DEVELOPMENT OF LB650 SUPERCONDUCTING RF CAVITY

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OUTLINE

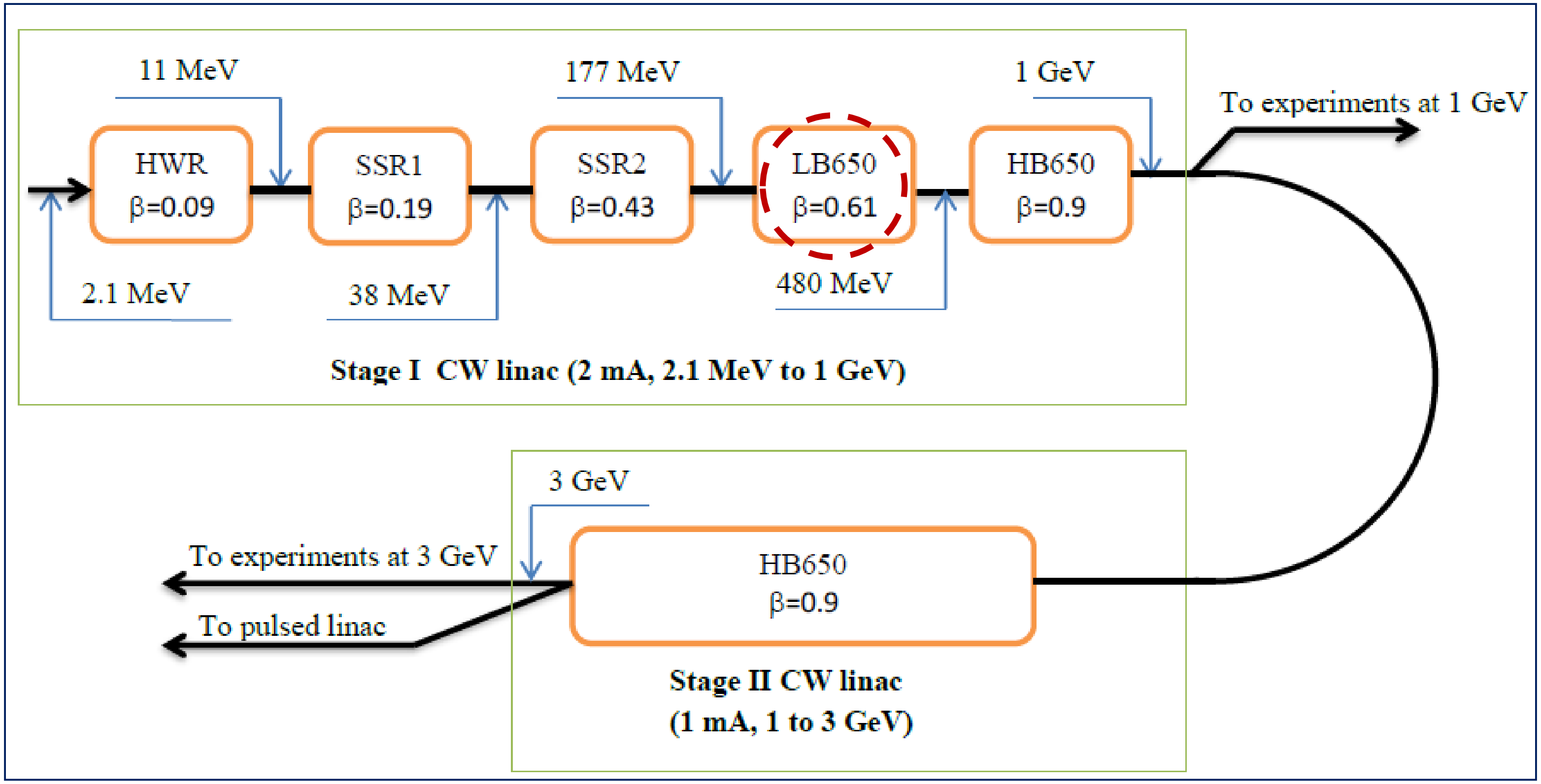
- ❑ **Introduction**
- ❑ **Initial Design of 650MHz Low β Cavity**
- ❑ **Fabrication and Measurement of 1-cell Aluminium Prototype Cavity and 5-cell Prototype Copper Cavity**
- ❑ **Fabrication and Measurement of 1-cell Niobium Cavity**
- ❑ **Single-Cell Niobium Cavity Processing and testing in Vertical Test Stand (VTS) at Fermilab**
- ❑ **Status of Final Design after release of Functional Requirement Specification (FRS) by Fermilab**
- ❑ **Summary**

INTRODUCTION

- **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)**

SRF Technology map for CW Proton Linac



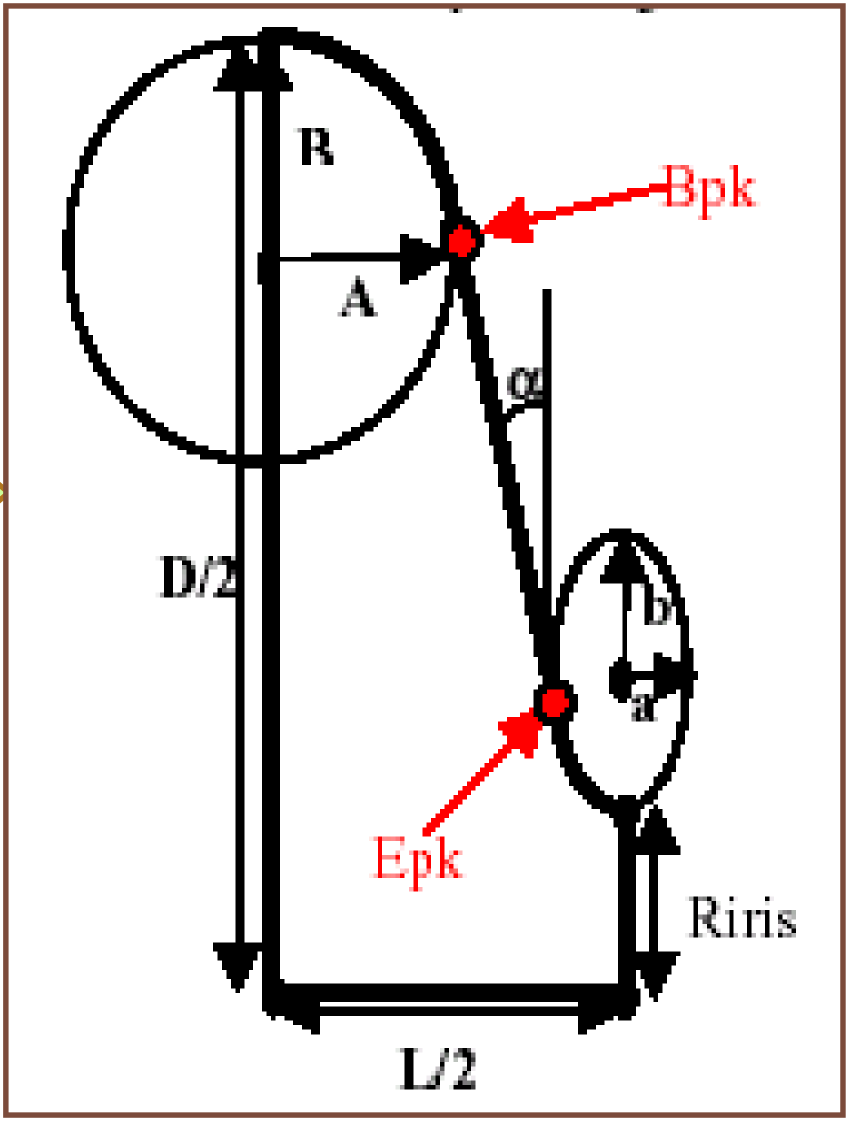
- **VECC Started with LB650 cavity design, considering operating accelerating gradient (E_{acc}) of 17 MV/m and keeping iris diameter and beam pipe diameter as 96mm.**

- **The cell shape has been designed to minimize the peak surface magnetic and electric fields, H_{peak} and E_{peak}, at accelerating gradient.**

CAVITY DESIGN

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

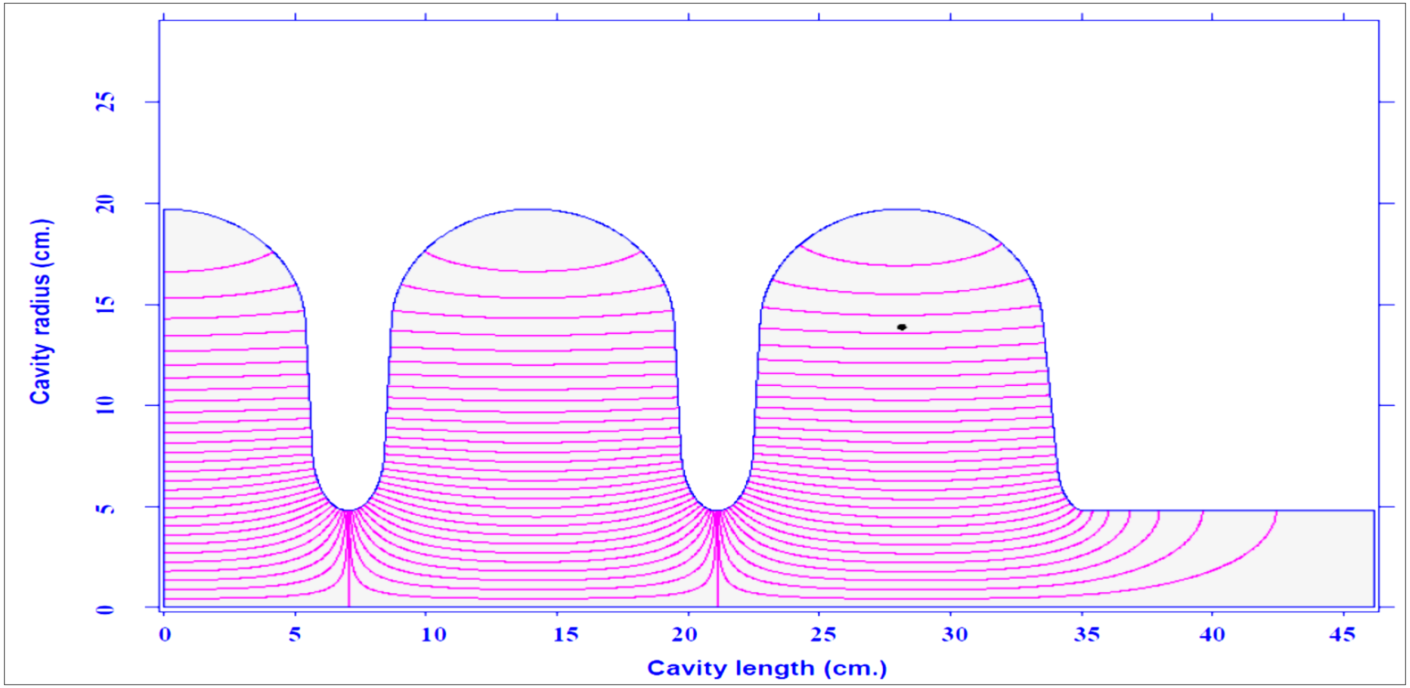
Criteria	RF parameters	Dependence on Geometry
Operation at High accelerating gradient, lower losses and field emission	Lower Epeak/ Eacc	improves when R_{iris} decreases, depends on iris shape
	Lower Bpeak/Eacc	improves when R_{iris} decreases, depends on equator shape
High accelerating gradient with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

Cavity EM Parameters

Parameters	Values
No. of Cells	5
Effective Length = 5*(βg.λ/2)	703.4 mm.
Iris Aperture	96 mm.
Wall angle for mid-cell	2.4^0
Wall angle for end-cell	4.5^0
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

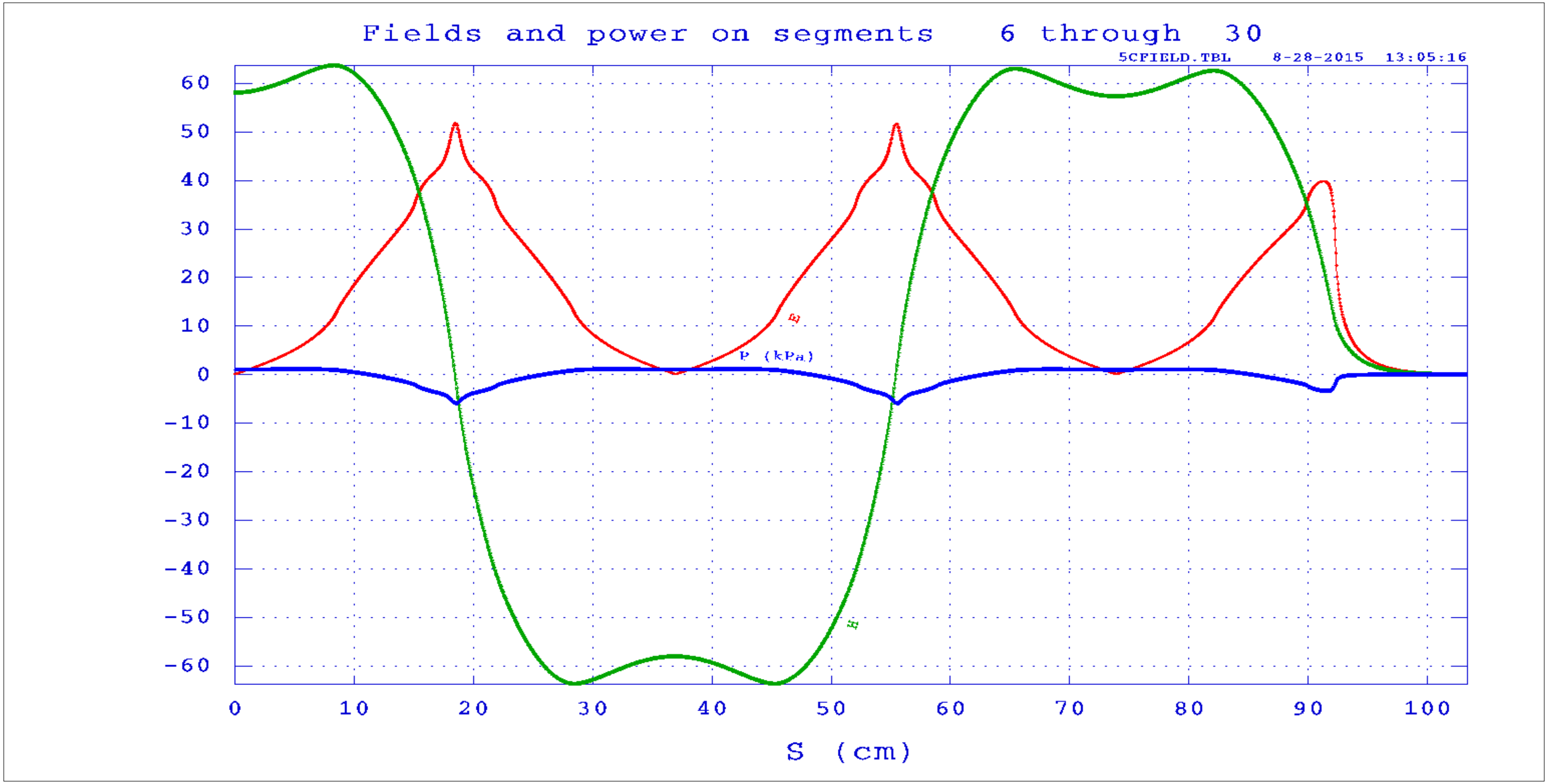
Electric field lines for accelerating mode (π-mode) at 649.999 MHz.The geometry of end cell of the cavity is optimized to have good field flatness over the five cells.



Frequencies of other four fundamental modes (π/5, 2π/5, 3π/5 and 4π/5) are found at 641.991MHz, 644.218MHz, 646.955 MHz and 649.156 MHz respectively.

