DEVELOPMENT OF LB650 SUPERCONDUCTING RF CAVITY

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& team

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OUTLINE

- Introduction
- Initial Design of 650MHz Low β Cavity
- Fabrication and Measurement of 1-cell Aluminium Prototype Cavity and 5-cell Prototype Copper Cavity
- Fabrication and Measurement of 1-cell Niobium Cavity
- Single-Cell Niobium Cavity Processing and testing in Vertical Test Stand (VTS) at Fermilab
- Status of Final Design after release of Functional Requirement Specification (FRS) by Fermilab
- Summary
• In India, DAE laboratories and other institutes are now actively involved in research and development activities on SRF cavities and associated technologies for the proposed high current, high energy proton linear accelerators like ISNS/IADS and also for the FERMILAB PIP-II program under Indian institutions- Fermilab collaboration (IIFC).

• As part of the above activities, VECC has been involved in the design, analysis and development of a 650 MHz, β=0.61, 5-cell elliptical shape Superconducting RF linac cavity (LB650 SRF Cavity)
• VECC Started with LB650 cavity design, considering operating accelerating gradient ($E_{\text{acc}}$) of 17 MV/m and keeping iris diameter and beam pipe diameter as 96mm.

• The cell shape has been designed to minimize the peak surface magnetic and electric fields, $H_{\text{peak}}$ and $E_{\text{peak}}$, at accelerating gradient.
Geometrical parameters of Elliptical Cavity:

- Equator ellipse aspect ratio (B/A)
- Iris ellipse aspect ratio (b/a)
- Side wall inclination (α)
- Cavity iris radius ($R_{iris}$)
- Cavity equator radius, D/2
- Cavity length, L=$\beta\lambda/2$
### CAVITY DESIGN

#### Dependence of RF parameters on Geometric parameters

<table>
<thead>
<tr>
<th>Criteria</th>
<th>RF parameters</th>
<th>Dependence on Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation at High accelerating gradient, lower losses and field emission</td>
<td>Lower Epeak/Eacc</td>
<td>improves when $R_{iris}$ decreases, depends on iris shape</td>
</tr>
<tr>
<td></td>
<td>Lower Bpeak/Eacc</td>
<td>improves when $R_{iris}$ decreases, depends on equator shape</td>
</tr>
<tr>
<td>High accelerating gradient with lower stored energy and low cryogenic losses</td>
<td>Higher (R/Q).G</td>
<td>improves when $R_{iris}$ decreases, depends on equator shape</td>
</tr>
<tr>
<td>Coupling of modes between cells</td>
<td>$%K_{cc}$</td>
<td>Improves when $R_{iris}$ increases, # of cells decreases</td>
</tr>
<tr>
<td>Field flatness</td>
<td></td>
<td>Improves when $R_{iris}$ increases, $%K_{cc}$ increases, no. of cell decreases</td>
</tr>
</tbody>
</table>

#### Cavity EM Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Cells</td>
<td>5</td>
</tr>
</tbody>
</table>
| Effective Length $= 5*\left(\beta g.\lambda/2\right)$ | 703.4 mm.
| Iris Aperture                   | 96 mm.   |
| Wall angle for mid-cell         | 2.4°     |
| Wall angle for end-cell         | 4.5°     |
| $E_{peak}/E_{acc}$              | 3        |
| $B_{peak}/E_{acc}$              | 4.84     |
| $R/Q$                           | 296      |
| $G$                             | 200      |
| Cell-to-cell coupling, $%K_{cc}$ | 1.24%    |
CAVITY DESIGN

Electric field lines for accelerating mode ($\pi$-mode) at 649.999 MHz. The geometry of end cell of the cavity is optimized to have good field flatness over the five cells.

Frequencies of other four fundamental modes ($\pi/5$, $2\pi/5$, $3\pi/5$ and $4\pi/5$) are found at 641.991 MHz, 644.218 MHz, 646.955 MHz and 649.156 MHz respectively.
Electric and magnetic field profile and Lorentz force (Radiation pressure) on the surface of the cavity at accelerating field 17 MV/m.
Maximum radiation pressure (Lorentz Force) is 6 Kpa at iris region and 1.1 kPa at equator region.
CAVITY DESIGN: HOM Analysis

- Transverse and longitudinal HOMs for the cavity at 650 MHz, $\beta=0.61$ -- analysis done
- No trapped mode with high effective impedance observed.
Multipacting is a phenomenon of resonant electron multiplication in cavity and strongly depends on shape of the cavity and material of the cavity.

