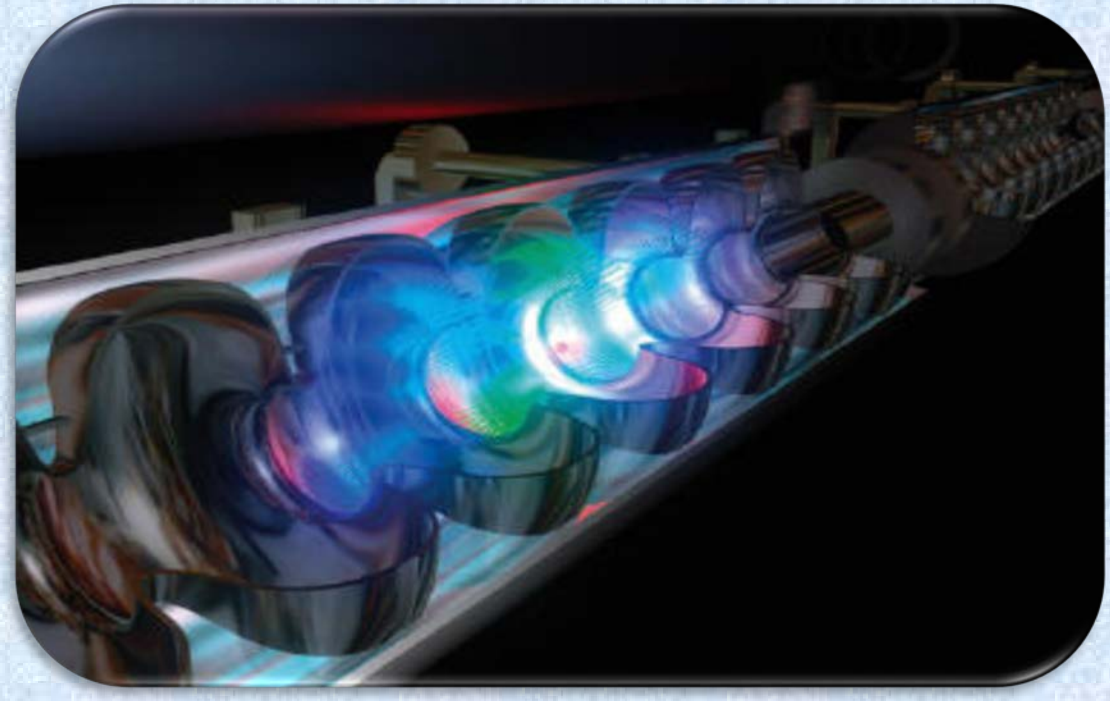
Superconducting RF cavities Fabrication



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RRCAT

DAE-BRNS Workshop on "Technology Development of SCRF cavities"
18-21 July, 2017 , RRCAT Indore

Out line

- Introduction
- Types of SCRF cavities
  - Low, Medium and High Beta
- SCRF cavity manufacturing challenges
- High β Elliptical SCRF cavity fabrication techniques
- High β Elliptical SCRF Cavity fabrication
  - Single cell cavity
    - Fabrication, Inspection and Qualification
  - Multi-cell cavity
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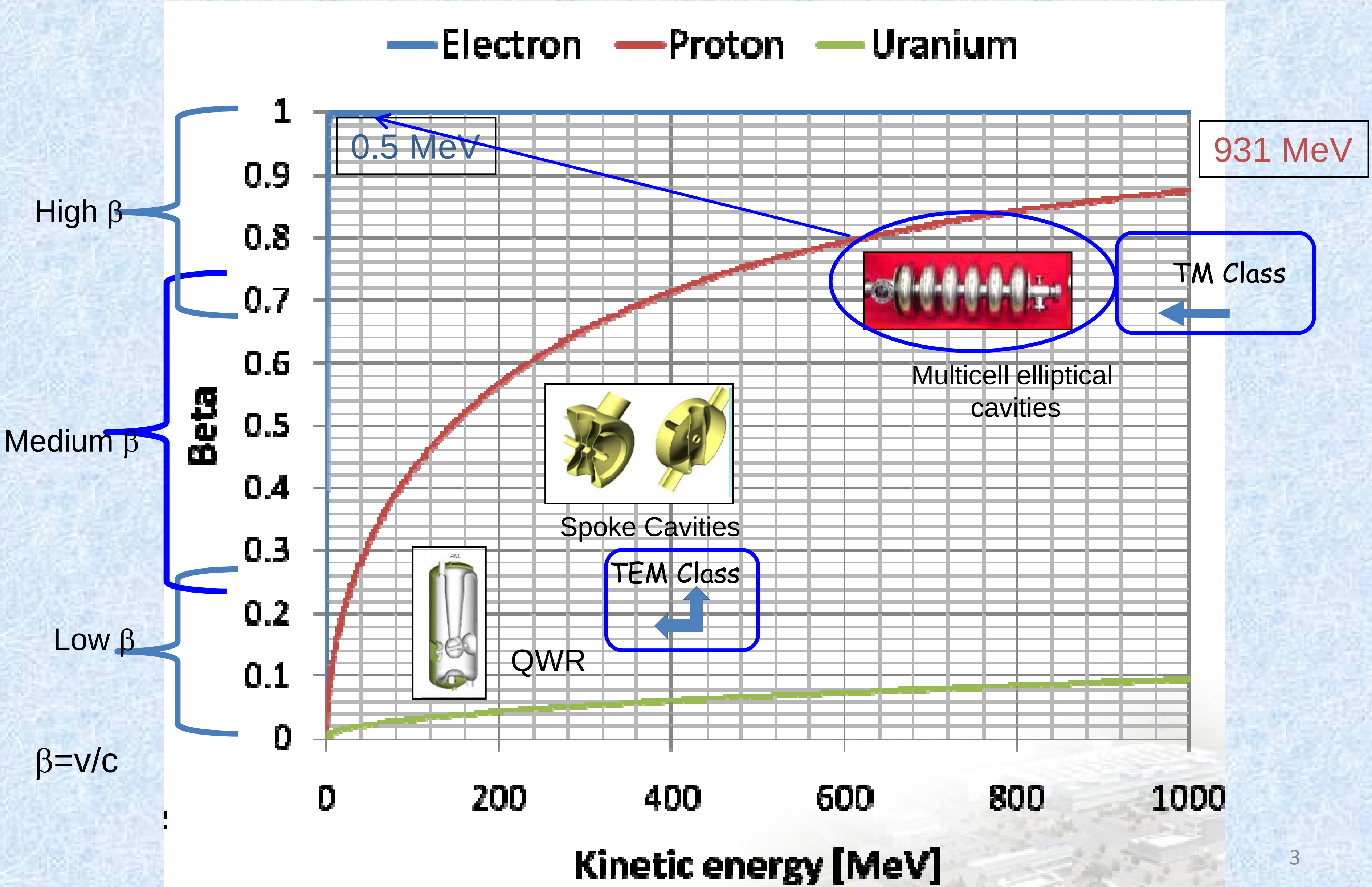
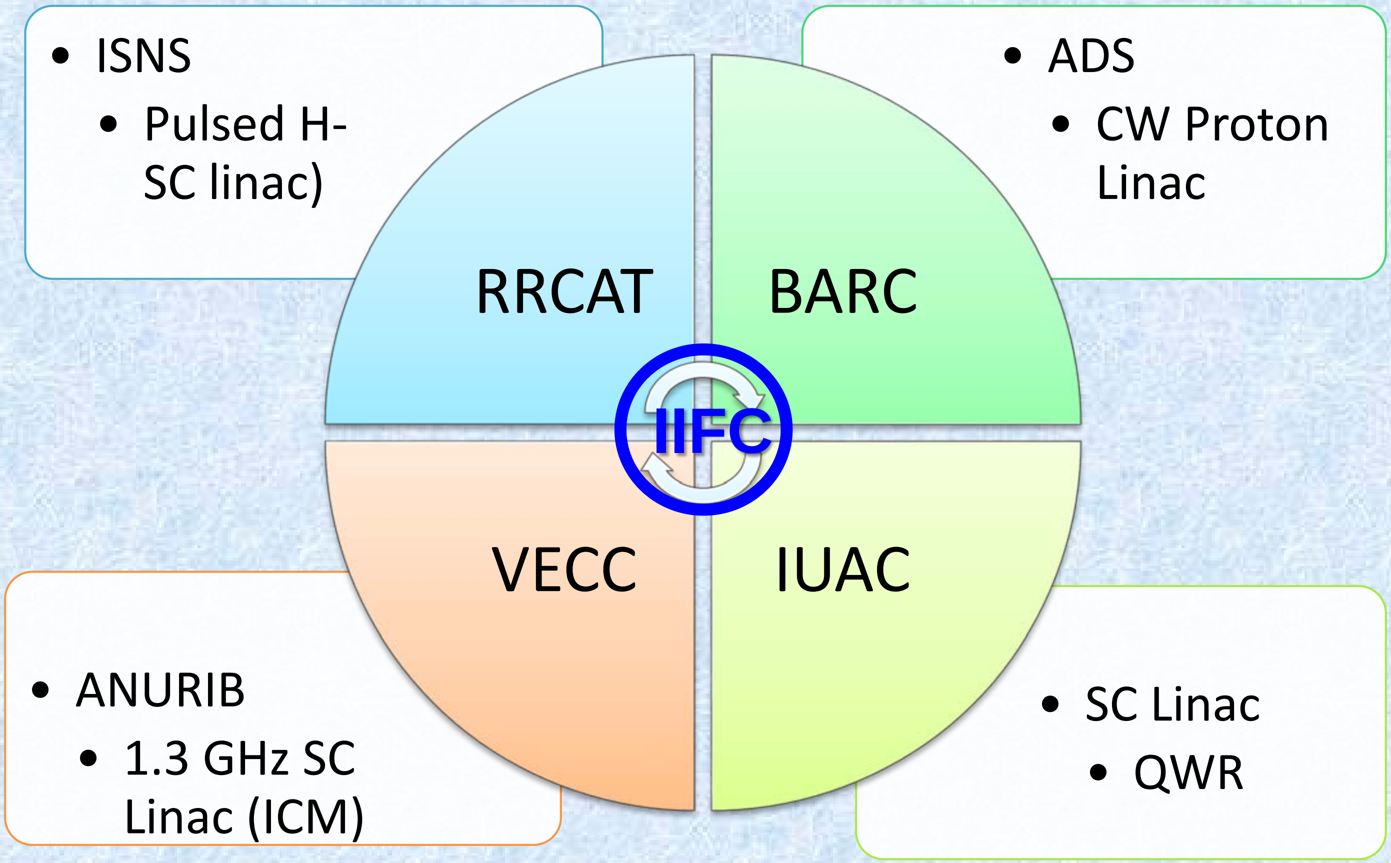
Choice of accelerating cavity as a function of Accelerator Energy and Beta



Commonality of interest in Superconducting RF Science and technology between four major institute working in SC accelerator activity



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SCRF cavity manufacturing challenges

The challenge of SCRF cavity fabrication lies in the fact that one has to mechanically fabricate an electrical structure at 300 K with precise control of EM field having working temperature of 2K for Physics application.

