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and

CERN

2D Analysis of Thermomechanical Response to Unbalanced Currents in Quenching Superconducting Magnets

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2D Analysis of thermomechanical response to unbalanced currents in quenching superconducting magnets

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Bachelorthesis für Tina Griesemer

Aufgabenstellung

Coupling-Loss Induced Quench (CLIQ) is a system recently developed at CERN for the protection of superconducting magnets against dangerous consequences of a transition from the superconducting to the normal conducting state. A CLIQ unit, through a capacitive discharge, introduces current oscillations in two parts of a magnet that in turn generate coupling losses and heat up a magnet. The aim of the bachelor thesis is the understanding of the mechanical impact of unbalanced currents in the magnet, in combination with the thermal strain due to the magnet quench. On the one hand a CLIQ discharge results in a homogeneous temperature distribution inside the coil. On the other hand, the unbalanced current oscillations generate Lorentz forces acting non-uniformly on coil turns. Therefore, the mechanical model will be coupled with existing electrothermal models developed in COMSOL to quantify those two phenomena.

Titel (deutsch):	2D–Analyse von thermomechanischen Reaktionen auf unsymmetrische elektrische Ströme in supraleitenden Magneten während einem Quench
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Abstract

At the moment, the Large Hadron Collider (LHC) is the biggest particle accelerator in the world. The implemented superconducting magnets, based on the superconducting material Nb-Ti, control and accelerate the beam. Superconducting magnets have higher performance such as zero resistivity, through which higher magnetic fields are reachable. To get to the superconducting state, the operating point has to be below a specific value for the current density, the magnetic field, and the temperature. The transfer from superconducting to normal conducting state is called a quench. New magnet types, based on the new superconducting material Nb_3Sn, are in development for the upgrade of the LHC to the High Luminosity-LHC (HL-LHC). These new magnets will operate at higher magnetic field compared to existing ones. Therefore, it is necessary to use a new material because Nb-Ti cannot reach the requested magnetic field strength. However, Nb_3Sn is brittle, which implies that more accurate quench simulations, in particular mechanical ones, with Finite Element Analysis (FEA) programmes are in need. The required physical phenomena to be simulated for magnets are electromagnetism, thermal, and mechanics. The time scaling is different for the electromagnetic-thermal and mechanical simulation. In addition, mechanical models of CERN magnets were already developed in a mechanical FEA programme. The aim of this thesis is the coupling of electromagnetic-thermal and mechanical analyses. Thus, an external current is provided to the electromagnetic-thermal simulation, and selected information is unidirectionally exchanged with the mechanical FEA programme. With the simple geometry of a busbar, the coupling possibilities are studied to find and elaborate a coupling proof of concept. The acquired knowledge is used for a model of the 11 T dipole magnet, which will be installed in the HL-LHC. In addition, a newly developed protection system (CLIQ) that works with imbalanced currents provides the current for the electromagnetic-thermal analysis of the 11 T magnet, in order to analyse its mechanical behaviour. The results of the mechanical FEA are only compared with the critical stress and strain by considering the order of magnitude.

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Glossary

Abbrevations

ALICE	A Large Ion Collider Experiment
APDL	ANSYS Parametric Design Language
ATLAS	A Toroidal LHC ApparatuS
B	Magnetic Field
B_C	Critical Magnetic Field
CERN	European Organization for Nuclear Research
CLIQ	Coupling-Loss Inducted Quench
CMS	Compact Muon Solenoid
E	Young's Modulus
F_L	Lorentz Force
FEA	Finite Element Analysis
HL-LHC	High Luminosity Large Hadron Collider
J	Current density
J_C	Critical Current Density
L	Luminosity
L	Inductance [electrical]
LEIR	Low Energy Ion Ring
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty
Nb	Niobium
Nb-Ti	Niobium Titanium
Nb_3Sn	Niobium Three Tin
PS	Proton Synchrotron
PS Booster	Proton Synchrotron Booster
Q	Heat

QH	Quench Heaters
r	Radius
R	Resistance
Sn	Tin
SPS	Super Proton Synchrotron
t	Time
T	Temperature
$\triangle T$	Temperature Difference
T_0	Reference Temperature
T_C	Critical Temperature
u	Displacement
α_T	Coefficient of Thermal Expansion
ε	Strain
ε_C	Critical Strain
θ	Angle
ν	Poisson's Ratio
σ	Stress
σ	Electrical Conductivity [electrical]
σ_C	Critical Stress

Units

A	Ampere
K	Kelvin
MPa	Mega Pascal
m	Meter
N	Newton
N/m	Newton per Meter
N/m^3	Newton per Cubic Metres
Pa	Pascal
s	Second

T	Tesla
TeV	Tera Electron-volt
V	Volt
W/m^3	Watt per Cubic Metres

1. Introduction

"No amount of experimentation can ever prove me right; a single experiment can prove me wrong." - Albert Einstein

1.1. CERN

European Organization for Nuclear Research (CERN) is a research facility with a pioneering role in high energy physics. Its location is in Swiss next to the France border near Geneva and was founded in 1954. Presently CERN has 22 member states which are responsible for all important decisions about CERN, its activities, and the capital distribution. The aim is understanding the fundamental laws of nature to answer questions such as: *What is the universe made of? How did it start?* [1]

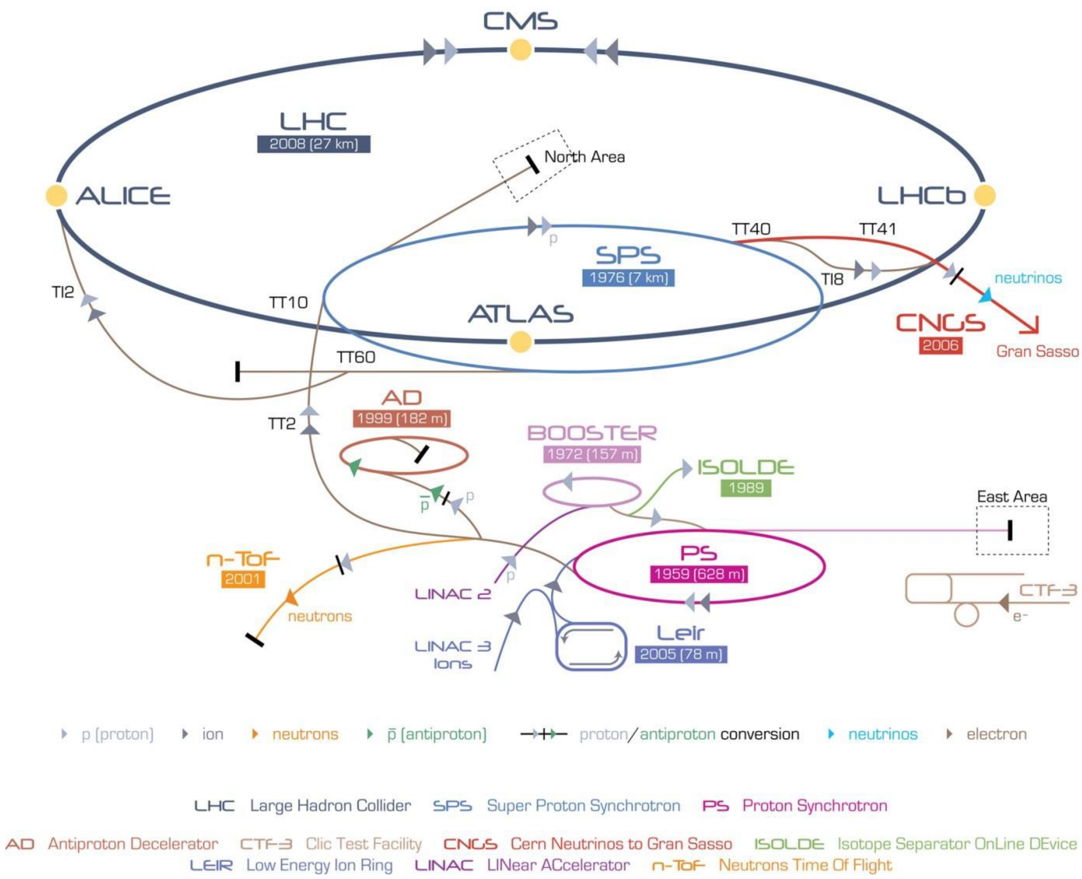


Figure 1.1: CERN Accelerator Complex [2]

Before particles access the Large Hadron Collider (LHC) they are gradually accelerated. With a small bottle of hydrogen gas and an electric field, protons are provided for the accelerators. The protons start in Linac 2, pass the Proton Synchrotron Booster (PS Booster), after which the next accelerator steps are the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS). In the end, the protons reach the LHC and have a final energy of 6.5 TeV after accelerating. It is also possible to inject lead ions into the LHC. Vaporized lead ions enter Linac 3 and pass the Low Energy Ion Ring (LEIR). Afterwards, the ions enter PS and follow the same route as the protons. [3]

In the LHC, two beams of particles are circulating in opposite directions. One goes clockwise and the other counter clockwise. When the beams reach their final energy level, they have a velocity near the speed of light and are ready to collide. Four detectors are installed to track different types of fundamental particles. A Large Ion Collider Experiment (ALICE) is a heavy-ion detector; A Toroidal LHC ApparatuS (ATLAS) is a general-purpose detector to investigate the fundamental laws, from Higgs boson to extra dimensions and dark matter; Compact Muon Solenoid (CMS) is a general-purpose detector as well, with the same aim but different construction; Large Hadron Collider beauty (LHCb) experiment can detect the slight differences between matter and antimatter [4].

Luminosity L is a quantity for measuring the number of interactions in particle accelerators per interaction region. It takes into account the number of particles per bunch N_1 and N_2, the revolution frequency f, the number of bunches N_b, and the approximated size of the beam cross section $4\pi\sigma_x\sigma_y$

$$L = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \quad [cm^{-2}s^{-1}] \tag{1.1}$$

and is normally given in $cm^{-2}s^{-1}$ [5]. An upgrade of the LHC is planned, with the aim to obtain higher luminosity. The improved LHC will be called HL-LHC (High Luminosity LHC). One project of the upgrade is to raise the number of collimators. Collimators clean the beam, which means that they absorb particles from the transverse beam tails. After passing a collimator, the beam cross section is smaller and the number of particles is also lower. However, the luminosity is barely changing because both effects nearly compensate each other. For implementing additional collimators more space is needed, which is obtained through the replacement of a main dipole by one collimator and two dipoles (Figure 1.2). The dipoles bend the beam, thus it is necessary to have the same bending force after the exchange. Therefore, the integrated magnetic field over the length of an existing main dipole has to be the same as of two new dipoles. Hence, a dipole with a higher magnetic field is required. To reach higher fields compared to the existing dipoles, new materials and designs are explored. Accordingly, simulations on electromagnetic, thermal and mechanical behaviour are necessary. [6]

(a) Main dipole of the LHC [7]

(b) Model of the main dipole replacement [8]

Figure 1.2: HL-LHC dipole project

1.2. Aims

When a magnet is superconducting, it has higher performance such as zero resistivity and higher magnetic fields are reachable. To get to this state the operating point has to be below a specific value for the current J, the magnetic field B, and the temperature T. The transition from superconducting to normal-conducting state is called a quench. The thesis aims at studying coupling between electromagnetic-thermal and mechanical phenomena occurring after a quench in the superconducting magnets. For this reason, two models representing both domains are coupled by means of area-based coupling. The main goals of the thesis, which are to be fulfilled consecutively, are listed below.

1. Develop a proof of concept coupling interface between two chosen FEA programmes to model a busbar:
   Simulation of electromagnetic-thermal model to send its results as input to mechanical analysis.

2. Modelling a magnet:
   Apply code modifications that are needed to perform mesh-based coupling from the mechanical FEA to an existing model of an 11 T magnet.

3. Analysis of the mechanical results:
   Once coupling is established, results are studied in order to quantify the maximum stress that could provide answers regarding to material degradation during magnet operation.

1.3. Strategies

The understanding of both FEA programmes that are used for the coupling is mandatory for this project. Especially the possibilities for information exchange are important. For the proof of concept, a simple geometry with academic variables (current, resistivity etc.), material properties and boundary conditions are chosen. The electromagnetic-thermal analysis provides the temperature distribution and the Lorentz forces as an input for the mechanical simulation (Figure 1.3). For some types of studies such as the effect of turn displacement on the magnetic field quality, it is necessary to return the displacement to the electrical-thermal FEA programme. However, these analyses are out of the scope of the thesis. This validated coupling interface is transferred to a model of an 11 T dipole magnet with its geometry, physical variables, material properties, and boundary conditions. These results are analysed with regard to the critical stress and strain during the operation of the magnet.

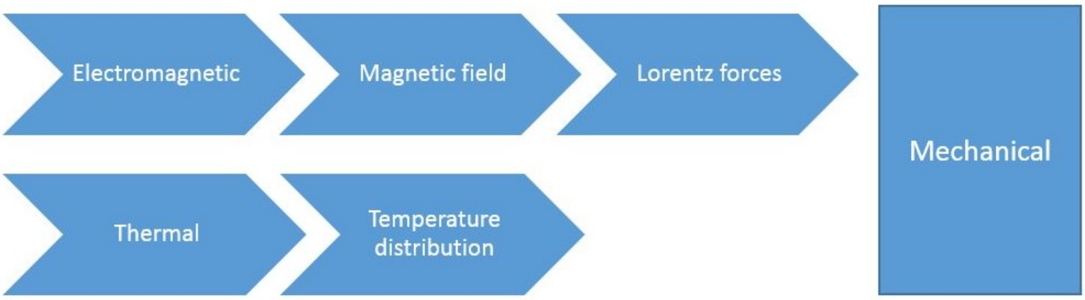


Figure 1.3: Coupling strategy

2. Superconducting Accelerator Magnets

The phenomenon of superconductivity was first discovered in 1911 by a Dutch physicist, Kamerlingh Onnes, when he cooled down metal under 4.2 K [9]. Afterwards, scientists found other metals where the superconducting state was attainable, though only certain metals possess this ability.

Superconductors are a momentous discovery for high field magnets. The superconductors operate with zero resistivity [10]. Thus, in this state the electrical power consumption is also zero, except for the refrigeration power. In order to operate at cryogenic temperatures, fluid helium is needed. This substance remains in a liquid state even at temperatures close to absolute zero. When the helium is superfluid, it has zero viscosity and extraordinarily high heat conductance. At these temperatures, superconductors are able to carry high current densities, which lead to high magnetic fields. Figure 2.1 displays the comparison of conventional iron yoke electromagnets and two superconductors, niobium titanium (Nb-Ti) and niobium-tin (Nb_3Sn). It shows the possibility of larger operating areas for superconducting material. Especially the magnetic field of iron-dominated magnets is limited at 2 T when Nb-Ti can still perform up to 10.5 T and Nb_3Sn can perform up to around 20.5 T at a temperature of 4.2 K.

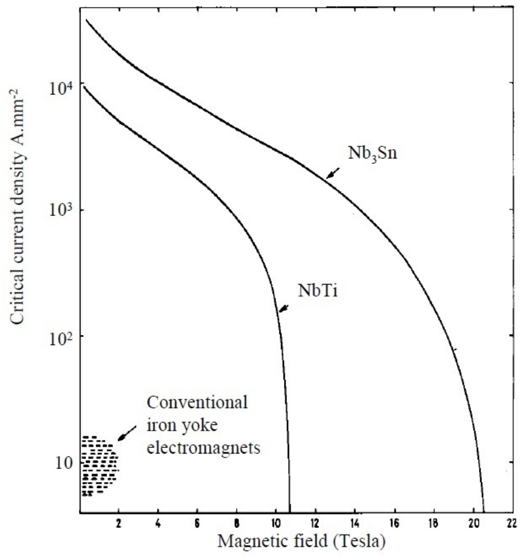


Figure 2.1: Superconducting and normal conducting material at 4.2 K [12]

This exemplifies that superconductors are more suitable for high field applications. They are used in a large number of different fields. For example, they are important for magnetic resonance tomography (medical technology), and the superconducting quantum interference device (measurement device) can operate with higher accuracy [11].

2.1. Superconductivity

The following parameters are the critical values for the superconducting state

- critical temperature T_C,
- critical magnetic field B_C,
- critical current density J_C.

The critical values in each case are measured when the two others are zero. The first and second depend on the material type, while the critical current density J_C depends on the production process of the superconducting wire [13]. Assuming T, B and J are the axis of a Cartesian coordinate system, the critical surface is the border of the superconducting state (Figure 2.2). If a point in this system is below this surface, the material is in superconducting state, and above the surface the material has normal conducting behaviour. The transition from superconductivity to normal state is called quench.

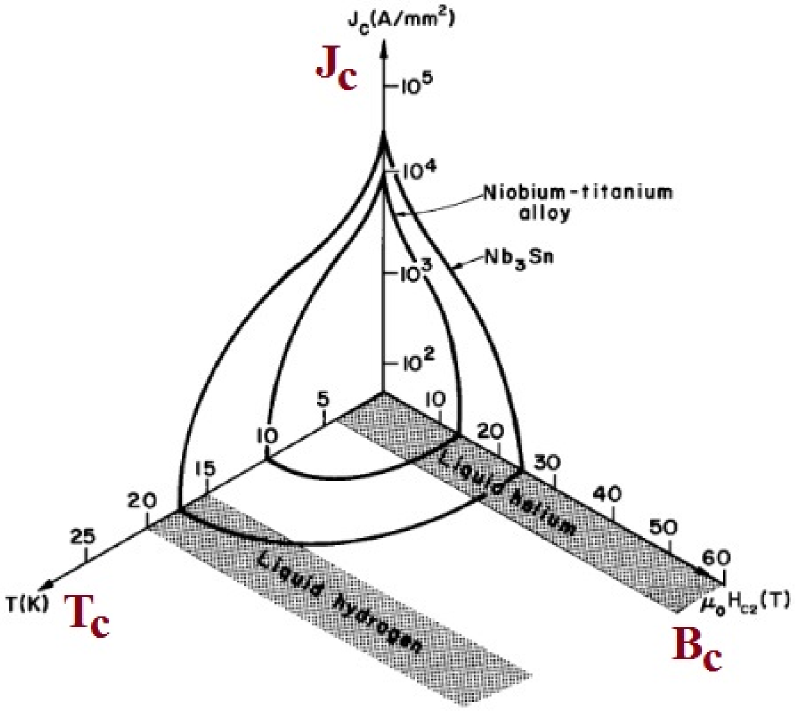


Figure 2.2: Critical surface of Nb-Ti and Nb_3Sn [12]

2.2. Composites

A superconducting material is always used with a non-superconducting stabiliser (mainly copper[1]); this combination is called a composite. The fraction of copper and superconducting material is selected for good electrical and mechanical performance, depending on the application area. When the material is quenching, the superconductors have higher resistivity than copper, so the current passes through the stabiliser. The temperature gradient leads to strain which results in stress. Figure 2.3 shows the different stress-strain curves of Nb-Ti, copper and a composite of both. Nb-Ti has stiff behaviour, while on the other side copper is easier to deform. The composite combines both attributes to get better stress-strain behaviour for withstanding the forces which act on a magnet during the operation. The following mechanical effects are acting on the magnets: "(1) static mechanical stresses related to the mass of the structure and preloading of the wire during winding, (2) stresses imposed by thermal contraction during cooldown from room temperature to liquid-helium temperature, and (3) electromagnetic forces during service" [14].

Figure 2.4 displays all typical low temperature superconductors. Nb-Ti has the lowest critical magnetic field B_C and temperature T_C in this comparison. However, it is the only one with ductile material behaviour of this group, as the rest are brittle. This is the reason why Nb-Ti is the most commonly used superconductor for large scale accelerators. It is also the superconducting material for the LHC, which is currently the largest particle accelerator in the world [4].

[1] more detailed information in [14] p. 141

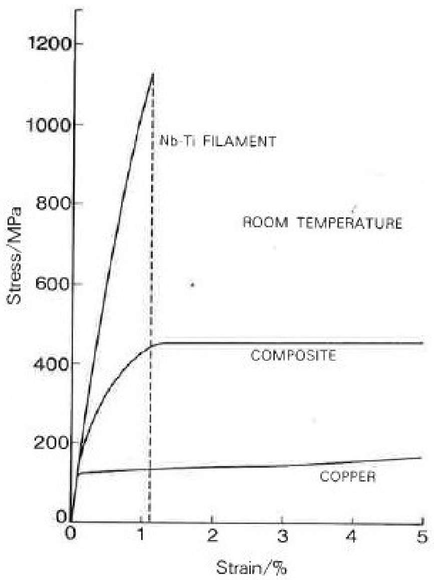


Figure 2.3: Stress-strain curves of Nb-Ti, copper and composite [14]

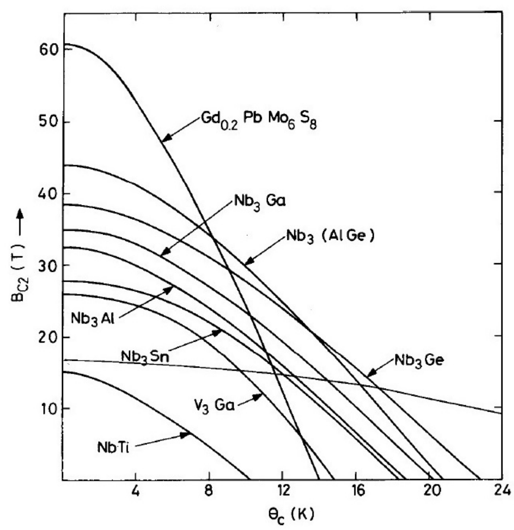


Figure 2.4: Conventional low temperature superconductors [12] [x-axis: T_C; y-axis: B_C]

For reaching higher magnetic fields, it is necessary to choose another superconducting material. Nb_3Sn seems promising to fulfil the requirements for an accelerator magnet. Table 2.1 summarises the comparison of Nb-Ti and Nb_3Sn, on which the following paragraphs are based. Figure 2.2 already displayed that the critical surface of Nb_3Sn is above that of Nb-Ti, which means that higher magnetic fields can be reached. The critical temperature T_C and magnetic field B_C are nearly doubled compared to Nb-Ti. Figure 2.5 displays the stress-strain curves of Nb-Ti and Nb_3Sn composites. In the image of Nb_3Sn, it is possible to see the appearance of multiple fractures. This directly leads to the phenomenon of decreasing critical current J_C when the absolute value of the strain is rising. In Figure 2.6, different samples are used to examine the change of J_C in deformation tests. The relative value of $J_C(|\varepsilon| = 1)/J_C(\varepsilon = 0)$ for Nb-Ti is around 0.89 - 0.98, and for Nb_3Sn it is smaller than 0.5.

