JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE START PROGRAM

3D modeling of test beam channels elements of the Linac-200 linear electron accelerator

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Contents

Abstract:

The linear electron accelerator Linac-200 at JINR is a new facility, constructed to provide electron test beams to carry out particle detectors R&D, to perform studies of advanced methods of electron beam diagnostics, and for applied research. The core of the facility is a refurbished MEA accelerator from NIKHEF. The key accelerator subsystems including magnetic, controls and vacuum were completely redesigned or deeply modernized. It is possible to perform research on electron beams with energies in the range of 5–200 MeV and pulsed currents from a single electron in a bunch up to 60 mA. This report addresses the detailed 3D modeling of the magnetic elements of the test beam channels, such as dipole, quadrupole and steering magnets, as well as vacuum chambers and structural elements. The outcomes of this modeling project include comprehensive CAD representations of each component, ensuring improved accuracy for simulations and enabling further developments

1. Introduction:

Linear electron accelerator Linac-200 is a unique facility intended for scientific and methodological research in the field of accelerator physics and technology, elementary particles detectors research and development, as well as fundamental and applied research in the fields of materials science and radiobiology. It is based on the MEA linear electron accelerator which was transferred to JINR from NIKHEF in the end of 90s.

Main accelerator structure unit is a station. The injector station A00 includes the electron gun, chopper, prebuncher and buncher. First accelerator station A01 includes one accelerating section and a klystron, which also feeds the RF equipment of the A00 station. All the rest stations include two accelerating sections and a klystron each.

Current setup (Fig. 1, 2) consists of 5 stations, A00–A04, and allows generation of the 200 MeV electron beam. It is possible to install additional stations to increase the energy of the accelerator.

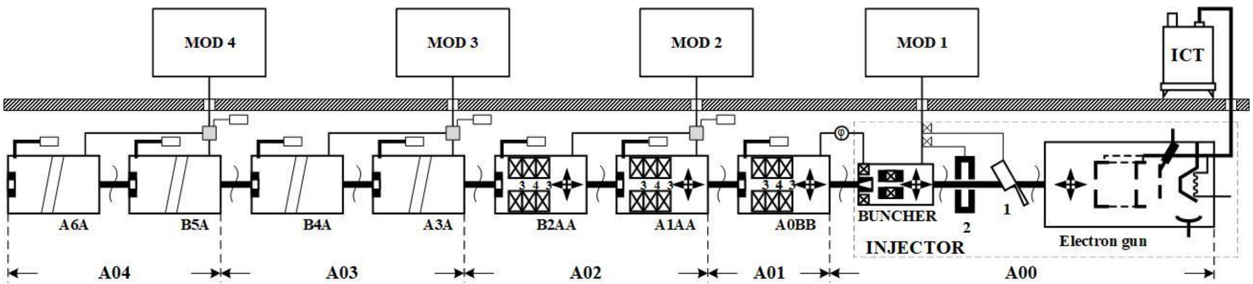

Figure 1 Linac-200 accelerator layout (1 – chopper, 2 – prebuncher)

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Figure 2 Photo of the Linac-200 linear electron accelerator

The electron beam is generated by the 400-kV DC triode-type electron gun with a thermionic cathode. The beam is available for users on three test beam channels: after stations A01, A03, and A04. Parameters of the Linac-200 electron beam available for users are presented in Table 1.

Table 1: Parameters of the Linac-200 electron beam

Parameter	A01	A03	A04
Electron energy, MeV	5–25	60–130	130–200
Pulse duration, μs	0,2–3,5		
Max. pulse current, mA	60		
Pulse repetition rate, Hz	1–25	1–10	

Beam is accelerated by the iris-loaded travelling wave structures. RF power is provided by the 20-MW Thomson TH 2129 klystrons. Each klystron feeds two accelerating sections. The exception is the first one, which feeds one accelerating section and bunching devices. Due to the modulator limitations only half of the klystrons peak power is used (i.e. each accelerating section receives 5MW of RF power). Linac-200 key acceleration & RF parameters are given in Table 2.

Table 2: Linac-200 key acceleration & RF parameters

Total Linac length, m	55
Number of short (3.7 m) sections	3
Number of long (7.3 m) sections	4
Frequency, MHz	2856
Wave type	TW
Field mode	2π/3
Filling time, μs	1.3
vg/c range	0.0093–0.0389
Shunt impedance, MΩ/m	56.5–48
Iris aperture: diameter, mm	32–17
thickness, mm	5.84
Number of klystrons	4
RF power: peak, MW	10
mean, kW	20

The main tasks of the accelerator are related to providing electron beams to:

- scientific and methodological work on the creation of elementary particle detectors at DLNP, VBLHEP and in scientific centers of JINR member states to support experiments at the NICA collider and external experiments.
- scientific and methodological work on the search for new methods and the creation of equipment for electron beam diagnostics.
- applied work in the field of radiation materials science, radiochemistry and radiobiology (LRB);
- conducting experiments in the field of nuclear physics (including the study of photonuclear reactions - a joint project of DLNP with colleagues from Vietnam under the leadership of Professor Le Hong Khiem);
- educational projects (jointly with the JINR UC).

The present report focuses explicitly on the detailed 3D modelling of the magnetic elements of the test beam channels, such as dipole, quadrupole and steering magnets, as well as the vacuum chambers and structural elements. The emphasis is on precision and accuracy in order to support further studies and operational optimization. The creation of detailed three-dimensional digital representations is the objective of this work, with the aim of providing a foundational platform for subsequent analytical studies, simulations, and systematic training programs.

2. Project Objectives

The primary objectives of this 3D modeling project are clearly defined as follows:

- **Creating accurate 3D models of Linac-200 components:** The detailed and precise digital representation of Linac-200 components is crucial for understanding their structural and operational characteristics. This objective involves meticulous measurement and replication of physical dimensions and configurations in a virtual environment.
- **Facilitating future simulations and diagnostics:** High-fidelity 3D models serve as foundational tools for simulations related to beam dynamics, thermal analyses, and diagnostics. This capability significantly enhances predictive accuracy, enabling preemptive identification of potential issues and optimization of accelerator performance.

3. Scope of Work

The scope of work for this project explicitly includes the 3D modeling of the following key components of the Linac-200:

- **Quadrupole lenses and steering magnets:** Integral to beam focusing and trajectory control, these magnets require precise modeling to ensure accurate representation of their magnetic fields and structural integrity.
- **Vacuum system:** Critical for maintaining optimal operating conditions within the accelerator, the vacuum system includes chambers, pumps, and gates, all of which were modeled to ensure comprehensive coverage of this subsystem.
- **Dipole magnets:** These magnets are essential for additional beam trajectory refinement. Dipole magnets act as bending magnets to deflect the beam and guide it out of the acceleration path to the test beam channels. Accurate 3D representations of their configuration and positioning were developed.

4. Methodology of 3D Modeling

To accurately model the components of Linac-200, industry-standard CAD software was employed, specifically SolidWorks and AutoCAD. SolidWorks was used for creating detailed 3D models and assemblies, while AutoCAD supported precise 2D sketches and dimension verification.

Dimensions were collected through two primary methods: firstly, by extracting measurements from existing 2D technical drawings whenever available; secondly, by conducting direct measurements in the laboratory for components lacking detailed documentation. This hands-on approach ensured the highest accuracy for all parts.

