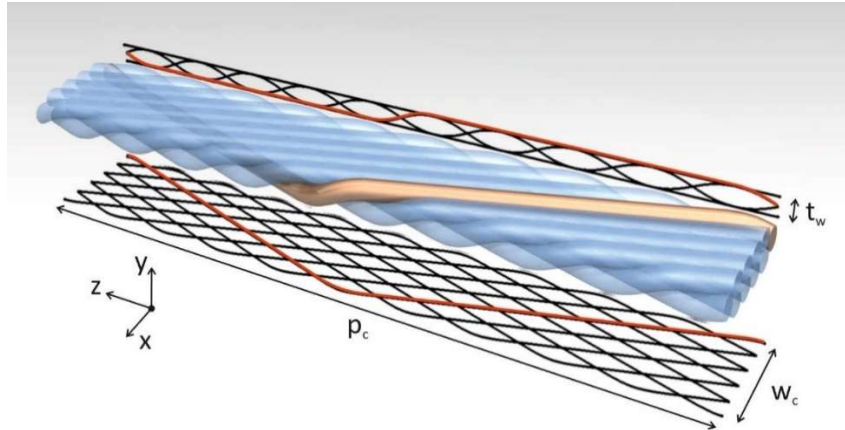


Figure 1.19 Rendered winding scheme of a Rutherford cable, schematics with 10 strands. Nine strands are depicted translucent; the one strand rendered with copper appearance is traced in red on the bottom and right view displaying internal guide of the cable.

The cable is formed out of the wires in the process called cabling [44]. The cabling machine, shown in the Figure 1.20, consists of three main subsystems:

- The spool wheel containing the spools of wires, which are fed to the Turk Head with the constant tension. The spools rotate around the main cable axis and own axis in order to avoid the torsion of the strand;
- The Turk Head guiding the wires through the fixed mandrel and into the four rotating plates. The adjustment of the plate allows obtaining the desired cable cross-section;
- The caterpillar providing the continuous pulling force, improving the process stability.



Figure 1.20 Cabling machine at CERN. Three sub-assemblies visible: spool wheel, Turk Head and caterpillar. Courtesy of CERN Superconducting Lab [45].

The cabling process imposes a large plastic deformation to the wires. One can see the polished cross section of the 40-Strand Rutherford cable in the Figure 1.21. The bottom left of the Figure 1.21 shows the undeformed strand, whereas the bottom right is an enlarged area of the largest strand plastic deformation occurring at the edge of the cable.

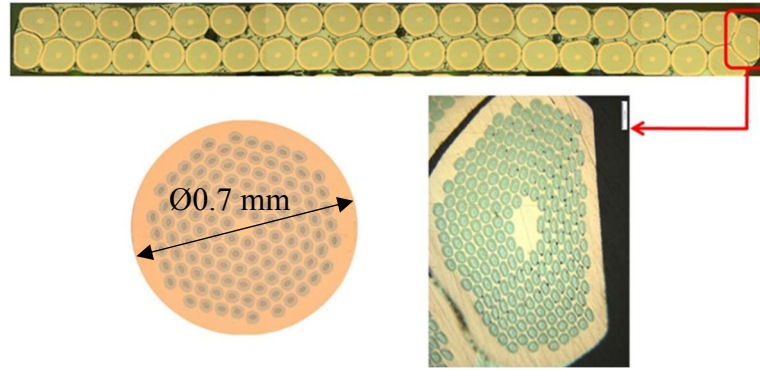


Figure 1.21 Top: cross section of 40-strand Rutherford cable. Bottom left: undeformed strand cross section. Bottom right: enlarged cable edge segment with plastically deformed strand [45].

The insulation of the Nb-Ti cable used in the LHC main dipole consists of three layers of Kapton polyamide film and a Kapton adhesive layer, shown in Figure 1.22. The insulation scheme is formed of two layers wrapped on a cable with a 50% overlap giving in total $50 \mu\text{m}$ thickness. The third $70 \mu\text{m}$ thick layer is wrapped around the cable with 2 mm spacing. In addition, an adhesive layer of $5 \mu\text{m}$ is applied to the outside of the wrapping in order not to bond the insulation to the cable and avoid the quenches due to energy release in case of a bond failure. The insulation provides the nominal 50 V adjacent turn protection in case of a quench and a porosity for an efficient helium cooling.

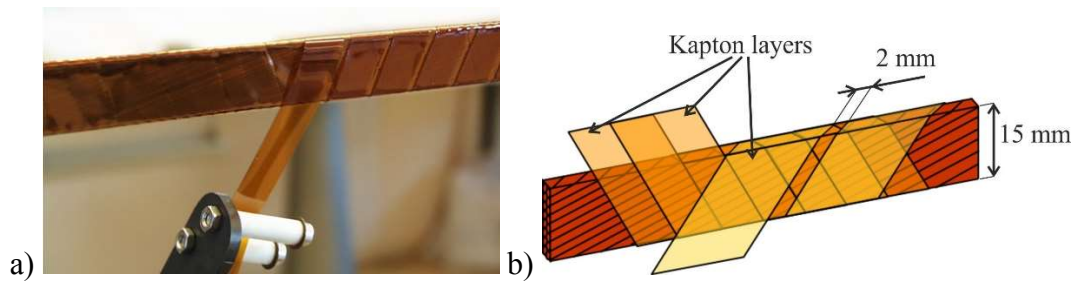


Figure 1.22 Kapton polyamide insulation process of Nb-Ti cable shown in a. The insulation scheme is shown in b.

However, due to the necessary heat treatment process of the Nb_3Sn cable after the coil winding [37], the insulation must additionally feature the temperature resistance of around 700°C . Due to this requirement, the Kapton polyamide insulation could not be used.

The presently used insulation scheme for the Nb_3Sn cable consists of the S-2 glass and Mica, shown in the scheme in Figure 1.18. The braiding machine, shown in Figure 1.23, was used to over-braid the cables with a so-called biaxial regular braid that allows obtaining the required structural rigidity. During the process, the c-shape mica foil is wrapped around the

cable right before the braiding, ensuring an additional dielectric strength. Such an insulation meets the required electrical breakdown of 10 kV and 700°C thermal resistivity, featuring around 0.2 mm thickness on each side [46].

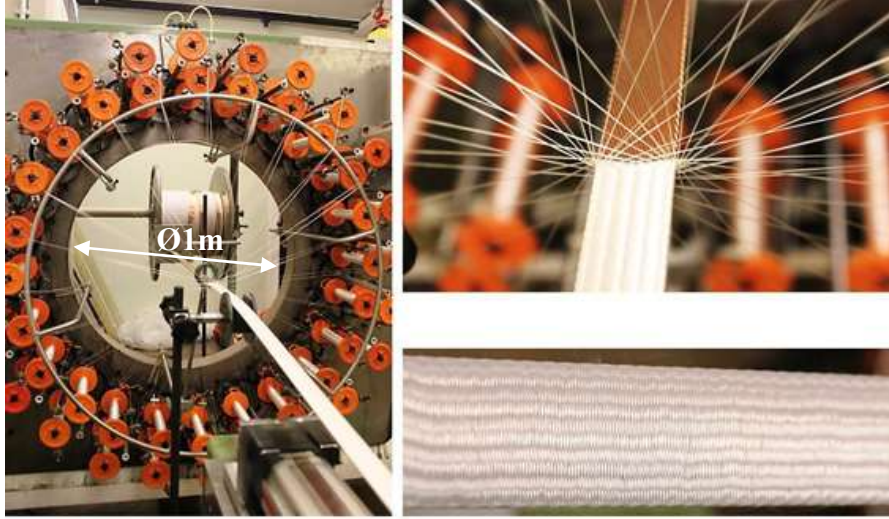


Figure 1.23 S-2 Glass braiding insulation of the Rutherford cable. Left: A 48 carrier braiding machine; Right-top: Rutherford cable during braiding; Right-bottom: Top view on the insulated cable [46].

1.2.3. COIL GEOMETRY

Despite the structure and assembly differences between the 11 T and MQXF, both magnets are designed with the $\cos\theta$ coil geometry. The coils are wound forming constant perimeter coil end [47], where both edges of the cable (i.e. thick and thin edge shown in Figure 1.18) follow the curve in space of the same length. The various coil-end designs commonly used in the accelerator magnets are shown in Figure 1.24.

The coil design is conditioned by the objective of optimizing the magnetic field and minimizing the conductor strain energy. Aiming to simplify the winding process, the shape of the coil minimizes the stresses coming from the bending of the superconductor at the coil extremities. The magnetic optimization includes the minimization of the integrated multipole coefficients, e.g. compensating for the field errors in the coil ends [48].

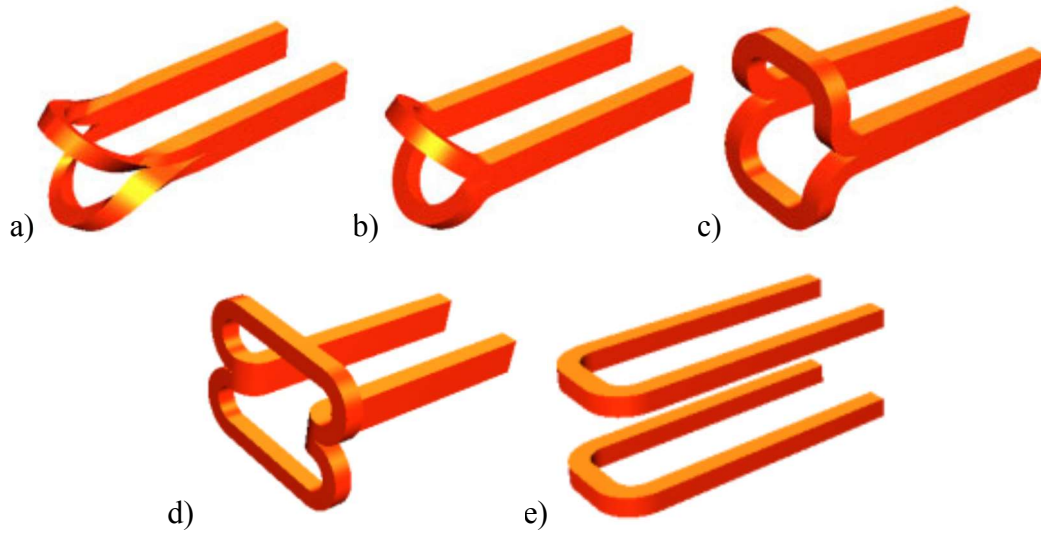


Figure 1.24 Coil-end dipole designs for accelerator magnets. a) $\cos\theta$ (constant perimeter); b) cranked saddle; c) bedstead; d) transversely cranked saddle; e) racetrack [32].

The coil design has a dominant influence on the magnetic field distribution. It is a subject of a demanding optimization process, with use of the ROXIE software developed at CERN [49]. One can see in Figure 1.25 the optimized cross-section with design variables, e.g. the amount of coil blocks, their azimuthal position α_a and orientation α_b . The applied technique allows finding a coil block arrangement featuring low multipole errors and a high dipole field [50].

The optimized cross-section is consistent in the straight segment of the coil. However, it is crucial to integrate it with the coil-end. This is achieved by applying the differential geometry methods with the objective of minimizing the mechanical stress on the cables; optimizing the integrated multipole content; and limiting the peak field [51]. The result of such a coil-end optimization can be seen in Figure 1.25 in orange.

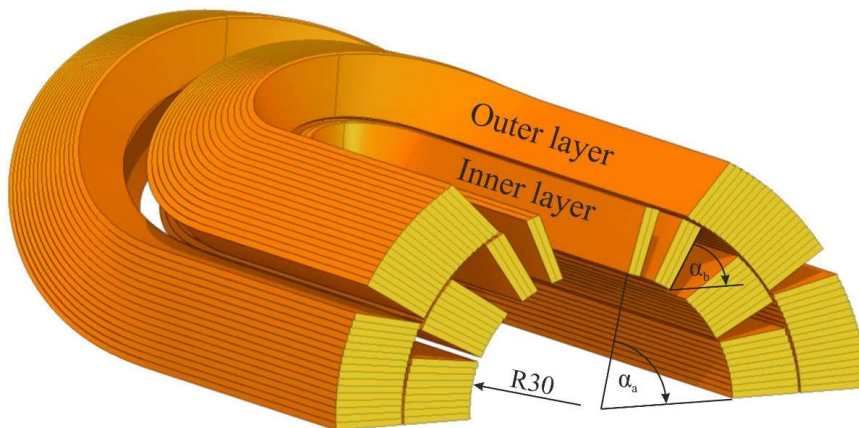


Figure 1.25 The optimized coil block arrangement and coil-end design of 11 T dipole return end. Marked inner- and outer-layer, as well as the coil block arrangement parameters α_a and α_b .

In order to realize the design, the computed geometry is used for defining the mechanical components of the assembly. These components aim to support the cable during winding and effectively filling the voids between the cable blocks. The components consists of:

- End-spacers – positioned at the coil-ends produced by Selective Laser Sintering (SLS) shown in Figure 1.26 [52];
- Central pole – stretching in the center of the coil, marked in Figure 1.27;
- Pole key – positioned at the extremities of the central pole, marked in Figure 1.27;
- Wedges – copper elements filling the voids in the straight coil segment.

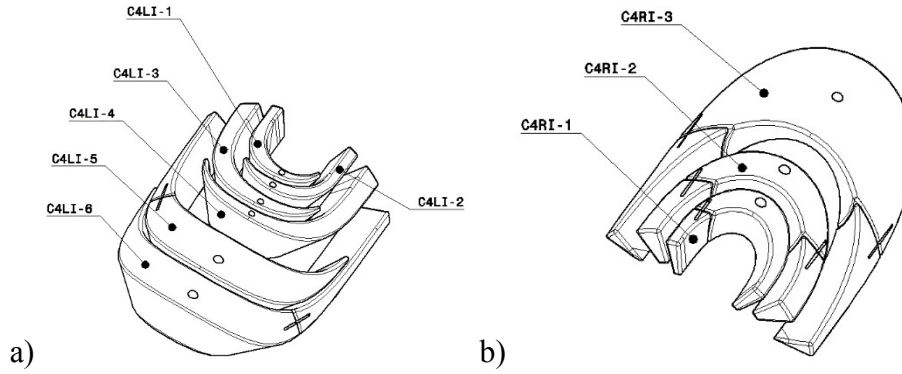


Figure 1.26 End-spacer set for the 11 T dipole inner-layer with indicated design identification. a) Lead-end (the coil connection side); b) Return end (the opposite connection side). Source: CERN drawing number: LHCMBH_C0047.

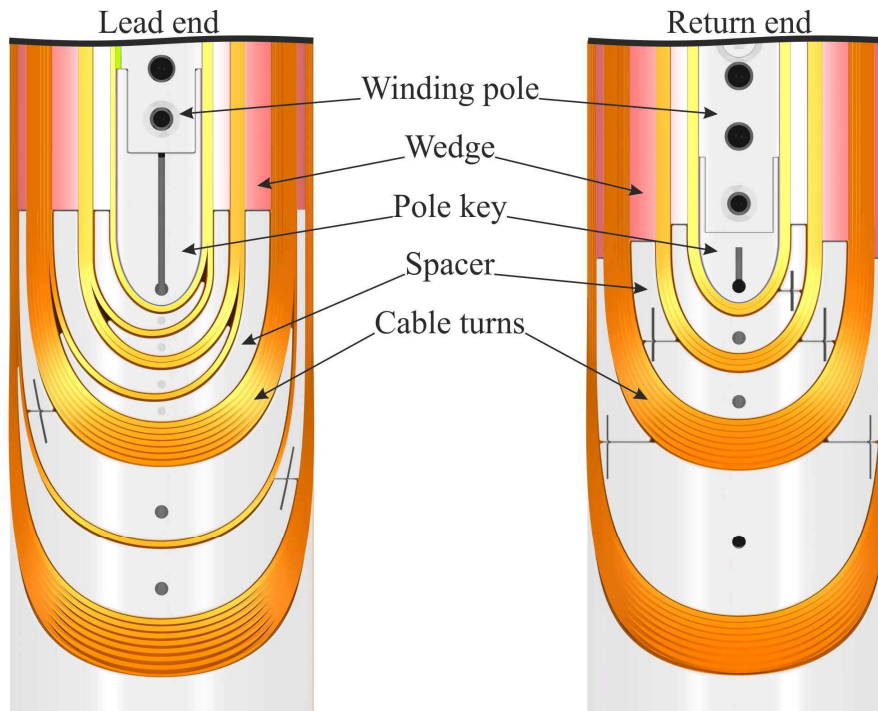


Figure 1.27 Top view on the winding assembly of 11 T dipole inner-layer. Left: Lead-end; Right: Return-end. Source: Adapted CERN drawing number: LHCMBHST0416.

2. SUPERCONDUCTING COIL WINDING

One aim of the coil fabrication is given by the optimization of all winding parameters to achieve the specified coil geometry. Figure 2.1 indicates all production steps from the conductor manufacturing towards the assembly of the cold mass. The coil production itself consist of five major production steps. One specific aspect of winding Nb₃Sn cable into a coil geometry is given by the fact that prior winding the cable has to be separated to its inner and outer layer spool. This is due to the fact that splicing in between two coil layers cannot yet be achieved.

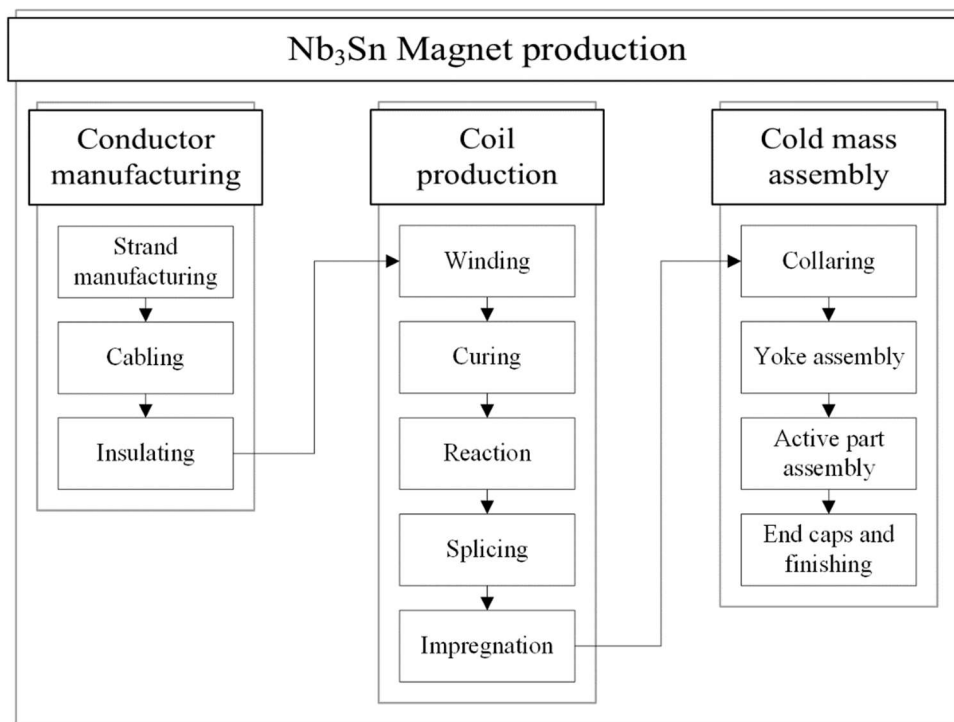


Figure 2.1 Flowchart of the magnet production consisting of the conductor manufacturing, coil production and cold mass assembly.

The 11 T coil production starts with the 650 m-long insulated cable wound on a single spool (see 1st spool in Figure 2.2). The total length of the cable is spooled on the 2nd spool and inspected for damage and insulation inconsistencies. Afterwards, the 260 and 390 m length of the cable are distributed on two spools, used for the inner- and outer-layer winding respectively. Any excess of the cable is distributed equally between the two. This procedure is necessary in order to start winding from the inner-layer windings adjacent to the pole. The description of the production steps of the Nb₃Sn superconducting coils are based on the equipment and procedures used for production of the 11 T and MQXFB coils in LMF.

In this chapter the winding process is described, which consists of:

- The description of the kinematics of the winding machine and the matrices of homogeneous transformation, shown in chapter 2.1;
- The manual operations during winding and necessary corrections, presented in chapters 2.2 and 2.3;
- The description of observed winding defects occurring during winding of prototype coils, in chapter 2.4;
- And qualification of the cable deformation based on the bending momentum, described in chapter 2.5.

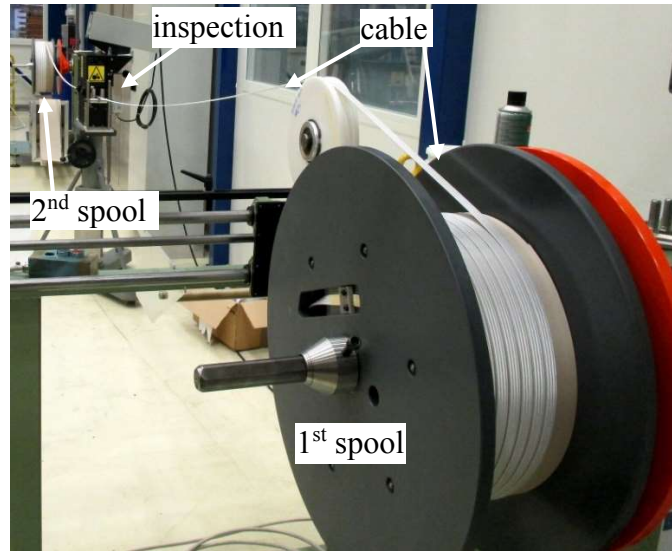


Figure 2.2 Cable batch inspection and re-spooling process. Preparation for winding.

2.1. WINDING MACHINE KINEMATICS

The winding is a process of forming a coil (see Figure 1.25) from the cable on a spool. This is performed with use of the Winding Machine (WM) featuring five Degrees of Freedom (DOF), shown in Figure 2.3. The WM consists of three assemblies: the gantry (shown in Figure 2.3), the winding head (shown in Figure 2.4), and the mandrel (shown in Figure 2.5).

The gantry assembly is based on a principal of the Cartesian coordinate robot. It features three prismatic DOF that allows translating the winding head longitudinally along the mandrel length (Y-axis), changing the side (X-axis) and adjusting the height (Z-axis).

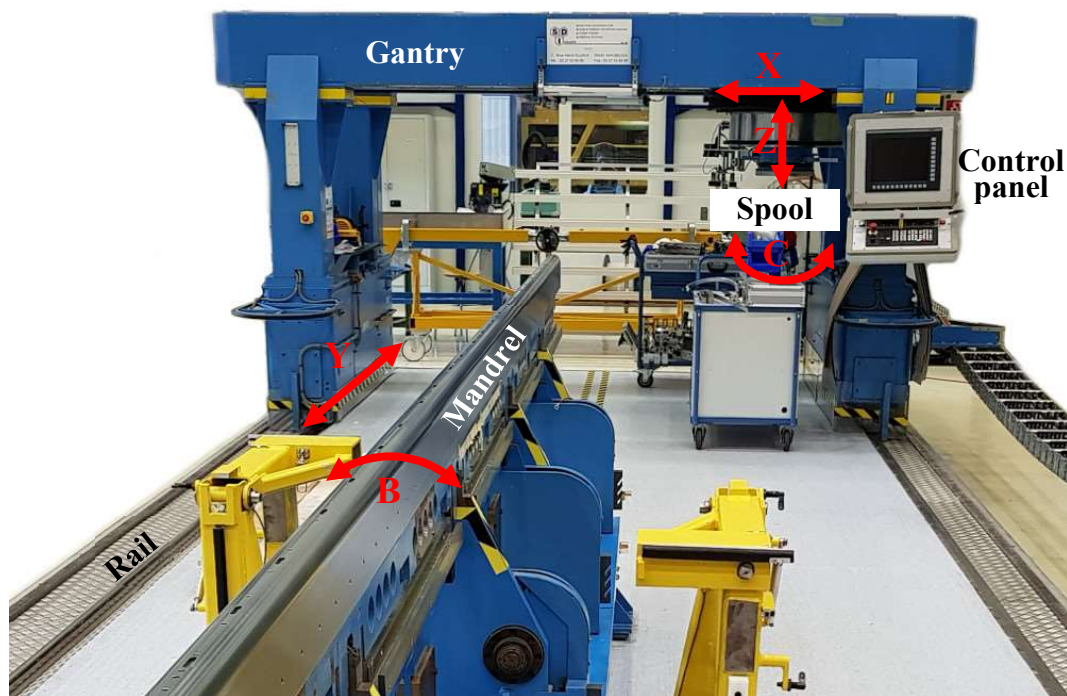


Figure 2.3 The Winding Machine for 11 T dipole coil. Four DOF: X, Y, Z, B and C marked in red.

During winding, the spool is installed on the winding head shown in Figure 2.4, which realizes following objectives:

- Provides one rotational DOF of the spool, i.e. the rotation about its central axis (C-axis in Figure 2.3);
- Tensions the cable with the magnetic brake attached to the winding head. The brake allows to apply torque between 2 Nm up to 200 Nm;
- Measures the tension force of the cable with the radial force measuring axle Honigmann® RFS 150 E, featuring rated measuring range of 0-500 N. The cable is fed through three pulleys, and the winding tension is measured by a force transducer mounted on the middle pulley;
- The installed displacement sensor Scaime® PT1A-15 allows to measure the vertical position of the cable with respect to the spool. The sensor allows to measure the length of 381 mm. The pulley assembly can move along the vertical axis in order to follow the position of the cable while unwinding from the spool. The vertical displacement of the assembly is measured, and serves to correct the position of the Z-axis.

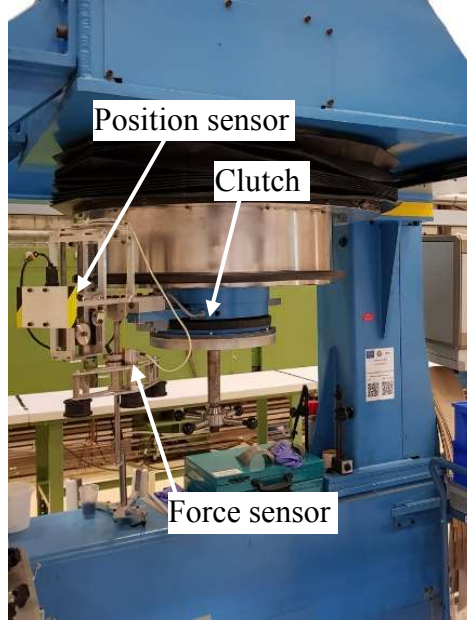


Figure 2.4 The winding head with clutch-based tensioning system.

The mandrel, shown in Figure 2.5, features one revolute DOF (B-axis in Figure 2.3), which aims to provide the tangency of the cable bottom edge and the mandrel cylindrical surface during winding.

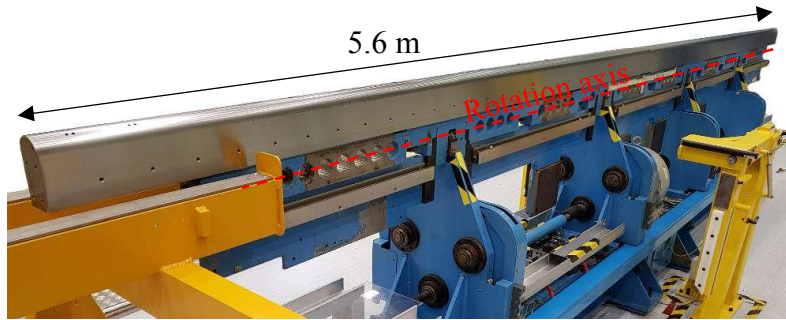


Figure 2.5 11 T rotational winding mandrel.

In order to describe the WM kinematics, a 5 DOF mathematical model was developed, following the Denavit-Hartenberg notation [53]. The link-frame assignment of individual joints is shown in Figure 2.6. The base coordinate system is shown as frame $\{0\}$. The gantry and winding head kinematics is described by links $\{0\} \dots \{4\}$, while the mandrel kinematics is described by links $\{0\}$ and $\{m\}$. The joint variables are indicated as q_i and θ_i , and the geometrical relations between the links are indicated as a_i and d_i .

The frames $\{1\}$, $\{2\}$ and $\{3\}$ describe the translation along the main axes (Y, X, and Z respectively), and the rotation of the spool is included in the frame $\{4\}$. The mandrel rotation is described by the frame $\{m\}$.

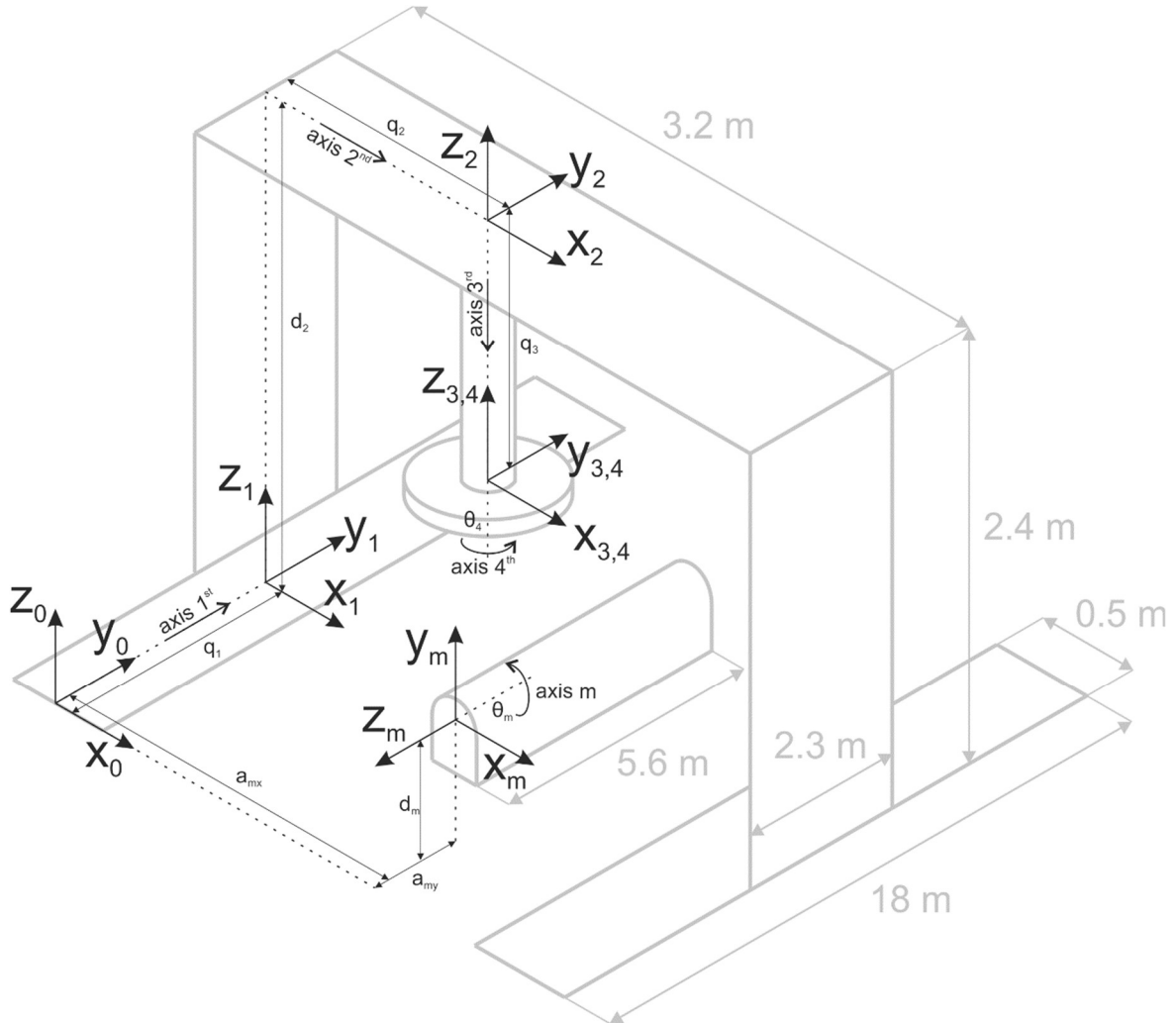


Figure 2.6 Assignment of link frames for the 11 T Winding Machine. Dimensions in m.

While the cable unwinds, it moves in the vertical direction with respect to the spool, i.e. along the Z_4 -axis. The relative position of the cable to the spool is continuously measured and compensated, in order to ensure the correct positioning of the bottom edge of the cable with respect to the winding mandrel throughout the winding process. The scheme of the vertical position compensation is shown in Figure 2.7, where C_s is the compensation value defined in equation (2.1).

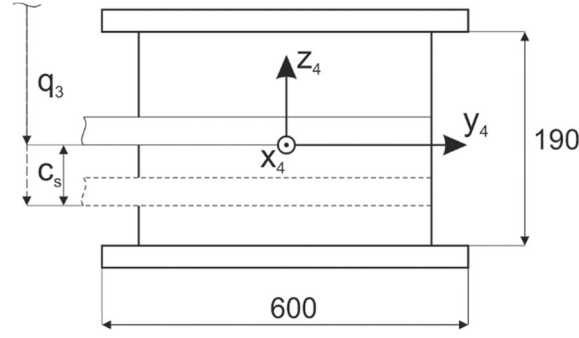


Figure 2.7 Cable position compensation C_s . Dimensions in mm.

$$C_s = f(C_{\text{sensor}}) \quad (2.1)$$

Where:

C_s – Compensation distance;

C_{sensor} – Value provided by the linear displacement sensor.

The rotation angle of the mandrel ensures the adjacency of the cable and the winding pole or previous cable turn. The axis of rotation, perpendicular to Figure 2.8 in Z_m , is not in the center of the mandrel radius. Due to this reason, by applying the angle θ_m the maximal vertical position of the mandrel in Y_m differs by C_m , as illustrated. Therefore, the position of the spool is compensated by the amount given in equation (2.2).

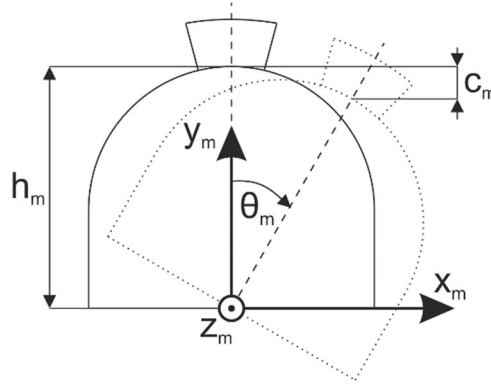


Figure 2.8 The mandrel rotation θ_m and resulting height difference of C_m .

$$C_m = h_m \cdot \sin \theta_m \quad (2.2)$$

The WM link-frames are described in Table 2.1, along with the geometrical parameters, joint variables, and available range.

Table 2.1 The Winding Machine link-frame description and parameters.

Description	Frame	Joint type	Variable	Range	Parameter (mm)
Mandrel	m	Revolute	θ_m	$-90^\circ; 90^\circ$	$a_{mx} = 1635$ $a_{my} = 6000$ $d_m = 1070$ $h_m = 150$
Origin	0	-	-	-	-
Gantry	1	Prismatic	q_1	3.0 m; 12.0 m	-
Cross-beam	2	Prismatic	q_2	0.7 m; 2.0 m	$d_2 = 2380$
Spool height	3	Prismatic	q_3	1.1 m; 1.5 m	-
Spool rotation	4	Revolute	θ_4	continuous	-

The link-frame location shown in Figure 2.6, allows computing the position and orientation of the spool in the base coordinate system $\{0\}$, as the product of consecutive matrices of homogeneous transformation, as shown in equation (2.3).

$${}^0_4T = \prod_{i=0}^4 {}^{i-1}_iT \quad (2.3)$$

The matrices of homogeneous transformation between first three prismatic joints are shown in equations (2.4)-(2.6) .

$${}^0_1T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & q_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2.4)$$

$${}^1_2T = \begin{bmatrix} 1 & 0 & 0 & q_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2.5)$$

$${}^2_3T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -q_3 - C_s - C_m \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2.6)$$

The revolute joint homogeneous transformation matrix from link {3} to {4}, describing a spool rotation, is given in equation (2.7).

$${}^3_4T = \begin{bmatrix} \cos \theta_4 & -\sin \theta_4 & 0 & 0 \\ \sin \theta_4 & \cos \theta_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2.7)$$

Following the equation (2.3), the product of matrices shown in equations (2.4)-(2.7) results with a matrix of homogeneous transformation from the origin {0} and a center of the spool {4}.

$${}^0_4T = {}^0_1T {}^1_2T {}^2_3T {}^3_4T = \begin{bmatrix} \cos \theta_4 & -\sin \theta_4 & 0 & q_2 \\ \sin \theta_4 & \cos \theta_4 & 0 & q_1 \\ 0 & 0 & 1 & d_2 - q_3 - C_s - C_m \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2.8)$$

The matrix of homogeneous transformation between the origin and center of mandrel including the swiveling of the mandrel is given in equation (2.9).

$${}^0_mT = \begin{bmatrix} \cos \theta_m & -\sin \theta_m & 0 & a_{mx} \\ 0 & 0 & -1 & a_{my} \\ \sin \theta_m & \cos \theta_m & 0 & d_m \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2.9)$$

The winding is programmed by the number of reference points along the spool path. Each point explicitly defines five parameters, i.e. the position of the center of the spool (p_x, p_y, p_z), the winding tension (F_{set}) and the mandrel rotation angle (θ_{m_set}). The position of the spool is defined in base coordinate system, i.e. the link-frame {0}. The winding function is given in equation (2.10).

$$W = f(p_x, p_y, p_z, F_{set}, \theta_{m_set}) \quad (2.10)$$

The following equations compute the configuration of the joint variables in order to achieve the position and orientation given by the winding function.

The inverse kinematic equations of prismatic joints derived from (2.8), are stated in (2.11)-(2.13).

$$q_1 = p_y \quad (2.11)$$

$$q_2 = p_x \quad (2.12)$$

$$q_3 = d_2 - p_z - C_s - C_m \quad (2.13)$$

The orientation of the mandrel revolute DOF θ_m is equal to the one given in the winding program θ_{m_set} , as shown in (2.14).

$$\theta_m = \theta_{m_set} \quad (2.14)$$

The revolute DOF of the spool θ_4 aims to minimize the deviation between the measured tension force F_{sensor} and a desired force given in the winding function F_{set} , given by equations (2.15) and (2.16).

$$\Delta F = F_{\text{set}} - F_{\text{sensor}} \quad (2.15)$$

$$\theta_4 = f(\Delta F \rightarrow 0) \quad (2.16)$$

The diagram of the WM control system is shown in Figure 2.9. The procedural input is the winding function W , i.e. a discrete function of five parameters. The data-points are imported as the text file and monitored on the WM control panel. The operator located on-site can interfere with the execution of the program by adjusting the speed, correcting the position, pausing or reversing the winding cycle at any given moment. This is to enable a multitude of manual activities required by the process, described below. The linear trajectory is generated between the consecutive points of the program.

The feedback loop consists of three blocks:

- Axis position sensors (encoders), providing the actual configuration of the joints;
- Tension force, providing the measurement of the actual cable tension F_{sensor} ;
- Cable position sensor, providing the cable position relative to the spool C_s .

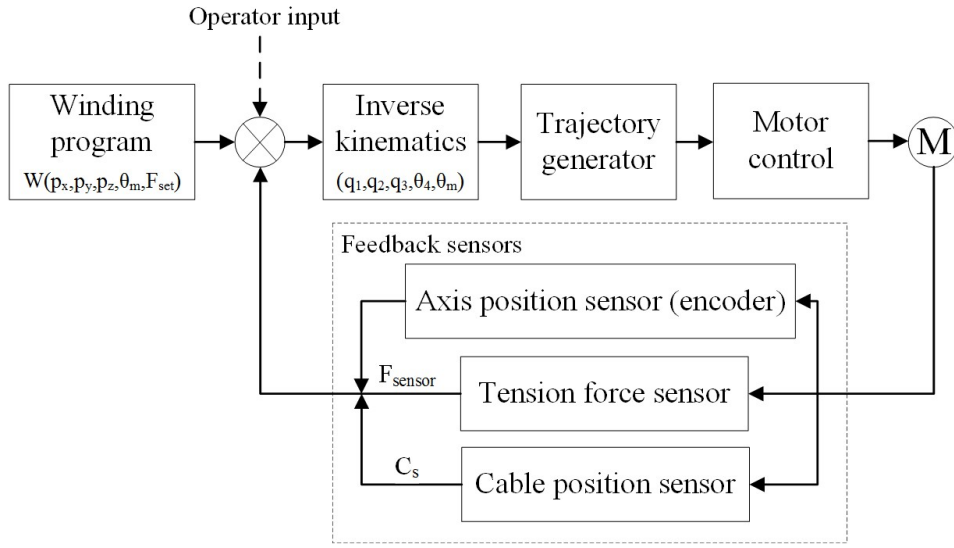


Figure 2.9 Control system diagram of the WM.

The winding program segment defining the spool position and mandrel orientation is shown in Figure 2.10. In Figure 2.10a one can see the programmed position marked with a circle, the liner interpolation between consecutive points is marked with a thin solid line, and the mandrel position is marked with a thick solid line. One full travel of the spool around the mandrel is defined with 24 points. The straight coil section, marked with an arrow in Figure 2.10a, is defined with two points distant of about 5 m. One can see a more dense distribution of the points while approaching the ends of the coil, as shown at the top and at the bottom in Figure 2.10a. This defines a turn of the spool and allows for an accurate control of the rapidly changing mandrel angle θ_m . The Figure 2.10b shows the programmed mandrel angle of three initial inner-layer turns, marked with circle. The linear interpolation between the consecutive points is shown with a solid line.

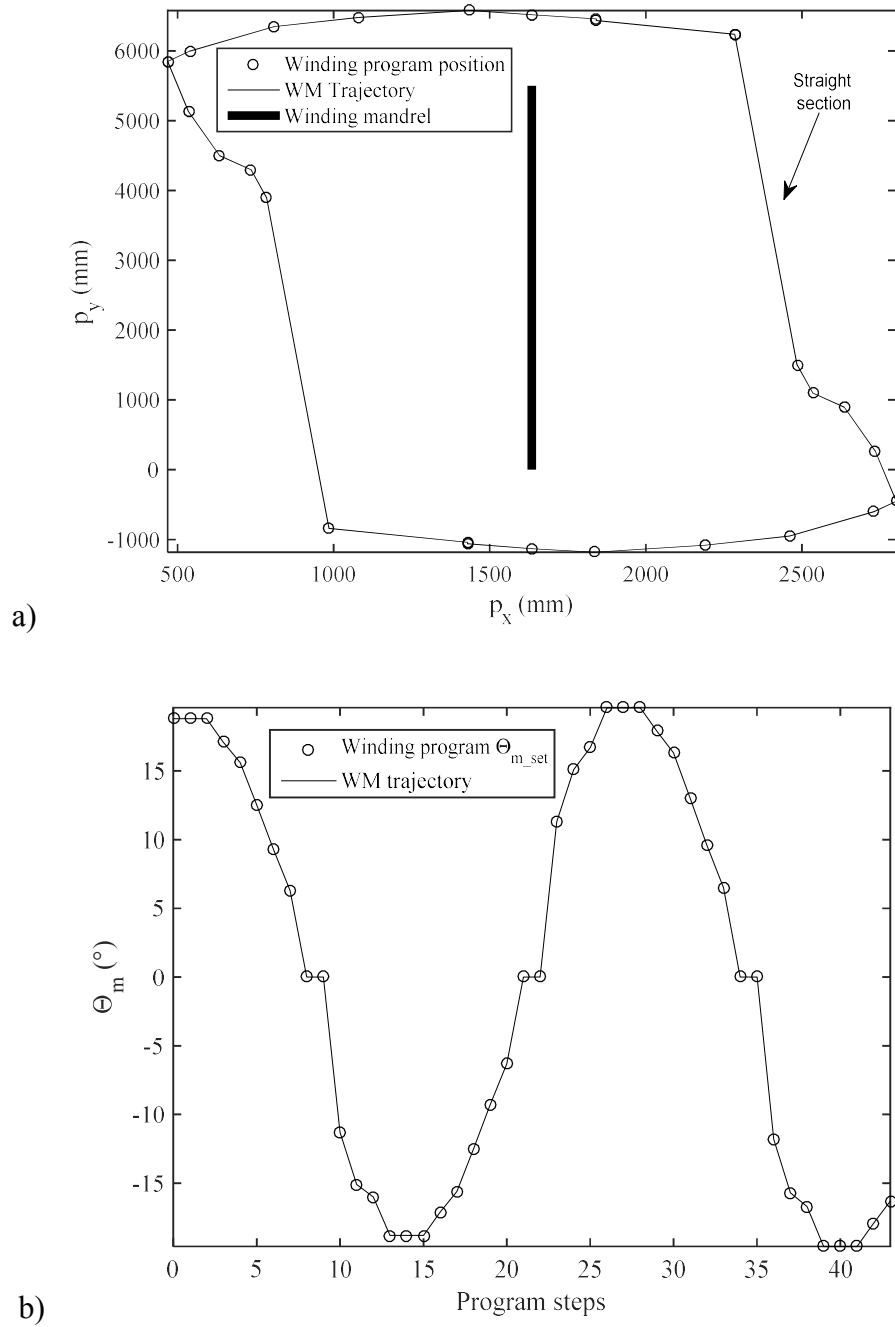


Figure 2.10 Winding program defining the spool position (shown in a) and the mandrel rotation angle (shown in b) for the 11 T inner-layer winding.

2.2. OPERATIONS DURING WINDING

Positioning the cable on the winding mandrel begins with the layer-jump, i.e. the transition segment of the coil between the inner- and the outer-layer, presented in Figure 2.11. The available splicing technology does not allow creating a joint between the unreacted Nb₃Sn cables, thus both layers are wound with one length of cable.



Figure 2.11 11 T layer-jump. Dimensions in mm.

The short circuit detection between the central pole and the cable is present throughout a winding process. The insulation of the cable and the pole may be damaged or strained, especially while applying the external forces, e.g. with clamps or during a coil-end turn. In case of a short-circuit occurrence the process is stopped, and the repair takes place.

The detachable mechanical clamps are used in order to bring an additional constraint to the wound cable. Two types of supports are used in the straight segment of the coil. The polymer guide featuring a cylindrical surface confines the cable layers radially (i.e. towards the winding mandrel), as shown in Figure 2.12a. The side clamp features a rectangular surface, and constraints the cable layer azimuthally (i.e. towards the winding pole), shown in Figure 2.12b.

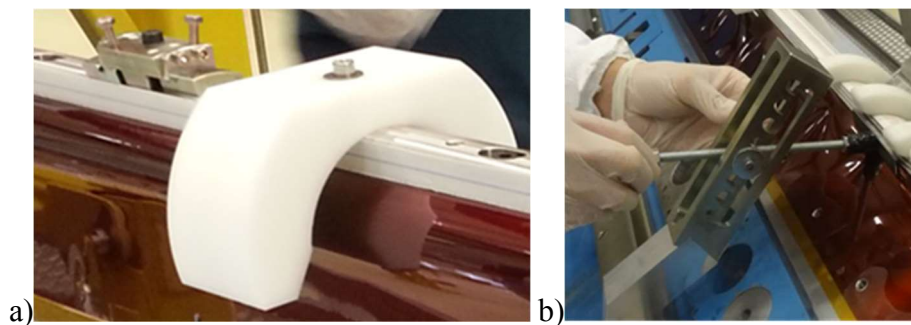


Figure 2.12 11 T straight segment clamps. a) polymer guide; b) side clamp.

Both coil-ends are supported with the head tools, presented in Figure 2.13a. The supports are attached to the pole and allows for manual positioning of several cylindrical pushers confining the cable radially. In addition, during the coil-end winding the operator manipulates the cable with the guiding tool in order to minimize the occurrence of the cable deformation. The guide, shown in Figure 2.13b, is not fasten to any element of the machine and is manually slid along the cable insulation. The operator often applies a torsion to the cable, and therefore tightens the strands.

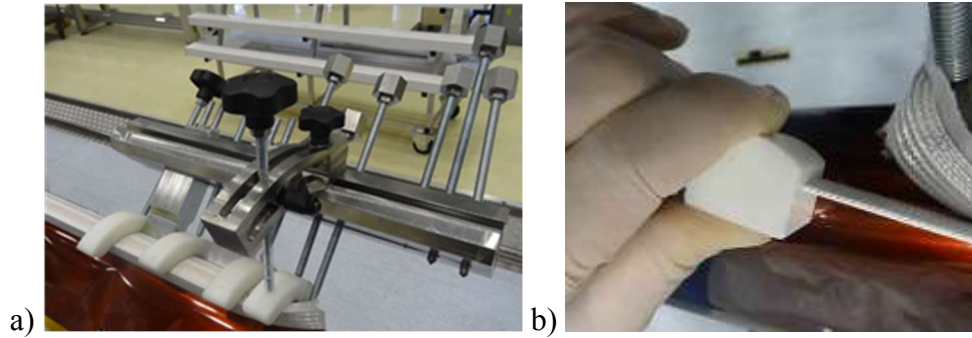


Figure 2.13 11 T coil-end support. a) head tool; b) guiding tool; c) tactile examination and manual cable twisting.

The spacers and copper wedges are insulated and placed according to the coil design. Each spacer is supported from the top with the screw coming from the head tool, as shown in Figure 2.14a. The insulated copper wedges are filling the longitudinal gap resulting from the coil block arrangement. For the 11 T coil a 2.5 mm clearance is left between the wedge segments, as shown in Figure 2.14b. This is in order to provide a space for the thermal expansion of a copper during heat treatment cycle in 650°.

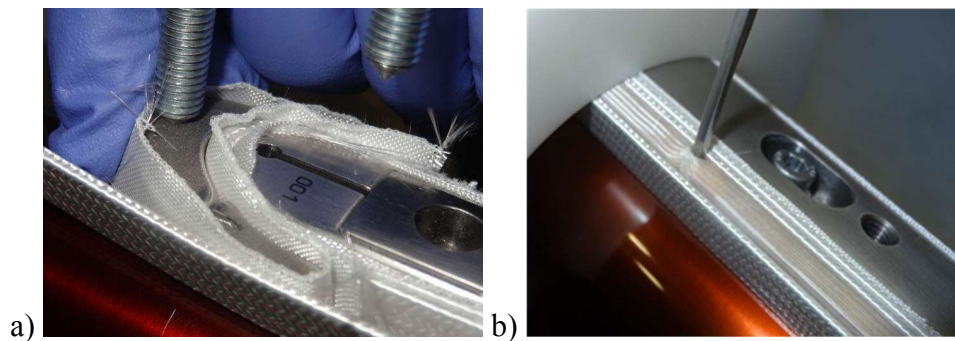


Figure 2.14 Positioning of the spacer (a) and the insulated copper wedge (b).

