Charge – LB650 Preliminary Design Review – March 31, 2017

• Does the design of the dressed cavity adhere to proper engineering principles and applicable codes?
• Does the cavity meet the scientific needs as outlined in the Functional Requirement Specification?
• Does the design address the tuning requirements and minimize multipacting issues?
• Does the Fabrication Plan/Specification clearly identify the fabrication process to ensure that the design is practical and achievable?
• Has it been demonstrated that the cavity will function and interface properly with the proposed helium vessel, tuner, coupler, and cryomodule?
Agenda

- Sumit Som: Introduction and goal of this review (5 min)
- Sudeshna Seth:
  - Overview of FRS and supporting documentation (10 min)
  - Summary of RF analysis from previous reviews (10 min)
  - Summary of multipacting from previous reviews (10 min)
  - Summary of LFD and dF/dP analysis from previous reviews (10 min)
- Sundeep Ghosh:
  - Cavity Stiffener Ring Configuration based on LFD, dF/dP and cavity stiffness for dressed cavity (15 min)
  - Cavity Stress analysis of the dressed Cavity for five different load conditions (20min)
  - Mechanical Modal Analysis (10min)
Agenda - continued

• Pranab Bhattacharyya:
  – Fabrication of bare cavity (45 min)
    • 3-D model
    • 2-D drawings
    • Weld sequence planning
    • Design Status
    • Status of Engineering Note
• All: Integration of Fermilab Helium Vessel with LB650 bare cavity (10 min)
  • 3-D model
  • 2-D drawings
• All: Integration of Fermilab Tuner with cavity (10 min)

For more details refer to Teamcenter no. ED0006010
EM Design and study of Multipacting

Stiffener ring optimization on the basis of LFD, df/dP, Cavity stiffness and tuning sensitivity

Stress Analysis and modal Analysis of dressed LB650 with optimum stiffener ring configuration

2D-drawing and 3-D model of Bare LB650 Cavity

End group and helium vessel, similar to HB650, have been used for stiffener ring optimization, stress analysis and modal analysis.

Sumit Som
Indian Institutions and Fermilab Collaboration

Design of 650 MHz Low Beta (0.61) Cavity (using new FRS) and compliance with FRS Criteria

Sudeshna Seth
VECC,Kolkata
EM Design for 5-cell LB650 Cavity with 118mm dia Beam Pipe, 83 mm Mid-cell Iris Dia and 2 degree Wall Angle

<table>
<thead>
<tr>
<th>RF Parameters</th>
<th>Inner cells (mm)</th>
<th>End half cell (mm)</th>
</tr>
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<tbody>
<tr>
<td><strong>D</strong></td>
<td>389.292</td>
<td>389.292</td>
</tr>
<tr>
<td><strong>R_{iris}</strong></td>
<td>41.5</td>
<td>59</td>
</tr>
<tr>
<td><strong>L/2</strong></td>
<td>52.14</td>
<td>53.52</td>
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<tr>
<td><strong>A</strong></td>
<td>56</td>
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<td>10.8</td>
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<td>70.335</td>
</tr>
<tr>
<td><strong>α</strong></td>
<td>2°</td>
<td>2°</td>
</tr>
<tr>
<td>Equator flat</td>
<td>0</td>
<td>3.79</td>
</tr>
<tr>
<td>Iris Flat</td>
<td>2.61</td>
<td>0</td>
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<table>
<thead>
<tr>
<th>RF Parameters</th>
<th>Superfish simulation Result</th>
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<tbody>
<tr>
<td><strong>E_p/E_a</strong> (at optimal β)</td>
<td>2.307 (\text{at specified energy gain at optimal } β) (39.04\text{MV/m at specified energy gain at optimal } β)FNAL FRS: (\leq 40 \text{MV/m}) (at optimal β)</td>
</tr>
<tr>
<td><strong>B_p/E_a</strong> (at optimal β)</td>
<td>4.383 (\text{at specified energy gain at optimal } β) (74.157 \text{mT at specified energy gain at optimal } β)FNAL FRS: (\leq 75 \text{mT}) (at optimal β)</td>
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<tr>
<td><strong>R/Q</strong> (at optimal β)</td>
<td>346Ω</td>
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<tr>
<td><strong>E_p/E_a</strong> (at Geometric β)</td>
<td>2.43</td>
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<tr>
<td><strong>B_p/E_a</strong> (at Geometric β)</td>
<td>4.61</td>
</tr>
<tr>
<td><strong>R/Q</strong> (at Geometric β)</td>
<td>329.3</td>
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<tr>
<td><strong>G</strong></td>
<td>164.3</td>
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<tr>
<td><strong>Field flatness</strong></td>
<td>99.95%</td>
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\[\pi\text{-mode:650.007 MHz}\]
EM Design of LB650 with 118 mm Beam Pipe and 2° Wall Angle