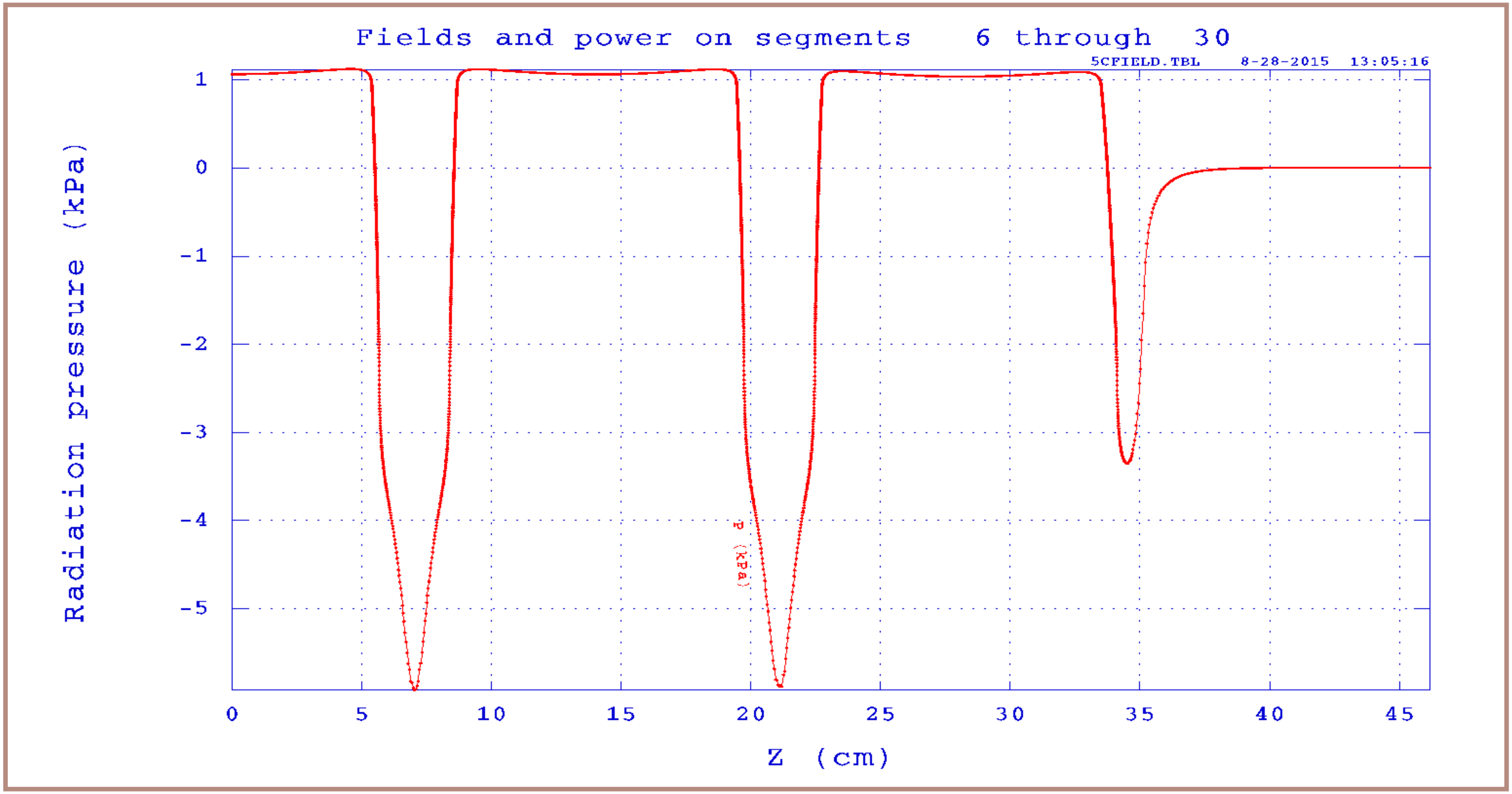
CAVITY DESIGN

Electric and magnetic field profile and Lorentz force (Radiation pressure) on the surface of the cavity at accelerating field 17 MV/m.



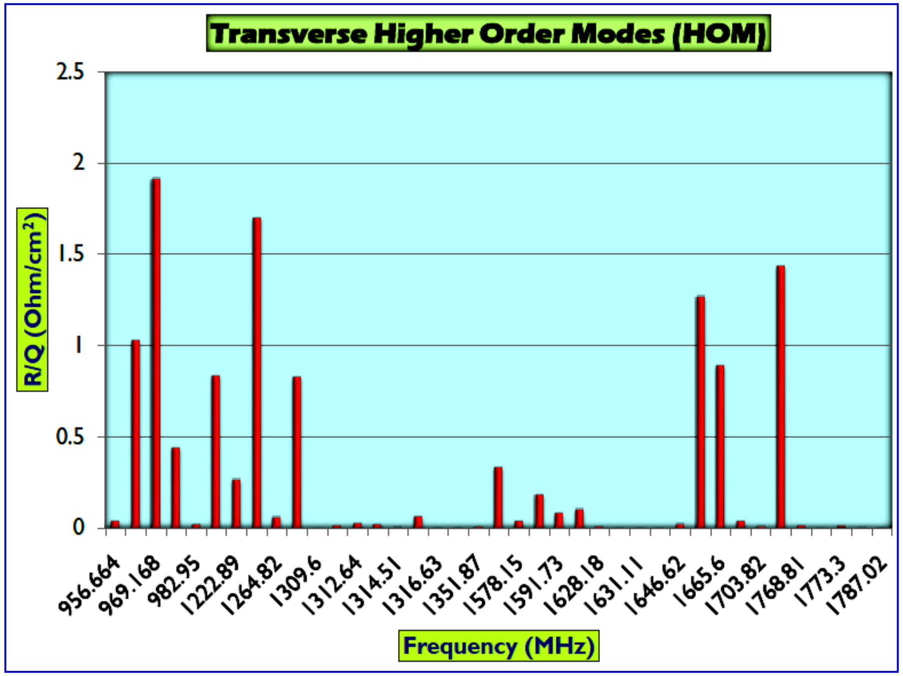
CAVITY DESIGN

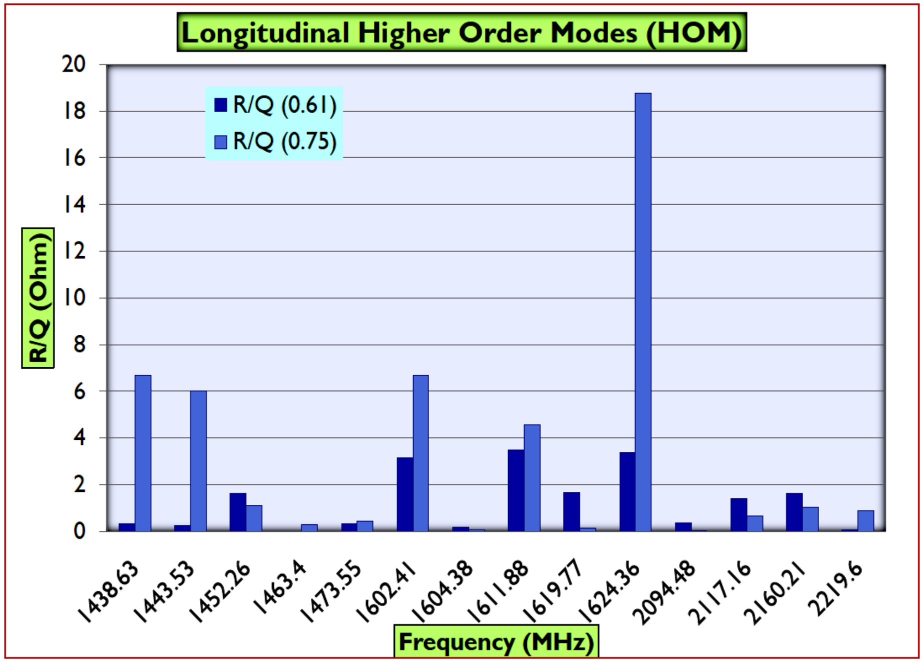
Maximum radiation pressure (Lorentz Force) is 6 Kpa at iris region and 1.1 kPa at equator region.



CAVITY DESIGN: HOM Analysis

- Transverse and longitudinal HOMs for the cavity at 650 MHz, β=0.61--analysis done
- No trapped mode with high effective impedance observed.





MULTIPACTING STUDY

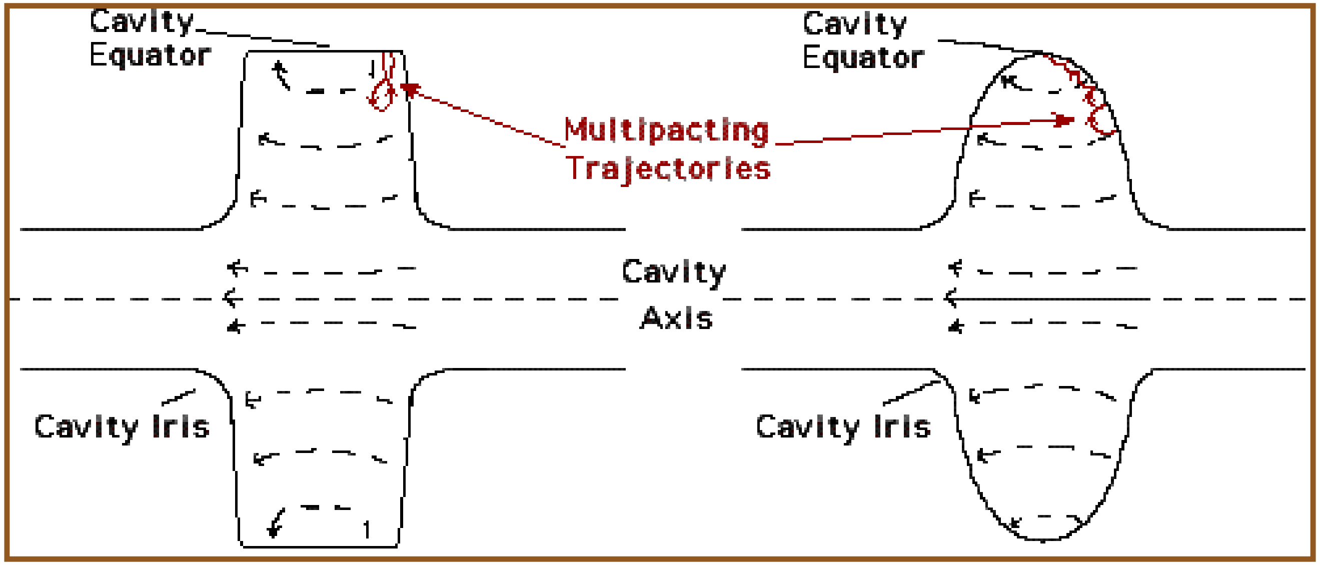
Multipacting is a phenomenon of resonant electron multiplication in cavity and strongly depends on shape of the cavity and material of the cavity

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**

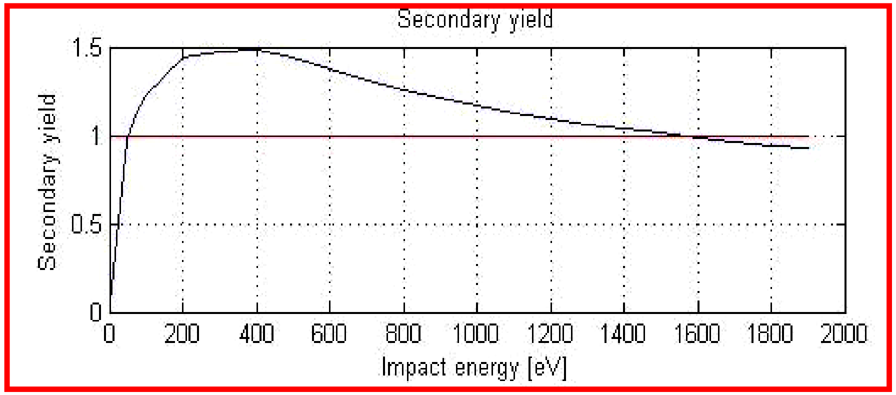
Key to eliminate multipacting ⇒ the fields should be such that emitted e^- will drift towards the equator (where E field NOT strong enough for secondary emission to recur)⇒ stops avalanche effect

Rectangular shape ⇒ spherical or elliptical shape

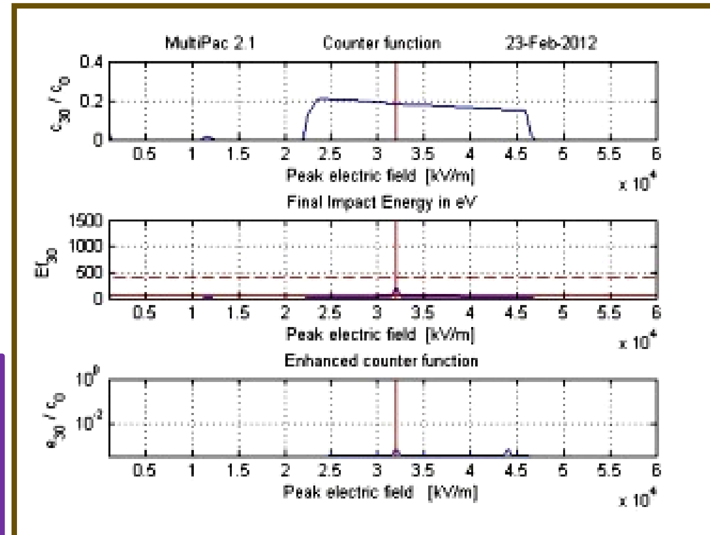


MULTIPACTING STUDY

MP SIMULATION BY 2D MULTIPAC CODE



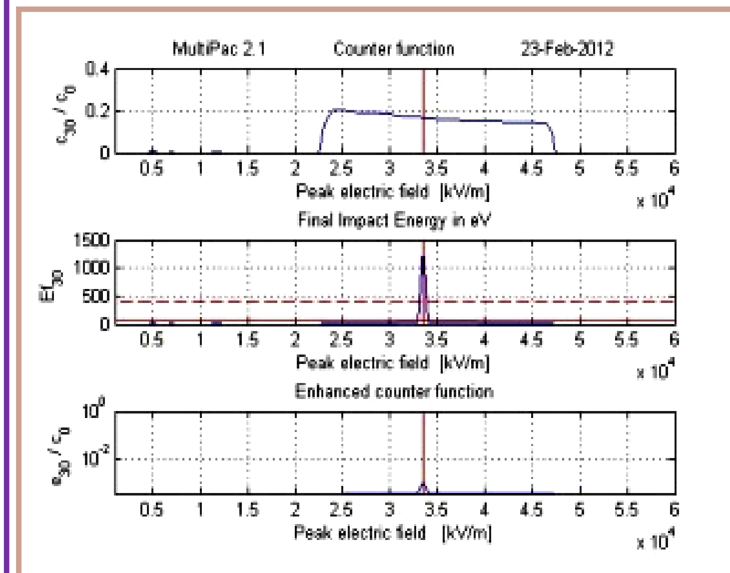
Mid Cell



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.



End Cell

Multipacting simulation using 3D CST Particle Studio

Furman Model of Secondary Electron emission (consisting of three types of scattering particles) has been taken into account in CST code.

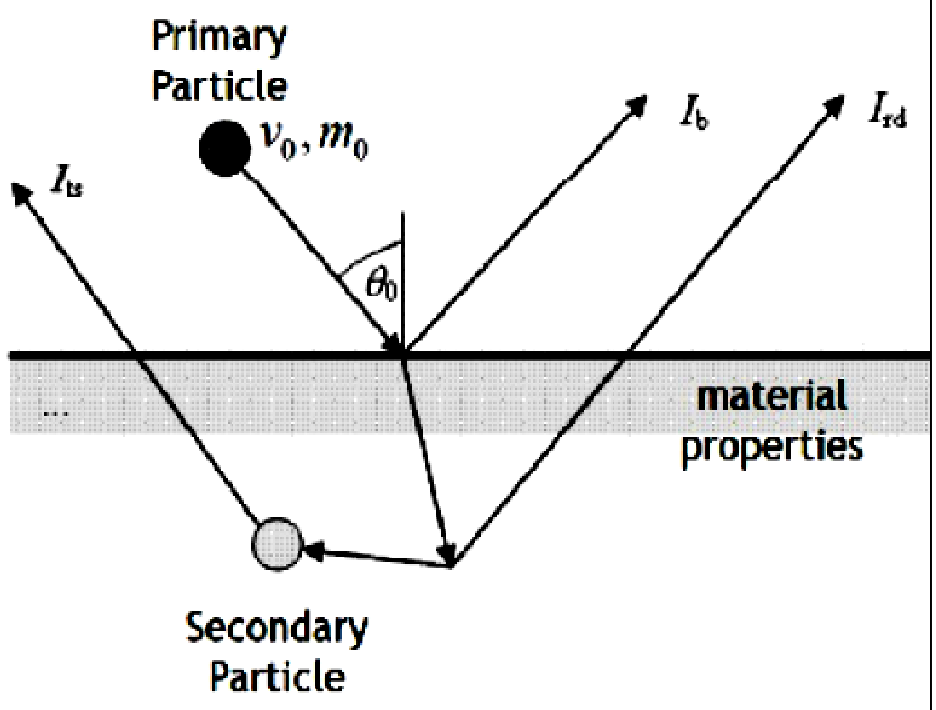
- Secondary emission:
  A primary particle hitting a metal surface can cause the emission of so-called secondary particles.

  - Depends on kinetic energy and material properties

  - Self consistent model according to Furman.

[M.A. Furman, M.T.F. Pivi, "Simulation of secondary electron emission based on a phenomenological probabilistic model", LBNL-52807, SLAC-PUB-9912]

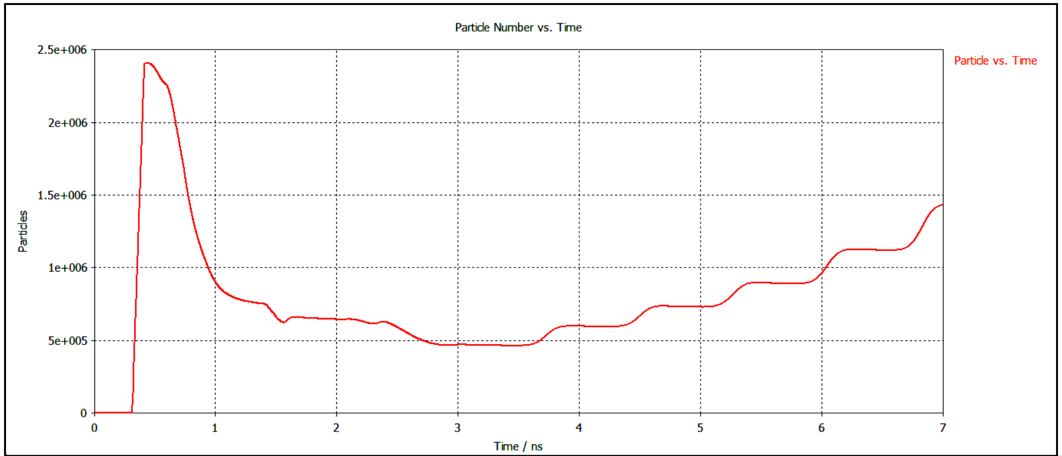
  - Statistical behaviour.