Mechanical Fabrication

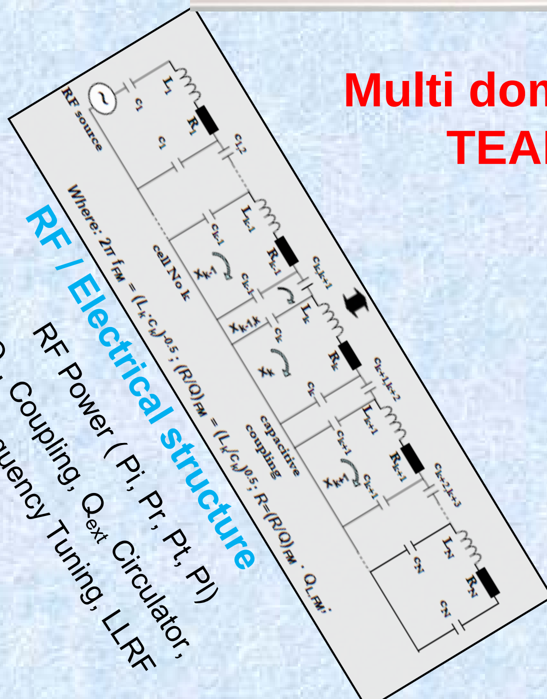
Engineering design,

Fabrication (Forming, Machining, Welding)

Processing

Cryogenics, 4.2 K, 2 K, LHe, LN_2
VTS, HTS

Multi domain activity
TEAM Work

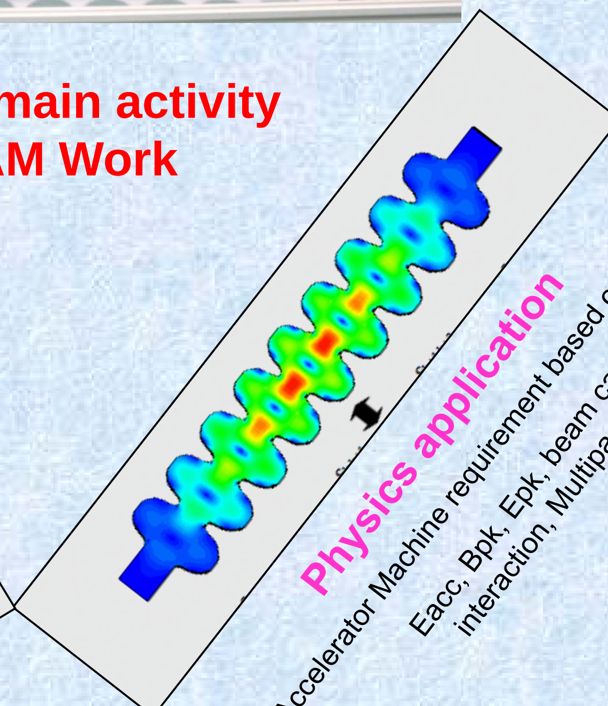


RF / Electrical structure

RF Power (Pi, Pr, Pt, Pl)

Q_o, Coupling, Q_{ext} Circulator,

Frequency Tuning, LLRF



Physics application

Accelerator Machine requirement based on User demand

Eacc, Bpk, Epk, beam cavity interaction, Multipacting,

A proper exposure and understanding of all related science and technology is a must for good cavity Fabrication.

SCRF cavity manufacturing challenges

The SCRF cavities are made of material which is costlier then Sliver !

Working temp. 300 K , operating temperature 2K !!

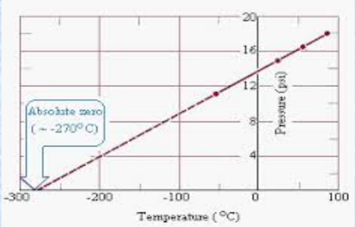
whose performance is affected by micron size impurities !!!

High Q ☺ but operating bandwidth very very small ☹!!!!

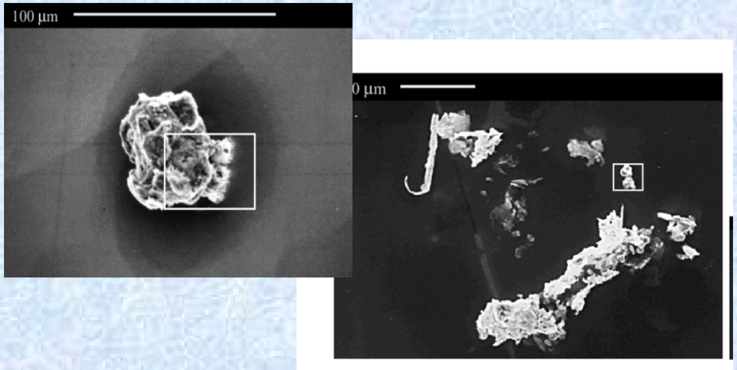
SCRF Cavity

Nb Jewelry

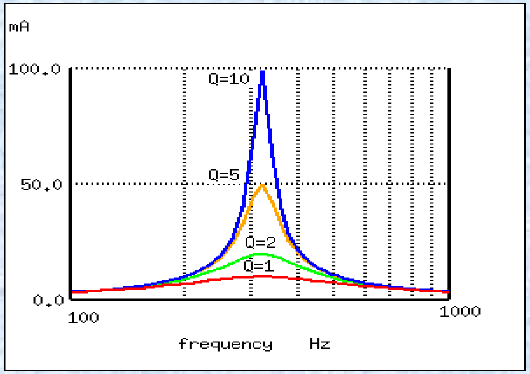
RRR Nb ~ Rs. 60000 per Kg
Silver ~ 40000 per Kg



Change in dimensions and Frequency issues



Micron size defects Acting as poison for the cavity performance



Very low operating band width due to very very high Q

CASE STUDY : 1.3 GHz SCRF cavity

Δf (bandwidth) = $1.3 \times 10^9 / 3 \times 10^6$ = 430 Hz

$\Delta f / \Delta l$ = 315 KHz/mm ➡ 315 Hz/µm

➡ Mechanical bandwidth 1.36 µm !!!

CASE STUDY 650 MHz SCRF cavity

Δf (bandwidth) = $650 \times 10^6 / 1.1 \times 10^7$ = 60 Hz

$\Delta f / \Delta l$ = 150 KHz/mm ➡ 150 Hz/µm

➡ Mechanical bandwidth 0.4 µm !!!

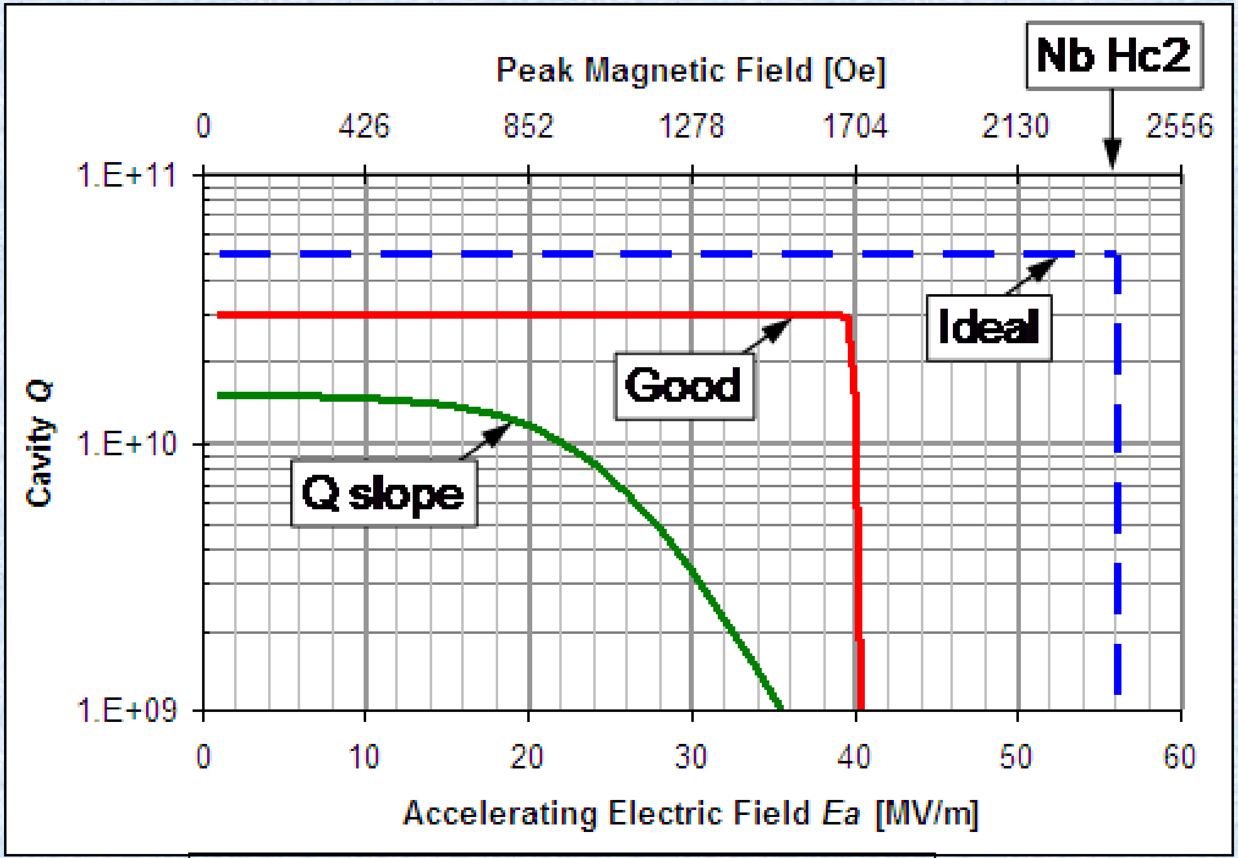
SCRF cavity manufacturing challenges

The SCRF cavities are made of material which is costlier then Sliver !

whose operating temperature is close to Absolute Zero !!