The modeling process followed these steps:

- **Data collection and verification:** Gathered 2D drawings and conducted lab visits to measure real components.
- **Sketching and base feature creation:** Developed accurate base sketches in AutoCAD and SolidWorks.
- **3D modeling:** Used SolidWorks to extrude, revolve, and apply necessary features, ensuring dimensional fidelity.
- **Assembly construction:** Combined individual parts into assemblies to replicate the physical setup.
- **Validation:** Cross-checked models against physical parts and available drawings to confirm correctness.

5. Detailed 3D Modeling of Linac-200 Components

5.1 Quadrupole Magnet Modeling

Functionality and Importance:

Quadrupole magnets play a crucial role in particle accelerators like Linac-200. Their primary function is to focus and control the trajectory of the electron beam. By generating a precise magnetic field gradient, quadrupole magnets stabilize the beam horizontally and vertically.

Key Dimensions and Characteristics:

- **Length:** 300 mm (derived from laboratory measurements)
- **Inner diameter:** 50 mm
- **Outer diameter:** 150 mm
- **Magnetic poles:** Four symmetric poles arranged radially.

3D Modeling Process:

SolidWorks software was utilized to achieve precise and highly detailed modeling of the quadrupole magnets. Each magnet was constructed through multiple steps:

- Initial sketches from available technical drawings.
- Detailed modeling of magnet coils, poles, and iron cores.

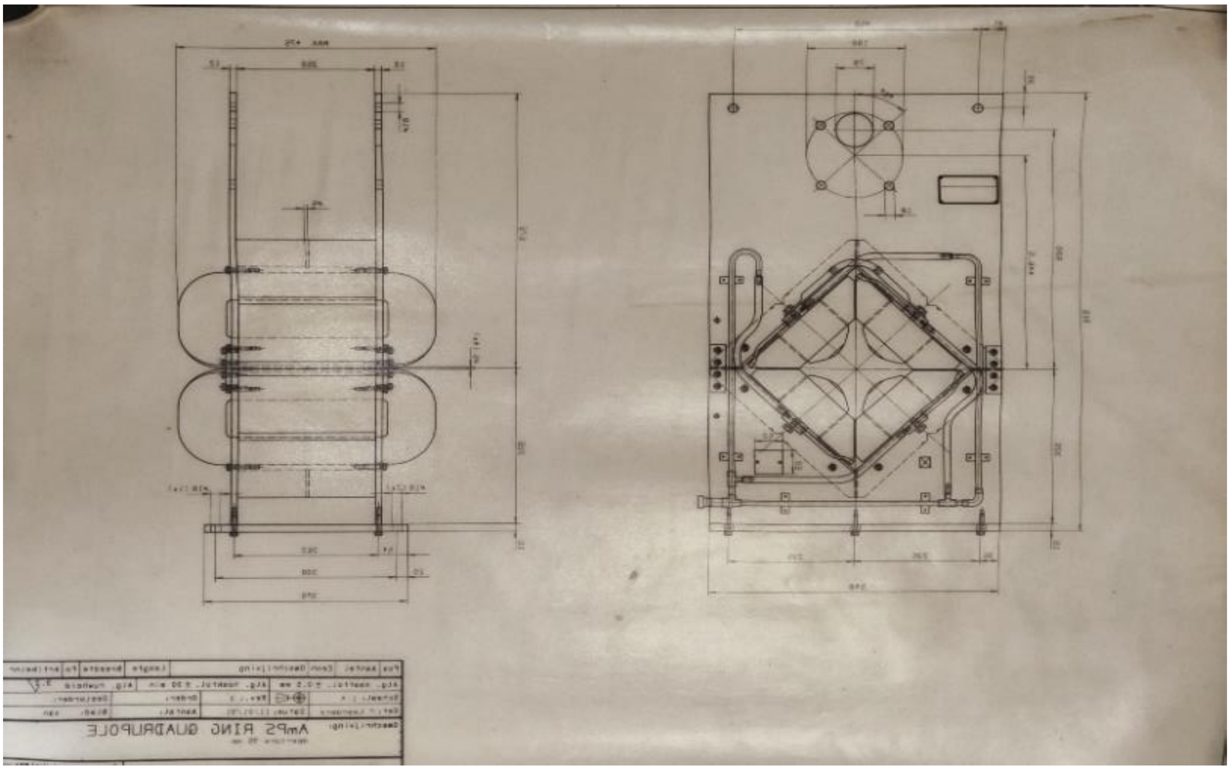

Figure 3 (2D drawing of Quadrpool Magnet)

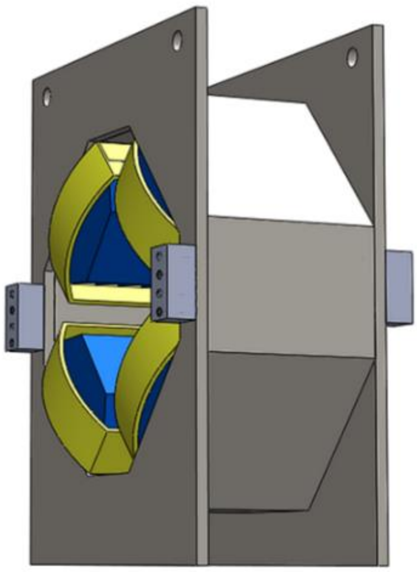

Figure 4 (side view of 3Dmodling for Quadrpool magnet)

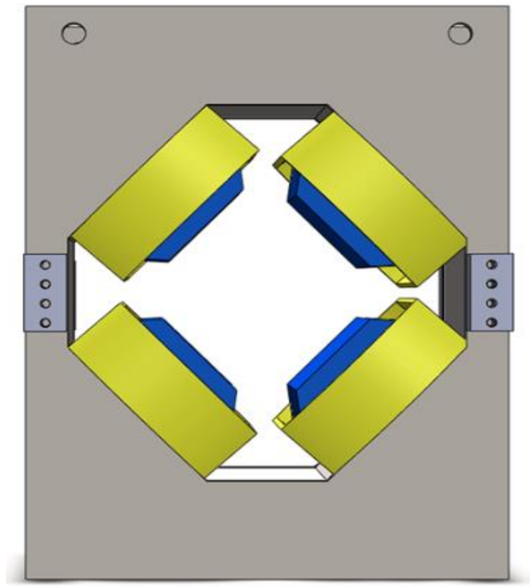

Figure 5(Front view of 3Dmodling for Quadrpool magnet)

Figure 6 (Lab photo Quadrpool magnet)

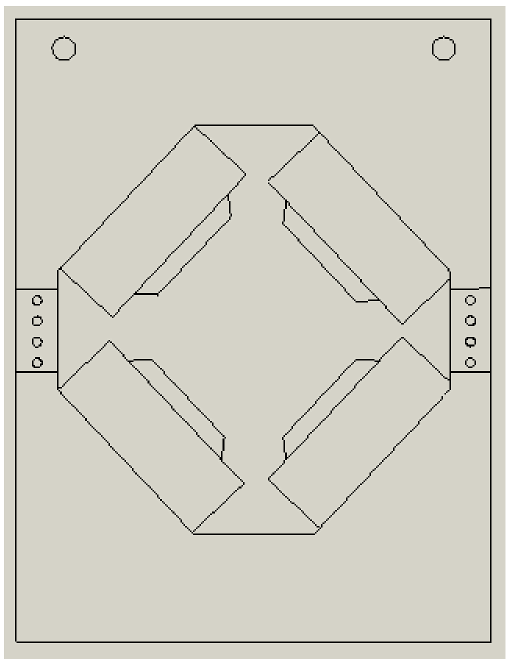

Figure 7 (2D drawing for the Quadroppol extracted from Solidworks)

5.2 Dipole Magnet

Functionality and Importance:

Dipole magnets are essential components within the Linac-200 accelerator, responsible primarily for directing and steering the electron beam along precise paths. Unlike quadrupoles, dipoles generate uniform magnetic fields that bend the beam trajectory. This controlled beam bending enables the accelerator to direct electrons into experimental areas, manipulate beam paths, and measure electron energies accurately using bending magnet arrangements.