This exemplifies the strain sensitivity of Nb_3Sn and leads directly to the next difficulty, which is illustrated in Figure 2.7. When the absolute value of the strain is grater than zero ($|\varepsilon| > 0$), then

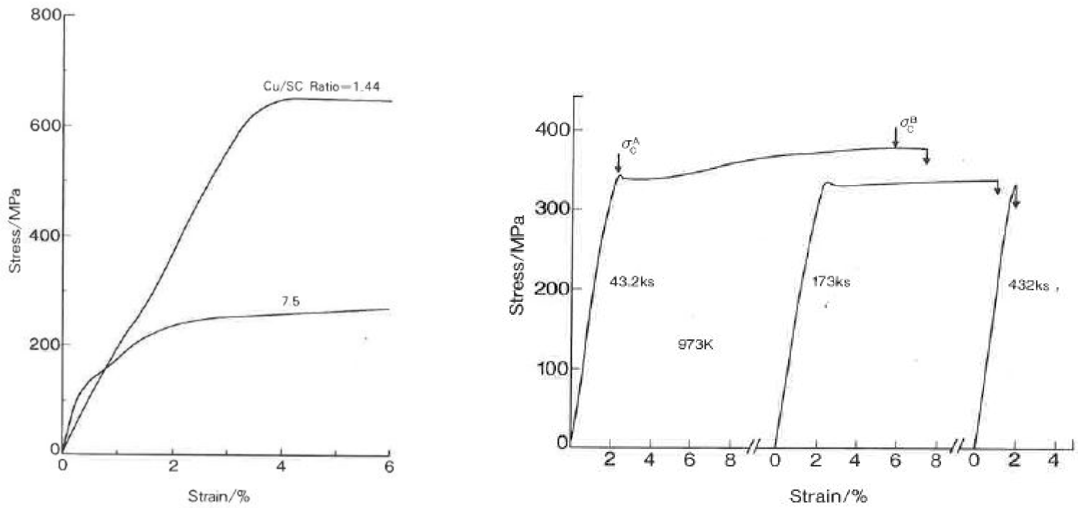
$$J_C(|\varepsilon| > 0) < J_C(\varepsilon = 0) \quad [A]. \tag{2.1}$$

If only elastic deformation is occurring, the critical current J_C can still reach the maximum performance at $\varepsilon = 0$, because the strain is reversible. However, after crossing

Table 2.1: Comparison of Nb-Ti and Nb_3Sn properties

	Nb-Ti	**Nb_3Sn**
T_C	9.2 K [A]	18 K [A]
B_C	15 T [A]	28 T [A]
Material behaviour	ductile [A]	brittle [A]
$J_C(\varepsilon)/J_C(\varepsilon = 0)$	slightly strain sensitive (0.89 - 0.98) [B]	strain sensitive [A] (<0.5) [B]
Fracture	single fracture [C] (Angle of 45° and honeycomb surface at 4.2 K)	multiple fractures [D]
ε_C at 4.2 K	15 % [E]	1.5 % [E]
σ_C	150 - 200 MPa (Damage of insulation) [F]	150 - 200 MPa (Conductor degradation) [F]

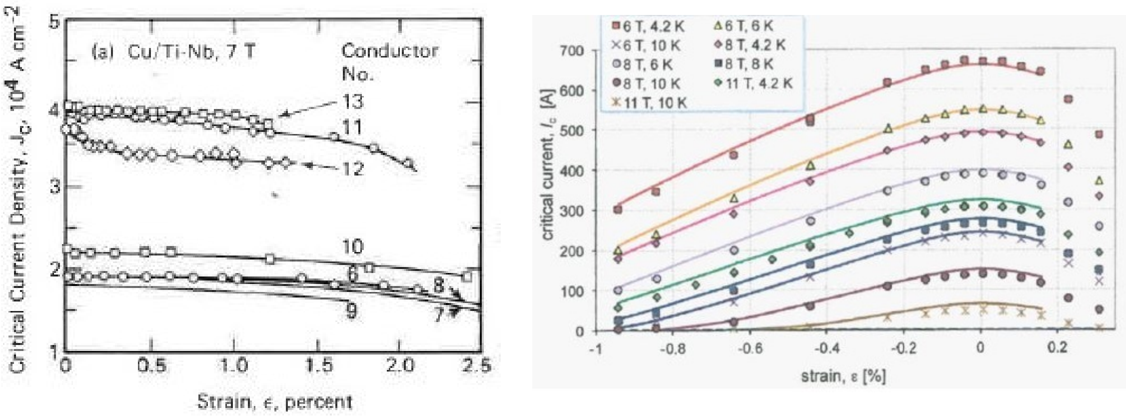
[A] Reference [15]
[B] Figure 2.6 a)
[C] Reference [16]
[D] Reference [14]
[E] Reference [17]
[F] Reference [18]



(a) Nb-Ti

(b) Nb_3Sn at room temperature

Figure 2.5: Stress-strain curves of Nb-Ti and Nb_3Sn composites [14]



(a) Nb-Ti [17]

(b) Nb_3Sn [19]

Figure 2.6: Critical current J_C over strain ε of Nb-Ti and Nb_3Sn

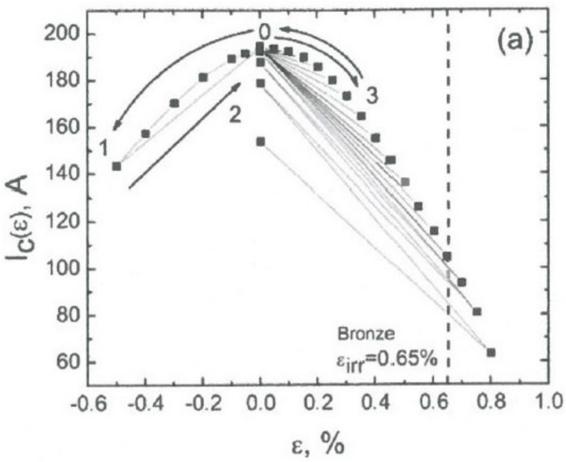


Figure 2.7: Critical (irreversible) strain [19]

the border to plastic deformation, the critical current J_C can never reach the maximum performance, as the strain is now irreversible. Hence, the critical strain ε_C is created virtually at 4.2 K and zero-field. While ε_C is at 15 % for Nb-Ti, the value for Nb_3Sn is at 1.5 %, which is 10 times lower.

Subject to high stresses the degradation for a Nb-Ti magnet occurs in the insulation, which is around the wires, and for Nb_3Sn it happens in the conductor. For both cases the critical stress σ_C is about 150 - 200 MPa. In addition, the forces which are acting on Nb_3Sn coils are stronger. These body forces are called Lorentz forces f_L and affect conductors that are carrying a current density J such as the coil. The Lorentz force density is

$$\vec{f_L} = \vec{J} \times \vec{B} \quad [N/m^3] \ [18]. \tag{2.2}$$

2.3. Design of Superconducting Accelerator Magnets

For the upgrade of the LHC to the HL-LHC a stable and homogeneous magnetic field of the 11 T dipole magnet is necessary. Therefore this section describes the structure of an 11 T dipole and the mechanical reasons for using its specific design.

2.3.1. Coil

Figure 2.8 illustrates the theoretical design for a homogeneous magnetic field of a dipole coil. The current density is applied uniformly in the areas of the intersecting circles. In a polar coordinate system (r, θ), the distribution is given by a cosine curve. This leads to the distribution of the current $J = J_0 \ cos(\theta) \ [A/m^2]$.

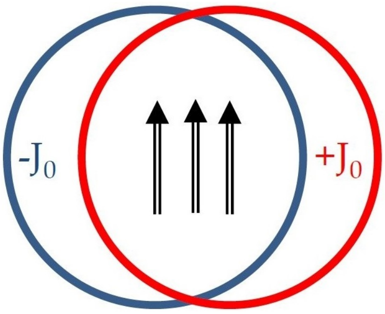


Figure 2.8: Theoretical design of a dipole magnet [15]

Figure 2.9 shows the cross section of a dipole magnet. The coil is made of cables, which are called turns. The distribution of the current is approximated by arranging blocks with individual turn numbers. However, the cables generate their own magnetic field which results in imperfections of the main magnet field. In addition, eddy-currents appear in the cables. This is why the strands and cables are twisted to reduce distortion; this scheme is called Rutherford cable (Figure 2.10 (a), (b)).

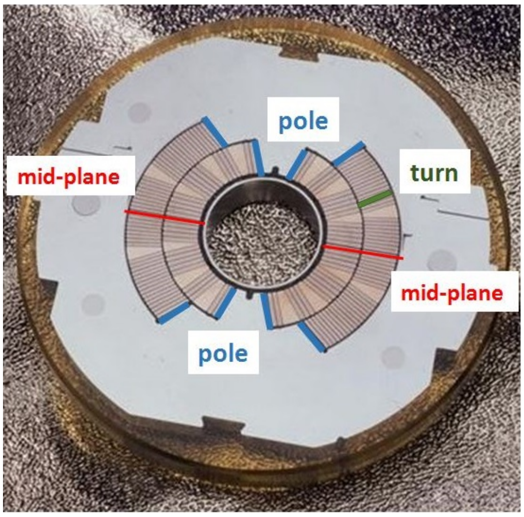
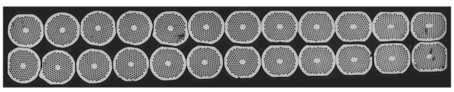


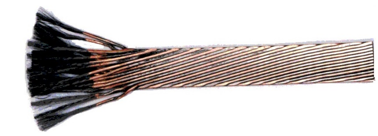
Figure 2.9: Cross section of a dipole coil with collar [22]

The superconductor of the 11 T dipole is Nb_3Sn. Figure 2.10 (c), (d) show two concepts of a Nb_3Sn strand structure. The filaments are surrounded by copper and they contain niobium (Nb) and tin (Sn). In this condition, it is possible to form the strands in the required position because the materials are not brittle. After winding the coils, the Rutherford cable gets heated up, and Nb and Sn combine to the brittle superconducting material Nb_3Sn.

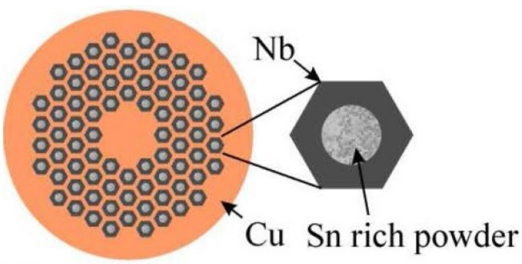
The coil has protection particular for mechanical reasons. Inter-filament spacing is small so that the filaments support each other during operation, since it is harder than copper. The strands are twisted to obtain more stability, and they have a copper core



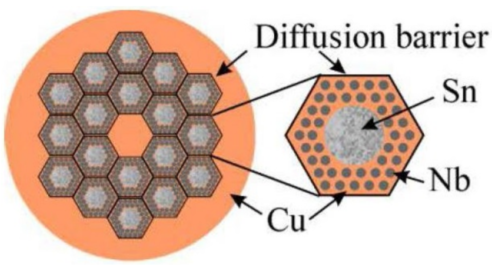
(a) Strands in a cross section of a Rutherford cable [20]



(b) Rutherford cable [20]



(c) Cross section of one Nb_3Sn strand with powder in tube (PIT) process [15]



(d) Cross section of one Nb_3Sn strand with internal tin process [15]

Figure 2.10: Structure of a Nb_3Sn cable [20]

and shell to reduce the degradation of the cable. The insulation around the Rutherford cables, which is needed for electrical operation, has to withstand high pressures. Furthermore, the minimum bending radius of the cable is important, as otherwise strands would pop out during winding, which is also known as de-cabling. [15]

With different coil structures, it is possible to build various magnets such as dipoles, quadrupoles, sextupoles etc. The most common used magnet types are the dipole and quadrupole magnets. Dipoles bend the beam, while quadrupoles focus the particles in the beam. There are 1232 dipoles and 386 quadrupols in the LHC [21]. A large number of other magnets for beam correction (sextupoles, octupoles, decapoles etc.) and insertion are installed.

2.3.2. Structure

Figure 2.11 displays the azimuthal Lorentz forces which are acting on a dipole magnet. It is necessary to protect the magnets against displacement and deformation. Otherwise the orientation of the magnetic field would change, influencing the path of the beam. To support the coil, collars are installed around. They are made of non-magnetic material, such as stainless-steel or aluminium. In addition, the collars are only a few millimetres thick and have lamination between each other to limit the effect of the eddy-currents. They are built of two parts. Figure 2.11 shows a long collar at the bottom and a short one on the top. Only the long collars generate stress

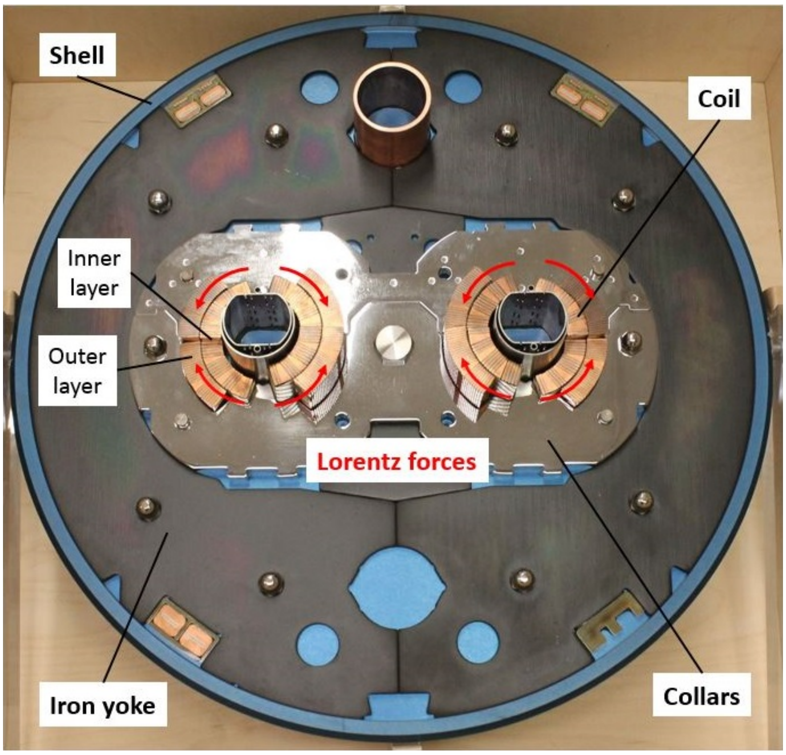


Figure 2.11: Structure of an LHC dipole [23]

and the short ones act as space fillers. The collars are used alternating to achieve better rigidity, so that the following collars have the short at the bottom and the long at the top.

The next element of the structure is the iron yoke around the collars. The purpose of the yoke is twofold: because of the magnetic material the iron yoke enhances the B-field, and furthermore it is in contact with the collars to support the rigidity and to limit the radial displacement of the coil. The yokes as well are a few millimetres thick and have lamination between each other to limit the eddy currents.

The last part of the structure is the shell. Two half shells are welded around the iron yoke with high tension. For a dipole of the LHC the tension is approximately 150 MPa [18]. The shell encloses the liquid helium and improves also the rigidity. There are two vertical gaps between the iron yoke before the welding process. They are closed after welding so that the yoke is in a tight contact. Also, after the cool down when the magnet is shrunk, the gaps remain closed.

2.3.3. Pre-Stress

Lorentz forces and shrinking due to cool down lead to deformation and azimuthal displacement of the turns inside the coil towards the mid-plane. Particularly the thermal contraction is different for coil, collars, iron yoke and shell. To restrict motion of the turns, the coil is under compression at cryogenic temperature and nominal field. High stresses are administered while manufacturing; this stress is called pre-stress.

To limit coil motion from cool down to nominal field, different types of shims are used (Figure 2.12). The pole shims (3) squeeze the coil while the pole adjustment shims (1) produce extra pressure on the poles. To stop radial expansion at the mid-planes, collar/yoke shims (2) are applied but only on the left and right side of a collar. The highest fraction of pre-stress is due to the collars. The oversized coil (compared to the collars), the shims, and the collars are put in a collaring press and pressure is applied to a specific value. During this process, the collars get locked with so-called keys. When the press releases the collars, they have a ”spring back” because of the locking and the applied deformation.

Figure 2.13 illustrates the process of the stress in an LHC main dipole coil from collaring press to nominal field. The highest stress of the coil occurs in the collaring press, which is above 120 MPa. After the ”spring back” it returns to 70 MPa. Because of the shrinking after cool down the stress decreases to 40 MPa. At this point, the values of the inner and outer layer of the coil start to disperse. The effect of the magnetic field becomes visible. While the stress decreases at the poles, it rises at the mid-planes. The Lorentz forces push the upper part down and the lower part towards the mid-planes. This leads to less stress at the poles and more stress at the mid-planes.

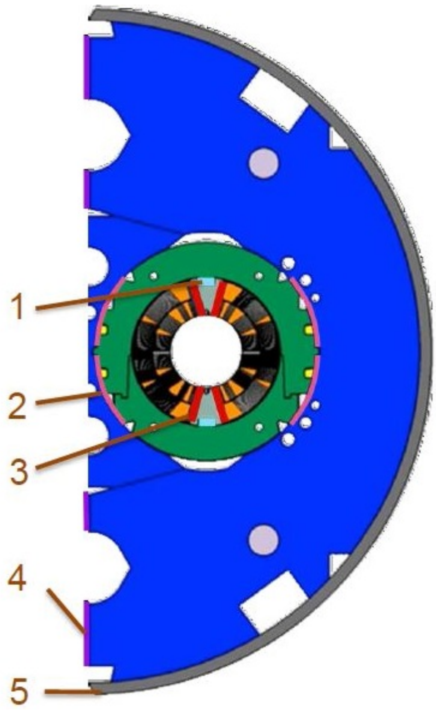


Figure 2.12: Shims in an 11 T twin aperture: (1) Pole adjustment shim, (2) Collar/yoke shim, (3) Pole shim; (4) Gap (closed at room temperature and during run); (5) Shell [18]

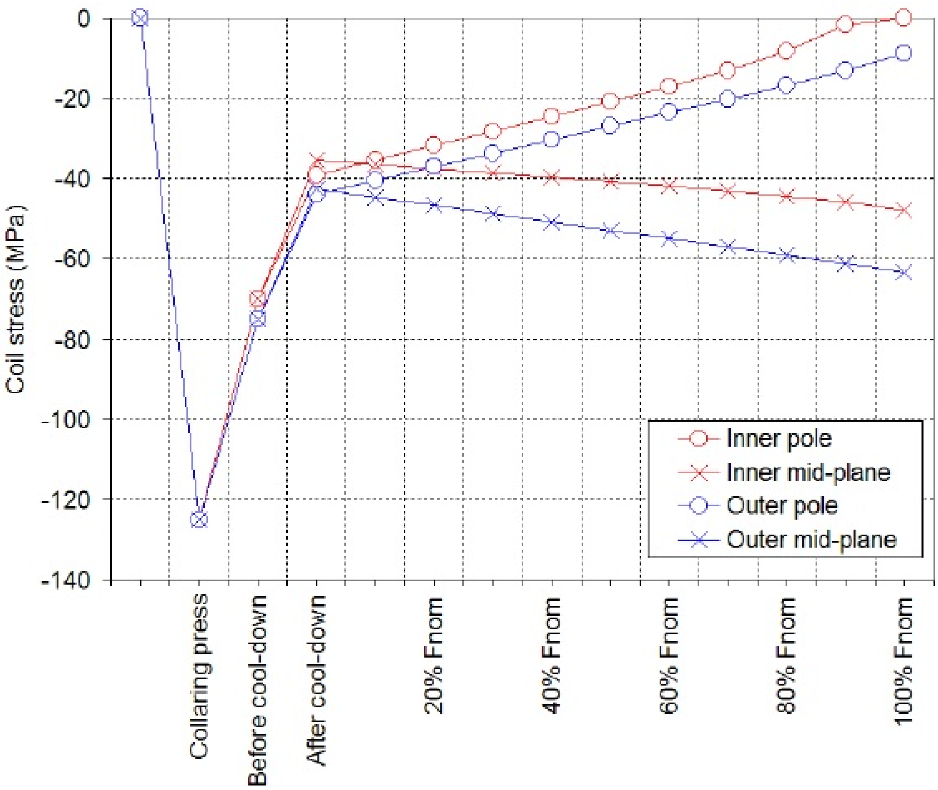


Figure 2.13: Stress process of an LHC main dipole coil [18]

To guarantee tight contact between pole and coil at nominal field, a security margin in terms of pre-stress exists. Sometimes this margin is higher than 20 MPa. The pre-stress is proportionally to the total displacement. In addition, less motion means reduced frictional energy dissipation. However, the connection between a quench and pre-stress is still controversial. [18]

2.4. Quench

When a superconductor passes over from the superconducting to the normal-conducting state, it is called quench. If the working point is below the critical surface, it requires the release of energy due to friction, particle showers, or eddy-current losses during current ramp-up or the occurrence of cooling problems, to cause a quench [13, 24]. After the quench, the working point is above the critical surface.

In the superconducting state the current only flows through the filaments (superconducting material) due to their zero resistivity. After a quench, the resistivity of the superconductor is much higher compared to copper. This is the reason why the current starts to flow through the copper, and Joule heating occurs there. Normally, only one spot quenches, not the whole coil at the same time. This point is called hot-spot. The liquid helium takes the heat away. However, it is less effective for cooling when it gets to the gas state and is even neglected in most quench simulations. If the temperature increases too quickly, the quench propagates.

High temperatures can cause melting of the copper, which is a permanent damage of the coil. Hence, protection is important for a long lifespan of a magnet.

2.4.1. Protection Systems

Two strategies for protection are used. One is a passive protection to react without sensors and actuators. The other one is a active protection when a quench is detected it is triggered. It is important to detect a quench to react in time. Examples are

- External energy dissipation:
    - By-pass Diode [passive],
    - Energy Extractor [active],
    - Parallel Resistor [passive],
- Internal energy dissipation:
    - Quench Heaters (QH) [active],
    - Coupling-Loss Inducted Quench (CLIQ) [active].

Example of the LHC Main Dipole Circuit

Figure 2.14 shows an example of the LHC main dipole circuit. The circuit contains 154 dipole magnets with protection and two energy extractors. The quench detection system monitors the voltage $u_{det}(t)$ by comparing two voltages $u_1(t)$ and $u_2(t)$ of two magnet apertures. Without a quench, the detected voltage is

$$u_{det}(t) = |u_1(t) - u_2(t)| = |L_1 \frac{di_{cir}(t)}{dt} - L_2 \frac{di_{cir}(t)}{dt}| \approx 0 \quad [V] \tag{2.3}$$

with the inductance of a magnet L and the current $i_{cir}(t)$. If magnet 1 is quenching, its resistance is $R_1 \neq 0$ and the detected voltage is changing to

$$u_{det}(t) = |u_1(t) - u_2(t)| = |L_1 \frac{di_{cir}(t)}{dt} + R_1 i_{cir} - L_2 \frac{di_{cir}(t)}{dt}| \approx |R_1 i_{cir}| \quad [V]. \tag{2.4}$$

For the case that both magnets are quenching which could lead to $u_{det}(t) \approx 0$ the magnet voltage is compared to the voltage of its neighbours. When the voltage $u_{det}(t) > 100\,mV$ for 10 ms the quench detection system triggers the active protection system. The *quench heaters* are directly fired and the power converter is switched off. A QH is an insulated stainless steel strip glued on top of the outer layers of the coil. After triggering, it generates heat to quench larger portions of the coil. This means the resistance of the magnet is further increasing because of quench spreading. If the forward voltage i_{cir} is above 6 V, the *by-pass diode* is turned on and i_{cir} commutes to the diode. The magnet dynamics are detached from the circuit and the magnet current i_{mag} discharges through the diode against the forward current i_{cir}. After about 300 ms, the switch opens to insert the *energy extractor* into the circuit. All the energy in the circuit now discharges in a safe and controlled way. A *parallel resistor* is installed to dampen transient voltage waves which are travelling along the circuit. [25]

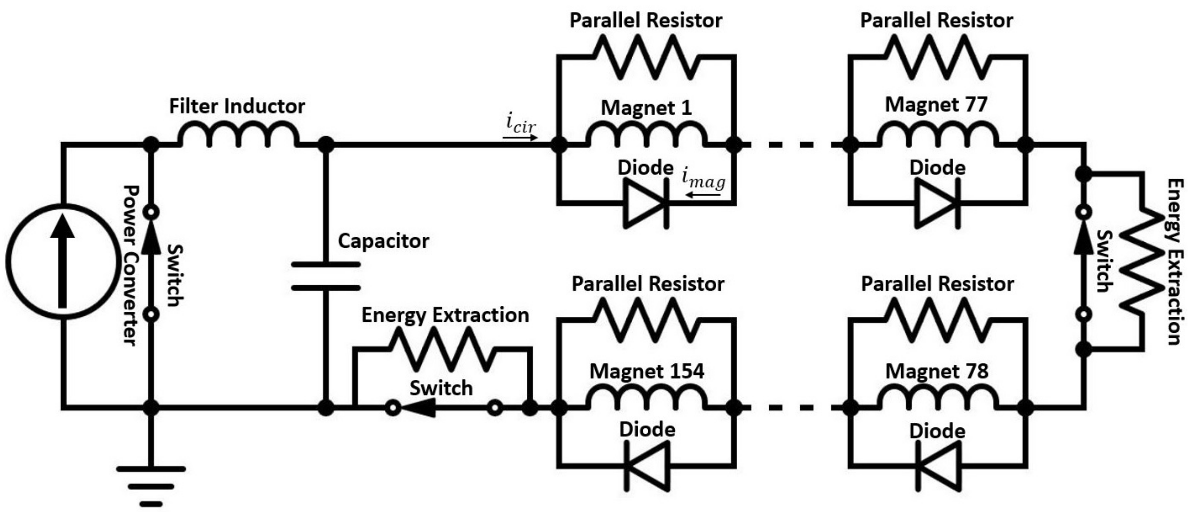


Figure 2.14: LHC Main Dipole Circuit

CLIQ

A new protection system was invented specifically for magnets with higher energies. It is called Coupling-Loss Inducted Quench (CLIQ). In Figure 2.15, a discharge due to the CLIQ system is displayed. The currents I_A and I_B flow trough the upper and lower part of a coil. When CLIQ is applied to the coil, the current I_C is subtracted to I_A and added to I_B (Figure 2.16). Coupling losses occur in the superconducting wires and cables due to the described current change. Heat is generated directly inside the conductor. Compared to existing quench protection systems CLIQ can offer

- faster response,
- more homogeneous temperature distribution,
- lower hot-spot temperature,
- lower failure risk,
- for the same size and price.[2] [26]

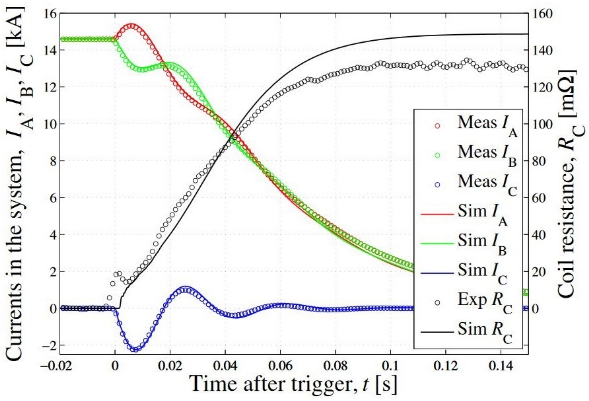


Figure 2.15: CLIQ discharge [27]

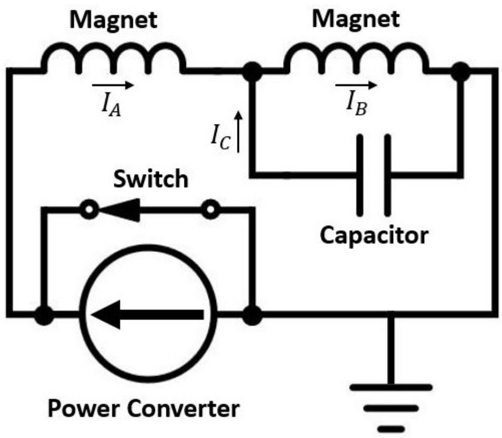


Figure 2.16: CLIQ schematic

2.4.2. Analysis

To protect the magnet against damage due to insufficient quench protection it is necessary to predict transients occurring after a quench. Therefore multiphysics simulations are done. During a quench, electromagnetic, thermal and mechanical analyses need to be studied. On the one hand the electromagnetic-thermal and mechanical analyses have different time scales and on the other hand a lot of magnets at CERN are already created in a mechanical analysis programme. Hence, a flexible coupling method for the electromagnetic-thermal and the mechanical analyses is desirable.

