DESIGN AND FABRICATION OF FRIB HPECR PLASMA CHAMBER*

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Abstract

FRIB utilizes a 28-GHz HPECR ion source as the front-end device for generating high-intensity, high-charge-state ion beams. In the middle of the device is a plasma chamber, located within the ion source vacuum vessel and positioned inside the strong axial and radial magnetic fields required for ECR plasma confinement.

This paper presents the mechanical design, fabrication process, and performance of the current chamber. During initial fabrication, four sets of components were machined. Only one assembly achieved full functional success. Lessons learned including issues related to material deformation, cooling-channel integrity, and interference fitting, were incorporated into a refined fabrication process with higher success. Fabrication results for the improved design will be presented at the conference, including dimensional metrology, cooling and flow performance. Based on the demonstrated validity and robustness of the improved process, the design methodology is extrapolated to future plasma chambers capable of handling up to 10 kW of 28-GHz RF power. Such an upgrade will be required to enable FRIB's planned operational power ramp-up, ultimately contributing to the delivery of up to 400 kW primary beam power onto the Production Target.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) are under user operation with primary power gradually increased from 1 kW to 20 kW+ [1-3].

At the very beginning of the FRIB beamline is High Power Electron Cyclotron Resonance HPECR ion source [4-5]. The 28-GHz HPECR ion source produces high-intensity, high–charge-state beams for heavy-ion accelerator operations, which would set the beam current, quality and stability throughout FRIB accelerator facility. Reliability and availability at the ion source level translates directly into facility uptime and experimental outcome.

A critical subassembly of this device is the plasma chamber, which defines the ECR plasma boundary, provides thermal management, and mechanically interfaces the injection and extraction systems. Therefore, its mechanical /thermal design and fabrication quality directly influence plasma stability, beam quality, and source operational reliability

This paper summarizes the design requirements, fabrication challenges, and successful process refinements for the current <5 kW (RF power) plasma chamber design, as well as considerations for scaling toward a 10 kW (RF power) version.

MECHANICAL DESIGN

Space Constrain

Figure 1 shows FRIB HPECR ion source layout. Plasma chamber is constrained on the outer diameter to the superconducting magnet (three superconducting axial solenoid coils and one sextupole magnet composed of six radial coils, 165 mm warm bore of cryostat), and inner diameter (143.5 mm) to be big to have large plasma volume. The superconducting magnet is required of radial sextupole field at the plasma chamber radius of at least 2.0 T. Plasma chamber is supported from injection side and attached to extraction side with a bellow. Alignment tolerance is +/- 0.25 mm.

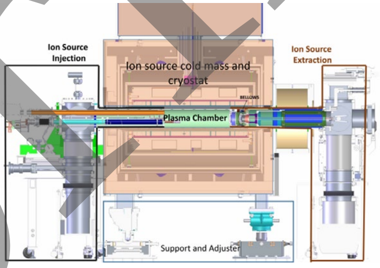

Figure 1: Layout of FRIB HPECR Ion Source

The space in between outer bore and inner diameter is a small gap to accommodate fabrication error, multilayer Kapton insulation foil rated for 30 kV X-Ray shielding, layer in between cooling water and air, cooling water layer, a wall between water cooling and vacuum space (plasma volume). The plasma chamber design requires balancing: wall thickness (conduction path/structural integrity) and cooling channel geometry (heat removal capacity/manufacturability):

- Larger wall thickness and smaller water channels: improves structural stiffness and dimensional stability; Increases thermal resistance, resulting in higher inner wall temperatures; higher water speed leading to higher conduction coefficient, but higher pressure drop; increase blockage risk
- Smaller wall thickness and larger water channels: enhances heat transfer to coolant; Increases susceptibility to deformation and channel instability; Improve flow capacity and reduce pressure drop; increasing fabrication risk

Vacuum Interface

FRIB plasma chamber has interface at both ends to be ConFlat CF type seal with copper gaskets with knife edge portion in Stainless Steel. This design allows ultra-high vacuum for plasma volume and requires high accuracy on

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the orientation of the effective cooling area relative to the 6 heating concentrated areas related to the sextuple magnet used for radial plasma confinement.