Electric field lines for other four fundamental modes of elliptical shape
5-cell cavity (¼ geometry shown)
EM Design of LB650 with 118 mm Beam Pipe and 2° Wall Angle

- As per FRS, Bandwidth 65Hz (Q_L = 1x10^7) and Q_0 > 1.5x10^{10}
- As per FRS, LB650 cavity has to fit the HB650 power coupler
- For calculating Q_{ext} for the coupler with LB650 cavity, Coupler dimensions have been taken from a Coupler model available in team center
  - Outer Dia = 72.9 mm, inner Dia = 12.7 mm and antenna as per the Coupler model obtained from team center (Model of the antenna “inner conductor with antennatip_main coupler.sat” is uploaded in Sangam)

<table>
<thead>
<tr>
<th>L (mm)</th>
<th>H (mm)</th>
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<tr>
<td>85</td>
<td>60</td>
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<tr>
<td>90</td>
<td>55</td>
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<tr>
<td>95</td>
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<td>100</td>
<td>45</td>
</tr>
<tr>
<td>105</td>
<td>40</td>
</tr>
<tr>
<td>110</td>
<td>35</td>
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</table>

QL = 1x10^7

Main Coupler port position (L) for LB650 Cavity has been chosen same as that of HB650 as this satisfies the FRS criteria of 65Hz bandwidth
Multipacting simulation results for LB650 with 118mm Beam Pipe and 2° wall angle using 3D CST Particle Studio

- **60 mm. of equator region has been simulated.**
- **Multipacting Analysis has been carried out for both mid-cell and end-cell.**

- **Multipacting has been found up to 4.8 MV/m.**

- **Multipacting rate is very high in the region of 2.5 MV/m.**

- **At 4.8 MV/m, increase in particle due to multipacting is very low.**

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**Particle vs. time (ns) at 2.6 MV/m (mid cell)**

**Particles after 16ns at 2.6MV/m (midcell)**
Multipacting simulation results for LB650 with 118mm Beam Pipe and 2\(^\circ\) wall angle using 3D CST Particle Studio

Particle vs. time (ns) at 4.7 MV/m (endcell)

Particle vs. time (ns) at 17.5 MV/m (midcell) (no multipacting)

Particle after 30ns at 4.7 MV/m (endcell)

Particle vs. time (ns) at 17.5V/m (end cell) (No multipacting)
## Dimensions of 650 MHz, 5-cell, $\beta=0.61$, Niobium Cavity

