4

मेहिपा हेतु त्वरक संरचना अभियांत्रिकी अभिकल्पन एवं संबंधित विकास

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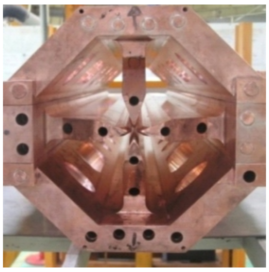
चतुर्ध्रुवीय रेडियो आवृत्ति (आरएफक्यू)

सारांश

यह शोध पत्र, मध्यम ऊर्जा उच्च तीव्रता प्रोटॉन त्वरक (मेहिपा) के लिए सामान्य प्रचालन एवं अति-चालकता आरएफ त्वरण गुहिकाओं के लिए किए गए ताप-संरचनात्मक,बहु-भौतिकी तथा गुहिका विकास से संबंधित अध्ययन प्रस्तुत करता है। उच्च ताप अभिवाह स्थितियों में आरएफ तापन, ताप विरूपण, शीतलन प्रदर्शन एवं आवृत्ति पृथक्करण का मूल्यांकन करने के लिए रेडियो आवृत्ति चतुर्ध्रुव (आरएफक्यू) एवं ड्रिफ्ट ट्यूब लिनॉक (डीटीएल) गुहिकाओं का ताप-यांत्रिक विश्लेषण किया गया है। अति-चालक एसएसआर-बी गुहिकाओं के लिए, लोरेंट्ज़ फोर्स डिट्यूनिंग (एलएफडी) और पतली उच्च-शुद्धता वाली नायोबियम संरचनाओं की यांत्रिक स्थिरता का मूल्यांकन करने के लिए युग्मित विद्युत चुम्बकीय-संरचनात्मक विश्लेषण किए गए हैं। विनिर्माण क्षमता, आयामी सटीकता एवं दोष नियंत्रण में सुधार के लिए नायोबियम घटकों के गठन हेतु गहन रेखाचित्रण प्रक्रिया अनुकरण भी किए गए हैं। शोध पत्र में, फर्मीलैब पीआईपी-II परियोजना हेतु विकसित गुहिका विकास, संविरचन पद्धति एवं एसएसआर-2 गुहिकाओं के प्रमुख निर्माण पहलुओं पर भी चर्चा की गई है।

4

Engineering Design and Related Development for MEHIPA Accelerating Structures

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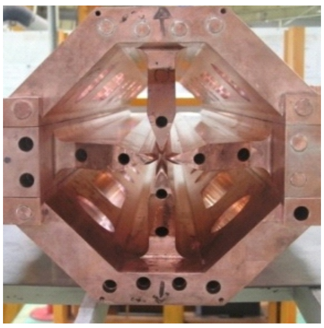
Radio frequency quadrupole (RFQ)

ABSTRACT

The MEHIPA Phase-I (40 MeV) accelerator comprises type of three accelerating structures: Radio Frequency Quadrupole (RFQ), Drift Tube Linac (DTL), and Superconducting Single-Spoke Resonator (SSR-B). Multiple finite element method (FEM)-based analyses are required to finalize their engineering design. The RFQ and DTL require detailed thermo-structural analyses to optimize cooling schemes and evaluate water-cooling-based RF control. The RFQ exhibits high thermal sensitivity, where ±1°C variation in inlet water temperature results in ±100 kHz de-tuning. A gradual water-flow increment scheme has been developed to support high-duty-cycle continuous-wave (CW) operation. For the DTL, three-dimensional computational fluid dynamics (CFD) analyses with conjugate heat transfer have been performed to assess drift tube cooling, while two-dimensional thermal analyses have been carried out for the DTL tank. The thin-walled SSR-B cavity requires coupled structural and electromagnetic optimization to determine material thickness and stiffener geometry while ensuring ASME Section VIII, Division 2 compliance. This paper outlines deep-drawing simulations and forming limit diagram (FLD) characterization for the novel spherical SSR-B design developed at BARC. It further discusses the cavity development, fabrication methodology, and key manufacturing aspects of SSR-2 cavities developed for the Fermilab PIP-II project.

KEYWORDS: *Medium Energy High Intensity Proton Accelerator (MEHIPA), Drift tube linac (DTL), Radio frequency quadrupole (RFQ), Lorentz Force Detuning (LFD)*

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Introduction

Proton beam acceleration in MEHIPA phase-I will be carried out using Normal Conducting RFQ (3 MeV), Alvarez-type DTL (10 MeV), and superconducting SSR-B cavities (40 MeV), operating at 325 MHz (3-D model shown in Fig.1).

RF power dissipation on cavity surfaces causes heating, thermal deformation, and RF detuning. Hence, thermo-structural design of RFQ and DTL cavities focuses on minimizing frequency shifts. Since RF losses are confined within the skin depth region (few microns), the heat load is treated as a surface phenomenon with peak value around 90 kW/m².

Single spoke resonators (SSR-B) for MEHIPA are dumbbell shaped cavities made up of thin sheet of high RRR Niobium. They are positioned subsequent to DTL (11MeV beam energy onwards) and operate at cryogenic temperature. Thin sheet construction enables compression based tuning; however makes cavity prone to deformation due to vacuum and Helium pressure and also to RF based (Lorentz force) detuning, which are addressed by multi-physics and structural analysis. Manufacturing of SSR cavities are done by deep drawing of niobium sheet, followed by electron beam welding of formed parts.

