Engineering Design of Superconducting RF Cavity

Navneet Kumar Sharma
PLSC Division
RRCAT, Indore

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9. Microphonics - df/dP Analysis
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12. Design of Expansion Bellows

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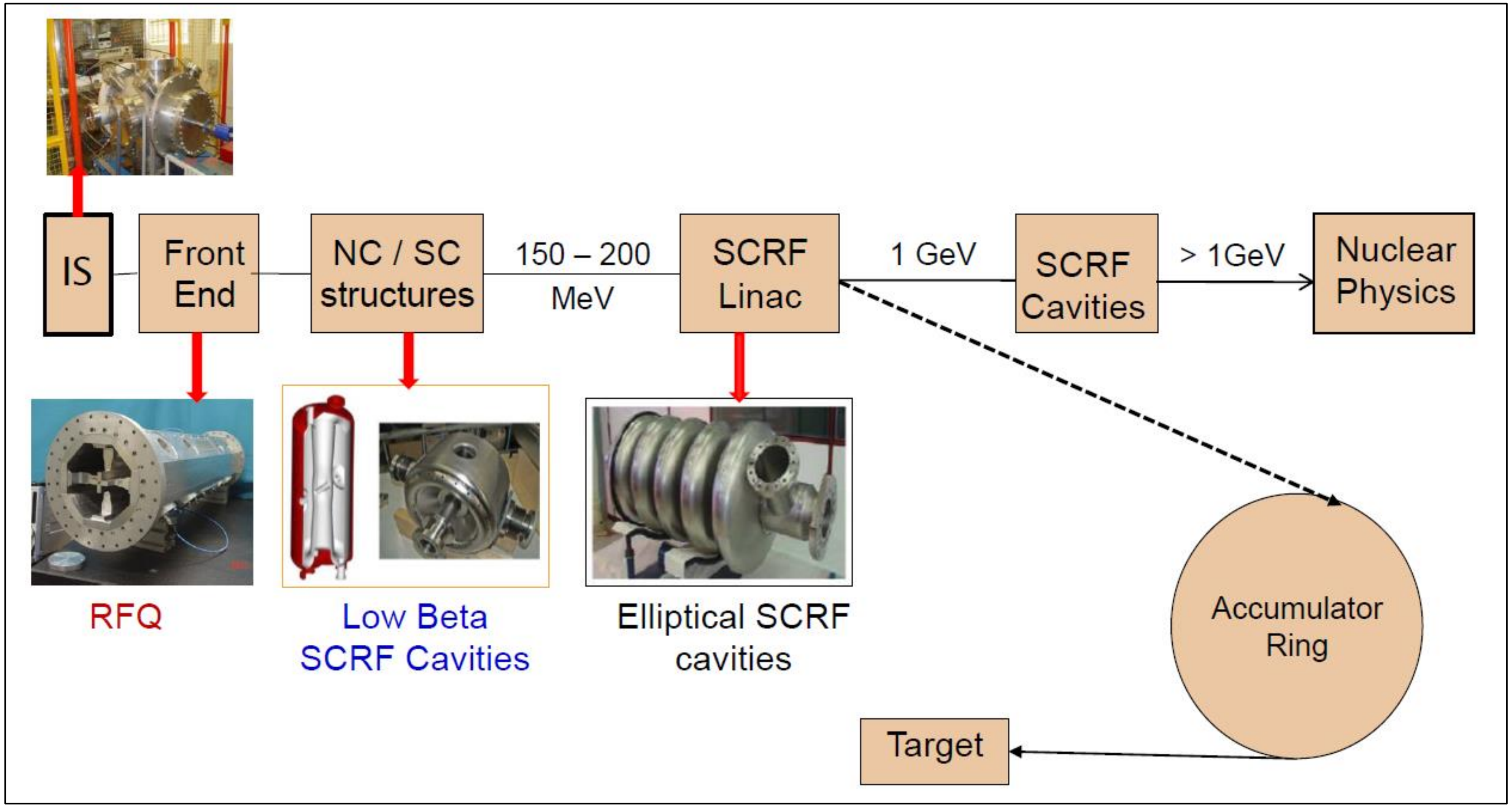
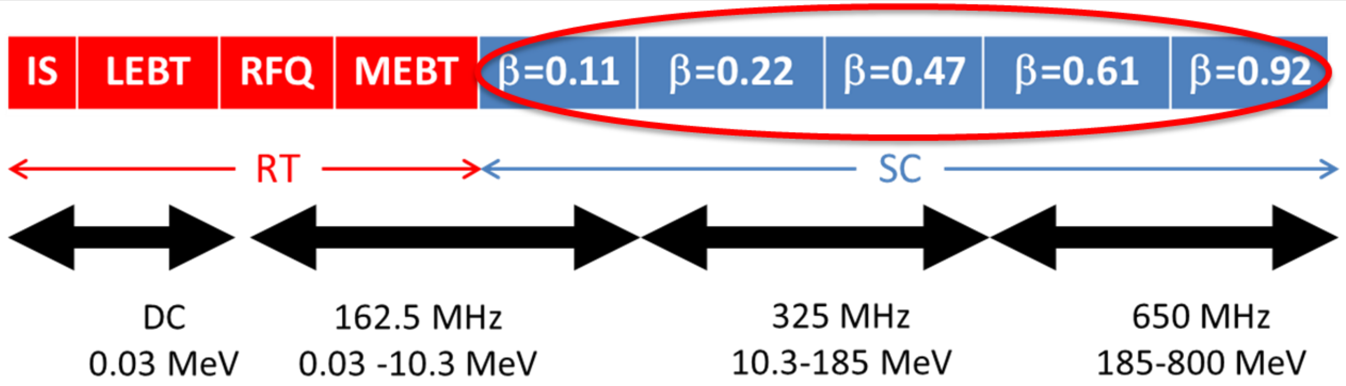
1. Introduction



Superconducting RF cavity technology shall be building block for high intensity proton accelerator for proposed Indian Spallation Neutron Source (ISNS).

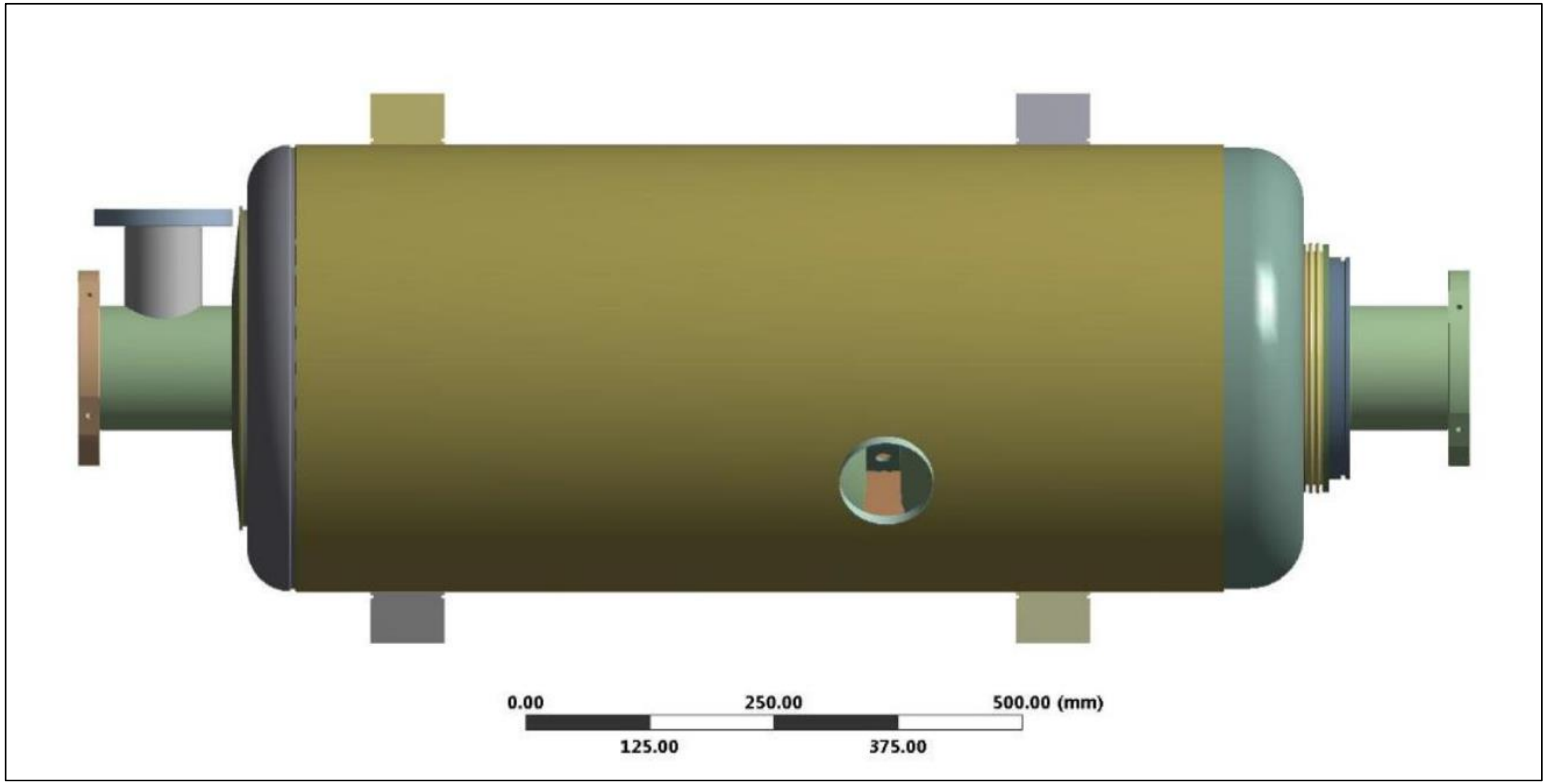
Proton Improvement Plan -II (PIP-II) FNAL USA



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-10.3	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	10.3-35	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.47)	325	35-185	35/21/7	SSR, solenoid
LB 650 (β_g=0.61)	650	185-500	33/22/11	5-cell elliptical, doublet
HB 650 (β_g=0.92)	650	500-800	24/8/4	5-cell elliptical, doublet

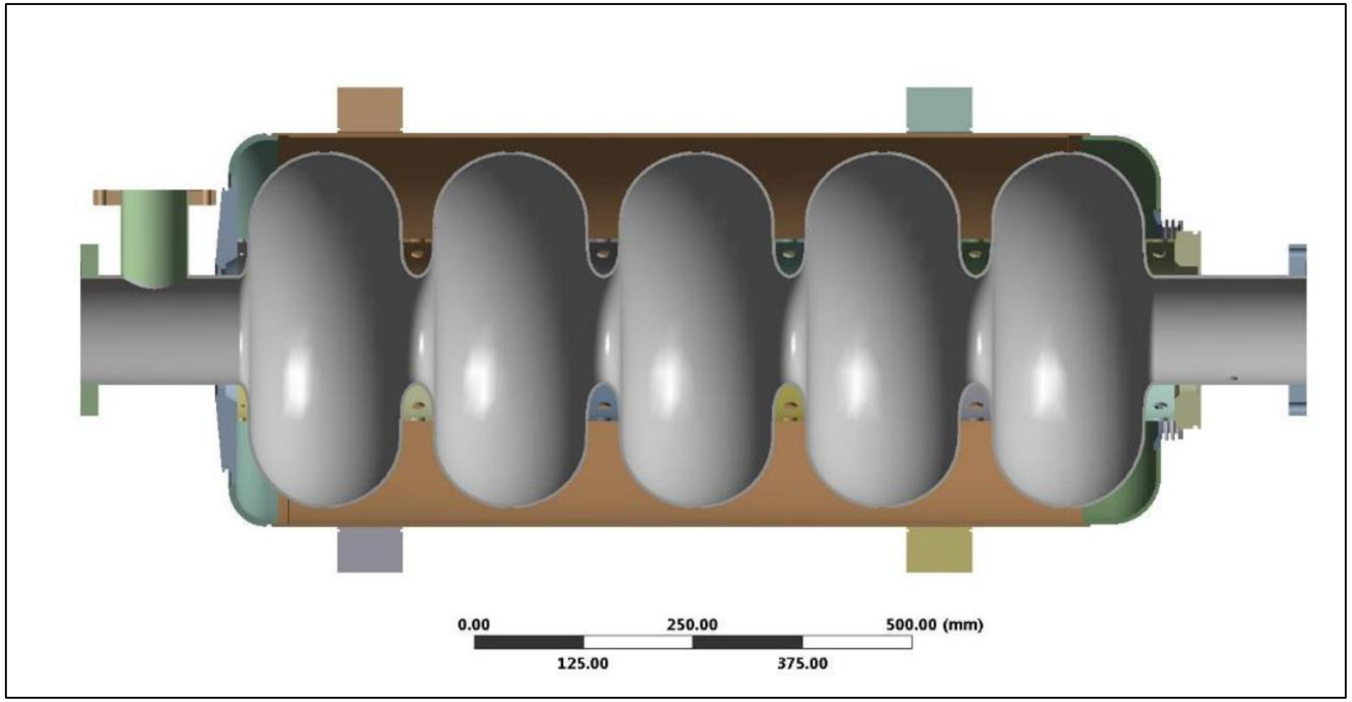
This presentation is based on work carried out by me as a Guest Engineer in Fermilab for HB 650 Beta 0.92 SCRF cavity design in year 2015-16.