Requires two conditions:

1. Electron motion is in synchronism with RF frequency (resonance condition)

2. Impact energy is such that Secondary electron emission coefficient > 1

Key to eliminate multipacting ⇒ the fields should be such that emitted e⁻ will drift towards the equator (where E field NOT strong enough for secondary emission to recur) ⇒ stops avalanche effect

Rectangular shape ⇒ spherical or elliptical shape
Using 2D code MultiPac, multipacting analysis has been carried out for both mid cell and end cell of 650 MHz elliptical cavity and No multipacting has been found up to the accelerating electric field 20 MV/m. For both mid-cell and end-cell, impact energy of electron is less than 50 eV (secondary electron yield < 1) for all the electric fields except a small region between 30 MV/m to 35 MV/m where it increases up to around 200 eV for mid-cell and 1400 eV for end-cell.

Based on 2D analysis, we can conclude that there is No possibility of multipacting as the relative enhanced electron counter is less than 1 for whole range.
Furman Model of Secondary Electron emission (consisting of three types of scattering particles) has been taken into account in CST code.

- Secondary emission:
  A primary particle hitting a metal surface can cause the emission of so-called secondary particles.

  ➢ Depends on kinetic energy and material properties

  ➢ Self consistent model according to Furman.


➢ Statistical behaviour.
Multipacting simulation results for 650MHz, $\beta=0.61$ SCRF Cavity using 3D CST Particle Studio

- **30 mm. of equator region has been simulated.**

- **Mesh:** min 0.37 mm., max 0.74 mm.

- **Multipacting has been found between 5.8 MV/m to 11.5 MV/m**

- **Multipacting rate is very high in the region of 6.8 MV/m.**

- **At 11.6 MV/m, increase in particle due to multipacting is very low.**

Particle vs. time(ns) at 5.8 MV/m

Particles after 7ns at 5.8 MV/m
Multipacting simulation result for 650MHz, $\beta=0.61$Cavity using CST Particle Studio

Particle Vs time(ns) at 6.8MV/m (Strong Multipacting)

Particle after 6ns at 6.8MV/m

Particle Vs time(ns) at 9MV/m

Particle after 20ns at 9MV/m
Multipacting simulation data for 650MHz, $\beta=0.61$ Cavity using CST Particle Studio

Particle Vs time(ns) at 11.5 MV/m (slow multipacting)

Particle after 50ns at 11.5MV/m

Particle Vs time(ns) at 4.5MV/m (No Multipacting)

Particle Vs time(ns) at 22.5MV/m (No Multipacting)
MULTIPACTING STUDY

- CST particle studio is very sophisticated 3D code for multipacting analysis in superconducting elliptical cavity, but has some difficulties in simulation related to small size of multipacting area.
- In SC elliptical cavities, multipacting usually exists in areas near equator and sizes of these areas are too small as compared to basic dimensions of elliptical cavity.
- Multipacting occurs in a electric field which is weak as compared to accelerating electric field.
- Hence, only a small volume, 30mm along the equator diameter, has been simulated in CST particle studio to reduce simulation time and mesh cell dimensions minimum 0.37 mm. and maximum 0.74 mm.
- Multipacting has been found between accelerating electric field 5.8 MV/m to 11.5 MV/m.

The maximum rate of multipacting has been predicted around accelerating gradient 6.8 MV/m. Particle after 6ns at 6.8MV/m.

- A small convexity in the equator region suppresses the multipacting significantly. However, the convexity does not change the cavity parameters, like, peak surface fields, quality factor, R/Q etc.
- Practically, this small convexity gets introduced automatically during electron beam welding, which in turn may become beneficial.
SRF Cavity is subjected to cryogenic temperature and external pressure under operating conditions

Loading:
- Uniform Temperature = 2K
- External Pressure = 3 atm

Boundary Condition: Both end fixed

Finite Element Axisymmetric modeling for 5-cell SRF cavity
• Primary stress linearization along the thickness of iris (where the stress intensity value is maximum)

• Primary membrane stress integral intensity is 44 MPa, which is well within the allowable limit of 103 MPa.