CDM, BARC has fabricated SSR-2 cavities for the Fermi lab PIP-II project as part of Indian institute and Fermilab collaboration (IIFC), which are discussed in later sections*.

RFQ Thermal Design and RF Detuning

Thermal analysis of 2-D element of RFQ cross section (1/8th symmetry model, Fig.2) has been done using FEM solver based on heat flux data obtained from RF heat dissipation simulation which is limited to skin depth of inner surface exposed to RF. Considering simplicity of calculation and conservative approach, heat generation is taken as surface phenomenon (heat flux). Thermal analysis assumes heat transfer coefficient obtained though correlation: $Nu=0.023Re^{0.8}Pr^{0.4}$. Temperature, obtained as result, is used to obtain thermal deformation. Complete details are available in Ref.1.

Thermal deformations in term of Δx and Δy are used in relation to get RF detuning

$\Delta f = \sum_{i=1}^{12}(\partial f/\partial x \, \Delta x + \partial f/\partial y \, \Delta y)$ where $\partial f/\partial x$ and $\partial f/\partial y$ are the RF sensitivity constants.

Detuning Control by LCW Temperature Variation

Baseline LCW inlet temperature for coolant channel H1/H2 is 16°C and for H3/H4, it is 20°C. Due to very high RF sensitivity, minor variation of 0.1°C alone is sufficient to detune

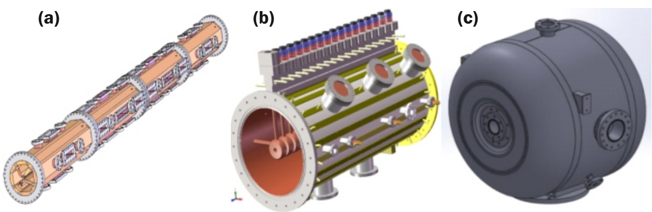


Fig.1: (a) Vane-type RFQ. (b) Alvarez Type DTL Segment. (c) Single Spoke Resonator.

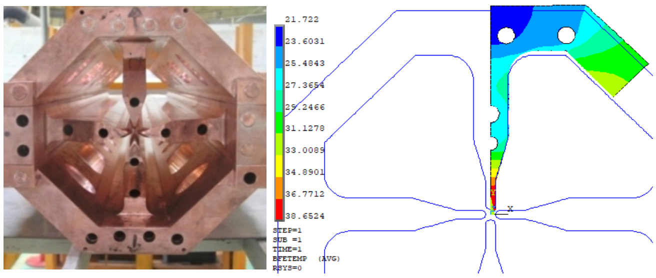


Fig.2: (a) RFQ (b)Temperature profile of 1/8th symmetry RFQ segment (°C).

the RFQ. Considering Q_L (loaded quality factor) around 3500, uncompensated small detuning of ±25kHz can result into RF power reduction by around~20% in the RFQ. Table-1 summarizes individual and combined effect of all coolant channels on RF detuning.

Detuning Control by LCW Flow Variation

When RFQ is operating at lower RF Duty Level (%SF), coolant channels can be supplied with the lower LCW flow instead of baseline 3.5 m/s. A possible regime (Fig.3) of flows was worked out. H1 being closest to the proton beam, it is better to initiate the cooling at the lowest possible SF. However, up to 0.1% SF, H1 channel supply results into appreciable detuning therefore cannot be switched ON. H4 having lower impact on detuning can be switched ON, however needs to have higher inlet temperature at 21°C. 1% SF onwards, full 3.5 m/s supply in H4 can be turned on and also very low supply in H1 can be initiated here. Up to 60% SF, there is hardly any need of any other coolant channel supply, while H1 supply is gradually ramped up. At 60% SF, H2 supply needs to be switched ON. At 150% SF, H3 supply becomes necessary to reduce the temperature.

DTL Thermal design and RF Detuning

Thermal analysis of DTs and the DTL tank was performed to ensure effective cooling. DTs are usually analyzed using computational fluid dynamics (CFD) technique with conjugate heat transfer (Navier-Stokes equation, energy equation and turbulent model equation), while the DTL tank can be conveniently evaluated using 2D correlations (dittus-bolter equation).

Cooling scheme: The cooling scheme provides directional flow in drift tubes (DTs), where water enters through the outer 0 annular passage in the stem (Fig.4), circulates to achieve 360 cooling of RF-exposed surfaces, and exits through an inner return pipe. For the DTL tank, cooling is achieved using straight, open rectangular channels running longitudinally from one end to the other.

Table 1: Inlet Water (LCW) temperature vs RF

RFQ Channels (ø10mm)	dF/dT_inlet (kHz/±1°C)	dF/dT_inlet (kHz/±0.1°C)
H1	-55.5	-5.55
H2	-46.4	-4.64
H3	14.14	1.41
H4	84.57	8.45
RF DetuningdF for in-phase temperature variation →		-0.31kHz/±0.1°C
RF DetuningdF,Worst case scenario →		-20.06kHz/±0.1°C
Total available water tuning range →		-101 to 98kHz/±0.1°C