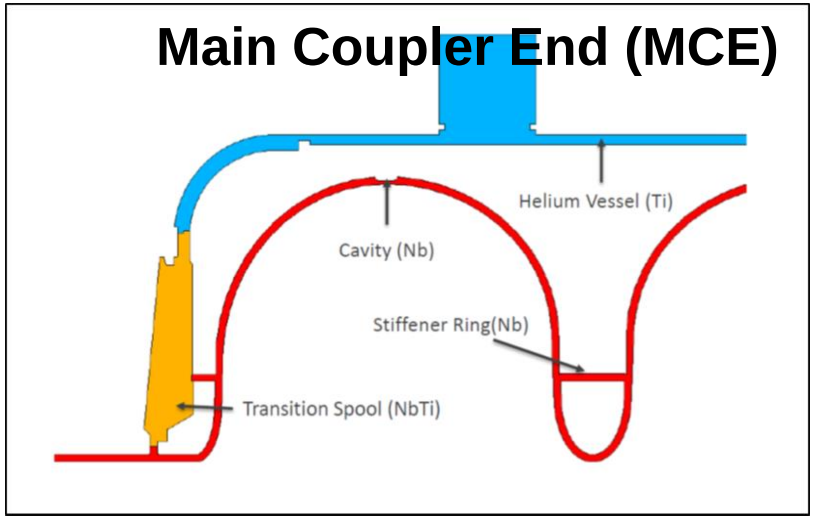
Dressed Superconducting RF Cavity

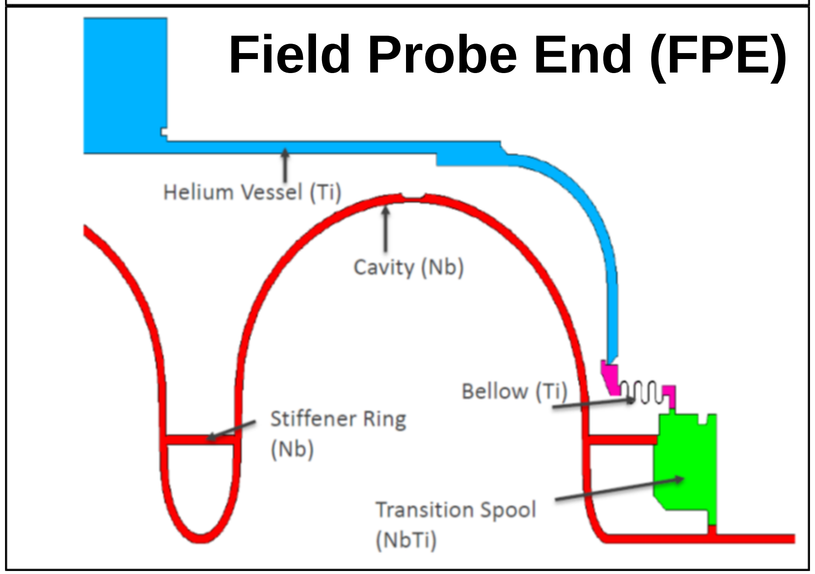


CAD model of dressed 650 MHz SCRF cavity

Dressed Superconducting RF Cavity







Cross section for dressed 650 MHz SCRF cavity and nomenclature for components

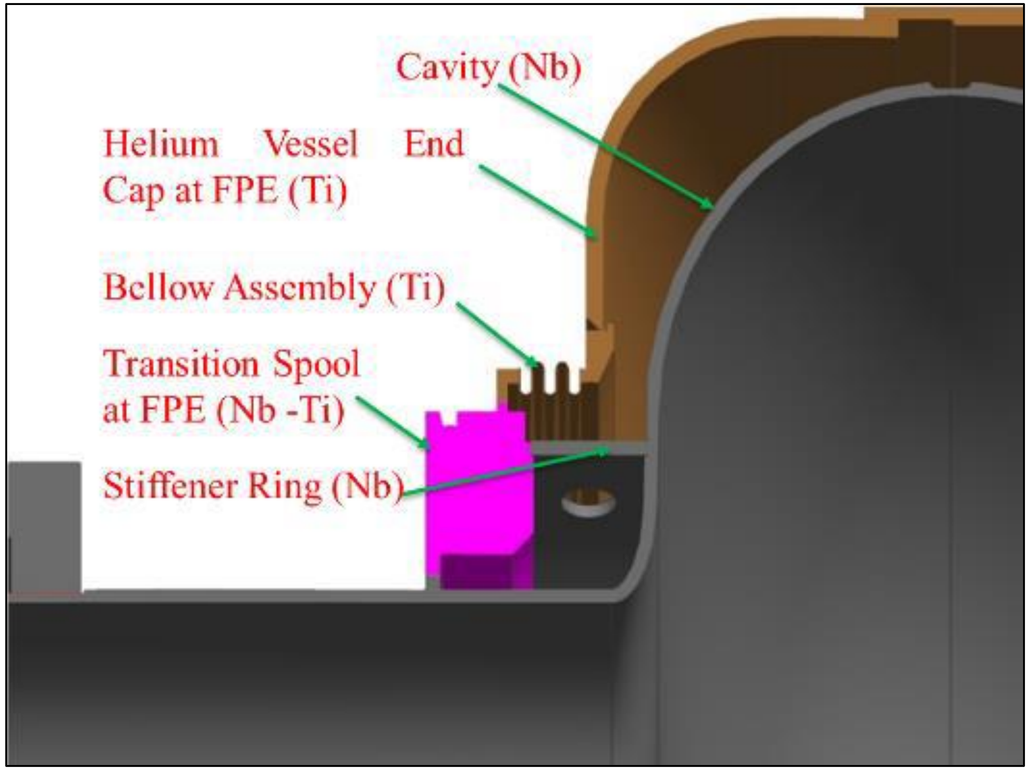
2. Scope of Engineering Design

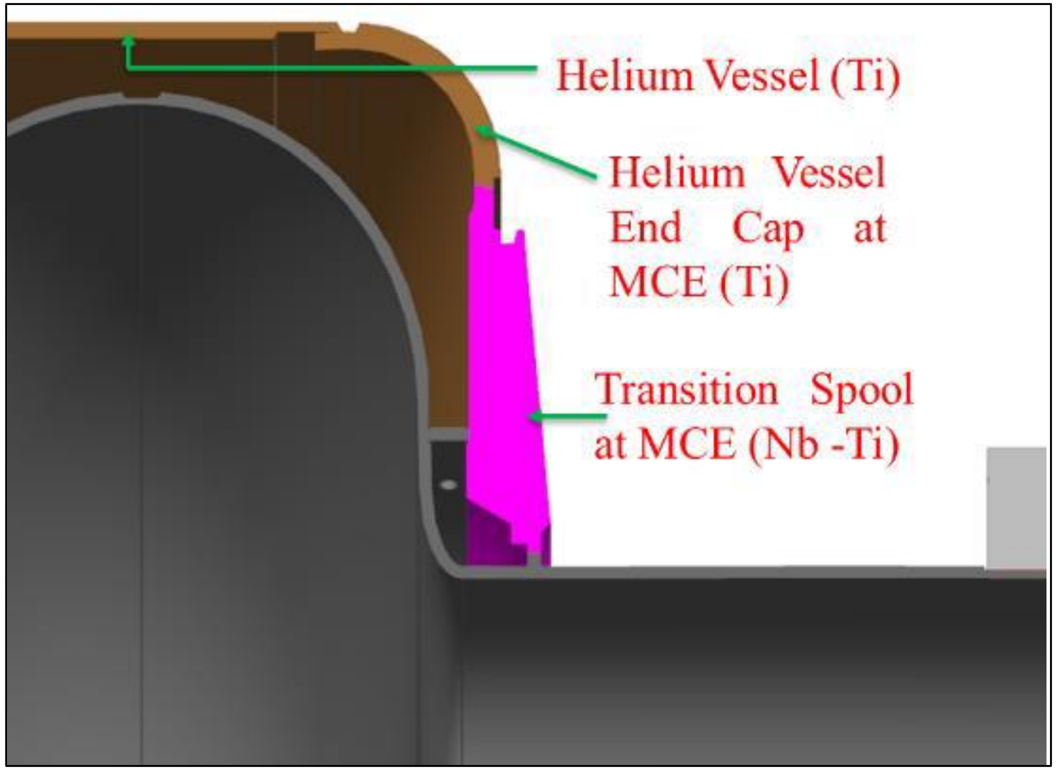
- Design of dressed SCRF cavity components based on ASME guidelines.
- Qualify dressed SCRF cavity for structural stability for 5 possible operating load cases.
- Minimize Lorentz Force Detuning (LFD)
- Minimize sensitivity to microphonics due to He pressure fluctuations (df/dP) and mechanical vibrations
- To keep the stiffness and tuning sensitivity at suitable level to allow for tuning.

Parameter	Value
Operating mode	Pulsed with CW capability
Peak Current	2 mA
Max Leak Rate (room temp)	$< 10^{-10}$ atm-cc/sec
Operating gain per cavity	19.9 MeV
Maximum Gain per cavity in VTS	> 24 MeV
Operating power dissipation per cavity at 2 K	< 32.5 W
Sensitivity to He pressure fluctuations	< 25 Hz/mbar (dressed cavity)
Lorentz Force Detuning coefficient	< 1 Hz/(MV/m)^2
Loaded quality factor Q_l	$1.1 \cdot 10^7$
Field Flatness of dressed cavity	> 90%
Operating temperature	2.0 K
Operating Pressure	30 mbar
MAWP	2 bar (300K), 4 bar (2K)
RF power input per cavity	up to 100 kW (CW, operating)
Cavity longitudinal stiffness	< 5 kN/mm
Tuning sensitivity	> 150 kHz/mm

Dressed Cavity Functional Requirements

3. Materials





Field Probe End (FPE)

Main Coupler End (MCE)

Material Properties

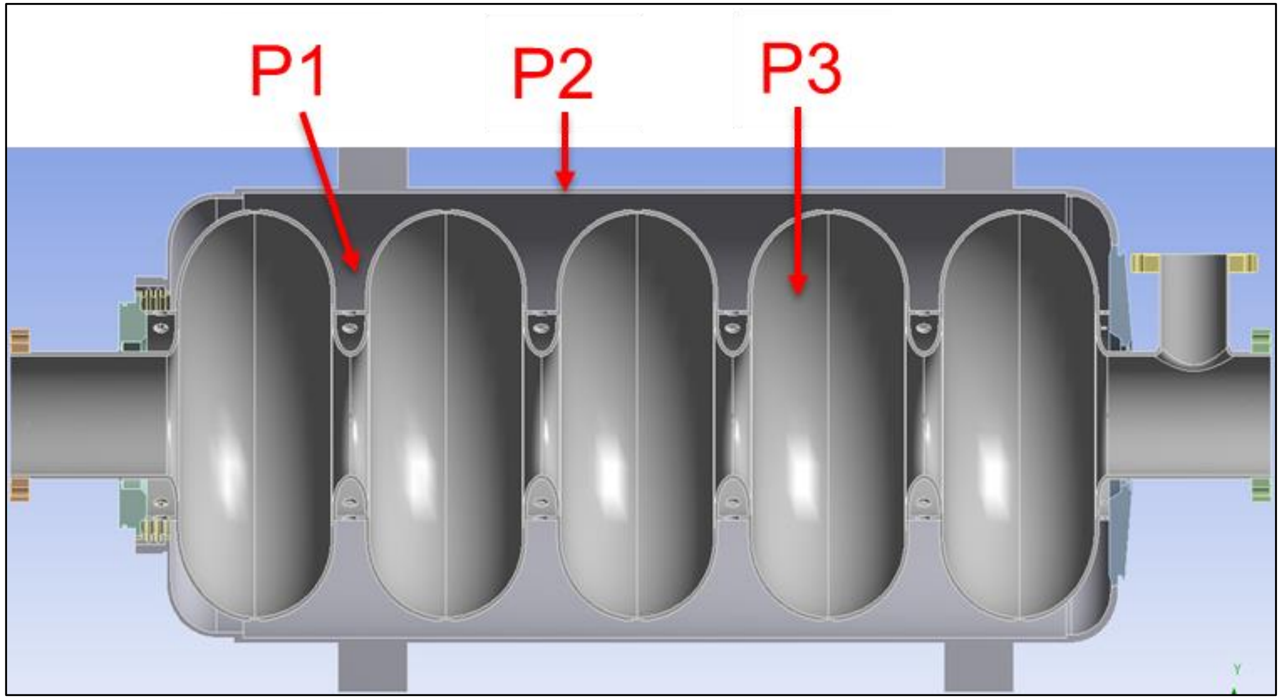
Material	Elastic Modulus [GPa]	Yield Strength [MPa]		Ultimate Strength [MPa]	
		293 K	2 K	293 K	2 K
Nb	105	38	317	115	600
55 Ti-45Nb	62	476	476	545	45
Ti Gr. 2	107	276	834	345	1117

Reference: Fermilab specifications 5500.000-ES-371110 titled as "Material Properties for Engineering Analysis of SRF cavities."

4. Loads and Allowable Stresses

Pressure Loadings:

1. Pressure loading P1 in liquid helium volume of titanium helium vessel.
2. Pressure loading P2 in insulating vacuum volume outside of helium vessel (In case of insulating vacuum failure).
3. Pressure loading P3 in niobium cavity volume through which the beam passes (In case of beam vacuum failure conditions).



Volumes for Pressure Loadings

Condition 1 is regular operating condition, whereas 2 and 3 are accidental conditions.

Maximum Allowable Working Pressure

Room Temperature (293 K) Requirement

- During initial cool down and warm up of cavity, the pressure in cavity usually reaches up to 1.5 bar.
- Relief valve setting with some allowances to avoid its actuation at normal working conditions

MAWP = 2 bar (at room temperature)

- The vessel will be pressure tested for 2 bar at room temperature.

Cold Conditions (2K) Requirement

- Loss of insulating vacuum or loss of beam vacuum
- Rapid boiling of helium and pressure rise in the cavity. Hence a larger MAWP is required for cold conditions. Since material strength increases at 2K

MAWP = 4 bar (at cold conditions)

Due to lower allowable stress for material at room temperature, the 2 bar pressure condition is more stringent during cavity mechanical design.

Load Types

The cavity is subjected to 5 basic loads:

1. Pressure (internal and external)
2. Gravity (self weight of dressed cavity)
3. Liquid helium weight

Results primary and secondary stresses.

4. Thermal contraction from room temperature (293 K) to cold operating conditions (2 K)
5. Lever tuner displacement of 2 mm

Displacement controlled loads which produce secondary stresses only

Allowable Stresses

Stress Limits:

$$P_m \leq S$$
$$P_m + P_b \leq 1.5\, S$$
$$P_m + P_b + Q \leq 3\, S$$

P_m : Primary Membrane Stress

P_b : Primary Bending Stress

Q : Secondary Stress

	Allowable Stress (S) for materials	
Material	2 K	293 K
Nb	171	25
Ti-45Nb	156	156
Gr. 2Ti	319	99

Material	Stress Category (MPa)					
	Pm		$P_m + P_b$		$P_m + P_b + Q$	
	2 K	293K	2 K	293K	2 K	293K
Nb	171	25	256.5	37.5	513	75
Ti-45Nb	156	156	234	234	468	468
Gr. 2Ti	319	99	478.5	148.5	957	297

ASME BPV code Section VIII Division 2 Subsection 5.2 provides guidelines for stress limits for material for various stress categories.

Allowable Stresses for Welding Joints

Code Requirements for welding joints

- ❖ All welded joints of Categories A and B shall be of Type 1 or Type 2 of Table UW-12. (According Section VIII Div. 1 Subsection C Part UNF-19 a).
- ❖ Welded joints shall be examined by liquid penetrant method. (Section VIII Div. 1 Subsection C Part UNF- 58 b).
- ❖ All electron beam welds shall ultrasonically examined along entire length. (Section VIII Div 1 Subsection B Part UW-11 e).

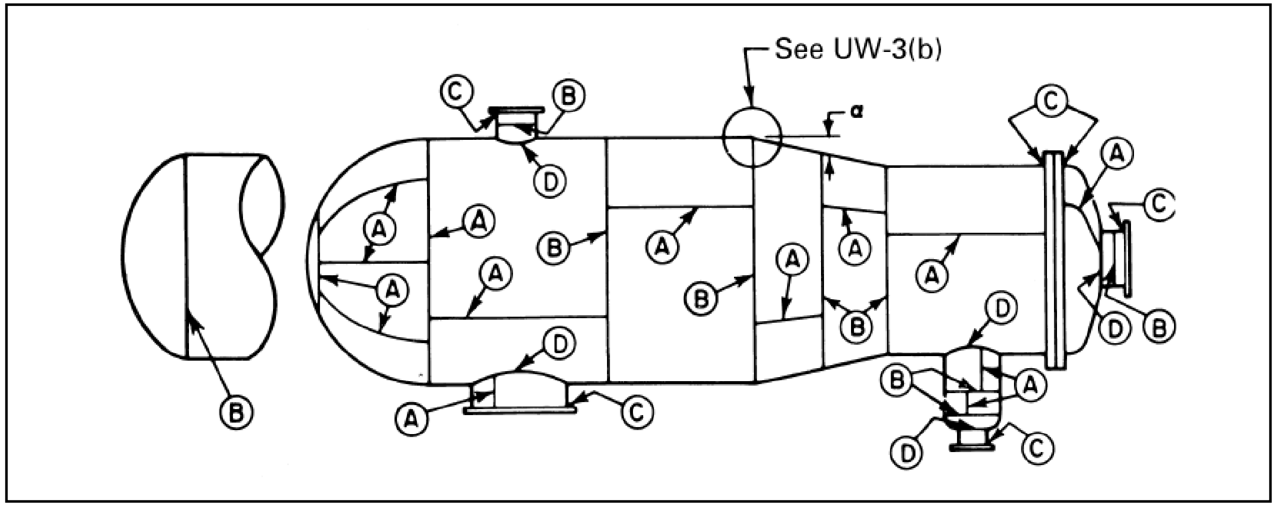
Due to dressed cavity geometry and stringent functionality, NDE requirements are not fully satisfied.

Allowable stresses for welding joints shall be lowered by joint efficiency factor provided by ASME BPV Code Section VIII Division 1 Subsection B Part UW 12.

Weld Joint Efficiency

<u>Weld Joint Efficiency is determined by:</u>

- Weld Type No. (1,2,3,4,5,6,7)
- Welded Joint Category (A,B,C,D)
- Degree of Radiographic Examination (Full, Spot or No radiography)



Weld Type	Description
1	Double welded butt joint
2	Single welded butt joint with backing strip
3	Single welded butt joint without backing strip
4	Double full fillet lap joint
5	Single full fillet lap joint with plug welds
6	Single full fillet lap joint

Welded Joint Category	Description
A	All longitudinal welds in shell and nozzles and all welds in heads and Hemispherical head to shell weld joint.
B	All circumferential welds in shell and nozzle and Head to shell joint (other than Hemispherical).
C	Flange welds.
D	Nozzle attachment welds.

5. Design by Rules – ASME section VIII Division 1

- Dressed SCRF cavity should be designed in accordance with ASME Boiler and Pressure Vessel Code Section VIII Division-1 to the greatest extent possible.