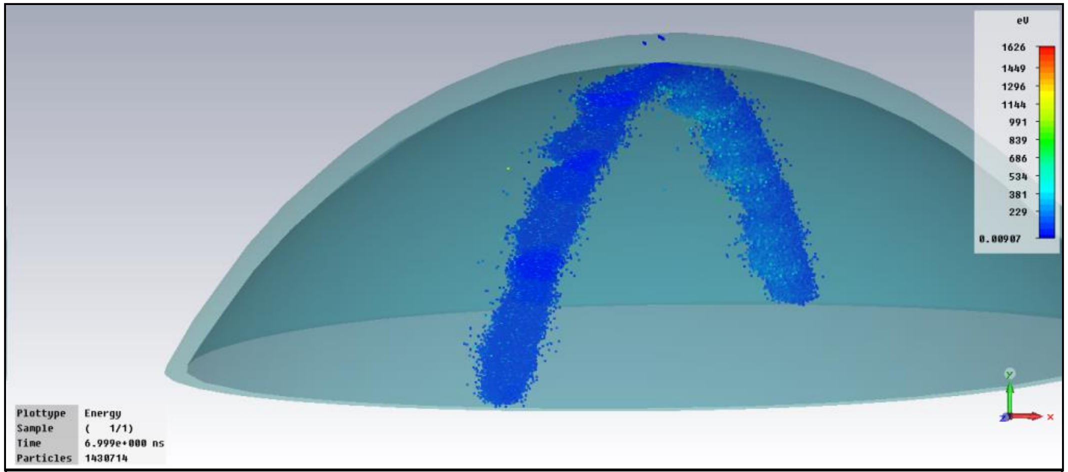
ts: true secondary electrons
b: backscattered electrons
rd: rediffused electrons

Multipacting simulation results for 650MHz, β=0.61 SCRF Cavity using 3D CST Particle Studio

- 30 mm. of equator region has been simulated.
- Mesh: min 0.37 mm., max 0.74mm.
- 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 partcle due to multipacting is very low.

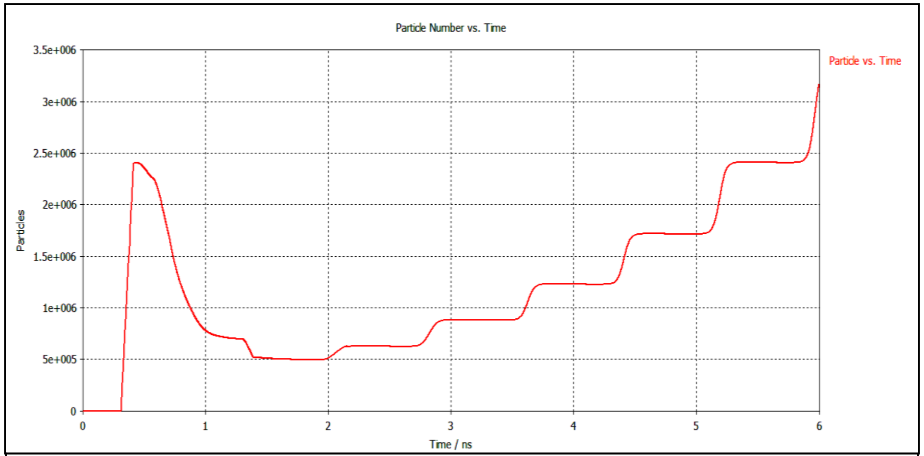


Particle vs. time(ns) at 5.8 MV/m

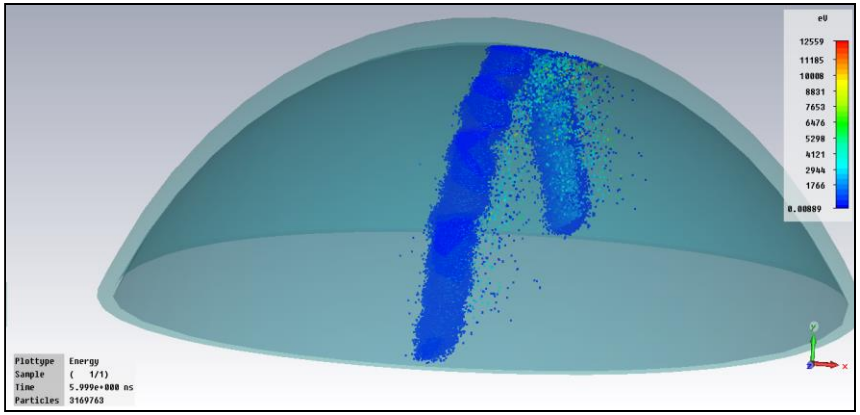


Particles after 7ns at 5.8 MV/m

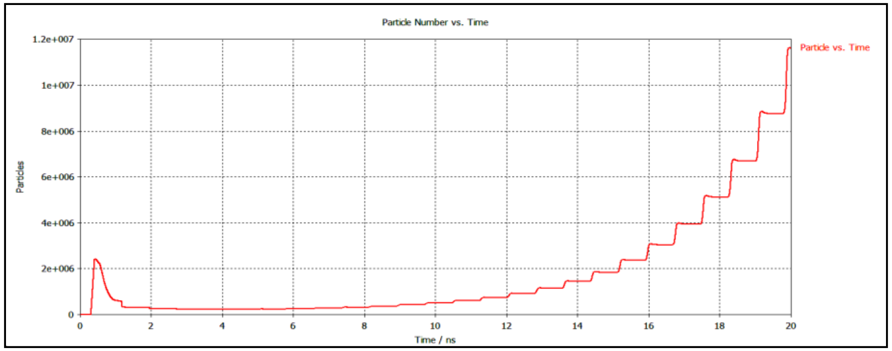
Multipacting simulation result for 650MHz, β=0.61Cavity using CST Particle Studio



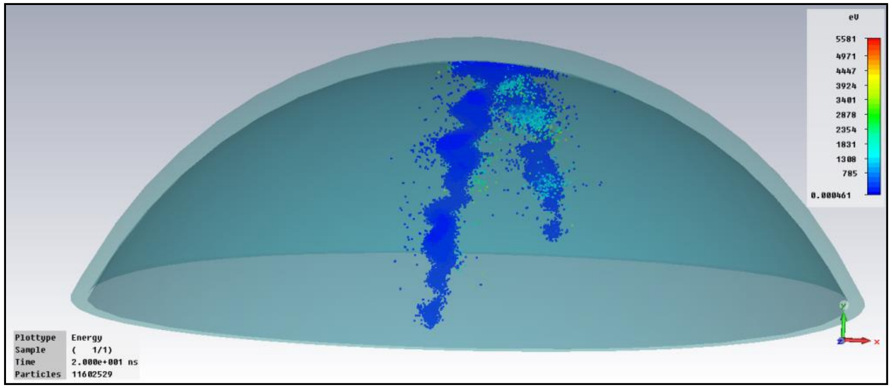
Particle Vs time(ns) at 6.8MV/m (Strong Multipacting)



Particle after 6ns at 6.8MV/m

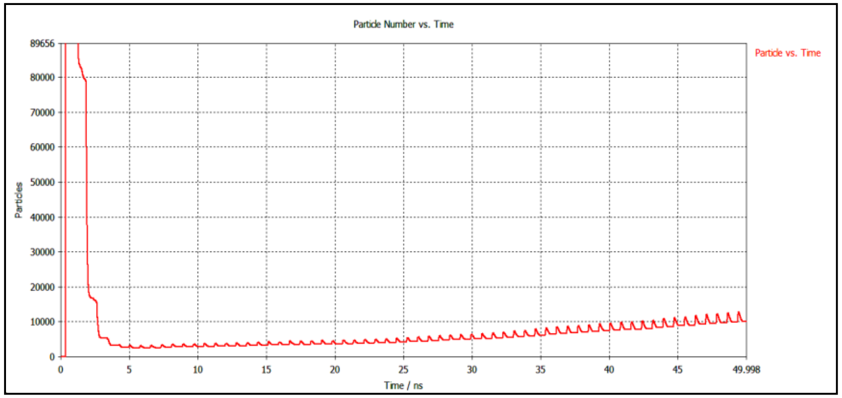


Particle Vs time(ns) at 9MV/m

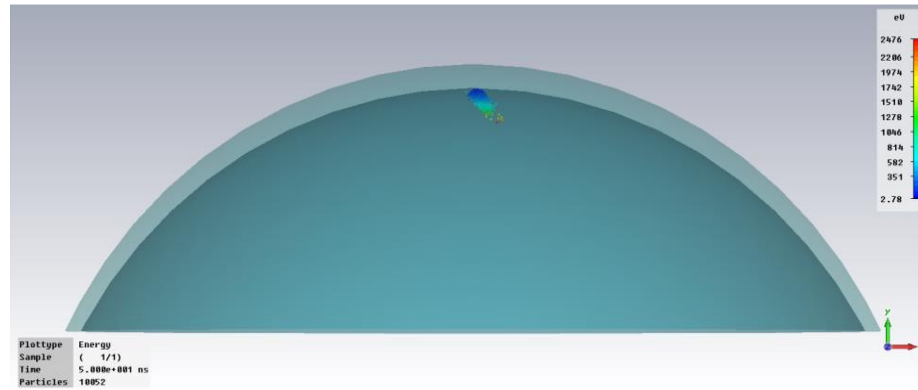


Particle after 20ns at 9MV/m

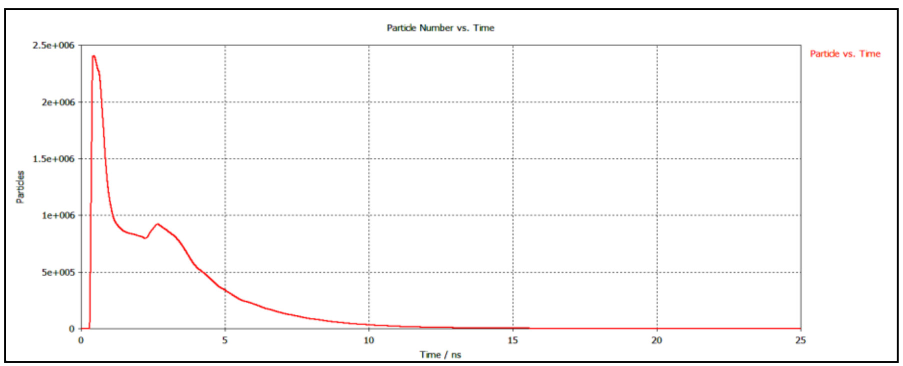
Multipacting simulation data for 650MHz, β=0.61 Cavity
using CST Particle Studio



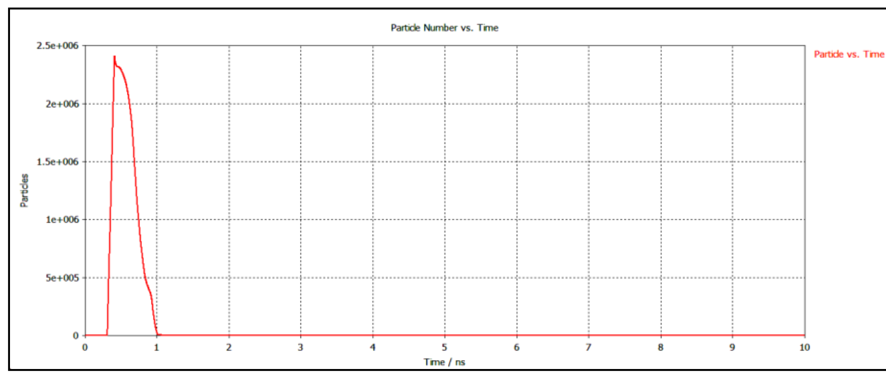
Particle Vs time(ns) at 11.5 MV/m (slow multipacting)



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)

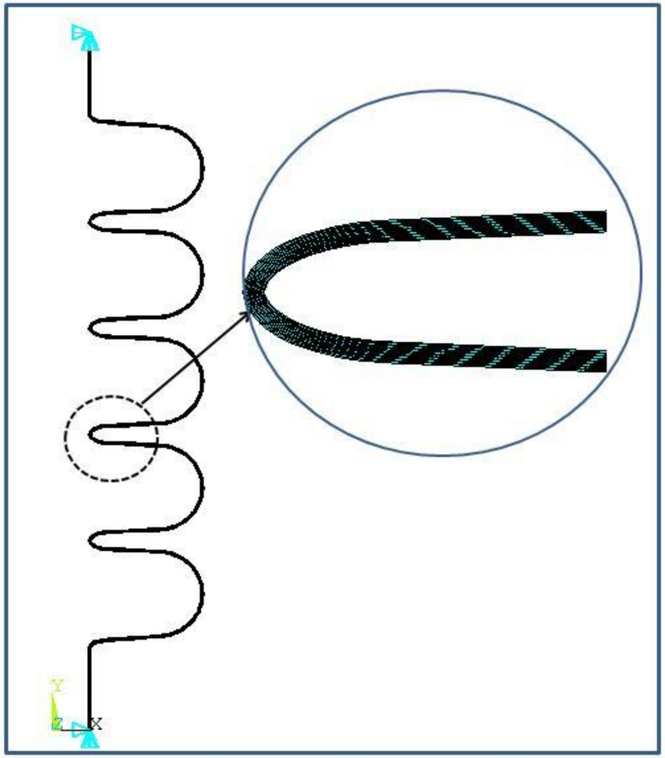
MULTIPACTING STUDY

- 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.

Cavity structural analysis: formulation detail

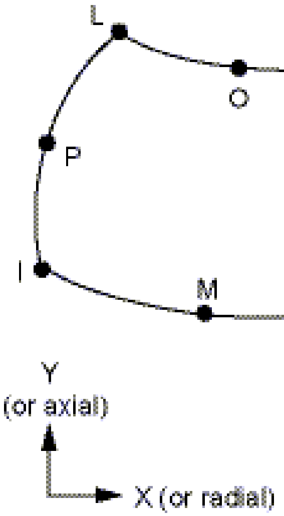


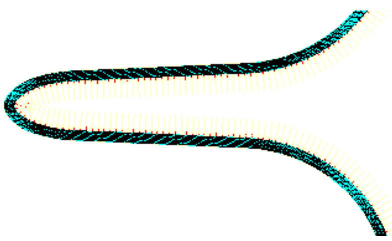
SRF Cavity is subjected to cryogenic temperature and external pressure under operating conditions

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

Boundary Condition: Both end fixed

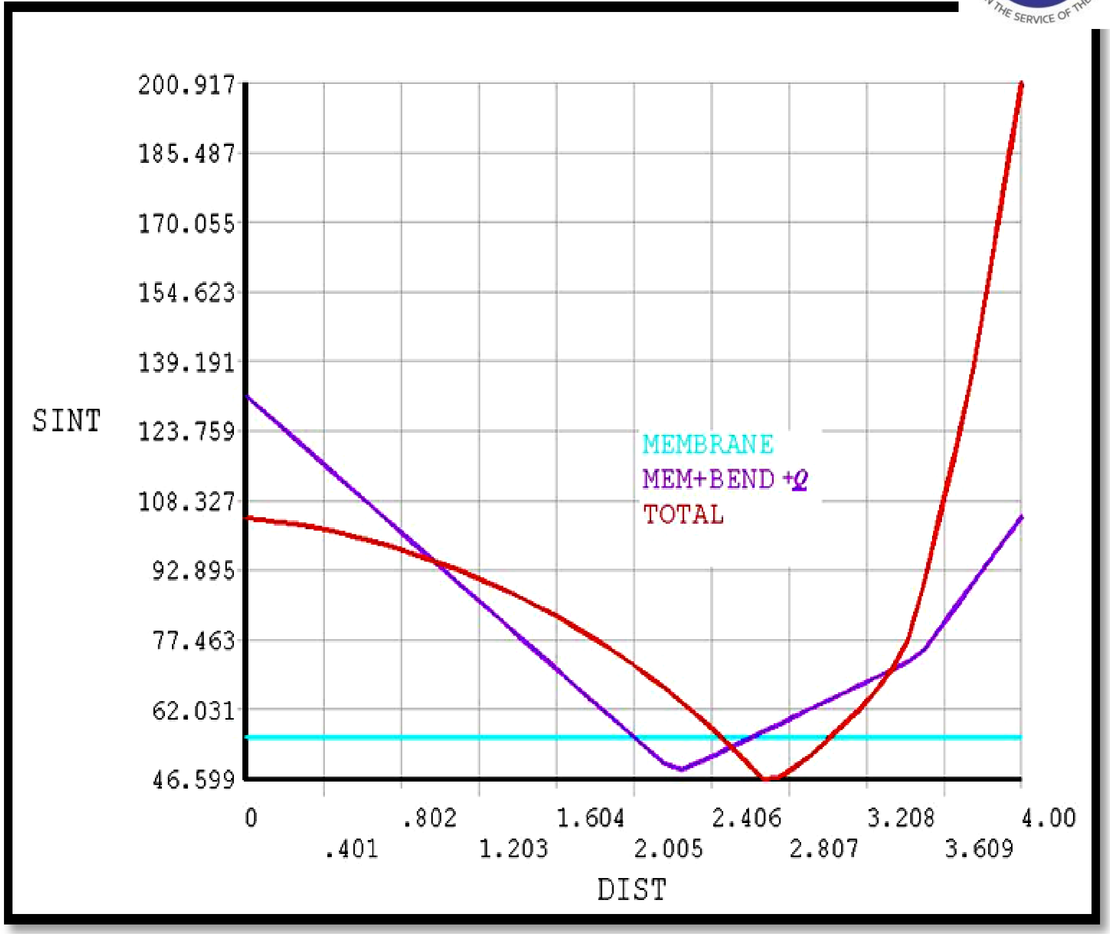
Finite Element Axisymetric modeling for 5-cell SRF cavity





Stress Plot

- 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.