3D Modeling Process and Screenshots:

Dipole magnets were modeled precisely using SolidWorks, aided by initial dimension sketches created in AutoCAD. The process included:

- Creation of initial dimension sketches based on provided 2D drawings and additional lab measurements.
- Detailed modeling of iron core structures and coil configurations, accurately representing physical magnet construction.

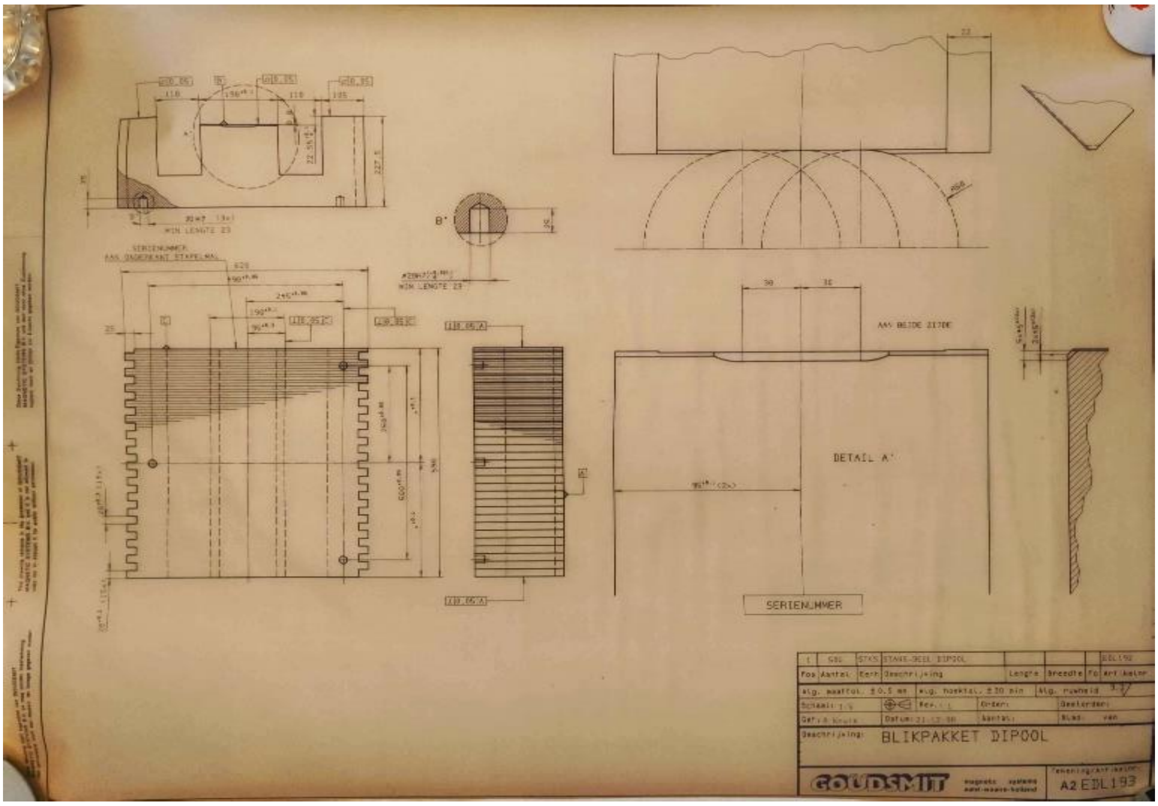

Figure8 (2D drawing for side view the Dipole magnet)

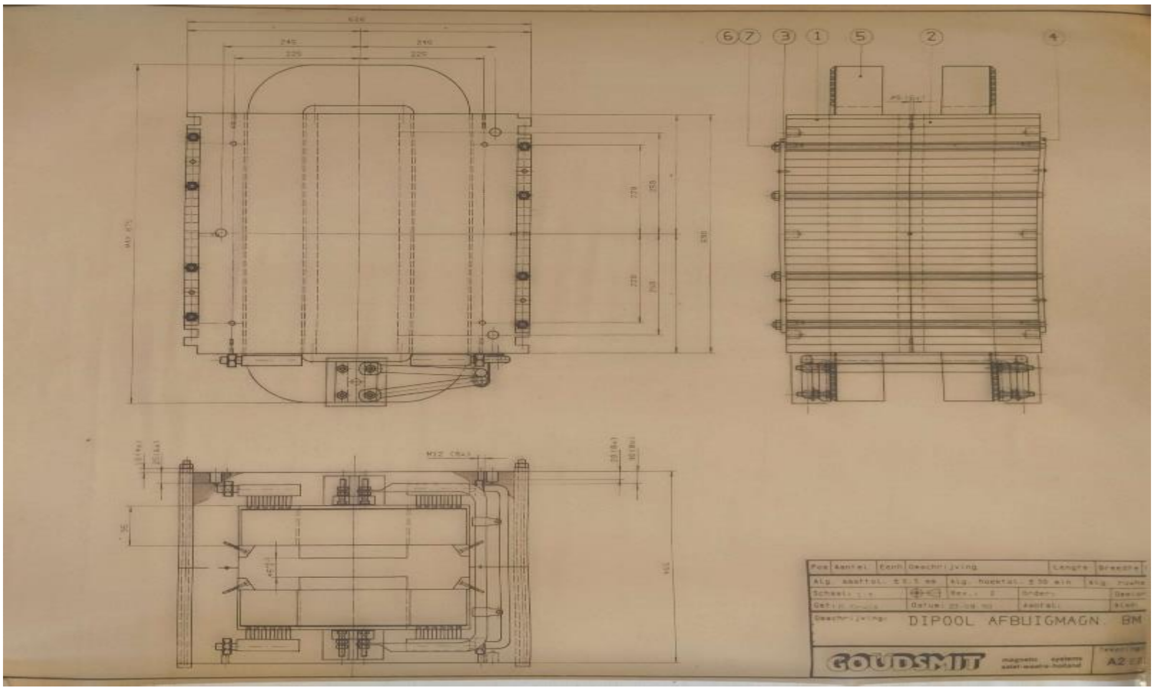

Figure 9 (2D drawing for Dipole magnet Top and side views)

