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Document Title	Detailed Specification of an In-Vacuum Switchable beam dump system for the High-Energy Cave of the Super-FRS
Description	A switchable beam dump system for the high-energy cave of the Super-FRS.
Division/ Organization	Super-FRS
Field of Application	FAIR GmbH and GSI GmbH

Document History

Version	Prepared/Checked by	Date	Date of Release	Comments
V001	S. Purushothaman	26.07.2025		Checked by - VAC: N. Kurichiyanil - Radiation safety: E. Kozlova
V002	S. Purushothaman	04.03.2026		Changed according to Comments from - QA: R. Maendl and F. Gressier - Radiation safety: D. Gassmann - PAS: Christine Betz



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Abstract

This specification covers the construction, and testing of an in-vacuum switchable beam dump system for the high-energy cave of the Super-FRS. The document defines the requirements for the mechanical, vacuum physical, technical, and metallurgical characteristics of the component. The document also stipulates the requirements regarding the dimensions, the testing, and the inspection of the component.

Item details	Number of items to be delivered	CID	AID	PSP
Vacuum chamber for the switchable beam dump system for the Super-FRS (SFRS) and its support frame.	1	CID:07000803419	AID:0004714	2.4.11.5
Switchable beam dump unit and the interlock system for the radiation protection mechanism of the Super-FRS (SFRS).	1	CID: 1100034919	AID:0004715	

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1. Purpose and Classification of the Document

This document defines the built-to-print technical specification for the in-vacuum switchable beam dump system (beam dump chamber assembly) to be integrated into the Super-FRS beamline at the FAIR facility.

The design authority rests with FAIR GmbH / GSI GmbH (hereinafter referred to as “the Company”). The Company provides the released 3D models, 2D drawings, interface definitions, and boundary conditions forming the contractual design baseline.

The Contractor is responsible for the manufacturing, assembly, inspection, testing, and delivery of the system strictly in accordance with:

- The released drawing package
- This technical specification
- All referenced FAIR Technical Guidelines
- Applicable European standards

This document forms part of the Technical Part of the Contract. Commercial and legal conditions are defined in the Commercial Part of the Contract.

1.1. Manufacturing Design Review (MDR) and Contractor Responsibility

Although this procurement is classified as built-to-print, the Contractor shall perform a comprehensive and independent technical evaluation of the complete design package prior to the commencement of manufacturing. This Manufacturing Design Review (MDR) shall include verification of:

- Completeness and internal consistency of all documentation
- Manufacturability of all components
- Assembly feasibility
- Maintainability and accessibility of safety-relevant components

Any identified inconsistencies, risks, ambiguities, omissions, or potential improvements shall be formally communicated to the Company without delay. Proposed modifications shall be submitted exclusively via the Engineering Change Request (ECR) procedure. No deviations from the released design are permitted without prior written approval from the Company.

Notwithstanding the built-to-print nature of this contract, the Contractor remains fully responsible for achieving all specified functional, safety, mechanical, and vacuum performance requirements. Compliance with released drawings does not relieve the Contractor of responsibility for overall system performance, including the successful completion of the Factory Acceptance Test (FAT).

The Contractor’s obligation to exercise professional engineering diligence applies throughout all project phases, including manufacturing, assembly, testing, and documentation.

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2. Abbreviations, Terms and Definitions

Table 1: Abbreviation, Terms and Definitions.

Abbreviation Term	Definition
FAIR GmbH	Facility for Antiproton and Ion Research GmbH
GSI	GSI Helmholtzzentrum für Schwerionenforschung GmbH
PSP	Project Structure Plan
PSS	Personal Safety System
PAS	Personnel Access Safety
FAT	Factory Acceptance Test
SAT	Site Acceptance Test
MDR	Manufacturing Design Review
FEM	Finite Element Method
EDMS	Electronic Document Management System
Super-FRS	Superconducting Fragment Separator
NCR	Non-conformity report
ECR	Engineering change request

3. Scope of the Technical System

3.1. System Overview

The beam dump system shall operate under high vacuum (HV) conditions and must be capable of switching between two well-defined operational modes:

- **Beam Pass Mode:** In this state, the system functions as a standard beam vacuum chamber, allowing the beam to propagate through to the downstream experimental area without obstruction. Personnel access is restricted in both upstream and downstream zones.
 - PAS signal is in the “unsafe” (beam **not** dumped) condition.
- **Beam Dump Mode:** In this state, the system intercepts the beam in the upstream section by means of internal shielding, thereby enabling personnel access to the downstream experimental area. This mode ensures that the necessary radiation protection is in place by limiting the radiation-controlled area to the upstream region.
 - The default safe condition is the beam dump mode, i.e. when the beam is blocked.
 - PAS signal is in the “safe” (beam dumped) condition
- General requirements
 - Power or pressure loss must not trigger a change in state. The system must retain its last mechanically secured position (either beam-transmission or beam-blocking mode).

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- Switching between modes requires powered actuation, and feedback to the PAS (Personnel Access Safety) system must remain in the unsafe state during this transition.
- Only once the beam-blocking elements are fully inserted and locked, shall the PAS feedback signal indicate a safe condition.

Figure 1 illustrates the layout of the experimental areas and the modular shielding wall.