Primary Membrane + Bending + Secondary Stress

$(P_m+P_b+Q < 3Sm)$

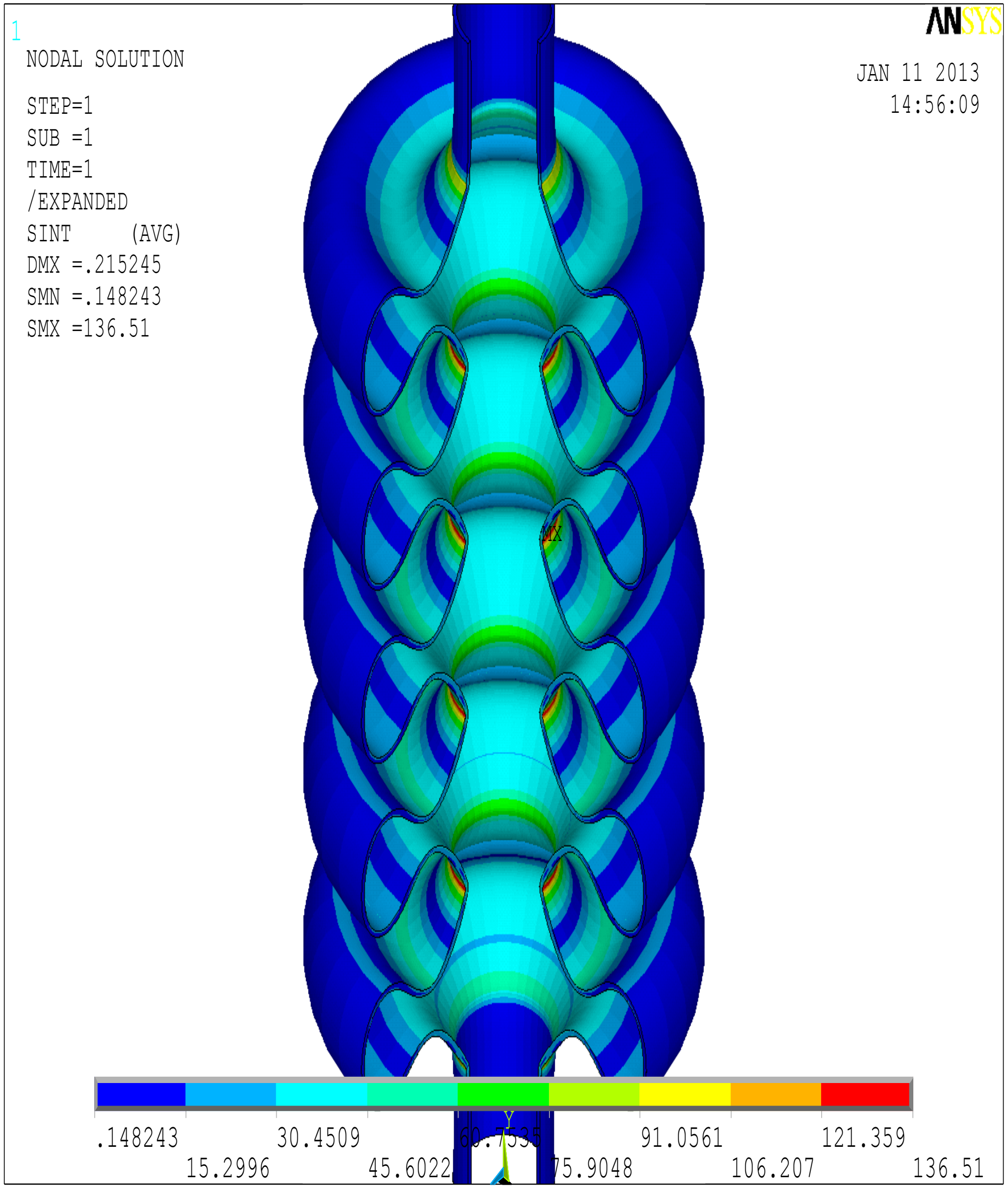
P_m+P_b+Q =131 MPa < 309 MPa (3Sm)

Mechanical properties of niobium

Temperature (K)	Young's Modulii (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Design Allowable Strength (MPa)
295	97.9	50	100	33.33
2	97.9	310	310	103.3

Results :Different Stress Plot

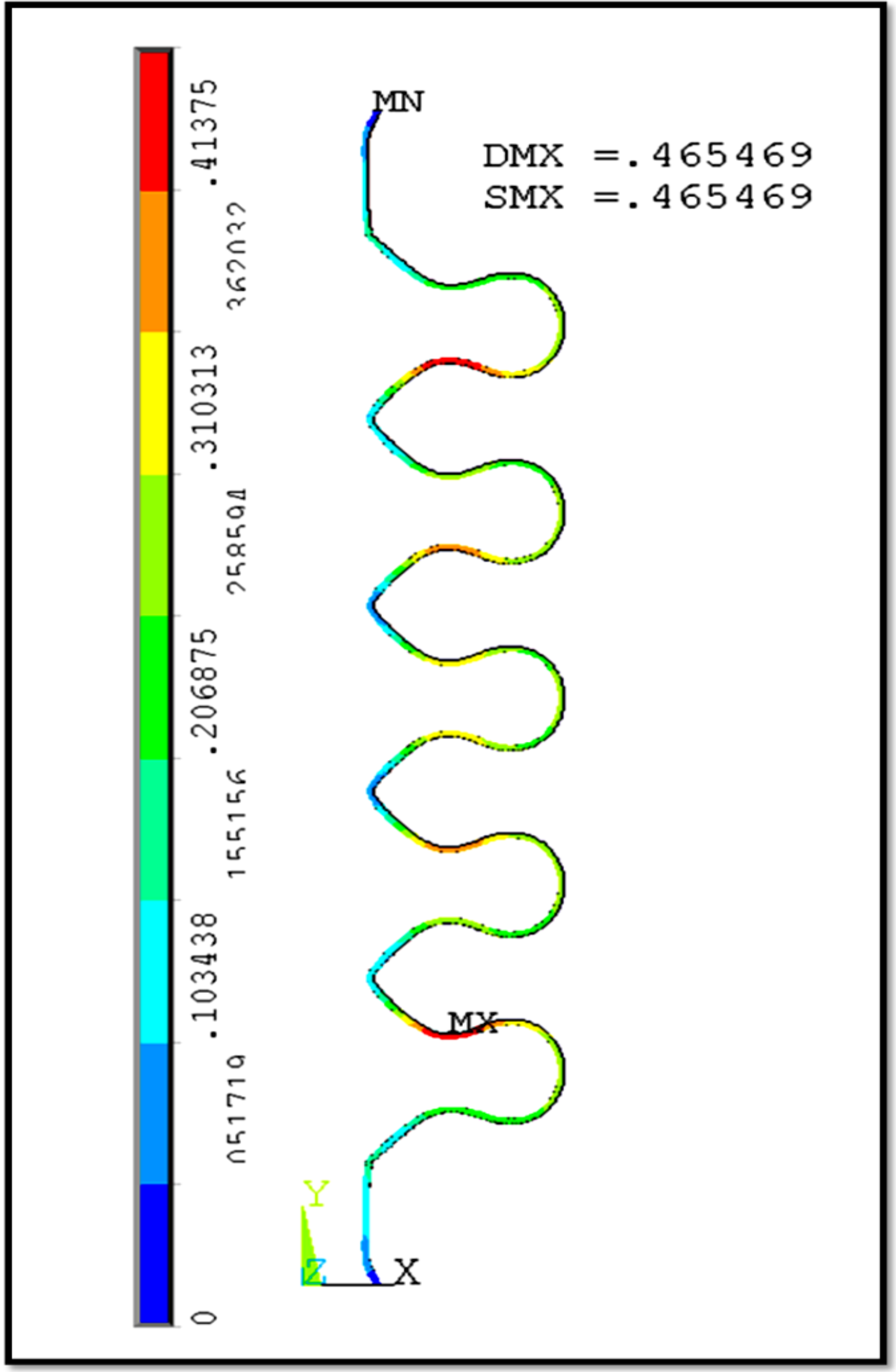
Stress calculations as per ASME Pressure Vessel Code Section-III for niobium



Stress intensity (at Iris) across the thickness of 5-cell, 650 MHz, β=0.61, cavity

Deformation

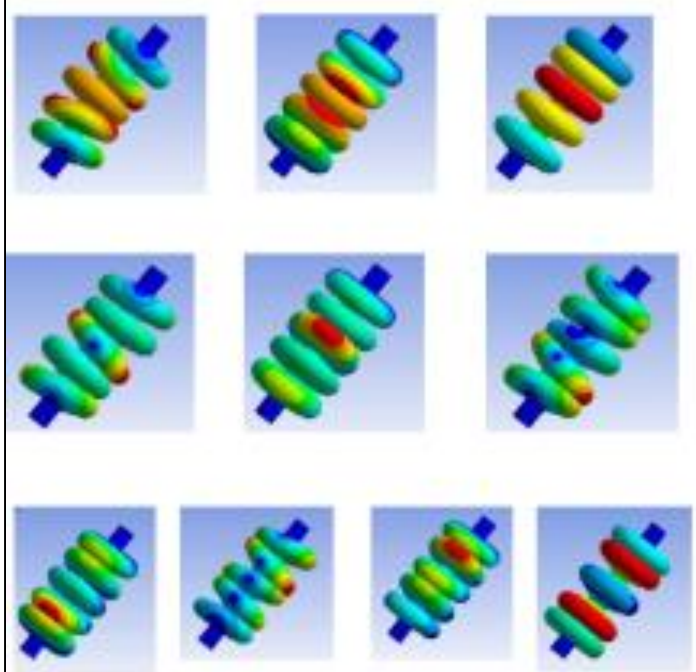
The maximum deformation due to combined loading is obtained as 0.465 mm.



Plot of deformation for
5-cell, 650 MHz, β=0.61 cavity

Mechanical modal analysis of 650 MHz SCRF 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.**

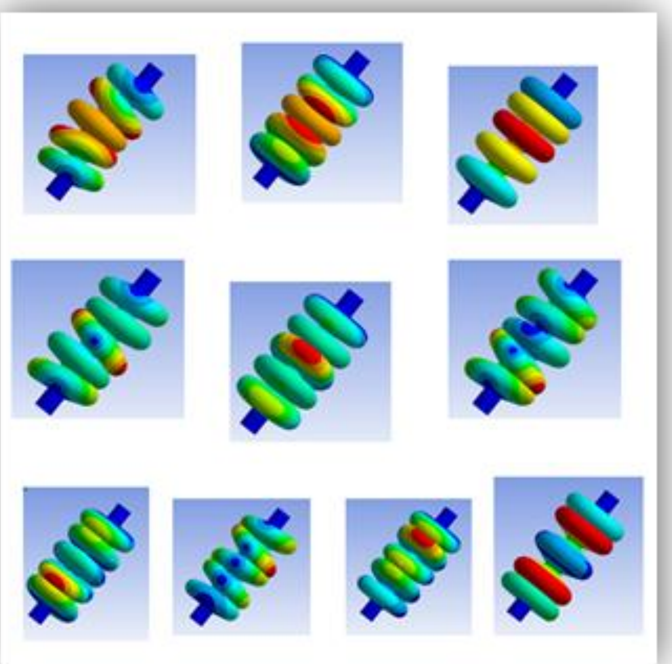


Mode	Frequency [Hz]
1.	3.0625
2.	5.9953
3.	8.6136
4.	10.776
5.	11.161
6.	24.688
7.	26.005
8.	27.449
9.	28.538
10.	57.485

Mechanical modal analysis (without stiffener)

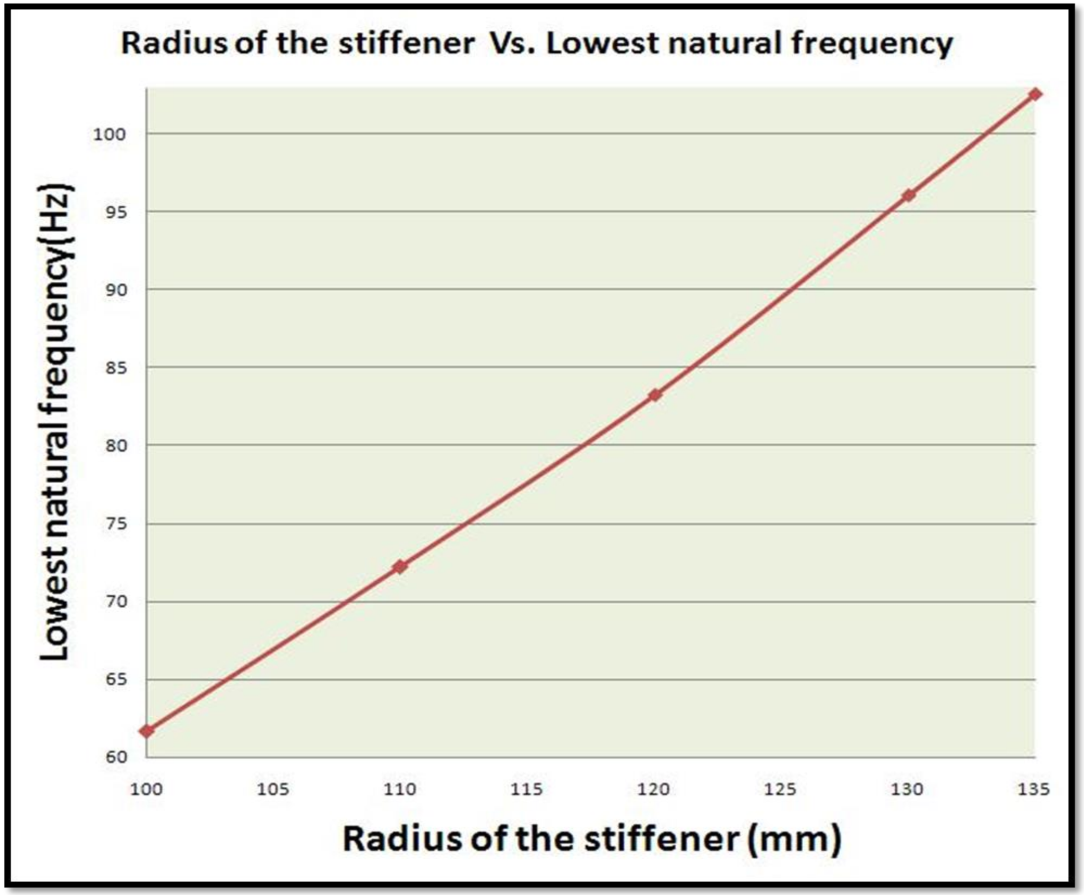
Mechanical modal analysis of 650 MHz SCRF Cavity

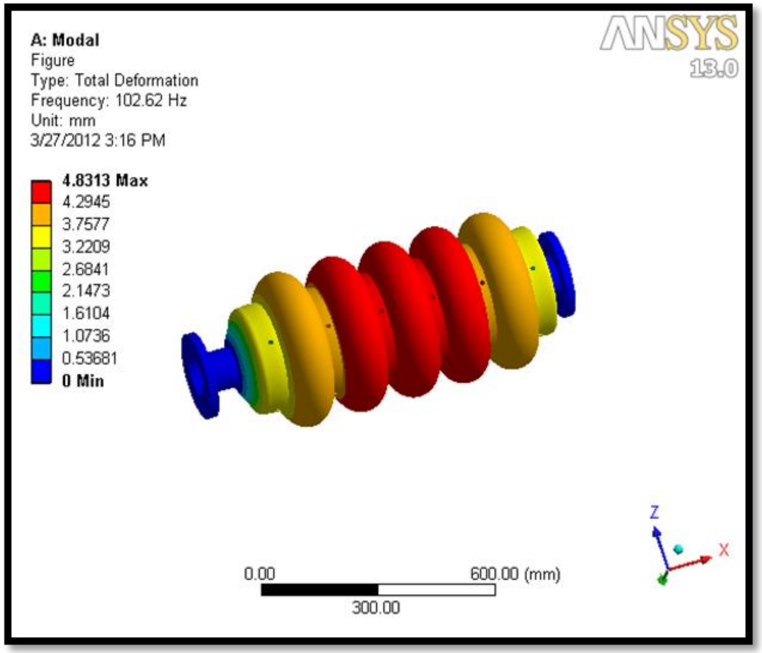
The natural frequencies and mode shapes are determined for the 5-cell cavity alone for different end support condition.



