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DEVELOPING A DIGITAL TWIN OF CERN'S ELECTRON BEAM TEST BENCH BASED ON A SIMULATOR-INDEPENDENT MBSE SYSTEM DESCRIPTION

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The Electron Beam Test Stand (EBTS) is a modular electron beam testing facility at CERN that began operations in early 2022. It features a hollow electron beam source that moves along a beam line approximately 3 meters long, guided by several resistive solenoids. The entire beam-line operates under ultra-high vacuum conditions (below $2\text{e-}8$ mbar), within radiation-controlled areas, and uses high-voltage equipment. Despite the presence of critical safety interlocks, most control mechanisms remain manually operated, posing risks to users due to significant X-ray radiation from the accelerated electron beam and the use of high-voltage equipment.

The primary goal of this thesis is to develop a modular and standardised digital twin of the entire test stand to monitor, predict, control, and gather data in a fully automated manner. The research hypothesis explored is whether a simulator-independent description of the system—the 'electron beam test stand'—is feasible and can act as a blueprint for a Digital Twin. To test this hypothesis a Model-Based Systems Engineering (MBSE) model is developed that describes the physical twin—EBTS at CERN—in a simulator-independent manner. This MBSE model then serves as the 'blueprint' for the Digital Twin, which is seen as an experimentable system model that meets the stated requirements.

The Digital Twin is designed to enable complete remote operation, enhancing accessibility and reducing worker exposure to hazardous conditions. Additionally, real-time simulation and analysis capabilities are critical for examining beam dynamics, and overall system performance, thereby speeding up experimental setups and improving research outcomes. Establishing comprehensive system requirements within the Model-Based Systems Engineering (MBSE) framework, and adopting the Systems Modelling Language (SysML), is crucial for ensuring systematic and efficient system development. The SysML model is subsequently validated and simulated to confirm its accuracy and reliability.

The development of a digital twin, which includes data acquisition, control systems, and automated operations, is another essential task aimed at replicating the physical system's behavior. The configuration of hardware involving NI Compact RIO, data acquisition modules, control systems, and power supplies is crucial for realising the digital twin's functionality. In parallel, software development which includes user interface design, cloud-based data management, and the implementation of soft interlocks, facilitates seamless system operation and data handling. Documentation of standardised processes finally ensures ease of adaptation to different test benches, enhancing repeatability and scalability across various experimental setups.

Kurzfassung

Der Elektronenstrahlprüfstand (EBTS) am CERN, der seit Anfang 2022 in Betrieb ist, spielt eine zentrale Rolle bei Elektronenstrahlexperimenten, insbesondere bei der Entwicklung der Hollow Electron Lens für den High Luminosity - Large Hadron Collider (HL-LHC), ist jedoch auf manuelle Kontrollsysteme angewiesen. Dadurch sind die Bediener aufgrund von Hochspannungsgeräten und Röntgenstrahlung erheblichen Sicherheitsrisiken ausgesetzt. In dieser Arbeit wird die Entwicklung eines modularen und standardisierten digitalen Zwillings des EBTS vorgeschlagen, der die Betriebssicherheit, die Effizienz und die Datenverwaltung verbessern und damit die mit dem manuellen Betrieb verbundenen Risiken verringern soll.

Die Forschungsarbeit untersucht die Hypothese, ob ein simulatorunabhängiges Modell des EBTS mit Hilfe von Model-Based Systems Engineering (MBSE) effektiv entwickelt und als „Blaupause“ für die Entwicklung des digitalen Zwillings verwendet werden kann. Unter Verwendung der simulatorunabhängigen Systems Modelling Language (SysML) wird in dieser Arbeit eine umfassende Darstellung der Struktur, des Verhaltens und der Verbindungen des EBTS entwickelt, die dann in einem digitalen Zwillingsrahmen abgebildet wird.

Das Modell definiert umfassende Systemanforderungen und Verhaltensweisen mithilfe der SysML-Sprache, und die Entwicklung des digitalen Zwillings mit integrierten Funktionen für die Datenerfassung, die Steuerung und den automatisierten Betrieb wird durchgeführt. Die Hardwarekonfiguration umfasst NI CompactRIO, Datenerfassungsmodule, Steuersysteme, Vakuummessgeräte und Stromversorgungen. Die Softwareentwicklung ergänzt dies durch UI-UX-Design und robustes cloudbasiertes Datenmanagement. Der digitale Zwillings nutzt das LabVIEW-Framework und lässt sich in die bestehende Dateninfrastruktur des CERN integrieren: CCDE (Control Configuration Data Editor), NXCALS (Next CERN Accelerator Logging Service) und CMW (Controls Middleware) Server.

Darüber hinaus beinhaltet der digitale Zwillings prädiktive Simulationen für Magnetfelder und führt eine Quantifizierung der Unsicherheit für die Größe und Position des Querstrahls durch, was den Einblick in das Systemverhalten vertieft. Diese Arbeit zeigt, wie ein digitaler Zwillings, der auf einem simulatorunabhängigen MBSE-Framework aufbaut, den Betrieb und die Sicherheit komplexer experimenteller Prüfstände wie dem EBTS verändern kann und als Prototyp für zukünftige Anwendungen in ähnlichen Umgebungen dient.

Keywords: Digitaler Zwillings, Elektronenstrahlprüfstand (EBTS), Simulatorunabhängig, Modellbasierte Systemtechnik (MBSE), Fernbetrieb, Echtzeitsimulation, Vorhersagesimulationen, Quantifizierung von Unsicherheiten

Abstract

The Electron Beam Test Stand (EBTS) at CERN, operational since early 2022, plays a pivotal role in electron beam experiments, particularly for the Hollow Electron Lens development for High Luminosity - Large Hadron Collider (HL-LHC) but is challenged by its reliance on manual control systems. This exposes operators to significant safety risks due to high voltage apparatus and X-ray radiation. This thesis proposes the creation of a modular and standardised digital twin of the EBTS, designed to enhance operational safety, efficiency, and data management, thus reducing the risks associated with manual operations.

The research investigates the hypothesis whether a simulator-independent model of the EBTS can be effectively developed using Model Based System Engineering (MBSE) and used as a 'blueprint' for its digital twin development. Utilising the simulator-independent Systems Modelling Language (SysML), the thesis develops a comprehensive representation of the EBTS's structure, behaviour, and interconnections which is then mapped into a digital twin framework.

The model defines comprehensive system requirements and behaviours through the SysML language, and the development of the digital twin with integrated functionalities for data acquisition, control systems, and automated operations is carried out. The hardware configuration includes NI CompactRIO, data acquisition modules, control systems, vacuum gauges, and power supplies. Software development complements this with UI-UX design and robust cloud-based data management. The digital twin leverages the LabVIEW framework and integrates with CERN's existing data infrastructure: CCDE (Control Configuration Data Editor), NXCALS (Next CERN Accelerator Logging Service), and CMW (Controls Middleware) Server.

Additionally, the digital twin incorporates predictive simulations for magnetic fields and conducts uncertainty quantification for the transverse beam size and location, enhancing the depth of insights into the system behaviour. This thesis demonstrates how a digital twin, built on a simulator-independent MBSE framework, can transform the operation and safety of complex experimental test stands such as the EBTS, serving as a prototype for future applications in similar settings.

Keywords: Digital Twin, Electron Beam Test Stand (EBTS), Simulator-Independent, Model Based Systems Engineering (MBSE), Remote Operation, Real-Time Simulation, Predictive Simulations, Uncertainty Quantification

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Glossary

BDB	Beam Diagnostic Box.
BGC	Beam Gas Curtain.
BPM	Beam Position Monitor.
CCDE	Control Configuration Data Editor.
CERN	European Organization for Nuclear Research.
CMW	Controls Middleware.
EBTS	Electron Beam Test Stand.
ECTS	Electron Cooler Test Stand.
FEC	Front-End Computer.
FESA	Front-End Software Architecture.
HEL	Hollow Electron Lens.
HL-LHC	High Luminosity LHC.
LHC	Large Hadron Collider.
MBSE	Model Based System Engineering.
NEWTS	Novel Electron Window Test Stand.
PE	Physical Entity.
SMDT	State Machine Diagram Transfer.
SysML	Systems Modeling Language.
TEDSMA	Template-based Event Driven State Machine Architecture.
UML	Unified Modelling Language.
USB	Universal Serial Bus.
VE	Virtual Entity.
XMI	XML Metadata Interchange.
YAG:Ce	Yttrium Aluminium Garnet: Cerium activated.

1 Introduction

European Organisation for Nuclear Research (CERN) and Particle Accelerators: European Organization for Nuclear Research (CERN), represents the epitome of scientific inquiry and CERN collaboration. CERN is a research organisation that operates some of the largest particle accelerators in the world. Established in 1954 near Geneva, Switzerland, CERN currently comprises of 23 member states and 11 associate member states. It employs over 2,660 scientific, technical, and administrative staff members, and hosts about 12,400 users from institutions in more than 70 countries [1]. The primary goal of research at CERN is fundamental physics. Focusing on particle/high energy physics, CERN has made significant contributions in the field and also in other related domains. CERN gathers its expertise in three main pillars namely: Accelerators, Detectors, and Computing. The accelerator complex at CERN comprises a series of interconnected particle accelerators shown in figure 1.1 designed to elevate particles to progressively higher energies. Each accelerator within this system serves to increase the energy of a particle beam before transferring it to the subsequent accelerator in the sequence. At the end of the sequence is the Large Hadron Collider (LHC), where particle beams are propelled to a remarkable 6.5 TeV per beam. The collision of the particle beam at the Large Hadron Collider (LHC) occurs at four interaction points. These interaction points house four different experiments: A Toroidal LHC Apparatus (ALICE), Compact Muon Solenoid (CMS), Large Hadron Collider Beauty (LHCb) and A Toroidal LHC Apparatus (ATLAS). These experiments house detectors which can precisely measure and track the collision remnants of two colliding proton or ion beams. Data from the detectors are first passed through triggers to gather only relevant data, which is then stored and processed all over the world in the Worldwide LHC Computing Grid. Through its relentless pursuit of knowledge and unwavering commitment to excellence, CERN continues to inspire scientific innovation and shape our understanding of the universe, enriching both fundamental physics and applied sciences on a global scale.

1.1 Electron Beam Research at CERN

Electron beam research at CERN encompasses a wide range of experimental techniques and technologies, including the utilisation of technologies such as Hollow Electron Lenses [3] and electron cooling [4]. These cutting-edge methods play crucial roles in various aspects of particle physics research, enhancing our ability to explore fundamental interactions and phenomena. Hollow Electron Lenses represent a sophisticated approach to manipulating charged particle beams. By employing carefully controlled electron beams, these lenses can mitigate beam-beam interactions and mitigate instabilities in high-intensity particle beams. This technology is

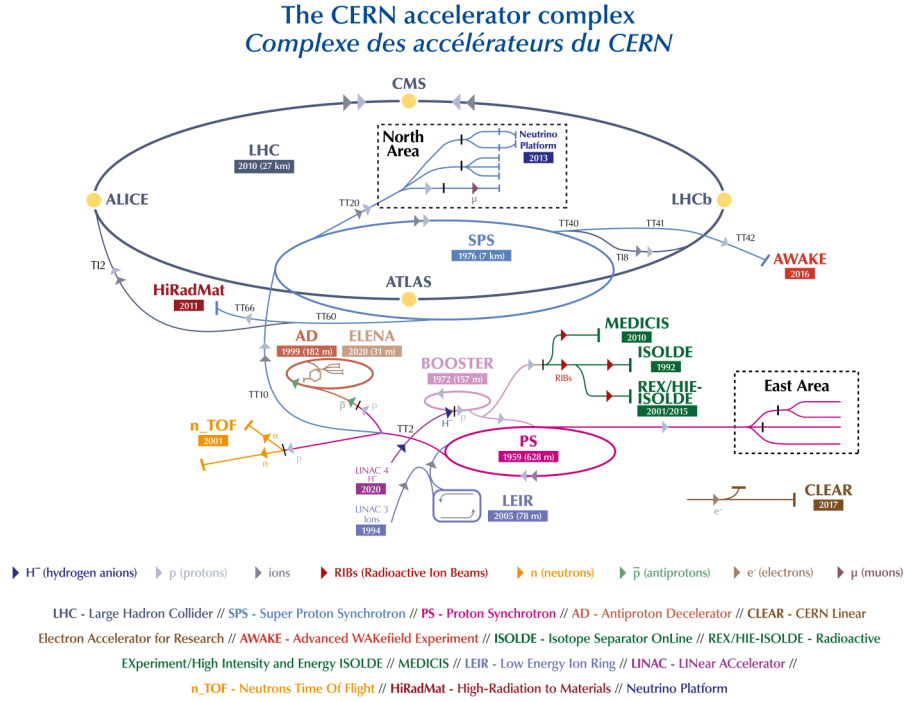


Figure 1.1: Entire CERN Accelerator Complex with all Accelerators, Collision and Fix Target Experiments [2]

particularly valuable in particle accelerators where dense bunches of particles are accelerated to high energies and collide with each other. By effectively shaping and steering the particle beams, hollow electron lenses contribute to improving beam quality and stability, which is essential for conducting precise and reliable experiments. Electron cooling is another essential technique utilised in particle accelerators for enhancing beam quality. In electron cooling, a low-energy electron beam is overlapped with a high-energy ion beam, leading to the transfer of energy and momentum from the ions to the electrons. As a result, the ion beam's velocity spread and transverse emittance are reduced, leading to a denser and more focused beam. This process effectively "cools down" the ion beam, increasing its density and improving its quality for various applications, including high-energy collision experiments. Furthermore, electron beams play a vital role in experiments conducted at CERN's Antiproton Decelerator (AD), where they are utilised for precision measurements of antimatter properties and fundamental symmetries. Beyond particle physics, electron beams find application in diverse research endeavours, including material science and medical applications, across CERN's experimental facilities. The Electron Beam Test Stand (EBTS) is a joint project at CERN in collaboration with the Accelerator Research and Innovation for European Science and Society (ARIES) initiative, specifically designed as part of the High Luminosity Large Hadron Collider (HL-LHC) project. Perveance of an electron beam defines the significance of the space charge effect on the beam's motion. Since electron beam motion is dominated mainly by the space charge effect, perveance be-

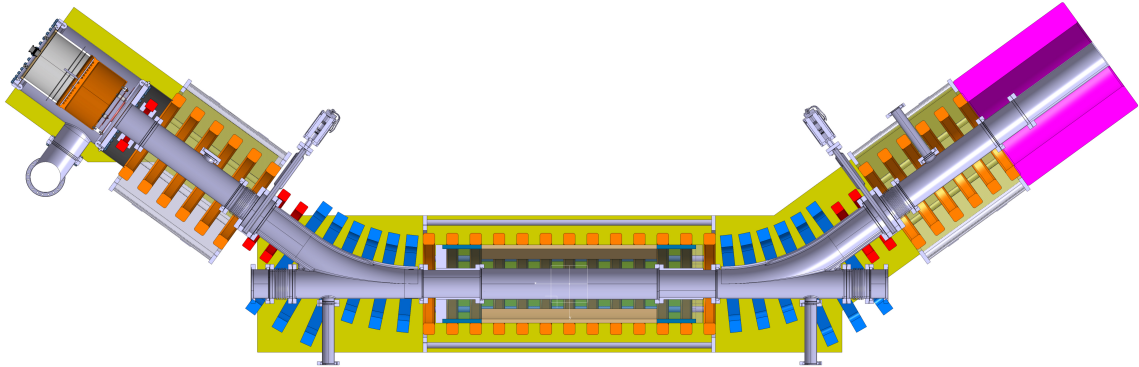


Figure 1.2: Cross Sectional View of the ECTS with all major components in the system. The tank-like structure on the top leftmost corner is the electron gun, while the pink structure on the rightmost end is the collector. The Orange and Blue Coils are Solenoids which create a magnetic field to manipulate the electron beam

comes a crucial parameter for study. This specialised testing facility includes a high-perveance electron gun that generates a hollow electron beam. It is supported by a magnetic system consisting of resistive solenoid magnets equipped with both horizontal and vertical corrector coils. Equipped with a range of sophisticated beam measurement tools, the EBTS holds significant promise as a valuable resource for the advancement of electron beam technologies, particularly in the field of sources and equipment for electron cooling systems. Many such independent electron beam research setups are currently in use or development at CERN. One of them is the above-mentioned EBTS which was primarily built for the Hollow Electron Lens Project. Other test stands include Electron Cooler Test Stand (ECTS) and Novel Electron Window Test Stand (NEWTS) which were built for Electron Cooling and ultra-thin beam exit window characterisation respectively. All three test stands are completely independent of each other, but primarily use similar instrumentation, data acquisition and control systems.

1.2 Data Acquisition and Control Systems for Electron Beam Test Stands

The above-mentioned test stands generally comprise an electron gun which primarily works on the principle of Thermionic Emission. The gun is controlled by multiple high-voltage power supplies used to heat the filament, extract the beam, and also electrostatically accelerate the beam from the heated cathode. Numerous Solenoids or Einzel Lenses are deployed to bend or shape the beam in a desired orientation. Multiple beam instrumentation devices are installed on the beamline to measure properties of the electron beam which include but are not limited to Beam Current, Beam Shape, Beam Position, Charge Distribution, and Beam Energy. The entire system operates under Ultra-High Vacuum Regime (lower than 1.0×10^{-8} mbar), and the

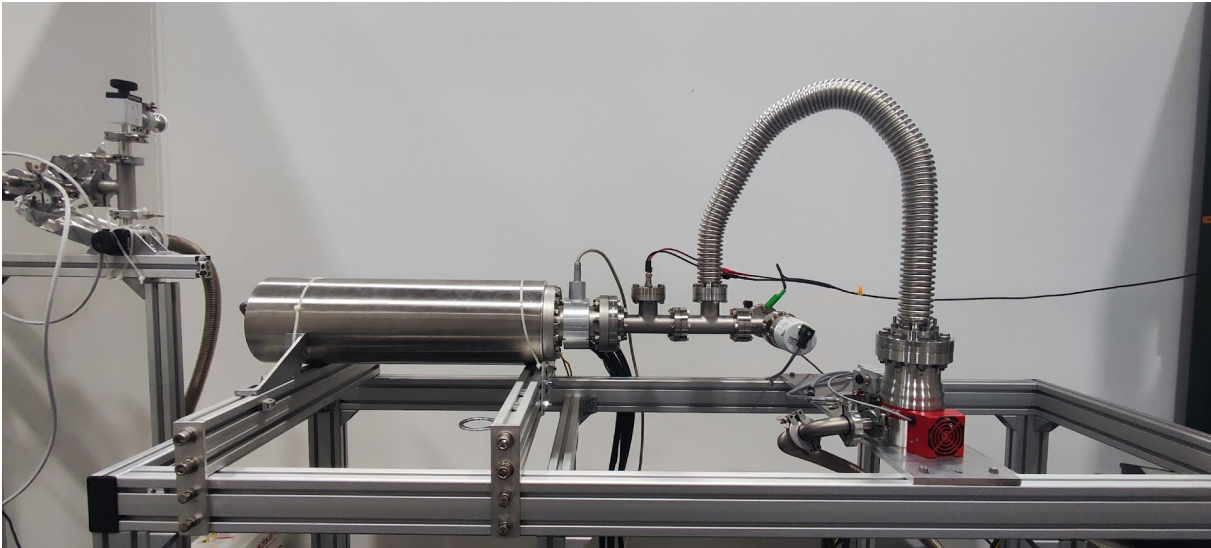


Figure 1.3: NEWTS Test Stand with a recommissioned Electron Gun and a temporary Beam Pipe with a Faraday Cup inside to measure the extracted current through the BNC Feed-through

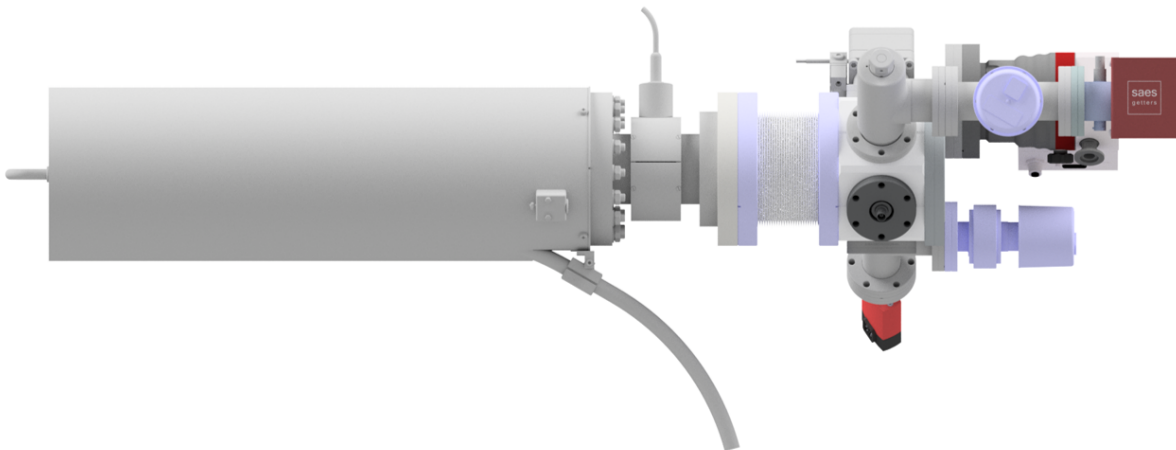


Figure 1.4: Proposed addition to NEWTS Test Stand which includes beam diagnostic instrumentation

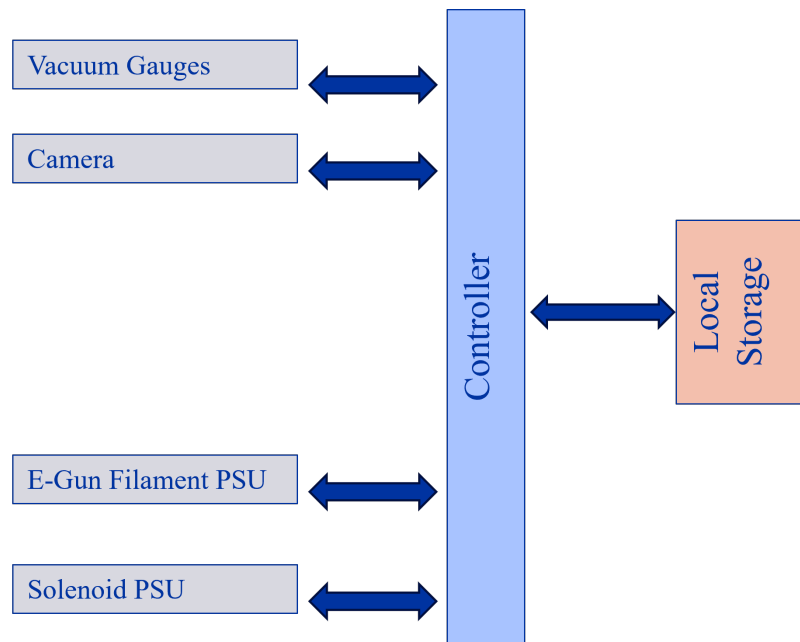


Figure 1.5: Present control architecture for EBTS with all instruments and sensors connected to the controller and data stored locally for all relevant information from the Test Stand

electron beam impinging on screens and other materials generates X-Ray Radiation, which is why all the test stands are located inside areas designated as Controlled Radiation Areas. All above-mentioned test benches with their supporting Power Supplies, Actuation systems, sensing devices, etc are connected via respective cabling to a standard 19-inch rack setup. Specifically for EBTS, numerous racks as shown in figure 1.6 are placed adjacent to the test stand within the confines of the lab house all of this equipment. Electron gun power supplies, solenoid power supplies, vacuum gauges, etc. are connected to an industrial controller. The controller currently being used for the EBTS is the National Instruments PXIe. NI-PXIe is an industrial computer that is a test and measurement platform that combines a controller with measurement instruments in a multi-slot chassis. It is developed to be an open standard for test hardware. The architecture of PXIe makes it possible to synchronise measurements across multiple modules or multiple chassis [5]. The ECTS currently does not use a standardised industrial controller due to legacy implementation reasons. But efforts would be taken in the future to move towards a more standardised platform. The current Data Acquisition and Control Architecture for the EBTS is as shown in figure 1.5. All the instrumentation and sensors are directly connected to the controller which runs independently. All data is stored locally on the system and access to the test stand has to be done by physically being present in the laboratory.



Figure 1.6: Four 19-inch control racks for EBTS with a locally connected monitor (left) for control and data access

1.3 Proposal for MBSE and Digital Twins for Modular Experimental Test Stands

The reliance on manual controls not only heightens the risk to human operators but also limits the efficiency and scalability of experimental setups. To address these challenges, this thesis proposes the development of a Digital Twin for the EBTS that utilises a Model-Based Systems Engineering (MBSE) approach. This innovative approach aims to enhance operational safety, efficiency, and data management, thereby reducing the risks associated with manual operations. Since the test stand is not a fixed system, but an ever-changing experimental test stand, the central hypothesis of this thesis is that a simulator-independent MBSE model can be effectively developed and utilised as a blueprint for constructing a Digital Twin of the EBTS. This involves developing a comprehensive model that captures the structure, behavior, and interconnections of the EBTS using a simulator-independent language. This model is expected to serve not only as a detailed representation of the EBTS but also as a functional system capable of simulating real-world behaviours and interactions.

The test stands mentioned in section 1.1 have been meticulously designed to possess a high degree of modularity, enabling them to accommodate various experiments and validate intricate beam instrumentation before integration into the operational framework of the accelerator complex shown in figure 1.1. Given the dynamic nature of their construction and the evolving objectives concerning experimental outcomes, maintaining and preserving these test stands requires diligent attention. Typically, an independent researcher or a team undertakes this responsibility through a knowledge dissemination approach, encompassing physical records, computer-aided design (CAD) schematics, circuit diagrams, and exhaustive details pertinent to a particular iteration of the test bench. Consequently, the heavy reliance on document-based practices and oral

tradition presents a formidable challenge in onboarding new researchers who might potentially oversee the operation of these test stands. Furthermore, the unavailability of an expert during certain periods incapacitates the entire test stand, rendering its capabilities dormant. Such inefficiencies could be circumvented by embracing enhanced system management methodologies facilitated by MBSE and the implementation of operational Digital Twins.

MBSE is identified as a strategic approach to address the complexity of systems engineering through the use of formalised models rather than traditional document-based information exchange. The integration of MBSE with Digital Twin technology allows for real-time, dynamic modelling and analysis of the EBTS, facilitating better decision-making, predictive maintenance, and system optimisation. MBSE includes models to support requirements, design, configuration, and behaviour of the system. There exists communication between the system developers focusing on different aspects of the same system. MBSE can be implemented to maintain a central body of knowledge for the system and it aims to replace document-centred methods with model-based, and machine-readable methodologies [6].

In recent years, Digital Twin has become increasingly relevant with the development of intelligent systems [7], which has become essential to modern industrial developments and production paradigms [8]. Digital Twin refers to virtual and real mapping by constructing the mapping relationship between the digital virtual entity and physical entity. It maps the physical entity in the physical space to the digital space and has functions such as data mapping, analysis and decision-making, and control execution [9]. It uses data to simulate the behaviour of physical entities in the real environment and to increase or expand the ability of physical entities through virtual real interaction feedback, data fusion analysis, decision iteration optimisation, and other means. Digital Twin technology integrates intelligent sensing technology, co-simulation technology, data analysis technology, and intelligent control technology, which can effectively synchronise virtual and physical products by making full use of data such as physical models, sensor updates, and operation history. By establishing a twin model of a physical entity and using sensor monitoring, data transmission, and other technologies, Digital Twin achieves real-time interactive mapping with the physical entity in the digital space, reflecting the full life cycle of the physical entity.

An MBSE approach along with a Digital Twin for the Electron Beam Test Stand (EBTS) at CERN is proposed for several reasons, out of which the core motivation stems:

- **Modularity and Standardisation:** The EBTS Digital Twin, developed using Model-Based Systems Engineering (MBSE), provides a modular and standardised representation of the test stand. This not only ensures consistency in system descriptions but also serves as a blueprint for future experiments and test facilities. The modularity allows for easy adaptation to different scenarios and environments, contributing to the versatility of the Digital Twin.