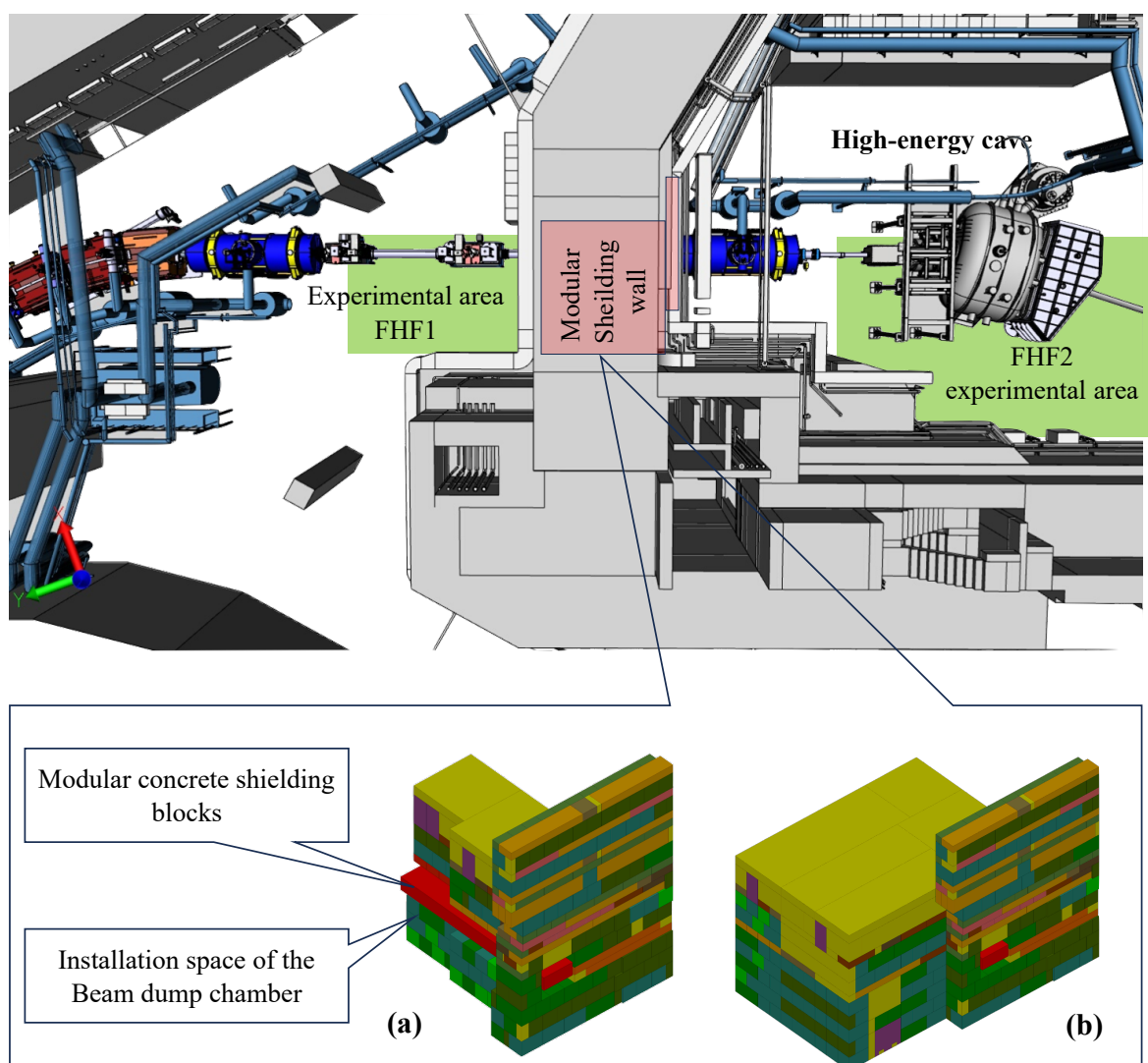


Figure 1: Schematic of the early and first-science configuration of the Super-FRS and its experimental focal plane areas (shaded in green). The experimental areas FHF1 and the High-Energy Cave are located within the High-Energy Branch. These areas are separated by a modular concrete shielding wall, 5.7 m thick, featuring a rectangular opening (1.12 m × 1.00 m) along the beam axis to accommodate beam dump chamber. **Inset:** (a) Configuration showing the installation space reserved for the beam-dump chamber (highlighted in red) within the shielding structure composed of modular concrete blocks. (b) Fully assembled configuration after installation, with the shielding blocks completely enclosing the beam-dump chamber area.

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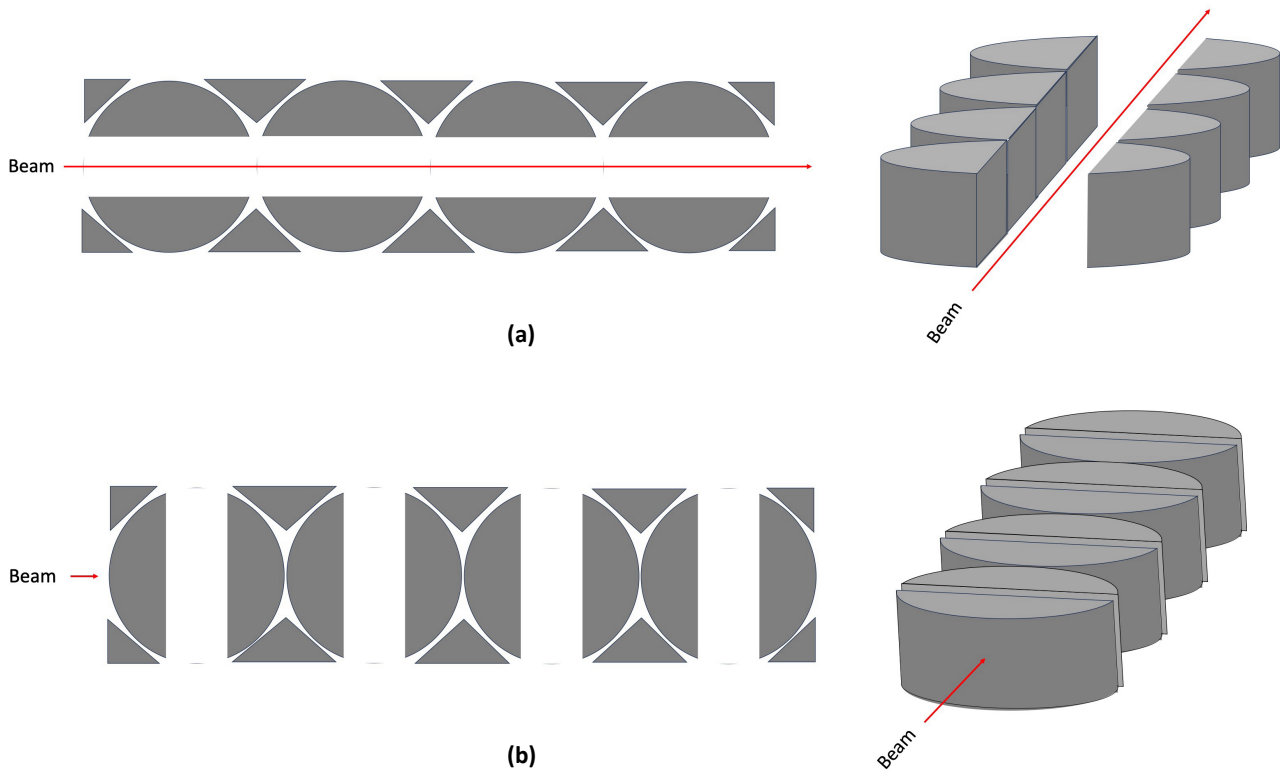