The plasma chamber doesn't have pump directly mounted on. Instead, it is pumped by nearby injection turbo pump (rated 1,500 L/s pumping speed) and extraction turbo pump (rated 2,000 L/s pumping speed). During last few years of FRIB operation, the vacuum level in this area can reach E-10 Torr range with no beam operation, and E-8 Torr with beam operation. Compared to O-ring seal design, the S.S. knife edge design has the disadvantages:

Difficulties connecting to plasma chamber material

- No adjustment of aligning effective cooling areas to heating concentrated areas
- ConFlat gasket is limited by ID of the Copper gasket. In area requiring larger bore, narrower Copper gasket is used (In this case, a normal OD and ID for 6” CF Copper gasket is 4.74” and 4.01”, while the narrow gasket's ID is 4.25” with the same OD)

Material Consideration

Aluminum alloys is used as plasma chamber main material from a deliberate engineering selection, which reflects a balance between thermal performance, manufacturability, reliability, and lifecycle cost under sustained high-power operation, also due to its high secondary electron emission which is favorable for best plasma performance.

Aluminum alloys (e.g., 6061, 5083) provide moderately high thermal conductivity (~150–200 W/m·K). While the conductivity is half the number of OFHC Copper, the cooling is sufficient when combined with effective cooling design: directly cooling channels; targeted cooling at hot spots (high power density spots); and high flow rates. Aluminum alloys offer advantages in machinability, weldability, cost and weight. Copper would require furnace brazing, while at the same time leads to higher diffusion.

Stainless steel knife edges and a bimetal (Stainless Steel to Aluminum) the flange is used at both ends. Mature product (Aluminum flange with a Stainless-Steel knife-edge seal) offers all-metal sealing and weld-up to aluminum chambers.

X-Ray Shielding Layer

Outside the plasma chamber is X ray shielding, which provides both heat load reduction to nearby superconducting magnet cryostat (increase superconducting magnet stability and cryogenic system efficiency) as well as minimize radiation exposure to surrounding area, so that it is accessible outside high voltage cage area during ion source operation. The shielding is in air side and uses High Z material due to its high mass attenuation coefficient even with compact thickness. Two options are used for two plasma chambers: 2 mm thickness 99%+ Tungsten solid tube in 5 segments; and 9 layers of 0.2 mm thickness Tantalum foils. During operation, the shield is an integrated part of the plasma chamber, while the shielding material can be taken away from one chamber to another if needed. The material cost for high-Z material increased greatly during last few years.

FABRICTION

Fabricating the HPECR plasma chamber is challenging because it combines thin-wall precision machining, leak-tight internal cooling circuits, and high-integrity aluminum welds in a geometry that must survive thermal cycling, magnetic constraints, and UHV requirements. The difficulty is not any single step—it's the coupling between machining tolerances, weld technology, and functional performance.

Interference Fitting

The plasma chamber cooling channels are formed using a shrink-fit (interference-fit) assembly between two concentric aluminum components:

- Inner tube machined with the cooling channel features
- Outer tube as the pressure boundary and structural enclosure

During assembly, the outer tube is heated (~220 °C), thermally expanded and installed over the inner tube. Upon cooling, the resulting interference creates: a mechanically locked interface; as small as possible cross-channel flow. Additional Aluminum welding on both ends afterwards. This approach minimizes weld exposure in critical cooling regions and preserves channel geometry. Our initial design has interference fitting of 0.010” (0.25 mm), while the planned expansion is 0.024” (0.61 mm). Unfortunately, due to out of circularity condition, the initial batch of assembly only achieved 1 functional chamber out of 4 sets of materials. Several improvements were applied, resulting in higher success rate

- Reduced interference to 0.003” (76 um)
- Better control of circularity for both tubes
- Higher power (2.5 kW) heater for higher temperature and fast temperature rise
- Dedicated fixture for the assembly process, Fig. 2

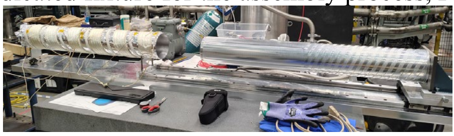

Figure 2: Assembly fixture and setup to insert inner tube into outer tube

For 1st try, actively cool inside tubing by dry ice or nitrogen was used. We expected to cool inside so that the clearance is larger, but the result was counter-productive in that the thin layer of ice formed due to cold temperature reduced the clearance, and as long as the inner tube and outer tube, the outer tube shrinks and got stuck. The following tries implement higher power heating without inner cooling, and all tries have been successful.

Welding Joints

Following the interference-fit assembly of the cooling channel structure, the next critical fabrication step is closure welding of the plasma chamber. On each axial end of the chamber, three circumferential aluminum-to-aluminum weld joints are required to establish the final pressure and vacuum boundaries. Figure 3 (a) shows the welding design at injection side, (b)/ (c) shows photos of the actual welding joints. These welds simultaneously define and isolate three distinct domains:

- Cooling water circuit (LCW)
- Vacuum region (plasma chamber volume)
- Ambient (air) environment

Because these domains operate under different pressure, cleanliness, and leak-rate requirements, each weld type imposes unique functional constraints.