[2] more detailed information in [27]

3. Proof of Concept: Busbar

This chapter describes a method of coupling electromagnetic-thermal and mechanical analysis. As a proof of concept, a simple geometry, academic variables, and material properties are chosen. The studied object is a busbar.

3.1. Motivation

Simulation coupling is the process of exchanging selected inputs and outputs of two programmes with each other. These pieces of information are results of solving the FEA programmes. Different methods of coupling exist. The exchange can be uni- or bidirectional and the transfer frequency can vary [28].

The two utilised FEA programmes are commercial ones. COMSOL is chosen for electromagnetic-thermal analysis and ANSYS APDL is used for mechanical simulations. On the one hand commercial software requires the purchase of licenses. However, they have a lot of physical modules implemented, such as electrical, mechanical, and fluid. On the other hand, in-house software requires writing a lot of code to perform the same task, which means paying salaries for developers and maintenance effort.

The justifications for creating a coupling interface are twofold. One reason is the different time scales of the electromagnetic-thermal and the mechanical analyses. The joule heating and the thermal diffusion occur relatively quickly while deformation is slower. Therefore, unequal time steps for the solving are necessary. The other reason is the time saving due to previously created models in the mechanical FEA programme. Usually the mechanical simulations of superconducting magnets are performed with ANSYS APDL.

3.2. Introduction

For the proof of concept, the simple geometry of a busbar is chosen. Figure 3.1 displays the COMSOL the model for electromagnetic-thermal analysis. To simulate a magnetic field, it is necessary to have two busbars and apply air around them. The outer boundary of the circle is an infinite element, so that the magnetic field lines are closing within the model. Figure 3.2 shows the ANSYS model for the mechanical analysis. The location and orientation of the Cartesian coordinate systems and the size of the busbars are the same for both models.

Only basic knowledge of COMSOL is necessary to understand its structure and to find possibilities for exporting information. On the other hand, deep knowledge in ANSYS is required, since writing APDL code and getting reliable results is the main part of these studies. Table 3.1 contains important parameters of both busbar models.

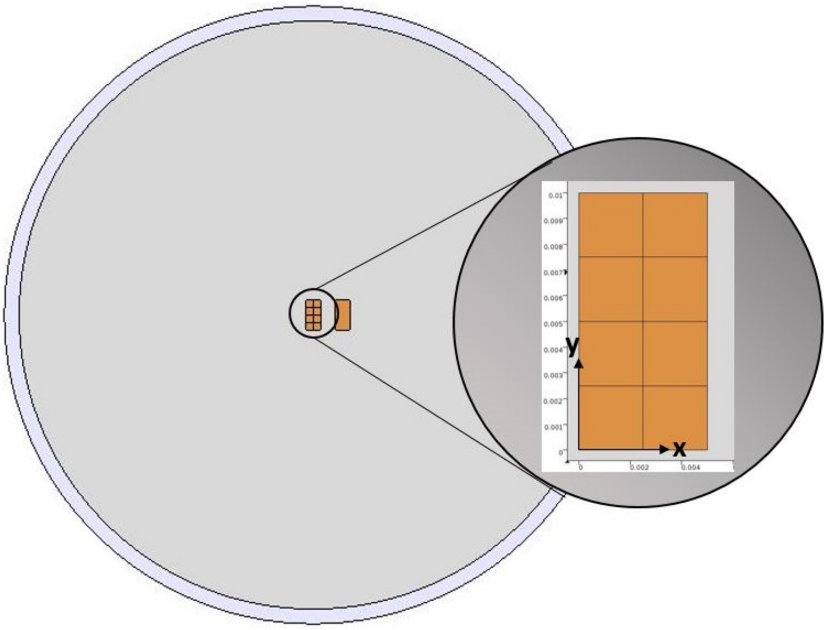


Figure 3.1: Busbar in COMSOL

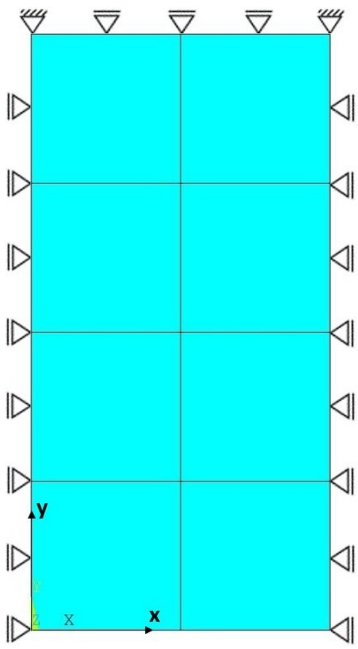


Figure 3.2: Busbar in ANSYS (bearings for proof of reliable results)

Table 3.1: Information about the busbar

Parameter	Value
High	10 mm
Wide	5 mm
Thickness	1 m
Reference temperature	$T_0 = 10\,K$
Applied current [COMSOL]	$J(t) = 10\frac{A}{s} \cdot t\ [A]$ $J(10\,s) = 100\,A$
Electrical conductivity [COMSOL]	$\sigma = 6 \cdot 10^7\,\frac{S}{m}$
Young's modulus (x and y) [ANSYS]	$E = 110 \cdot 10^9\,Pa$
Coefficient of thermal expansion (x and y) [ANSYS]	$\alpha_T = 4 \cdot 10^{-3}\,\frac{1}{K}$
Poisson's ratio [ANSYS]	$\nu = 0.35$
Applied testing temperature [ANSYS] Resulting temperature difference	$T_{Test} = 20\,K$ $\triangle T = 10\,K$
Physical modules in COMSOL model	Magnetic Fields (mf), Heat Transfer in Solids (ht)
Element type in ANSYS APDL code	Structural solids (Plane82, KEYOPT(3) = 3)

3.3. Monolithic Electromagnetic-Thermal Model

The external current density J flows through the busbars in opposite directions and increases linearly during the simulation (Figure 3.3). The current of the left busbar flows in the positive z-direction (out of the plane) while the current of the right busbar flows in the negative z-direction (in the plane). With this input the COMSOL model provides solution based on the physics of magnetic fields (mf) and heat transfer in solids (ht). The material properties used in the model are listed in the Table 3.1. The generated heat Q due to the current is

$$Q = \frac{J(t)^2}{A^2\sigma} \quad [W/m^3] \tag{3.1}$$

for each busbar, with the external current density $J(t)$, the area of each busbar A, and the electrical conductivity σ. However, only the results of the left busbar are considered, because only this area is coupled with ANSYS for the mechanical analysis. With respect to the direction of the current $\vec{J}$, the magnetic field $\vec{B}$, and

$$\vec{F}_L = \vec{J} \int dl \times \vec{B} \quad [N] \tag{3.2}$$

the direction of the Lorentz force F_L is in the negative x-direction for the left busbar. The direction of the magnetic field between the busbars is in the negative y-direction and the resulting magnetic field lines are displayed in Figure 3.4.

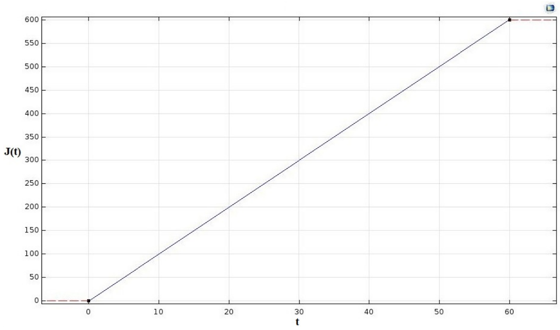


Figure 3.3: Plot of external current density J applied on the busbars

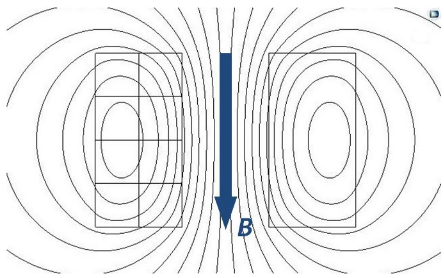
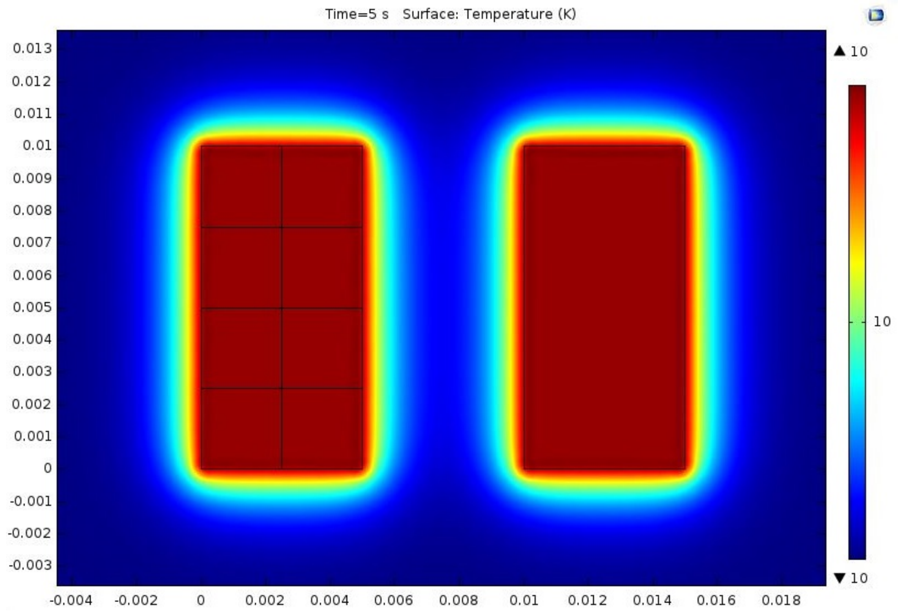


Figure 3.4: Magnetic field lines in the model of the busbars

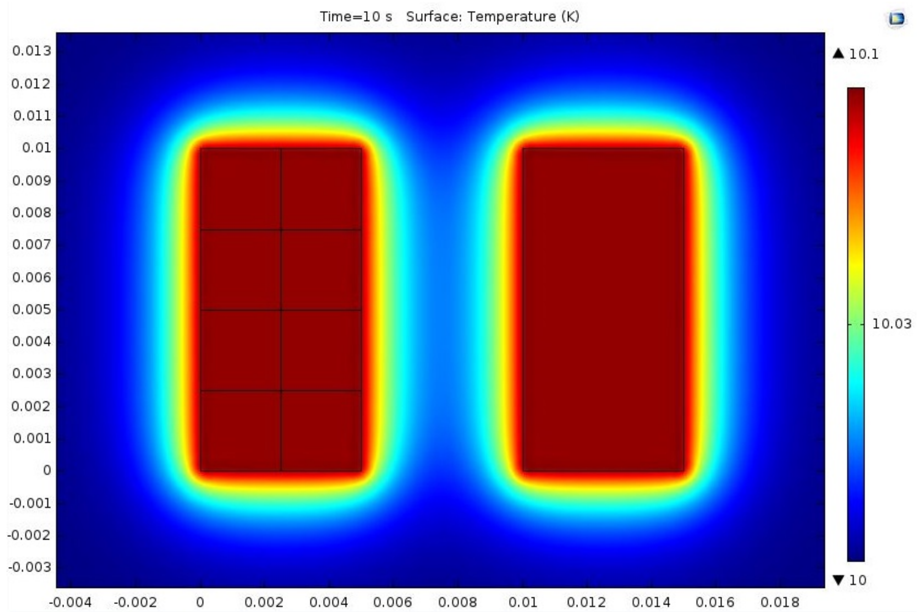
The current density and the resistance cause heat generation which changes the temperature distribution in the busbar. Lorentz forces act on the busbars which is the vectorial product of current density and the magnetic field. The temperature difference $\triangle T$ as well as the Lorentz forces F_L, influence mechanical quantities such as stress and strain. Therefore, both are provided as inputs for the mechanical analysis.

At time $t = 0\,s$ no forces are acting on the busbars and the temperature is still the reference temperature $T_0 = 10\,K$, which means $\triangle T = 0\,K$. This is expected, as the applied current density is $J(t = 0\,s) = 0\,A$. The following Figures 3.5, 3.6, and 3.7 are comparisons of the time $t = 5\,s$ and $t = 10\,s$ which means the currents $J(t = 5\,s) = 50\,A$ and $J(t = 10\,s) = 100\,A$.

The temperature distributions are displayed in Figure 3.5. The highest value is $T(t = 5\,s) = 10.009\,K$ at $t = 5\,s$ and $T(t = 10\,s) = 10.065\,K$ $t = 10\,s$, so the temperature difference is small with $\triangle T(t = 5\,s) = 0.009\,K$ and $\triangle T(t = 10\,s) = 0.065\,K$. Figure 3.6 shows the distributions of the Lorentz forces in x-direction. Analysing only the left busbar, the forces are acting on the right side in the negative x-direction and on the left side in the positive x-direction. However, the forces on the right side are higher which leads in general to a Lorentz force in the negative x-direction which was expected. The higher current $J(t = 10\,s)$ leads to nearly four times higher forces compared to the current of $J(t = 5\,s)$. This is expected because the Lorentz force is proportional to the square of the current density. When the current is doubled then the Lorentz force gets four times bigger. The distribution of the Lorentz forces in the y-direction is displayed in Figure 3.7. The absolute values are symmetric to the horizontal axis of the busbars. The forces push the top of the busbars down and the bottom of the busbars up. The forces are also nearly four times higher for the current $J(t = 10\,s)$ compared to the current $J(t = 5\,s)$.

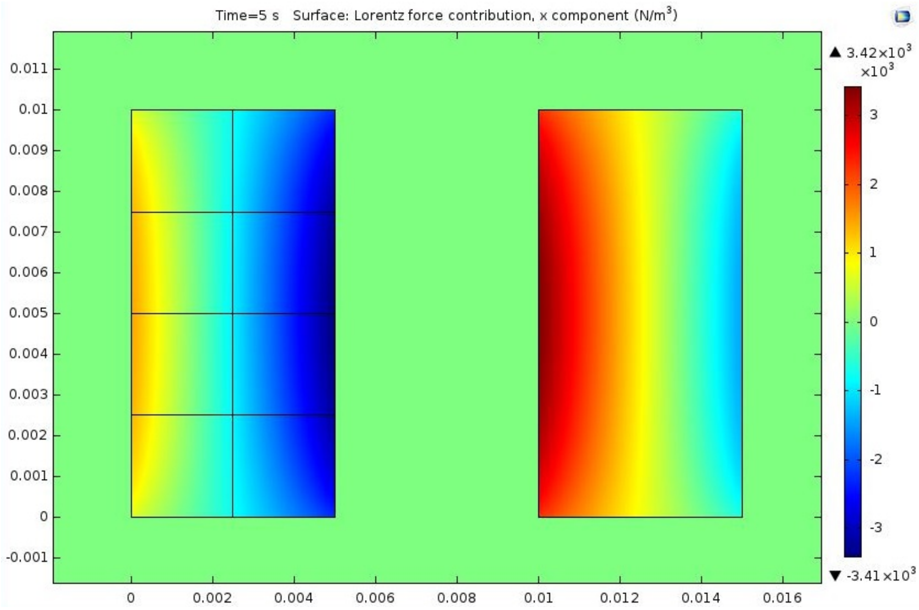


(a)

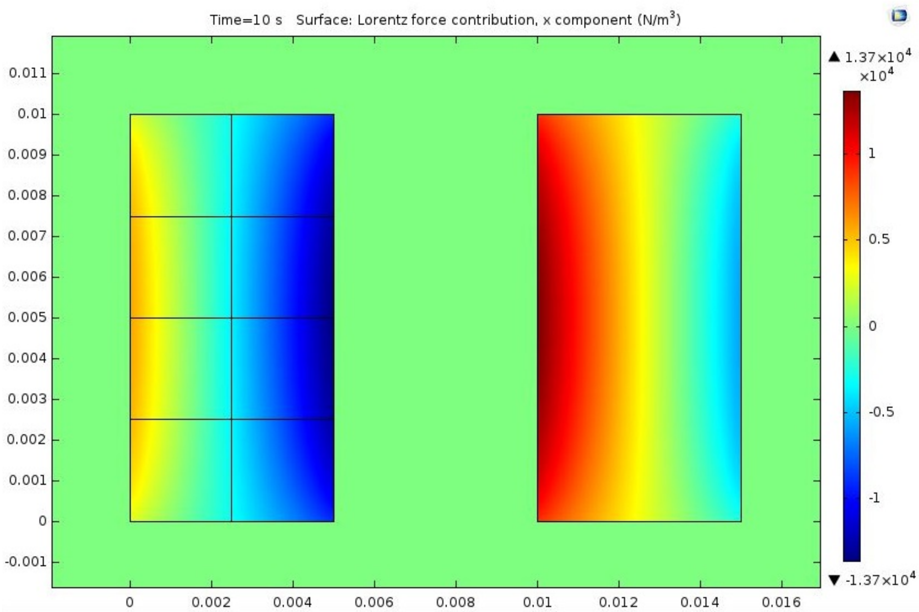


(b)

Figure 3.5: Temperature distribution in the busbars (a) at $t = 5\,s$ and (b) at $t = 10\,s$

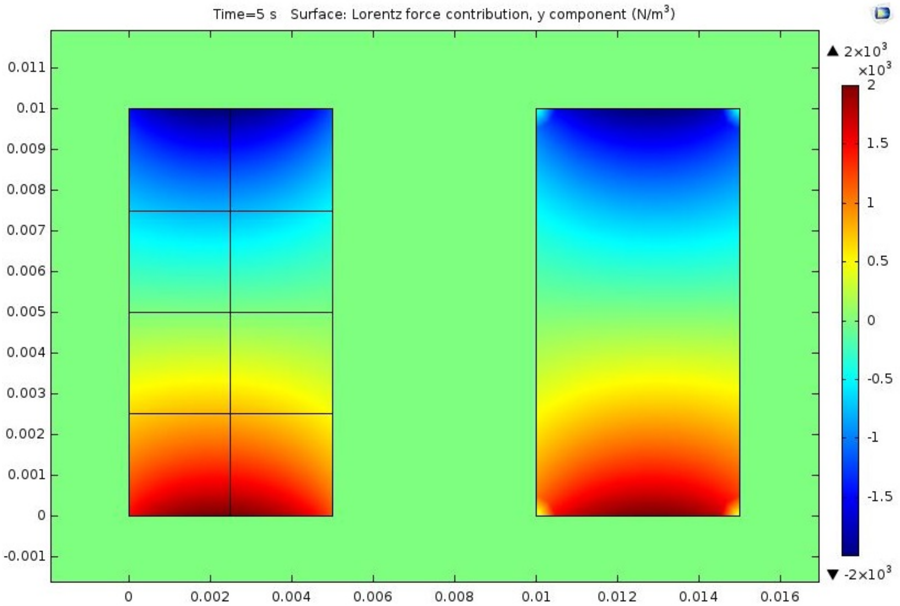


(a) scale of 10^3

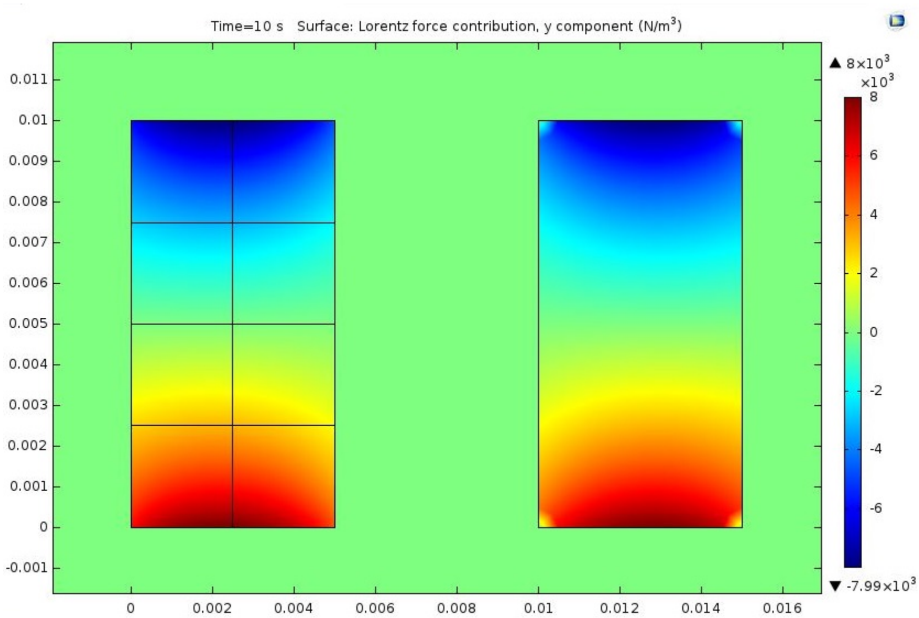


(b) scale of 10^4

Figure 3.6: Lorentz force distribution in the x-direction in the busbars (a) at $t = 5\,s$ and (b) at $t = 10\,s$



(a) scale of 10^3



(b) scale of 10^3

Figure 3.7: Lorentz force distribution in the y-direction in the busbars (a) at $t = 5\,s$ and (b) at $t = 10\,s$

3.4. Analysis of a Monolithic Mechanical Model

To validate the written APDL code, a comparison between the ANSYS results and analytic calculations is done (Appendix A.3, First Solving). A uniform temperature $T_{Test} = 20\,K$ is applied to the busbar. With the reference temperature $T_0 = 10\,K$, the temperature of the busbar is increased by $\triangle T = 10\,K$. The values of the material properties are listed in Table 3.1. The bearing fixes the movement in the x-direction of the left and right boundary, and in the y-direction of the top boundary. This means the edges in the upper left and right corner have zero transversal displacement (Figure 3.2).

The busbar can move freely in the negative y-direction and is blocked in the other directions. Therefore, with rising temperature the size of the busbar grows only in the negative y-direction. This means that the stress in the y-direction is

$$\sigma_y = 0 \quad [N/m^2]. \tag{3.3}$$

The size of the busbar is not changing in the x-direction, because of this the strain in the x-direction is

$$\varepsilon_x = 0 \quad [\%]. \tag{3.4}$$

The relation between stress and strain is given by the following formulas

$$\varepsilon_x = \frac{1}{E}(\sigma_x - \nu\sigma_y) + \alpha_T \triangle T \quad [\%], \tag{3.5}$$

$$\varepsilon_y = \frac{1}{E}(\sigma_y - \nu\sigma_x) + \alpha_T \triangle T \quad [\%], \tag{3.6}$$

whereby the first addend is the elastic strain

$$\varepsilon_{x,el} = \frac{1}{E}(\sigma_x - \nu\sigma_y) \quad [\%], \tag{3.7}$$

$$\varepsilon_{y,el} = \frac{1}{E}(\sigma_y - \nu\sigma_x) \quad [\%], \tag{3.8}$$

and the second is the thermal strain

$$\varepsilon_{th} = \alpha_T \triangle T \quad [\%]. \tag{3.9}$$

Using (3.3) and (3.4), one can obtain (3.5) and (3.6) as

$$0 = \frac{1}{E}\sigma_x + \alpha_T \triangle T \quad [\%], \tag{3.10}$$

$$\varepsilon_y = \frac{1}{E}(-\nu\sigma_x) + \alpha_T \triangle T \quad [\%]. \tag{3.11}$$

Transforming (3.10) results in the stress in the x-direction

$$\sigma_x = -\alpha_T E \triangle T \quad [N/m^2], \tag{3.12}$$

and (3.11) results in the strain in they-direction

$$\varepsilon_y = \underbrace{\alpha_T \nu \triangle T}_{\varepsilon_{y,el}} + \underbrace{\alpha_T \triangle T}_{\varepsilon_{th}} = \alpha_T \triangle T(\nu + 1) \quad [\%]. \tag{3.13}$$

From (3.10) it follows the elastic strain in the x-direction

$$\varepsilon_{x,el} = -\varepsilon_{th} = -\alpha_T \triangle T \quad [\%]. \tag{3.14}$$

Table 3.2 summarises results of the analytic calculations compared to the results of the simulation with ANSYS APDL code. By comparing the rows, it can be seen that all entries are the same except for the stress in the y-direction and the strain in the x-direction. Numerical errors of the finite element method are the reason for this deviation ($\sigma_{y,A} \ll \sigma_{x,A}$, $\varepsilon_{x,A} \ll \varepsilon_{y,A}$).

Table 3.2: Comparison between analytic calculations and results of the ANSYS code

Analytic calculations	**ANSYS**
$\sigma_x = -\alpha_T E \triangle T = 4 \cdot 10^{-3}\,\frac{1}{K} \cdot 110 \cdot 10^9\,Pa \cdot 10\,K = -4.4 \cdot 10^9\,\frac{N}{m^2}$	$\sigma_{x,A} = -4.4 \cdot 10^9\,\frac{N}{m^2}$
$\sigma_y = 0\,\frac{N}{m^2}$	$\lvert\sigma_{y,A}\rvert < 4 \cdot 10^{-3}\,\frac{N}{m^2}$
$\varepsilon_x = 0\,\%$	$\lvert\varepsilon_{x,A}\rvert < 4 \cdot 10^{-14}\,\%$
$\varepsilon_y = \alpha_T \triangle T(\nu + 1) = 4 \cdot 10^{-3}\,\frac{1}{K} \cdot 10\,K\ (0.35 + 1) \cdot 100\,\% = 5.4\,\%$	$\varepsilon_{y,A} = 5.4\,\%$
$\varepsilon_{th} = \alpha_T \triangle T = 4 \cdot 10^{-3}\,\frac{1}{K} \cdot 10\,K \cdot 100\,\% = 4\,\%$	$\varepsilon_{th,A} = 4\,\%$
$\varepsilon_{x,el} = -\varepsilon_{th} = -4\,\%$	$\varepsilon_{x,el,A} = -4\,\%$
$\varepsilon_{y,el} = \alpha_T \nu \triangle T = 4 \cdot 10^{-3}\,\frac{1}{K} \cdot 0.35 \cdot 10\,K \cdot 100\,\% = 1.4\,\%$	$\varepsilon_{y,elA} = 1.4\,\%$

The results of the developed ANSYS APDL code are in good agreement with analytical calculations. With a working monolithic code it is possible to continue the study. The next step is the coupling, which means the exchange of the Lorentz forces and the temperature distribution from COMSOL to ANSYS.