Figure 2: Schematic illustration of the mechanical switching mechanism. (a): In the “beam-pass” configuration, the semi-cylindrical absorber blocks are arranged such that the beam passes unobstructed through aligned cut-outs. (b): In the “beam-dump” configuration, the blocks are rotated to form a continuous absorbing structure, fully intercepting the beam path.

Figure 2 illustrates a conceptual mechanism for switching the system between Beam Pass and Beam Dump modes. In Beam Pass Mode, the shielding blocks are aligned such that a rectangular aperture allows full transmission of the beam through the chamber. In Beam Dump Mode, the shielding blocks are repositioned into the beam path to fully absorb the beam.

The mechanical transition between these two modes must be safe, reliable, and fully compatible with continuous vacuum operation. The switching mechanism shall ensure repeatability, sealing integrity, and robustness throughout the operating cycles. The switch between the modes is expected to occur fewer than 20 times per year, and the switching process may be slow, taking several minutes.

The beam dump system is designed to:

- Intercept high-intensity ion beams up to 1 GeV/u and 10^7 particles/s
- Integrate into a 100 cm x 112 cm x 570 cm opening in a modular concrete shielding wall (see Figure 3). Any design changes proposed by the Contractor shall comply with the defined installation space and the installation drawings provided by the Company. **Detailed installation space drawings will be provided by the Company.**
- Operate under HV conditions at pressures below 10^{-7} mbar
- Provide two operational modes: beam pass and beam dump modes

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The shielding configuration must ensure complete absorption of the primary beam in the dump mode and full transmission in the pass mode. The geometry and material composition must be optimized to provide effective shielding and mechanical robustness, ensuring functionality over the full operational lifetime.

Main components include:

- A vacuum chamber
- Shielding blocks inside the chamber
- A beam interception mechanism enabling two-state operation
- A motor-driven actuation system including gearbox
- Safety interlock systems.
 - Hardware and software engineering
 - Manufacturing and delivery of the cabinets
- Support structures and interfaces for secure wall integration and retrieval of the chamber for possible maintenance.

3.2. Scope of Delivery

The Contractor shall manufacture, assemble, test, and deliver the system strictly in accordance with the released drawing package and this specification.

The Contractor shall perform a technical review of the provided design documentation prior manufacturing and notify the Company of any identified inconsistencies, risks, or improvement potential. Any proposed modifications require written approval via the Engineering Change Request (ECR) procedure.

The Contractor shall deliver:

- A vacuum-integrated beam-dump chamber system consisting of a vacuum chamber designed to house the shielding block assembly. The system shall include the following main components as defined in the released drawings:
 - A vacuum chamber assembly integrating the beam-dump units and the switching mechanism.
 - Integrated beam-dump shielding blocks sized and positioned to meet the radiation-protection requirements and manufactured in accordance with the released drawings and the Bill of Materials (BOM).
 - A motor-driven switching mechanism in accordance with the released mechanical drawings. The drive system shall include the specified electric motor, gearbox, and spur-gear transmission for synchronization of the shielding block rotation.
 - A support frame system designed to bear the total system load and incorporating the mechanical interface required for installation and removal of the chamber from the shielding wall in case of failure.
 - An integrated alignment mechanism and redundant mechanical end-stops serving as radiation-safety interlock signal actuators, as defined in the electrical and mechanical drawings.
 - All interface supports and installation tooling required for system integration, as specified in the drawing package.
- Hardware and software engineering required for implementation of the approved electrical design.

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- PLC unit, including CPU, I/O modules, safety modules where specified, and programming in accordance with the approved electrical documentation. Full source code and software documentation.
- Motor control system, including motor control box, power electronics, protection devices, and all associated components as specified in the electrical drawings.
- Manufacturing, assembly, and delivery of all electrical control cabinets, including the PLC cabinet and motor control box, in accordance with the released documentation.
- Installation work of the electrical control system and cabinets at GSI, including mounting, cabling, termination, and interface connection as specified in the drawing package.
- All required documentation in accordance with Section 6, including electrical schematics, PLC software documentation, parameter lists, cable lists, and as-built documentation.

3.3. Spare Parts

The Contractor shall supply:

Two (2) complete sets of spare parts for all non-standard vacuum sealing elements used within the delivered system.