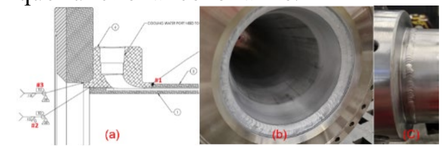

Figure 3: (a) the welding design at injection side, (b) and (c): photos of the actual welding joints.

The welding of the aluminum plasma chamber requires skilled operator control and process qualification through representative test welds to establish appropriate parameters, including heat input, travel speed, shielding gas flow, and joint preparation. Given the combined requirements of structural integrity and vacuum compatibility, parameter development was performed prior to production welding. The plasma chamber utilizes both:

- Fillet welds (for structural and sealing interfaces)
- Butt groove welds with partial penetration, where geometry and access constraints limit full-penetration configurations

The resulting welds exhibit a uniform “stacked-dime” appearance characteristic of stable GTAW (Gas Tungsten Arc Welding) / TIG (Tungsten Inert Gas) operation, indicating consistent heat input, controlled weld pool behavior and stable travel speed and filler deposition

Across all circumferential joints, the welds demonstrate high continuity and uniform bead profile and no visible defects such as: Arc stop/start marks; Crater cracking; underfill or excessive reinforcement.

This level of consistency is critical for:

- Maintaining leak-tight performance, particularly for vacuum and water-to-vacuum interfaces
- Minimizing stress concentration and distortion
- Ensuring repeatability across multiple fabricated units

The achieved weld quality confirms that, with proper parameter development and welder expertise, reliable aluminum welding can be achieved for complex, multi-boundary plasma chamber assemblies.

OPERATION STATUS

Initial operation of the Facility for Rare Isotope Beams HPECR ion source has relied on a single plasma chamber, with RF power constrained to mitigate thermal risk. To improve operational robustness and support progressive power ramp-up, two additional plasma chambers are under fabrication and qualification, providing critical redundancy and reducing downtime associated with component failure. In parallel, a next-generation micro-channel plasma chamber is being developed as the ultimate solution for high-power operation, enabling targeted heat removal at localized hot spots and extending the achievable RF power envelope.

Aluminum Alloy with Low Conductivity Water

FRIB ion source uses dedicated water skids to produce low conductive water (LCW) as cooling water. The LCW has requirements of 6 ± 1 MΩ-cm resistance, with < 100 ppb oxygen level and 5-micron filter size. There is concern of reaction between Aluminum Alloy and LCW, which the protective oxide layer would destabilize and lead to carrion & ion release. The Aluminum Alloy together with other metals can cause galvanization as mixed metal system are risky.

There are two plasma chambers (both in Aluminum 6061) for two ion sources under FRIB operation. We observed no performance deterioration (leak, blockage, etc.), one after 8 years, and other one after 5 years. Below control measures are used: control water pH tightly (typically ~6.8–7.2); minimize dissolved oxygen; avoid direct galvanic coupling to copper; and optimize water speed.

Future Improvement and Upgrade

Future improvement includes increase the water pressure to the plasma chamber only. Currently the water skids provide supply pressure of 80 psi and return pressure of 25 psi with current flowrate for each channel 2 GPM. If a booster is used, the supply pressure can be increased to 145 psi, which lead to the higher flow rate (estimate ~3 GPM) and provide better cooling.

A key upgrade path for extending the operational capability of the 28 GHz HPECR ion source at FRIB to higher RF power levels (10 kW) is the implementation of a micro-channel-cooled plasma chamber. The design strategy focuses on localized enhancement of heat removal precisely at the regions of maximum thermal loading. At the 6 highest heat power density spots, the effective cooling is improved, while the effective thickness (between vacuum space and water space) is larger. At the same time, this requires better control of orientation of the chamber geometry, and have better water requirements on particulate contamination.

The micro-channel plasma chamber represents a targeted, high-impact upgrade focused on the dominant thermal limitation of the current design. By concentrating enhanced cooling capability at precisely identified hot spot locations, the approach maximizes performance gain while managing fabrication complexity. This strategy provides a practical and scalable pathway toward higher power operation of the HPECR ion source.

SUMMARY

This paper presents an overview of design, and analysis of plasma chambers for FRIB 28 GHz HPECR ion source. The discussion also includes insights into their fabrication processes, operational performance and experience gained during commissioning and routine operation, as well as planned upgrades and improvements.

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