- ASME BPV Code Section VIII Division 1 rules shall be applied for following designs.
  - Minimum thickness of helium vessel under Internal Pressure
    - Warm conditions (293 K)
    - Cold conditions (2 K)
  - Design of Helium Vessel for External Pressure
  - Design of Penetrations for Helium Vessel
  - Design of Unreinforced Bellow Expansion Joint for Helium Vessel Assembly

5. Design by Rules – ASME section VIII Division 1

- For many features of cavity, helium vessel and its loadings, ASME BPV Codes Section VIII Division 1 has no rules.

    - Niobium and Niobium Titanium are non code materials.

    - Nb cavity does not conform to the geometries covered in Division 1.

    - Division 1, UG-22(h) provide guidelines for thermal contractions for pressure vessel design, but have no rules to cover the cavity geometry.

    - The cavity is subjected to a controlled displacement loading from the tuner. There are no rules in Div. 1 covering such a loading.

For those cases, where guidelines are not available within the scope of ASME Boiler and Pressure Vessel Code Section VIII Division-1, the provisions of ASME Section VIII Division-1 Sub-section U-2(g) have been applied.

Design by Rules – ASME section VIII Division 1

- **According to ASME BPV Code, Section VIII, Division 1, Subsection U-2(g),**

  "This Division 1 of Section VIII does not contain rules to cover all details of design and construction. Where complete details are not given, it is intended that the manufacturer, subject to the acceptance of the inspector, shall provide details of design and construction which will be as safe as those provided by the rules of this division."

- This paragraph of the Code allows alternative analyses to be used in the absence of Code guidelines.

- ASME Section VIII Division 1, U-2 (g) requirements are satisfied by Design by Analysis rules covered under Section VIII Division 2.

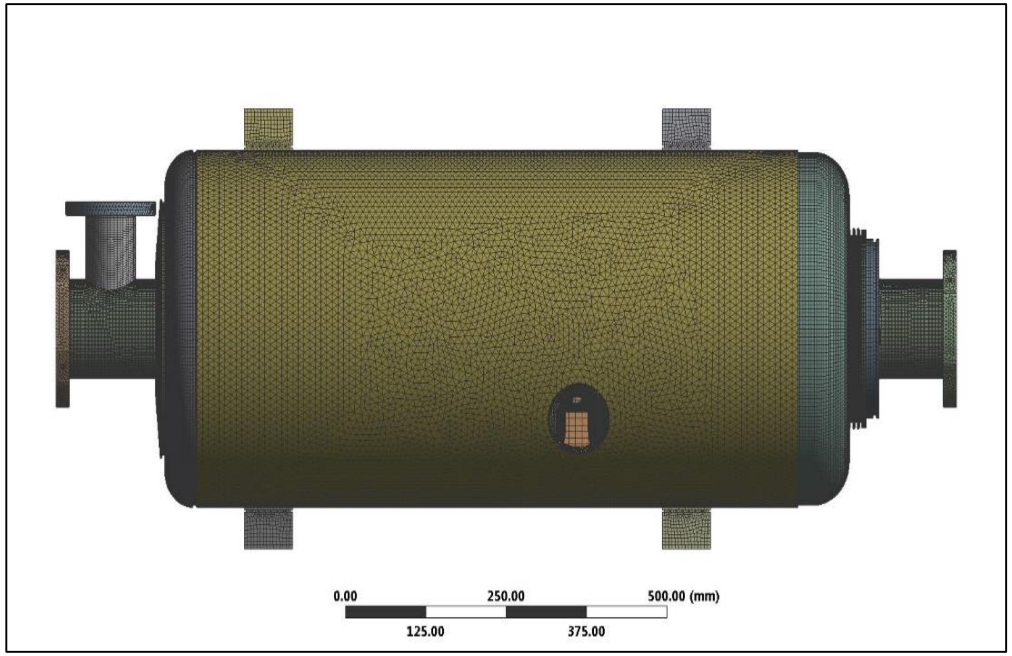
6. Elastic Stress Analysis

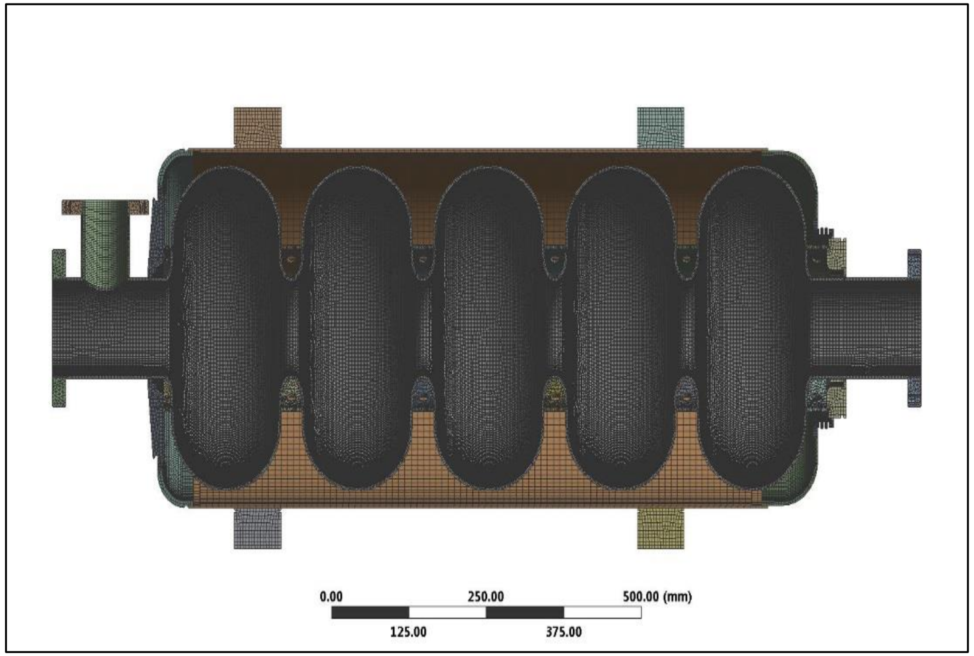
ASME BPV Code Section VIII Division 2 Part 5 Subsection 5.2.2 provides guidelines for Elastic Stress Analysis Method.

Steps

- Analysis to calculate Von Mises stress – according subsection 5.2.2.1(b)
- Stress Categorization (Primary membrane, bending and secondary stresses) – according subsection 5.2.2.2.
- Linearization of stress results for stress classifications – according subsection 5.2.2.3
- Assessment Procedure - according subsection 5.2.2.4

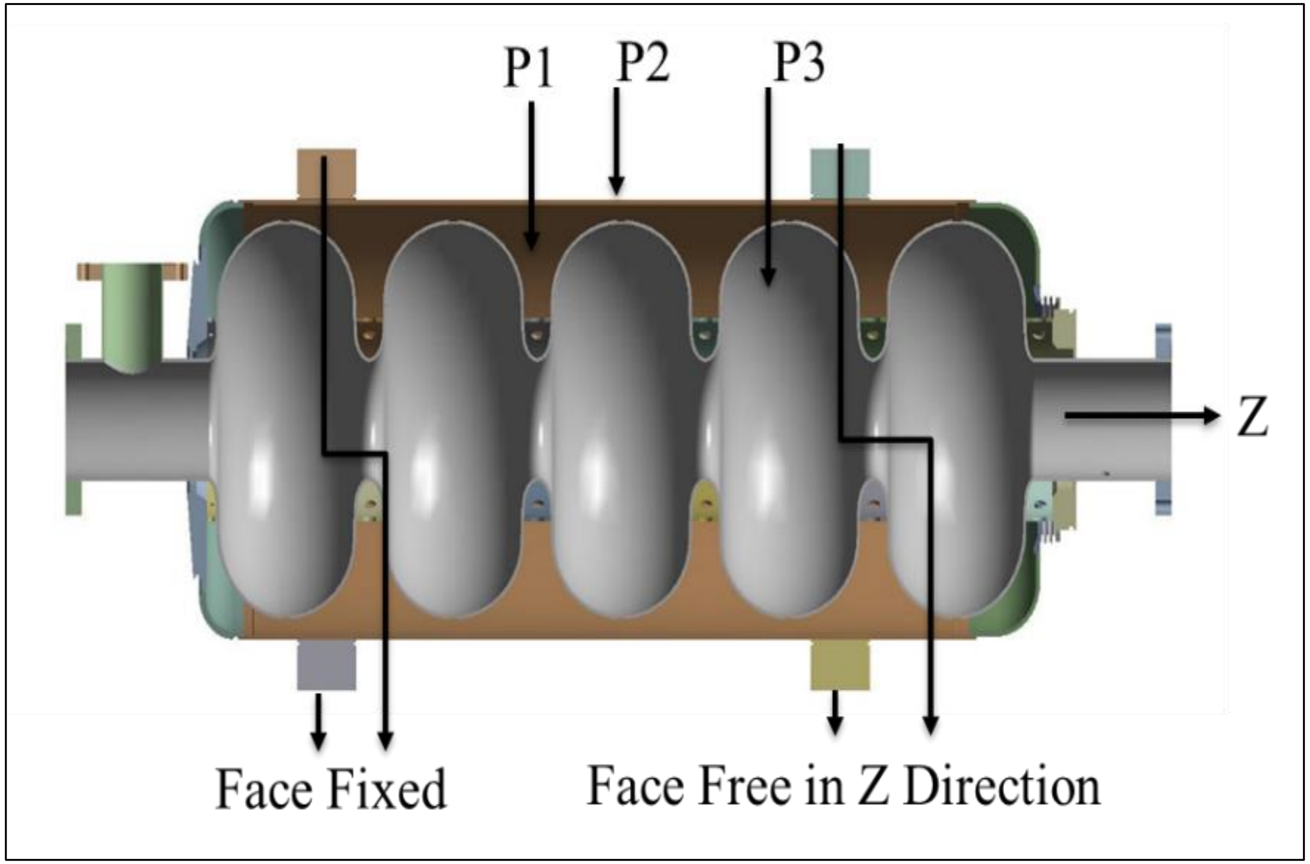
Meshed Model for Stress Analysis





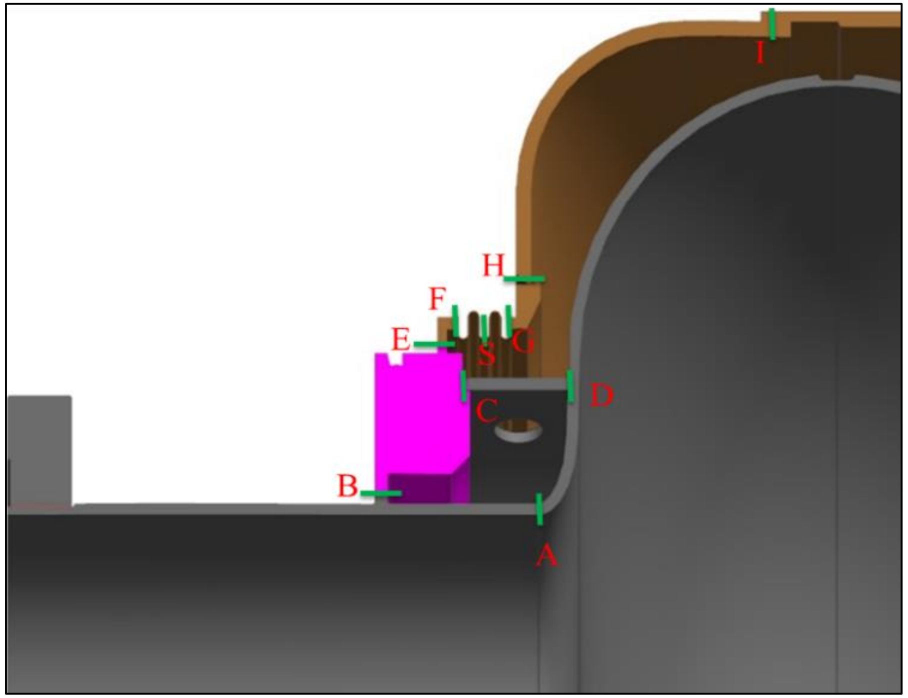
Number of elements ~ 1000000

Loads and Constraints

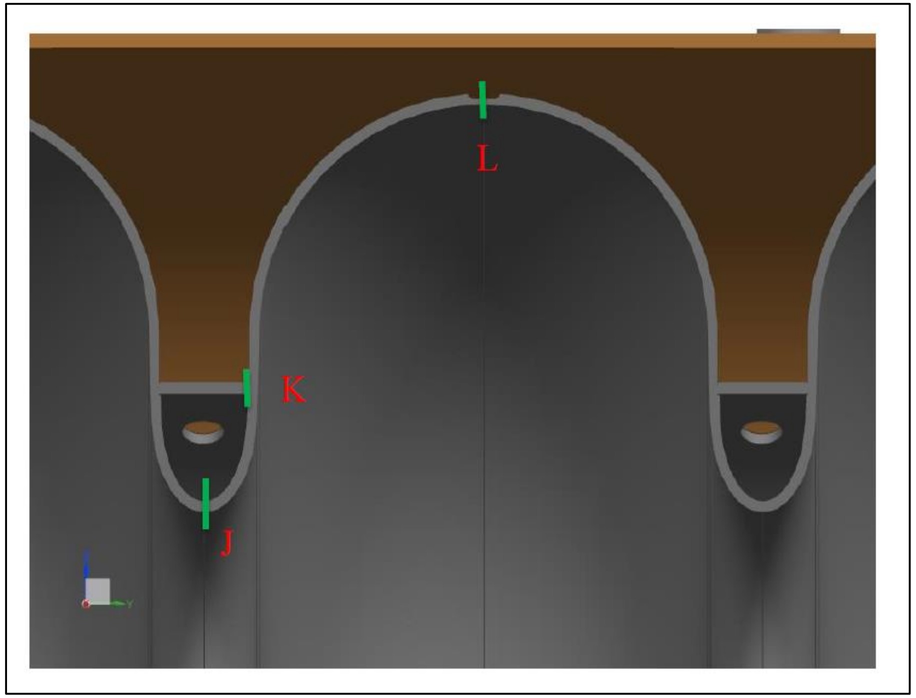


Helium vessel support lugs at main coupler end are fixed and support lugs at field probe end are free to move in axial direction.

