FCC-ee Interaction Region Mock-up Project
(ESPP_A_FCCMDI)

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1 FCC-ee IR Mock-up: Motivation and contest

A technological R&D initiative to develop a full-scale mock-up of the FCC-ee interaction region, to be constructed in Frascati, was approved in 2023. This project is co-funded as a special initiative for the European Strategy for Particle Physics 2026 Update (ESPPU) by the Executive Board of INFN and CERN under a dedicated Memorandum of Understanding (MoU). It complements the Feasibility Study of the FCC-ee Machine-Detector Interface (MDI), as outlined in the RD_FCC section of this activity report.

The project is named ESPP_A_FCCMDI.

This project aligns with Working Package 1 (WP1) on "Global System Design and Integration" within the ECFA Detector R&D Collaboration on "Mechanics & Cooling of Future Vertex and Tracking Systems" (DRD8 WP1).

The technological efforts initiated through this project are closely linked to accelerator studies on beam optics, beam dynamics, machine-induced backgrounds, and the design and integration of vertex and luminosity calorimeter detectors. The objective is to test technological solutions and address key assembly challenges.

A full-scale mock-up, including prototype components, provides valuable insights beyond what can be obtained from 3D CAD models and FEM simulations. It allows for a detailed assessment of service components such as cables and pipes, which are often difficult to accurately represent in CAD. Furthermore, it offers a comprehensive view of the installation sequence and potential obstacles, helping to prevent issues related to access, especially after significant radiation exposure of local components (e.g., LumiCal, quadrupoles, cryostats). A realistic full-scale mock-up also facilitates convergence on a single optimized design when multiple options are under consideration. Ultimately, the IR mock-up will serve as a platform for further studies on stability, alignment, and vibrations.

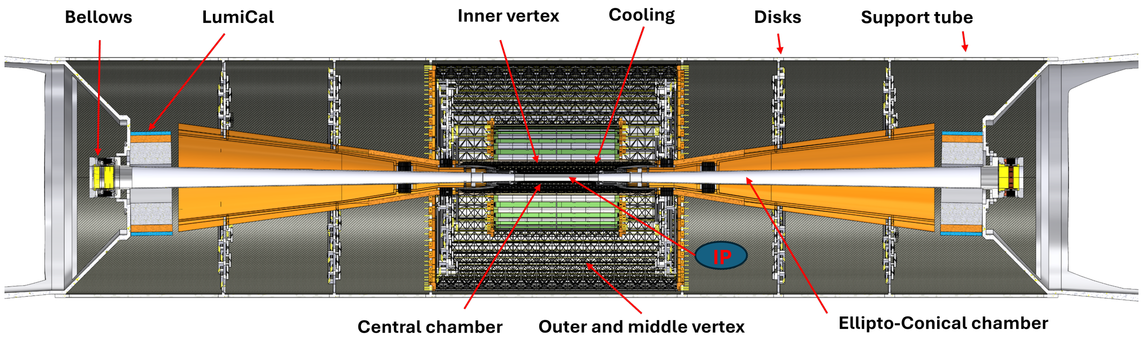

Figure 1: Machine-Detector Interface region of the FCC-ee, illustrating all elements to be assembled in the IR mock-up project.

2 Main Components of the FCC-ee IR mock-up

The key components of the IR mock-up include:

- Central beam pipe with active cooling;
- ellipto-conical beam pipe with active cooling;
- IR bellows;
- Inner vertex detector with air cooling;
- Outer vertex detector;
- Support tube;
- Luminosity calorimeter.

Figure 1 illustrates all assembled elements of the actual FCC-ee MDI. The project aims to develop a full-scale mock-up with prototypes of these components. Design and simulation studies must be complemented by physical prototyping and implementation tests to evaluate technical solutions for integration challenges. This includes the integration of the vertex and LumiCal detectors into the support tube, with a focus on paraffin and water cooling for the pipes and air cooling for the inner vertex detector.