- **Experimentation and Optimisation:** The Digital Twin acts as an experimentable system model, allowing researchers to simulate and optimise various operational scenarios. This capability is invaluable for testing hypotheses, refining control strategies, and exploring the potential of the EBTS in different research contexts.
- **Safety Enhancement:** The EBTS involves exposure to significant X-ray radiation and high-voltage apparatus, posing inherent safety challenges. A Digital Twin allows for the development and implementation of automated safety protocols, reducing the reliance on manual controls and minimising the risk to operators. This is particularly important in high-risk environments where the accelerated electron beam can generate hazardous radiation.
- **Remote Operation:** A Digital Twin enables complete remote operation of the EBTS. This is essential for situations where physical access may be limited or when conducting experiments in hazardous conditions. Remote operation enhances operational flexibility, allowing researchers to control and monitor the EBTS from a safe distance.
- **Real-time Monitoring and Prediction:** The Digital Twin serves as a virtual representation of the physical EBTS, facilitating real-time monitoring and prediction of system behaviour. By continuously collecting and analysing data from the Digital Twin, operators can identify potential issues, predict performance trends, and take proactive measures to ensure the smooth operation of the electron beam test facility.
- **Efficient Data Collection and Analysis:** Advanced beam instrumentation, such as Yttrium Aluminium Garnet: Cerium activated (YAG:Ce) screens, Faraday cups, and Beam Position Monitors, generates a significant amount of data during experiments. A Digital Twin streamlines data acquisition and analysis processes, allowing for efficient handling of large datasets. This is critical for extracting meaningful insights from experiments and improving the overall efficiency of the research conducted at the EBTS.

By addressing the unique challenges presented by the EBTS at CERN, this thesis would not only contribute to the safety and efficiency of this particular test stand that is EBTS but also demonstrate the potential of Digital Twins to transform the operation and management of complex experimental test stands in general. The development of a Digital Twin based on a simulator-independent MBSE framework serves as a prototype for future implementations across various settings.

1.4 Overview

The core hypothesis of this thesis investigates whether a simulator-independent MBSE model can be effectively developed and utilised as a blueprint for the Digital Twin of the EBTS. This hypothesis challenges the traditional, simulation-dependent approaches by proposing a flexible, scalable, and more accessible model that can be adapted across various systems without the constraints of specific simulation platforms.

This thesis presents the development of a Digital Twin for the EBTS at CERN, leveraging MBSE to create a modular and standardised digital representation of the test stand. The Digital Twin aims to improve the test stand's operational safety, efficiency, and data management by enabling complete remote operation and real-time monitoring and control of the system. This approach not only mitigates the risks associated with manual operations involving high-voltage equipment and X-ray radiation but also provides a scalable framework that could be adapted to other experimental test stands at CERN.

A brief overview and context of the research are provided in this chapter which sets the stage by introducing CERN, its mission, the role of electron beam technology, and the specific objectives and hypotheses of the thesis. The motivation is supported by reviewing the state of the art in developing MBSE-based Digital Twins in chapter 2. Extending the current state of the art, a detailed description of the MBSE approach used to model the EBTS and the integration of this model into a Digital Twin framework as a 'blueprint' is explained in great detail in chapter 3. This blueprint is then developed into a comprehensive Digital Twin framework, presented in Chapter 4. Step-by-step development of the twin and inclusion of simulation models have been detailed. Building upon the framework built for Digital Twin, the system implementation is presented for the particular case of EBTS. Chapter 5 covers all technical aspects of applying the Digital Twin model at the EBTS, including hardware configurations and software development of the twin infrastructure. It also discusses how the Digital Twin is made accessible to users and examines the findings of the initial hypothesis. Lastly, the summary of the research outcomes and potential directions for future research expanding the scope of Digital Twins at CERN and beyond is concluded in chapter 7.

2 State of the Art

This chapter analyses the current state of the art in MBSE based Digital Twin development methodologies. The test stands to hold the potential to leverage the structured approach of MBSE to enhance system interconnectivity and optimise system performance. The creation of Digital Twins through MBSE has been recognised as a starting point for system optimisation across various domains, with the establishment of conceptual frameworks that can be used as research test stands for further development and optimisation.

MBSE provides a structured framework for organising modelling, simulation, and analysis artefacts, which is crucial for the complexity of aerospace systems and system-of-systems. Isolated MBSE tools are no longer sufficient without a flexible infrastructure to support model integration, tool interoperability, experimentation, and data collection. A demonstrated example of a Digital Twin-enabled MBSE test bed is built for experimentation with UAV swarms for dynamic scenario execution, monitoring, visualisation and control [10]. The paper clearly defines the methodology which employs a smart dashboard to support rigorous experimentation. The combination of MBSE languages, tools, and methods has been instrumental in developing Digital Twins, enhancing system interconnectivity and simplifying system optimisation.

2.1 MBSE Descriptions for Experimental Test Stands

Model-Based Systems Engineering (MBSE) is a perspective towards system design and development that emphasises the use of models to represent and analyse different aspects of a system. The approach shifts from traditional document-centric engineering to a focus on models throughout the system life cycle. This paradigm is increasingly being applied to the development and testing of complex systems, including experimental test stands.

A prototype MBSE research testbed serves as a versatile platform for experimenting with a range of modelling, analysis, simulation, verification, and validation techniques [11]. The paper discusses the development of a MBSE test bed aimed at facilitating experimentation and research in complex system modelling, analysis, simulation, verification, and validation. It outlines the key features, including infrastructure support, security measures, scenario authoring capabilities, multi-domain system modelling, simulation characteristics, and advanced repositories. Although it is primarily designed to support researchers in aerospace and automotive industries, the research on using prototype MBSE test beds can be easily extensible to other domains, by providing a platform for exploring diverse modelling approaches and collecting

performance data under different conditions and assumptions. The paper also provides a Python XMI translation tool that automatically populates the asset container in Unity 3D from SysML models. This example of an automated conversion tool provides the basis for employing the MBSE methodology for the translation into Digital Twins. This thesis builds upon the technology to provide the possibility of a similar utility tool for LabVIEW, which is used as a backbone infrastructure in developing Digital Twin for EBTS. This is explained in detail in chapter 5.

Kaslow et al. explore the application of MBSE to CubeSat missions, utilising the System Modelling Language (SysML) [12]. The paper outlines the evolution of MBSE practices within the context of CubeSat projects, starting from the development of a CubeSat reference model applied to the Radio Aurora Explorer (RAX) mission to incorporating behaviours and interfacing with Commercial Off the Shelf (COTS) simulation tools in subsequent phases. The paper discusses the alignment of the models with the CubeSat life-cycle stages, stakeholder identification, and the CubeSat operational domain. The next steps involve validating the models by applying them to a hypothetical mission and rolling out the CubeSat Reference Model to aerospace engineering courses and programs. Overall, the research highlights the potential of MBSE to improve the design, analysis, and verification of CubeSat missions, providing a structured approach for system development from conceptualisation to decommissioning.

Madni et al. presents an MBSE tested designed for rapid and cost-effective prototyping and evaluation of system modelling approaches [13]. The test bed allows experimentation with different models, algorithms, and operational scenarios. Key lessons learned from the prototype implementation include the importance of adapting the complexity of the system model to the complexity of the scenario, starting with simple scenarios to ensure safety requirements are met and progressively complicating scenarios while ensuring safety. The paper also highlights the reuse of system and environment models to reduce development time, the use of a scenario-driven dashboard for dynamic monitoring, and the integration of virtual simulation with real-world systems to create Digital Twins for enhanced verification and validation activities. Future directions include the creation of formal ontologies, human-systems integration, adversarial modelling, reinforcement learning techniques, support for distributed simulation standards, and ontology-enabled reuse and interoperability. Overall, the test bed offers a flexible and efficient environment for exploring and advancing MBSE approaches in system development.

2.2 Simulator Independent Modelling Language

Systems Modeling Language (SysML) is commonly used in MBSE to create comprehensive models that specify, analyse, design, optimise, and verify complex systems [14]. SysML is a graphical modelling language that supports the analysis, specification, design, verification, and validation of complex systems. SysML can represent the following aspects of systems, components, and other objects.

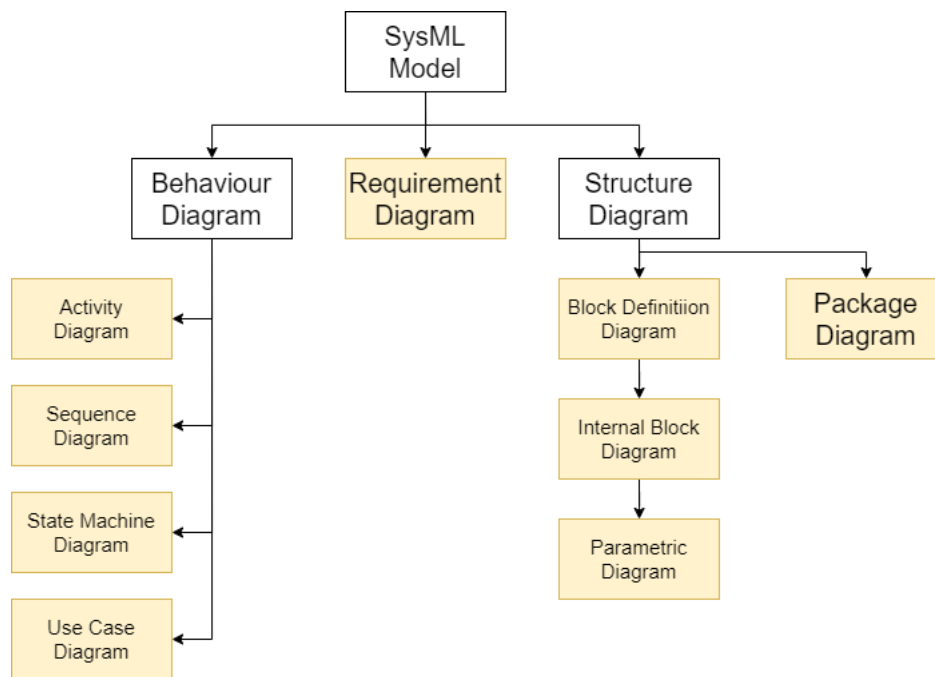


Figure 2.1: Standard Nine SysML Diagrams to describe a system

- Structure, interrelation, and classification.
- Behaviour based on functions, messages, and states.
- Limitations on physical and operational properties.
- The distribution between behaviour, structure, and limitations.
- Requirements and their relationship with other conditions, design elements, and test cases.

SysML includes 9 diagrams: package diagram, requirement diagram, behaviour diagram (activity diagram, sequence diagram, state machine diagram, use case diagram), parametric diagram, structure diagram (block definition diagram, internal block diagram)

The premise of this thesis is that the creation of a rapid model structure, constructed by modelling guidelines would facilitate the modelling of system-based Digital Twins at more manageable MBSE learning curves, without compromising the ability to adequately represent the system [15]. A generic Four Pillars of SysML (Including V&V) have been identified which can sufficiently represent the system based on the desired level of fidelity: [16] [17] [18] [19]:

- **Structure Model:** The system structure model provides a high-level representation of the experimental test stand, with all its structural details and relationships between each other. This model defines the layout of the test stand, the arrangement of subsystems, and the flow of data between different components.

- **Requirements Model:** The requirements model captures the functional and non-functional requirements of the experimental test stand. These are text-based requirements which help define the capabilities, performance criteria, and constraints that the system must satisfy. This model establishes a clear and traceable link between stakeholder needs and system specifications, facilitating requirement analysis, validation, and verification throughout the development life cycle.
- **Behavioural Models:** Behavioural models describe the dynamic behaviour of the experimental test stand, including its operational modes, sequences of actions, and state transitions. These models may include state machines, activity diagrams, or sequence diagrams, providing details about how the system functions under different conditions.
- **Verification and Validation Models:** Verification and validation models support the assessment of the experimental test stand's compliance with specified requirements. These models include test scenarios, simulation models, and formal verification techniques to ensure that the system behaves as intended and achieves its intended objectives.

2.3 Development of MBSE-based Digital Twins

There have been a lot of variations in the definition of Digital Twins. Each definition is adapted to a particular application and then further built up on it. But there are a few aspects which can be seen as a common element.

A Digital Twin is a concept introduced in 2002 by Michael Grieves. A Digital Twin is loosely defined as a virtual representation of a physical entity. The physical entity can be a system, process or service. It facilitates real-time monitoring and analysis of data to proactively identify issues, schedule preventive maintenance, minimise downtime, and strategize for future updates and innovations [20] [15]. Digital Twins have been emerging in engineering disciplines to better manage systems based on real-time data collected in different parts of the system [21]. The basic framework of Digital Twin consists of three parts, physical space, virtual space and communication layer which map between both spaces. The bidirectional mapping and interoperability of physical space and virtual space are realised through data interaction. Intelligent decision is realised through iterative optimisation and interaction between two spaces [22]

A Digital Twin rooted in a system-based approach is centred on the tangible physical entity, incorporating diverse models to achieve a precise depiction of reality. These models encapsulate a singular, comprehensive representation of the truth and encompass holistic details regarding the interconnectedness of system components in logical, physical, and functional terms, making them particularly well-suited for simulation purposes. The utilization of models and the imperative for traceability to establish a unified truth source render MBSE an inherent and apt method for modelling a system-based Digital Twin. [23]. The nascent stage of Digital Twin technologies and the need for further research in aspects such as implementation framework design, data processing, storage, and security is acknowledged. This framework aims to facilitate the creation of Digital Twins using MBSE languages, tools, and techniques. A step-by-step framework for developing digital shadows and Digital Twins, with a focus on verifying repeatability, has been laid out. Digital Twin technologies and specifically integration with MBSE methodologies can ultimately enhance the capabilities of experimental test stands and other complex systems.[24]

When combined with Digital Twins, MBSE approaches can be extended from technology development and manufacturing for which MBSE was originally designed, to operation and service. [25]. This is possible because Digital Twins can provide an effective implementation for achieving end-to-end integration in a system. This combination creates an interconnectedness and closes the gap between product design, product development, production planning, production and associated services [26]. Even though a system-based (MBSE) Digital Twin can offer better insights into the system to be developed or already developed, the developments are associated with considerable resource expenditure and costs. These challenges are also consistent with the steep learning curve, which is often considered one of the challenges of MBSE adoption. Krishnan et al. [27] developed a health monitoring and prognosis of electric vehicles (EV) permanent magnet synchronous motor by creating intelligent Digital Twin (i-DT) in MATLAB or Simulink to realise the performance monitoring of the motor both in-house and remotely. Finally, the simulation results indicated that the developed i-DT twins the present health of the EV motor remotely and in-house and can be implemented in vehicular systems.

2.3.1 Value imparted towards EBTS through Digital Twins

The development of MBSE-based Digital Twins offers significant value across various phases of the system life cycle. At its core, the Digital Twin model aims to replace wasted physical resources, such as time, energy, and materials, with information. By quantifying tasks in terms of resource costs, the model illustrates how information can mitigate waste during task execution. While information acquisition and usage entail resource costs, these are typically lower than the costs of wasted physical resources. Throughout the system life cycle, Digital Twins provide tangible benefits in the Creation, Development, Operation and Disposal Phase. [20]

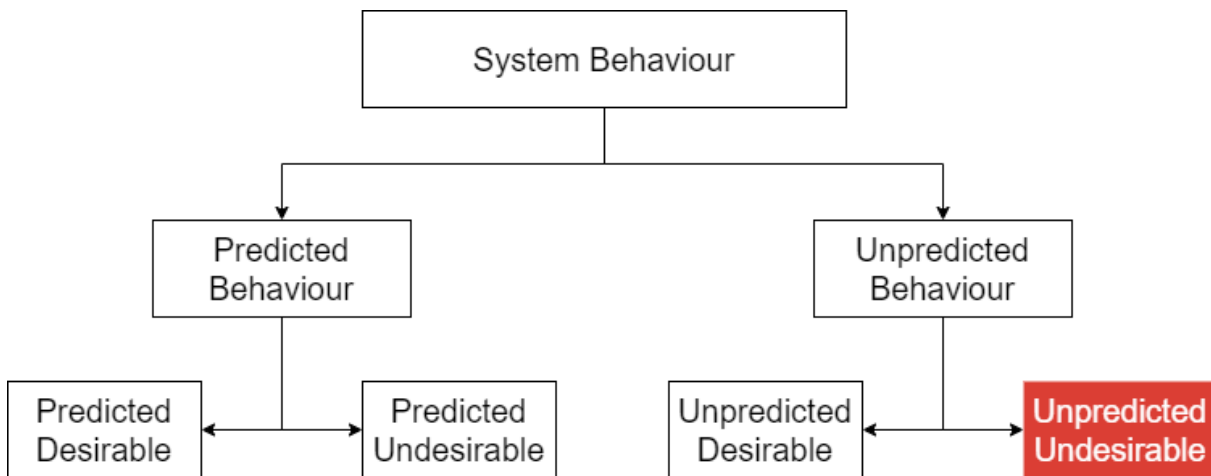


Figure 2.2: Identification and Characterising system behaviour and elimination of Unpredicted Undesirable behaviour with help of Digital Twins [20]

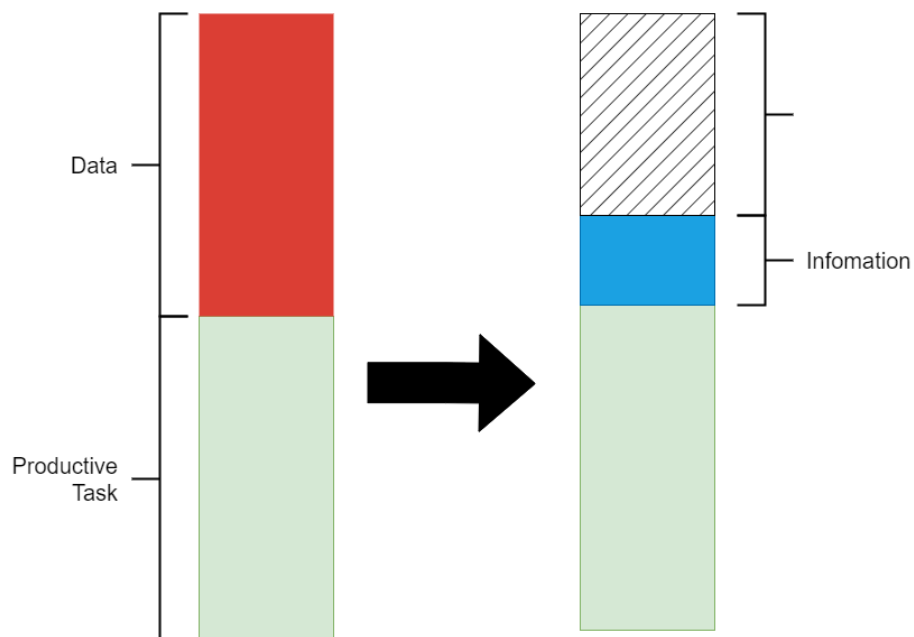


Figure 2.3: Identification of information inefficiencies and streamlining the conversion of data to information is identified as one of the key improvements by the implementation of a Digital Twin [20]

- **Data to Information:** Despite the generation of massive data in product life cycles, there is a challenge in efficiently utilising this data due to its isolated and delayed nature; Digital Twins offer a solution by enabling real-time, bidirectional data exchange. In the context of Digital Twins, addressing information inefficiency is paramount to realising their full potential as shown in figure 2.3 Information inefficiency refers to the sub-optimal utilisation or management of data and knowledge within the Digital Twin ecosystem, leading to missed opportunities, increased costs, and diminished effectiveness. If information is not leveraged efficiently, the potential for resource optimisation remains unrealised. Digital Twins should enable organisations to minimise resource wastage by providing accurate, timely, and actionable information for decision-making across various life cycle phases.[20] [28] [29]
- **Fault Tolerant Systems:** Fault-tolerant systems play a crucial role in ensuring the reliability and resilience of Digital Twins. Figure 2.2 outlines a framework provided by Grieves et. al. for characterising emergent behaviour in systems, dividing it into four categories: Predicted Desirable (PD), Predicted Undesirable (PU), Unpredicted Desirable (UD), and Unpredicted Undesirable (UU) [20].

The UU category, highlighted in the emergent behaviour framework, embodies the potential for serious or even catastrophic issues. These are the events that are not planned for in the system's design phase and can lead to significant downtime, financial loss, or danger to human operators. By modelling these behaviours within a digital twin, engineers can create a virtual space to explore the consequences of these emergent behaviours under controlled conditions. Through simulations, the digital twin allows for the examination of the system under rare or extreme conditions without the risk of real-world damage. This proactive exploration is critical for devising robust mitigation strategies, refining system design for greater fault tolerance, and developing automated safety protocols. Consequently, focusing on UU behaviours ensures that contingency plans are in place, thus bolstering the system's resilience and reliability. In experimental or laboratory contexts, where unexpected downtime or failures can be expensive and hazardous, the ability of digital twins to foresee, analyse, and prepare for UU behaviours is invaluable. It ensures that systems can not only recover quickly from unforeseen events but also learn from them, thereby continuously evolving towards higher levels of sophistication and safety.

The task of process monitoring involves detecting abnormalities, malfunctions, and potential external attacks within industrial processes and control systems. In the context of Digital Twins, fault-tolerant systems are essential for promptly identifying and mitigating faults or attacks, especially in large-scale plant-wide operations. [30]. The use of Digital Twins allows for the retention of actual organisational structures, which enhances fault localisation accuracy and the interpretability of fault propagation paths. By establishing a Digital Twin network, real-time performance-related information can be continuously collected and analysed, enabling plant-wide performance degradation analysis. The Di-

igital Twin has the potential to have a major impact on the reduction of wasted resources in the life cycle of the system. Estimated Failure Based on the Pressure Drop (specific to the application case) has been developed by Solari et al. to show the use case for categorised fault detection with available past data to infer from [31].

2.3.2 Utilisation of SysML for Designing Digital Twins

The integration of model-based systems engineering (MBSE) techniques in the design and implementation of Digital Twins represents a promising avenue for advancing engineering practices. The key task of determining the fidelity of Digital Twin models, requiring a delicate balance between simulation accuracy and resource-intensive development efforts poses a significant hurdle to widespread adoption.

MBSE processes can be leveraged to define Digital Twin requirements and integrate Digital Twin development earlier in the system's life cycle, thus enhancing operational system health and performance metrics. A six-step process has been proposed [32] for a complete operational overview of a Digital Twin starting from the development of requirements and MBSE models. The key milestone, Step 4: Implementation derives insights from the system's design to drive the development of the Digital Twin. Also, there have been developments to enforce a simplified MBSE modelling approach which can help overcome the steep learning curve associated with MBSE, enabling the design of system-based Digital Twins with balanced fidelity and cost.

A systematic development of system-based Digital Twins by synthesising modelling paradigms has been achieved for a holistic representation of real-world systems. A proposition comprises of a streamlined eight-step MBSE modelling framework tailored specifically for system-based Digital Twins. The framework systematically guides the generation of a simulation model that serves as the base of an actionable virtual twin. An established open-source modelling platform 'Papyrus' has been used to develop a SysML model of a system. A Python parser is devised to facilitate the seamless conversion of information from SysML models into the simulation model, thereby expediting the modelling process. [33]

Wilking et al. explores how SysML diagrams can serve as a foundation for the behaviour and structure of Digital Twins, ultimately enabling machine-readable representations that facilitate their operation. The goal of the demonstrator discussed in the paper is to assess whether SysML models can effectively serve as an information database and flow of actions for Digital Twins, particularly in scenarios involving industrial equipment such as a two-staged gear drive. The key challenge addressed is transforming the consistent and accessible visualisation of SysML diagrams into a machine-recognisable format to operationalize the Digital Twin [34].

The behaviour of the Digital Twin is modelled using executable state machines exported from SysML, allowing for the interpretation of real-time sensor data and the execution of appropriate actions, such as running simulations and providing recommendations to the user. The paper demonstrates how SysML facilitates the creation of a Digital Twin's behaviour structure, enabling a seamless integration of model-driven behaviour into the system's operation. Effort compensation is observed in the creation of executable code from SysML diagrams, with the simplification of complex behaviours into machine-readable formats [13].

Looking at the current state of the art, Digital Twins offer significant advantages in the testing and development of complex systems, such as the Electron Beam Test Stand (EBTS) at CERN. In the context of test benches, Digital Twins enable a virtual representation of the physical entities and systems involved in the testing process. By creating a digital counterpart of the EBTS, including its electron gun, magnetic system, beam instrumentation, and supporting components, researchers can conduct simulations and tests in a virtual environment. This allows for a comprehensive analysis of the system's behaviour under various conditions, without the need for physical access to the EBTS. Digital Twins facilitate real-time interactive mapping with the physical entity in the digital space, reflecting the full life cycle of the test stand. This capability enhances the efficiency of testing processes, enables remote monitoring and control, and supports the optimisation of performance through data fusion analysis and decision iteration. Applying Digital Twin technology to test benches, like the EBTS, contributes to advancing electron beam technologies by allowing for iterative optimisations, predictive maintenance, and an overall improved understanding of the system's dynamics.

3 System Description and Modelling

3.1 Methodology for System Description

The EBTS has served as a critical testbed for prototype components essential for the HL-LHC HEL, including the electron gun, the BGC and the BPM. The collector prototype is slated for installation and testing in 2024. The EBTS is equipped with an electron gun, collector, BPM, and multiple beam profile monitors, rendering it a versatile facility for the comprehensive characterisation of electron guns, collectors, beam pulse modulators, and various beam instrumentation. Furthermore, its compatibility with DN-100 installation makes it an appealing resource for collaborators seeking to validate equipment for electron coolers and related applications.

Since the entire system is modular, care has been taken to develop a system description which can be easily extended or modified. The first step in developing a MBSE model is the requirements modelling. The requirements for the Digital Twin are considered as the base as it is referenced by other entities in the model for verification and validation. The structure of the physical model is replicated via block diagrams which also include the data flows between the physical entities. These are modelled as 'ports' and data 'flow' between them. The data flows are detailed in internal block diagrams. Each physical entity in the system is considered to have a certain state at any point in time. The entity can transition between the states via certain actions. The set of states and actions is a finite set and the entity must be in any one of its feasible states. This is considered as a base implementation if the model is implemented towards building a Digital Twin. The state-action pairs are conceptualised in a state-machine diagram. The development of such diagrams is shown in figure 3.1.

3.2 Electron Beam Test Stand (EBTS)

3.2.1 Motivation for the development of EBTS

The EBTS at CERN has been designed and constructed to address the objectives outlined in ARIES WP16 (Intense, RF Modulated, E-Beams (IRME)) [35, 36, 37], as well as HL-LHC WP5 (Collimation) and WP13 (Beam Instrumentation). The key objectives include:

- Designing and building a test stand capable of evaluating an electron gun, equipped with instrumentation for measuring both transverse and longitudinal profiles of the RF-modulated electron beam.

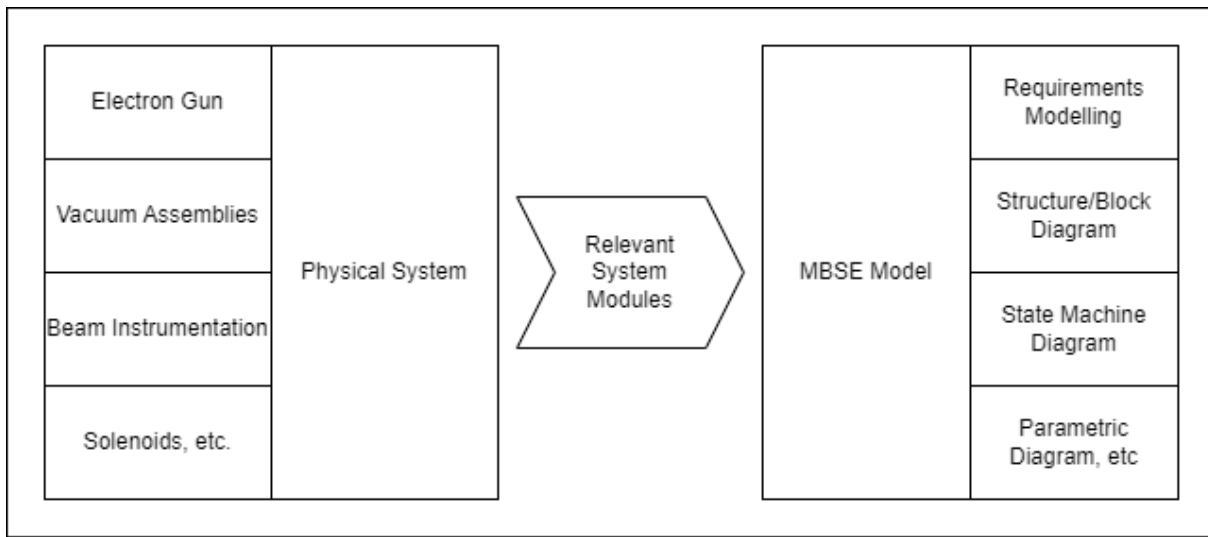


Figure 3.1: Development of System Description from Physical Model

- Conducting measurements to characterize the properties of the RF-modulated electron beam generated by the gun within this test stand.
- Prototyping components, such as the electron gun, collector, and BPM, to potentially implement hollow electron lenses (HEL) for active beam-halo control in the HL-LHC.
- Developing a gas curtain monitor to precisely align the electron and proton beams within the hollow electron lens.