Stress Classification Lines

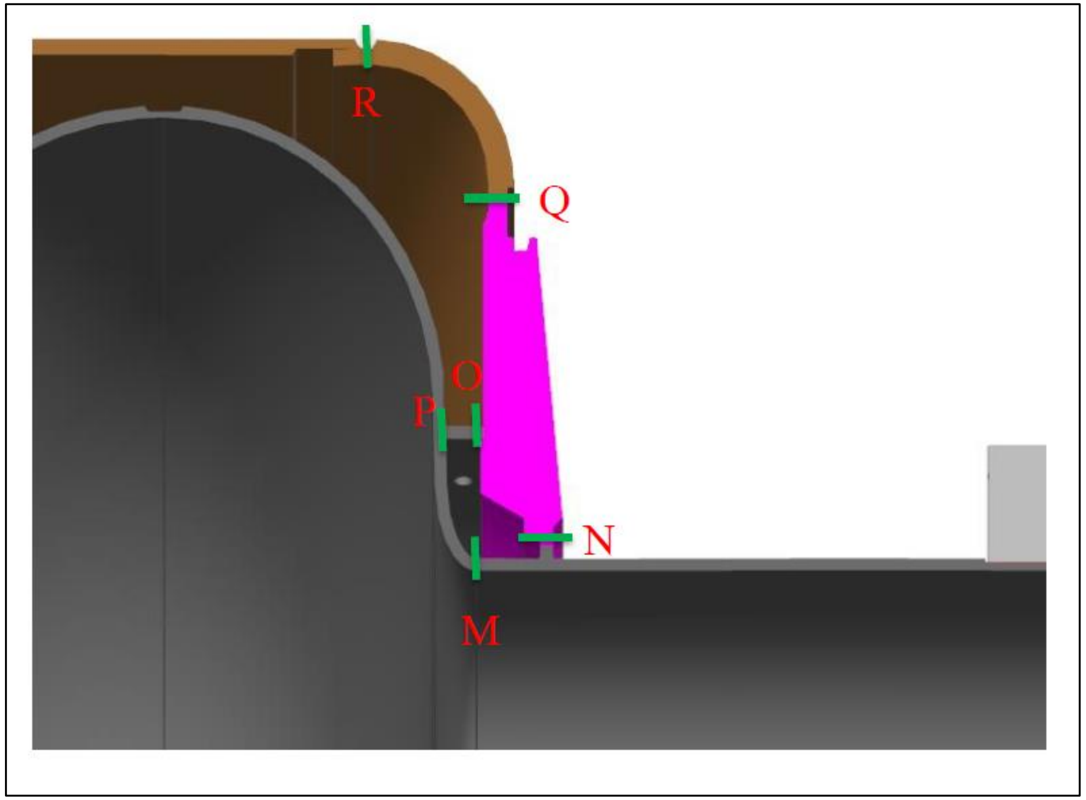


Stress Classification Lines (SCL) for Field Probe End (FPE)



Stress Classification Lines (SCL) for Regular Cell

Stress Classification Lines



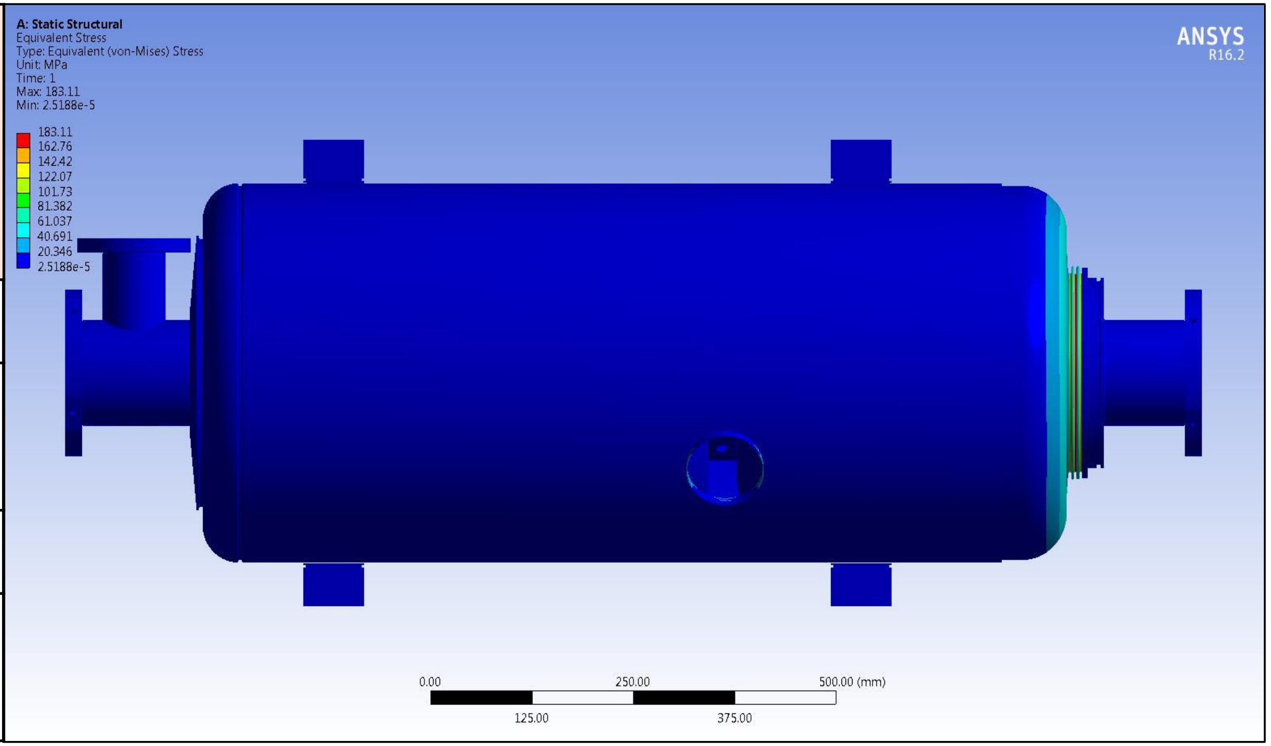
Stress Classification Lines (SCL) for Main coupler End (MCE)

Load Case-1

- To ensure safety of the system for 2 bar pressure at room temperature (293 K).
- It is a warm pressurization condition at room temperature.
- Effect of gravity loading is included in the analysis.
- Cavity is under vacuum and cooldown has not started.
- Material properties corresponding to 293 K used during simulations
- Tuner stiffness of 68 kN/mm at field probe end transition spool

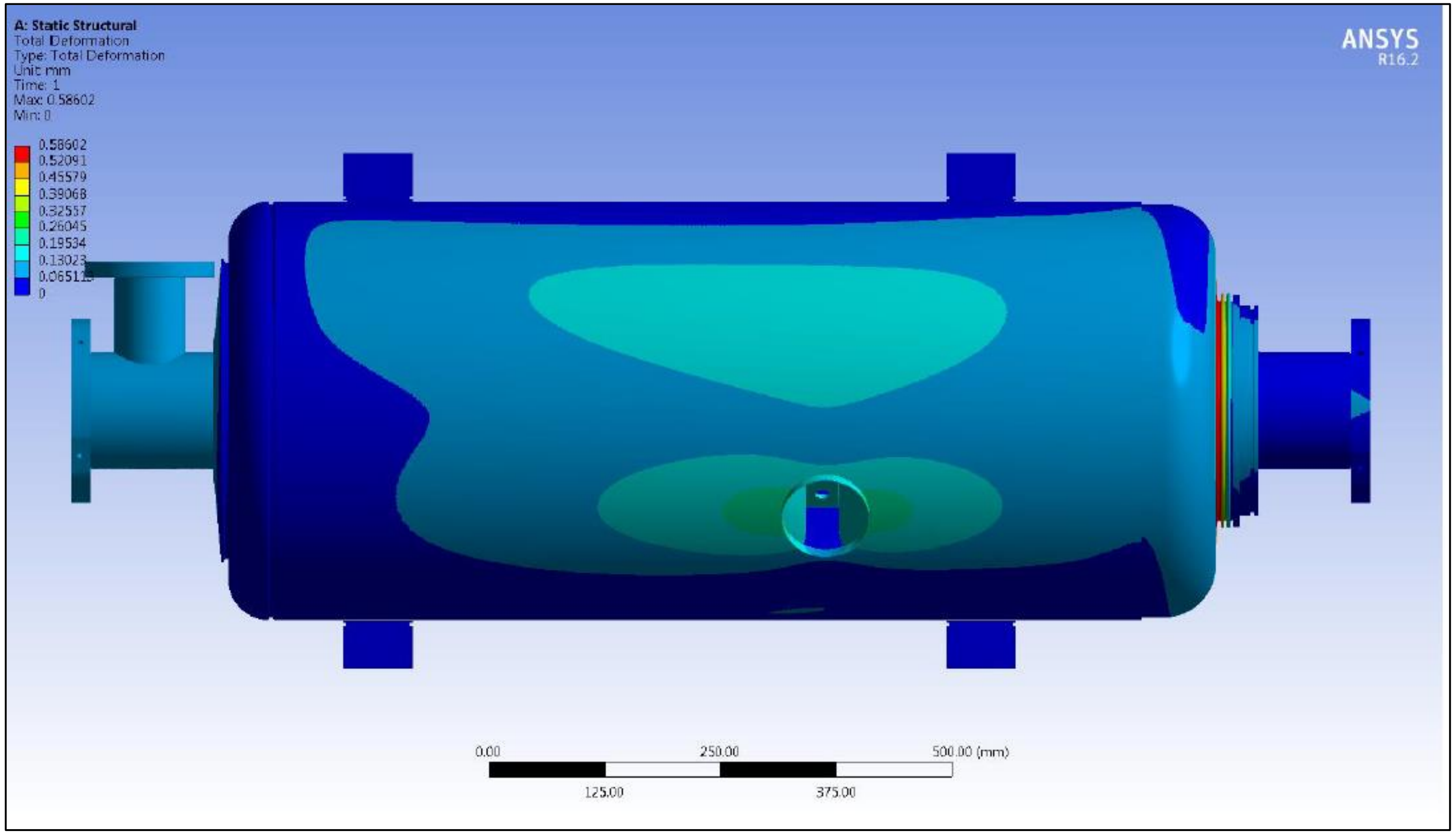
Load Case 1 Results: Stress Distribution

Component	Material	Simulated Maximum Stress (MPa)	Yield Stress (MPa)
Cavity	Nb	17	38
Helium vessel	Ti	64	276
Bellow	Ti	183	276
Transition Spool	Nb-Ti	34	476



Simulated stresses for components is less than the yield strength of material.

Load Case 1 Results: Displacement Pattern



Maximum displacement ~ 580 microns

Load Case-2

- Load case 2 checks the safety of the system for 4 bar pressure at 2 K.
- It is a cold pressurization condition at 2K, where full liquid helium inventory is there in helium vessel.
- During analysis effect of various loadings including maximum 4 bar pressure, gravity loading and weight of liquid helium inventory on cavity have been evaluated.
- It is a cold operation condition where all primary loadings have been considered.
- Material properties corresponding to 2 K have been used during simulations.

Load Case-3

- Load case 3 checks the safety of the system corresponding to secondary loadings condition at 2 K.
- In this case cavity is cooled down from 293 K to 2 K temperature.
- Tuner is engaged to provide 2 mm displacement from field probe end.
- No primary loading have been considered during analysis.
- Secondary stresses developed in the cavity are of prime concern.
- Temperature dependent material properties from 293 K to 2 K have been used during simulations.
- Tuner stiffness of 68 kN/mm have been applied at field probe end transition spool.

Load Case-4

- Load case 4 checks the safety of the system for all possible primary and secondary loading conditions.
- It is the worst case scenario that may exist during cavity operation.
- Helium vessel has its full liquid helium inventory with a maximum pressure of 4 bar at 2K.
- Effect of gravity loading and weight of liquid helium inventory on cavity have been also incorporated.
- Cavity is cooled down from 293 K to 2 K temperature.
- Tuner is engaged to provide a 2 mm displacement at field probe end transition spool.
- Temperature dependent material properties from 293 K to 2 K have been used during simulations.

Load Case-5

- These loading condition may occur under accidental conditions.
- Normal cavity operation involves pressurized liquid helium volume, insulating vacuum and beam vacuum conditions.
- During accidental condition, it may happen that the insulating or beam vacuums are spoiled and the liquid helium space simultaneously evacuated.
- This reverses the normal operational stress state of the cavity assembly.
- In this case 1 bar internal pressure acts on cavity and 1 bar external pressure acts on helium vessel.
- Material properties corresponding to 293 K have been used during simulations. Effect of gravity loading is also incorporated.

Load Case Summary

Load Case	Loads	Condition Simulated	Applicable Temperature	Applicable Stress Categories
1	1. Gravity 2. P_1 = 2 bar 3. $P_2 = P_3 = 0$	Warm Pressurization	293 K	Pm, P_L, Q, Pm + P_b , P_L + Q
2	1. Gravity 2. Liquid Helium head 3. P_1 = 4 bar 4. $P_2 = P_3 = 0$	Cold operation, full LHe, maximum pressure – no thermal contraction	2 K	Pm, P_L, Q, Pm + P_b , P_L + Q
3	1. Cool down to 2 K 2. Tuner displacement of 2 mm	Cool down and tuner extension, no primary loads	2 K	Q
4	1. Gravity 2. Liquid Helium head 3. Cool down to 2 K 4. Tuner extension of 2 mm 5. P_1 = 4 bar 6. $P_2 = P_3 = 0$	Cold operation, full LHe inventory, maximum pressure – primary and secondary loads	2 K	Q
5	1. Gravity 2. P_1 = 0 3. $P_2 = P_3$ = 1 bar	Insulating and beam vacuum upset, helium volume evacuated	293 K	Pm, P_L, Q, Pm + P_b , P_L + Q

7. Design by Analysis – ASME Section VIII Division 2

ASME BPV Code Section VIII Division 2 Part 5 guidelines shall be followed for Design by Analysis.

The design by analysis requirements are based on protection against the following failure modes.

I. Plastic collapse - according to 5.2.2.

II. Ratcheting - according to 5.5.6.1.

III. Local failure - according to 5.3.2

IV. Buckling - according to 5.4.1.2.

V. Fatigue assessment - according to 5.5.2.3

Protection Against Plastic Collapse

- ASME section VIII Division 2 Part 5 Subsection 5.2.2 provide guidelines for protection against plastic collapse using elastic stress analysis methods.

  > "Elastic Stress Analysis Method – Stresses are computed using an elastic analysis, classified into categories, and limited to allowable values that have been conservatively established such that a plastic collapse will not occur."

- Stress analysis for each load case was carried out.
- Stress classification lines for each load case were identified.
- Stresses and displacements were evaluated.
- Stress linearization was performed to evaluate primary membrane, primary bending and secondary stresses. Simulated stresses were compared with allowable stresses.
- Simulated stresses are lower than allowable stresses.

Protection against plastic collapse is ensured using elastic stress analysis method.

Load Case – 1 Stress Linearization Results

SCL	Material	Weld	Simulated Membrane Stress (MPa)	Weld Joint Efficiency	Allowable Stress (MPa)	Ratio (Simulated/ Allowable stress)
A	Nb-Nb	1	4.83	0.7	14	0.35
B	Nb-55Ti45Nb	2	1.09	0.6	12	0.09
C	Nb-55Ti45Nb	3	0.97	0.6	12	0.08
D	Nb-Nb	4	7.30	0.6	12	0.61
E	55Ti45Nb -Ti	5	0.88	0.6	47.4	0.02
F	Ti-Ti	6	0.89	0.6	47.4	0.02
G	Ti-Ti	7	30.41	0.6	47.4	0.64
H	Ti-Ti	8	11.86	0.6	47.4	0.25
I	Ti-Ti	9	7.64	0.45	35.5	0.21
J	Nb-Nb	10	4.61	0.6	12	0.38
K	Nb-Nb	11	5.82	0.6	12	0.49
L	Nb-Nb	12	7.62	0.6	12	0.64
M	Nb-Nb	13	3.18	0.7	14	0.23
N	Nb-55Ti45Nb	14	4.17	0.6	12	0.35
O	Nb-55Ti45Nb	15	2.21	0.6	12	0.18
P	Nb-Nb	16	7.72	0.6	12	0.64
Q	55Ti45Nb - Ti	17	4.22	0.6	47.4	0.09
R	Ti - Ti	18	1.71	0.6	47.4	0.04

SCL	Material	Weld	Simulated (Membrane + Bending) Stress (MPa)	Weld Joint Efficiency	Allowable Stress (MPa)	Ratio (Simulated/ Allowable stress)
A	Nb-Nb	1	6.83	0.7	21	0.33
B	Nb-55Ti45Nb	2	1.83	0.6	18	0.10
C	Nb-55Ti45Nb	3	2.32	0.6	18	0.13
D	Nb-Nb	4	10.49	0.6	18	0.58
E	55Ti45Nb -Ti	5	1.94	0.6	71.1	0.03
F	Ti-Ti	6	2.57	0.6	71.1	0.04
G	Ti-Ti	7	31.98	0.6	71.1	0.45
H	Ti-Ti	8	22.23	0.6	71.1	0.31
I	Ti-Ti	9	10.43	0.45	53.32	0.20
J	Nb-Nb	10	8.96	0.6	18	0.50
K	Nb-Nb	11	8.13	0.6	18	0.45
L	Nb-Nb	12	14.14	0.6	18	0.79
M	Nb-Nb	13	4.71	0.7	21	0.22
N	Nb-55Ti45Nb	14	6.14	0.6	18	0.34
O	Nb-55Ti45Nb	15	2.96	0.6	18	0.16
P	Nb-Nb	16	10	0.6	18	0.56
Q	55Ti45Nb - Ti	17	8.53	0.6	71.1	0.12
R	Ti - Ti	18	3.03	0.6	71.1	0.04

Simulated (Pm) and (Pm + Pb) are less than allowable stress.

Protection Against Ratcheting

- ASME Section VIII Division 2 Subsection 5.5.6 provide guidelines for protection against ratcheting.

