Superconducting RF cavities Fabrication

Avinash Puntambekar
Head, SCRF Cavity Development Section
Proton LINAC & SC Cavity Division
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 $\beta$ Elliptical SCRF cavity fabrication techniques
• High $\beta$ Elliptical SCRF Cavity fabrication
  • Single cell cavity
    • Fabrication, Inspection and Qualification
  • Multi-cell cavity
    • Fabrication, Inspection and Qualification
• Summary
Choice of accelerating cavity as a function of Accelerator Energy and Beta

\[ \beta = \frac{v}{c} \]

Low \( \beta \)  
Medium \( \beta \)  
High \( \beta \)

\( \beta = \frac{v}{c} \)

Choice of accelerating cavity as a function of Accelerator Energy and Beta

- Electron
- Proton
- Uranium

Kinetic energy [MeV]

0.5 MeV  
931 MeV

- Multicell elliptical cavities
- Spoke Cavities
- QWR
- TEM Class
- TM Class
Commonality of interest in Superconducting RF Science and technology between four major institute working in SC accelerator activity

- ISNS
  - Pulsed H-SC linac)

- ANURIB
  - 1.3 GHz SC Linac (ICM)

- ADS
  - CW Proton Linac

- SC Linac
  - QWR
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
    • Fabrication, Inspection and Qualification
• Summary
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.

Engineering design,
Fabrication (Forming, Machining, Welding)

Processing
Cryogenics, 4.2 K, 2 K, LHe, LN₂
VTS, HTS

Multi domain activity
TEAM Work

RF / Electrical structure
Q₀, Coupling, P₀, Pt, Pi, Frequency Tuning, LRF

Physics application
Accelerator Machine requirement based on User demand
Eacc, Bok, 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 than Silver!

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

whose performance is affected by micron size impurities !!!

High Q 😊 but operating bandwidth very very small 😞!!!!

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

Very low operating bandwidth due to very very high Q

Change in dimensions and Frequency issues

CASE STUDY: 1.3 GHz SCRF cavity
\[ \Delta f \text{ (bandwidth)} = \frac{1.3 \times 10^9}{3 \times 10^6} = 430 \text{ Hz} \]
\[ \Delta f / \Delta l = 315 \text{ KHz/mm} \rightarrow 315 \text{ Hz/µm} \]

Mechanical bandwidth 1.36 µm !!!

CASE STUDY 650 MHz SCRF cavity
\[ \Delta f \text{ (bandwidth)} = \frac{650 \times 10^6}{1.1 \times 10^7} = 60 \text{ Hz} \]
\[ \Delta f / \Delta l = 150 \text{ KHz/mm} \rightarrow 150 \text{ Hz/µm} \]

Mechanical bandwidth 0.4 µm !!!
SCRF cavity manufacturing challenges

The SCRF cavities are made of material which is costlier than Silver!
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 than 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 “Built to print” not “Built to performance”.

Out line

• Introduction
• Types of SCRF cavities
  • Low, Medium and High Beta
• SCRF cavity manufacturing challenges
• High $\beta$ Elliptical SCRF cavity fabrication techniques
• High $\beta$ Elliptical SCRF Cavity fabrication
  • Single cell cavity
    • Fabrication, Inspection and Qualification
  • Multi-cell cavity
    • Fabrication, Inspection and Qualification
• Summary
High $\beta$ 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 $\beta$ Elliptical Cavity manufacturing technique

Spinning

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 ( < $1 \times 10^{-6}$ 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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power</td>
<td>15 kW (150 kV x 100 mA)</td>
</tr>
<tr>
<td>Inner size of chamber</td>
<td>3650 x 1500 x 1950 mm³</td>
</tr>
<tr>
<td>Vacuum ready pressure</td>
<td>&lt; $4 \times 10^{-4}$ mbar in 15 minutes</td>
</tr>
<tr>
<td>Ready for welding pressure</td>
<td>&lt; $2 \times 10^{-6}$ mbar in 30 minutes</td>
</tr>
<tr>
<td>Online optics</td>
<td>With CCD camera and suitable illumination system</td>
</tr>
<tr>
<td>Rotary Manipulator</td>
<td>Dual spindle Rotary and Tilt rotary</td>
</tr>
<tr>
<td>CNC Control axis</td>
<td>7 axis (4 Mechanical + 3 electrical)</td>
</tr>
</tbody>
</table>
Out line

