Development of Quarter Wave and Spoke Resonators at Inter University Accelerator Centre

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Outline

- TEM Class Niobium Resonators
- Development of Quarter Wave Resonators for the IUAC Superconducting Linac
- Development of Prototype Low Beta Resonator for the High Current Injector Project
- Development of Single Spoke Resonator SSR1 for Fermilab
- Conclusion

TEM Class Niobium Resonators

SC Cavities - Classification

Superconducting Accelerating Cavities

- Those operating in Transverse Magnetic (TM) mode: they are usually elliptical in shape, with several cells in a single structure. Generally referred to as “Cavities”, they are used for accelerating electrons, protons etc. which are moving at high speeds.
- Those operating in Transverse Electric & Magnetic (TEM) mode: they are usually cylindrical in shape with one or more conducting elements in them. Generally referred to as “Resonators”, they are used for accelerating heavy ions or slow moving protons.

TM & TEM Class Comparison

- TM class cavities are utilized for β >0.5
- They are designed to operate at hundreds of MHz (0.65-1.3 GHz)
- They operate at 2K.

- TM class cavities generally have lower peak magnetic field.
- They have generally large apertures.

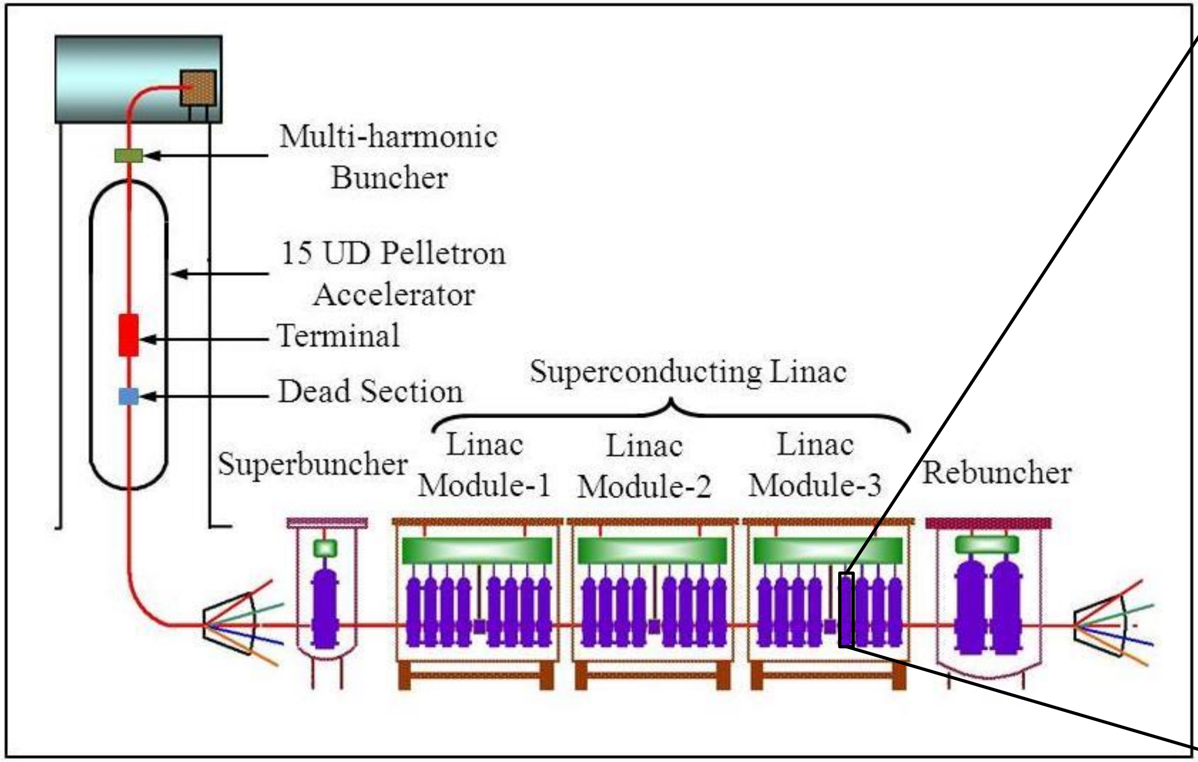
- TEM class resonators are utilized for β <0.5
- They are (generally) designed to operate at around 100-150 MHz
- They (generally) operate at 4K.
- TEM class resonators exhibit higher shunt impedance.
- They do not have large apertures.

This talk will be restricted to TEM Class Resonators only.

QWRs for the IUAC Superconducting LINAC

Superconducting LINAC at IUAC

At the heart of the Superconducting LINAC at IUAC is a Niobium Quarter Wave Resonator (QWR) that accelerates the ion beam to high energies. The QWR operates at 97 MHz frequency.



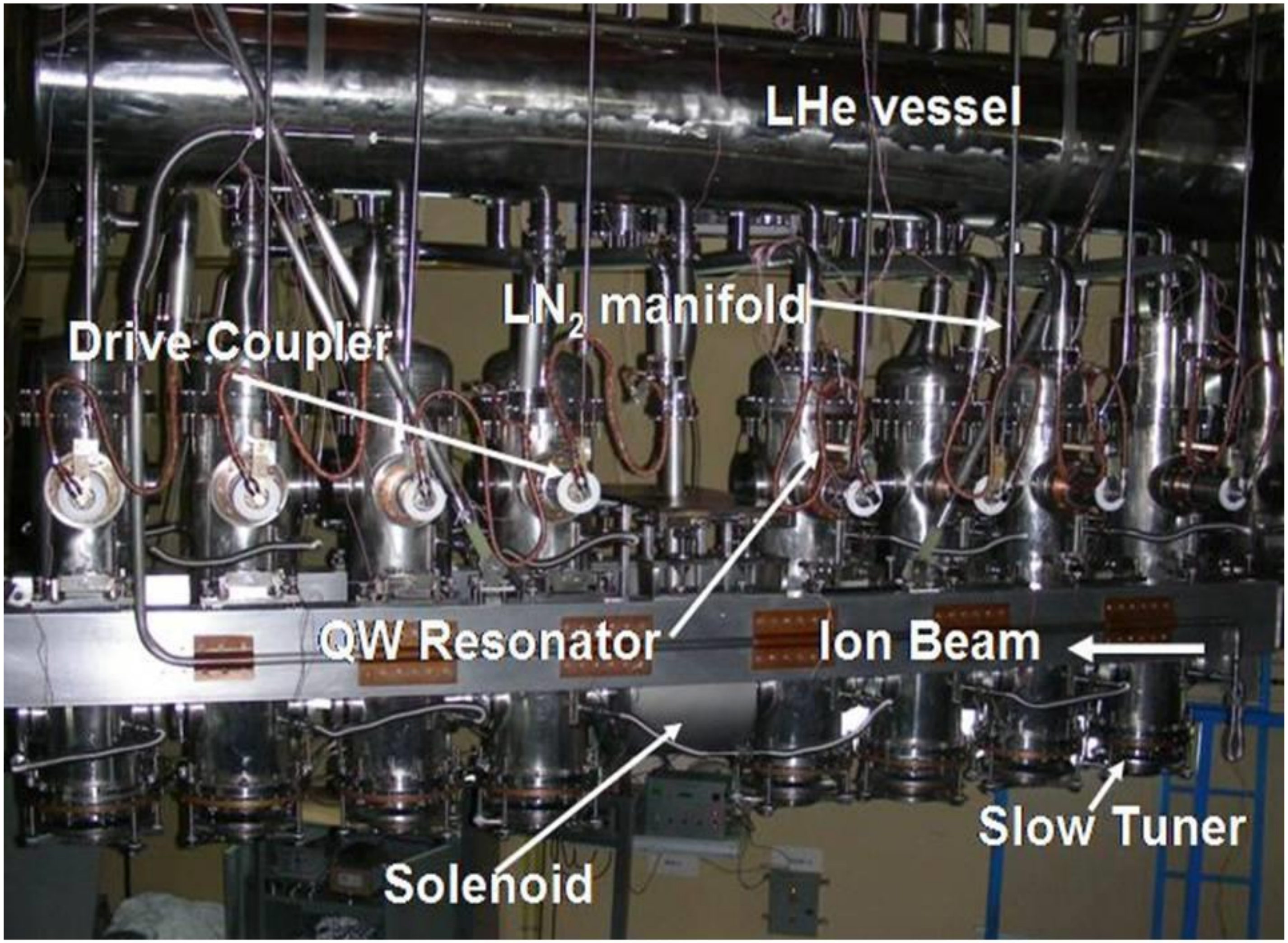
15 UD Tandem Pelletron Accelerator and Superconducting Linear Accelerator (SC LINAC)

Quarter Wave Resonator: β=0.08; the operating temp. is 4.2 K

SC LINAC Modules

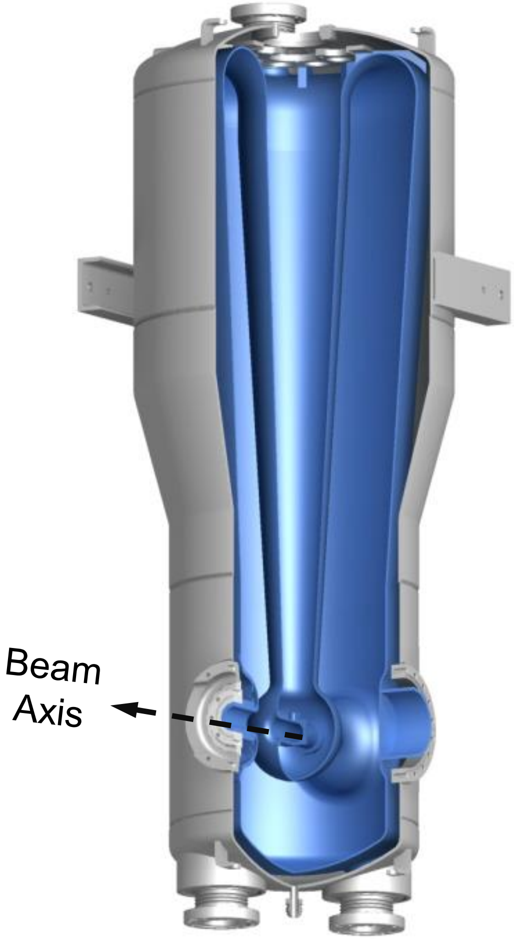
The Superconducting LINAC at IUAC. It has been in operation for the past several years and experiments are being done regularly using this facility.

LINAC Module: Inside



The inside of a LINAC Cryomodule at IUAC. Each Module has eight QWRs and a superconducting solenoid magnet to focus the ion beams.

Quarter Wave Resonator

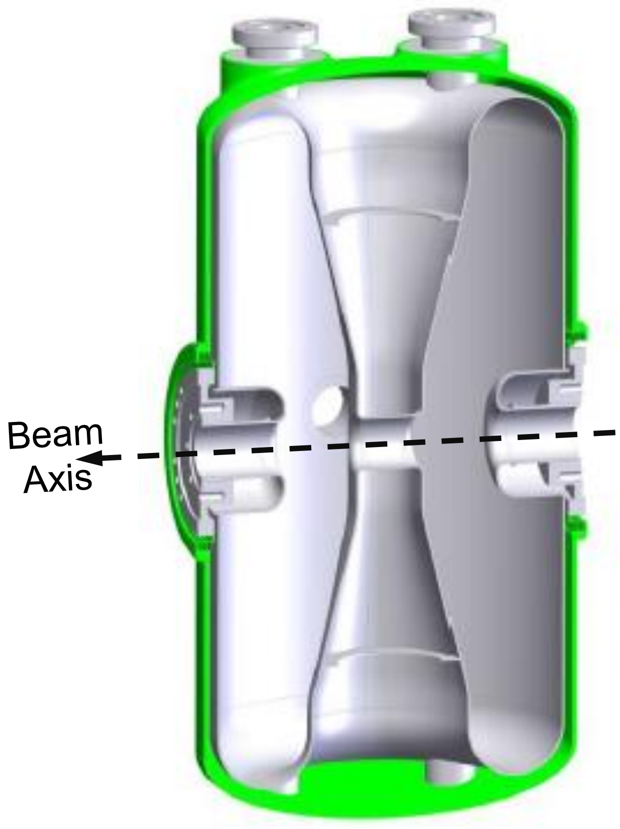


A typical Quarter Wave Resonator

Advantages of QWR

- Being a 2-gap structure, it has a wide range of velocity acceptance. This means that one design may be sufficient to accelerate several different ion species.
- Higher gradients achievable (in general) as compared to HWRs.
- Lower stored energy.
- Simple structure to build and operate (as compared to an HWR, or an SLR).
- Low cost of construction.

Quarter Wave Resonator



A Half Wave Resonator

Disadvantages of QWR

- Energy gain per individual unit is smaller compared to say, a three-gap HWR or SLR.
- This means that more number of resonators are required to reach the design beam energy.
- It is not a symmetric structure, unlike a two gap HWR whose central conductor is shorted at both ends.
- Prone to mechanical vibrations.