<table>
<thead>
<tr>
<th>Dimensional Parameters</th>
<th>COLD Dimension (inside) (From EM Design) (mm.)</th>
<th>COLD Dimension Pre-BCP treatment of 250 $\mu$m (mm.)</th>
<th>WARM Dimension Inside (for fabrication) (mm.)</th>
<th>WARM Dimension Inside (for Stress Analysis) (mm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equator radius</td>
<td>194.646</td>
<td>194.396</td>
<td>194.674</td>
<td>194.9243</td>
</tr>
<tr>
<td>Iris radius</td>
<td>41.5</td>
<td>41.25</td>
<td>41.30899</td>
<td>41.55935</td>
</tr>
<tr>
<td>A</td>
<td>52.14</td>
<td>51.89</td>
<td>51.9642</td>
<td>52.21456</td>
</tr>
<tr>
<td>B</td>
<td>56</td>
<td>55.75</td>
<td>55.82972</td>
<td>56.08008</td>
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<tr>
<td>a</td>
<td>12.95</td>
<td>13.2</td>
<td>13.21888</td>
<td>12.96852</td>
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<td>b</td>
<td>23.55</td>
<td>23.8</td>
<td>23.83403</td>
<td>23.58368</td>
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<tr>
<td>Iris radius (for end cell)</td>
<td>59</td>
<td>58.75</td>
<td>58.83401</td>
<td>59.08437</td>
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<tr>
<td>A (for end cell)</td>
<td>53.52</td>
<td>53.27</td>
<td>53.34618</td>
<td>53.59653</td>
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<td>B (for end cell)</td>
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<td>47.75</td>
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<td>a (for end cell)</td>
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<td>b (for end cell)</td>
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<td>25.73675</td>
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<tr>
<td>Equator flat (end cell)</td>
<td>3.79</td>
<td>3.79</td>
<td>3.79542</td>
<td>3.79542</td>
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<tr>
<td>Iris flat (mid cell)</td>
<td>2.61</td>
<td>2.61</td>
<td>2.613732</td>
<td>2.613732</td>
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<tr>
<td>Half cell length (L/2)</td>
<td>70.335</td>
<td>70.335</td>
<td>70.43558</td>
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</tbody>
</table>

These Dimensions of Cavity inner wall have been used in the LB650 3-D model for calculation of LFD and $df/dP$

These Dimensions of Cavity inner wall have been used in 2-D drawing for fabrication

These Dimensions of Cavity inner wall have been used in the LB650 3-D model for Stress Analysis (5 different load conditions)
Frequency of LB650 Niobium Cavity in after Fabrication and after 250µm BCP (at room temperature)

Frequency of LB650 cavity after Fabrication (Warm) = 649.786 MHz

Frequency of LB650 cavity after 250µm BCP (Warm) = 649.086 MHz
Placement of Stiffener Ring based on FRS criteria for LFD and df/dP

- Analysis for LFD and df/dP have been carried out for three different configuration of stiffener ring to find out the optimized stiffener ring position.
- Classical Ansys has been used for calculation of LFD and df/dP

Design 1: Single stiffener ring both at end cell and mid-cell and stiffener ring radius is same for mid & end cells

Design 2: Single stiffener ring both at end cell and mid-cell and stiffener ring radius is different for mid & end cells

Design 3: Double stiffener rings at mid-cell and single stiffener ring at end cell
Cavity Stiffness : with optimum Stiffener Ring Position

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Stiffness of Bare cavity (kN/mm)</th>
<th>Stiffness of Bare cavity + Helium Vessel (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single stiffener at 70 mm for mid-cells &amp; 90 mm for end cells (Design2)</td>
<td>0.72</td>
<td>1.66</td>
</tr>
<tr>
<td>Double stiffeners at 70 mm &amp; 109 mm for mid-cells &amp; single stiffener at 100 mm for end cells (Design3)</td>
<td>2.353</td>
<td>3.264</td>
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</tbody>
</table>

Cavity stiffness value for both the Configuration, satisfy FRS criteria (<5kN/mm)
Tuning Sensitivity : with optimum Stiffener Ring Position

- Cavity Deformation simulated in Ansys with 1mm displacement and 2 mm displacement at one end of LB650 cavity (Stiffener ring Rmid=70mm/109mm and Rend =100mm )

- Electromagnetic Analysis are carried out in Ansys for undeformed cavity and for both the deformed cavities (with 1 mm and 2mm displacement)

- Model of undeformed and deformed cavities are exported to CST Microwave studio from Ansys and RF Simulation Carried out

- Tuning Sensitivity Calculated in both Ansys and CST.

<table>
<thead>
<tr>
<th></th>
<th>1mm Displacement</th>
<th>2mm Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency Shift</td>
<td>Tuning Sensitivity</td>
</tr>
<tr>
<td>Ansys</td>
<td>244.7 kHz</td>
<td>244.7 kHz/mm</td>
</tr>
<tr>
<td>CST</td>
<td>245.2 kHz</td>
<td>245.2 kHz/mm</td>
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</tbody>
</table>

Tuning Sensitivity of the cavity (for Stiffener ring position Rmid=70mm/109mm and Rend =100mm ) satisfies FRS criteria(>180kHz/mm)
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Mechanical Design of dressed LB650 cavity