The in-situ control of the winding process relies on the dimensional measurement of the cable and spacers. The consecutive turns are controlled with depth gauge by measuring one value,

i.e. the distance between the tip of the wound cable and the reference surface of the mandrel, as indicated by ‘bottom distance’ in Figure 2.15.

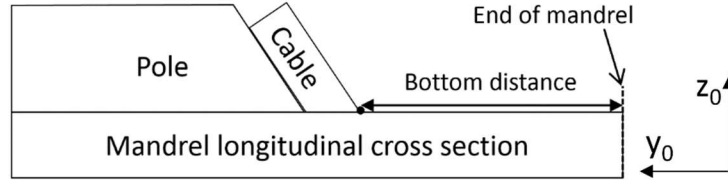


Figure 2.15 Scheme of QC performed during winding of 11 T.

The winding is finished by assembling the saddles and block pushers at the coil extremities, depicted in Figure 2.16a. Afterwards the coil is prepared for the curing process, that includes e.g. placing the inner pushers (Figure 2.16b); applying the ceramic binder (Figure 2.16c); and positioning the half-shells (Figure 2.16d). The curing process features heating up the coil to 160°C and applying the 50-80 bar pressure vertically. The curing process aims to bring additional stiffness and secures mechanically the cable position with the ceramic binder.

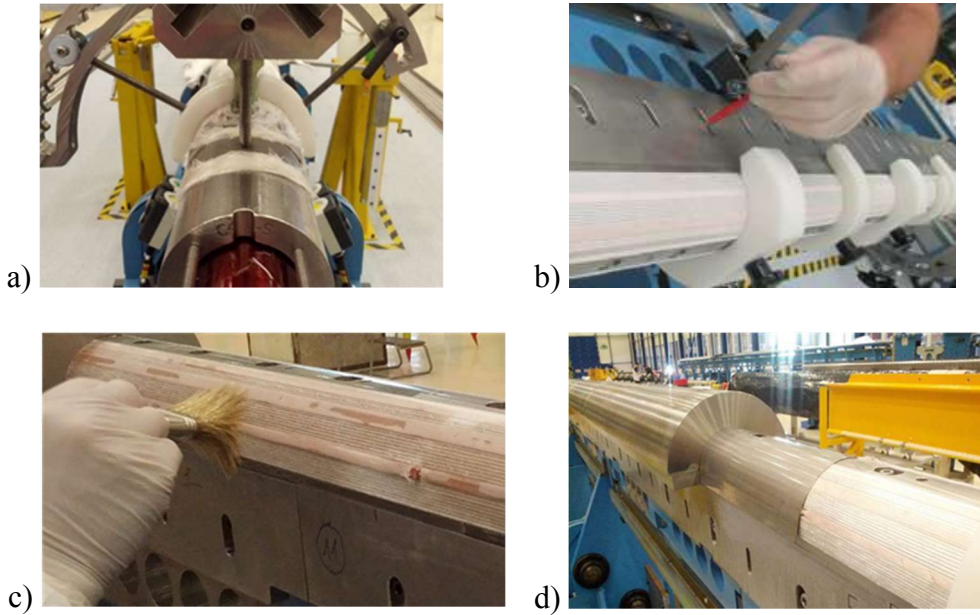


Figure 2.16 Finalizing the coil winding (shown in a) and preparation for curing: fixing the lateral pushers (shown in b), putting the ceramic binder on the windings (shown in c), and fixing the half-shells (shown in d).

The quality survey of the layer during winding is organoleptic and based on operator's experience. It consists of an observation and a tactile feedback of the cable surface. In case of observing a defect, the operator may decide to interrupt the process and perform the repair.

The repair procedure depends on the type of defect and may include a local manual cable manipulation, reversing the program step, loosening or tightening the clamp, and releasing the tension.

While executing the winding procedure the operator's tasks are extensive, effectively making it a semi-automatic process. The operator is involved in multiple activities requiring dexterity and precision, e.g.:

- Mounting the central pole and keys (see Figure 1.27);
- Assembling the layer jump with tooling (see Figure 2.11);
- Clamping and releasing radial and azimuthal clamps for each layer (as shown in Figure 2.12 and Figure 2.13a);
- Placing the additional insulation layers on the pole and spacers (as can be seen in Figure 2.14a);
- Surveying the quality of a wound cable layer;
- Taking the cable position measurements (shown in Figure 2.15);
- Carrying out the cable repair, if required.

2.3. MANUAL CABLE CORRECTION

The winding machine kinematics is merely a supplement of a cable layer positioning, which needs to be finalized by the operator. This is caused by the cable torsion (indicated in Table 2.2) required by the coil design, impossible to achieve with the current WM kinematics (shown in Figure 2.6). One can see the cable being inclined at an angle α_i to the horizontal Y_0 -axis, as shown in Figure 2.17. None of the available winding machine DOF allows controlling the spool or cable rotation about X_0 -axis, therefore the manual correction is necessary. Due to this reason, the winding is programmed to ease the operator adjustment of the cable position. The distance separating the cable spool and the winding mandrel is larger than 1 m (see winding program in Figure 2.10a), which ensures a sufficient cable-overhang flexibility.

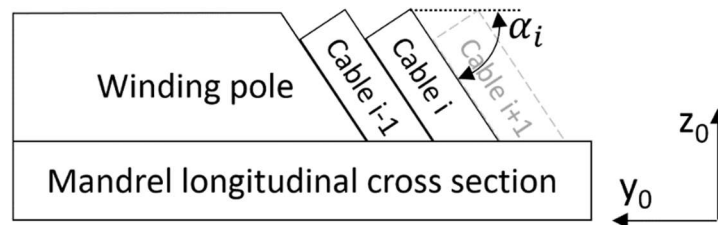


Figure 2.17 Schematic longitudinal cross section of the coil-end with three consecutive turns of the cable and the twist angle α .

The nominal angle α_i extracted from the perfect coil geometry (CAD), between the cable external surface and the Y_0 -axis, is shown in Figure 2.18. Four functions of the angle versus the cable turn 'i' are shown, representing four coil ends (two for the inner- and two for the outer-layer).

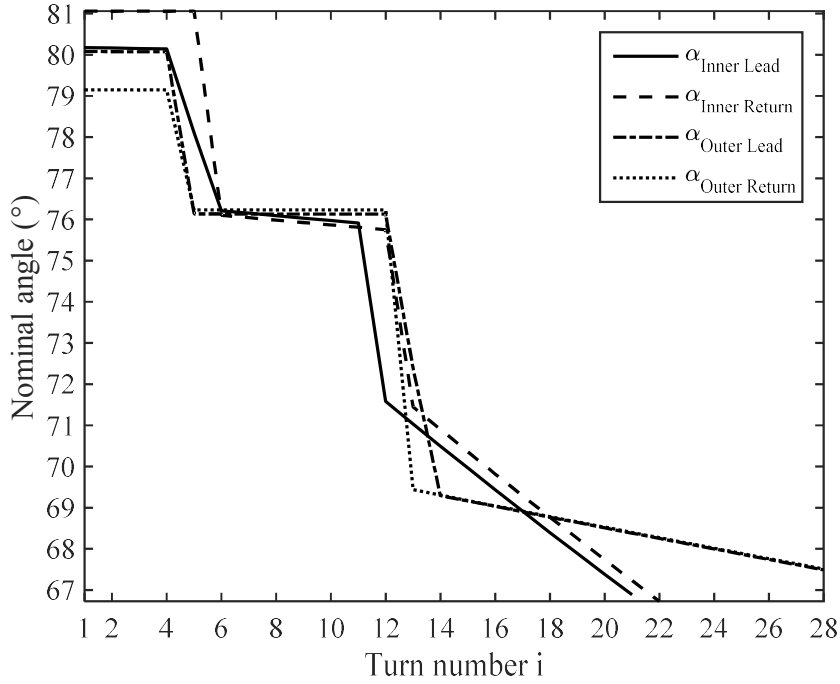


Figure 2.18 Nominal cable twist angle α_i of MQXFB V7 coil in a function of cable turn number i . Four functions present both sides of the coil (Lead and Return) of inner- and outer-layer.

One can see that the inclination for initial turns equals roughly 80° and declines to as low as 67° . In order to put it to perspective, the manual correction of the cable, i.e. the displacement of the top edge of the 15 mm-high cable relative to the bottom edge for the inclination angle of 67° is estimated in equation (2.17). The displacement of 5.9 mm is close to four-fold of the average cable thickness of 1.5 mm.

$$\sin(90^\circ - 67^\circ) \cdot 15 \text{ mm} = 5.9 \text{ mm} \quad (2.17)$$

Understandably, the final twist angle α also depends on the adjacency with the winding pole or previous layer of the cable, indicated as 'i-1' in Figure 2.17. Meaning that the cable torsion can be partially compensated by the increased winding tension (F_{set} in the winding function equation (2.10)). However, following the on-site experience of the winding operators, the benefit of the higher tension is countered by the increased unwanted cable deformation, like

popping of the individual strands or larger divergence from the mandrel, as described in chapter 2.4.

2.4. OBSERVED WINDING DEFECTS

The cable distortion was observed during the winding process of the 11 T and MQXF coils. The defects were occurring mainly in the coil-ends. The cosine- θ coil end design (see Figure 1.25) imposes a complex stress conditions on the cable, i.e. combined easy-way and hard-way bending as well as the torsion (see Table 2.2). The following pictures are extracted from the winding reports prepared in the LMF section at CERN.

One can see the strand pop-out in Figure 2.19, occurred during the test winding of the 11 T dipole. The tests were performed with the uninsulated copper cable, featuring the 11 T conductor dimensions (see Table 1.1). The attempt was to prepare the detailed magnet production procedures. The deformation occurred in the inner-layer, marked with a red dashed line. Thanks to the lack of opaque insulation layer, the direct detection and repair of a deformation was feasible.

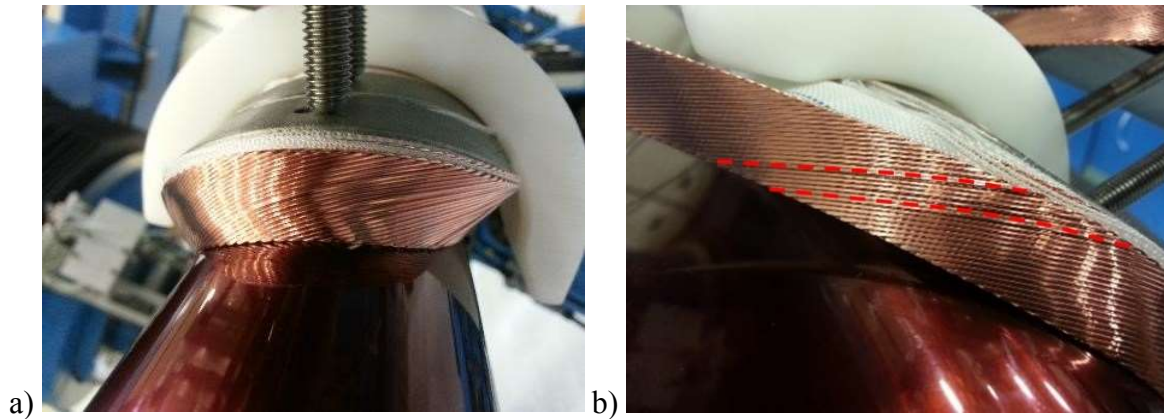


Figure 2.19 The strand pop-out observed during test winding of the 11 T coil with use of Cu Rutherford cable.

The protrusion is shown in Figure 2.20, visible as a gap between the mandrel and the cable. The pictures come from the 11 T winding with Nb₃Sn insulated cable. The dashed red line indicates the raised bottom edge of the cable, and the dashed green line marks the intended cable position. The repair requires applying the radial force with the head tool (see Figure 2.13), in order to achieve the adjacency, effectively eliminating the gap. However, the deformation induced during the process is within the elastic region, and after a removal of the clamp a residual gap remains.

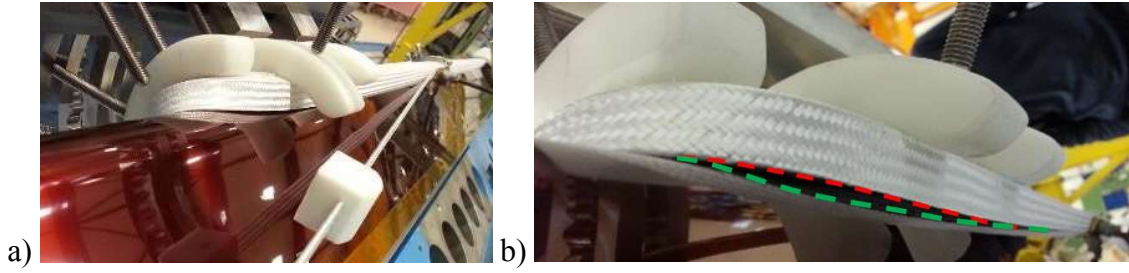


Figure 2.20 The cable protrusion observed during winding of the 11 T coil with use of Nb₃Sn Rutherford cable.

2.5. QUALIFICATION OF THE RUTHERFORD CABLE DEFORMATION

The cable deformation types were determined by applying the bending momentum in the main axes in the center of the cable cross-section (see Figure 2.21a). The goal of this exercise was to observe the characteristic deformation, which may occur during winding. The insulation was removed prior the qualification, in order to ensure an unobstructed strand observation. The bending momentum tensor is defined in (2.18). The undeformed cable (i.e. featuring no applied momentum) and a coordinate system is shown in Figure 2.21.

$$\vec{M} = \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (2.18)$$

Where:

$\vec{M}$ – Momentum tensor matrix;

M_x – Momentum tensor in X-axis;

M_y – Momentum tensor in Y-axis;

M_z – Momentum tensor in Z-axis.

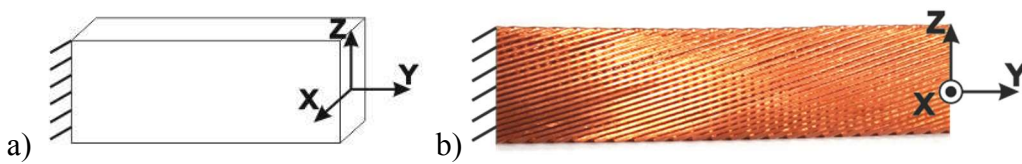
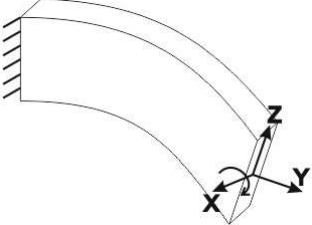
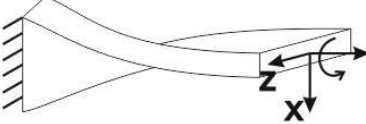
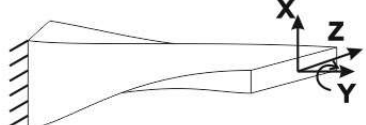
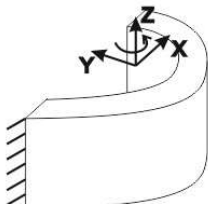
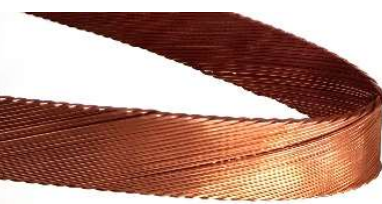


Figure 2.21 The profile of the stripe (a) and the Rutherford cable (b) for $\vec{M} = \theta$.

Table 2.2 presents an overview of the characteristic cable deformation, which occurs when applying a bending momentum in the main axis. One can see that the momentum in X-axis triggers an opening of the cable, i.e. a misalignment and formation of large gaps between the strands. The same type deformation occurs regardless of the momentum direction. The deformation observed when applying a bending momentum in the Y-axis is direction dependent. The positive momentum results in so-called decabbling, i.e. the instantaneous separation of all the strands. Whereas, the negative momentum tightens the strands. The bending about the Z-axis provokes the strands to move out of the cable side-plane (the pop-out), as well as the cable to shift along the Z-axis (the protrusion) [48], [54].

Table 2.2 Typical defects of the Rutherford cable due to bending.

$\vec{M}$	Stripe behavior	Rutherford cable behavior	Defect/ Stress state
$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}$			Opening/ Hard-way bending
$\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$			Decabbling/ Torsion
$\begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}$			Tightening/ Torsion
$\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix}$			Strand pop-out and protrusion/ Easy-way bending

3. RESEARCH QUESTIONS AND SCOPE OF WORK

The superconducting coil winding process is a complex task that incorporates multiple manual operations requiring high dexterity and precision (see chapter 2.2). These tasks are complemented by the WM ensuring the realization of the main process kinematics, described in chapter 2.1. As shown in Figure 2.1, the winding is an initial stage of the coil production, that aims to provide a nominal $\cos\theta$ coil geometry (see Figure 1.25). During winding, the Rutherford cable exhibits certain defects deteriorating the quality of a wound segment, such as the strand pop-out or protrusion (shown in chapter 2.4). The control of the cable deformation and positioning is important, when considering the coils wound with the stress-sensitive Nb_3Sn superconductor (see chapter 1.2.1). One should note that defects occurring during the winding process can have a major impact also on subsequent production steps. The repeatability of geometrical quality is crucial considering that the curing, reaction, and impregnation are closed cavity processes. The moulds for each production step are designed following the nominal dimensions of the coil geometry. Therefore, the geometry excess results with an increased stress level seen by the cable during these operations. It is therefore crucial to study the winding deformation based on experiments and numerical simulations in order to quantify these fabrication errors and their impact on the production tolerances.

Rutherford type cables have not been studied so far regarding their winding performance. Therefore **the main goal of this thesis is to develop the experimental procedure for evaluating the Rutherford-type cable winding quality and provide an analysis of cable deformation observed during the coil winding process.** The experimental setup is developed to carry out a winding test campaigns. The laboratory setup allows to observe a cable deformation not interfering with the full-size winding machine. In addition, the scanning device and analysis algorithm is developed in order to quantify the deformation.

This investigation is carried out based on numerical and experimental campaigns. Therefore, **the second aim of the work is to demonstrate the possibility of simulating the Rutherford cable deformation due to winding with use of the Finite Element Analysis (FEA).** This includes a development of a result analysis algorithm, with a purpose of extracting deformation indicators.

The detection and measurement of the strand displacement is hindered by the opaque S-2 Glass and Mica insulation layers. Therefore, **the third goal of the research is to investigate a technique allowing determining the position of the strands underneath the insulation.**

The study carried out in European Organization for Nuclear Research intends to prove the following hypothesis: there is a possibility to experimentally evaluate the cable characteristics for automated winding process of superconducting coils.

The scope of work therefore includes:

- Development of a simulation in order to investigate the pressure distribution of the wound cable due to winding tension;
- Development of a non-linear model allowing investigating the deformation of an individual strand due to winding;
- Analysis of the simulation results focusing on the winding deformation;
- Inspection of the insulation layers by use of the active thermography imaging technique;
- Conducting a comparative analysis of the laser triangulation and structural light surface scanning devices;
- Design of a winding device capable of providing a specimen in adjustable conditions;
- Design of a laboratory scanning device, capable of providing the specimen scan with adequate resolution and repeatability;
- Conducting a comparative analysis of three laser triangulation distance sensors available on the market;
- Development of a scan analysis method providing individual indicators of the Rutherford cable deformation types;
- Conducting two test campaigns following a developed methodology, in order to find the best winding tension and direction for given conditions, as well as test the influence of the cable pre-torsion on a winding quality;
- Explore the possibility to investigate the reaction heat treatment process with developed methodology, as well as the digitization of the wound cable volume by the computed tomography;
- Execution and analysis of the enhanced quality control during coil winding;
- Proposition of the future outline regarding the improvement of the winding machine derived from the conducted tests.

4. NUMERICAL MODELLING OF THE WINDING PROCESS

In order to obtain a high and repeatable quality of the coil winding, it was crucial to identify and study the phenomena driving the cable mechanical deformation. The Finite Element Method (FEM) was used in order to study the mechanical relations of the winding process. Two objectives were formulated, i.e. investigation of the stress distribution of the cable due to various winding tension (shown in chapter 4.1), and investigation of the cable behavior due to bending (shown in chapter 4.2) [55]. Both models are described in this chapter, and the summary is provided in chapter 4.3.

4.1. STRESS DISTRIBUTION OF THE WOUND CABLE

In order to study the internal stress in the cable induced by the tensioning force, the FEA model was developed. The geometry of the model is based on a simplified CAD design of the pole end-key of the outer layer of 11 T coil. One can see the picture of the end-key and dimensions shown in Figure 4.1. In order to avoid the large deformation of the cable, and thus the requirement of defining the elastic material properties, the initial position of the cable is artificial, and designed as adjacent to the spacer. For the end-key the structural steel material was chosen, while for the cable the copper alloy was used featuring the elastic properties (i.e. Young's Modulus, and Poisson's ratio) shown in Table 4.1.

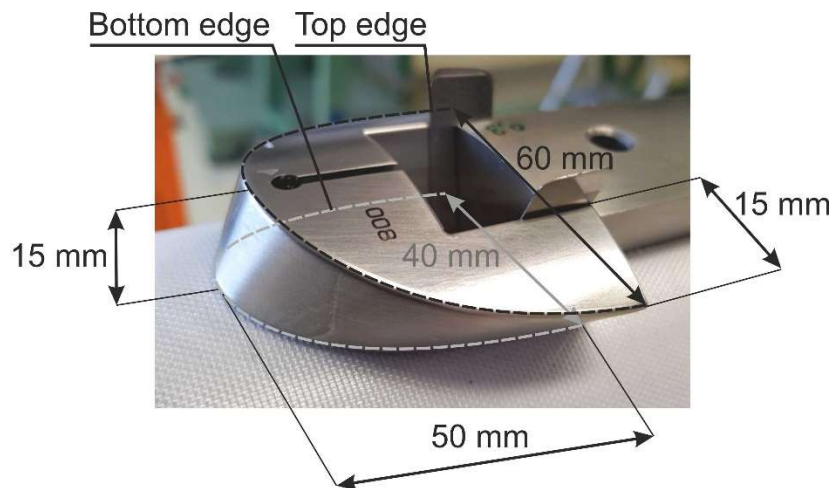


Figure 4.1 11 T coil outer layer return end-key used for model.

Table 4.1 Material isotropic elasticity definition

Material	Body	Young's Modulus (GPa)	Poisson's ratio
Structural Steel	End-key	200	0.30
Copper Alloy	Cable	110	0.34

4.1.1. SETUP DEFINITION

The cable is modelled as one body of homogeneous material, featuring 1.5 mm thickness and adjacency to the end-key side face. The final geometry of the model is shown in Figure 4.2. The cable (shown in green) and the end-key (shown in gray) share the same symmetry plane, which allows to simplify the model geometry and minimize the computation time. The tensioning force acting on the cable plane is perpendicular to the cable surface and parallel to the Z-axis. The force varies in value depending on the load case (i.e. 150 N or 300 N). The model constraints are shown in Table 4.2.

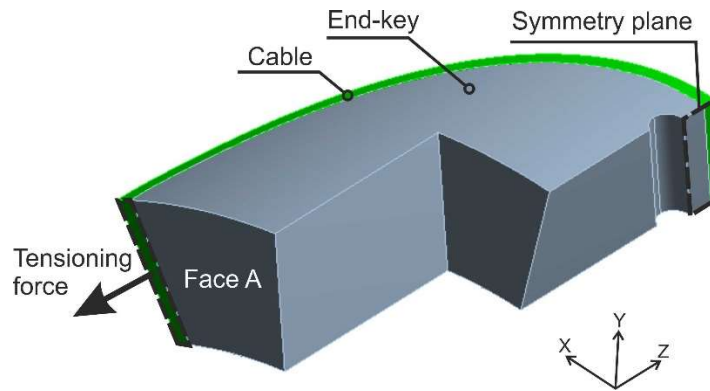


Figure 4.2 Simulation setup of the cable pressure model.

Table 4.2 Model constraints.

Body	Translation constraint in		
	X-axis	Y-axis	Z-axis
End-key	Symmetry plane	Bottom surface	Face A
Cable	Symmetry plane	Bottom surface	Free

The contact surface between the end-key and the cable is shown in Figure 4.3. The frictionless contact type is used, featuring the Augmented Lagrange formulation. The 3D 8-node contact elements are used.

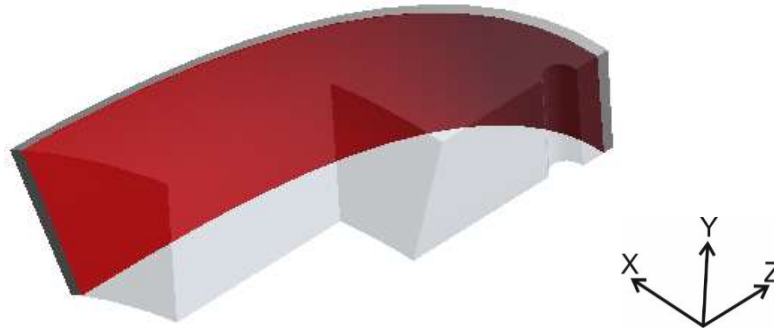


Figure 4.3 Contact face between cable and spacer bodies.

Four variants of model mesh densities were considered. The number of nodes and elements included in each variant, as well as the final computation time is shown in Table 4.3. The results of considered mesh variants did not exhibit any singularities, i.e. the local stress concentrations shown by single nodes. Therefore, in order to minimize the computation time, the variant 1 was chosen for obtaining further results, shown in Figure 4.4.

Table 4.3 Considered model mesh densities.

Mesh variant	1	2	3	4
Nodes	26k	142k	581k	2998k
Elements	5k	31k	131k	708k
Computation time (min)	3	12	25	40

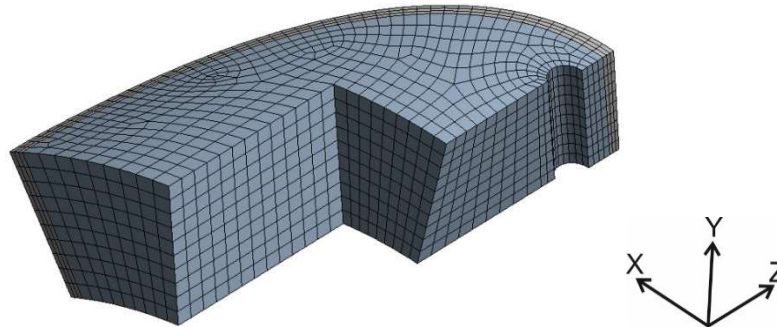


Figure 4.4 Model meshed with use of 3-D 20-Node elements. Mesh density variant number 1.

4.1.2. RESULTS

The simulation was performed with two load case scenarios, i.e. with tensioning force of 150 N and 300 N. The equivalent von Mises stress results of the cable body are shown in Figure 4.5. The results are showing the contact face of the cable (facing the end-key).The

Figure 4.5a shows 150 N load case, while Figure 4.5b is presenting 300 N load. The stress shown in both cases is inhomogeneous, and the indicated peak stress is located in the same position of the cable. The maximal values are 15 MPa and 34 MPa.

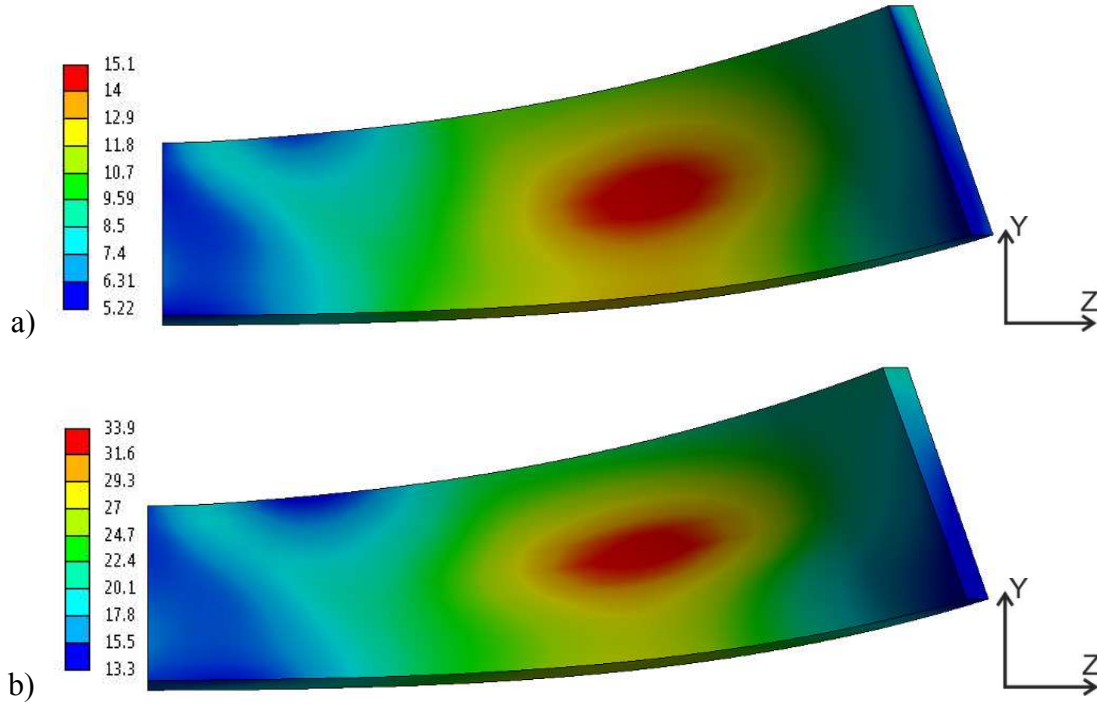


Figure 4.5 Equivalent von Mises stress of the cable side facing the spacer in MPa. a) 150 N of tension. b) 300 N of tension.

Following the obtained results, one can conclude that the presented model allows observing the pressure distribution of the wound cable. However, due to its simplifications, i.e. considering the cable as the homogeneous solid body, and defining the model geometry after pole winding, the model cannot serve to investigate the Rutherford cable deformation phenomena. Therefore, in the following chapter an improved cable modelization based on individual strands is presented.

4.2. SIMULATION OF THE WINDING PROCESS

One can see in the Figure 2.19 and Figure 2.20 that the wound cable is bent in 3-axes in order to obtain a $\cos-\theta$ coil shape. The winding simulation is developed with use of a Rutherford cable geometry which is based on a premise of simplifying the cable bending to 1-axis with use of a cylindrical support, as shown in Figure 4.15. This allows for minimizing the setup complexity in comparison to the $\cos-\theta$ coil-end, and allows comparison with the experimental

results [54]. In order to investigate a relative displacement of a strand in the cable matrix, the cable is modelled with the individual strand bodies. The literature describes two, three-dimensional, “hierarchical models” of the Rutherford cable, used in mechanical analysis [56], [57], which are intended for a mechanical calculation of a filament degradation due to the applied stress. The mesh of the presented model is compared to those mentioned in the literature (Table 4.9). The winding simulation consists of a 10 mm diameter cylinder and a 20 mm-long cable. The model geometry is defined in a CAD system. Each strand is designed as a continuous geometry, which allows for a precise mesh control, i.e. defining the number of longitudinal and transversal mesh elements.

4.2.1. WINDING SIMULATION SETUP

The support pole used in the 11 T dipole is machined from the titanium alloy (Ti-6Al-4V, AMS 4911), while the outer surface of the cable is made from copper. Due the high material stiffness difference, the cylinder is simulated as a rigid body. Plastic deformation is introduced in order to avoid the artificially high stress in the cable. The winding tension is usually applied between 15 and 25 kg. During winding the strands are plastically deformed. Therefore, the plastic material characteristic was used for the simulation, derived from the tensile test of the 132/169 Nb₃Sn strand featuring 0.7 mm diameter. The result of the test performed in the material measurement laboratory at CERN, is shown in Figure 4.6 (continuous line). The initial segment of the curve was used in order to compute the Young’s Modulus of $E=90$ GPa that is used for defining the elastic region. Due to the lack of Poisson ratio measurement, the value of 0.34 was used that represents the value used for copper material. The elastic region of the strand is defined by the multilinear isotropic hardening property, with twelve points extracted from the stress-strain characteristic of the strand tensile test, marked with circles in Figure 4.6.

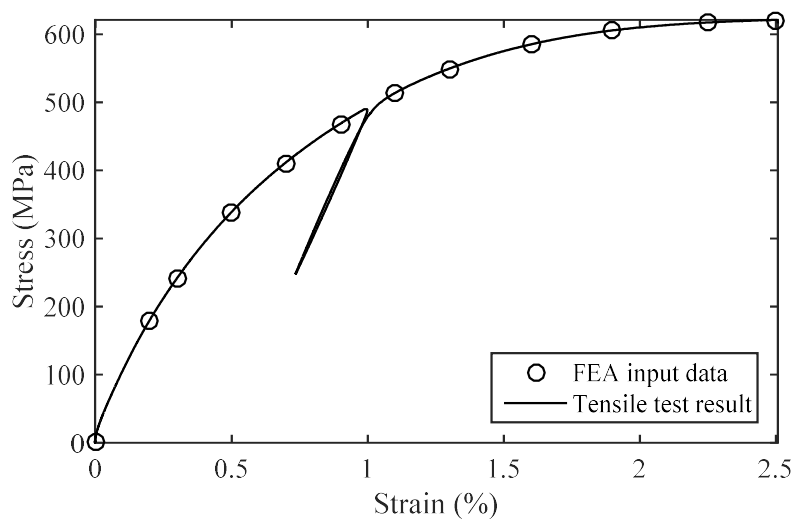


Figure 4.6 Tensile test results of the Nb₃Sn 132/169 0.7 mm strand. $E=90$ GPa, $\nu=0.34$.

4.2.2. X-RAY ABSORPTION TOMOGRAPHY OF 40-STRAND RUTHERFORD CABLE

In order to analyze the geometry of the 40-strand Nb₃Sn Rutherford cable, two tomograms were obtained, one of a single cable (called sample A) and one of a cable stack (called sample B). One can see the prepared specimens in Figure 4.7. The X-ray absorption tomography was performed by Federal Institute for Materials Research and Testing (BAM, Germany) with the energy of 215 kV.



Figure 4.7 Specimens of 40-strand Nb₃Sn 132/169 cable prepared for X-ray absorption tomography. Top: Sample B, a stack of four cables (18 mm x 12 mm x 150 mm). Bottom: Sample A, a single cable (15 mm x 2 mm x 150 mm).

Due to the differences in sample dimensions, as shown in Table 4.4, the tomogram voxel size of the sample A (8.83 μm) is smaller than the sample B (10.5 μm). Therefore, the obtained cross section image of the sample A, shown in Figure 4.8, features a higher resolution than the tomogram of sample B, allowing distinguishing individual filaments in the strand.

Table 4.4 Features of tomography specimens.

	Unit	Sample A	Sample B
Description	-	One cable	Stack of four cables
Cable	-	40-Strand Rutherford	40-Strand Rutherford
Strand	-	132/169 Nb ₃ Sn	132/169 Nb ₃ Sn
External dimensions (H x W x L)	mm	15 x 2 x 150	18 x 12 x 150
Tomography energy	kV	215	215
Voxel size	μm	8.83	10.5

One can see two enlarged cable sections at the bottom of the figure. The highest strand deformation is present at the edges of the cable. The red line marks a real outline of the strand, while the green dashed circle of 0.7 mm diameter represents a strand cross section before cabling. A discrepancy between the red and green lines illustrates the amount of plastic deformation of the strand. In addition, one can notice that the strands on the edges of the cable are represented with darker gray than the strands in the middle. This is caused by the sample geometry, i.e. a large relative difference between the width and height of the sample (width to height ratio of 1:7.5). In attempt of minimizing this phenomenon, the sample B was prepared featuring a more favourable width to height ratio of 1:1.5.

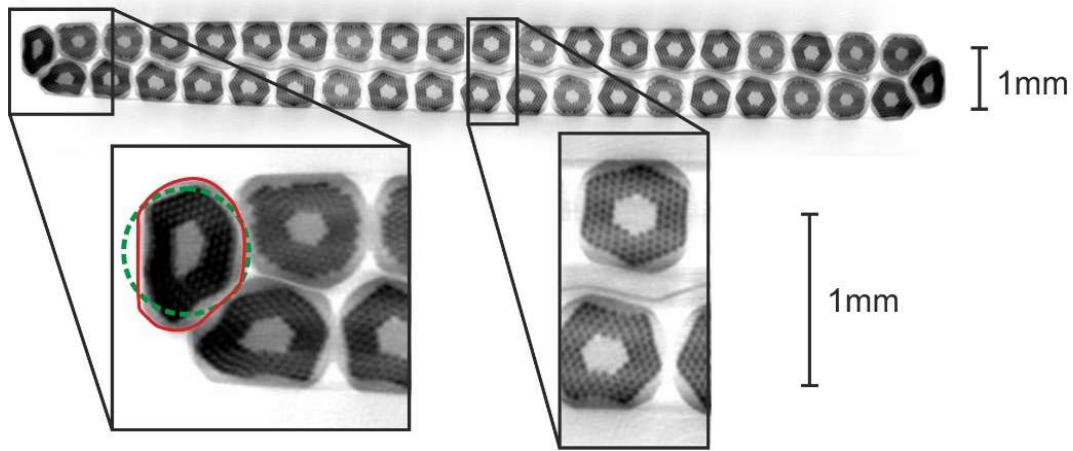


Figure 4.8 Transversal cross section extracted from a tomogram of the sample A. Visible strand deformation on the edge and brightness difference.

The tomogram of the sample B is shown in Figure 4.9. One can see the three dimensional representation of a scanned fragment of the specimen at the top of the figure. The central cross section of a scanned stack is shown in the middle of the figure. On the enlarged sections at the bottom of the figure, one can see that the grayscale representation of the strands is improved in comparison to the sample A. As in the previous example, the strand transversal deformation is most severe at the edges of the cable.

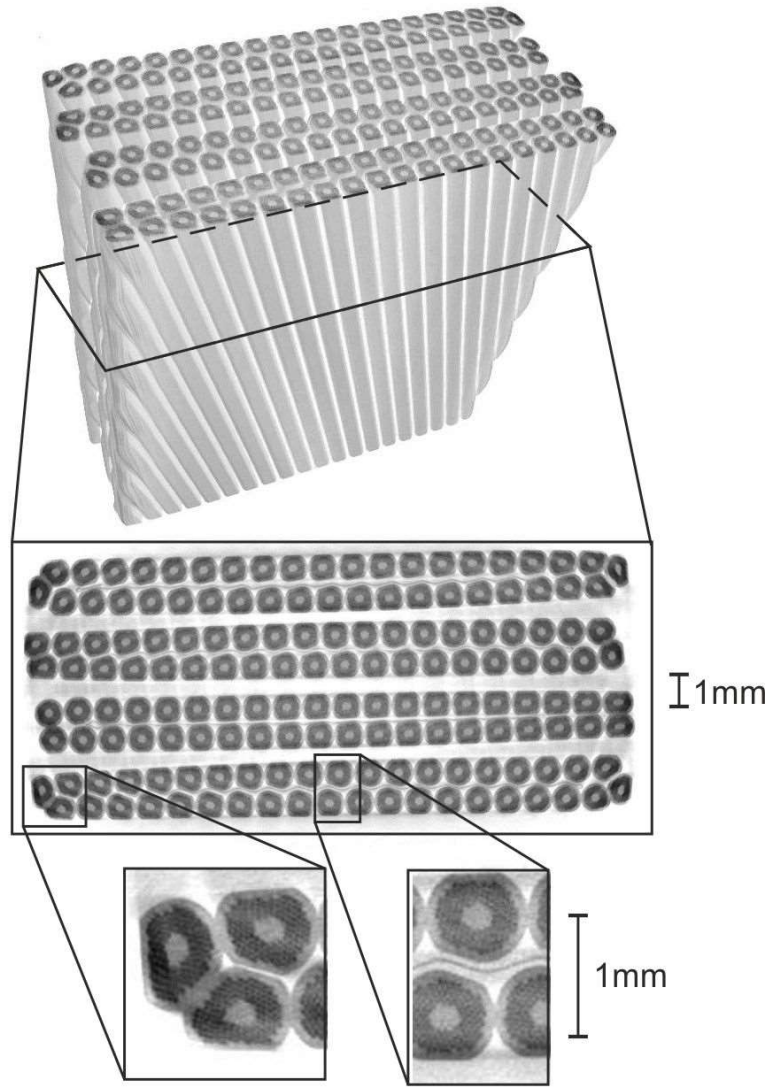


Figure 4.9 Three dimensional reconstruction of a tomogram of the sample B. Transversal cross section in the middle, with enlarged cable edge and middle sections at the bottom.

4.2.3. GEOMETRY DEFINITION

In order to simplify the initial development of a discrete cable geometry for simulation purpose, the cabling strand deformation shown in Figure 4.8 is omitted. The simulated cable consists of the strands maintaining the same diameter along the whole length.

The Rutherford cable contains a stainless steel core, which is introduced in order to increase the interstrand contact resistance [58]. The core is a flat foil of 0.15 mm thickness. The extracted stainless steel core, shown in Figure 4.10, shows multiple imprints induced during the cabling process. The core is considered giving negligible rigidity to the cable; therefore, it is not taken into account in the presented model.

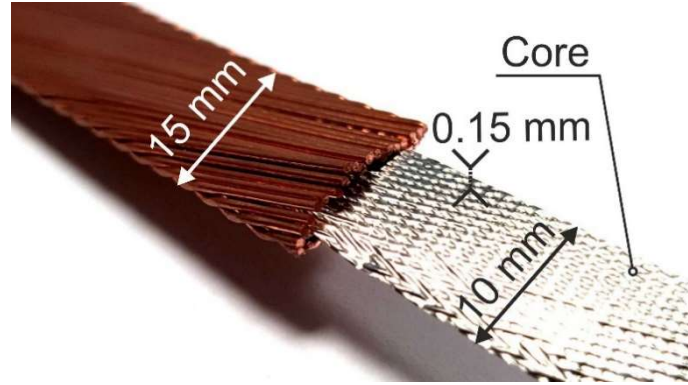


Figure 4.10 40-strand Rutherford cable with visible stainless steel core.

The S-2 Glass sleeve AGY S-2® 11TEX 636 and Mica C-shape COGEBI FIROX®, shown in Figure 4.11, are the outermost layers of the cable [14]. The S-2 Glass insulation is braided on the cable with a constant feed of the Mica foil (as described in [46] and discussed in chapter 1.2.2). The cable is enclosed by the insulation, which provides a mechanical support to the cable. In order to avoid the additional constraint, the insulation layers are not included in the simulated cable geometry

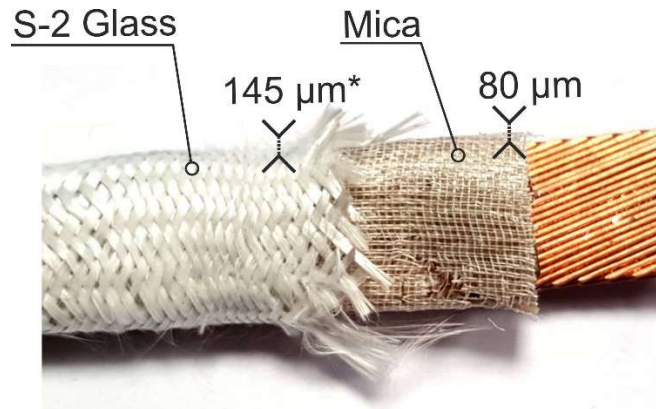


Figure 4.11 S-2 Glass and Mica insulation of 11 T cable. * S-2 Glass thickness measured before reaction at 5 MPa.

The winding process, described in chapter 2.1, introduces 3-axis bending (shown in Table 2.2). The position of the wound cable is given by the winding machine kinematics and a pole geometry. The geometry of the first turn of the inner layer of 11 T pole is shown in Figure 4.12. One can see the radius of the end key on the right side of the figure. The varying radius from roughly 16 to 26 mm causes a twist of the cable. In addition, the cylindrical mandrel support at the bottom induces a hard-way bending. In order to simplify the bending conditions, the winding pole is modelled as a cylinder, inducing only the easy-way cable bending (Z-axis in Table 2.2).

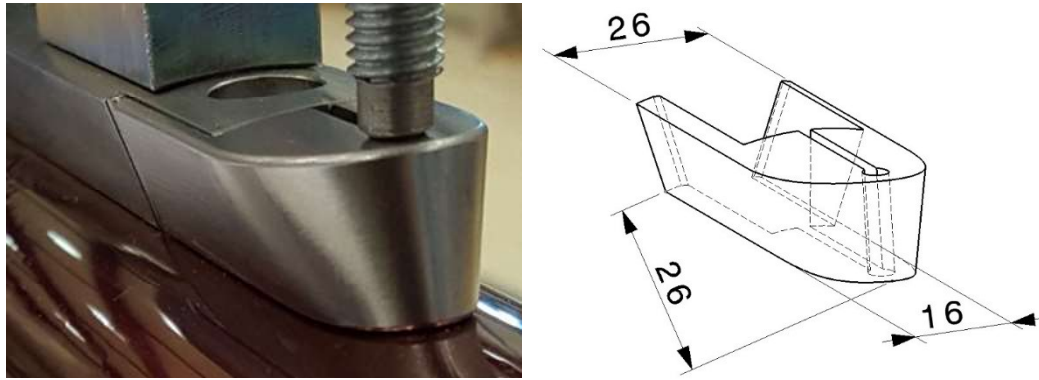


Figure 4.12 Inner layer opposite connection side pole of 11T dipole. Left: Picture of the pole assembly before winding. Right: Dimensions of the end key of the pole.

The summary of all geometrical features and considered simplifications of the presented model, are shown in Table 4.5.

Table 4.5 Geometrical features of the model.

Body	Feature	Value	Model
Strand	Diameter	0.7 mm	0.7 mm
	Cabling deformation	Present	Omitted
Cable	Keystone angle	0.79°	Omitted
	Stainless steel core	0.15 mm	Omitted
	Insulation	S-2 Glass and Mica	Omitted
	Number of strands	40	10
Pole	Bending	3-axis	1-axis
	Radius	16 to 26 mm	10 mm

The strand body is defined with a guide curve positioned in the centre of each strand, shown in Figure 4.13.

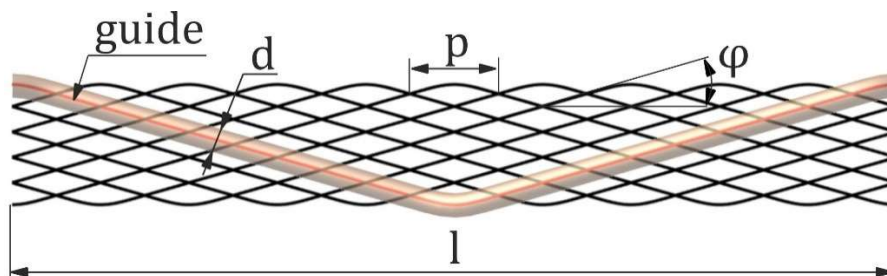


Figure 4.13 Side view of the 10-Strand Rutherford cable guide curves and one strand geometry. Pitch angle $\varphi=16^\circ$, strand diameter $d=0.7$ mm, strand turn $p=2.54$ mm.

The minimal repeatable period of the cable is a turn of the strand p . Its value is related with a pitch angle φ and strand diameter d according to the following equation:

$$p = \frac{d}{\sin(\varphi)} \quad (4.1)$$

In order to obtain the length of the cable l containing the full period of each strand (pitch length), the quantity of strands n needs to be equal to the quantity of a strand turns p , which is described by equation (4.2).

$$l = n * p \quad (4.2)$$

The simulated cable geometry is presented in Figure 4.14. The geometry consists of 10 strands featuring 0.7 mm diameter, which is equal to the nominal strand diameter used in 11 T cable (shown in Table 1.1).

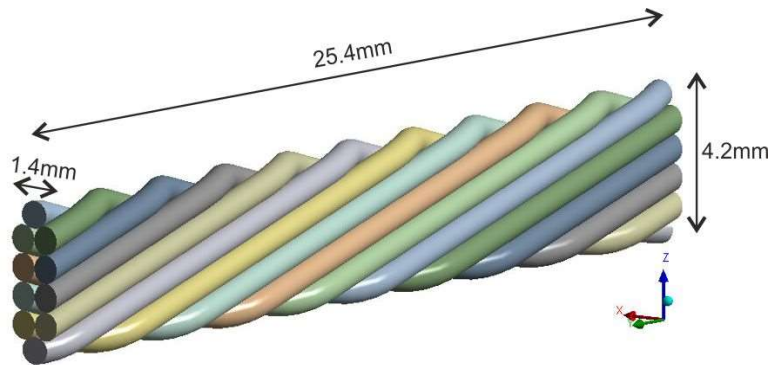


Figure 4.14 Modelled geometry of 10-strand Rutherford cable used in simulation. Pitch angle $\varphi=16^\circ$, strand diameter $d=0.7$ mm, strand turn $p=2.54$ mm.

The winding model setup is shown in Figure 4.15. The cable overall length is 25.4 mm, which presents 10 minimal periods according to formula (4.2). This configuration gives a geometry with a full period of each strand. The winding force F is defined in order to induce a turning movement of the cable around a fixed cylinder surface.

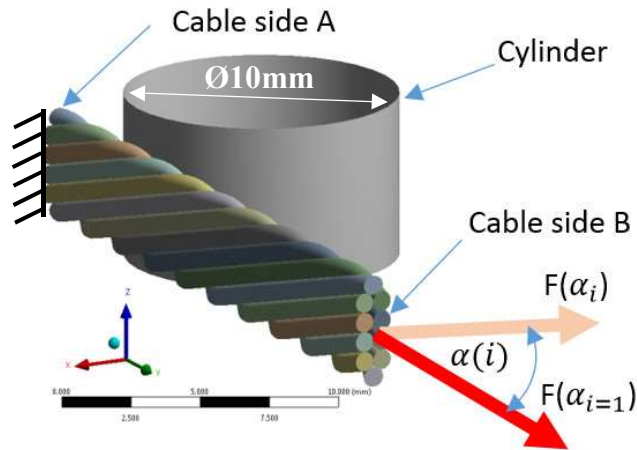


Figure 4.15 The winding model setup. Pitch angle $\varphi=16^\circ$, strand diameter $d=0.7$ mm, strand turn $p=2.54$ mm, cylinder diameter 10 mm.