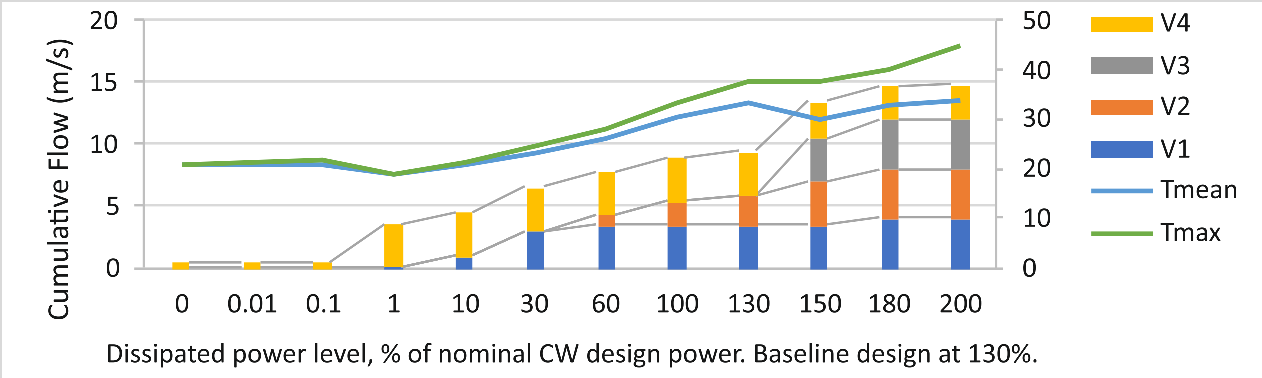


Fig.3: RFQ LCW flow (H1-H4) & T_{mean}/T_{max} (°C) for Various RF power level.

In MEHIPA DTL, DTs see peak heat flux ~91 kW/m² (2.4–3.9 kW per DT), and the tank ~32 kW/m². The cooling estimation assumes LCW inlet temperature of 20°C, and inlet velocity of 2m/s for DT and 3m/s for DTL tank (to avoid material erosion). The cooling design maintains temperatures well below 100°C to avoid boiling and limit thermal deformation (complete details in Table-2), with PMQ casing temperature restricted much below 60°C (to avoid demagnetization). Total RF-induced detuning estimates guide tuner range and mechanical offset requirements which, in terms of RF detuning, should be within few 10s of kHz.

Dynamic control of RF detuning: Inlet fluctuation within ±0.2°C with DTL tank sensitivity of around -8kHz/ °C keeps frequency variation within bandwidth. Complete details are available in Ref.2

Table 2: Cooling requirement of DTL for RF detuning

	Design parameters/Constraints	Requirements/Permissible Range
1.	Maximum temperature	a. <100°C, to avoid boiling of cooling water b. To be minimized for better electrical conductivity and lower RF detuning
2.	Maximum temperature (Magnet)	<60°C, to avoid de-magnetization of PMQ
3.	Maximum temperature variation	<10 °C, to avoid differential thermal deflection of DTs
4.	Thermal deflection (DT center)	a. <50 µm w.r.t. tank centerline b. <50 µm w.r.t mean DT center position c. To be minimized to check RF detuning
5.	Pressure drop	a. <differential static head available b. Should satisfy velocity constraint
6.	Water flow velocity	a. <2-2.5m/s (copper) b. <6-7m/s(steel)
7.	Inlet water temperature range	19-22.5°C

Fig.5 illustrutes maximum and average temperature of a DT with variation in water inlet velocity and variation of LCW inlet flow velocity to maintain constant RF detuning at varying duty factor.

SSR Structural, Multi-physics and Process/Deep Drawing Design

The structural, multi-physics, and process design of the SSR cavity plays a crucial role in achieving stable RF performance and manufacturability. Detailed analyses were carried out to optimize cavity stiffness, thermal behavior, RF characteristics, and deep drawing feasibility while ensuring compliance with stringent accelerator requirements.

SSR Structural Design

A set of analyses towards ensuring structural integrity were done and qualified as ASME, VIII-2. This included MAWP, local plastic failure, buckling, weld joint safety, and von-misses qualification are shown below in Fig.7, Table-4 & Table-5. Among the evaluated cases, the condition corresponding to 2bar external pressure at room temperature is identified as the more critical.

Stress-linearization

Maximum von-Mises stress at maximum stress locations breaches allowable stress (42.5MPa). Stress linearization technique is utilized to qualify those locations. The breakup of membrane, bending and peak stress along stress concentration line (SCLs) at maximum equivalent stress

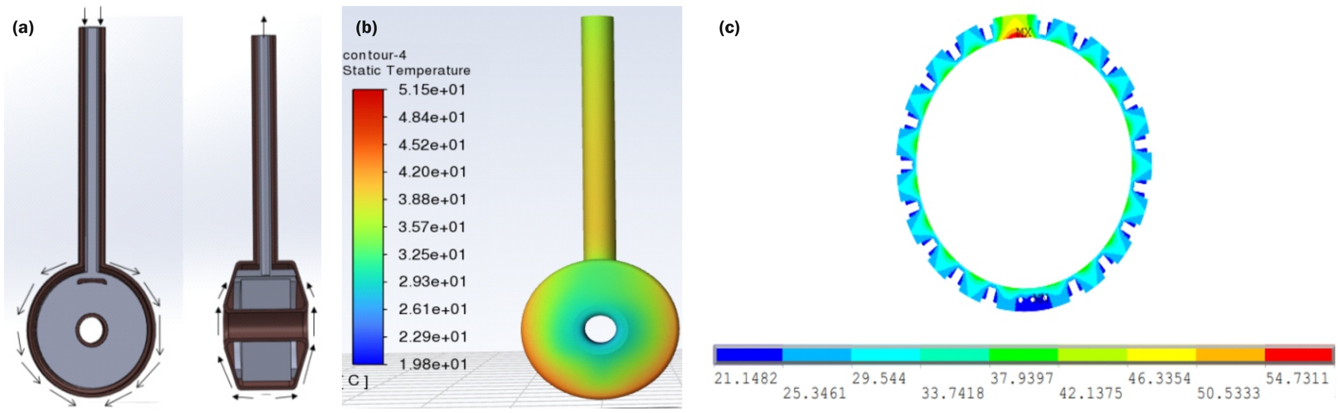


Fig.4: (a) DT LCW Flow (b) DT Temperature (c) DTL Tank Temperature.