- Safety of a component from progressive distortion under repeated loadings is ensured by protection against ratcheting requirement.

$$\Delta S_{n,k} \le S_{PS}$$

$\Delta S_{n,k}$ = Primary plus secondary equivalent stress range

S_{PS} = Allowable limit on primary plus secondary stress range

- Since there is no stress reversal in cavity during normal operation, therefore for ratcheting purpose, $\Delta S_{n,k}$ and S_{PS} will have same values of primary plus secondary stresses and allowable stresses as evaluated by stress analysis for all load cases.

- From stress analysis, simulated (Pm + Pb + Q) are always lesser than allowable (Pm + Pb + Q). Therefore dressed SCRF cavity qualifies for protection against ratcheting.

Protection Against Local Failure

- ASME Section VIII Division 2 Subsection 5.3 provides guidelines for protection against local failure.
- These requirements apply to all components where the thickness and configuration of the component are established by using design by analysis rules.
- It is not necessary to evaluate protection against local failure, if the component design is in accordance with design by rules based on Section VIII Division 1.
- Elastic Analysis Tri-axial Stress Limit method has been applied for ensuring protection against local failure. It states that the sum of principle stresses at each point in the material must be less than or equal to four times of allowable stress of material at operating temperature.

$$\sigma 1 + \sigma 2 + \sigma\ 3 \leq 4S$$

$\sigma 1, \sigma 2, \sigma 3$ = principal stresses at any point in the assembly

S = allowable stress for material at operating temperature

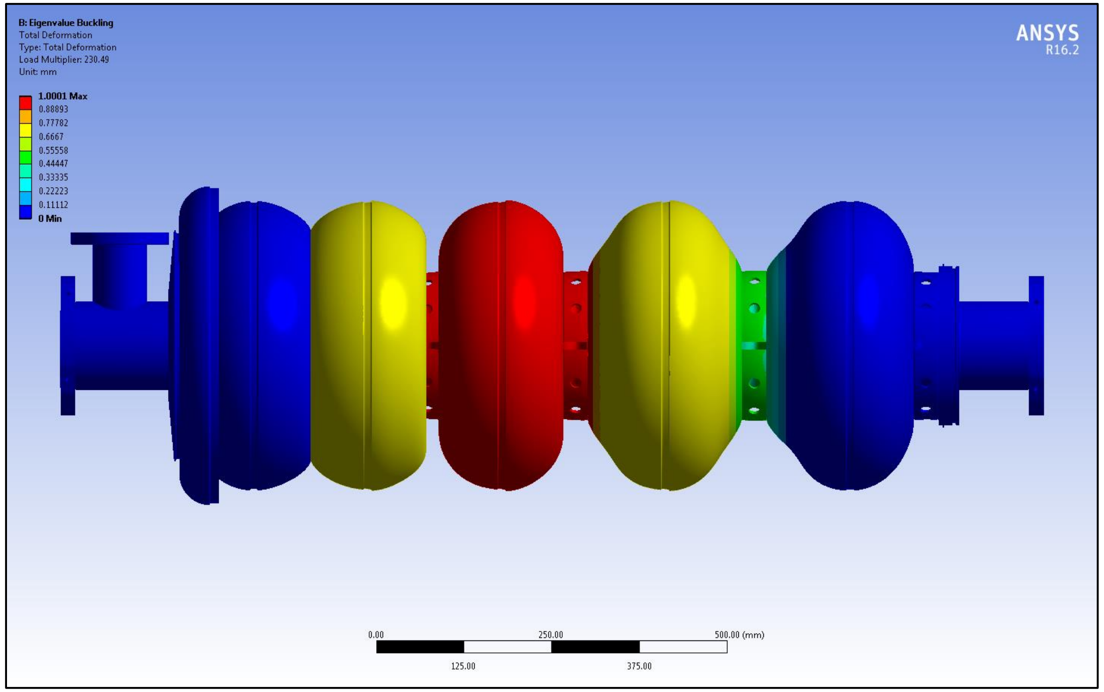
Protection Against Local Failure

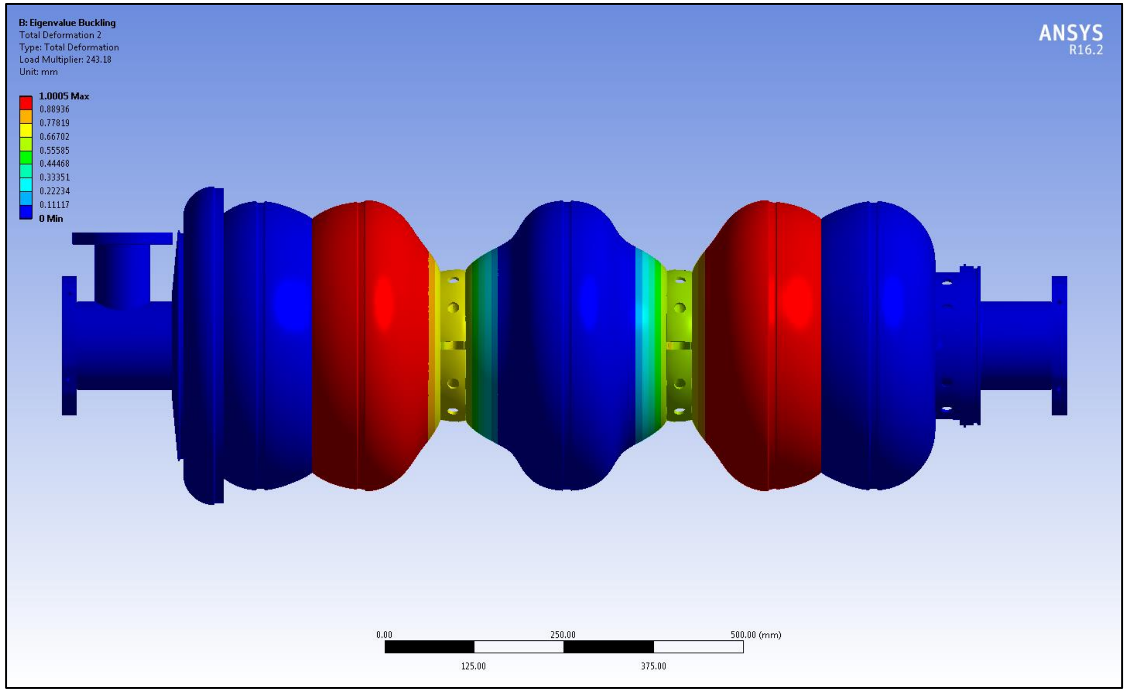
S. No.	Load Case	Component	Material	Maximum ($\sigma1 + \sigma2 + \sigma3$) (MPa)	Allowable Stress (MPa)	Ratio (Maximum/Allowable)
1	1	Cavity	Nb	45	48	0.94
2		Transition Spool	55 Ti- 45 Nb	57	300	0.19
3		Helium Vessel	Ti Gr. 2	88	190	0.46
4		Bellow	Ti Gr. 2	250	316	0.79
5	2	Cavity	Nb	89	329	0.27
6		Transition Spool	55 Ti- 45 Nb	114	300	0.38
7		Helium Vessel	Ti Gr. 2	176	612	0.29
8		Bellow	Ti Gr. 2	495	1020	0.49
9	3	Cavity	Nb	170	329	0.52
10		Transition Spool	55 Ti- 45 Nb	210	300	0.70
11		Helium Vessel	Ti Gr. 2	419	612	0.68
12		Bellow	Ti Gr. 2	159	1020	0.16
13	4	Cavity	Nb	215	329	0.65
14		Transition Spool	55 Ti- 45 Nb	226	300	0.75
15		Helium Vessel	Ti Gr. 2	447	612	0.73
16		Bellow	Ti Gr. 2	638	1020	0.63
17	5	Cavity	Nb	22	48	0.46
18		Transition Spool	55 Ti- 45 Nb	29	300	0.10
19		Helium Vessel	Ti Gr. 2	44	190	0.23
20		Bellow	Ti Gr. 2	146	316	0.46

Protection Against Collapse from Buckling

- ASME Section VIII Division 2 Subsection 5.4 provides guidelines for protection against collapse from buckling.
- A linear elastic buckling analysis of niobium cavity was performed using ANSYS Workbench.
- The critical pressure was found to be 230 bar using linear elastic buckling analysis.
- A design factor was applied to the predicted critical pressure to evaluate maximum allowable external working pressure.
- According to code guidelines, if buckling analysis is performed using an elastic stress analysis without geometric nonlinearities, a minimum design factor of $\Phi_B = 2 / B_{cr}$ should be used, where, B_{cr} is Capacity Reduction Factor for component.
- According subsection 5.4.1.3(c), for spherical shells under external pressure, capacity reduction factor shall be 0.124.
- Design factor of 16 was applied for predicted critical pressure to determine MAWP.
- MAWP was evaluated as ~ 14 bar, which is greater than the required MAWP of 1 bar external.

Protection Against Collapse from Buckling





First Buckling Mode Shape of Cavity

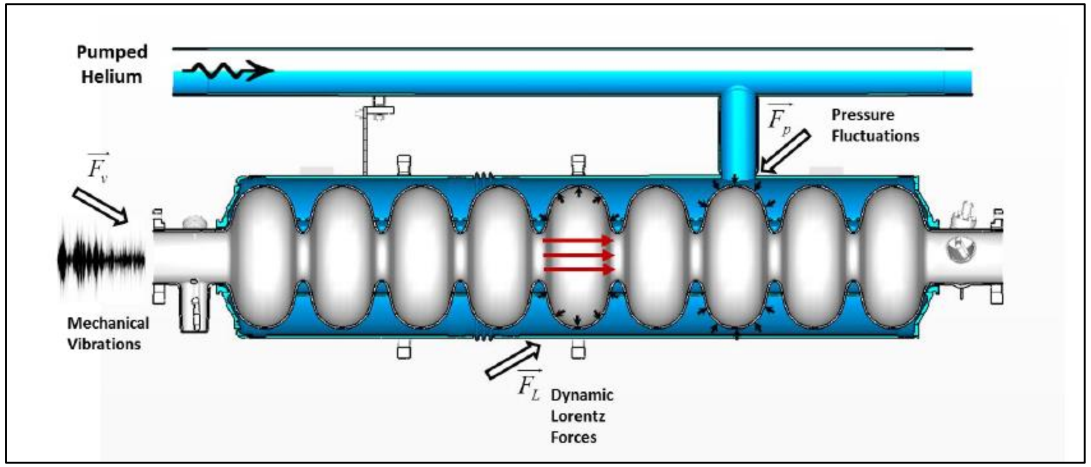
Second Buckling Mode Shape of Cavity

Fatigue Assessment

- ASME Section VIII Division 2 Part 5 Subsection 5.5.2.3 provide guidelines for Fatigue Assessment.
- In this procedure, a load history based on design specifications is established.
- The load history determines the total number of load cycles experienced by the Dressed SRF Cavity and compared with guidelines given in the codes.
- For dressed cavity assembly, load history consists of pressurization, cool down and tuning cycles. The estimated numbers for cycle are as follows.
  - Pressurization ($N\Delta F$) = 200
  - Cool Down ($N\Delta T$) = 100
  - Tuning ($N\ \Delta Tuner$) = 200
- As per guidelines sum of all cycles should be less than 1000 for fatigue assessment.
- Sum of all load cycles = 200 +100 + 200 = 500, which is less than 1000.
- Therefore, no fatigue assessment is necessary for dressed cavity assembly.

Sources of Frequency Detuning

- Lorentz Force Detuning - RF field inside cavity interacts with cavity walls, which is proportional to electromagnetic field energy. (Minimize LFD)
- Helium Pressure – Helium pressure variation in cryogenic system exerts fluctuating pressures on cavity walls, which results in cavity deformations and frequency detuning. (Minimize df/dP)
- Mechanical Vibrations – Mechanical vibrations of motor, pump etc. reaches on cavity through piping system and leads to cavity deformation. (cavity natural frequency should be away from disturbance frequency. Modal analysis of dressed cavity is performed.)

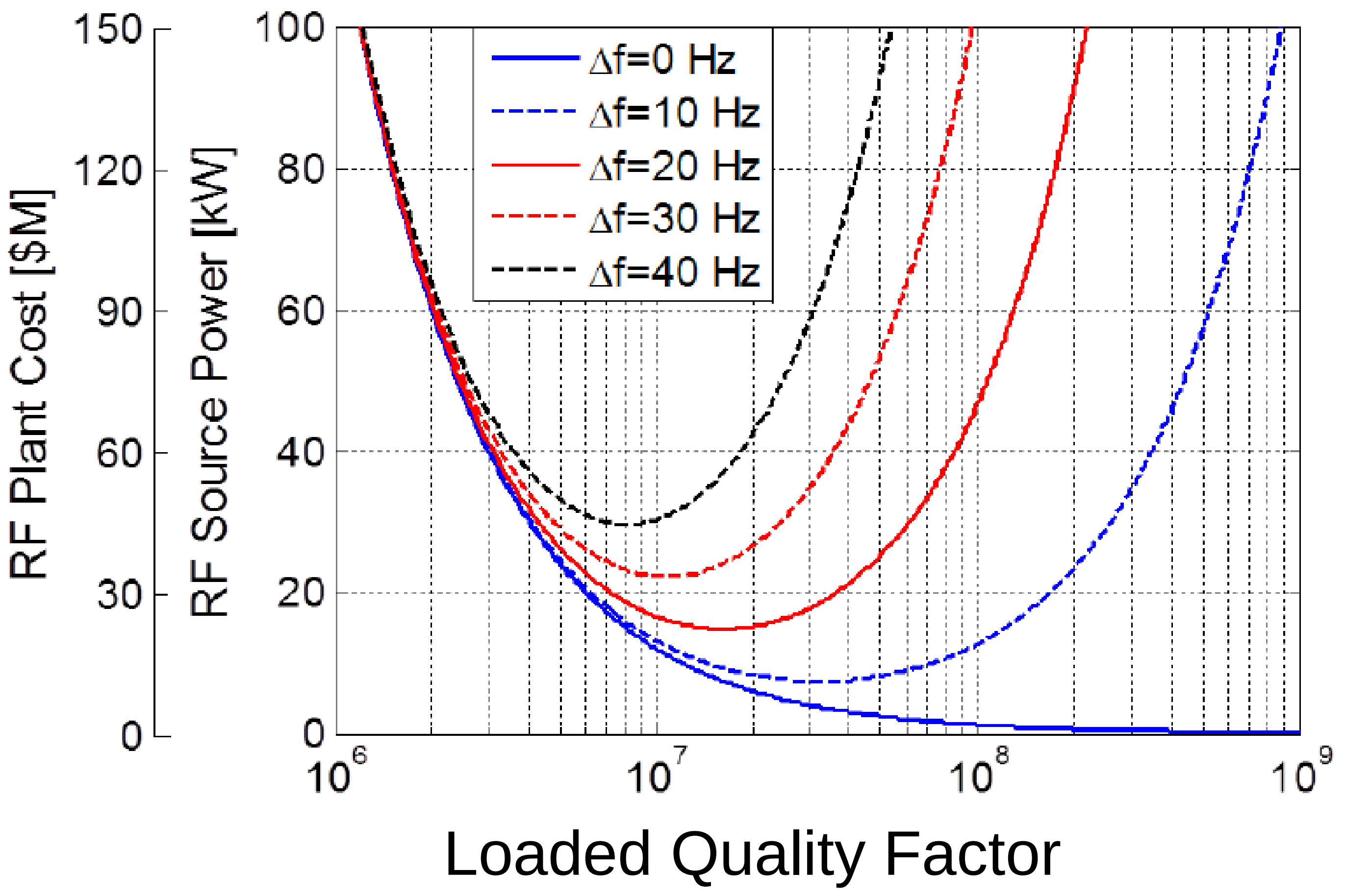


Reference: Mohamed Awida Hasan "Multiphysics Analysis of RF Cavities for Particle Accelerators: Perspective and Overview" COMSOL Conference, Boston 2016

RF plant cost increases significantly with increase in frequency detuning.

Effect of Frequency Detuning on RF Power Requirements

- SCRF cavity operates at a specific frequency with narrow bandwidth and high quality factor.
- Amount of RF source power needed to drive the cavity is highly dependent on the frequency shift.
- At loaded quality factor 0f 10^7-10^8, RF power requirement increases sharply with frequency detuning.