• Introduction
• Types of SCRF cavities
  • Low, Medium and High Beta
• SCRF cavity manufacturing challenges
• High $\beta$ Elliptical SCRF cavity fabrication techniques
• High $\beta$ Elliptical SCRF Cavity fabrication
  • Single cell cavity
    • Fabrication, Inspection and Qualification
  • Multi-cell cavity
    • Fabrication, Inspection and Qualification
• Summary
SCRF cavities manufacturing activity at RRCAT

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

1. LINAC design
2. Cavity EM design
3. Cavity Engineering Design
4. Cavity design for manufacturing
5. QA plan
6. Design and development of tooling and fixtures
7. Fabrication drawings
8. Component Fabrication + QA
9. Sub assembly fabrication + QA
10. Final fabrication
11. Final QA
12. High Power Cold Testing
13. Dressing
14. Low Power Cold testing
15. Processing

Built to performance
Built to print limit
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 2K
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 $L = L_{\text{nom}} + \delta L_{\text{equ}} + \delta L_{\text{iris}} + 1$ mm ($L_{\text{nom}} =$ nominal length, $\delta L_{\text{equ.}} =$ welding shrinkage at equator, $\delta L_{\text{iris}} =$ 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 $\mu$m chemical cleaning of half cells (inner and outer surface), rinsing, storage
9. 3 $\mu$m 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.
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
Out line

• Introduction
• Types of SCRF cavities
  • Low, Medium and High Beta
• SCRF cavity manufacturing challenges
• High $\beta$ Elliptical SCRF cavity fabrication techniques
• High $\beta$ Elliptical SCRF Cavity fabrication
  • Single cell cavity
    • Fabrication, Inspection and Qualification
  • Multi-cell cavity
    • Fabrication, Inspection and Qualification
• Summary
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.
Single cell Cavity manufacturing stages

- Forming tool
- Forming of cells
- Machined parts ready for welding
- EB welding
- Welded Half cell assembly
- Mechanical inspection
- EB welding
- 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

<table>
<thead>
<tr>
<th>Half cell assembly</th>
<th>Length before (mm)</th>
<th>Frequency before (MHz)</th>
<th>Length after (mm)</th>
<th>Frequency after (MHz)</th>
<th>F- Sensitivity coeff $K_{eq}$ MHz/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb-125</td>
<td>197.84</td>
<td>1289.536</td>
<td>196.82</td>
<td>1292.531</td>
<td>3</td>
</tr>
<tr>
<td>Nb-127</td>
<td>198.42</td>
<td>1291.315</td>
<td>197.29</td>
<td>1294.197</td>
<td>2.6</td>
</tr>
</tbody>
</table>
**Single cell Cavity manufacturing stages**

<table>
<thead>
<tr>
<th>Niobium cell</th>
<th>Total length (mm) (392 ±1)</th>
<th>Parallelism (mm)</th>
<th>Shrinkage equator (mm)</th>
<th>Frequency (MHz) 300K</th>
<th>Quality factor 300 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 GHz 1-cell cavity</td>
<td>393.52</td>
<td>0.10</td>
<td>0.47</td>
<td>1296.926</td>
<td>9076</td>
</tr>
<tr>
<td>650 MHz 1-cell cavity</td>
<td>567.617</td>
<td>0.42</td>
<td>1.1</td>
<td>648.58474</td>
<td>12094</td>
</tr>
</tbody>
</table>
1.3 GHz single cell SCRF cold testing results

Quench at 19 MV/m,
Q > 1.0 E+10

Quench at 23 MV/m,
Q > 1.5 E+10

Quench at 35 MV/m, (40 MV/m @ 1.8K)
Q > 2 E+10

Quench at 37.5 MV/m,
Q > 8.9 E+09

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 $Q > 4 \times 10^{10}$ at 2K,
Design parameters: $17$ MV/m with $Q = 2 \times 10^{10}$ at 2 K.
Out line

- Introduction
- Types of SCRF cavities
  - Low, Medium and High Beta
- SCRF cavity manufacturing challenges
- High $\beta$ SCRF cavity fabrication techniques
- High $\beta$ Elliptical Cavity fabrication
  - Single cell cavity
    - Fabrication, Inspection and Qualification
  - Multi-cell cavity
    - Fabrication, Inspection and Qualification
- Summary
Elliptical cavity manufacturing stages

1.3 GHz Nine cell SCRF cavity

Short End EG

Long End EG
Cavity Frequency Change and control

\[ f / \text{MHz} \]