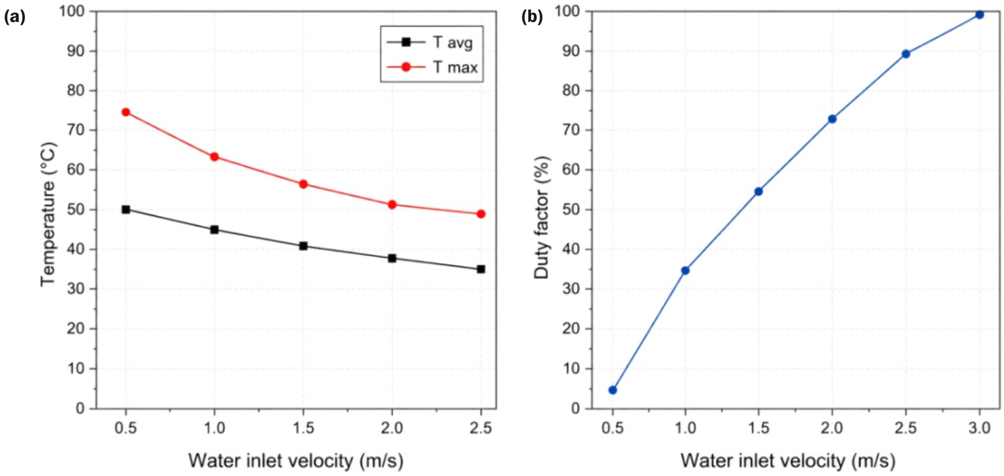


Fig.5: (a) DT Temperature vs LCW Inlet flow. (b) DT LCW flow change required to maintain the RF Detuning.

Table 3: Summary SSR-B design.

		Design Parameter	Target Value	Achieved
Operational Requirements	1	Stiffness of Cavity (kN/mm)	<35	10
	2	LFD No., Hz/(MV/m)^2	<-4.5	-4.38
	3	Course Frequency Tuning Range (kHz)	>135	~200
	4	Tuning Sensitivity (kHz/mm)	> 250	472.4
	5	Max von-Mises Stress (MPa)	<42.5(S)	>42.5*
	6	RF Detuning vsCryogenic Pressure Variations, - (Hz/mbar)	<25	6.5
Safety Requirements. Qualification:ASME SectionVIII, Div-2	7	Maximum Allowable Working Pressure, MAWP (bar)	2.05 (RT)/4.1	4.93/21
	8	Buckling Pressure (bar)	> 4.1	24
	9	Protection against Local plastic failure	-	Safe
	10	Weld joint safety	σ_{eq} < S.Ė	Qualified
Process/ Forming Analysis	11	Thinning	<15%	25%
	12	Tearing	None	None
	13	No. of forming stages	≤3	2

location has been shown in Fig.8. The results confirm that the selected wall thickness of 3.25 mm provides an optimal structural integrity.

SSR Multi-physics Studies

In normal conducting DTL/RFQ structures, RF behavior is primarily governed by geometry, with negligible feedback from electromagnetic forces due to high structural stiffness, resulting in essentially one-way coupling (structure ⟶ RF). In contrast, SSR cavities exhibit strong two-way RF–structural coupling, where Lorentz forces, along with Helium pressure, can deform the thin-walled niobium structure and significantly shift the resonance frequency. Therefore, multi-physics analysis is required for SSR to accurately capture this interaction and predict detuning behavior, ensuring stable RF performance and reliable operation. The LFD coefficient (k) is

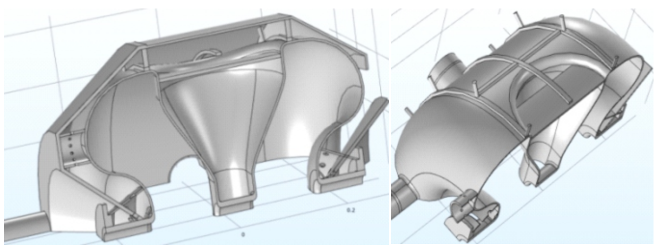


Fig.6: SSR jacketed cavity and Bare Cavity (1/4th symmetry

given by $\Delta f = kE_{acc}^2$ where E_{acc} is accelerating gradient field and Δf is frequency shift (derived from relation $\frac{\Delta f}{f} = \frac{\int_{\Delta v}(\mu_0 \vec{H}^2 - \varepsilon_0 \vec{E}^2)dv}{\int_v(\mu_0 \vec{H}^2 - \varepsilon_0 \vec{E}^2)dv}$). V represents the complete volume of the cavity and ΔV represents the volume inside the cavity where the deformation