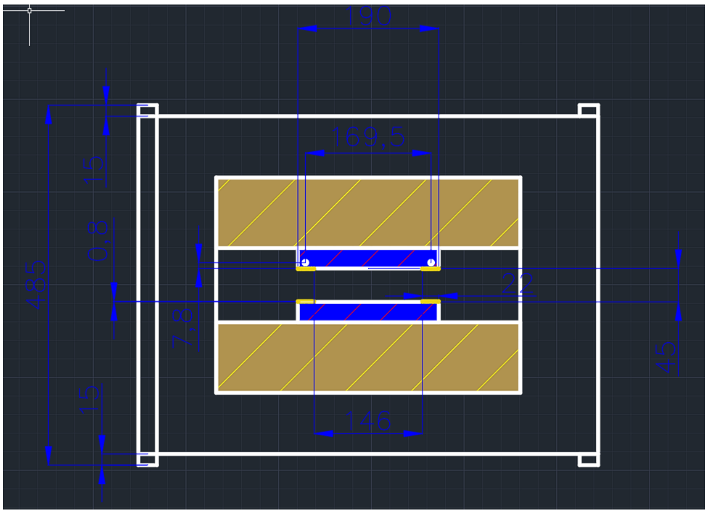

Figure 10 (2D drawing with dimensions on AutoCAD)

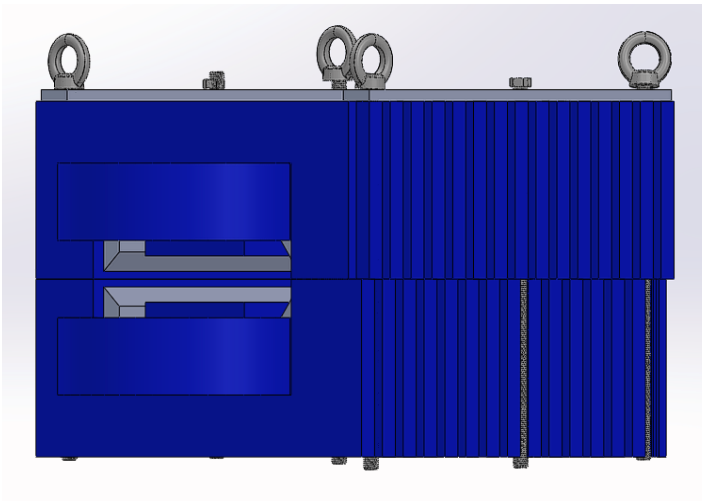

Figure 11 (the 3D modeled Side view of Dipole magnet)

Modifications:

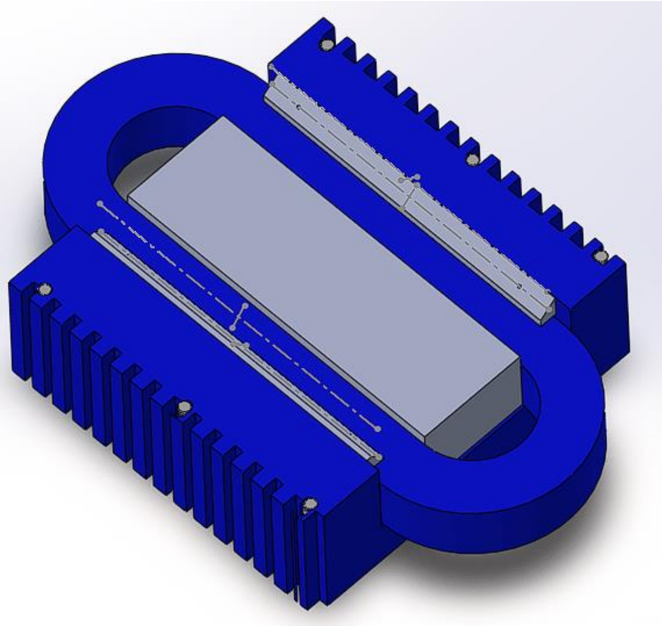

Figure 12 (Befor modification)

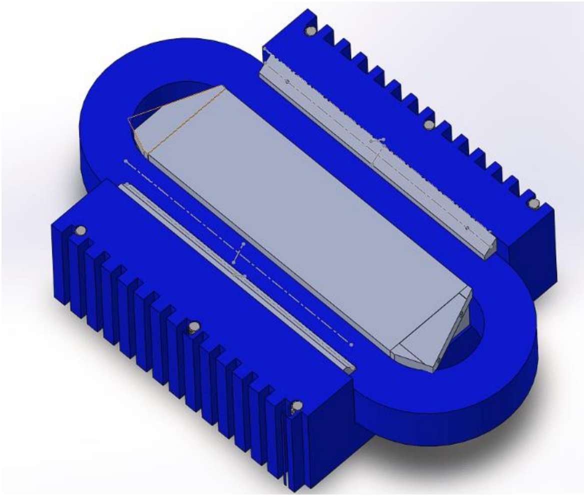

Figure 13 (After Modification)

Figure 14 (after manufacturing)

5.3 Vacuum System Modeling

Importance:

The vacuum system is critical in maintaining beam quality by minimizing interactions between electrons and residual gas molecules. It ensures stable accelerator operation by reducing energy losses, scattering, and contamination of sensitive components.

Components Detailed in Modeling:

- **Vacuum chambers:** Cylindrical chambers designed for optimal flow characteristics.
- **Turbopumps:** High-capacity pumping units modeled to represent actual operational layout and interfacing accurately.

Modeling Details and Screenshots:

Using AutoCAD for initial 2D sketches and SolidWorks for subsequent 3D development, detailed models of vacuum system components were created. Particular attention was given to realistic details such as:

- Flanges and sealing surfaces ensure accurate vacuum-tight connections.
- Internal geometries of pumps and valves represented accurately.
- Detailed exploded views highlighting component interactions

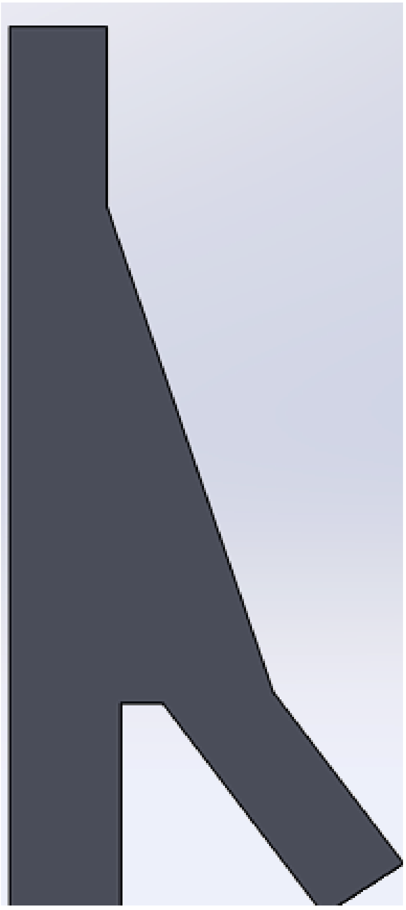

Figure 15 (3 D model for the separator part of vacuum system)

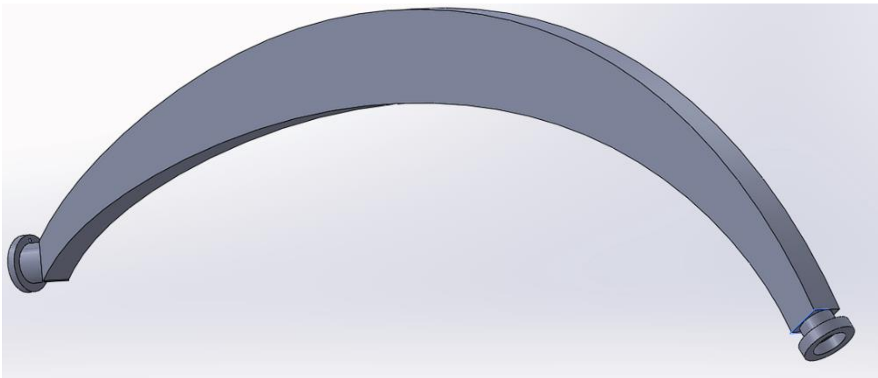

Figure 16 (3D model for the Arc part of the vacuum system)

5.4 Beam Steering Magnet Modeling

Function:

Beam Steering Magnet are integral to the accelerating sections of Linac-200, specifically in maintaining stable electron trajectories within both short and long accelerating sections. These magnets control beam steering and alignment.