- **Cavity in Cryomodule**
- **Cavity Vertical Test**
- **Pretuning Target**
- **EP or CP limit**
- **Field Flatness Tuning**
- **Cryomodule Vacuum**
- **LHe Pressure**
- **Temperature**
- **Permittivity**
- **Pressure**

**Key Points**:
- **Final Frequency Target**
- **Key Frequency Point**
- **Measurable Frequency Point**
- **Unmeasurable Frequency Point**
- **Controllable Frequency Change**
- **Uncontrollable Frequency Change**
- **Tuning Available Region**

**Horizontal Test Tuner Tuning Range**
- Typically Slow tuner 500 kHz, Piezo 1 kHz

**Vertical Test Power Source Range**
- **CBP**
- **EP or CP**

**Pretuning Length and Tolerance Range**
- **Tuner Preload (HT)**
- **Field Flatness Tuning**

**9-CELL CAVITY**
- **Cavity Length Range (~ 2 mm)**
- **Pretuning Length Tolerance Range**

**DUMBBELLS**
- **Dumbbell Length Target**
- **Dumbbell Reform Length Target**

**HALF CELLS**
- **Half cell Length**

**Measurement Points**:
- **Key Frequency Point**
- **Measurable Frequency Point**
- **Unmeasurable Frequency Point**
- **Controllable Frequency Change**
- **Uncontrollable Frequency Change**

**Additional Measurements**:
- **Cavity Frequency Change and control**
- **Horizontal Test Tuner Tuning Range**
- **Vertical Test Power Source Range**
- **Pretuning Length and Tolerance Range**
- **Tuner Preload (HT)**
- **Field Flatness Tuning**

**Graphical Representation**
- **Cryomodule Vacuum**
- **LHe Pressure**
- **Temperature**
- **Permittivity**
- **Pressure**

**Legend**
- **Final Frequency Target**
- **Key Frequency Point**
- **Measurable Frequency Point**
- **Unmeasurable Frequency Point**
- **Controllable Frequency Change**
- **Uncontrollable Frequency Change**
- **Tuning Available Region**

**Note**
- The graph is a comprehensive representation of the various tunable parameters and their effects on cavity frequency change and control.
SCRF cavity fabrication process planning

Fabrication drawings

Quality control documents

Various Welding Fixtures
End Group Fabrication stages

Machined parts

Welding sub assembly stages

Completed End Group

<table>
<thead>
<tr>
<th>Cell ID</th>
<th>Length (mm)</th>
<th>Π-mode frequency (MHz)</th>
<th>Quality Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>144 Long End Cell</td>
<td>163.98</td>
<td>1296.5850</td>
<td>1880</td>
</tr>
<tr>
<td>164 Short End Cell</td>
<td>163.30</td>
<td>1294.4005</td>
<td>1922</td>
</tr>
</tbody>
</table>

Leak rate of $< 1 \times 10^{-10}$ mbar l/sec

RF Measurement and qualification
Dumb-bell fabrication, testing and qualification

Dumbbell fabrication

RF Measurement

Dumbbell qualification

Mech. Inspection
Dumbbell RF tuning

Nb 159-181 trimming and tuning case history

K tune = +2.8 MHz/mm
K trim = -2.7 MHz/mm

- Cooling to 2K
- Equator weld shrinkage
- Target @ 300K
- Trimming
- Tuning
- Weld shrinkage
- Standard trimming operation
- Standard Tuning operation
- Target after final welding
- Target before final weld
- Pi mode frequency of the dumbell
Multi-cell SCRF cavity

End Group and Dumb-bells

1.3 GHz nine cell SCRF cavity

E B Welding stages

1.3 GHz Five-cell SCRF cavity

Field Flatness as fabricated 77 %

Field Flatness after tuning = 98%

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Basic Size / Tolerance</th>
<th>Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1247.4 ±3</td>
<td>1246.98</td>
</tr>
<tr>
<td>Perpendicularity (Front flange)</td>
<td>0.8</td>
<td>0.49</td>
</tr>
<tr>
<td>Perpendicularity (Back flange)</td>
<td>0.8</td>
<td>0.25</td>
</tr>
<tr>
<td>Concentricity Equator #1 to 9</td>
<td>0.8</td>
<td>0.52 to 0.94 (min to max)</td>
</tr>
</tbody>
</table>
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 Q₀ of 8x10⁹ at 2K during

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 Q₀ of 2 x 10¹⁰
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%.

“SCRF cavity qualification

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

Thank You for your kind attention