The force vector has a constant value of 200 N and acts on all 10 faces of cable side B. The angle α between the force F and Y-axis is changing in the course of the simulation from 0° to 180° in ten defined load-steps. One can see the X-axis and Y-axis force component values shown in Table 4.6 and plotted in Figure 4.16.

Table 4.6 Force F components and value in each simulation step.

Step i	1	2	3	4	5	6	7	8	9	10
X (N)	0.0	-68.4	-128.6	-173.2	-197.0	-197.0	-173.2	-128.6	-68.4	0.0
Y (N)	200.0	187.9	153.2	100.0	34.7	-34.7	-100.0	-153.2	-187.9	-200.0
Value (N)	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0

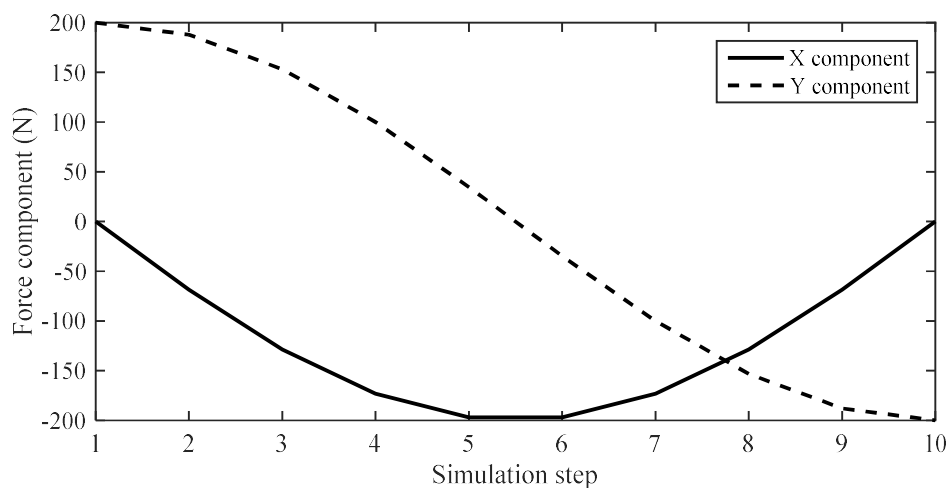


Figure 4.16 Components of winding force F .

The boundary conditions of the model are shown in Table 4.7. The modelled cylinder is a rigid body fixed in 6 DOF. The strands are fixed on the side A in 6 DOF. On the side B, the strands are constrained in 3 DOF, i.e. Z-translation, X-rotation, and Y-rotation. The faces of the cable on the B-side cannot displace in relation to each other.

Table 4.7 Boundary conditions.

Body	Geometry	Support	Load
Strand	Face side A	Fixed 6 DOF	-
	Face side B	Fixed 3 DOF (T_z , R_x , R_y)	Force (200N/10)
Cylinder	Whole body	Fixed 6 DOF	-

The contact parameters of the model are presented in Table 4.8. The contact interfaces are defined with use of the three-dimensional 8-node contact elements. These elements feature the quadratic shape function, which allows for a good curved surface adjacency in the application with a coarse mesh, and improve the initial contact conditions by minimizing the gap and the penetration size. The initial gap is 0 mm and the penetration size is $1.08 \cdot 10^{-15}$ mm indicating adequate initial contact condition. The friction coefficient is 0.2, taken as an initial value throughout the simulation. The contact element definition between the cable faces and the cylinder is configured asymmetric, allowing for a more efficient contact analysis due to the contact force projection on the strand face.

Table 4.8 Contact definition.

Interface	Strand to strand	Strand to cylinder
Type	Frictional	Frictional
Contact element	3D 8-node	3D 8-node
Formulation	Augmented Lagrange	Augmented Lagrange
Friction coefficient	0.2	0.2
Behaviour	Symmetric	Asymmetric

The cable is meshed by dividing each strand along its guide curve. The longitudinal sections are further subdivided by sectioning the edge of the cable with use of the edge-sizing feature. The model was discretized with use of 20-node 3-D solid quadratic elements. These elements allow for a good representation of a complex surface geometry. The modelled cable mesh quality is shown in Figure 4.17. The maximal mesh quality (equal 1) is obtained by the finite element in shape of a cube. Whereas the value 0 represents the mesh element with zero or negative volume. Therefore, the higher indicator value is more desirable. One can see in Figure 4.17b the total volume of the element in a function of mesh quality. Over 50% of mesh

elements are in the range of 0.7, and 10% are in the range of 0.3. The presented cable mesh is considered adequate for the study ensuring a computation time of lower than 12 h. The mesh quality can be improved in further iterations by a larger amount of longitudinal and radial strand segments.

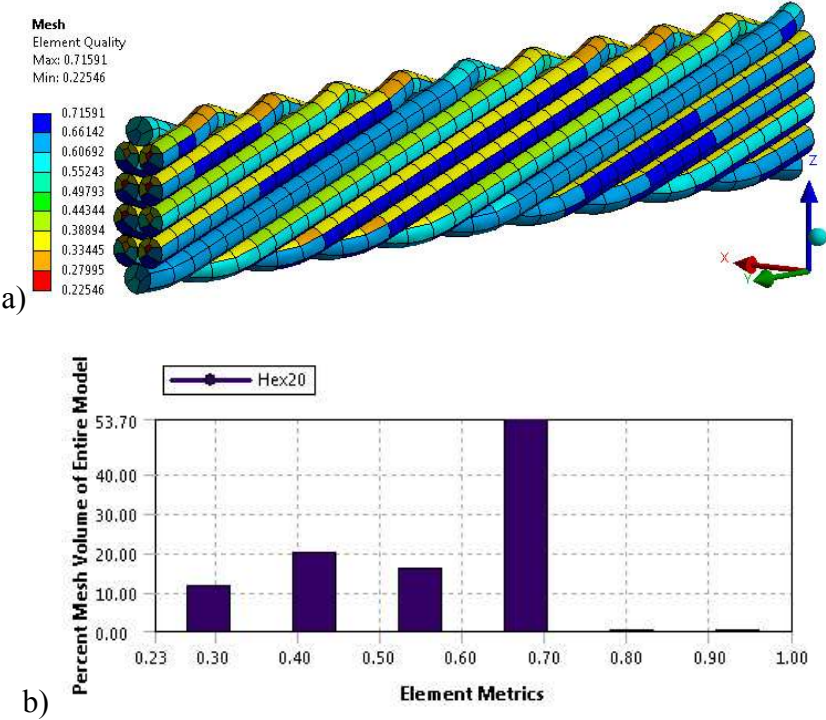


Figure 4.17 The mesh quality of the cable. a) Mesh quality ratio of the external elements of the cable. b) Mesh quality ratio in a function of total element volume.

The Table 4.9 shows the comparison of the cable mesh densities described in literature. The defined geometry of the presented winding model feature a low-density mesh, which allowed obtaining a relatively fast convergence time, of roughly 12 h.

Table 4.9 Mesh density comparison of the literature Rutherford cable models.

Model	Length (mm)	Strands	Nodes/mm/strand
P. Manil [56]	10	9	2778
D. Arbelaez [57]	2.5	12	189833
Winding model	25	10	70

4.2.4. RESULT ANALYSIS

The total deformation of the model is shown in Figure 4.18. One can see a dashed arrow indicating the direction of winding. The simulated cable geometry is characterized by the following parameters: the pitch angle of $\varphi=16^\circ$, strand diameter of $d=0.7$ mm, and the strand turn of $p=2.54$ mm. The cylinder features 10 mm diameter. The maximal obtained deformation equals 27.3 mm. The cable side-A exhibits no displacement, due to the fixed support, while the side-B is displaced for 27.3 mm bent by the winding force F .

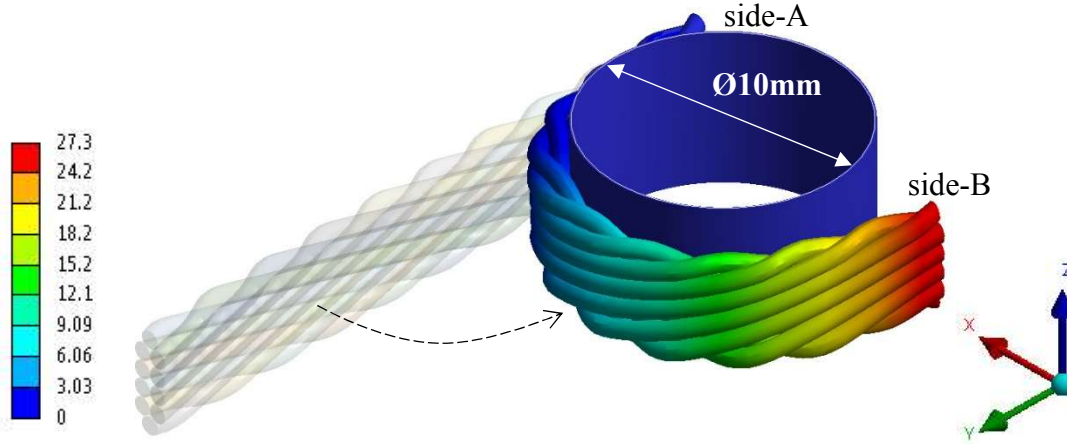


Figure 4.18 Total deformation of the winding simulation in mm. A direction of winding is marked with dashed arrow.

The highly deformed geometry of the cable after winding hinders the observation as certain segments of the cable overlap each other. Therefore, some of the results are displayed on an undeformed model with deformation scaling equal to 0, and for both sides of the cable, i.e. facing the cylinder and opposite. The rigid cylinder body is omitted to ease the presentation of those results. The equivalent elastic strain is shown in Figure 4.19. The maximal value of 0.69% is concentrated close to the side-B.

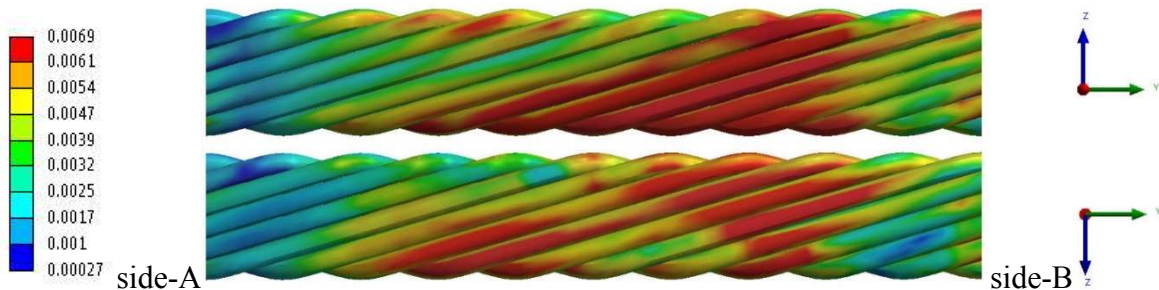


Figure 4.19 Equivalent elastic strain in mm/mm. Scaling equal to 0. Top: side not facing cylinder; Bottom: side facing cylinder.

The equivalent total strain of a final step of a simulation is presented in Figure 4.20. One can see the highest strain concentration of 9.1% close to the edges of the cable on the side opposite to the cylinder. The middle part of the cable in contact with the cylinder shows roughly 5% of total strain.

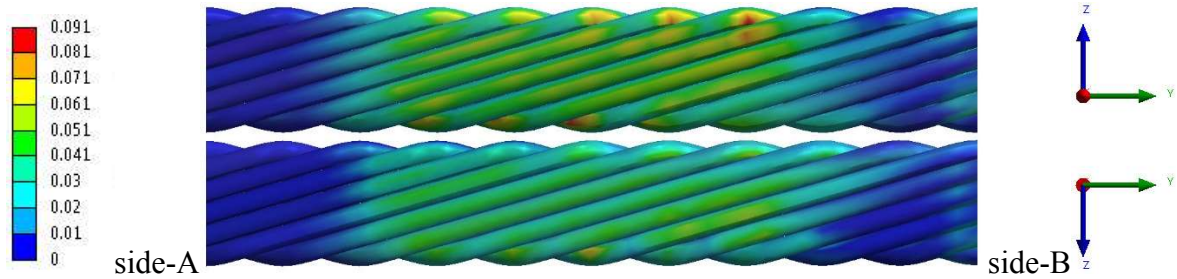


Figure 4.20 Equivalent total strain in mm/mm. Scaling equal to 0. Top: side not facing cylinder; Bottom: side facing cylinder.

The directional deformation in the Z-axis of the deformed model is shown in Figure 4.21a, while the undeformed in Figure 4.21b. One can see the strands close to the side-B of the cable protruding downwards in the Z-axis direction. The maximal absolute value of the cable protrusion is 0.61 mm, which is 87% of the strand diameter.

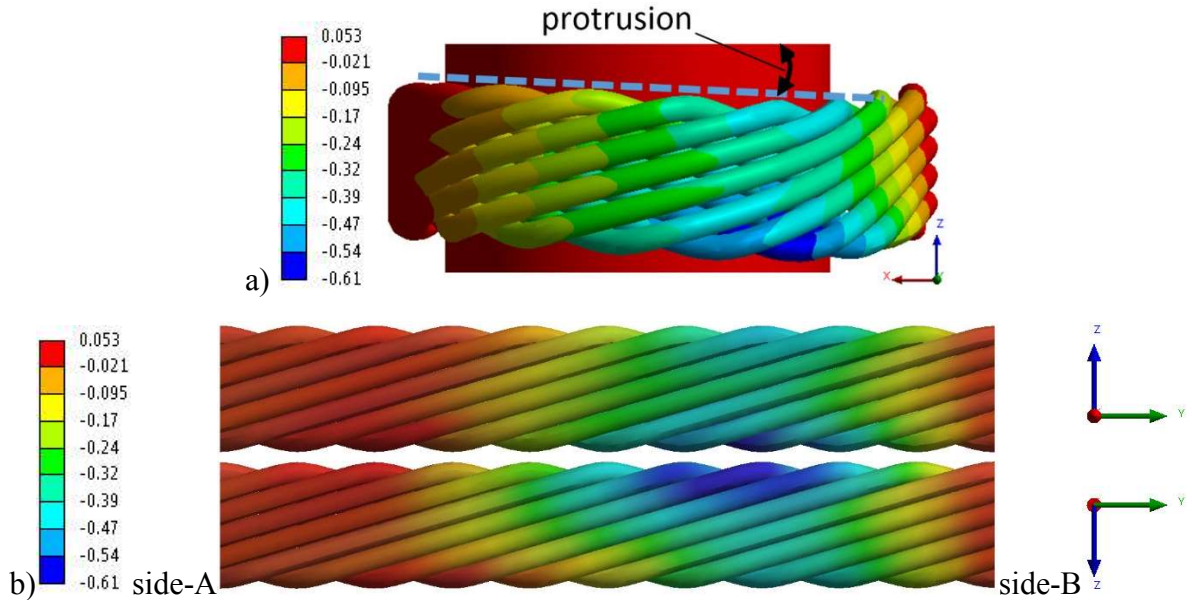


Figure 4.21 Directional deformation in Z-axis in mm. Scaling equal to 0. a) deformed cable with marked protrusion. b) Undeformed results Top: side not facing cylinder; Bottom: side facing cylinder.

It was interesting to see the difference in the distance of individual strands from the cylinder center, in order to investigate the strand pop-out cable deformation. The result combine the directional displacement in X- and Y-axes, which is shown in Figure 4.22. The sides A and B of the cable show the largest distance (over 8 mm), and in the middle part the local deviation of the edges from the cable varies from 6.27 mm up to 6.36 mm.

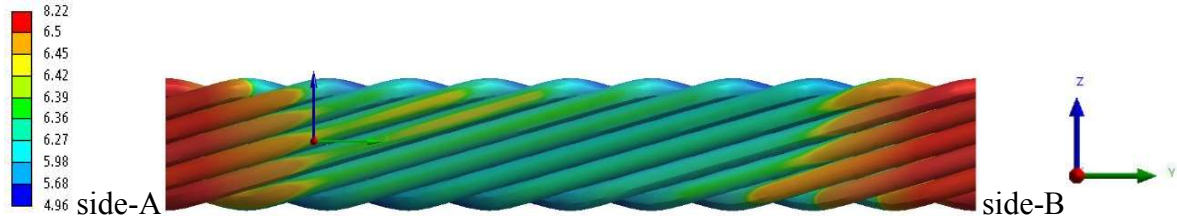


Figure 4.22 Distance from the center of the cylinder in mm. Side not facing cylinder.

The summary of the maximal and minimal deformation and strain resulting from the simulation are given in Table 4.10. The directional (i.e. along the main X-, Y-, and Z-axes) and equivalent results are shown.

Table 4.10 Maximal and minimal values of the deformation and strain of the winding model. Normal results (along the main axes) and total/equivalent results are shown.

		Directional along main axes						Total/ Equivalent	
		X		Y		Z		Max	Min
Result	Unit	Max	Min	Max	Min	Max	Min		
Deformation	mm	0.00	-18.40	0.00	-23.60	0.00	-0.60	27.30	0.00
Elastic Strain	%	0.68	-0.67	0.82	-0.60	0.27	-0.29	0.69	0.03
Plastic Strain	%	6.74	-6.31	6.50	-3.49	3.30	-4.08	8.59	0.00
Total Strain	%	7.42	-6.98	7.32	-4.10	3.58	-4.37	9.28	0.03

4.2.5. GUIDE CURVE INTERPRETATION

The results obtained with the ANSYS post-processor, presented in chapter 0, lack the information of the cable position in which the deformation occurs. This is crucial when considering the comparison with the experimental results presented in [54] or in following chapter 7. It was essential to develop an algorithm in order to extract the results in a function of an initial cable position. The guide curve coordinates, i.e. the line in the center of each strand shown in Figure 4.13, are extracted from the CAD software. The simulation results are then interpolated along the guide curve coordinates, with use of the APDL script. The

interpolated results and the reference position of the guide curve are saved in the external file. Afterwards, the file is imported and further analyzed with the Matlab® software.

The undeformed position of the guide curves, representing an initial position of the cable exported from the CAD software is shown in Figure 4.23. The strand numbering is indicated on the right side of the figure.

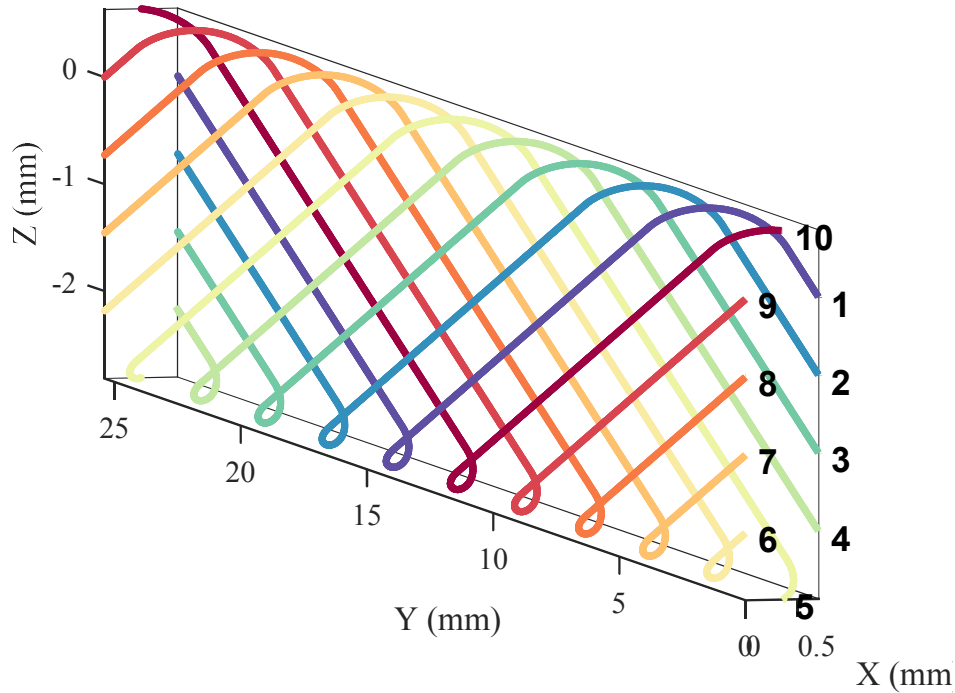


Figure 4.23 Initial (undeformed) position of the guide curves with assigned strand numbers.

The simulation results in Figure 4.24 show the position of the strands, characterized by the guide curves. Each strand is represented individually by the function of the initial position and the interpolated displacement of an associated finite element. Such a data presentation allows to distinguish the strands easily. The additional advantage of this method is given by the insensitivity to the model mesh. This is due to the applied interpolation of the results along the guide curve given from CAD.

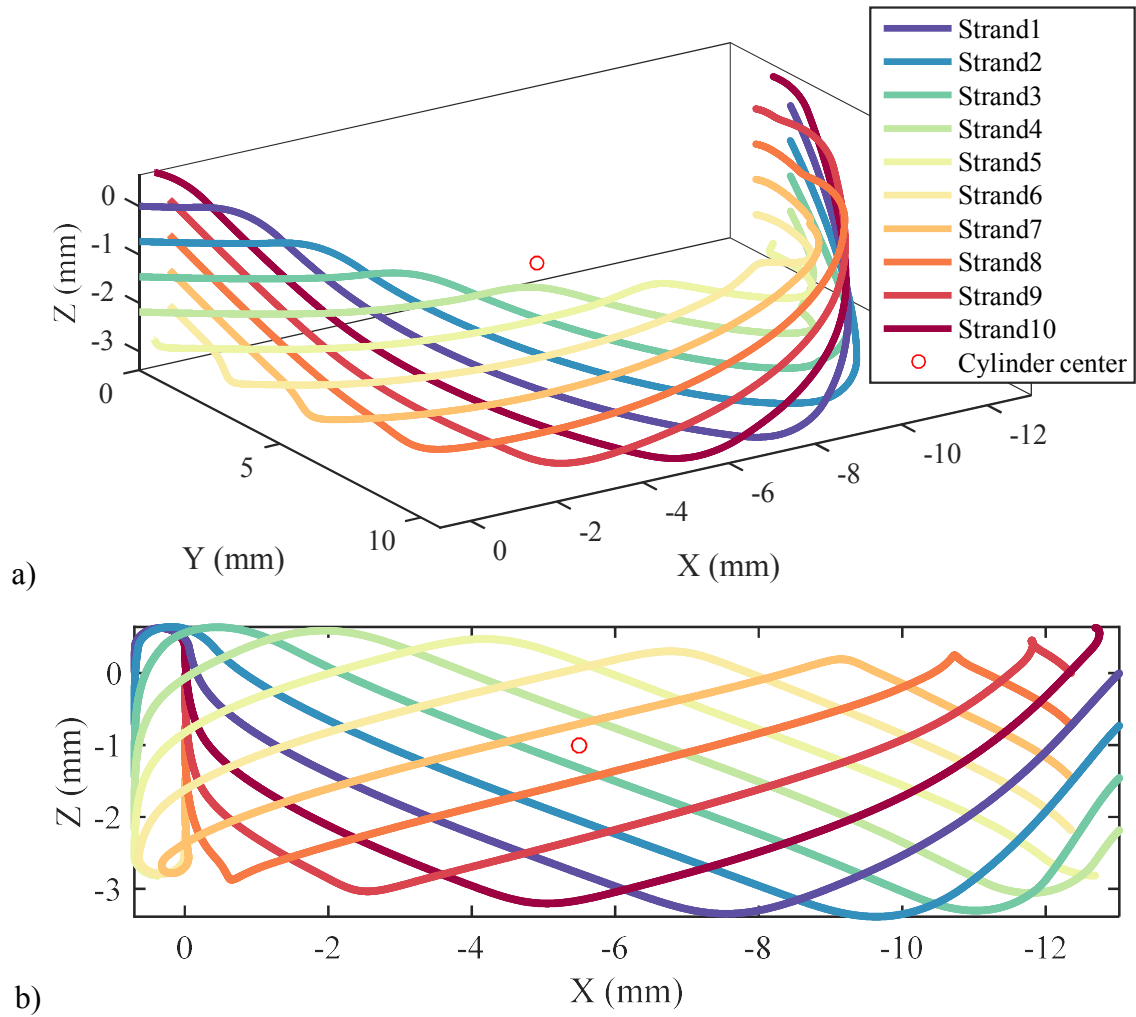


Figure 4.24 Guide curve position of 10 simulated strands after winding (in mm): a) Isometric view. b) X-Z plane view.

The directional deformation along the main axes X, Y and Z is shown in Figure 4.25. The results are displayed in a function of the initial cable length. The displacement in Z direction (UZ) on the right side of figure, allows investigating the protrusion of individual strand due to winding. The largest protrusion of 0.6 mm is shown by the strand number 2, while the smallest by the strand number 9. The displacement in Z-direction equals zero at the cable extremities, due to the applied boundary conditions.

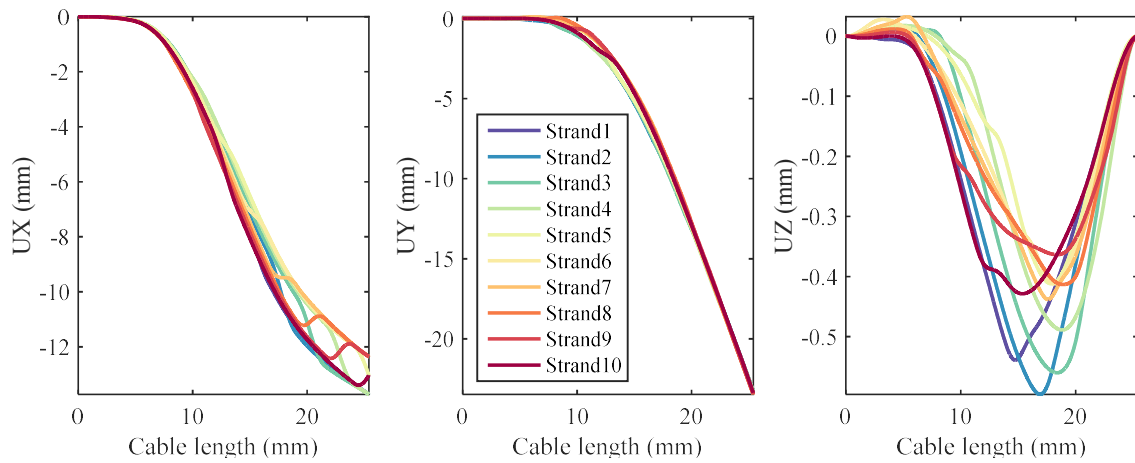


Figure 4.25 Directional displacement in X (UX), Y (UY), and Z (UZ) axes of individual strand.

The protrusion is analyzed for the whole cable, taking into account all of the deformations of individual strands in given cable position. The average (continuous line), maximal (dotted line), and minimal (dashed line) directional displacement in Z-axis is shown in Figure 4.26. One can see the protrusion phenomena as the displacement in the Z-axis. The maximal protrusion value equals 0.6 mm, which is 86% of a strand diameter occurring in 16.8 mm of the initial cable length.

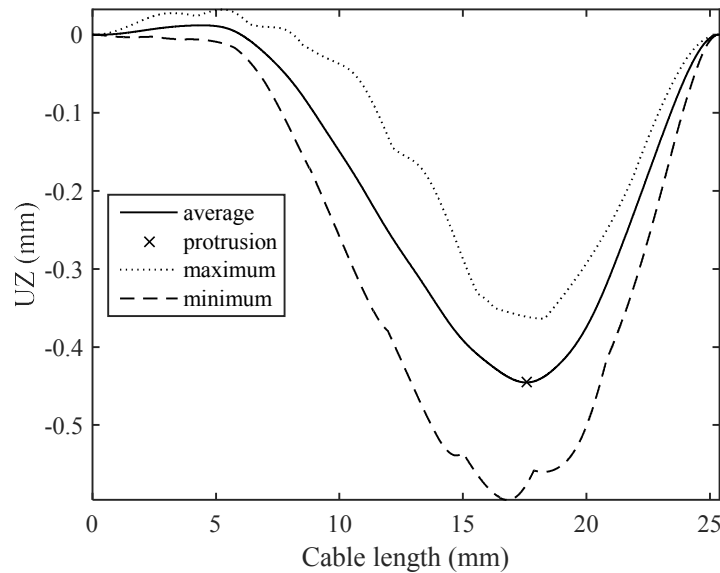


Figure 4.26 Average, maximal and minimal directional deformation of the whole cable in Z-axis (UZ). The extreme value of cable average protrusion marked with cross.

The investigation of the strand pop-out deformation requires creating a winding path, i.e. the ideal position of the wound cable. In the presented simulation, the winding path consists of a half cylinder and two straight sections, as indicated by a solid black line in Figure 4.27. The local cable thickness is computed perpendicular to the winding path.

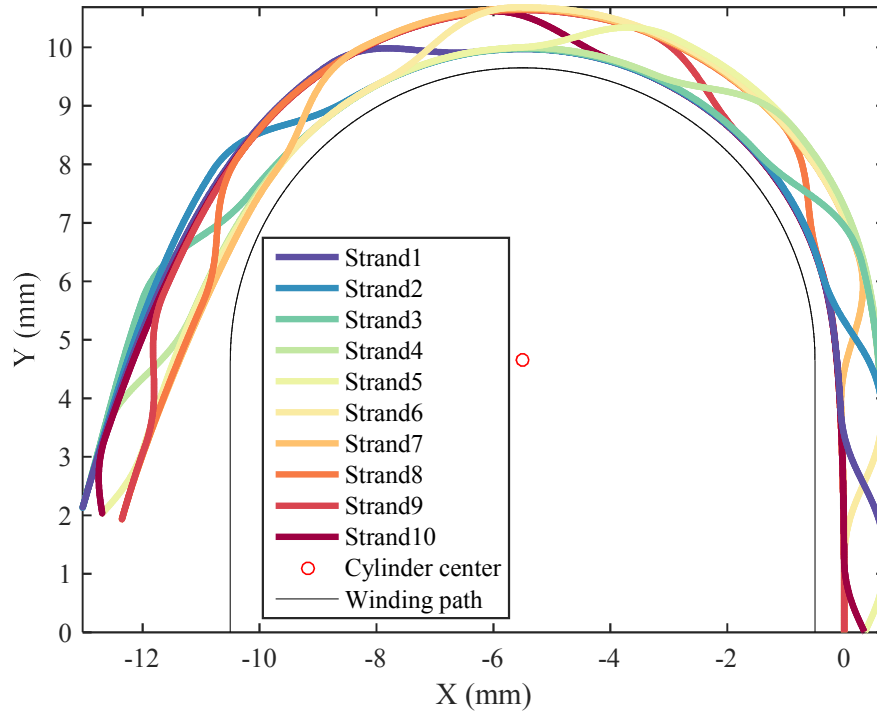


Figure 4.27 Position of individual strands on the XY-plane, and the winding path marked with a solid black line (mm).

The results in Figure 4.28 show the cable thickness, maximum and minimum normal deviation of the cable from the winding path as a function of the cable length. One can see a marked minimal and maximal cable thickness at 16 mm and 21.4 mm of the winding path. The absolute difference equals 0.36 mm, which is 51% of the strand diameter.

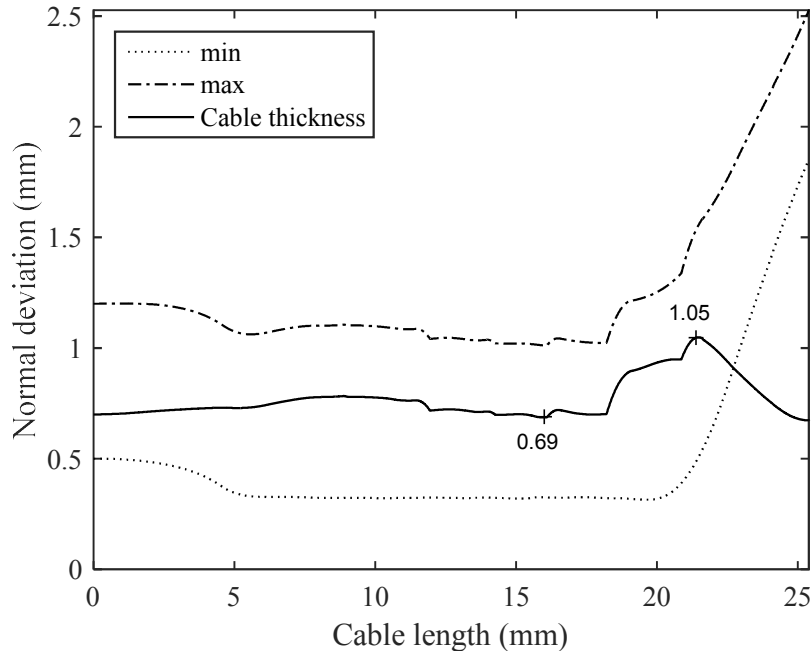


Figure 4.28 Maximal and minimal deviation of the strands from the winding path (dotted and dash-dot line). The cable thickness is shown with a solid line.

4.3. CONCLUSION AND FURTHER DEVELOPMENT

The FEA model of the winding was presented. The material definition, the geometrical simplifications, and the boundary conditions of the winding model are described and discussed in chapter 4.2.1. The challenges of post-processing are addressed by the guide curve analysis. This allows displaying the indicators of the protrusion and the strand pop-out as a function of the cable length (see chapter 0).

The presented model and analysis method allows simulating the winding process, while paying special attention to the Rutherford cable deformation. Although the initial results are encouraging, the model requires further development aiming to increase the amount of strands and maintaining the simulation convergence time. This may be achieved by re-defining the geometry or simplifying boundary conditions.

The current stage of the model development does not allow for a direct comparison with the experimental results shown in [54]. Nevertheless, an investigation of the friction coefficient or material parameters influence on the resulting deformation should be possible. The continuation of the model development would allow to further investigate numerically the observed deformation phenomena. The presented computation allow confirming initial observations only based on FEA. Therefore the main goal was to develop an experimental setup allowing to validate the described deformations.

5. SURFACE DIGITIZATION METHODS

Three technologies are investigated in this chapter allowing digitizing the surface of an examined object. The active thermography is analyzed in chapter 5.1, focusing on determination of relative position of the Nb₃Sn strands localized underneath the standard insulation layers (i.e. S-2 Glass and Mica). Afterwards in chapter 5.2, the spatial resolution of three devices is compared in order to perform the highest quality 3D scan of a winding specimen. The scanners represent laser triangulation and structural light technologies.

5.1. ACTIVE THERMOGRAPHY

The tests were performed in order to investigate the possibility of detecting the position of an individual strand underneath the insulation. The insulation layers include the S-2 glass and Mica. The Active Thermography (AT), non-destructive material testing method, was examined. In this chapter the principle of the AT technique will be presented as well as the results obtained at the West Pomeranian University of Technology in Szczecin (ZUT, Poland) and Federal Institute for Materials Research and Testing (BAM, Germany).

The AT technology principle is based on introducing a heat on the inspected part, and analysis of the thermal image. An energy source is required to generate a thermal contrast detectable by the InfraRed (IR) camera. The object surface temperature is affected by the propagation of the heat flow. The initial surface temperature gradient variation is subtracted from the gathered data after the excitation in order to remove the thermal background and improve the contrast. The detected thermal contrast differences reveal the internal material discontinuities. The excitation source and analysis is determined by the chosen method. There are three main analysis methods: Pulse, Transient and Lock-in.

The pulse measuring principle requires a short energy pulse. High-energy flash systems are most commonly used, e.g. a flash lamp. The main advantage of this inspection method is a short examination time, ranging from less than one second up to few seconds. The temperature contrast error is influenced by the reflections from the environment, the surface geometry variations, the non-uniform heating, and the emissivity variations.

The transient method requires the heat to be applied in a rectangular form. The inspection time is longer, in examined case roughly 20 seconds. This allows the use of a low-cost excitation source, such as a halogen lamp.

The lock-in analysis method requires a periodical harmonic-modulated excitation source. The definition of a precise signal wave requires a dedicated controller. By the modulation of a frequency of an excitation source, the depth range can be adjusted. The measurement time is longer in comparison to the transient or pulse method.

5.1.1. EXPERIMENTAL SETUP

The setup used to perform the AT tests is shown in Figure 5.1. The FLIR® camera model X6550 has been used, with the parameters detailed in Table 5.1. The camera provides an optical stabilization with a drift compensation. The dedicated power supply has been used in order to generate the power for the excitation and the camera. The FLIR® software is utilized to synchronize and control the excitation, and to perform an image analysis. The excitation source is the Hensel halogen lamp, which is capable of operating in the required modes.

Table 5.1 IR camera configuration.

Parameter	Details
Camera	FLIR X6550 sc
Imaging resolution	640 x 512 px
Detector type	Indium Antimonide (InSb)
Aperture	3f
Screen resolution	800 x 480 px
Spectral range	1.5-5.1 μm

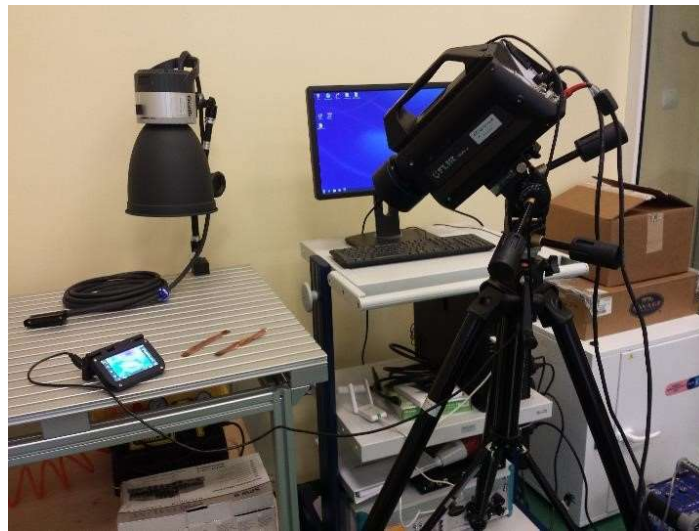


Figure 5.1 The measurement setup used for the AT investigation.

5.1.2. OBTAINED RESULTS

Figure 5.2 depicts an initial undeformed 150 mm-long Nb₃Sn cable sample. In order to study the cable deformation, two specimens were manually deformed. The deformed specimens

were characterized by the side plane openings and strand pop-outs. The initial tests were performed without the insulation, in order to allow visual verification of the results. The deformed specimens are presented on the right side of Figure 5.3.



Figure 5.2 The undeformed thermography specimen, 150 mm-long uninsulated Nb₃Sn cable.

Due to the thermal reflection of the environment, the temperature distribution in the sample induced by a halogen lamp was inefficient. This is caused by the high reflectivity of a copper surface. One can see the higher temperature of the cable, marked in red and white on the LCD in Figure 5.3. Whereas in reality, the surface of the copper was close to the surrounding aluminum table.



Figure 5.3 Uninsulated cable specimens, thermal reflex visible on LCD screen in red and white.

In order to ensure the lower reflectivity of the surface, the black insulation tape was adhered to the cable side plane. The short tape fragment did not change the strand position or cover all the strands, allowing further observation. The tape-insulated specimens are shown in Figure 5.4.



Figure 5.4 The tape-insulated specimens. a) sample A, strongly deformed; b) sample B, slightly deformed.

The pulse AT analysis method has been used to obtain the thermogram of the sample A, shown in Figure 5.5. The figure shows the frames from 0.25 s, 0.5 s, and 0.75 s after starting the test (i.e. halogen impulse). The displayed contrast is adjusted in the post-processing in order to fit a full color range. One can see that the insulation tape has much lower surface reflectivity, resulting in an improved contrast. The temperature distribution shows a high fluctuation between adjacent strands, with visible void volume. The background temperature is displayed in blue color.

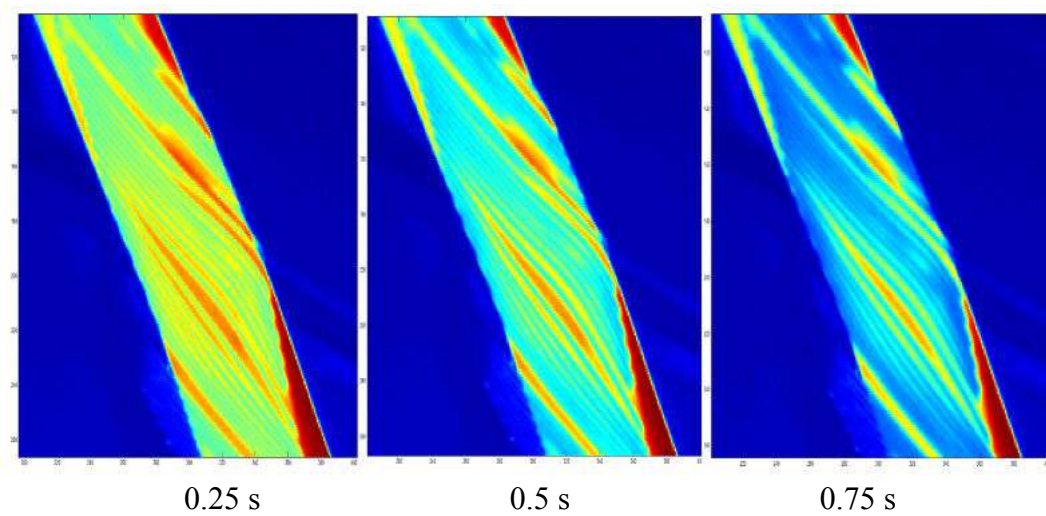


Figure 5.5 The Pulse AT test of sample A indicating the time after triggering the test.

The cable specimen, shown in Figure 5.6, with S-2 glass and Mica insulation was tested. The cable comes from the 11 T project, featuring the dimensions defined in Table 1.1. The pulse, lock-in and transient methods were used in order to obtain the thermograms.

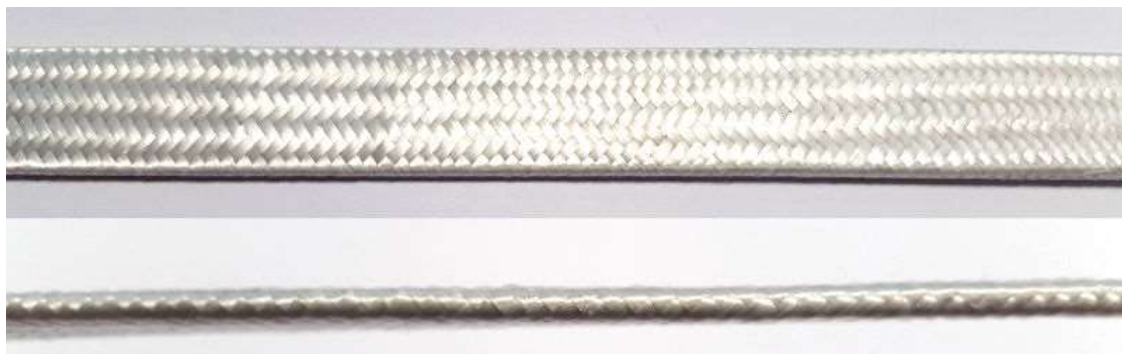


Figure 5.6 Sample C. The Nb₃Sn cable with S-2 glass and Mica insulation.

The thermograms in Figure 5.7 present the results of the AT post-processing. The methods were tested with various strength, amplitude and frequency of the excitation. The presented results include the cable side with the Mica gap. Due to the initial thermograms showing low contrast, the black paint coating was applied on the surface aiming to minimize the surface reflection. The results below include the painted specimen on the left side of each thermogram.

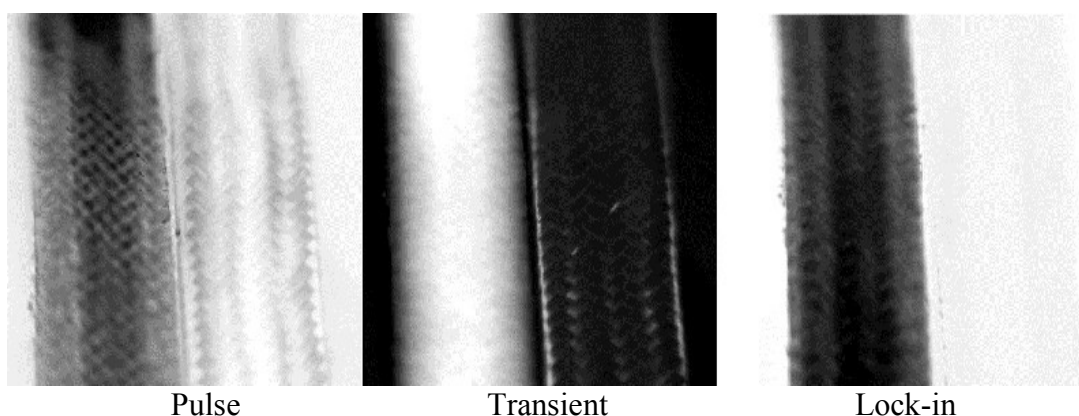


Figure 5.7 Thermograms of insulated sample C with different analysis methods. Specimen painted black on the left side of each thermogram.

The thermograms shown in Figure 5.8 present the results obtained in BAM. Alongside the two Nb₃Sn specimens, one Nb-Ti cable has been tested in order investigate the capabilities of this technology. The Nb-Ti is insulated with the Kapton tape, as described in chapter 1.2.2. Both sides of the specimens were tested. One can see the darker area of the Nb₃Sn cable in Figure 5.8a, resulting from the gap of the C-shaped Mica layer. The Nb-Ti specimen reveals partially the strand position underneath the insulation. One can see the second side of the specimens in Figure 5.8a.

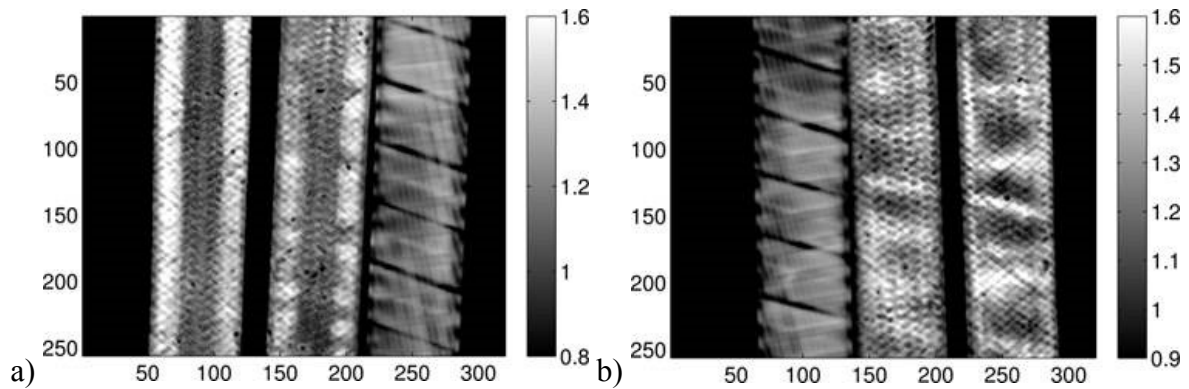


Figure 5.8 The AT analysis of insulated Nb_3Sn and Nb-Ti obtained by BAM. (a) and (b) present two sides of the specimens.

5.1.3. CONCLUSION

The active thermography investigation was performed at the West Pomeranian University of Technology in Szczecin (ZUT, Poland) and Federal Institute for Materials Research and Testing (BAM, Germany). The aim of the tests was to detect the Nb_3Sn strand position underneath the S-2 glass and Mica insulation layers. The results obtained by both facilities, have shown that used AT system is not able to identify the strand position through the insulation layers. This is due to the AT high sensitivity on temperature dissipation and heat transfer disturbance that occurs within the specimen's volume.

The S-2 Glass and Mica insulation layers are hindering the temperature measurement. The recorded temperature distribution on the S-2 Glass surface was highly homogeneous. The void volume inside the tested specimen is filled with air, featuring low temperature conductivity. As a result, the heat dissipates into a large volume, before being detected by the camera sensor. In addition, the S-2 glass sleeve features a structure braided of $9\text{ }\mu\text{m}$ -diameter yarns. This forms a complex outer surface, where the temperature radiation is additionally distorted before reaching the camera. Following these conclusions, the further investigation of a technology was abandoned.

5.2. SURFACE SCANNING DEVICES

The conducted research is aiming to digitize the position of each strand of the winding specimen presented in Figure 6.4, with use of the devices available on the market. The tested devices represent two principles of a surface scanning, i.e. the laser triangulation (described in chapter 6.2.3) and the structural light [59]. In addition to the primary surface scanning technology, the presented devices utilize auxiliary methods in order to obtain a final workspace dimensions, e.g. photogrammetry or rotary encoders. The evaluation of the

obtained scans consists of a visual and numerical comparison of the spatial resolution and amount of details. One can see the list of tested devices in Table 5.2. The following description intends to provide a brief introduction into the considered scanning techniques.

Table 5.2 The tested scanning devices.

Device	Technology	Auxiliary system
Faro [®] Scanarm HD	Laser triangulation	Rotary encoders
Leica [®] Absolute Scanner LAS-20-8	Laser triangulation	Rotary encoders Photogrammetry
Leica [®] T-Scan 5	Laser triangulation	Rotary encoders Photogrammetry
Gom [®] Atos	Structural light	Photogrammetry

The Faro[®] Scanarm HD is a manually operated manipulator with the rotary encoders on each rotational joint providing the base positioning of the end-effector. The triangulation laser head with articulated mirror is attached to the end-effector. This allows positioning the cloud of points collected with the laser head, and the arm's reference coordinate system.

The tested Leica[®] devices consists of two main components, i.e. the laser tracker tripod (shown on the left of Figure 5.9) equipped with a high performance camera, and a handle (shown on the right of Figure 5.9) with a laser head. The tripod allows defining the handle position and orientation and provides the reference coordination system. The position of the handle is obtained by tracking the mirror in its center. In order to define the orientation of the handle, the IR diodes on its surface are used for photogrammetric transformation [59].



Figure 5.9 Specimen scanning with Leica[®] LAS device. Left: tracking tripod. Right: Scanning handle.

The Atos[®] device, shown in Figure 5.10, consists of a light source and two cameras. The measurement is based on the fringe patterns projected on the object. Their distribution is recorded with two cameras, in order to obtain the depth information. The consecutive scans are patched together by the additional markers used for photogrammetric fitting. The obtained resolution and available workspace is dependent on a chosen lens system.

