DEVELOPMENT OF 650 MHz CAVITIES FOR THE GeV PROTON ACCELERATORS IN PROJECT-X

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FRIOB03_talk

Outline of the Talk

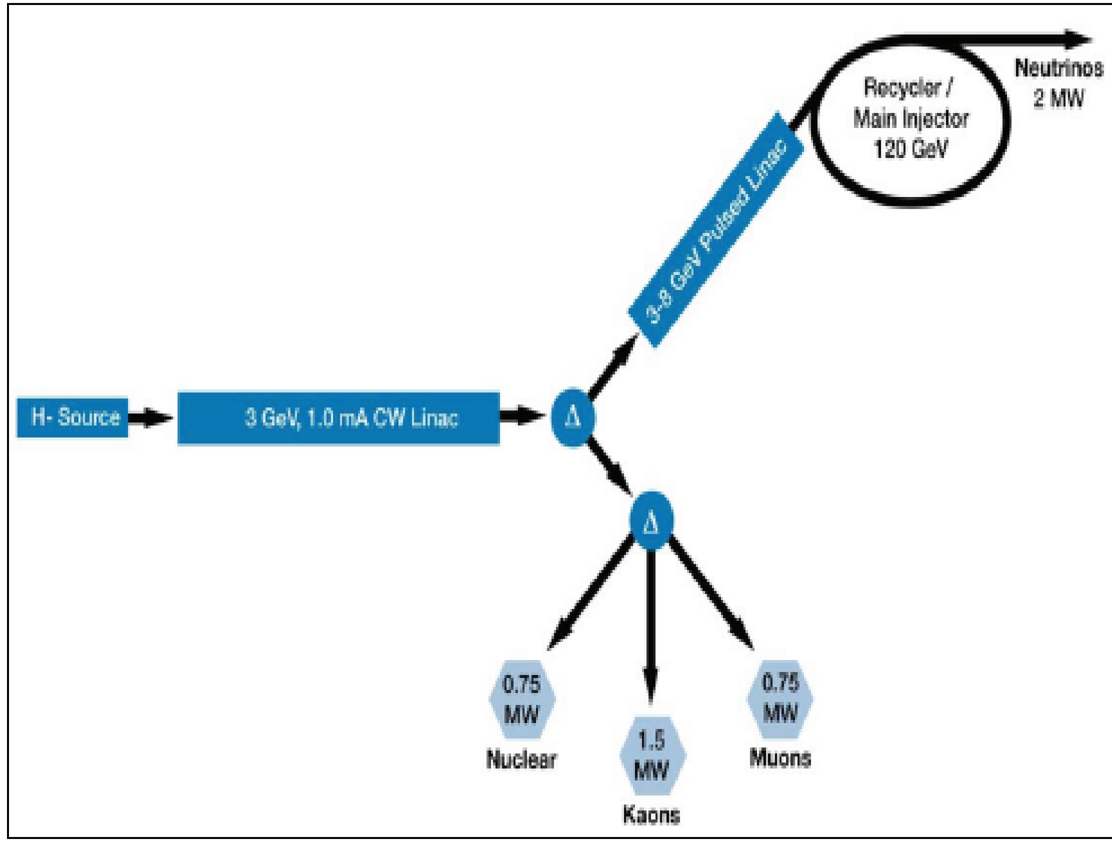
- Introduction
- 650 MHz, β=0.61, Cavity parameters
- Cavity simulation result
- Cavity shrinkage
- Higher Order Modes (HOMs)
- Multipacting investigation – 2D & 3D Analysis
- Mechanical modal analysis
- Structural analysis
- Prototype cavity fabrication and CMM measurement
- Niobium material for the cavity
- Summary

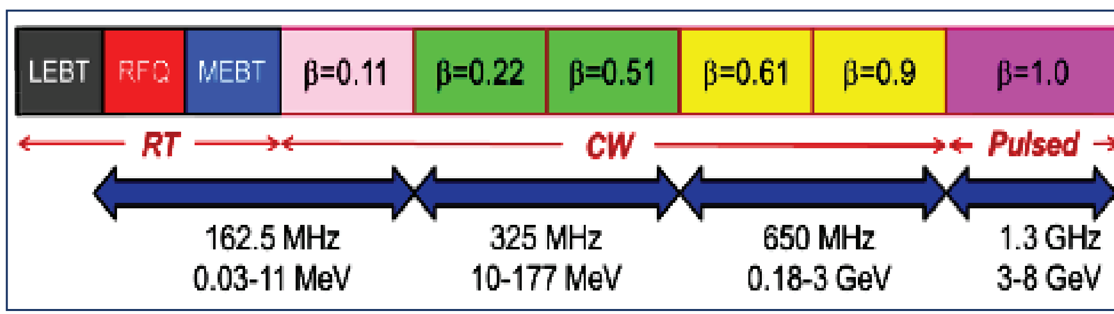
Introduction

- **Project X is a GeV range high intensity proton linear accelerator being developed at Fermilab, USA in collaboration with various American labs and Indian laboratories as well.**