Design Specifications and Dimensions:

- **Dimensions:** Length ~ 200–300 mm, width ~ 150 mm, thickness ~ 100 mm (confirmed through lab measurements).
- **Material:** Iron cores with embedded coil windings for generating precise magnetic fields.

Modeling and Visualization:

Detailed SolidWorks models were generated by:

- Initial dimension collection through provided CAD drawings and direct lab measurements.
- Creation of detailed coil representations and housing structures.
- Inclusion of precise mounting brackets and alignment fixtures to replicate actual installation conditions.

Visualization

- Orthogonal views for dimensional clarity.
- Detailed coil winding visualizations.
- Assembly perspective illustrating alignment with beamline components.

Figure 17 (3D model of the Beam string magnet)

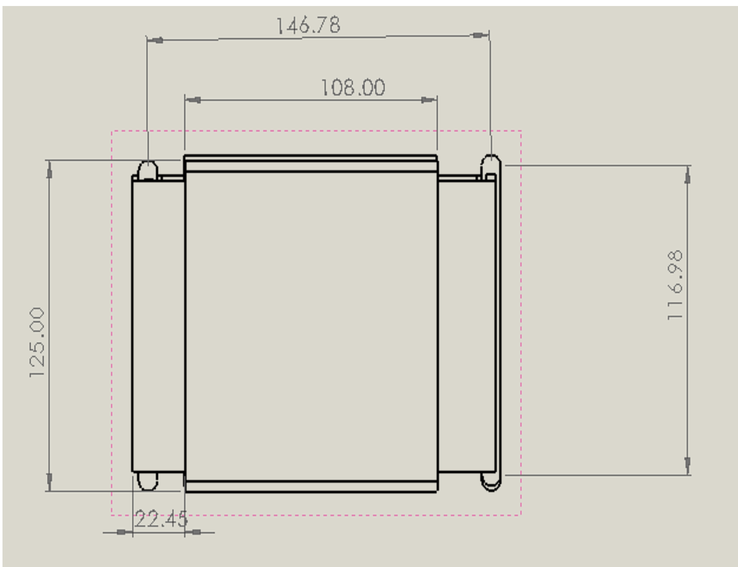

Figure 18 (2D model of the Beam string magnet by solid works)

5.5 Base stand for holding the components

To ensure both stability and rotational flexibility for the dipole magnet within the beamline system, a custom-designed base stand was developed and manufactured. This stand was specifically engineered to:

- Support the high mass of the dipole magnet reliably during operation and maintenance.
- Allow controlled rotation of the magnet using integrated mechanical supports, enabling precise angular adjustments for beam alignment.

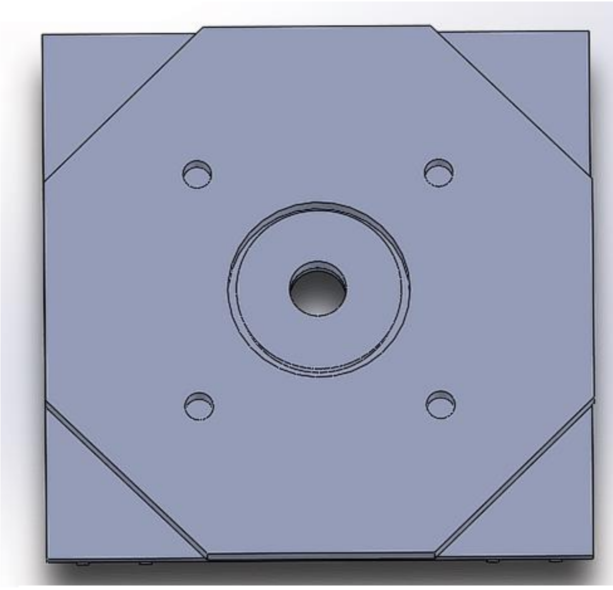

Figure 19 (the 3D model of Dipole magnet holder and rotator bases)

Figure 20 (Holder and rotator after manufacturing)

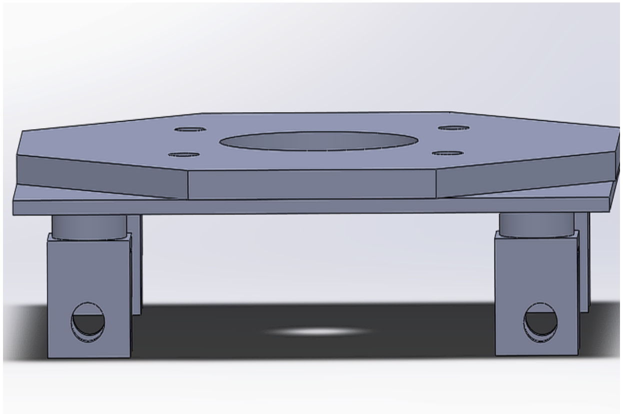

Figure 21 (holder and rotator side view)

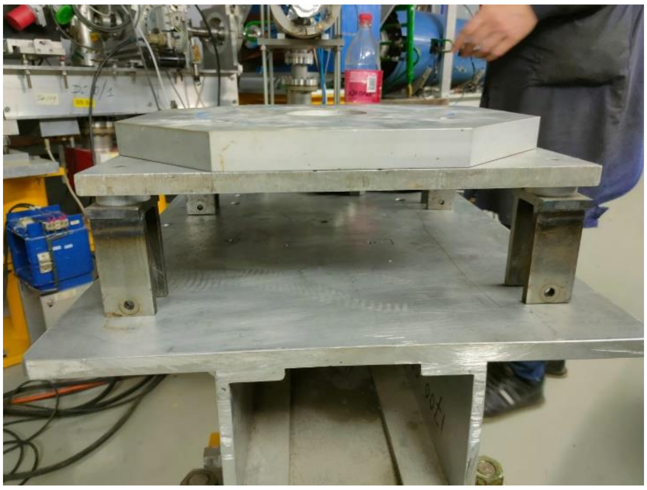

Figure 22(holder and rotater after manufacturing side view)

The full base assembly for channel one will be as shown in the next figure:

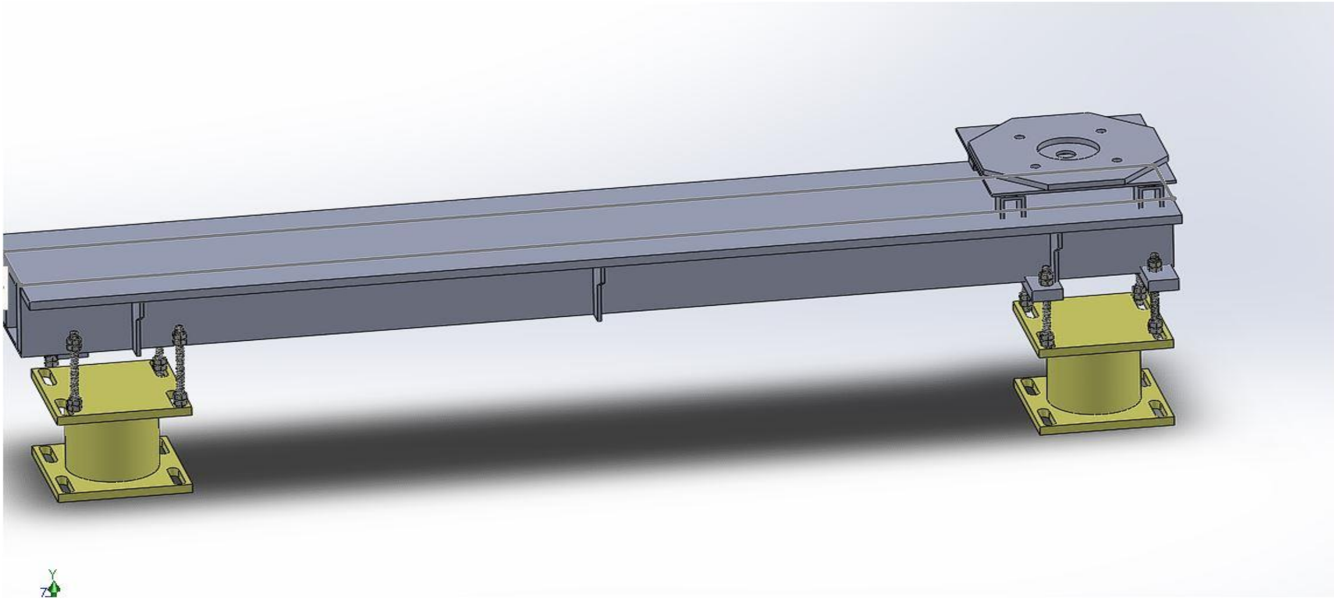

Figure23 (the 3D model of channel's Base holder)

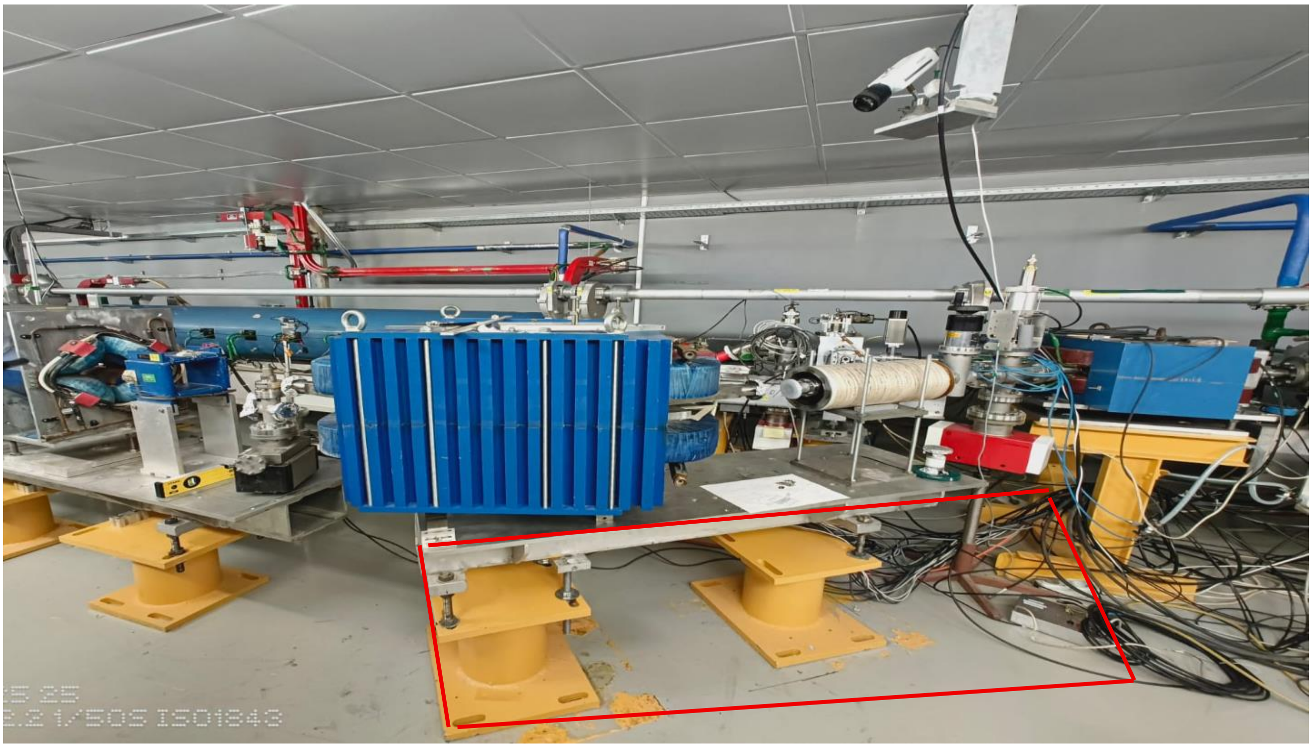

Figure24 (Lab view of the channel one base holder)

5.6 Complete Accelerator System Assembly

Final Assembled Model:

Channel 3 was modeled, while Channel 1 was both modeled and upgraded. The upgrade of Channel 1 involved replacing the bending magnet and the vacuum chamber, as well as adding a solenoid for enhanced beam focusing between the first and second dipole magnets. Below are images illustrating Channel 1 before and after the modifications:

Interactions and Alignments Highlighted:

- Precise alignment of quadrupole magnets with beam pathways, ensuring accurate simulation potential for future diagnostics.
- Accurate interfacing of vacuum system components, with proper seals and connection points verified digitally.
- Integration of Beam Steering Magnet within the overall accelerator structure, ensuring correct spacing and orientation relative to other elements.

Comprehensive Assembly Screenshots:

Full assembly isometric views clearly displaying all components and their interrelationships.