The key components for Hollow Electron Lens (HEL), as depicted in Figure 3.4, include the electron gun and pulse modulator for generating the pulsed hollow electron beam. Two beam position monitors are employed to precisely locate the proton and electron beams in the interaction region. The minimally invasive beam profile monitor, known as the Beam Gas Curtain (BGC), acts as an overlap monitor for both beams. Additionally, a collector serves as an electron beam dump. The setup also features superconducting solenoids, compensation magnets, and steering coils to guide and control the beams within their designated orbits. The HEL prototype components to be tested at the EBTS include the electron gun, Beam Position Monitor (BPM), BGC, and electron collector.

3.2.2 Hardware Infrastructure

The EBTS layout, emphasises HEL components outlined in green in figure 3.2. Resistive solenoids, capable of producing a maximum axial magnetic field of 0.4 Tesla, guide the electron beam, each featuring horizontal and vertical correctors for precise beam control. A sector valve divides the EBTS into two independent volumes, allowing separate interventions. The upstream volume houses the Beam Diagnostic Box (BDB), providing electron beam assessment even when downstream instruments are unavailable. The EBTS supports modular installations,

offering versatility for testing electron guns, collectors, beam profile monitors, beam position monitors, pulse modulators, power converters (including high voltage ones), and control and interlock systems.

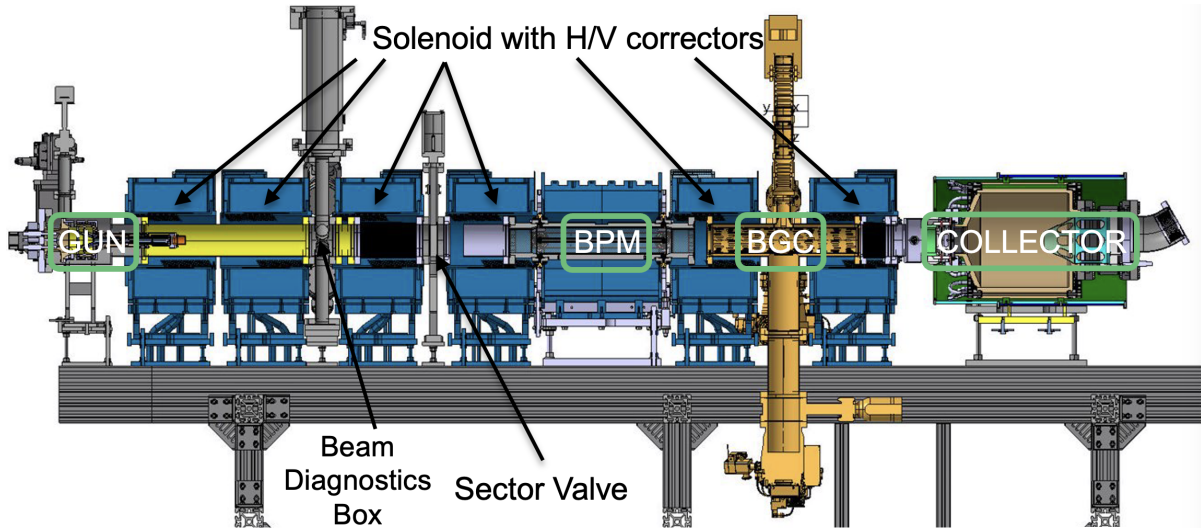


Figure 3.2: 3D model of the EBTS with all major components with Electron Gun (Left), Solenoids with Horizontal and Vertical Corrector, Beam Diagnostic Box (BDB), Beam Position Monitor (BPM), Beam Gas Curtain (BGC), Collector, and Sector Valves.

Electron Gun

The EBTS currently employs the HEL Gun v3. This gun features a hollow cathode with a 16.10 mm outer diameter and 8.05 mm inner diameter, capable of providing a current density of 3.33 A/cm² at an operating temperature of 950°C. Within the EBTS, the electron gun delivers a beam current of up to 5 A and a beam energy of up to 15 keV. For pulse modulation, a Marx generator [38] is used, offering a rapid 200 ns rise/fall time and an adjustable pulse duration ranging from 1 to 100 microseconds. The system supports a repetition frequency between 1 Hz and 1 kHz.

Beam Instrumentation

- **Beam Profile Monitors:** The YAG:Ce screens and Pin-Hole Faraday cup are positioned at the BDB location, while the BTV screen and BGC are located at the position labelled BGC. A YAG: Ce screen, when inserted into the beamline, is perpendicular to the electron beam direction of motion. The photons generated at the screen travel downstream and pass through an optical viewport before they are collected by a scientific camera (Manufacturer: Thorlabs, Model: CS135MU)

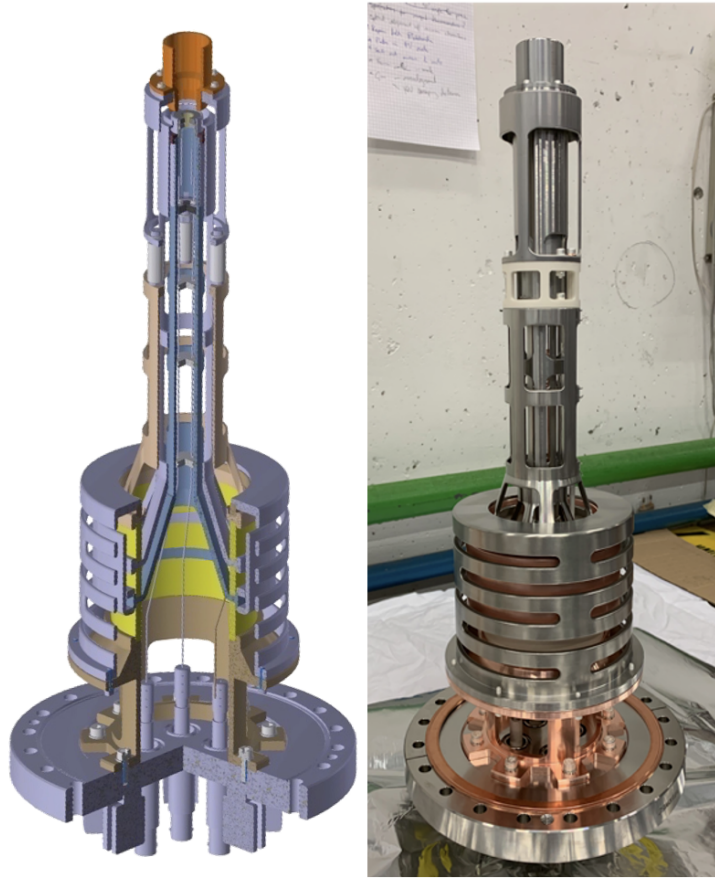


Figure 3.3: HEL electron gun 3D model (left) installed at the EBTs and image of the assembled gun (right). The entire assembly is inside an Ultra-High Vacuum Environment during operation.

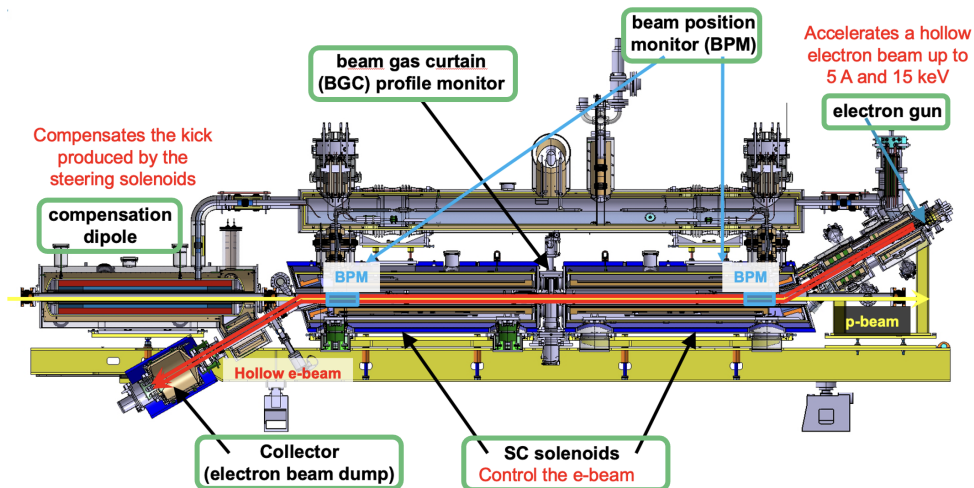


Figure 3.4: 3D model of a preliminary design of the HEL for High Luminosity LHC (HL-LHC). The EBTs is built to test and characterise the hollow electron beam required for the operation of HEL

- **Pin-Hole Faraday cup:** The Pin-Hole Faraday cup, located on the vertical linear translator on the BDB, consists of seven pins with a 10mm pitch in a hexagonal arrangement, each pin featuring a 0.2mm aperture. The entire Faraday cup assembly is adjustable in XYZ directions within a range of ± 20 mm. This type of Faraday cup offers the advantage of withstanding very high electron beam intensities. Furthermore, acquiring the beam profile only necessitates an electrical feed-through, eliminating the need for a camera or viewport.
- **BTV Screens:** The BTV (or Beam TV) consists of a screen positioned at an angle (between 45 and 60 degrees depending on the light emission pattern) w.r.t. the electron beam direction of motion, and a camera (Manufacturer: Basler, Model: acA1920-40gm) collecting the light through a viewport perpendicular to the beam direction. A high-speed gated intensifier (Manufacturer: Hamamatsu, Model: C9547-01) is optionally used.
- **Beam Position Monitor (BPM):** At the HEL, the BPM serves to independently measure the transverse positions of the proton and electron beams using vertical and horizontal strip-line electrodes. Located between the sector valve and the BGC, the HEL BPM prototype at the EBTS has an outer diameter of 100mm and an inner diameter of 80mm, with a strip-line length of 400mm and a width of 12.4mm. The BPM has been designed to work with a 200ns rise/fall time which is set by the requirements of the electron beam at the HEL.
- **Electron Collector:** The most downstream component of the EBTS is the electron collector. This HEL collector prototype features an 80mm entrance aperture and can be biased up to +5 kV relative to the cathode potential. Designed to absorb continuous beam power of up to 25 kW, it is operable in both DC and pulsed mode. Utilising this collector poses challenges due to stringent vacuum requirements and the need to minimise secondary electron emission. Its operation demands a high-voltage platform and demineralized cooling water, both of which are currently unavailable at the EBTS. Efforts are underway to provide these essential facilities.

3.2.3 Current Data Acquisition and Control Systems for the EBTS

The data acquisition and control system of the EBTS is an integral component that facilitates the monitoring, prediction, and automation of various operational processes. The entire comprehensive list of instruments to be controlled from which data has to be acquired is detailed in fig 3.5. The test stand itself is built on top of an aluminium frame, from which the cables are routed 3.6 towards a set of standard 19-inch racks.

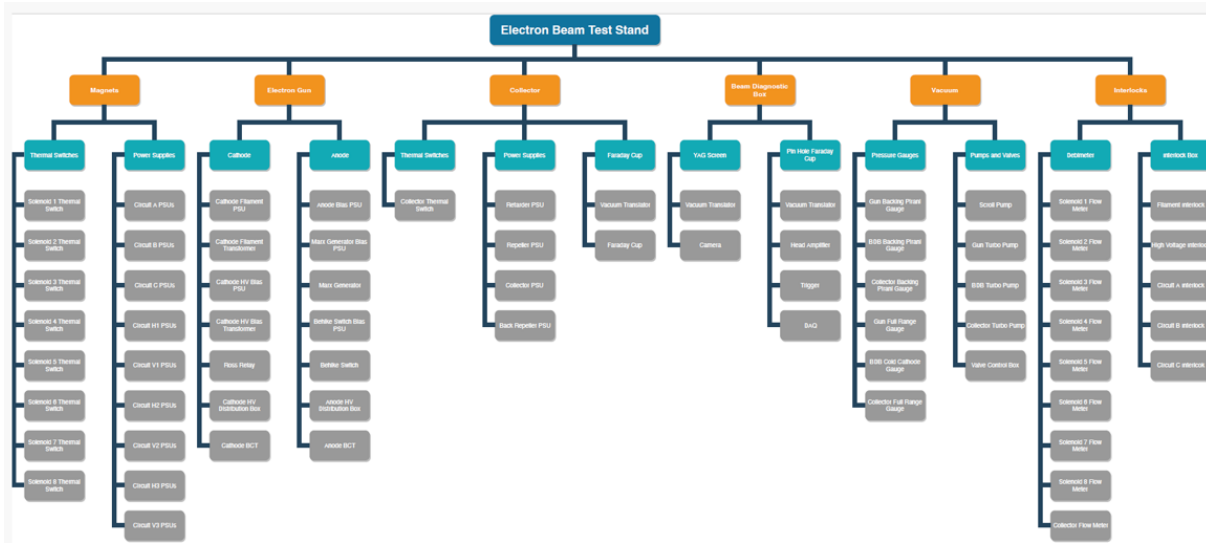


Figure 3.5: All Existing Instruments at the EBTS

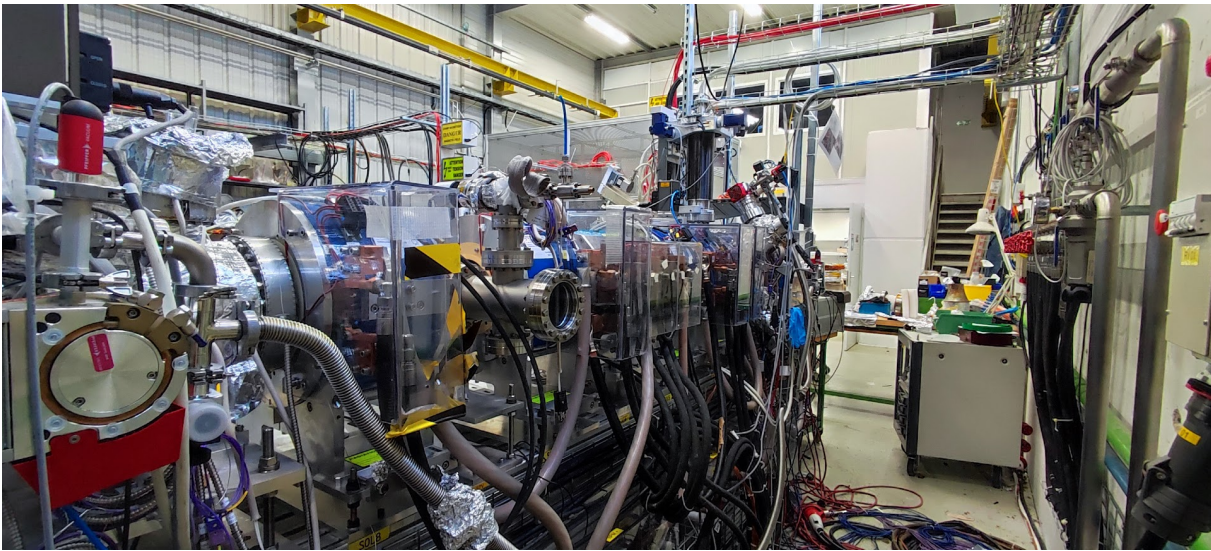


Figure 3.6: Low and High Voltage Routed Cables from the Back-Side of EBTS going towards the Control Rack in figure 1.6

3.3 Development of a MBSE based model for the Electron Beam Test Bench

MBSE involves three main elements [39] which work together to provide a functional framework for the entire system replacing the traditional document-based approach enabling system contributors and stakeholders to collaborate throughout a system life cycle for convenient data exchange and a centralised understanding of a physical system status.

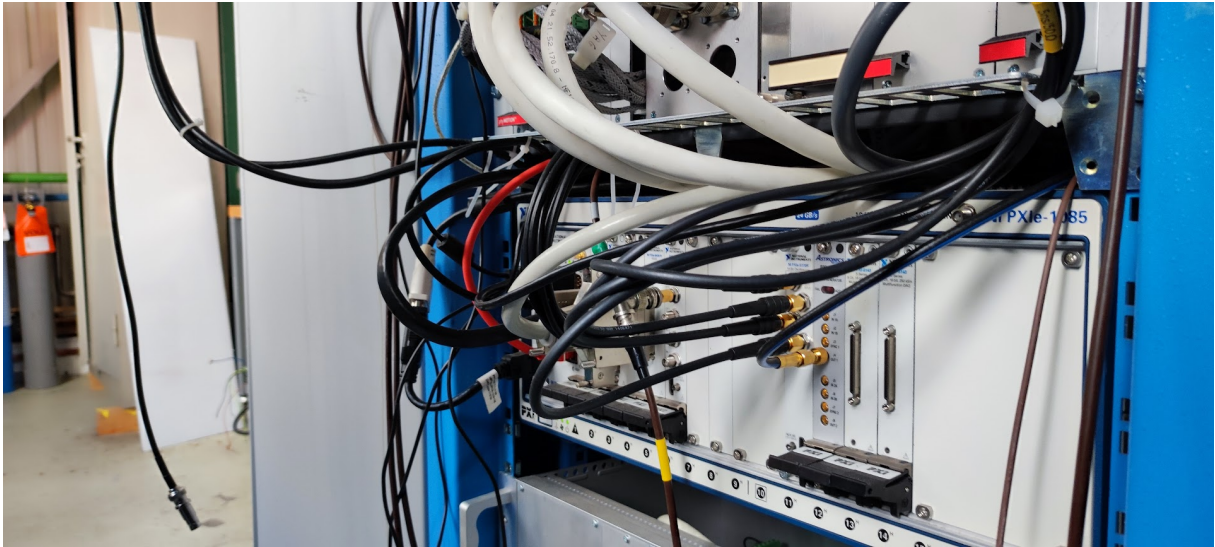


Figure 3.7: National Instruments PXIe acting as the controller for the EBTS as shown in figure 1.5

1. **Modelling Language:** A modelling language is present to communicate an abstract idea that the model captures. The modelling language is formal, with strict syntax. System-modelling languages already exist that have a well-defined schema to model with the help of diagrams such as the SysML and Unified Modelling Language (UML). A valid model requires that the modelling language's rules for entities and relationships be followed. SysML has strict syntax and rules for relationships and connections between elements, which helps to avoid ambiguity. If the model is built with sufficient fidelity, the SysML-based model can be dynamically simulated to observe model performance. This research proposes the possibility of SysML to build models for systems which can then be used for Digital Twin development [24].
2. **Modelling Method:** MBSE does not lay down any specific process or workflow on how to methodologically model a system. Instead, it lays down a framework which includes four major domains: structure, requirements, behaviour, verification and validation. This is detailed previously in section 2.2.
3. **Modelling Tool:** Numerous commercial and open-source modelling tools exist which support the use of SysML to create models. Some of them include Enterprise Architect, Cameo Systems Modeller, Papyrus, Capella, etc. The most important features which were considered before the selection were the possibility to export the model in XML Metadata Interchange (XMI) formats, support for the latest version of SysML (1.6), and preference for non-commercial licenses given due to their open-source nature. Papyrus was hence selected as the modelling tool to model the EBTS at CERN.

Using SysML within MBSE ensures that all aspects of the system are properly documented from the conceptual stage to the detailed design. It supports verification and validation processes by

ensuring that the system design accurately meets the specified requirements. The development of the SysML model for the EBTS involved the following four standard steps:

1. **Definition of Scope and Purpose:** It is imperative to establish the scope and purpose of the system under study. This necessitates a comprehensive examination of the problem or opportunity being addressed by the system, along with a thorough identification of stakeholders and users. For the task of developing a model for the Electron Beam Test Bench, the purpose is solely to build a Digital Twin from the resulting model. The scope of the model and the Digital Twin are limited to the instruments controlling the electron gun, solenoids and other instrumentation on the beam line. The model fidelity does not include any structural details in the sense of Mechanical or Electrical structure. It should sufficiently provide how abstract instrument variants communicate with each other and how the entire system works as an ensemble of such instruments.
2. **Modelling the defined scope:** Based on the scope, four main diagrams are established which include: Requirements Diagram, Block Definition Diagram, State Machine Diagram, and Sequence Diagram. These four diagrams can sufficiently model the fidelity required to understand the system configuration and are deemed enough to assist in building a Digital Twin based on the model.
3. **Creation of Diagrams:** The model is now created in Papyrus, in SysML 1.6 with the help of the four diagrams mentioned above. The Requirements Diagram encapsulates all the necessary details which need to exist in the model. This is validated by cross-referencing entities to ensure the requirements are always met regardless of any change in the model. The block definition diagram shows the interconnectivity of varied instrument clusters along with the conceptual system schematic. This diagram represents the system structure as a whole. Each of the entities, representing a real-world instrument or device in the real world is modelled as a single block. These are always active in a certain 'state' and can transition into another 'state' by performing a certain action. This entire system of state-action pairs is modelled in a State Machine Diagram. Every entity and controller, if any is provided with a State Machine Diagram to describe its functioning. The Sequence Diagram is modelled at the end to show the process of performing a certain experiment on the test stand.
4. **Verification and Update:** The Requirements verification is done to ensure the critical functionalities are always met regardless of the model status. The requirement of magnet power supplies to operate, or not be in states *Initialise* or *Configure* when the debimeter reads a value of less than a certain threshold is verified before they are energised. Likewise, the vacuum interlocks, over current protection, high voltage protection, and rapid increase in filament voltage which is modelled as a threshold set on the magnitude of voltage change, are some examples where operational verification of the system occurs. Constant updates of the model can be maintained as long as the requirements are met. This provides an excellent point of view in terms of building models for experimental test stands.

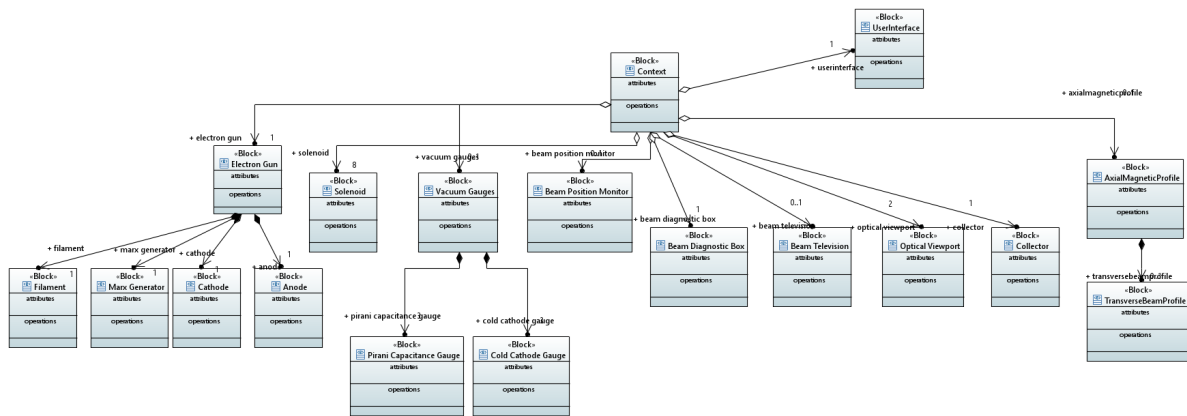


Figure 3.8: Simplified SysML Block Definition Diagram for the entire EBTS detailing all major components installed on the beam line

Electron Gun Filament Conditioning: Filament conditioning plays a crucial role in optimising the performance and longevity of thermionic emission cathodes, particularly those utilising directly heated, filament-based designs. These cathodes rely on thermionic emission to generate electron beams. Filament conditioning involves subjecting the cathode's filament to controlled heating cycles, typically in vacuum environments. The objective is to stabilise the filament's microstructure and surface properties, ensuring consistent and reliable electron emission over the prolonged operation. This process helps mitigate issues such as filament evaporation and degradation, which can arise due to high operating temperatures and ion bombardment. One key aspect of filament conditioning is the optimisation of operating parameters, including temperature and current, to strike a balance between efficient electron emission and filament longevity. By carefully calibrating these parameters during conditioning, manufacturers can tailor the cathode's performance to specific application requirements while maximising its operational lifespan. Filament conditioning is an essential step in the fabrication and optimisation of thermionic emission cathodes, ensuring their reliability and performance in the operation of EBTS.

State Machine Diagram for Electron Gun Filament Ramp Controller: The System Modelling Language (SysML) model for the electron beam filament ramp action encompasses a series of states reflecting the sequential phases of the process. The initial state is "Initialise," which sets the groundwork for subsequent actions. Following this, the model transitions to "Initialise Pressure Gauge" and "Initialise Power Supply," ensuring that both the pressure gauge and power supply are appropriately set for the upcoming operations. The SysML model then advances to "Configure Power Supply," where the specific parameters for the power supply are established. Subsequently, the system enters the "Read Values" state, acquiring essential data from sensors and gauges. The final phase is the "Ramp Filament Voltage," where the SysML model orchestrates the gradual increase of filament voltage until the desired level is reached. Once the target voltage is achieved, the model transitions to the "Exit" state, indicating the successful completion of the electron beam filament ramp action. This State Machine Diagram representation

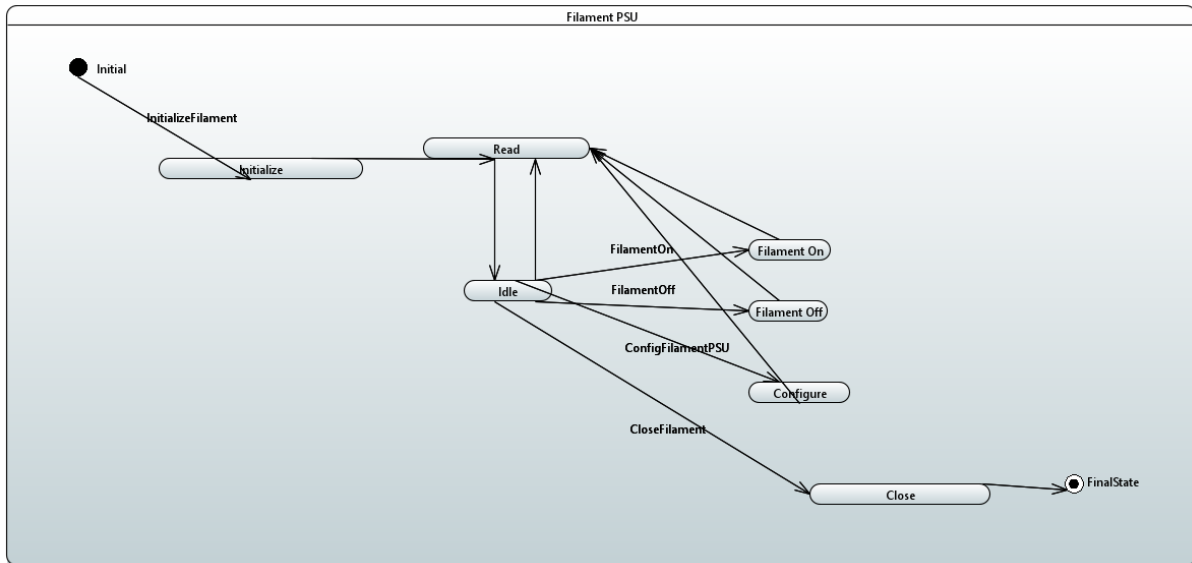


Figure 3.9: SysML model showing the State Machine Diagram for Electron Beam Filament Power Supply - BK Precision 9805B

provides a comprehensive and visual framework for understanding the sequential progression of states in the electron beam filament ramping process, aiding in system design, analysis, and communication among entities.

3.4 Extension of MBSE Model into Digital Twin Blueprint

The extension of Model-Based Systems Engineering (MBSE) models into Digital Twin blueprints constitutes bridging the conceptual gap between abstract system representations encapsulated within MBSE frameworks and the tangible, actionable insights demanded by Digital Twin implementations. Referring to Chapter 5, the implementation requires the entities to have clearly defined functionalities in the form of 'States' and 'State Transitions'. This is obtained from the State Machine Diagram from the SysML Model. The export of the State Machine Diagram in XMI format is done for an Electron Gun Filament Power Supply, which in the case of EBTS is specifically BK Precision 9805B. Figure 3.12 shows the snippet of how the XMI file looks, and how states and state transitions are defined in this format. A Python script can be easily built to parse the XMI document and extract this information from the SysML Model. Figure 5.2 and 5.3 show the result after the translation of XMI into LabVIEW.

Since the implementation is proposed to be done in LabVIEW, a minimal standard toolkit is available to test the hypothesis of building a state machine from the extracted 'States' and 'State Transitions'. LabVIEW State Diagram Toolkit [40] provides an excellent diagram editor to visualise the state transitions and track the system. It automatically converts the state machine extracted, from the SysML Model into a simple state machine architecture in LabVIEW.