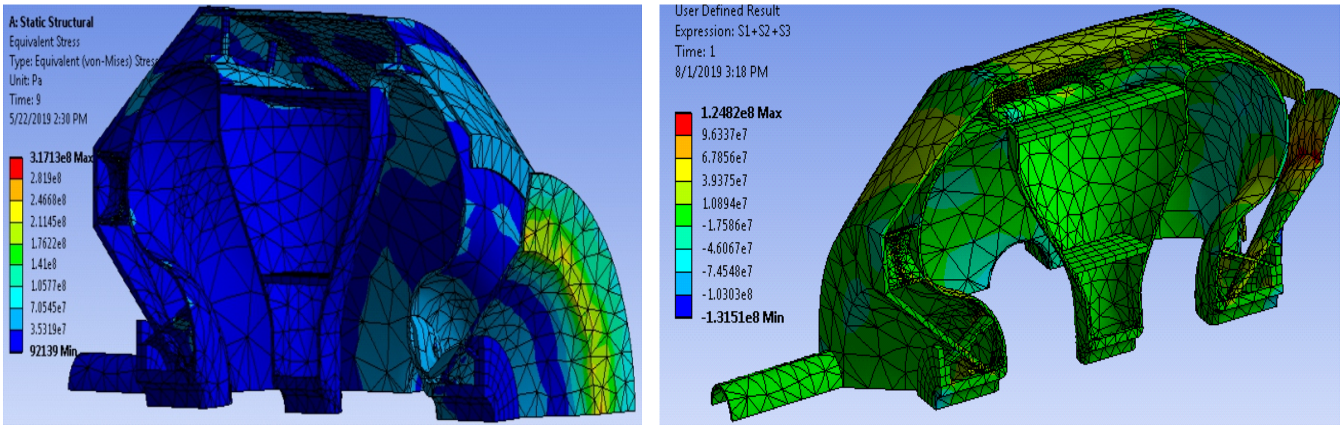


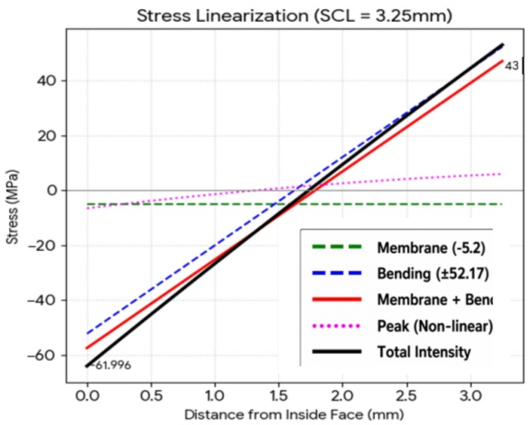
Fig.7: Von-Mises eq. stress at Critical Pressure-MAWP. Sum of principle stress (S1+S2+S3) plot for local plastic failure.

Table 4: MAWP, ASME Qualification.

Load Case->	1	2	3	4
Loads->	P+D	P+D+T1	P+D+T2	P+D+T1+T2
Temperature (K)	293	293	2	2
Pr_c (Collapse Pr in bar)	7.4	10.3	28	28
MAWP = Pr_c /1.5 for RT and Pr_c/1.3 for 2K	4.93	6.8	21	21
Min MAWP Required	2.05	2.05	4.1	4.1
Safe on ASME Criterion?	Safe	Safe	Safe	Safe

Table 5: Local Plastic Failure, ASME Qualification.

Load Case ->	1	2	3	4
Loads->	P+D	P+D+T1	P+D	P+D+T1
Temperature (K)	293	293	2	2
P (bar)	2.05	2.05	4.1	4.1
S1+S2+S3 (MPa, Max, including Peak Stress) at RT/2K	96.31/124.78	96.33/124.8	192.63/249.5	192.67/249
4S	170/392	170/392	682/1274	682/1274
Safe on ASME Criterion?	Safe	Safe	Safe	Safe



Stress type	Allowable limit	Value achieved
Membrane stress, σ_m	≤S (42.5MPa)	-5.2MPa
Bending stress, σ_b	≤1.5S (64MPa)	±52.1MPa
$\sigma_m + \sigma_b$	≤1.5S	-55MPa, 48MPa
$\sigma_m + \sigma_b + \sigma_p$ σ_p = Peak stress	≤2S (85MPa)	-61MPa, 43MPa

S : Allowable Stress.*

Fig.8: Linearized stress intensity plot over stress concentration line (SCL) at maximum stress value location and linearized max stress intensity values.

(Fig.9) has occurred. Detailed multi-physics analysis has been carried out to quantify both Lorentz Force Detuning (LFD) coefficient *k* and helium pressure sensitivity $\partial f/\partial p$ which are critical parameters governing frequency stability in superconducting RF operation. For the finalized geometry with a niobium wall thickness of 3.25 mm, an optimized stiffener configuration has been implemented to enhance structural rigidity. This design achieves a Lorentz force detuning coefficient of −4.38 Hz/(MV/m)^2 and a helium pressure sensitivity of −6.5 Hz/mbar, indicating controlled frequency shifts under field and pressure variations (Ref.3).