3.5. Coupling method

Figure 3.8 displays the coupling method. The COMSOL model runs first with the current density J and the average Lorentz forces F_L and temperature T over area are extracted from the results. The ANSYS model calculates based on the received values the displacement u, stress σ, and strain ε. The mechanical results are saved after each coupling step. This coupling step is repeated several times till the mechanical results do not make any further changes.

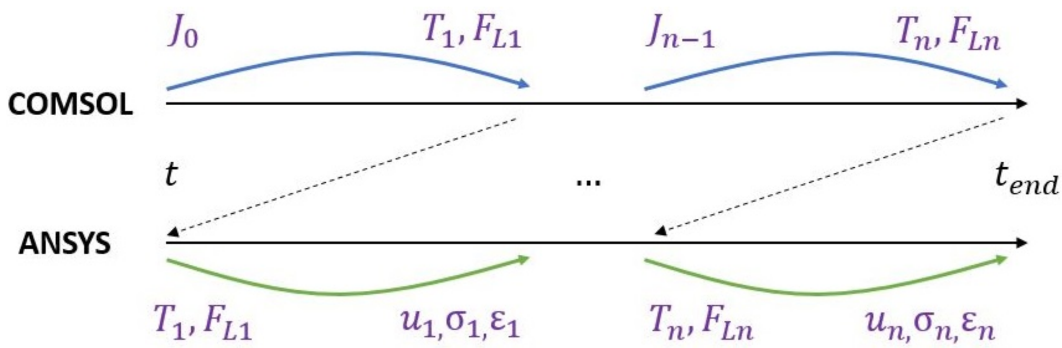


Figure 3.8: Information exchange for applied unidirectional coupling scheme

The easiest approximation for 2D models is area based coupling. This coupling method does not depend on mesh information of both models. Area based coupling means that the results in COMSOL are averaged over selected area. These values are transferred to the corresponding areas in the ANSYS model. In order to observe displacement due to the influence of the exchanged information, the bearings are changed.(Figure 3.9). The busbar is divided in 8 areas of the same size. These areas have the same location in both COMSOL and ANSYS models.

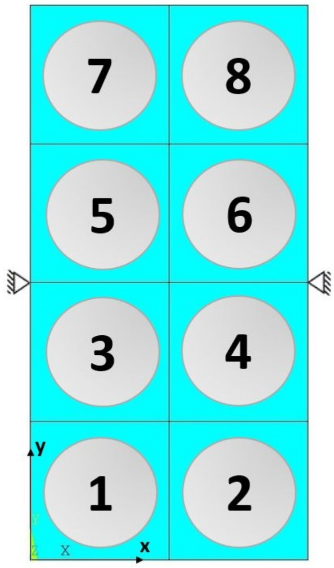


Figure 3.9: Busbar with area numbering and bearings for coupling

With values in the x- and y-direction for the Lorentz force and the temperature, there are three values per area which have to be exchanged. Hence, the busbar has 24 values for the exchange. The COMSOL model is running at $t = 10\,s$, which leads to the applied current $J(10\,s) = 100\,A$. The results of the operation are displayed in Table 3.3. To get the Lorentz force in the unit N/m, it is necessary to multiply the output of COMSOL with the the area $A_{Surf} = 6.25 \cdot 10^{-6}\,m^2$. The COMSOL results are provided to the ANSYS code in an extra file (Appendix A.2).

Table 3.3: Results of the COMSOL busbar model at $J(10\,s) = 100\,A$

	T *in* K	$F_{L,x}$ *in* N/m^3	$F_{L,y}$ *in* N/m^3	$F_{L,x}$ *in* N/m	$F_{L,y}$ *in* N/m
Area 1	10.1	455	5084	$2.8 \cdot 10^{-3}$	$31.8 \cdot 10^{-3}$
Area 2	10.1	-7317	4635	$-45.7 \cdot 10^{-3}$	$29.0 \cdot 10^{-3}$
Area 3	10.1	1024	1461	$6.4 \cdot 10^{-3}$	$9.1 \cdot 10^{-3}$
Area 4	10.1	-8544	1291	$-53.4 \cdot 10^{-3}$	$8.1 \cdot 10^{-3}$
Area 5	10.1	1024	-1461	$6.4 \cdot 10^{-3}$	$-9.1 \cdot 10^{-3}$
Area 6	10.1	-8544	-1291	$-53.4 \cdot 10^{-3}$	$-8.1 \cdot 10^{-3}$
Area 7	10.1	455	-5084	$2.8 \cdot 10^{-3}$	$-31.8 \cdot 10^{-3}$
Area 8	10.1	-7317	-4635	$-45.7 \cdot 10^{-3}$	$-29.0 \cdot 10^{-3}$

The electromagnetic-thermal model provides the average Lorentz force for each area. In the mechanical model, forces are applied per node. It is important that the same total force is transferred from COMSOL to ANSYS. Therefore, the provided force is divided by the number of nodes in the area. In addition, it is necessary that the divided forces are summed up and do not overwrite each other at the borders of the areas. Figure 3.10 displays an example how to apply the Lorentz force to ANSYS. COMSOL provides the average Lorentz force for surface 1 $F_1 = 20\,N$ and for surface 2 $F_2 = 40\,N$. Each surface consists of 4 nodes which lead to the divided forces of $F_{1,div} = 5\,N$ and $F_{2,div} = 10\,N$ per node. To get the total force from COMSOL of $F_{t,C} = 60\,N$, it is necessary to sum up the forces at the nodes, which are at the border of the two surfaces. This means that the force of the two nodes at the border is $F_B = 15\,N$. Then the total force which is applied in ANSYS is also $F_{t,A} = 60\,N = F_{t,C}$.

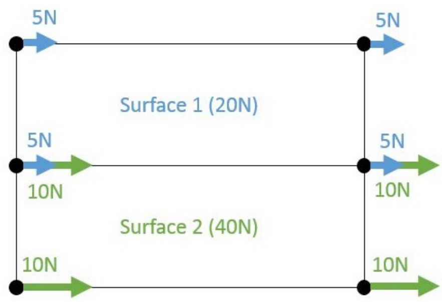


Figure 3.10: Example: How to apply the Lorentz force in ANSYS

The left and the right boundary have in each case one point in the middle fixed against displacement (Figure 3.9). The ANSYS APDL code for the coupling is reported in the Appendix A.3. The selected element type is 'PLANE82' which is employed for 2D analyses of structural solids and has an 8-node geometry (Figure 3.11). In addition, the element has plane stress with a thickness of 1 m. The code creates an output as a '*.txt'-file which contains the node number and coordinates of the node with the maximum equivalent stress, the node with maximum equivalent strain, and the node with the maximum vector sum of the displacement.

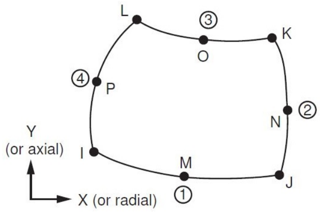


Figure 3.11: PLANE82 geometry: 8-node elements [29]

To validate the ANSYS results, the displacement plots are examined when one time (1) only the Lorentz force is transferred and the other time (2) only the temperature ($\triangle T > 0$) is applied. (1) Figure 3.12 shows the displacement in the x-direction when the Lorentz forces are the only input for the code. It can be seen that the forces act in negative x-direction because of the movement of the busbar in this direction. This is the expected behaviour like it was mentioned before in Chapter 3.3. (2) Since $\triangle T > 0$, the busbar is growing in size. This effect is visible in the Figures 3.13 and 3.14 which show the displacement in the x- and y-direction when only the temperature is exchanged. In addition, the absolute values are axis-symmetric to the horizontal and vertical centre line. This is also expected, because the applied temperature is uniform.

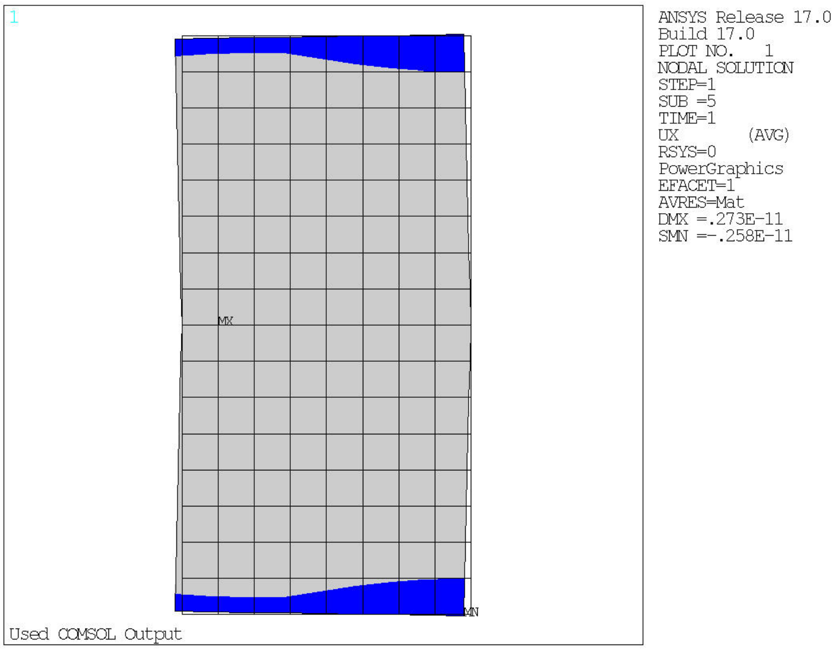


Figure 3.12: Displacement in the x-direction (only Lorentz forces applied) of the busbar [displacement scale factor of $5 \cdot 10^7$]

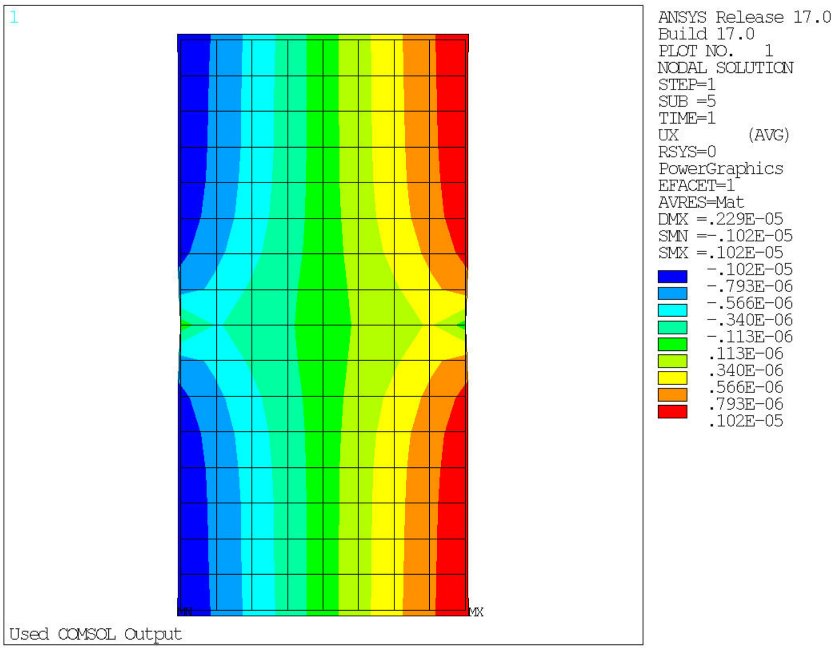


Figure 3.13: Displacement in the x-direction (only temperature applied) of the busbar [displacement scale factor of 50]

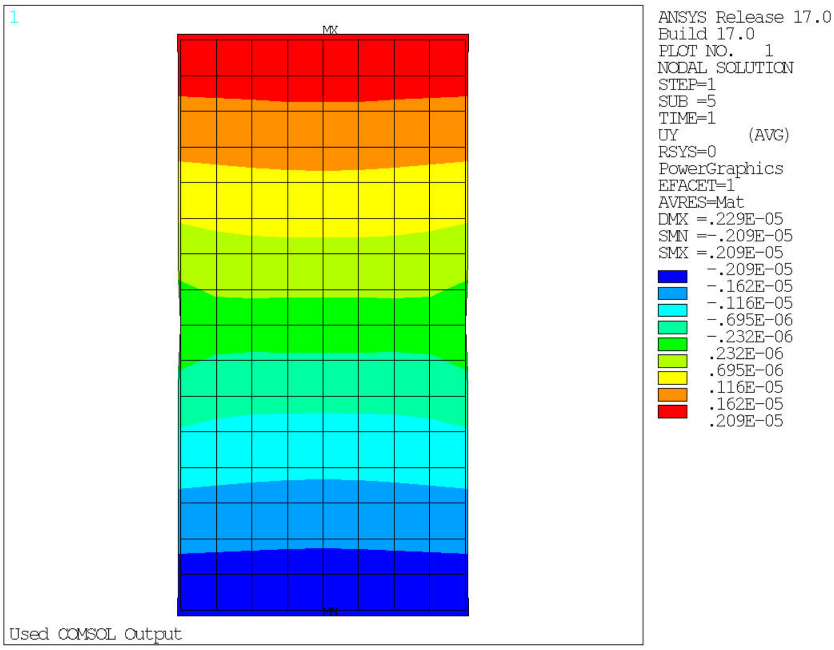


Figure 3.14: Displacement in the y-direction (only temperature applied) of the busbar [displacement scale factor of 50]

3.6. Conclusion

The area coupling is accomplished and the results are as expected. For a quench analysis, it is important to detect if the stress and strain are above the critical values. With the method of area coupling only average values are exchanged. This causes a loss of information of the highest temperatures and Lorentz forces. These values could lead to results above the critical stress and strain. Therefore, mesh-based coupling is indispensable. However, a specific tool is needed to achieve this coupling method due to the different mesh of the models.

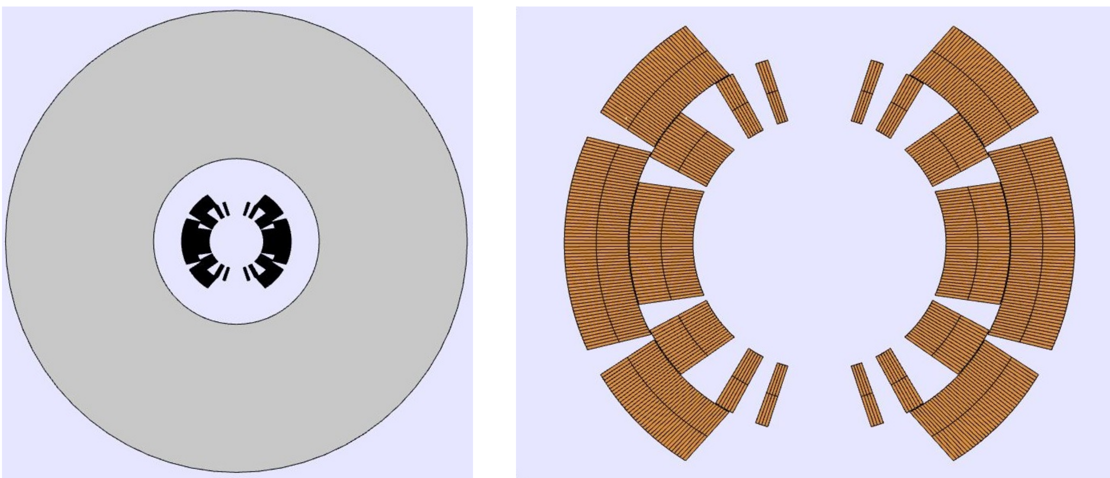
4. Coupling of an 11T Dipole Magnet

The acquired knowledge from the busbar is now used to couple two models of a superconducting magnet. The model is an 11 T dipole magnet which is a part of the HL-LHC project[1]. This magnet has peak magnetic field of 11 T, stronger than the main dipoles in the LHC with 8.33 T. The superconducting material in the 11 T dipole is Nb_3Sn, which is brittle. Therefore, mechanical analyses are essential for supporting the design of a magnet and its protection methods to minimise the likelihood of damage during operation.

4.1. Introduction

The electromagnetic-thermal model of an 11T single-aperture dipole magnet is displayed in Figure 4.1. The coordinate system is located in the middle of the magnet. The model is symmetric to the x-axis (horizontal) and the y-axis (vertical). It also has a simplified collar, yoke and shell but the position and turn numbers of the coil are equal to ones present in the real magnet. In the electromagnetic-thermal analysis model no movement occurs. This is why it was possible to choose the material type

[1] more detailed information in [6]

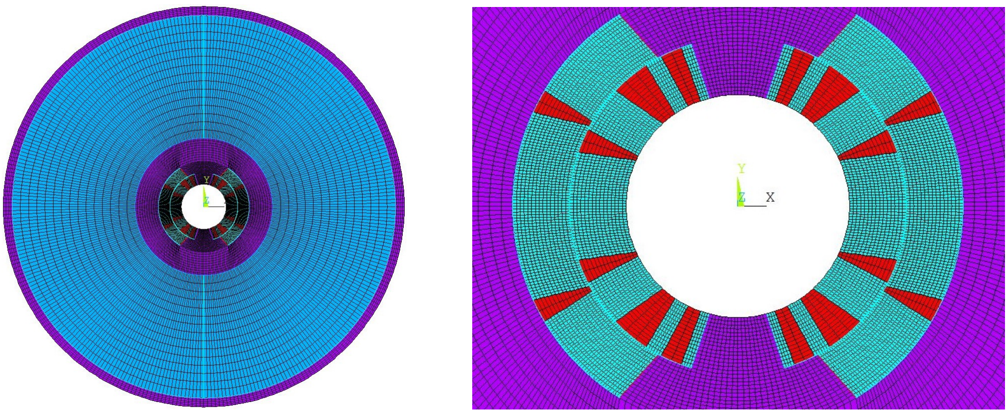


(a) Full model (b) Coil

Figure 4.1: Geometry of the 11 T Dipole Magnet in COMSOL

air for the collars which has nearly the same electromagnetic and thermal material properties as stainless steel. The material type of the yoke is iron, and for this analysis it is not necessary to implement a shell. It is important that the blocks are not in contact with each other because of the current flow. The used material for the coil is Nb_3Sn, of which the material properties are influenced by the production process. Each quadrant of the magnet coil has six blocks with a total number of 56 turns. The coil accordingly has a total number of 224 turns.

The mechanical model with an equivalent geometry is shown in Figure 4.2. The coordinate system has the same location and orientation as in the COMSOL model. The collar, yoke, and shell are also simplified. The collar surrounds the coil and the material is stainless steel. The iron yoke has two gaps between the left and the right side of the magnet, which is closed after the welding of the shell. It remains closed during operation. The shell completely surrounds the yoke and has in the model the same material as the collars. To generate pre-stress, shims are implemented at the inner and outer poles of the coil. Another shim is used between the collar and yoke. The coil is made out of Nb_3Sn and has the same number and location of turns per blocks compared to the COMSOL model. The wedges are made of copper. For the mechanical analysis, insulation is not necessary. Therefore, the inner and outer layer of the coil are in direct contact.



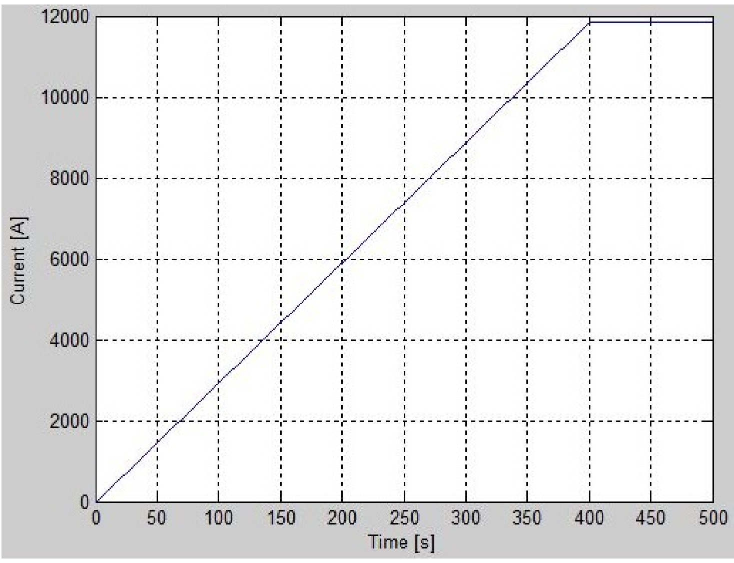
(a) Full model (b) Coil

Figure 4.2: Geometry of 11 T Dipole Magnet in ANSYS

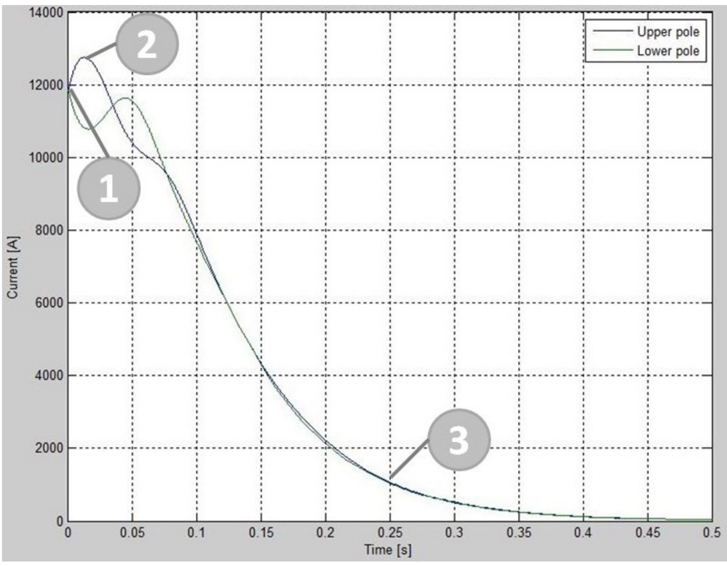
The superconducting material Nb_3Sn is still new in the field of magnets for large scale apertures. As had been previously mentioned in Chapter 2.3.1, there are still two different production processes of Nb_3Sn strands. In addition, its material properties are still under study for the new developed magnets, such as the 11 T dipole magnet.

4.2. Electromagnetic-Thermal Model

The electromagnetic-thermal model of the 11 T magnet uses the same physics modules (magnetic fields and heat transfer in solids) as the busbar model in COMSOL. The reference temperature is $T_0 = 1.9\,K$ and the material properties of the model are non-linear functions depending on the temperature, the magnetic field, the current density, and/or the residual resistance ratio (RRR) of copper. The RRR of a material defines the ratio of the resistivity just above its critical temperature T_C and room temperature [13]. The current is applied as it is displayed in Figure 4.3 and is divided



(a) Ramp-up and plateau



(b) CLIQ discharge

Figure 4.3: External current density applied on the 11 T COMSOL model

into three steps. The first step is the current ramp-up, which is a linear function from 0 kA to 11.85 kA. The next step is called plateau, where the current is at a constant value. At this point the magnet works with a nominal field. The current flows on the left side of the coil in the negative z-direction (in the plane), and on the right side in the positive z-direction (out of the plane). The Lorentz forces act azimuthally and radially, meaning that the coil is pressed towards the mid-plane, and pushed to the left and right side.

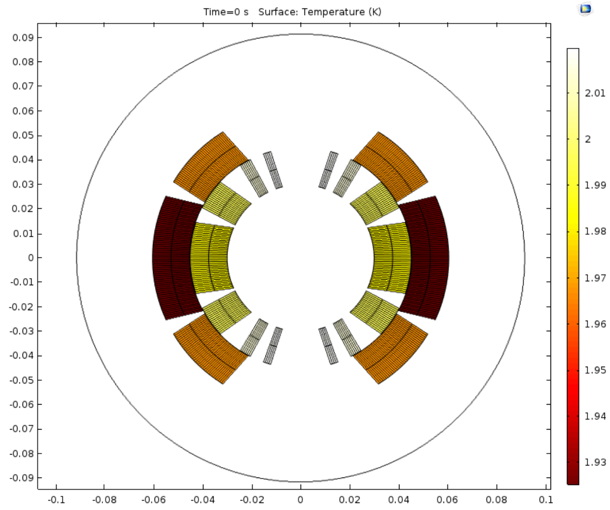
When the magnet is quenching, the quench protection systems are fired and the current discharges. In this simulation, the protection system 'Coupling Loss-Induced Quench' (CLIQ) is applied and its discharge is displayed in Figure 4.3 (b). The current density in the upper and lower pole oscillate to generate heat faster[2]. The coupling is done at three points of the CLIQ discharge. The first point is at the end of the plateau, when the current is still at 11.85 kA. The next one is at $t = 0.013\,s$ which is the peak of the first oscillation, when the current in the upper pole is higher than the value of the plateau. The third point is at $t = 0.25\,s$, when a lot of heat was generated by the quench protection system. For each turn, it is possible to extract the average values of the temperature and the Lorentz force. The area coupling is done with each turn of the magnet model. With the exchange of three values per turn, 672 values need to be extracted and transferred.

The temperature distribution of the COMSOL model is displayed in Figure 4.4. At Point 1, the highest temperature is around 2.02 K which is located at the inner layer of the poles. At Point 2, the highest value is around 27.5 K at the inner layer of the mid-planes. At Point 3, the peak value is around 82.5 K at the inner layer of the mid-planes and the pole (bottom). After CLIQ is triggered (Point 1), the temperature rises steadily.