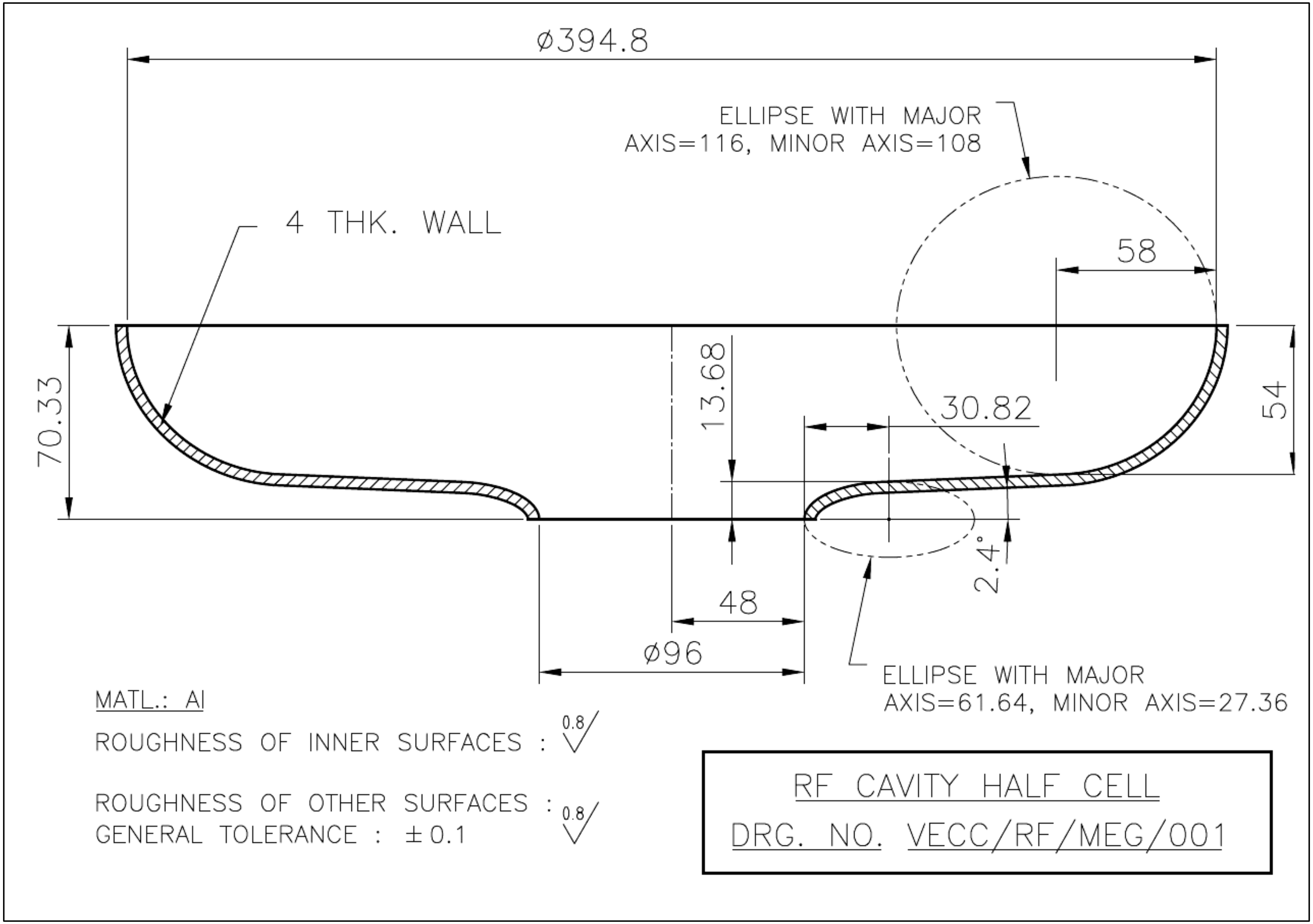
	Modal Frequencies (Hz)	
	Both End Fixed	One End Free
650 MHz Cavity β=0.6	51.952	24.705
	101.72	73.351
	146.16	119.15
	182.75	158.05
	189.39	186.75
	419.78	353.67
	442.33	421.16
	467.10	444.88
	485.8	469.09
	975.59	486.47

Stiffened cavity modal analysis

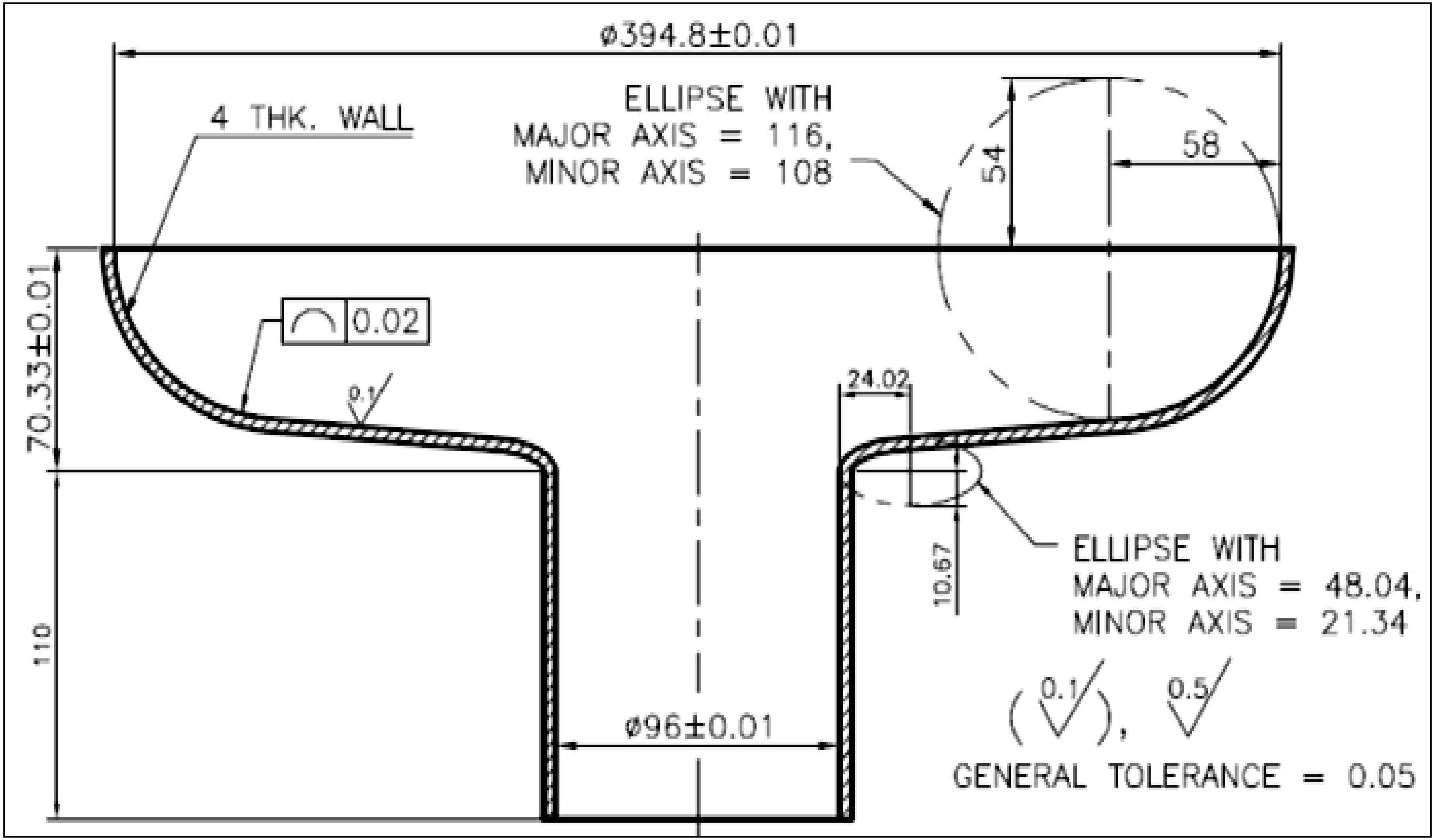




Engineering drawing for half-cell (mid-cell)



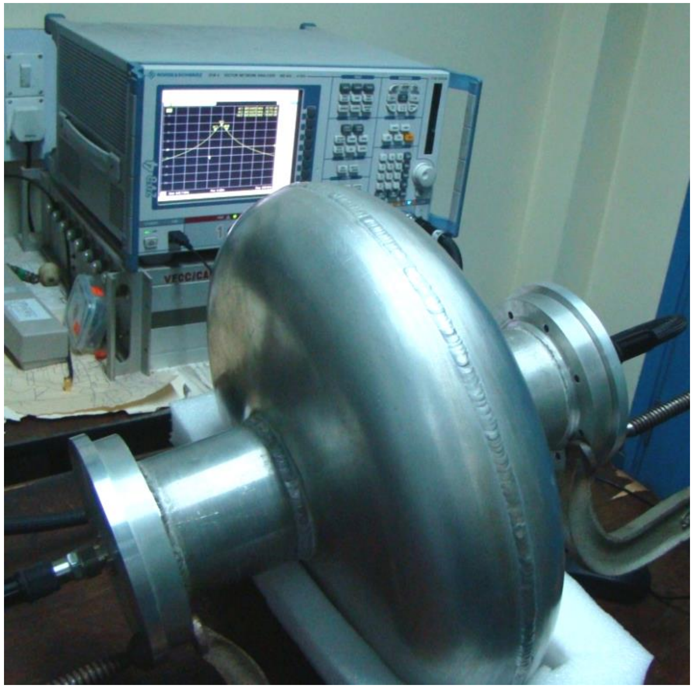
Engineering drawing for half-cell (End-cell)



CAVITY FABRICATION

- ❑ 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.

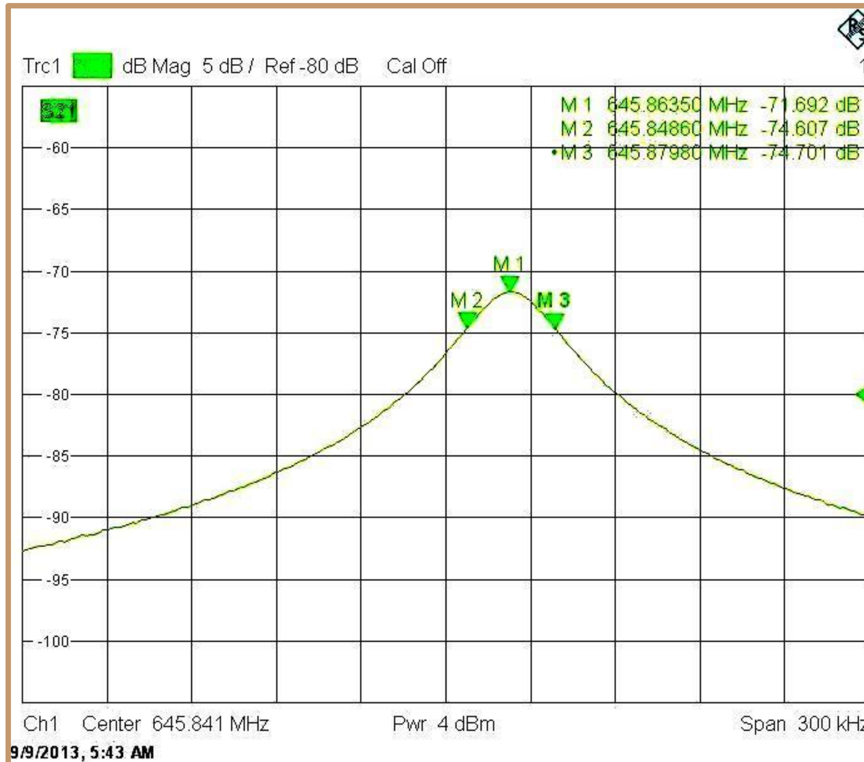
SINGLE CELL PROTOTYPE CAVITY(Aluminium)- VNA MEASUREMENT



Resonant frequency,

f_0 = 645.86350 MHz

Simulated Value for the Geometry (Superfish)=645.3MHz



Half power (–3dB) Bandwidth,

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

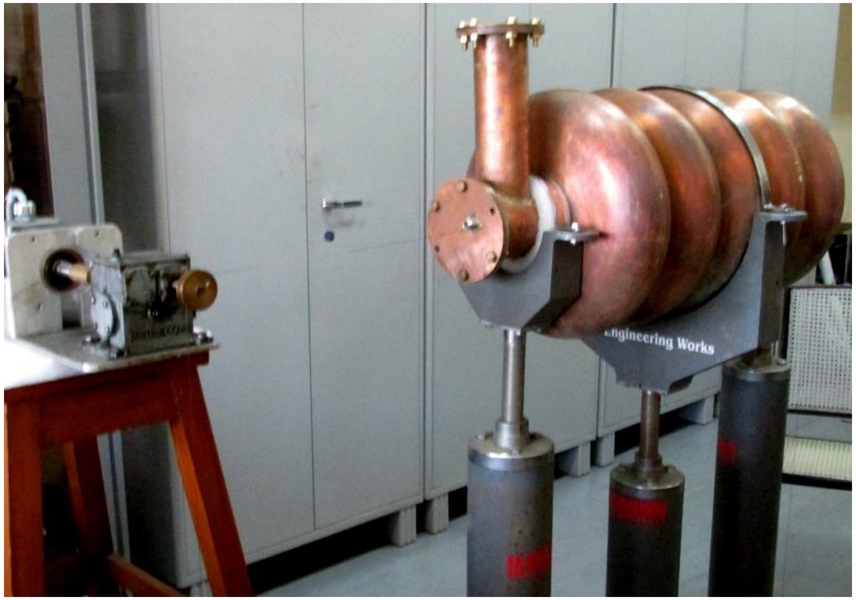
[f_1 = 645.84860 MHz;

f_2 = 645.87980 MHz]

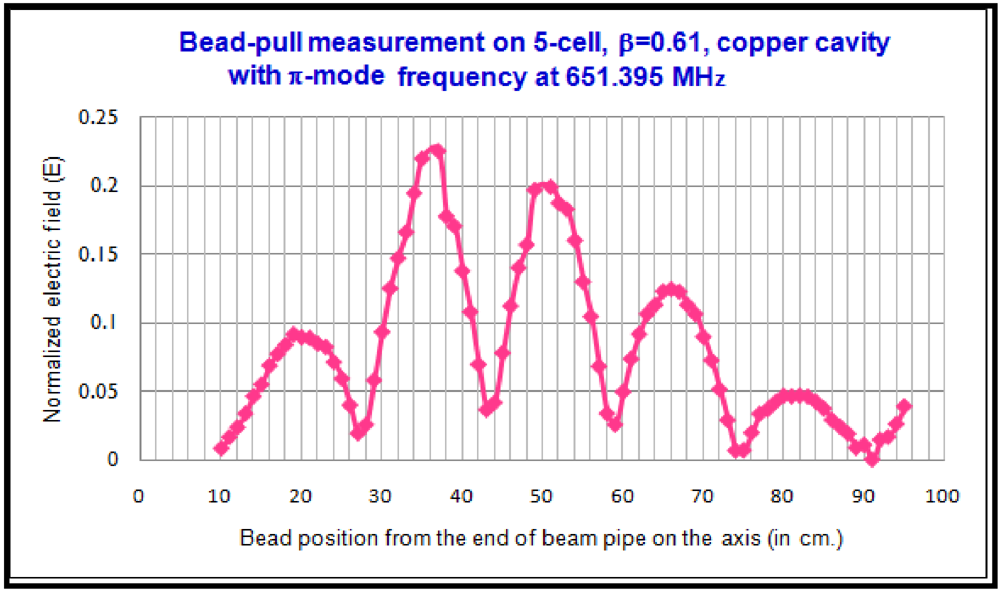
$Q = f_0 / \Delta f$ = 20700.