And operating frequency bandwidth few ppm !!!

whose performance is affected by micron size impurities !!!!



Typical Performance curve of SCRF cavity

SCRF cavity manufacturing challenges

The SCRF cavities are made of material which is costlier then Sliver !

whose operating temperature is close to Absolute Zero !!

And operating frequency bandwidth few ppm !!!

whose performance is affected by micron size impurities !!!!

To make the SCRF cavity perform close to ideal performance, its manufacturing and processing requires a highly specialized technology.

Highly controlled quality of material

Mechanical & Electrical –RRR (Chemical)

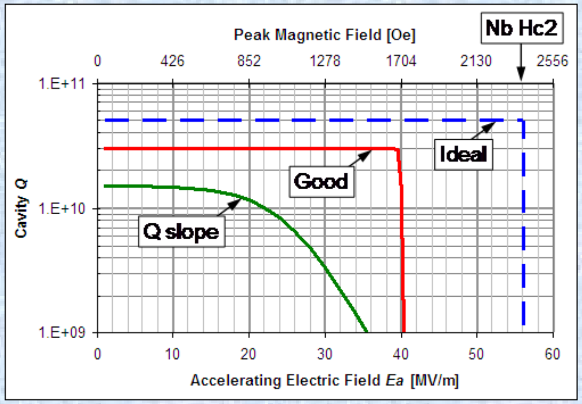
Ultra clean handling of parts during all manufacturing stages

Special forming, welding techniques, machining difficulties (soft)

Stringent control on mech. dimension to control Frequency

Special processing

EP, BCP, CBP, HT, HPR, Clean room (Class 100 & 10)



Any type of non conformity in the manufacturing and/or processing can be found only after final testing at 2 K. By this time there is substantial value addition to the cavity and hence too late to know that.

There are very few (< 10) SCRF cavity manufacturing companies all around the world.
Till today the cavities are made " **<u>Built to print</u>**" not **<u>"Built to performance</u>**".

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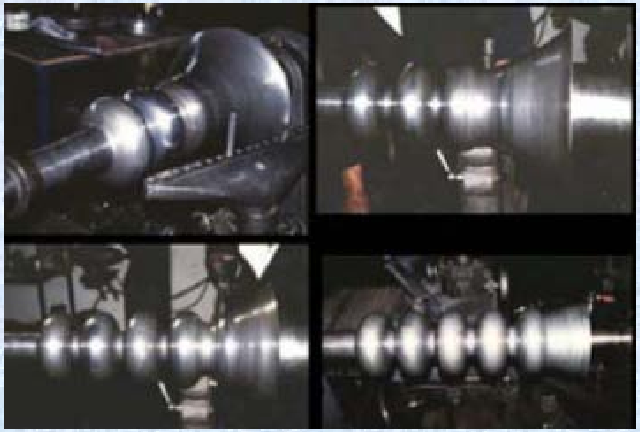
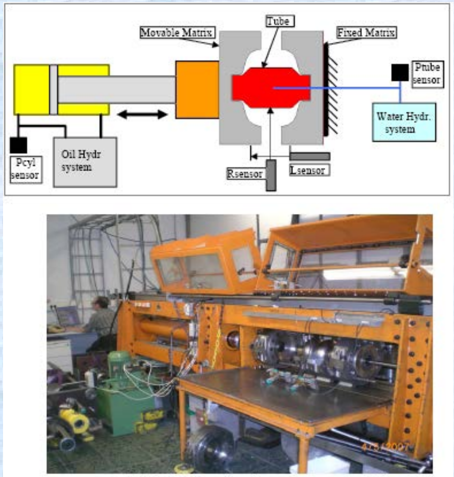
High β Elliptical Cavity manufacturing technique

- Bulk Niobium
  - Seamless
    - Spinning
    - Hydroforming
  - Seam welded
    - E B Welding
    - Laser Welding
- Thin Film
  - Deposition of Nb film on the copper surface
- Additive manufacturing

High β Elliptical Cavity manufacturing technique



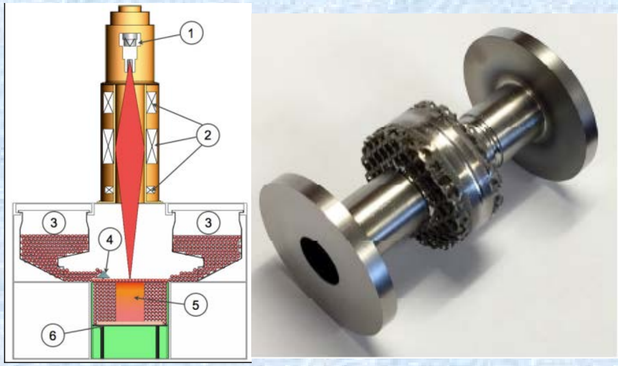
Spinning



DESY hydroforming machine
HYDROFORMA

1.3 GHz Single-cell and Multi-cell cavities have been produced and have been tested to rated performance.

LEP NB coated Cu cavities
15 MV/m @400 MHz



EB Additive manufacturing

Technical requirements for welding of SCRF cavity

- SCRF cavities are made of high RRR Niobium made with impurities controlled to ppm level.
- Niobium has high reactivity with atmospheric agents above 200 °C.
- The melting point of Niobium is also high (> 2400 °C)
- Joints must also be vacuum leak tight at cryogenic working conditions.
- For the optimum RF performance the smoothness of joints is very critical.

Joining of high RRR Nb cavity using EB Welding in high vacuum ($\le 1 \times 10^{-6}$ mbar) is a qualified and approved method to meet these technical requirements.

- Close machining tolerance (50 μm) required.
- Weld parameter development with minimum weld trials simulating thermal mass.
- Controlled and repeatable weld shrinkages.
- Weld joint should not be mechanically strong but also RF quality.
- Full penetration joints are the real nerve tester.

Major specification of machine

Beam power	15 kW **(150 kV x 100 mA)**
Inner size of chamber	3650 x 1500 x 1950 LxBxH mm^3
Vacuum ready pressure	< $4x10^{-4}$ mbar in 15 minutes
Ready for welding pressure	< $2x10^{-6}$ mbar in 30 minutes
Online optics	With CCD camera and suitable illumination system
Rotary Manipulator	Dual spindle Rotary and Tilt rotary
CNC Control axis	7 axis (4 Mechanical + 3 electrical)