- Non-standard vacuum seals are defined as any sealing components that:
- Are not standard CF copper gaskets compliant with ISO 3669, or
- Are custom-manufactured sealing geometries, or
- Are proprietary sealing elements specific to the switching mechanism (e.g., dynamic rotary feedthrough seals, special metal seals, intermediate evacuation seals).

Each spare set shall include all sealing components required to replace the complete sealing interface once.

All spare parts shall:

- Be identical in material, specification, and surface quality to the installed components,
- Be individually packaged and clearly labeled,
- Be delivered with material certificates where applicable.

4. System Specification

4.1. Technical Requirements for System Components.

- **Required open aperture in Beam Pass Mode:** The system must provide a rectangular aperture with a horizontal opening of 380 ± 0.5 mm and a vertical opening of 430 ± 5 mm. The remaining cross-section of the chamber shall be shielded with a minimum of 3 meters of iron.
- **Beam Dump Mode configuration:** In this mode, the system must switch to a configuration in which the entire cross-section of the vacuum chamber is blocked by iron shielding. This configuration ensures the required radiation protection.

The system incorporates a switching mechanism that enables transition between the two operational modes. The mechanism provides the mechanical movement, actuation method, positioning accuracy, and fail-safe locking and/or interlock functions required for safe operation.

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- The switching mechanism shall ensure:
- Vacuum integrity in all operational states, including during and after switching,
- Preservation of the required radiation-shielding effectiveness in both modes, and
- Long-term mechanical reliability over the specified operational lifetime.

The safety switches are designed to be accessible for inspection and replacement without requiring removal of the chamber from its installed position.

4.2. Material selection

The Contractor shall use only the materials specified in the approved mechanical drawings and documentation. Substitution of materials is not permitted without prior written approval from FAIR GmbH.

The Contractor must adhere to the Technical Guideline, Material Selection and Radiation [1], which specifies approved and restricted materials for use in radiation-exposed environments. Materials with high activation potential such as Europium, Iridium, Scandium, Tantal, Cobalt, Cesium, Chromium and Tellurium must be strictly avoided. Furthermore, no organic or synthetic materials are permitted inside the vacuum chamber or in regions directly exposed to primary or secondary radiation fields.

4.3. Vacuum requirements

Operational pressure of the vacuum chamber is $\leq 1 \times 10^{-7}$ mbar. The following vacuum properties have to be fulfilled by the vacuum chambers:

Table 2: Vacuum requirement of the components.

Criteria	Requirement
The outgassing rate	After 10h of pumping ○ $\leq 1 \times 10^{-9}$ mbar l / s.cm2
Integral leakage rate	$< 1 \times 10^{-9}$ mbar·l/s.
Residual Gas Composition	After 24 hours pumping: ○ All peaks from masses between 18 and 45 have to be 100 times lower than the peak from mass 18, except peak from masses 28 and 44 ○ All peaks from masses higher than 45 have to be 1000 times lower than the peak from mass 18

4.4. Welded joints

- The Contractor shall describe in detail the production and distortion-control plan to achieve the specified tolerances during the Manufacturing Design Review (MDR).
- The Contractor shall submit a detailed welding concept as part of the Manufacturing Design Review (MDR). Any filler material used shall be identical or metallurgically compatible with the specified base material.

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- Prior to welding, all joint edges shall be thoroughly cleaned and properly prepared. Weld seams shall be continuous where required. Weld size and volume shall be minimized to the extent permitted by structural and vacuum requirements.
- Welding shall be performed in a manner that prevents unacceptable distortion. Appropriate measures (e.g., controlled welding sequence, clamping, heat input control) shall be taken to ensure that required tolerances are maintained.
- Weld seams shall be free from porosity, cracks, inclusions, cold shuts, undercut, or underfill.
- Deviations from these requirements are permitted only with prior written approval from FAIR GmbH. External weld seams shall be fully executed to prevent voids or trapped volumes.
- CF flanges shall be welded only after complete machining. Reworking of sealing surfaces after welding is not permitted. Measures shall be taken to prevent deformation of the flange and knife-edge during welding.
- Proposed modifications to weld lips require prior coordination and written approval from FAIR GmbH.
- Stabilization welds or tack welds covering vacuum-tight weld seams shall be interrupted or designed to allow helium flow during leak testing.

All welding work shall be performed exclusively by qualified and certified personnel. Manual welding shall be carried out by welders certified in accordance with DIN EN ISO 9606-1. Automated welding processes shall be operated by personnel qualified in accordance with DIN EN ISO 14732.

A welding specification (WPS) corresponding to the welding task must be available. The qualification of the specifications must be carried out in accordance with the task-specific and regulatory-compliant requirements according to DIN EN ISO 15610 to 15614 .

Non-destructive testing (NDT) of weld seams shall be conducted by certified personnel in accordance with DIN EN ISO 9712 (Qualification and certification of NDT personnel).

- Vacuum-side weld seams shall comply with DIN EN ISO 5817, Quality Level B.
- External welds and load-bearing support frame welds shall comply with DIN EN ISO 5817, Quality Level C as a minimum.

See FAIR Technical Guideline for Welding Practices [2].

4.5. Functional Requirements (Parameter List)

- General tolerances: ISO 2768-1 mK
- General tolerances for welded designs: EN ISO 13920 BF
- CF-Flanges up to DN 250: ISO 3669:2020

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4.6. Interfaces

4.6.1. Vacuum Interfaces

- All vacuum interfaces shall be manufactured in accordance with the released mechanical drawings.

4.6.2. Mechanical Support Structure

The Contractor shall manufacture and assemble the support structure for integration of the beam dump chamber system into the shielding wall environment strictly in accordance with the released mechanical drawings.