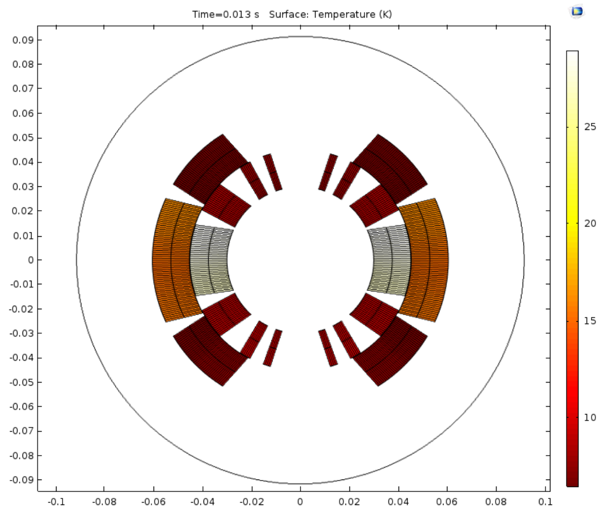
Figure 4.5 shows the Lorentz forces in the x-direction. The highest value is around $6.5 \cdot 10^9\, N/m^3$ at Point 1 and around $7 \cdot 10^9\, N/m^3$ at Point 2. At Point 3, the highest value is around $8 \cdot 10^7\, N/m^3$ which is 100 times smaller compared to the other points and the current is nearly 12 times smaller. The forces push the coil to the left and right side as expected.

The Lorentz forces in the y-direction are displayed in Figure 4.6. At Point 1, the highest force in the y-direction is around $3.5 \cdot 10^9\, N/m^3$ which is nearly half of the highest value of the x-direction. While the forces in the x-direction rise from Point 1 to Point 2, the Lorentz forces in the y-direction decrease to around $3 \cdot 10^9\, N/m^3$. At Point 3, the highest value is around $4 \cdot 10^7\, N/m^3$ which is also nearly 100 times smaller compared to Points 1 and 2. In addition, the plots visualise that the coil is pressed to the mid-plane. The average temperature and Lorentz force in the x- and y-direction for each turn of the three points are provided to the ANSYS code in an extra file (Appendix A.4).

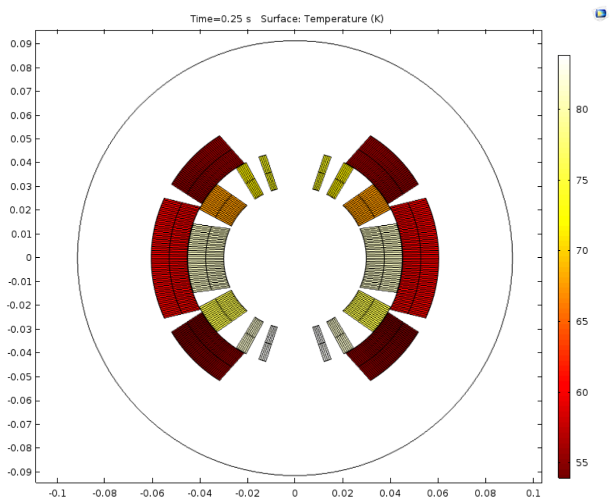
[2] more detailed information in [27]



(a) Point 1 (scale from 1.93 K to 2.02 K)

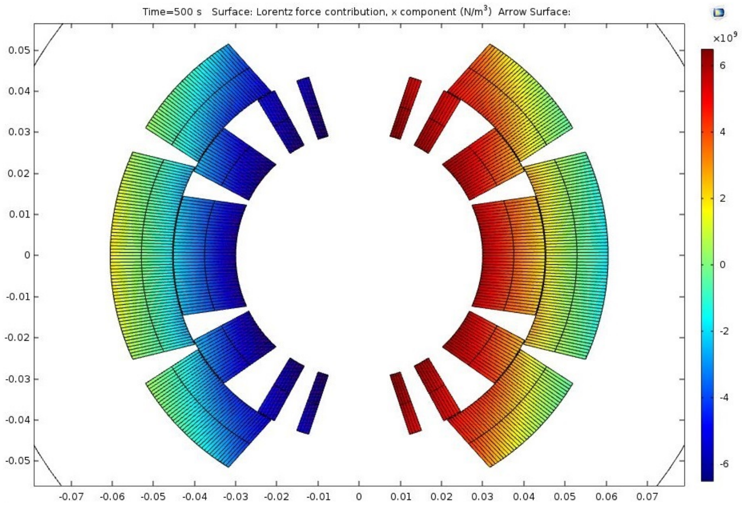


(b) Point 2 (scale from 7.5 K to 27.5 K)

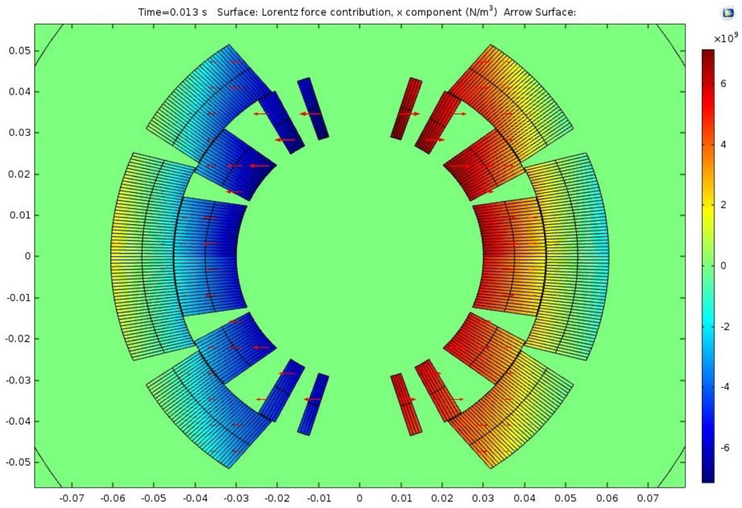


(c) Point 3 (scale from 55 K to 82.5 K)

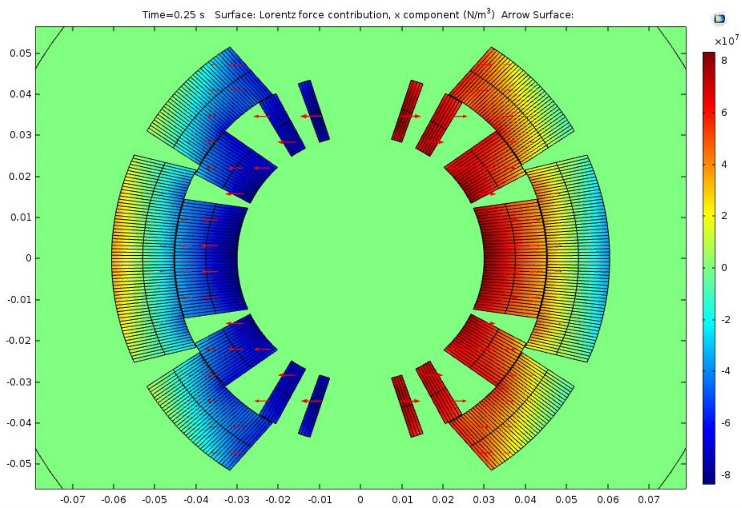
Figure 4.4: Temperature distribution of the 11 T COMSOL model



(a) Point 1 (scale of 10^9)

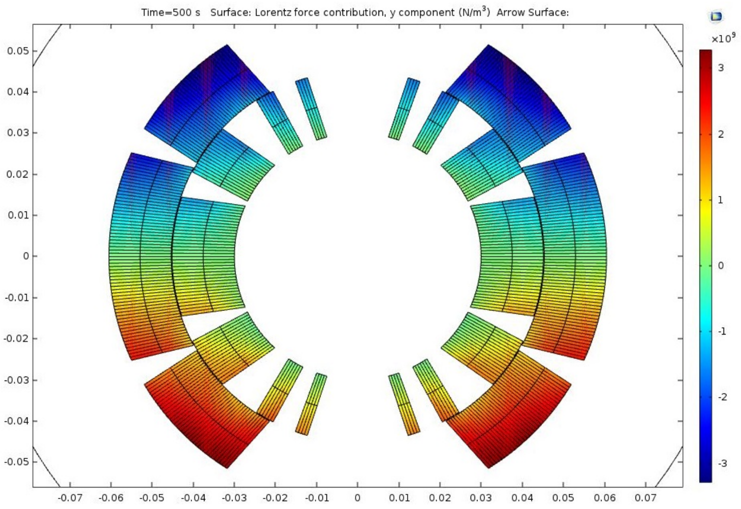


(b) Point 2 (scale of 10^9)

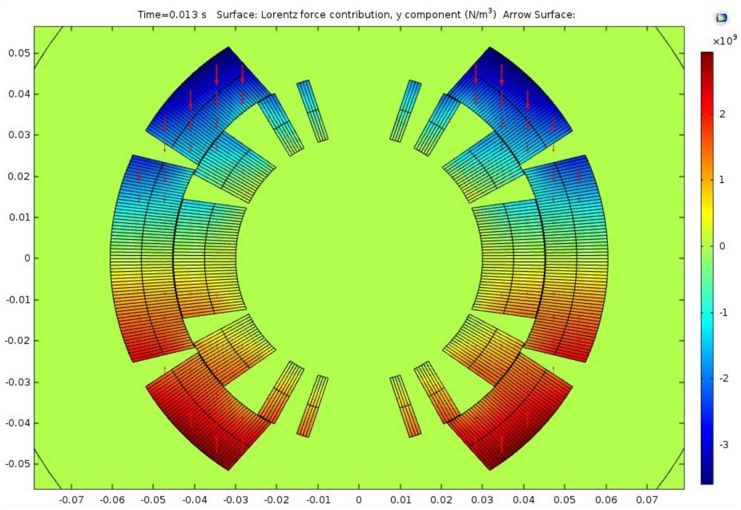


(c) Point 3 (scale of 10^7)

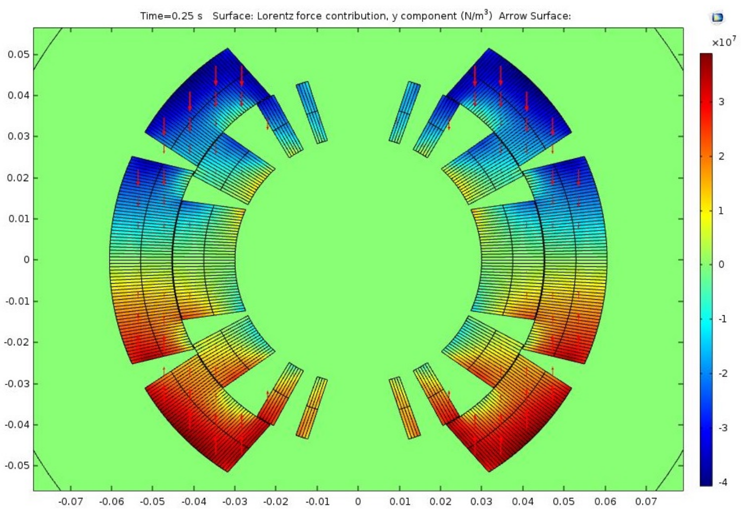
Figure 4.5: Lorentz force in the x-direction of the 11 T COMSOL model



(a) Point 1 (scale of 10^9)



(b) Point 2 (scale of 10^9)



(c) Point 3 (scale of 10^7)

Figure 4.6: Lorentz force in the y-direction of the 11 T COMSOL model

4.3. Mechanical Model

The mechanical model of the 11 T dipole magnet has the element type 'PLANE183', which is used for 2D analyses of structural solids, and has an 8-node geometry. It is a current-technology element which is a newer version of the element type of the busbar.

The reference temperature of the ANSYS model is $T_0 = 1.9\,K$. For each material the Young's modulus, the Poisson's ratio, and the coefficient of thermal expansion is provided. The Young's modulus is a linear function depending on the temperature while the two others are constant. For generating pre-stress, shims are implemented in the model. The shims at the inner and outer layer of the poles have a thickness of 0.15 mm and the shim between the collars and the yoke is 0.05 mm. The gap between the yoke is 0.04 mm at the collars and 0.1 mm wide at the shell. The mid-plane of the magnet is fixed against transversal displacement and the vertical axis, which is located between the poles, cannot move in the x-direction. In addition, sliding is added between inner and outer layer of the coil, coil and collars, collars and yoke, and yoke and shell.

The ANSYS APDL code for the 11 T dipole magnet is reported in the Appendix A.5. The simulation has two solving steps. The first step is only analysing the effect of the pre-stress. Neither extra force nor temperature is applied. The second solving step is using the provided COMSOL results as an input for the analysis. For the first load step the code generates a plot of the coil for the equivalent stress. For the second load step, plots of the vector sum of the displacement, and the equivalent stress and strain of the coil are generated. In addition, a '*.txt'-file with the maximum values of the plots and their node numbers and coordinates is as a result of the analysis performed and saved.

4.4. Area Coupling

With monolithically working codes in COMSOL and ANSYS the area coupling can be performed. The average values of the temperature and the Lorentz force in the x- and y-direction are exchanged per turn. With three values per turn and a total number of 224 turns, 672 vales need to be exchanged. To achieve organised variable names, the numbering has the following structure

- quadrant number,
- block number,
- turn number of the block.

The numbering of the quadrants is derived from the quadrant numbers in a Cartesian coordinate system. The block numbers start at the inner layer from the mid-plane to the pole, then at the outer layer again from the mid-plane to the pole. The numbering of the turns starts new in each block, beginning from the mid-plane to the pole.

For example, the third turn in the first quadrant of the fifth bock has the component name 'turn153' and the COMSOL values are 'temp153' (temperature), 'forcx153' (Lorentz force in the x-direction) and 'forcy153' (Lorentz force in the y-direction).

The coupling method for the 11 T dipole magnet between COMSOL and ANSYS is identical to the busbar method. However, the difference is information exchange which is limited to the coil domain. In the coupling, the collars, yoke and shell do not take part. The coupling is done at three points of the CLIQ discharge (Figure 4.3). The results of the ANSYS code are shown in Table 4.1.

Table 4.1: Results of the 11 T dipole magnet in ANSYS

	Point 1	**Point 2**	**Point 3**	**Critical**
σ_{max}	311 MPa	316 MPa	324 MPa	150-200 MPa
ε_{max}	0.78 %	0.79 %	0.81 %	1.5 %

On one hand, the average Lorentz force in the y-direction per turn is decreasing and on the other hand the average temperature is rising per turn at the three points. The Lorentz force in the x-direction is slightly rising from Point 1 to Point 2 and strongly decreasing from Point 2 to Point 3. By comparing the maximum stress σ_{max} at the three points the value is rising which means the influence of the temperature is greater than the Lorentz force. In addition, the maximum strain ε_{max} is also increasing due to the relation of stress and strain. The maximum stress is above the critical stress which can lead to damage of the conductor. However, the maximum strain is about half of the critical strain.

4.5. Conclusion

The area coupling with an 11 T dipole magnet was accomplished. The values for stress and strain are in the expected scale. Although the maximum stress is above the critical value it is no severe issue. One reason is that a lot of simplifications are done with the geometry of the 11 T model. In addition, the material properties of the mechanical model are linear functions which are close to real values but have to be proved for correctness. The critical stress is an indicator for the appearance of damage when the stress is above this specific value in the conductor. The value of 150-200 MPa is not especially determined for an 11 T dipole magnet but a general value for the material Nb_3Sn. The critical strain is the value for the transition from elastic to plastic material behaviour. The value of 1.5 % is virtually simulated for Nb_3Sn at 4.2K and zero-field. Both critical values are generalised for the material Nb_3Sn and not precisely generated for the analysis of an 11 T dipole magnet. Hence, the maximum and the critical values should only be compared by considering the order of magnitude.

5. Conclusion and Outlook

The coupling of the two FEA programmes, COMSOL (electromagnetic-thermal) and ANSYS (mechanical), was performed. The thesis describes the implementation of the selected coupling scheme along with an analysis of the obtained results.

At first, the method of area coupling was applied to a busbar model to achieve a coupling proof of concept. In the next step, the concept of area coupling was transferred to a realistic model of an 11 T dipole magnet. The results of this coupling are in realistic scale for magnets which is proved by comparing the maximum stress and strain with their critical values.

A disadvantage of area coupling is the exchange of average values. Due to this circumstance, information loss can be caused by neglecting the maximum values. Especially for mechanical analyses the maximum stress and strain are important. When the average values are exchanged, the results of the mechanical analysis tend to have lower maximum stress and strain compared to a mesh-based coupling. Therefore, mesh-based coupling is proposed to be the next coupling method.

Due to the difference of the mesh of both models a special tool is required to fulfil mesh-based coupling. The tool MpCCI allows this coupling method for ANSYS APDL and MATLAB. With an additional MATLAB code it is possible to run the COMSOL programme. To prove if the results of the MpCCI algorithm are correct, two simulation methods with the busbar model are performed. In method (1), MpCCI is transferring a constant value which is acting on all nodes in COMSOL to all nodes of the ANSYS mesh. In method (2), the same constant value is applied direct to all nodes of the monolithic ANSYS model. For the evaluation, the displacement of all nodes in ANSYS is compared for method (1) and (2). In the first test a uniform temperature is used, the second test is performed with a uniform force in the x-direction and the last test is simulated with a uniform force in the y-direction. The displacement of both methods shows identical results for all tests. Hence, mesh-based coupling with MpCCI is promising to achieve reliable results for magnet simulations such as the 11 T dipole magnet model.

A. Appendix

A.1. ANSYS APDL Script: Proof of Concept Validation

```
FINISH
/CLEAR

!--------------------General Stuff & Parameters--------------------!
/FILNAME,Busbar_Test
/UNITS,SI
/CONFIG,RESUPREC,0
/PREP7
/NERR,5

TREF,10
DOF,TEMP
*SET,elperli,4     !Changing mesh

!------------------------Material Properties----------------------!
ET,1,PLANE82     !Legacy Element:  2-D 8-Node Structural Solid
KEYOPT,1,3,3
R,1,1

MPTEMP,1,1.8,293
MPDATA,EX,1,1,110.E+09,110.E+09
MPDATA,PRXY,1,1,0.35,0.35
MP,ALPX,1,4e-3

!----------------------------Geometry----------------------------!
NUMSTR,KP,1
NUMSTR,LINE,1
NUMSTR,AREA,1

!--------------------Keypoints----------------------!
*SET,yloc,0
*SET,kpnr,1
*DO,i,1,5
  *SET,xloc,0
  *DO,j,1,3
    K,kpnr,xloc,yloc
    *SET,xloc,xloc+0.0025
      *SET,kpnr,kpnr+1
  *ENDDO
  *SET,yloc,yloc+0.0025
*ENDDO

!----------------------Lines------------------------!
!Horizontal!
*SET,kpnr,1
*DO,i,1,5
  *DO,j,1,2
    L,kpnr,kpnr+1,elperli
    *SET,kpnr,kpnr+1
  *ENDDO
  *SET,kpnr,kpnr+1
```

```
*ENDDO

!Vertical!
*SET,kpnr,1
*DO,i,1,12
  L,kpnr,kpnr+3,elperli
  *SET,kpnr,kpnr+1
*ENDDO

!---------------------Areas------------------------!
*SET,kpnr,1
*DO,i,1,4
  *DO,j,1,2
    A,kpnr,kpnr+1,kpnr+4,kpnr+3
    *SET,kpnr,kpnr+1
  *ENDDO
  *SET,kpnr,kpnr+1
*ENDDO

!----------------------Mesh------------------------!
*SET,kpnr,1
*SET,anr,1
TYPE,1
REAL,1
MAT,1
*DO,i,1,4
  *DO,j,1,2
    ASEL,S,,,anr
    AATT,1,1,1
    AMAP,anr,kpnr,kpnr+1,kpnr+4,kpnr+3
    *SET,kpnr,kpnr+1
    *SET,anr,anr+1
  *ENDDO
  ALLSEL
  *SET,kpnr,kpnr+1
*ENDDO

!-------------------Constraints--------------------!
ALLSEL
NSEL,S,LOC,X,0
D,ALL,UX,0

ALLSEL
NSEL,S,LOC,X,0.005
D,ALL,UX,0

ALLSEL
NSEL,S,LOC,Y,0.01
D,ALL,UY,0

FINISH

!----------------------------Solver----------------------------!
/SOLU

ALLSEL
/TITLE,Test due to reliable results
TUNIF,20
LSWRITE
SOLVE

OUTRES,ALL,ALL
NSUBST,5
SOLVE

FINISH
```

```
!--------------------------Postprocessor-------------------------!
/POST1

/AUTO,1
/DSCALE,1,OFF
/PLOPTS,INFO,1
/PLOPTS,LEG1,1
/PLOPTS,LEG2,0
/PLOPTS,LEG3,1
/PLOPTS,FRAME,1
/PLOPTS,TITLE,1
/PLOPTS,MINM,1
/PLOPTS,FILE,0
/PLOPTS,WINS,1
/PLOPTS,WP,0
/PLOPTS,DATE,0
/TRIAD,OFF

/DSCALE,ALL,2

/RGB,INDEX,100,100,100, 0
/RGB,INDEX, 80, 80, 80,13
/RGB,INDEX, 60, 60, 60,14
/RGB,INDEX,  0,  0,  0,15

!-----------------------Plots----------------------!
PLNSOL,S,X,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar_Test000,JPG,,Test_stress_x,JPG,

PLNSOL,S,Y,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar_Test000,JPG,,Test_stress_y,JPG,

PLNSOL,EPEL,X,1
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/REPLOT
/SHOW,CLOSE
/RENAME,Busbar_Test000,JPG,,Test_el_strain_x,JPG,

PLNSOL,EPEL,Y,1
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/REPLOT
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PLNSOL,EPTH,X,1
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/REPLOT
/SHOW,CLOSE
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PLNSOL,EPTH,Y,1
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/REPLOT
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PLNSOL,EPTT,X,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar_Test000,JPG,,Test_tt_strain_x,JPG,
```

```
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/REPLOT
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PLNSOL,U,X,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar_Test000,JPG,,Test_displacement_x,JPG,

PLNSOL,U,Y,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar_Test000,JPG,,Test_displacement_y,JPG,
```

A.2. ANSYS APDL Script: Input File made of COMSOL Output for 2D Coupling of a Busbar

```
!---------------------------Input Values--------------------------!
!...1 = Lower part:  Left_Bottom
!...2 = Lower part:  Right_Bottom
!...3 = Lower part:  Left_Top
!...4 = Lower part:  Right_Top
!...5 = Upper part:  Left_Bottom
!...6 = Upper part:  Right_Bottom
!...7 = Upper part:  Left_Top
!...8 = Upper part:  Right_Top

!Temperature!
*SET,temp1,10.1
*SET,temp2,10.1
*SET,temp3,10.1
*SET,temp4,10.1
*SET,temp5,10.1
*SET,temp6,10.1
*SET,temp7,10.1
*SET,temp8,10.1

!Lorentz forces x-direction!
*SET,forcx1,2.84E-03
*SET,forcx2,-4.57E-02
*SET,forcx3,6.40E-03
*SET,forcx4,-5.34E-02
*SET,forcx5,6.40E-03
*SET,forcx6,-5.34E-02
*SET,forcx7,2.84E-03
*SET,forcx8,-4.57E-02

!Lorentz forces y-direction!
*SET,forcy1,3.18E-02
*SET,forcy2,2.90E-02
*SET,forcy3,9.13E-03
*SET,forcy4,8.07E-03
*SET,forcy5,-9.13E-03
*SET,forcy6,-8.07E-03
*SET,forcy7,-3.18E-02
*SET,forcy8,-2.90E-02
```