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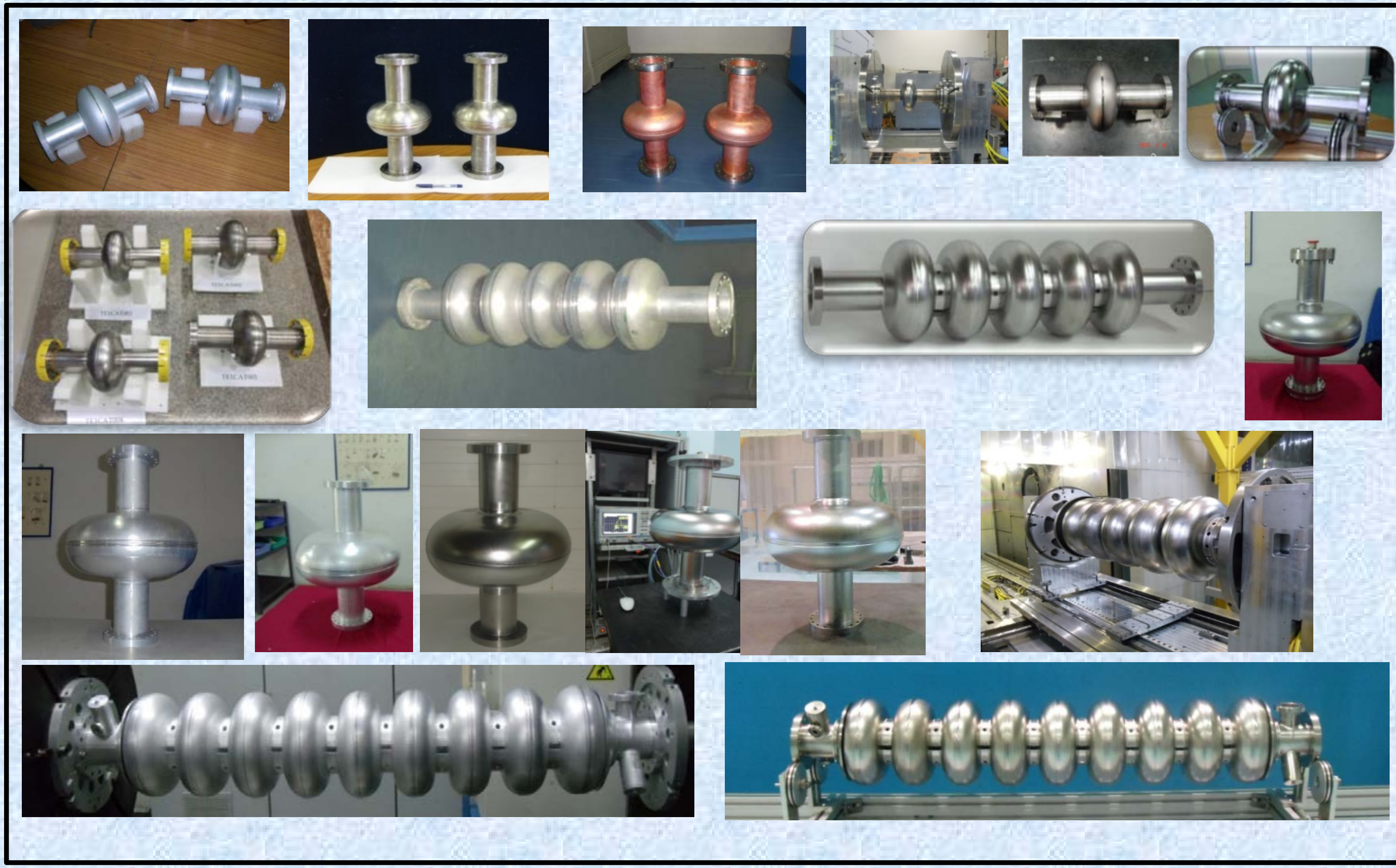
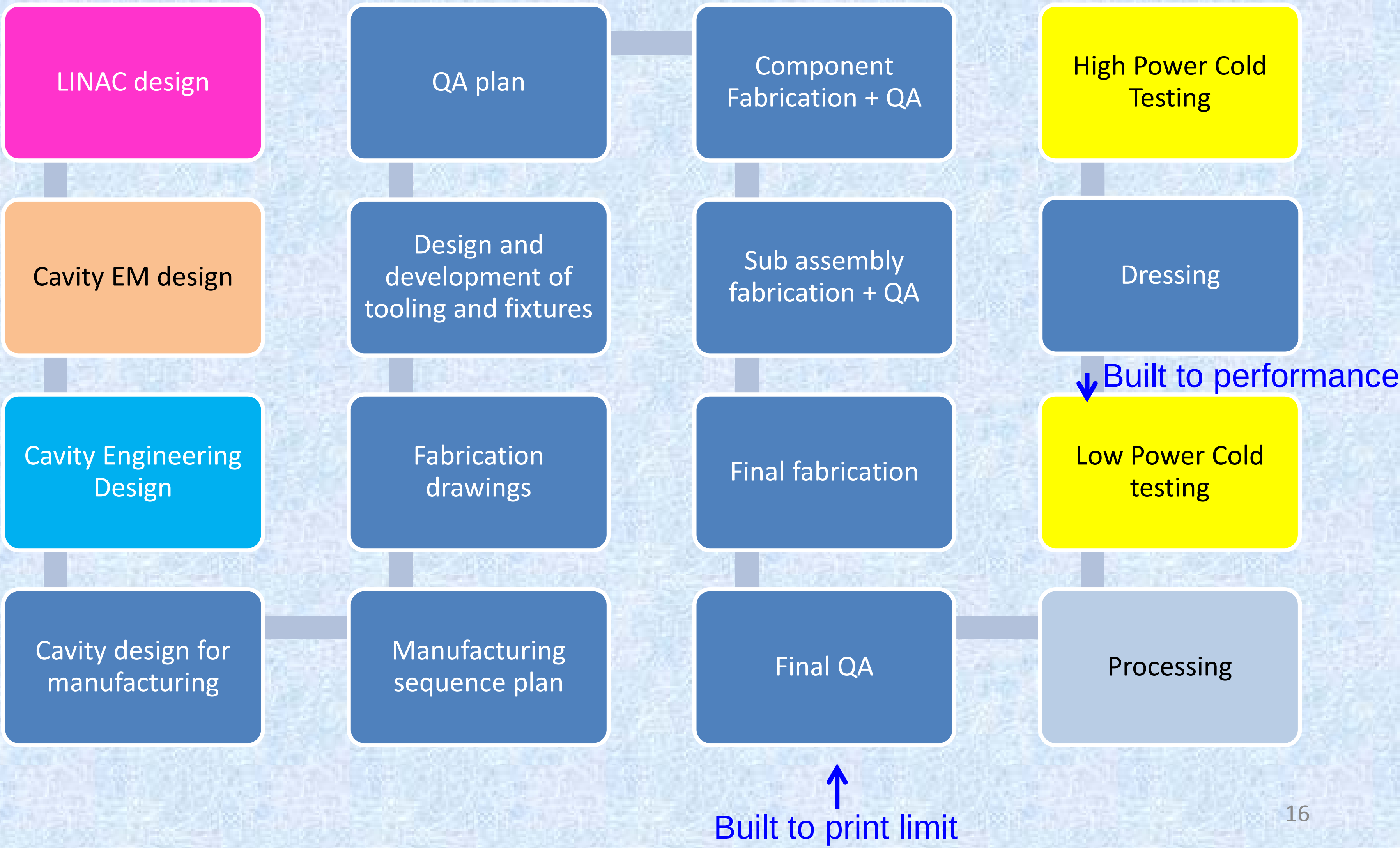
SCRF cavities manufacturing activity at RRCAT



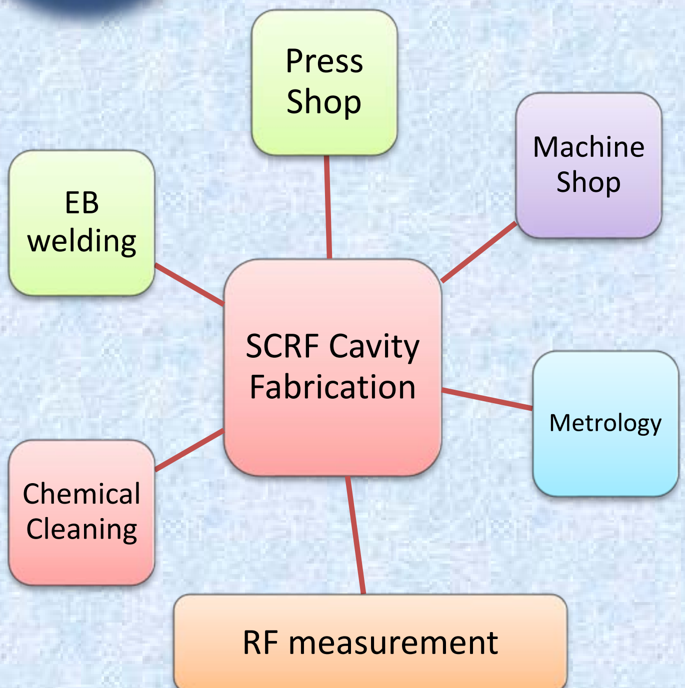
Galaxy of various 1.3 GHz and 650 MHz RF cavities made at RRCAT

Activity Flow Chart



Stages of cavity manufacturing

Manufacturing of SC cavities is an iterative process among various activities



Functional Requirements
Rated performance Q vs E_{acc} Control on Frequency, Field Flatness at 2K
RF quality weld joint

Engineering Requirements:
Fabricability and Geometrical tolerances
Control on Frequency, Field Flatness at 300K
Mechanically rigid to sustain different loads
Weld joint to be mechanically strong and vacuum leak tight joints at 2 K

Single-cell Cavity / Multi-cell Cavity Manufacturing Recipe

In the following overview the sequence of cavity fabrication is summarized.

Aim : Target frequency at Operating temperature keeping every thing clean

1. Optical, mechanical inspection of Nb sheets
2. Cutting Nb sheets to disc
3. Deep drawing of half cells ("inner side" of half cells!)
4. Cutting half cells to length $L = L_{nom} + \delta L_{equ} + \delta L_{iris} + 1$ mm (L_{nom} = nominal length, $\delta L_{equ.}$ = welding shrinkage at equator, δL_{iris} = welding shrinkage at iris + stiffening ring)
5. Prepare welding steps at iris and stiffening ring
6. Degreasing, ultrasonic cleaning, rinsing
7. Frequency measurement, selection of half cells for dumb-bells
8. 20 μm chemical cleaning of half cells (inner and outer surface), rinsing, storage
9. 3 μm chemical cleaning at iris area, rinsing
10. Welding of iris within 8 hours after step 9
11. Welding of stiffening ring
12. Frequency measurement of half-cell assembly / dumb-bells.

Single-cell Cavity / Multi-cell Cavity Manufacturing Recipe

13. Cutting equators of half-cell assembly/dumb-bells to right length according to frequency measurement ("12"), machining welding area.
14. Degreasing
15. Frequency measurement of half-cell assembly/dumb-bells, selection of dumb-bells for welding sequence of cavity
16. Degreasing of half-cell assembly/dumb-bells
17. 20 μm chemical cleaning of half-cell assembly/dumb-bells
18. Inspection of "inner" surface for defects, if OK, continue at step 23
19. In case of defects, Grinding of defects
20. 20 μm chemical cleaning of dumb- bells for cleaning of surface from grinding dirt
21. Go back to step 18
22. Storage of half-cell assembly/dumb-bells
23. 3 μm chemical cleaning at equator region of the dumb-bell to be welded
24. Welding of two half-cell assembly/dumb-bells at equator within 8 hours after step 23
25. Repeat step 23 with longer cavity section

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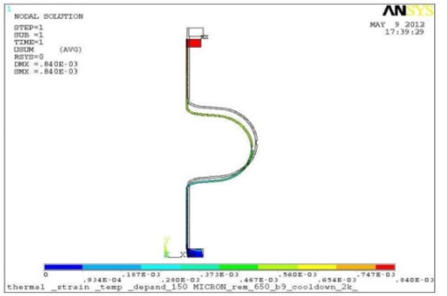
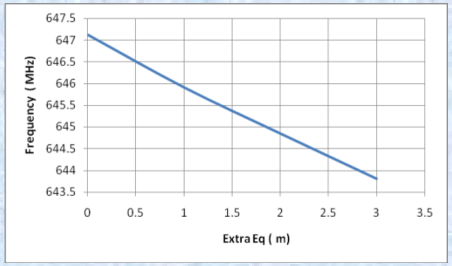
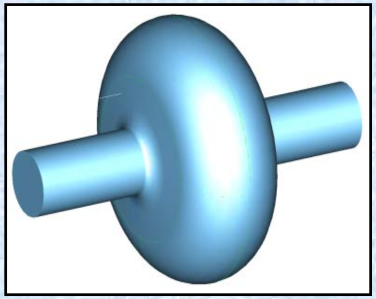
Single cell cavity fabrication development stages

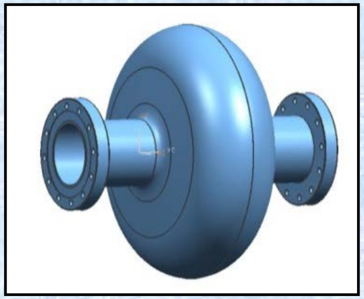
- RF Model ➡ Mechanical design model.
- Design for manufacturing
  - 3-D Modeling in UGNX
  - Detail dimensions with tolerances to suit manufacturability
  - Weld joint design
- Frequency estimation
  - For change in frequency with temperature
  - With extra length of equator to estimate K_{eq} (verified by actual measurements)
- Development of manufacturing process and QA plan
- Qualification
  - Geometrical inspection,
  - RF measurements
  - Leak testing at 300 K & 77K.