• Combined stress intensity of primary membrane and bending is 120 MPa, which is well within allowable limit of 154 MPa (=1.5 x 103 MPa).

• Combined stress integral intensity (=primary membrane stress + bending stress + secondary stress) of 4 mm. thick niobium sheet is 131 MPa, which is well within the allowable limit of 309 MPa (=3 x 103 MPa), as per ASME code.

• Various stress plots indicate that they are within allowable limits.

### Mechanical properties of niobium

<table>
<thead>
<tr>
<th>Primary Membrane + Bending + Secondary Stress</th>
<th>Temperature (K)</th>
<th>Young's Modulii (GPa)</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Design Allowable Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_m + P_b + Q &lt; 3Sm)</td>
<td>295</td>
<td>97.9</td>
<td>50</td>
<td>100</td>
<td>33.33</td>
</tr>
<tr>
<td>(P_m + P_b + Q = 131) MPa &lt; 309 MPa (3Sm)</td>
<td>2</td>
<td>97.9</td>
<td>310</td>
<td>310</td>
<td>103.3</td>
</tr>
</tbody>
</table>
Results: Different Stress Plot

Stress calculations as per ASME Pressure Vessel Code Section-III for niobium

Stress intensity (at Iris) across the thickness of 5-cell, 650 MHz, $\beta=0.61$, cavity
The maximum deformation due to combined loading is obtained as 0.465 mm.

Plot of deformation for 5-cell, 650 MHz, $\beta=0.61$ cavity.
• Structural analysis carried out using ANSYS 3D code.
• Stresses are within the allowable limit.
• Mechanical modal analysis (without stiffener) shows frequency within 100 Hz.
The natural frequencies and mode shapes are determined for the 5-cell cavity alone for different end support condition.

<table>
<thead>
<tr>
<th>Modal Frequencies (Hz)</th>
<th>Both End Fixed</th>
<th>One End Free</th>
</tr>
</thead>
<tbody>
<tr>
<td>51.952</td>
<td>24.705</td>
<td></td>
</tr>
<tr>
<td>101.72</td>
<td>73.351</td>
<td></td>
</tr>
<tr>
<td>146.16</td>
<td>119.15</td>
<td></td>
</tr>
<tr>
<td>182.75</td>
<td>158.05</td>
<td></td>
</tr>
<tr>
<td>189.39</td>
<td>186.75</td>
<td></td>
</tr>
<tr>
<td>419.78</td>
<td>353.67</td>
<td></td>
</tr>
<tr>
<td>442.33</td>
<td>421.16</td>
<td></td>
</tr>
<tr>
<td>467.10</td>
<td>444.88</td>
<td></td>
</tr>
<tr>
<td>485.8</td>
<td>469.09</td>
<td></td>
</tr>
<tr>
<td>975.59</td>
<td>486.47</td>
<td></td>
</tr>
</tbody>
</table>
Stiffened cavity modal analysis

Radius of the stiffener Vs. Lowest natural frequency

Lowest natural frequency (Hz)

Radius of the stiffener (mm)
Engineering drawing for half-cell (mid-cell)

MATL.: AI
ROUGHNESS OF INNER SURFACES : 0.8/
ROUGHNESS OF OTHER SURFACES : 0.8/
GENERAL TOLERANCE : ± 0.1

RF CAVITY HALF CELL
D RG. NO. VECC/RF/MEG/001
Engineering drawing for half-cell (End-cell)
A prototype 1-cell aluminium cavity and a prototype 5-cell copper cavity have been fabricated using die-punch assembly to check the procedures for forming and to make sure the desired frequency and field flatness could be obtained.

RF characterisation has been carried out for both the prototypes using Vector Network Analyser and Bead pull measurement set up

Die Punch Assembly has been designed in house and fabricated at local industry using crome plated mild steel.
SINGLE CELL PROTOTYPE CAVITY (Aluminium) - VNA MEASUREMENT

Resonant frequency, $f_0 = 645.86350$ MHz

Simulated Value for the Geometry (Superfish) = 645.3 MHz

Half power (−3dB) Bandwidth,

$\Delta f = f_2 - f_1 = 31.2$ kHz.