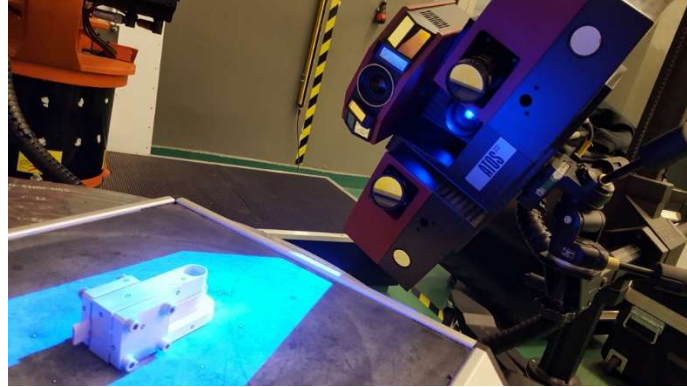


Figure 5.10 Specimen scanning with Gom[®] Atos device.

5.2.1. EVALUATION

The scans were post-processed with the provided manufacturer software, obtaining the 3D meshed surface of the winding specimen. The obtained scans are shown in Figure 5.11 to Figure 5.14. Due to the three-dimensional nature of the results, it was challenging to choose the benchmark method and compare the scans. It is considered that the obtained higher spatial resolution (i.e. realistic specimen topology representation) results with a larger amount of visible cable surface undulations.

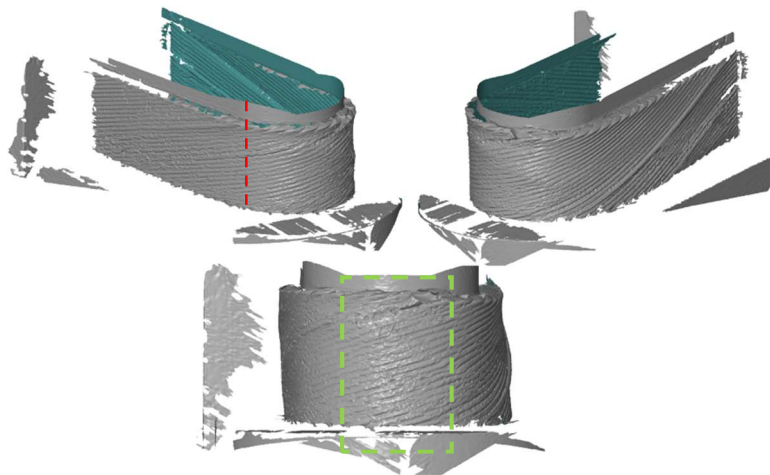


Figure 5.11 Faro[®] Scanarm HD. Meshed specimen scan for a device comparison.

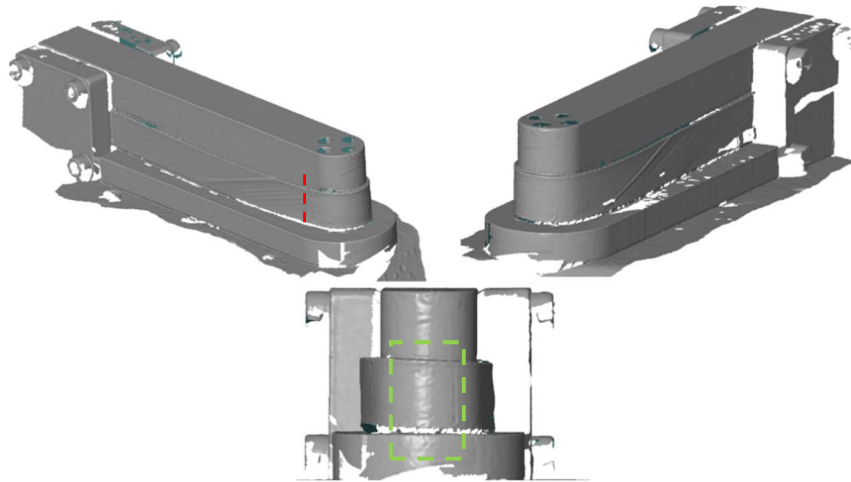


Figure 5.12 Leica® LAS. Meshed specimen scan for a device comparison.

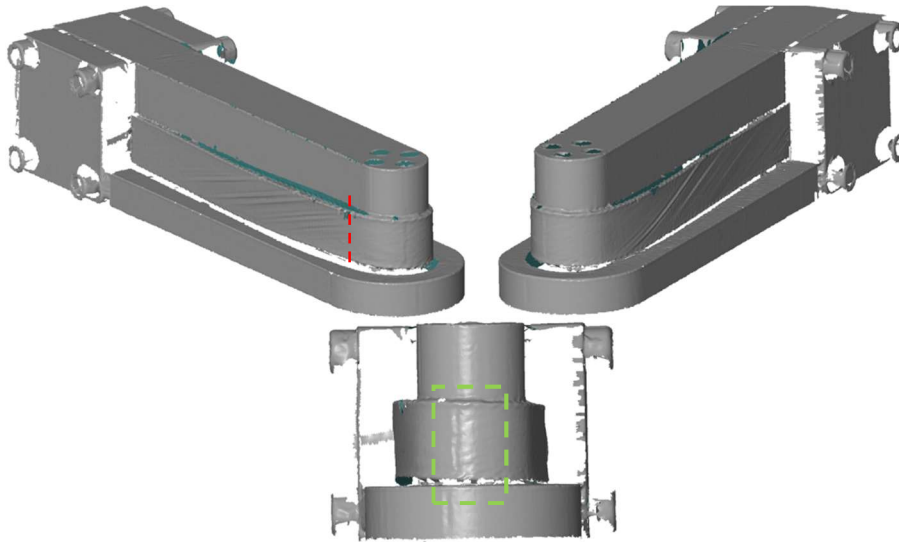


Figure 5.13 Leica® T-Scan 5. Meshed specimen scan for a device comparison.

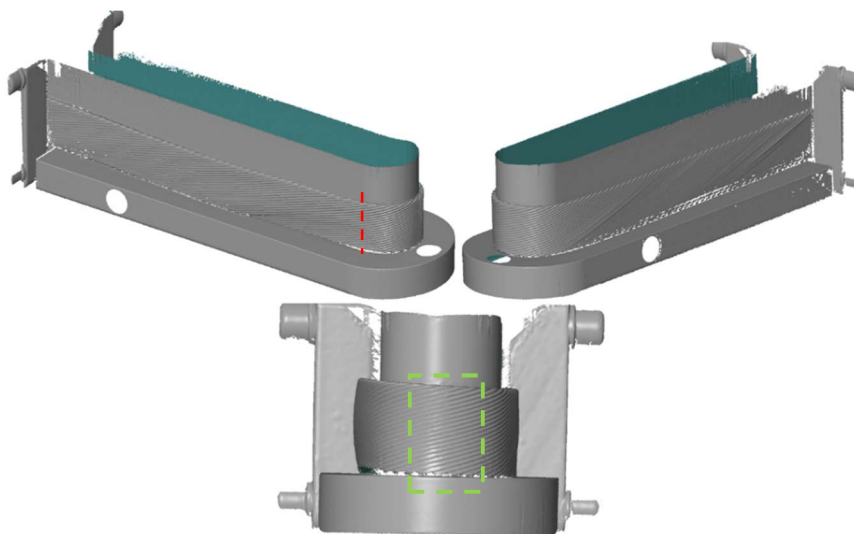


Figure 5.14 GOM® ATOS. Meshed specimen scan for a device comparison.

The green dashed rectangle shown in the Figure 5.11 to Figure 5.14 defines the area of interest, displayed side by side in Figure 5.15. Whereas the data overlapping the red dashed lines is shown in Figure 5.16.

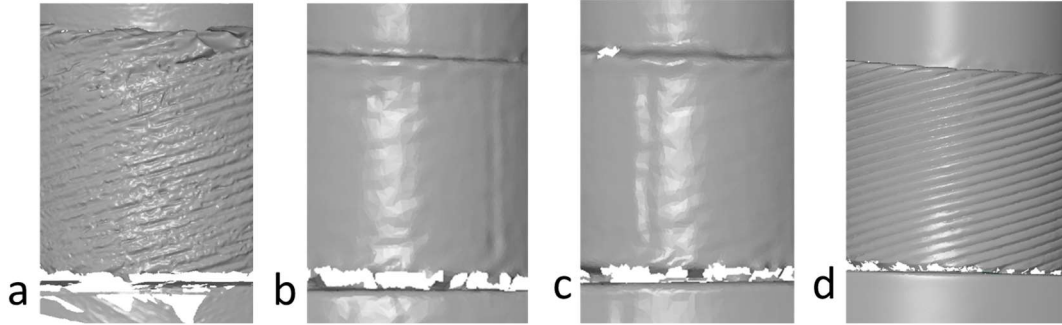


Figure 5.15 Cable area close-up of scans with: a) Faro® Scanarm HD, b) Leica® LAS, c) Leica® T-Scan 5 and d) Gom® ATOS.

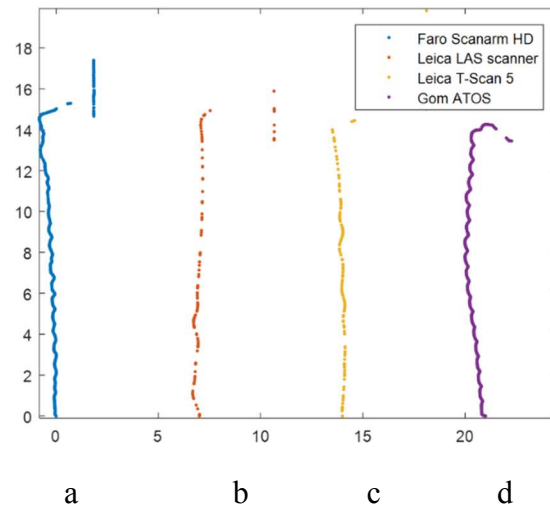


Figure 5.16 Scan cross-section of cable area (in mm). a) Faro® Scanarm HD, b) Leica® LAS, c) Leica® T-Scan 5 and d) Gom® ATOS.

Observing the Figure 5.15, one can see a significant difference in the spatial resolution of the cable region. In Figure 5.15 the b) and c) scans display the cable region as nearly flat surface. The strands are blurred and impossible to separate. In contrary, one can easily distinguish the strands in Figure 5.15a and Figure 5.15d where the latter is the most detailed.

The Figure 5.16 is generated in order to compare the vertical line resulting as a cross-section of each meshed surface. The interesting region represents the cable, ranging roughly from 2 mm to 14 mm on the vertical axis. The higher amount of points is a result of a higher mesh density of the scan, thus more data describing the cable spatial position. The important feature

defining the device performance can be observed as the amount of undulations in the cable region. This is a result of a higher spatial resolution, thus better cable representation. The best cable representation is obtained by d), followed by a), c) and b).

5.2.2. CONCLUSION

In conclusion, both tested technologies proved being capable of scanning the specimen wound with the Rutherford cable featuring the 0.7 mm strand diameter. The resulting scan quality varies for each tested device, and the best obtained result is achieved with the Gom[®] Atos, followed by the Faro[®] Scanarm HD, Leica[®] T-Scan 5 and Leica[®] LAS.

The scan quality of the Gom[®] Atos is sufficient, therefore this device was utilized for the initial verification of the in-house scanner (as described in chapter 6.2.2). However, two factors were limiting the use of this device during the specimen analysis. The obtained scan does not feature any structure allowing for an efficient deformation analysis. The cloud of points needs to be post-processed in order to define the cable area of the specimen and relate the deformation to the sample holder surface. This is a time-consuming and manual process. Additionally, the scanning process requires manual displacement of the device around the measured piece.

Due to these reasons, an in-house scanner was designed and built, providing the high quality specimen scan in a programmable process, described in the following chapter.

6. DEVELOPMENT OF THE WINDING TEST EQUIPMENT

In order to wind specimens in controllable environment, it was essential to develop the device allowing to adjust the winding conditions. The description of the winding device is presented in chapter 6.1. The obtained winding specimen required a geometrical analysis in order to assess the cable deformation, therefore the scanning device was designed. The winding scanner description is shown in chapter 6.2. The winding specimen was assessed according to the methodology described in chapter 6.3, which provided indicators capable to represent three types of cable deformations. In addition, the cable springback angle was measured according to the procedure shown in chapter 6.4.

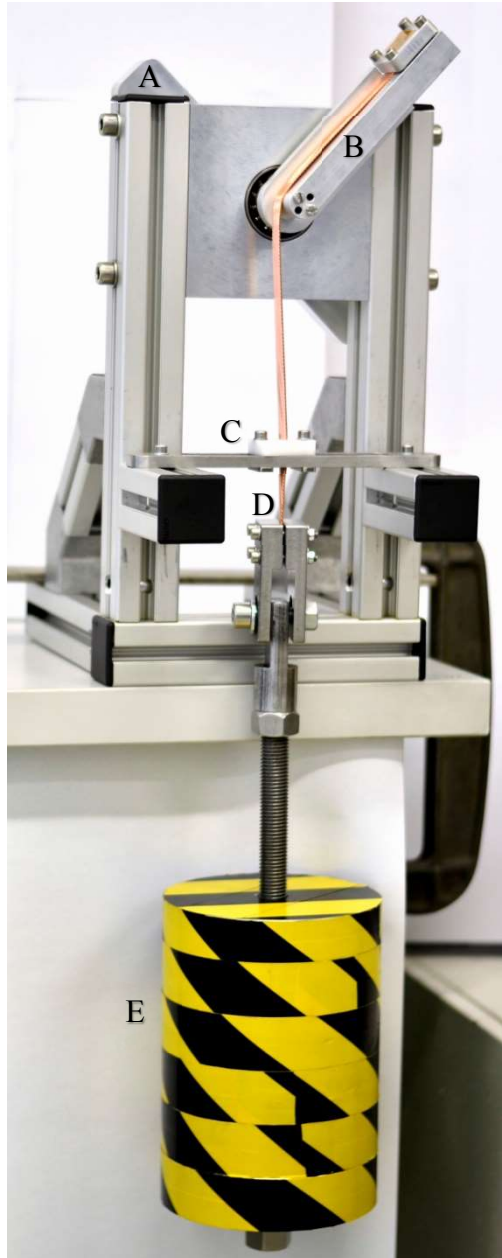
6.1. WINDING FRAME

The Winding Machine (WM), shown in Figure 2.3, is designed in order to provide consistent conditions throughout a long-duration winding process and to handle a long batch of the cable. The procedure requires on-site presence of at least two operators, and short winding occupies the machine for at least one working day. The cable deformation is related to several factors, namely: the type of strand and cable (see chapter 1.2.2), the winding function (defined in equation (2.10)), the human interference (as stated in chapter 2.3), and the type of bending (see Table 2.2). It is necessary to control all these factors, in order to provide the repeatable and adjustable conditions during specimen preparation. Therefore the dedicated winding test bench was developed.

The Winding Frame (WF), shown in Figure 6.1, was developed in order to perform a comparative study of the mechanical deformation of the Rutherford cable due to winding.

The WF features the following functions:

- The winding process kinematics of the WM including the tensioning system;
- Compact laboratory dimensions;
- Single-operator usability;
- Adjustable winding parameters and repeatable conditions;
- Capability of providing a representative specimen for the deformation study.



- A. Winding crank – manually turned by the operator in order to wind the specimen.
- B. Winding sample holder – providing the support to the cable.
- C. Cable angular guide – maintaining the cable feeding position and orientation.
- D. Winding mass clamp – the frictional clamp between the cable and tensioning mass.
- E. Winding mass – adjustable load providing the cable tension.

Figure 6.1 The Winding Frame. Dimensions including the hanging mass: 50 x 100 x 50 (cm).

6.1.1. SPECIMEN PREPARATION

In order to reproduce the winding process described in chapter 2, it was essential to develop the solution offering a suitable tensioning system. In the WM, the tension is provided by the magnetic break, which requires the force measurement system, the electric motor and an over length of the cable on the spool. This arrangement has an impact on the simplicity of the equipment. Therefore, the winding frame design is based on a premise of altering the

longitudinal winding mandrel axis from a horizontal to vertical, thus aligning the required tension direction with the gravity. The tension force is provided by the mass suspended on the lower end of the cable, and maintained throughout the specimen winding. The specimen is rotated 180° about its cylinder, as shown in Figure 6.2. The operator is able to wind a 40 cm-long cable specimen by manually turning the crank (marked A in Figure 6.1) without any auxiliary system. The process is easily controlled and fully mechanical.

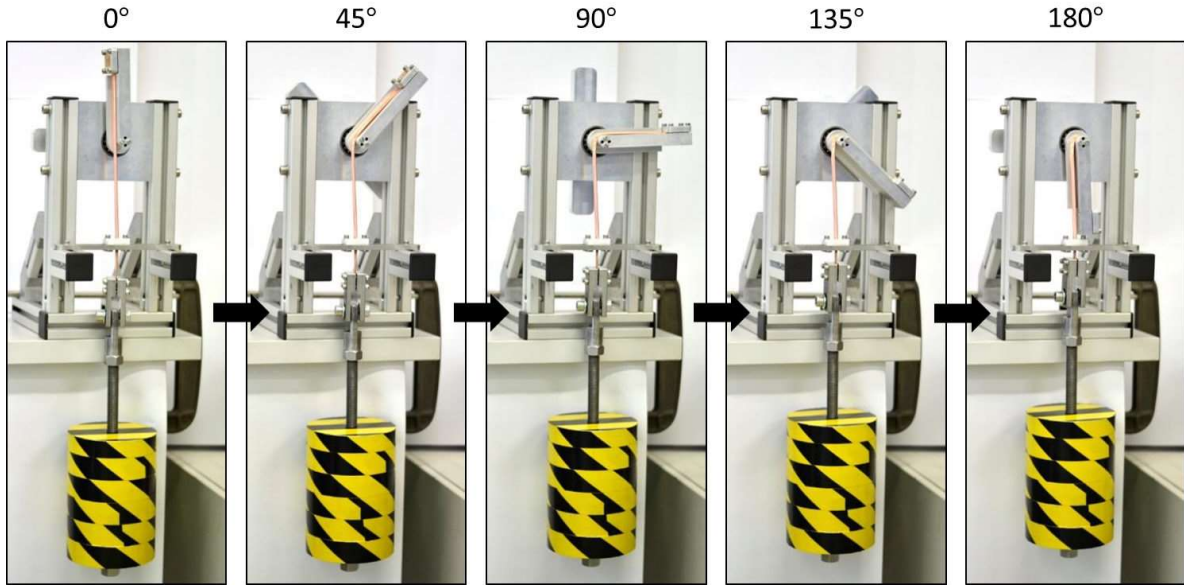


Figure 6.2 Specimen winding example. Five steps of sample holder rotation from 0° to 180°.

In Figure 6.2. The 30 kg winding mass (E in Figure 6.1) is raised up, while the cable is wound in the soft-bending configuration on the specimen cylinder (see Table 2.2). Throughout the winding, the angular guide (C in Figure 6.1) is in contact with the cable, providing the consistent position and orientation of the cable in fixed distance from the cylinder center. This is to avoid the unwanted twisting of the cable under tension opposite to its lay.

One can see in Figure 6.3 the comparison of kinematic schemes of the WM (on the left side) and the WF (on the right side). The sample holder is designed based on premises of: representing the easy-way winding, minimizing the representative length of the cable, and minimizing the complexity of a specimen winding to 1 Degree of Freedom (DOF). The simplification of the winding conditions eliminates the need of rotating the mandrel (angle θ_m), and the spool height adjustment Z_4 . The translation of the spool on the XY is realized by the rotation of the specimen about its cylinder axis (A_f rotational DOF).

One can see the ‘resulting displacement’ dashed line, shown in Figure 6.3, which shows the relative movement of the spool and mass around the fixed pole. In both cases, the relative displacement is comparable.

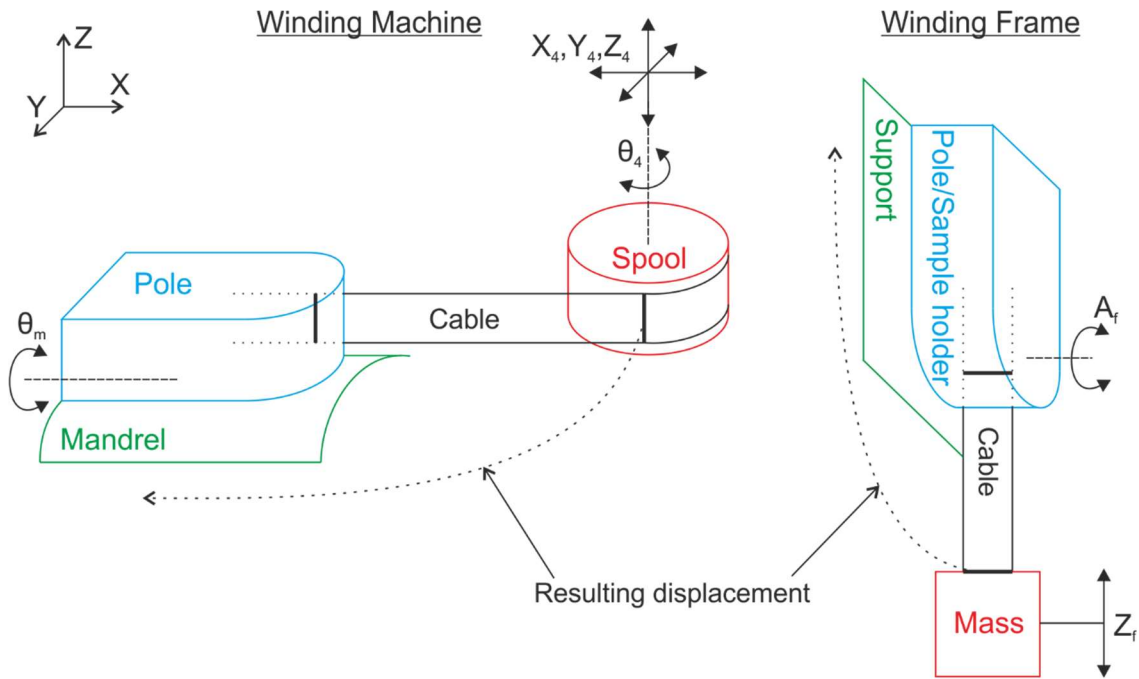


Figure 6.3 The kinematics scheme of the Winding Machine and the Winding Frame.

The specimen wound with the 11 T copper cable is shown in Figure 6.4. The envelope, strand pop-out and protrusion deformations can be seen. The straight section of the winding surface is 110 mm-long, which is 10 mm longer than the pitch length of the tested cables (roughly 100 mm). It is considered as the minimal representative length that allows studying the Rutherford geometry. It was essential to use a possibly short length of the cable while assuring good representation of the deformation. The diameter of the cylinder is 20 mm, which is the average of two extreme diameters of the 11 T pole (minimal 15.4 mm and maximal 25 mm, shown in Figure 4.12).

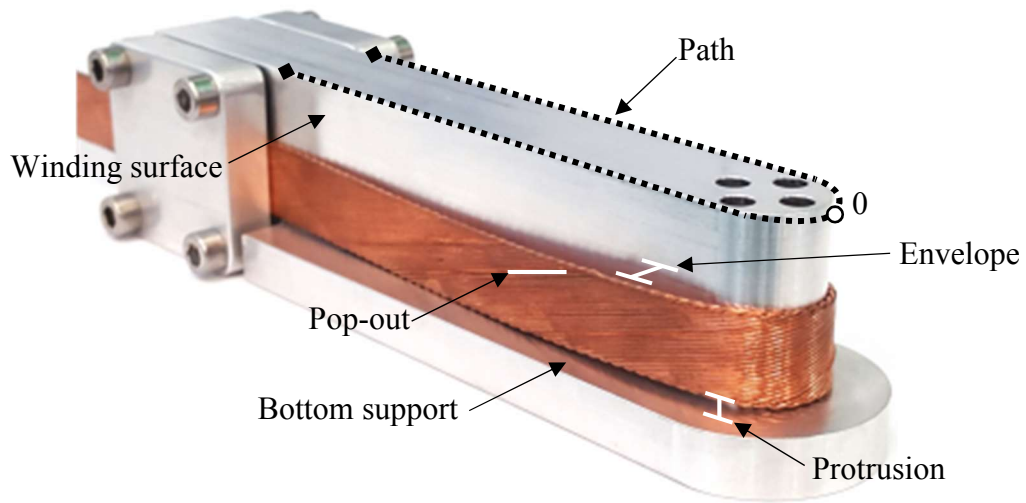


Figure 6.4 Winding specimen d20L160 with visible cable deformations, wound with the 11 T Cu cable.

The ‘path’, marked in the Figure 6.4 with a dotted line, defines the winding surface, with its origin situated at the tip of the cylinder. It is used afterwards as the reference for the deformation analysis, explained in chapter 6.3. There are three cable deformation types to be observed in the figure above:

1. Envelope – a distance between the winding surface and the cable;
2. Pop-out – a local alteration of the cable thickness, caused by at least one strand coming out of the cable side plane;
3. Protrusion – a distance of the cable from the bottom support.

One can see that the 11 T coil winding defects described in chapter 2.4 are reproduced with use of the WF.

6.1.2. ADJUSTABLE PARAMETERS

The WF design allows adjusting the parameters of the specimen winding that are considered most relevant for the study. The available modifications are listed in Table 6.1 and defined on the draft in Figure 6.5.

The parameters are grouped in four categories: frame, pole, run and cable. The frame group includes the position and orientation of the angular guide as well as the tensile load, which is the weight of the suspended mass. The angular guide is made of the PTFE in order to lower the contact friction of the guide-cable interface. The pole category defines the dimensions of the sample holder, e.g. the cylinder diameter or the clamp length. The testing cycle can be differentiated by the three parameters. The direction represents the rotation of the sample holder around the cylinder axis, where a counterclockwise specimen rotation (i.e. a clockwise

winding) signifies the favourable winding direction. Consequently, the opposite rotation is defined as the unfavourable. The cable category defines the precut length of the cable used for winding.

Table 6.1 The Winding Frame parameters.

Group	Designation		Symbol	Unit
Frame	Angular guide	X position	Ax	(mm)
		Y position	Ay	(mm)
		Z position	Az	(mm)
		angle	Aalpha	(°)
		thickness	At	(mm)
		aperture	Aa	(mm)
	Tensile load		M	(kg)
Pole	Identification		Pid	-
	Cylinder diameter		Pd	(mm)
	Clamp length		Pc	(mm)
Run	Direction	Favourable - 1	Dir	-
		Unfavourable - 0		
	Mandrel support	Yes - 1	Sup	-
		No - 0		
	Cylinder surface	Material	Mat	-
		Friction coeff	μ	-
Cable	Pre-cut cable length		L	(mm)

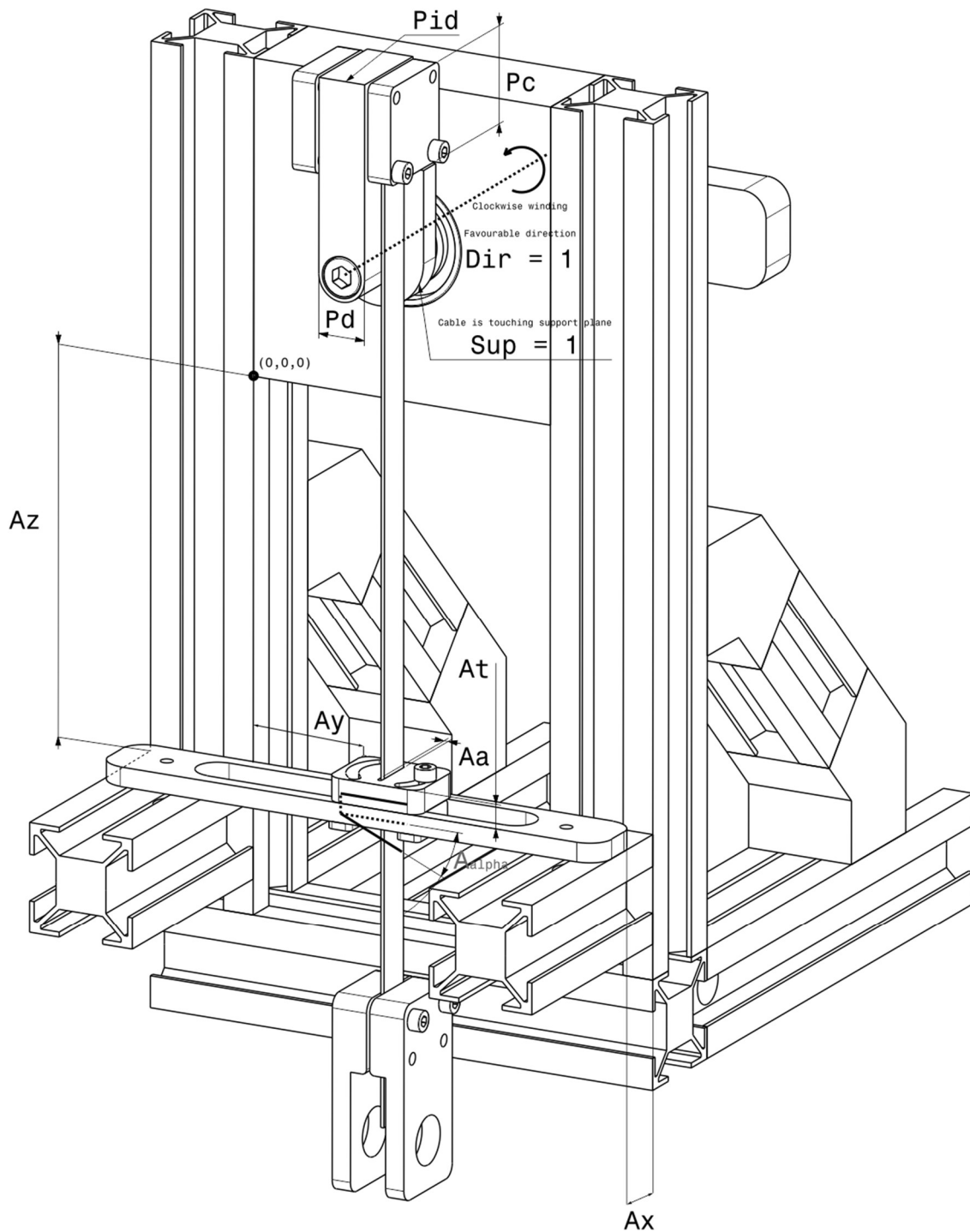
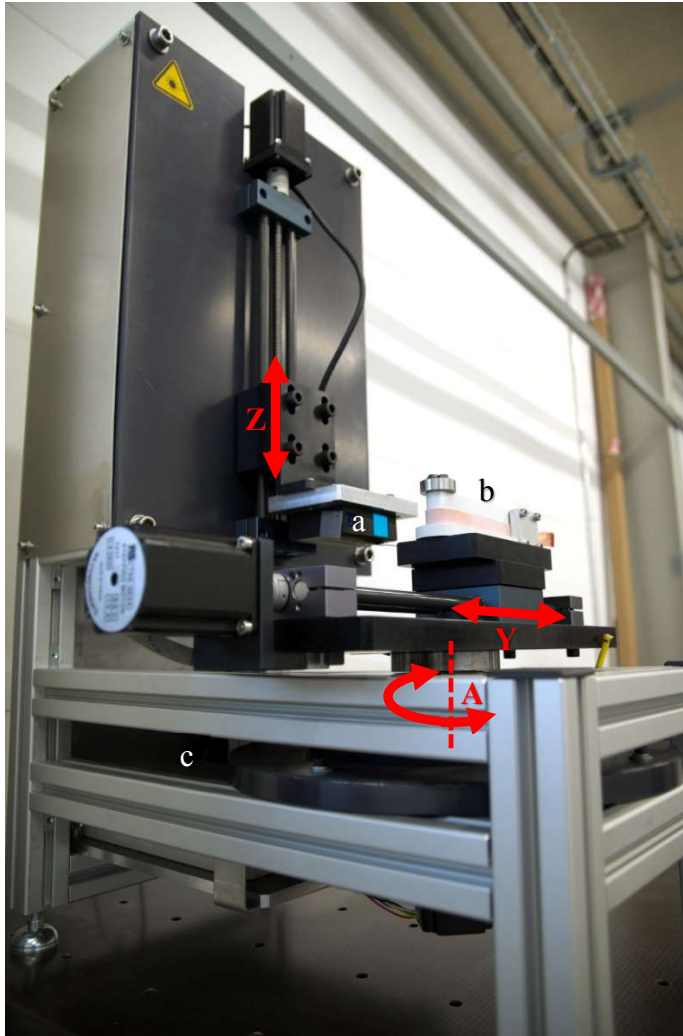


Figure 6.5 Definition of the adjustable parameters of the winding frame.

6.2. WINDING SCANNER

The Winding Scanner (WS) was designed, aiming to provide the high quality specimen surface digitization in a structured and automatic process, in order to quantify the observed cable deformation. The WS, shown in Figure 6.6, is a three DOF device allowing performing a three-dimensional scan of an object with use of the triangulation laser head.

The main frame of the scanner is made of Bosch® aluminum profiles. The monolithic structure consist of two assemblies, i.e. the base platform and the measurement column. The base platform houses two DOF allowing to translate horizontally and rotate the specimen table, as indicated by A and Y in Figure 6.6. The measurement column contains of one DOF, which allows displacing the measurement head vertically, as shown by Z in Figure 6.6. The measurement head is a Panasonic® HL-C208B. The choice of the laser device was preceded with a market research. The evaluation is presented and discussed in chapter 6.2.3, followed by the technical specification in Table 6.4. The actuators used in order to execute the kinematics are Direct Current (DC) stepper motors. The same motor model is used for all DOF, featuring 1.8° step angle and 1.32 Nm of holding torque for 9 V driving voltage. One can see the winding scanner mechanical characteristics shown in Table 6.2.



- a. Laser head – Panasonic® HL-C208B.
- b. Winding specimen (Ø20 mm cylinder).
- c. Control box – 9 VDC and 24 VDC power supplies.

Figure 6.6 The winding scanner with main features (a, b, and c) and indicated DOF (Y, Z, and A).

Table 6.2 The winding scanner mechanical features.

Axis	A	Y	Z
DOF	Revolute	Prismatic	Prismatic
Motors	9VDC Stepper motor	9VDC Stepper motor	9VDC Stepper motor
Motor step (°)	1.8	1.8	1.8
Motor peak torque (Nm)	1.32	1.32	1.32
Purpose	Table rotation	Table horizontal translation	Laser head vertical translation
Transmission	Direct coupling	Lead screw: 2 mm per turn	Lead screw: 2 mm per turn
Positioning resolution	1.8°	0.01 mm	0.01 mm

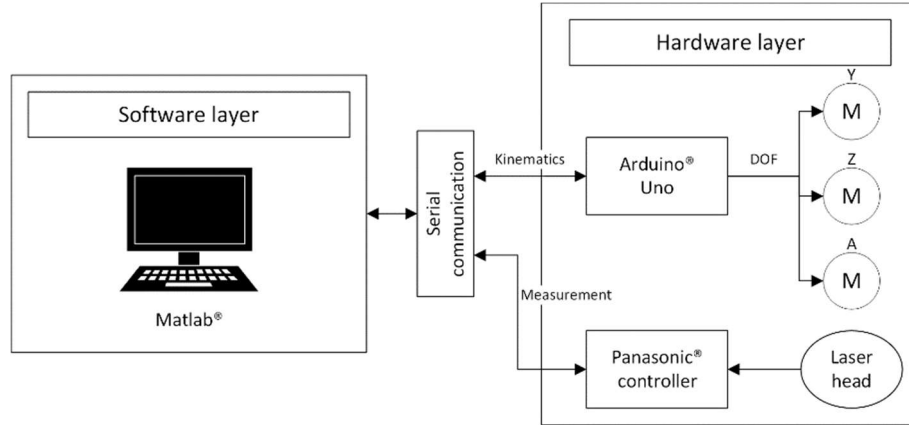


Figure 6.7 The winding scanner control scheme.

The WS is controlled with the Matlab® software running on the PC. The control system consists of two communication branches operating in parallel, i.e. the kinematics and the measurement, as can be seen on the scheme in Figure 6.7. The communication is handled via the RS232 serial communication protocol. The Arduino® Uno board and the Motor Shield v1.2 extension are used in order to control the motors. Two motor shields had to be used due to the limitation of maximal two DC Stepper motors per shield. Two switched-mode power supplies were used, providing the 9 V for the motors, and the 24 V for the laser head and the Panasonic® controller. The obtained torque of the motors is sufficient for realizing the programmed movement and maintaining the position. Utilizing the stepper motors reduced the need of using the additional sensors providing the position feedback.

The mechanical scheme of the WS is shown in Figure 6.8. The translational DOF (Y and Z) are realized by driving the leadscrew with the attached carriage. The rotational DOF (A) is obtained by direct coupling of the motor and the shaft of the transferring the momentum directly to the specimen table.

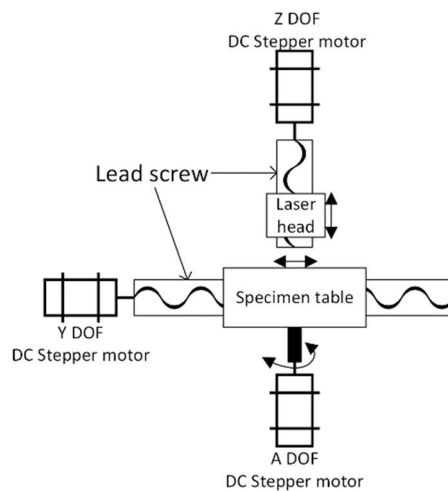


Figure 6.8 The mechanical scheme of the winding scanner.

In order to eliminate the oscillations hindering the measurement quality, the scanning process is semi-static. The distance from the sensor to the specimen is measured when the motors maintain a steady position. After a successful measurement, the movement is continued. Additionally, the scanner is situated on a sturdy table featuring a welded frame and heavy tabletop. This provides a solid support and passive vibration insulation with respect to external sources.

6.2.1. OPERATION PRINCIPLE

The obtained scan is a representation of the outer surface of the specimen, in form of points with the identified position in three-dimensional space. The specimen scan is assembled of lines, i.e. group of measurement points collected during one vertical passage of the laser head. One scanned line is shown in Figure 6.9. Each line is assigned to the position on the winding path (shown in Figure 6.4) according to the measurement step. The perpendicularity of the laser beam in the cylindrical segment of the specimen is provided by the rotation of the table, as shown in Figure 6.10c and d. The initial analysis of the scan separates the three segments of the specimen: the cable, the winding surface and the bottom support (defined in Figure 6.4). The scanned line is normalized with the winding surface segment. One can see the winding surface in Figure 6.9, featuring zero in the vertical axis. This method allows obtaining a higher scan reliability by keeping it less sensitive to the environmental conditions, like vibrations or airflows.

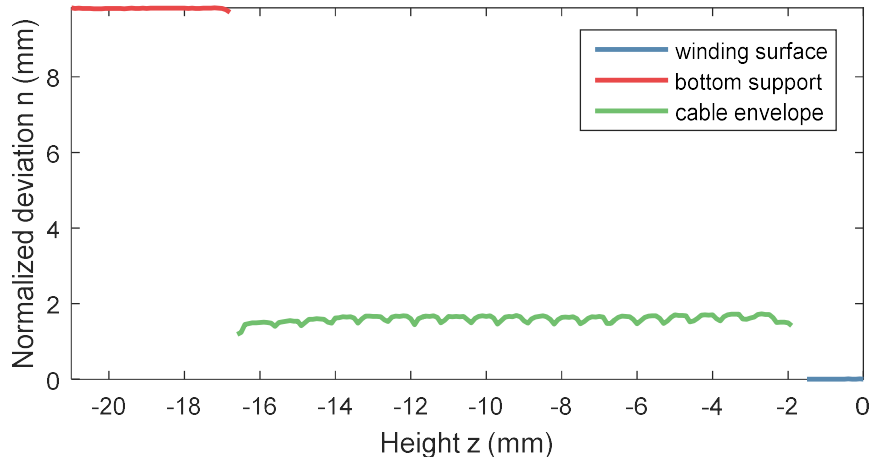


Figure 6.9 One scanned line of the winding specimen.

The specimen position during the scan is defined in three segments. First and last are longitudinal displacements translating the table and specimen between the cylinder quadrants and the winding path edges, those positions are depicted in the Figure 6.10a, b, e, and f. The middle part consists of the 180° table rotation, shown in the Figure 6.10c and d.

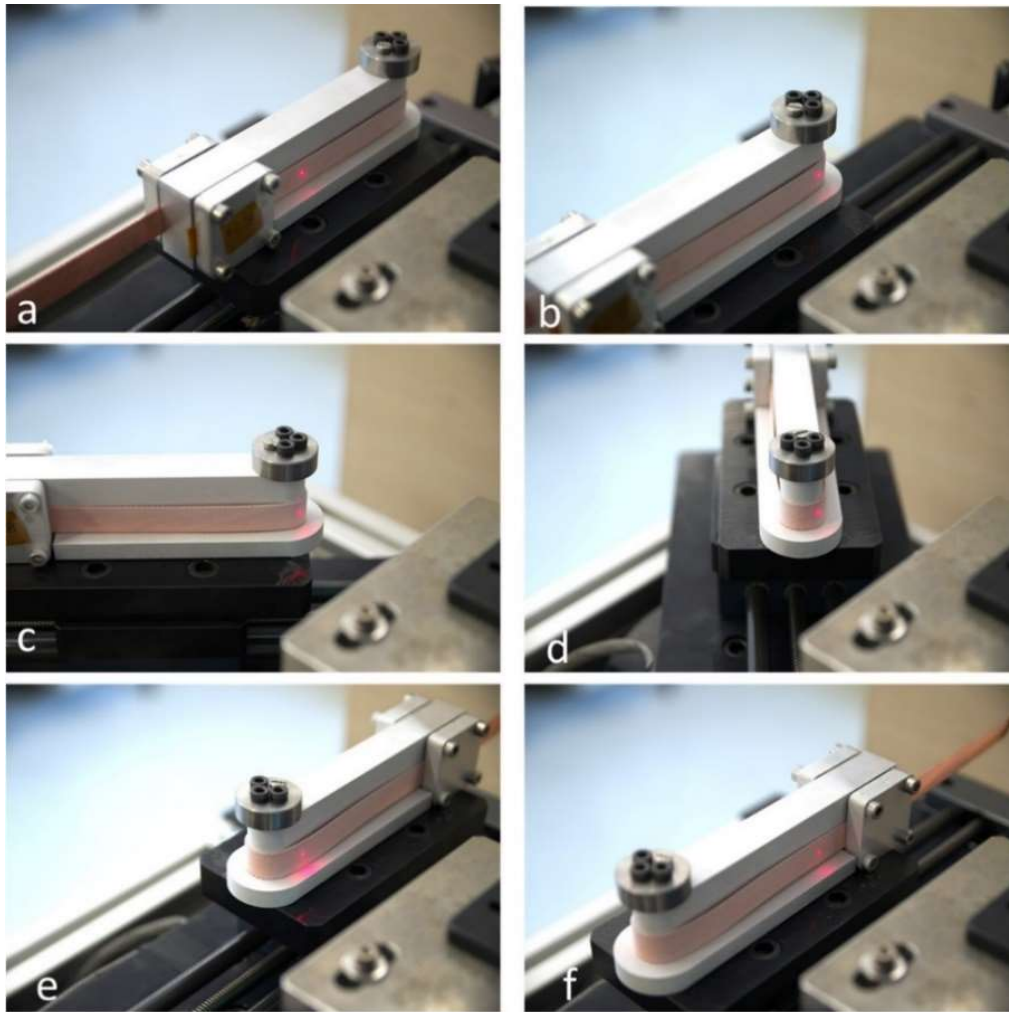


Figure 6.10 Depicted table displacement during the scan. (a) and (b) shows the table translation while scanning the left side of the specimen; (c) and (d) shows the table rotation while scanning the cylinder segment of the specimen; (e) and (f) shows the table translation while scanning the right side of the specimen.

The three-dimensional Cartesian coordinate system interpretation of the scan assembled of 91 vertical lines is shown in Figure 6.11. One can distinguish the points describing the cable area, the winding surface above, and the bottom support below the cable. The resolution of the scan in the longitudinal direction, i.e. along the winding path, can be adjusted by defining the steps of the table longitudinal displacement and rotation. The displacement steps of the laser head define the vertical resolution.

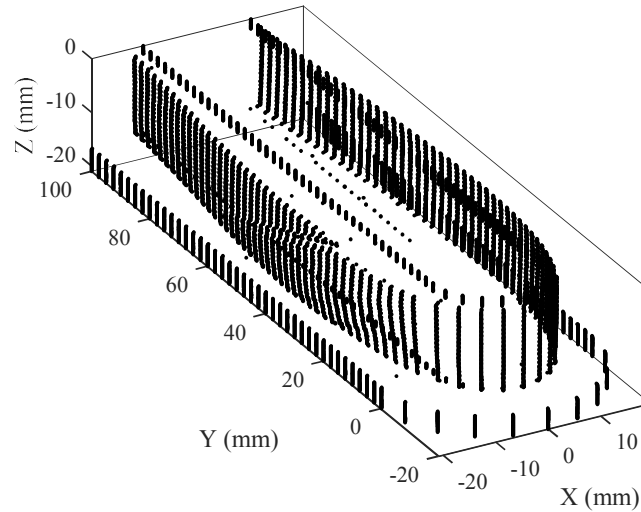


Figure 6.11 Three-dimensional scan of a winding specimen assembled of 91 vertical lines. Sample holder cylinder diameter equals $\varnothing 20$ mm.

6.2.2. MEASUREMENT VALIDATION

In order to determine the accuracy of the scan, the comparison with a market device was performed. The WS was compared to the scanner considered the best in given work conditions i.e. the Gom[®] Atos, as discussed in chapter 5.2. Five specimens were wound with the same cable and winding parameters and scanned with WS and Atos. One can see the wound specimens prepared during the test in Figure 6.12. Four specimens are wound with the uninsulated cable (from b to e), and one is wound with the insulated cable (a) in order to test the capabilities of both systems. Provided the fact that the optical methods perform less in combination with reflective surfaces, the evaluation was focussing on the uninsulated specimens.

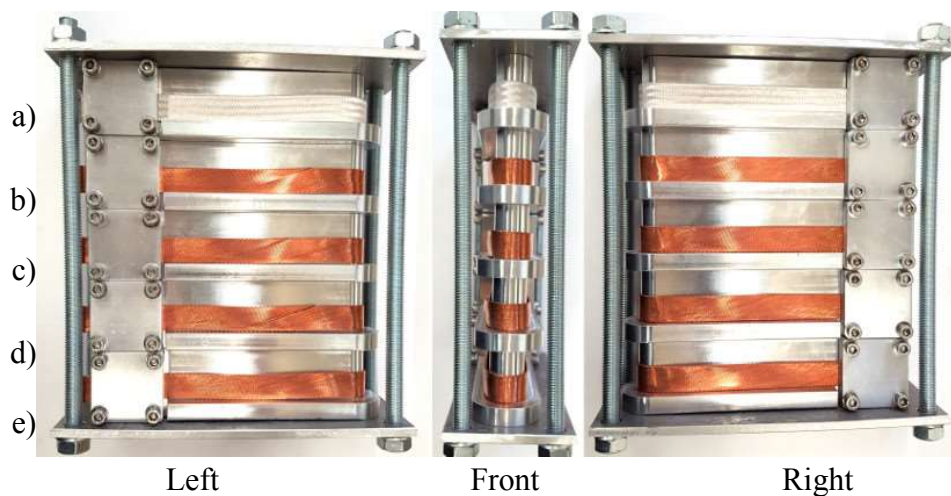


Figure 6.12 Views on five winding specimens. Wound with insulated cable (a) and uninsulated cable (b to e).

The scanning setup including the Atos device is depicted in Figure 6.13. Due to the reflective surfaces, i.e. the aluminum (sample holder) and copper (cable external layer), the scan contained a substantial amount of noise. Consequently, the surface of the specimens were coated with a layer of a chalk powder. The substance is applied manually with a spray, and can be noticed as a thin whitening layer on the specimen.

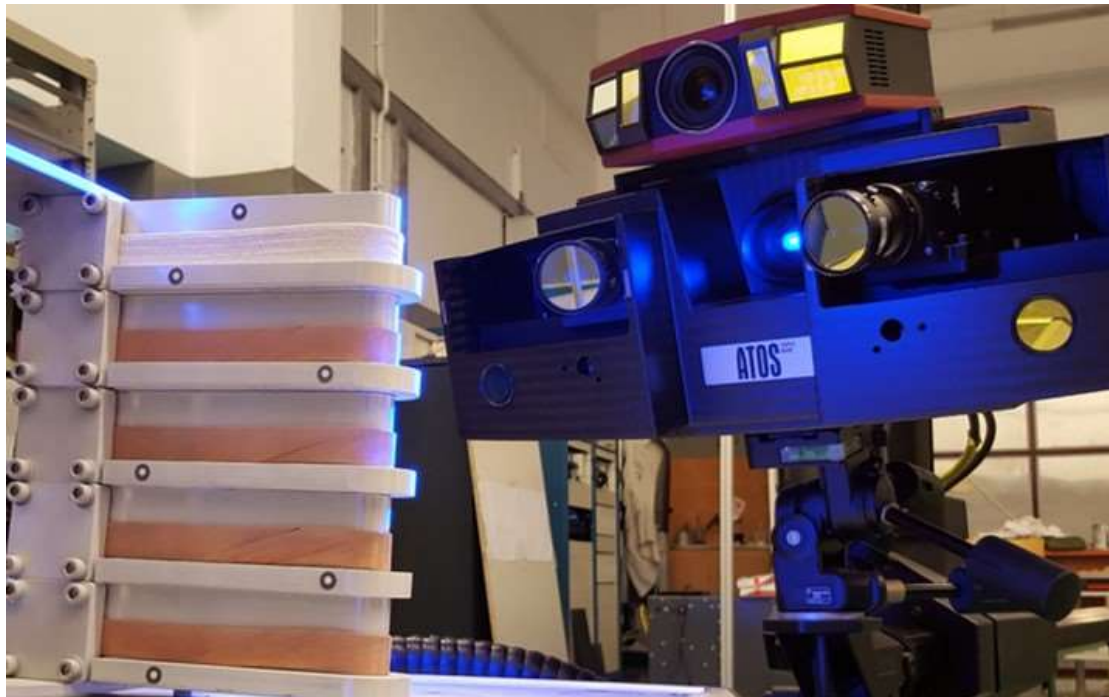


Figure 6.13 Scanning process of specimens with Gom® Atos. Left: winding specimens. Right: Gom® Atos scanner.

The left side of the resulting Atos meshed scan is shown in Figure 6.14. The high resolution of the scan allows distinguishing the strand pop-out and protrusion occurring in the similar area of the specimens. The cable deformations are marked with white and blue arrows respectively.