The support structure shall include the specified installation and transfer interface enabling insertion, positioning, and removal of the chamber for maintenance or failure scenarios.

The alignment feet will be provided by FAIR GmbH (Company supply). The Contractor shall ensure that the chamber base and interface geometry are manufactured in accordance with the released drawings to allow proper installation onto the Company-supplied alignment feet.

No deviation from the specified interface geometry, load assumptions, or tolerances is permitted without prior written approval from FAIR GmbH.

4.6.3. Handling Interfaces

- The vacuum chamber shall be equipped with certified lifting points as specified in the released mechanical drawings. The lifting points shall be clearly marked and rated for the full system load.
- The beam dump unit(s) shall be equipped with certified lifting points in accordance with the drawing package to ensure safe crane handling during installation and disassembly.
- Handling interfaces e.g., reinforced zones or forklift pockets), where specified in the drawings, shall be manufactured accordingly to ensure mechanical integrity and safe operation during transport.
- The Contractor shall provide a lifting and handling plan as part of the documentation package. The plan shall include the total weight, center of gravity location, permissible lifting configurations, and recommended lifting equipment.
- All lifting points and handling interfaces shall comply with applicable safety standards and shall be verified for the specified loads.

4.7. System Environment and Constraints

The chamber and its support structure shall be permanently enclosed within the modular concrete shielding wall.

During installation, one lateral side of the shielding wall shall remain open to allow side access for insertion of the beam dump chamber (see [Figure 3](#)). After completion of installation and alignment, the shielding wall shall be closed with the designated modular concrete blocks. The project timeline for the beam dump system is therefore strictly coupled to the installation schedule of the shielding wall.

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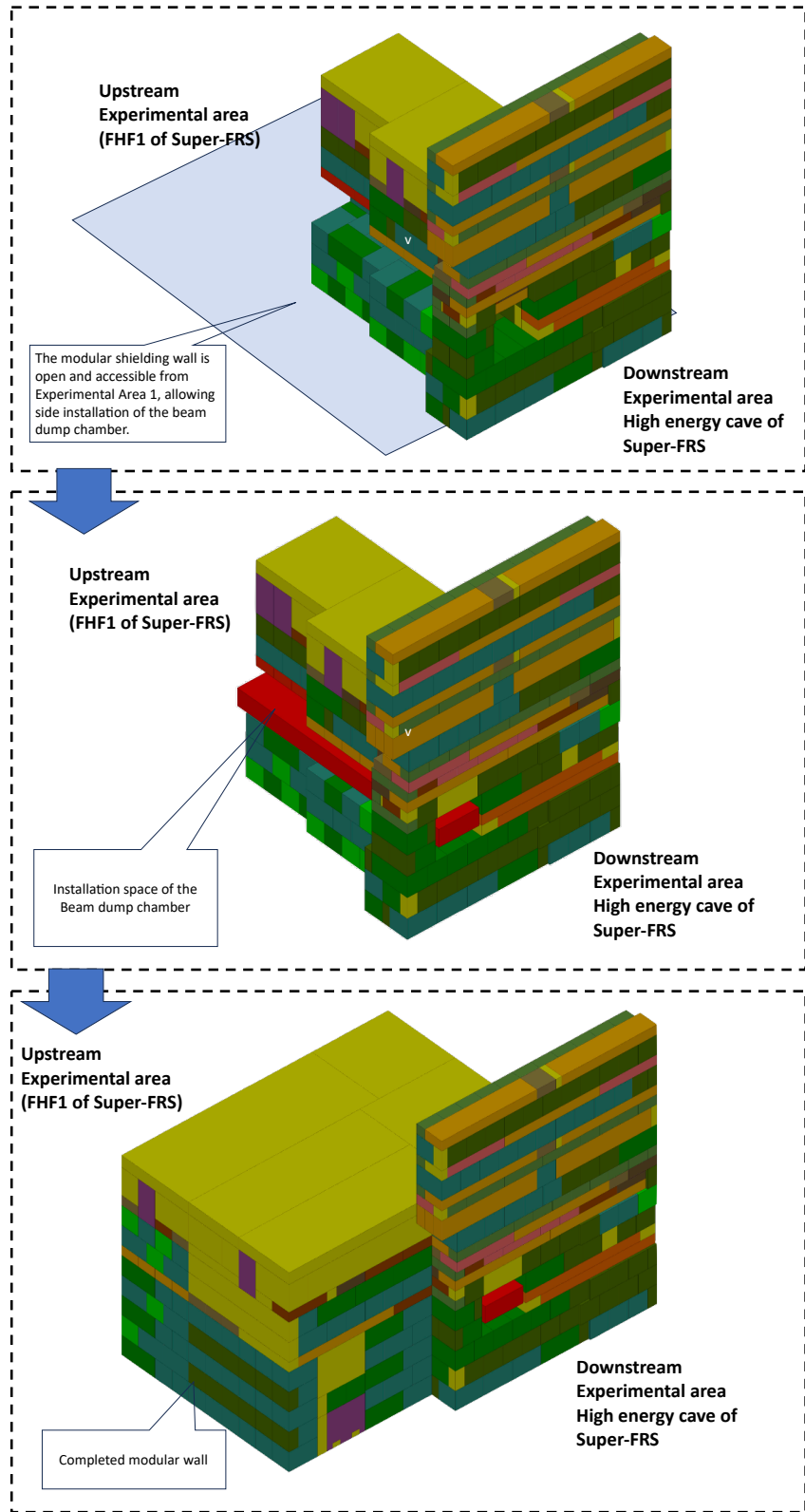


Figure 3: Installation sequence and spatial context of the beam dump chamber within the modular shielding wall between Experimental Area 1 (FHF1 of Super-FRS) and Experimental Area 2 (High Energy Cave of Super-FRS).