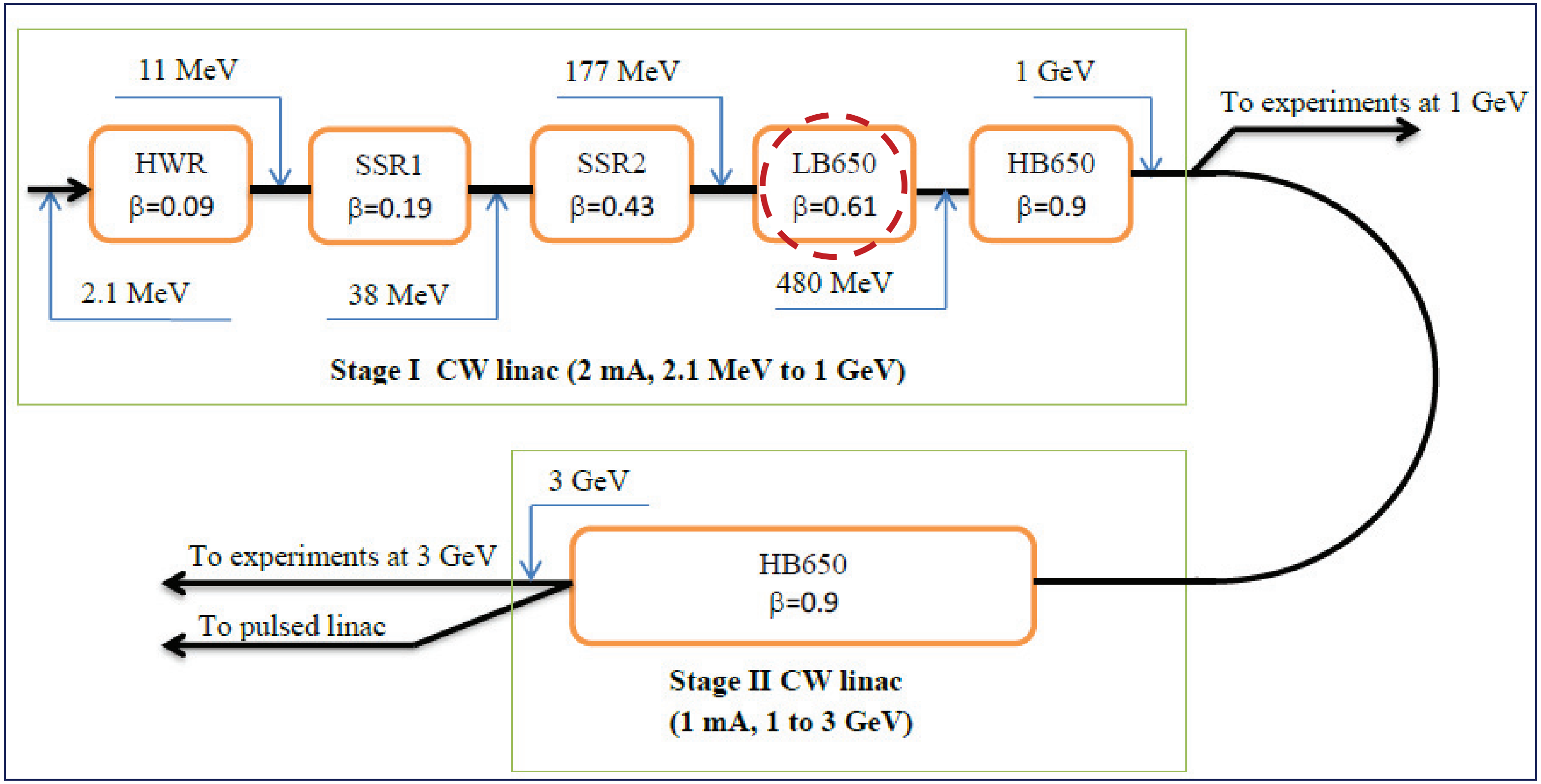
- **In stage- I & II of the project, the CW linac structures with different velocity factor (beta) accelerate proton up to 3 GeV at an average beam current of 1 mA.**

- **Acceleration from 177 MeV to 3 GeV, will be provided by two families of 5-cell SRF cavities operating at 650 MHz and designed to β_G=0.61 and β_G=0.9.**