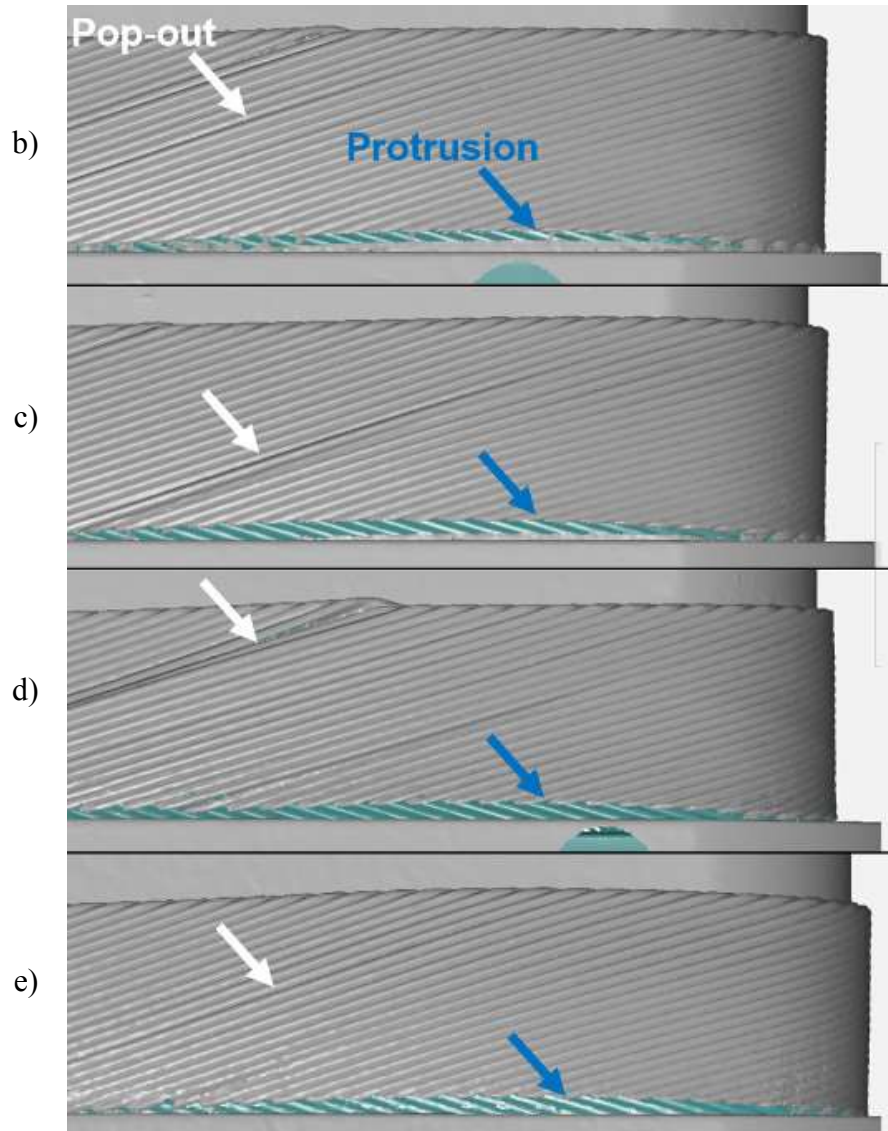
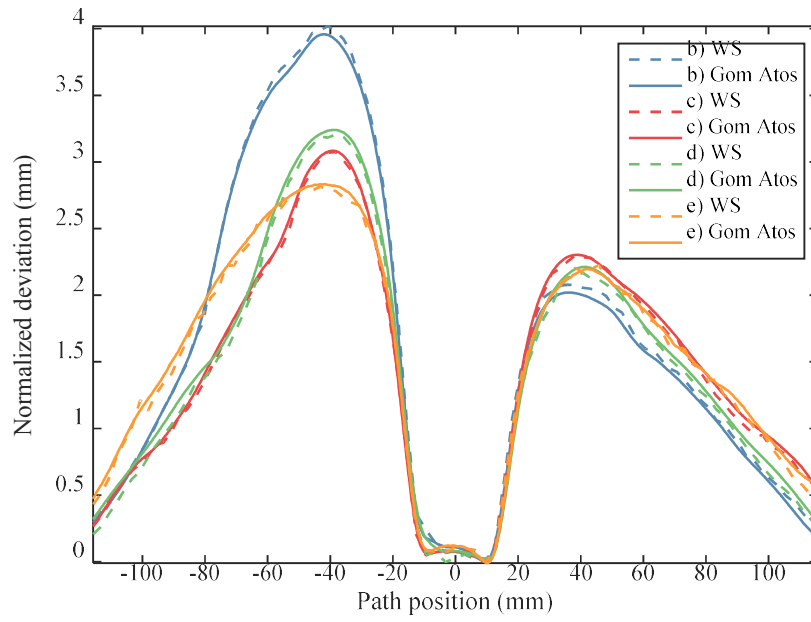
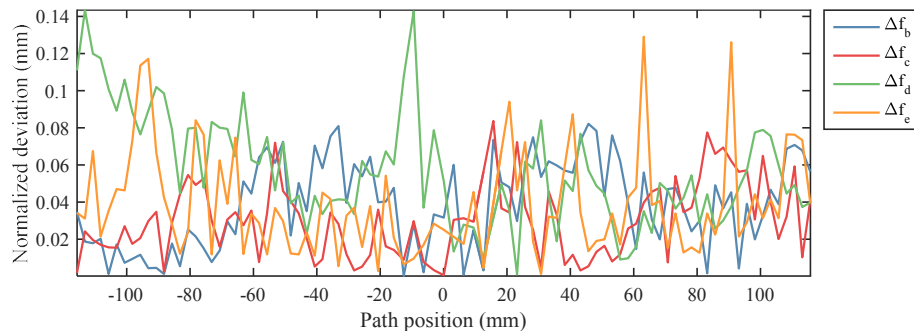


Figure 6.14 The resulting scan of specimens with Gom[®] Atos, left side view. Arrows indicates visible strand pop-out (white) and protrusion (blue).

The scan of the specimens was performed with the WS, according to the principle described in chapter 6.2.1. The post-processing was performed in order to compare the obtained results. The maximal deviation of the cable in function of the path position was computed. One can see the computed cable deformation of specimens b) to e) in Figure 6.15. Each specimen is represented by the same color. In Figure 6.15a, The WS results are marked with a dashed line, while the Atos results are shown with a solid line. The resulting functions of absolute difference Δf computed by subtracting the deviations of the corresponding specimen scans taken with both devices are shown in Figure 6.15b.



a)



b)

Figure 6.15 Winding specimen scans taken with WS and Atos. Average envelope of four specimens is shown in a), and a deviation Δf is shown in b).

In Table 6.3 one can see the average and standard deviation of the Δf functions of absolute difference. The average values range between 30 and 57 μm , and the standard deviation ranges between 28 and 42 μm .

Table 6.3 The average and the deviation from Δf for each specimen, shown for four specimens.

Specimen	Average $ \overline{\Delta f} $	Deviation $\sigma_{ \Delta f }$
b)	39 μm	31 μm
c)	30 μm	28 μm
d)	57 μm	34 μm
e)	39 μm	42 μm

The provided data proves that the WS scan quality is comparable with the Gom[®] Atos. The WS scans were performed with the laser measurement head Panasonic[®] HG-C1050 offering the measurement resolution of 30 μm (see Table 6.4). It should be noted that the scans with respective devices were taken with three month delay, which could impact the observed measurement error. Based on the provided results and defined conditions, the WS is considered sufficient for the winding study. The repeatability of the WS is determined in the following chapter.

6.2.3. LASER HEAD RESEARCH AND REPEATABILITY COMPUTATION

The performance of the WS relies on the quality of the utilized laser head. The tests were performed in order to improve the repeatability of the scan and determine the possible upgrades. This chapter describes the evaluation of the laser head performance for the given conditions and criteria.

Depending on the surface feature of the measured object, two types of a triangulation laser heads are distinguished: diffusive and specular. The specular type is intended for the highly reflective objects, e.g. mirrors or polished surfaces. The aluminum and copper features a diffusing surface, therefore the diffusive laser type was chosen. Multiple high-end laser heads offer both types of measurement after an adjustment. One can see the principle of the laser triangulation in Figure 6.16. The laser beam emitter, usually a semiconductor, projects a cylindrical beam on the object. Afterwards, the diffused light is focused with a lens on a receiver. A variation of the distance between the emitter and the object, results with a displacement of the received beam spot on a CMOS sensor.

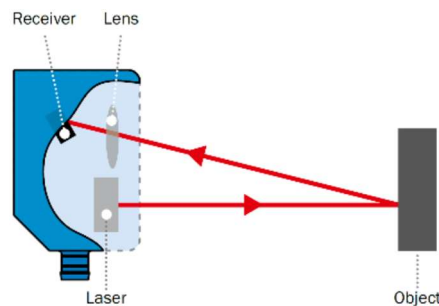


Figure 6.16 1D measurement. Point laser triangulation principle for diffusive objects. Source: Sick.

The laser triangulation technology used in the laser heads is sensitive to the object reflection. The reflective or round surfaces are compromising the measurement quality. To minimize the error the intensity of the emitted beam is adjusted, which effectively lowers the energy of

the reflection. In addition, the obtained result contains the signal quality feedback, i.e. received light intensity.

In order to investigate the measurement repeatability of the WS, the same winding specimen was scanned three times. The specimen was removed between the subsequent scans in order to include the positioning error. One scan of the specimen consists of 19201 measurement points. The repeatability is computed according to the ISO 9283:1998. The standard deviation of the three values obtained in the same position in three consecutive scans, is defined in equation (6.1). The repeatability RP is computed following the equation (6.2).

$$\sigma_l = \sqrt{\frac{\sum_{i=1}^N (l_i - \bar{l})^2}{N - 1}} \quad (6.1)$$

$$RP = 3 * \sigma_l \quad (6.2)$$

Due to the assumed symmetricity of an error, the measured value L features the accuracy described with the equation (6.3).

$$L = \pm \frac{3}{2} \sigma = \pm \frac{RP}{2} \quad (6.3)$$

The accuracy of the measured value is evaluated based on two sets of measured values. First it is computed by use of the whole specimen data, i.e. all 19201 points, resulting with L_W . And second is based on the computed cable average envelope deformation, i.e. 91 points, expressed with L_A . The scanned specimen was not treated with any surface matting spray in order to perform the test in the worst working conditions. Three laser heads were tested, featuring the parameters listed in Table 5.2. The distribution of the standard deviation used for computing the L_W is shown in Figure 6.17. Whereas, the standard deviation distribution for computing L_A is shown in Figure 6.18. One can see that the average deviation value is marked on each distribution graph with a dashed vertical red line.

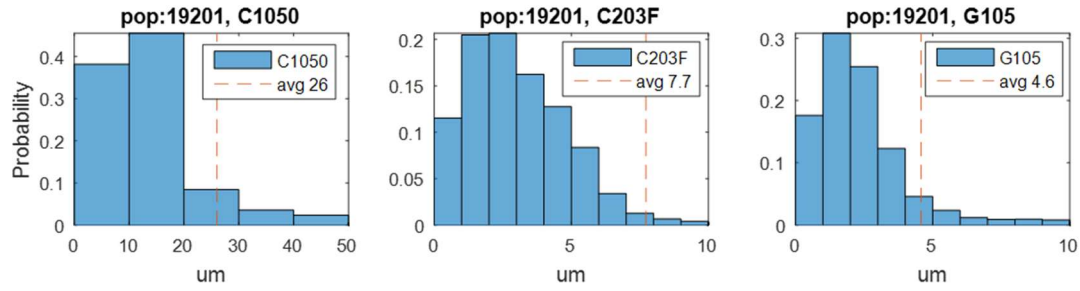


Figure 6.17 The standard deviation distribution of 19201 measurement points for L_W computation. From left to right: HG-C1050, HL-G105-S-J, and HL-C203F laser head. The average deviation marked with red dashed line.

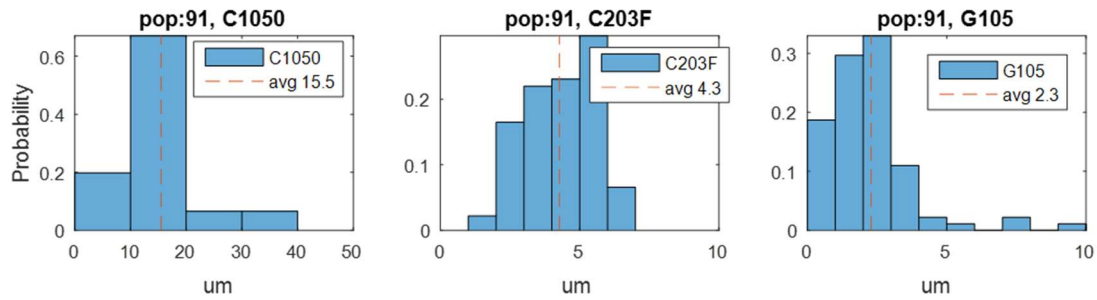


Figure 6.18 The standard deviation distribution of 91 measurement points for L_A computation. From left to right: HG-C1050, HL-G105-S-J, and HL-C203F laser head. The average deviation marked with red dashed line.

The resulting accuracy is shown in the Table 6.4 along with the technical specification of the laser heads.

Table 6.4 Laser parameters and computed accuracy.

Laser head	HG-C1050	HL-G105-S-J	HL-C203F	HL-C208C
Resolution	30 μm	2.5 μm	0.025 μm	0.15 μm
Measurement center	50 mm	85 mm	30 mm	85 mm
Measurement range	± 15 mm	± 20 mm	± 5 mm	± 20 mm
Beam spot	$\varnothing 70 \mu m$	0.75 x 1.25 mm	$\varnothing 30 \mu m$	$\varnothing 100 \mu m$
Sensitivity adjustment	No	No	Yes	Yes
Signal quality feedback	No	Yes	Yes	Yes
Accuracy of the whole scan L_W	$\pm 39 \mu m$	$\pm 11.6 \mu m$	$\pm 6.9 \mu m$	n/a
Accuracy of the analysis L_A	$\pm 23.3 \mu m$	$\pm 6.5 \mu m$	$\pm 3.5 \mu m$	n/a

The best accuracy is achieved with the HL-C203F, i.e. 6.9 μm and 3.5 μm . This laser head features the highest measurement resolution of 25 nm, and an additional sensitivity adjustment. However, in order to keep the setup flexible, it was important to keep the measurement range larger than ± 15 mm. This is in order to maintain the capability of measuring different specimen geometries or cable dimensions. In order to meet this requirement, the HL-208C laser head was chosen. It provides a 0.15 μm measurement resolution and a measurement range of ± 20 mm. In addition a sensitivity adjustment allows to minimize the impact of observed surface reflections. According to the performed tests, the chosen laser head shall provide the accuracy between 3.5 and 6.5 μm , which is considered as sufficient for the described research.

6.3. DEFORMATION ANALYSIS METHODOLOGY

In order to be able to compare the specimen geometries e.g. wound with different parameters or sample holder, it was essential to develop a dedicated analysis algorithm. The goal is to provide the representative deformation indicators, which describe the defined types of the cable deformation (i.e. the envelope, the strand pop-out and the protrusion, shown in Figure 6.4). In this chapter, the analysis algorithm will be presented based on the specimen wound with 11 T copper cable, 5 kg winding tension, and favourable winding direction. The analysis starts with the raw scan, i.e. matrix containing the WS programmed kinematics and values measured by the laser head.

6.3.1. CARTESIAN TRANSFORMATION

The raw scan function f_1 , defined with a position of each DOF and measured distance, is transformed into the f_2 function, defined with the Cartesian coordinates. The transformation is expressed in equation (6.4) and the resulting function is shown in Figure 6.19.

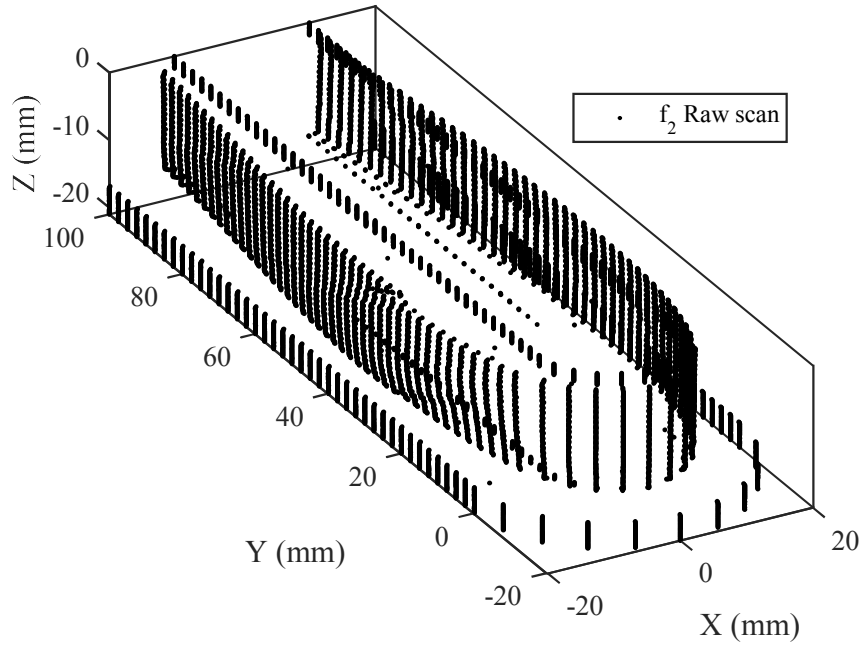


Figure 6.19 The WS scan Cartesian transformation.

$$f_1(Y, Z, A, d) \cdot T_1 \rightarrow f_2(x, y, z) \quad (6.4)$$

Where:

f_1 – Raw scan function;

Y – Table translation;

Z – Measurement head translation;

A – Table rotation;

d – Measured distance;

T_1 – Transformation matrix;

f_2 – Scan in Cartesian coordinates;

x, y, z – Cartesian coordinates.

6.3.2. DATA SEPARATION

The scan data f_2 is selected with use of the differential filters, in order to obtain three functions containing the winding surface f_3 , the cable envelope f_4 , and the bottom support f_5 . These functions are shown in the Figure 6.20 with blue, green and red colors respectively. The data separation is described with the equation (6.5).

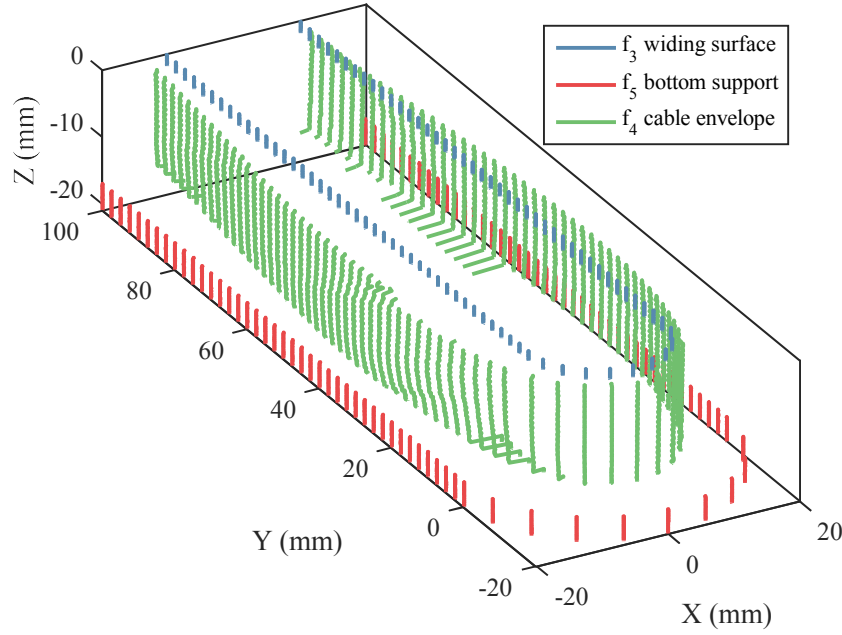


Figure 6.20 Separated functions of the winding surface, the cable and the bottom support. Axes in millimeters.

$$f_2(x, y, z) \rightarrow \begin{cases} f_3(x_w, y_w, z_w) \\ f_4(x_c, y_c, z_c) \\ f_5(x_s, y_s, z_s) \end{cases} \quad (6.5)$$

Where:

f_3 – Winding surface data function;

x_w, y_w, z_w – Winding surface coordinates;

f_4 – Cable data function;

x_c, y_c, z_c – Cable coordinates;

f_5 – Bottom support data function;

x_s, y_s, z_s – Bottom support coordinates.

6.3.3. VIRTUAL UNWINDING AND NORMALIZATION

This step consists of two sub steps. The virtual unwinding, described with the equation (6.6), allows displaying the specimen scan unwrapped along the winding path (defined in Figure 6.4). The normalization, described with the equation (6.7), corrects the position of each scanned line based on the average position of the winding surface. The unwound and normalized functions of the winding surface, the cable envelope and the winding support are shown in Figure 6.21.

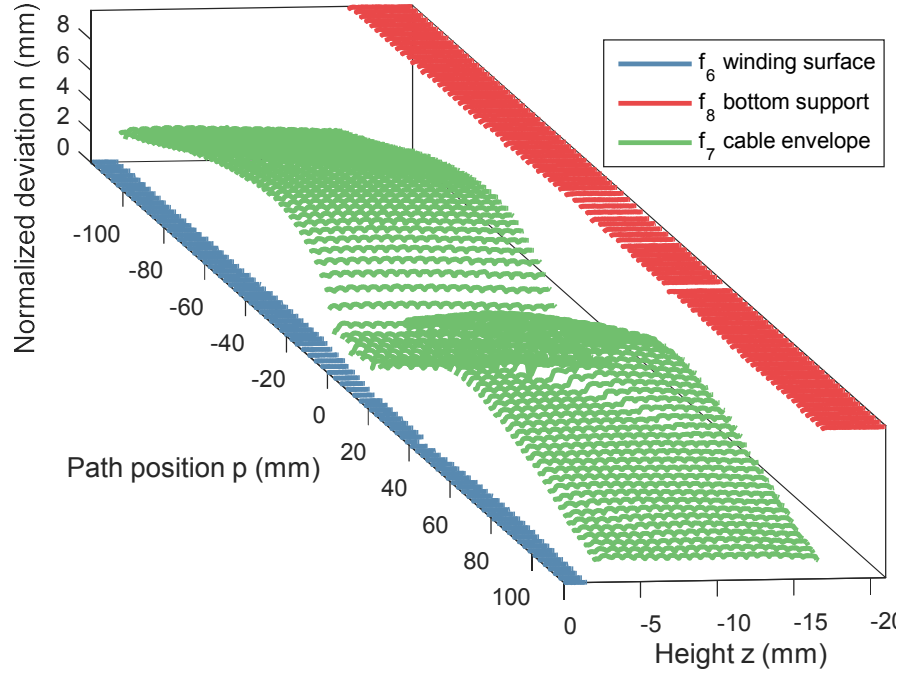


Figure 6.21 Virtual unwinding and normalization. Axes in millimeters.

$$\begin{aligned} f_3(x_w, y_w, z_w) & \rightarrow f_6(p_w, z_w, e_w) \\ f_4(x_c, y_c, z_c) & \rightarrow f_7(p_c, z_c, e_c) \\ f_5(x_s, y_s, z_s) & \rightarrow f_8(p_s, z_s, e_s) \end{aligned} \quad (6.6)$$

$$\begin{aligned} & f_9(p_w, z_w, n_w) \left\{ \begin{aligned} n_w &= |e_w - \bar{e}_w| \\ n_c &= |n_c - \bar{e}_w| \\ n_s &= |n_s - \bar{e}_w| \end{aligned} \right. \\ & \rightarrow f_{10}(p_c, z_c, n_c) \\ & f_{11}(p_s, z_s, n_s) \end{aligned} \quad (6.7)$$

Where:

f_6 – Virtually unwound scan function of winding surface;

f_7 – Virtually unwound scan function of cable;
 f_8 – Virtually unwound scan function of bottom support;
 p_w, p_c, p_s – Path position of winding surface, cable and bottom support;
 z_w, z_c, z_s – Height of winding surface, cable and bottom support;
 e_w, e_c, e_s – Deviation of winding surface, cable and bottom support;
 f_9 – Normalized scan function of winding surface;
 f_{10} – Normalized scan function of cable envelope;
 f_{11} – Normalized scan function of bottom support;
 n_w, n_c, n_s – Normalized deviation of winding surface, cable and bottom support.

6.3.4. DEFORMATION FUNCTIONS

Four deformation functions are computed using the f_{10} normalized scan function of the cable envelope, listed below:

1. The average envelope, described in the equation (6.8), i.e. the average distance of the cable envelope from the winding surface.

$$D_1(p_c, \overline{n_c}) \quad (6.8)$$

2. The maximal envelope, described in the equation (6.9), i.e. the maximal distance of the cable envelope from the winding surface.

$$D_2(p_c, \max(n_c)) \quad (6.9)$$

3. The strand pop-out deformation function, described in the equation (6.10), i.e. a subtraction of the maximal and average envelope functions.

$$D_3(p_c, \max(n_c) - \overline{n_c}) = D_2 - D_1 \quad (6.10)$$

4. The protrusion function, described in equation (6.11), i.e. a maximal cable position in the vertical direction, i.e. cable height.

$$D_4(p_c, \max(z_c)) \quad (6.11)$$

The deformation functions are depicted in Figure 6.22. One can see both envelope functions (D_1 and D_2) approaching minimal values in the specimen cylindrical area, which ranges roughly from -15 mm to 15 mm of the path position.

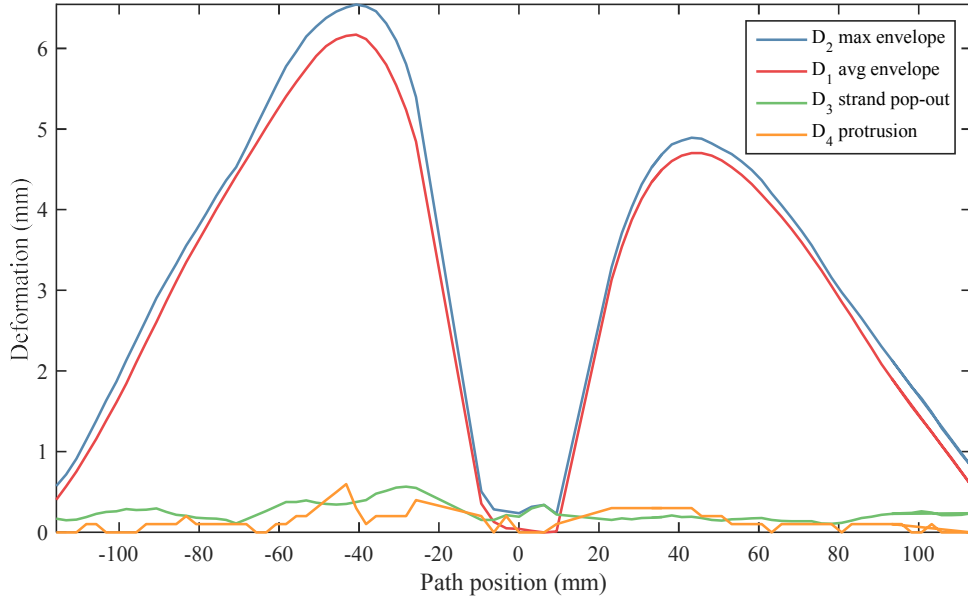


Figure 6.22 The specimen deformation functions.

6.3.5. INDICATOR COMPUTATION

In order to obtain the representative value describing the particular cable deformation, the deformation functions are post-processed. Three of the aforementioned deformation shape functions are integrated, i.e. the average envelope D_1 from equation (6.8), the strand pop-out D_3 from equation (6.10) and the protrusion D_4 from equation (6.11). Due to the strand pop-out function being computed with use of the average and the maximal cable envelope functions, the maximal envelope D_2 from equation (6.9) is not integrated.

One can see the lack of symmetry in the Figure 6.22 with respect to the cylinder tip, positioned in the origin of the path position. In order to be able to represent this phenomenon, two types of indicators were computed. The indefinite integrals: P_1 , P_2 and P_3 ; and definite integrals: from P_4 to P_9 . The indefinite integral of the average envelope is shown in equation (6.12).

$$P_1 = \int D_1 dp_c = \sum \bar{n}_c \quad (6.12)$$

The indefinite integral of the strand pop-out is shown in the equation (6.13).

$$P_2 = \int D_3 dp_c = \sum (\max(n_c) - \bar{n}_c) \quad (6.13)$$

The indefinite integral of the protrusion is shown in the equation (6.14).

$$P_3 = \int D_4 dp_c = \sum \max(z_c) \quad (6.14)$$

One can see the indefinite integral functions in Figure 6.23. The functions are monotonically increasing due to the permanently positive domain.

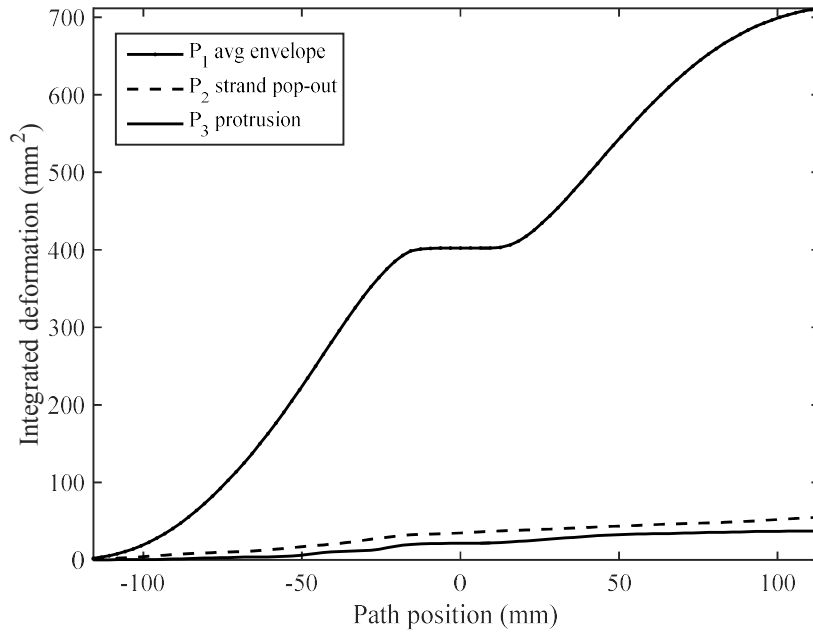


Figure 6.23 Indefinite integral functions.

The origin of the path position (i.e. the tip of the cylinder) divides the specimen on the left and right side, consisting of the negative and positive values of the path position respectively. The left side definite integral of the average envelope is shown in the equation (6.15).

$$P_4 = \int_{\min(p_c)}^0 D_1 dp_c = \sum_{i=\min(p_c)}^0 (\overline{n_c})_i \quad (6.15)$$

The left side definite integral of the strand pop-out is shown in the equation (6.16).

$$P_5 = \int_{\min(p_c)}^0 D_3 dp_c = \sum_{i=\min(p_c)}^0 (\max(n_c) - \overline{n_c})_i \quad (6.16)$$

The left side definite integral of the protrusion is shown in the equation (6.17).

$$P_6 = \int_{\min(p_c)}^0 D_4 dp_c = \sum_{i=\min(p_c)}^0 (\max(z_c))_i \quad (6.17)$$

The right side definite integral of the average envelope is shown in the equation (6.18).

$$P_7 = \int_0^{\max(p_c)} D_1 dp_c = \sum_{i=0}^{\max(p_c)} (\overline{n_c})_i \quad (6.18)$$

The right side definite integral of the strand pop-out is shown in the equation (6.19).

$$P_8 = \int_0^{\max(p_c)} D_3 dp_c = \sum_{i=0}^{\max(p_c)} (\max(n_c) - \overline{n_c})_i \quad (6.19)$$

The right side definite integral of the protrusion is shown in the equation (6.20).

$$P_9 = \int_0^{\max(p_c)} D_4 dp_c = \sum_{i=0}^{\max(p_c)} (\max(z_c))_i \quad (6.20)$$

The definite integral functions are shown in the Figure 6.24. The negative part of the abscissa is occupied with the left side (P_4, P_5, P_6), and positive side with the right side (P_7, P_8, P_9) of the definite integrals. Observing the figure below, one can immediately state the lack of side symmetricity present in the scanned specimen. The integrated deformation functions of the left side are greater than the right side.

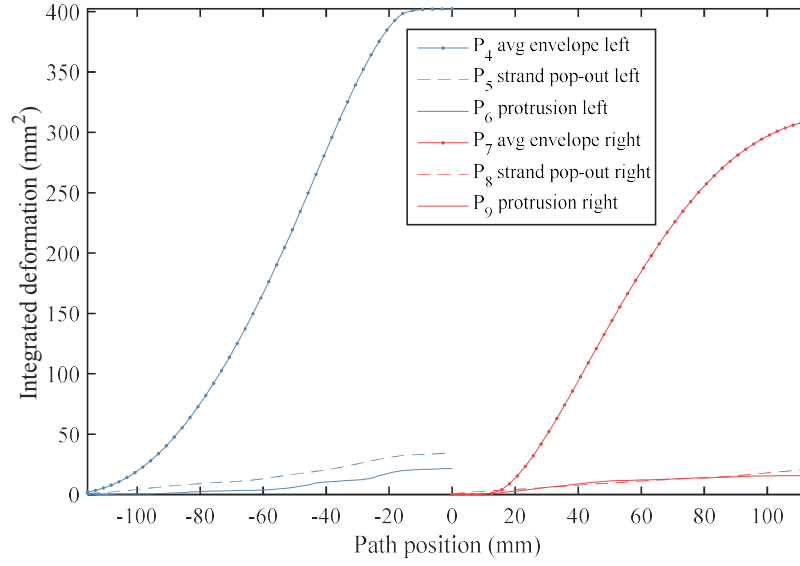


Figure 6.24 Definite integral functions.

The following relations are true for the equations from (6.12) to (6.20).

$$P_1 = P_4 + P_7 \quad (6.21)$$

$$P_2 = P_5 + P_8 \quad (6.22)$$

$$P_3 = P_6 + P_9 \quad (6.23)$$

6.3.6. WINDING MATRIX AGGREGATION

The winding matrix is aggregated out of the P indicators. It is described in three forms, simplified, extended and normalized. Each type is generated in order to ease the observation of particular feature. The equations shown below present the numerical results of the scan displayed throughout this chapter. The simplified winding matrix, shown in equation (6.24), is containing the indefinite indicators. It describes three deformation types with the smallest amount of indicators.

$${}^S W = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} = \begin{bmatrix} 763.2 \\ 58.9 \\ 48.3 \end{bmatrix} \quad (6.24)$$

The extended winding matrix is shown in equation (6.25). It combines the integrals in a 3 x 2 matrix, where the first column corresponds to the left side indicators, and the second to the right side indicators. In this case, two values correspond to the same deformation type. The lack of symmetry is visible and correspond to the observation of the specimen.

$${}^E W = \begin{bmatrix} P_4 & P_7 \\ P_5 & P_8 \\ P_6 & P_9 \end{bmatrix} = \begin{bmatrix} 409.3 & 353.9 \\ 39.0 & 20.0 \\ 23.5 & 24.8 \end{bmatrix} \quad (6.25)$$

The normalized winding matrix, shown in equation (6.26), is defined in a 3 x 3 matrix. The first column contains the higher deformation value of both sides. The second and third columns are left and right side deformation values divided by the value from the first column. The normalized winding matrix presents one value per each deformation type (first column). The lack of symmetry is clearly noticeable (second and third columns), and due to the normalization easy to comprehend, since the higher deformation is normalized to “1”.

$${}^N W = \begin{bmatrix} P_{4|7} & P_4/P_{4|7} & P_7/P_{4|7} \\ P_{5|8} & P_5/P_{5|8} & P_8/P_{5|8} \\ P_{6|9} & P_6/P_{6|9} & P_9/P_{6|9} \end{bmatrix} = \begin{bmatrix} 409.3 & 1 & 0.9 \\ 39.0 & 1 & 0.5 \\ 24.8 & 0.9 & 1 \end{bmatrix} \quad (6.26)$$

Where:

$P_{4|7}$ – Higher value of P_4 and P_7 ;

$P_{5|8}$ – Higher value of P_5 and P_8 ;

$P_{6|9}$ – Higher value of P_6 and P_9 .

6.3.7. ANALYSIS EXAMPLE

In order to visualize the deformation represented by the winding matrices, two specimens are presented with the significantly different cable distortion. Both specimens are wound with the 11 T Nb₃Sn cable with 30 kg winding mass and favourable winding direction. One can see in Figure 6.25a a much smaller cable deformation, in comparison to the specimen in Figure 6.25b. The cable on the right side features a clearly visible strand pop-out, and after a further examination a larger protrusion deformations.

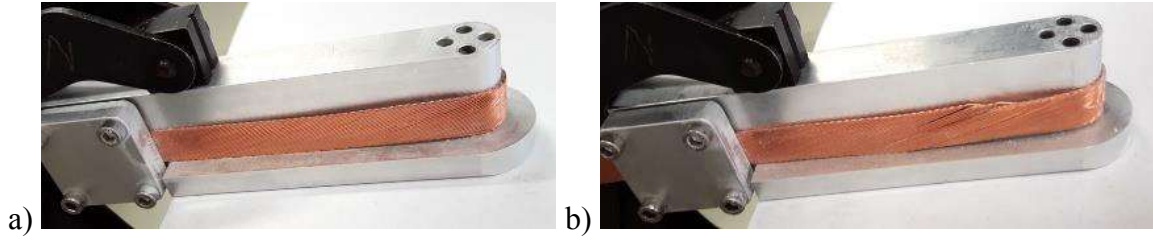


Figure 6.25 Photography of specimens. a) small cable deformation, specimen #3.14; b) large cable deformation #3.13.

The raw scans of both specimens are depicted in Figure 6.26. One can see that the cables are correctly represented, based on the visible difference.

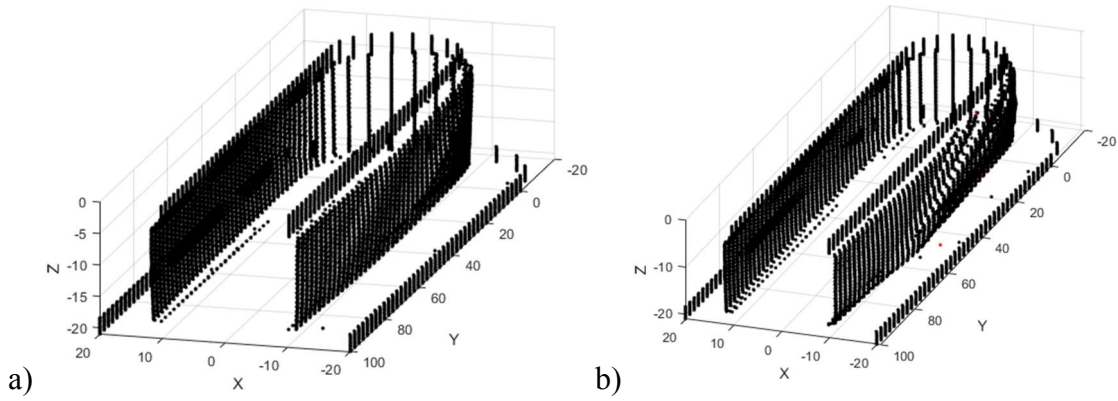


Figure 6.26 Raw scan of example specimens. a) small cable deformation, specimen #3.14; b) large cable deformation, specimen #3.13. Axes in millimeters.

The simplified, extended and normalized matrices of both specimens are shown in the equations (6.27), (6.28) and (6.29) respectively. Based on the shown results, the sample #3.14 shows much smaller deformations, particularly the pop-out and protrusion. The specimen #3.13 presents a roughly ten times larger protrusion indicator.

$$^sW_{\#3.14} = \begin{bmatrix} 227.9 \\ 46.9 \\ 33.8 \end{bmatrix}; \quad ^sW_{\#3.13} = \begin{bmatrix} 256.8 \\ 78.3 \\ 347.3 \end{bmatrix} \quad (6.27)$$

$$^EW_{\#3.14} = \begin{bmatrix} 127.5 & 100.4 \\ 27.7 & 19.2 \\ 25 & 8.8 \end{bmatrix}; \quad ^EW_{\#3.13} = \begin{bmatrix} 160.7 & 96.1 \\ 58.9 & 19.4 \\ 161.5 & 185.8 \end{bmatrix} \quad (6.28)$$

$${}^N W_{\#3.14} = \begin{bmatrix} 127.5 & 1 & 0.8 \\ 27.7 & 1 & 0.7 \\ 25 & 1 & 0.4 \end{bmatrix}; \quad {}^N W_{\#3.13} = \begin{bmatrix} 160.7 & 1 & 0.6 \\ 58.9 & 1 & 0.3 \\ 185.8 & 0.9 & 1 \end{bmatrix} \quad (6.29)$$

6.4. SPRINGBACK MEASUREMENT

The springback measurement is performed in order to evaluate the elastically driven change of the cable shape after releasing one mechanical clamp. The example of the cable deformation after a clamp release is shown in Figure 6.27. The measured angle is situated between the loose end of the cable and the straight winding surface, marked with the red arrow. The result is considered being related to the elastic energy stored in the cable after winding.

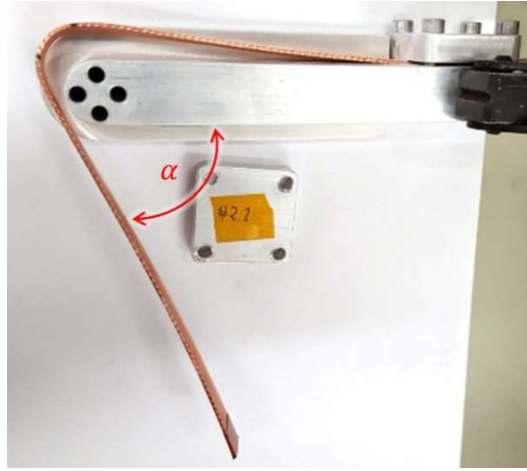


Figure 6.27 Winding specimen springback angle after releasing clamp on the right side.

Based on the shape of the half-released cable, five characteristic points were distinguished, allowing proceeding with the measurement and observation. All of the points are shown in Figure 6.28.

The description of characteristic points:

- A. The top cable clamp edge; the origin,
- B. The extreme point on the cable in Y+ direction; measured,
- C. The extreme point on the cable in X- direction; measured,
- D. The closest point to the winding surface; indicated if in contact or not,
- E. The free edge of the cable; measured,
- F. The Bottom edge of the cable at the edge of support surface; measured.

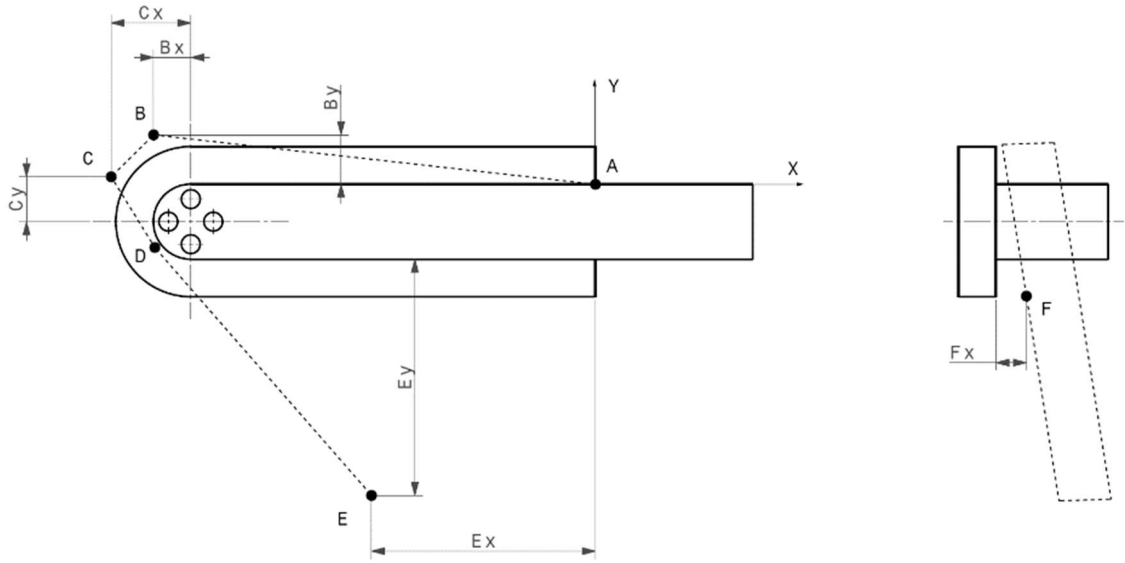


Figure 6.28 Draft with the characteristic points for springback measurement. Solid line: specimen. Dashed line: presumed cable position.

The origin is defined in point A. The B, C, E and F points are measured with the caliper, taking the references shown in Figure 6.28. The point D is an indicator of the cable contact with the winding surface. The specimen is described with one springback angle value as shown in equation (6.30).

$$\alpha = 180 + \arctan\left(\frac{E_Y - C_Y}{E_X - C_X}\right) \quad (6.30)$$

7. WINDING CAMPAIGNS

In order to investigate the influence of the winding parameters on the cable deformation, the test campaigns were launched. The specimen winding and deformation analysis were performed according to method described in chapter 6.

Five different Rutherford type cables were available for the tests. The test campaign was consisting of Rutherford cable made from Nb₃Sn, Nb-Ti and Cu material. The parameters of the tested cables are shown in Table 7.1. In this chapter the cable type is referred according to the ‘cable name’ indicated in the table. The indicated ‘leading project’ name provides the reference magnet design that was driving the development of the cable.

The winding scanner, shown in Figure 6.6, is programmed in order to provide the same distribution of point for each scanned specimen. One scan lasts roughly 1 hour, and consists of 91 lines (as shown in Figure 6.9), respectively 19201 measurement points. The program features the following scan resolution: vertical axis (Z DOF) of 0.1 mm, horizontal axis (Y DOF) of 2.5 mm, and rotational axis (A DOF) of 18°.

Three specimens are wound per each parameter set, giving a unique opportunity to study not only the quality but also the reproducibility of the winding defects. Consequently, the deformation indicators are examined focusing on:

1. Performance – an average deformation indicator value of three specimens wound with the same set of parameters; demonstrating the amount of the cable deformation;
2. Stability – a standard deviation of indicator values of three specimens wound with the same set of parameters; demonstrating the reproducibility of the cable deformation.

The setup and the aim of the winding campaigns are described in chapters 7.1 and 7.2. The results are displayed in chapters 7.1.1 and 7.2.1, and discussed in chapters 7.1.2 and 7.2.2.

Table 7.1 Nominal cable parameters.

Cable name	11T Cu	11T RRP	Nb-Ti	MQXF	FRESCA2
Strand design	Annealed copper	Nb ₃ Sn RRP 54/61	Nb-Ti	Nb ₃ Sn RRP 132/169	Nb ₃ Sn RRP
Number of strands	40	40	28	40	40
Cu/non-Cu	n/a	0.89	1.6-1.7±0.03	1.2±0.1	1.25
Strand diameter	0.7 mm	0.7 mm	1.07 mm	0.85 mm	1 mm
Cross section (H; W)	14.7 mm; 1.25 mm	14.7 mm; 1.25 mm	15.1 mm; 1.9 mm	18.15 mm; 1.52 mm	21.4 mm; 1.82 mm
Cross section area	18.38 mm ²	18.38 mm ²	28.69 mm ²	27.59 mm ²	38.95 mm ²
Keystone angle	0.77°	0.77°	1.25±0.05°	0.4°	0°
Insulation	Uninsulated	Removed / Insulated ¹	Removed	Removed	Removed
Leading project	11 T Dipole trials	11 T HL-LHC Dipole [60]	LHC Main Dipole [61]	MQXF HL-LHC Quadrupole [62]	FRESCA 2 Dipole [63]

7.1. WINDING TENSION AND DIRECTION

The winding campaign was conducted in order to investigate the influence of the winding mass (i.e. 5, 20, and 30 kg) and the winding direction (i.e. favourable and unfavourable shown in Figure 7.1) on the winding quality. The initial results of this investigation were published in [64].

¹ The S-2 glass and Mica insulated cable was used in part of the pre-torsion study.



Figure 7.1 Favourable and unfavourable winding directions.

The winding frame is used in order to wind the specimens, with parameters defined in Table 7.2. The parameters in column ‘test value’ marked in black are kept constant, and in red are changed according to the tested case. The tested cables 11T Cu, 11T RRP, Nb-Ti, MQXF, and FRESCA2 are non-insulated and are described in Table 7.1. There are six combinations of chosen parameters. Three specimens were wound per combination, giving a total amount of 18 specimens per tested cable. The same sample holder geometry featuring 20 mm cylinder diameter (see Figure 7.1) is used throughout the test.

Table 7.2 The WF parameters used in the winding mass and direction investigation.

Group	Designation		Symbol	Unit	Test value
Frame	Angular guide	X position	Ax	(mm)	10
		Y position	Ay	(mm)	61 (favourable) or 41 (unfavourable)
		Z position	Az	(mm)	112
		angle	Aalpha	(deg)	0
		thickness	At	(mm)	10
		aperture	Aa	(mm)	4
	Tensile load		M	(kg)	5, 20 or 30
Pole	Identification		Pid	-	d20L160
	Cylinder diameter		Pd	(mm)	20
	Clamp length		Pc	(mm)	39
Run	Direction	Favourable - 1	Dir	-	0 or 1
		Unfavourable - 0			
	Mandrel support	Yes - 1	Sup	-	1
		No - 0			
	Cylinder surface	Material	Mat	-	Aluminium
		Friction coeff	μ	-	-
Cable	Pre-cut cable length		L	(mm)	400

7.1.1. OBTAINED RESULTS

In this chapter the analyzed results of 98 measurements are presented. The discussion is given in the following chapter 7.1.2. The results are structured according to the analysis methodology described in chapter 6.3. The first set of results are provide the performance and stability of the envelope, pop-out, protrusion. Figure 7.2 and Figure 7.3 represents the analyzed data in function of the winding mass and the winding direction. Figure 7.4 and Figure 7.5 provide results based on averaged winding mass for the favourable and unfavourable winding direction. In addition, Figure 7.6 indicates the specimen symmetry. Furthermore, Figure 7.7 shows the analysis of the springback measurement (see Figure 6.28). The measurement conditions are presented in Figure 7.8.