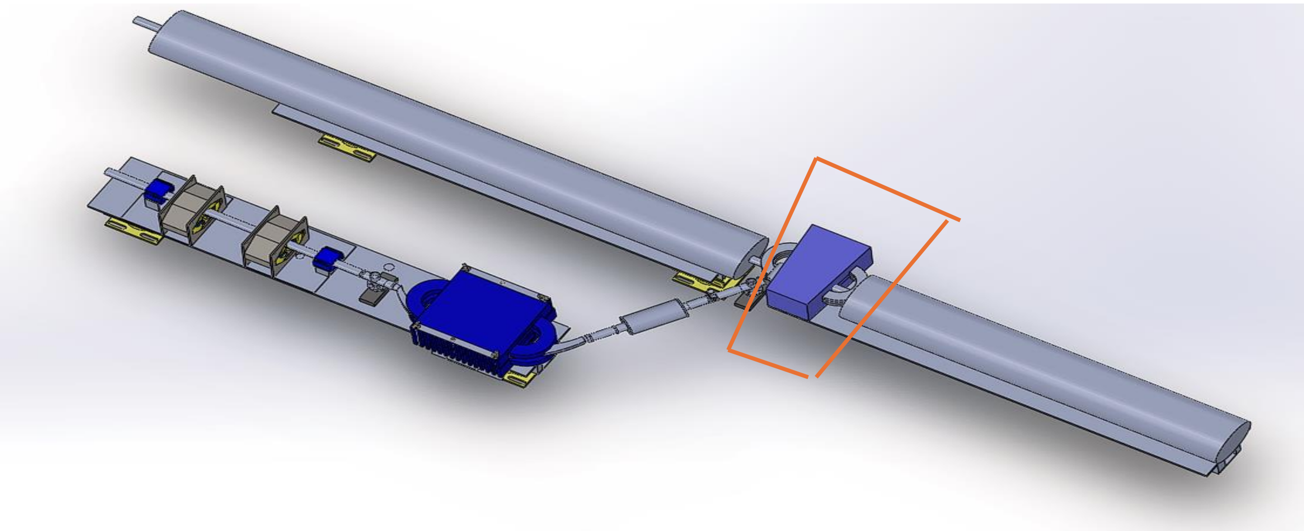

Figure 25 (channel one full assembly Top view)

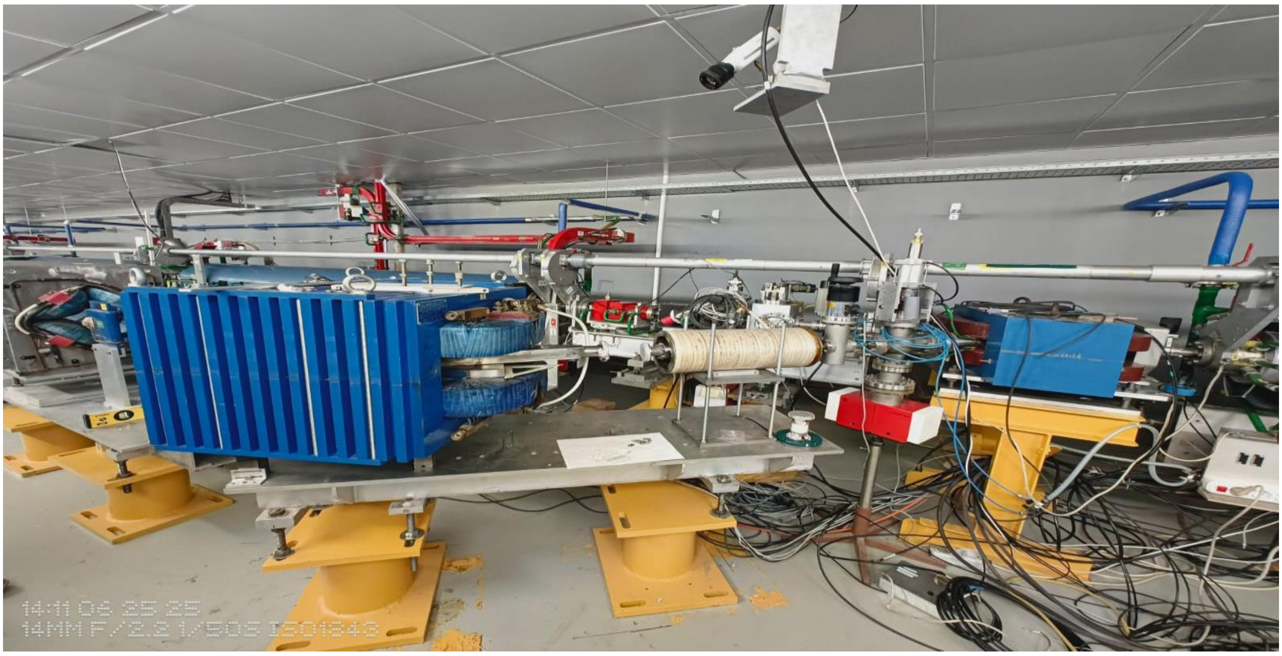

Figure26 (Lab view for channel 1)

The channel three assembly has the same parts as in channel one but has a little bit different in vacuum system and the holding bases.

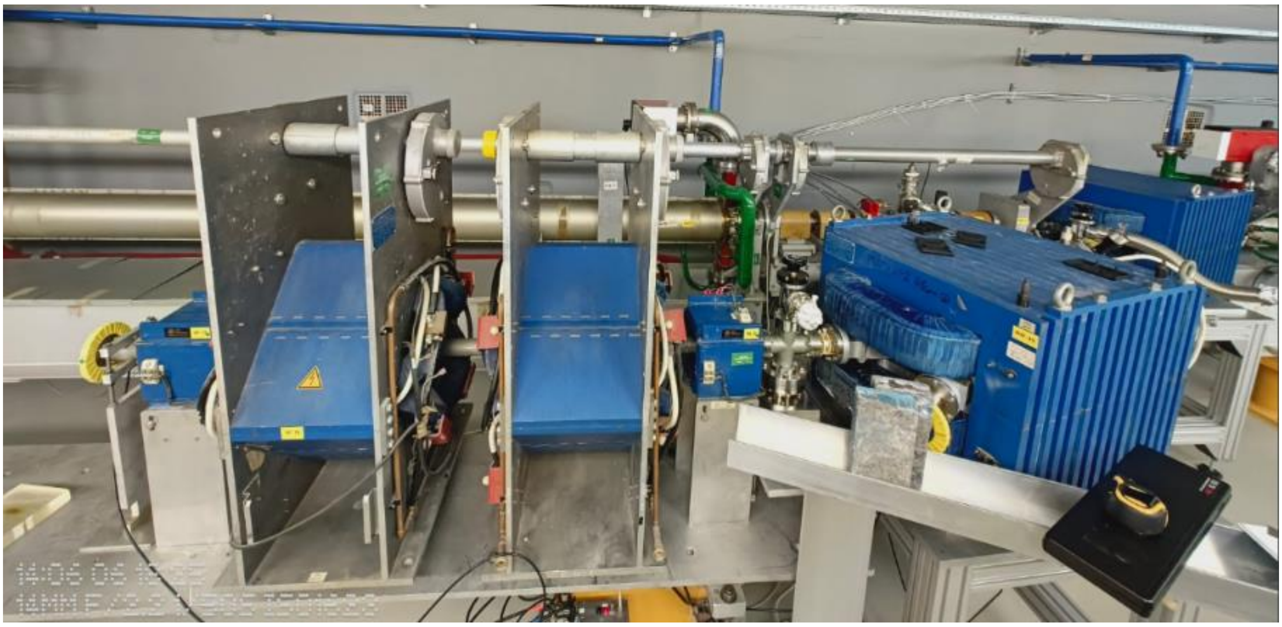

Figure27 (channel three full assembly top view)