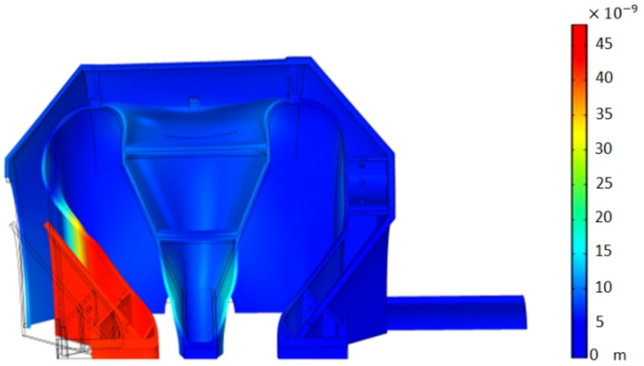


Fig.9: Displacement profile of SSR-B cavity due to Lorentz.

Deep Drawing Structural Studies for SSR end-wall

SSR cavity design emphasizes manufacturability and mechanical stability, particularly in niobium sheet metal forming and structural performance under vacuum and helium pressure loads. Process optimization is essential to control thinning and ensure consistent quality. Thinning in SSR cavity forming must be minimized to maintain structural stiffness, ensuring resistance to vacuum and helium pressure loads while reducing detuning effects. It also improves manufacturing quality, weld integrity, surface finish, and optimizes costly niobium material utilization. Most important part of SSR is end-wall in which quality control over deep drawing process is challenging. To minimize wastage in high RRR Nb consumption for projects such as MEHIPA, it is essential to minimize thinning.

FLD (Forming Limit Diagram) is used to predict failure or excessive thinning and was obtained through the Nakajima Test (test sample in Fig.10). As a prototype study, the FLD for ETP copper has been generated and used for the FEM analysis of the cavity end-wall. Fig.11 shows the FLD for both single-stage and double stage deep drawing analysis.

Lankford coefficients, given by $r = \frac{\varepsilon_{width}}{\varepsilon_{thickness}}$, are required to know anisotropic behaviour of material obtained through tensile test. r_0, r_{45}, and r_{90} are different 'r' values at 0°, 45° and 90° to the rolling directions. For high RRR niobium, r_0~1.66; r_{45}~1; r_{90}~2.3 Ref.4

a. Planar anisotropy, $\Delta r = \frac{r_0 - 2r_{45} + r_{90}}{2}$, *~0.98 for high RRR Nb*

b. Normal anisotropy, $\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4}$, *~1.49 for high RRR Nb*

Optimization of deep-drawing parameters and multi-staging of forming process are employed to get the desired

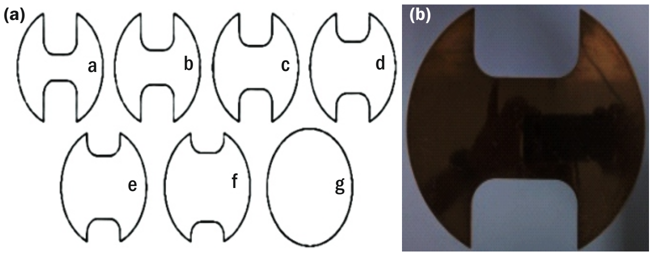


Fig.10: (a) Different test specimen used for Nakajima test. (b) Typical Nakajima Test Sample.

