DEVELOPMENT AND TECHNICAL FEASIBILITY OF THE FIGURE-8 STORAGE RING CONCEPT FOR HIGH CURRENT BEAM STORAGE

S. Schwarz*[1,2], M. Droba[2], O. Meusel[2], H. Podlech[2], K. I. Thoma[2]
[1]FAIR - Facility for Antiproton and Ion Research in Europe GmbH
[2]Goethe-University Frankfurt, Frankfurt am Main, Germany

Abstract

The Figure-8 Storage Ring (F8SR) is an innovative concept for storing low-energy proton and ion beams below 1 MeV in a compact, stellarator-like geometry embedded in magnetic fields of 6 T–7 T. Previous studies established feasibility of the magnetic lattice and indicated the potential for long confinement times at high stored current. This paper concentrates on the mechanical engineering development toward a Technical Design Concept, with emphasis on the ring support structure, magnet-cryostat integration, cryogenic and electrical supply infrastructure, vacuum hardware integration, and installation in a realistic accelerator hall. The assessment indicates that the concept is technically feasible using established accelerator engineering methods, provided that alignment stability, thermal contraction management, well-defined magnetic force load paths, and vibration control are treated as top-level requirements from the earliest design stage.

INTRODUCTION

High-current storage of low-energy proton and ion beams is a key enabling capability for beam–plasma interaction experiments and fusion-relevant beam-driven systems. At energies below 1 MeV, beam lifetime and operational robustness are strongly influenced by space-charge effects, beam–gas interactions, and sensitivity to lattice and alignment errors. These constraints motivate compact ring architectures with strong focusing, good symmetry properties, and ultra-high vacuum (UHV) performance [1–3]. The Figure-8 Storage Ring (F8SR) addresses the requirements for a symmetric figure-eight shape of the central axis embedded in a strong magnetic field environment of approximately 6 T–7 T. In addition to beam-optical advantages, the figure-eight layout imposes distinct mechanical challenges: the machine combines non-trivial three-dimensional geometry with superconducting magnets, cryogenic distribution, high-current power conversion, and UHV beam pipes, all within a limited installation envelope. General layout with the detailed design of the EX-2 section is depicted on Fig. 1.

Earlier work emphasized orbit stability, lattice definition, and diagnostic and vacuum feasibility. The next step is the consolidation of scientific requirements into an integrated Technical Design Concept (TDC) that defines interfaces, assembly sequences, maintainability, and safety provisions. The present paper focuses on the mechanical and infrastructural aspects that dominate technical feasibility: the structural concept of the ring support frame, the integration of superconducting magnet cryostats and vacuum chambers, the routing and isolation of cryogenic and electrical services, and the integration into an accelerator hall including foundations, access, and safety systems.

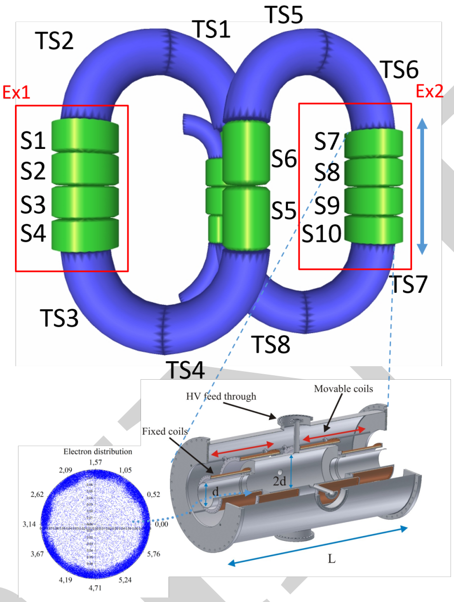

Figure 1: General layout of the F8SR (TS-toroidal sectors, S-solenoidal sectors, EX- Experimental area). Possible electron distribution generated in EX-2 is shown as well (left-down).

INTEGRATION OF SUPERCONDUCTING MAGNETS AND CRYOSTATS

Mechanical Interfaces & Force Management

Magnetic fields in the 6 T–7 T range strongly suggest superconducting coils (e.g., NbTi or Nb_3Sn technology) housed in individual cryostats. The cryostat contains a cold mass (coils and supporting structure), thermal shields, and a vacuum vessel. Mechanically, the principal challenge is to support the cold mass with sufficient stiffness while limiting conductive heat flow to the helium temperature stage. Low-thermal-conductivity suspension elements (such as GFRP or titanium rods) are arranged to carry gravitational loads and anticipated magnetic-force components. Because the ring geometry introduces curvature and potentially non-planar orientations, the suspension system must provide controlled stiffness in the transverse directions to avoid micro-motions that could degrade field reproducibility or trigger quenches.