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Routine removal of the chamber for maintenance is not foreseen. Removal shall only be required in the event of a critical failure. In such a case, the chamber shall be retrievable by pulling it out along the support structure toward the beam entrance side, in accordance with the defined installation and handling concept.

4.8. Radiation Safety

Operation of the Super-FRS beam dump system involves high-intensity heavy-ion beams. necessitating rigorous radiation shielding measures, especially when the system is in **beam dump mode**. ^{208}Pb at 1 GeV/u with intensities of 10^7 particles/s. Radiation protection aspects of the system in **beam dump mode** were considered to estimate the required shielding thickness. The beam dump and its surrounding shielding are designed to ensure compliance with occupational radiation limits, thereby protecting personnel and infrastructure in adjacent experimental areas.

In **beam dump mode**, the full cross-section of the chamber interior **shall be blocked with iron shielding**. **NO** gaps are permitted along the beam direction within the beam path (i.e., the open aperture). In all other regions of the vacuum chamber, the **maximum permissible gap is 10 mm**.

4.8.1. Safety Integration with PAS

The beam dump system is a safety-relevant component of the FAIR Personnel Access System (PAS) and shall be integrated into the Personnel Safety System (PSS) in accordance with the approved electrical and safety design documentation.

The safety function of beam blocking and status feedback shall achieve **Performance Level PL e in accordance with EN ISO 13849-1**. The preferred reference standard of the Company for functional safety is IEC 61508.

4.8.2. Safety State Definition

For PAS/PSS integration, the system shall provide a binary safety state:

- SAFE state: Beam Dump Mode (beam fully blocked and mechanically locked).
- UNSAFE state: Any other condition, including Beam Pass Mode, intermediate positions, switching movement, fault conditions, or loss of power.

The PAS shall receive a SAFE signal only when the beam dump is fully inserted and verified by redundant position monitoring.

In beam transmission mode, during switching, or in the event of power or pneumatic failure, the PAS feedback shall remain in the UNSAFE state.

4.8.3. Machine Safety and Beam Enable Logic

For machine operation and beam control logic, both end positions shall be positively monitored and communicated:

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- Confirmed Beam Dump Mode (block inserted).
- Confirmed Beam Pass Mode (beam path fully unobstructed).

Beam transmission shall only be enabled when the system is positively confirmed to be in Beam Pass Mode.

Any intermediate position, inconsistent position signals, or loss of feedback shall inhibit beam transmission.

4.8.4. Position Monitoring and Redundancy

The position monitoring system, including redundancy, diversity, switch configuration, and mechanical actuation concept, shall be implemented strictly in accordance with the approved Beam Stopper reference design and the released electrical documentation.

The Contractor shall manufacture, assemble, and wire all safety-relevant components as specified in the approved design documents. No deviation from the defined safety architecture is permitted without prior written approval from FAIR GmbH.

All safety-relevant components shall be installed and adjusted to ensure correct and reproducible position detection as defined in the approved documentation.

4.8.5. Electrical and PLC Integration

The electrical system, including PLC architecture, safety logic, signal interfaces, and wiring concept, shall be implemented strictly in accordance with the approved electrical design documentation.

The Contractor shall supply and install the complete electrical interface up to the local terminal box as defined in the released drawings.

The local terminal box and PLC unit are part of the delivery and shall be manufactured, assembled, wired, and programmed in accordance with the approved documentation. The locations of interface points and PLC cabinets are defined by the Company.

All hardware components, including PLC type, I/O modules, safety modules, power supplies, and signal interfaces, shall be implemented exactly as specified in the released electrical documentation.

The Contractor shall program the PLC according to the approved control and safety logic. Full program access and source code shall be provided to the Company as part of the delivery.

All safety-relevant contacts shall be potential-free and wired as specified in the approved design. Contacts connected to failsafe inputs shall be positively driven as defined in the documentation.

Internal cabling within the vacuum chamber shall be routed as specified in the mechanical and electrical drawings to prevent direct exposure to the ion beam. Any deviation requires prior written approval from FAIR GmbH.

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4.8.6. Reliability and Maintenance

The system shall be manufactured and assembled in accordance with the approved design documentation, taking into account operation in a radiation environment.

Safety-relevant components identified in the approved documentation (e.g., position switches, patch panels, and associated hardware) shall be installed in a manner that allows replacement as specified in the design.

5. Procedure

5.1. Overall Procedures

Within an agreed period after contract award, the Contractor shall submit a detailed project schedule covering manufacturing, testing, and delivery phases in accordance with the approved design documentation.

- The schedule shall include at minimum:
- Manufacturing Design Review (MDR)
- Production phase
- Factory Acceptance Test (FAT)
- Delivery (packing and transport)
- Installation and Site Acceptance Test (SAT)

During project execution, the Contractor shall provide a monthly progress report describing:

- Activities completed during the previous month
- Activities planned for the following month
- Deviations from the agreed project schedule, including corrective actions

The project progress and reports shall be reviewed in regular coordination meetings between the Company and the Contractor.

The Contractor shall complete and submit the “Progress Report Spreadsheet” provided by the Company. This report shall reflect the status of manufacturing, material procurement, major components, cleaning, vacuum testing, inspection activities, and delivery status.