$[ f_1 = 645.84860$ MHz;
$f_2 = 645.87980$ MHz $]$

$Q = f_0 / \Delta f = 20700.$
Five-cell Copper prototype fabricated using the mid-cell dimensions

Bead pull measurement setup including stepper motor gear arrangement, VNA and PC

Bead-pull measurement on 5-cell, \( \phi = 0.61 \), copper cavity with \( \pi \)-mode frequency at 651.395 MHz
Bead-pull measurement on 5-cell, $\beta=0.61$, copper cavity with 0-mode frequency at 643.61 MHz

Bead position from the end of beam pipe on the axis (in cm.)

Normalized electric field ($E$)

Bead-pull measurement on 5-cell, $\beta=0.61$, copper cavity with mode-1 frequency at 645.14 MHz

Bead position from the end of beam pipe on the axis (in cm.)

Normalized electric field ($E$)

Bead-pull measurement on 5-cell, $\beta=0.61$, copper cavity with mode-2 frequency at 647.055 MHz

Bead position from the end of beam pipe on the axis (in cm.)

Normalized electric field ($E$)

Bead-pull measurement on 5-cell, $\beta=0.61$, copper cavity with mode-3 frequency at 649.46 MHz

Bead position from the end of beam pipe on the axis (in cm.)

Normalized electric field ($E$)
The half cell has been fabricated from 600 mm x 600 mm x 4 mm thick niobium sheet (RRR ≥ 300), using die-punch assembly made of chrome plated SS. The beam pipes are also rolled from 4 mm thick niobium sheet.

Niobium blank was pressed to form half cell, using a hydraulic press at the vendor’s site, Kolkata.

4 mm thick Nb Sheet was rolled into the beam pipe in VECC workshop.
Niobium half cells, beam pipes and fixtures developed at VECC Workshop for Electron Beam Welding purposes.
Electron Beam Welding of Half cells, beam pipes and flanges has been carried out with the help of Electron Beam Welding (EBW) facility at IUAC, New Delhi.

- Rolled beam pipes are electron beam welded longitudinally.
- Two half cells are joined at the equator region by EBW from both inside and outside.
- Trimming and machining of beam pipe were done at VECC for weld edge preparation to match with the NbTi flange and to the half-cell iris.
- Beam pipes were then welded to NbTi Flange.
- EBW of the joint between the beam pipe and iris of the cavity has been done from the outside to build single cell cavity.
RF measurement of two half cells has been done using vector network analyser (VNA) to find out the deviation from the designed frequency in order to improve further.

Inspection of the half cells was carried out using in-house CMM.
After welding of the beam pipes and iris region, the frequency and the quality factor (Q) of the final single cell niobium cavity are measured to be 636 MHz and 9880 respectively.

The decrease in frequency after iris welding is due to unanticipated shrinkage and deformation at iris region caused by some difficulties we faced during iris welding process to get full penetration at welded region. Several number of welding passes were required.

The process encountered a problem of blow through at iris joint. This is successfully taken care of by machining the blow-through to a regular shape and fixing a niobium button at the blow through at IUAC.
Cavity Inspection after Electron Beam Welding

- Cryo-shocking with LN$_2$: 3 cycles
- Subsequent MSLD: leak rate $\sim$ 1.3E-9 mbar-lit/sec
• Qext Measurement of VTS couplers
  - Required External Quality factor \( Q_{\text{ext-FPC}} : 1E+10 \) and \( Q_{\text{ext-FP}} : 1E+12 \)

• RF Measurement with VTS couplers
  - The inner conductors were trimmed to achieve required \( Q_{\text{ext}} \)

• Optical Inspection of cavity RF surface at FNAL
  - No major defects were found