IUAC QWR

$f = 97$ MHz

β (= v/c) = 0.08

@ $E_{acc} = 1$ MV/m

$U_0 = 0.110$ J

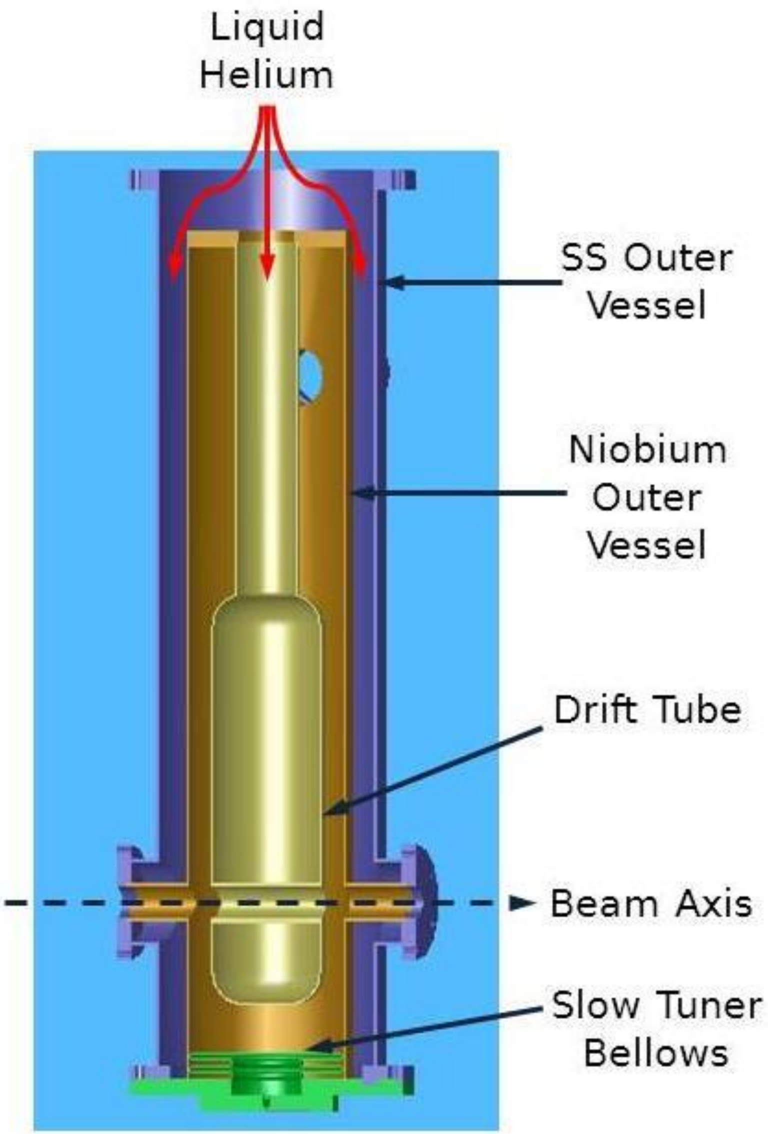
$E_P = 3.9$ MV/m

$B_P = 131$ G

$L_{eff} \approx 16$ cm

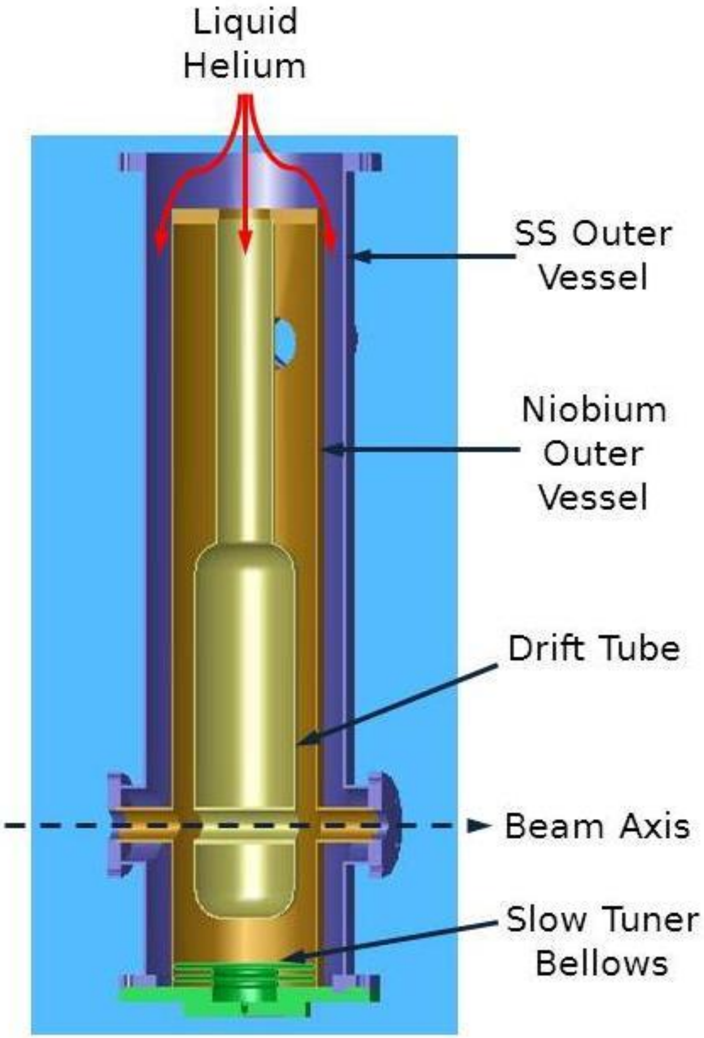
$QR_s = 17.3$

Parameters of IUAC QWR



IUAC QWR – Design Features

- Heavy capacitive loading to foreshorten the Central Conductor. The idea was to:
  - shorten the resonator length to accommodate it in the Beam Hall.
  - increase its mechanical frequency to reduce microphonic pickup.
- First design in the world to have a niobium cavity jacketed by an outer stainless steel vessel. This design has now become almost universal.
- Niobium slow tuner bellows at the open-end of the resonator for frequency tuning. Initial version had gas based tuning system. Presently the bellows are moved using a Piezo.



IUAC QWR

SRF Infrastructure at IUAC

- Collaboration with Argonne National Laboratory, USA in early ‘90s to design and develop a prototype Niobium Quarter Wave Resonator for IUAC Linac*.
- IUAC decides to set up its own SRF infrastructure around 1998-99 to build Superconducting Niobium Resonators indigenously for its Linac project.
- IUAC becomes the first laboratory in India to commission in early ‘2002** the SRF infrastructure required for indigenously constructing superconducting niobium cavities.
- Since then several different cavity designs have been successfully developed, designed and built using this infrastructure.

*K.W. Shepard, A. Roy & Prakash N. Potukuchi, Proc. of 1997 Particle Accelerator Conference, May 12-16, 1997, Vancouver, B.C., Canada

**Prakash N. Potukuchi, Invited Talk in Proc. of 14th International Conference on RF Superconductivity SRF2009, Sept. 20-25, 2009, Berlin, Germany

SRF Infrastructure at IUAC

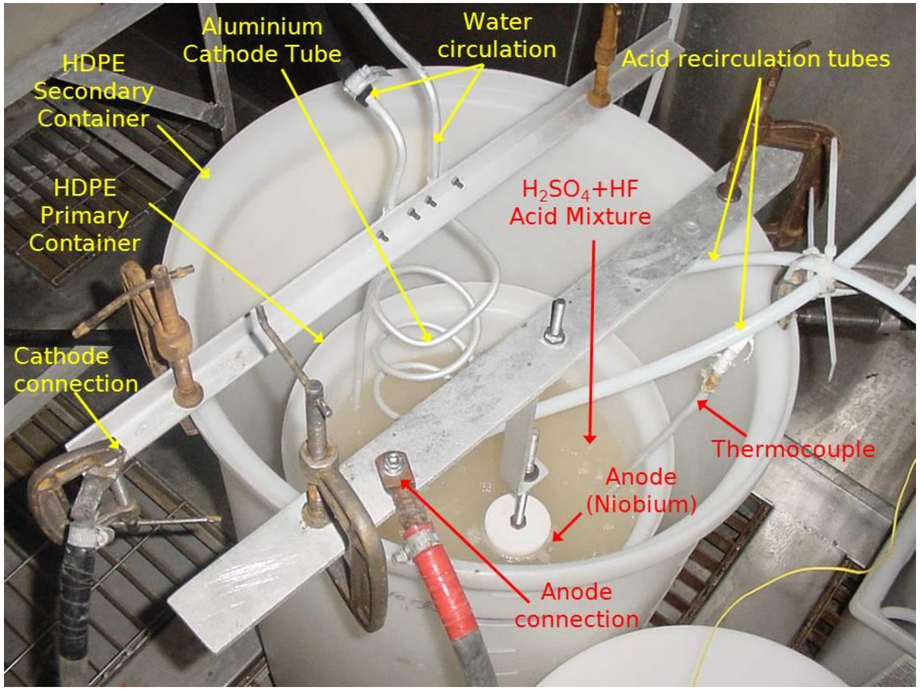
Electron Beam Welding facility

Bottom Loading type
High Vacuum Furnace (HVF)

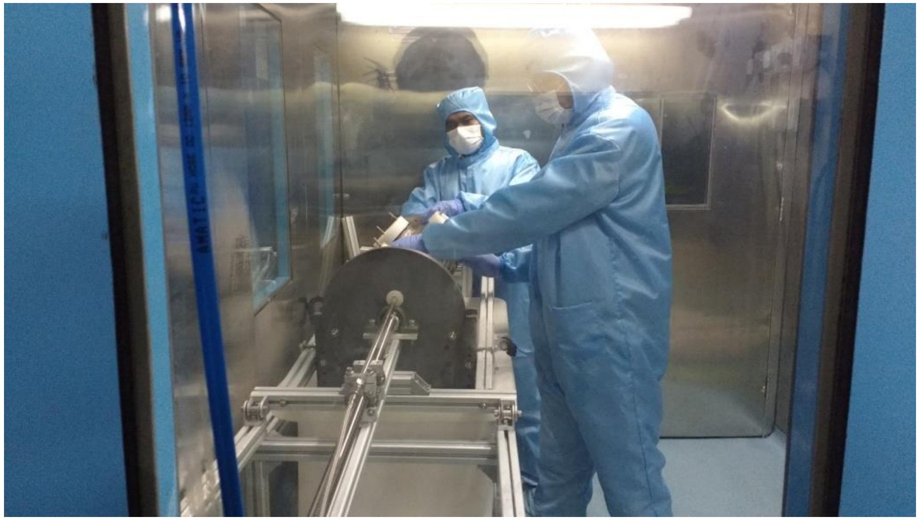
Beam Power: 15 KW; Voltage: 60 KV, Current: 150 mA
Chamber Size: 1 m × 1 m × 2.5 m
Pumping: 2 × 8000 l/s DPs with water cooled Baffles
Welding Pressure $\leq 5 \times 10^{-5}$ mbar
Control: CNC with PC & Touch Screen

Max Temp.: 1300 °C
Chamber Vacuum: 5×10^{-6} mbar
Chamber Size: Φ0.6 m × 1 m
Control: SCADA & PC
RGA installed: 1-100 amu

SRF Infrastructure at IUAC



Electropolishing in progress in the Surface Preparation Laboratory



High Pressure Rinsing (HPR) facility installed in a Class-100 Clean Room; photograph shows HPR of a QWR in progress.

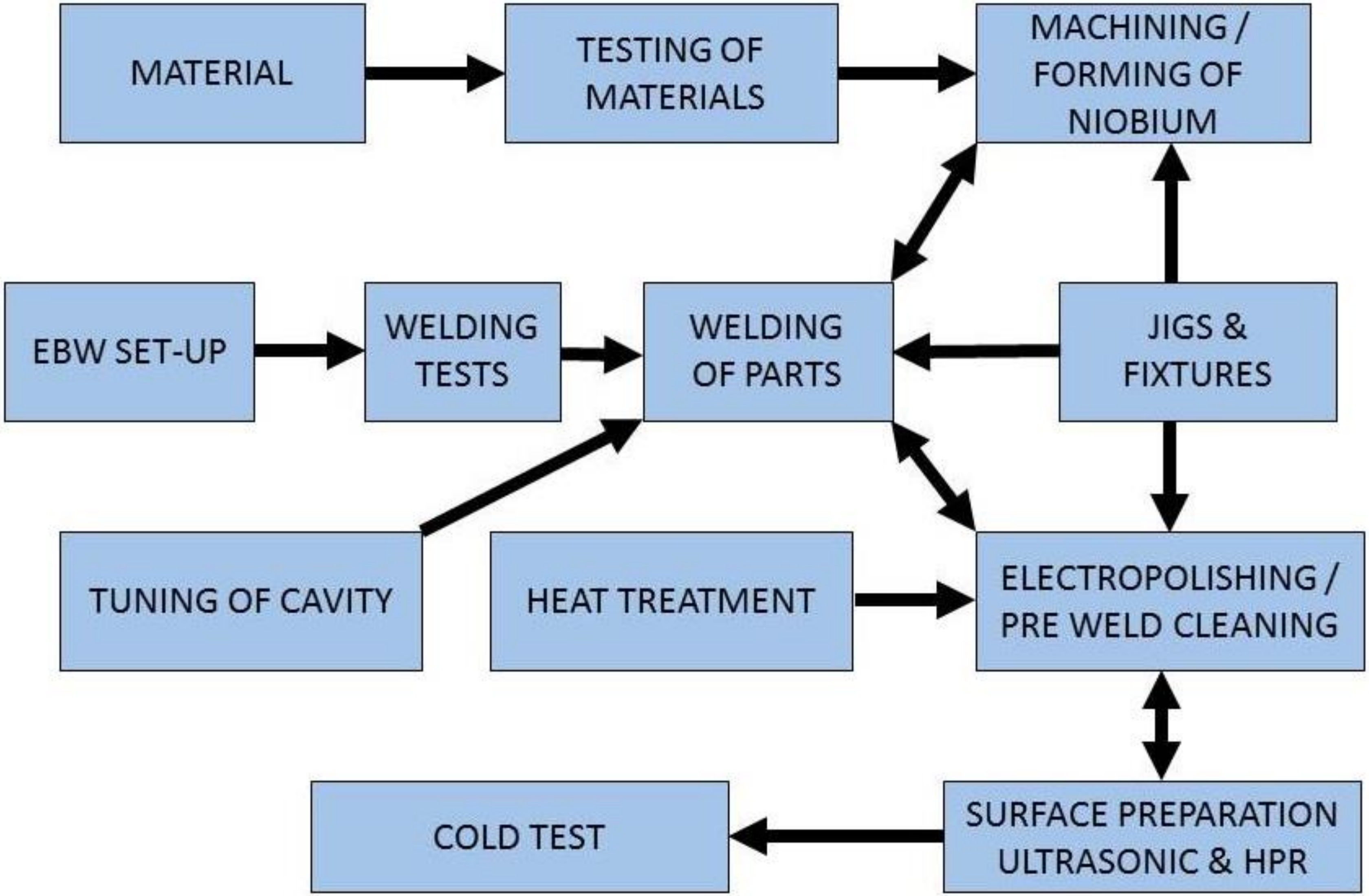
Surface Preparation Laboratory

- Large Fume Hood
- DC Power Supply: 0-20 V, 1000 A
- Large Ultrasonic Cleaners (27 kHz & 68 kHz)
- DI Water Plant: 200 lph
- Chiller, Sink, Fridge, Acid Pump, etc.