3 IR Beam pipe design and first tests

To fully exploit the performance of advanced vertex detectors under development for FCC-ee, the IR beam pipes must outperform existing SuperKEKB technology by approximately 30%. This requires pushing current technological limits in terms of material thickness while ensuring ultra-high vacuum (UHV) conditions and structural integrity to prevent buckling.

At the Z pole, the substantial heat loads from beam wakefields and potential synchrotron radiation losses necessitate active cooling. The central beam pipe is an 18 cm-long cylinder with a double-layer wall structure, allowing liquid paraffin coolant to flow between two concentric AlBeMet cylinders. These cylinders, each 0.35 mm thick, are separated by a 1 mm gap, resulting in an external diameter of 23.4 mm. An internal 5 μm gold coating enhances electrical conductivity,

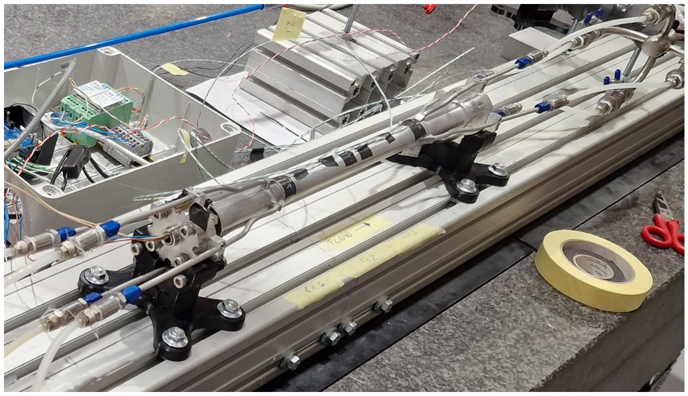

Figure 2: Full-scale aluminum prototype of the central beam pipe, used for initial thermal tests with water.

minimizing beam-induced heating and shielding the vertex detector from residual high-energy synchrotron radiation.

The prototype cooling system validation was conducted using an aluminum version of the central beam pipe, manufactured via laser welding. Initial water-based tests at the end of 2024 successfully confirmed theoretical expectations.

Since November 2024, FCC-ee IR beam pipe prototype tests have been conducted in a dedicated experimental hall within Building 5 of the accelerator division's mechanical workshop (see Fig. 3).

The first phase of the mock-up activities focuses on thermal testing of the central beam pipe. The cooling system has been developed, and initial tests with water are ongoing (see Fig. 4). The test setup includes a cooling circuit, temperature sensors, precision pressure gauges, and flow meters, operating at flow rates between 0.5 and 2 l/min. An internal ohmic heater simulates the wakefield heat load, with a nominal power of 54 W, adjustable up to 100 W. Initial water-based tests confirm the expected thermal performance, with a measured pressure drop of 0.13 kPa.

Unfavorable scenarios were performed, increasing the power up to 100 W while reducing the coolant flow rate to 0.5 l/min and increasing its inlet temperature to 22$^{\mathrm{o}}$C. This result confirms the effectiveness of the cooling system even in non-ideal working scenarios of the cooling system during operations.

The final design of the ellipto-conical beam pipes has been completed, and fabrication is underway for 2025 thermal tests. These pipes will be aluminum and electron-beam-welded to a second central beam pipe. Their cooling manifolds will be integrated directly into the structure, with performance validation using a setup similar to that of the central beam pipe.