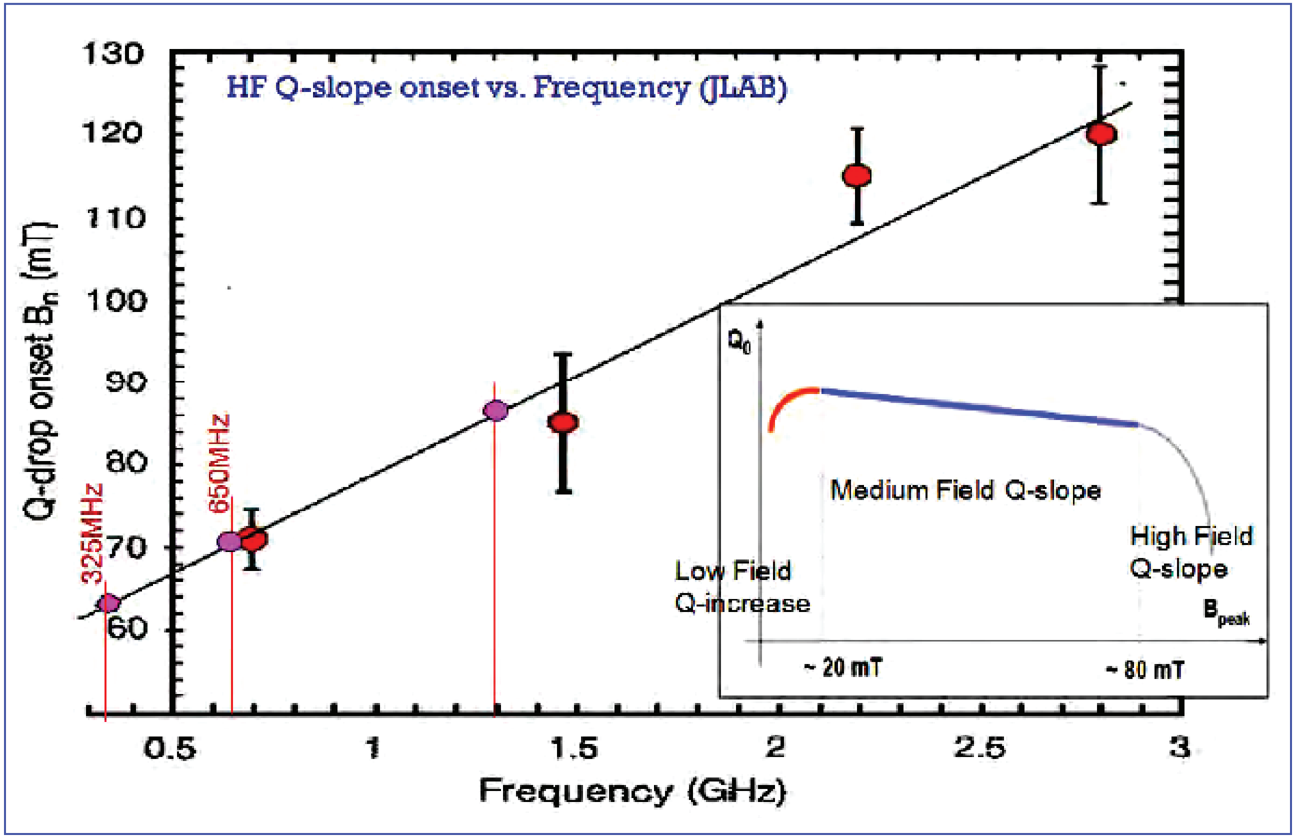
SRF Technology map for CW Proton Linac of Project X



- β refers to the cavity optimum β for HWR, SSR1, and SSR2 and the cavity geometrical β for LB650 and HB650.
- Cavity shape is optimized to decrease the field enhancement factors (magnetic and electric) in order to improve the interaction between the beam and the cavities.
- The cavity aperture should be as small as possible subject to following considerations: Field flatness, Beam losses, Mechanical stability, Reliable surface processing.

LB650 Cavity parameters

- Working gradient chosen as 17 MV/m to provide the peak surface magnetic field (B_p) that allows operation below high-field Q-slope;
- For frequency of 650 MHz, $B_p \leq 70$ mT.
- $E_p \leq 40 – 50$ MV/m, in order to avoid the risk of strong field emission.



High-field Q-slope vs. Frequency

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LB650 Cavity parameters

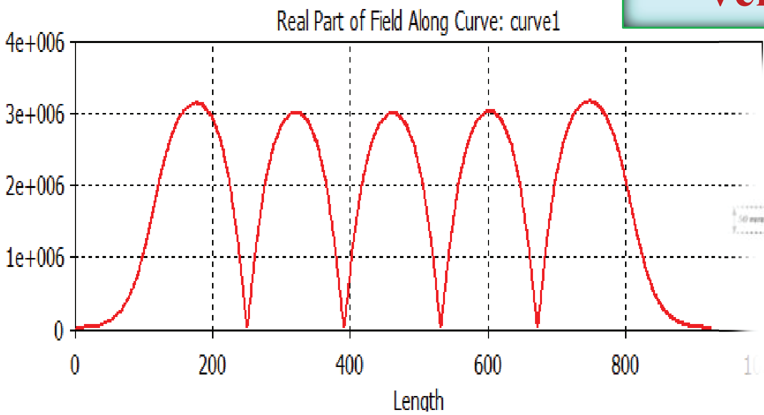
- **According to Linear perturbation theory – for a given relative error in the frequencies of the cavity cells the field flatness is determined by *δf*, between the operating frequency (f_π) and the frequency of the neighbouring mode.**
- ***Field flatness factor, $f_\pi / \delta f$*** **$\approx N^2 / k$** [k = cell to cell coupling, N = no. of cell]
- **Cavity with fewer cells shows a smaller coupling coefficient for a given field flatness**
- **For 650 MHz cavity, $\delta f / f_\pi = 5 \times 10^{-4} \rightarrow k > 1.25\%$**
- **The aperture selected for the cavity represents a trade-off between requirements related to the cell-to-cell coupling and beam loss. The experiences with other labs determine that these cavities can operate with tolerable beam loss within 100 mm. aperture. So, we have adopted 96 mm. aperture for 650 MHz, β=0.61 cavity.**

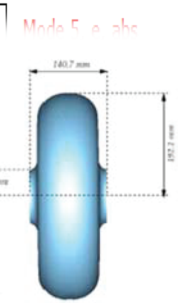
650 MHZ, β=0.61, ELLIPTICAL CAVITY SIMULATION

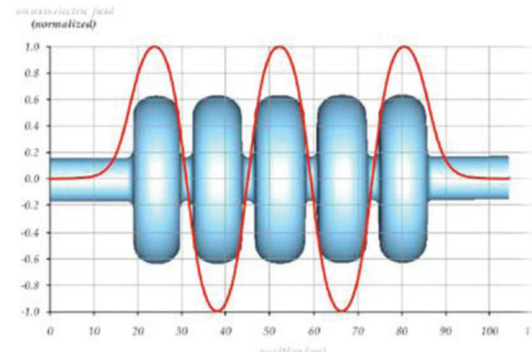
Accelerating mode

Field flatness: Very good!