Test Cryostat Facility

- Φ1 m × 2.5 m
- Partly buried
- μ Metal shield
- Variable Drive Coupler
- Lead Shielding

Resonator Fabrication



MATERIAL

TESTING OF MATERIALS

MACHINING / FORMING OF NIOBIUM

EBW SET-UP

WELDING TESTS

WELDING OF PARTS

JIGS & FIXTURES

TUNING OF CAVITY

HEAT TREATMENT

ELECTROPOLISHING / PRE WELD CLEANING

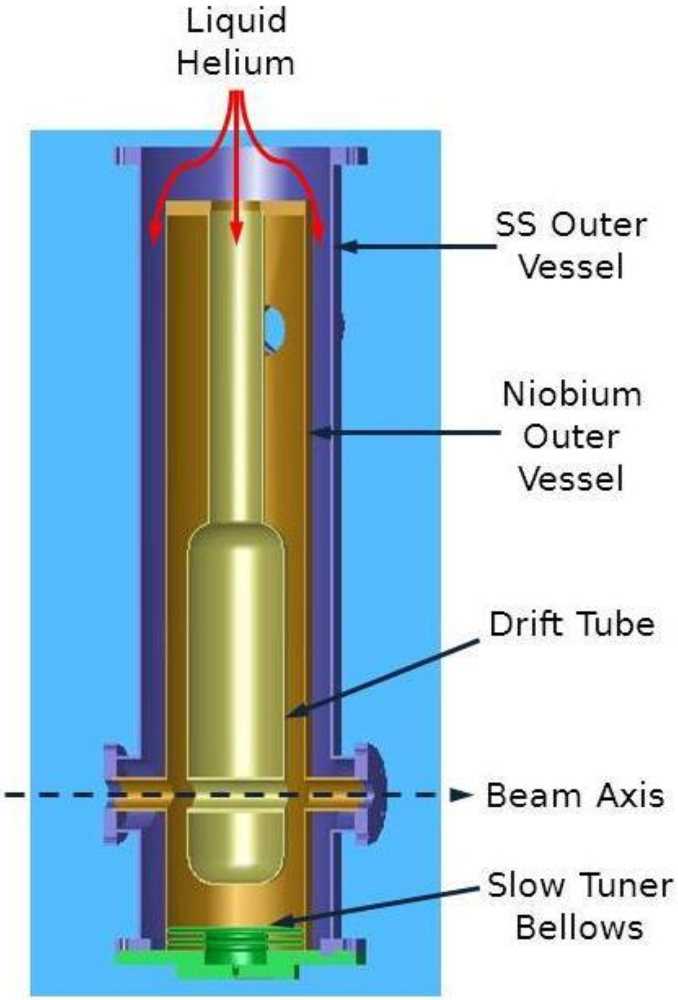
COLD TEST

SURFACE PREPARATION ULTRASONIC & HPR

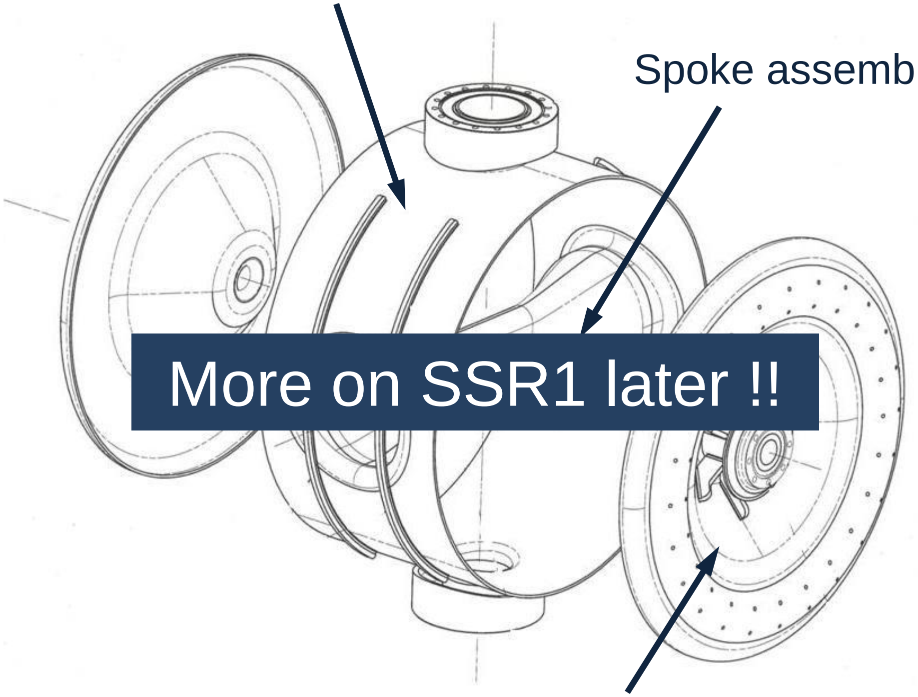
TEM Class Resonator Fabrication

- In general TEM-Class Resonators are more difficult to fabricate compared to TM-Class Elliptical Cavities.
- In TM-Class Elliptical Cavities:
    - There is high degree of symmetry.
    - Involves joining Half Cells.
    - End Groups are (perhaps) most challenging.
    - Several stiffeners need to be attached.
- In TEM-Class Resonators:
    - In general there is no symmetry.
    - Components / Sub-Assemblies are all of different shapes.
    - Individual components can become challenging to build.
    - Bigger structures, such as the Spoke Resonator, need several stiffeners to be attached.
- Many issues are, however, common in both the classes.

Examples



IUAC QWR



Outer Shell assembly along with the two Coupler Ports

Spoke assembly

More on SSR1 later !!

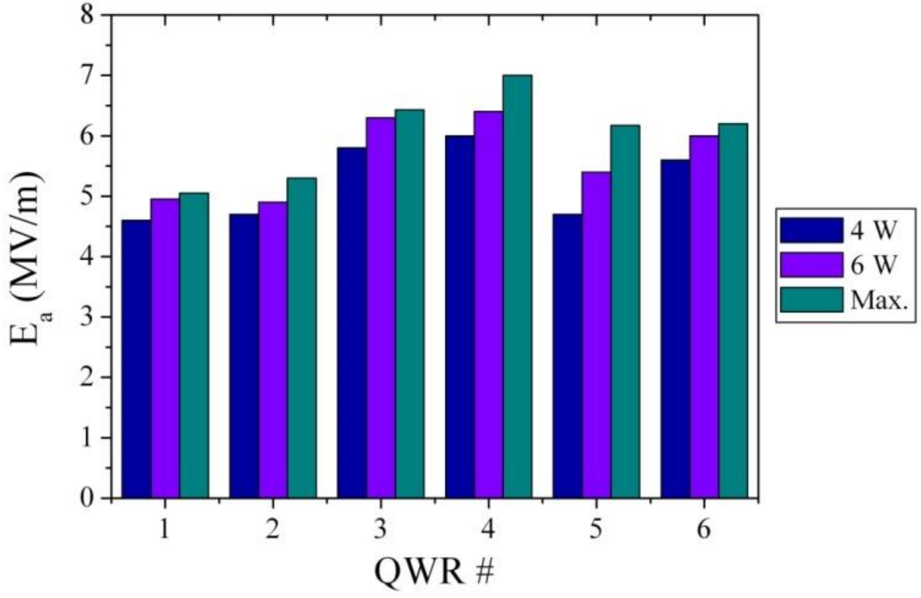
End Wall assembly along with Daisy & Donut Ribs

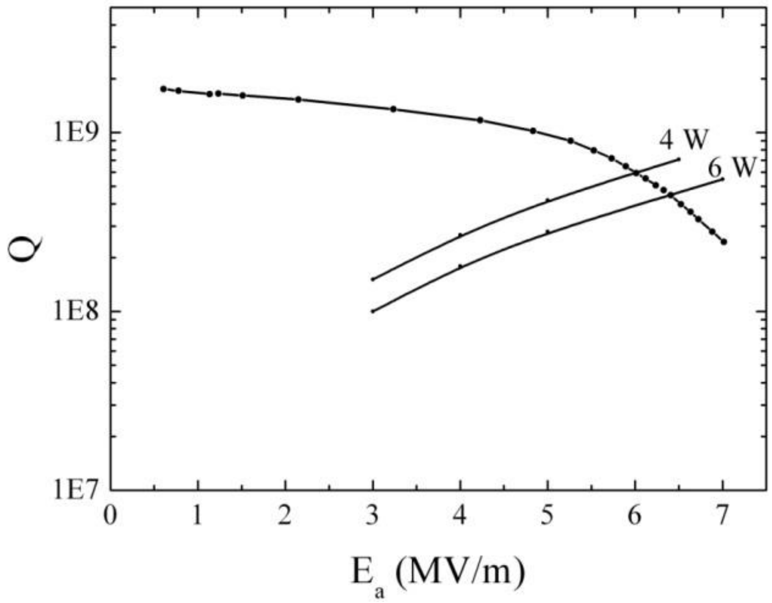
Single Spoke Resonator SSR1

Fabrication of QWRs at IUAC

Quarter Wave Resonators (QWR) developed indigenously for the Superconducting LINAC using the SRF infrastructure at IUAC.

Performance of Indigenous QWRs





Offline performance of indigenously built QWRs for the IUAC SC Linac.

The Design Goal is E_{acc}=4 MV/m ≤ 6 W RF Power.

- QWR#4 CW Gradients:
  - 4 MV/m @ 1 W
  - 6 MV/m @ 4 W
  - 6.4 MV/m @ 6 W
  - 7 MV/m @ max power
- Max Pulsed Gradient (25% DC):
  - 8.8 MV/m max

- QWR#4:
  @ 8.8 MV/m, B_{peak}=116 mT
- Highest reported value of B_{peak} in a TEM class Niobium Resonators is around 118 mT (at MSU). The IUAC result compares very well with that.

Beam Energy – IUAC SC LINAC

Beam	Pelletron Energy (MeV)	LINAC Energy (MeV)	Total Energy (MeV)
			Pelletron + LINAC
^{28}Si^{12+}	130	80.9	210.9
^{30}Si^{12+}	130	48.8	178.8
^{35}Cl^{13+}	150	109.4	259.4
^{37}Cl^{13+}	150	95.0	245.0
^{48}Ti^{15+}	168	131.7	299.7

LINAC Run: Summary

- Beam energies from LINAC are not the maximum energies which can be obtained from it. Rather, the beam energies are what the users wanted.
- The maximum beam energy that can be obtained from the LINAC at the moment is ~11 MV/q. We believe that this can be pushed up to ~13-14 MV/q.
- Typical beam currents ~few pnA (clearly a limitation; HCI to address it).
- Typical Δt ~200 ps on the target; best Δt measured on target ~185 ps (NAND).

High Current Injector (HCI)

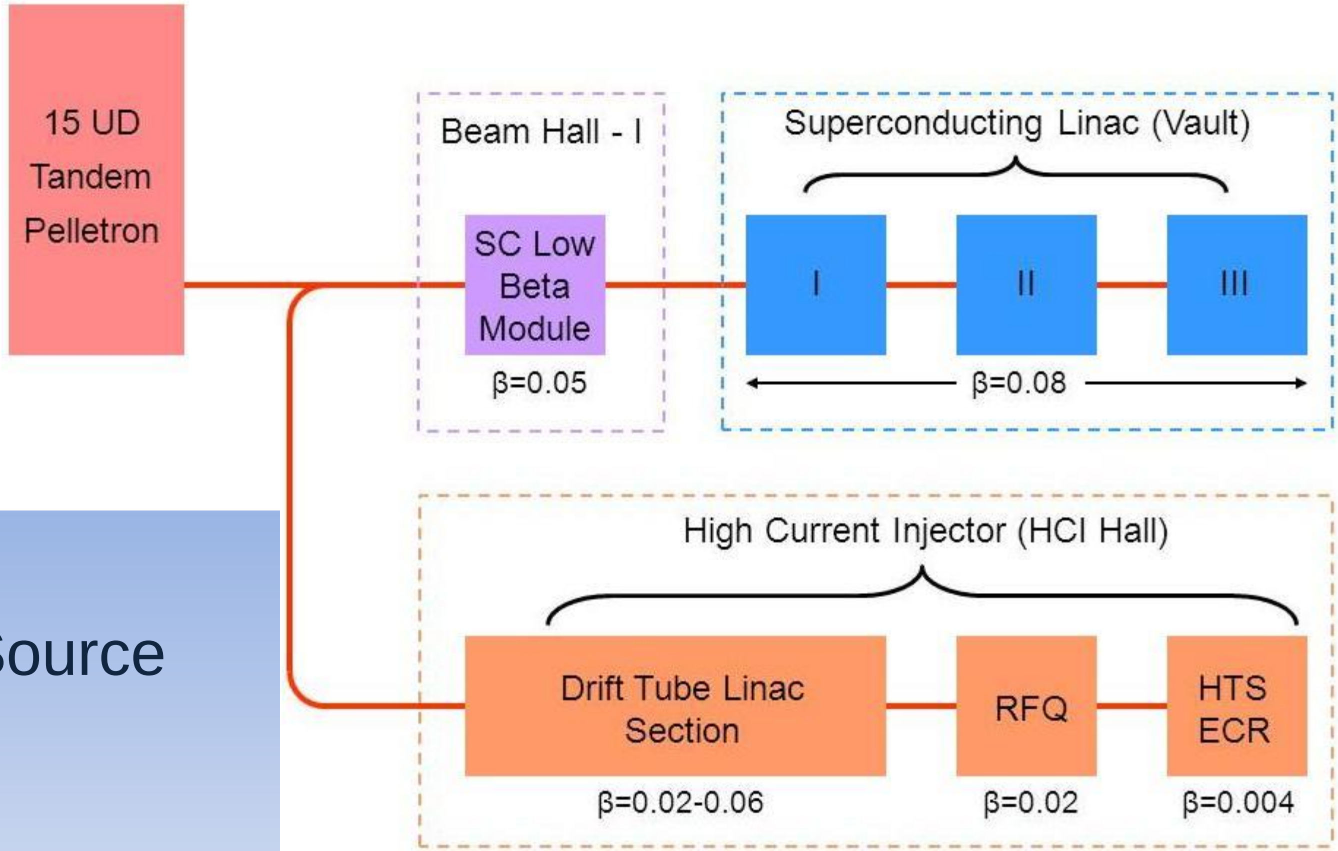
(higher beam currents and noble gases)

High Current Injector (HCI)

An alternate injector, named High Current Injector (HCI), is currently under development at IUAC.