5- CELL PROTOTYPE COPPERCAVITY- BEADPULL MEASUREMENT

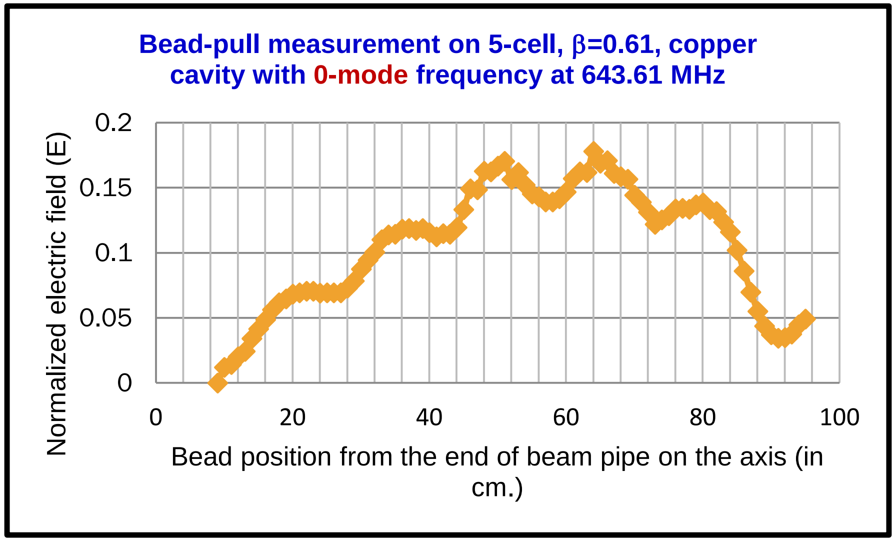
Five-cell Copper prototype fabricated using the mid-cell dimensions

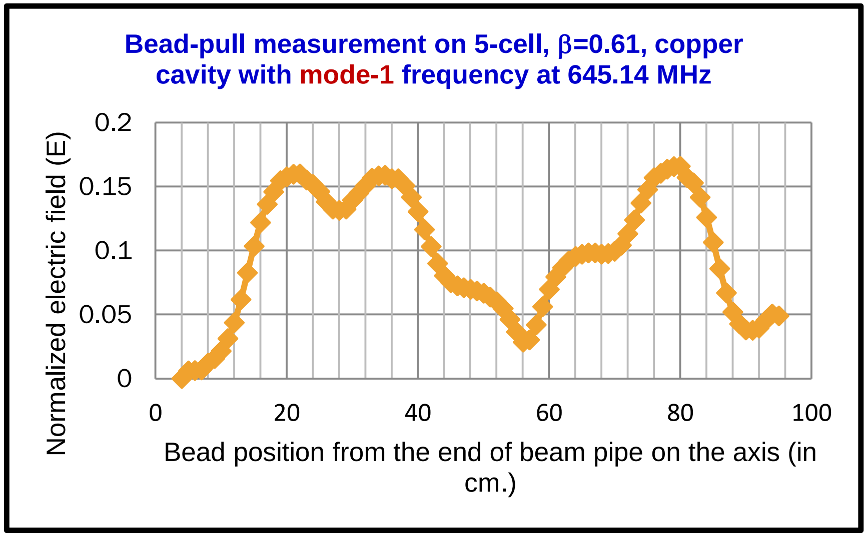


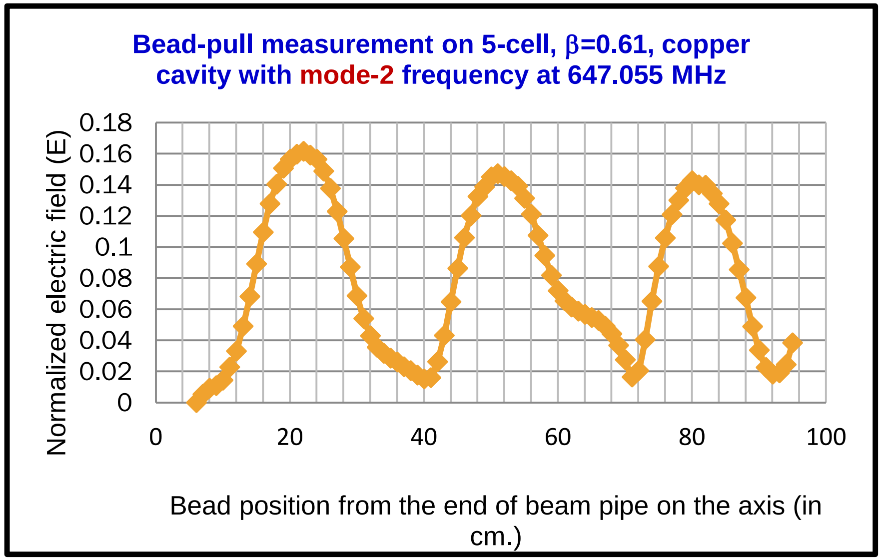
Bead pull measurement setup including stepper motor gear arrangement, VNA and PC

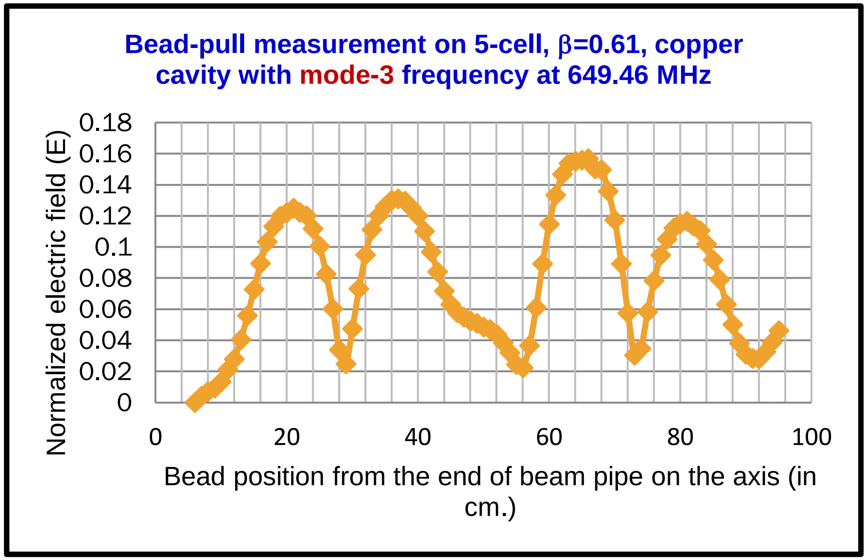


5- CELL PROTOTYPE COPPER CAVITY: BEADPULL MEASUREMENT









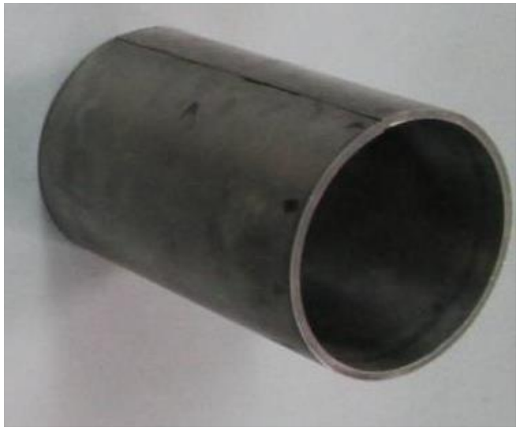
SINGLE CELL NIOBIUM CAVITY FABRICATION

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 crome plated SS. The beam pipes are also rolled from 4 mm thick niobium sheet.

Niobium blank of dimension O.D. 515.7 mm × I.D. 70 mm blank machined from Niobium Sheet at VECC Workshop before Deep Drawing.

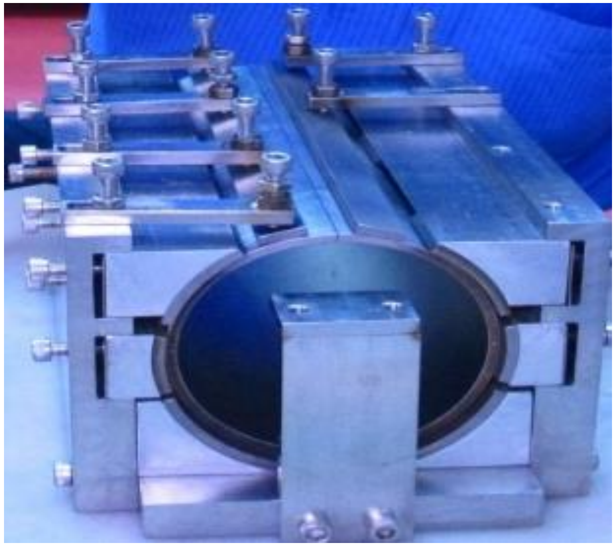
Niobium blank was pressed to form half cell, using a hydraulic press at the vendor's site, Kolkata.

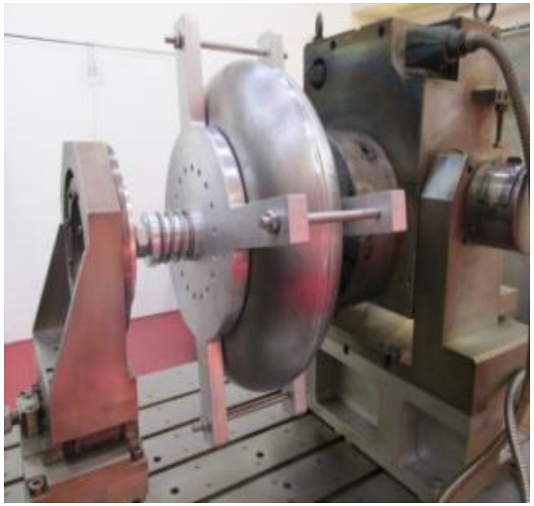
4 mm thick Nb Sheet was rolled into the beam pipe in VECC workshop

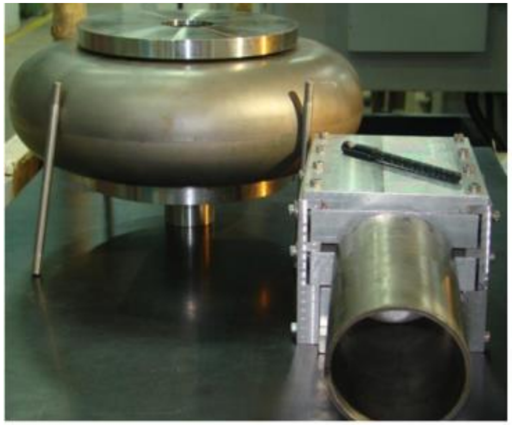


SINGLE CELL NIOBIUM CAVITY FABRICATION

Niobium half cells , beam pipes and fixtures developed at VECC Workshop for Electron Beam Welding purposes.







SINGLE CELL NIOBIUM CAVITY FABRICATION

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.

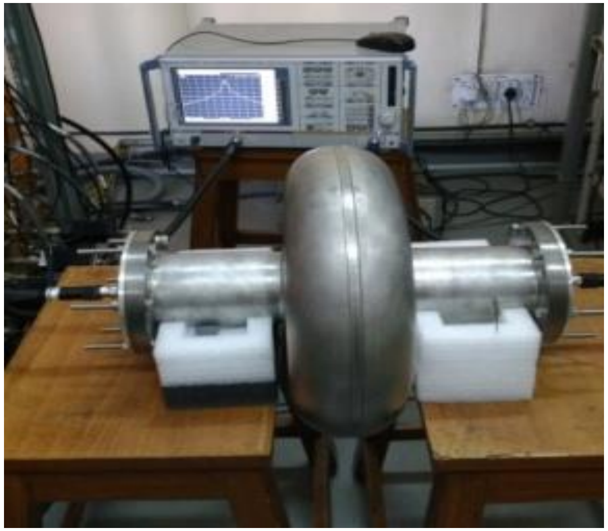
- **Rolled beam pipes are electron beam welded longitudinally.**
- **Two half cells are joined at the equator region by EBWfrom both inside and outside**
- **Trimming and machining of beam pipe were done at VECC for weld edge preparation to match with the NbTi flange and to the half-cell iris**
- **Beam 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.**

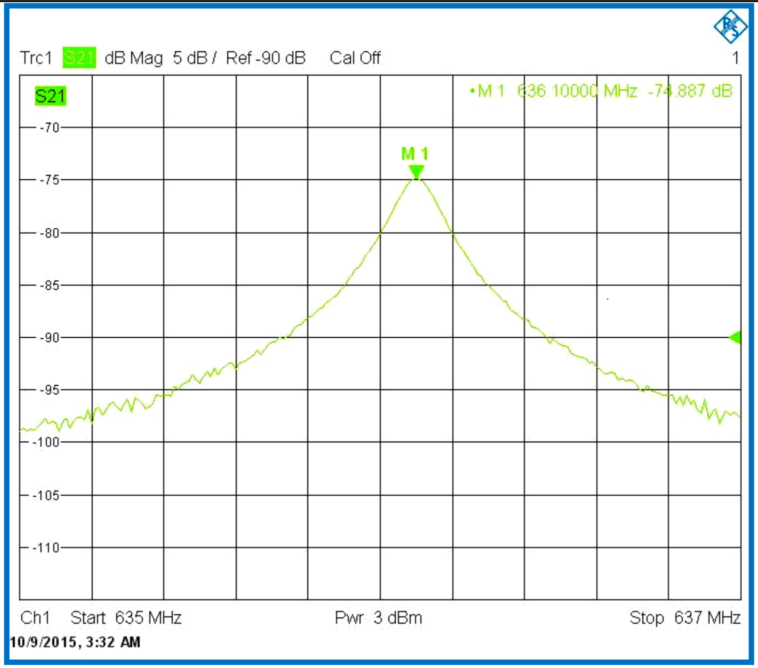
SINGLE CELL NIOBIUM CAVITY- MEASUREMENT

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

SINGLE CELL NIOBIUM CAVITY- MEASUREMENT





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 .

SINGLE CELL NIOBIUM CAVITY- MEASUREMENT

Cryo-shocking

MSLD

Cavity Inspection after Electron Beam Welding

- Cryo-shocking with LN_2 : 3 cycles
- Subsequent MSLD : leak rate ~ 1.3E-9 mbar-lit/sec

SINGLE CELL NIOBIUM CAVITY-MEASUREMENT AND PROCESSING AT FERMILAB

- Qext Measurement of VTS couplers
  - **Required External Quality factor $Q_{ext\text{-}FPC}$:1E+10 and $Q_{ext\text{-}FP}$: 1E+12**
- RF Measurement with VTS couplers
  - **The inner conductors were trimmed to achieve required Q_{ext}**
- Optical Inspection of cavity RF surface at FNAL
  - **No major defects were found**

Measured Values of VECC cavity with FNAL VTS couplers

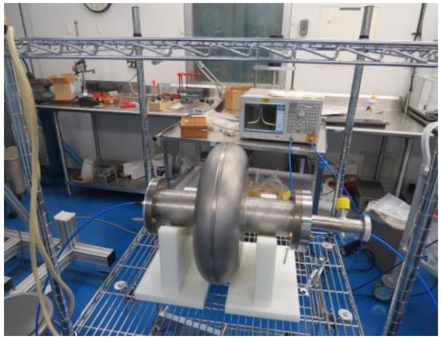
Qext measurements after trimming antennas									
		Cavity Orientation							
F, MHz	Q			S11	Q1		S21 [dB]	S21	Q2
635.7	9500		LR	0.62	5.04E+04	Coupler Antenna	-61.20	8.71E-04	9.45E+09
						Pickup Antenna	-79.70	1.04E-04	6.69E+11
	2.48		RL	0.63	5.16E+04	Coupler Antenna	-61.2	8.71E-04	9.22E+09
						Pickup Antenna	-80.1	9.89E-05	7.15E+11

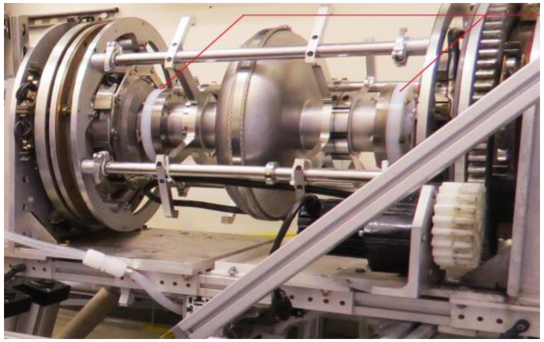
1-CELL NIOBIUM CAVITY: MEASUREMENT and PROCESSING (Electro-polishing) at FERMILAB

- Cathode Masking for uniform material removal ~ Typically the surface area ratio cavity : unmasked cathode =10:1
- Cathode stationary , Cavity rotates @ 1 rpm
- Major parameters for polishing : 1. acid temperature 2. Acid flow 3. Cavity Temperature 4. Voltage-Current operating point 5. Acid Mixture concentration etc.
- 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%).
- Pre-cool acid to 15^{o}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

SINGLE CELL NIOBIUM CAVITY-MEASUREMENT AND PROCESSING AT FERMILAB

- Inner conductor of VTS couplers were trimmed to required Qext
  - External Quality factor $Q_{ext-FPC}$:1E+10 and Q_{ext-FP} : 1E+12
- RF Measurement with VTS couplers
- Electro polishing at Argonne National Lab(ANL)
  - 120 μm bulk EP (Total process time : 560 minutes)
  - Total 120μm (55μm+65μm) 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^{o}C by heat exchanger
  - Optimum temperature for polishing is 30-35^{o}C