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<table>
<thead>
<tr>
<th>Qext measurements after trimming antennas</th>
<th>Cavity Orientation</th>
<th>F, MHz</th>
<th>Q</th>
<th>S11</th>
<th>Q1</th>
<th>S21 [dB]</th>
<th>S21</th>
<th>Q2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupler Antenna</td>
<td>635.7</td>
<td>9500</td>
<td>LR</td>
<td>0.62</td>
<td>5.04E+04</td>
<td>-61.20</td>
<td>8.71E-04</td>
<td>9.45E+09</td>
</tr>
<tr>
<td>Pickup Antenna</td>
<td>-79.70</td>
<td>1.04E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.69E+11</td>
</tr>
<tr>
<td>Coupler Antenna</td>
<td>2.48</td>
<td>9500</td>
<td>RL</td>
<td>0.63</td>
<td>5.16E+04</td>
<td>-61.2</td>
<td>8.71E-04</td>
<td>9.22E+09</td>
</tr>
<tr>
<td>Pickup Antenna</td>
<td>-80.1</td>
<td>9.69E-05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.15E+11</td>
</tr>
</tbody>
</table>
Cathode Masking for uniform material removal ~ Typically the surface area ratio cavity : unmasked cathode =10:1

Cathode stationary, Cavity rotates @ 1 rpm


Acid Mixture(electrolyte): Hydrofluoric and sulfuric acid in a volume ratio of 1:9, using typical commercial strengths HF (40%) and H₂SO₄ (98%).

Pre-cool acid to 15°C by heat exchanger

Five cell cavities have larger surface are: typical values 16-18 Volt/280-350 Amp

Typical current per surface are is ~ 200 A / sq m
• Inner conductor of VTS couplers were trimmed to required $Q_{\text{ext}}$
  - External Quality factor $Q_{\text{ext-FPC}}: 1E+10$ and $Q_{\text{ext-FP}}: 1E+12$
• RF Measurement with VTS couplers
• Electro polishing at Argonne National Lab (ANL)
  - 120 $\mu$m bulk EP (Total process time: 560 minutes)
  - Total 120$\mu$m (55$\mu$m+65$\mu$m) removed in two consecutive days in 4 hours and 5.2 hours
  - Process parameters strictly controlled during the process
  - Acid Mixture (electrolyte): Hydrofluoric and Sulfuric acid in a volume ratio of 1 : 9, using typical commercial strengths HF (40%) and $H_2SO_4$ (98%).
  - Operated @ 18 Volt/60 Amp
  - Typical current per surface are is ~ 200 A / sq m
  - Pre-cool acid to 15°C by heat exchanger
  - Optimum temperature for polishing is 30-35°C
- Ultrasonic thickness measurement after EP
- Ultrasonic cleaning after EP for 24 hours
- High pressure rinsing at ANL for 30 minutes
- The cavity ready for high temperature baking
- 800°C baking at FNAL for 3 hours
  - No unwanted species were found during degassing
  - Typical vacuum furnace pressure: ~1E-8 torr
  - This annealing aims at achieving higher Q by removal of hydrogen gas from the RF surface which got absorbed at different stages of surface processing
- Optical Inspection of cavity RF surface at FNAL (The surface defects like sputtered material from electron beam welding, pits and scratches due to fabrication process are inspected)
  - No defects were found
- Light EP: 20 µm and Final HPR at ANL
- VTS Assembly at FNAL
VTS Test Results of LB650 VECC Single cell cavity

Maximum Gradient: 34.5 MV/m @ 2K

No Quench at full RF power ~ 200 W

30 MV/m $E_{acc}$ (Accelerating Gradient) at unloaded cavity quality factor $Q_0 = 1.5E+10$

$E_{acc}$ & $Q_0$ Greater than required in FRS
VTS Test Results of VECC-LB650 Single cell cavity

Highest Accelerating gradient for 650MHz low beta segment (LB650) cavity

Cavity sustained
Bpeak > 120 mT
Epeak > 70 MV/m

Manufacturing process qualification for future development.

Successful collaborative effort of VECC/DAE, IUAC, FNAL and ANL.
First version of FRS Released in September 2015 and Cavity Design changed as per FRS

As the design progresses, FRS has been modified according to the design results.