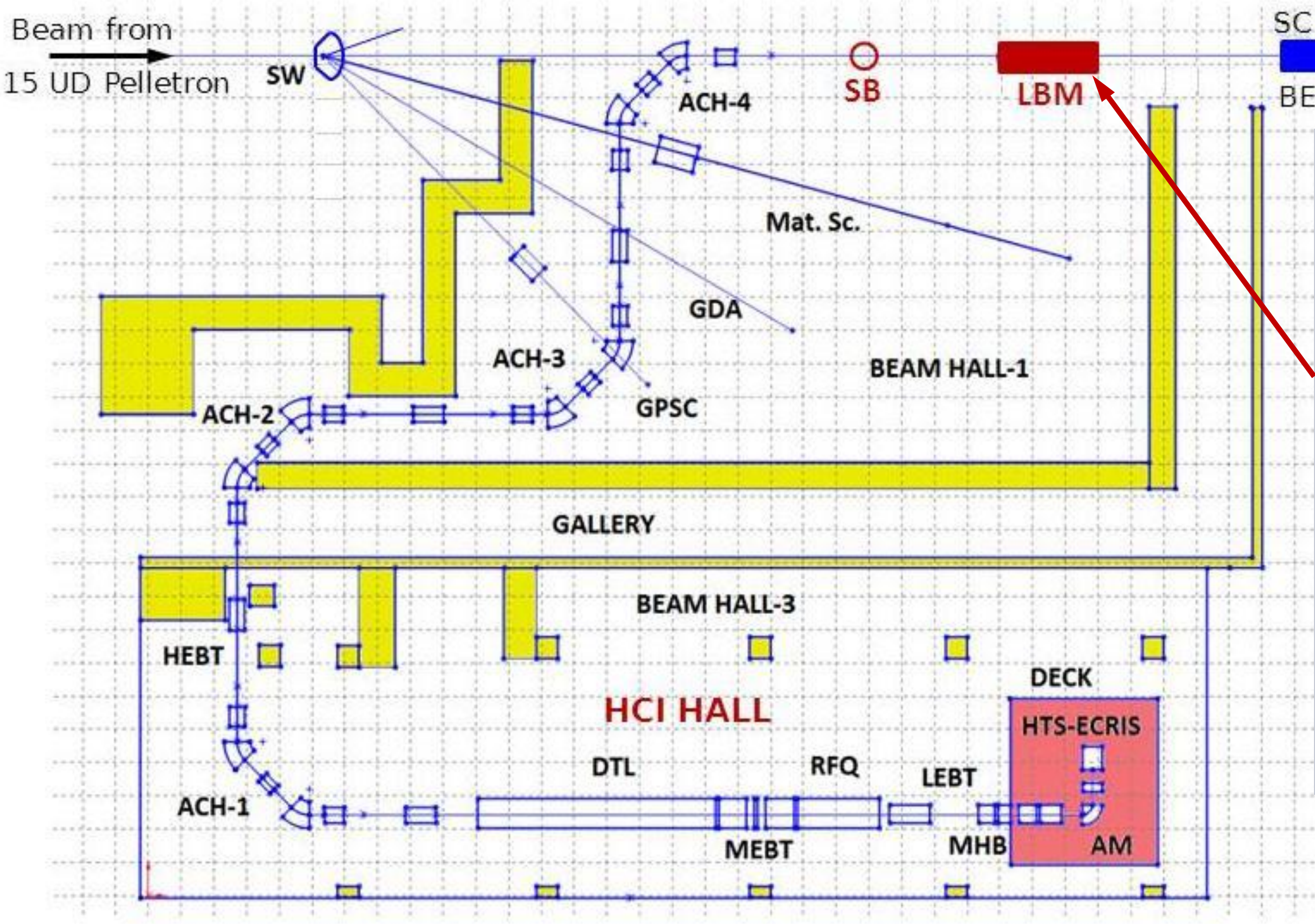
HCI @ IUAC:

- HTS-ECR Ion Source
- RT-RFQ
- 6 DTL Tanks
- Superconducting Low Beta Module (SC LBM)

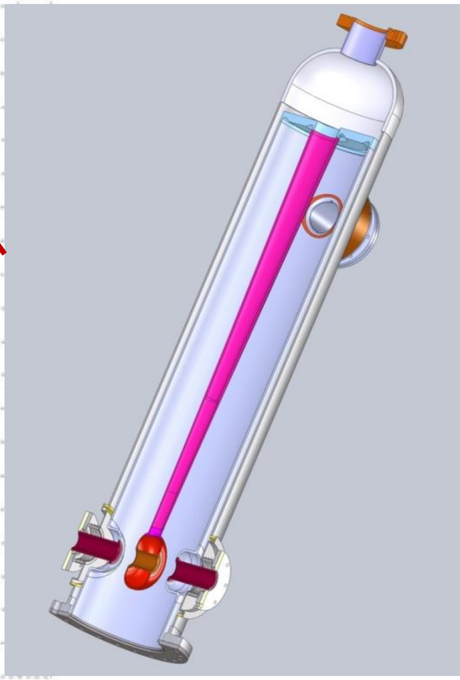


Block diagram of the proposed High Current Injector (HCI) system at IUAC. The dashed boxes indicate the location of the various components.

Low Beta Resonator (LBR)



Layout showing the High Current Injector along with the proposed location of the Low Beta Module (LBM).



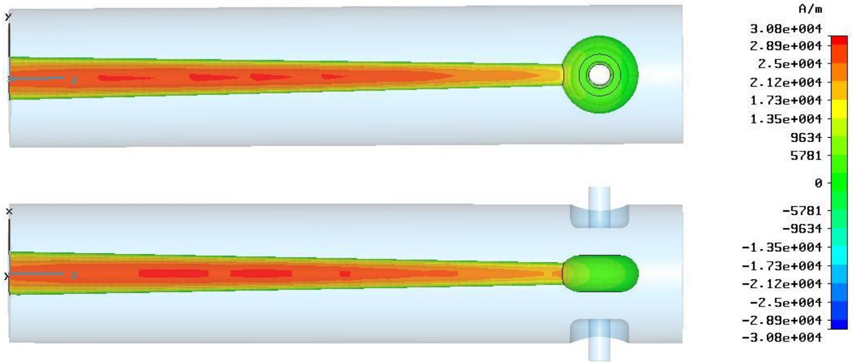
The niobium Low Beta Resonator designed and developed at IUAC for the Low Beta Module.

8 LBRs in the LBM

LBR - Design Goals

The development of the Low Beta Resonator (LBR) aimed at carefully designing a niobium resonator with:

- low values of peak electric & magnetic fields,
- small value of stored energy,
- high values of shunt impedance and geometry factor,
- little or no low level electron multipacting,
- high energy gain to provide sufficient cushion for velocity-matching of beams from HCI into the Superconducting Linac,
- simple design which could be built using the available infrastructure at IUAC,
- physical dimensions which could fit within the existing height of Beam Hall-I.

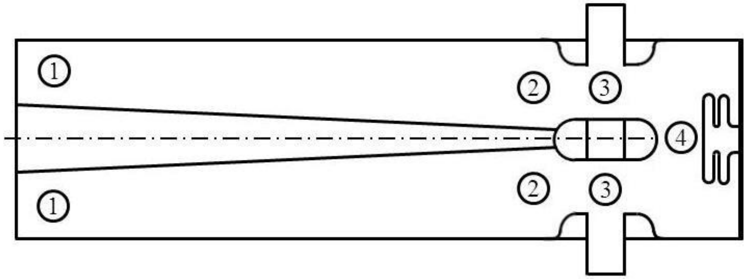


CST-MWS Model of Low Beta Resonator.

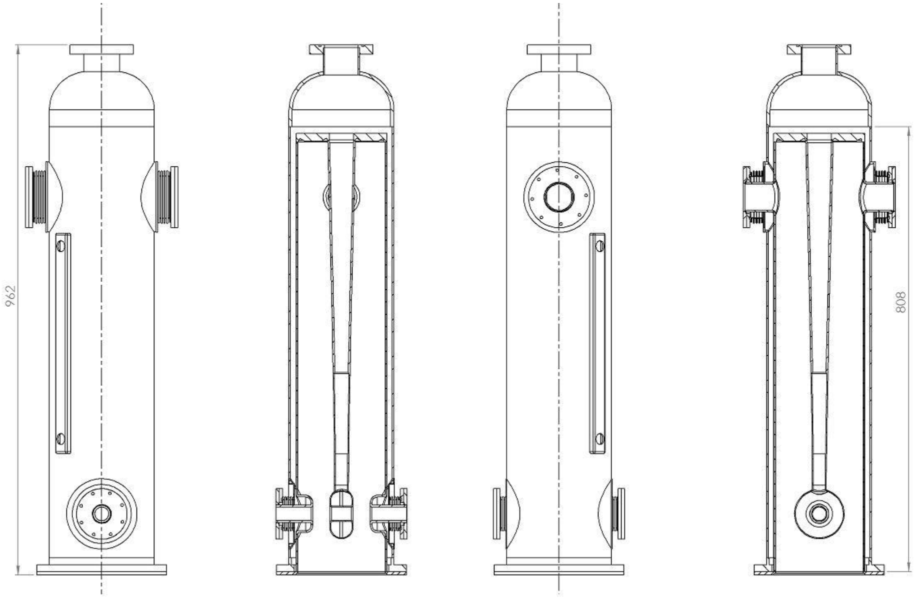
Major sub-assemblies of the Low Beta Resonator: niobium outer housing, tapered niobium central conductor and top flange, and stainless steel outer helium vessel.

LBR - Parameters

Site	Site at the Resonator	Gap (cm)	K (eV)
1	Coaxial line and outer housing at the shorted end.	5.45	1272
2	Coaxial line and outer housing at the open end.	6.69	1916
3	Drift tube and beam ports on the outer housing	3.1	411
4	Drift tube and slow tuner top	4.1	720



Possible two point multipacting sites. At site 3, multipacting is not expected to be severe due to the openings in the beam ports.

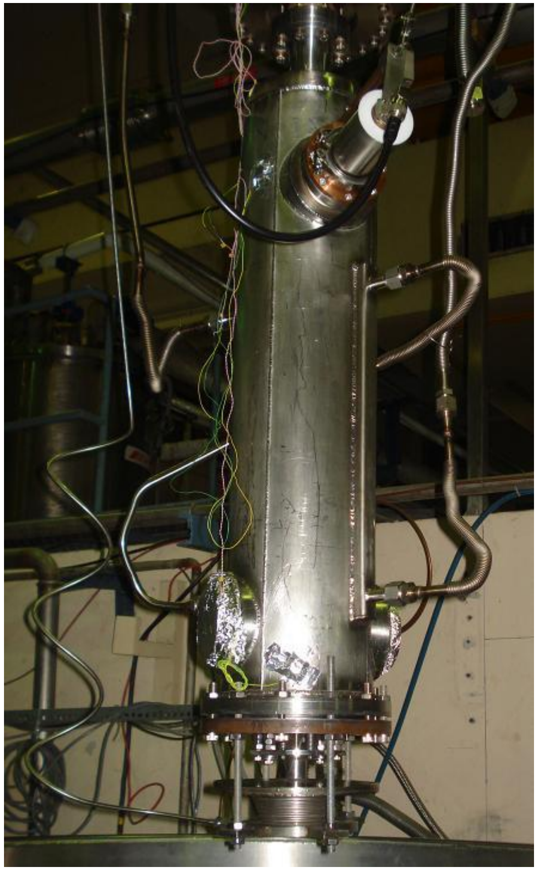


Engineering design of the Low Beta Resonator.

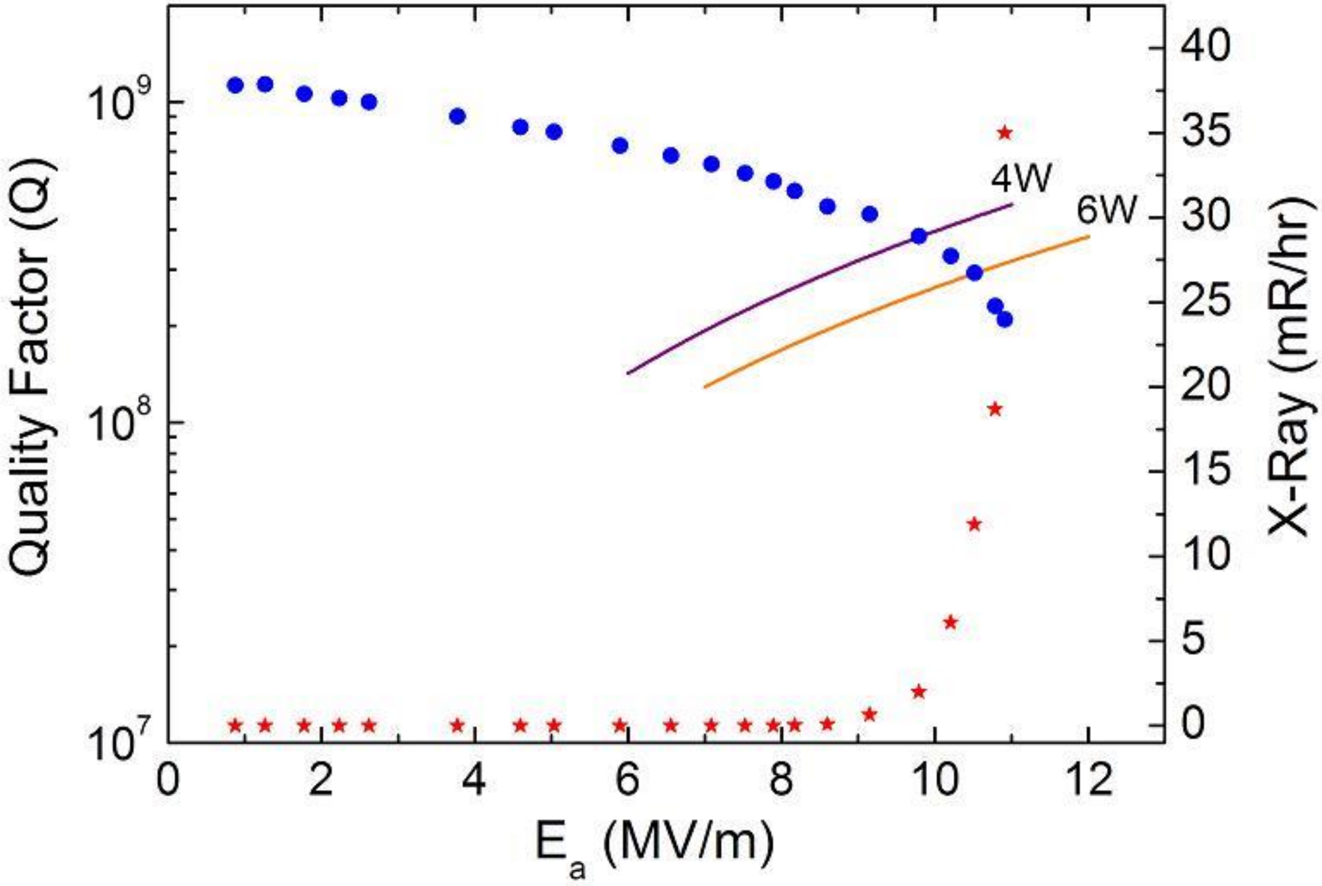
Parameter	Value
β_0	0.051
f	97 MHz
U_0	26 mJ
B_{peak}	64.2 G
E_{peak}	3.45 MV/m
R_{sh}/Q	650 Ω
QR_s	16.1
E_a	6.2 MV/m
V_{Gain}	0.63 MV

Key parameters (referenced @ 1 MV/m gradient), of LBR.