4.2.2 Supporting Documents

In addition, the Contractor has to provide the following:

- A mechanical stability analysis, i.e. a stress analysis by using, for example, FEM simulations.
 - Once the chamber is positioned in its final location, the remaining gaps in the installation space will be filled with modular concrete blocks. If a 20 cm gap above the chamber is considered, this will result in approximately 2.3 tons of additional weight. The design of the support structure must account for the mechanical calculations.
- Production/manufacturing process plan
- Inspection and test procedures
- QA – Plan (as specified in Section 7)

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- Risk assessment
- Operation Manual (In English and German)
- Installation instructions
- Proof of compliance with applicable European directives.
- Material test certificates shall be provided in accordance with DIN EN ISO 10204.
 - Load-bearing and vacuum-relevant components shall be supplied with Inspection Certificate 3.1.
 - Non-safety-relevant components may be supplied with Works Certificate 2.2, subject to approval by the Company.

5.2. Production Phase

The production shall follow the released process and control plan. Mechanical designs shall follow the rules of Component Reference by the FAIR Technical Guideline F-TG-ZT-3.75e [3].

A QR code tag according to [4] must be attached on the outer surface of the chamber visible after installation. The code to be used will be provided by the Company as a graphic file and contains the CID number. The QR Code can be laser-marked, burnt, etched or engraved directly on the curved flange surface.

The production phase ends with an approval of the factory acceptance tests which will be accompanied by the Company.

6. Quality Assurance, Tests and Acceptance

6.1. Quality Assurance System of the Contractor

Herein, all the measures shall be described in detail or referenced, which ensure that the present specifications will be fulfilled. The complete Quality Acceptance process is written down in *General Specification* [5].

Contractor shall be certified according to DIN EN ISO9001. The contractor shall install a quality assurance system which allows quality planning, quality steering, quality measurement and quality improvement. It is important that very close information exchange between contractor and company is ensured. It is the responsibility of the Contractor to ensure that the subcontractors shall follow the required quality assurance system during the manufacturing.

For details see FAIR General Specifications [5].

6.2. Factory Acceptance Test (FAT)

The appointment for the Factory Acceptance Test has to be announced to the Company at least 30 days ahead so that the presence of the firm representatives can be guaranteed. The Contractor provides all tools which are necessary for the acceptance procedure. After the release of the factory acceptance test by the Company, the distribution can take place. All FAT tests shall be carefully recorded in protocols. All test documentation shall be submitted to the FAIR GmbH.

FAIR GmbH provides an acceptance certificate (see FAIR Technical Guideline [6]), where all measurements and tests have to be documented. Contractor can use their own protocol if available

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but this shall be presented in CDR or FDR.

6.2.1. Visual inspection

- The Contractor has to examine the internal and external surfaces of the vacuum chamber for any defect, scratch, dirt, contamination, dent and any form of color that may originate from the welding or annealing.
- All welded parts must not have any scale, void, or blow holes and there is no visible evidence for inclusions or any color from the welding. The welding seams have to follow DIN EN ISO 5817 quality class B.
- The sealing flanges and the knife edges must be clean and free from any defect.
- The inspection of the internal parts has to be done with special care, in order not to cause any contamination or scratches inside the chamber.

6.2.2. Mechanical acceptance test

The contractor is requested to carry out a Mechanical acceptance test according to Technical Guideline [7]. The check will be done at the contractor site.

The final cleaning of the vacuum component must be done after the mechanical inspection because it includes the check of the vacuum surfaces. If a re-work is necessary after the mechanical inspection, the required tolerances have to be proved again.

In addition to manufacturing the system in accordance with the approved design documentation, the Contractor shall provide the Structural Verification

A mechanical verification of the manufactured support structure and chamber components, confirming compliance with the loads defined in the approved design documentation.

The verification shall consider:

The dead weight of the chamber assembly, and

The additional shielding load of approximately 2.3 tons resulting from modular concrete blocks placed above the chamber,

The verification may be performed using analytical calculations or FEM simulations. The purpose of this verification is to confirm compliance with the approved design, not to redesign the system.

6.2.3. Functional Testing

The Contractor shall perform functional testing of the complete mechanical and electrical system prior to delivery.

The functional tests shall include, at minimum:

- Verification of correct rotation and synchronized movement of the shielding blocks
- Verification of end-position detection (beam dump and beam pass positions)
- Verification of mechanical locking (if applicable)

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- Verification of drive system operation (motor, gearbox, brake, encoder where applicable)
- Verification of control system functionality and signal transmission to the local terminal box
- Verification of correct status indication (SAFE / UNSAFE logic as defined in the approved design)

The functional test results shall be documented and form part of the Factory Acceptance Test (FAT).

6.2.4. Vacuum acceptance test

The Contractor must provide the information of the leak rate, outgassing rate, and the residual gas composition during the vacuum acceptance test (see Section 4.3).

The proof of HV aptitude of the system has to be done in a dedicated HV test setup of the contractor. Inspection and testing shall be performed using properly calibrated measuring and test equipment. Contractor shall make sure that the vacuum system is not contaminated with the hydrocarbons during the acceptance tests. The test procedure is described in detail in FAIR Technical Guideline [8].

- Leak testing shall be performed with a calibrated He leak detector. The integral leakage rate shall be $<1 \times 10^{-9}$ mbar·l/s. The contractor shall provide a proposal for leak test procedure.
- Pump down curve shall be recorded and presented in the FAT report.
- RGA data must be recorded and presented in the FAT report.

6.2.5. Functional Testing

A functional verification of the safety interface shall be performed in accordance with the approved electrical and safety design documentation.

- The verification shall include testing of the safety-related signals and system response under the following operational scenarios:
 - Normal operation (steady-state beam dump and beam pass positions)
 - Mode switching between beam dump and beam pass
 - Power loss conditions
 - Defined fault conditions (e.g., position switch failure, actuator fault)
 - Interruption and restoration of safety signals

The test shall confirm correct SAFE / UNSAFE state behavior as defined in the approved safety concept.

Testing shall be documented, witnessed by the responsible safety authority, and repeated after any maintenance or modification affecting safety functions.