Design of new cavity has been carried out keeping iris diameter 83 mm and beam pipe diameter as 118mm

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonating frequency</td>
<td>650</td>
<td>MHz</td>
</tr>
<tr>
<td>Shape, number of cells</td>
<td>Elliptical, 5 cells</td>
<td></td>
</tr>
<tr>
<td>Geometrical Beta ($\beta_g$)</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>65</td>
<td>Hz</td>
</tr>
<tr>
<td>Energy gain at optimal $\beta$</td>
<td>11.9</td>
<td>MeV/m</td>
</tr>
<tr>
<td>Peak surface electric field ($E_{pk}$) at operating gradient</td>
<td>$&lt; 40$MV/m at specified energy gain at optimal $\beta$</td>
<td>MV/m</td>
</tr>
<tr>
<td>Peak surface magnetic field ($B_{pk}$) at operating gradient</td>
<td>$&lt; 75$mT at specified energy gain at optimal $\beta$</td>
<td>mT</td>
</tr>
<tr>
<td>Quality factor ($Q_0$) at 2K</td>
<td>$&gt; 1.5 \times 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Dynamic Cryogenic Load</td>
<td>$&lt; 25$</td>
<td>W</td>
</tr>
<tr>
<td>Lorentz Force Detuning (LFD) Coefficient ($K_{LFD}$)</td>
<td>$&lt; (-) 1.25$</td>
<td>Hz/(MV/m)$^2$</td>
</tr>
<tr>
<td>Frequency variation due to helium pressure fluctuation ($df/dP$)</td>
<td>$&lt; 25$ (dressed cavity)</td>
<td>Hz/mbar</td>
</tr>
<tr>
<td>Stiffness</td>
<td>$&lt; 5$</td>
<td>kN/mm</td>
</tr>
</tbody>
</table>
FRS BASED CAVITY DESIGN

• Higher order mode analysis (upto 2.5 GHz) for both longitudinal and transverse modes of LB 650 cavity.

• R/Q values for higher order monopole modes and higher order dipole modes are calculated.

• R/Q values for higher order monopole modes is less than 5Ω for all the passbands.

1450.87MHz (monopole)

984.47MHz (dipole)
FRS BASED CAVITY DESIGN

- Multipacting Analysis has been carried out for both mid-cell and end-cell in CST Particle Studio
- 60mm of the equator region is simulated
- No multipacting at Accelerating Gradient (17MV/m)
Lorentz force Calculated at specified energy gain of 11.9 Mev) by Superfish

\[ P = \frac{\mu_0 H_s^2 - \varepsilon_0 E_s^2}{4} \]

\[ \Delta f = K_L \cdot E_{\text{acc}}^2 \]

As per FRS, To achieve Bandwidth 65Hz (\( Q_L = 1 \times 10^7 \)), values of \( Q_{\text{ext}} \) for the coupler Calculated for different values of L and H, using CST Microwave studio

EM field in RF cavity exerts pressure (Radiation Pressure/Lorentz Force) on the cavity wall ⇒ Small deformation of cavity walls

Net deformation ⇒ bending inward at Iris and outward at Equator ⇒ Freq. shift
FRS BASED CAVITY DESIGN

- Frequency Detuning of the dressed cavity due to Lorentz force has been calculated.
- Frequency Detuning of the dressed cavity due to Helium Pressure Fluctuation has been calculated.
- Cavity stiffness with bare cavity and dressed cavity Calculated.
- Stiffener ring positions has been decided on the basis of FRS criteria for above three parameters.
- Classical Ansys has been used.

Dressed Cavity with its different components.
FRS BASED CA VITY DESIGN

Design-A: Two stiffener rings for mid cells & one for end cells

Fabrication and cavity field flatness tuning are complicated, but FRS criteria for $dF/dP$ and $LFD$ satisfied

<table>
<thead>
<tr>
<th>$LFD$ (Hz/(MV/m)$^2$)</th>
<th>$1.21 &lt; 1.25$ (satisfies FRS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dF/dP$ (Hz/mbar)</td>
<td>$12 &lt; 25$ (satisfies FRS)</td>
</tr>
</tbody>
</table>

Design-B: Single stiffener ring for mid & end cells

Fabrication and cavity field flatness tuning are easy, but FRS criteria for $dF/dP$ needs to be modified