Reference: Mohamed Awida Hasan "Multiphysics Analysis of RF Cavities for Particle Accelerators: Perspective and Overview" COMSOL Conference, Boston 2016

8. Lorentz Force Detuning

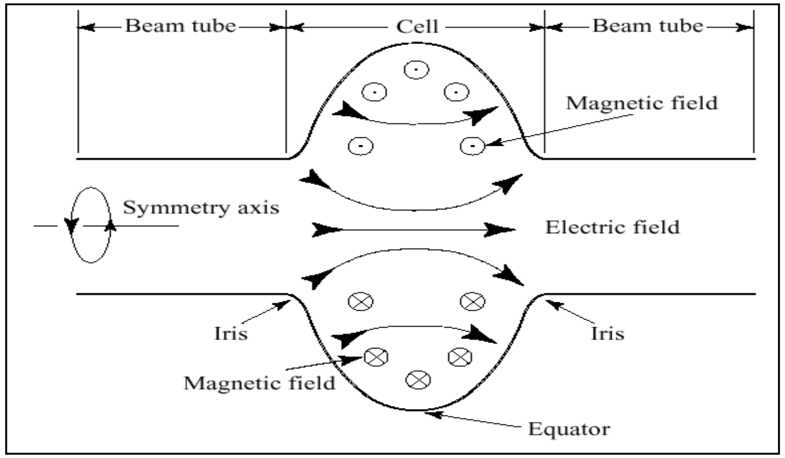
- Due to RF power, an electro-magnetic field is set up in SCRF cavity.
- This results flow of charge in a thin surface layer of cavity walls.
- The movement of charges in electromagnetic field is affected by Lorentz forces.
- The pressure exerted on cavity wall due to this interaction is called Radiation Pressure.
- $P = \frac{1}{4}(\mu_0 * H * H - \varepsilon_0 * E * E)$

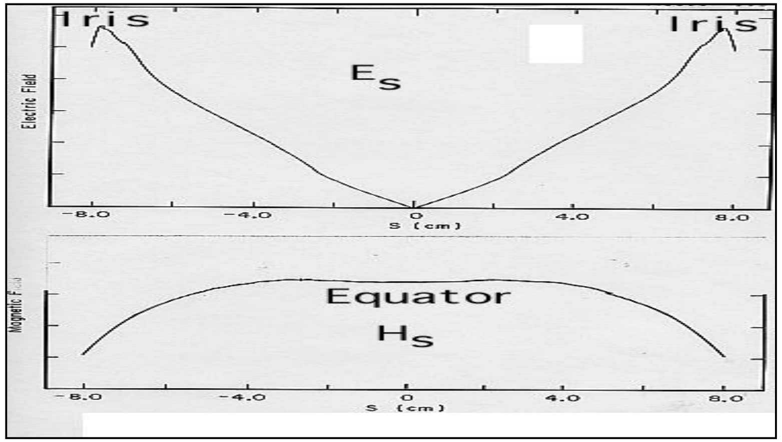
  E = Electric field intensity (V/m)

  H = Magnetic field intensity (H/m)

  μ_0 = Permeability of free space ($4\pi\times10^{-7}$ H·m^{-1})

  ε_0 = Permittivity of free space (8.85×10^{-12} F/m)

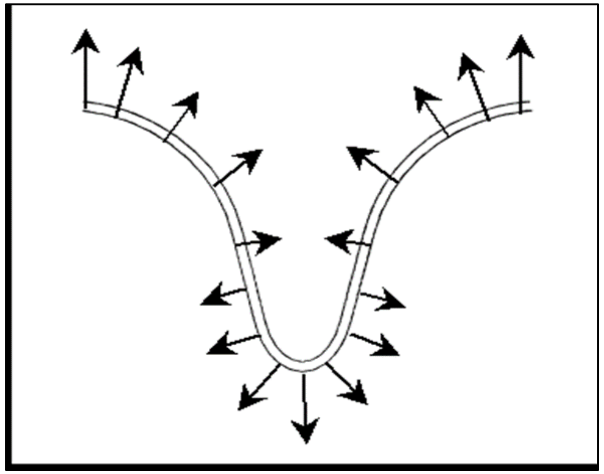


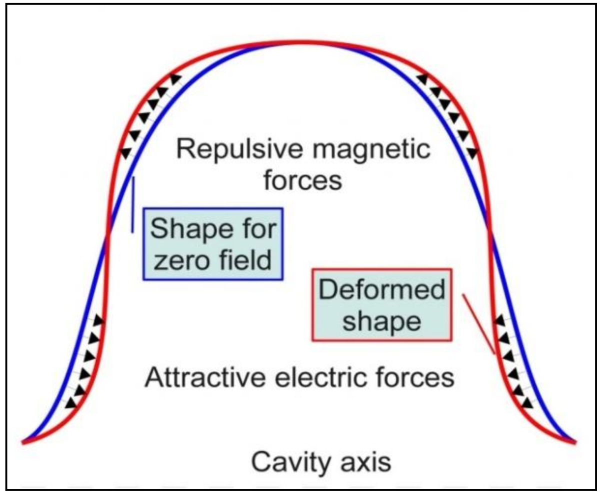


Radiation pressure changes cavity volume and hence leads to frequency shift known as Lorentz Force Detuning (LFD).

Static and Dynamic LFD

- ❖ Radiation pressure due to magnetic field (mainly at equator) is positive and it is negative due to electric field (mainly at iris).
- ❖ Pressure tries to deform cavity outwards at equator region and inward at iris region.
- ❖ For CW operation, Lorentz Forces are constant with time throughout the operation and detuning caused is called Static LFD.
- ❖ For pulse mode operation, Lorentz Forces are applied during the pulse only and there are no force up to the next pulse. Again in the next pulse Lorentz Forces are acted on the cavity. Thus Lorentz Forces shows transient behaviour in the pulsed mode operation and detuning is called dynamic LFD.





LFD is crucial for pulsed mode operation, where the dynamics of the detuning plays an important role.

Minimization of LFD

- LFD for SCRF cavity is minimized by employing stiffeners and optimizing their locations.
- RF – Structural – RF coupled FEA is performed to evaluate LFD for various stiffener ring locations.
- LFD is characterized by Lorentz Force detuning Coefficient (KL), defined as,

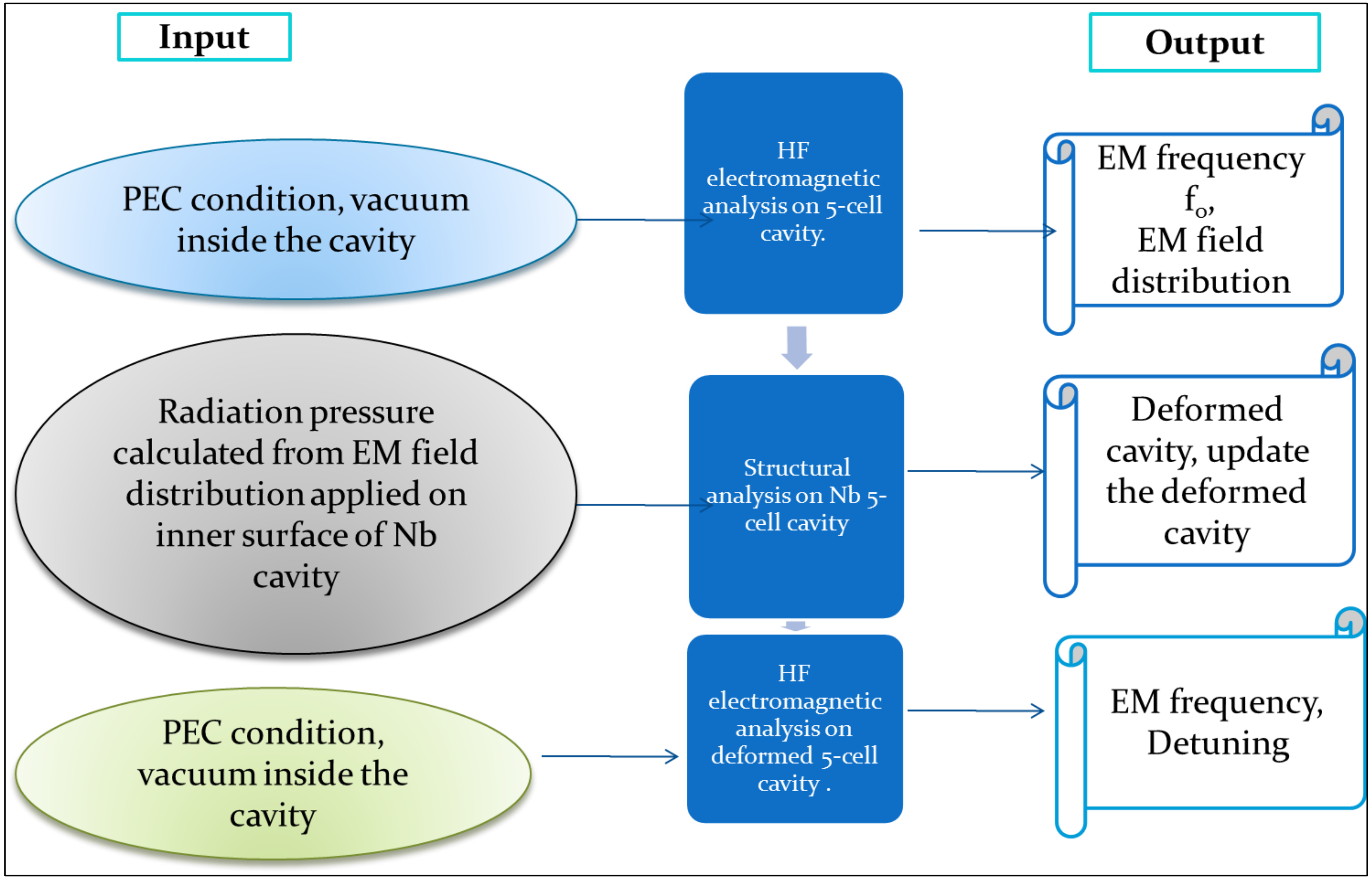
$$\Delta f = K_L * (E_{acc})^2$$

Δf = Frequency shift (Hz)

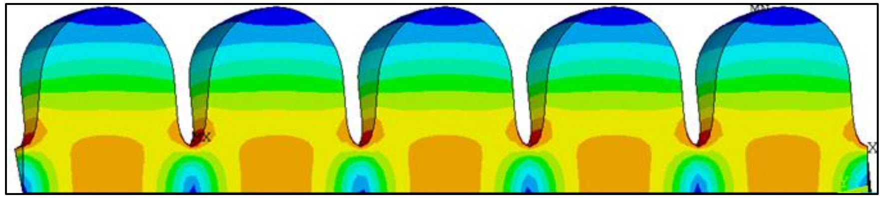
E_{acc} = Accelerating gradient (MV/m)

- Typically for 650 MHz cavity, $K_L < 1$ Hz / $(MV/m)^2$
- For CW operation, static detuning is constant with time and compensated by the tuner feedback.
- For pulse mode operation of cavity, Piezo-electric tuners are employed to minimize LFD effect. Piezo provides pulsed deformation in cavity to reduce the effect of LFD.