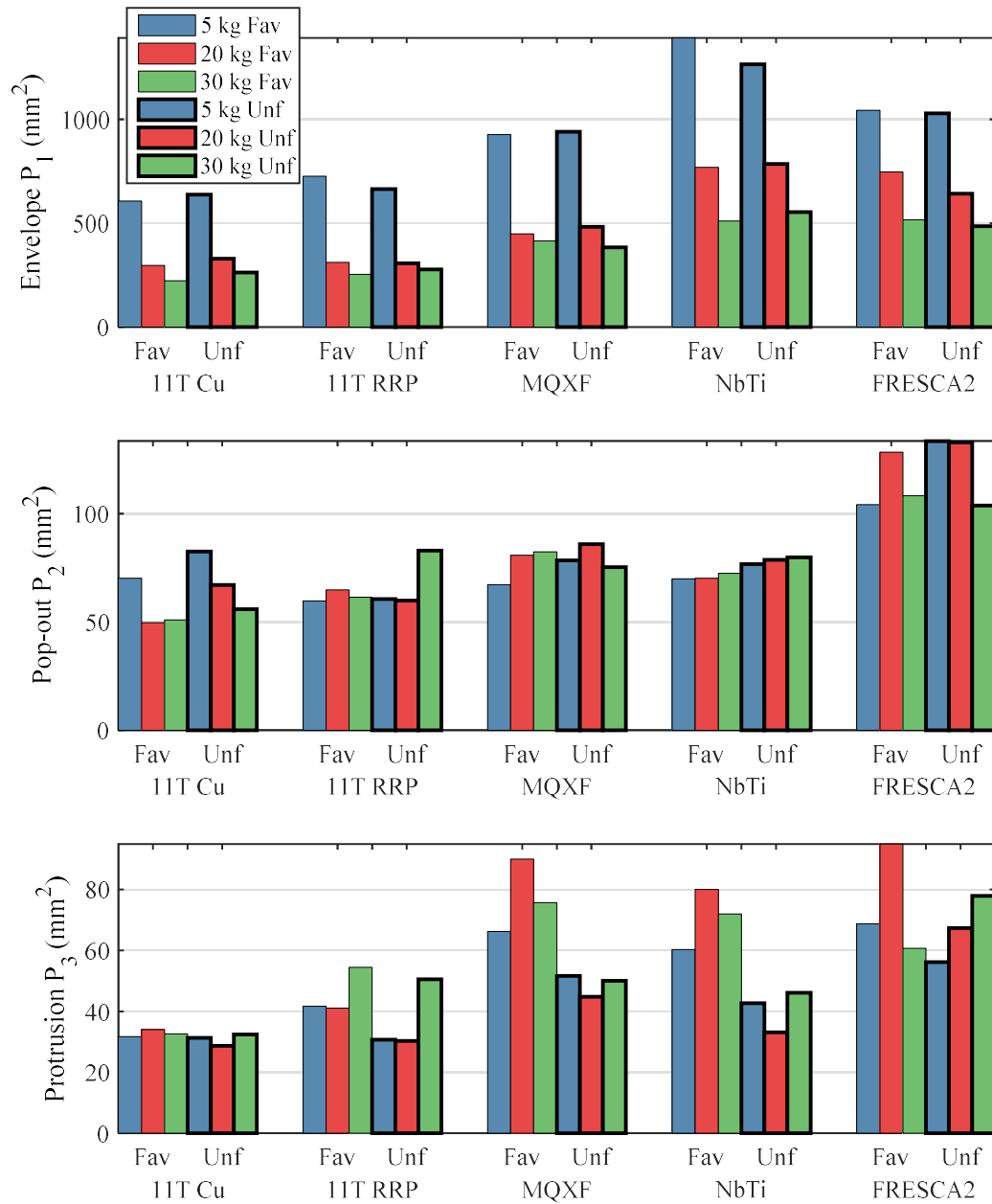


Figure 7.2 The average winding performance of three specimens, represented by the bar height. Five cables tested (indicated on horizontal axis) with various winding mass (indicated by the color of the bar, see legend) and different winding direction (favourable thin outline, unfavourable thick outline, see legend). Top: the average envelope P_1 ; Middle: the strand pop-out P_2 ; Bottom: the protrusion P_3 .

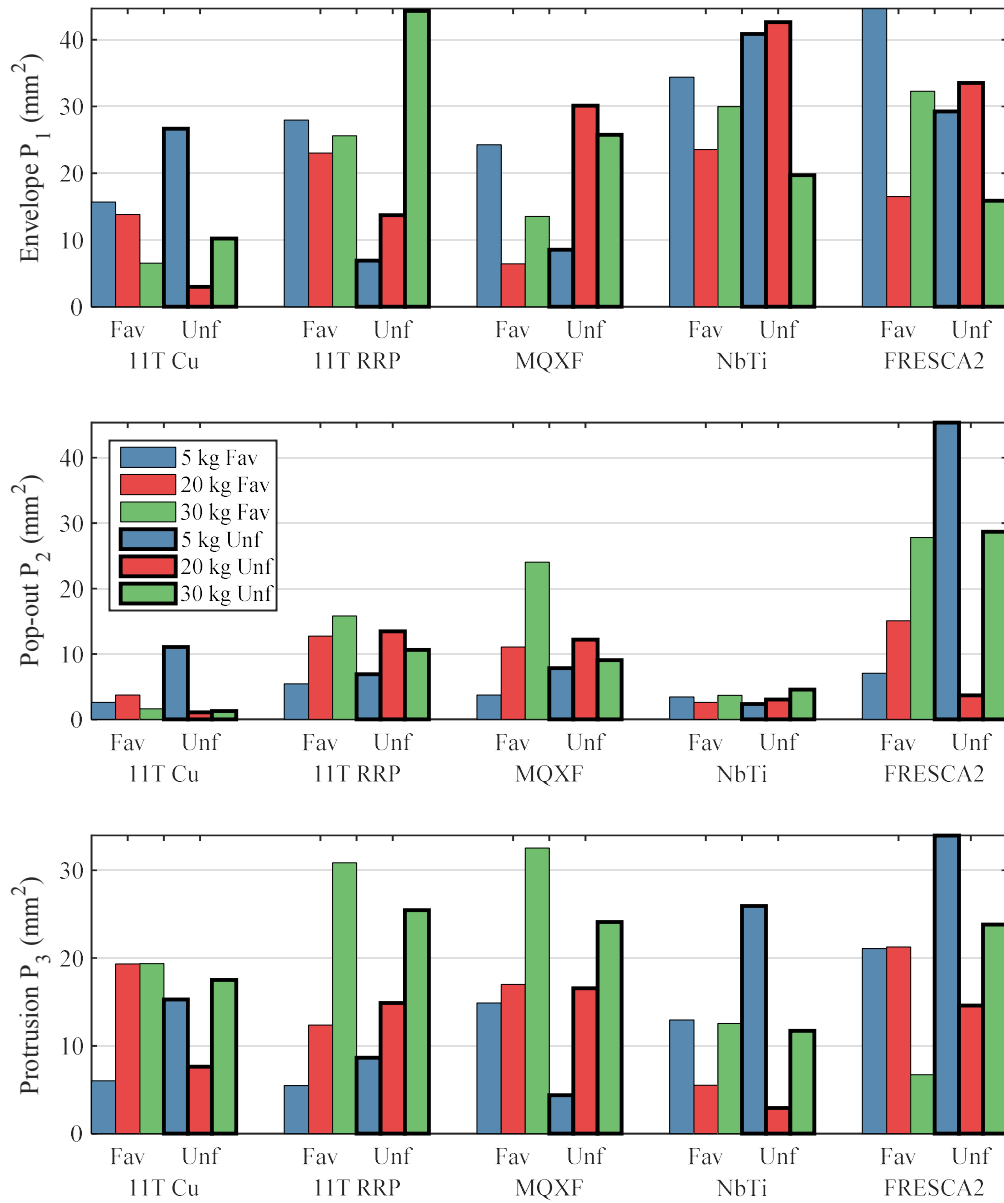


Figure 7.3 The winding stability of three specimens, represented by the bar height. Five cables tested (indicated on horizontal axis) with various winding mass (indicated by the color of the bar, see legend) and different winding direction (favourable thin outline, unfavourable thick outline, see legend). Top: the average envelope P_1 ; Middle: the strand pop-out P_2 ; Bottom: the protrusion P_3 .

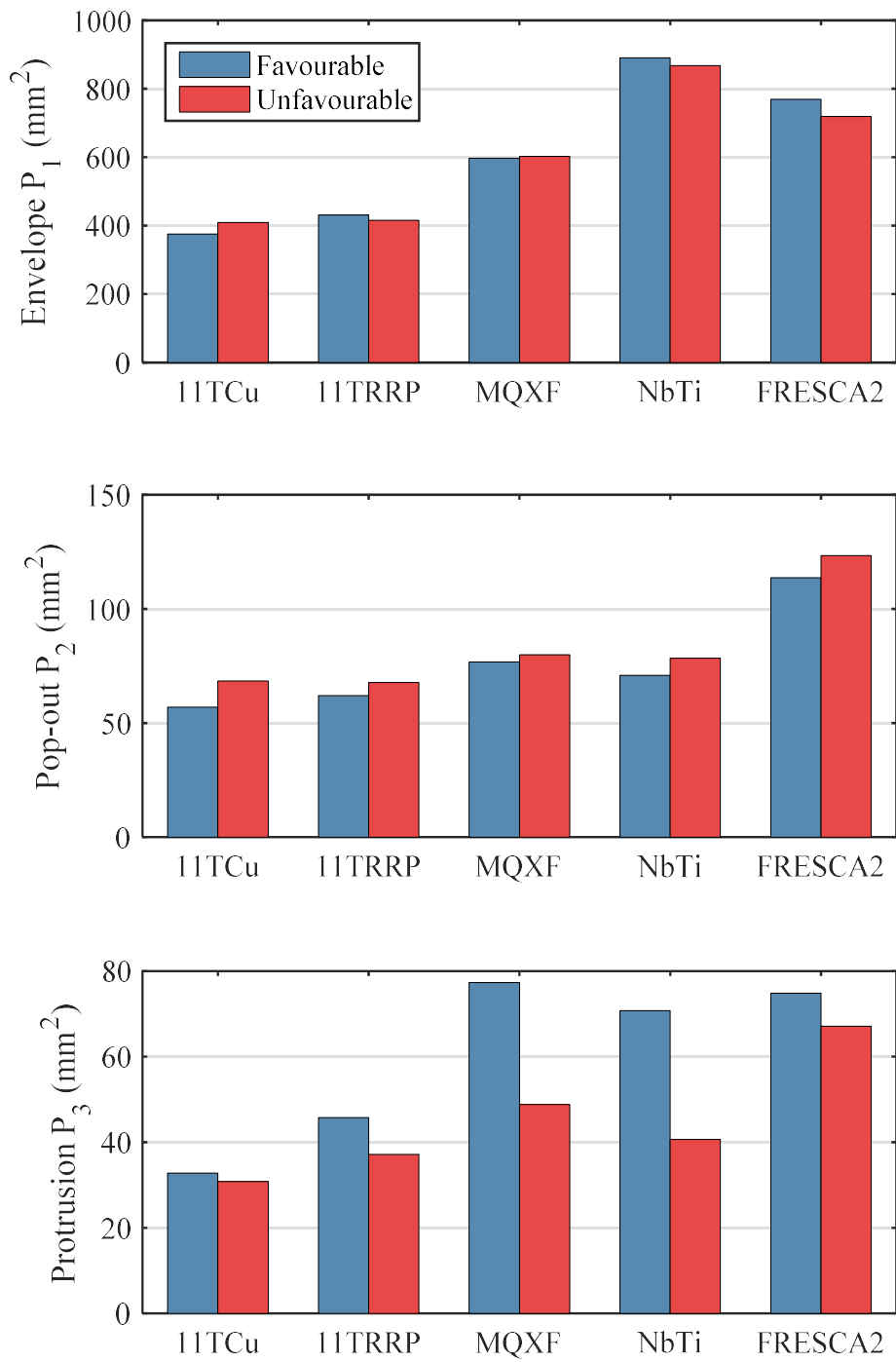


Figure 7.4 The average performance results of five tested cables, indicated on the horizontal axis. The bar height represents the average deformation of specimens wound with various winding mass, for each direction separately.

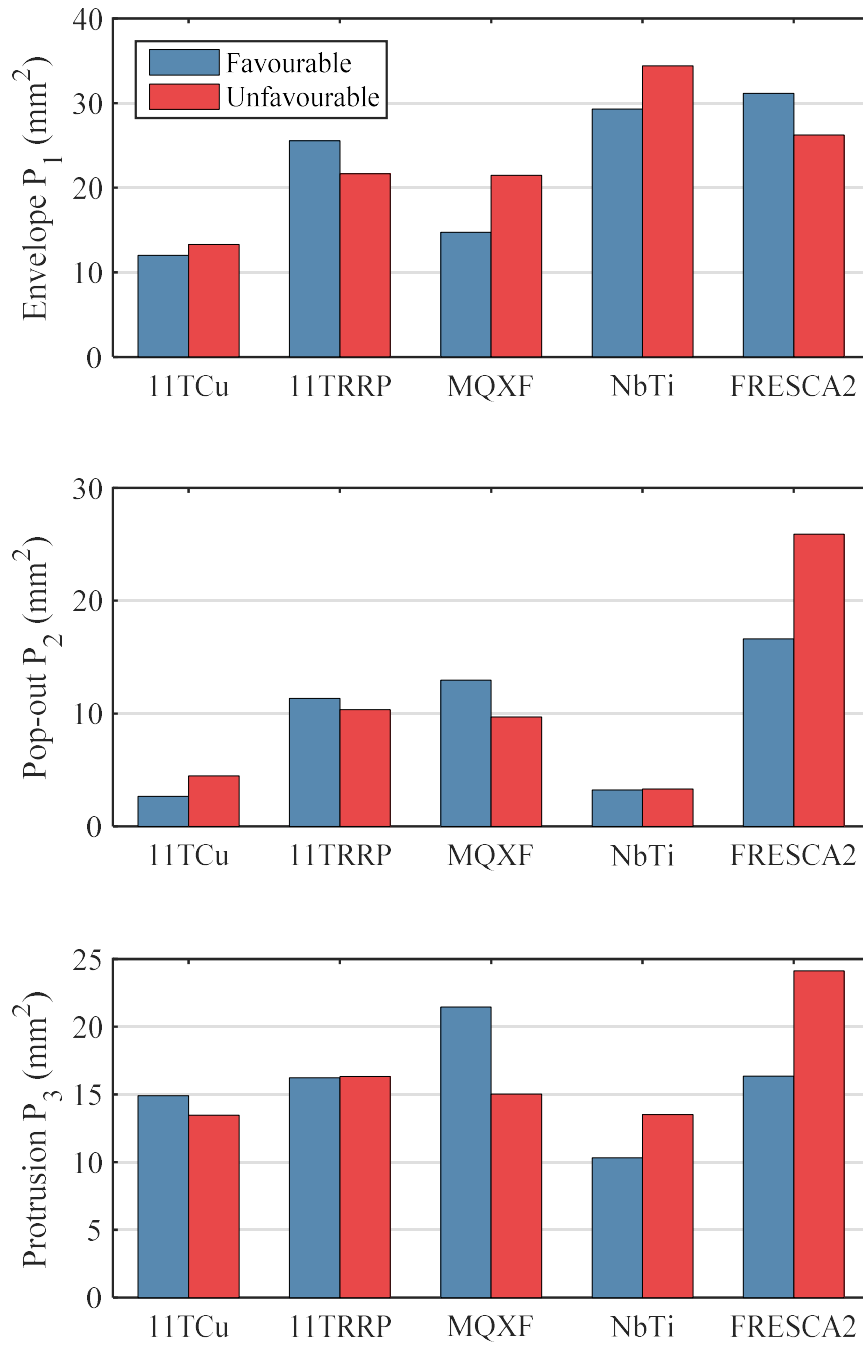


Figure 7.5 Stability results of 5 tested cables. The bar height represents the standard deviation of specimens wound with various winding mass, for each direction separately.

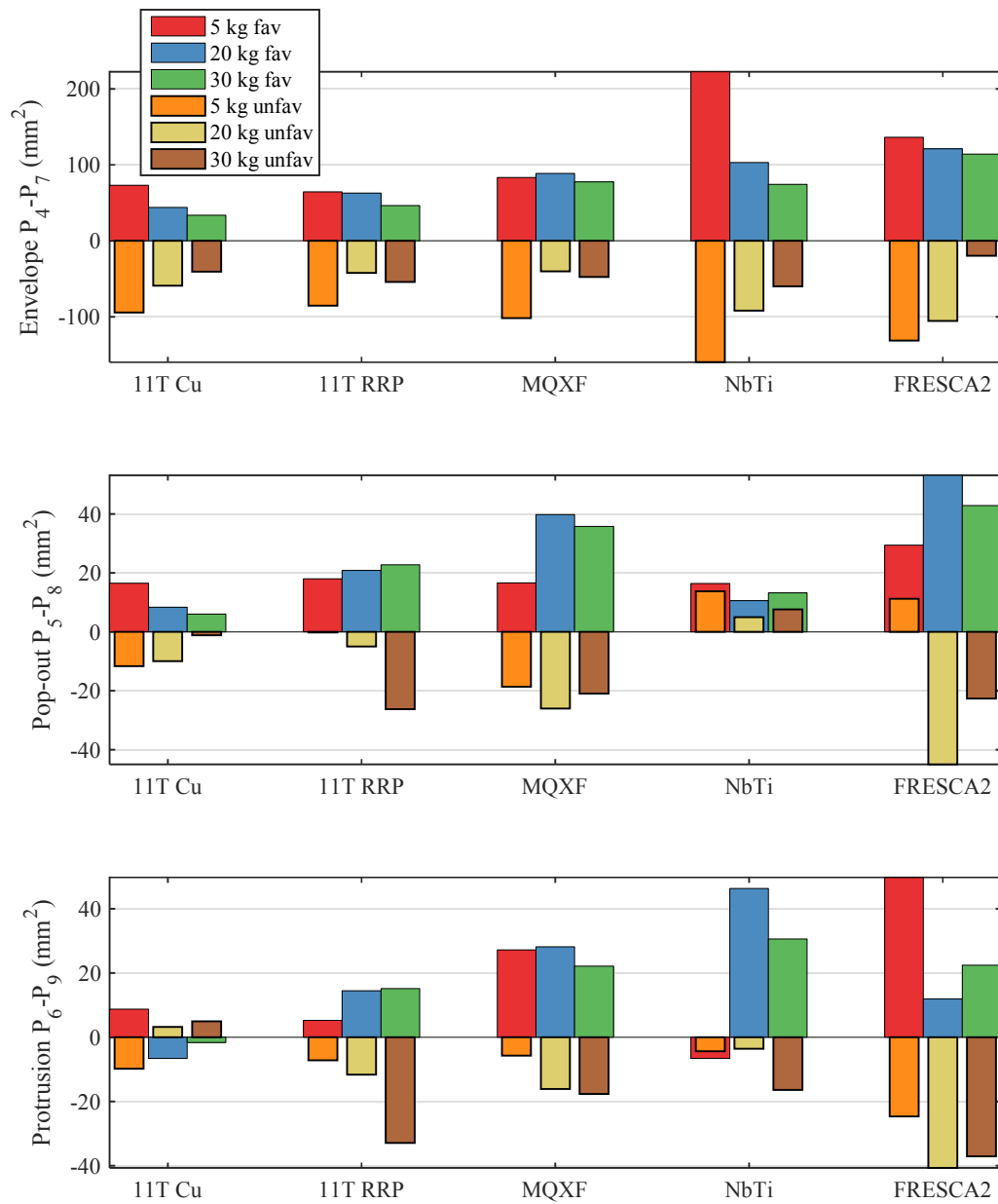


Figure 7.6 Specimen envelope, pop-out and protrusion side-symmetry. The bar height represents the averaged result of the subtraction of the left and right side of the deformation indicator.

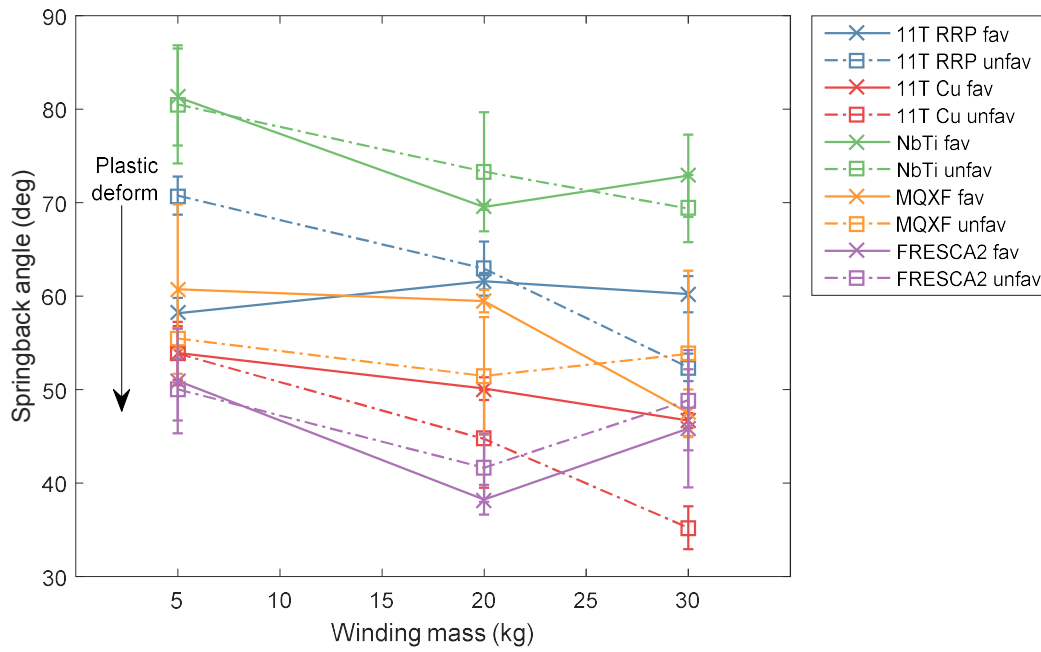


Figure 7.7 The springback angle measurement of five cables.

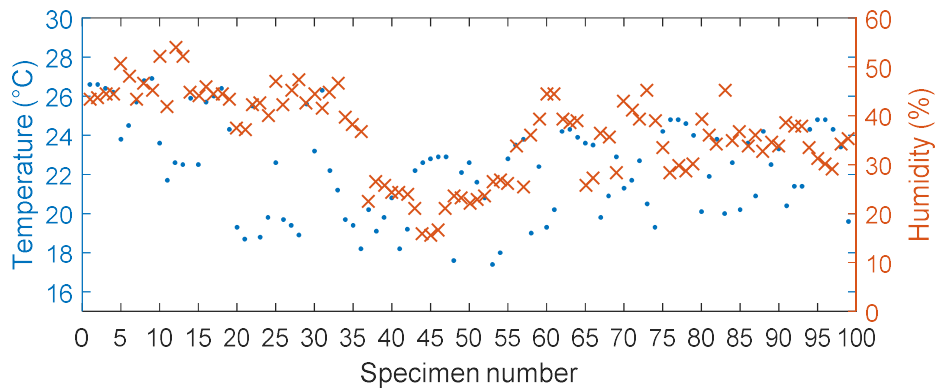


Figure 7.8 Temperature (marked with blue dot) and humidity (marked with orange cross) of the air in the laboratory at the beginning of the specimen scan.

7.1.2. DISCUSSION AND CONCLUSION

Following the deformation and analysis methodology shown in chapter 6.3, one can keep in mind that a smaller indicator signifies a better winding quality, which can be seen as more desirable for the quality of the winding process.

The winding performance is shown in Figure 7.2. The results displayed in three axes correspond to the deformation indicators, i.e. the average envelope P_1 at the top; the strand

pop-out P_2 in the middle; and the protrusion P_3 at the bottom. Each bar represents the average indicator value of three specimens wound in given conditions. As indicated in the legend, the blue color illustrates the 5 kg winding tension, the red color 20 kg tension, and the green 30 kg tension. The winding direction is differentiated with the line width of the bar, where the thin line is the favourable direction and the thick is the unfavourable (see Figure 7.1). The results of each cable are grouped in six adjacent bars in the following order: 11T Cu, 11T RRP, MQXF, Nb-Ti, and FRESA2, as indicated on the horizontal axis.

The envelope deformation of all cables is largely dependent on the applied winding mass. The higher tension reduces the deformation, regardless the winding direction. One can see a large improvement between the 5 kg and 20 kg, followed by the smaller improvement between the 20 kg and 30 kg. All tested cables exhibit the smallest envelope deformation with 30 kg winding mass. The maximal deformation is obtained by the Nb-Ti cable for 5 kg tension in favourable direction, and the minimal by the 11T Cu cable for 30 kg in favourable direction.

The pop-out exhibit a smaller difference of the results within one cable, in comparison with the envelope. The best performance is obtained by the 11T RRP cable for 20 kg tension in favourable direction, whereas over twofold worse is obtained by the FRESA2 cable for 5 kg tension in unfavourable direction.

The best protrusion performance is obtained by the 11T Cu cable, whereas the worse is obtained by the FRESA2 cable for 20 kg and favourable direction.

The stability results are presented in Figure 7.3. These are displayed following the same convention as the performance results. The best protrusion and strand pop-out stability results are obtained for the cable 11T Cu for 20 kg winding mass in unfavourable direction. The worse results of the strand pop-out and protrusion stability are obtained by the FRESA2 cable for 5 kg winding tension in unfavorable direction. Regarding the middle axis, one can see a better strand pop-out stability of the Nb-Ti cable, in comparison with the Nb₃Sn based cables. This result is in agreement with the experience coming from the winding operators, who evaluate the Nb-Ti cable as easier to wind.

The performance result of five tested cables is shown in Figure 7.4. The three axes present three deformation types. The two bars representing favourable (in blue) and unfavourable (in red) winding direction correspond to one cable type, marked on the horizontal axis. Each bar presents an average value of 5, 20 and 30 kg of applied winding tension. This presentation of the results intends to ease the observation by lowering the amount of bars representing each cable from six to two.

The top-chart shows the envelope indicator, which has shown the largest dependence on the strand material and the cable cross section. It describes the cable adjacency to the winding surface. Understandably, cable of less ductile material or larger transversal cross section require larger force in order to achieve a similar strain. Therefore, more ductile 11T Cu and 11T RRP cables with 0.7 mm strand diameter achieved better performance than 1 mm diameter FRESA2 or Nb-Ti cables.

The pop-out performance shown in the middle-chart is comparable for all tested cables, except for the FRESCA2, achieving roughly two times worse performance than 11T Cu.

The protrusion shown in the bottom-chart clearly ranks the 11T Cu and 11T RRP cables as the best performing, with the FRESCA2 cable achieving the least performance.

Additionally, the result has shown the large difference between favourable and unfavourable winding direction. For the Nb-Ti cable, one can see the performance of favourable winding direction reaching even 40% higher value in comparison to the unfavourable.

The stability results are shown in Figure 7.5. The top-chart displays the envelope deformation, where the most stability is observed in 11T Cu, and the least in Nb-Ti cable. The results appear dependent on the material stiffness and cable cross section, e.g. number and diameter of the strands. The reproducibility of the pop-out deformation is displayed in the middle-chart, where one can see that the most stable are the Nb-Ti and the 11T Cu cables. The FRESCA2 cable is over four times less stable, with 11T RRP and MQXF cables placed in-between. The protrusion stability, presented in the bottom-chart, places the Nb-Ti as the best, followed by the 11T Cu and 11T RRP cables. The MQXF and FRESCA2 cables show the large difference between the winding directions.

The specimen side-symmetry, shown in Figure 7.6, is investigated by subtracting the indicators corresponding to the left (P_4, P_5, P_6) and the right side (P_7, P_8, P_9) of the specimen. The subtracted indicators, defined in chapter 6.3, are marked in the vertical axis. The positive value of the bar indicates a larger deformation of the left side of the specimen, whereas the negative value of the bar indicates the larger deformation of the right side of the specimen. As shown in the legend, the blue, red and green bar colors indicate 5 kg, 20 kg and 30 kg winding mass respectively for the favourable winding direction. The unfavourable winding direction is presented by orange, beige, and brown colors for 5 kg, 20 kg and 30 kg winding mass.

Assuming a symmetric behavior of the cable, the bars representing a result of the same winding mass (e.g. red and orange) should be of equal absolute value and opposite sign. Therefore, the lack of balance is a measure of an asymmetric behavior of the cable. In addition, a specimen wound in favourable direction with the assumed symmetric cable should feature larger deformation on the left side of the specimen (i.e. positive values of the bars in Figure 7.6). Consequently, the winding in unfavourable direction should result with more deformation on the right side of the specimen. This phenomenon is dictated by the direction of the bending.

The envelope symmetry is shown at the top of Figure 7.6. One can see that according to the assumed perfect behavior, the specimens wound in favourable direction exhibit more deformation on the left side of the specimen (i.e. positive values), and the unfavourable on the right side (i.e. negative values). The lack of symmetry of the Nb-Ti cable strand pop-out can be observed by the overlapping bars in the middle-chart.

Considering the presented results of the performance (Figure 7.2), the stability (Figure 7.3) and the side-symmetry (Figure 7.6) as the criteria of the winding quality, one can define the

parameters leading to the least amount of deformation. Those parameters are presented in Table 7.3. Each cable is represented by one column divided for the inner and outer layer. The inner layer presents the winding mass (M) and the winding direction (Dir) providing the least amount of deformation. Whereas the outer layer winding direction is determined as the opposite, due to the necessity of winding both coils with one length of cable (as discussed in chapter 2). The Nb-Ti superconducting cable does not require winding in both directions, yet it is presented in the same manner for comparison reasons. The rows of the table are indicating the criteria and the deformation type. The mass is given in kilograms, the favourable winding direction is signified by 1 and the unfavourable by 0.

In order to adjust the winding mass and direction shown in Table 7.3, one needs to define the objective for the minimization of the cable deformation. For example, in order to obtain the best strand pop-out performance for the MQXF cable, the inner layer should be wound in the unfavorable direction, and outer layer in favourable direction both with 5 kg winding mass. In addition, this configuration will provide the highest strand pop-out stability and the least side-symmetry deformation. The best strand pop-out stability of the 11T RRP cable can be achieved with the 5 kg winding mass, wound in favourable direction. The presented method is capable of defining the recommended winding parameters minimizing the cable deformation in the tested parameter range.

Table 7.3 Winding mass and direction providing the best quality for given criteria. Mass (M) given in kg. Dir equal 1 defines the favourable winding direction, whereas 0 – unfavourable.

Criterion	Cable Layer	11T Cu		11T RRP		MQXF		Nb-Ti		FRESCA2	
		Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
Performance	Deformation	M Dir	M Dir	M Dir	M Dir	M Dir	M Dir	M Dir	M Dir	M Dir	M Dir
	Envelope	30 1	30 0	30 1	30 0	30 0	30 1	30 1	30 0	30 0	30 1
	Pop-out	20 1	30 0	5 1	20 0	5 1	30 0	5 1	5 0	30 0	5 1
	Protrusion	20 0	5 1	20 0	20 1	20 0	5 1	20 0	5 1	5 0	30 1
Stability	Envelope	20 0	30 1	5 0	20 1	20 1	5 0	30 0	20 1	30 0	20 1
	Pop-out	20 0	30 1	5 1	5 0	5 1	5 0	5 0	20 1	20 0	5 1
	Protrusion	5 1	20 0	5 1	5 0	5 0	5 1	20 0	20 1	30 1	20 0
Side-symmetry	Envelope	30 1	30 0	20 0	30 1	20 0	30 1	30 0	30 1	30 0	30 1
	Pop-out	30 0	30 1	5 0	5 1	5 1	5 0	20 0	20 1	5 0	5 1
	Protrusion	30 1	20 0	5 1	5 0	5 0	30 1	20 0	5 1	20 1	5 0

The springback angle measured according to the method described in chapter 6.4 is shown in Figure 7.7. Each cable is represented by a different color. The favourable direction is indicated by a solid line and a cross marker. The unfavourable winding direction is indicated by a dashed line and a square marker. The winding mass is indicated on the horizontal axis, whereas the springback angle is indicated on the vertical axis. The springback angle is related to the stored elastic energy in the cable after winding. The marked value is the average angle of three specimens wound with given parameters, and the error bars are showing the standard deviation. The decreasing angle can be correlated with a larger plastic deformation of the cable. The largest springback angle on average (i.e. the least plastic deformation) is obtained by the Nb-Ti cable, whereas the smallest (i.e. the most plastic deformation) by the FRESCA2 cable. One can see the common trend of the results, i.e. the decreasing springback angle with increasing winding mass. This is due to the cable being closer to the winding surface with increased winding mass, as indicated by the envelope performance (shown in 7.2).

The temperature and humidity is indicated in Figure 7.8. The conditions are measured in close proximity to the WS at the beginning of each scan indicated on the horizontal axis. The temperature ranges from 18°C to 27°C, and the humidity from 20% to 50%.

7.2. CABLE PRE-TORSION

The winding machine (shown in Figure 2.3) lacks a DOF allowing maintaining the tangency of the cable feed with respect to the winding surface, as described in chapter 2.3. Additional DOF can be beneficial for the winding performance and stability, due to the tightening of the cable (see Table 2.2). In order to investigate the influence of cable tightening on the winding quality, the pre-torsion study was conducted. The pre-torsion is the angular offset which is maintained by the guide throughout the winding process (see Figure 7.9). The 11T RRP cable was tested in two variants: without the insulation, and with the S-2 Glass and Mika insulation layers. The nominal parameters of the cable are shown in Table 7.1.

The winding frame is used in order to wind the specimens, with parameters defined in Table 7.4. The parameters in column ‘test value’ marked in black are kept constant, and in red are changed according to the tested case. Three pre-torsion angle values are tested: 0°, 22.5°, and 45°. In total 9 specimens are wound with insulated cable, and 6 with uninsulated cable. The results of 3 specimens wound with the uninsulated cable, 20 kg tension, and 0° pre-torsion are retrieved from the previous campaign (see chapter 7.1). The same sample holder geometry featuring 20 mm cylinder diameter (see Figure 7.1) is used throughout the test.

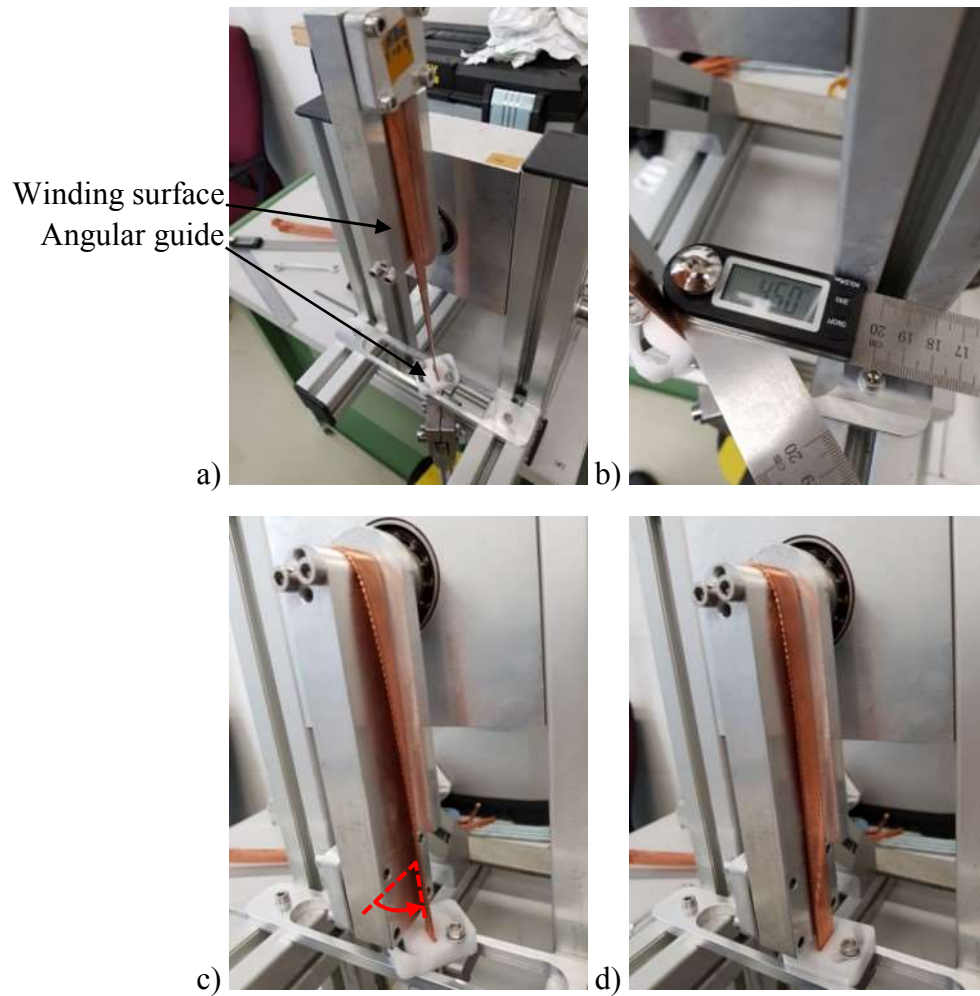


Figure 7.9 Specimen winding with 45° pre-torsion; a) clamping the cable; b) measuring the torsion angle; c) specimen winding; d) adjustment to clamp.

Table 7.4 The Winding Frame parameters used in the test campaign.

Group	Designation		Symbol	Unit	Test value
Frame	Angular guide	X position	Ax	(mm)	10
		Y position	Ay	(mm)	61
		Z position	Az	(mm)	112
		angle	Aalpha	(deg)	0, 22.5 or 45
		thickness	At	(mm)	10
		aperture	Aa	(mm)	4
	Tensile load		M	(kg)	20
Pole	Identification		Pid	-	d20L160
	Cylinder diameter		Pd	(mm)	20
	Clamp length		Pc	(mm)	39
Run	Direction	Favourable - 1	Dir	-	1
		Unfavourable - 0			
	Mandrel support	Yes - 1	Sup	-	1
		No - 0			
	Cylinder surface	Material	Mat	-	Aluminium
		Friction coeff	μ	-	-
Cable	Pre-cut cable length		L	(mm)	400

7.2.1. OBTAINED RESULTS

In this chapter the analyzed results of 18 measurements are presented. The discussion is given in the following chapter 7.2.2. The results are structured according to the analysis methodology described in chapter 6.3. The performance and the stability of the uninsulated cable is shown in Figure 7.10 and Figure 7.11. The performance and stability comparison of the insulated and uninsulated cable is shown in Figure 7.12. The measurement conditions are presented in Figure 7.13.

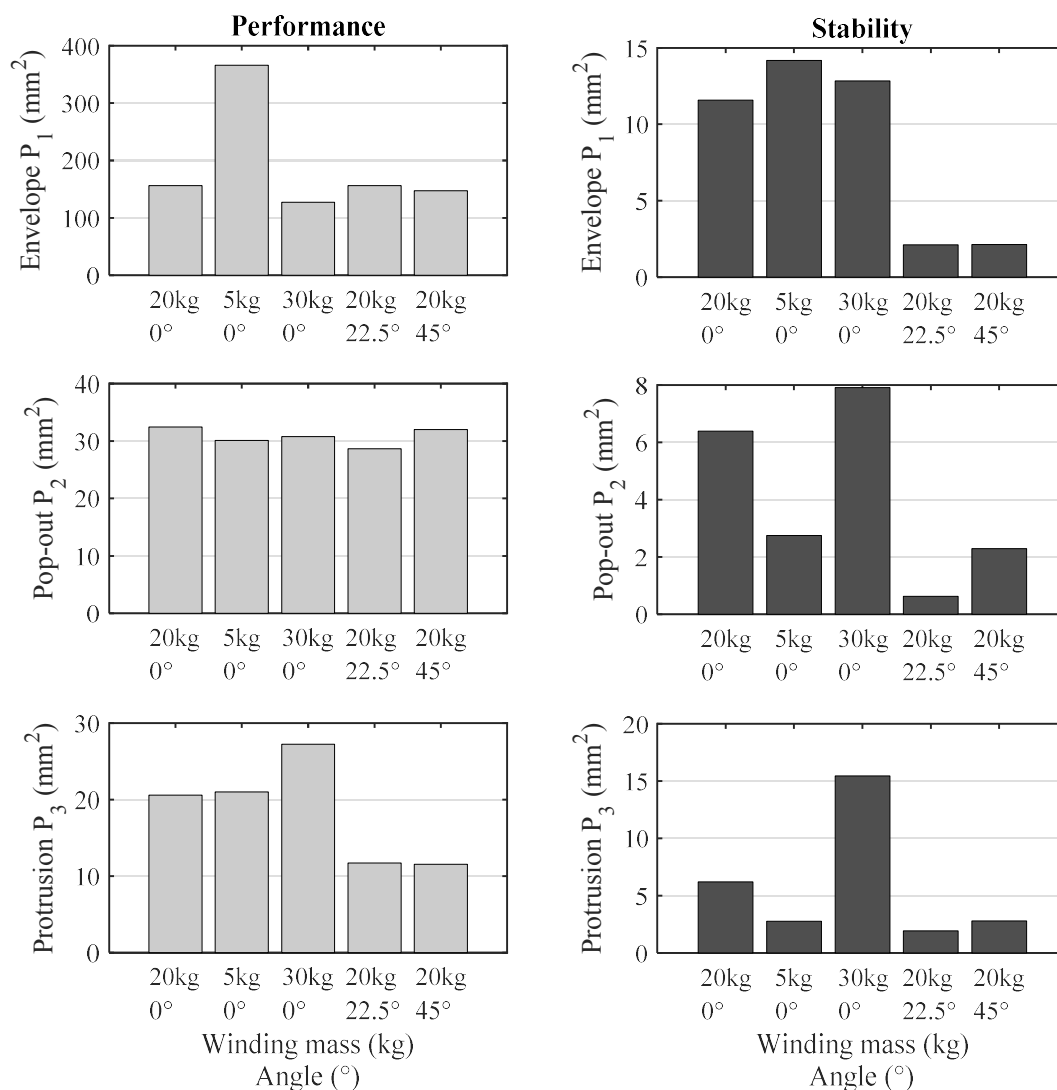


Figure 7.10 Performance and stability of uninsulated cable vs winding mass and angle

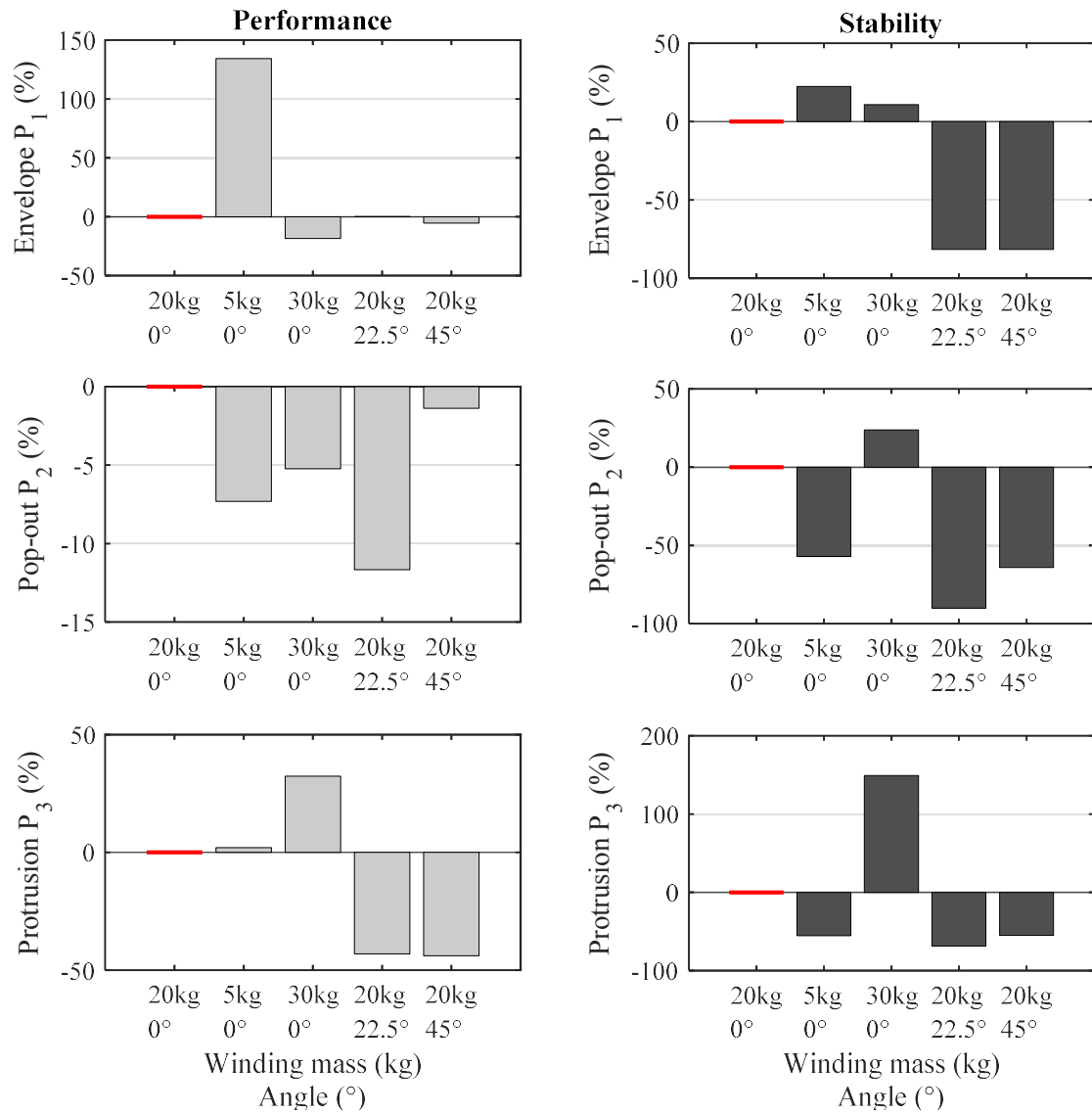


Figure 7.11 Percentage change of uninsulated cable performance and stability vs winding mass and angle.

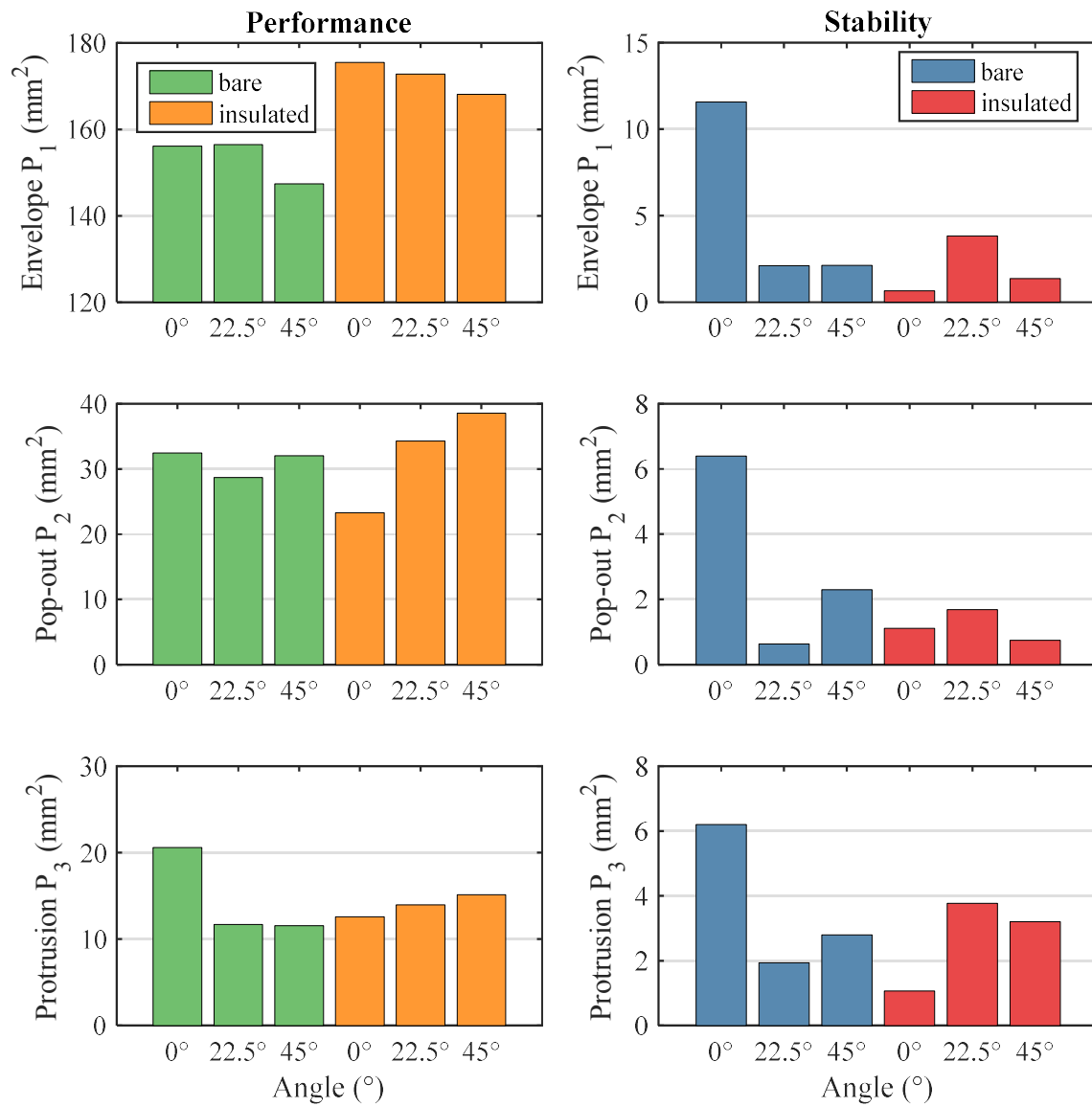


Figure 7.12 Insulated and uninsulated cable performance and stability vs winding mass and angle.