Prototype LBR - 4.2K Test Result



Low Beta Resonator being loaded in the Test Cryostat.

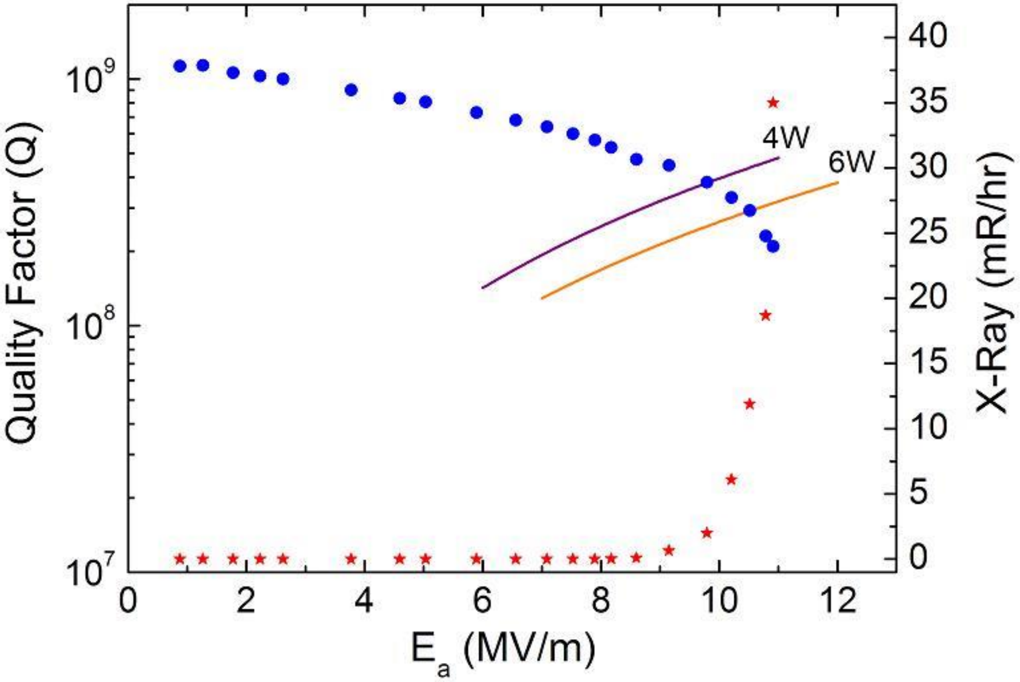


Resonator Q as a function of Accelerating Gradient E_a in MV/m at 4.2 K.

IUAC

Prototype LBR Result - Analysis

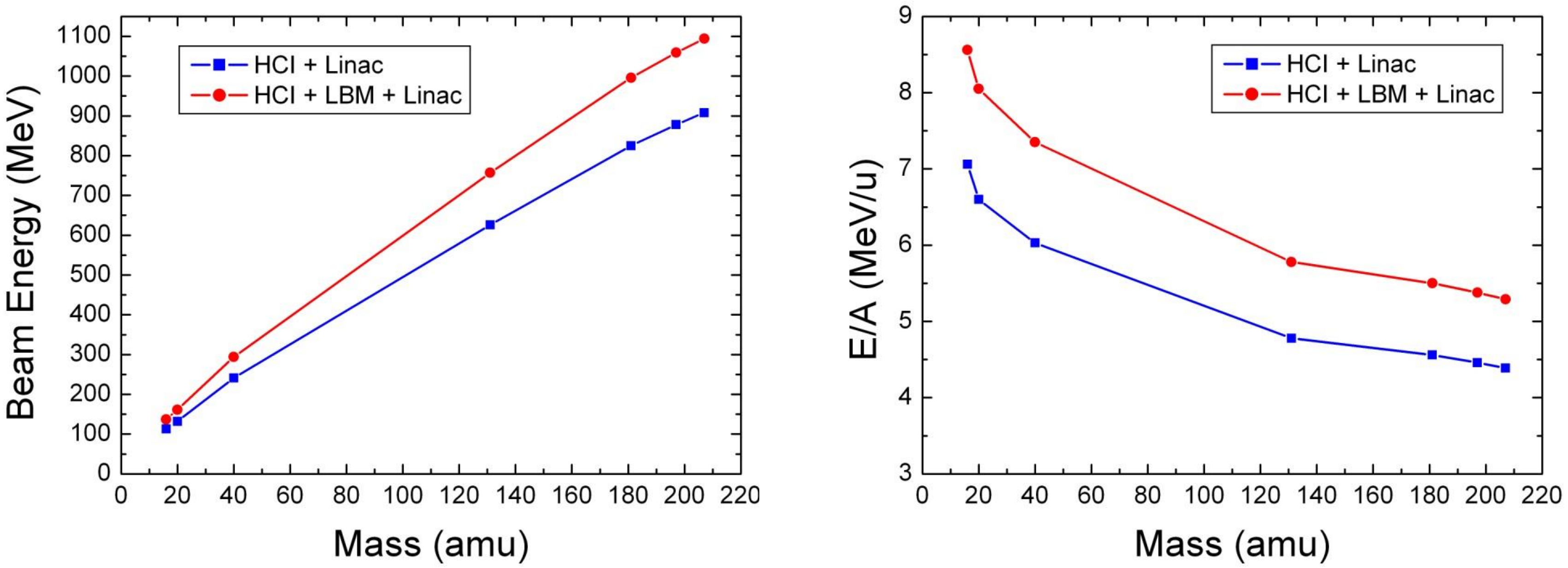
- The design accelerating gradient of 6 MV/m is achieved with <1 W RF input power.
- At the design cryogenic load of 6 W, the accelerating gradient is 10.5 MV/m.
- Max CW accelerating gradient of ~11 MV/m corresponds to E_p~40 MV/m and B_p~70 mT.
- Max Pulsed accelerating gradient at 10% duty cycle was ~13 MV/m.



Scope for Improvement

- Q_0 (at low gradients) of $1.25\times10^9 \Rightarrow R_s$ ~13 nΩ; which is still about 25% higher !!
- Large X-Ray emission coupled with the fact that max B_p~70 mT ⇒ cavity is field emission limited (Q drops after ~9 MV/m & X-Ray rises between 9-11 MV/m).
- HPR is the next logical step. For this, the rinsing wand and movement mechanism are presently being modified (existing arrangement is suited for Linac-QWRs).

HCI+SC Linac - Energy Gain



Energy Gain (left) and Energy per nucleon (right) as a function of ion mass for the High Current Injector (HCI) + Superconducting Linac, and High Current Injector + Low beta Module (LBM) + Superconducting Linac. A foil stripper is assumed between HCI and LBM in both the cases. The calculations are done with the Low Beta Resonators in the LBM operating at 6 MV/m accelerating gradient and the QWRs in the SC Linac at 3.5 MV/m accelerating gradient.

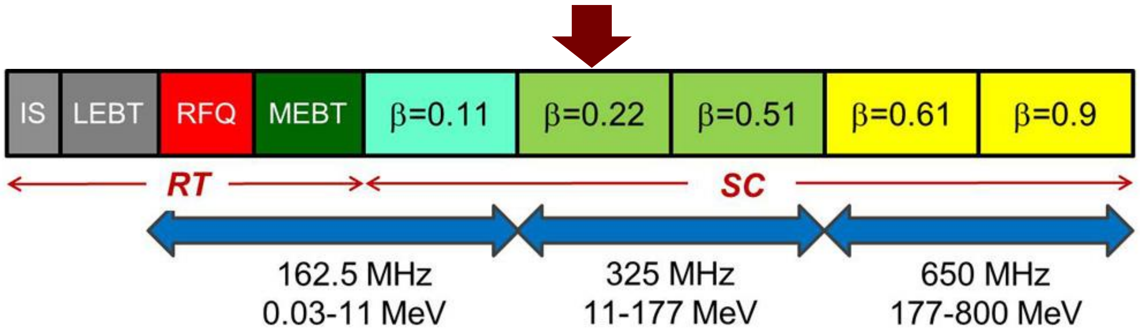
Single Spoke Resonator SSR1

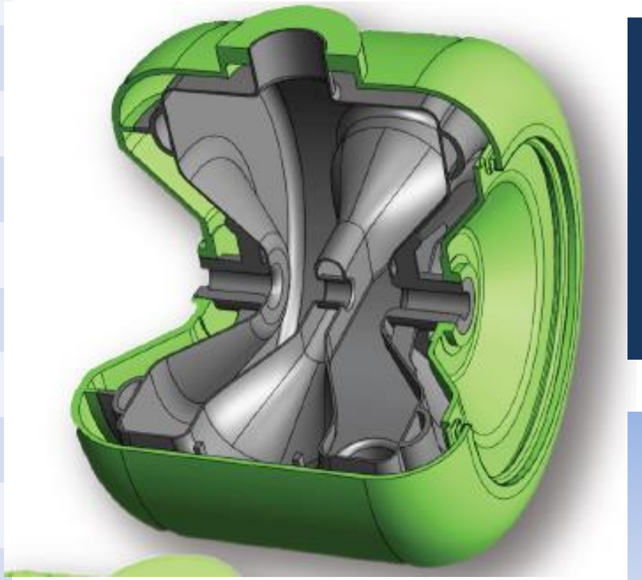
PIP-II at Fermilab

	SSR1
β	0.222
E_p/E_{acc}	3.84
B_p/E_{acc}	5.81 mT/(MV/m)
Aperture	30 mm
Diameter	492 mm
L_{EFF} (βλ)	205 mm
G	84 Ω
R/Q	242 Ω
Oper. Gradient	12 MV/m
Q_0 at E_{acc}	> 0.5 10^{10}
Operating B_{MAX}	70 mT
Operating E_{MAX}	46 MV/m
Tuning constant	40 N/kHz
Sensitivity	< 25 Hz/torr
P (RT, CT)	2 bar, 4 bar

SSR1 Parameters

Single Spoke Resonator - SSR1



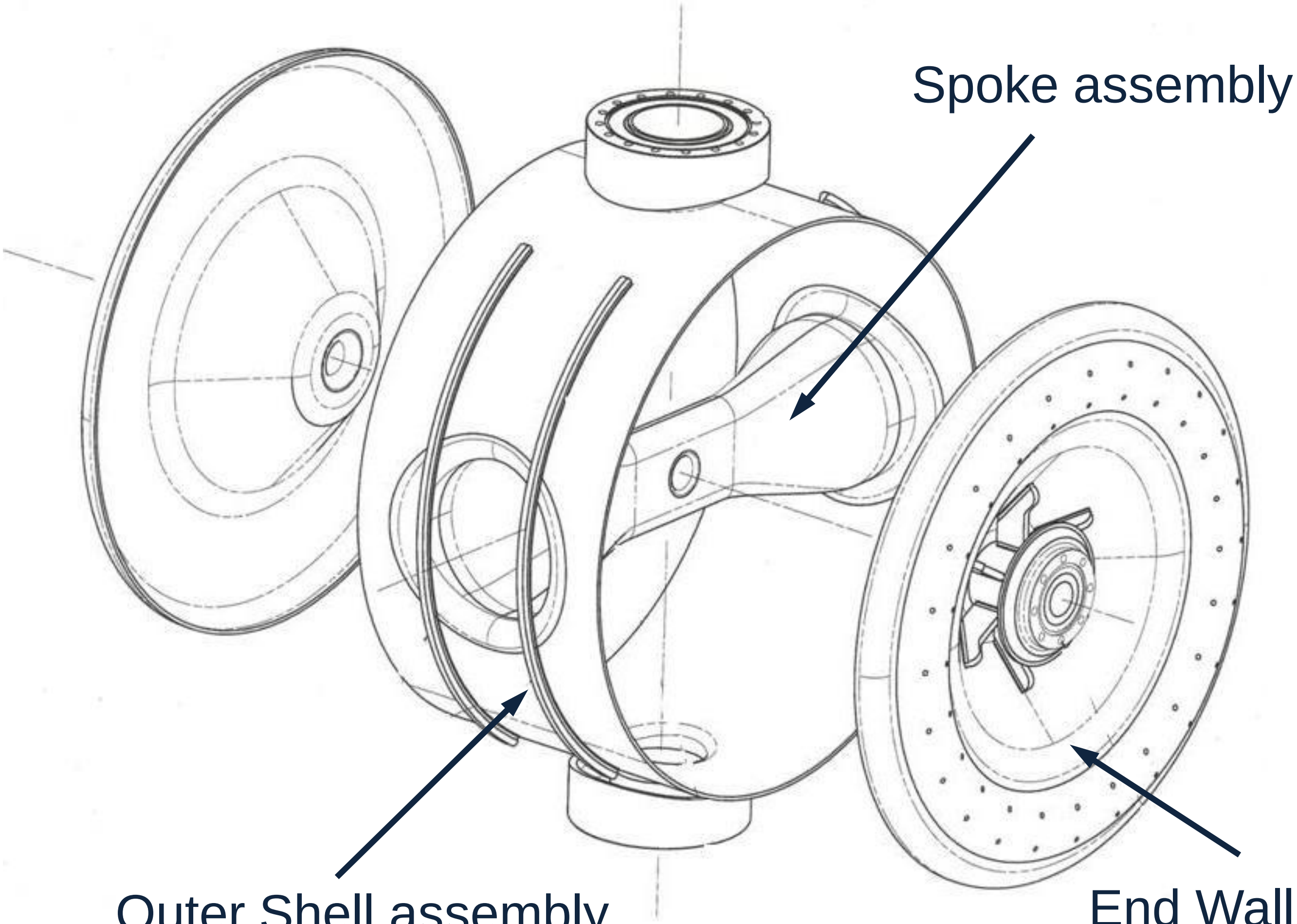


SSR1: Niobium (grey) & Outer SS Jacket (green).