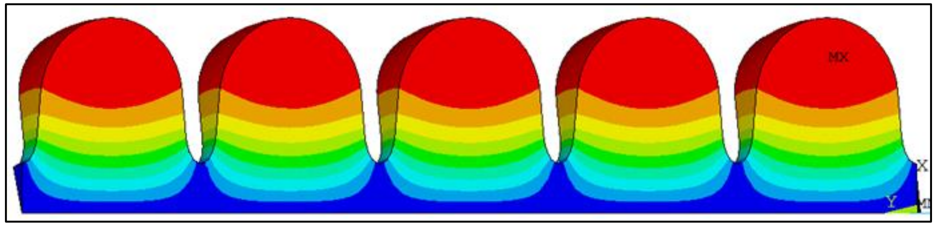
Flowchart for LFD Evaluation



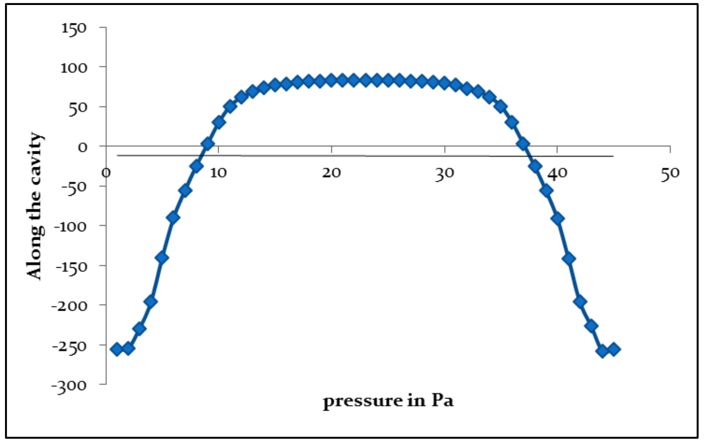
Results - LFD calculations



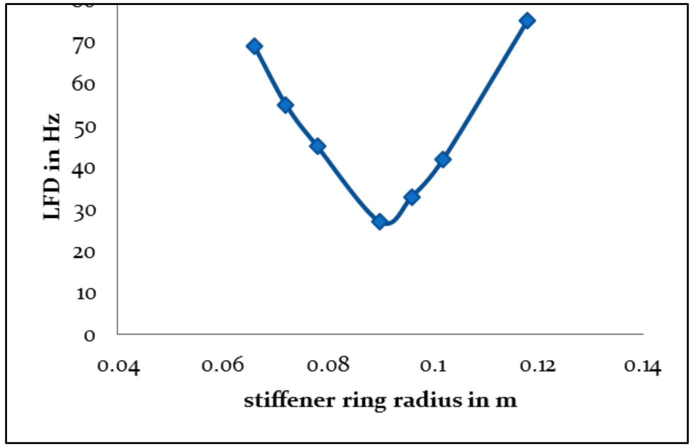
Electric Field Distribution



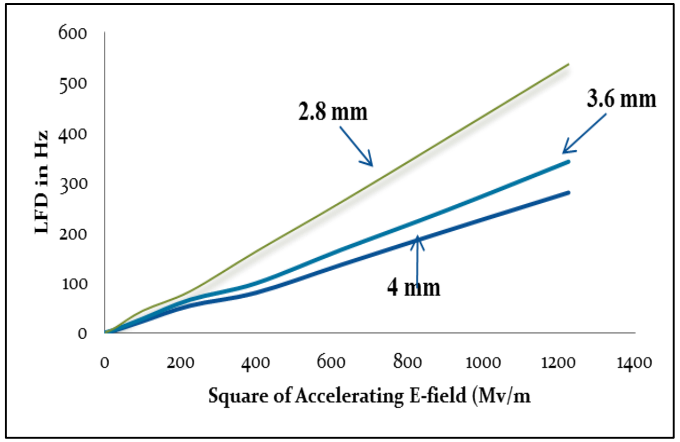
Magnetic Field Distribution



Lorentz Pressure Distribution



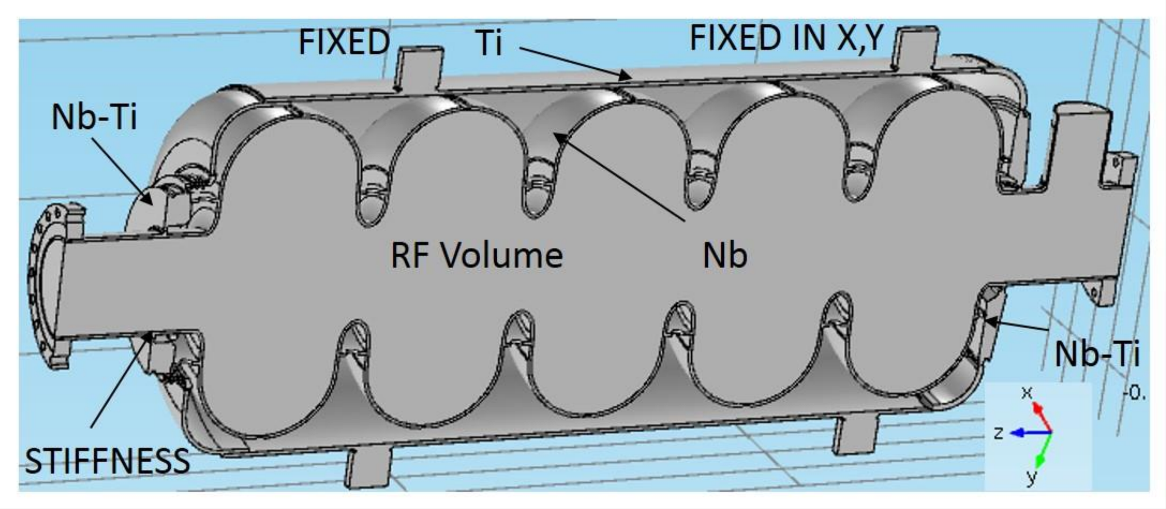
Effect of stiffener ring radius on LFD

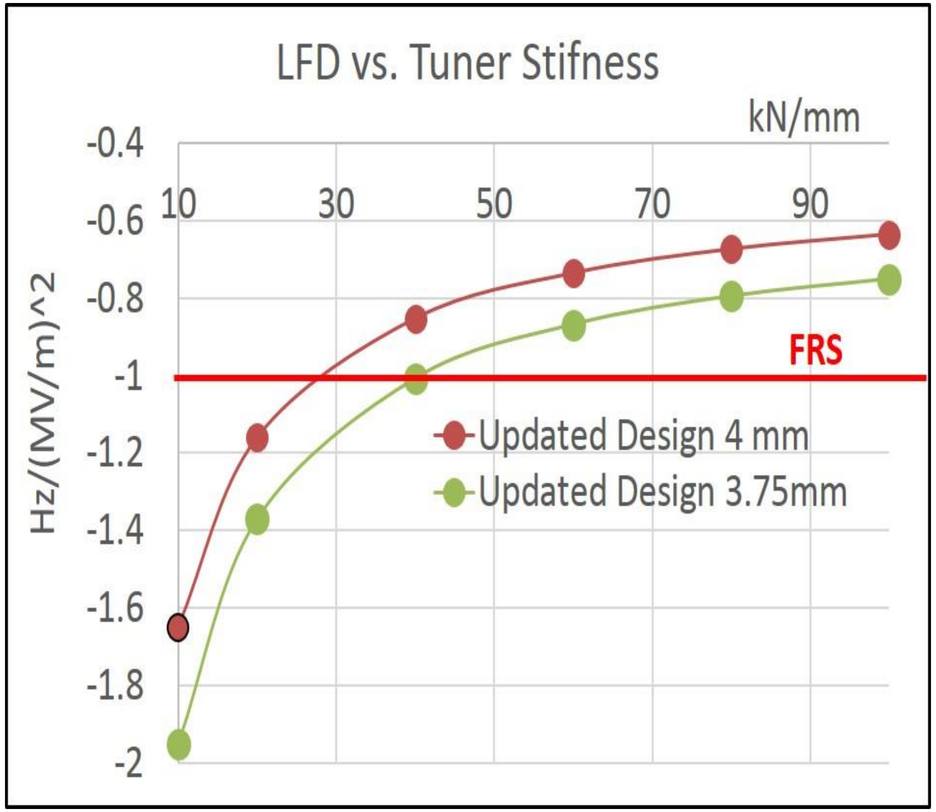


Effect of wall thickness on LFD

Reference: HBNI M. Tech. Thesis "Optimization of Design and Lorentz Force Tuning Methodology for SCRF Cavities" by Nitin Nigam, RRCAT, Indore 2012.

Results - LFD calculations





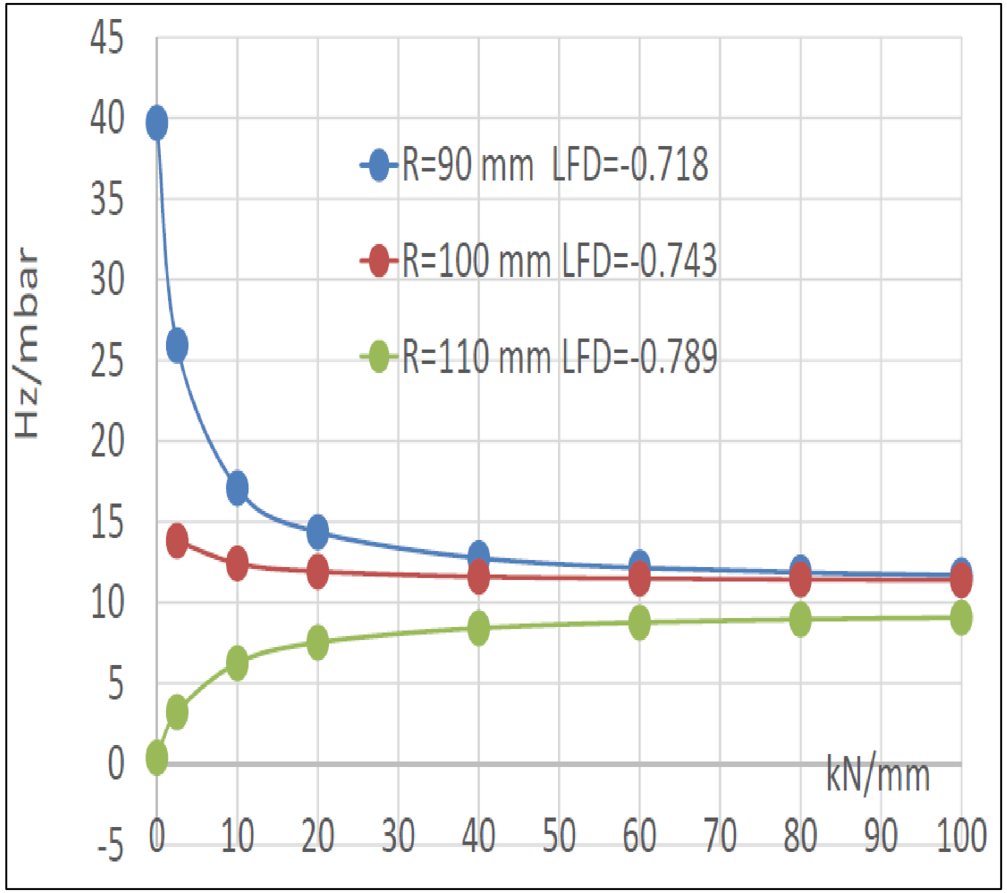
For gradient E_{acc}=20 MV/m and tuner stiffness 40 kN/mm, the frequency shift due to Lorentz forces will be between 340 Hz and 400 Hz depending on the cavity wall thickness.

Dependence of LFD vs. tuner stiffness for 4mm and 3.7mm cavity wall thickness.

Reference: Fermilab Technical Division report “Engineering Analysis of Beta 0.92 650 MHz 5 Cell SRF Cavity Assembly” by N K Sharma, V K Jain and I Gonin.

9. Microphonics - df/dP Analysis

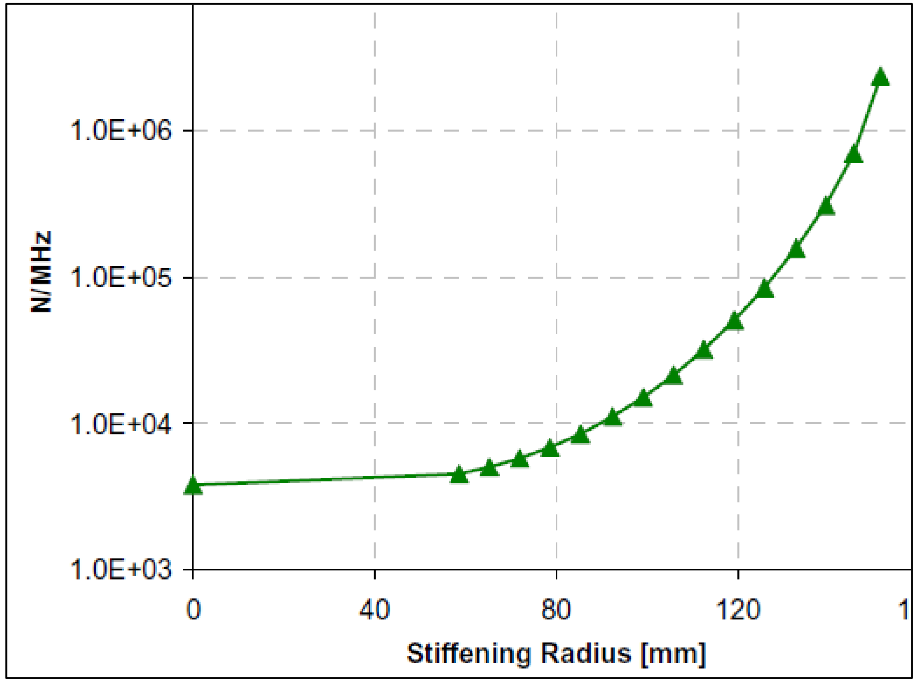
- The fluctuations of the liquid helium bath pressure amd mechanical vibrations are main sources of microphonics.
- The pressure sensitivity coefficient, df/dP is used to characterize the influence of the helium pressure variation on the detuning of the cavity.
- Larger df/dP may cause serious cavity detuning and instability of cavity operation.
- The mechanical design of the SRF cavity needs to have a lower df/dP.
- To reduce df/dP, cavity stiffness needs to be increased by iterating stiffener ring locations.

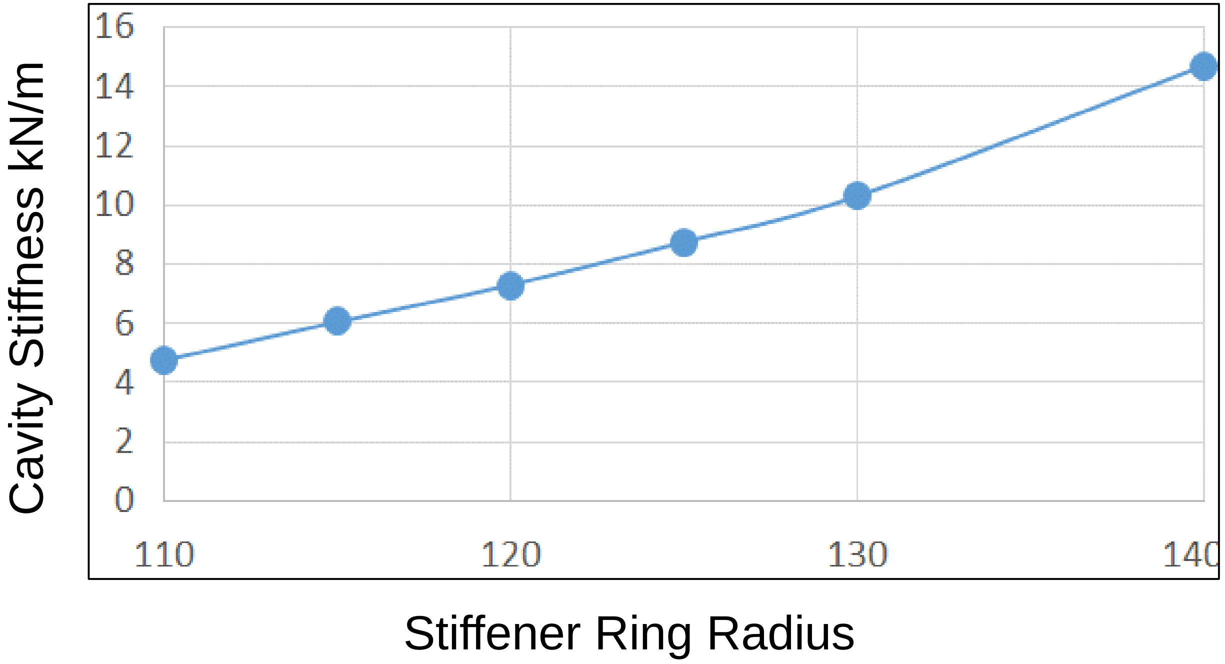


Effect of Stiffener Ring radius on df/dP

Reference: Fermilab Technical Division report “Engineering Analysis of Beta 0.92 650 MHz 5 Cell SRF Cavity Assembly” by N K Sharma, V K Jain and I Gonin.

Microphonics - df/dP Analysis





Effect of Stiffener Ring radius on Tuning Sensitivity

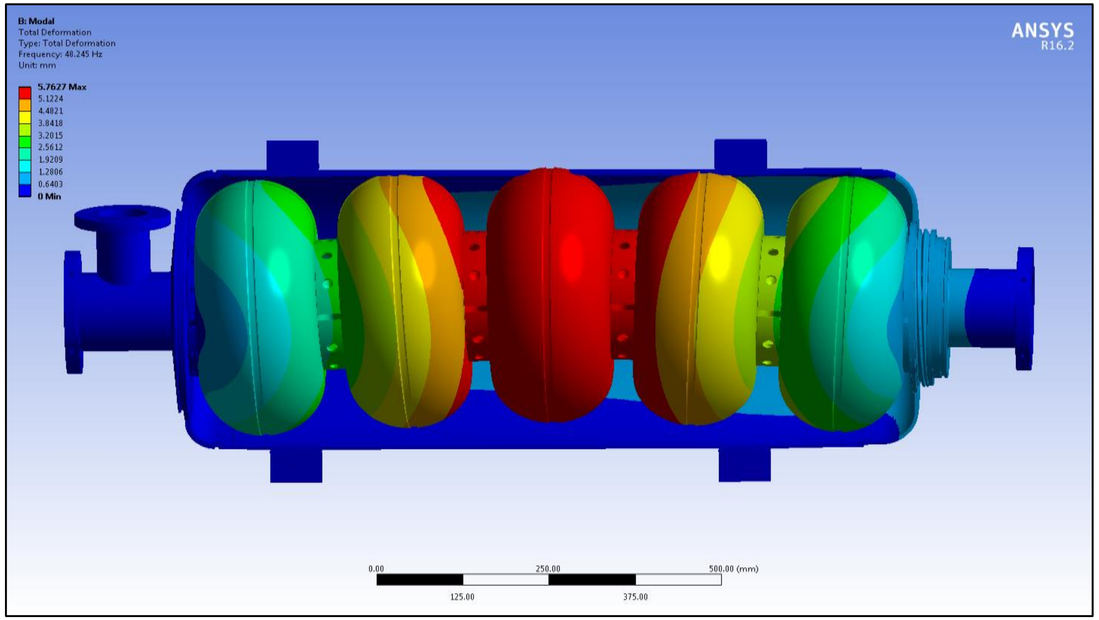
Effect of Stiffener Ring radius on Cavity Stiffness

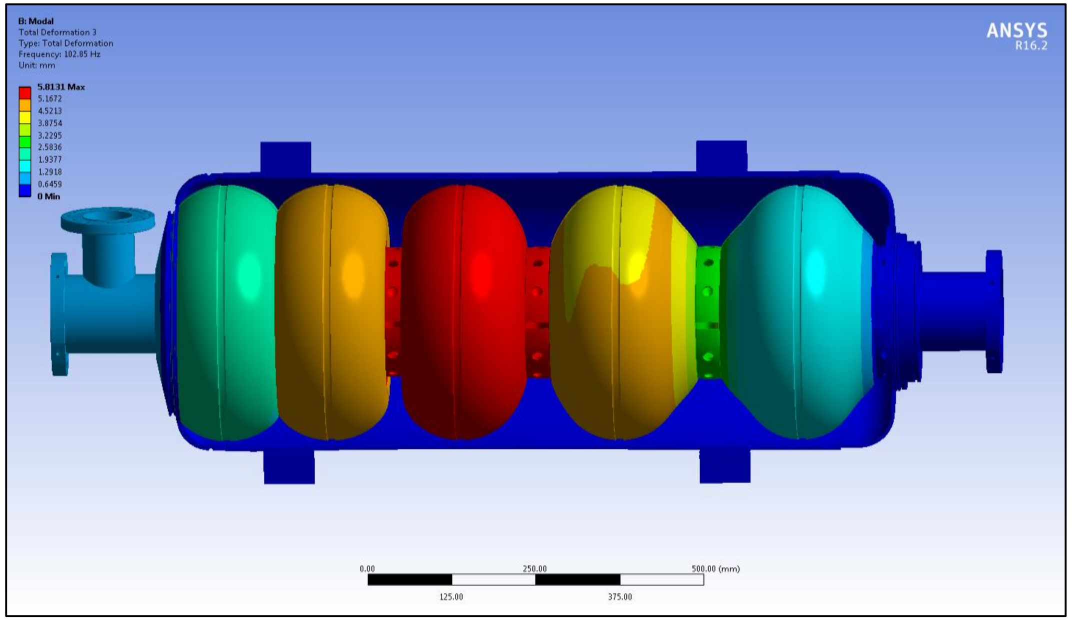
Increase in stiffener ring radius lowers df/dP, but it raises cavity stiffness and makes cavity tuning difficult. Optimization is required between df/dP and cavity stiffness during cavity design.