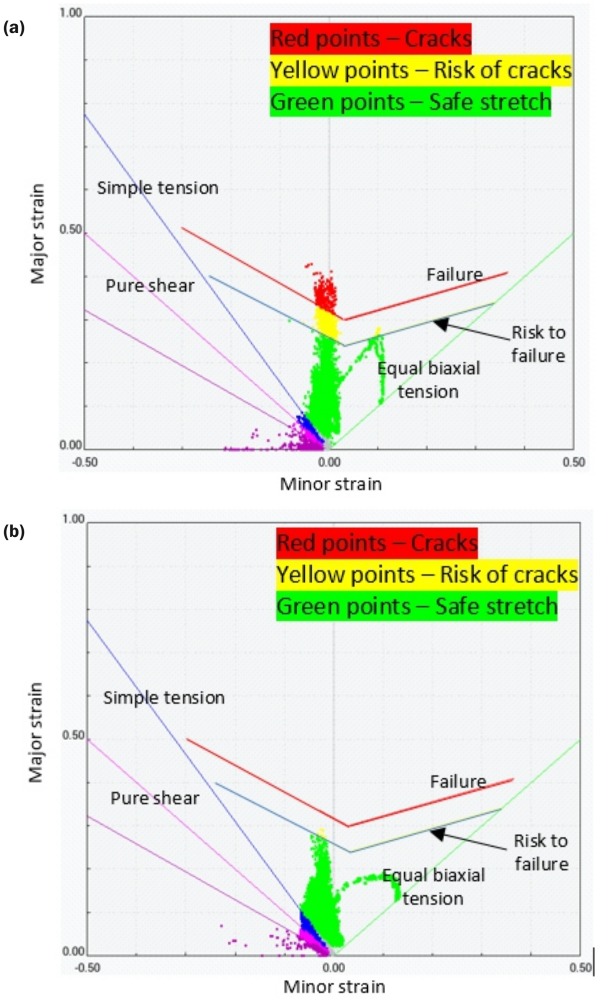


Fig.11: SSR end-wall FLD plot for (a) single-stage (b) 2-stage

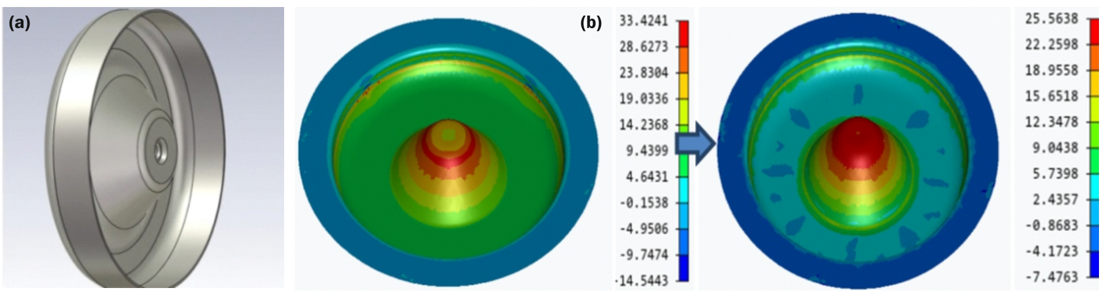


Fig.12: (a) SSR end-wall. (b) Its thinning %, Single stage vs Two-stage deep

Fig.13: (a) Spoke Collar. (b) End-wall.

outcome. Reduction in maximum thinning from 33% to 25%, achieved by increasing the number of forming stages from one to two, is illustrated in Fig.12. Further, it can be reduced up to 10-15% range by further optimization of parameters such as blank size, friction etc.

Fabrication of SSR Cavities

As part of the Indian Institutes and FermiLab Collaboration (IIFC), the Department of Atomic Energy (DAE) is fabricating Spoke cavities designated as SSR-2 as an in-kind contribution for the PIP-II accelerator at Fermilab, USA. The fabrication expertise and process knowledge gained through this collaboration is being leveraged for the indigenous development of SSR cavities for Indian accelerator programs, including MEHIPA Phase-1. The key fabrication methodologies and processes involved in the development of SSR-2 cavities are detailed in this section.

Overview

The SSR2 bare cavity is a superconducting radio-frequency (SRF) accelerating structure developed for the PIP-II project. Operating at 325 MHz, these high-purity niobium cavities are designed to accelerate ions across the 35–185 MeV energy range within seven cryomodules. The cavity is optimized for a velocity factor of β_opt = 0.472 and operates in Continuous Wave (CW) mode at 2.0 K in super fluid helium. The mechanical design emphasizes stability against microphonics and helium pressure fluctuations, with specified longitudinal stiffness below 16 kN/mm and tuning sensitivity below 250 kHz/mm. Comprehensive manufacturing, assembly, and quality assurance procedures for the SSR2 cavities were developed at the Centre for Design and Manufacturing (CDM), BARC. Owing to the stringent performance requirements of superconducting linear accelerators, the cavities demand extremely high precision during forming, machining, cleaning, and electron beam welding. The fabrication process is carried out in two stages: development of the ultra-high-purity niobium bare cavity, followed by integration with the helium vessel to form the jacketed cavity assembly.

The Bare Cavity Fabrication

The performance of the SSR-2 cavity critically depends on the integrity of its raw material and fabrication processes. The cavity is manufactured from high-purity niobium (RRR > 300), which is highly sensitive to contamination and mechanical damage. Accordingly, stringent handling procedures are implemented throughout fabrication to prevent surface defects and cross-contamination. The complex spoke and end-wall geometries (Fig.13) are produced through precision deep drawing using specially developed tooling. Subsequently, all formed components are finish-machined on advanced CNC systems to achieve tight dimensional tolerances and precise fit-up for the Electron Beam Welding (EBW) process.

The bare cavity represents the electromagnetic heart of the system. Niobium readily reacts with oxygen, nitrogen, and hydrogen at elevated temperatures, all primary structural and RF-surface welds is performed in a high-vacuum EBW chamber. Components undergo chemical etching i.e., Buffered Chemical Polishing (BCP) and ultrasonic cleaning before entering the vacuum chamber. The welding parameters (beam current, focus, speed, etc) are developed to ensure full penetration while explicitly preventing anomalies on RF side of welds, which can trap chemical residues and degrade RF performance. The assembly progresses from rolled components seam weld, sub-components weld to form the sub-assemblies & final welds of the sub-assemblies to close the bare cavity (Fig.14).

During the manufacturing of the bare cavity (Fig.15), Visual, Dimensional & CMM inspection are carried out. Radiographic and Ultrasonic Testing are done wherever required. Final bare cavity is qualified to ensure helium leak rate of 1×10^{-10} mbar. l/s. Room temperature RF measurements are conducted which also involves controlled mechanical deformations (inelastic tuning) of the cavity to ensure the cavity meets the required frequency profile.

Helium Vessel Jacketing (Dressing) of Cavity

The SSR-2 niobium cavity operates in a superconducting state by immersion in liquid helium. For this, the bare cavity is enclosed within a titanium Grade-2 helium jacket. The jacket assembly and cavity integration are carried out using precision TIG welding of formed and machined titanium components. During welding, RF pickups, oxygen monitors, and temperature sensors are used to continuously monitor cavity health and avoid RF degradation. The completed jacketed cavity is qualified through pressure and leak testing of the annular

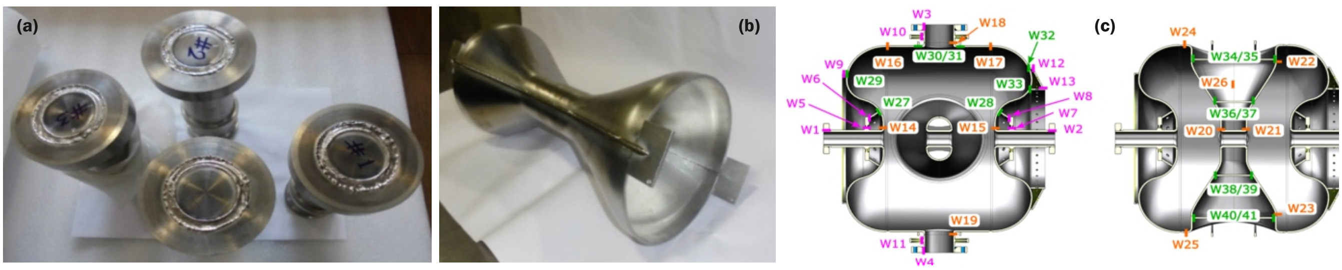


Fig.14: (a) Beam Pipe Sub-assembly. (b) Spoke Sub-assembly. (c) Cross Section View of 3-D CAD Showing All EB Welds.