IUAC has successfully developed two niobium Single Spoke Resonators SSR1 for PIP-II project.

At 2K, both the SSR1 Spoke Resonators have exceeded the PIP-II design goal.

SSR1 - Exploded View



Spoke assembly

Outer Shell assembly along with the two Coupler Ports

End Wall assembly along with Daisy & Donut Ribs

SSR1 Construction - Challenges

- Size: 0.5 m diameter × ~0.3 m Long.
- Major components are all die formed from sheet material (typical in bulk niobium cavities).
- Peculiar shape of the Spoke.
- End Wall is formed from a single sheet.
- Dimensional Accuracy:
    - High dimensional accuracy (< 1 mm) required to achieve the final design frequency.
    - Power density in EBW is very large, therefore radial mismatch of >0.1 mm between mating components becomes very difficult to tolerate.

SSR1 Development at IUAC

- All the dies required for forming, i.e. End Wall, Half Spoke, Spoke to Shell Collar, Donut Rib and Coupler Port Pullout, were designed & developed.
- All the machining fixtures required for holding and manipulating the job were designed & developed.
- All fixtures required for holding & manipulating for Electron Beam Welding were designed & developed.
- The three major sub-assemblies of SSR1, namely the Outer Shell, End Wall and Spoke, were individually electropolished (EP). For this, all the required EP fixtures were designed & built.
- EBW Parameters for joining the various niobium parts and sub-assemblies of SSR1 were developed.

SSR1 Development at IUAC

- The development work was carried out in the face of little or no contingency of niobium material available to the IUAC team.
- Therefore several trials had to be taken using copper material during each step of the process.

Spoke assembly

End Wall

- Lack of material contingency also meant that we had to tread very-very carefully during every step of the development. This of course slowed down the pace of the work.

cont’d.. SSR1 Development at IUAC

- The copper components were used for other developments, e.g. for drawing the Coupler Port pullout in case of the Shell.
- They were used to understand the technical challenges that would be faced with the niobium sub-assemblies.

Spoke-to-Shell Collar

Outer Shell

- This approach provided opportunity for process optimization and helped us in understanding the technical issues better, thereby reducing the risk during the construction of the niobium parts.

SSR1 Sub-Assemblies

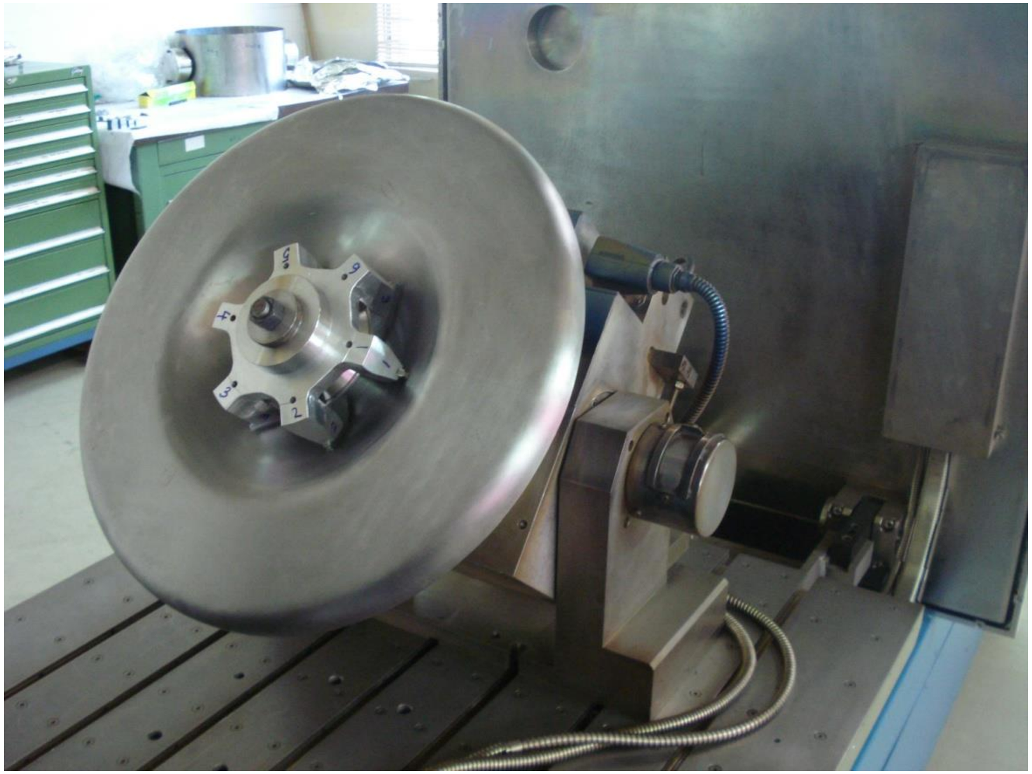
SSR1 - Outer Shell

An Outer Shell after pulling out both the Coupler Ports.

SSR1 - Outer Shell

SSR1 niobium Outer Shell along with its Coupler Ports.

SSR1 - End Wall



Left: Niobium End Walls after forming and attaching of the Beam Ports. Top: An End Wall setup in the EBW machine at IUAC for attaching the Daisy Ribs.

SSR1 - End Wall

An End Wall assembly (left), and its electropolished RF surface (right).

SSR1 - Spoke Assembly

Niobium Spoke assembly after EBW of the two halves.

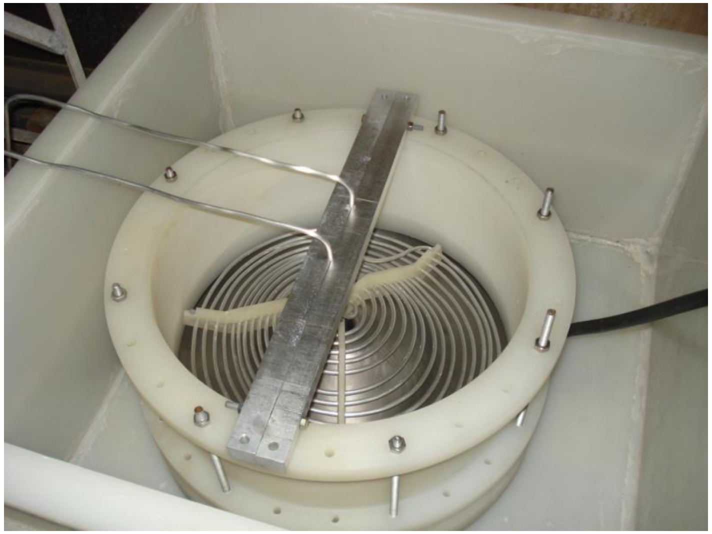
SSR1 - Spoke Assembly

Top: niobium Spoke to Shell Collar. Right: a complete Spoke assembly after attaching both the *Spoke to Shell Collars* and the *Beam Port*.

SSR1 - Spoke Assembly

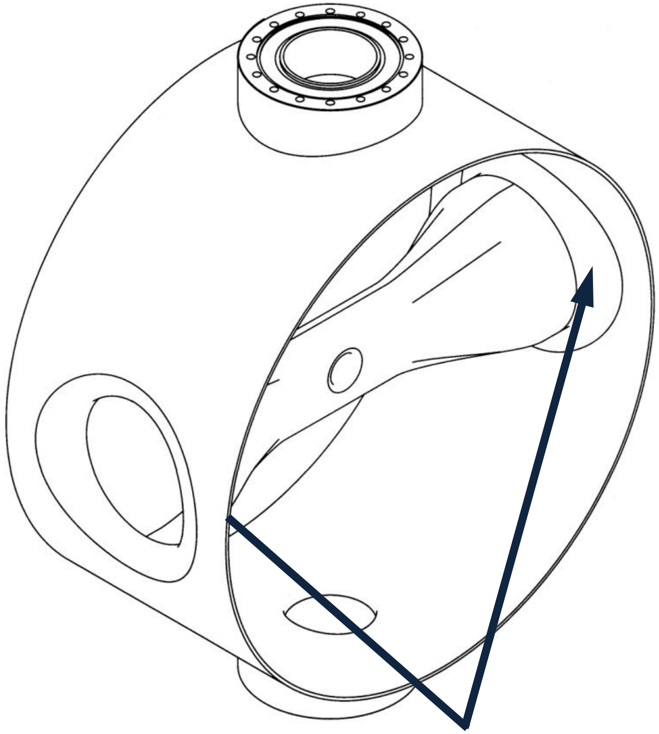
Niobium Spoke assembly after electropolishing.

Electropolishing

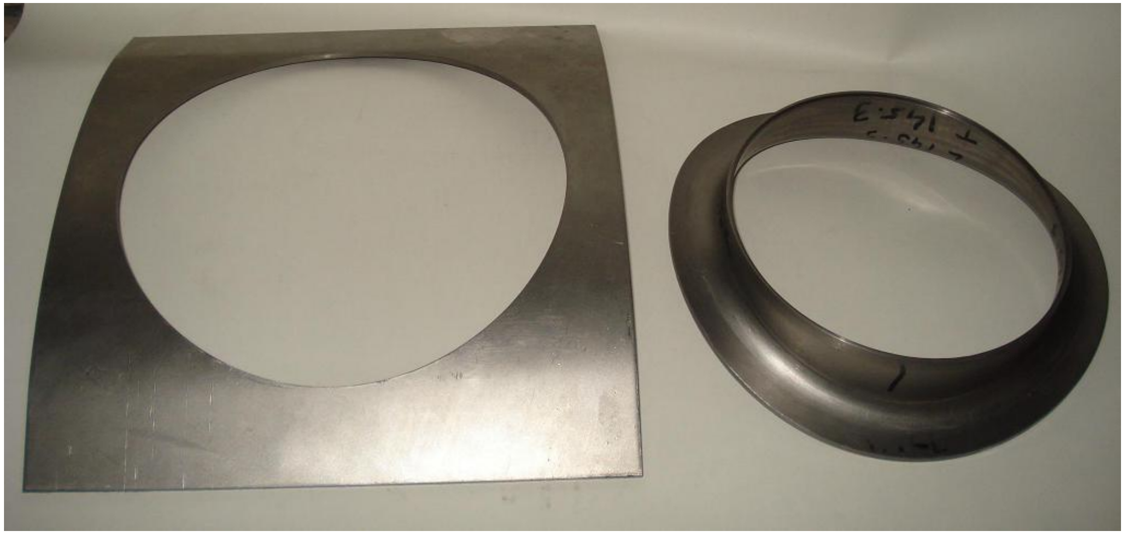


Clockwise from top: EP setup for Spoke, Shell and End Wall. Pictures for the Spoke and End Wall were taken before filling the acid in the bath.

Assembly



The magnetic field is highest here; these EBW joints are therefore very-very critical.



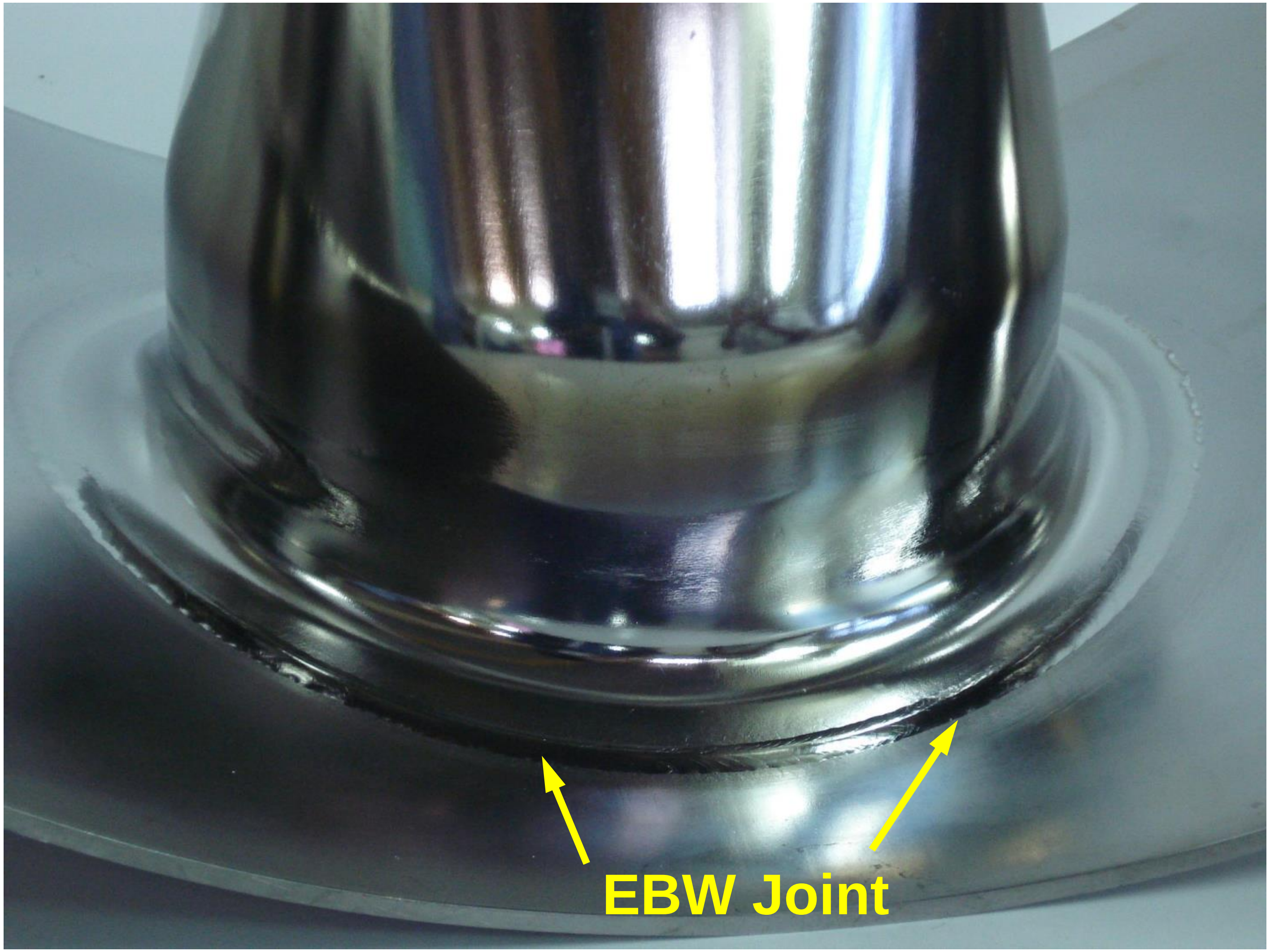
EBW trials were taken on samples of the same joint diameter and shape, to develop the parameter for this critical weld.