10. Modal Analysis

- Mechanical vibration within cryomodule may be transferred to cavity system and excite its mechanical resonances.
- Deformations amplitude caused by mechanical resonance may result in cavity deformations and hence frequency shift in the electromagnetic resonance frequency.
- Dressed cavity must have mechanical resonant frequency well away from these disturbances.
- Frequency well above 50 Hz is desired during cavity design.
- Modal analysis of dressed cavity is performed to evaluate mechanical resonance frequency and mode shapes.

Modal Analysis



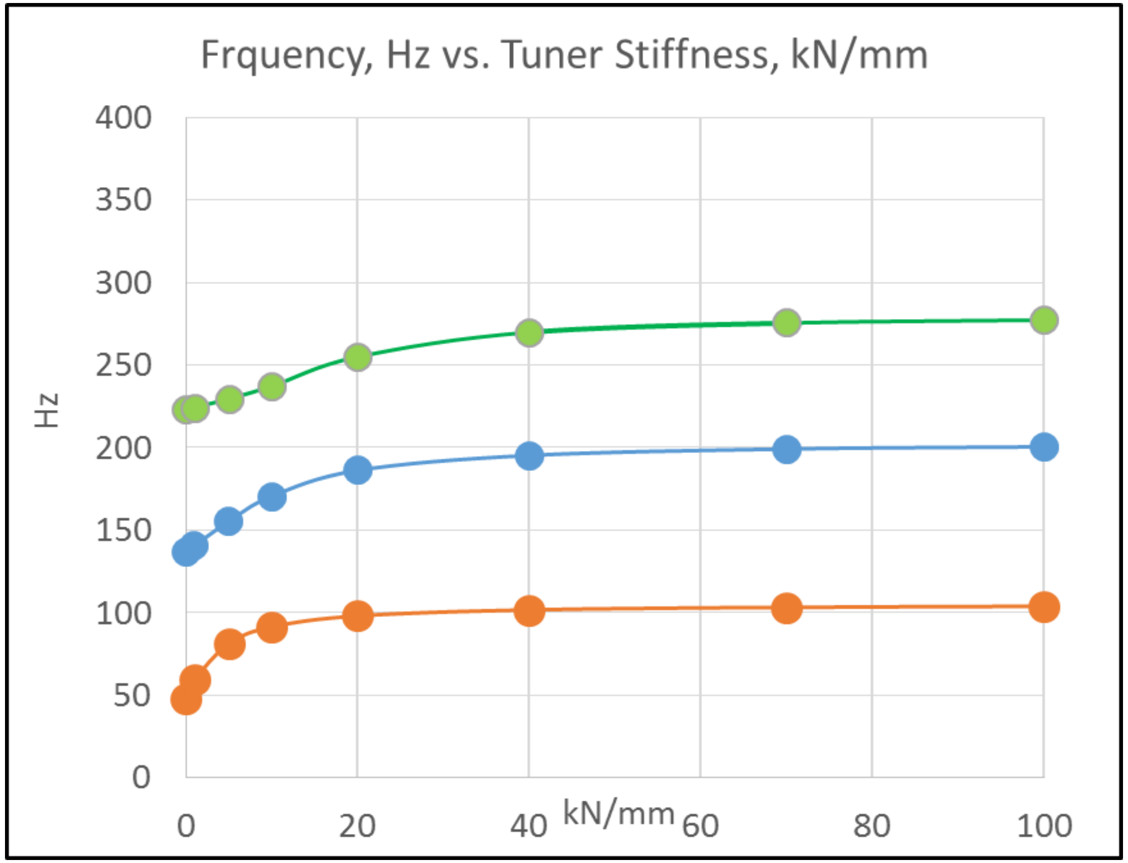


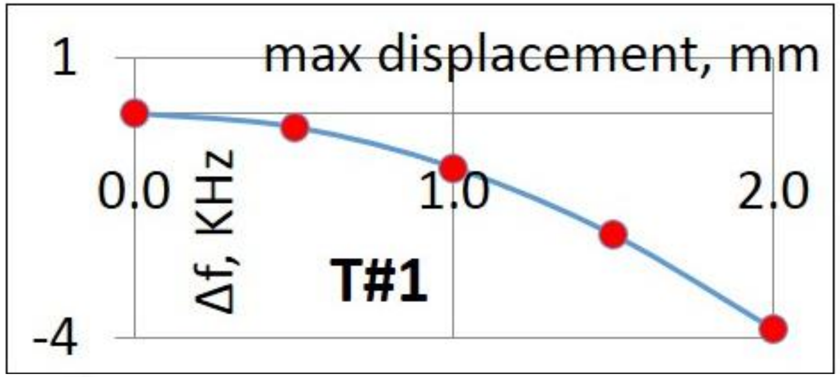
First Mode Shape Frequency ~ 48 Hz
(Transverse Mode)

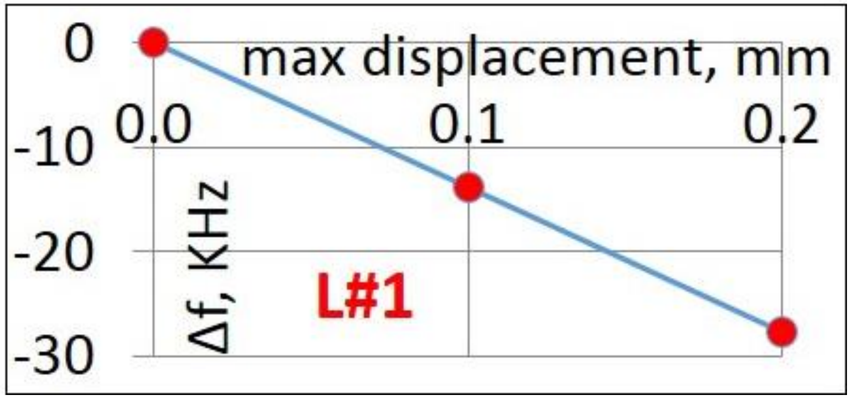
Second Mode Shape Frequency ~ 103 Hz
(Longitudinal Mode)

Longitudinal modes will result higher frequency detuning than transverse modes.

Modal Analysis







Mechanical frequencies for first 3 longitudinal modes

Longitudinal modes have more effect on RF frequency shift.

Reference: Fermilab Technical Division report "Engineering Analysis of Beta 0.92 650 MHz 5 Cell SRF Cavity Assembly" by N K Sharma, V K Jain and I Gonin.

11. Design of Helium Vessel for Internal Pressure

- ASME Section VIII Division 1 Part UG-27(C) (1) provide guidelines for calculating minimum wall thickness required for internal pressure for helium vessel.

$$t = \frac{P.R}{S.E - 0.6\,P}$$

  - t = Thickness of Helium Vessel
  - P = Internal Pressure
  - R = Inside radius of helium vessel
  - E = Efficiency of seam weld, no radiography
  - S = Maximum Allowable Stress for Grade 2 Titanium

- Internal Maximum Allowable Working Pressure (MAWP) for helium vessel is 2 bar at 293 K and 4 bar at 2K.
- Helium vessel must satisfy minimum wall thickness requirements prescribed by Code for these pressures.

Design of Helium vessel for Internal Pressure

For warm conditions at 293 K

P = 2 bar
R = 220 mm
S = 79 MPa (for Ti Gr. 2 material)
E = Efficiency of seam weld (Type 3 TIG weld, one sided butt weld, no radiography) = 0.6
Calculating, Minimum required thickness of helium vessel, **t = 0.96 mm**

For cold conditions at 2 K

P = 4 bar
R = 220 mm
S = 255 MPa (for Ti Gr. 2 material)
E = 0.6 (Type 3 TIG weld, no radiography)
Calculating, Minimum required thickness of helium vessel, **t = 0.59 mm**

Minimum thickness used for helium vessel = 3 mm

Helium Vessel satisfies minimum thickness requirements of UG-27 for internal pressure at warm as well as cold temperature.

Design of Helium vessel for External Pressure

- ASME Section VIII Division 1 Part UG-28(C) provide guidelines for calculating minimum wall thickness required for cylindrical shell under external pressure.
- Procedure uses charts provided in ASME Section II Part D.
- These charts are based on geometric and material characteristics of the vessel.
- Helium vessel fabricated from Titanium Gr. 2 material should sustain external working pressure of 1 bar.
  - Length of helium vessel shell, L = 936 mm
  - Outside diameter, Do = 450 mm
  - Thickness, t = 3 mm (minimum)

Design of Helium vessel for External Pressure

- ❖ Using code procedures
  - ➢ $L/D_o = 2.08$
  - ➢ $D_o/t = 150$
  - ➢ E = 107 GPa
  - ➢ Factor A = 0.00035 (Using ASME Section II, Part D, Subpart 3, Figure G)
- ❖ Allowable External Working Pressure (P) = (2/3) * Factor A * E*(t / D_0)
- ❖ Calculating, P ~ 1.7 bar

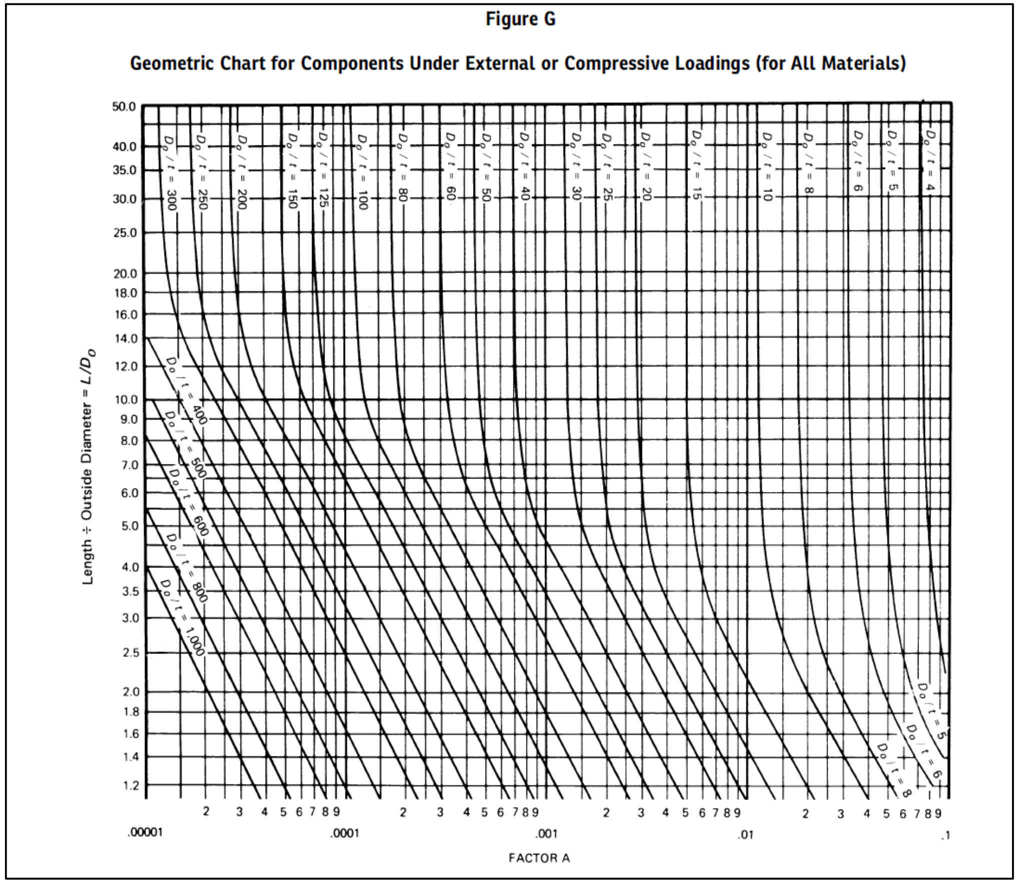
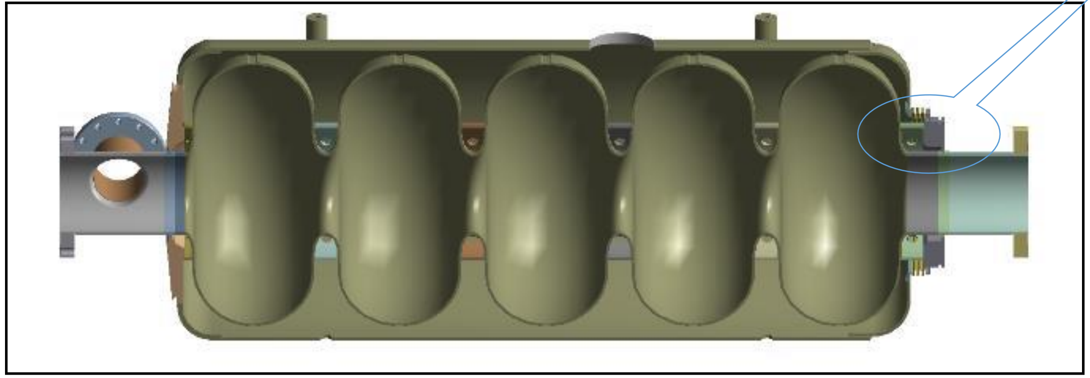


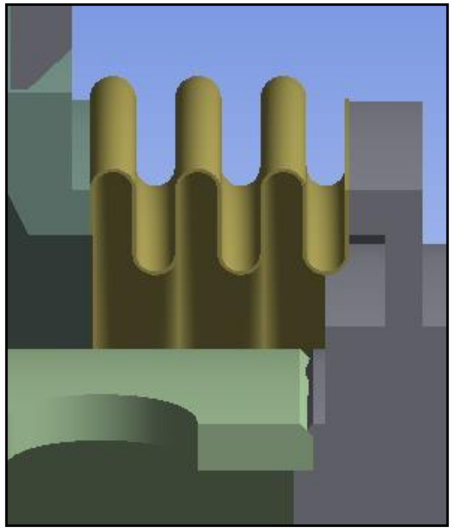
Chart used for Factor A Calculations

Helium Vessel satisfies minimum thickness requirements of ASME Section VIII Division 1 UG-28 for external pressure.

12. Design of Bellow

1. Internal Maximum Allowable Working Pressure (MAWP) at Room Temperature (293 K) = 2 bar
2. Internal MAWP at Cold Temperature (2 K) = 4 bar
3. External Pressure = 1 bar
4. Maximum Axial Displacement = 2 mm





Allowable Stress for Ti Gr2
- 79 MPa at 293 K
- 255 MPa at 2 K

Due to lower allowable stress of material at room temperature, the 2 bar pressure condition is more stringent during bellow design.

Design by Rules – Bellow Expansion Joints

ASME BPV Code Section VIII Division 1 Mandatory Appendix 26 “Bellows Expansion Joints” guidelines are followed for Bellow design.

“The suitability of an expansion joint for the specified design pressure, temperature and axial displacement shall be determined by the methods described herein.”

HB 650 dressed cavity bellow has been designed to satisfy following code requirements.

1. Internal Pressure Capacity (according subsection 26-6.3)
2. Instability due to Internal Pressure (according subsection 26-6.4)
3. External Pressure Capacity (according subsection 26-6.5.1)
4. Instability due to External Pressure (according subsection 26-6.5.2)
5. Fatigue Evaluation (according subsection 26-6.6)

Conclusions

- Engineering design of Beta 0.92, 650 MHz 5 Cell SRF dressed cavity assembly has been carried out in accordance with ASME guidelines.
- ASME Section VIII Division 1 rules have been applied for titanium helium vessel and titanium bellow design. From geometry and material point of view, design rules for these components are provided in Division 1 and they have been followed.
- However, niobium cavity has geometry, material and loadings, such that, these are not covered in Division 1, design by rules. Therefore, U-2(g) provision of Division 1 is invoked in cavity design and design by analysis using ASME Section VIII Division 2 have been followed.
- Structural stability of cavity is ensured by design process.
- Studies carried out for frequency detuning caused by LFD and microphonics have been presented.
- The simulations carried out will be useful to meet the cavity technical and functional requirement specifications.

Thank You.