Sundeep Ghosh
VECC, Kolkata
Structural analyses of LB650 cavity under several load cases
Different types of loads used in the load cases

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)
Boundary conditions of LB650 cavity for all load cases

A: Fixed Support
B: Displacement (X = 0, Y = 0, Z = free)
C: Displacement 2 (X = free, Y = 0, Z = 0)
D: Displacement 3 (X = free, Y = 0, Z = free)
Design by Analysis approach is followed for design qualification as per ASME Sec. VIII-Div. II

**Nomenclature:**

$P_m = \text{Primary membrane stress}$

$P_l = \text{Primary local membrane stress}$

$P_b = \text{Primary bending stress}$

$Q = \text{Secondary Stress}$

$S_m = \text{Minimum of two-third yield stress or one-third of ultimate stress}$

**Stress Classification Lines (SCLs):** Paths taken across various weld joints on which stress intensity is categorized into membrane and bending stress intensities
Load Case - 1

- Gravity
- \( P_2 = 0.205 \) MPa

Condition Simulated: Warm Pressurization

Applicable Temperature of allowable stress limits = 293 K

Key points:
- Only primary load is applied \((P_2)\)
- The applicable stress categories on SCLs at equator and iris weld regions are ‘\(P_m\)’ and ‘\(P_m+P_b\)’. The geometries on either sides of weld joints at these regions are symmetric in nature.
- All other SCLs are taken at several weld joints having geometric discontinuities. The stresses developed in these regions are secondary in nature for satisfying displacement compatibility at junctions, even though the applied load is primary in nature. Hence, \(P_l\) and \(Q\) have been taken into account in these regions.

<table>
<thead>
<tr>
<th>Material</th>
<th>SCL</th>
<th>PI (Mpa)</th>
<th>Allowable Limit = 1.5Sm (Mpa)</th>
<th>Ratio</th>
<th>Pm (or PI) + Pb + Q (Mpa)</th>
<th>Allowable Limit = 3Sm (Mpa)</th>
<th>Ratio</th>
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<td>Nb Welds</td>
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<td>6.6053</td>
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Contour plot of total displacement for load case-1
Load Case - 2

- Gravity
- P2 = 0.41 Mpa
- Hydrostatic pressure of Liquid Helium Head

Condition Simulated: Cold operation, full LHe and maximum pressure of Liquid Helium

Applicable Temperature of allowable stress limits = 2 K

Key points:
- Only primary loads applied (Helium pressures)
- Thermal contraction from room temperature to 2 K not considered.
- Secondary stress (Q) criteria has been introduced due to discontinuity stresses at the SCLs taken at weld joints other than equator and iris regions

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<th>Allowable Limit = 3Sm (Mpa)</th>
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Contour plot of total displacement for load case-2
Load Case – 3

✓ Cool down to 2 K
✓ Tuner extension of 1.5 mm

Condition Simulated: Cool down and tuner extension

Applicable Temperature of allowable stress limits = 2 K

Key points:
➢ No primary load is present
➢ Secondary loads (strain controlled loads) applied consisting of
  i. Thermal load due to cool down
  ii. Displacement at tuner end
➢ Applicable stress category is Secondary Stress Intensity 'Q'

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Contour plot of total displacement for load case-3
**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

**Condition Simulated:** Cold operation with tuner extension, full LHe inventory and maximum He pressure

Applicable temperature of allowable stress limits = 2 K

**Key points:**
- Primary loads applied (Liquid Helium Pressure)
- Secondary loads consists of
  - Thermal load due to cool down
  - Displacement at tuner end
- Applicable stress category is ‘Pl (or Pm) + Pb + Q’

### Stress intensities on SCLs

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<th>Material</th>
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| Nb-Ti-Ti       | 40  | 37.018                   | 280.8                       | 0.13183
Contour plot of total displacement for load case-4
Load Case – 5

✓ Gravity
✓ $P_1 = P_2 = 0.1 \text{ MPa}$

**Condition Simulated:** Insulating and beam vacuum upset, helium volume evacuated

Applicable Temperature of allowable stress limits = 293 K

**Key points:**
- Only primary load is applied ($P_1 & P_2$)
- Secondary stress has come into picture due to discontinuity stress at junctions of weld joints except equator and iris regions

### Stress intensities on SCLs

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<th>$P_l$ (Mpa)</th>
<th>Allowable Limit at 1.5Sm (Mpa)</th>
<th>Ratio</th>
<th>$Pm$ (or $P_l$) + $P_b + Q$ (Mpa)</th>
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Contour plot of total displacement for load case-5
Comments

- 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 are not found out in the present study. It will be carried out in our next study.