A.3. ANSYS APDL Script: 2D Coupling of a Busbar

```
FINISH
/CLEAR

!---------------------------Input File----------------------------!
*USE,COMSOL_Input.txt

!-------------------General Stuff & Parameters-------------------!
/FILNAME,Busbar
/UNITS,SI
/CONFIG,RESUPREC,0
/PREP7
/NERR,5

TREF,10
DOF,TEMP
*SET,elperli,4     !Changing mesh

!-----------------------Material Properties----------------------!
ET,1,PLANE82     !Legacy Element
KEYOPT,1,3,3
R,1,1

MPTEMP,1,1.8,293
MPDATA,EX,1,1,110.E+09,110.E+09
MPDATA,PRXY,1,1,0.35,0.35
MP,ALPX,1,4e-3

!----------------------------Geometry----------------------------!
NUMSTR,KP,1
NUMSTR,LINE,1
NUMSTR,AREA,1

!-------------------Keypoints----------------------!
*SET,yloc,0
*SET,kpnr,1
*DO,i,1,5
  *SET,xloc,0
  *DO,j,1,3
    K,kpnr,xloc,yloc
    *SET,xloc,xloc+0.0025
      *SET,kpnr,kpnr+1
  *ENDDO
  *SET,yloc,yloc+0.0025
*ENDDO

!---------------------Lines------------------------!
!Horizontal!
*SET,kpnr,1
*DO,i,1,5
  *DO,j,1,2
    L,kpnr,kpnr+1,elperli
    *SET,kpnr,kpnr+1
  *ENDDO
  *SET,kpnr,kpnr+1
*ENDDO

!Vertical!
*SET,kpnr,1
*DO,i,1,12
  L,kpnr,kpnr+3,elperli
  *SET,kpnr,kpnr+1
*ENDDO
```

```
!---------------------Areas------------------------!
*SET,kpnr,1
*DO,i,1,4
  *DO,j,1,2
    A,kpnr,kpnr+1,kpnr+4,kpnr+3
    *SET,kpnr,kpnr+1
  *ENDDO
  *SET,kpnr,kpnr+1
*ENDDO

!----------------------Mesh------------------------!
*SET,kpnr,1
*SET,anr,1
TYPE,1
REAL,1
MAT,1
*DO,i,1,4
  *DO,j,1,2
    ASEL,S,,,anr
    AATT,1,1,1
    AMAP,anr,kpnr,kpnr+1,kpnr+4,kpnr+3
    *SET,kpnr,kpnr+1
    *SET,anr,anr+1
  *ENDDO
  ALLSEL
  *SET,kpnr,kpnr+1
*ENDDO

!---------------------Component--------------------!
*SET,anr,1
*DO,i,1,8
  ASEL,S,,,anr
  *SET,name,STRCAT('area',CHRVAL(anr))
  CM,name,AREA
  ALLSEL
  *SET,anr,anr+1
*ENDDO

!-------------------Constraints--------------------!
ALLSEL
NSEL,S,LOC,X,0
NSEL,R,LOC,Y,0.005
D,ALL,UX,0
D,ALL,UY,0

ALLSEL
NSEL,S,LOC,X,0.005
NSEL,R,LOC,Y,0.005
D,ALL,UX,0
D,ALL,UY,0

FINISH

!----------------------------Solver----------------------------!
/SOLU
ALLSEL
/TITLE,Used COMSOL Output

!-------Input:-------!
*DO,t,1,8
  CMSEL,S,area%t%
  NSLA,S,1
  *GET,num,NODE,0,COUNT
  BF,ALL,TEMP,temp%t%
  FCUM,ADD
  F,ALL,FX,forcx%t%/num
  F,ALL,FY,forcy%t%/num
```

```
*ENDDO

LSWRITE
OUTRES,ALL,ALL
NSUBST,5
SOLVE

FINISH

!--------------------------Postprocessor-------------------------!
/POST1

/AUTO,1
/DSCALE,1,OFF
/PLOPTS,INFO,1
/PLOPTS,LEG1,1
/PLOPTS,LEG2,0
/PLOPTS,LEG3,1
/PLOPTS,FRAME,1
/PLOPTS,TITLE,1
/PLOPTS,MINM,1
/PLOPTS,FILE,0
/PLOPTS,WINS,1
/PLOPTS,WP,0
/PLOPTS,DATE,0
/TRIAD,OFF

/RGB,INDEX,100,100,100, 0
/RGB,INDEX, 80, 80, 80,13
/RGB,INDEX, 60, 60, 60,14
/RGB,INDEX,  0,  0,  0,15

/DSCALE,ALL,5      !50

!--------------------Output File-------------------!
*CFOPEN,Output,txt

CSYS,1
ALLSEL
ESLA
NSLE,S,CORNER
NSORT,S,EQV,1
*GET,S_Max,SORT,,MAX
*GET,N_S_Max,SORT,,IMAX *GET,LX_S_Max,NODE,N_S_Max,LOC,X
*GET,LY_S_Max,NODE,N_S_Max,LOC,Y

*VWRITE,
('Node ',' ','x coord',' ','y coord',' ','Max ','Stress ','EQV')
*VWRITE,N_S_Max,LX_S_Max,LY_S_Max,S_Max
(F7.0,' ',2(F9.4),' ',F20.3,' ')


ALLSEL
ESLA
NSLE,S,CORNER
NSORT,EPTT,EQV,1
*GET,E_Max,SORT,,MAX
*GET,N_E_Max,SORT,,IMAX
*GET,LX_E_Max,NODE,N_E_Max,LOC,X
*GET,LY_E_Max,NODE,N_E_Max,LOC,Y

*VWRITE, ('Node ',' ','x coord',' ','y coord',' ','Max ','Strain ','EQV')
*VWRITE,N_E_Max,LX_E_Max,LY_E_Max,E_Max
(F7.0,' ',2(F9.4),' ',F15.7,' ')


ALLSEL
```

```
ESLA
NSLE,S,CORNER
NSORT,U,SUM,1
*GET,U_Max,SORT,,MAX
*GET,N_U_Max,SORT,,IMAX
*GET,LX_U_Max,NODE,N_U_Max,LOC,X
*GET,LY_U_Max,NODE,N_U_Max,LOC,Y

*VWRITE,
('Node ',' ','x coord',' ','y coord',' ','Max ','Disp ','SUM')
*VWRITE,N_U_Max,LX_U_Max,LY_U_Max,U_Max
(F7.0,' ',2(F9.4),' ',F8.2,' ')

*CFCLOS

!-----------------------Plots----------------------!
PLNSOL,S,X,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar000,JPG,,Busbar_stress_x,JPG,

PLNSOL,S,Y,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar000,JPG,,Busbar_stress_y,JPG,

PLNSOL,EPTT,X,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar000,JPG,,Busbar_tt_strain_x,JPG,

PLNSOL,EPTT,Y,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar000,JPG,,Busbar_tt_strain_y,JPG,

PLNSOL,U,X,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar000,JPG,,Busbar_displacement_x,JPG,

PLNSOL,U,Y,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,Busbar000,JPG,,Busbar_displacement_y,JPG,
```

A.4. ANSYS APDL Script: Input File made of COMSOL Output for 2D Coupling of an 11 T diplole model

```
!--------------------------Input Values--------------------------!
!xxxx%q%%b%%t%
!%q% = Quadrant number
!%b% = Block number
!%t% = Turn number inside the block
!nblock1,9
!nblock2,8
```

```
!nblock3,3
!nblock4,2
!nblock5,16
!nblock6,18
!First value = Point 1
!Second value = Point 2
!Third value = Point 3

!--------------------Temperature--------------------!
!Quadrant 1!
*SET,temp111,1.9        !26.0385; 78.0565
*SET,temp112,1.9        !26.2435; 78.0565
*SET,temp113,1.9        !26.4015; 78.0575
*SET,temp114,1.9        !26.5235; 78.0615
*SET,temp115,1.9        !26.6185; 78.0655
*SET,temp116,1.9        !26.6915; 78.0715
*SET,temp117,1.9        !26.7455; 78.0775
*SET,temp118,1.9        !26.7835; 78.0845
*SET,temp119,1.9        !26.8035; 78.0915

*SET,temp121,1.9        !6.1126; 75.2405
*SET,temp122,1.9        !6.1077; 75.2475
*SET,temp123,1.9        !6.1006; 75.2585
*SET,temp124,1.9        !6.0928; 75.2735
*SET,temp125,1.9        !6.0853; 75.2905
*SET,temp126,1.9        !6.079; 75.3065
*SET,temp127,1.9        !6.0748; 75.3205
*SET,temp128,1.9        !6.073; 75.3305

*SET,temp131,1.9        !5.4441; 69.6074
*SET,temp132,1.9        !5.4452; 69.6084
*SET,temp133,1.9        !5.4463; 69.6094

*SET,temp141,1.9        !5.5296; 80.0565
*SET,temp142,1.9        !5.5303; 80.0575

*SET,temp151,1.9        !15.8515; 58.5795
*SET,temp152,1.9        !15.9295; 58.5785
*SET,temp153,1.9        !16.0055; 58.5835
*SET,temp154,1.9        !16.0845; 58.5925
*SET,temp155,1.9        !16.1685; 58.6055
*SET,temp156,1.9        !16.2565; 58.6225
*SET,temp157,1.9        !16.3485; 58.6415
*SET,temp158,1.9        !16.4445; 58.6635
*SET,temp159,1.9        !16.5435; 58.6865
*SET,temp1510,1.9       !16.6415; 58.7105
*SET,temp1511,1.9       !16.7365; 58.7325
*SET,temp1512,1.9       !16.8265; 58.7535
*SET,temp1513,1.9       !16.9075; 58.7715
*SET,temp1514,1.9       !16.9765; 58.7865
*SET,temp1515,1.9       !17.0285; 58.7975
*SET,temp1516,1.9       !17.0575; 58.8025

*SET,temp161,1.9        !4.71; 52.2721
*SET,temp162,1.9        !4.7065; 52.2831
*SET,temp163,1.9        !4.7004; 52.3031
*SET,temp164,1.9        !4.6929; 52.3321
*SET,temp165,1.9        !4.6851; 52.3701
*SET,temp166,1.9        !4.6779; 52.4141
*SET,temp167,1.9        !4.6721; 52.4651
*SET,temp168,1.9        !4.6683; 52.5191
*SET,temp169,1.9        !4.6668; 52.5771
*SET,temp1610,1.9       !4.6677; 52.6361
*SET,temp1611,1.9       !4.6707; 52.6941
*SET,temp1612,1.9       !4.6758; 52.7501
*SET,temp1613,1.9       !4.6824; 52.8041
*SET,temp1614,1.9       !4.6901; 52.8521
```

```
*SET,temp1615,1.9        !4.6984; 52.8931
*SET,temp1616,1.9        !4.7065; 52.9271
*SET,temp1617,1.9        !4.7135; 52.9511
*SET,temp1618,1.9        !4.7178; 52.9641

!Quadrant 2!
*SET,temp211,1.9         !26.0385; 78.0565
*SET,temp212,1.9         !26.2435; 78.0565
*SET,temp213,1.9         !26.4015; 78.0575
*SET,temp214,1.9         !26.5235; 78.0615
*SET,temp215,1.9         !26.6185; 78.0655
*SET,temp216,1.9         !26.6915; 78.0715
*SET,temp217,1.9         !26.7455; 78.0775
*SET,temp218,1.9         !26.7835; 78.0845
*SET,temp219,1.9         !26.8035; 78.0915

*SET,temp221,1.9         !6.1121; 75.2435
*SET,temp222,1.9         !6.1073; 75.2495
*SET,temp223,1.9         !6.1002; 75.2615
*SET,temp224,1.9         !6.0924; 75.2765
*SET,temp225,1.9         !6.0849; 75.2935
*SET,temp226,1.9         !6.0786; 75.3095
*SET,temp227,1.9         !6.0744; 75.3235
*SET,temp228,1.9         !6.0727; 75.3325

*SET,temp231,1.9         !5.4441; 69.6074
*SET,temp232,1.9         !5.4452; 69.6084
*SET,temp233,1.9         !5.4463; 69.6094

*SET,temp241,1.9         !5.5296; 80.0565
*SET,temp242,1.9         !5.5303; 80.0575

*SET,temp251,1.9         !15.8515; 58.5795
*SET,temp252,1.9         !15.9295; 58.5785
*SET,temp253,1.9         !16.0055; 58.5835
*SET,temp254,1.9         !16.0845; 58.5925
*SET,temp255,1.9         !16.1685; 58.6055
*SET,temp256,1.9         !16.2565; 58.6225
*SET,temp257,1.9         !16.3485; 58.6415
*SET,temp258,1.9         !16.4445; 58.6635
*SET,temp259,1.9         !16.5435; 58.6875
*SET,temp2510,1.9        !16.6415; 58.7105
*SET,temp2511,1.9        !16.7365; 58.7335
*SET,temp2512,1.9        !16.8265; 58.7535
*SET,temp2513,1.9        !16.9075; 58.7715
*SET,temp2514,1.9        !16.9765; 58.7865
*SET,temp2515,1.9        !17.0285; 58.7975
*SET,temp2516,1.9        !17.0575; 58.8025

*SET,temp261,1.9         !4.71; 52.2722
*SET,temp262,1.9         !4.7065; 52.2822
*SET,temp263,1.9         !4.7004; 52.3032
*SET,temp264,1.9         !4.693; 52.3322
*SET,temp265,1.9         !4.6852; 52.3702
*SET,temp266,1.9         !4.678; 52.4142
*SET,temp267,1.9         !4.6722; 52.4652
*SET,temp268,1.9         !4.6683; 52.5192
*SET,temp269,1.9         !4.6668; 52.5772
*SET,temp2610,1.9001     !4.6677; 52.6352
*SET,temp2611,1.9001     !4.6707; 52.6942
*SET,temp2612,1.9001     !4.6758; 52.7502
*SET,temp2613,1.9001     !4.6824; 52.8032
*SET,temp2614,1.9001     !4.6901; 52.8522
*SET,temp2615,1.9001     !4.6984; 52.8932
*SET,temp2616,1.9001     !4.7065; 52.9272
*SET,temp2617,1.9001     !4.7135; 52.9512
*SET,temp2618,1.9001     !4.7178; 52.9642
```

```
!Quadrant 3!
*SET,temp311,1.9           !25.7955; 78.0595
*SET,temp312,1.9           !25.5805; 78.0645
*SET,temp313,1.9           !25.4095; 78.0725
*SET,temp314,1.9           !25.2755; 78.0825
*SET,temp315,1.9           !25.1725; 78.0945
*SET,temp316,1.9           !25.0975; 78.1075
*SET,temp317,1.9           !25.0465; 78.1195
*SET,temp318,1.9           !25.0145; 78.1305
*SET,temp319,1.9           !24.9985; 78.1395

*SET,temp321,1.9001        !6.4499; 73.8886
*SET,temp322,1.9001        !6.4483; 73.8946
*SET,temp323,1.9001        !6.4479; 73.9056
*SET,temp324,1.9001        !6.4496; 73.9196
*SET,temp325,1.9001        !6.4536; 73.9356
*SET,temp326,1.9001        !6.4595; 73.9516
*SET,temp327,1.9001        !6.4664; 73.9646
*SET,temp328,1.9001        !6.4728; 73.9736

*SET,temp331,1.9           !12.6124; 79.2794
*SET,temp332,1.9           !12.6344; 79.2814
*SET,temp333,1.9           !12.6594; 79.2824

*SET,temp341,1.9001        !15.5425; 80.8055
*SET,temp342,1.9001        !15.5525; 80.8065

*SET,temp351,1.9           !15.7715; 58.5855
*SET,temp352,1.9           !15.7085; 58.5965
*SET,temp353,1.9           !15.6665; 58.6135
*SET,temp354,1.9           !15.6435; 58.6345
*SET,temp355,1.9           !15.6395; 58.6605
*SET,temp356,1.9           !15.6525; 58.6895
*SET,temp357,1.9           !15.6795; 58.7215
*SET,temp358,1.9           !15.7205; 58.7555
*SET,temp359,1.9           !15.7695; 58.7895
*SET,temp3510,1.9          !15.8265; 58.8235
*SET,temp3511,1.9          !15.8855; 58.8555
*SET,temp3512,1.9          !15.9455; 58.8845
*SET,temp3513,1.9          !16.0005; 58.9085
*SET,temp3514,1.9          !16.0485; 58.9285
*SET,temp3515,1.9          !16.0855; 58.9425
*SET,temp3516,1.9          !16.1065; 58.9505

*SET,temp361,1.9001        !5.0166; 51.5892
*SET,temp362,1.9001        !5.0177; 51.5992
*SET,temp363,1.9001        !5.0212; 51.6192
*SET,temp364,1.9001        !5.0284; 51.6472
*SET,temp365,1.9001        !5.0404; 51.6832
*SET,temp366,1.9001        !5.0578; 51.7252
*SET,temp367,1.9001        !5.081; 51.7732
*SET,temp368,1.9001        !5.1099; 51.8262
*SET,temp369,1.9001        !5.1439; 51.8812
*SET,temp3610,1.9001       !5.1819; 51.9372
*SET,temp3611,1.9001       !5.2226; 51.9932
*SET,temp3612,1.9001       !5.2645; 52.0472
*SET,temp3613,1.9001       !5.3062; 52.0972
*SET,temp3614,1.9001       !5.3459; 52.1432
*SET,temp3615,1.9001       !5.382; 52.1832
*SET,temp3616,1.9001       !5.4127; 52.2152
*SET,temp3617,1.9001       !5.4359; 52.2382
*SET,temp3618,1.9001       !5.4493; 52.2512

!Quadrant 4!
*SET,temp411,1.9           !25.7955; 78.0595
*SET,temp412,1.9           !25.5805; 78.0645
```

```
*SET,temp413,1.9         !25.4095; 78.0725
*SET,temp414,1.9         !25.2755; 78.0825
*SET,temp415,1.9         !25.1725; 78.0945
*SET,temp416,1.9         !25.0975; 78.1075
*SET,temp417,1.9         !25.0465; 78.1195
*SET,temp418,1.9         !25.0145; 78.1305
*SET,temp419,1.9         !24.9985; 78.1395

*SET,temp421,1.9001      !6.4499; 73.8886
*SET,temp422,1.9001      !6.4483; 73.8946
*SET,temp423,1.9001      !6.4478; 73.9056
*SET,temp424,1.9001      !6.4495; 73.9196
*SET,temp425,1.9001      !6.4536; 73.9356
*SET,temp426,1.9001      !6.4595; 73.9516
*SET,temp427,1.9001      !6.4664; 73.9646
*SET,temp428,1.9001      !6.4727; 73.9736

*SET,temp431,1.9         !11.7494; 79.1694
*SET,temp432,1.9         !11.7714; 79.1704
*SET,temp433,1.9         !11.7984; 79.1724

*SET,temp441,1.9         !15.5435; 80.8055
*SET,temp442,1.9         !15.5525; 80.8065

*SET,temp451,1.9         !15.7715; 58.5855
*SET,temp452,1.9         !15.7085; 58.5965
*SET,temp453,1.9         !15.6665; 58.6135
*SET,temp454,1.9         !15.6435; 58.6345
*SET,temp455,1.9         !15.6395; 58.6605
*SET,temp456,1.9         !15.6525; 58.6895
*SET,temp457,1.9         !15.6795; 58.7215
*SET,temp458,1.9         !15.7205; 58.7555
*SET,temp459,1.9         !15.7695; 58.7895
*SET,temp4510,1.9        !15.8265; 58.8235
*SET,temp4511,1.9        !15.8855; 58.8555
*SET,temp4512,1.9        !15.9455; 58.8845
*SET,temp4513,1.9        !16.0005; 58.9085
*SET,temp4514,1.9        !16.0485; 58.9285
*SET,temp4515,1.9        !16.0855; 58.9425
*SET,temp4516,1.9        !16.1065; 58.9505

*SET,temp461,1.9         !5.016; 51.5891
*SET,temp462,1.9         !5.0171; 51.5991
*SET,temp463,1.9         !5.0206; 51.6191
*SET,temp464,1.9         !5.0278; 51.6471
*SET,temp465,1.9         !5.0398; 51.6831
*SET,temp466,1.9         !5.0572; 51.7251
*SET,temp467,1.9         !5.0804; 51.7731
*SET,temp468,1.9         !5.1093; 51.8261
*SET,temp469,1.9         !5.1433; 51.8811
*SET,temp4610,1.9        !5.1813; 51.9371
*SET,temp4611,1.9        !5.222; 51.9931
*SET,temp4612,1.9        !5.2639; 52.0471
*SET,temp4613,1.9        !5.3056; 52.0971
*SET,temp4614,1.9        !5.3453; 52.1431
*SET,temp4615,1.9        !5.3815; 52.1831
*SET,temp4616,1.9        !5.4121; 52.2151
*SET,temp4617,1.9        !5.4354; 52.2381
*SET,temp4618,1.9        !5.4487; 52.2511

!------------------Lorentz force x------------------!
!Quadrant 1!
*SET,forcx111,85270      !91653; 1333.5
*SET,forcx112,85409      !91669; 1332.4
*SET,forcx113,85684      !91853; 1329.3
*SET,forcx114,86093      !92202; 1324.1
*SET,forcx115,86628      !92713; 1316.4
```

```
*SET,forcx116,87279       !93374; 1305.9
*SET,forcx117,88033       !94170; 1291.6
*SET,forcx118,88866       !95077; 1271.5
*SET,forcx119,89741       !96056; 1240.1

*SET,forcx121,87657       !94219; 1223.2
*SET,forcx122,90435       !97340; 1268.4
*SET,forcx123,93679       !101010; 1301.9
*SET,forcx124,97179       !104950; 1329.1
*SET,forcx125,100880      !109140; 1356.8
*SET,forcx126,104810      !113610; 1385.6
*SET,forcx127,108980      !118390; 1415.7
*SET,forcx128,113460      !123540; 1446.7

*SET,forcx131,111260      !121290; 1447.8
*SET,forcx132,117500      !128380; 1493.3
*SET,forcx133,123480      !135190; 1544.3

*SET,forcx141,118670      !129700; 1536.4
*SET,forcx142,126080      !138040; 1631.9

*SET,forcx151,-1978.5     !-2173.2; -49.724
*SET,forcx152,-1777.6     !-2054.7; -46.825
*SET,forcx153,-1375       !-1715.6; -40.043
*SET,forcx154,-769.28     !-1153.9; -29.382
*SET,forcx155,42.062      !-365.93; -14.805
*SET,forcx156,1062.1      !653.37; 3.7848
*SET,forcx157,2294.9      !1909.6; 26.569
*SET,forcx158,3745        !3408.8; 53.86
*SET,forcx159,5418        !5157.5; 86.221
*SET,forcx1510,7320.2     !7160.2; 124.73
*SET,forcx1511,9435       !9368.6; 167.84
*SET,forcx1512,11570      !11540; 200.04
*SET,forcx1513,13566      !13568; 221.24
*SET,forcx1514,15408      !15443; 235.05
*SET,forcx1515,17100      !17169; 242.31
*SET,forcx1516,18684      !18811; 249.24

*SET,forcx161,17722       !18174; 261.27
*SET,forcx162,21353       !22097; 307.55
*SET,forcx163,25010       !26069; 359.19
*SET,forcx164,28766       !30167; 413.74
*SET,forcx165,32657       !34425; 470.93
*SET,forcx166,36699       !38860; 530.67
*SET,forcx167,40897       !43475; 592.7
*SET,forcx168,45200       !48210; 648.23
*SET,forcx169,49372       !52820; 686.5
*SET,forcx1610,53396      !57296; 722.36
*SET,forcx1611,57347      !61709; 758.47
*SET,forcx1612,61288      !66123; 796.62
*SET,forcx1613,65288      !70612; 838.5
*SET,forcx1614,69423      !75259; 886.02
*SET,forcx1615,73793      !80173; 942
*SET,forcx1616,78581      !85521; 1022.8
*SET,forcx1617,84079      !91623; 1122.6