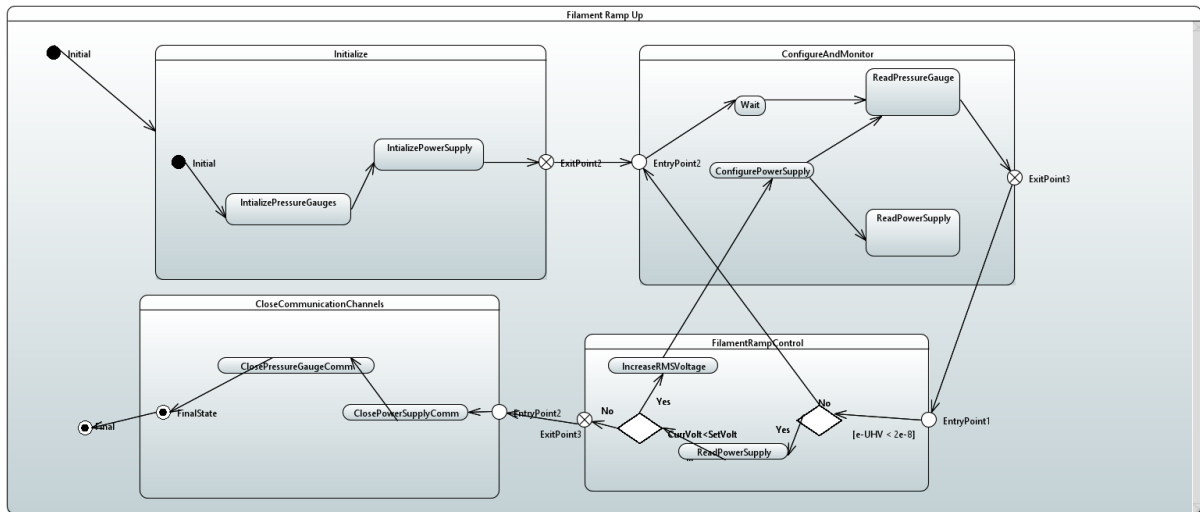


Figure 3.10: SysML model showing the State Machine Diagram for Electron Beam Filament Ramp Up Controller

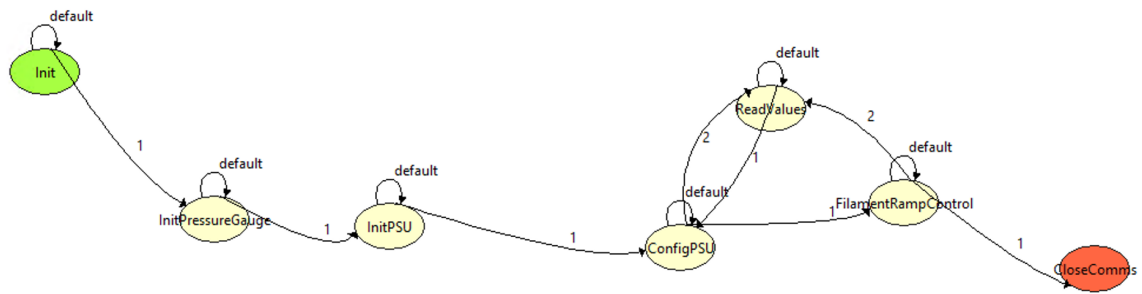


Figure 3.11: LabVIEW State Diagram Toolkit implemented for Electron Beam Filament Ramp Up Control

Figure 3.11 shows the toolkit being used for the Electron Gun Filament Ramp Up Control. This process of conversion of a SysML model State Machine Diagram to a LabVIEW State Machine Architecture is here on forth termed as State Machine Diagram Transfer (SMDT). This implementation is currently manually done. States and State Transitions are manually fed from the SysML Model into the Toolkit one by one. Also the toolkit models every entity in the SysML model separately and does not include the inter-entity dependencies to build the entire system. The Toolkit provides a starting point to develop plugins which can develop the entire system with added functionalities. In the process of development of a Digital Twin for the Electron Beam Test Bench at CERN, this framework is taken into account and adds numerous other features like the T Pattern and Event Driven Queued State Machine Architecture to build the entire interconnected system from the SysML Model.

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Figure 3.12: XMI Export of the State Machine Diagram of Electron Gun Filament Power Supply showing States, External Signals, and State Transitions based on xmi:id

4 Communication and Digital Twin Architecture

LabVIEW is utilised for control and data acquisition due to its versatility, robustness, and widespread adoption within CERN. LabVIEW offers a user-friendly graphical programming environment that enables rapid development and deployment of custom control and monitoring systems, making it well-suited for the complex and dynamic experimental setups at CERN.

National Instruments CompactRIO is favoured in this particular application towards electron beam test benches due to its ruggedness, compact form factor, price and flexibility. The extension of capabilities via hot-swappable modules which support all kinds of communication interfaces is the greatest advantage. CompactRIO systems offer embedded real-time processing capabilities, FPGA programmable, and as mentioned before, modular I/O options, from high-speed data acquisition to real-time control in harsh environments. The controller for EBTS is transitioned from a NI PXIe-based system to a NI CompactRIO, which would then be the same as the one being used for other test stands at CERN such as NEWTS and ECTS. NI cRIO-9047 [41] has been confirmed as the controller to be used in both EBTS and NEWTS.

4.1 Communication Interface

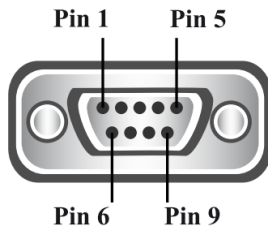
The instruments, modelled as entities in section 3.3 communicate with each other in the physical realm with certain protocols. The majority of them communicate via Serial Communication. These include RS232 and RS485 standards. RS232 communication provides short-range communication up to 15 metres and RS485 can be used for longer distances up to 1200 metres with higher speed. The connectors for these communication cables are either a RJ45/RJ50 port or a 9-pin D-Sub connector. The pin outs for the same are detailed in figure 4.4, 4.5, 4.2, 4.3. Some power supplies' communication is handled via Universal Serial Bus (USB) standard. The interlocks particularly are read out as a 5 V signal on 48 different channels. It is noteworthy that not all channels are currently interfaced with hardware interlocks, thereby allowing for future expansion by accommodating additional interlock functionalities. The entire communication infrastructure of the instruments in EBTS are listed in figure 4.6.



Figure 4.1: National Instruments Compact RIO [42] which will be used as the standard controller for both EBTS and NEWTS

Pin #	Signal
Pin 1	DCD
Pin 2	RXD
Pin 3	TXD
Pin 4	DTR
Pin 5	GND
Pin 6	DSR
Pin 7	RTS
Pin 8	CTS
Pin 9	RI

RS232 Pinout (9 Pin Male)



Pin #	Signal
Pin 1	TXD-
Pin 2	TXD+
Pin 3	RTS-
Pin 4	RTS+
Pin 5	GND
Pin 6	RXD-
Pin 7	RXD+
Pin 8	CTS
Pin 9	CTS+

RS422/485 Pinout (9 Pin)

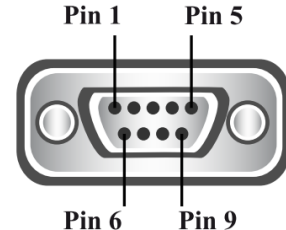
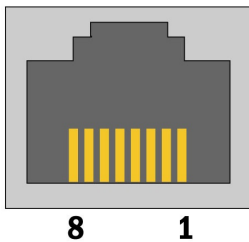


Figure 4.2: D-SUB 9 RS232 Pin out [43]

Figure 4.3: D-SUB 9 RS422 Pin out [43]

RJ45 RS-232 (DCE) Serial Connector

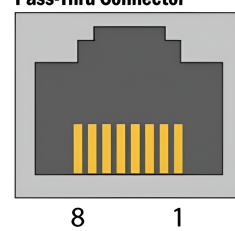


Pin Out

Pin #	Signal
1	TD
2	RD
3	CTS
4	5VDC Output
5	N/C
6	RTS
7	N/C
8	GND

Figure 4.4: RJ45 RS232 Pin out [43]

RJ45 (RS-485 IN/OUT) Pass-Thru Connector



Pin Out

Pin #	Signal
1	9-30 VDC Source
2	9-30 VDC Source
3	Not connected
4	485+
5	485-
6	Common (GND)
7	Common (GND)
8	Common (GND)

Figure 4.5: RJ45 RS422 Pin out [43]

4.2 Digital Twin: Environment and Infrastructure

To represent a Digital Twin of the Electron Beam Test Stand (EBTS), the concept of a Digital Twin can be delineated through a framework comprising five integral dimensions proposed by

Sr No	Sub-System	Instrument	Model	Interface
1	Solenoid - Main	Circuit A PSU (A.1 - Master)	Delta Electronika SM15-400	15 Pin Analog (PSC488)
2		Circuit A PSU (A.2 - Slave)	Delta Electronika SM15-400	
3		Circuit B PSU (B.1 - Master)	Delta Electronika SM45-140	15 Pin Analog (PSC488)
4		Circuit B PSU (B.2 - Slave)	Delta Electronika SM45-140	
5		Circuit B PSU (B.3 - Slave)	Delta Electronika SM45-140	
6		Circuit B PSU (B.4 - Slave)	Delta Electronika SM45-140	
7		Circuit B PSU (B.5 - Slave)	Delta Electronika SM45-140	
8		Circuit B PSU (B.6 - Slave)	Delta Electronika SM45-140	
9		Circuit C PSU (C.1 - Master)	Delta Electronika SM45-140	15 Pin Analog (PSC488)
10		Circuit C PSU (C.2 - Slave)	Delta Electronika SM45-140	
11		Circuit C PSU (C.3 - Slave)	Delta Electronika SM45-140	
12		Circuit C PSU (C.4 - Slave)	Delta Electronika SM45-140	
13	Solenoid - Correctors	Corrector PSU 1 (SOL_12_H)	EA-PS-3016-40 B	15 Pin Analog
14		Corrector PSU 2 (SOL_12_V)	EA-PS-3016-40 B	15 Pin Analog
15		Corrector PSU 3 (SOL_34_H)	EA-PS-3016-40 B	15 Pin Analog
16		Corrector PSU 4 (SOL_34_V)	EA-PS-3016-40 B	15 Pin Analog
17		Corrector PSU 5 (SOL_7_H)	BK Precision 1901 B	USB-B
18		Corrector PSU 6 (SOL_7_V)	BK Precision 1901 B	USB-B
19		Corrector PSU 7 (SOL_8_H)	BK Precision 1901 B	USB-B
20		Corrector PSU 8 (SOL_9_V)	BK Precision 1901 B	USB-B
21	Electron Gun	Cathode Filament PSU	BK Precision 9805	RS232 (9 Pin) & USB-B
22		Cathode (HV Bias) PSU	HCE35-20000P	15 Pin Analog
23		Ross Relay	Custom	4 pin Burndy
24		Anode Bias PSU		
25		Marx Generator Bias PSU		
26	Vacuum Gauge	Camera (End of Beam Line)		
27		Electron Gun Backing Pirani	PfeifferTPG 366	USB-B
28		Electron Gun Full Range		
29		BDB Backing Pirani		
30		BDB Cold Cathode		
31		Collector Backing Pirani		
32		Collector Full Range		
33	Vacuum Valves	Electron Gun Turbo - Front		
34		Electron Gun Turbo - Back		
35		BDB Turbo - Front		
36		BDB Turbo - Back		
37		Collector Turbo - Front		
38		Collector Turbo - Back		
39	Vacuum Pumps	Sector Valve		
40		Electron Gun Turbo Pump	Pfeiffer HiPace 80	-
41		BDB Turbo Pump	Pfeiffer HiPace 80	-
42		Collector Turbo Pump	Pfeiffer HiPace 80	-
43		Scroll Pumps	Edwards nXDS10i	15 Pin Analog
44	Interlock Box	Solenoid 1 Thermal Switch		Burndy 48 Pin
45		Solenoid 2 Thermal Switch		
46		Solenoid 3 Thermal Switch		
47		Solenoid 4 Thermal Switch		
48		Solenoid 5 Thermal Switch		
49		Solenoid 6 Thermal Switch		
50		Solenoid 7 Thermal Switch		
51		Solenoid 8 Thermal Switch		
52		Collector Thermal Switch		
53		Solenoid 1 Flow Meter		
54		Solenoid 2 Flow Meter		
55		Solenoid 3 Flow Meter		
56		Solenoid 4 Flow Meter		
57		Solenoid 5 Flow Meter		
58		Solenoid 6 Flow Meter		
59		Solenoid 7 Flow Meter		
60		Solenoid 8 Flow Meter		
61		Filament Interlock		
62		High Voltage Interlock		
63		Circuit A Interlock		
64		Circuit B Interlock		
65		Circuit C Interlock		
66	Beam Diagnostic Box	Pin Hole Faraday Cup Acquisition		SM-B (7 Channels)
67		Pin Hole Faraday Cup Translator		
68		YAG Translator		
69	Beam Television	YAG Camera		USB
70		YAG Translator		
71		Intensifier		
72	Collector	Camera		GigE + Trigger
73		Back Repeller PSU	HCE35-20000P	15 Pin Analog
74		Repeller PSU	HCE35-20000N	15 Pin Analog
75		Retarder PSU	HCE35-20000N	15 Pin Analog
76		Collector PSU		

Figure 4.6: EBTS Complete Instrument List and Communication Protocol

Tao et al. [44]. This outline presents a structured approach to understanding the operational and functional architecture of the Digital Twin. The five dimensions in the case of EBTS are:

1. **Physical Entity/Twin:** The Physical Entity (PE) or the Physical Twin encapsulates the tangible elements comprising the actual hardware, software, and service components constituting the system. This represents the EBTS system as it is physically deployed in CERN. Included are all physical components of the system such as the hollow electron beam source, resistive solenoids, the beamline infrastructure, and the associated safety interlocks and high voltage apparatus necessary for ultra-high-vacuum and radiation operation. Furthermore, the PE extends to services supporting the system functionality such as communication cables, adaptors, and environment entities such as Air Supply, Electricity Supply, etc. Together, these tangible and operational components collectively form the physical entity of the EBTS, representing the concrete manifestation of the system's infrastructure and capabilities within the experimental environment.
2. **Virtual Entity:** The Virtual Entity (VE) refers to the digital representation of the PE's structure and behavior. The VE can be defined as an established model of the EBTS that is independent of its simulation platform. This model is constructed in SysML as a systemic representation in SysML of the structure, behavior, and interrelations of all components of the system as found in the PE. The VE is an experimentable platform for every function and setting of the PE which allows live simulations and analysis to be performed thereon. Through the VE, users can simulate and analyse various scenarios, assess system performance, and conduct experiments in a virtual environment, thereby facilitating predictive modelling, optimisation, and experimentation before implementation in the physical realm.
3. **Services:** Services refers to the functionalities that the Digital Twin requires for operation. These include capabilities for real-time monitoring, predictive maintenance, control, and data analysis. The services utilise data generated from simulations of the VE to enhance decision-making processes, optimise operational parameters, and mitigate risks associated with the manual operation of the EBTS. Significantly, the integration of CERN's CMW server and NXCALS data infrastructure plays a pivotal role in these services. The CMW Server is supported with an NXCALS subscription, as a comprehensive data acquisition system, ensures that vast amounts of operational data are effectively captured, and made accessible outside the local hardware abstraction layer.
4. **Data:** Data serves as the repository where relevant and valuable information generated from the operation, simulation, and monitoring of the system is stored for both immediate and future utilisation. This repository encompasses a wide range of data types, including experimental measurements, simulation results, system parameters, performance metrics, and diagnostic records. The data stored in the repository is derived from various sources, such as sensors, instruments, simulation models, and user interactions with the system.

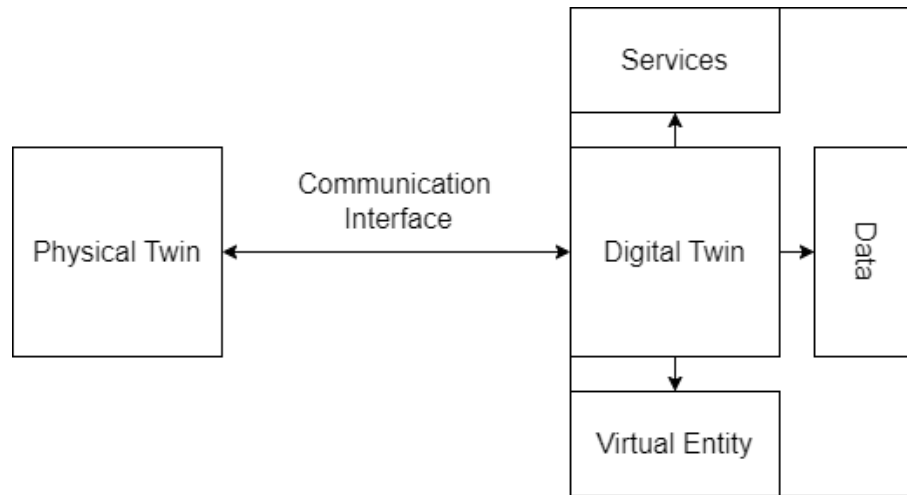


Figure 4.7: Five Dimensions of Digital Twin

5. **Communication Interface:** Connections represent the communication channels and interfaces between the physical and digital entities. This includes the data flow mechanisms that allow for bidirectional interaction between the PE and the VE, ensuring that updates and changes in one are reflected in the other. The communication interfaces between the PE and the controller which houses the VE, are detailed in section 4.1

Digital Twin Implementation: Two methods were proposed and comparative analysis were done for performance, reliability and the ease of execution. The first would be running the entire Digital Twin locally as a single application on the controller. The architecture is shown in figure 4.9. Although the application runs locally, there is a provision to publish the data to NXCALS via a subscription service to the CMW server. The disadvantage of this mode of architecture is that all the communication ports are blocked by the single application running on the controller. If any interventions or new development needs to be done, the only way is to halt the application, which in turn halts the data flow from the physical entity to the virtual entity and the cloud database. The addition of new controllers or new instruments would necessitate the intervention, which halts the data flow.

To mitigate this a second architecture is proposed as shown in figure 4.10. Here individual drivers are implemented for each entity, which independently publishes data to the CMW server. This is done with each individual application acting as a Front-End Computer (FEC) modelled as a Front-End Software Architecture (FESA) Class in the Control Configuration Data Editor (CCDE) application. These FECs are installed next to the sources to preserve the signal integrity as much as possible. The acquired data is sent through the Ethernet network, processed in an application server, and displayed on workstations running a dedicated application. Hence, this architecture allows the Digital Twin to run in a cloud-based environment, instead of a local infrastructure. This provides a Hardware Abstraction Layer, which prevents downtime due to any physical intervention. Although the architecture in figure 4.10 provides a significant advantage, due to ease of implementation, the architecture in figure 4.9 was preferred for the time

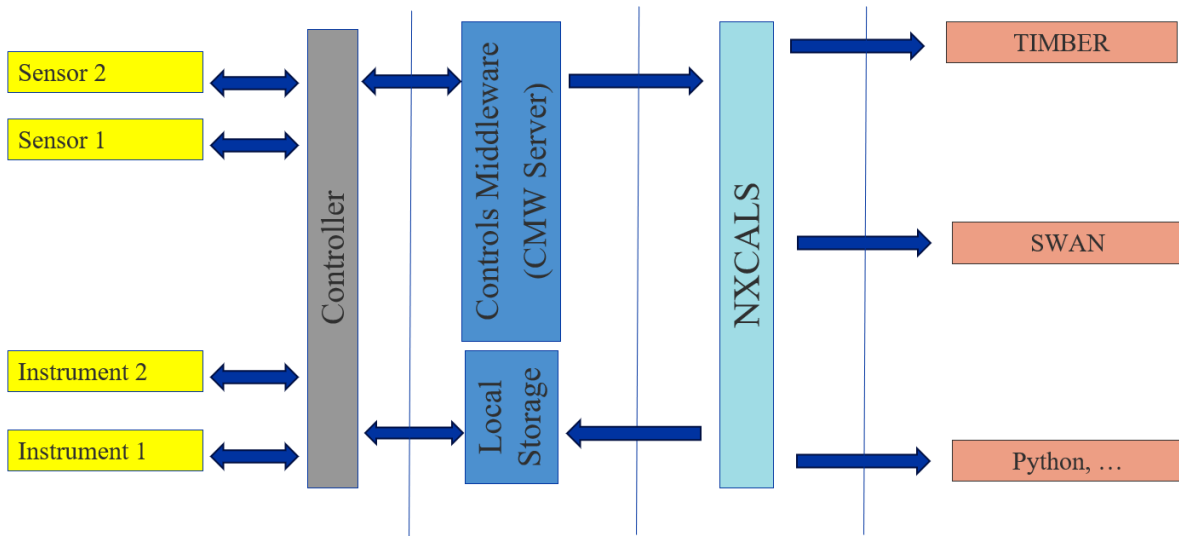


Figure 4.8: Proposed Architecture for Digital Twin Implementation

being, and plans to migrate the architecture have been prepared. The conceptual architecture depicted in the figure 4.8 represents a Digital Twin system designed to integrate physical components, control systems, and data analysis tools, for the EBTS. The detailed breakdown of the conceptual architecture is as follows:

- **Local Hardware Infrastructure**

- **Sensors:** These are the devices that collect real-time data from the physical environment or the physical test bench. They can measure various parameters like temperature, pressure, electromagnetic fields, or radiation, depending on the test stand's requirements.
- **Instruments:** These are specialised equipment that either actively interacts with the test bench (e.g., to modify conditions or initiate processes) or passively gathers data (like spectrometers or advanced imaging systems). Instruments may provide more complex or processed data than simple sensors.
- **Controller:** This is the central processing unit that receives input from sensors and instruments and uses this information to make real-time decisions. It may execute control algorithms to manage operations on the test stand, ensuring they proceed within the designated parameters.

- **Broker/Middleware Layer**

- **CMW server:** CMW stands for Controls Middleware, which is a software layer that facilitates communication and data exchange between the controller and other digital systems. It acts as a server that not only processes the data but also provides interoperability among different system components.

- **Local Storage:** A storage solution closely integrated with the middleware, likely used for the immediate and temporary caching of data before it is sent to the logging service. This may serve as a buffer to ensure data integrity during high-frequency acquisition phases or in case of communication delays with the logging service.
- **Logging service**
 - **NXCALS:** NXCALS is the database and storage system (Next CERN Accelerator Logging Service), handling large volumes of structured and unstructured data generated by the sensors and instruments. It may also serve as a historical data repository for time-series analysis, predictive maintenance, and long-term performance assessment.
- **Data Access and Visualisation**
 - **TIMBER:** A CERN-specific data logging and retrieval service that interfaces with NXCALS, enabling structured data queries and management.
 - **SWAN:** service for web-based analysis at CERN, which offers a collaborative environment for scientific analysis and computation within a cloud-based infrastructure.
 - **Python, etc:** Represents the use of Python or any other programming language for various purposes including data analysis, algorithm development, and operational scripting, reflecting its integration into the data analysis workflow of the Digital Twin system.

In this setup, the controller is the key player that ensures operational control over the physical test bench, while the CMW Server plays a crucial role in data handling and protocol management, ensuring seamless communication across the system. NXCALS acts as a repository and historical reference, critical for long-term analysis and predictive modelling. TIMBER, SWAN, and Python represent the multiple approaches to data access, analysis, and visualisation. This structured data flow supports the Digital Twin's adaptive and predictive capabilities,

4.2.1 Incremental Twin Development and Priority Lineup

The concept of Incremental Twin Development, employing State Machine Diagram Transfer (SMDT) and the implementation of Template-based Event Driven State Machine Architecture detailed in section 5.1, has proven effective in the progressive creation of Digital Twins, as demonstrated in the development of the Electron Beam Test Stand (EBTS) at CERN. This approach allows for the Digital Twin to be built and refined gradually, mirroring updates and enhancements in the physical system through the systematic transfer of state machine diagrams and a structured, template-based framework. This not only ensures consistency and modularity but also facilitates the integration of new features or adaptation to changing requirements with reduced complexity.

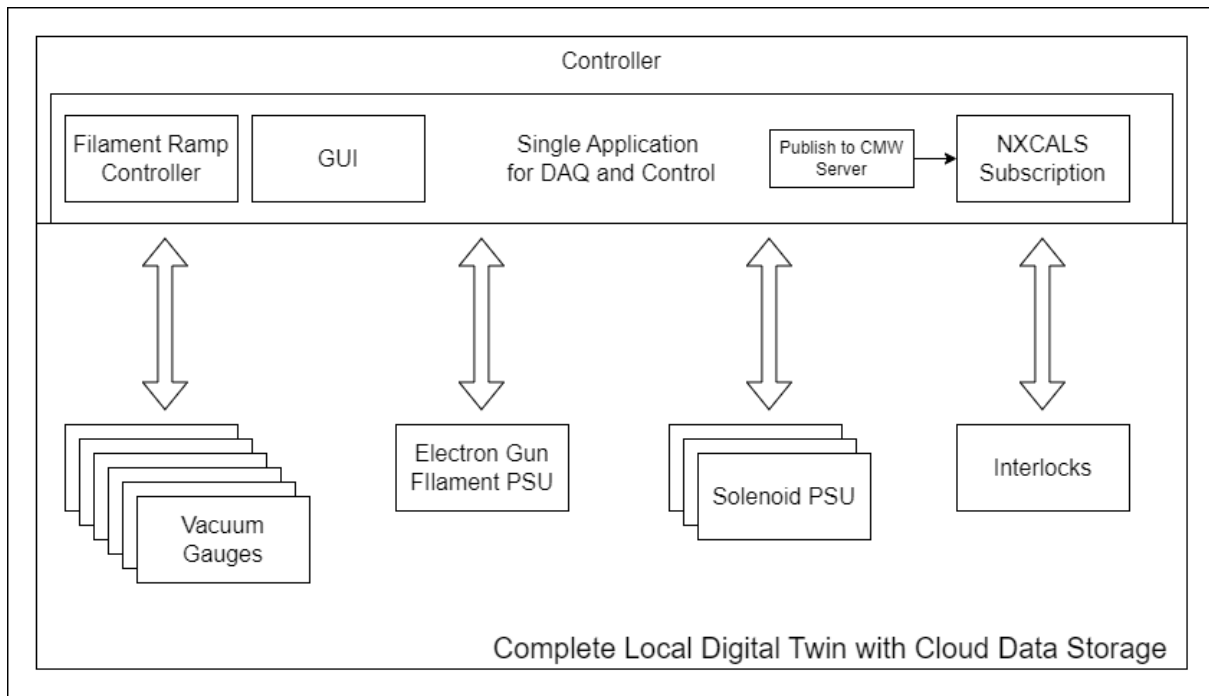


Figure 4.9: Proposal 1: Local Digital Twin Operation

At the EBTS, a Priority Lineup strategy was adopted, where only instruments of core importance were selected initially based on specific use cases. This method enables rapid development of the most critical components of the Digital Twin first, setting a foundation that can be expanded comprehensively over time. Such a strategy exemplifies how Digital Twins do not need to be fully developed before becoming operational but can instead evolve as 'working prototypes'. This phased development approach significantly decreases both the upgrade time and the downtime of the system, allowing for continuous improvements and expansions as necessary.

The existence of this workflow at EBTS showcases a scalable and flexible development model that can be applied to other complex systems, illustrating that Digital Twins can be effectively built up incrementally. This method not only aligns with modern agile development practices but also offers a practical pathway for managing the complexities inherent in replicating sophisticated systems like those found in experimental test benches.