Data: Generated by VECC







Results: Very good!

kc = 1.24%
(R_{iris}=48 mm.)

	$\frac{A}{B}$ mm./mm.	$\frac{a}{b}$ mm./mm.	Equator radius D/2 mm.	Iris radius R_{iris} mm.	Half-cell L/2 (inner) mm.	$\frac{R}{Q}$ Ω	G=Q.Rs Ω	E_{acc} MV/m	$\frac{E_p}{E_{acc}}$	$\frac{B_p}{E_{acc}}$	$f_{\pi-mode}$ MHz	Remarks
VECC Design1 Result	$\frac{54}{58}$	$\frac{11.99}{27}$	198.175	48	70.335	290	197	16.95	3.34	4.90	650.000	2D SUPERFISH 3D CST MWS $\left(\frac{a}{b}\right)_{end}=\frac{20.66}{46.54}$ $\left(\frac{A}{B}\right)_{end}=\frac{45.94}{49.35}$ α=3.6 deg Energy=118.8 J Mesh size=0.05
VECC Design2 Result	$\frac{54}{58}$	$\frac{13.68}{30.82}$	197.4	48	70.335	296	200	17.00	3.00	4.84	649.99869	2D SUPERFISH 3D CST MWS $\left(\frac{a}{b}\right)_{end}=\frac{10.67}{24.02}$ $\left(\frac{A}{B}\right)_{end}=\frac{54}{58}$ α =2.4 deg (mid) =4.5 deg (end) Energy=118.8 J Mesh size=0.05

Comparative Chart for Design Parameters for LB650 Cavity

Name of the lab designed	$\frac{A}{B}$ (mm./mm.)	$\frac{a}{b}$ (mm./mm.)	Equator radius D/2 (mm.)	Iris radius R_{iris} (mm.)	Half-Cell Length L/2 (inner) (mm.)	$\frac{R}{Q}$ (Ω)	G (=Q.R$_s$) (Ω)	E_{acc} (MV/m)	$\frac{E_{pk}}{E_{acc}}$	$\frac{B_{pk}}{E_{acc}}$ [mT/(MV/m)]	$f_{\pi-mode}$ (MHz)	Remarks
Fermilab (FNAL)	$\frac{54}{58}$	$\frac{14}{25}$	194.95	42	70.335	378	191	17.0	2.26	4.21	650	2D SLANS code L/2 = 71.385 (end-cell) α = 2.0 deg. (mid-cell) = 2.7 deg. (end-cell) E = 92.7 J
Jefferson Lab (JLAB)	$\frac{50.46}{45}$	$\frac{15}{22}$	192.10	50	65.456	297	190	17.3	2.71	4.78	650	2D SUPERFISH code Equator flat = 0.976 mm.(mid-cell) = 0.5047 (end-cell) α = 0 degree E = 118.8 J
VECC	$\frac{54}{58}$	$\frac{13.68}{30.82}$	197.40	48	70.335	296	200	17.0	3.00	4.84	650	2D SUPERFISH, 3D CST MWS, α = 2.4 deg. (mid-cells) = 4.5 deg. (end-cells), $\left(\frac{a}{b}\right)_{end-cells} = \frac{10.67}{24.02}$ Energy = 118.8 J

- A small cavity wall slope (α) gives more freedom to decrease the field enhancement factor. However, α value is limited by surface processing and mechanical stability requirements.
- In mid-cells, α=2.4^0 selected to maintain low field enhancement factor.

CAVITY SHRINKAGE

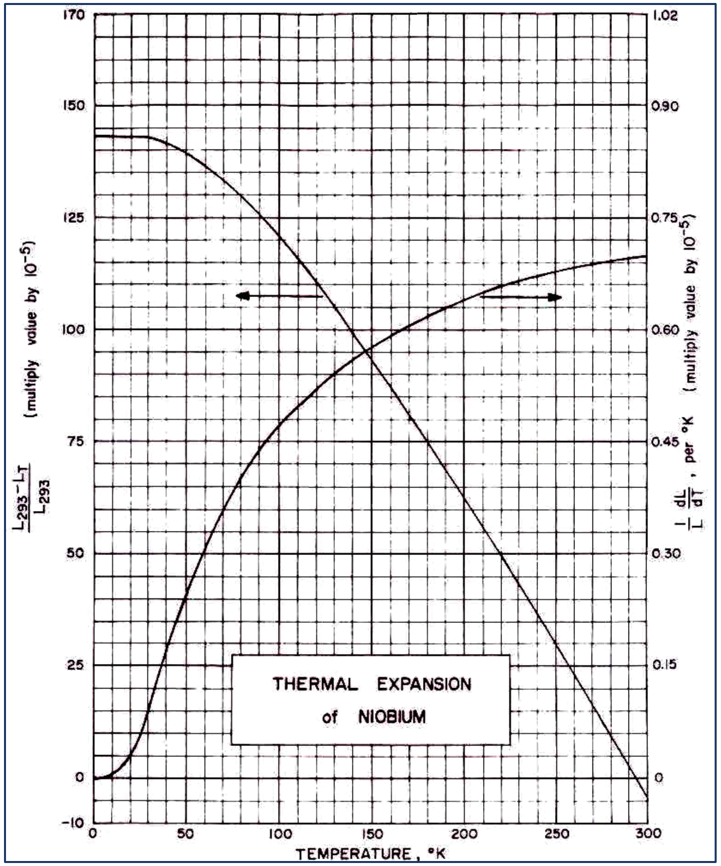
DUE TO THERMAL CONTRACTION OF NIOBIUM

- The dimensions of the cavity are adjusted taking into account the 150μm total chemical treatment and thermal shrinkage from room temperature to 2K.