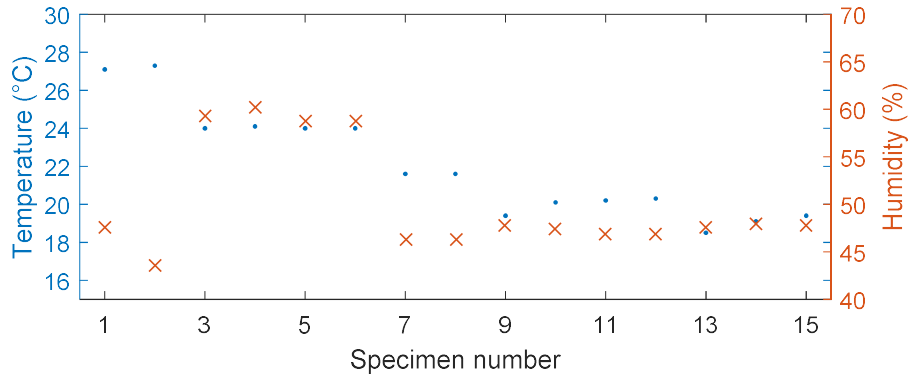


Figure 7.13 Temperature (marked with blue dot) and humidity (marked with orange cross) of the air in the laboratory at the beginning of the specimen scan.

7.2.2. DISCUSSION AND CONCLUSION

One can see the performance and stability results of the uninsulated cable shown with absolute values in Figure 7.10. The horizontal axes specify the winding mass and the pre-torsion angle. The results of the winding with 5 kg and 30 kg of winding mass and 0° pre-torsion are added for reference (obtained during the measurements described in chapter 7.1). The leftmost bar indicates the specimen wound with 20 kg mass and 0° pre-torsion, followed by two specimens wound with 5 kg and 30 kg. The fourth and fifth specimens were wound with a 20 kg winding mass and a pre-torsion angle of 22.5° and 45° respectively.

The performance and stability results in Figure 7.11 indicate the deviation in percent from the reference sample given by the 20 kg and 0° (marked with red line). The applied pre-torsion contributes to an improved performance, i.e. the envelope improved by 10%; the pop-out improved by 12%; and the protrusion improved by 40%. In addition, the stability of all deformations improved by 50%. The range of the obtained deformation for various winding masses and various pre-torsion angles underlines that twist angle is equally relevant for the winding quality, as the winding mass. The cable pre-torsion (tightening) ensures less winding deformation and higher repeatability.

The measurement results of the insulated and uninsulated cables are shown in Figure 7.12. The performance is presented on the left-hand side with three axes corresponding to three deformation types. The results of the uninsulated (bare) cable are shown in green, while the insulated are shown in orange. The stability is shown on the right-hand side of the figure, with blue bars indicating uninsulated cable and the red color indicating insulated. The horizontal axis indicates the pre-torsion angle, ranging from 0° (lack of pre-torsion) to 45°. The best envelope and protrusion stability of the insulated cable is achieved without pre-torsion (i.e. 0°). The best stability against strand pop-out events is achieved for the 45°. The insulation layer has shown to positively impact the winding stability, which is underlined by the large difference in the results for the bare and insulated cables wound without

pre-torsion. The absolute performance and stability difference for the 22.5° and 45° of the pre-torsion angle is within comparable range for both insulation variants. This indicates that the winding quality is dependent on the pre-torsion angle regardless of the insulation presence. However, the Mica and S-2 glass layers bring additional torsional rigidity and lateral support to the strands in the cable. Due to this reason, the initial stability of the cable (i.e. for 0°) is improved with respect to the uninsulated cable.

The temperature and humidity is indicated in Figure 7.13. The conditions are measured in close proximity to the WS at the beginning of each scan indicated on the horizontal axis. The temperature ranges from 19°C to 27°C, and the humidity from 45% to 60%.

7.3. COMPLEMENTARY EXPERIMENTS USING THE WINDING SPECIMEN

As has been shown in the previous chapters the winding parameters have a crucial impact on the coil geometry. Nevertheless, subsequent manufacturing steps (see Figure 2.1) have been identified to also impact the quality of the coil geometry. After the winding process the wound coil is cured at temperatures of 160°C and subjected to the Reaction Heat Treatment (RHT) with temperatures in the range of 650°C. Therefore, it was investigated which additional experiments could be performed with the developed winding specimen and analysis technique. One attempt was given by the verification of the cable relaxation after the RHT process. The chapter 7.3.1 will describe the experiment carried out in order to verify the impact of the RHT cycle on the wound specimen. In addition, the winding specimen was subjected to Computed Tomography (CT) examination, achieving results presented in chapter 7.3.2.

7.3.1. DEFORMATION DUE TO REACTION HEAT TREATMENT

The reaction heat treatment is performed in order to produce the A15 phase Nb₃Sn from the precursor material in the filaments [65]. The difference in mechanical properties due to the structural and chemical changes, as well as the various thermal expansion of the constituents may result with the unaccounted stresses in the cable [66]–[68]. As can be seen in Figure 7.14 the large gaps in the order of 2 mm are developed after RHT and opening of the reaction mould of the 11 T prototype coil. The largest gap was visible in-between the pole-key and the first cable turn.

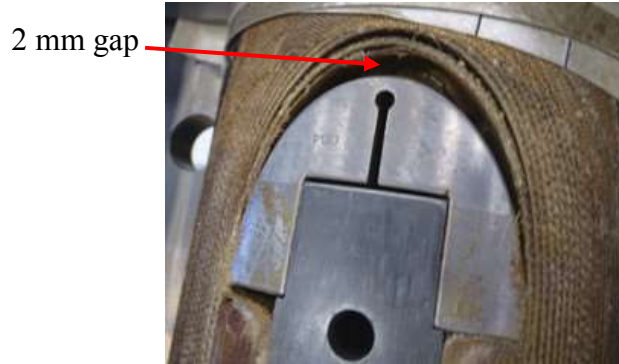


Figure 7.14 Gap between the outer-layer return key and the cable of the 11 T coil after RHT.

In order to investigate the deformation of the wound cable due to the RHT, one specimen was wound with the WF and parameters shown in Table 7.5. The uninsulated 11T RRP cable was used featuring nominal parameters defined in Table 7.1. The sample holder is machined with use of 316LN stainless steel, which corresponds to the pole material utilized during RHT of the 11 T coil. The cable is clamped on the sides of the specimen as shown in Figure 7.15a throughout the RHT.

Table 7.5 Winding parameters of HT specimen.

Group	Designation		Symbol	Unit	Test value
Frame	Angular guide	X position	Ax	(mm)	10
		Y position	Ay	(mm)	61
		Z position	Az	(mm)	112
		angle	Aalpha	(deg)	0
		thickness	At	(mm)	10
		aperture	Aa	(mm)	4
	Tensile load		M	(kg)	20
Pole	Identification		Pid	-	d20L160
	Cylinder diameter		Pd	(mm)	20
	Clamp length		Pc	(mm)	39
Run	Direction	Favourable - 1	Dir	-	1
		Unfavourable - 0			
	Mandrel support	Yes - 1	Sup	-	1
		No - 0			
	Cylinder surface	Material	Mat	-	316LN (stainless steel)
		Friction coeff	μ	-	-
Cable	Pre-cut cable length		L	(mm)	450

The specimen was subjected to the RHT cycle of the MQXF coil (available at the time of performing a test). The picture of the specimen before and after RHT is shown in Figure 7.15. A larger cable deformation is visible (e.g. of the cable envelope) of reacted specimen in comparison with the unreacted. One can easily distinguish between the non-reacted (a) and reacted (b) specimen since later is showing a copper oxidation even when the process has been carried out under Argon inert gas atmosphere.

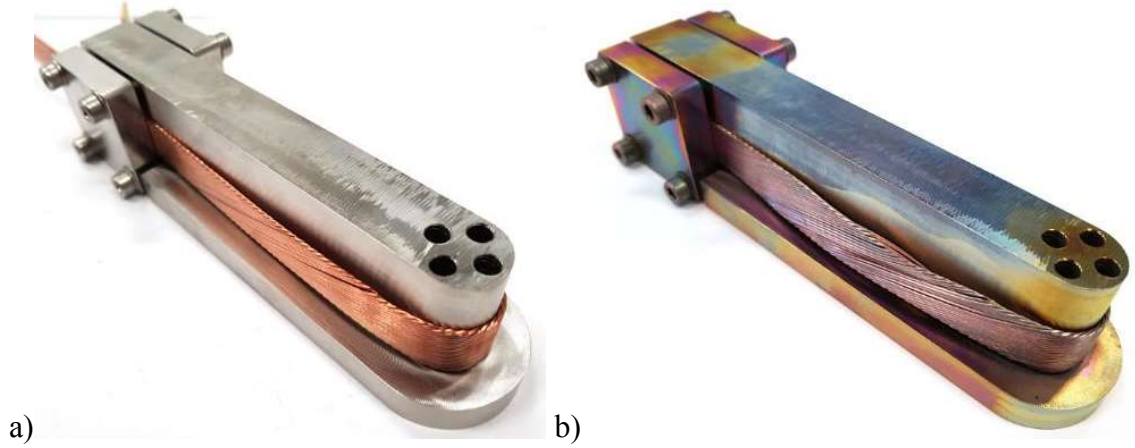


Figure 7.15 The picture of the unreacted (a) and reacted (b) specimen.

The WS scanning program was adjusted in order to obtain a high spatial resolution, i.e. vertical axis (Z DOF) of 0.02 mm, horizontal axis (Y DOF) of 0.5 mm, and rotational axis (A DOF) of 3.6°. This configuration results with approximately 500k measurement points. The scan of the specimen before and after reaction is shown in Figure 7.16. One can easily identify the deformation of the cable in the presented scans.

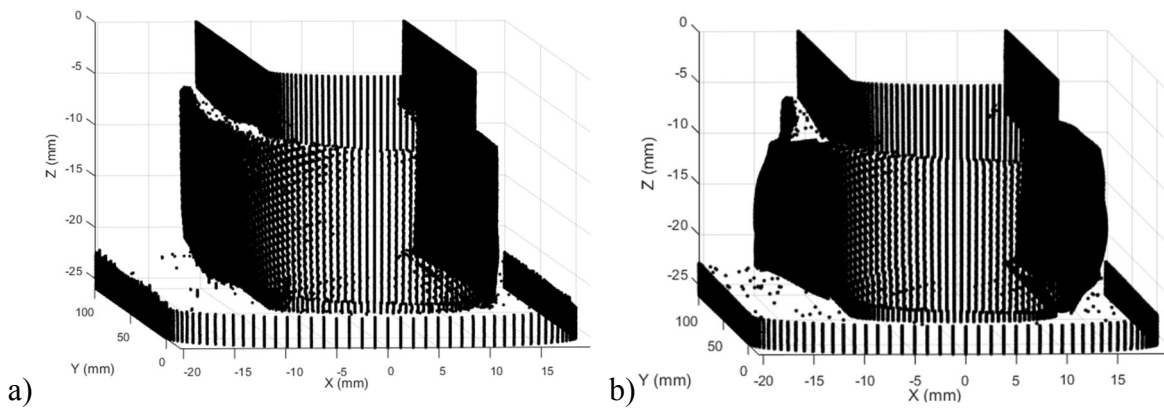


Figure 7.16 The WS measurement points of the unreacted (a) and reacted (b) specimen.

The scans are analyzed following the methodology shown in chapter 6.3. The average envelope of the specimen before (D_{1U} blue solid line) and after (D_{1R} red solid line) reaction is shown in Figure 7.17. One can see that the specimen shows a larger deformation after the reaction.

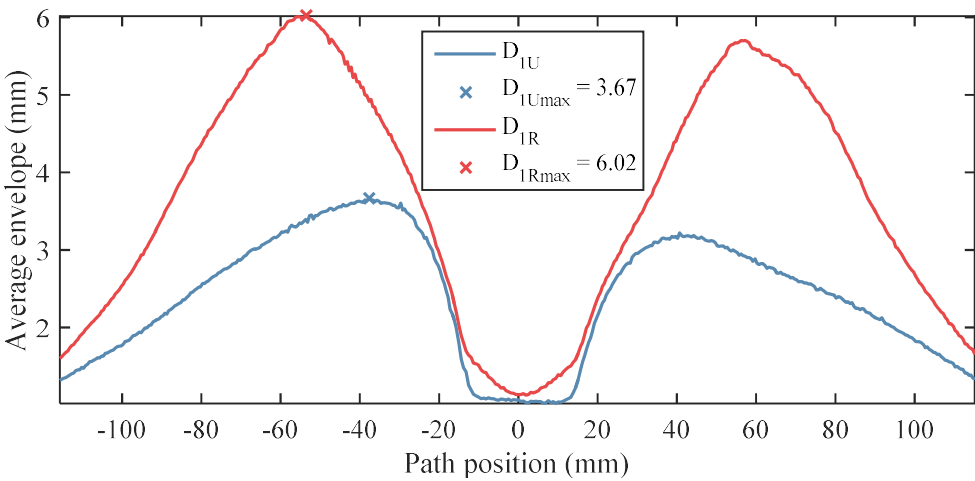


Figure 7.17 The average envelope deformation functions of unreacted (D_{1U}) and reacted (D_{1R}) specimen. Maxima marked with cross.

The difference between the reacted and the unreacted envelope deformation ΔD_1 is shown in Figure 7.18. The resulting function achieves the maximum of 2.8 mm. The larger cable envelope is observed after reaction.

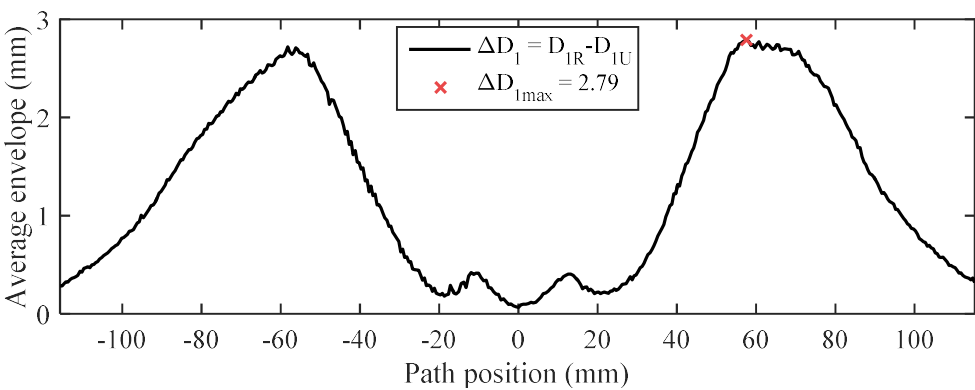


Figure 7.18 The difference between the reacted and unreacted average envelope deformation of the cable. Maximum marked with cross.

The minimal deformation can be seen in the middle of the graph, i.e. at the tip of the cylinder (see Figure 7.18). The maximal deformation is located in the middle of the straight section of the specimen.

As can be seen from figure 7.14 the developed gap in the longitudinal direction does in the first view not correlate with the results observed on the specimen (see fig 7.15). Nevertheless, one should take note that the coil is supported inside a cavity (reaction fixture), which is only allowing a volumetric growth of 3%. This can explain why the coil growth is only observed in the longitudinal direction, while on the specimen no boundary is present in a lateral direction.

The topic of thermal expansion of Nb₃Sn conductor is of crucial importance for the HL-LHC coil fabrication, therefore measurements are carried out in a separate study. The presented approach using the winding specimen is considered of less importance for the thesis. The developed scenario of continuing these tests would consist of the following steps:

- Winding of the single strand, in order to obtain the reference data comparable with literature [65]–[68];
- Utilizing the insulated cable, in order to examine the influence of the additional lateral support of the cable;
- Introducing the longitudinal support of the cable, in order to investigate the closed cavity boundary conditions present during the coil reaction.

7.3.2. CABLE VOLUME DIGITIZATION WITH COMPUTED TOMOGRAPHY

In order to explore the possibility of obtaining the 3D specimen deformation data with use of a non-destructive method, the Computed Tomography (CT) of the winding specimen was performed. The aim was to generate the meshed volume of a wound cable that could be used to inspect the normal thickness of the cable. The specimen, shown in Figure 7.19, was subjected to the CT scan. The sample was prepared on the WS featuring a 20 mm diameter sample holder, a 20 kg winding mass in the favourable winding direction. The 11T Cu cable was used, featuring the nominal parameters shown in Table 7.1.

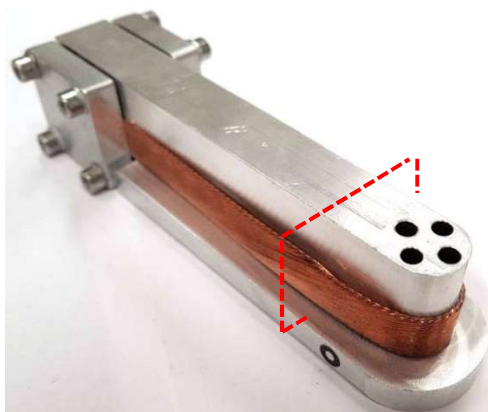


Figure 7.19 Winding specimens subject to tomography. Transversal cross section marked with red dashed line.

The neutron tomography was performed in the ANTARES cold neutron radiography and tomography facility in Munich [69], with the parameters listed in Table 7.6. The tomography was obtained courtesy of Mr. Burkhard Schillinger and Mr. Christian Scheuerlein. We acknowledge the MLZ Munich for beam time at the ANTARES beam line.

Table 7.6 Parameters of ANTARES neutron tomography.

Cold neutrons λ	2 to 5 Å (0.2 to 0.5 nm)
Voxel edge size	28.2 μm
Field of view	2160 px $\times$ 2560 px
No. of projections	876
Time per projection	45 s (acquisition time $\sim$ 11 h)

The obtained reconstructed tomogram consists of series of cross section images of the specimen. The example tomogram image is shown in Figure 7.20, which corresponds to the cross section marked with red dashed line in Figure 7.19. The resulting grayscale is proportional to the beam energy absorbed by the material. One can see the almost white copper strands on both sides of the specimen, aluminum sample holder shown in gray, and a background in black.

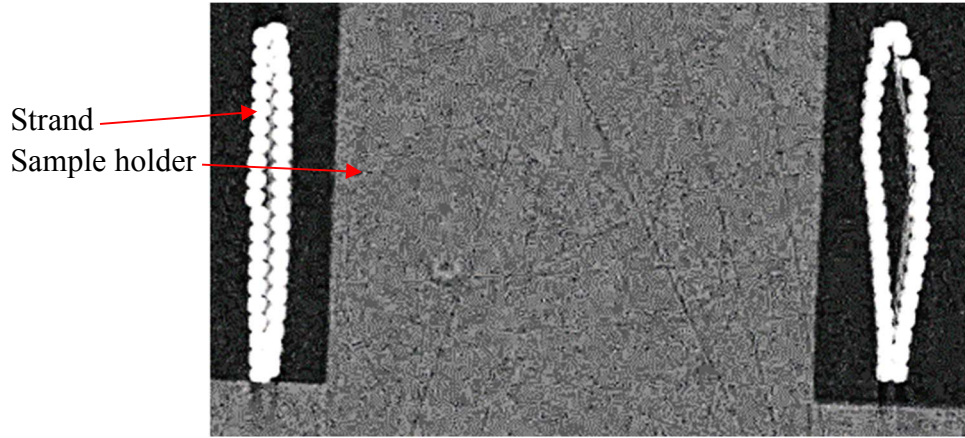


Figure 7.20 Reconstructed frame of a tomogram. Transversal cross section of the specimen.

The tomography image is binarized based on a brightness threshold, in order to determine the pixels corresponding to the cable, and the sample holder. The 3D cloud of point of the cable and the sample holder is shown in Figure 7.21. The orientation of obtained tomogram is a result of a physical positioning of the specimen in the workspace. Prior the deformation analysis, the tomogram was reoriented with use of the cylindrical mounting holes, shown in Figure 7.21b. The central line was tracked in the center of two mounting holes in order to compute the correction angles.

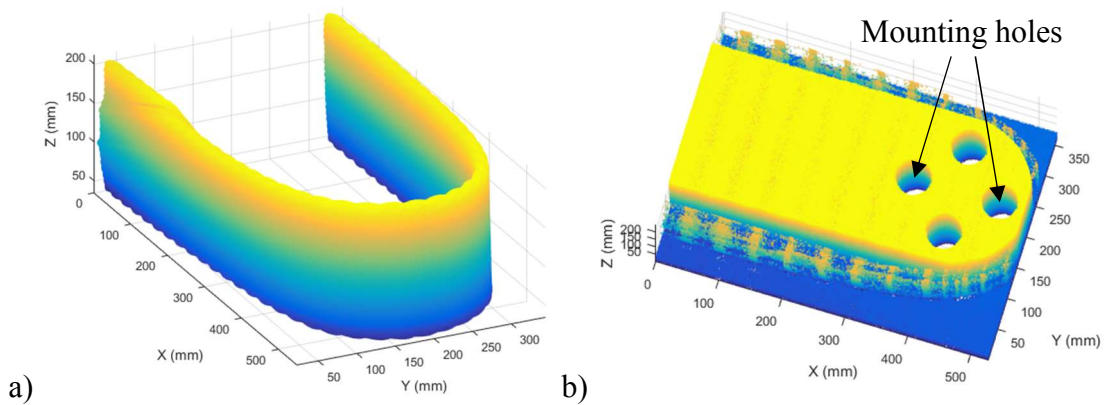


Figure 7.21 Cloud of points of the cable (a) and sample holder (b).

One can see the aligned and shifted cloud of points of the cable, shown in Figure 7.22. The red solid line indicates the winding path, and the red asterisk indicates the origin overlapping the center of the winding cylinder.

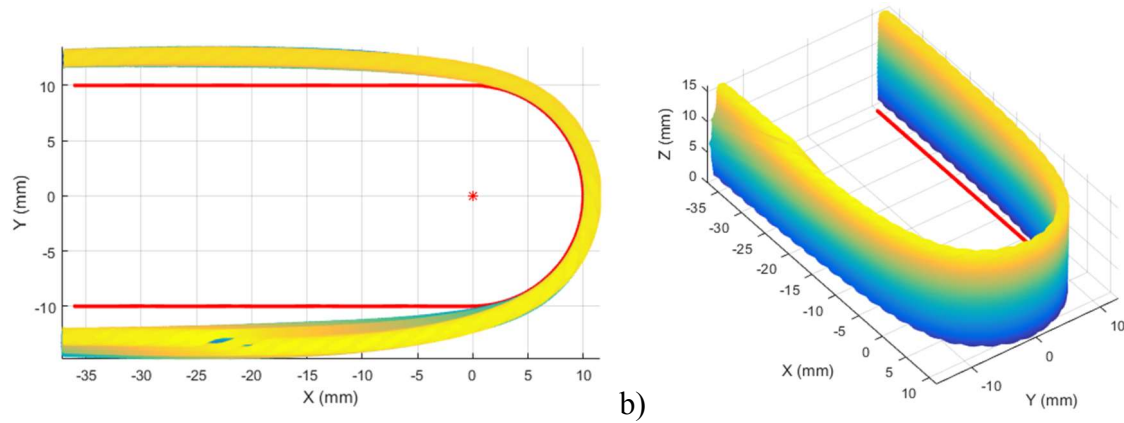


Figure 7.22 Tomography reconstructed cable with the winding path marked in red; a) top view; b) perspective view.

The cloud of points of the cable was used in order to generate the mesh in the CAD software, shown in Figure 7.23. One can see the level of detail of the obtained mesh on the right side of Figure 7.23.

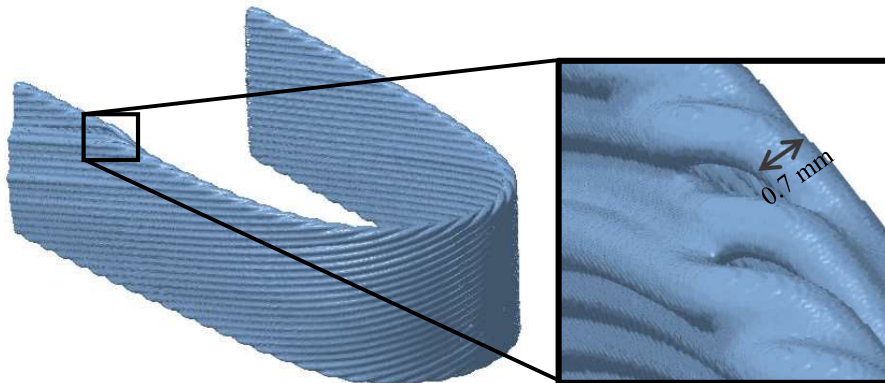


Figure 7.23 The meshed cable surface with enlarged section.

The results shown in Figure 7.22 were analyzed in order to obtain the cable envelope deformation, as described in chapter 6.3. The maximal normal distance from the winding path, shown in Figure 7.24, was computed and compared with the results obtained with the WS. The tomogram includes roughly 100 mm of the winding path. Both presented functions show similar results, the discrepancy may be caused by the angular misalignment of the tomogram.

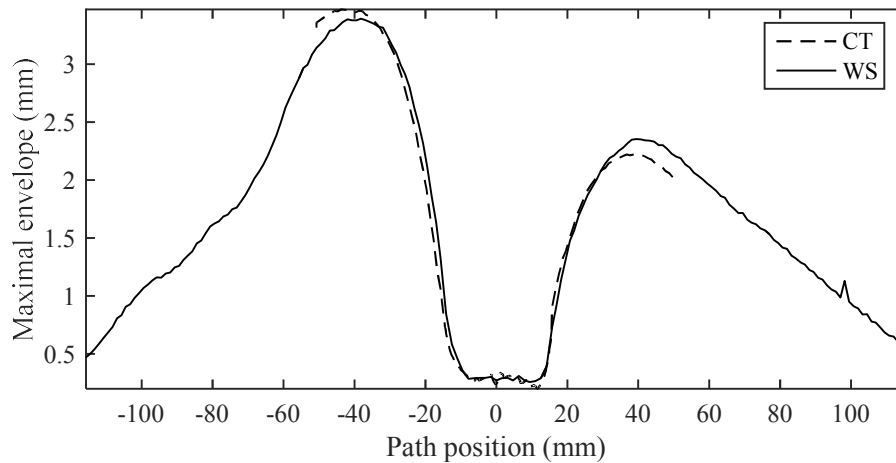


Figure 7.24 Maximal normalized envelope deformation. The comparison of tomogram analysis (CT) and winding scanner results (WS).

The tomography was analyzed further, in order to compute the local maximal thickness of the cable, shown in Figure 7.25. The thickness is computed in the normal direction from the winding path. The minimal thickness, positioned in the middle of the graph (i.e. tip of the cylinder), equals 1.4 mm, whereas the maximal thickness is positioned on the left side and measures 3.1 mm.

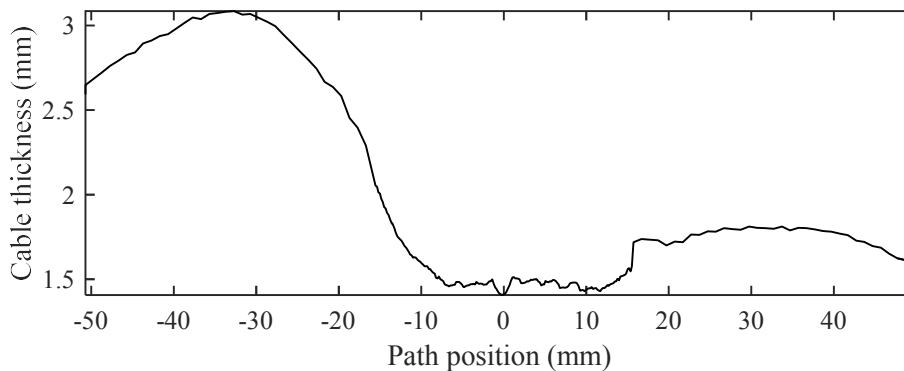


Figure 7.25 Normal thickness of the cable computed from the tomogram.

The CT is a powerful tool that can be used to investigate the cable or strand deformation in a non-destructive way. The presented tomography provides the 3D data describing the cable position. In the obtained tomogram, one can distinguish the separate strands and the voids between them. The sample holder can be used in order to position the specimen, and perform the analysis with regard to the winding path. The obtained cloud of points can be used in order to compute the cable thickness (as shown in Figure 7.25).

8. SUPPLEMENTARY GEOMETRICAL MEASUREMENT DURING THE COIL FABRICATION

The experience gained during the development of the winding test devices (described in chapter 6), as well as the conclusions drawn from the laboratory tests (see chapter 7), allowed determining the critical areas of the winding process to be improved. The contribution to the winding and curing procedures is described in this chapter.

Currently, the Quality Control (QC) during winding of 11 T and MQXFB coils consist solely of measuring the bottom position of the cable, as shown in Figure 2.15. It was crucial to propose the supplementary measurements, in order to investigate not only the cable position, but also the orientation deviation and the protrusion from the winding mandrel. These needed to be easily implemented in order to fit in the coil production procedures with no significant delay. Therefore, the standard mechanical measurement tools were used (i.e. depth and wedge gauge), which do not require special training or dedicated acquisition systems. The measurements were executed throughout the winding and curing of the MQXFB quadrupole coil in LMF (coil CERN ID: CR107).

The summary of the geometrical measurements performed during the winding and curing of the MQXFB CR107 quadrupole coil are shown in Table 8.1. As can be seen, the measurement applied within the standard procedure is given by the bottom position of the cable (marked with ‘x’). The proposed measurements are marked with ‘+’, and include: the top position and the protrusion measurement during winding, as well as the image analysis determining the cable top position after winding and curing. One can see the definition of the production step in the top row. The measurements after each wound cable turn, are marked in column ‘during’, while the column ‘after’ indicates the measurement performed after finalizing the procedure.

The scheme of performed geometrical measurements is shown in Figure 8.1.

Table 8.1 Geometrical measurements of MQXFB CR107 quadrupole coil performed in LMF.

Symbol	Method	Description	Winding		Curing
			During	After	After
Db	Depth gauge	Bottom cable position	x		
Dt	Depth gauge	Top cable position	+		
Pj, Po	Wedge	Cable protrusion	+		
It	Image	Top cable position		+	+

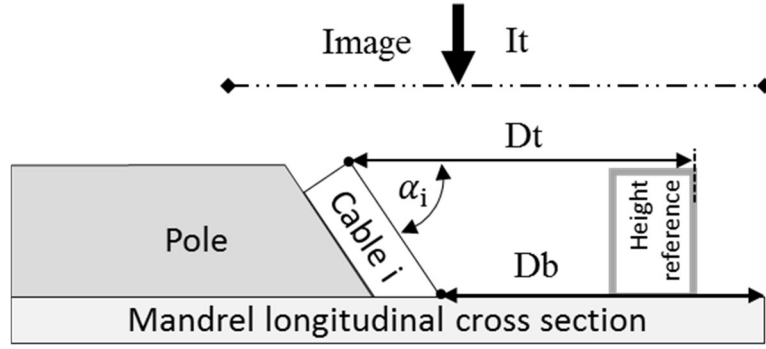


Figure 8.1 Scheme of geometrical measurements performed during MQXFB CR107 coil production.

The top and bottom position of the cable (D_t and D_b respectively) are measured with the depth gauge after each wound turn, as shown in Figure 8.2. The utilized depth gauge features a 0.01 mm resolution, ± 0.03 mm accuracy, and 0 to 300 mm measurement range. The bottom position is measured from the reference surface (end of mandrel) along the mandrel surface. The top position is measured with a reference piece assembled on the mandrel (marked 'height reference' in Figure 8.1), which provides a consistent height.

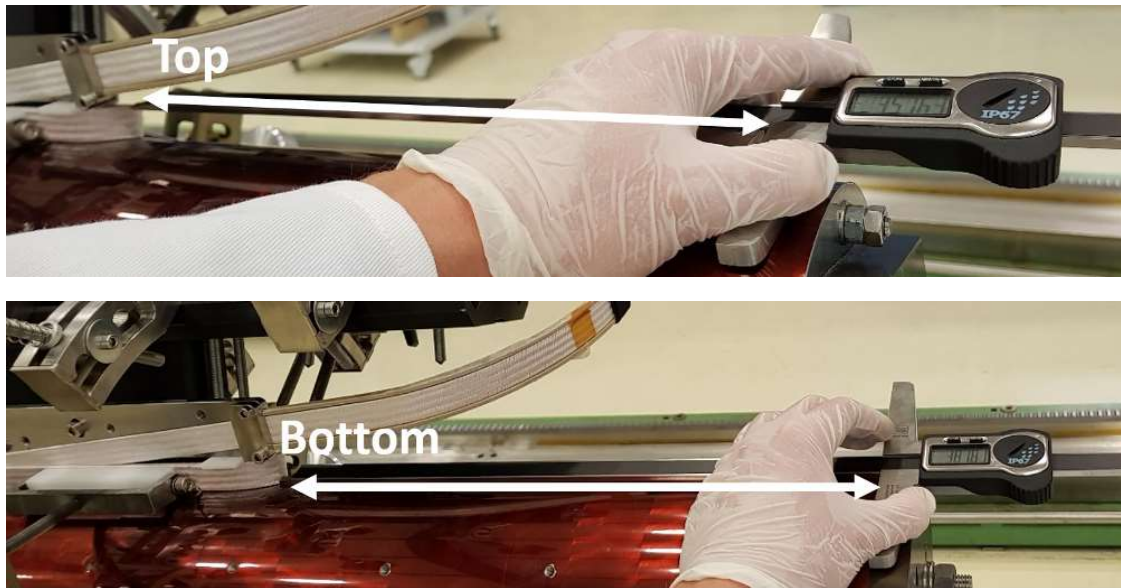


Figure 8.2 Depth gauge measurement of the top position of the cable D_t (on the top) and the bottom position of the cable D_b (on the bottom).

The maximal distance between the mandrel surface and the bottom edge of the cable is determined on both sides of the coil (i.e. layer jump side, and opposite) after each wound turn. The protrusion is measured manually with the wedge gauge of 50 μ m resolution and

50 μm to 1500 μm measurement range. One can see the measurement in Figure 8.3, performed for the inner layer on the layer jump side.



Figure 8.3 Protrusion measurement during winding with the wedge gauge of 50 μm resolution.

The position of the cable turn top edge is determined with use of the obtained image. The picture is taken with the scale, as shown at the top of Figure 8.4. Afterwards, the image is analysed allowing to determine the distance along the measurement axis (dashed line). The image analysis is conducted with a dedicated Matlab[®] script, where the central axis and the position of the cable are marked manually. The displayed image, taken with a camera featuring 12 Mpx sensor, provides a measurement resolution of 48 μm . The measurement resolution, i.e. the scaled distance between adjacent pixels, may differ $\pm 2 \mu\text{m}$ due to the camera position. In order to minimize this difference, the camera was positioned at the same height and in the same orientation relative to the coil head for each taken photograph. One can see the position of the cable (It) marked with red dots in Figure 8.4.

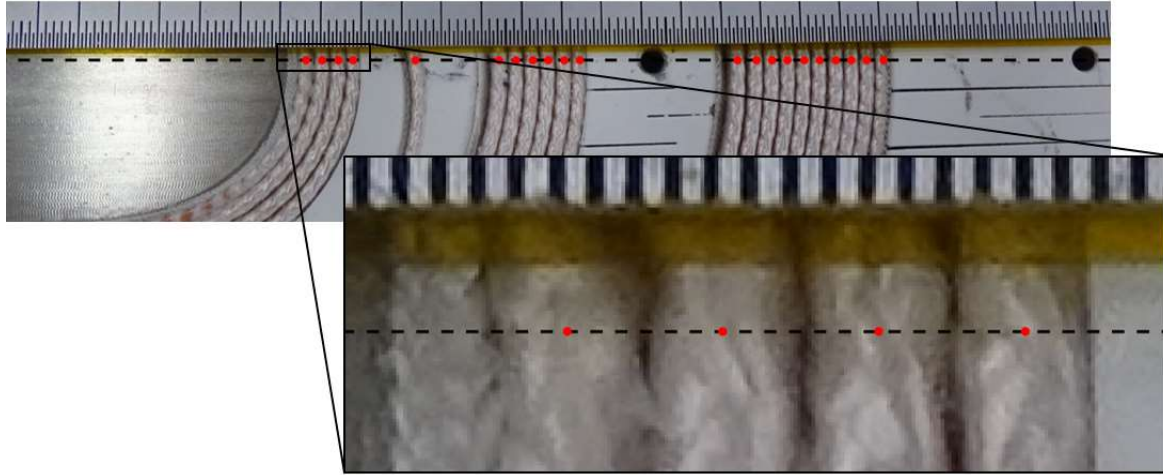


Figure 8.4 Image used for determining the relative turn position after winding (I_t). Top: Raw picture; Bottom: Enlarged section with red dots indicating the position of the cable along the main axis (dashed line).

In order to differentiate the values concerning each coil-end, the subscripts shown in Table 8.2 are used. The nominal values include additionally the ‘N_’ prefix as can be seen in the legend in Figure 8.5.

Table 8.2 Subscript defining the position of the coil.

Position of the coil	Subscript
Inner layer Return end	IR
Inner layer Lead end	IL
Outer layer Return end	OR
Outer layer Lead end	OL

The nominal values are extracted from the CAD drawing. One can see the top and bottom cable position of the MQXFB quadrupole coil (CERN iteration ID: V7) in Figure 8.5. For ease of the interpretation the zero nominal position is located at the bottom of first turn of the cable (i.e. adjacent to the winding pole).

The nominal twist angle α is computed from the nominal position, and is shown in Figure 8.6.

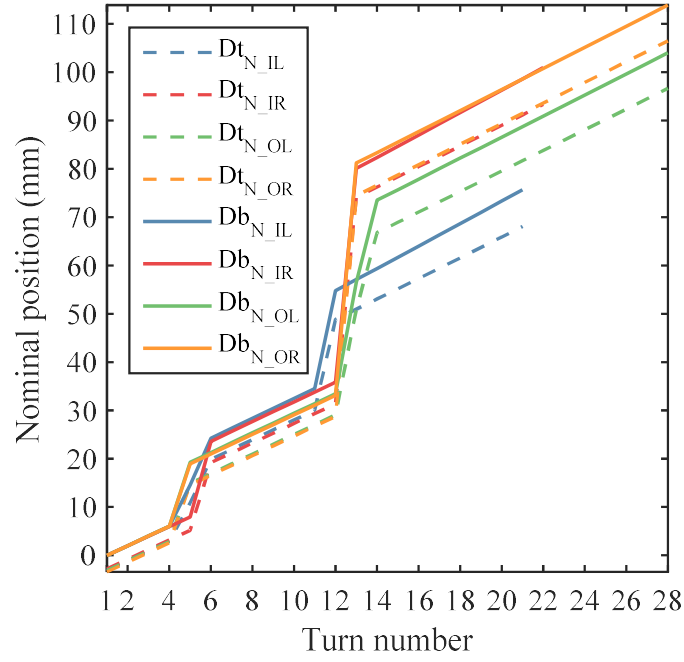


Figure 8.5 Nominal top (Dt) and bottom (Db) position of the cable for MQXFB V7 coil.

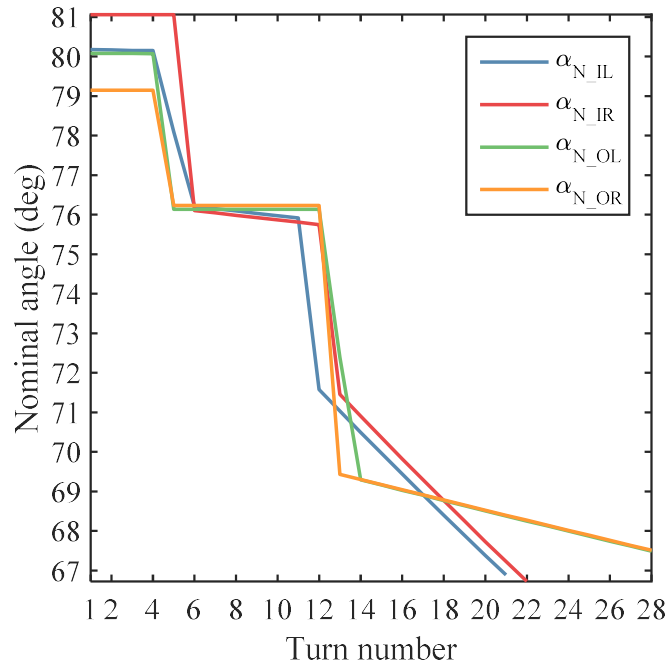


Figure 8.6 Nominal twist angle (α) of the cable for MQXFB V7 coil.

8.1.1. MEASUREMENT RESULTS

The following graphs are presenting the measurement results taken during the winding of the MQXFB CR107 coil according to the previously explained method. The results are discussed in chapter 8.1.2.

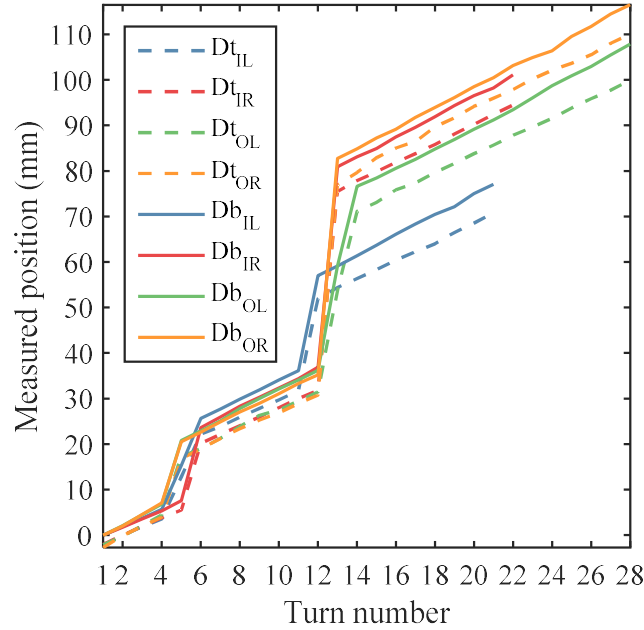


Figure 8.7 Measured top (Dt) and bottom (Db) position of the cable during winding of the MQXFB CR107 coil.

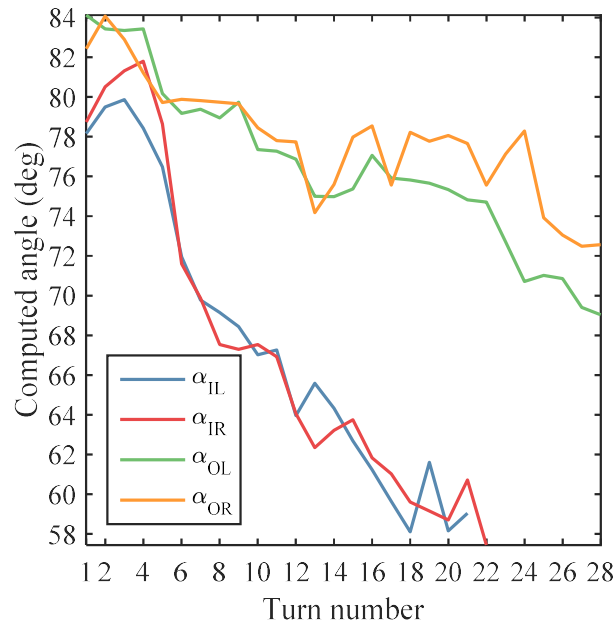


Figure 8.8 Twist angle (α) computed from top and bottom position of the cable during winding of MQXFB CR107 coil.

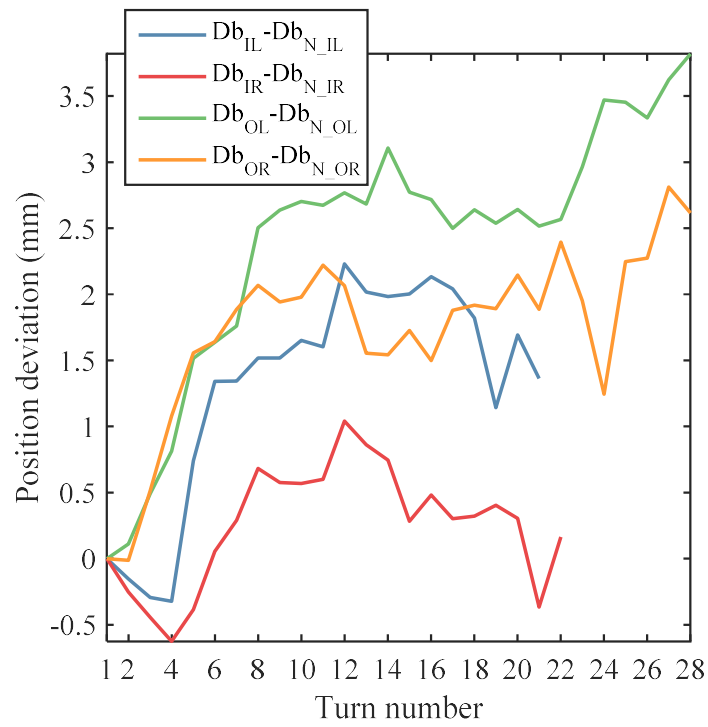


Figure 8.9 Bottom cable position (Db) deviation from nominal of four coil-ends.

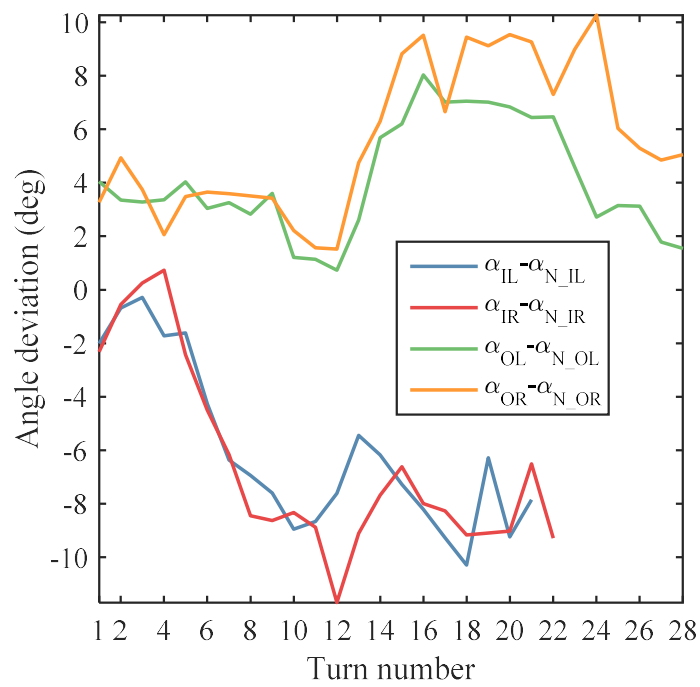


Figure 8.10 Computed angle (α) deviation from nominal of four coil-ends.

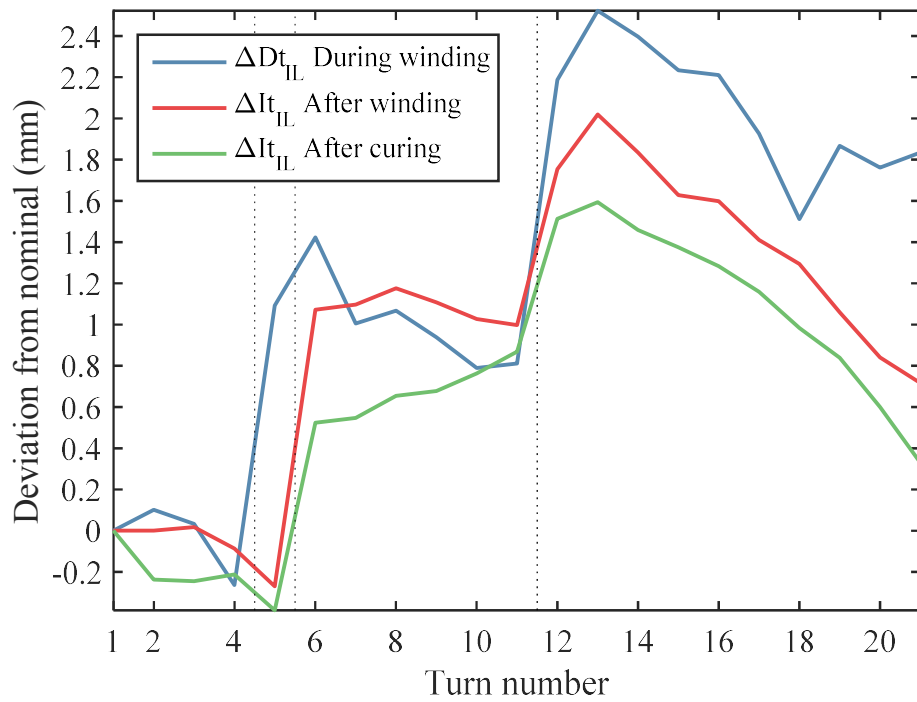


Figure 8.11 Top position of the cable measured during winding (ΔDt_{II} marked in blue), after winding (ΔIt_{II} marked in red), and after curing (ΔIt_{II} marked in green) of inner layer lead end.

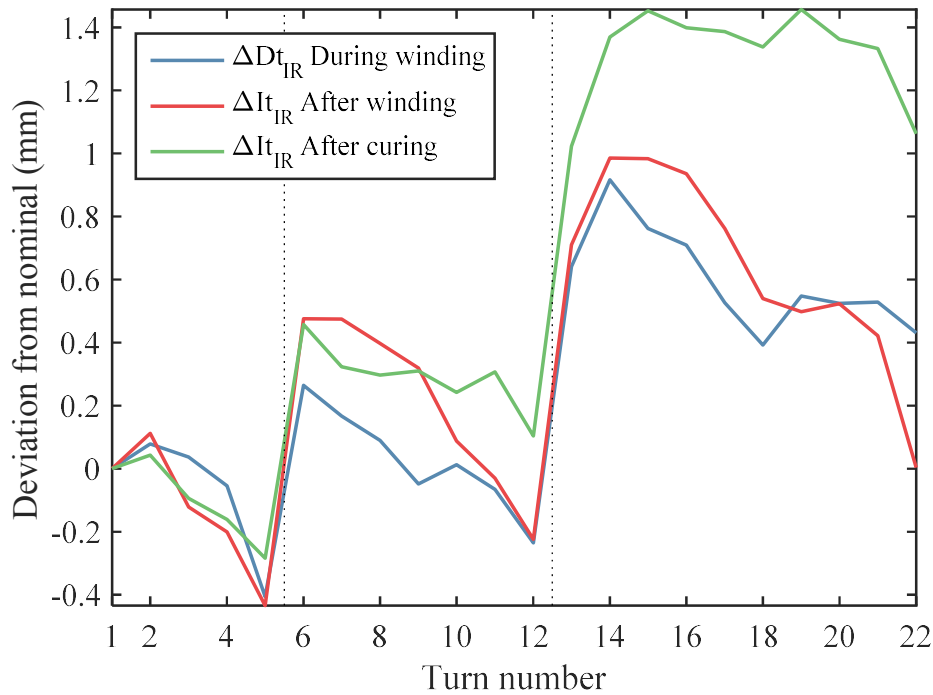


Figure 8.12 Top position of the cable measured during winding (ΔDt_{IR} marked in blue), after winding (ΔIt_{IR} marked in red), and after curing (ΔIt_{IR} marked in green) of inner layer return end.