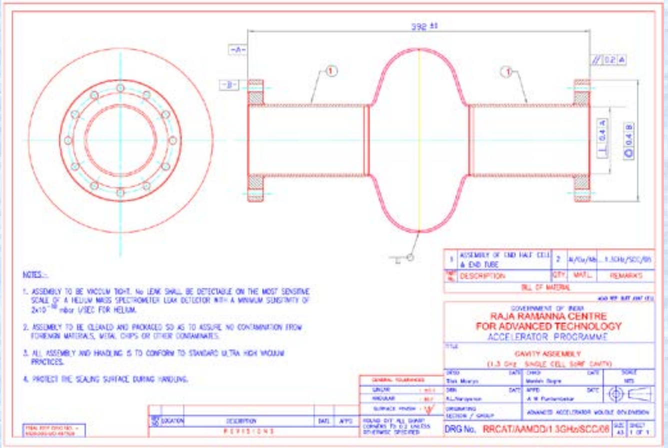




3-D design model
single cell Cavity



Mechanical model
Single-cell Cavity



Fabrication drawing single cell Cavity

Single cell Cavity manufacturing stages

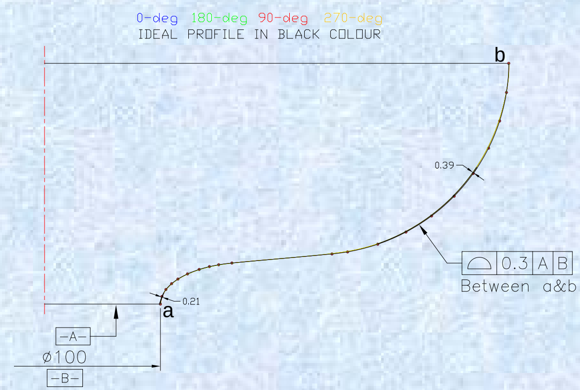

Forming tool

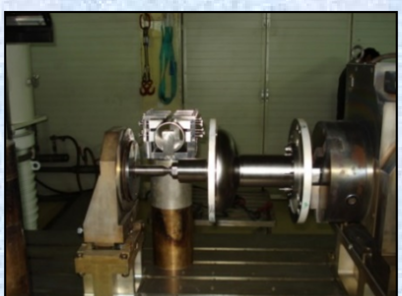

Forming of cells


Mechanical inspection


Machined parts ready for welding


EB welding




EB welding


Welded Half cell assembly

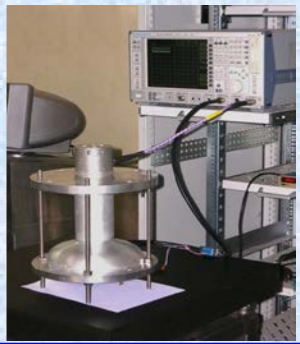

Handling of parts

Single cell Cavity manufacturing stages

Steps before equator welding

Mechanical Measurement → Frequency Measurement → Estimation of trimming length → Trimming of equator length → Ready for Equator weld with weld shrinkage allowance

Mechanical inspection



RF Measurement

Equator trimming

Half cell assembly	Length before (mm)	Frequency before (MHz)	Length after (mm)	Frequency after (MHz)	F- Sensitivity coeff' K_{eq}' MHz/mm
Nb-125	197.84	1289.536	196.82	1292.531	3
Nb-127	198.42	1291.315	197.29	1294.197	2.6

Single cell Cavity manufacturing stages

Final Equator welding

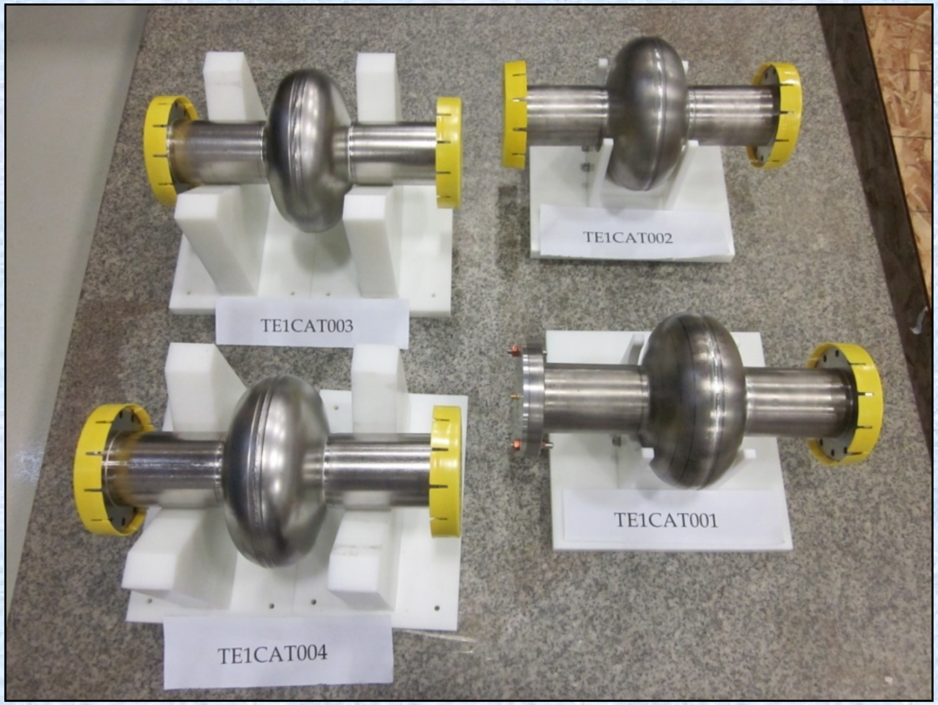
Dimensional measurement

Frequency measurement

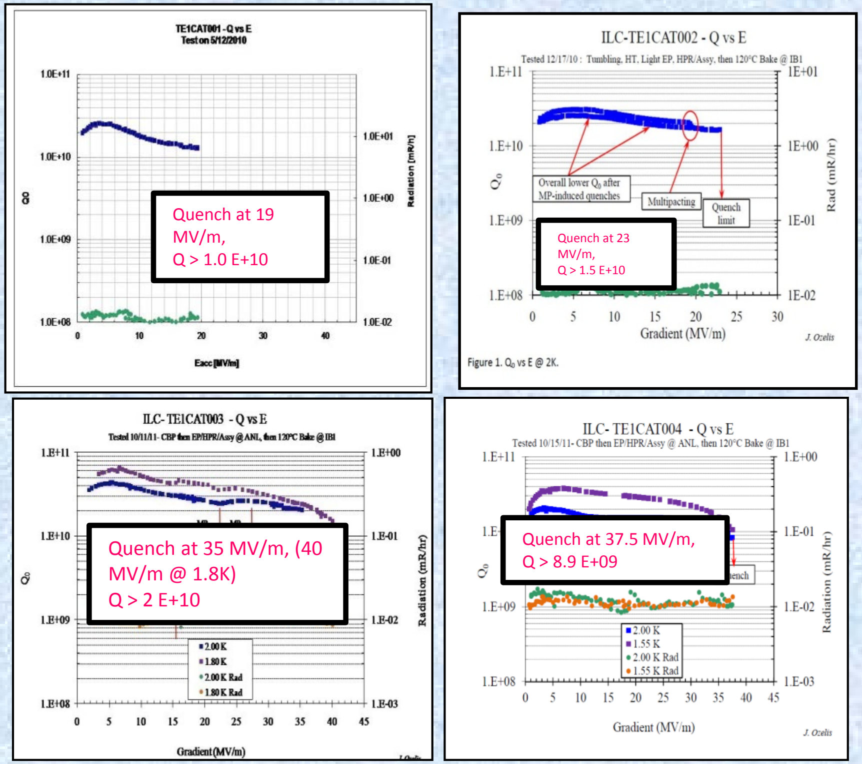
Vacuum leak testing

Niobium cell	Total length (mm) (392 ±1)	Parallelism (mm)	Shrinkage equator (mm)	Frequency (MHz) 300K	Quality factor 300 K
1.3 GHz 1-cell cavity	393.52	0.10	0.47	1296.926	9076
650 MHz 1-cell cavity	567.617	0.42	1.1	648.58474	12094