- The stiffness of bellow assembly is found out by separate analysis and it comes out around 410 N/mm.
Stiffness calculation of bellows without end flanges

Boundary conditions used:
- **A:** $X = \text{free}$, $Y = \text{free}$, $Z = 0$ (symmetric plane)
- **B:** $X = 0$, $Y = \text{free}$, $Z = \text{free}$ (symmetric plane)
- **C:** $X = \text{free}$, $Y = 0$, $Z = \text{free}$ (fixed bottom)
- **D:** $X = \text{free}$, $Y = 1 \text{ mm}$, $Z = \text{free}$ (to make top convolution move parallel to the bottom convolution, i.e. to avoid bending)

Results:
- Reaction force (in -Y direction) at bottom convolution after solution = 100.78 N
- Stiffness for 1/4th Model = $100.78/1 = 100.78$ N/mm
- Stiffness of total model = $4 \times 100.78 \approx 403$ N/mm

Stiffness of bellow with end flanges was 412 N/mm, hence almost matching.
Modal Analysis of LB650 cavity
Boundary conditions for modal analysis

Tuner is not considered (i.e. tuner stiffness = 0)
List of modal frequencies of LB650 cavity

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Animations of several modes in order

1st Longitudinal Mode at 47.6 Hz

1st Transverse Mode at 50.2 Hz

2nd Transverse Mode at 55.3 Hz

3rd Transverse Mode along Z at 93.5 Hz
Indian Institutions and Fermilab Collaboration

Weld Plan Sequence for fabrication of LB650

Pranab Bhattacharya
VECC,Kolkata
End Cell

Mid Cells

End Cell

Coupler Port

Beam tube

Stiffener “B” (in two sectors)

Stiffener “A” (in two sectors)

Stiffener “C” (in two sectors)

Tuner End
5 CELL LOW BETA 650 CAVITY ASSEMBLY

COUPLER END ASSEMBLY

DUMBELL ASSEMBLY

FIELD PROBE END ASSEMBLY
DUMBELL ASSEMBLY
Measurement of frequency will be carried out

Measurement of frequency will be carried out

Measurement of frequency will be carried out

Measurement of frequency will be carried out and trimming at equator region will be done accordingly.
Measurement of frequency will be carried out and trimming at equator region will be done accordingly after welding no 6 and welding no 7.
Measurement of frequency will be carried out and trimming at equator region will be done accordingly after welding A and after welding no B
Coupler End ASSEMBLY
Field Probe End ASSEMBLY
LB650 bare cavity drawing from VECC
Report comments

• MP rate found to be very high @ 2.5 MV/m. In previous analysis from June 28th it was high at 4.8 MV/m.
• Need to calculate loaded Q for HOMs.
• No MP analysis done in end groups and coupler port, still required.
• We should perform thermal analysis of the beam pipes.
• Modal analysis has been done for 0 tuner stiffness and should be repeat for realistic stiffness 68 kN/mm.
• RF coupler tip dimensions from Sergey K should be shared with Sudeshna – re-calculate with new tip.
• HOM analysis should include RF coupler in geometry.
• Used latest HB650 dressed cavity as a basic model for all analysis.
• Bare and dressed cavity 3G loading for transportation analysis.
Report comments – continued

- 2D & 3D design lug is changed – maintain similar model for calculations.
- Bare cavity vacuum analysis required for leak test and VTS purpose.
- Venting analysis need to be done.
- The stress are checked at weld joint locations only. Also required to take maximum stress locations for each components.
- Tuner stiffness needs to be included in mechanical analyses.
- Bellows welding postponed later for allowing 800 C baking.
- Weld sequence plan required for end groups need another review.
- Didn’t discuss the helium vessel design, 3-d model or 2-d drawing status or tuner integration.