*SET,forcx1618,90315      !98534; 1233

!Quadrant 2!
*SET,forcx211,-85270      !-91653; -1333.5
*SET,forcx212,-85409      !-91669; -1332.4
*SET,forcx213,-85684      !-91853; -1329.3
*SET,forcx214,-86093      !-92202; -1324.1
*SET,forcx215,-86628      !-92713; -1316.4
*SET,forcx216,-87279      !-93374; -1305.9
*SET,forcx217,-88033      !-94170; -1291.6
*SET,forcx218,-88866      !-95077; -1271.5
*SET,forcx219,-89741      !-96056; -1240.1
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*SET,forcx221,-87656     !-94217; -1223.2
*SET,forcx222,-90435     !-97340; -1268.4
*SET,forcx223,-93679     !-101010; -1301.9
*SET,forcx224,-97179     !-104950; -1329.1
*SET,forcx225,-100880    !-109140; -1356.8
*SET,forcx226,-104810    !-113610; -1385.7
*SET,forcx227,-108980    !-118380; -1415.8
*SET,forcx228,-113460    !-123540; -1447

*SET,forcx231,111260     !121290; 1447.8
*SET,forcx232,117500     !128380; 1493.3
*SET,forcx233,123480     !135190; 1544.3

*SET,forcx241,118670     !129700; 1536.4
*SET,forcx242,126080     !138040; 1631.9

*SET,forcx251,1978.2     !2172.9; 49.72
*SET,forcx252,1777.4     !2054.4; 46.822
*SET,forcx253,1374.9     !1715.3; 40.04
*SET,forcx254,769.12     !1153.7; 29.38
*SET,forcx255,-42.201    !365.75; 14.803
*SET,forcx256,-1062.3    !-653.54; -3.7862
*SET,forcx257,-2295      !-1909.8; -26.57
*SET,forcx258,-3745.1    !-3409; -53.861
*SET,forcx259,-5418      !-5157.5; -86.222
*SET,forcx2510,-7320.1   !-7160.1; -124.74
*SET,forcx2511,-9435.3   !-9368.9; -167.85
*SET,forcx2512,-11570    !-11541; -200.03
*SET,forcx2513,-13566    !-13568; -221.23
*SET,forcx2514,-15407    !-15442; -235.04
*SET,forcx2515,-17099    !-17168; -242.32
*SET,forcx2516,-18685    !-18812; -249.25

*SET,forcx261,-17722     !-18175; -261.26
*SET,forcx262,-21353     !-22097; -307.55
*SET,forcx263,-25010     !-26070; -359.19
*SET,forcx264,-28767     !-30167; -413.74
*SET,forcx265,-32657     !-34425; -470.93
*SET,forcx266,-36700     !-38861; -530.66
*SET,forcx267,-40898     !-43476; -592.68
*SET,forcx268,-45200     !-48209; -648.22
*SET,forcx269,-49370     !-52818; -686.51
*SET,forcx2610,-53395    !-57295; -722.36
*SET,forcx2611,-57347    !-61708; -758.46
*SET,forcx2612,-61288    !-66123; -796.62
*SET,forcx2613,-65288    !-70613; -838.49
*SET,forcx2614,-69424    !-75261; -885.98
*SET,forcx2615,-73792    !-80172; -942.04
*SET,forcx2616,-78578    !-85518; -1022.7
*SET,forcx2617,-84076    !-91620; -1122.6
*SET,forcx2618,-90311    !-98529; -1233

!Quadrant 3!
*SET,forcx311,-85270     !-77914; -1298.7
*SET,forcx312,-85409     !-78148; -1296
*SET,forcx313,-85684     !-78486; -1291.5
*SET,forcx314,-86092     !-78923; -1285.1
*SET,forcx315,-86627     !-79451; -1276.5
*SET,forcx316,-87279     !-80063; -1265.3
*SET,forcx317,-88032     !-80746; -1250.4
*SET,forcx318,-88866     !-81478; -1230.1
*SET,forcx319,-89744     !-82226; -1198.9

*SET,forcx321,-87657     !-79967; -1184
*SET,forcx322,-90434     !-82392; -1226.7
*SET,forcx323,-93678     !-85197; -1258.2
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*SET,forcx324,-97178      !-88231; -1283.4
*SET,forcx325,-100880     !-91422; -1309.3
*SET,forcx326,-104810     !-94781; -1336.3
*SET,forcx327,-108980     !-98331; -1364.5
*SET,forcx328,-113460     !-102110; -1393.7

*SET,forcx331,-111260     !-99975; -1395.7
*SET,forcx332,-117500     !-105310; -1438.3
*SET,forcx333,-123480     !-110420; -1486.2

*SET,forcx341,-118670     !-106370; -1479.6
*SET,forcx342,-126080     !-112800; -1570.3

*SET,forcx351,1978.2      !1759.4; 47.53
*SET,forcx352,1777.4      !1490.9; 43.019
*SET,forcx353,1374.8      !1040.1; 34.99
*SET,forcx354,769.09      !407.69; 23.437
*SET,forcx355,-42.233     !-406.87; 8.3034
*SET,forcx356,-1062.3     !-1405; -10.525
*SET,forcx357,-2295       !-2589.2; -33.24
*SET,forcx358,-3745       !-3963; -60.158
*SET,forcx359,-5417.9     !-5531.1; -91.835
*SET,forcx3510,-7319.9    !-7300.8; -129.32
*SET,forcx3511,-9435.6    !-9284.3; -171
*SET,forcx3512,-11571     !-11334; -201.74
*SET,forcx3513,-13566     !-13248; -221.84
*SET,forcx3514,-15407     !-15007; -234.84
*SET,forcx3515,-17099     !-16616; -241.59
*SET,forcx3516,-18688     !-18103; -248.11

*SET,forcx361,-17725      !-16951; -262.48
*SET,forcx362,-21354      !-20236; -306.33
*SET,forcx363,-25010      !-23529; -355.51
*SET,forcx364,-28767      !-26899; -407.5
*SET,forcx365,-32657      !-30379; -462.02
*SET,forcx366,-36699      !-33984; -518.96
*SET,forcx367,-40897      !-37719; -578.09
*SET,forcx368,-45199      !-41540; -630.81
*SET,forcx369,-49372      !-45227; -666.72
*SET,forcx3610,-53398     !-48759; -700.43
*SET,forcx3611,-57348     !-52210; -734.47
*SET,forcx3612,-61288     !-55642; -770.54
*SET,forcx3613,-65288     !-59118; -810.25
*SET,forcx3614,-69424     !-62710; -855.43
*SET,forcx3615,-73793     !-66502; -908.8
*SET,forcx3616,-78581     !-70701; -986.1
*SET,forcx3617,-84081     !-75574; -1081.6
*SET,forcx3618,-90319     !-81112; -1187

!Quadrant 4!
*SET,forcx411,85270       !77914; 1298.7
*SET,forcx412,85409       !78148; 1296
*SET,forcx413,85684       !78486; 1291.5
*SET,forcx414,86093       !78923; 1285.1
*SET,forcx415,86627       !79451; 1276.5
*SET,forcx416,87279       !80063; 1265.2
*SET,forcx417,88032       !80746; 1250.4
*SET,forcx418,88866       !81478; 1230.1
*SET,forcx419,89741       !82221; 1198.9

*SET,forcx421,87655       !79967; 1183.8
*SET,forcx422,90434       !82392; 1226.6
*SET,forcx423,93679       !85197; 1258.1
*SET,forcx424,97179       !88232; 1283.4
*SET,forcx425,100880      !91422; 1309.3
*SET,forcx426,104810      !94780; 1336.3
*SET,forcx427,108980      !98330; 1364.4
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*SET,forcx428,113460     !102100; 1393.7

*SET,forcx431,111260     !99976; 1395.8
*SET,forcx432,117500     !105310; 1438.1
*SET,forcx433,123480     !110410; 1485.4

*SET,forcx441,118670     !106370; 1479.1
*SET,forcx442,126080     !112800; 1569.9

*SET,forcx451,-1978.5    !-1759.7; -47.535
*SET,forcx452,-1777.6    !-1491.2; -43.023
*SET,forcx453,-1375.1    !-1040.4; -34.995
*SET,forcx454,-769.31    !-407.91; -23.441
*SET,forcx455,42.103     !406.72; -8.3058
*SET,forcx456,1062.3     !1404.9; 10.524
*SET,forcx457,2295.1     !2589.2; 33.24
*SET,forcx458,3745.3     !3963.2; 60.158
*SET,forcx459,5418.3     !5531.4; 91.833
*SET,forcx4510,7320.3    !7301.1; 129.32
*SET,forcx4511,9435      !9283.7; 170.99
*SET,forcx4512,11570     !11333; 201.73
*SET,forcx4513,13566     !13247; 221.83
*SET,forcx4514,15406     !15006; 234.84
*SET,forcx4515,17099     !16615; 241.58
*SET,forcx4516,18688     !18103; 248.12

*SET,forcx461,17725      !16950; 262.45
*SET,forcx462,21354      !20236; 306.33
*SET,forcx463,25010      !23529; 355.51
*SET,forcx464,28767      !26899; 407.51
*SET,forcx465,32658      !30379; 462.02
*SET,forcx466,36700      !33984; 518.96
*SET,forcx467,40898      !37720; 578.06
*SET,forcx468,45199      !41541; 630.77
*SET,forcx469,49370      !45225; 666.74
*SET,forcx4610,53395     !48756; 700.47
*SET,forcx4611,57347     !52209; 734.51
*SET,forcx4612,61289     !55642; 770.59
*SET,forcx4613,65290     !59120; 810.3
*SET,forcx4614,69426     !62711; 855.41
*SET,forcx4615,73791     !66501; 908.76
*SET,forcx4616,78578     !70699; 986.04
*SET,forcx4617,84079     !75572; 1081.6
*SET,forcx4618,90314     !81107; 1187.1

!------------------Lorentz force y------------------!
!Quadrant 1!
*SET,forcy111,-1122.5    !4327.3; 12.255
*SET,forcy112,-3377.4    !1503.3; -7.4662
*SET,forcy113,-5662.2    !-1322.9; -27.932
*SET,forcy114,-7999      !-4184.4; -49.9
*SET,forcy115,-10413     !-7117.2; -74.196
*SET,forcy116,-12934     !-10163; -101.81
*SET,forcy117,-15601     !-13371; -133.96
*SET,forcy118,-18469     !-16810; -172.37
*SET,forcy119,-21633     !-20616; -220.59

*SET,forcy121,-8276.4    !-6197.1; -46.133
*SET,forcy122,-10589     !-8826.9; -56.668
*SET,forcy123,-12812     !-11484; -92.018
*SET,forcy124,-15163     !-14267; -130.46
*SET,forcy125,-17673     !-17216; -177.5
*SET,forcy126,-20406     !-20401; -235.31
*SET,forcy127,-23450     !-23917; -307.17
*SET,forcy128,-26946     !-27912; -401.08

*SET,forcy131,-15544     !-15554; -328.31
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*SET,forcy132,-18997      !-19563; -368.49
*SET,forcy133,-22300      !-23376; -414.72

*SET,forcy141,-16276      !-17250; -281.98
*SET,forcy142,-17216      !-18390; -294.77

*SET,forcy151,-1598.3     !2093.2; -4.5629
*SET,forcy152,-4792.7     !-1506.4; -58.373
*SET,forcy153,-7979.6     !-5031.8; -110.84
*SET,forcy154,-11153      !-8522.5; -161.72
*SET,forcy155,-14308      !-11992; -211
*SET,forcy156,-17436      !-15439; -258.63
*SET,forcy157,-20530      !-18858; -304.53
*SET,forcy158,-23577      !-22236; -348.45
*SET,forcy159,-26562      !-25553; -389.83
*SET,forcy1510,-29459     !-28776; -427.46
*SET,forcy1511,-32190     !-31786; -453.34
*SET,forcy1512,-34628     !-34529; -466.19
*SET,forcy1513,-37002     !-37281; -486.18
*SET,forcy1514,-39481     !-40192; -515.83
*SET,forcy1515,-42230     !-43441; -559.04
*SET,forcy1516,-45510     !-47355; -631.6

*SET,forcy161,-34158      !-35476; -441.91
*SET,forcy162,-37391      !-39021; -483.68
*SET,forcy163,-40250      !-42200; -519.38
*SET,forcy164,-42783      !-45047; -548.01
*SET,forcy165,-45001      !-47568; -569.51
*SET,forcy166,-46899      !-49753; -583.28
*SET,forcy167,-48453      !-51573; -587.75
*SET,forcy168,-49597      !-52956; -576.54
*SET,forcy169,-50311      !-53892; -564.37
*SET,forcy1610,-50861     !-54654; -563.6
*SET,forcy1611,-51366     !-55359; -569.64
*SET,forcy1612,-51899     !-56088; -582.1
*SET,forcy1613,-52526     !-56913; -601.52
*SET,forcy1614,-53316     !-57906; -628.96
*SET,forcy1615,-54343     !-59147; -666.02
*SET,forcy1616,-55713     !-60735; -716.64
*SET,forcy1617,-57401     !-62693; -756.62
*SET,forcy1618,-59278     !-64878; -796.99

!Quadrant 2!
*SET,forcy211,-1122.7     !4327; 12.257
*SET,forcy212,-3377.6     !1503; -7.4645
*SET,forcy213,-5662.5     !-1323.3; -27.931
*SET,forcy214,-7999.3     !-4184.7; -49.899
*SET,forcy215,-10413      !-7117.6; -74.194
*SET,forcy216,-12934      !-10163; -101.8
*SET,forcy217,-15602      !-13371; -133.96
*SET,forcy218,-18470      !-16811; -172.37
*SET,forcy219,-21633      !-20616; -220.59

*SET,forcy221,-8278.2     !-6199; -46.124
*SET,forcy222,-10590      !-8827.8; -56.665
*SET,forcy223,-12812      !-11484; -92.009
*SET,forcy224,-15163      !-14267; -130.44
*SET,forcy225,-17673      !-17216; -177.48
*SET,forcy226,-20405      !-20401; -235.29
*SET,forcy227,-23450      !-23917; -307.14
*SET,forcy228,-26946      !-27912; -401.05

*SET,forcy231,-15544      !-15554; -328.31
*SET,forcy232,-18997      !-19563; -368.49
*SET,forcy233,-22300      !-23376; -414.72

*SET,forcy241,-16276      !-17250; -281.98
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*SET,forcy242,-17216     !-18390; -294.77

*SET,forcy251,-1598.6    !2092.9; -4.5648
*SET,forcy252,-4793      !-1506.7; -58.376
*SET,forcy253,-7979.9    !-5032.1; -110.84
*SET,forcy254,-11154     !-8522.9; -161.72
*SET,forcy255,-14308     !-11992; -211
*SET,forcy256,-17436     !-15440; -258.63
*SET,forcy257,-20530     !-18859; -304.53
*SET,forcy258,-23577     !-22236; -348.45
*SET,forcy259,-26562     !-25554; -389.83
*SET,forcy2510,-29459    !-28777; -427.46
*SET,forcy2511,-32191    !-31787; -453.33
*SET,forcy2512,-34628    !-34529; -466.18
*SET,forcy2513,-37001    !-37281; -486.19
*SET,forcy2514,-39482    !-40192; -515.83
*SET,forcy2515,-42232    !-43443; -559.07
*SET,forcy2516,-45511    !-47356; -631.61

*SET,forcy261,-34158     !-35476; -441.9
*SET,forcy262,-37391     !-39021; -483.67
*SET,forcy263,-40251     !-42201; -519.38
*SET,forcy264,-42783     !-45048; -548
*SET,forcy265,-45001     !-47569; -569.5
*SET,forcy266,-46899     !-49753; -583.27
*SET,forcy267,-48453     !-51573; -587.74
*SET,forcy268,-49596     !-52954; -576.55
*SET,forcy269,-50311     !-53892; -564.4
*SET,forcy2610,-50862    !-54655; -563.61
*SET,forcy2611,-51368    !-55361; -569.64
*SET,forcy2612,-51900    !-56090; -582.1
*SET,forcy2613,-52527    !-56914; -601.52
*SET,forcy2614,-53316    !-57906; -628.95
*SET,forcy2615,-54342    !-59145; -666.19
*SET,forcy2616,-55713    !-60735; -716.59
*SET,forcy2617,-57402    !-62694; -756.75
*SET,forcy2618,-59280    !-64880; -797.15

!Quadrant 3!
*SET,forcy311,1122.4     !5729.2; 28.912
*SET,forcy312,3377.3     !7460.5; 44.214
*SET,forcy313,5662.2     !9240; 60.641
*SET,forcy314,7999       !11079; 78.854
*SET,forcy315,10413      !12994; 99.604
*SET,forcy316,12934      !15006; 123.81
*SET,forcy317,15601      !17144; 152.63
*SET,forcy318,18468      !19451; 187.71
*SET,forcy319,21629      !21987; 232.56

*SET,forcy321,8279.7     !9840.1; 61.923
*SET,forcy322,10590      !11801; 70.058
*SET,forcy323,12812      !13597; 102.78
*SET,forcy324,15163      !15524; 138.54
*SET,forcy325,17673      !17604; 182.67
*SET,forcy326,20406      !19896; 237.26
*SET,forcy327,23450      !22482; 305.42
*SET,forcy328,26946      !25498; 394.9

*SET,forcy331,15541      !15306; 322.14
*SET,forcy332,18996      !18193; 359.8
*SET,forcy333,22302      !20980; 403.12

*SET,forcy341,16277      !15118; 273.84
*SET,forcy342,17216      !15870; 285.42

*SET,forcy351,1598.4     !4743.5; 46.433
*SET,forcy352,4792.8     !7582.4; 94.755
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*SET,forcy353,7979.7      !10428; 142.03
*SET,forcy354,11153       !13259; 188.06
*SET,forcy355,14308       !16064; 232.76
*SET,forcy356,17436       !18836; 276.08
*SET,forcy357,20530       !21567; 317.9
*SET,forcy358,23577       !24247; 357.95
*SET,forcy359,26562       !26866; 395.69
*SET,forcy3510,29459      !29404; 429.9
*SET,forcy3511,32192      !31822; 452.7
*SET,forcy3512,34629      !33929; 463.24
*SET,forcy3513,37000      !35910; 481.17
*SET,forcy3514,39481      !37955; 508.6
*SET,forcy3515,42232      !40209; 549.32
*SET,forcy3516,45509      !42879; 618.45

*SET,forcy361,34155       !32216; 435.17
*SET,forcy362,37390       !35103; 473.94
*SET,forcy363,40250       !37615; 507.03
*SET,forcy364,42782       !39812; 533.39
*SET,forcy365,45000       !41711; 552.96
*SET,forcy366,46898       !43310; 565.16
*SET,forcy367,48452       !44590; 568.44
*SET,forcy368,49597       !45492; 556.66
*SET,forcy369,50313       !45993; 544.15
*SET,forcy3610,50862      !46346; 542.95
*SET,forcy3611,51365      !46666; 548.37
*SET,forcy3612,51899      !47022; 560.04
*SET,forcy3613,52527      !47473; 578.43
*SET,forcy3614,53316      !48079; 604.53
*SET,forcy3615,54343      !48915; 639.91
*SET,forcy3616,55714      !50095; 688.24
*SET,forcy3617,57402      !51538; 726.12
*SET,forcy3618,59275      !53123; 764.36

!Quadrant 4!
*SET,forcy411,1122.6      !5729.5; 28.91
*SET,forcy412,3377.5      !7460.8; 44.21
*SET,forcy413,5662.4      !9240.2; 60.637
*SET,forcy414,7999.1      !11079; 78.848
*SET,forcy415,10413       !12994; 99.597
*SET,forcy416,12934       !15006; 123.8
*SET,forcy417,15602       !17145; 152.61
*SET,forcy418,18470       !19453; 187.68
*SET,forcy419,21633       !21991; 232.48

*SET,forcy421,8278        !9838; 62.103
*SET,forcy422,10590       !11801; 70.059
*SET,forcy423,12813       !13597; 102.77
*SET,forcy424,15164       !15525; 138.53
*SET,forcy425,17673       !17604; 182.67
*SET,forcy426,20406       !19896; 237.26
*SET,forcy427,23450       !22482; 305.44
*SET,forcy428,26947       !25499; 394.9

*SET,forcy431,15541       !15306; 322
*SET,forcy432,19000       !18197; 359.8
*SET,forcy433,22313       !20992; 403.14

*SET,forcy441,16283       !15126; 274.52
*SET,forcy442,17221       !15875; 285.58

*SET,forcy451,1598.6      !4743.7; 46.434
*SET,forcy452,4793        !7582.6; 94.755
*SET,forcy453,7979.8      !10428; 142.03
*SET,forcy454,11153       !13259; 188.05
*SET,forcy455,14308       !16064; 232.75
*SET,forcy456,17436       !18836; 276.07
```

```
*SET,forcy457,20530      !21567; 317.89
*SET,forcy458,23577      !24248; 357.95
*SET,forcy459,26562      !26866; 395.68
*SET,forcy4510,29459     !29404; 429.89
*SET,forcy4511,32191     !31821; 452.7
*SET,forcy4512,34629     !33929; 463.26
*SET,forcy4513,37001     !35911; 481.17
*SET,forcy4514,39481     !37955; 508.6
*SET,forcy4515,42233     !40210; 549.31
*SET,forcy4516,45511     !42881; 618.42

*SET,forcy461,34157      !32217; 435.27
*SET,forcy462,37391      !35103; 473.98
*SET,forcy463,40250      !37615; 507.05
*SET,forcy464,42783      !39812; 533.4
*SET,forcy465,45001      !41711; 552.96
*SET,forcy466,46899      !43310; 565.16
*SET,forcy467,48452      !44590; 568.45
*SET,forcy468,49596      !45491; 556.66
*SET,forcy469,50310      !45991; 544.24
*SET,forcy4610,50863     !46346; 542.98
*SET,forcy4611,51368     !46669; 548.38
*SET,forcy4612,51901     !47024; 560.03
*SET,forcy4613,52527     !47473; 578.38
*SET,forcy4614,53314     !48078; 604.45
*SET,forcy4615,54339     !48912; 639.9
*SET,forcy4616,55714     !50096; 688.25
*SET,forcy4617,57403     !51540; 726.18
*SET,forcy4618,59279     !53127; 764.48
```