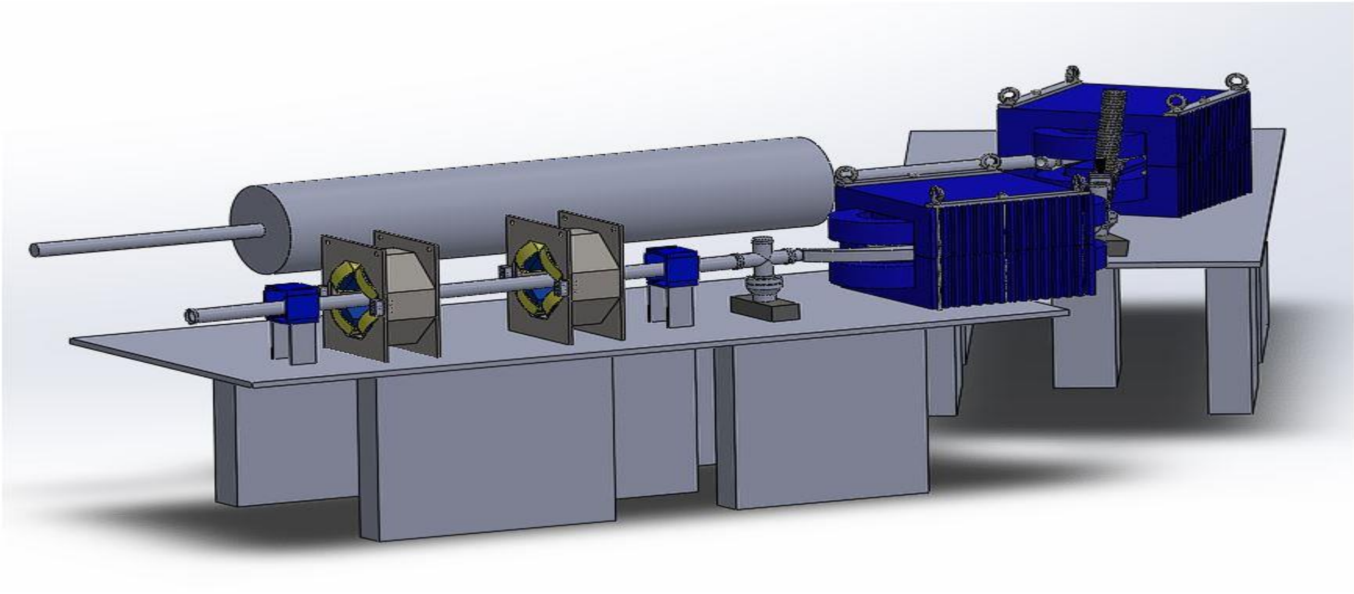

Figure28 (channel three side view)

6. Results and Discussion

The completed 3D models of Linac-200's components include quadrupole magnets, dipole magnets, Beam Steering Magnet, vacuum assemblies, and related support structures — represent a high-fidelity digital reconstruction of the physical setup. The models accurately replicate the physical geometries, spatial relationships, and connection interfaces critical for understanding the operational flow of the accelerator.

Achieved Level of Accuracy and Detail:

Dimensionally, the models maintain tolerances within a few millimeters, aligning closely with actual laboratory measurements and manufacturer-provided technical drawings. For components with complex internal features (e.g., winding configurations of the magnets, seals within vacuum valves), the modeling process focused on capturing the functional aspects essential for visual understanding and future design iterations. Small, non-critical internal details were abstracted only when they did not affect the integrity.

The use of **SolidWorks** and **AutoCAD** facilitated precise sketching and solid body generation, while laboratory cross-checks ensured that each part's scale and interface points matched real-world counterparts. This high level of accuracy means the models can be confidently reused for layout planning, system upgrades, or training new engineers and researchers.

Utility of the 3D Models:

Beyond documentation, these models serve multiple purposes:

- **Training Aid:** They provide new team members and visiting researchers with an intuitive understanding of Linac-200's inner workings without needing immediate access to the physical hardware.
- **Planning Future Modifications:** Engineers can test virtual layouts for potential upgrades, such as adding new focusing elements or adjusting vacuum pump placements.
- **Simulation Integration:** The models are ready for use in advanced computational tools (e.g., electromagnetic or thermal solvers) to simulate beam paths, thermal loads on coils, or pressure profiles in vacuum channels.
- **Safety and Maintenance Planning:** Maintenance staff can use exploded views to study disassembly procedures and plan for confined-space work or component replacements.

7. Future Work and Research Opportunities

Building upon the solid foundation laid by this project, several avenues for further work are recommended:

1. **Refinement of Complex Internal Details:**
   Although the current models accurately depict all critical external and functional internal features, additional effort can be devoted to modeling intricate coil winding paths, internal coolant flow channels, and fastener details for bolts and supports. This would enhance the models' realism for training or advanced simulations.
2. **Dynamic Simulations:**
   Import the completed models into finite element software (e.g., ANSYS or COMSOL Multiphysics) to perform:
   - Magnetic field distribution simulations for each magnet type.
   - Thermal dissipation analyses under various operating loads.
   - Structural stress evaluations for support frames during operation and maintenance.
3. **Beam Dynamics Integration:**
   Use the geometric data as input for particle tracking codes to simulate how electron beams interact with modeled focusing and bending magnets. This can help refine alignment strategies and verify beam stability under different magnetic settings.
4. **Expand Modeling to Additional Stations:**
   Extend the 3D modeling work to other stations within Linac-200, gradually building a complete

digital twin of the full accelerator line. This would benefit future expansions, such as the planned additional accelerating stations reaching up to 800 MeV.

5. **Development of Interactive VR Training Modules:**
   Convert the detailed models into immersive virtual reality or augmented reality training tools. This would allow students and new operators to explore Linc 200 virtually, understanding spatial relationships and operational workflows without interrupting live accelerator operations.

8. Conclusion

This project successfully delivered a comprehensive, high-fidelity 3D representation of Linac-200 test beam channels. Through the meticulous use of SolidWorks and AutoCAD, combined with accurate dimension gathering from technical drawings and on-site measurements, a robust digital replica of key components quadrupole magnets, dipole magnets, Beam Steering Magnet, and the vacuum system was developed.

The completed models bridge the gap between theoretical knowledge and hands-on understanding, providing researchers, engineers, and students with an invaluable tool for visualization, planning, and training. Additionally, the groundwork laid by this project creates clear pathways for integrating the models into advanced beam dynamics studies, thermal simulations, and maintenance planning.

On a personal and professional level, this endeavor has strengthened practical skills in precision engineering, CAD design, technical documentation, and accelerator physics fundamentals. It demonstrates a readiness to contribute to complex multidisciplinary projects in modern research facilities, paving the way for continued growth in the field of accelerator technology and applied physics.

9. Reference:

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2. J. Haimson, "A low emittance high duty factor injector linac," in *Proceedings of the 4th Particle Accelerator Conference (PAC'71)*, Chicago, IL, USA, JACoW Publishing, Mar. 1971, pp. 592–595.

3. F. B. Kroes *et al.*, "Improvement of the 400 kV linac electron source of AmPS," in *Proceedings of the 3rd European Particle Accelerator Conference*, Berlin, Germany, JACoW Publishing, Mar. 1992, pp. 1032–1034.

4. A. Trifonov et al. "Linac-200: a new electron test beam facility", Proceedings of 41st International Conference on High Energy physics PoS(ICHEP2022), 2022, V. 414, pp. 1094–1098. doi:10.22323/1.414.1094

5. All parts that have been modeled by SolidWorks and AutoCAD for channel one and three can be find on : https://drive.google.com/drive/folders/1eDdzdVN8ieWeBCNPm9z0Nku6OTj0NppW?usp=sharing