The following instruments are in constant operation during routine experiments on the EBTS. Hence these were given priority over others. This thesis focuses on developing a standard approach to easily scale up other instruments. Only a few instruments out of these are selected based on the ease of communication interface and the need for autonomous operations. The entire list of instruments to be added includes:

- TPG366 Pfeiffer Vacuum Gauges (6 Gauges)
- Electron Gun

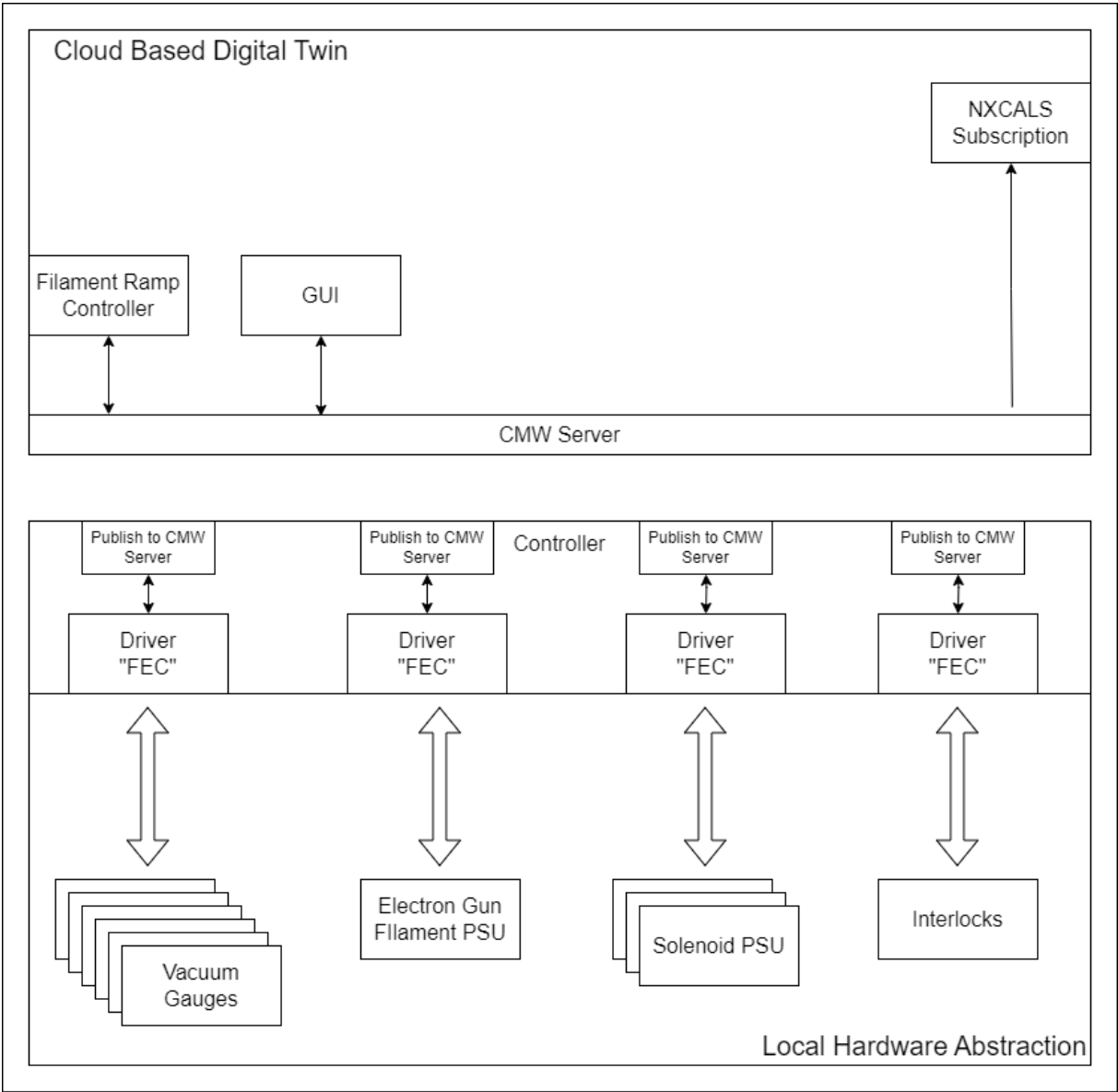


Figure 4.10: Proposal 2: Cloud Digital Twin Operation

- Filament Power Supply
- Solenoid Power Supplies (3 Master Supplies)
 - Circuit A (1 Master 2 Slave)
 - Circuit B (1 Master 5 Slave)
 - Circuit C (1 Master 3 Slave)
- Corrector Power Supplies (12 Supplies)
- BDB Camera (YAG Screen)
- BTV Camera (OTR Screen)
- Electron Gun
 - Cathode Power Supply
 - Anode Power Supply
 - Marx Generator
 - Ross Relay
- Collector Power Supply
- Faraday Cup

4.3 Uncertainty Quantification and Anomaly Detection Methodology

The development and operation of the Digital Twin for the Electron Beam Test Stand (EBTS) integrate methodologies in uncertainty quantification and anomaly detection, which satisfy one of the main goals for developing the Digital Twin. The implementation of both Uncertainty Quantification and Anomaly Detection is detailed in section 5.2

Uncertainty Quantification: Uncertainty in the EBTS Digital Twin stems from two main sources [45]: *aleatory uncertainty* due to inherent variability, such as sensor errors or material inconsistencies, and *epistemic uncertainty* resulting from limited data or model simplifications. The uncertainty quantification process involves probabilistic simulations where uncertainties are systematically quantified to enhance the model's fidelity and predictions. These methods assess the impact of uncertainties on model outputs, allowing for adjustments in the Digital Twin to mirror the physical EBTS with higher accuracy.

Anomaly Detection: Anomaly detection in the EBTS Digital Twin is executed through a combination of data-driven analytics and event-driven architectures. By employing Template-based Event Driven State Machine Architecture detailed in section 5.1, the system is capable of recognising deviations from expected operational parameters, which are indicators of potential faults or system failure. This architecture facilitates the monitoring of state transitions in operational workflows, enabling the Digital Twin to alert operators about anomalies in real time. Critical Parameters such as the Vacuum Pressure in the beamline are continuously monitored for huge spikes which denote a leak. The spikes are identified by a differential analysis. If the slope of the vacuum curve increases beyond a certain threshold and the difference in the values varies significantly over a time frame of 1 second, an Anomaly is generated which informs the user of a leak.

4.4 Extension of Digital Twin Architecture to other Test Benches at CERN

Extending the Digital Twin architecture developed for the Electron Beam Test Stand (EBTS) to other test benches at CERN, such as the Electron Cooler Test Stand (ECTS), the Novel Electron Window Test Stand (NEWTS), and other potential facilities, involves scaling the MBSE Model to accommodate the unique characteristics and operational requirements of each experimental environment. All these test stands to use similar equipment, including vacuum gauges, pumps, solenoids, power supplies, electron guns, and other related equipment. The main hypothesis on which this thesis is based is the MBSE model can act as a 'blueprint' for the development of Digital Twin. This is tested by developing a simplified SysML model of Novel Electron Window Test Stand, thereafter SMDT is performed. A similar implementation of Template-based Event Driven State Machine Architecture is developed thereafter. The User interface of the Digital Twin with a backbone infrastructure mentioned in figure 4.8 is shown in figure 4.11. This proves that the workflow presented in section 3.3 onwards is a truly extensible process. The detailed implementation of the workflow particularly for the case of the Electron Beam Test Stand (EBTS) is described in Chapter 5. The Digital Twin's modular nature allows for integration and scalability, offering a framework that can be adapted for other test benches or complex systems within CERN's vast experimental setup. As the Digital Twin accumulates more data over time, its predictive models become increasingly refined, thus enhancing the system's accuracy and reliability. This Digital Twin implementation exemplifies a cutting-edge approach to test stand operation, moving CERN towards a future where manual processes are augmented by intelligent, data-driven systems. With the EBTS as a prototype, the potential for broader applications is expansive, showcasing the Digital Twin's capacity to transform complex experimental environments into manageable and optimisable systems.

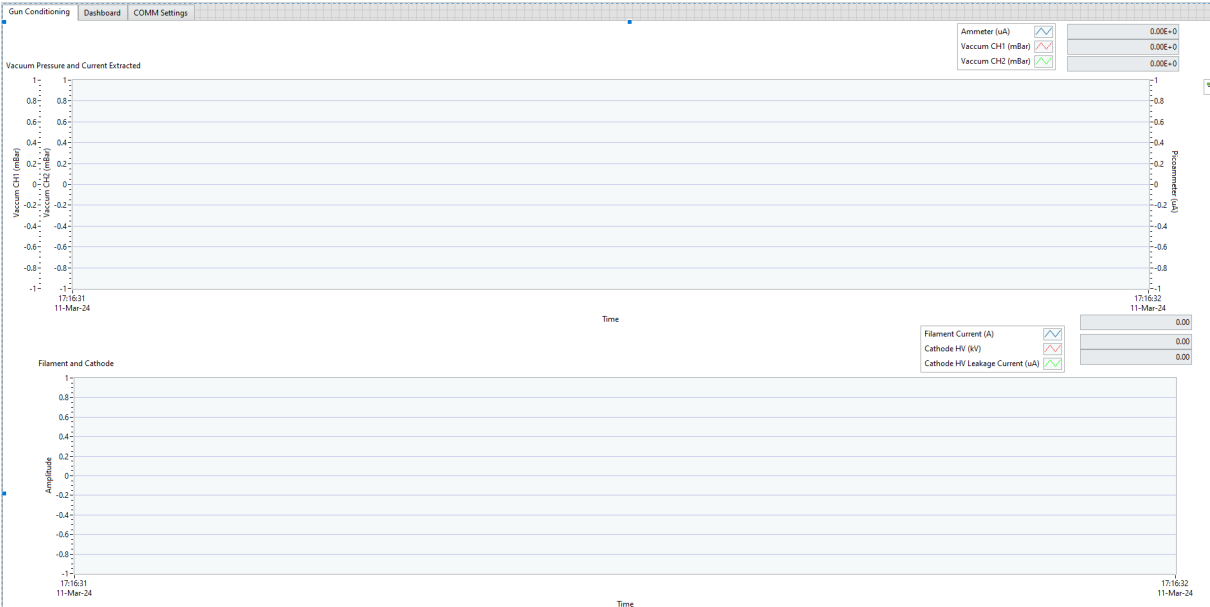


Figure 4.11: NEWTS Digital Twin User Interface

5 Digital Twin Implementation at the EBTS

This chapter implements the architecture and framework developed in chapter 3 and 4 for the particular case of Electron Beam Test Bench (EBTS) detailed in Section 3.2. The hypothesis of the MBSE model of EBTS acting as a 'blueprint' for the Digital Twin explained in chapter 3 is used as the background to implement the entire Digital Twin. This workflow is explained in great technical detail here. This chapter starts by building upon the section 3.4 which shows the State Machine Diagram Transfer (SMDT) into LabVIEW via the State Diagram Toolkit. The Template-based Event Driven State Machine Architecture (TEDSMA) is presented here and all virtual entities of the EBTS are combined to form a single system Digital Twin of the EBTS using an extendable T-Pattern Design. The implementation of the Digital Twin represents a synergy between physical entities and their virtual representations, facilitating monitoring, predictive analysis, and smooth operational performance.

System Composition: The core of the Digital Twin system at the EBTS encompasses a five-dimensional model as proposed in Section 4.7:

1. **Physical Test Bench:** All the hardware components including sensors, instruments, solenoids, electron guns and controlling devices form the tangible aspect of the EBTS. They perform the crucial function of actual beam testing under various operational conditions.
2. **Virtual Twin:** This digital counterpart operates within an industrial controller, mirroring the physical operations in real-time. It comprises modules for data driving, operation management, human-machine interaction, the Digital Twin model, signal processing, state monitoring, and data analysis.
3. **Twinning Communication Protocols:** These protocols ensure seamless data flow and synchronisation between the physical components and the virtual twin. The protocols implemented are described in section 4.1, which include RS232, RS485, USB, and Analog Interfaces.
4. **Cloud Services:** The data is streamed directly via a Controls Middleware (CMW) server into NXCALS. This infrastructure has already been set up by CERN via CCDE.
5. **Data Storage and Handling:** The data is permanently stored in NXCALS and can be accessed from any system at CERN via TIMBER. The user interface of TIMBER is shown in figure 5.33.

In a normal running state, in real-time, the physical information acquisition system can collect test bench operation data and transform it into real physical quantities through sensors during the normal operation of the EBTS. The physical quantities are converted into digital data utilising the data acquisition interfaces. In the case of EBTS, RS-232, and RS485, Analog Interfaces are used more often than others.

On the software front, the operation of the Digital Twin monitoring system is anchored in the Windows operating system, integrating tools like LabVIEW and Python, along with manufacturer-specific software like Pylon (from Basler). The controller interfaces with the data acquisition hardware via drivers to capture real-time signals from the EBTS. The signal processing module processes the raw signals, translating them into a format that the Digital Twin can utilise.

The data are then fed into the Digital Twin model, which acts as an experimentable system, simulating the physical test bench's behavior. Conclusively, the data analysis module interprets the gathered data, distilling key features and insights which are used for enhancing operational strategies, predictive maintenance, and automated control processes. CMW acts as the bridge between the physical hardware and the computational elements of the Digital Twin. It serves as a data router, managing the flow of information from the data acquisition interfaces to the virtual twin and ensuring that the data is processed according to the twin's requirements. NXCALS operates as the main repository for historical and real-time data logging. This service archives operational data, thereby supporting the Digital Twin with a vast dataset for real-time analysis as well as historical data access. The integration of CMW and NXCALS into the EBTS Digital Twin infrastructure demonstrates a state-of-the-art approach to system management and predictive analysis.

5.1 Template-based Event-Driven State Machine Architecture (TEDSMA)

5.1.1 Queued State Machine in LabVIEW

A Queued State Machine in LabVIEW is a design pattern commonly used for managing complex systems with multiple states, complex state transitions or modes of operation. It is developed for systems that need to handle asynchronous events or perform tasks in parallel to each other. Each task or module which handles a single instrument or a control algorithm is allotted a queue on which state definitions and state transitions (shown in figure 5.2) are queued based on priority. Data required for a particular state is also queued into the allotted queue (shown in figure 5.3). The three main advantages offered by Queued State Machine Architecture are:

1. **State-Driven Execution:** Each action is encapsulated within a specific state. The Queued State Machine executes by transitioning from one state to another based on events it processes.

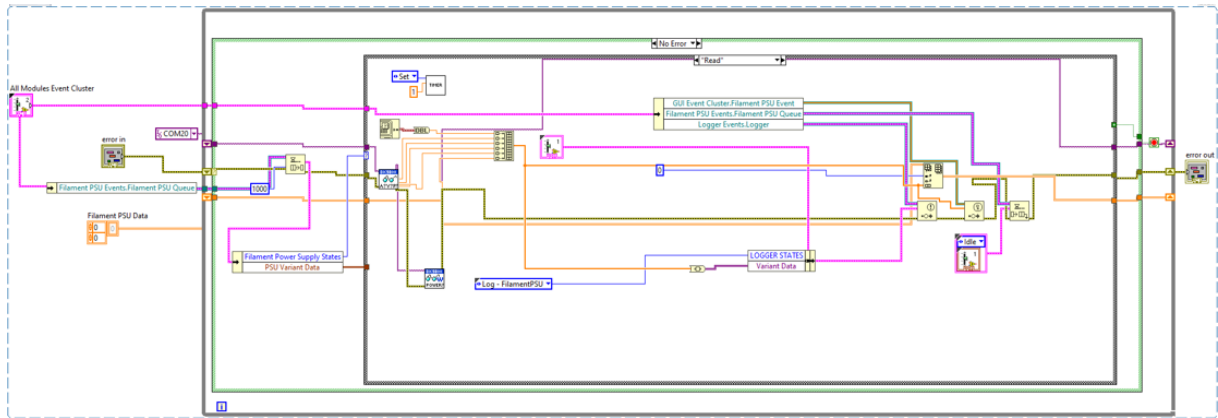


Figure 5.1: Template-based Event-Driven State Machine for Filament Power Supply

2. **Independent Queue Structure:** The queue stores the list of states and data required for that particular state. This queue dictates the next state of the system, ensuring that all events are handled in the order they are received.
3. **Decoupling of Event Handling and State Execution:** By separating event handling from the individual state execution, the Queued State Machine enhances modularity and provides a simple and scalable approach to develop flexible solutions for the EBTS.

To make this exact architecture for the EBTS, the states and state transitions are directly imported from the XMI diagram shown in figure 3.12. This currently is being done manually one by one, but it clearly shows the workflow needed to be adopted to make this entire process automatic. Partial automation is done by the LabVIEW State Diagram Toolkit detailed in section 3.4. The core ideas of the architecture and its implementation are listed below:

LabVIEW's State Machine Template: LabVIEW's Simple State Machine template provides the basic structure to define execution sequences. Within this structure, the code's execution flow is determined by states that are pending responses from external entities, defining the system's behaviour.

Event Handling and State Transitions: The Event Handler Loop in this architecture functions as a message dispatcher, reacting to user interactions or system events by sending or queuing messages to the queue. The State Machine Loop serves as the message consumer, responding to queued messages by executing state transitions and associated actions. By adopting this producer-consumer model, the system is flexible and functional enough to decouple event generation from state management as mentioned in one of the main advantages of this architecture, leading to a responsive and modular Digital Twin.

Defining States, Events, and Actions: In the context of the EBTS Digital Twin, "states" would represent the various operational modes of the system (e.g., Initialise, Read, Configure, Close). "Actions" are the specific responses executed by the Digital Twin in reaction to events, from data logging to system adjustments, based on the current state and event context. "Events" are significant occurrences, such as sensor readings breaching thresholds or user commands that

prompt transitions between states.

Message Queue Management: By employing a Queued State Machine design, the Digital Twin system can handle asynchronous events and manage transitions effectively. Messages related to system performance, diagnostics, and user commands are queued and processed in a controlled manner, ensuring systematic responses to complex scenarios and more importantly no command is missed.

Continuous Execution and Decision-Making: The Digital Twin operates within a While loop for ongoing state execution and response which is capable of running indefinitely or until a stop condition is met. Each iteration of the loop evaluates the current state and pending events, making decisions on the fly.

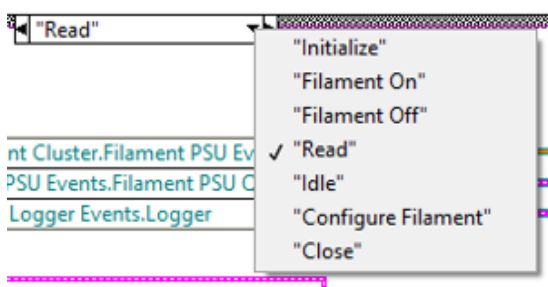


Figure 5.2: State Definitions for Filament Power Supply

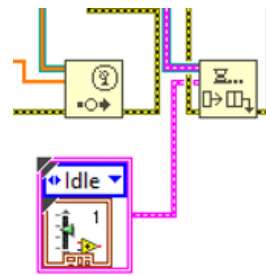


Figure 5.3: State Transition into 'Idle' for Filament Power Supply

The Queued State Machine design pattern brings together elements from the Producer/Consumer, Event Handler, and State Machine design patterns. In this setup, an Event Handler Loop acts as a message sender, and a State Machine Loop acts as a receiver. Messages can be added to a queue through UI events or from different states within the state machine. Additionally, the Queued State Machine design can allow feedback from the State Machine to the Event Handler using User Events. The Digital Twin for EBTS can be developed with a clear structure for handling states, events, and actions. This approach provides a reliable and efficient means to simulate and monitor complex systems. This entire framework is here-on-forward termed as Template-based Event-Driven State Machine Architecture (TEDSMA). TEDSMA is used for every individual entity extracted from the State Machine Diagram Transfer. The XMI file contains all the information on the entity 'States' and 'State-Transitions' which are used to directly define the State Machine Architecture in LabVIEW.

5.1.2 T Pattern Design

The T Pattern Design for state machines in LabVIEW is an architectural pattern that combines aspects of the traditional state machine with additional branches for handling parallel processes. It is named for its structural resemblance to the letter "T" as seen in figure 5.4 where the main

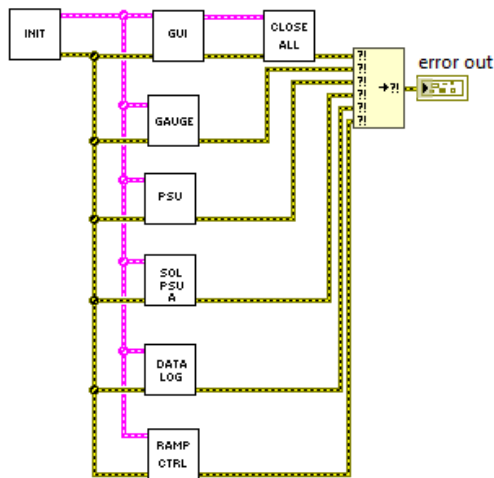


Figure 5.4: T Pattern Design

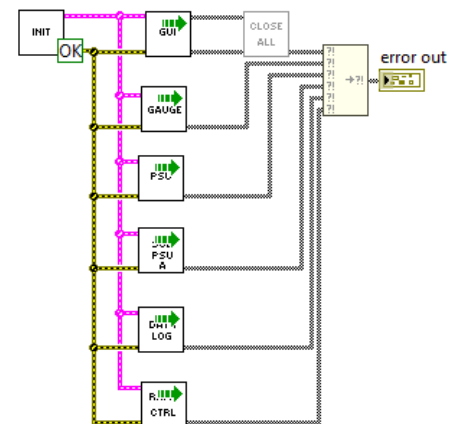


Figure 5.5: T Pattern Design under Execution

state machine runs along the vertical bar of the "T" and branches off into additional sequences or processes at various points, which form the horizontal part of the "T". Each branch, including the main path, manages its state transitions but can influence or be influenced by other branches. This is typically handled through an independent queue structure already implemented via the TEDSMA.

Execution Process: The system begins at an initialisation state, where all necessary communication ports are allocated, and initial conditions are set. This includes setting up any hardware interfaces, initialising data structures, and preparing queues. Each branch can be designed to operate as an independent loop, handling its specific tasks as shown in figure 5.5. Branch loops can also be conditionally triggered based on events or states in the main path. Synchronisation between modules if necessary can be maintained via already existing queue structures. The termination state is present in the main path where all branches are safely shut down by the Close All Module. This involves sending termination signals to each branch by the GUI, ensuring they finish their current tasks and free any resources they are using.

Extending T Pattern Design: Figure 5.6 shows the implemented modules and the possibility of extending the pattern to include as many modules as deemed necessary to portray the full extent of EBTS. Each new module is integrated as a part of the main vertical path. The main path starts with the initialization (INIT) state and follows through states like GUI, GAUGE, PSU, SOL PSU, DATA LOG, and RAMP CTRL, before reaching the CLOSE ALL state which serves as a shutdown sequence. By systematically extending the T Pattern with additional modules, the LabVIEW application acting as the execution mechanism for the digital twin can grow to accommodate the full scope of the Electron Beam Test System (EBTS) without sacrificing the clarity and maintainability of the design. Each module, like those shown in the figure, represents a functional unit that can be independently developed, tested, and maintained.

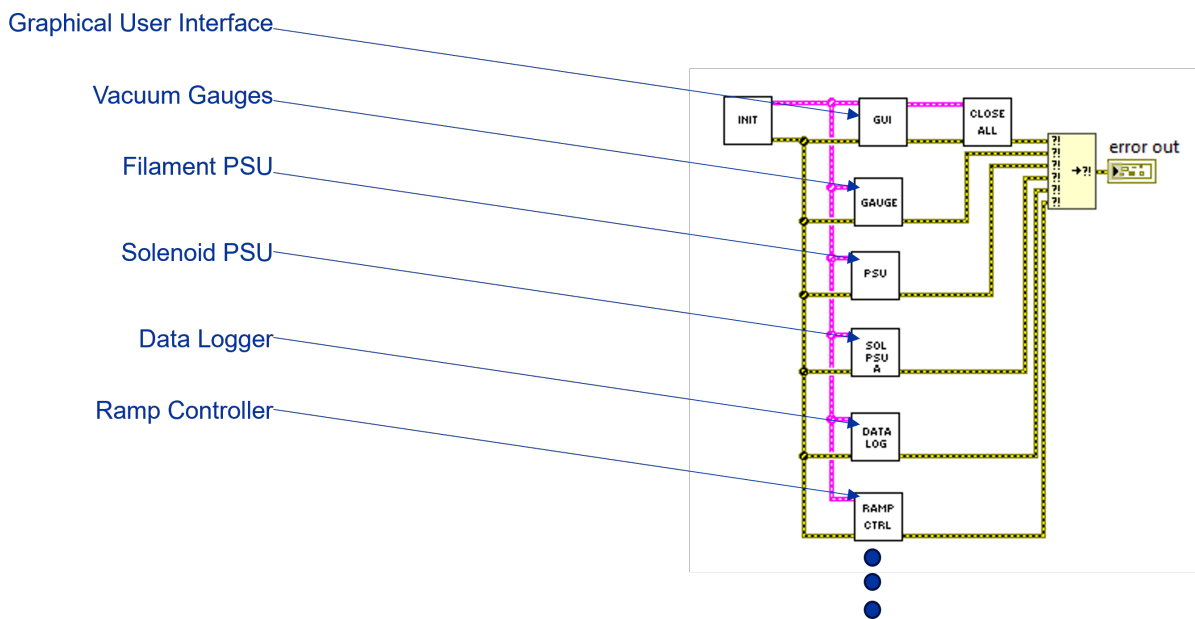


Figure 5.6: Extension of T Pattern

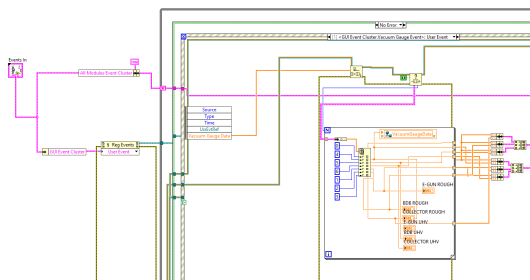


Figure 5.7: Accessing Event Data for Graphical User Interface

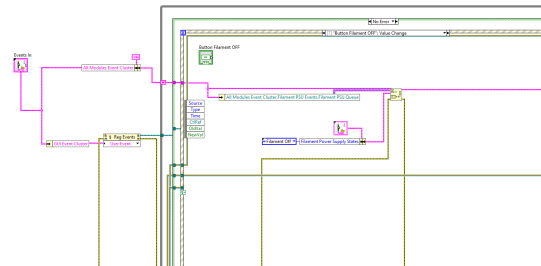


Figure 5.8: Accessing Event Data from Graphical User Interface

Events and Accessing Event Data: The graphical user interface (GUI) in a LabVIEW application is a pivotal point for user interaction and control. Accessing event data for (shown in figure 5.7) and from (shown in figure 5.8) the GUI involves the event structure that captures user actions such as button clicks, value changes, or other control manipulations. Inside the event structure, each event case corresponds to a particular interaction, from which specific data can be extracted and used to update the system or respond to the user. Each frame within the event structure corresponds to a unique GUI event, where the specific data associated with the event—like control references, time of the event, or additional user-defined data—is bundled and processed. This modular handling of GUI events ensures that the application remains responsive and that the user’s input is accurately reflected in real time.

5.2 Development of Simulation Models for Magnetic Field and Beam Size

The development of a predictive model for the transverse beam shape along the axial magnetic field in a solenoid as a simulation entity involves computational physics, numerical methods, and real-time data processing. Two specific models are created and the entire workflow is executed such that the expected beam size at any given Z-plane can be predicted even before the EBTS is operational. The beam size solely depends upon the filament from where the electron beam is extracted, and the magnetic field along the beam line. Since the filament for a certain state of the EBTS is fixed, only the magnetic field due to the eight solenoids and their independent correctors is taken into account. Although there are eight magnets, only three electrical circuits exist to power these solenoids. These are namely Circuit A, Circuit B, and Circuit C.

5.2.1 Solenoid Simulation Correction

Before any experiments at the EBTS are performed, simulations of the same are performed in CST Studio Suite to analyse the beam size and trajectory. The experiment is performed to validate the simulations. However there are numerous errors during the setup of the simulation itself, and the final results are not the same as the experiment results. This necessitates the simulation model be improved. For this specific purpose, the simulation results of a single magnet, are compared with the measured values of a magnetic field using a hall probe around the solenoid. The difference between the two profiles for a single solenoid is shown in figure 5.10 and 5.11. The tails of the curve of the solenoid do not seem to match which shows an unaccounted design parameter in the simulation. This is the first step of model correction in the simulation model in CST Studio Suite. Once the acceptable levels of error margins are attained, the magnetic field profile of a single magnet is extracted and stored as a delimited text file, to be accessed by the second simulation model.