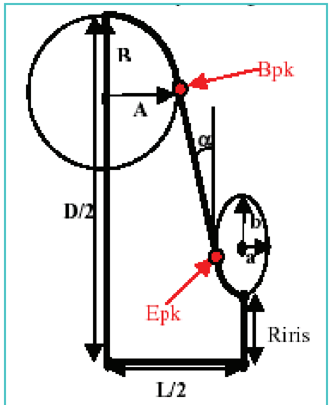
- Due to BCP, 150μm of material will be removed.
- The aperture and equator radius are decreased by 150μm.
- Ellipse centres and half cell length do not change appreciably.
- Half axis in Iris area are increased by 150μm.
- Half axis in equator area are decreased by 150μm
- **Linear thermal expansion/contraction coefficient (α_{Nb}) of niobium is,**

$\alpha_{Nb} = (L_{293} - L_2)/L_{293} = 142 \times 10^{-5}$ /^{0}K

- α_{Nb} Non-linear !!



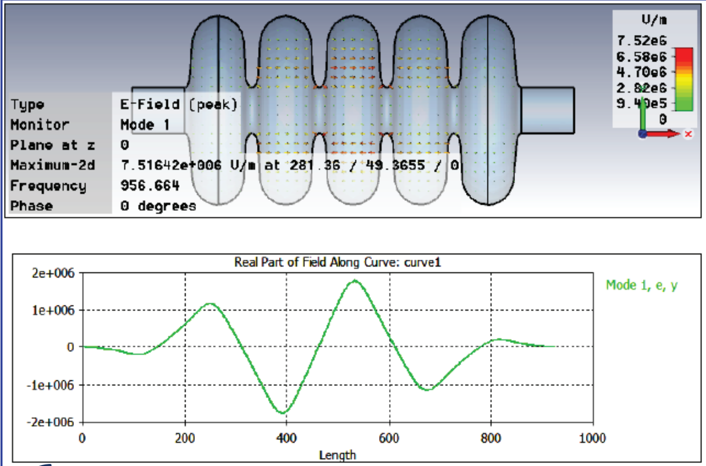
$$L_{COLD} = \frac{(L_{WARM} + 0.15)}{(1 + \alpha_{Nb})}$$



Dimensions of 650 MHz, 5-cell, β=0.61, Niobium Cavity

Dimensional Parameters	COLD Dimension (inside) (as designed) (mm.)	COLD Dimension Pre- BCP treatment of 150 μm (mm.)	WARM Dimension inside (as Fabricated) (mm.)
Equator radius	197.400	197.250	197.53
Iris radius	48.000	47.850	47.92
A	54.000	53.850	53.93
B	58.000	57.850	57.93
a	13.680	13.830	13.85
b	30.820	30.970	31.01
a (for end cell)	10.670	10.820	10.84
b (for end cell)	24.020	24.170	24.21
Half cell length (L/2)	70.335	70.335	70.44

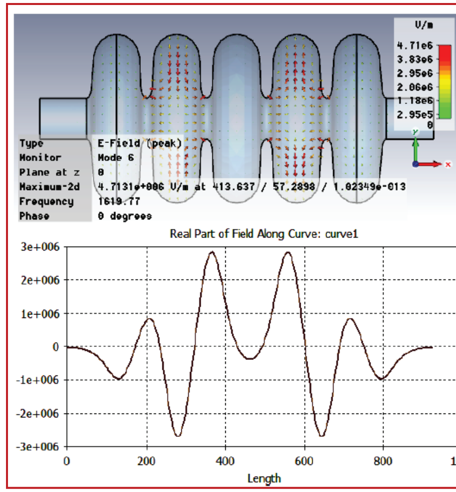
Higher order modes (HOMs)