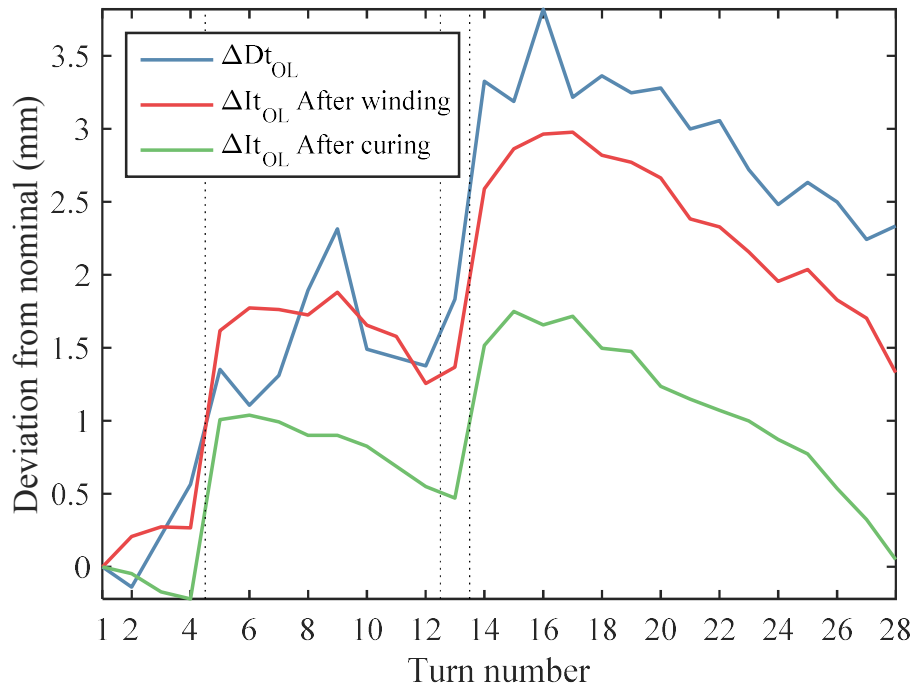


Figure 8.13 Top position of the cable measured during winding (ΔDt_{OL} marked in blue), after winding (ΔIt_{OL} marked in red), and after curing (ΔIt_{OL} marked in green) of outer layer lead end.

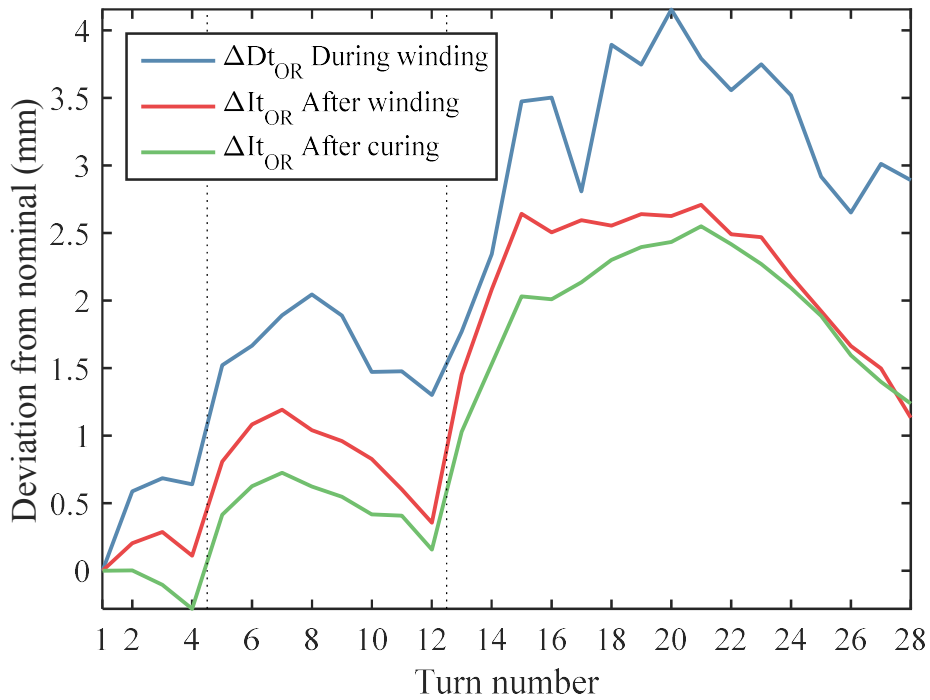


Figure 8.14 Top position of the cable measured during winding (ΔDt_{OR} marked in blue), after winding (ΔIt_{OR} marked in red), and after curing (ΔIt_{OR} marked in green) of outer layer return end.

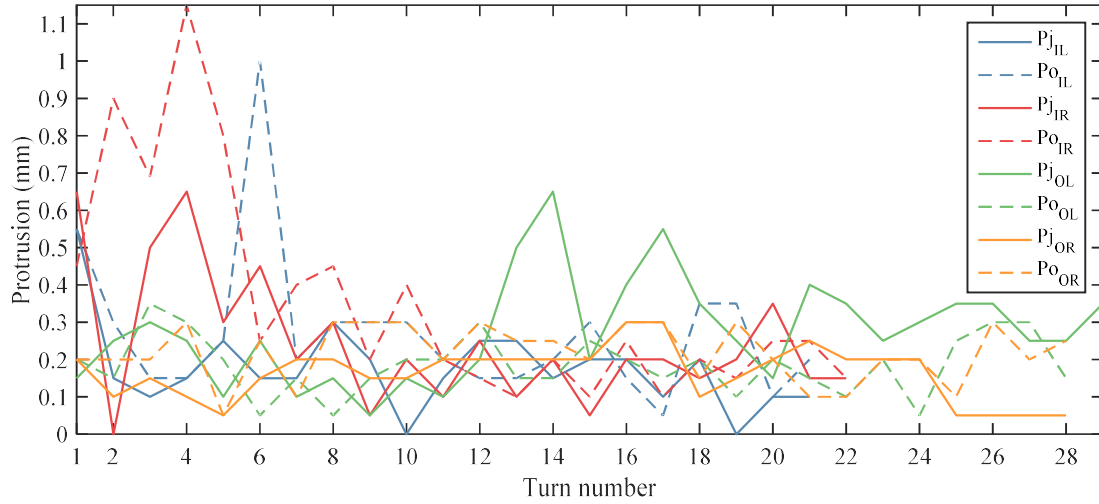


Figure 8.15 Protrusion measurement during winding of MQXFB CR107.

8.1.2. DISCUSSION

The obtained measurement of the cable top and bottom position of four coil ends are shown in Figure 8.7. The top position D_t is displayed with a dashed line, while the solid line corresponds to the bottom position D_b . These values served to compute the twist angle α of four coil ends, as shown in Figure 8.8.

One can see the computed deviation of the cable bottom position in Figure 8.9. The inner layer (shown in blue and red) exhibits smaller deviation than the outer layer and achieves maximal value in the 12th turn, i.e. 2.2 and 1 mm for lead and return end respectively. The outer layer (shown in green and yellow) achieves the largest deviation close to the last turn, i.e. 3.7 and 2.6 mm for lead and return side respectively. The lead end shows larger deviation with comparison to the return end, which may be caused by the layer jump proximity and unsymmetrical coil end design.

The deviation of the measured and nominal angle is shown in Figure 8.10. One can see that the inner layer deviation (red and blue) achieves negative values of as low as -12° , i.e. more flat or parallel with the mandrel. On the other hand, the outer layer covers the positive deviation scale with the maximal value of 10° , i.e. skewing towards perpendicular with the mandrel. The angular deviation of the first turns (the closest to the winding pole) achieves nonzero values i.e. -2° and 4° . It is understood that the angular deviation is at least partially corrected while winding of the following turns or due to positioning of the spacers (see Figure 1.27).

The investigation of the top position deviation during winding, after winding, and after curing was conducted as well by computing the deviation from nominal. The results of each coil end

are displayed in Figure 8.11 to Figure 8.14. The deviation of the top position during winding measured with the depth gauge is shown in blue line. The deviation after winding determined by the image analysis is shown in red, while the measurement after curing (also carried out by image analysis) is shown in green. The spacer position is marked with the dotted vertical lines. According to the expectations, the cable position after curing shows the smallest deviation from nominal for the inner layer lead coil end (Figure 8.11), and the outer layer (Figure 8.13 and Figure 8.14). However, one can see in Figure 8.12 that after curing the return end of the inner layer shows much larger deviation than during or after winding.

The protrusion measurement is shown in Figure 8.15. The solid line corresponds to the jump side, while the dashed line shows the opposite jump side. One can see that the maximal protrusion of 1.2 mm is indicated for the 4th turn of the inner layer on the opposite jump side. The summary of the measured values as well as the average is shown in Table 8.3. In addition, the winding direction is marked with an arrow. As an example, the first row of the table describes that the winding was carried out from P_{oIL} (opposite jump side of the inner layer lead end) to P_{jIL} (jump side of the inner layer lead end). In the case of the outer layer and the inner layer lead end, the total and average protrusion is larger at the first side of the winding (i.e. at beginning of the turn).

Table 8.3 Summary of protrusion measurement.

f	Winding direction	Σf (mm)	$\bar{f}$ (mm)
P _{jIL}	↑	3.70	0.18
P _{oIL}		5.70	0.27
P _{jIR}	↓	5.40	0.25
P _{oIR}		7.79	0.35
P _{jOL}	↓	7.95	0.27
P _{oOL}		5.20	0.19
P _{jOR}	↑	4.55	0.16
P _{oOR}		6.10	0.22

9. COMPREHENSIVE SUMMARY

The CERN is presented with an unprecedented opportunity to develop the Nb₃Sn accelerator magnet technology within the High Luminosity LHC project and the FCC study (see chapter 1.1). Among many other technical challenges it necessitates to further develop existing infrastructure for the production of Nb₃Sn magnets. The Nb₃Sn superconductor was chosen for the development and construction of the next generation superconducting coils (described in chapter 1.2.2). These coils will be assembled to superconducting dipole and quadrupole magnets within the HL-LHC project. Furthermore, the Nb₃Sn conductor is also the baseline for studying future accelerators like the FCC. The Nb₃Sn 40-strand Rutherford type cable represents the series conductor currently used throughout the HL-LHC 11 T dipole and MQXFB quadrupole coil production (see chapter 2). During the coil winding of short model coils and full length prototype coils mechanical cable instabilities were observed (see chapter 2.4). So far, these were determined to occur on a random base and no fundamental analysis was carried out to gain knowledge on the cable winding characteristics.

In this thesis the challenge of winding Nb₃Sn-based coils was analysed and methods were developed in order to reproduce and quantify observed deformation throughout the coil winding process. Prior launching any analysis process the cable deformations were categorised according to their occurrence and their geometrical impact in chapter 2.5.

The thesis consists of five segments, as follows:

- In the first part, the numerical simulation of the winding with a 10-strand Rutherford cable was developed, aiming to investigate the cable deformation. The non-linear model, described in chapter 4, includes the Nb₃Sn strand elastic deformation as well as the frictional contact elements between individual strands. The developed guide curve analysis algorithm allow observing the protrusion and the strand pop-out in the function of the initial cable length. The current stage of the model does not allow a direct comparison with the experimental results due to the geometrical simplifications;
- In the second part of the thesis tests were performed on the insulation layers of the cable. It was shown that the opaque S-2 Glass and Mica insulation layers on the Nb₃Sn Rutherford cable deteriorates the detection of the strand deformation. The non-destructive Active Thermography technique was therefore tested, in order to determine the strand position underneath the insulation. The results obtained from two institutes are discussed in chapter 5.1. Due to the thermal transmittance of the braided structure of the S-2 glass, the method did not allow to identify the individual strands;
- The second part of the thesis aimed to define methods to quantify in a repetitive way the observed deformations. The development of a winding test frame is presented, which allows conducting the winding tests in a controllable environment not occupying the winding machines in use for production. Two laboratory devices were developed: the winding frame (see chapter 6.1) allowing winding short specimens

with 40 cm-long cable and adjustable winding parameters, and the winding scanner featuring 3 motorized DOF (see chapter 6.2) allowing performing high accuracy 3D scans of the specimen with use of the triangulation laser head. The sample holder geometry was designed to allow observing the characteristic Rutherford cable deformation (shown in chapter 2.4). With use of the developed scan analysis methodology, described in 6.3, the wound cable deformation was quantified individually for the described envelope, the strand pop-out, and the protrusion phenomena. Afterwards two winding campaigns were conducted following the developed winding, scanning and analysis method. Five Rutherford type cables were tested in order to determine the recommended winding tension and direction. The results discussed in chapter 7.1 allow for a relative comparison of the tested cables. The recommended winding mass and direction ensuring the minimal cable deformation for given criteria is stated in Table 7.3. In addition, the specimens were wound with the pre-torsion angle, in order to investigate the winding quality improvement due to the additional DOF of the winding machine. The results shown in chapter 7.2, indicate that such a modification of the machine kinematics will further improve the winding stability. The level of the improvement is comparable to the adjustment of the winding tension usually seen as the most relevant winding parameter driving the observed instabilities;

- In the fourth part, complementary tests were performed with use of the developed specimen winding method and geometry analysis. The Nb₃Sn cable deformation due to the reaction heat treatment was investigated. The envelope deformation deviation of one reacted specimen is shown in chapter 7.3.1. In addition, the computed tomography of the winding specimen was performed in order to compute the local thickness of the cable. The tomography investigation is shown in chapter 7.3.2;
- The fifth part of the thesis describes the contribution to the coil winding and curing quality control processes. The implemented geometrical measurements provide the cable position and orientation data, and allow to investigate the cable protrusion. These measurement steps were performed during the coil fabrication of MQXFB quadrupole CR107, and will also be implemented for the 11 T coil production. A summary of the results is presented in chapter 8.

The obtained research results allowed to prove the hypothesis put forward in the thesis.

As described in chapter 2.3, the machine presently used for winding of the Nb₃Sn coils necessitates the manual correction of the cable twist in the coil-head area. This pure manual adjustment is mandatory for winding a cos- θ coil (see Figure 1.25). The performed winding tests, described in chapter 7.2, have proven that an additional correction of the winding trajectory by adding a rotational DOF would be beneficial for the stability and quality of winding process.

As a short outline for future activities one could summarize that the development of an enhanced winding machine featuring an increased amount of DOF would be beneficial for the quality and repeatability of future coil winding activities. Such a project would require to not only study the implementation of the additional DOF but would also incorporate to study

all peripheral tooling required to maintain the coil position throughout the winding process. One proposal would therefore be to differentiate these tooling development (e.g. coil clamping device) and study their performance individually prior integration to a complete winding system. A very important sub-task in line with this development is the implementation of an adequate monitoring systems (instrumentation) allowing to track the geometrical performance of the coil during the winding process.

BIBLIOGRAPHY

- [1] M. Aicheler *et al.*, “A multi-TeV linear collider based on CLIC technology: CLIC conceptual design report,” *Cern Yellow Reports Monogr.*, no. ISBN: 978-92-9083-379-6, pp. 7–69, 2014.
- [2] E. Gschwendtner *et al.*, “AWAKE, the advanced proton driven plasma wakefield acceleration experiment at CERN,” *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 829, pp. 76–82, 2016.
- [3] E. M. Dunne *et al.*, “Global atmospheric particle formation from CERN CLOUD measurements,” *Science (80-.)*, vol. 354, no. 6316, pp. 1119–1124, 2016.
- [4] S. Rothe *et al.*, “Laser ion beam production at CERN-ISOLDE: new features - more possibilities,” *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms*, vol. 376, pp. 91–96, 2016.
- [5] V. Choutko, A. Egorov, A. Eline, and B. Shan, “AMS data production facilities at science operations center at CERN,” *J. Phys. Conf. Ser.*, vol. 898, pp. 1–5, 2017.
- [6] O. Brüning and P. Collier, “Building a behemoth,” *Nature*, vol. 448, no. 7151, pp. 285–289, 2007.
- [7] W. Herr and B. Muratori, “Concept of luminosity,” *Cern Accel. Sch. Intermed. Course Accel. Phys.*, vol. 2, no. 3, pp. 361–378, 2003.
- [8] O. Brüning and L. Rossi, “The high luminosity large hadron collider,” *World Sci. Publ. Co. Pte. Ltd*, no. ISSN: 1793-1339, pp. 1–31, 2015.
- [9] M. Benedikt and F. Zimmermann, “Future circular colliders,” *Proc. XXVII Int. Symp. Lept. Phot. Interact. High Energies*, no. CERN-ACC-2015-165, 2015.
- [10] S. Myers, “LHC commissioning and first operation,” *Int. Part. Accel. Conf.*, no. CERN-ATS-2010-123, pp. 1–7, 2010.
- [11] G. Aad, T. Abajyan, B. Abbott, and J. Abdallah, “Observation of a new particle in the search for the standard model higgs boson with the ATLAS detector at the LHC,” *Phys. Lett. Sect. B Nucl. Elem. Part. High-Energy Phys.*, vol. 716, no. 1, pp. 1–29, 2012.
- [12] C. Patrignani, “Review of particle physics,” *Chinese Phys. C*, vol. 40, no. 10, pp. 349–421, 2016.
- [13] L. Rossi, “LHC upgrade plans: options and strategy,” *Int. Part. Accel. Conf.*, pp. 908–912, 2011.
- [14] G. Apollinari *et al.*, “High-luminosity large hadron collider (HL-LHC). Technical design report V.0.1,” *Cern Yellow Reports Monogr.*, vol. 4, 2017.
- [15] F. Savary *et al.*, “Progress on the development of the Nb3Sn 11T dipole for the high luminosity upgrade of LHC,” *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, 2017.

- [16] F. Lackner *et al.*, “Status of the long MQXFB Nb₃Sn coil prototype production for the HiLumi LHC,” *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, 2017.
- [17] O. Kononenko, Z. Li, R. Calaga, and C. Zanon, “Multiphysics analysis of crab cavities for high luminosity LHC upgrade,” *Proc. North Am. Part. Accel. Conf.*, 2017.
- [18] E. Quaranta *et al.*, “Towards optimum material choices for HL-LHC collimator upgrade,” *Proc. Int. Part. Accel. Conf.*, 2016.
- [19] S. Caspi, “Test results of Nb₃Sn quadrupole magnets using a shell-based support structure,” *Proc. Work. Accel. Magn. Supercond. Des. Optim.*, pp. 117–119, 2008.
- [20] P. Ferracin *et al.*, “Magnet design of the 150 mm aperture low-beta quadrupoles for the High Luminosity LHC,” *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 1–6, 2014.
- [21] B. Auchmann, S. Russenschuck, and N. Schwerg, “Discrete differential geometry applied to the coil-end design of superconducting magnets,” *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 1165–1168, 2007.
- [22] S. Caspi *et al.*, “Canted-cosine-theta magnet (CCT) - a concept for high field accelerator magnets,” *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 1–4, 2014.
- [23] D. Tommasini *et al.*, “The 16 T dipole development program for FCC,” *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, 2017.
- [24] L. Rossi, “State-of-the art superconducting accelerator magnets,” *IEEE Trans. Appl. Supercond.*, vol. 12, no. 1, pp. 219–227, 2002.
- [25] H. K. Onnes, “Further experiments with liquid helium. C. On the change of electric resistance of pure metals at very low temperatures, etc. IV. The resistance of pure mercury at helium temperatures,” *Commun. from Phys. Lab. Univ. Leiden*, no. 120b, pp. 261–263, 1991.
- [26] T. G. Berlincourt and R. R. Hake, “Pulsed-magnetic-field studies of superconducting transition metal alloys at high and low current densities,” *Bull. Am. Phys. Soc.*, vol. 2, no. 7, pp. 338–341, 1962.
- [27] T. G. Berlincourt, “Emergence of Nb-Ti as supermagnet material,” *Cryogenics (Guildf.)*, vol. 27, no. 6, pp. 283–289, 1987.
- [28] B. T. Matthias, T. H. Geballe, S. Geller, and E. Corenzwit, “Superconductivity of Nb₃Sn,” *Phys. Rev.*, vol. 95, no. 6, p. 1435, 1954.
- [29] W. Goldacker *et al.*, “Roebel assembled coated conductors (RACC): preparation, properties and progress,” *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 3398–3401, 2007.
- [30] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, “Theory of superconductivity,” *Phys. Rev.*, vol. 108, no. 5, pp. 1175–1204, 1957.
- [31] A. A. Abrikosov, “On the magnetic properties of superconductors of the second group,” *Soviet Physics JETP*, vol. 5, no. 6, 1957.

- [32] S. Russenschuck, “Field computation for accelerator magnets,” *WILEY-VCH Verlag GmbH Co. KGaA*, no. ISBN: 978-3-527-40769-9, 2010.
- [33] P. L. Kapitza, “Viscosity of liquid helium below the λ -point,” *Nature*, vol. 141, p. 74, 1938.
- [34] J. Allen and A. Misener, “Flow of liquid helium II,” *Nature*, vol. 141, no. 2. pp. 75–75, 1938.
- [35] P. Lebrun and L. Taviani, “Cooling with superfluid helium,” *Proc. CAS-CERN Accel. Sch. Supercond. Accel.*, no. CERN–2014–005, 2014.
- [36] J. Schwartz *et al.*, “Status of high temperature superconductors based magnets and the conductors they depend upon,” *Proc. EuCARD-AccNet-EuroLumi Work. High-Energy Large Hadron Collid.*, pp. 1–11, 2011.
- [37] F. Lackner *et al.*, “Analysis of temperature uniformity during heat treatment of Nb₃Sn coils for the high-luminosity LHC superconducting magnets,” *IEEE Trans. Applied Supercond.*, vol. 26, no. 4, 2016.
- [38] L. F. Goodrich, N. Cheggour, J. W. Ekin, and T. C. Stauffer, “Critical-current measurements on an ITER Nb₃Sn strands: effect of axial tensile strain,” vol. 17, no. 2, pp. 1398–1401, 2007.
- [39] M. B. Field, J. A. Parrell, Y. Zhang, and S. Hong, “Nb₃Sn conductor development for fusion and particle accelerator applications,” *AIP Conf. Proc.*, vol. 824, pp. 544–549, 2006.
- [40] E. Barzi, D. Turrioni, and a. V. Zlobin, “Progress in Nb₃Sn RRP strand studies and rutherford cable development at FNAL,” *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, 2014.
- [41] D. R. Dietderich and A. Godeke, “Nb₃Sn research and development in the USA - wires and cables,” *Cryogenics (Guildf.)*, vol. 48, no. 7–8, pp. 331–340, 2008.
- [42] E. Barzi and A. V. Zlobin, “Research and Development of Nb₃Sn Wires and Cables for High-Field Accelerator Magnets,” *IEEE Trans. Nucl. Sci.*, vol. 63, no. 2, pp. 783–803, 2016.
- [43] G. E. Gallagher-Daggitt, “Superconductor cables for pulsed dipole magnets,” *Rutherford Lab. Memo. No. RHEL/M/A25*, 1973.
- [44] J. Royet and R. M. Scanlan, “Manufacture of keystone flat superconducting cables for use in SSC dipoles,” *IEEE Trans. Magn.*, vol. 23, no. 2, pp. 480–483, 1987.
- [45] J. Cabanes, M. Garlasche, B. Bordini, and A. Dallochio, “Simulation of the cabling process for Rutherford cables: an advanced finite element model,” *Cryogenics (Guildf.)*, vol. 80, no. 3, 2016.
- [46] S. S. Roy, P. Potluri, S. Canfer, and G. Elwood, “Braiding ultrathin layer for insulation of superconducting Rutherford cables,” *Journal of Industrial Textiles*, 2016.
- [47] H. I. Rosten, “The constant perimeter end,” *Rutherford Lab. RL-73-096*, 1973.

- [48] R. Bossert, J. Cook, and J. Brandt, “End designs for superconducting magnets,” *Fermilab Tech. Memo*, 1991.
- [49] S. Russenschuck, “ROXIE : a computer code for the integrated design of accelerator magnets,” *Proc. Eur. Part. Accel. Conf.*, no. CERN-LHC-Project-Report-276, pp. 2017–2019, 1999.
- [50] S. Russenschuck and T. Tortschanoff, “Mathematical optimization of superconducting accelerator magnets,” *IEEE Trans. Magn.*, vol. 30, no. 5, pp. 3419–3422, 1994.
- [51] B. Auchmann and S. Russenschuck, “Coil end design for superconducting magnets applying differential geometry methods,” vol. 40, no. 2, pp. 1208–1211, 2004.
- [52] F. Savary *et al.*, “Design, assembly, and test of the CERN 2-m long 11 T dipole in single coil configuration,” vol. 25, no. 3, 2015.
- [53] J. J. Craig, “Introduction to robotics,” *Pearson Educ. Inc.*, no. ISBN: 0-13-123629-6, pp. 1–135, 2005.
- [54] D. Pulikowski *et al.*, “Testing mechanical behavior of Nb₃Sn Rutherford cable during coil winding,” *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, 2017.
- [55] D. Pulikowski, F. Lackner, C. Scheuerlein, and M. Pajor, “Numerical modelling of a superconducting coil winding process with Rutherford type Nb₃Sn cable,” *J. Mach. Constr. Maint.*, pp. 13–19, 2017.
- [56] P. Manil, M. Mouzouri, and F. Nunio, “Mechanical modelling of low temperature superconducting cables at the strand level,” *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, 2012.
- [57] D. Arbelaez, S. O. Prestemon, P. Ferracin, A. Godeke, D. R. Dietderich, and G. Sabbi, “Cable deformation simulation and a hierarchical framework for Nb₃Sn Rutherford cables,” *J. Phys. Conf. Ser.*, vol. 234, no. 2, 2010.
- [58] L. Rossi and L. Bottura, “Superconducting magnets for particle accelerators,” *Reviews of Accelerator Science and Technology*, vol. 5, pp. 51–89, 2012.
- [59] K. Okarma and M. Grudzinski, “The 3D scanning system for the machine vision based positioning of workpieces on the CNC machine tools,” *Proceeding Int. Conf. Methods Model. Autom. Robot.*, pp. 85–90, 2012.
- [60] A. J. Wuis, B. Bordini, A. Ballarino, L. Oberli, and H. H. J. Kate, “Characterization of Nb₃Sn Rutherford cables for the LHC 11-T dipole magnet,” *Ieee Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 11–15, 2014.
- [61] L. Rossi, “Superconducting cable and magnets for the large hadron collider,” *LHC Proj. Rep. 694*, 2003.
- [62] P. Ferracin *et al.*, “Development of MQXF: the Nb₃Sn low- β quadrupole for the HiLumi LHC,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, pp. 4–10, 2016.
- [63] A. Milanese *et al.*, “Design of the EuCARD high field model dipole magnet FRESKA2,” *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, pp. 3–6, 2012.

- [64] D. Pulikowski, F. Lackner, C. Scheuerlein, F. Savary, D. Tommasini, and M. Pajor, “Windability tests of Nb₃Sn Rutherford cables for HL-LHC and FCC,” *IEEE Trans. Applied Supercond.*, vol. 28, no. 3, 2018.
- [65] M. Di Michiel and C. Scheuerlein, “Phase transformations during the reaction heat treatment of powder-in-tube Nb₃Sn superconductors,” *Supercond. Sci. Technol.*, vol. 20, no. 10, pp. L55–L58, 2007.
- [66] D. Bocian, G. Ambrosio, and G. M. Whitson, “Measurements of Nb₃Sn conductor dimension changes during heat treatment,” *Adv. Cryog. Eng.*, vol. 193, pp. 193–200, 2012.
- [67] D. R. Dietderich, J. R. Litty, and R. M. Scanlan, “Dimensional changes of Nb₃Sn, Nb₃Al and Bi₂Sr₂CaCu₂O₈ conductors during heat treatment and their implication for coil design,” *Adv. Cryog. Eng.*, vol. 44, pp. 1013–1020, 1998.
- [68] E. Rochepault *et al.*, “Dimensional changes of Nb₃Sn Rutherford cables during heat treatment,” *IEEE Trans. Applied Supercond.*, vol. 26, no. 4, 2016.
- [69] M. Schulz and B. Schillinger, “ANTARES: cold neutron radiography and tomography facility,” *J. Large-Scale Res. Facil.*, vol. 1, 2015.

LIST OF FIGURES

Figure 1.1	The CERN accelerator complex. Source: CERN Document Server.	3
Figure 1.2	Overview of the four major experiments of the LHC. Left: the schematic view of the LHC with its octants and insertion regions (blue stars). Right: Aerial view of the Geneva area with the placement of LHC and four major experiments. Source: CERN Document Server.....	4
Figure 1.3	The LHC baseline showing the progression of the collision energy (red line) and luminosity (green line). The High Luminosity transition is shown after the Run 3 [14].	5
Figure 1.4	LHC luminosity plan up to third Long Shutdown (LS3). Peak luminosity shown with red dots; integrated luminosity shown with blue solid line [14].	6
Figure 1.5	11 T dipole full assembly, including two dipole magnets (LMBHA and LMBHB) and a collimator (LEN). Source: CERN Document Server.	7
Figure 1.6	11 T dipole cross section. Left: collared coil. Right: Cold mass assembly. Source: CERN Document Server.	7
Figure 1.7	MQXF triplet magnet cross section [20].	8
Figure 1.8	Schematic of 80 km tunnel for a Future Circular Collider at CERN. Source: CERN Document Server.	10
Figure 1.9	The Large Magnet Facility at CERN in 2017.....	11
Figure 1.10	The LHC arc lattice, consisting a quadrupole (MQ), dipoles (MBA, MBB) and other multipole correction magnets.	11
Figure 1.11	Diagram showing the cross-section of an LHC dipole magnet with cold mass and vacuum chamber. Source: CERN Document Server.	12
Figure 1.12	Magnetization in function of temperature of type-I (on the left) and type-II (on the right) superconductors.	13
Figure 1.13	Critical surface of Nb-Ti LHC superconductor [32].....	14
Figure 1.14	Engineering critical current density of most common type-II superconductors versus magnetic field. Measured in 4.2 K unless otherwise stated [36].....	15
Figure 1.15	Normalized critical current I_c/I_{cmax} at 4 K of reacted Nb ₃ Sn ITER strand as a function of intrinsic axial strain for magnetic fields from 12 T to 16 T [38]...	16
Figure 1.16	Transversal cross section of 1 mm diameter Nb-Ti strand. Enlarged section on the right side shows 8800 filament bundles in a hexagonal structure – called stack [42].	17

Figure 1.17 Overview on various types of developed RRP and PIT wires. Top row: cross section of RRP strands, courtesy of OST. Bottom row: cross section of PIT wires, courtesy of SMI and Bruker EAS [42].	17
Figure 1.18 Sketch of 40-Strand Rutherford Nb ₃ Sn cable cross-section with S-2 Glass and Mica insulation. Not to scale to visualize the keystone angle.	18
Figure 1.19 Rendered winding scheme of a Rutherford cable, schematics with 10 strands. Nine strands are depicted translucent; the one strand rendered with copper appearance is traced in red on the bottom and right view displaying internal guide of the cable.	18
Figure 1.20 Cabling machine at CERN. Three sub-assemblies visible: spool wheel, Turk Head and caterpillar. Courtesy of CERN Superconducting Lab [45].	19
Figure 1.21 Top: cross section of 40-strand Rutherford cable. Bottom left: undeformed strand cross section. Bottom right: enlarged cable edge segment with plastically deformed strand [45].	20
Figure 1.22 Kapton polyamide insulation process of Nb-Ti cable shown in a. The insulation scheme is shown in b.	20
Figure 1.23 S-2 Glass braiding insulation of the Rutherford cable. Left: A 48 carrier braiding machine; Right-top: Rutherford cable during braiding; Right-bottom: Top view on the insulated cable [46].	21
Figure 1.24 Coil-end dipole designs for accelerator magnets. a) cos- θ (constant perimeter); b) cranked saddle; c) bedstead; d) transversely cranked saddle; e) racetrack [32].	22
Figure 1.25 The optimized coil block arrangement and coil-end design of 11 T dipole return end. Marked inner- and outer-layer, as well as the coil block arrangement parameters α_a and α_b .	22
Figure 1.26 End-spacer set for the 11 T dipole inner-layer with indicated design identification. a) Lead-end (the coil connection side); b) Return end (the opposite connection side). Source: CERN drawing number: LHCMBH_C0047.	23
Figure 1.27 Top view on the winding assembly of 11 T dipole inner-layer. Left: Lead-end; Right: Return-end. Source: Adapted CERN drawing number: LHCMBHST0416.	23
Figure 2.1 Flowchart of the magnet production consisting of the conductor manufacturing, coil production and cold mass assembly.	24
Figure 2.2 Cable batch inspection and re-spooling process. Preparation for winding.	25
Figure 2.3 The Winding Machine for 11 T dipole coil. Four DOF: X, Y, Z, B and C marked in red.	26
Figure 2.4 The winding head with clutch-based tensioning system.	27

Figure 2.5	11 T rotational winding mandrel.....	27
Figure 2.6	Assignment of link frames for the 11 T Winding Machine. Dimensions in m..	28
Figure 2.7	Cable position compensation C_s . Dimensions in mm.....	29
Figure 2.8	The mandrel rotation θ_m and resulting height difference of C_m	29
Figure 2.9	Control system diagram of the WM.....	33
Figure 2.10	Winding program defining the spool position (shown in a) and the mandrel rotation angle (shown in b) for the 11 T inner-layer winding.	34
Figure 2.11	11 T layer-jump. Dimensions in mm.	35
Figure 2.12	11 T straight segment clamps. a) polymer guide; b) side clamp.	35
Figure 2.13	11 T coil-end support. a) head tool; b) guiding tool; c) tactile examination and manual cable twisting.	36
Figure 2.14	Positioning of the spacer (a) and the insulated copper wedge (b).	36
Figure 2.15	Scheme of QC performed during winding of 11 T.	37
Figure 2.16	Finalizing the coil winding (shown in a) and preparation for curing: fixing the lateral pushers (shown in b), putting the ceramic binder on the windings (shown in c), and fixing the half-shells (shown in d).	37
Figure 2.17	Schematic longitudinal cross section of the coil-end with three consecutive turns of the cable and the twist angle α	38
Figure 2.18	Nominal cable twist angle α_i of MQXFB V7 coil in a function of cable turn number i . Four functions present both sides of the coil (Lead and Return) of inner- and outer-layer.	39
Figure 2.19	The strand pop-out observed during test winding of the 11 T coil with use of Cu Rutherford cable.....	40
Figure 2.20	The cable protrusion observed during winding of the 11 T coil with use of Nb ₃ Sn Rutherford cable.....	41
Figure 2.21	The profile of the stripe (a) and the Rutherford cable (b) for $M = \theta$	41
Figure 4.1	11 T coil outer layer return end-key used for model.	45
Figure 4.2	Simulation setup of the cable pressure model.....	46
Figure 4.3	Contact face between cable and spacer bodies.	47
Figure 4.4	Model meshed with use of 3-D 20-Node elements. Mesh density variant number 1.	47
Figure 4.5	Equivalent von Mises stress of the cable side facing the spacer in MPa. a) 150 N of tension. b) 300 N of tension.	48
Figure 4.6	Tensile test results of the Nb ₃ Sn 132/169 0.7 mm strand. $E=90$ GPa, $\nu=0.34$. .	49

Figure 4.7	Specimens of 40-strand Nb ₃ Sn 132/169 cable prepared for X-ray absorption tomography. Top: Sample B, a stack of four cables (18 mm x 12 mm x 150 mm). Bottom: Sample A, a single cable (15 mm x 2 mm x 150 mm).	50
Figure 4.8	Transversal cross section extracted from a tomogram of the sample A. Visible strand deformation on the edge and brightness difference.	51
Figure 4.9	Three dimensional reconstruction of a tomogram of the sample B. Transversal cross section in the middle, with enlarged cable edge and middle sections at the bottom.	52
Figure 4.10	40-strand Rutherford cable with visible stainless steel core.	53
Figure 4.11	S-2 Glass and Mica insulation of 11 T cable. * S-2 Glass thickness measured before reaction at 5 MPa.	53
Figure 4.12	Inner layer opposite connection side pole of 11T dipole. Left: Picture of the pole assembly before winding. Right: Dimensions of the end key of the pole.	54
Figure 4.13	Side view of the 10-Strand Rutherford cable guide curves and one strand geometry. Pitch angle $\phi=16^\circ$, strand diameter $d=0.7$ mm, strand turn $p=2.54$ mm.	54
Figure 4.14	Modelled geometry of 10-strand Rutherford cable used in simulation. Pitch angle $\phi=16^\circ$, strand diameter $d=0.7$ mm, strand turn $p=2.54$ mm.	55
Figure 4.15	The winding model setup. Pitch angle $\phi=16^\circ$, strand diameter $d=0.7$ mm, strand turn $p=2.54$ mm, cylinder diameter 10 mm.	56
Figure 4.16	Components of winding force F.	56
Figure 4.17	The mesh quality of the cable. a) Mesh quality ratio of the external elements of the cable. b) Mesh quality ratio in a function of total element volume.	58
Figure 4.18	Total deformation of the winding simulation in mm. A direction of winding is marked with dashed arrow.	59
Figure 4.19	Equivalent elastic strain in mm/mm. Scaling equal to 0. Top: side not facing cylinder; Bottom: side facing cylinder.	59
Figure 4.20	Equivalent total strain in mm/mm. Scaling equal to 0. Top: side not facing cylinder; Bottom: side facing cylinder.	60
Figure 4.21	Directional deformation in Z-axis in mm. Scaling equal to 0. a) deformed cable with marked protrusion. b) Undeformed results Top: side not facing cylinder; Bottom: side facing cylinder.	60
Figure 4.22	Distance from the center of the cylinder in mm. Side not facing cylinder.	61
Figure 4.23	Initial (undeformed) position of the guide curves with assigned strand numbers.	62

Figure 4.24	Guide curve position of 10 simulated strands after winding (in mm): a) Isometric view. b) X-Z plane view.....	63
Figure 4.25	Directional displacement in X (UX), Y (UY), and Z (UZ) axes of individual strand.	64
Figure 4.26	Average, maximal and minimal directional deformation of the whole cable in Z-axis (UZ). The extreme value of cable average protrusion marked with cross.	64
Figure 4.27	Position of individual strands on the XY-plane, and the winding path marked with a solid black line (mm).	65
Figure 4.28	Maximal and minimal deviation of the strands from the winding path (dotted and dash-dot line). The cable thickness is shown with a solid line.	66
Figure 5.1	The measurement setup used for the AT investigation.	68
Figure 5.2	The undeformed thermography specimen, 150 mm-long uninsulated Nb ₃ Sn cable.	69
Figure 5.3	Uninsulated cable specimens, thermal reflex visible on LCD screen in red and white.	69
Figure 5.4	The tape-insulated specimens. a) sample A, strongly deformed; b) sample B, slightly deformed.	70
Figure 5.5	The Pulse AT test of sample A indicating the time after triggering the test.	70
Figure 5.6	Sample C. The Nb ₃ Sn cable with S-2 glass and Mica insulation.	71
Figure 5.7	Thermograms of insulated sample C with different analysis methods. Specimen painted black on the left side of each thermogram.	71
Figure 5.8	The AT analysis of insulated Nb ₃ Sn and Nb-Ti obtained by BAM. (a) and (b) present two sides of the specimens.	72
Figure 5.9	Specimen scanning with Leica® LAS device. Left: tracking tripod. Right: Scanning handle.	73
Figure 5.10	Specimen scanning with Gom® Atos device.	74
Figure 5.11	Faro® Scanarm HD. Meshed specimen scan for a device comparison.	74
Figure 5.12	Leica® LAS. Meshed specimen scan for a device comparison.	75
Figure 5.13	Leica® T-Scan 5. Meshed specimen scan for a device comparison.	75
Figure 5.14	Gom® ATOS. Meshed specimen scan for a device comparison.	75
Figure 5.15	Cable area clos-up of scans with: a) Faro® Scanarm HD, b) Leica® LAS, c) Leica® T-Scan 5 and d) Gom® ATOS.	76
Figure 5.16	Scan cross-section of cable area (in mm). a) Faro® Scanarm HD, b) Leica® LAS, c) Leica® T-Scan 5 and d) Gom® ATOS.	76

Figure 6.1 The Winding Frame. Dimensions including the hanging mass: 50 x 100 x 50 (cm).....	79
Figure 6.2 Specimen winding example. Five steps of sample holder rotation from 0° to 180°	80
Figure 6.3 The kinematics scheme of the Winding Machine and the Winding Frame.....	81
Figure 6.4 Winding specimen d20L160 with visible cable deformations, wound with the 11 T Cu cable.....	82
Figure 6.5 Definition of the adjustable parameters of the winding frame.....	84
Figure 6.6 The winding scanner with main features (a, b, and c) and indicated DOF (Y, Z, and A).	86
Figure 6.7 The winding scanner control scheme.....	87
Figure 6.8 The mechanical scheme of the winding scanner.....	87
Figure 6.9 One scanned line of the winding specimen.....	88
Figure 6.10 Depicted table displacement during the scan. (a) and (b) shows the table translation while scanning the left side of the specimen; (c) and (d) shows the table rotation while scanning the cylinder segment of the specimen; (e) and (f) shows the table translation while scanning the right side of the specimen.	89
Figure 6.11 Three-dimensional scan of a winding specimen assembled of 91 vertical lines. Sample holder cylinder diameter equals Ø20 mm.....	90
Figure 6.12 Views on five winding specimens. Wound with insulated cable (a) and uninsulated cable (b to e).....	90
Figure 6.13 Scanning process of specimens with Gom® Atos. Left: winding specimens. Right: Gom® Atos scanner.	91
Figure 6.14 The resulting scan of specimens with Gom® Atos, left side view. Arrows indicates visible strand pop-out (white) and protrusion (blue).....	92
Figure 6.15 Winding specimen scans taken with WS and Atos. Average envelope of four specimens is shown in a), and a deviation Δf is shown in b).	93
Figure 6.16 1D measurement. Point laser triangulation principle for diffusive objects. Source: Sick.....	94
Figure 6.17 The standard deviation distribution of 19201 measurement points for L_W computation. From left to right: HG-C1050, HL-G105-S-J, and HL-C203F laser head. The average deviation marked with red dashed line.	96
Figure 6.18 The standard deviation distribution of 91 measurement points for L_A computation. From left to right: HG-C1050, HL-G105-S-J, and HL-C203F laser head. The average deviation marked with red dashed line.	96
Figure 6.19 The WS scan Cartesian transformation.....	98

Figure 6.20	Separated functions of the winding surface, the cable and the bottom support. Axes in millimeters.....	99
Figure 6.21	Virtual unwinding and normalization. Axes in millimeters.....	100
Figure 6.22	The specimen deformation functions.....	102
Figure 6.23	Indefinite integral functions.....	103
Figure 6.24	Definite integral functions.....	105
Figure 6.25	Photography of specimens. a) small cable deformation, specimen #3.14; b) large cable deformation #3.13.....	107
Figure 6.26	Raw scan of example specimens. a) small cable deformation, specimen #3.14; b) large cable deformation, specimen #3.13. Axes in millimeters.....	107
Figure 6.27	Winding specimen springback angle after releasing clamp on the right side.....	108
Figure 6.28	Draft with the characteristic points for springback measurement. Solid line: specimen. Dashed line: presumed cable position.....	109
Figure 7.1	Favourable and unfavourable winding directions.....	112
Figure 7.2	The average winding performance of three specimens, represented by the bar height. Five cables tested (indicated on horizontal axis) with various winding mass (indicated by the color of the bar, see legend) and different winding direction (favourable thin outline, unfavourable thick outline, see legend). Top: the average envelope P_1 ; Middle: the strand pop-out P_2 ; Bottom: the protrusion P_3	114
Figure 7.3	The winding stability of three specimens, represented by the bar height. Five cables tested (indicated on horizontal axis) with various winding mass (indicated by the color of the bar, see legend) and different winding direction (favourable thin outline, unfavourable thick outline, see legend). Top: the average envelope P_1 ; Middle: the strand pop-out P_2 ; Bottom: the protrusion P_3	115
Figure 7.4	The average performance results of five tested cables, indicated on the horizontal axis. The bar height represents the average deformation of specimens wound with various winding mass, for each direction separately.....	116
Figure 7.5	Stability results of 5 tested cables. The bar height represents the standard deviation of specimens wound with various winding mass, for each direction separately.....	117
Figure 7.6	Specimen envelope, pop-out and protrusion side-symmetry. The bar height represents the averaged result of the subtraction of the left and right side of the deformation indicator.....	118
Figure 7.7	The springback angle measurement of five cables.....	119

Figure 7.8	Temperature (marked with blue dot) and humidity (marked with orange cross) of the air in the laboratory at the beginning of the specimen scan.	119
Figure 7.9	Specimen winding with 45° pre-torsion; a) clamping the cable; b) measuring the torsion angle; c) specimen winding; d) adjustment to clamp.	125
Figure 7.10	Performance and stability of uninsulated cable vs winding mass and angle.	127
Figure 7.11	Percentage change of uninsulated cable performance and stability vs winding mass and angle.	128
Figure 7.12	Insulated and uninsulated cable performance and stability vs winding mass and angle.	129
Figure 7.13	Temperature (marked with blue dot) and humidity (marked with orange cross) of the air in the laboratory at the beginning of the specimen scan.	130
Figure 7.14	Gap between the outer-layer return key and the cable of the 11 T coil after RHT.	132
Figure 7.15	The picture of the unreacted (a) and reacted (b) specimen.	133
Figure 7.16	The WS measurement points of the unreacted (a) and reacted (b) specimen.	133
Figure 7.17	The average envelope deformation functions of unreacted (D_{IU}) and reacted (D_{IR}) specimen. Maxima marked with cross.	134
Figure 7.18	The difference between the reacted and unreacted average envelope deformation of the cable. Maximum marked with cross.	134
Figure 7.19	Winding specimens subject to tomography. Transversal cross section marked with red dashed line.	136
Figure 7.20	Reconstructed frame of a tomogram. Transversal cross section of the specimen.	137
Figure 7.21	Cloud of points of the cable (a) and sample holder (b).	137
Figure 7.22	Tomography reconstructed cable with the winding path marked in red; a) top view; b) perspective view.	138
Figure 7.23	The meshed cable surface with enlarged section.	138
Figure 7.24	Maximal normalized envelope deformation. The comparison of tomogram analysis (CT) and winding scanner results (WS).	139
Figure 7.25	Normal thickness of the cable computed from the tomogram.	139
Figure 8.1	Scheme of geometrical measurements performed during MQXFB CR107 coil production.	141
Figure 8.2	Depth gauge measurement of the top position of the cable D_t (on the top) and the bottom position of the cable D_b (on the bottom).	141
Figure 8.3	Protrusion measurement during winding with the wedge gauge of 50 μm resolution.	142

Figure 8.4	Image used for determining the relative turn position after winding (I_t). Top: Raw picture; Bottom: Enlarged section with red dots indicating the position of the cable along the main axis (dashed line).	143
Figure 8.5	Nominal top (D_t) and bottom (D_b) position of the cable for MQXFB V7 coil.	144
Figure 8.6	Nominal twist angle (α) of the cable for MQXFB V7 coil.	144
Figure 8.7	Measured top (D_t) and bottom (D_b) position of the cable during winding of the MQXFB CR107 coil.	145
Figure 8.8	Twist angle (α) computed from top and bottom position of the cable during winding of MQXFB CR107 coil.	145
Figure 8.9	Bottom cable position (D_b) deviation from nominal of four coil-ends.	146
Figure 8.10	Computed angle (α) deviation from nominal of four coil-ends.	146
Figure 8.11	Top position of the cable measured during winding (ΔD_t marked in blue), after winding (ΔI_t marked in red), and after curing (ΔI_t marked in green) of inner layer lead end.	147
Figure 8.12	Top position of the cable measured during winding (ΔD_t marked in blue), after winding (ΔI_t marked in red), and after curing (ΔI_t marked in green) of inner layer return end.	147
Figure 8.13	Top position of the cable measured during winding (ΔD_t marked in blue), after winding (ΔI_t marked in red), and after curing (ΔI_t marked in green) of outer layer lead end.	148
Figure 8.14	Top position of the cable measured during winding (ΔD_t marked in blue), after winding (ΔI_t marked in red), and after curing (ΔI_t marked in green) of outer layer return end.	148
Figure 8.15	Protrusion measurement during winding of MQXFB CR107.	149

LIST OF TABLES

Table 1.1	Features of the 11 T superconducting cable.....	8
Table 1.2	Features of the MQXF superconducting cable.....	9
Table 2.1	The Winding Machine link-frame description and parameters.....	30
Table 2.2	Typical defects of the Rutherford cable due to bending.	42
Table 4.1	Material isotropic elasticity definition	46
Table 4.2	Model constraints.....	46
Table 4.3	Considered model mesh densities.....	47
Table 4.4	Features of tomography specimens.....	50
Table 4.5	Geometrical features of the model.....	54
Table 4.6	Force F components and value in each simulation step.....	56
Table 4.7	Boundary conditions.....	57
Table 4.8	Contact definition.....	57
Table 4.9	Mesh density comparison of the literature Rutherford cable models.....	58
Table 4.10	Maximal and minimal values of the deformation and strain of the winding model. Normal results (along the main axes) and total/equivalent results are shown.....	61
Table 5.1	IR camera configuration.....	68
Table 5.2	The tested scanning devices.....	73
Table 6.1	The Winding Frame parameters.....	83
Table 6.2	The winding scanner mechanical features.....	86
Table 6.3	The average and the deviation from Δf for each specimen, shown for four specimens.....	93
Table 6.4	Laser parameters and computed accuracy.....	96
Table 7.1	Nominal cable parameters.....	111
Table 7.2	The WF parameters used in the winding mass and direction investigation.....	112
Table 7.3	Winding mass and direction providing the best quality for given criteria. Mass (M) given in kg. Dir equal 1 defines the favourable winding direction, whereas 0 – unfavourable.....	123
Table 7.4	The Winding Frame parameters used in the test campaign.....	126
Table 7.5	Winding parameters of HT specimen.....	132

Table 7.6 Parameters of ANTARES neutron tomography.....	136
Table 8.1 Geometrical measurements of MQXFB CR107 quadrupole coil performed in LMF.....	140
Table 8.2 Subscript defining the position of the coil.	143
Table 8.3 Summary of protrusion measurement.	150