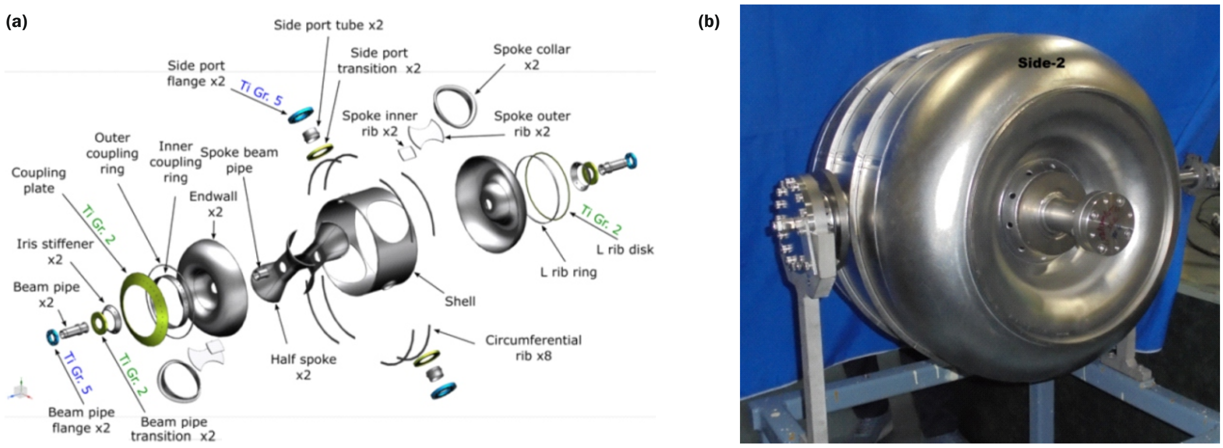


Fig.15: (a) SSR2 Bare Cavity Exploded View. (b) SSR2 Bare Cavity.

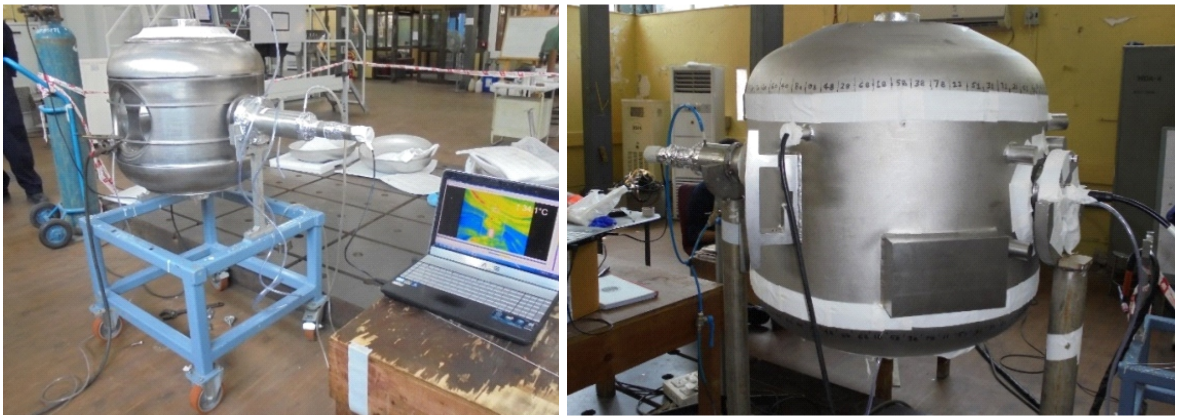


Fig.16: Bare Cavity preparation for Jacketing and Jacketing of Bare Cavity.

space (Fig.16). Comprehensive fabrication, weld, and inspection records are maintained to ensure traceability and manufacturing compliance.

Conclusions

This paper presents comprehensive thermo-structural, multi-physics, and cavity development studies carried out for the MEHIPA-Phase1 accelerator program. Thermal and RF detuning analyses of the RFQ and DTL established that precise control of LCW inlet temperature and flow rates is key to maintaining frequency stability. For SSR-B cavities, coupled electromagnetic-structural analyses achieved a Lorentz Force Detuning coefficient of −4.38 Hz/(MV/m)^2 and helium pressure sensitivity of −6.5 Hz/mbar, both within target specifications, with full structural qualification under ASME Section VIII, Div-2. Deep drawing process simulations demonstrated that two-stage forming significantly reduces niobium thinning, improving material utilization. The fabrication experience gained through the IIFC collaboration on SSR-2 cavities for Fermilab's PIP-II project has proven immensely valuable, directly strengthening India's indigenous capability in accelerator cavity development.

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