CST MWS RESULTS

Frequency: 956.664 MHz

Effective Transverse Impedance: 0.035434 Ω.cm⁻²



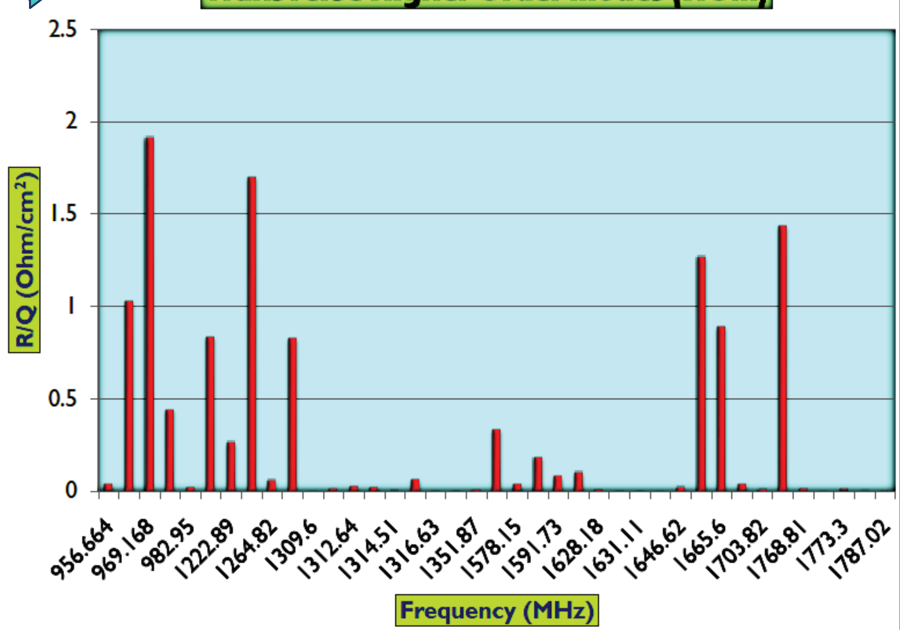
CST MWS RESULTS

Frequency: 1619.77 MHz

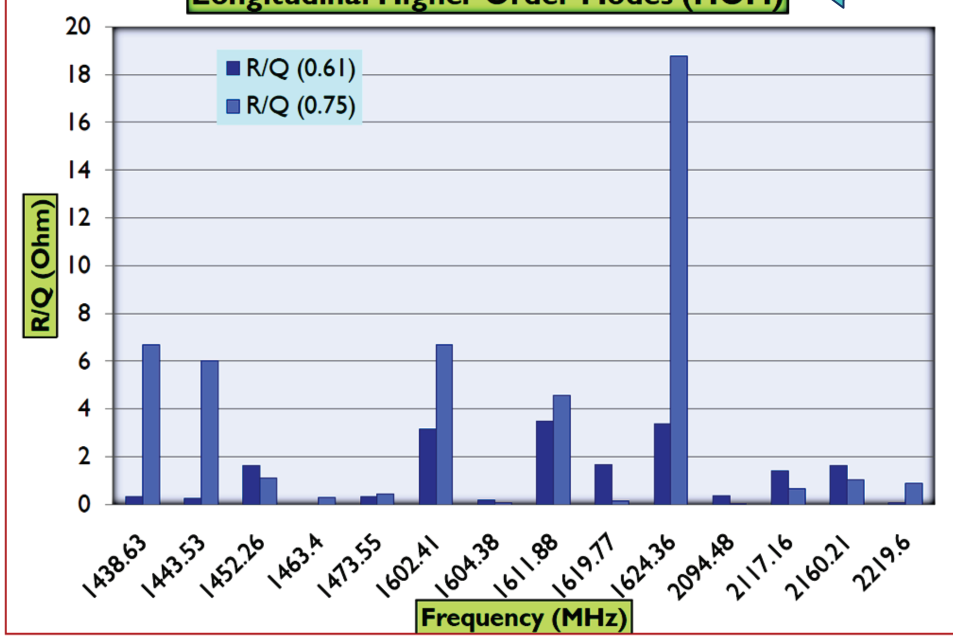
Effective Longitudinal Impedance:
1.66 Ω (β=0.61)
0.135 Ω (β=0.75)

- Transverse and longitudinal HOMs for the cavity at 650 MHz, β=0.61--analysis done
- No trapped mode with high effective impedance observed.
- HOM dampers are not necessary for required beam current.

Transverse Higher Order Modes (HOM)



Longitudinal Higher Order Modes (HOM)



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2D Multipacting Analysis of the Cavity

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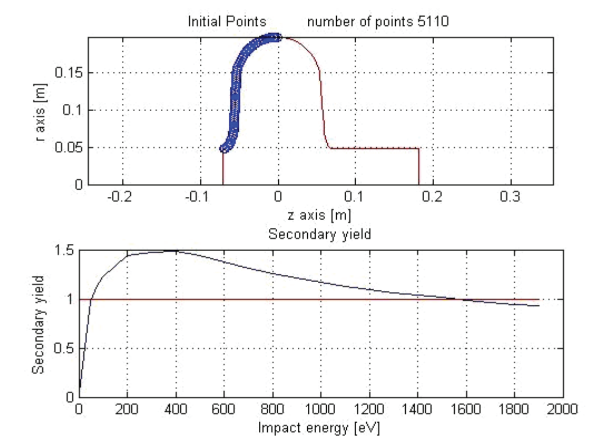
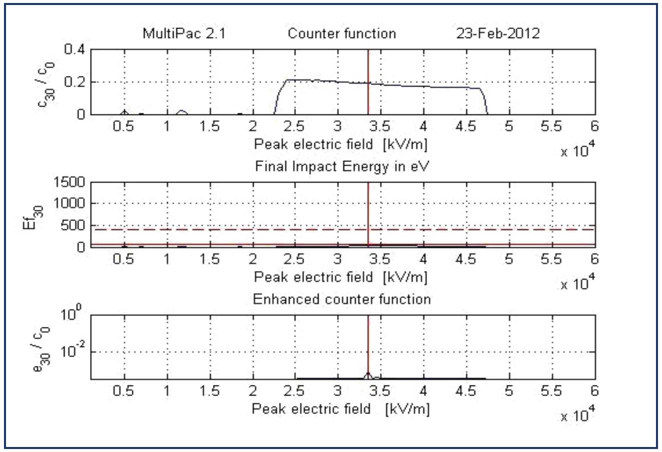
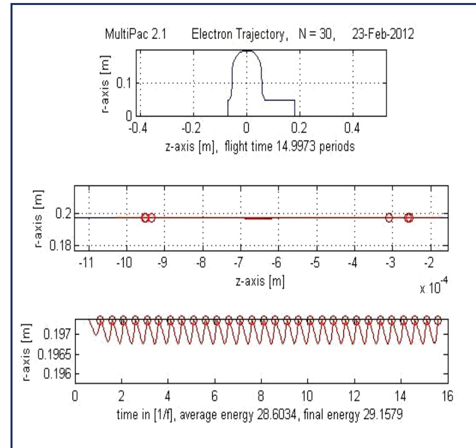