5.2.2 Combined Magnetic Field and Transverse Beam Size Prediction

Since the test stand comprises multiple such solenoids, interference effects increasingly dominate, and result in a non-uniform multi-modal magnetic field along the beam line as shown in figure 5.12. The dotted black line signifies the resulting magnetic field on the beam line. This model is a constantly evolving model and changes based on the current set on Circuit A, B and C. The current(I) in the solenoid is directly proportional to the Magnetic Field(B), by the relation:

$$B = \mu_0 n I \quad (5.1)$$

where μ_0 is the permittivity of free space and n is the number of turns in the solenoid coil

$$B \propto I \quad (5.2)$$

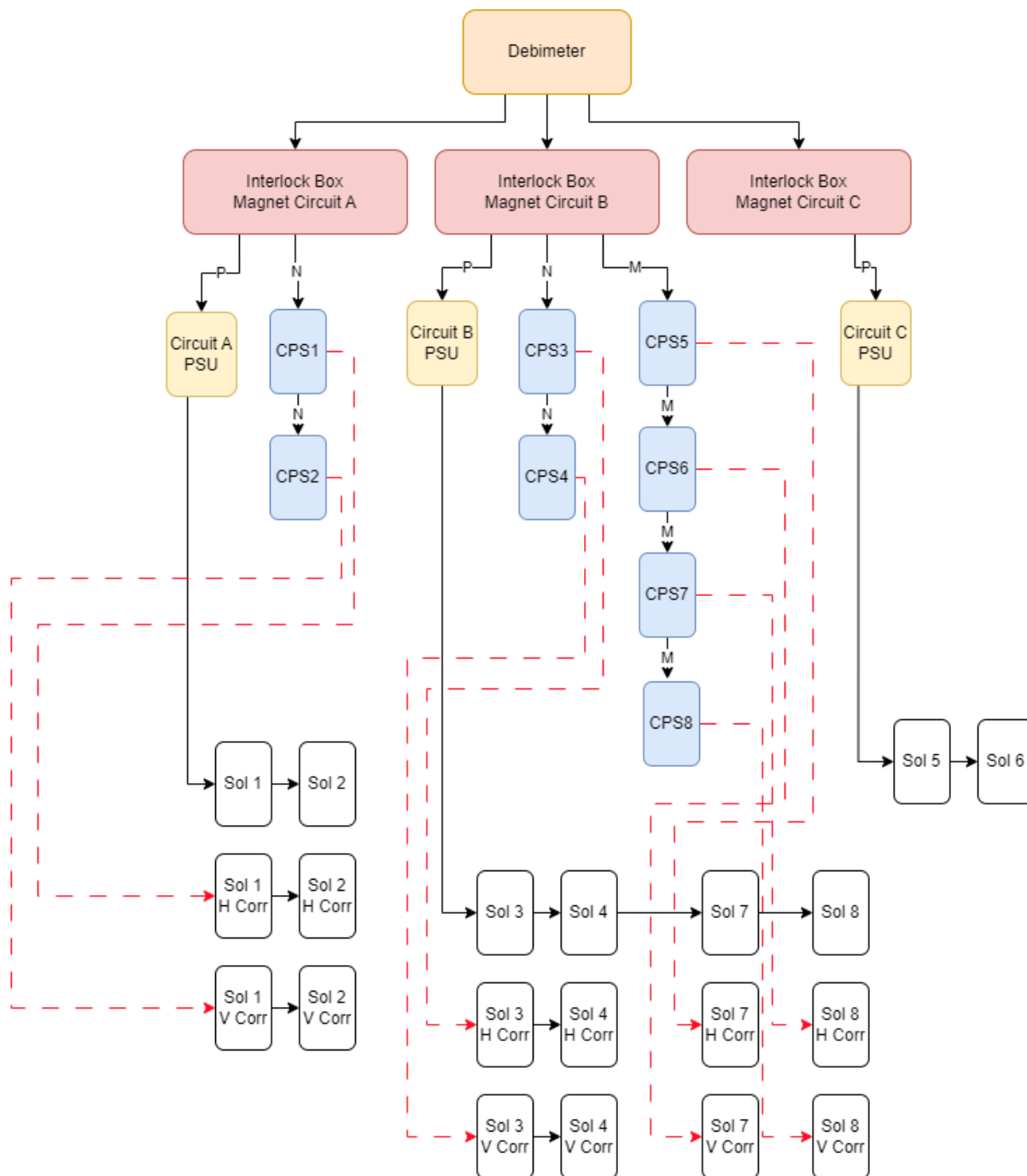


Figure 5.9: Solenoid Circuit Connections and Power Supply - Solenoid Shared Control

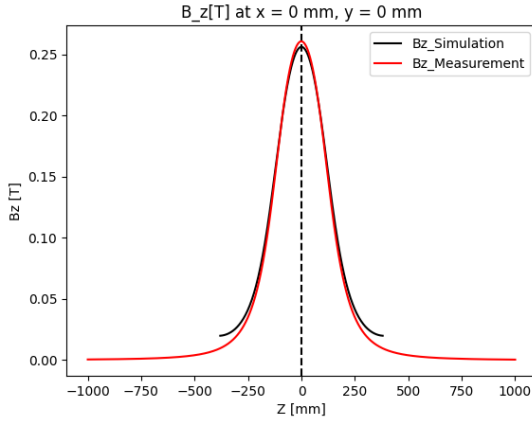


Figure 5.10: Solenoid with Two Aluminium End Plates

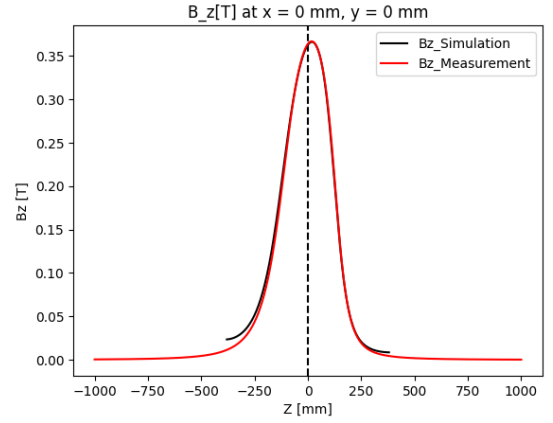


Figure 5.11: Solenoid with one Iron End, one Aluminium End Plate

All such individual magnetic fields are combined to form the combined field on the beam line.

When an electron beam is subjected to a magnetic field, the beam can experience focusing or "squeezing" depending on the configuration of the magnetic field. This effect can be understood through the principle of magnetic lensing, where the magnetic field acts like a lens to focus the beam of charged particles. The fundamental phenomenon behind this is still the Lorentz force, which causes the electrons to move in curved paths due to the magnetic field, thereby allowing for the manipulation of the beam's spread. The beam shape i.e. inner and outer radius of the electron beam is inversely related to the square root of the magnetic field at that specific location. With such a relational comparison, the electron beam size is also plotted alongside the combined magnetic field plot in figure 5.13.

$$\frac{B_1}{B_2} = \frac{r_2^2}{r_1^2} \quad (5.3)$$

5.2.3 Transverse Beam Size Correction and Uncertainty Quantification

The varying beam size over the beamline now can be directly used to predict the size before or during the experiment run. Since this is a pure prediction based on previous simulations, there are errors. The levels of uncertainty are currently unknown. And there is no possible method to measure the beam size in all the Z-locations. To mitigate this issue, two instruments - the Beam Diagnostic Box (BDB), and the Beam Television (BTV) are used to image the beam. The instruments have other use cases as well, but in this scenario, the beam image obtained is processed to obtain the inner radius and outer radius of the beam. The locations of the instruments on the beam-line, and the location on the Z-axis are shown in figure 5.14 and 5.15 respectively. The image acquisition is done with a CMOS camera and along with an Image Intensifier at the Beam Television to image the beam on an Optical Transition Radiation (OTR)

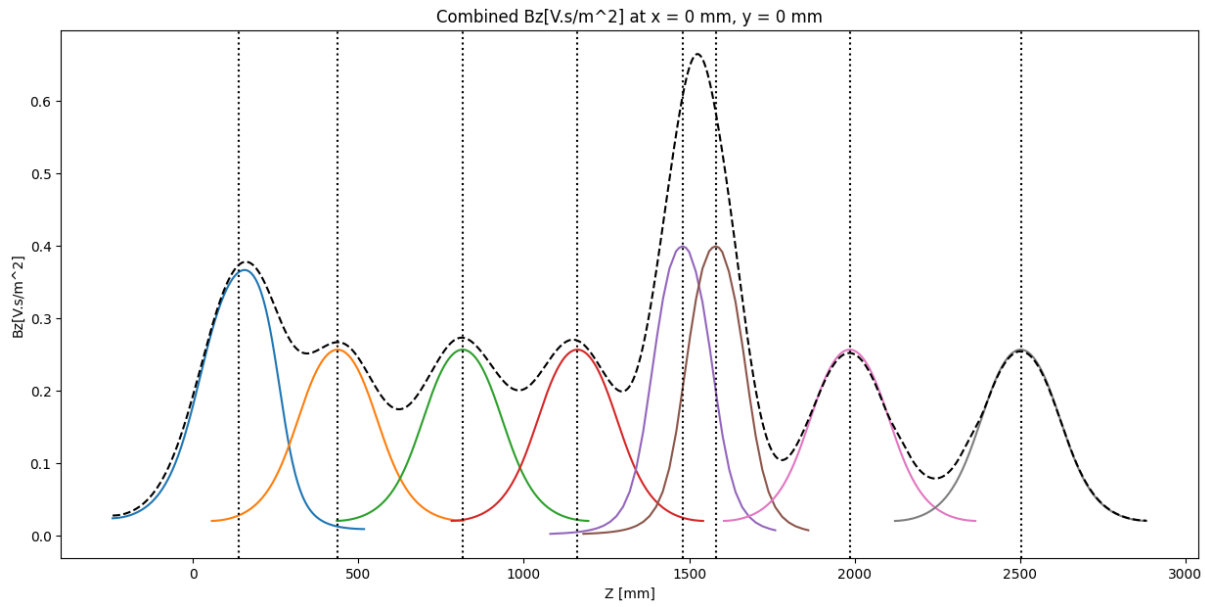


Figure 5.12: Interference of Multiple Solenoids to produce non-uniform Magnetic field along the Beam Line

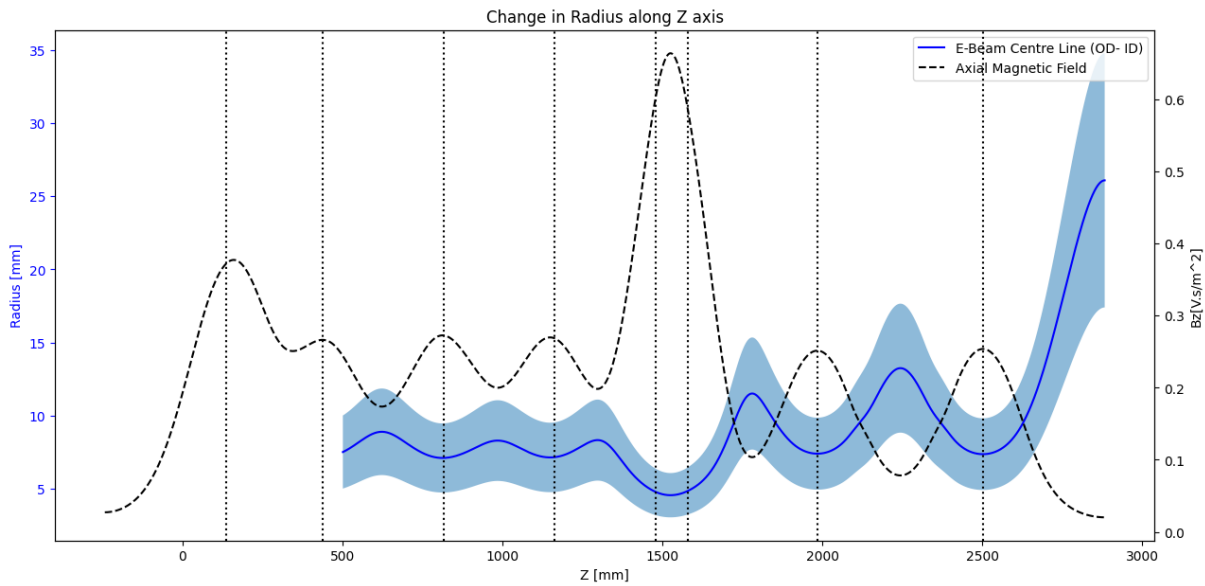


Figure 5.13: Change in Beam Size due to Variation in Magnetic Field

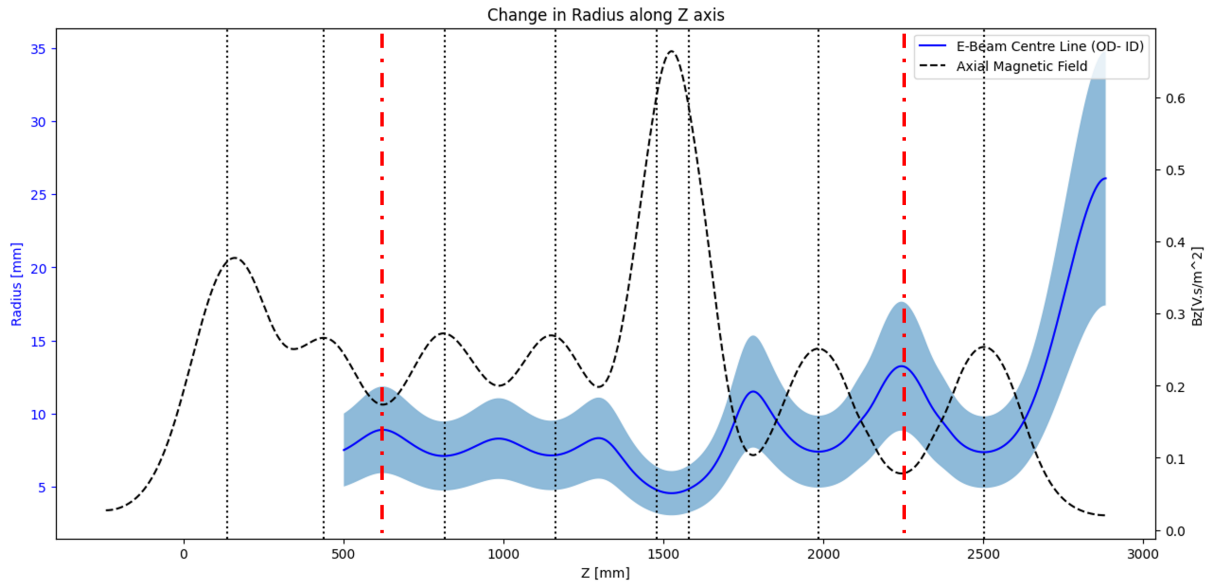


Figure 5.14: Measurement at 2 Z Plane Locations for Measurement Updates

Screen. The captured raw image looks like the image shown in figure 5.17 and 5.18. Since the screen size is physically fixed and known as a design parameter, the image can then be analysed to determine the beam size.

Three main image processing methods are employed on the raw image. Otsu Thresholding which performs simple automatic image thresholding and splits the image into two classes. The Mask generated is then used to form two masks with full circles. One represents the inner radius, and the other represents the outer radius. Then using region proposals on each of them independently, we identify the centre of masses of the two solid masks. This acts as the centre location of the beam. Also, the outer radii of the solid circular masks are generated which are the inner radii and outer radii of the original beam image. The two centres of masses are then averaged to acquire a better estimate of the beam centre. The process flow is shown in figure 5.16. The beam sizes are then plotted on the graph the shift in the centre line is computed and the error margins are plotted on the graph. However, the full capabilities for uncertainty quantification have not yet been realised. The uncertainty in measurements could stem from various sources, including misalignment of the solenoids, which affects the accuracy of the beam size predictions and measurements.

5.2.4 Anomaly Detection and Soft Interlocks

Two specific types of Anomaly detection are currently put in practice. The first is the anomaly occurring due to improper filament conditioning. As seen in figure 5.20, the angular beam intensities on the polar plot show a non-uniform variation at the top and bottom. The process of filament conditioning is explained in detail in section 3.3. anomalies can be detected by

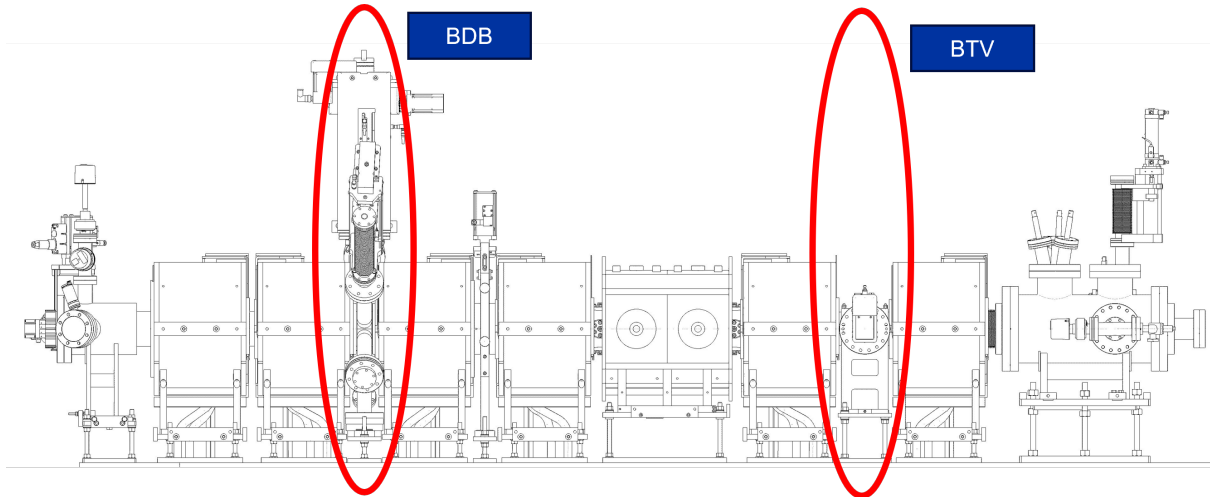


Figure 5.15: Measurement Instruments and Locations at the EBTS to perform Beam Size Updates

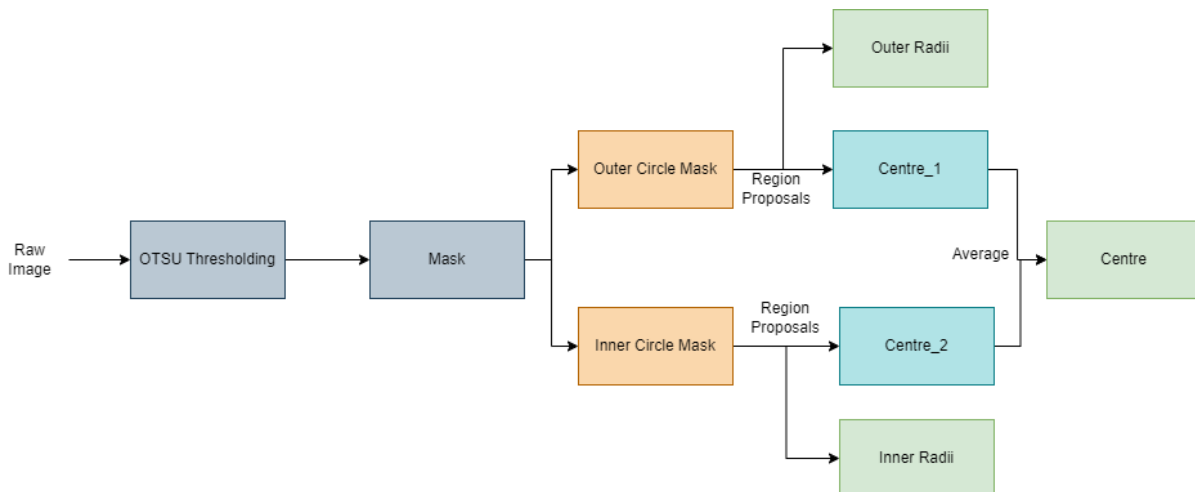


Figure 5.16: Centre and Radii identification from a Captured Beam Image at BDB and BTV

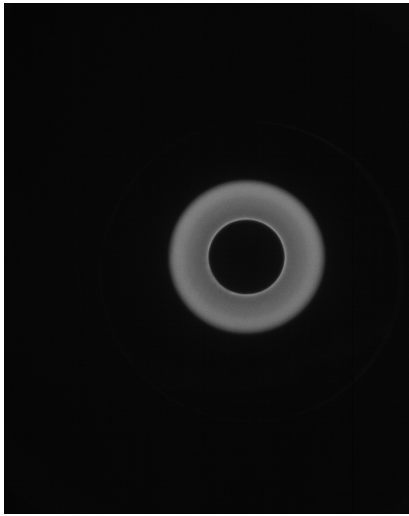


Figure 5.17: Transverse Beam Profile at Beam Diagnostic Box (BDB)- YAG:CE Screen

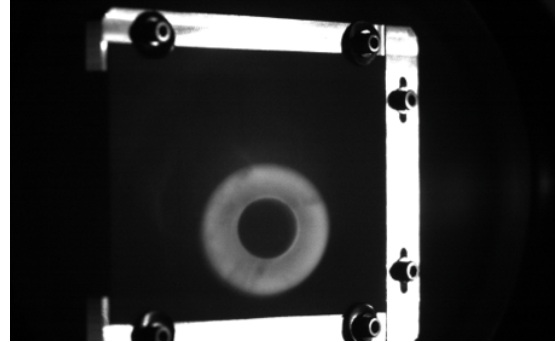


Figure 5.18: Transverse Beam Profile at Beam Television (BTV)- Glassy C Screen

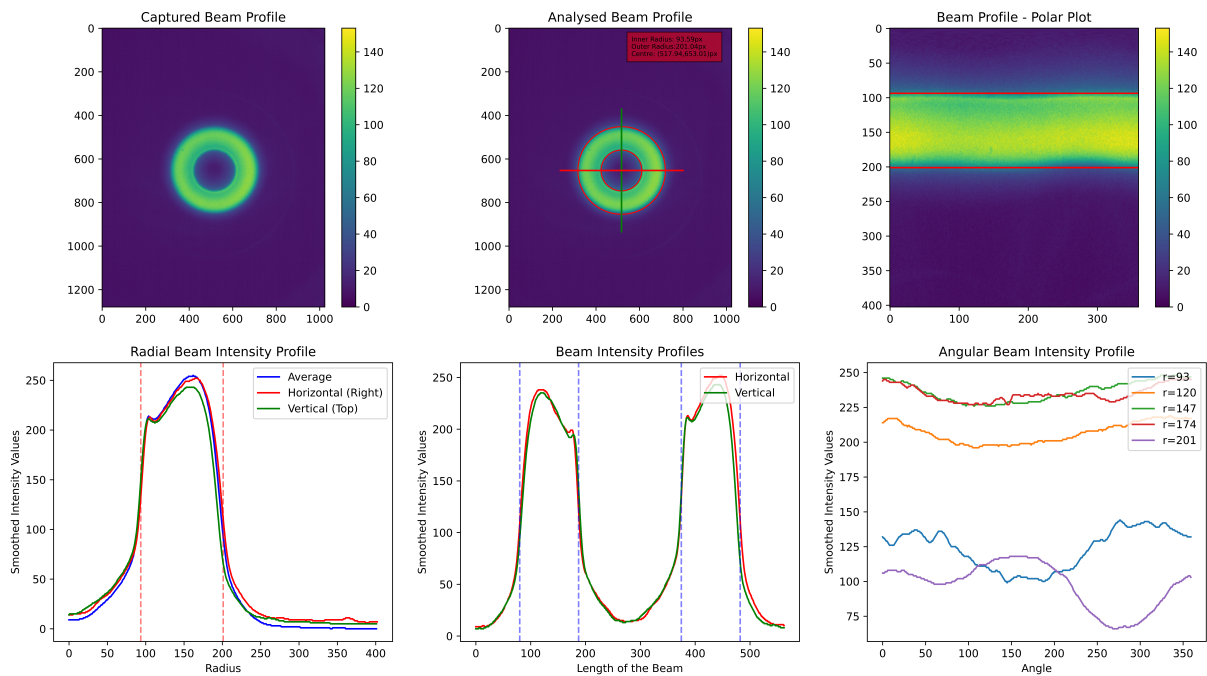


Figure 5.19: Beam Shape Analysis for Image from YAG:Ce Screen (BDB)

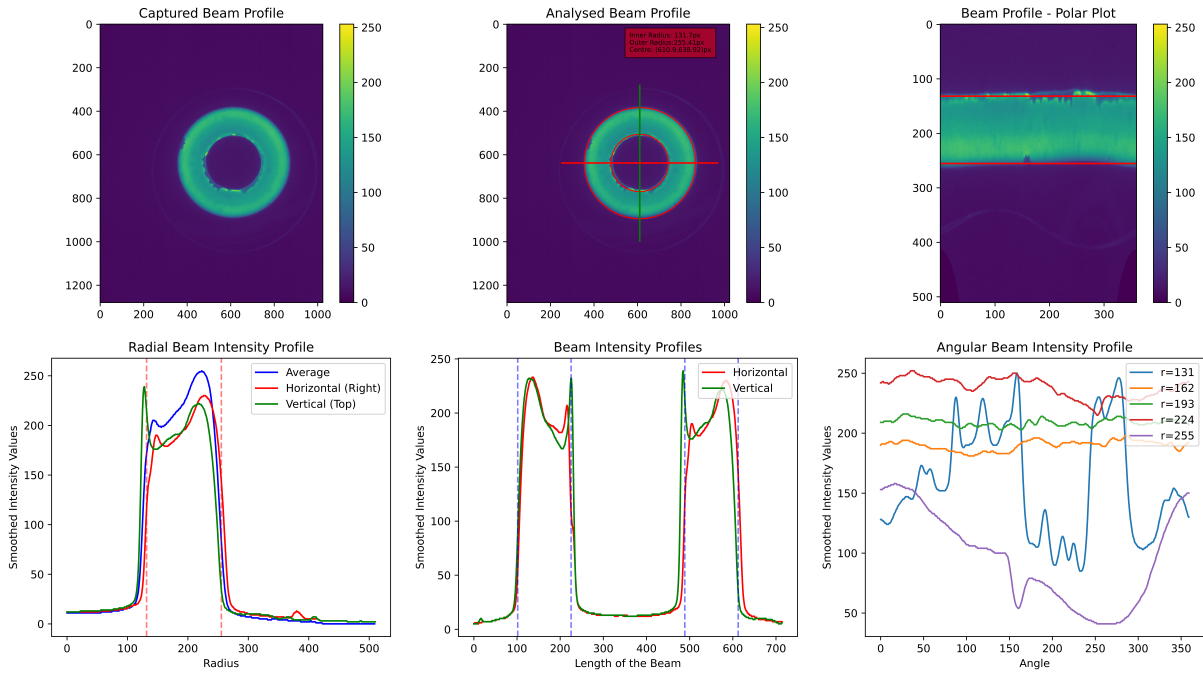


Figure 5.20: Example of Anomaly observed during Filament conditioning (refer section 5.4.2)

analysing the angular beam intensities displayed on a polar plot. The non-uniform variations at specific points (e.g., the top and bottom of the plot) can indicate issues with filament conditioning. Quantifying the deviation from average intensities helps assess the filament's condition post ramping/heating, which is crucial for ensuring beam quality aligns with theoretical and simulated expectations. Better ramping conditions are followed if the uncertainty is too large to conduct any experiments. Vacuum spikes potentially caused by high-voltage sparks within the vacuum chamber are another focus of anomaly detection. Looking at the figure 5.25, the sudden vertical jumps in vacuum between 04:00 and 05:30 are the vacuum spikes. When these spikes surpass a certain threshold, they trigger an immediate shutdown via a Ross Relay—part of a hardware interlock system. Integrating a software interlock might provide a more adaptable and possibly more reliable safeguarding mechanism, reducing dependence on the hardware interlock and allowing adjustments tailored to specific test bench applications. The use of both hardware and software interlocks provides a robust mechanism for immediate response to critical anomalies. The hardware interlock offers a fail-safe that triggers under specific conditions, while the software interlock adds a layer of flexibility and customisation, enhancing the system's responsiveness and adaptability to various testing scenarios.

5.3 Twinning

Twinning, in the development of Digital Twin of EBTS, represents a process for the synchronisation of the physical and virtual entities. Twinning is the act of ensuring the physical state of

the EBTS is accurately and continuously reflected within its virtual counterpart. This process involves real-time data acquisition and control which after certain processing steps is used to update the virtual entity[46].

Synchronisation of States: Twinning is not merely about data replication; it is the process through which any change in the physical EBTS is measured and instantaneously realised within the virtual model. This harmonisation ensures that for every parameter, such as temperature, vacuum pressure, or beam position, its value in the physical domain is mirrored in the digital domain.

Physical-to-Virtual and Virtual-to-Physical Twinning: This two-way interaction involves updating the virtual model based on physical changes and conversely, influencing physical operations based on virtual optimisations. When the EBTS undergoes modifications, sensors capture this evolution, feeding into the virtual twin. Simultaneously, the virtual environment, through predictive analytics and simulations, can foresee potential states and optimise them for efficiency or safety. These optimised parameters are then fed back into the physical EBTS, closing the loop of interaction.

Twinning Rate: The twinning rate defines the frequency at which the synchronisation between the physical and virtual entities occurs. In real-time twinning, changes in the physical EBTS are almost instantaneously reflected in the Digital Twin. This rapid response enables simultaneous actions between both entities, allowing the EBTS to adapt and optimise operations dynamically. For instance, if an anomaly is detected in the EBTS, the system can quickly adjust to mitigate the issue, reflecting these adjustments in the Digital Twin without delay. The controller to be used for the Digital Twin is the National Instruments CompactRIO. CompactRIO systems are well-suited for applications in the Industrial Internet of Things (IIoT), monitoring, and control due to their advanced processing capabilities, sensor-specific conditioned input/output, and an integrated software toolchain. The real-time processor ensures dependable and predictable performance, while the FPGA component excels in handling smaller tasks with high-speed logic and precise timing. This makes CompactRIO an optimal choice for a range of industrial applications where reliable performance and specialised functionality are paramount. [42].

This integration is a pivotal aspect of Digital Twin development, as it ensures comprehensive synchronisation and real-time interaction between the physical entities and their virtual counterparts. The diverse hardware systems, including the electron gun power supplies, vacuum gauges, and other critical components, are connected to the CompactRIO via specialised modules. The CompactRIO serves as a central controller, providing a robust platform for test engineers to implement and manage the Digital Twin development process. This architecture enhances the efficiency and accuracy of simulations by enabling synchronised measurements across various modules and ensuring a high level of control and monitoring. The use of CompactRIO for connecting diverse hardware systems lays the foundation for a sophisticated Digital

Twin that mirrors the full life cycle of the EBTS, facilitating advanced analysis, optimisation, and predictive analysis.