RF measurement


EP at ANL


Before EP

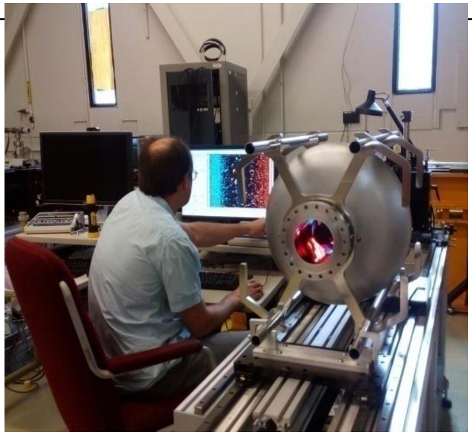

After EP

SINGLE CELL NIOBIUM CAVITY-MEASUREMENT AND PROCESSING AT FERMILAB

- 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**

HPR,ANL

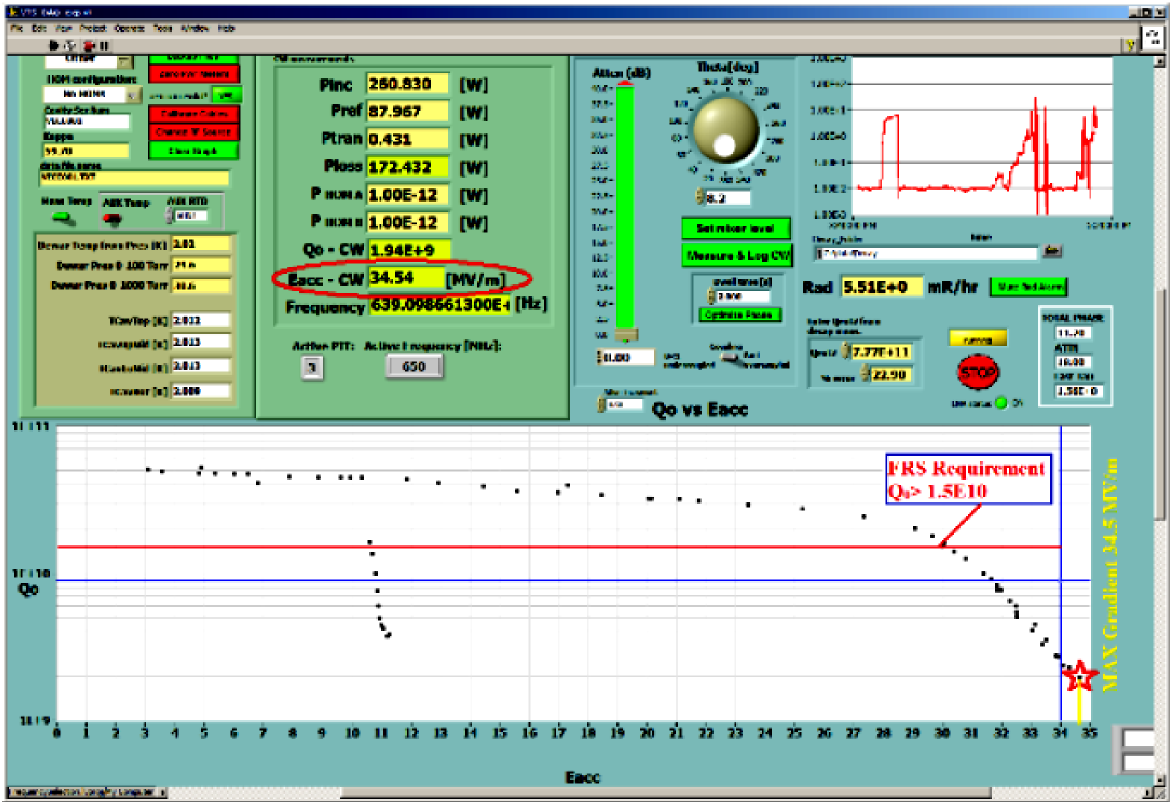
Baking, FNAL



Optical Inspection, FNAL

VTS Insert Assembly

VTS Test Results of LB650 VECC Single cell cavity



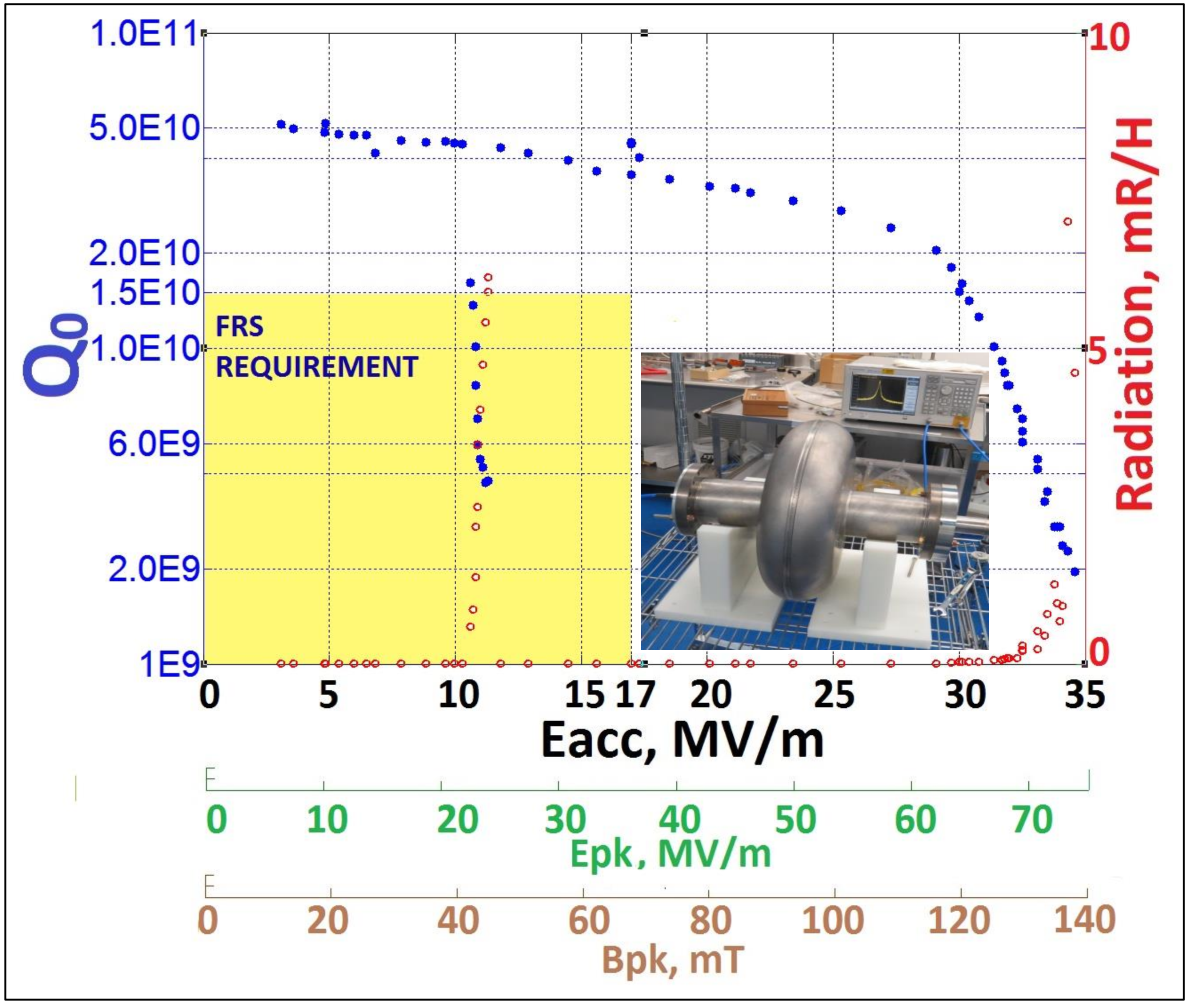
Maximum Gradient:34.5MV/m @2K

No Quench at full RF power ~ 200 W

30 MV/m Eacc (Accelerating Gradient) at unloaded cavity quality factor Q_0=1.5E+10

Eacc & Q_0 Greater than required in FRS

VTS Test Results of VECC-LB650 Single cell cavity



Test Results vs Functional Requirement Specifications(FRS)

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.

FRS BASED CAVITY DESIGN

- 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

Design parameters for new cavity as per FRS

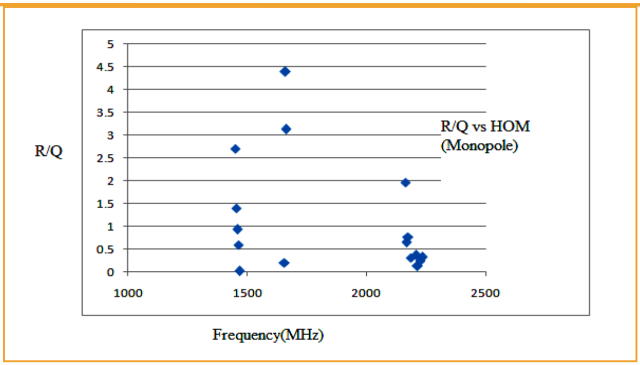
Parameters	Value	Unit
Resonating frequency	650	MHz
Shape, number of cells	Elliptical, 5 cells	
Geometrical Beta (β_g)	0.61	
Bandwidth	65	Hz
Energy gain at optimal β	11.9	MeV/m
Peak surface electric field (E_{pk}) at operating gradient	< 40MV/m at specified energy gain at optimal β	MV/m
Peak surface magnetic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

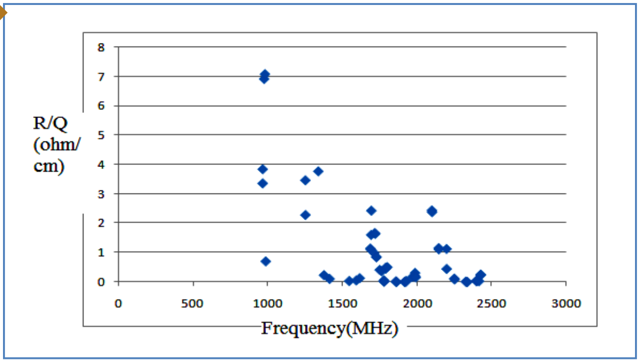
FRS BASED CAVITY DESIGN

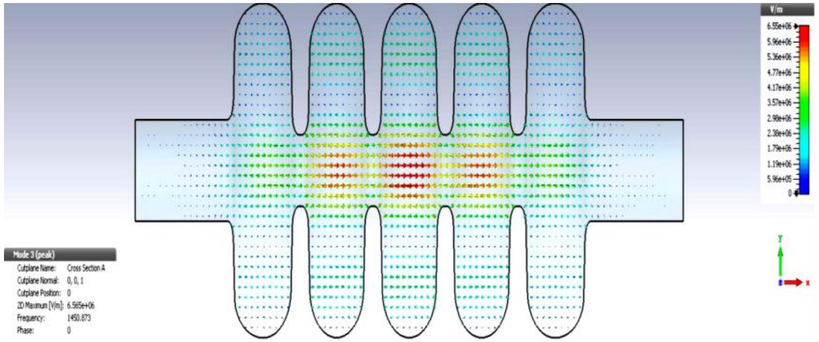
- Higher order mode analysis(upto 2.5 GHz) for both longitudinal and transverse modes of LB 650 cavity .

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

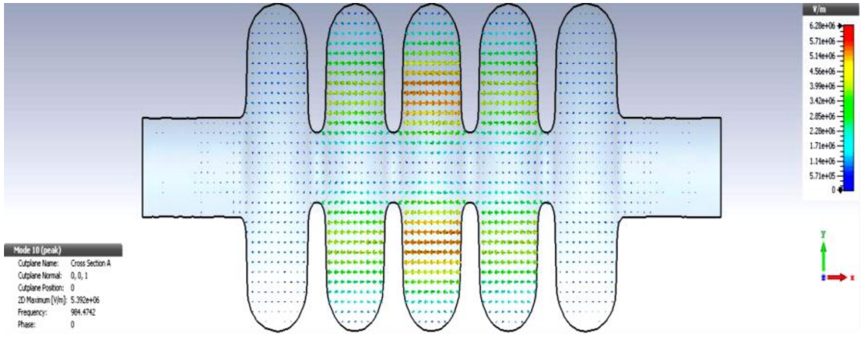
- R/Q values for higher order monopole modes is less than 5Ω for all the passbands







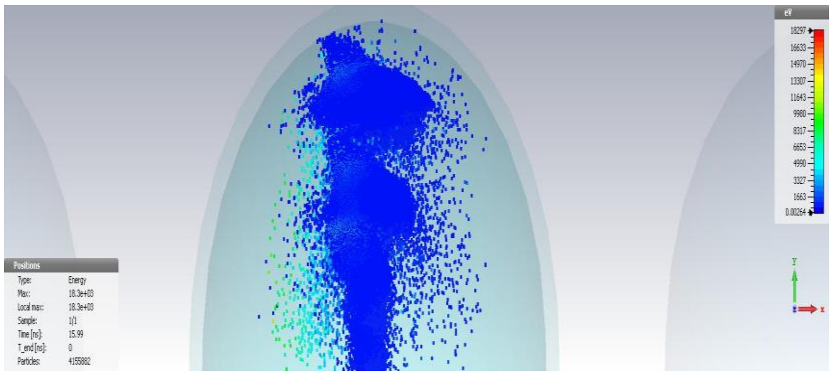
1450.87MHz(monopole)



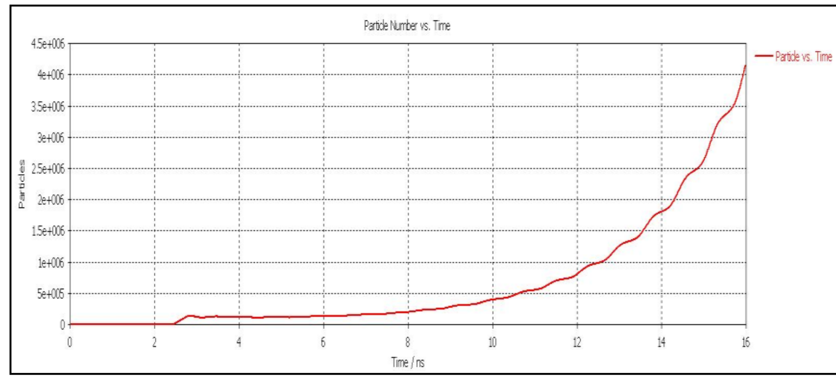
984.47MHz(dipole)

FRS BASED CAVITY DESIGN

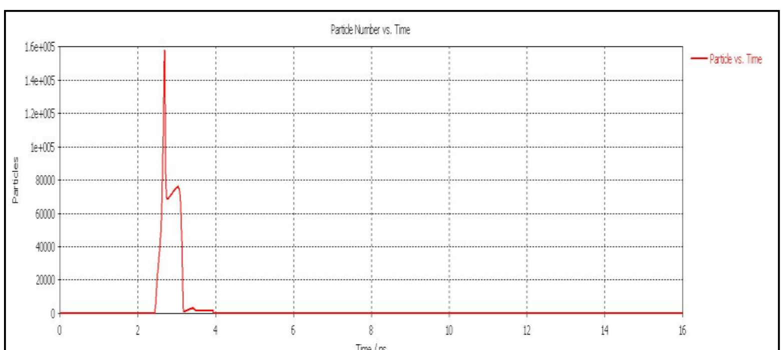
- **Multipacting Analysis has been carried out for both mid-cell and end-cell in CST Particle Studio**
- **60mm of the equator region is simulated**
- **No multipacting at Accelerating Gradient(17MV/m)**



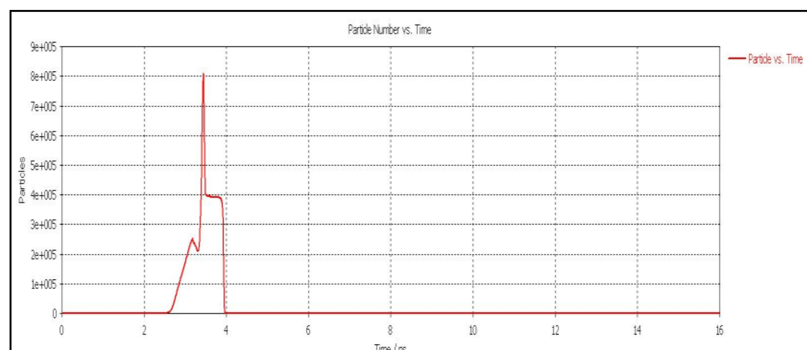
Particles after 16ns at 2.6MV/m (midcell)



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



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



Particle vs. time (ns) at 17.5V/m(end cell) (No multipacting)

FRS BASED CAVITY DESIGN

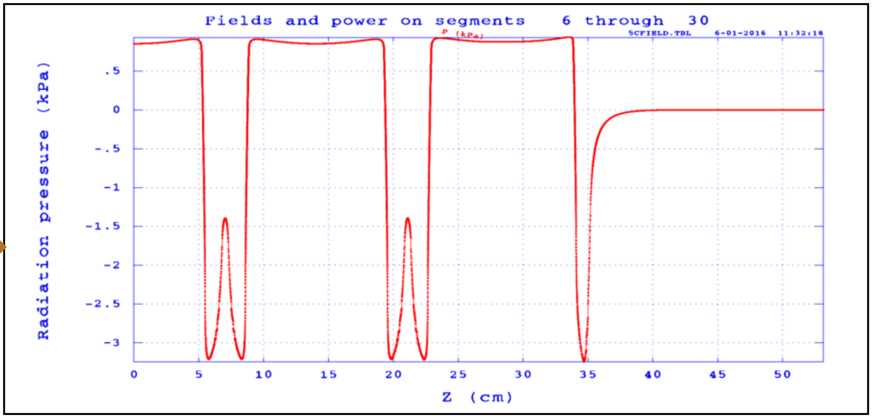
EM field in RF cavity exerts pressure (Radiation Pressure/Lorentz Force) on the cavity wall ⇒ Small deformation of cavity walls