1.3 GHz single cell SCRF cold testing results



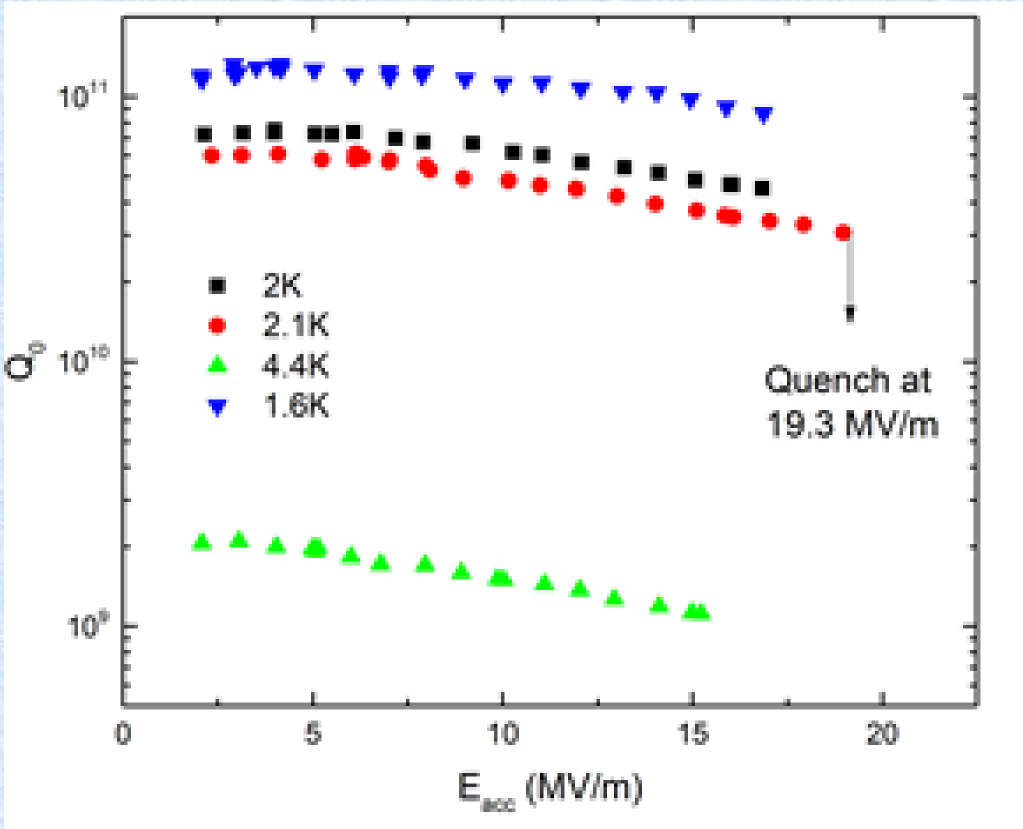
1.3 GHz Single cell SCRF cavities



2 K Test results of the 1.3 GHz Single cell SCRF cavities

Test results 650 MHz SCRF cavity

650 MHz Five cell cavity ready for cold test



Q vs E plot

Test Result : E_{acc} 19.3 MV/m with Q > $4x10^{10}$ at 2K, Design parameters 17 MV/m with Q= $2x10^{10}$ at 2 K.

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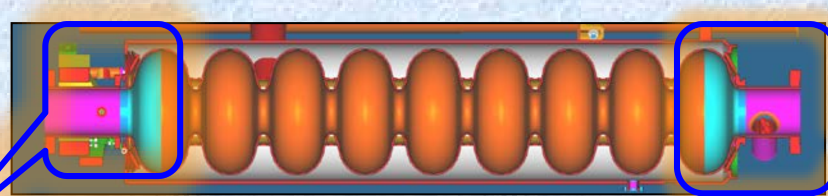
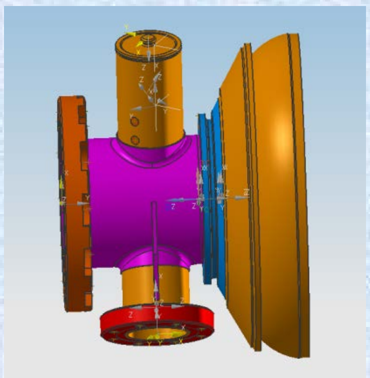
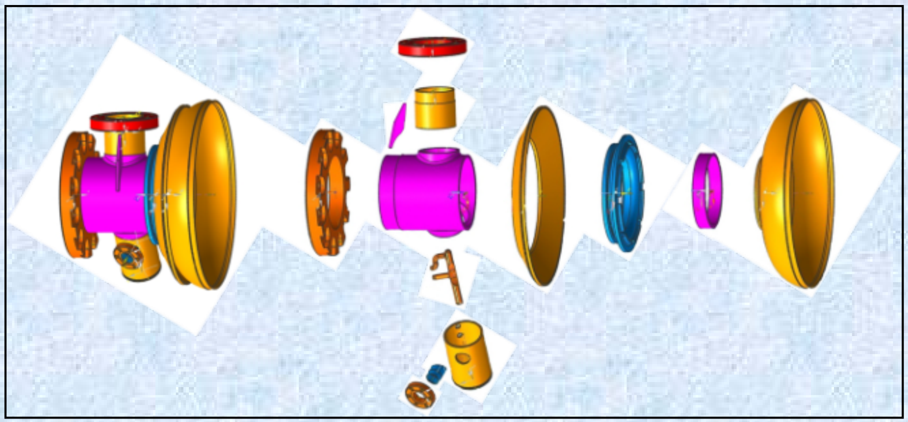
Elliptical cavity manufacturing stages

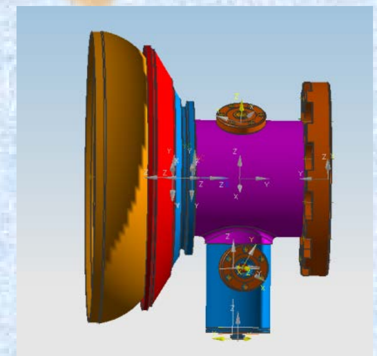


1.3 GHz Nine cell SCRF cavity

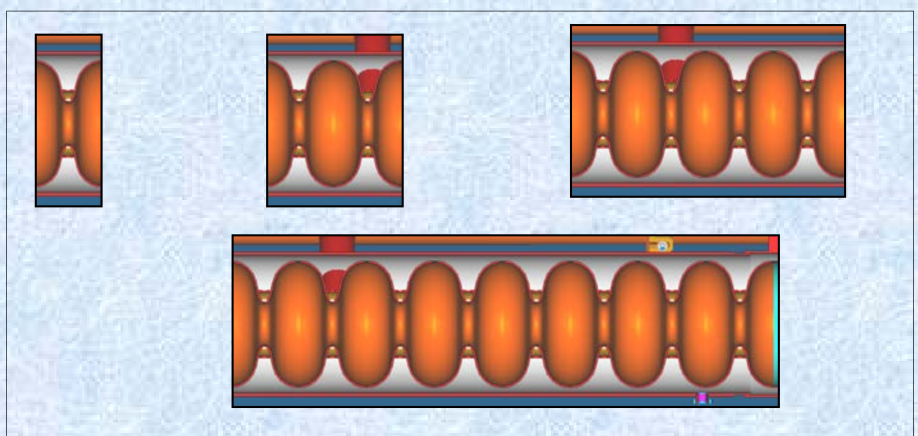


Short End EG

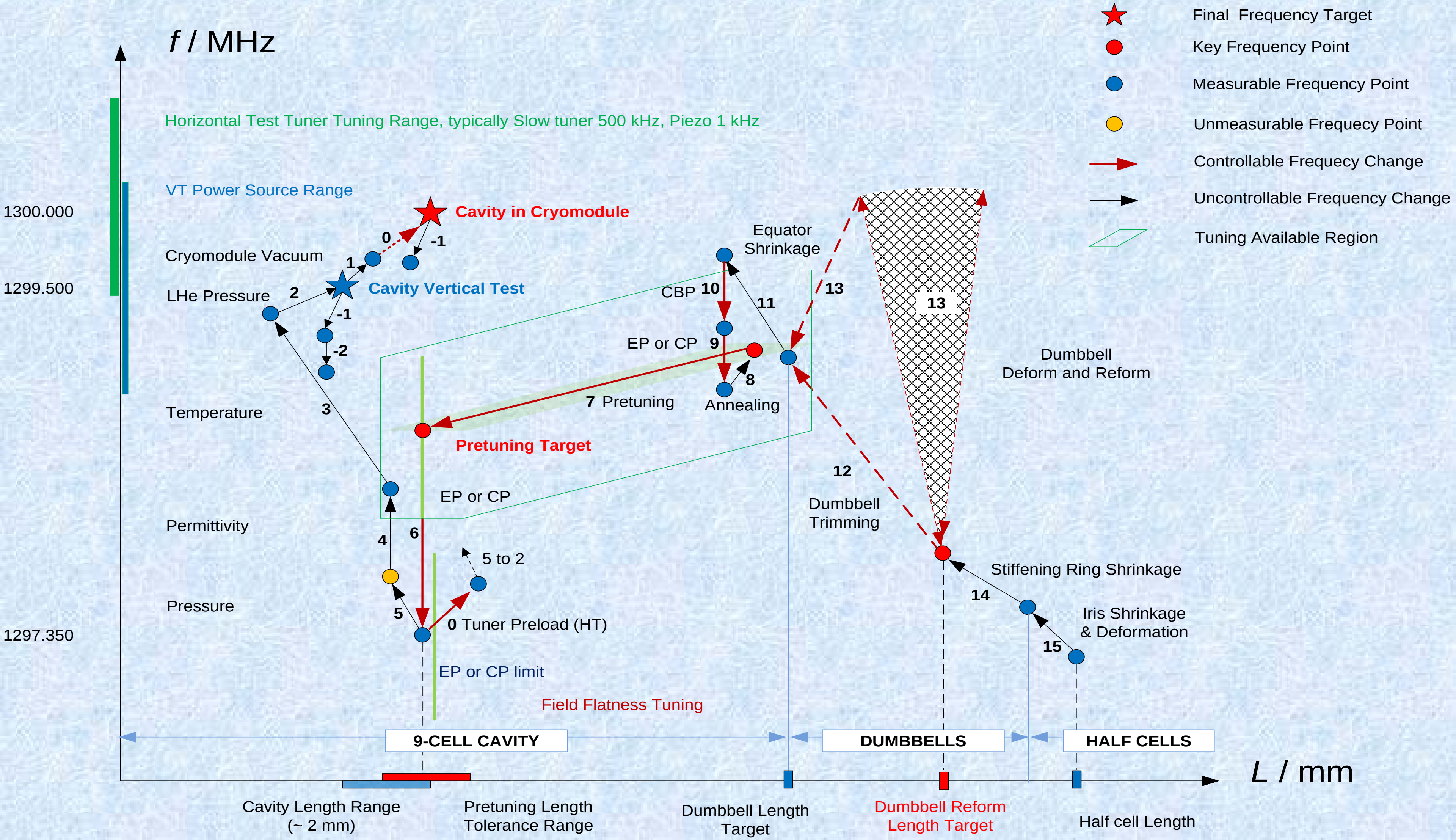




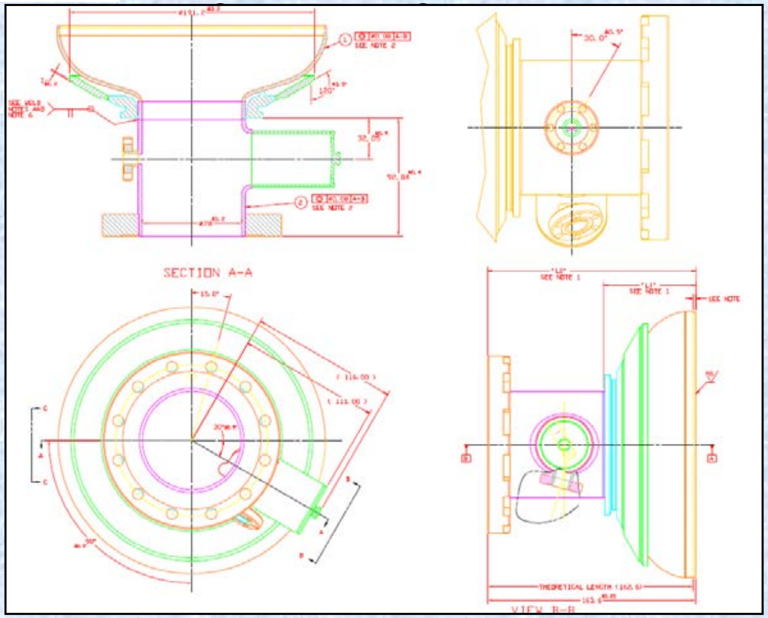
Long End EG



Cavity Frequency Change and control



SCRF cavity fabrication process planning



Fabrication drawings

2) Sub Assemblies:

2.8) Assembly Name: Short End Half Cell Assembly
Drawing #: RRCAT/LVCDS/CJQL/1.3GHz/NCC/29
FNAL Ref #: 4904.010-MD-400003

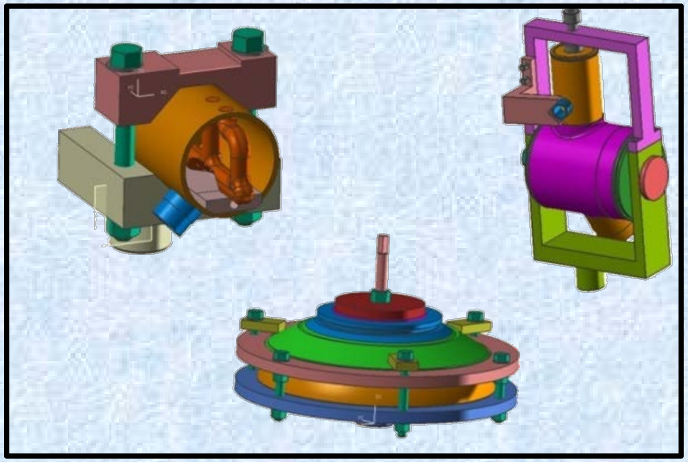
Measured Values:

Component	Dimension	Tolerance	Actual Value	Acceptable/ Not Acceptable	Remarks
Total Length	162.6*	±0.2			
Length NW 78 to End Disk Flange	93.5	±0.4			
Short End Tube	Ø78	±0.2			
	32.9	±0.5			
Short HOM Assembly	35°	±0.5°			
	15°	±0.5°			
NW40 Flange	88	±0.2			
Short End Cap Disk	1	±0.2			
	120°	±0.2°			
	Ø 200	±0.2			
	90°	±1°			

Frequency at 20°C measured in welded condition	Value (MHz)	Length		Remarks
		Total	Equator 1.00	
Theoretical				

	End tube Weldment		Half cell end Disk Weldment		Total
	71.5	+	94.1	=	165.6
After Welding					
shrinkage length (End tube weld)	shrinkage length (End tube weld		Extra length beyond flange		Total
0.5	0.5	+	2.0	=	3
	Total Length after welding		165.6 - 3.0	=	162.6*

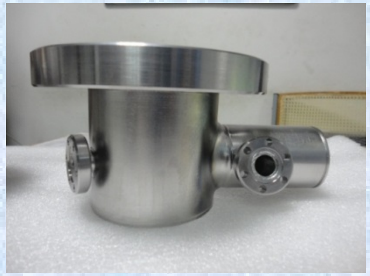
Quality control documents



Various Welding Fixtures

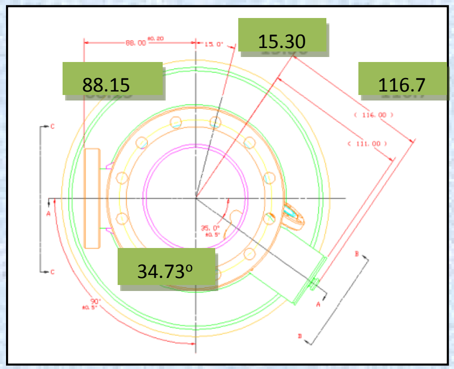
End Group Fabrication stages

Machined parts



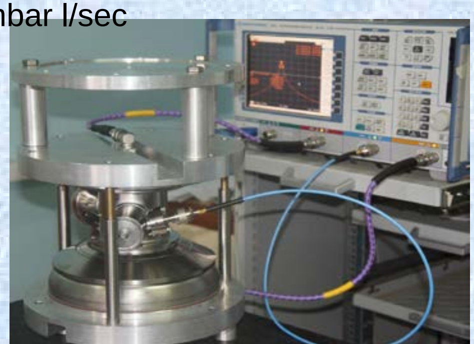
Welding sub assembly stages

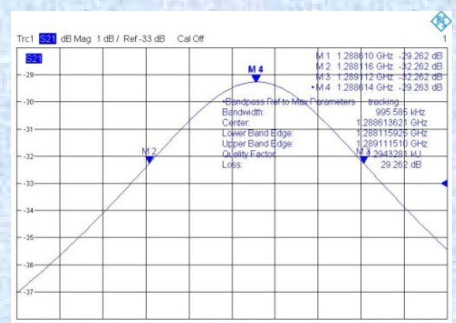
Completed End Group



Cell ID	Length (mm)	Π-mode frequency (MHz)	Quality Factor
144 Long End Cell	163.98	1296.5850	1880
164 Short End Cell	163.30	1294.4005	1922