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* S.Schwarz@iap.uni-frankfurt.de

A robust integration strategy separates internal and external mechanical responsibilities. Internally, the cold mass supports and alignment features are optimized for cryogenic performance and stability. Externally, the cryostat vacuum vessel is mounted on the warm support frame via adjustable interfaces that allow precision alignment without disturbing the internal suspension. This separation reduces the risk that alignment corrections introduce unintended stresses into the cryogenic structure.

Thermal Contraction & Alignment Stability

Thermal contraction during cooldown produces millimeter-scale length changes over meter-scale cryogenic components. Even when the primary support frame remains at room temperature, differential contraction between the cold mass, thermal shields, and vacuum vessel can induce stresses and alignment shifts if not accommodated. Therefore, the design must incorporate defined constraint directions and compliant degrees of freedom. A common approach is to fix the cold mass in one location (defining the reference point) and to guide contraction with sliding or flexural elements elsewhere. The sliding interfaces must avoid stick-slip behavior at low temperatures, and the suspension geometry must prevent unwanted rotations that would shift magnetic centers.

Validation of contraction behavior is ideally performed at prototype level using strain gauges, displacement sensors, and repeated thermal cycles. These measurements allow refinement of FEA models and support the definition of alignment procedures that account for warm-to-cold offsets. For a high-current storage ring, it is beneficial to treat the thermal alignment shift as a calibratable, repeatable transformation, rather than as an uncontrolled disturbance.

Quench, Pressure Relief & Mech. Robustness

Quench scenarios couple mechanical integrity with safety requirements. Rapid energy deposition can cause helium boil-off and transient pressure rises. Cryostat vessels and relief paths must therefore be designed for worst-case pressure loads and routed to safe discharge locations. Mechanically, this influences nozzle reinforcement, support of relief piping, and allowable reaction forces transmitted to the ring structure during a relief event. A well-defined design ensures that relief operation does not compromise alignment features and does not introduce excessive dynamic excitation into the support frame.

SUPPLY SYSTEMS: CRYOGENICS, ELECTRICAL POWER AND VACUUM

Cryogenic Plant Interface & Distribution Routing

The cryogenic system comprises a refrigeration and liquefaction plant, buffer storage, and a distribution network feeding each cryostat. The distribution network is often the dominant contributor to integration complexity because it must balance thermal efficiency, maintainability, and mechanical isolation. Vacuum-insulated transfer lines are routed along the ring perimeter or on dedicated bridges. Their supports must carry weight and manage mechanical loads while allowing thermal contraction. Expansion bellows provide flexibility for sealing and thermal motion, but they should not be relied upon as primary structural elements. Instead, mechanical supports define the load path while bellows and bayonets accommodate displacement.

Maintainability benefits from module-level isolation. Valves and demountable connections placed at module boundaries allow the removal of a single module with limited impact on the remainder of the ring. This approach requires service envelopes for tooling and lifting, as well as clear routing that does not block metrology lines of sight or access to alignment screws.

High-Current Electrical Infrastructure

Superconducting magnets require high-current power conversion, typically in the multi-kiloampere range, along with quench detection and energy extraction hardware. Mechanically, the electrical subsystem affects the machine through busbar routing, conductor support, and constraints on access and safety zoning. Water-cooled busbars and flexible braids are used to bridge between stationary equipment and cryostat feedthroughs, allowing alignment adjustment and thermal motion without overstressing joints. Current leads are a critical thermal interface; high-temperature superconducting stages can reduce heat load on the helium bath, but they impose strict requirements on positioning, seal preload, and thermal cycling compatibility.

To reduce heat and electromagnetic interference in the experimental area, power converters are typically placed in a separate technical room. This decision shifts complexity toward penetrations, tray routing, and fire safety measures. It also requires careful separation of high-current conductors from low-level diagnostic wiring to limit noise coupling into beam instrumentation.