Input for end-cell Cavity



Results for end-cell Cavity



end-cell Cavity (Equator)

- It is observed that impact energy is less than 50 eV for all peak electric fields except a small region between 30 to 35 MV/m, where it is around 200 eV.
- However, we can conclude that no multipacting can take place in the said cavity as the relative enhanced electron counter function is less than 1 for the whole range of peak electric field up to 60 MV/m
- It is observed for mid-cells and end-cells that even after 30 impacts of electrons at the equator region (at the radius of 197 mm.) of the cavity, the final impact energy is 28.4364 eV, which is well below 50eV
- unlikely to cross secondary electron emission yield for producing multipacting.
- Analysis using CST Particle Studio (3D) code is necessary for further investigation!

Multipacting simulation using 3D CST Particle Studio

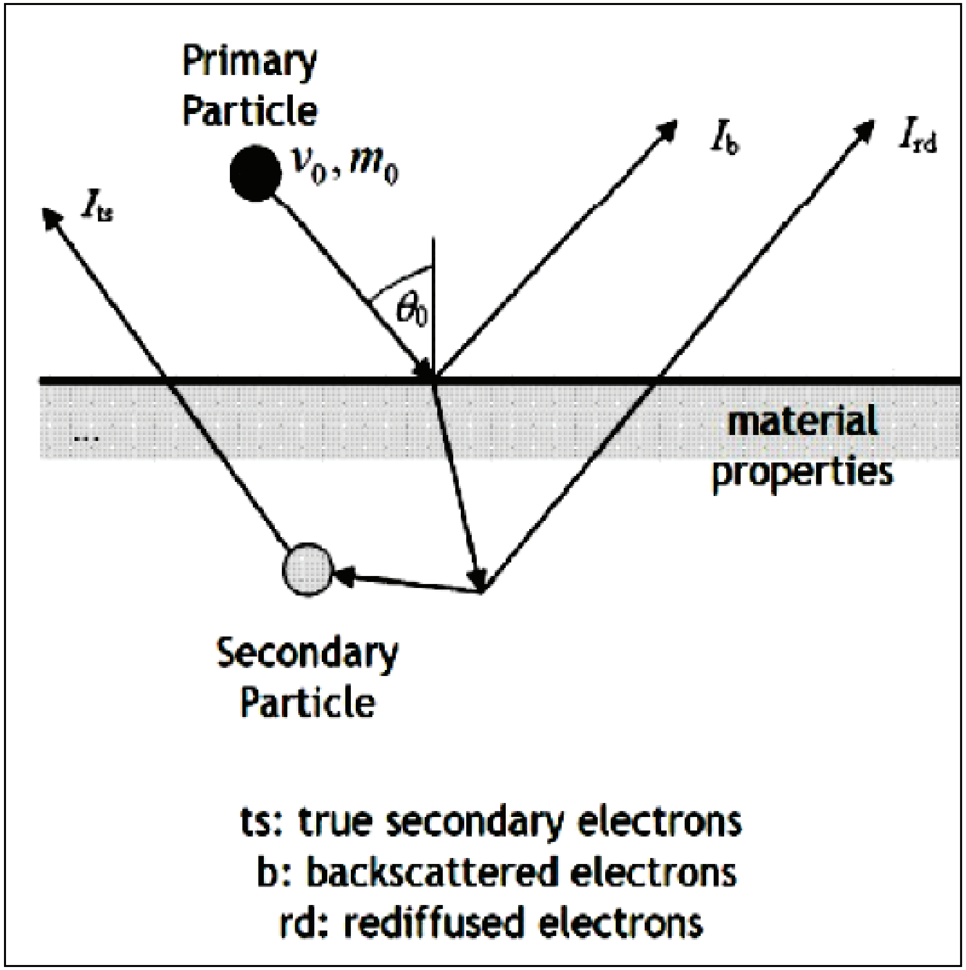
Furman Model of Secondary Electron emission (consisting of three types of scattering particles) has been taken into account in CST code.