<table>
<thead>
<tr>
<th>$LFD$ (Hz/(MV/m)$^2$)</th>
<th>$1.3 \sim 1.25$ (Satisfy FRS), slightly higher than criteria, but acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dF/dP$ (Hz/mbar)</td>
<td>$30 &gt; 25$ (does not Satisfy FRS)</td>
</tr>
</tbody>
</table>

Cavity stiffness values for both the Configurations (A and B), satisfy FRS criteria (<5kN/mm)
- Structural analyses of LB650 cavity under several load cases carried out for dressed cavity with optimum stiffener ring positions
- Double stiffener ring configuration has been analyzed so far for different load cases
- Software used: ANSYS Workbench
- Target-Contact pairs are taken across the weld joints which makes the problem non-linear in nature.

### Load Case 1
- **Gravity**
- **P₂ = 0.205 MPa**
- Warm Pressurization, Applicable Temperature of allowable stress limits = 293 K

### Load Case 2
- **Gravity**
- **P₂ = 0.41 Mpa**
- Hydrostatic pressure of Liquid Helium Head
- Cold operation(2K), full LHe and maximum pressure of Liquid Helium

### Load Case 3
- **Cool down to 2 K**
- **Tuner extension of 1.5 mm**

### Load Case 4
- **Gravity**
- **P₂ = 0.41 Mpa**
- Hydrostatic pressure of Liquid Helium Head
- **Cool down to 2 K**
- **Tuner extension of 1.5 mm**

### Load Case 5
- **Gravity**
- **P₁ = P₂ = 0.1 MPa**
- Insulating and beam vacuum upset, helium volume evacuated

### Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (Kg/m³)</th>
<th>Coefficient of thermal expansion (293K - 2K) (1/K)</th>
<th>Reference Temperature (K)</th>
<th>Young's Modulus (Pa)</th>
<th>Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>8590</td>
<td>4.81E-06</td>
<td>293K</td>
<td>1.05E+11</td>
<td>0.39</td>
</tr>
<tr>
<td>NbTi</td>
<td>5700</td>
<td>6.53E-06</td>
<td>293K</td>
<td>6.20E+10</td>
<td>0.36</td>
</tr>
<tr>
<td>Ti Grade-2</td>
<td>4528</td>
<td>5.15E-06</td>
<td>293K</td>
<td>1.07E+11</td>
<td>0.33</td>
</tr>
</tbody>
</table>
1. Gravity
2. Pressures: P1, P2 & P3
3. Tuner extension (cavity compression) by 1.5 mm
4. Cool down to 2 K
5. Hydrostatic pressure of Liquid Helium Head

(Density of LHe at 2 K = 147 Kg/m3)

Different types of loads used in the load cases
Boundary conditions of LB650 cavity for all load cases
Design by Analysis approach is followed for design qualification as per ASME Sec. VIII-Div.

STRESS CLASSIFICATION LINES (SCLS): Paths taken across various weld joints on which stress intensity is categorized into membrane and bending stress intensities

- All the weld joints of the half-cell cavities at equator and iris regions are safe from structural integrity point of view under all types of load cases.

- The stress intensities at the weld joints of both inner and outer stiffener rings with the elliptical cavities are within allowable limits.

- It is also found that the weld joints connecting the beam tube with end spools and those joining end spools with the helium vessel are also safe.

- The stress limits within the bellows will be carried out later.
SUMMARY

- 650 MHz, $\beta=0.61$, elliptical Superconducting RF linac cavity has been indigenously designed and developed by VECC, with the help of Electron Beam Welding (EBW) facility at IUAC, New Delhi.

- 1st prototype 1-cell LB650 cavity has been successfully tested in VTS at Fermilab and achieved maximum accelerating gradient of 34.5 MV/m.

- After release of FRS, EM design has been done and optimization of stiffener ring position has been carried out to meet FRS criteria.

- Structural analysis has been carried out for LB650 cavity with double stiffener ring.

- Fabrication of 5-cell LB650 cavity will start after finalization of the LB650 design.

- Fabrication of 1st 5-cell LB650 cavity is expected to be completed in 24 months after final review of the design of 5-cell LB650 cavity.