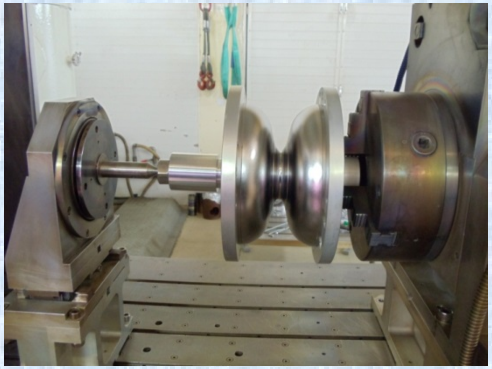
Leak rate of < 1 x 10^{-10} mbar l/sec



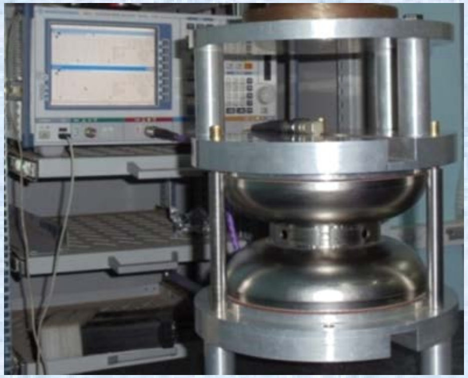


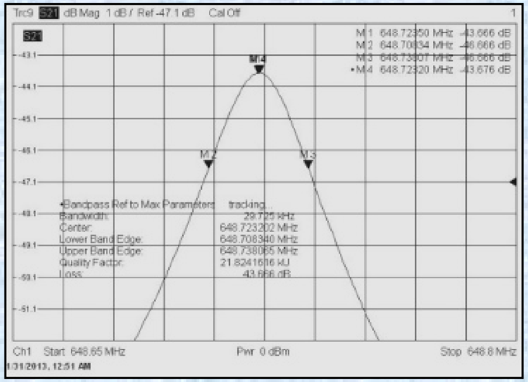
RF Measurement and qualification

Dumb-bell fabrication, testing and qualification



Dumbbell fabrication



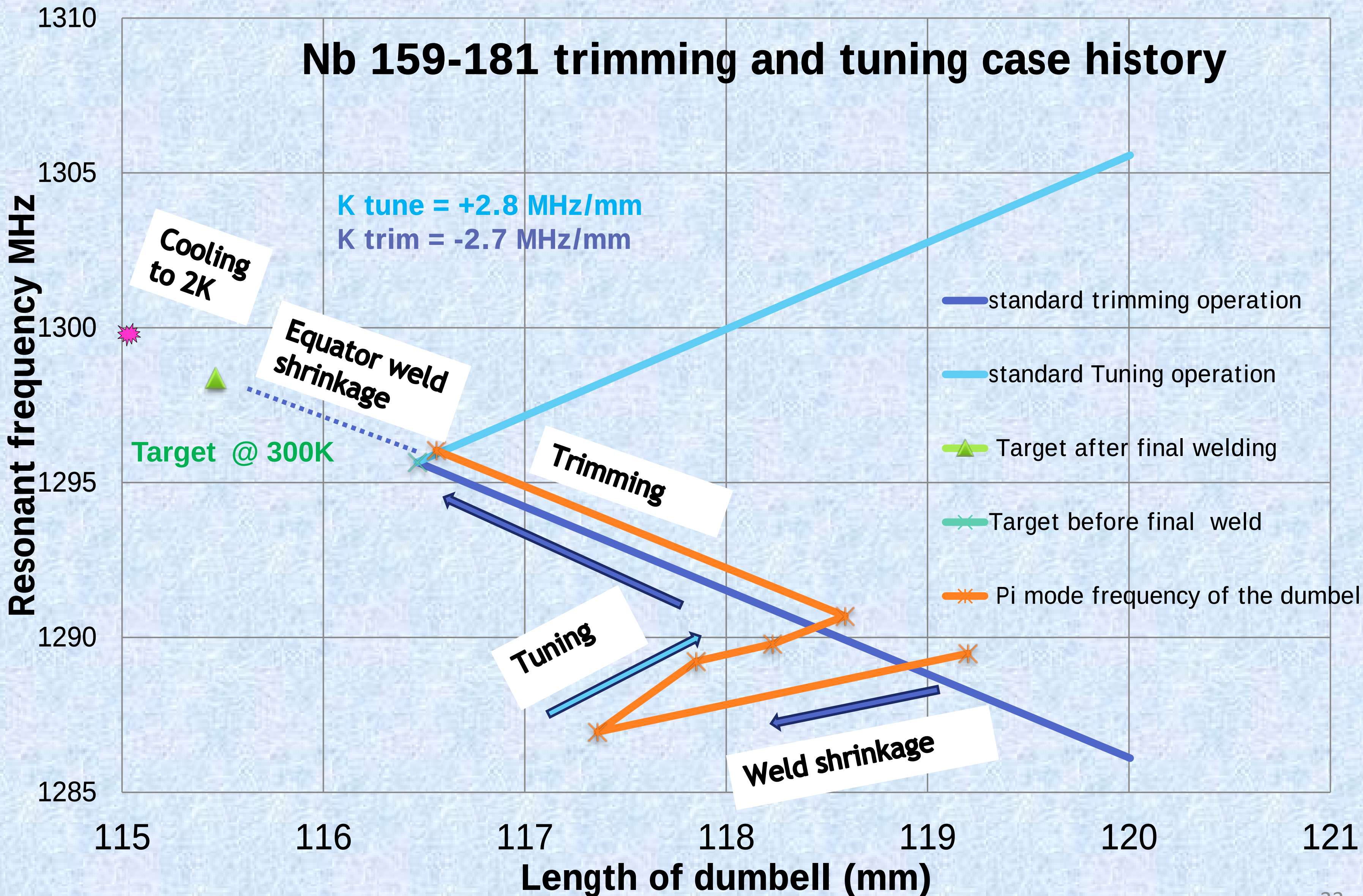


RF Measurement

Mech. Inspection

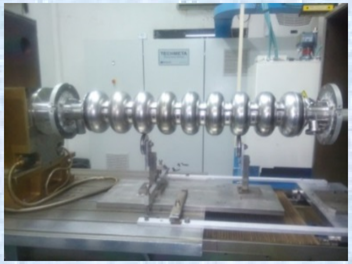
Dumbbell qualification

Dumbbell RF tuning



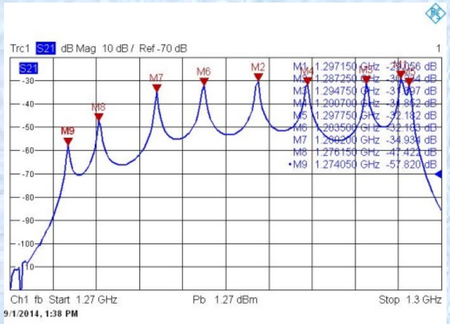
Multi-cell SCRF cavity

End Group and Dumb-bells

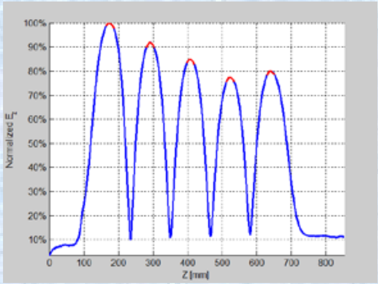


E B Welding stages

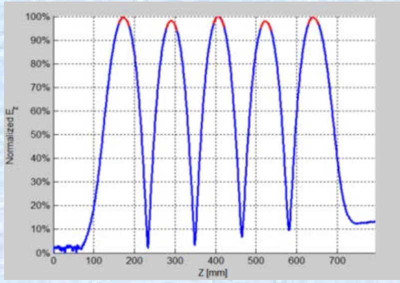
1.3 GHz nine cell SCRF cavity



RT π - Mode frequency (GHz) 1.297150



Field Flatness as fabricated 77 %

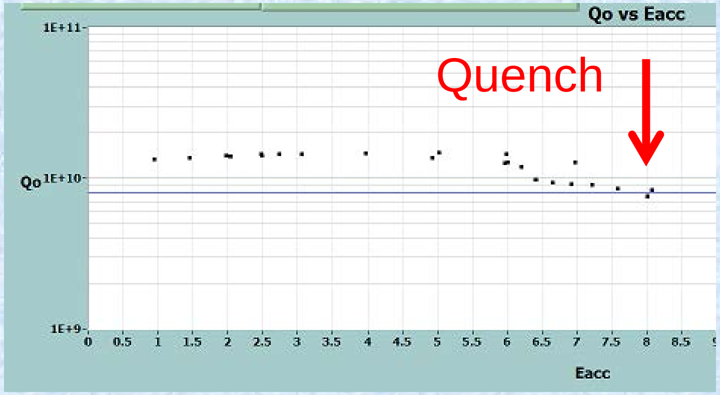


Field Flatness after tuning = 98%

1.3 GHz Five-cell SCRF cavity

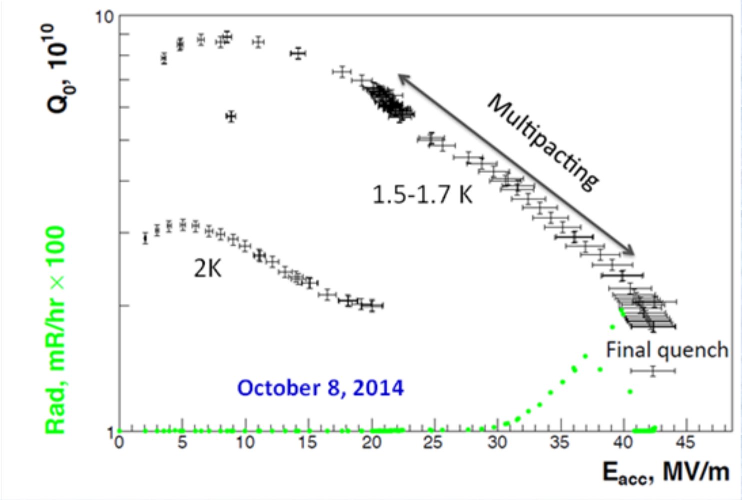
Dimension	Basic Size / Tolerance	Measured Value
Length	1247.4 ±3	1246.98
Perpendicularity (Front flange)	0.8	0.49
Perpendicularity (Back flange)	0.8	0.25
Concentricity Equator #1 to 9	0.8	0.52 to 0.94 (min to max)

1.3 GHz Five-cell cavity Cold test results



During first cold test run the cavity was quench limited to (Eacc) of 8.1 MV/m with Q_0 of $8x10^9$ at 2K during

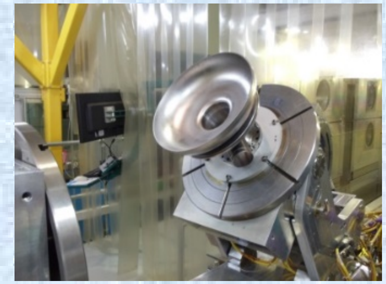
1.3 GHz Five cell cavity ready for cold test



Defect observed during optical inspection

Achieved accelerating gradient (Eacc) of 20.3 MV/m at 2 K and **42 MV/m** **at 1.5-1.7 K with** **Q_0 of 2×10^{10}**

HB650 MHz bare five-cell SCRF cavity



Cavity fabrication stages

“1st Five-cell SCRF cavity
RRCAT-HB92-5001”.
Total length 1403 mm

“RF qualification
Frequency at 300 K: 649.5922 MHz
Field Flatness (as fabricated) = 68%.

“Vacuum leak testing
Leak rate < 10^{-10} mbar-litres/s

SCRF cavity qualification

Summary

- Manufacturing of SC cavities is an iterative process among Press shop, Machine shop, Metrology, RF measurement, Chemical cleaning, EB welding and Final leak testing.
- The challenge of SCRF cavity fabrication lies in the fact that one has to mechanically fabricate an electrical structure at 300 K for precise control on EM field having working temperature of 2K.
- To make the SC cavity perform close to ideal performance, its manufacturing, processing, assembly and testing requires a highly specialized technology.
- Standard protocols are established for SCRF cavities fabrication for their successful operation is accelerators, which needs to be strictly adhered too.
- Vigil on cavity frequency and surface cleanliness are of utmost importance at each stage.

Acknowledgement

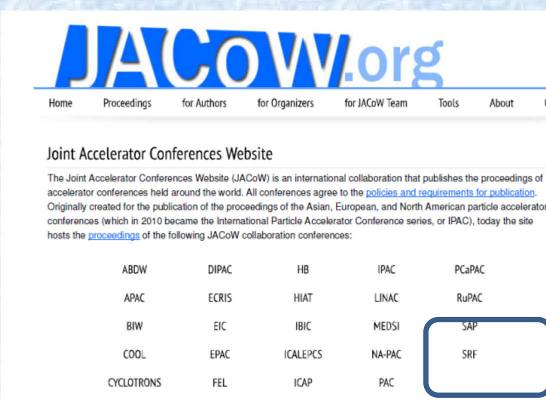
Team members from :

Industrial Accelerator Division,Pulsed High Power Microwave Division

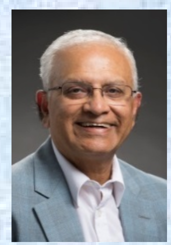
Design and Manufacturing Technology Division along with members of our Proton Linac and SC Cavities Division.

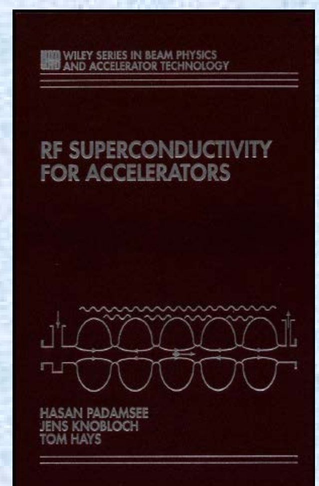
IUAC, New Delhi and Fermilab as collaborators

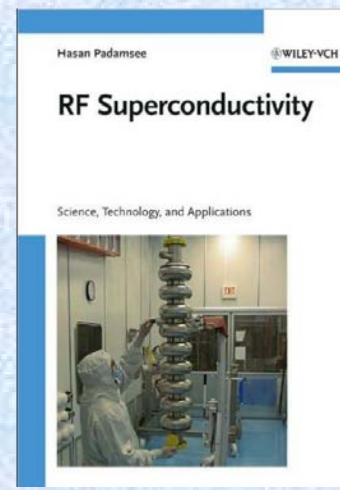
Reference



SRF







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Thank You for your kind attention