Net deformation ⇒ bending inward at Iris and outward at Equator ⇒ Freq. shift

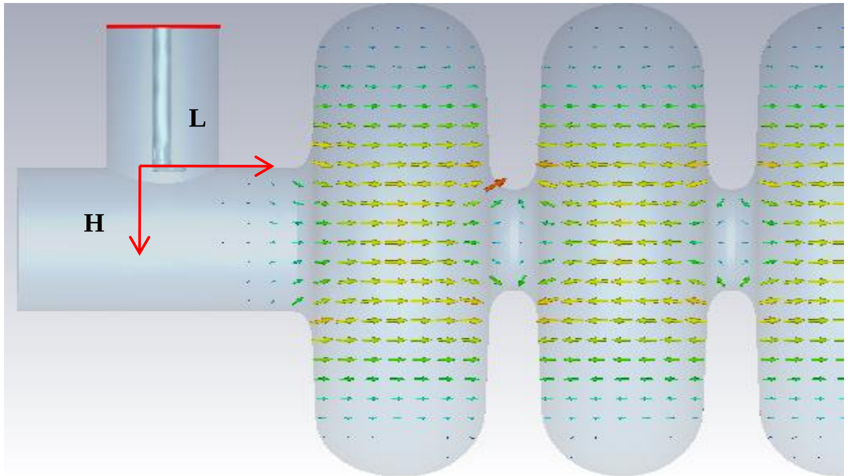
Lorentz force Calculated at specified energy gain of 11.9 Mev) by Superfish

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

$$\Delta f = K_L . E_{acc}^{\ 2}$$

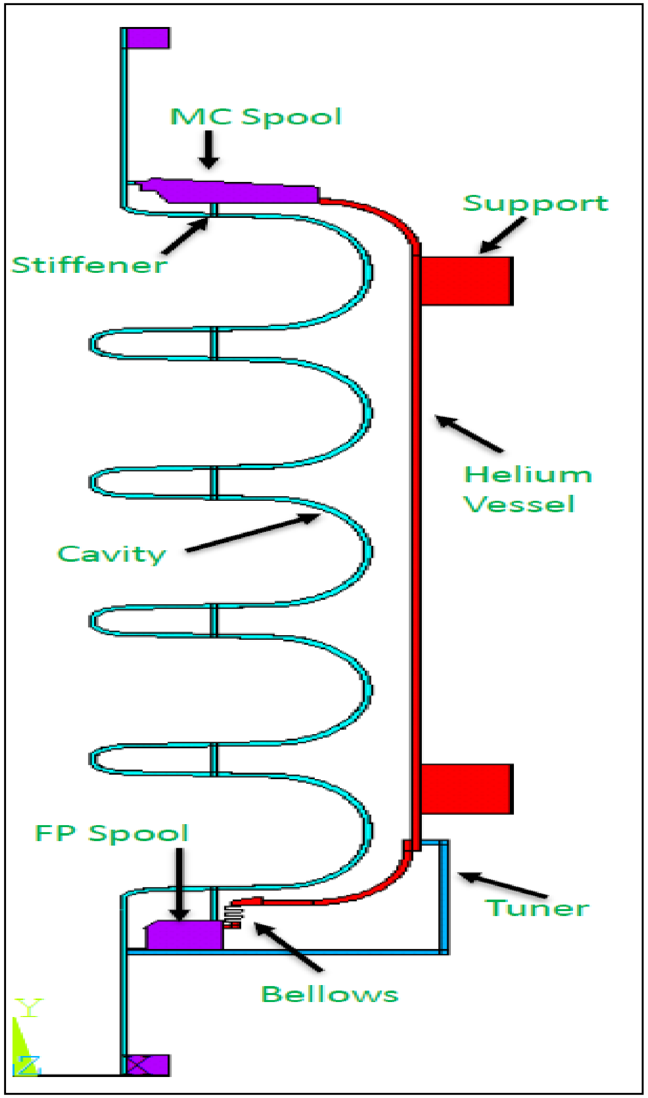


As per FRS , To achieve Bandwidth 65Hz(Q_L=1x10[7]),values of Q_{ext} for the coupler Calculated for different values of L and H, using CST Microwave studio



FRS BASED CAVITY DESIGN

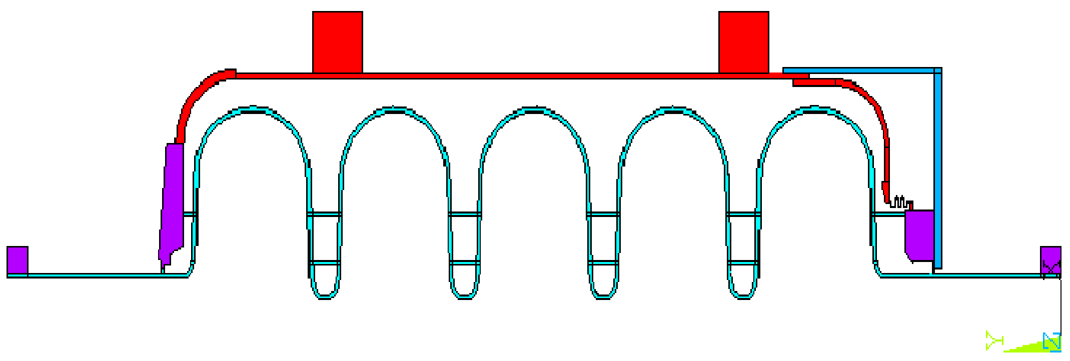
- ❑Frequency Detuning of the dressed cavity due to Lorentz force has been calculated
- ❑Frequency Detuning of the dressed cavity due to Helium Pressure Fluctuation has been calculated
- ❑Cavity stiffness with bare cavity and dressed cavity Calculated
- ❑Stiffener ring positions has been decided on the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



Dressed Cavity with its different components

FRS BASED CAVITY DESIGN

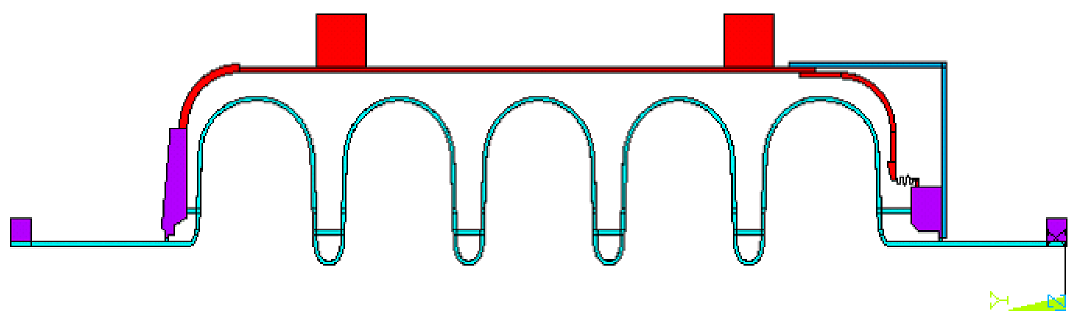
Design-A : Two stiffener rings for mid cells & one for end cells



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

LFD (Hz/(MV/m)2)	1.21 < 1.25 (satisfies FRS)
dF/dP (Hz/mbar)	12 < 25 (satisfies FRS)

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

LFD (Hz/(MV/m)2)	1.3 ~ 1.25 (Satisfy FRS), slightly higher than criteria, but acceptable
dF/dP (Hz/mbar)	30 >25 (does not Satisfy FRS)

Cavity stiffness values for both the Configurations (A and B), satisfy FRS criteria (<5kN/mm)

FRS BASED CAVITY DESIGN

- 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.

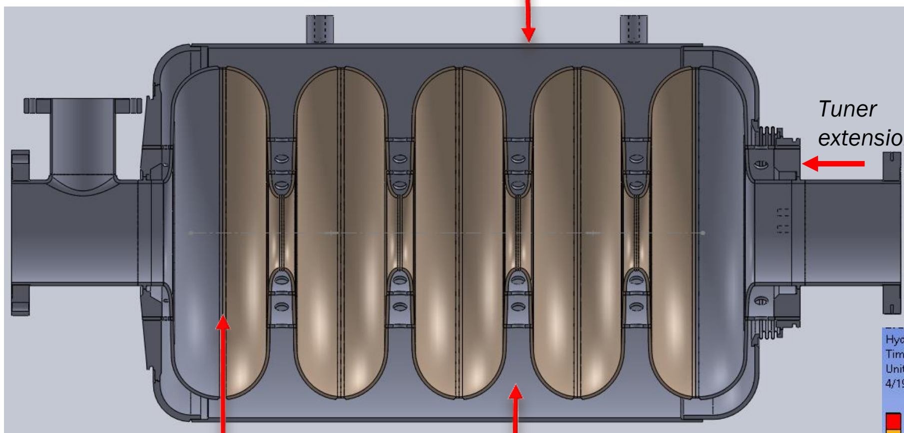
Load Case1	✓ Gravity ✓ P2 = 0.205 MPa Warm Pressurization, Applicable Temperature of allowable stress limits = 293 K
Load Case2	✓ Gravity ✓ P2 = 0.41 Mpa ✓ Hydrostatic pressure of Liquid Helium Head Cold operation(2K), full LHe and maximum pressure of Liquid Helium
Load Case3	✓ Cool down to 2 K ✓ Tuner extension of 1.5 mm
Load Case4	✓ Gravity ✓ P2 = 0.41 Mpa ✓ Hydrostatic pressure of Liquid Helium Head ✓ Cool down to 2 K ✓ Tuner extension of 1.5 mm
Load Case5	✓ Gravity ✓ P1 = P2 = 0.1 MPa Insulating and beam vacuum upset, helium volume evacuated

Material	Density (Kg/m3)	Coefficient of thermal expansion (293K - 2K) (1/K)	Reference Temperature (K)	Young's Modulus (Pa)	Poisson's Ratio
Nb	8590	4.81E-06	293K	1.05E+11	0.39
NbTi	5700	6.53E-06	293K	6.20E+10	0.36
Ti Grade-2	4528	5.15E-06	293K	1.07E+11	0.33

Material Properties

FRS BASED CAVITY DESIGN

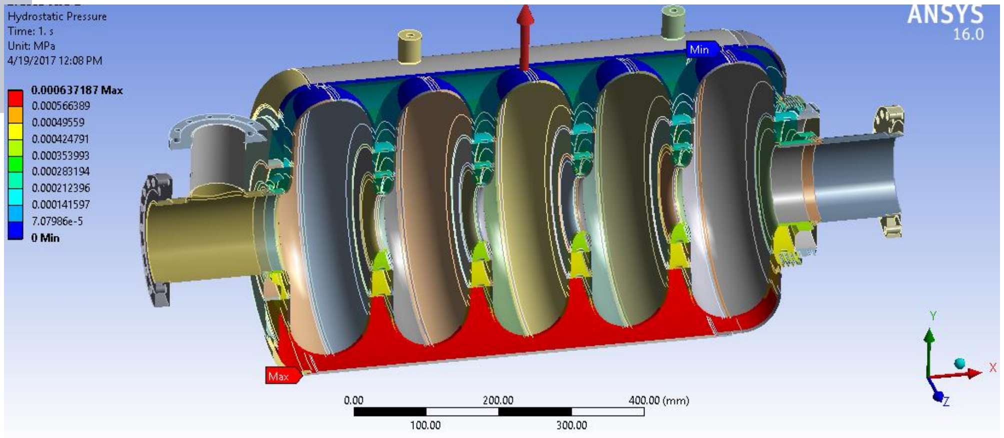
P3 (Air pressure outside Helium Vessel in case of insulation vacuum failure)



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)

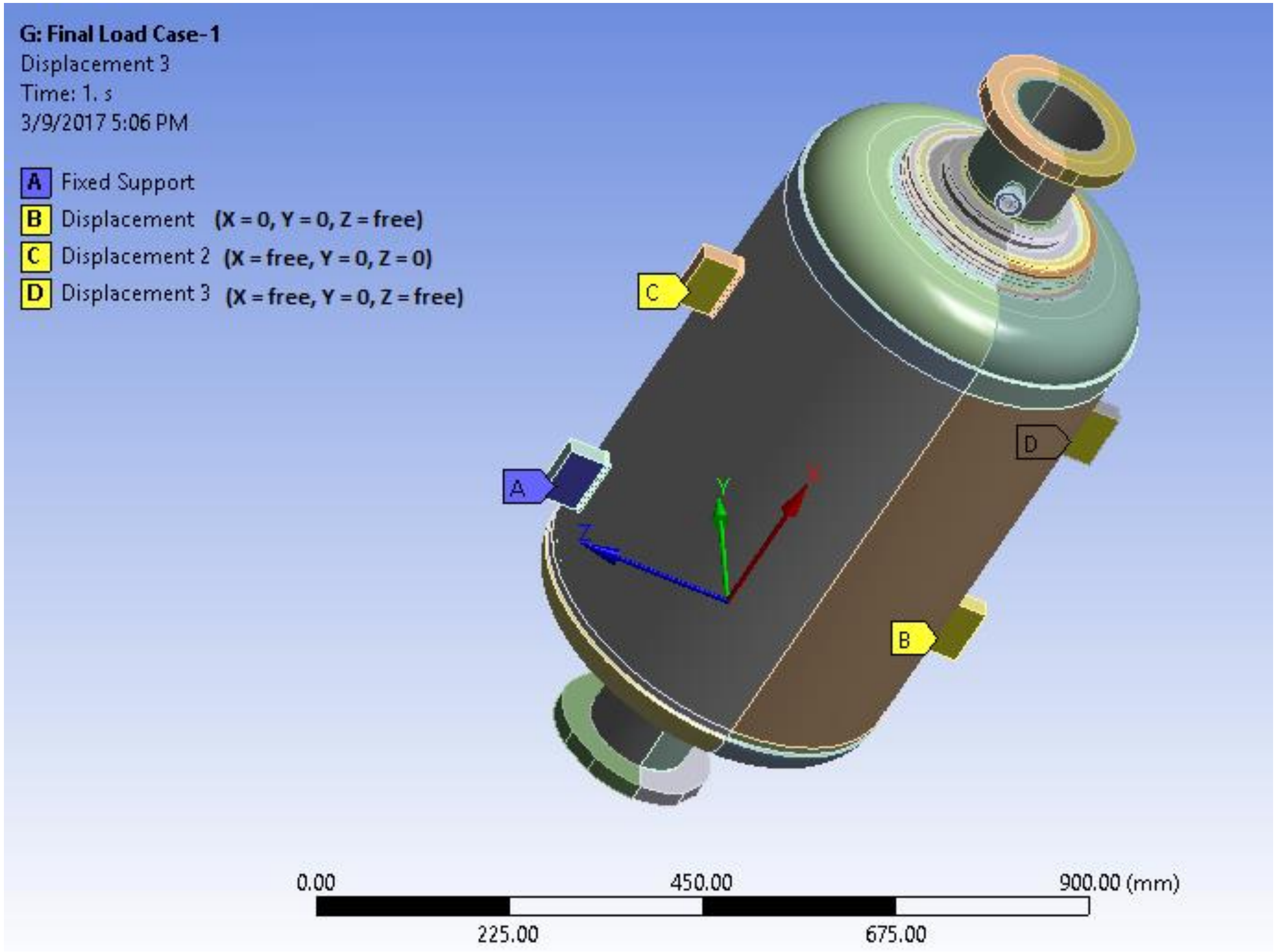
P1 (Air pressure inside cavity in case of beam vacuum upset)



P2 (Helium Pressure on all the surfaces directly in contact with Helium)

Different types of loads used in the load cases

FRS BASED CAVITY DESIGN

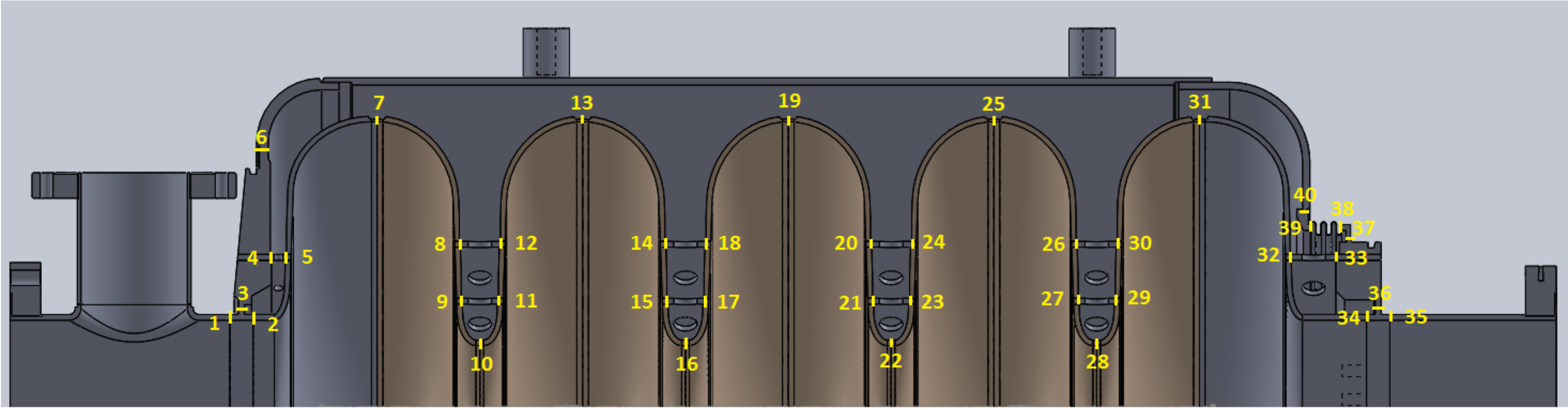


Boundary conditions of LB650 cavity for all load cases

FRS BASED CAVITY DESIGN

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, β=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.

THANK YOU