IUAC

Spoke and Shell Assembly

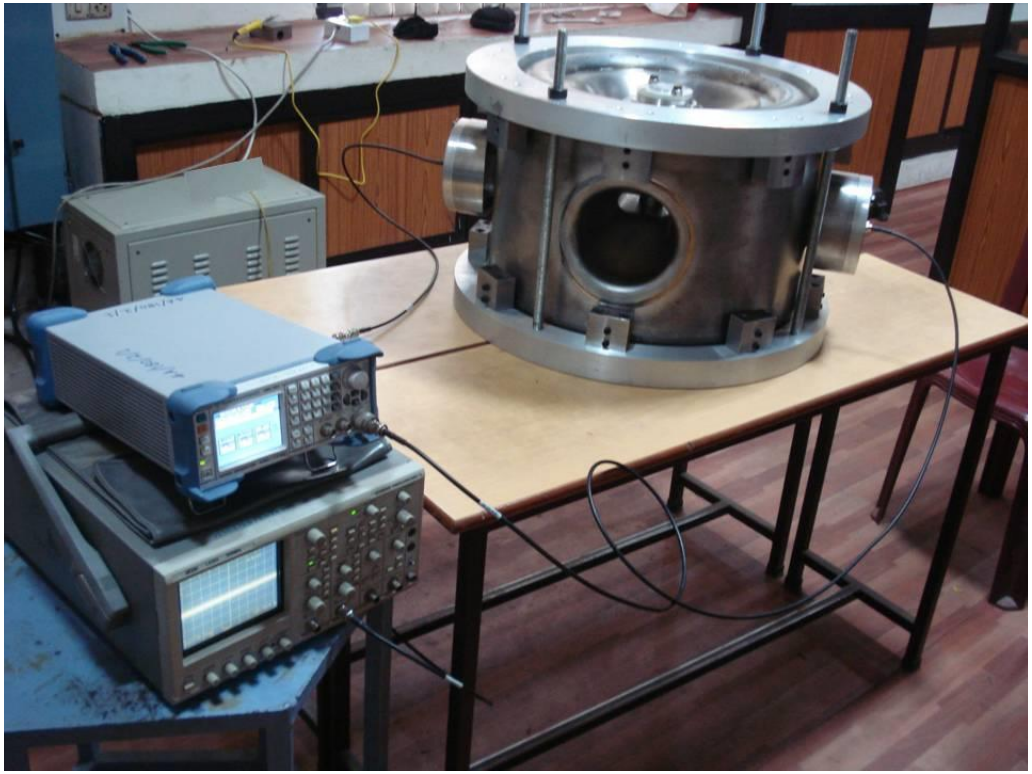
Completed Spoke and Shell assembly.

Spoke and Shell Assembly



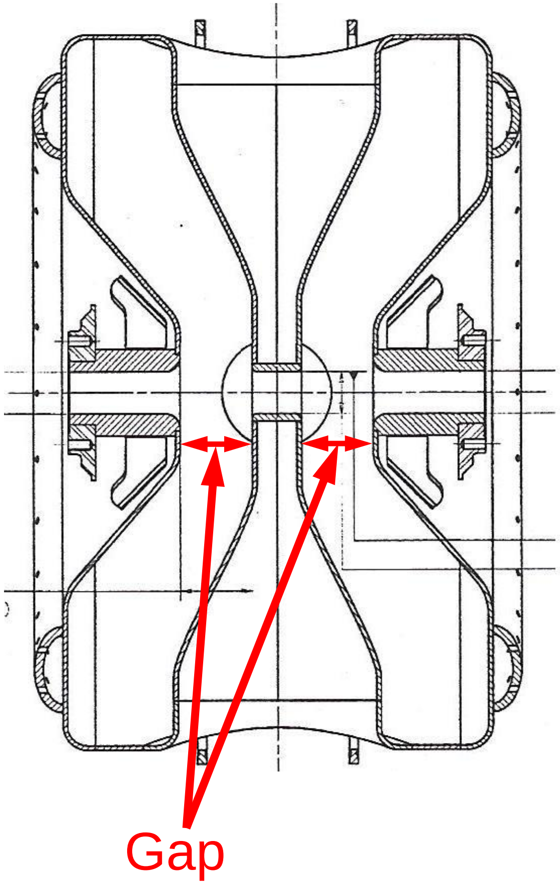
Close up view of the high magnetic field joint after EBW.

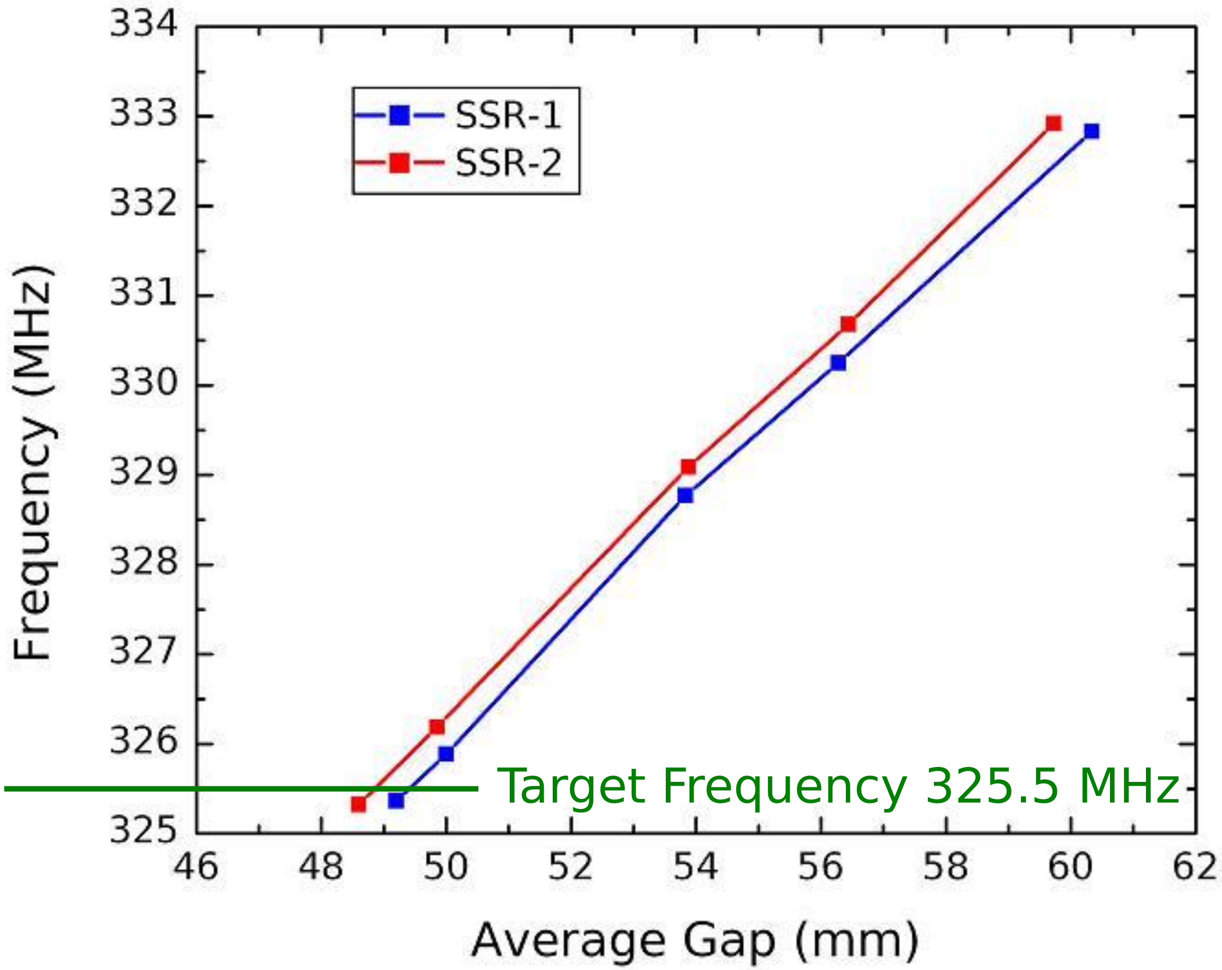
SSR1 - Frequency Tuning



Left: Measurement of the dimensions of the resonator assembly on a CMM.
Top: setup for the frequency measurement.

SSR1 - Frequency Tuning



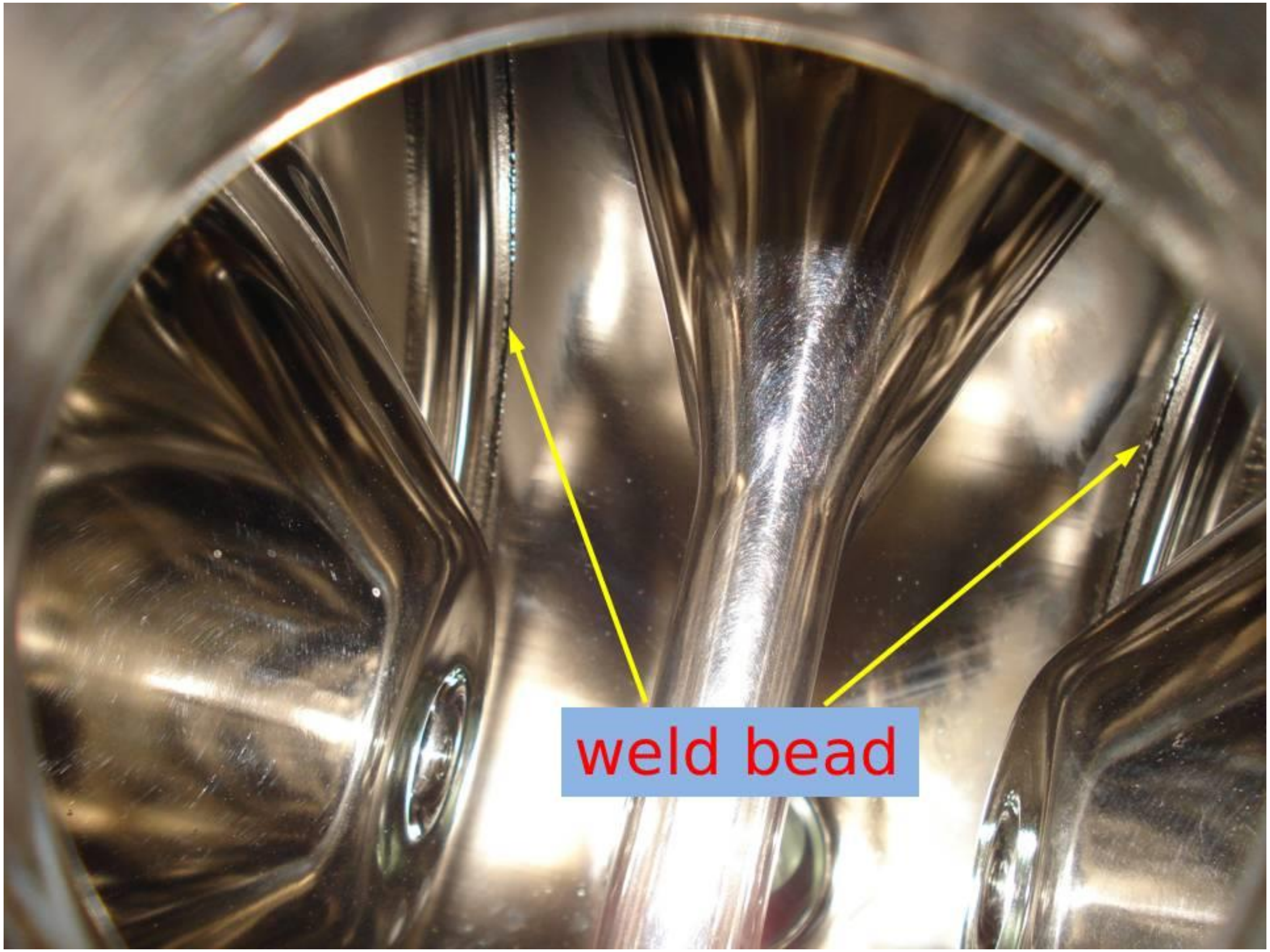


Resonator frequency as a function of the average gap length, for the two IUAC built SSR1 Spoke Resonators.

SSR1 - Final Assembly Prep.

A Niobium SSR1 resonator just before completion.