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6.3. Site Acceptance Test (SAT)

Formal acceptance of the delivered vacuum chamber system shall take place only after successful completion of the Site Acceptance Test (SAT A – Milestone M10 within the General Specification) at the FAIR GmbH site.

The SAT shall verify compliance of the delivered system with the approved design documentation and contractual specifications.

Any failure identified during SAT shall be rectified by the Contractor in accordance with the contractual conditions. Equipment not complying with the agreed specification may be rejected and returned at the Contractor's expense.

If the system must be returned to the Contractor's premises for repair or modification, the complete Factory Acceptance Test (FAT), as defined in Section 6.2, including all relevant additional tests, shall be repeated prior to redelivery.

6.4. Packaging, Transport and Installation

The shipping and packaging of vacuum components have to follow the FAIR Technical Guideline [9]. The system has to be packed without contamination and damage during packaging.

For shipping and storing, the chamber shall be sealed with blank Al flanges.

7. Documentation

No deviations from the approved design are permitted without written approval.

The Contractor shall provide the following documentation, as applicable, in accordance with the approved design documentation and contractual requirements:

- Manufacturing drawings used for production (as-built condition).
- Electrical wiring diagrams and control cabinet documentation (as-built condition).
- Assembly, installation, and disassembly instructions.
- As-built component list and bill of materials.
- As-built documentation confirming conformity with the released design documentation. An updated 3D model shall be provided in the case of deviations.
- Risk and hazard analysis covering assembly, transport, installation, and commissioning activities (excluding system-level functional safety design).
- Declaration of Conformity and related CE documentation.
- Risk assessment limited to manufacturing, handling, transport, installation, and CE compliance (according to ISO 12100). (System-level functional safety design and SIL/PL calculations remain the responsibility of the Company unless explicitly specified otherwise.)
- Maintenance and operational instructions (manual) delivered in both German and English.
- User manual delivered in both German and English.
- Material test certificates in accordance with DIN EN ISO 10204 (3.1 / 2.2 as applicable).
- All documentation, whether electronic or printed, shall become the property of the Company.
- Electronic documentation shall be uploaded to the FAIR web-based data management system (EDMS).
- The Company will provide EDMS access and define the project folder structure.

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- Document organization and numbering shall follow FAIR EDMS guidelines and shall be coordinated with the Company.
- All documents requiring approval shall undergo EDMS-based review and release procedures.
- Documentation not properly released and approved in EDMS will not be accepted.

7.1. Non-Conformance Reporting

Any deviation identified during manufacturing, inspection, or testing from the approved design documentation shall be documented in a Non-Conformance Report (NCR) and submitted electronically to the Company for approval prior to implementation.

7.2. Material related Documentation and Certificates

All relevant material certificates of construction materials used for the production of the vacuum chamber which confirm all relevant material properties shall be delivered.

Certificates for the used welding filler shall be delivered.

Necessary test certificates in accordance with DIN EN ISO 10204: works certificate 2.2 or certificate 3.1.

7.3. Process related Documentation

The process description for each welding process applied shall be delivered as well as the welder's certification.

Results of FEM calculations for the proof of mechanical stability of the chambers shall be delivered.

7.4. Technical drawings and CAD – Data

Any 3D model delivered in .stp or CATIA file formats must follow the FAIR Technical Guideline [10]. The data exchange guidelines are given in the FAIR Technical Guideline Data Exchange [11] and [12].

7.5. FAT documentation

In particular, for FAT documentation the protocol given in the FAIR Technical Guideline [6] can be used if the manufacturer has no own templates. In addition, all documents required by the “Vacuum Properties Acceptance Tests” and the final version of the CDR documents have to be delivered.

7.6. SAT documentation

The protocol of the SAT Part A test (which repeats FAT) shall be prepared in the same way as the FAT protocol according to the FAIR Technical Guideline [6]. If the SAT fails, the SAT record will be delivered to chamber manufacturer with the demand of repair or rework.

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8. Related Documents

8.1. Bibliography

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- [2] F-TG-QUA, "Recommendation: Guideline for the execution of welding practices for the FAIR project," EDMS ID: 2383347.
- [3] F-TG-ZT-3.75e, "Mandatory: FAIR Technical Guideline, Component Reference," EDMS ID: 1467107.
- [4] F-TG-B-0.5e, "Mandatory: FAIR Technical Guideline, Permanent Labelling of Components "," EDMS ID: 1229368.
- [5] F-GS-PMO-en, "Mandatory: FAIR General Specifications," EDMS ID: 1365092.
- [6] F-TG-V-7.15e, "Recommendation: FAIR Technical Guideline, Record for Factory Acceptance Test (FAT) of Vacuum.," EDMS ID: 1172908.
- [7] F-TG-V-7.1e, "Mandatory: FAIR Technical Guideline, Mechanical Acceptance Test for UHV Components," EDMS ID: 1172905.
- [8] F-TG-V-7.2e, "Mandatory: FAIR Technical Guideline, Vacuum Properties Acceptance Test without Bake-out.," EDMS ID: 1172906.
- [9] F-TG-V-9.1e, "Mandatory: FAIR Technical Guideline, Transport and Packaging of Vacuum Components.," EDMS ID: 1172926.
- [10] F-TG-MDS-de-KRL-V005, "Mandatory: FAIR Technical Guideline, Design Guideline," EDMS ID: 1229367.
- [11] F-TG-B-02e, "Mandatory: FAIR Technical Guideline, Data Exchange Guideline Part 1 (DRL T1)," EDMS ID: 1229366.
- [12] F-TG-B-03e, "Mandatory: FAIR Technical Guideline, Data Exchange Guideline Part 2 (DARL T2)," EDMS ID: 1259954.