Magnetic Field Energy

The magnetic field energy describes the amount of energy stored within a magnetic field. In this work, superconducting magnets are used for the accelerator design. Therefore, the stored magnetic field energy of the Figure-8 configuration is calculated in order to estimate the electromagnetic energy contained in the superconducting magnet system. The stored energy scales with the square of the magnetic flux density and linearly with the magnetic field volume. Consequently, high-field superconducting accelerator magnets can store significant amounts of energy, which is an important design parameter for quench protection, cryogenic stability, and overall machine safety. For the calculation of the magnetic field energy presented below, the assumptions listed in Table 1 are used.

$$E_B = \frac{B^2}{2\mu_0} V \approx 12.9\,\mathrm{MJ} \tag{1}$$

Thus, the stored magnetic field energy of the F8SR superconducting magnet configuration is approximately 12.9 MJ.

Table 1: Assumptions Used for Magnetic Field Energy

Parameter	**Value**
Magnetic flux density B	7 T
Beam pipe inner diameter d	200 mm
Magnetic volume V	0.661 252 506 431 m^3
Vacuum permeability μ_0	$4\pi \times 10^{-7}$ H/m

Vacuum System Design & Bake-Out Compatibility

High-current operation requires UHV conditions to reduce beam–gas interactions. The vacuum system is usually implemented with metallic beam pipes, all-metal seals, and distributed pumping. Mechanically, the beam pipe must maintain geometric continuity to avoid steps and misalignments that can cause impedance-related heating and local pressure rises.

The assumptions listed in Table 2 are used for the estimation of the required effective pumping speed of the beam pipe vacuum system.

The required effective pumping speed is estimated from the gas load according to

$$S_{\text{eff}} = \frac{Q}{p} \tag{2}$$

Total thermal outgassing load is

$$Q = q_A A = 1.3225{\times}10^{-9}\,\text{mbar}\,\text{l}\,\text{s}^{-1} \tag{3}$$

Using Eq. (2), the required eff. pumping speed becomes

$$S_{\text{eff}} = 1323\,\text{l}\,\text{s}^{-1} \tag{4}$$

The required number of pumping stations is estimated from

$$N = \frac{S_{\text{eff}}}{S_{\text{pump,eff}}} \tag{5}$$

The resulting number of pumping stations is N=7.

Table 2: Assumptions Used for the Vacuum Estimate

Parameter	**Value**
Beam pipe diameter d	200 mm
Inner surface area A	13 225 050.129 mm^2
Target pressure p	$1{\times}10^{-12}$ mbar
Specific outgassing rate q_A	$1{\times}10^{-14}$ mbar l s^{-1}cm^{-2}
Eff. pumping speed $S_{\text{pump,eff}}$	200 l s^{-1}

CONCLUSION

From a mechanical engineering perspective, the Figure-8 Storage Ring concept is technically feasible using current accelerator and cryogenic engineering practices. The focus has to be on the transition toward an integrated Technical Design Concept, including the mechanical support structure, superconducting magnet and cryostat integration, cryogenic and electrical infrastructure, ultra-high vacuum systems, and facility integration. Particular emphasis is placed on maintaining alignment stability, controlling thermal contraction effects, managing magnetic-force-induced loads, and minimizing vibration-induced motion. While the concept is considered technically feasible using established accelerator and cryogenic engineering technologies, several key challenges still need to be addressed, including subsystem integration, thermal and mechanical stability during operation, quench robustness, and long-term alignment preservation. In addition, the complete system including all infrastructure must fit within the strict installation envelope of 6 × 7m (see Fig. 2).

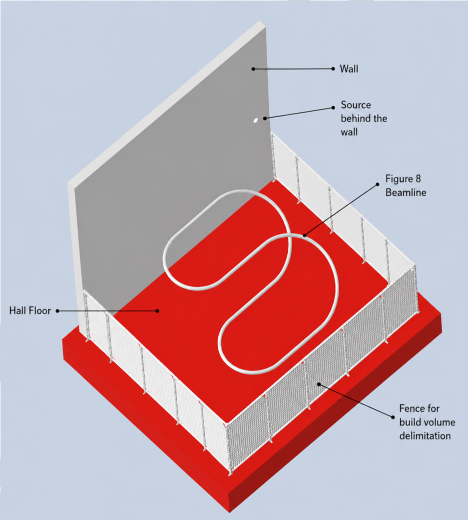

Figure 2: Layout of the beam transport line.

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