5.4 Remote Access and Autonomous Operation Capability

5.4.1 Remote Access

The controller is connected to the General Purpose Network (GPN) inside CERN via Ethernet outlets (shown in figure 5.22). The device needs to be registered in the CERN Network Registration portal, and the device is assigned a static IP address (shown in figure 5.21) from which it can be accessed from anywhere in the CERN network. This service provides complete remote access to the controller and can be used to acquire access to the digital twin running inside the controller.

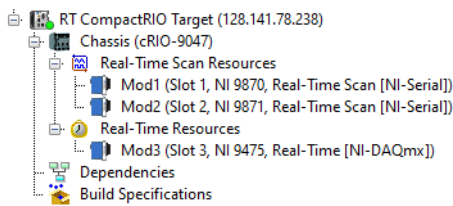


Figure 5.21: Network Connected Controller - NI cRIO



Figure 5.22: Ethernet Port: General Purpose Network Connection

5.4.2 Filament Conditioning, and Ramping

Filament conditioning plays a crucial role in optimising the performance and longevity of thermionic emission cathodes, particularly those utilising directly heated, filament-based designs. Filament conditioning involves subjecting the cathode's filament to controlled heating cycles in ultra-high vacuum environments. The objective is to stabilise the filament's micro-structure and surface properties, ensuring consistent and reliable electron emission over prolonged operation. One key aspect of filament conditioning is the optimisation of operating parameters, including

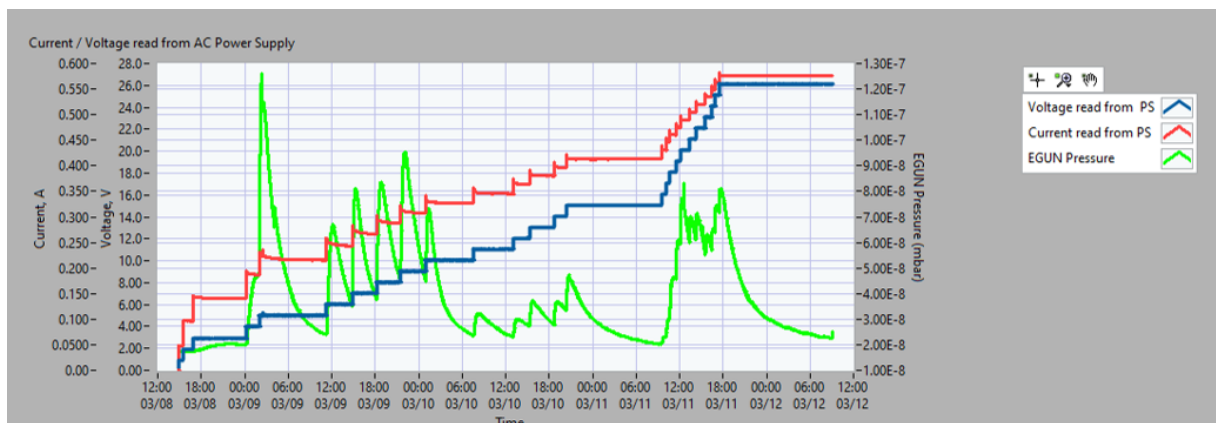


Figure 5.23: Vacuum Spikes Observed during Filament Ramping due to significant outgassing from the heated filament

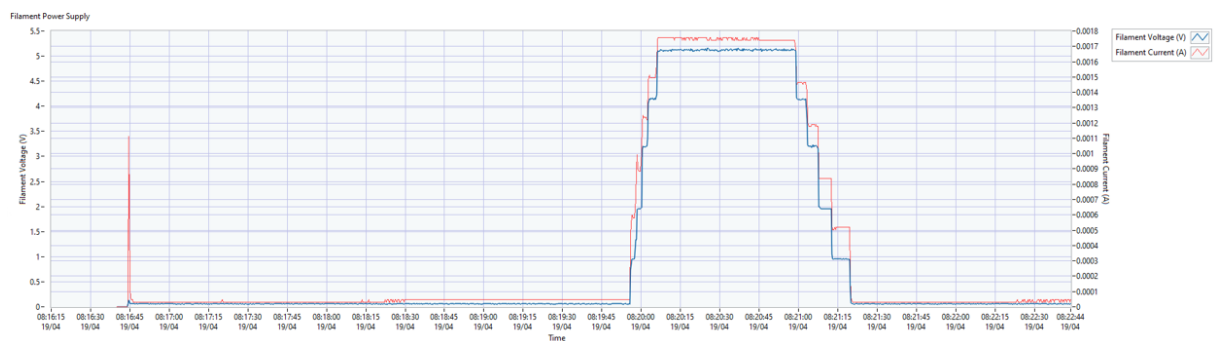


Figure 5.24: Demonstration of Ramp Controller showing the ability to program the ramp up and down sequence as desired

temperature and current, to strike a balance between efficient electron emission and filament longevity.

Filament conditioning involves initially ramping up the voltage, thereby the current passing through the filament to heat it. This heating causes outgassing and creates an immediate vacuum spike as seen in figure 5.23. There needs to be a wait time programmed before the vacuum reaches below a certain threshold until the ramping can begin. An autonomous ramp sequence has been set up as seen in figure 5.24, where the step time and vacuum threshold can be changed on the fly. A more detailed controller can be seen on the User Interface shown in figure 5.29. The ramp sequence has now been tested multiple times for both ramp-up and ramp-down operations with longer step times for better filament conditioning. Referring to figure 5.25, a slow ramp to be finished overnight has been programmed. A clear vacuum increase can be seen as the filament current increases. At higher filament currents, since the vacuum is not as good, high-voltage sparks start to occur which can be seen as a vacuum spike. Low spike amplitudes are good enough, as they provide high voltage conditioning. The start vacuum pressures are quite high due to the performance of other experiments before.

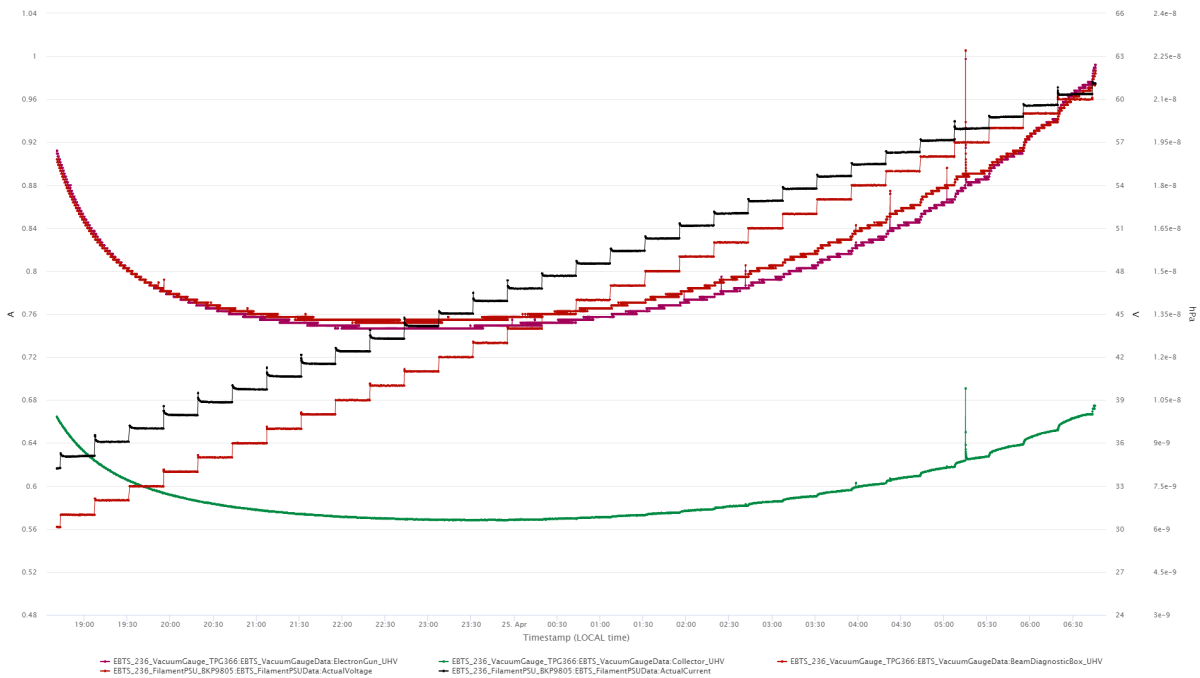


Figure 5.25: Complete Overnight Filament Ramp Sequence showing outgassing from the filament, increase in vacuum and vacuum spikes due to high voltage conditioning

5.5 Setting up Cloud Servers and Data Storage

Setting up cloud servers and data storage on NXCALS via the CMW server at CERN for the EBTS involves the integration of the Controls Middleware (CMW) Server and NXCALS to ensure efficient data communication and storage. The Controls Middleware (CMW) project plays a central role by providing a unified software communication infrastructure for CERN's accelerator controls. The Remote Device Access (RDA) implements the Accelerator Device Model and facilitates device I/O services. On the server side, the Server Framework supports timing-driven polling, crucial for CMW server construction. The OPC Gateway bridges OPC servers, enabling access to industrially controlled devices through the CMW Device API. A four-step procedure has to be followed to set up the CMW server, instantiate a device inside the server and then set up the NXCALS Subscription. The process is as follows:

1. **Creation of Device Class:** This sets up the data fields on what every instrument will share over the CMW Server. This instantiates a front-end computer for every device. The specific set of property fields with units has to be clearly described through which the instantiated device can stream the data. This acts as a "type" of device through which multiple devices can be instantiated. The creation of a device class can be seen in figure 5.26.

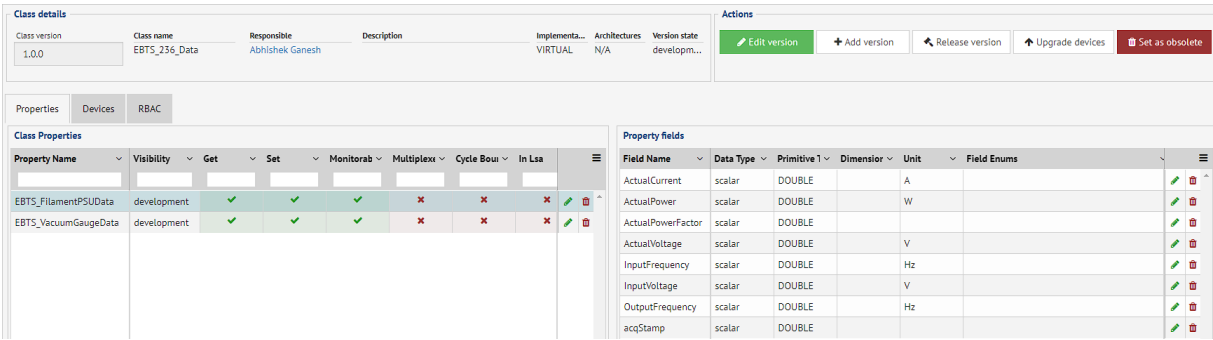


Figure 5.26: Device Class creation on CCDE for the EBTS

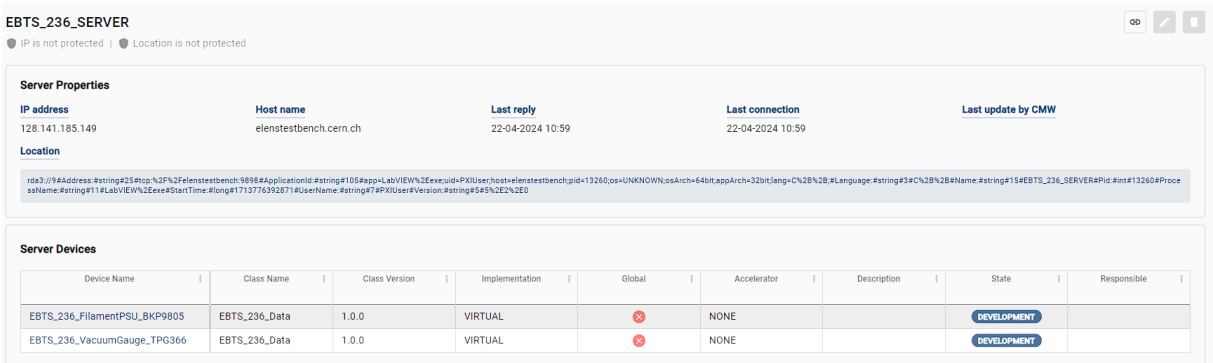


Figure 5.27: Creation of CMW Server as Middleware

- 2. Creation of CMW Server under the given Class:** A server holds the entire system information with all the devices under a single server. This middleware server is developed at CERN and provides a common software communication infrastructure for all accelerator-related devices. Every datapoint is timestamped with a nanosecond time accurate timestamp. This helps to synchronize different data from different devices into the same time frame. The creation of the CMW server as a middleware is shown in figure 5.27.
- 3. Instantiating a device under the CMW Server:** Using the device class created in step 1, new devices can now be added under the CMW server as shown in figure 5.28. This driver directly connects to the physical device via the controller. The streaming of data to the CMW server via the controller occurs through this instantiated device.
- 4. Setting up NXCALS Subscription for the device:** NXCALS subscription is an added feature to store the time series database published in the CMW server. A Continuous subscription service pings the CMW server to store the data in NXCALS. The advantage of NXCALS is the data access without actually knowing how to operate the test stand. This increases the number of users that can work on the data immediately, rather than having to wait and learn how to use the complicated test bench.

Subscription details

Enabled	Property Name	Selector	Timestamp Type	Responsible	
TRUE	EBTS_FilamentPSUD...		ACQUISITION	Abhishek Ganesh	
First update validated	First update logged	Max Payload	Max frequency	Notifications	
ENABLED	ENABLED	2097152		ENABLED	
Status	Status Time	In status since	Last Check Time	Error Message	Last data stats refresh ...
VALIDATION_OK	22-04-2024 09:56	0y 0mo 0d 14h 20m	22-04-2024 10:02		23-04-2024 00:16

Fields

Field Name	Filter	Variable				
ActualCurrent		EBTS_236_FilamentPSU_BKP9805:EBTS_Fila...				
ActualPower		EBTS_236_FilamentPSU_BKP9805:EBTS_Fila...				
ActualPowerFactor		EBTS_236_FilamentPSU_BKP9805:EBTS_Fila...				
ActualVoltage		EBTS_236_FilamentPSU_BKP9805:EBTS_Fila...				
InputFrequency		EBTS_236_FilamentPSU_BKP9805:EBTS_Fila...				
InputVoltage		EBTS_236_FilamentPSU_BKP9805:EBTS_Fila...				
OutputFrequency		EBTS_236_FilamentPSU_BKP9805:EBTS_Fila...				

Figure 5.28: Device Instantiation within a Device Class and CMW Server

5.6 User Interface and access to the Twin

The User Interface (UI) of the Electron Beam Test Stand (EBTS) Digital Twin system is a central component designed to enhance human-machine interaction and ensure operational oversight. This interface enables operators to interact seamlessly with the system, allowing them to monitor, control, and make informed decisions based on the data and analysis provided by the Digital Twin.

- Design and Customisation:** The UI, accessible through LabVIEW, offers a customisable environment tailored to meet the diverse needs and preferences of users. It is designed to provide a streamlined and intuitive means of interaction. The interface is structured into multiple tabs, each dedicated to a specific functionality or access mode of the test stand. This tab-based organisation ensures seamless navigation and quick access to necessary controls and information.
- Operational Features:** Operators interact with the Digital Twin through a dedicated interface that facilitates real-time monitoring and control of the EBTS operations. The UI allows operators to interpret data from analysis modules and make decisions that are critical to the functioning and efficiency of the EBTS.

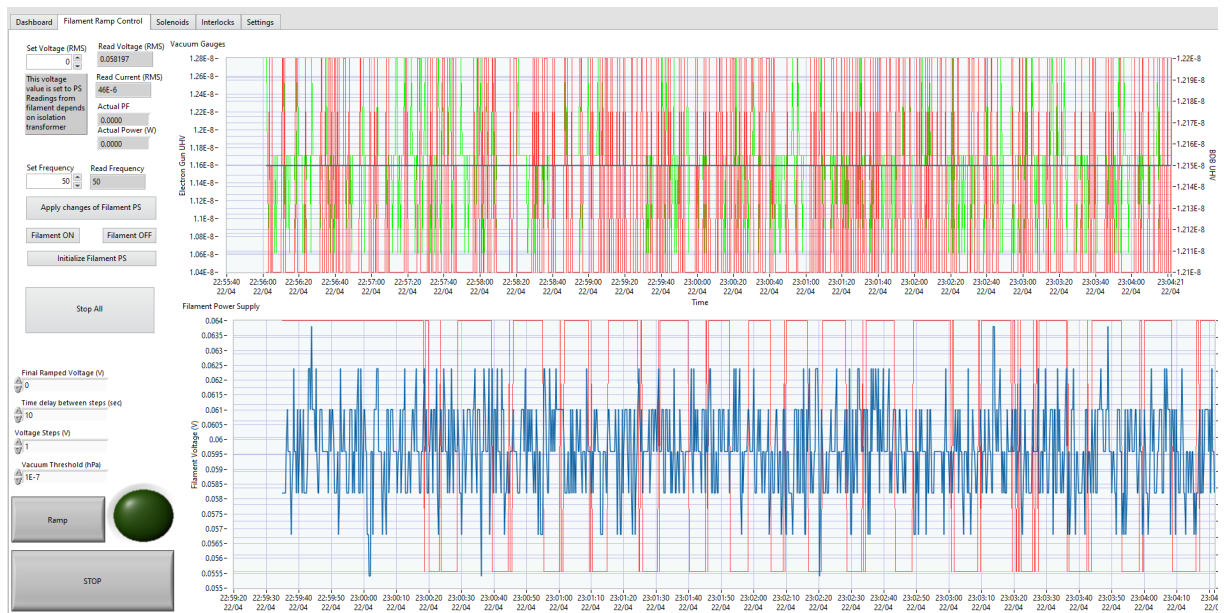


Figure 5.29: UI: Filament Ramp Controller Dashboard

- Filament Ramp Sequence:** This tab of the UI provides a dedicated module for managing the filament ramp sequence, which is critical for filament conditioning. Operators can program and monitor the sequence directly through the interface shown in figure 5.31, adjusting parameters such as ramp speed and timing to ensure desired performance. This module also includes safety features to prevent sudden jumps in voltage, vacuum spikes and other operational risks associated with the filament ramping process.
- Access to Hardware Interlocks:** The UI provides access to the hardware interlock status shown in figure 5.30. This allows a better understanding of the status of the EBTS, and tracking if any critical interlocks have been triggered. This is essential since now the Digital Twin provides almost complete remote access to the Test Stand. Hardware Interlocks completely shut down the Test Stand, and it will be difficult to remotely debug any issue if the interlock statuses are not accessible.
- Prediction of Transverse Beam Size:** Prediction of the transverse beam size using historical data and simulation results can be obtained directly from the dashboard. Since the data analysis process is memory intensive, live updates have not been implemented yet. Each time a button needs to be pressed as shown in figure 5.32 to obtain the latest graph. This predictive capability analyses past performance under similar operational conditions. The feature allows for preemptive adjustments to beam settings, helping to ensure accuracy and stability.
- Data Access via TIMBER:** All the data stored in NXCALS is accessible via TIMBER (timber.cern.ch) from inside the CERN network. The access interface is shown in figure 5.33. All past historical data is available here. Although this allows the local download of the data, custom scripts can be written in SWAN (swan.web.cern.ch) to manipulate data



Figure 5.30: UI: Interlock Status of EBTS

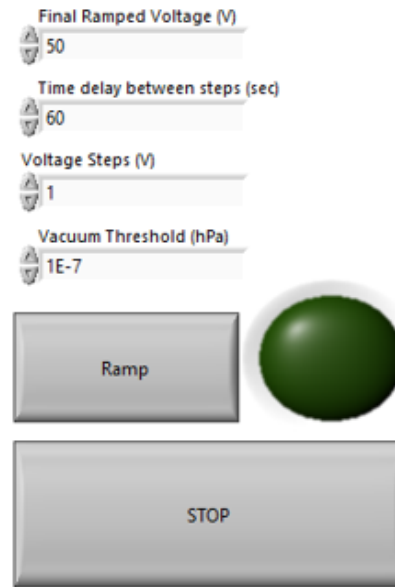


Figure 5.31: UI: Filament Ramp Controller

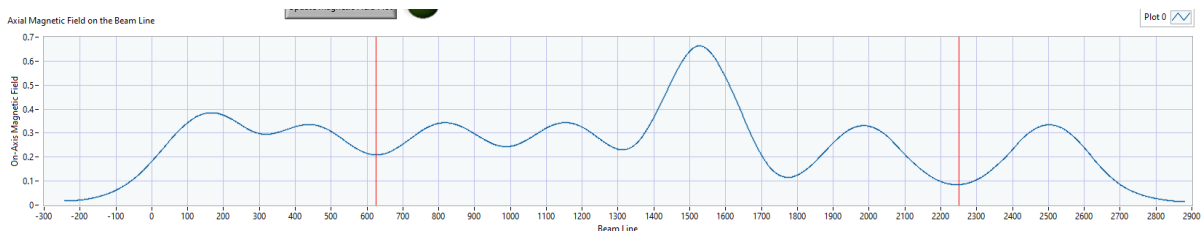


Figure 5.32: UI: Combined Magnetic Field over the Beam Line of EBTS

as per requirement. This data access method allows operators to access test bench data without actually operating the test bench, which is the biggest advantage of having the data uploaded to the cloud instantaneously.

The UI serves as a vital component of the Digital Twin, ensuring that human expertise can complement and verify the system's automated functionalities. This setup not only improves the operational efficiency of the EBTS but also ensures that the system remains adaptable and responsive to the evolving needs of the test environment.

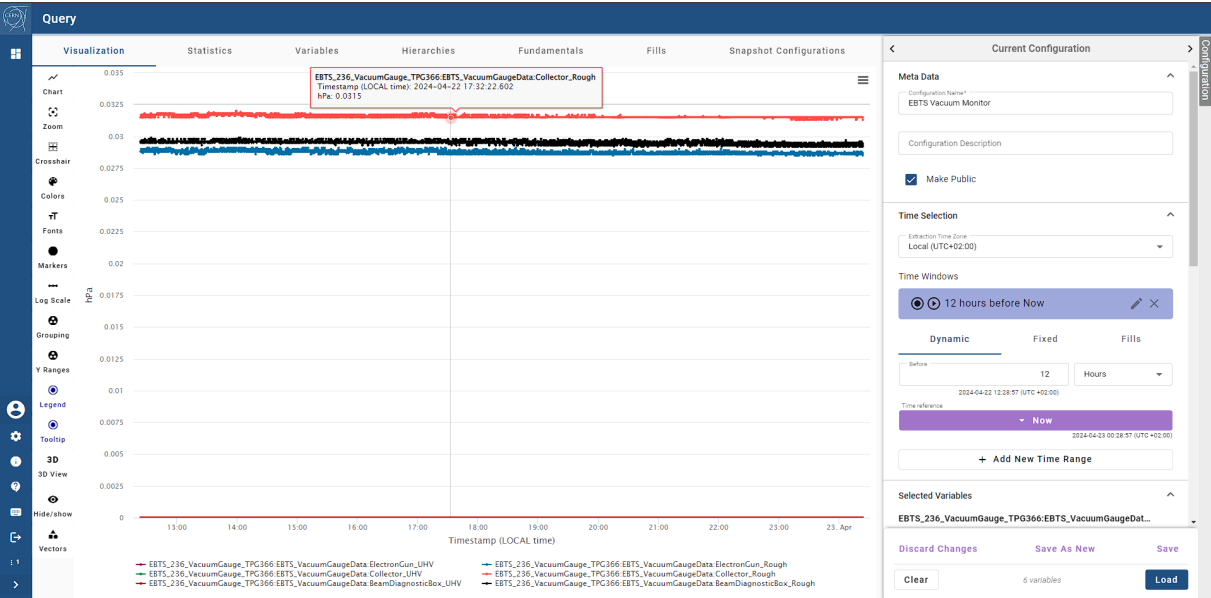


Figure 5.33: Data Visualisation via Timber

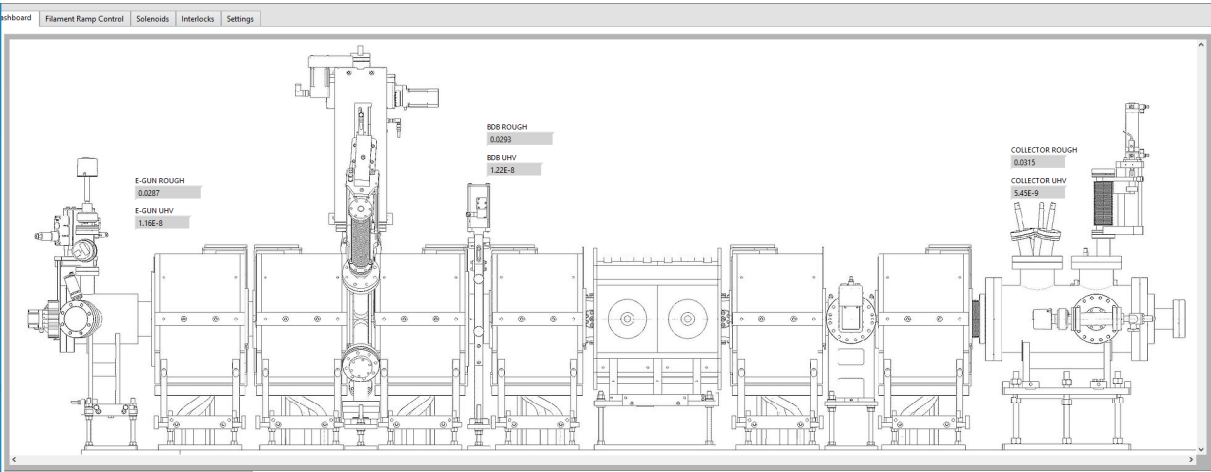


Figure 5.34: UI: Vacuum Gauge Readings over entire Beam Line of EBTS

6 Discussion

The development of a Digital Twin for the Electron Beam Test Stand (EBTS) offered insights into both the specific case of the EBTS and generalisable principles applicable to other systems. This research confirms the possibility of effectively using MBSE models as a 'blueprint' to develop Digital Twins, supporting the hypothesis. This entire workflow is explained in detail in chapters 3, 4 and 5. Unlike traditional simulation-dependent models, the MBSE approach facilitated a reduction in development time and cost by eliminating the need for specific simulation tools.

Regarding the operational improvements after the implementation of the Digital Twin, Safety, efficiency, and data management have been significantly improved. Real-time monitoring and remote operation capabilities have effectively minimised the risks associated with high-voltage equipment and X-ray radiation. The use of NXCALS to store entire historical data would be beneficial in the future to track changes over time and to perform research without physically accessing the test bench. Looking over to scalability and adaptability to other systems, the modular nature of the MBSE approach, State Machine Diagram Transfer (SMDT), and Template-based Event-Driven State Machine Architecture (TEDSMA) proposed and implemented in chapters 3 and 5 support the claim of scalability. This approach has shown flexibility across different simulation platforms and adaptability to other systems such as the ECTS and NEWTS.

While the model is inherently scalable, certain challenges in customisation to fit the specific requirements of different systems were identified. These challenges are primarily related to the integration of system-specific safety protocols and data interpretation methods. The proposed methodologies of SMDT and TEDSMA require the SysML model of the system to be built. One limitation noted was the initial steep learning curve associated with the MBSE tools and techniques. Without this effort, the development of the Digital Twin would have to be an independent task and would have to be developed from scratch.

Regarding the proposed implementation of the T Pattern Design, we were successful in demonstrating the scalable design architecture and concurrent running driver interfaces for every instrument. Handling data consistency, back-tracking, root cause analysis and synchronisation across different modules of the Digital Twin was challenging. We were able to achieve an acquisition time of around 500 ms between signals, but anything lower was almost impossible to achieve with the current architecture. This time difference between instrument readings is still an unsolved problem, due to concurrent applications not being able to synchronise with the system clock. But regardless, our application requirements do not demand any higher precision clocks.

Data storage in NXCALS has been the biggest advantage in terms of providing data access without physically accessing the test bench. However, the problem arises when there is a need to save images taken at BDB and BTV locations. These images are crucial for research purposes, and in the current implementation, the images are stored locally. Different parameters of the test bench result in different images of the electron beam, hence the images need to be tagged with a lot of information. Searching for these images is not an easy task while trying to post-process the data. Work is already in the pipeline to store the images in NXCALS, which has a 5 MB per upload limit. A local processing step has to be added to compress the image or crop out the beam from the image to reduce the image size.