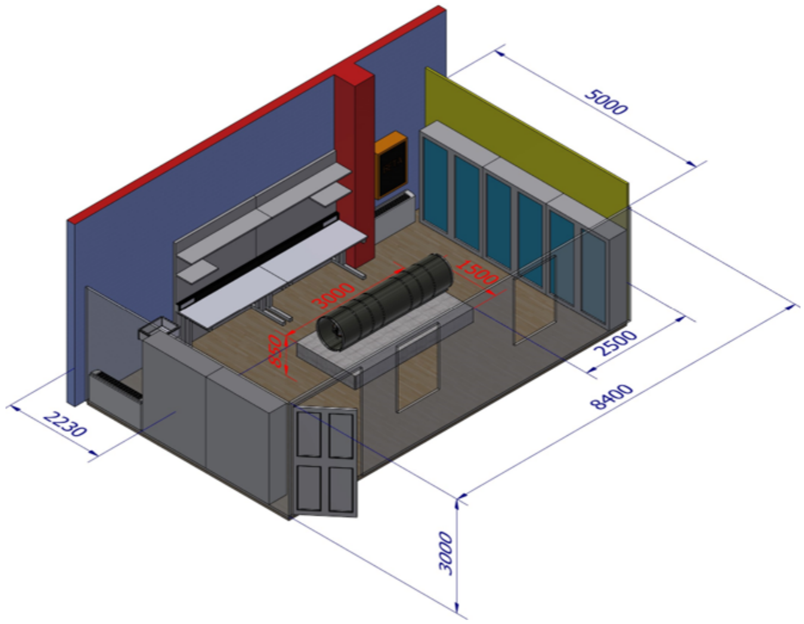

Figure 3: Rendering of the experimental hall for the FCC-ee IR mock-up in Building 5. The support tube, to be assembled in the final phase, is visible at the center.

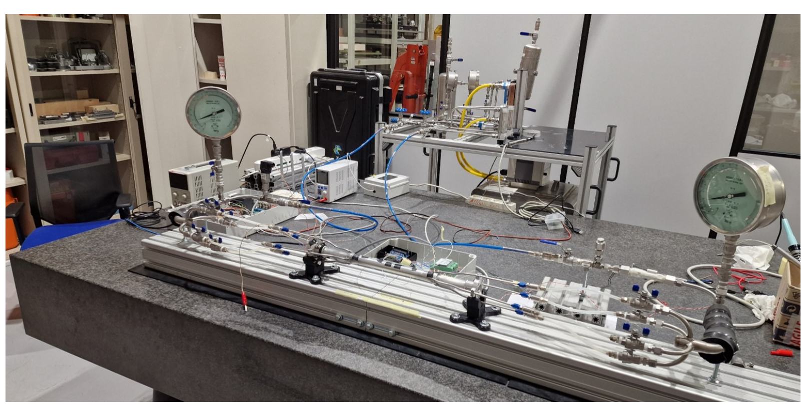

Figure 4: Experimental setup for thermal tests on the central beam pipe.

4 IR bellows

The IR bellows design is inspired on the successfully implemented ESRF-EBS storage ring model. Electrical continuity is ensured using copper-beryllium ($CuBe_2$) RF fingers, which surround the elliptical vacuum chamber. A blade pusher maintains the desired electrical contact.

The bellows will be attached between the conical chamber and the remote vacuum flange near the superconducting IR magnet system. Due to space constraints, they must be compact while allowing for misalignment adjustments and thermal expansion compensation. Electromagnetic interaction studies indicate that Higher Order Modes (HOM) absorbers and additional cooling are required at the Z pole (see Fig. 5).

Further studies to evaluate the impedance of the whole IR beam pipe including the bellows, the BPM, and the remote vacuum connection are foreseen to consolidate the present estimates, and are essential to finalise the design.

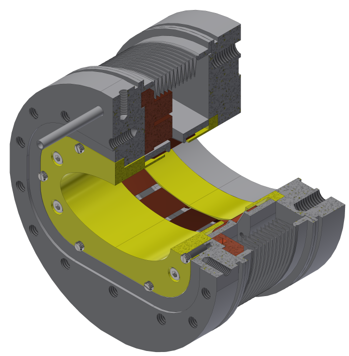

Figure 5: Proposed IR bellows with copper-beryllium RF fingers for electrical continuity, HOM absorber volume, and cooling pipe.

A prototype of the IR bellows is currently in development.

5 Outlook

The support tube design, developed in 2024, facilitates the integration of accelerator and detector components into a unified rigid structure. The vertex detector mock-up is under assembly at INFN-Pisa, where air cooling validation is underway. Final integration tests will ensure seamless assembly with accelerator components.

6 List of Talks in year 2024

1. M. Boscolo, Status of the FCC-ee IR mockup project and MDI validation, INFN MAC-CSN1 review, 21 March 2024

2. M. Boscolo, IR mockup status report, CSN1 meeting, 26 November 2024