End Walls to Shell EBW

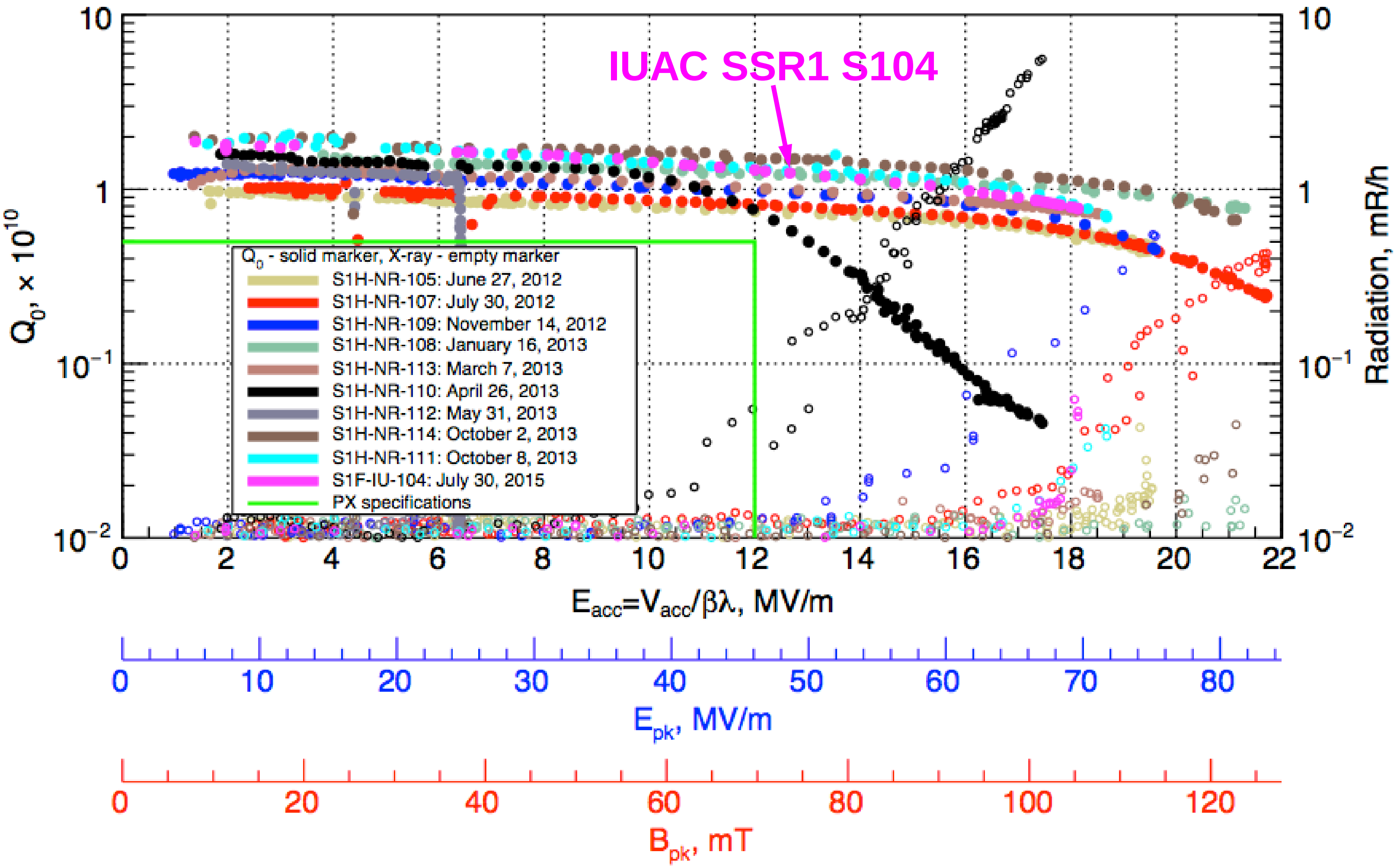


End Wall to Shell weld bead clearly visible inside the cavity.

Spoke Resonator - SSR1

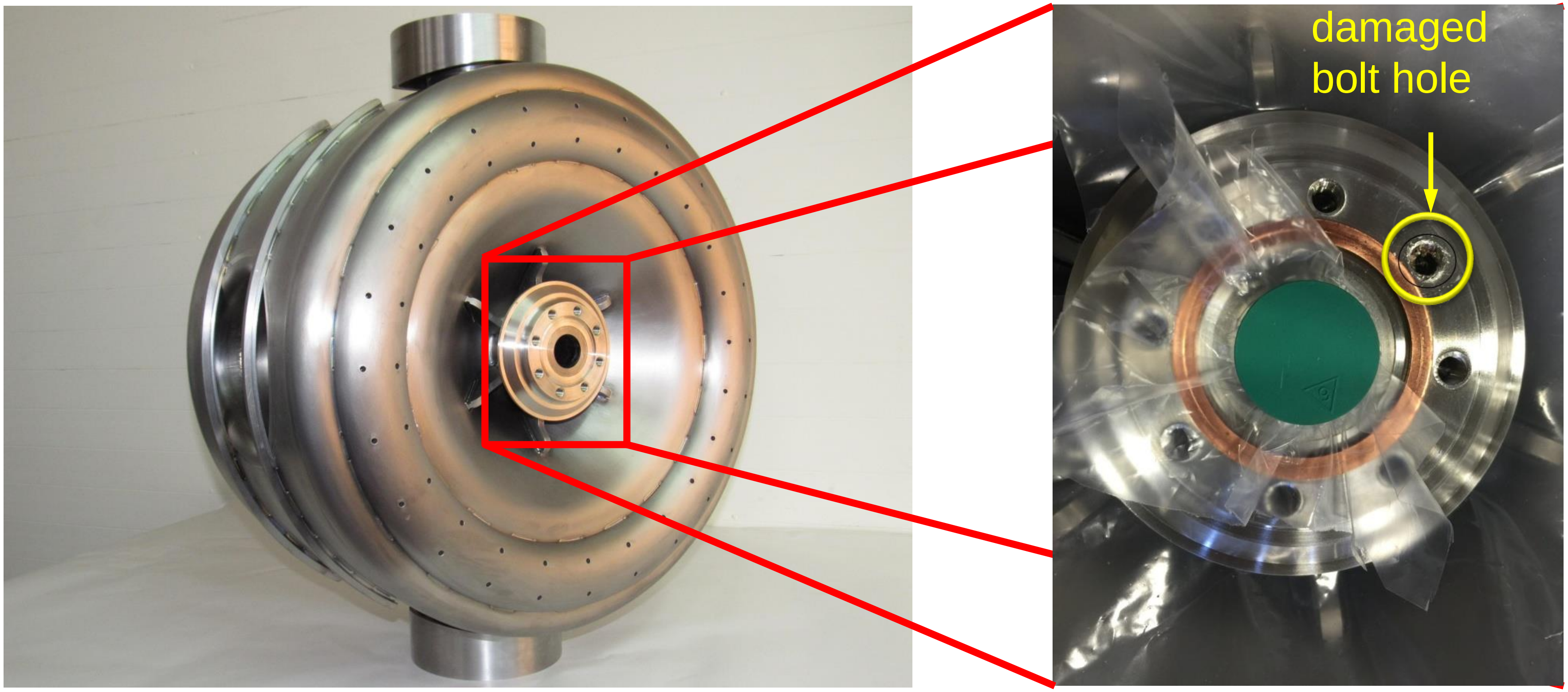
The two SSR1 Niobium Spoke Resonators developed at IUAC.

IUAC SSR1 S104 Test Result



2 K Test Result of SSR1 S104 developed at IUAC and tested at Fermilab. The PIP-II and PXIE Design Goals are E_{acc}=10 & 12 MV/m respectively at $Q>5\times10^9$.

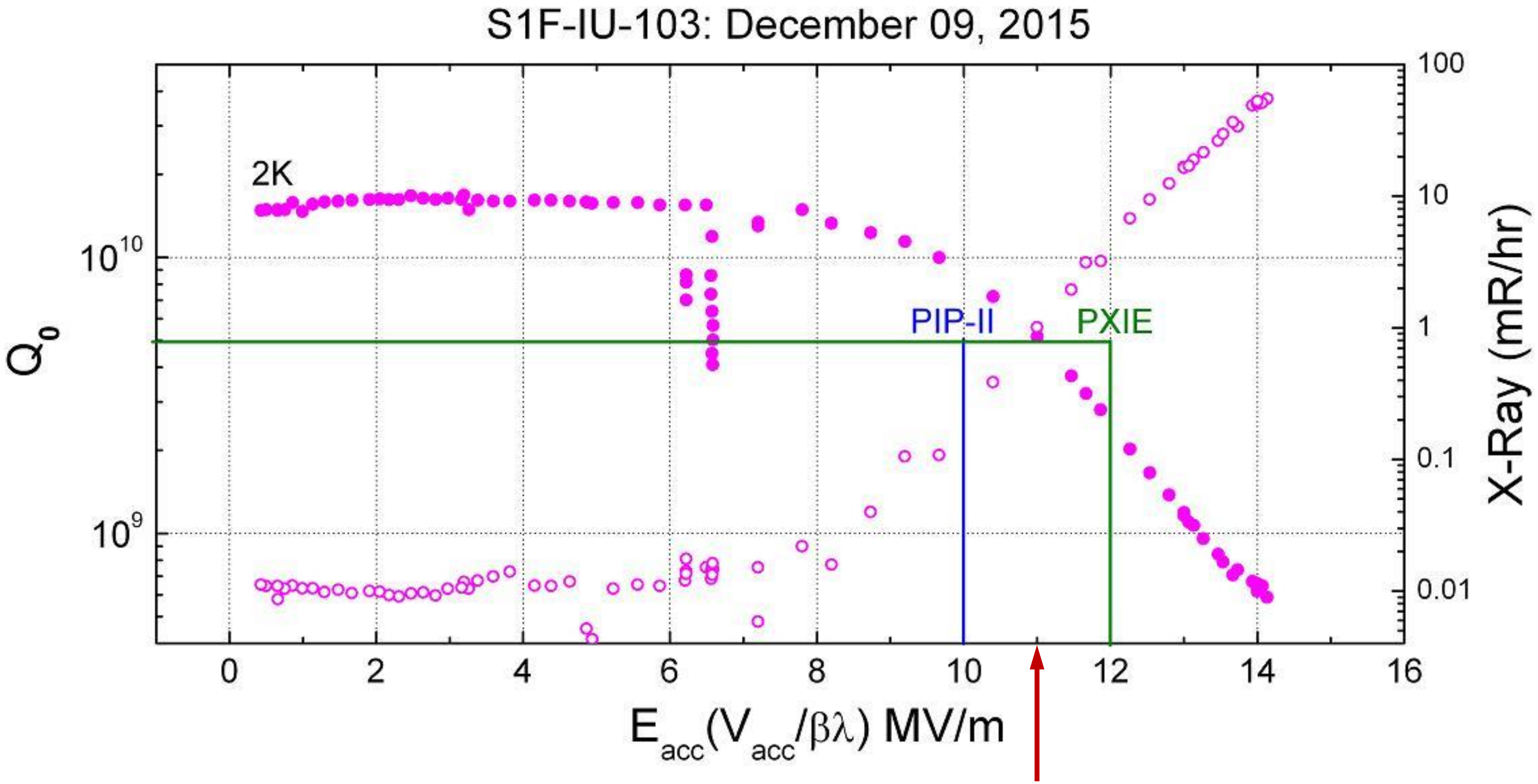
IUAC SSR1 S103 Accident



Beam Port hole of S103 that got damaged while processing at FNAL / ANL.

- The Beam Port flange with the repaired hole could not be made leak tight.
- This resulted in venting the Cavity twice.
- Leak was resolved in the second attempt after using an Indium coated copper gasket in the Conflat flange.

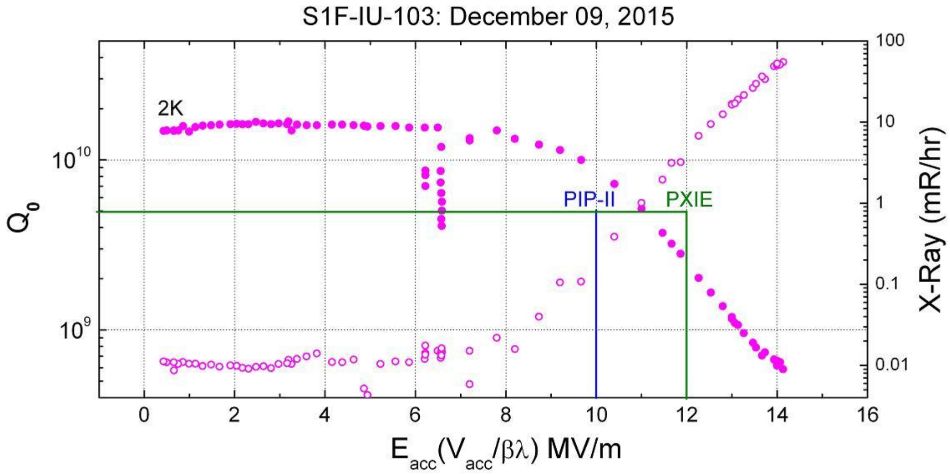
IUAC SSR1 S103 Test Result



@ $Q_0=5\times10^9$, E_{acc} ~11 MV/m
(exceeds PIP-II design goal, and almost there for PXIE design goal !!!)

2 K Test Result of SSR1 S103 developed at IUAC and tested at Fermilab. Note the rapid increase in X-Ray beyond E_{acc}=8 MV/m.

SSR1 S103 Result - Analysis



- Multipacting took ~ 6 hours to process.
- Quench field at 2K: 14 MV/m (X Ray ~55mR/hr).

- Since the cavity had to be vented twice, clearly it got contaminated.
- This is manifested in the heavy field emission loading (X Rays).
- It only means that more cleaning is required. This is neither special, nor particular, to this cavity.
- Experts at Fermilab and Scientists at IUAC are unanimous that the cavity will meet the PXIE design goal after another round of light BCP followed by HPR.
- Both, Fermilab and IUAC, teams are confident that the performance of S103 would be similar to S104.

Conclusions

- IUAC is the first laboratory in India to commission the necessary infrastructure more than one and a half decades ago, for building superconducting niobium cavities. It has successfully developed superconducting niobium QWRs for the in-house programmes.
- IUAC has successfully collaborated, and continues to collaborate, with several national and international laboratories for developing superconducting niobium cavities of different designs, velocities and frequencies.
- IUAC has successfully developed two Single Spoke Resonators SSR1 for Fermilab.
- The various niobium cavities designed and / or built by IUAC have achieved very high accelerating gradients at par with those achieved by leading laboratories working in this field.
- The SRF infrastructure at IUAC is continuously being upgraded to keep pace with state of the art developments globally.

Acknowledgements

The work presented in this talk is the result of the hard work of many people. Their contribution is gratefully acknowledged.

SRFSAT-2017

IUAC is organizing a 3 day Workshop sponsored by Dept. of Science & Technology, on Superconducting Radio Frequency Science and Technology – SRFSAT2017, during Sept. 20-22, 2017.

We look forward to see you at IUAC in the Workshop.

Contact email:

srfsat2017@gmail.com

Workshop on Superconducting Radio Frequency Science and Technology: SRFSAT-2017
20-22 September 2017
Inter University Accelerator Centre, New Delhi
Sponsored by Department of Science & Technology

As Indian laboratories embark on ambitious programmes of developing large linear accelerators based on superconducting radio frequency technology, SRF has become an important topic of research and development.

The goal of this workshop is to provide sound understanding of the basics of RF superconductivity, cavity design, electromagnetic simulations, cavity fabrication, processing & testing; and provide a platform for discussing scientific and engineering issues. There will be in-depth lectures with ample time for discussion and interaction.

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Thank you