A.5. ANSYS APDL Script: 2D Coupling of an 11 T dipole model

```
FINISH
/CLEAR

!-------------------Global Arguments Input File------------------!
*USE,COMSOL_Input_11T.txt

!-------------------General Stuff & Parameters-------------------!
/FILNAME,11T_Dipole_Magnet
/UNITS,SI
/CONFIG,RESUPREC,0
/PREP7
/NERR,5

*SET,plots,1          !Off:  0, On:  1
*SET,file,1           !Off:  0, On:  1

*SET,elperli1,15      !Changing mesh of turns
*SET,elperli2,2       !Changing mesh of turns

TREF,1.9
DOF,TEMP
*SET,pi,acos(-1)
*afun,deg

!------------------Coil Radius--------------------!
*SET,r1,30e-3
*SET,r3,60.5e-3
*SET,r2,(r1+r3)/2

*SET,collarth,31e-3
*SET,yokerout,255e-3
*SET,shellth,12e-3
```

```
!-----------Number of Turns per Block--------------!
*SET,nblock1,9
*SET,nblock2,8
*SET,nblock3,3
*SET,nblock4,2
*SET,nblock5,16
*SET,nblock6,18

!---------------------Loading----------------------!
*SET,shimin,150e-6
*SET,shimout,150e-6
*SET,shimcoll,50e-6
*SET,gapyokein,20e-6
*SET,gapyokeout,50e-6

!------------------Element & Material Properties-----------------!

ET,1,PLANE183
KEYOPT,1,3,3
R,1,1

ET,2,PLANE183
KEYOPT,2,3,3
R,2,0.5

!Coil!
MPTEMP,1,4.3,293
MPDATA,EX,1,1,40.E+09,40.E+09
MPDATA,PRXY,1,1,0.3,0.3
MP,ALPX,1,1.16E-05

!Stainless steel!
MPTEMP,1,4.3,293
MPDATA,EX,2,1,210.E+09,193.E+09
MPDATA,PRXY,2,1,0.28,0.28
MP,ALPX,2,9.83E-06

!Aluminum bronze!
MPTEMP,1,4.3,293
MPDATA,EX,3,1,120.E+09,110.E+09
MPDATA,PRXY,3,1,0.3,0.3
MP,ALPX,3,1.08E-05

!Iron!
MPTEMP,1,4.3,293
MPDATA,EX,4,1,224.E+09,213.E+09
MPDATA,PRXY,4,1,0.28,0.28
MP,ALPX,4,6.82E-06

!------------Elements for Contact Pairs------------!
!REAL constant and key option for the contact elements
!Keyopt(12)=0 standard (separation - sliding)
!Keyopt(9)=0 Include both initial penetration or gap
!Keyopt(9)=1 Exclude both initial penetration or gap
!Keyopt(9)=3 Include offset only (contact REAL constant, positive being interf), exclude both initial penetration or gap

!Sliding, with gap!
ET,11,CONTA172
KEYOPT,11,12,0
KEYOPT,11,9,0
MP,MU,11,0
R,11
R,11,,,, ,,
RMORE,,,,-0e-6, ,
ET,111,TARGE169
```

```
!Sliding, no gap!
ET,12,CONTA172
KEYOPT,12,12,0
KEYOPT,12,9,1
MP,MU,12,0
R,12
R,12,,,, ,,
RMORE,,,,-0e-6, ,
ET,112,TARGE169

!Shim:  Collar - Quadrant layer inner radius!
ET,13,CONTA172
KEYOPT,13,12,0
KEYOPT,13,9,3
MP,MU,13,0
R,13
R,13,,,, ,,
RMORE,,,,shimin, ,
ET,113,TARGE169

!Shim:  Collar - Quadrant layer outer radius!
ET,14,CONTA172
KEYOPT,14,12,0
KEYOPT,14,9,3
MP,MU,14,0
R,14
R,14,,,, ,,
RMORE,,,,shimout, ,
ET,114,TARGE169

!Shim:  Collar - yoke!
ET,15,CONTA172
KEYOPT,15,12,0
KEYOPT,15,9,3
MP,MU,15,0
R,15
R,15,,,, ,,
RMORE,,,,shimcoll, ,
ET,115,TARGE169

!----------------------------Geometry----------------------------!
*DO,q,1,4

!----------------Angles of Blocks-------------------!
*SET,ang11,0
*SET,ang12,0
*SET,ang13,18.65934
*SET,ang14,24.18836

*SET,ang21,26.69416
*SET,ang22,27.12536
*SET,ang23,43.35745
*SET,ang24,47.69625

*SET,ang31,55.95846
*SET,ang32,56.96191
*SET,ang33,62.86518
*SET,ang34,63.577431

*SET,ang41,70.5744
*SET,ang42,70.38467
*SET,ang43,74.23456
*SET,ang44,75.52425

*SET,ang51,0
*SET,ang52,0
```

```
*SET,ang53,24.62702
*SET,ang54,28.388

*SET,ang61,30.24952
*SET,ang62,30.92383
*SET,ang63,58.34695
*SET,ang64,61.82651

!-----------------Angles of Gap--------------------!
*SET,ang81,90-atan(gapyokein/(r3+collarth))
*SET,ang82,90-atan(gapyokeout/yokerout)

*SET,ang90,90

!-----------------------Begin Quadrant----------------------!
*IF,q,EQ,2,THEN
  *SET,ang11,180-ang11
  *SET,ang12,180-ang12
  *SET,ang13,180-ang13
  *SET,ang14,180-ang14

  *SET,ang21,180-ang21
  *SET,ang22,180-ang22
  *SET,ang23,180-ang23
  *SET,ang24,180-ang24

  *SET,ang31,180-ang31
  *SET,ang32,180-ang32
  *SET,ang33,180-ang33
  *SET,ang34,180-ang34

  *SET,ang41,180-ang41
  *SET,ang42,180-ang42
  *SET,ang43,180-ang43
  *SET,ang44,180-ang44

  *SET,ang51,180-ang51
  *SET,ang52,180-ang52
  *SET,ang53,180-ang53
  *SET,ang54,180-ang54

  *SET,ang61,180-ang61
  *SET,ang62,180-ang62
  *SET,ang63,180-ang63
  *SET,ang64,180-ang64

  *SET,ang81,180-ang81
  *SET,ang82,180-ang82

  *SET,ang90,ang90

*ELSEIF,q,EQ,3,THEN
  *SET,ang11,180+ang11
  *SET,ang12,180+ang12
  *SET,ang13,180+ang13
  *SET,ang14,180+ang14

  *SET,ang21,180+ang21
  *SET,ang22,180+ang22
  *SET,ang23,180+ang23
  *SET,ang24,180+ang24

  *SET,ang31,180+ang31
  *SET,ang32,180+ang32
  *SET,ang33,180+ang33
  *SET,ang34,180+ang34
```

```
  *SET,ang41,180+ang41
  *SET,ang42,180+ang42
  *SET,ang43,180+ang43
  *SET,ang44,180+ang44

  *SET,ang51,180+ang51
  *SET,ang52,180+ang52
  *SET,ang53,180+ang53
  *SET,ang54,180+ang54

  *SET,ang61,180+ang61
  *SET,ang62,180+ang62
  *SET,ang63,180+ang63
  *SET,ang64,180+ang64

  *SET,ang81,180+ang81
  *SET,ang82,180+ang82

  *SET,ang90,180+ang90

*ELSEIF,q,EQ,4,THEN
  *SET,ang11,-ang11
  *SET,ang12,-ang12
  *SET,ang13,-ang13
  *SET,ang14,-ang14

  *SET,ang21,-ang21
  *SET,ang22,-ang22
  *SET,ang23,-ang23
  *SET,ang24,-ang24

  *SET,ang31,-ang31
  *SET,ang32,-ang32
  *SET,ang33,-ang33
  *SET,ang34,-ang34

  *SET,ang41,-ang41
  *SET,ang42,-ang42
  *SET,ang43,-ang43
  *SET,ang44,-ang44

  *SET,ang51,-ang51
  *SET,ang52,-ang52
  *SET,ang53,-ang53
  *SET,ang54,-ang54

  *SET,ang61,-ang61
  *SET,ang62,-ang62
  *SET,ang63,-ang63
  *SET,ang64,-ang64

  *SET,ang81,-ang81
  *SET,ang82,-ang82

  *SET,ang90,-ang90

*ENDIF

!-----------------------Quadrant q------------------------!
*DO,b,1,6

!--------------------Block b----------------------!
NUMSTR,KP,%q%%b%000
NUMSTR,LINE,%q%%b%001
NUMSTR,AREA,%q%%b%001

!-----------------Keypoints-----------------!
```

```
CSYS,1

*SET,angin,(ang%b%4-ang%b%1)/nblock%b%
*SET,angout,(ang%b%3-ang%b%2)/nblock%b%
*SET,kpnr,%q%%b%100
*DO,t,0,nblock%b%
  *IF,b,LE,4,THEN
    K,kpnr,r1,ang%b%1+t*angin
    K,kpnr+100,r2,ang%b%2+t*angout
  *ELSE
    K,kpnr,r2,ang%b%1+t*angin
    K,kpnr+100,r3,ang%b%2+t*angout
  *ENDIF
  *SET,kpnr,kpnr+1
*ENDDO

!-------------------Lines--------------------!
CSYS,0

!Inner to outer!
*SET,kpnr,%q%%b%101
*DO,t,1,nblock%b%-1
  L,kpnr,kpnr+100,elperli1
  *SET,kpnr,kpnr+1
*ENDDO

!Inner & Outer!
*SET,kpnr,%q%%b%100
*DO,t,1,nblock%b%
  L,kpnr,kpnr+1,elperli2
  L,kpnr+100,kpnr+101,elperli2
  *SET,kpnr,kpnr+1
*ENDDO

!-------------------Areas--------------------!
*SET,kpnr,%q%%b%100
*DO,t,1,nblock%b%
  A,kpnr,kpnr+1,kpnr+101,kpnr+100
  *SET,kpnr,kpnr+1
*ENDDO

!--------------------Mesh--------------------!
*SET,kpnr,%q%%b%100
*SET,anr,%q%%b%001

TYPE,1
REAL,1
MAT,1

*DO,t,1,nblock%b%
  ASEL,S,,,anr
  AATT,1,1,1
  AMAP,anr,kpnr,kpnr+1,kpnr+101,kpnr+100
  ALLSEL
  *SET,kpnr,kpnr+1
  *SET,anr,anr+1
*ENDDO

!-----------------Components-----------------!
*SET,anr,%q%%b%001
*DO,t,1,nblock%b%
  ASEL,S,,,anr
  CM,turn%q%%b%%t%,AREA
  ALLSEL
  *SET,anr,anr+1
*ENDDO
```

```
*ENDDO

!-------------------------Wedges----------------------------!
NUMSTR,LINE,%q%7001
NUMSTR,AREA,%q%7001

!------------------Lines--------------------!
CSYS,1

*SET,kpnr,%q%1100
*SET,nr,1
*DO,i,1,4
  L,kpnr+nblock%nr%,kpnr+1000
  L,kpnr+100+nblock%nr%,kpnr+1100
    *SET,kpnr,kpnr+1000
  *SET,nr,nr+1
  *IF,i,GE,3,THEN
    *SET,kpnr,kpnr+1000
    *SET,nr,nr+1
  *ENDIF
*ENDDO

!------------------Areas--------------------!
*SET,kpnr,%q%1100
*SET,nr,1
*DO,i,1,4
  A,kpnr+nblock%nr%,kpnr+1000,kpnr+1100,kpnr+100+nblock%nr%
  *SET,kpnr,kpnr+1000
  *SET,nr,nr+1
  *IF,i,GE,3,THEN
    *SET,kpnr,kpnr+1000
    *SET,nr,nr+1
  *ENDIF
*ENDDO

!-------------------Mesh--------------------!
*SET,kpnr,%q%1100
*SET,anr,%q%7001
*SET,nr,1

TYPE,1
REAL,1
MAT,3

*DO,i,1,4
  ASEL,S,,,anr
  AATT,3,1,1
  AMAP,anr,kpnr+nblock%nr%,kpnr+1000,kpnr+1100,kpnr+100+nblock%nr%
  ALLSEL
  *SET,kpnr,kpnr+1000
  *SET,nr,nr+1
  *SET,anr,anr+1
  *IF,i,GE,3,THEN
    *SET,kpnr,kpnr+1000
    *SET,nr,nr+1
  *ENDIF
*ENDDO

!----------------Components-----------------!
*SET,anr,%q%7001
*DO,i,1,4
  ASEL,S,,,anr
  CM,wedge%q%%i%,AREA
  ALLSEL
  *SET,anr,anr+1
*ENDDO
```

```
!--------------Components for Coil and Wedges---------------!
!Name for Block 1!
ASEL,S,,,%q%1001,%q%1009
CM,block%q%1,AREA
ALLSEL

!Name for Block 2!
ASEL,S,,,%q%2001,%q%2008
CM,block%q%2,AREA
ALLSEL

!Name for Block 3!
ASEL,S,,,%q%3001,%q%3003
CM,block%q%3,AREA
ALLSEL

!Name for Block 4!
ASEL,S,,,%q%4001,%q%4002
CM,block%q%4,AREA
ALLSEL

!Name for Block 5!
ASEL,S,,,%q%5001,%q%5016
CM,block%q%5,AREA
ALLSEL

!Name for Block 6!
ASEL,S,,,%q%6001,%q%6018
CM,block%q%6,AREA
ALLSEL

!Name for Block layer inner radius!
CMSEL,S,block%q%1
CMSEL,A,block%q%2
CMSEL,A,block%q%3
CMSEL,A,block%q%4
CM,quadin%q%,AREA
ALLSEL

!Name for Block layer outer radius!
CMSEL,S,block%q%5
CMSEL,A,block%q%6
CM,quadout%q%,AREA
ALLSEL

!Name for Quadrant layer inner and outer radius!
CMSEL,S,quadin%q%
CMSEL,A,quadout%q%
CM,quad%q%,AREA
ALLSEL

!Name for Wedge layer inner radis!
ASEL,S,,,%q%7001,%q%7003
CM,wedin%q%,AREA
ALLSEL

!Name for Wedge layer outer radius!
ASEL,S,,,%q%7004
CM,wedout%q%,AREA
ALLSEL

!Name for Wedge layer inner and outer radius!
CMSEL,S,wedin%q%
CMSEL,A,wedout%q%
CM,wedge%q%,AREA
ALLSEL
```

```
!-------------------------Collar----------------------------!
NUMSTR,KP,%q%201
NUMSTR,LINE,%q%201
NUMSTR,AREA,%q%201

!-----------------Keypoints------------------!
CSYS,1

K,%q%201,r1,ang90
K,%q%202,r1,ang44
K,%q%203,r2,ang43
K,%q%204,r2,ang90

K,%q%205,r2,ang42
K,%q%206,r2,ang33
K,%q%207,r2,ang64
K,%q%208,r3,ang63
K,%q%209,r3,ang90

K,%q%210,r3,ang62
K,%q%211,r3,ang53
K,%q%212,r3,ang11
K,%q%213,r3+collarth,ang12
K,%q%214,r3+collarth,ang90

!-------------------Lines--------------------!
CSYS,1
L,%q%201,%q%202,9
CSYS,0
L,%q%202,%q%203,15
CSYS,1
L,%q%203,%q%204,9
CSYS,0
L,%q%204,%q%201,15

CSYS,1
L,%q%203,%q%205,3
L,%q%205,%q%206,5
L,%q%206,%q%207,1
CSYS,0
L,%q%207,%q%208,15
CSYS,1
L,%q%208,%q%209,18
CSYS,0
L,%q%209,%q%204,15

CSYS,1
L,%q%208,%q%210,32
L,%q%210,%q%211,6
L,%q%211,%q%212,24
CSYS,0
L,%q%212,%q%213,10
CSYS,1
L,%q%213,%q%214,80
CSYS,0
L,%q%214,%q%209,10

!-------------------Areas--------------------!
A,%q%201,%q%202,%q%203,%q%204
A,%q%204,%q%203,%q%205,%q%206,%q%207,%q%208,%q%209
A,%q%209,%q%208,%q%210,%q%211,%q%212,%q%213,%q%214

!--------------------Mesh--------------------!
TYPE,2
REAL,2
MAT,2
```

```
ASEL,S,,,%q%201
AATT,2,2,2
AMAP,%q%201,%q%201,%q%202,%q%203,%q%204

ASEL,S,,,%q%202
AATT,2,2,2
AMAP,%q%202,%q%204,%q%207,%q%208,%q%209

ASEL,S,,,%q%203
AATT,2,2,2
AMAP,%q%203,%q%209,%q%212,%q%213,%q%214

ALLSEL

!-----------------Components-----------------!
!Name for collar!
ASEL,S,,,%q%201,%q%203
CM,collar%q%,AREA
ALLSEL

!--------------------------Yoke-----------------------------!
NUMSTR,KP,%q%301
NUMSTR,LINE,%q%301
NUMSTR,AREA,%q%301

!-----------------Keypoints------------------!
CSYS,1
K,%q%301,r3+collarth,ang11
K,%q%302,yokerout,ang12
K,%q%303,yokerout,ang82
K,%q%304,r3+collarth,ang81

!-------------------Lines--------------------!
CSYS,0
L,%q%301,%q%302,15
CSYS,1
L,%q%302,%q%303,80
CSYS,0
L,%q%303,%q%304,15
CSYS,1
L,%q%304,%q%301,80
CSYS,0

!-------------------Areas--------------------!
A,%q%301,%q%302,%q%303,%q%304

!--------------------Mesh--------------------!
TYPE,1
REAL,1
MAT,4

ASEL,S,,,%q%301
AATT,4,1,1
AMAP,%q%301,%q%301,%q%302,%q%303,%q%304

ALLSEL

!-----------------Components-----------------!
!Name for yoke!
ASEL,S,,,%q%301
CM,yoke%q%,AREA
ALLSEL

!---------------------------Shell--------------------------!
NUMSTR,KP,%q%401
NUMSTR,LINE,%q%401
NUMSTR,AREA,%q%401
```

```
!-----------------Keypoints------------------!
CSYS,1
K,%q%401,yokerout,ang11
K,%q%402,yokerout+shellth,ang12
K,%q%403,yokerout+shellth,ang90
K,%q%404,yokerout,ang90

!-------------------Lines--------------------!
CSYS,0
L,%q%401,%q%402,5
CSYS,1
L,%q%402,%q%403,80
CSYS,0
L,%q%403,%q%404,5
CSYS,1
L,%q%404,%q%401,80
CSYS,0

!-------------------Areas--------------------!
A,%q%401,%q%402,%q%403,%q%404

!--------------------Mesh--------------------!
TYPE,1
REAL,1
MAT,2

ASEL,S,,,%q%401
AATT,2,1,1
AMAP,%q%401,%q%401,%q%402,%q%403,%q%404

ALLSEL

!-----------------Components-----------------!
!Name for shell!
ASEL,S,,,%q%401
CM,shell%q%,AREA
ALLSEL

!-----------------------Contact pair-----------------------!
!Collar - Quadrant layer inner radius!
CSYS,1
REAL,13
MAT,13
!Generate the target surface
CMSEL,S,quadin%q%
LSLA,S,1
LSEL,R,LOC,X,(r1+r2)/2
LSEL,R,LOC,Y,(ang43+ang44)/2
NSLL,S,1
ESLN,S,0
TYPE,13
ESURF,ALL
ALLSEL
!Generate the contact surface
CMSEL,S,collar%q%
LSLA,S,1
LSEL,R,LOC,X,(r1+r2)/2
LSEL,R,LOC,Y,(ang43+ang44)/2
NSLL,S,1
ESLN,S,0
TYPE,113
ESURF,ALL
ALLSEL

!Collar - Quadrant layer outer radius!
CSYS,1
```

```
REAL,14
MAT,14
!Generate the target surface
CMSEL,S,quadout%q%
LSLA,S,1
LSEL,R,LOC,X,(r2+r3)/2
LSEL,R,LOC,Y,(ang63+ang64)/2
NSLL,S,1
ESLN,S,0
TYPE,14
ESURF,ALL
ALLSEL
!Generate the contact surface
CMSEL,S,collar%q%
LSLA,S,1
LSEL,R,LOC,X,(r2+r3)/2
LSEL,R,LOC,Y,(ang63+ang64)/2
NSLL,S,1
ESLN,S,0
TYPE,114
ESURF,ALL
ALLSEL

!Quadrant layer inner radius - collar (radial)!
CSYS,1
REAL,12
MAT,12
!Generate the target surface
CMSEL,S,quadin%q%
CMSEL,A,wedin%q%
LSLA,S,1
LSEL,R,LOC,X,r2
LSEL,R,LOC,Y,ang64,ang43
NSLL,S,1
ESLN,S,0
TYPE,12
ESURF,ALL
ALLSEL
!Generate the contact surface
CMSEL,S,collar%q%
LSLA,S,
LSEL,R,LOC,X,r2
LSEL,R,LOC,Y,ang64,ang43
NSLL,S,1
ESLN,S,0
TYPE,112
ESURF,ALL
ALLSEL

!Quadrant layer outer radius - collar (radial)!
CSYS,1
REAL,12
MAT,12
!  Generate the target surface
CMSEL,S,quadout%q%
CMSEL,A,wedout%q%
LSLA,S,1
LSEL,R,LOC,X,r3
LSEL,R,LOC,Y,ang12,ang63
NSLL,S,1
ESLN,S,0
TYPE,12
ESURF,ALL
ALLSEL
!Generate the contact surface
CMSEL,S,collar%q%
LSLA,S,1
```

```
LSEL,R,LOC,X,r3
LSEL,R,LOC,Y,ang12,ang63
NSLL,S,1
ESLN,S,0
TYPE,112
ESURF,ALL
ALLSEL

!Quadrant layer inner radius - Quadrant layer outer radius!
CSYS,
REAL,12
MAT,12
!Generate the target surface
CMSEL,S,quadin%q%
CMSEL,A,wedin%q%
LSLA,S,1
LSEL,R,LOC,X,r2
LSEL,R,LOC,Y,ang12,ang33
NSLL,S,1
ESLN,S,0
TYPE,12
ESURF,ALL
ALLSEL
!Generate the contact surface
CMSEL,S,quadout%q%
CMSEL,A,wedout%q%
LSLA,S,1
LSEL,R,LOC,X,r2
LSEL,R,LOC,Y,ang12,ang33
NSLL,S,1
ESLN,S,0
TYPE,112
ESURF,ALL
ALLSEL

!Collar - yoke!
CSYS,1
REAL,15
MAT,15
!Generate the target surface
CMSEL,S,collar%q%
LSLA,S,1
LSEL,R,LOC,X,r3+collarth
NSLL,S,1
ESLN,S,0
TYPE,15
ESURF,ALL
ALLSEL
!Generate the contact surface
CMSEL,S,yoke%q%
LSLA,S,1
LSEL,R,LOC,X,r3+collarth
NSLL,S,1
ESLN,S,0
TYPE,115
ESURF,ALL
ALLSEL

!Yoke - shell!
CSYS,1
REAL,12
MAT,12
!Generate the target surface
CMSEL,S,yoke%q%
LSLA,S,1
LSEL,R,LOC,X,yokerout
NSLL,S,1
```

```
ESLN,S,0
TYPE,12
ESURF,ALL
ALLSEL
!Generate the contact surface
CMSEL,S,shell%q%
LSLA,S,1
LSEL,R,LOC,X,yokerout
NSLL,S,1
ESLN,S,0
TYPE,112
ESURF,ALL
ALLSEL

!------------------------End Quadrant-----------------------!
*ENDDO

!-------------------------Components------------------------!
!Name for all Quadrants layer inner radius!
CMSEL,S,quadin1
CMSEL,A,quadin2
CMSEL,A,quadin3
CMSEL,A,quadin4
CM,coilin,AREA
ALLSEL

!Name for all Quadrants layer outer radius!
CMSEL,S,quadout1
CMSEL,A,quadout2
CMSEL,A,quadout3
CMSEL,A,quadout4
CM,coilout,AREA
ALLSEL

!Name for Coil!
CMSEL,S,coilin
CMSEL,A,coilout
CM,coil,AREA
ALLSEL

!Name for all Wedge layer inner radis!
CMSEL,S,wedin1
CMSEL,A,wedin2
CMSEL,A,wedin3
CMSEL,A,wedin4
CM,wedin,AREA
ALLSEL

!Name for Wedge layer outer radius!
CMSEL,S,wedout1
CMSEL,A,wedout2
CMSEL,A,wedout3
CMSEL,A,wedout4
CM,wedout,AREA
ALLSEL

!Name for total Wedge layer in and out!
CMSEL,S,wedin
CMSEL,A,wedout
CM,wedge,AREA
ALLSEL

!Name for total Collar!
CMSEL,S,collar1
CMSEL,A,collar2
CMSEL,A,collar3
CMSEL,A,collar4
```

```
CM,collar,AREA
ALLSEL

!Name for total Yoke!
CMSEL,S,yoke1
CMSEL,A,yoke2
CMSEL,A,yoke3
CMSEL,A,yoke4
CM,yoke,AREA
ALLSEL

!Name for total Shell!
CMSEL,S,shell1
CMSEL,A,shell2
CMSEL,A,shell3
CMSEL,A,shell4
CM,shell,AREA
ALLSEL

!----------------Contact Pairs of Quadrants-----------------!
!Gap:  Quadrant 1 - Quadrant 2!
CSYS,1
REAL,11
MAT,11
!Generate the target surface
CMSEL,S,yoke1
LSLA,S,1
LSEL,R,LOC,X,r3+collarth,yokerout
LSEL,R,LOC,Y,90-atan(gapyokein/(r3+collarth)),90-atan(gapyokeout/yokerout)
NSLL,S,1
ESLN,S,0
TYPE,11
ESURF,ALL
ALLSEL
!Generate the contact surface
CSYS,1
CMSEL,S,yoke2
LSLA,S,1
LSEL,R,LOC,X,r3+collarth,yokerout
LSEL,R,LOC,Y,90+atan(gapyokein/(r3+collarth)),90+atan(gapyokeout/yokerout)
NSLL,S,1
ESLN,S,0
TYPE,111
ESURF,ALL
ALLSEL

!Gap:  Quadrant 3 - Quadrant 4!
CSYS,1
REAL,11
MAT,11
!Generate the target surface
CMSEL,S,yoke3
LSLA,S,1
LSEL,R,LOC,X,r3+collarth,yokerout
LSEL,R,LOC,Y,270-atan(gapyokein/(r3+collarth)),270-atan(gapyokeout/yokerout)
NSLL,S,1
ESLN,S,0
TYPE,11
ESURF,ALL
ALLSEL
!Generate the contact surface
CSYS,1
CMSEL,S,yoke4
LSLA,S,1
LSEL,R,LOC,X,r3+collarth,yokerout
LSEL,R,LOC,Y,270+atan(gapyokein/(r3+collarth)),270+atan(gapyokeout/yokerout)
NSLL,S,1
```

```
ESLN,S,0
TYPE,111
ESURF,ALL
ALLSEL

!--------------------------End Geometry--------------------------!

!-------------------Constraints--------------------!
CSYS,0
ALLSEL
NSEL,R,LOC,X,0
D,ALL,UX,0
!D,ALL,UY,0

ALLSEL
NSEL,R,LOC,Y,0
D,ALL,UX,0
D,ALL,UY,0

FINISH

!-----------------------------Solver-----------------------------!
/SOLU
AUTOTS,ON
NROPT,FULL
NEQIT,150
ALLSEL

/TITLE,Pre-Stress
ALLSEL
LSWRITE
OUTRES,ALL,ALL
NSUBST,5
TIME,1
SOLVE

/TITLE,Coupling with COMSOL
*DO,q,1,4
  *DO,b,1,6
    *DO,t,1,nblock%b%
      CMSEL,S,turn%q%%b%%t%
      NSLA,S,1
      *GET,num,NODE,0,COUNT
      FCUM,ADD
      BF,ALL,TEMP,temp%q%%b%%t%
      F,ALL,FX,forcx%q%%b%%t%/num
      F,ALL,FY,forcy%q%%b%%t%/num
    *ENDDO
  *ENDDO
*ENDDO
ALLSEL
LSWRITE
OUTRES,ALL,ALL
NSUBST,5
TIME,2
SOLVE

FINISH

!--------------------------Postprocessor-------------------------!
/POST1

/AUTO,1
/DSCALE,1,OFF
/PLOPTS,INFO,1
/PLOPTS,LEG1,1
/PLOPTS,LEG2,0
```

```
/PLOPTS,LEG3,1
/PLOPTS,FRAME,1
/PLOPTS,TITLE,1
/PLOPTS,MINM,1
/PLOPTS,FILE,0
/PLOPTS,WINS,1
/PLOPTS,WP,0
/PLOPTS,DATE,0
/TRIAD,OFF

/RGB,INDEX,100,100,100, 0
/RGB,INDEX, 80, 80, 80,13
/RGB,INDEX, 60, 60, 60,14
/RGB,INDEX, 0, 0, 0,15

!------------------------First Solver-----------------------!
SET,1
ALLSEL
CMSEL,S,coil
ALLSEL,BELOW,AREA

!-----------------------Plots----------------------!
*IF,plots,EQ,1,THEN,
PLNSOL,S,EQV,1
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,11T_Dipole_Magnet000,JPG,,11T_Dipole_Magnet_pre-stress_eqv,JPG,
*ENDIF

!-----------------------Second Solver-----------------------!
SET,2

*IF,file,EQ,1,THEN,
!----------------Maximum Values file---------------!
*CFOPEN,Output,txt

CSYS,1
ALLSEL
CMSEL,S,coil
ESLA
NSLE,S,CORNER
NSORT,S,EQV,1
*GET,S_Max,SORT,,MAX
*GET,N_S_Max,SORT,,IMAX
*GET,LX_S_Max,NODE,N_S_Max,LOC,X
*GET,LY_S_Max,NODE,N_S_Max,LOC,Y

*VWRITE,
('Node ',' ','x coord',' ','y coord',' ','Max ','Stress ','EQV')
*VWRITE,N_S_Max,LX_S_Max,LY_S_Max,S_Max
(F7.0,' ',2(F9.4),' ',F20.3,' ')


ALLSEL
CMSEL,S,coil
ESLA
NSLE,S,CORNER
NSORT,EPTT,EQV,1
*GET,E_Max,SORT,,MAX
*GET,N_E_Max,SORT,,IMAX
*GET,LX_E_Max,NODE,N_E_Max,LOC,X
*GET,LY_E_Max,NODE,N_E_Max,LOC,Y

*VWRITE,
('Node ',' ','x coord',' ','y coord',' ','Max ','Strain ','EQV')
*VWRITE,N_E_Max,LX_E_Max,LY_E_Max,E_Max
```

```
(F7.0,' ',2(F9.4),' ',F15.7,' ')


ALLSEL
CMSEL,S,coil
ESLA
NSLE,S,CORNER
NSORT,U,SUM,1
*GET,U_Max,SORT,,MAX
*GET,N_U_Max,SORT,,IMAX
*GET,LX_U_Max,NODE,N_U_Max,LOC,X
*GET,LY_U_Max,NODE,N_U_Max,LOC,Y

*VWRITE,
('Node ',' ','x coord',' ','y coord',' ','Max ','Disp ','SUM')
*VWRITE,N_U_Max,LX_U_Max,LY_U_Max,U_Max
(F7.0,' ',2(F9.4),' ',F8.2,' ')

*CFCLOS
*ENDIF

!-----------------------Plots----------------------!
*IF,plots,EQ,1,THEN,
ALLSEL
CMSEL,S,coil
ALLSEL,BELOW,AREA

PLNSOL,EPTT,EQV,0
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,11T_Dipole_Magnet000,JPG,,11T_Dipole_Magnet_tt_strain_eqv,JPG,

PLNSOL,U,SUM,0
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,11T_Dipole_Magnet000,JPG,,11T_Dipole_Magnet_displacement_sum,JPG,

PLNSOL,S,EQV,0
/SHOW,JPEG
/REPLOT
/SHOW,CLOSE
/RENAME,11T_Dipole_Magnet000,JPG,,11T_Dipole_Magnet_stress_eqv,JPG,
*ENDIF
```

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Eidesstattliche Erklärung

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Erklärung zur Abschlussarbeit gemäß §22, Abs. 7 APB
Hiermit versichere ich, die vorliegende Abschlussarbeit ohne Hilfe Dritter nur mit den angegebenen Quellen und Hilfsmitteln angefertigt zu haben. Alle Stellen, die aus den Quellen entnommen wurden, sind als solche kenntlich gemacht worden. Diese Arbeit hat in gleicher Form oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.

Darmstadt, den 11.09.2016

T. Griesemer
Unterschrift