This leads to another problem, of limited local computing power available on the controller. First, the analysis of the acquired image to calculate the centre and radii of the beam as shown in figure 5.19, takes up a lot of compute power. Hence, there is a limitation on the frequency of running the analysis script. In addition to this, intelligent cropping of every image will use much more computing power than what is available on the controller. As mentioned before, the current implementation solves this by storing everything locally and reducing the frequency of running the analysis script.

Considering the initial work undertaken at EBTS, more efforts would have to be taken to make the Digital Twin more robust. As of now, only State Machine Diagrams from the SysML model have been used to build the Digital Twin. A lot of information about the model is lost by ignoring the rest of the model views. Future research could focus on improving the transfer of data from the model more efficiently and building a high-fidelity digital twin.

7 Conclusion and Future Outlook

This thesis has successfully demonstrated the development of a Digital Twin for Electron Beam Test Stand (EBTS) utilising a Model-Based Systems Engineering (MBSE) approach. The research was centred on devising a methodology where the EBTS could be described in a manner independent of any specific simulation platform. This approach ensures that the Digital Twin can be adapted for various simulation environments or potentially integrated into broader systems without being tied to a single technology. The MBSE framework facilitated this by enabling a structured, logical representation of all system components and behaviours in a universally understandable format through SysML (Systems Modelling Language). The adoption of the Systems Modelling Language (SysML) to define a simulator-independent description allowed for detailed and accurate modelling of the EBTS's architecture, behaviours, and inter-connections, which were vital in the development of a robust Digital Twin framework. This framework not only supported real-time operations but also facilitated predictive analytics for system dynamics and performance.

The core aspect of the research explored the practicality of translating an MBSE-based model directly into a Digital Twin by using the model as a 'blueprint'. State Machine Diagram Transfer (SMDT) and Template-Based Event Driven State Machine Architecture (TEDSMA) have been proposed in Sections 3.4 and 5.1 which semi-automatically facilitate this translation. The workflow is demonstrated twice by applying it to EBTS and NEWTS. The working existence of the Digital Twin for two independent test stands supports the hypothesis that an MBSE-based SysML model can be directly used to develop a Digital Twin. The Digital Twin significantly mitigates the risks associated with the high-voltage equipment and X-ray radiation inherent in the EBTS operations. These elements work together to enable complete remote operation and real-time simulation capabilities, significantly reducing risk to human operators and improving operational flexibility.

Although the project confirms the potential of MBSE to standardise the development of Digital Twins across various applications, its scalability and adaptability to systems beyond those tested still require further empirical validation. Future research should focus on optimising the data transfer from SysML models to enhance the fidelity of Digital Twins. This would ensure that the promising results seen in controlled environments can be replicated in more varied and dynamic settings.

The Digital Twin developed for the EBTS represents a significant step forward in the application of MBSE to Digital Twin technology. It serves as a prototype that not only enhances the operation and safety of the EBTS but also sets a precedent for future Digital Twin implementations with more robust and versatile system designs.

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8 Appendix

8.1 Magnetic measurement results of the Solenoids

8.1.1 PXMLCAANWC-CR000006 solenoid

Two nested CCT correction coils (MCLAA06) are integrated into the solenoid, creating a dipole field. The solenoid and the corrector coils were measured in static conditions before and after replacing one of the two end plates with an aluminium one to increase the field magnetic length. The field maps and the magnetic field transfer function were measured at several current levels. The solenoid will be part of an electron beam test stand, which will be used to evaluate the components of the hollow electron lens (HL-LHC WP5), and its function inside the test stand is to confine the electron beam and prevent it from becoming unstable. The solenoid hosts two nested CCT correction coils (MCLAA06) connected in anti-series to form a dipole magnet, having a field direction of 45 °. The measurement campaign aims to obtain the axial and radial field components as a function of the longitudinal position of the main magnet and the two CCT coils, the magnet transfer function, and the magnetic length. The magnet, in the as-delivered conditions, has an end plate made of aluminium and the other end plate made of soft iron. After the first set of measurements, the soft iron end plate was replaced by another aluminium one to increase the magnetic length. The measurements were repeated to assess the difference between the two configurations.

8.1.2 Measurement Procedure

The measurements were performed using a translating fluxmeter, which had been designed for a former project. The fluxmeter consists of a PCB array of induction coils, as shown in Fig. 3, consisting of five concentric disks and 16 quadrant sector coils attached to a carbon fiber tube, which is slid through the magnet aperture. The movement of the fluxmeter inside a magnetic field determines an induced voltage at the terminal of the coils. The induced voltage is acquired using digital integrators triggered by a linear encoder, having a resolution of 0.11 mm. The axial field component ($B_z(Z_k)$) and the radial field component ($B_r(Z_k)$) are respectively determined as

$$B_z(Z_k) = \frac{\Phi(Z_k)}{A_j} \quad (8.1)$$

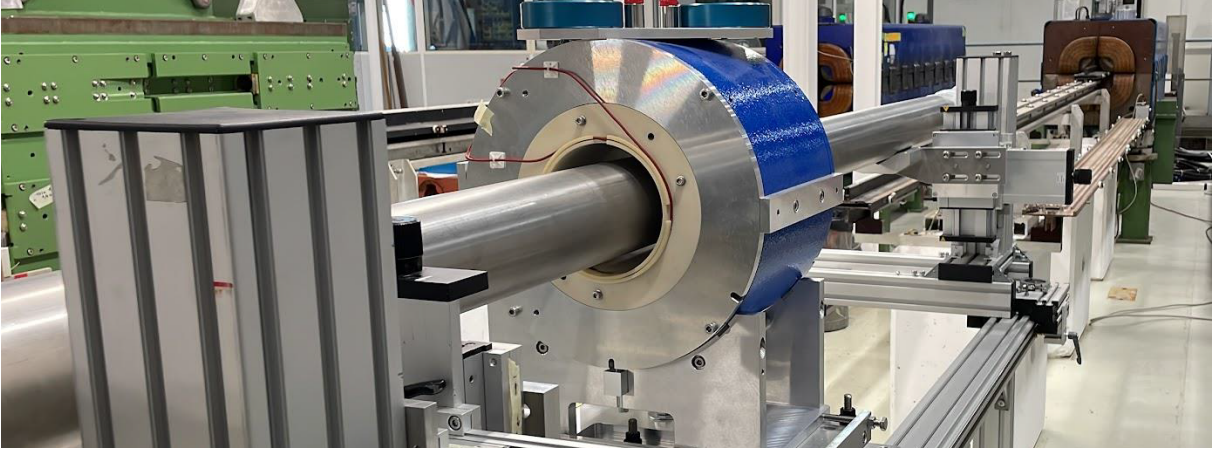


Figure 8.1: A photograph of the solenoid setup for measurement

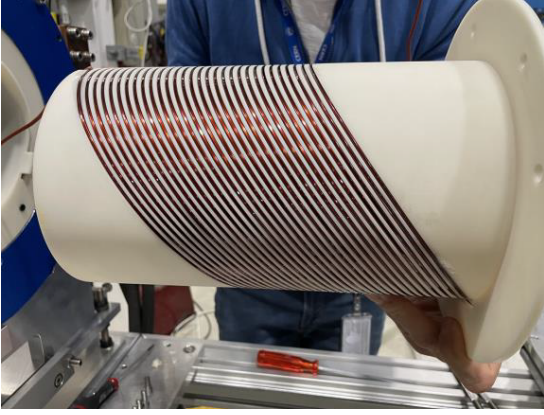


Figure 8.2: Vertical CCT correction coil

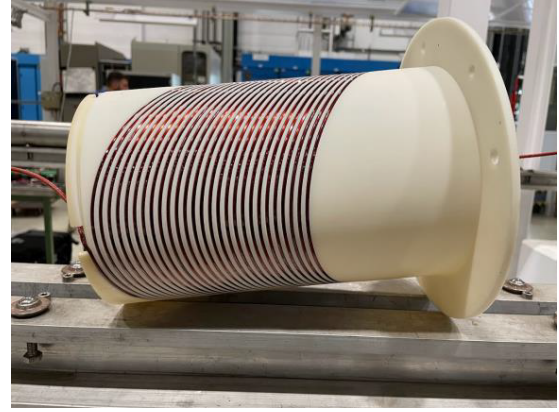


Figure 8.3: Horizontal CCT correction coil

$$B_r(Z_k) = \frac{\Phi(Z_{k+1}) - \Phi(Z_k)}{2\pi r_j Z_k N_j} \quad (8.2)$$

where Z_k is the k -th position on the longitudinal/axial axis, A_j and r_j , the effective coil surface and the radius of the j -th coil in the array, and N_j is the number of the sensing turns of the j -th coil. Only the outermost disk coil was used for the measurements presented in this document.

The main field generated by the solenoid was measured after pre-cycling the magnet five times between -900 A and 900 A. The pre-cycling was applied after degaussing the magnet. The measurements were performed between 0 and 900 A, with the current increased by 100 A at each step.

The field components of the nested dipole magnet were measured by powering the CCT coils between 5 and 20 A independently, with the current increased by steps of 5 A. Given the low field levels, the remnant field of the solenoid was subtracted from the measured field profiles

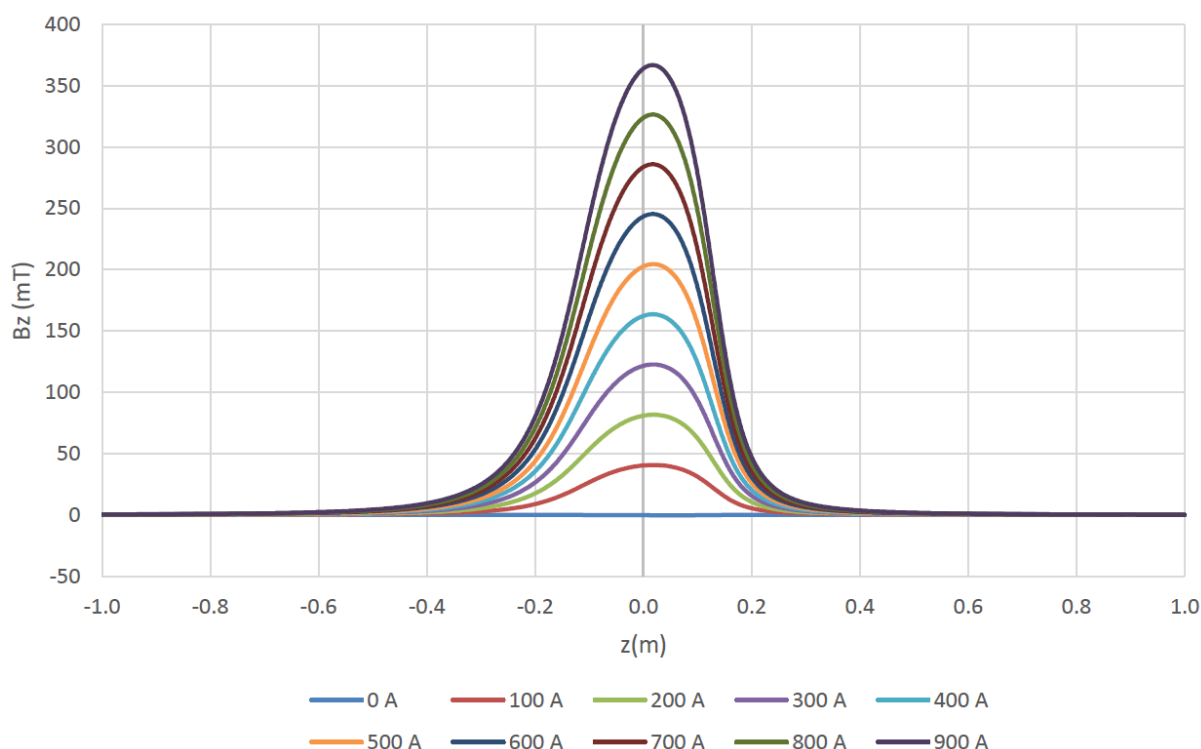


Figure 8.4: Iron End Plate: Main axial field profile for different current levels as a function of the longitudinal position

to decouple the main field contribution from the correction field. The position $z = 0$ is set in correspondence with the magnet longitudinal centre.

The measurement results are presented in the following Figures. The corresponding values of the field profiles can be found in the file PXMLCAANWCCR000006MLCAA06.xlsx, attached to this EDMS document 2801211. All the results were obtained by averaging three consecutive measurements. The standard deviation of the axial peak field is lower than 6 units and lower than 1 unit at 900 A.

8.2 Interlock Circuit Diagrams

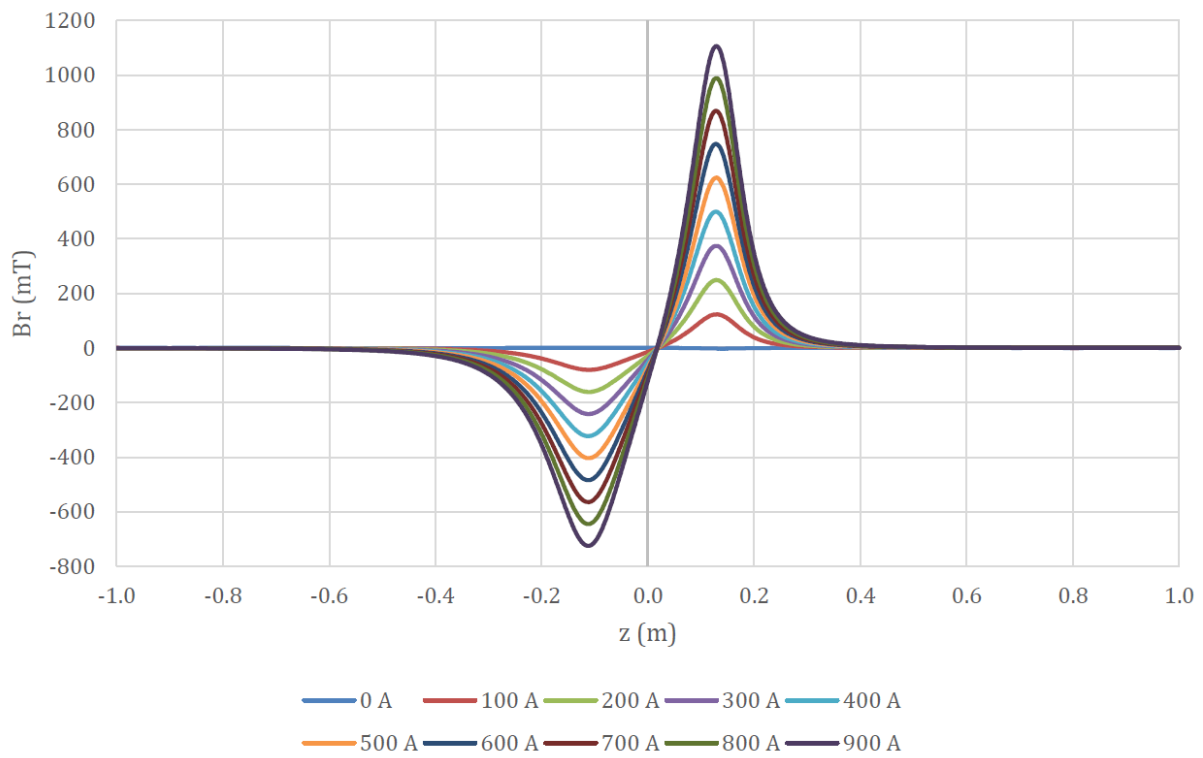


Figure 8.5: Iron End Plate: Main radial field profile as a function of the longitudinal position, for different current levels

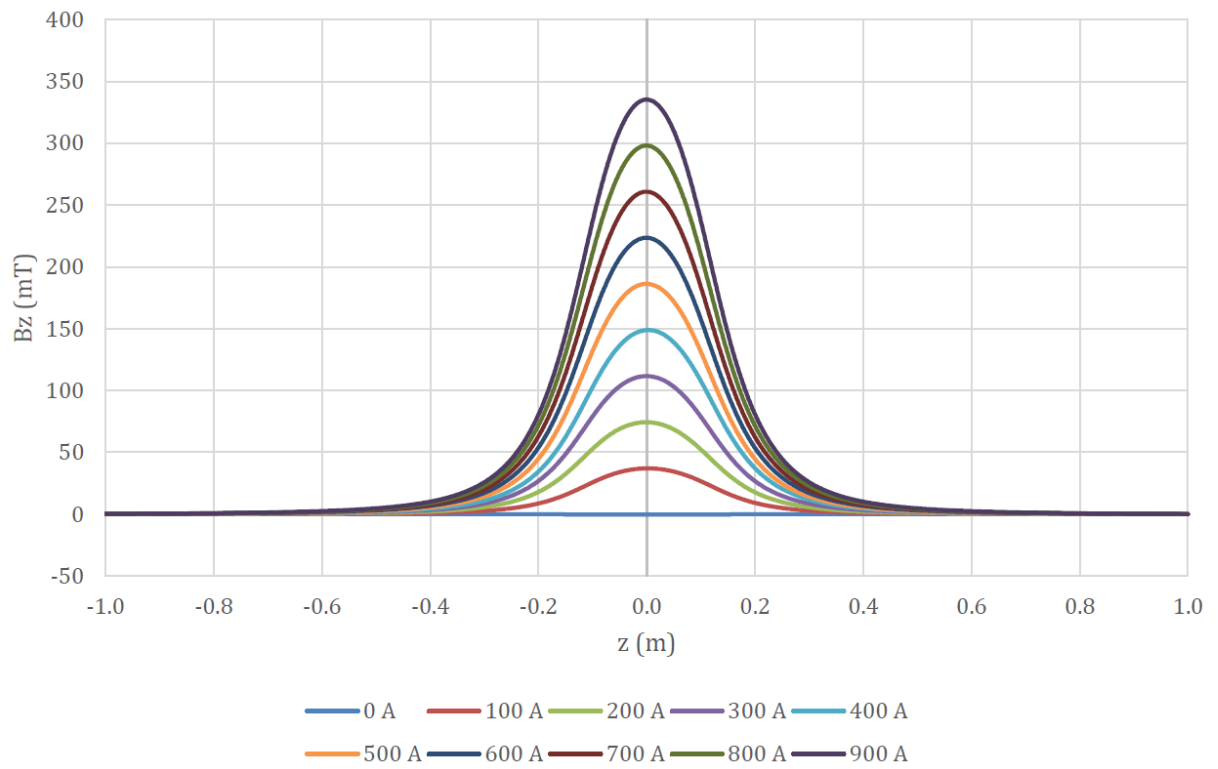


Figure 8.6: AL End Plate: Main axial field profile as a function of the longitudinal position, for different current levels. The standard deviation of the peak field is lower than 6 units

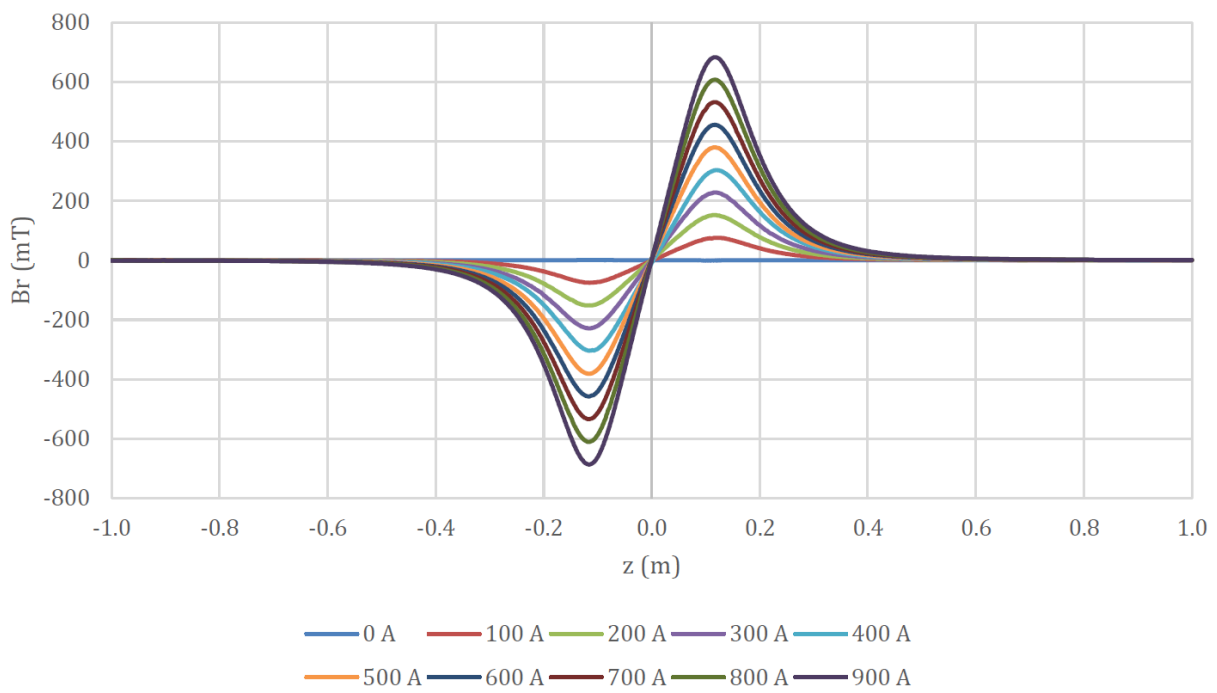


Figure 8.7: AL End Plate: Main radial field profile as a function of the longitudinal position, for different current levels

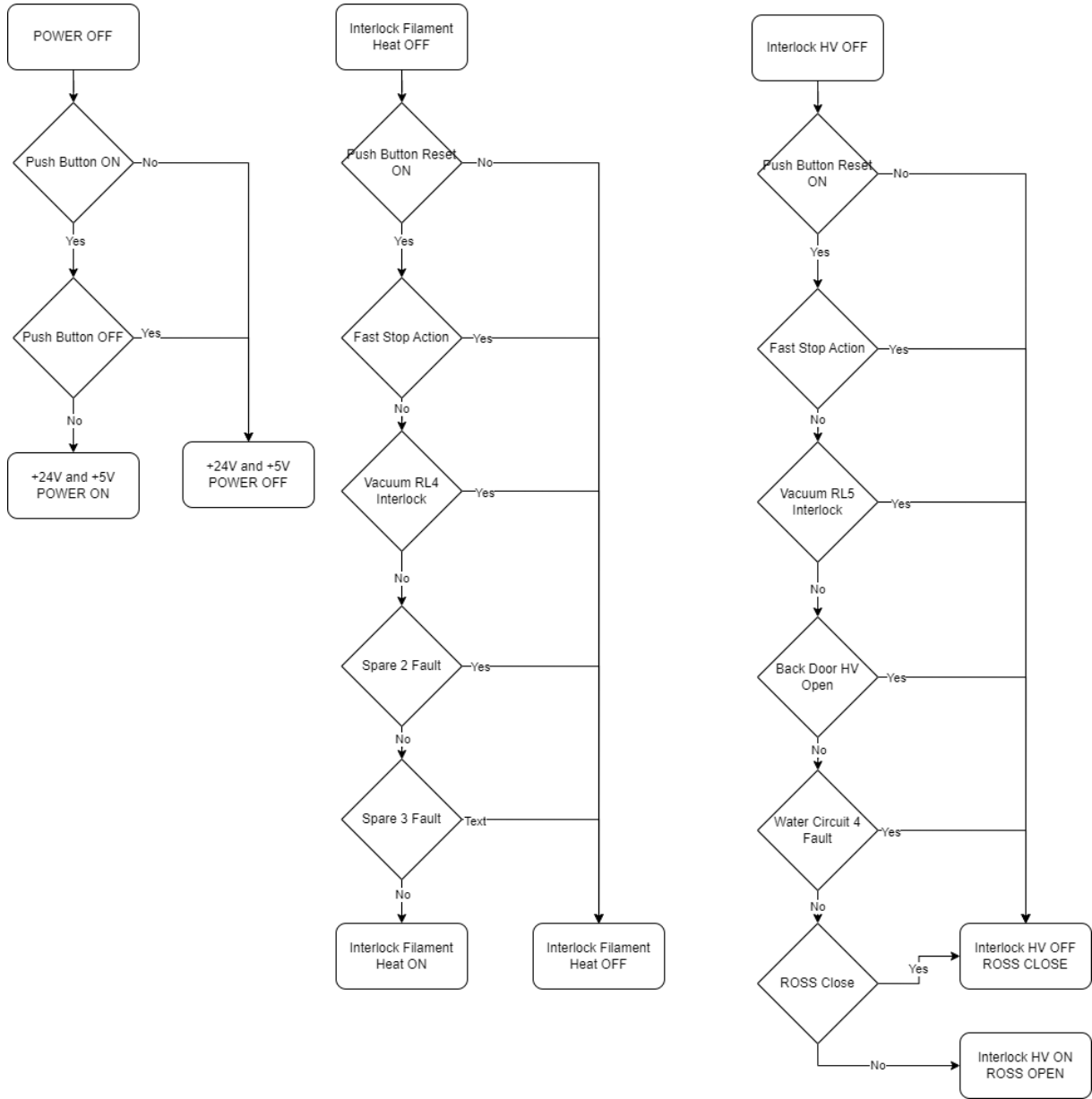


Figure 8.8: Hardware Interlock Setup for Controller Supply, Filament Heating and High Voltage Interlock System

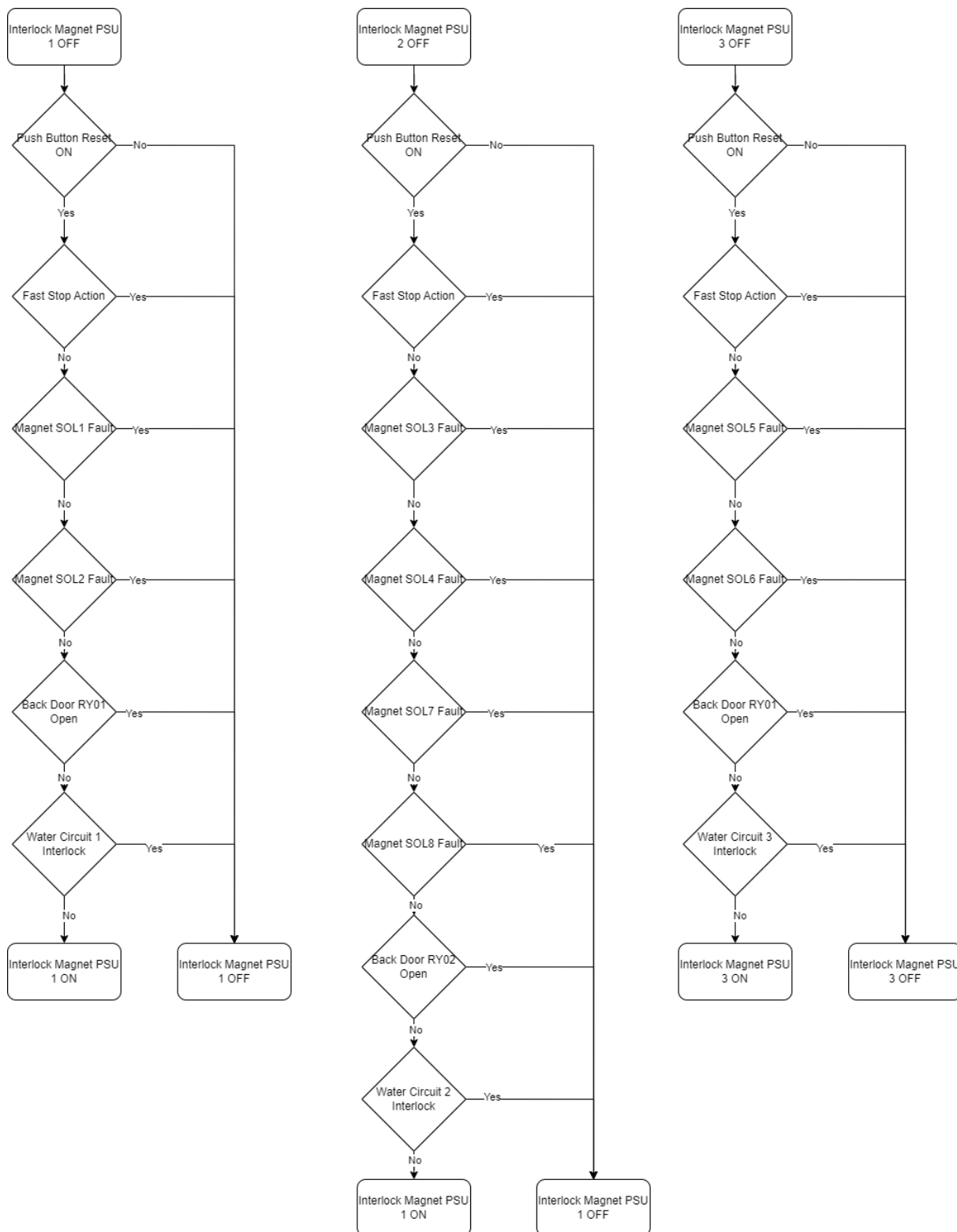


Figure 8.9: Hardware Interlock Setup for three solenoid circuit power supply