- **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.**

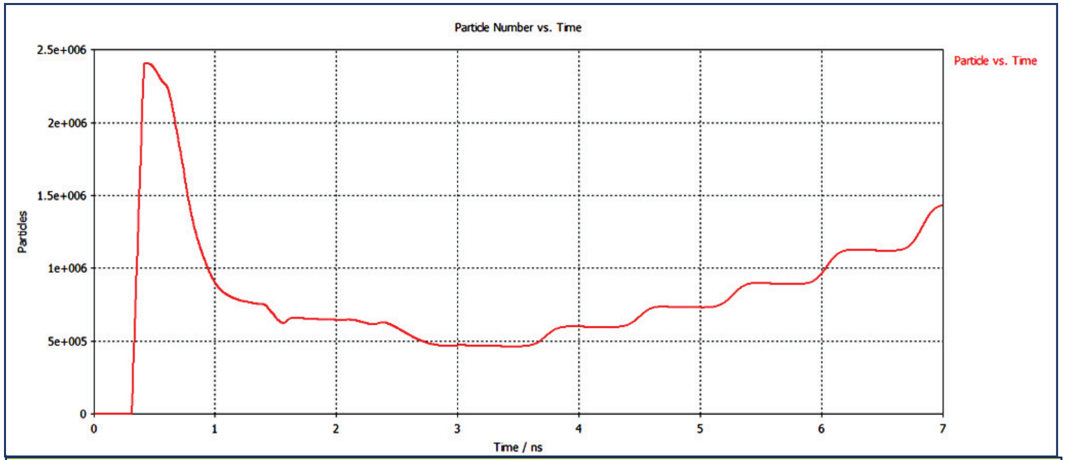
[M.A. Furman, M.T.F. Pivi, "Simulation of secondary electron emission based on a phenomenological probabilistic model", LBNL-52807, SLAC-PUB-9912]

  - **Statistical behaviour.**

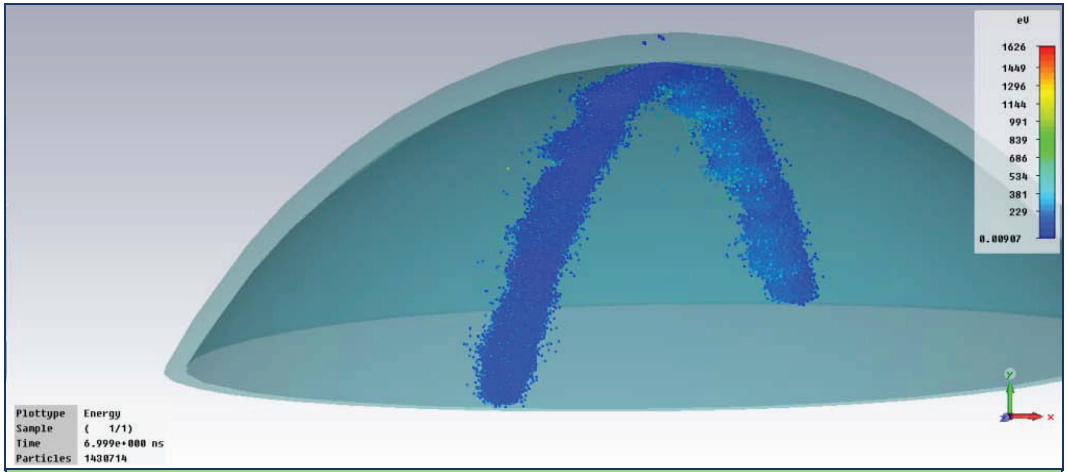


Multipacting simulation results for 650MHz, β=0.61 SCRF Cavity using 3D CST Particle Studio

- 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.

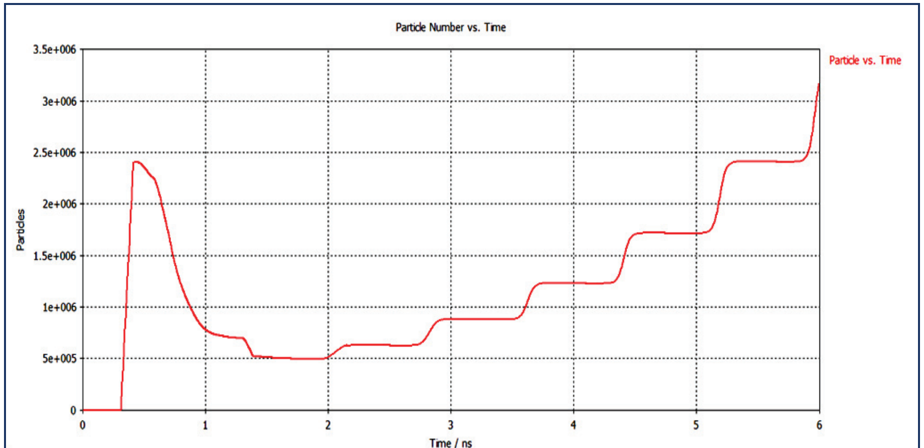


Particle vs. time(ns) at 5.8 MV/m

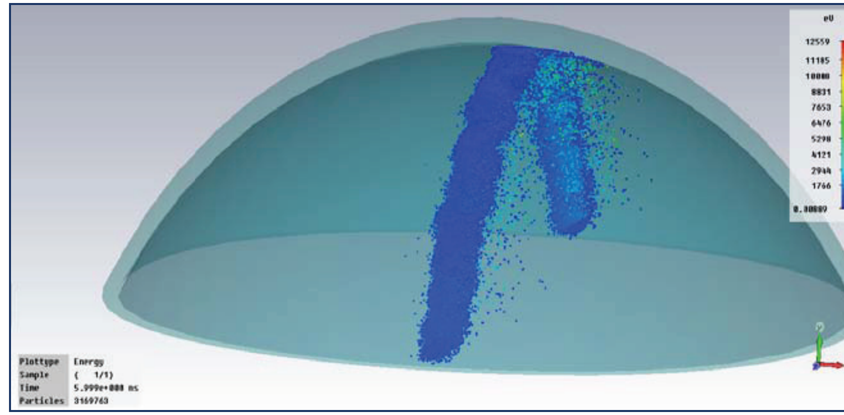


Particles after 7ns at 5.8 MV/m

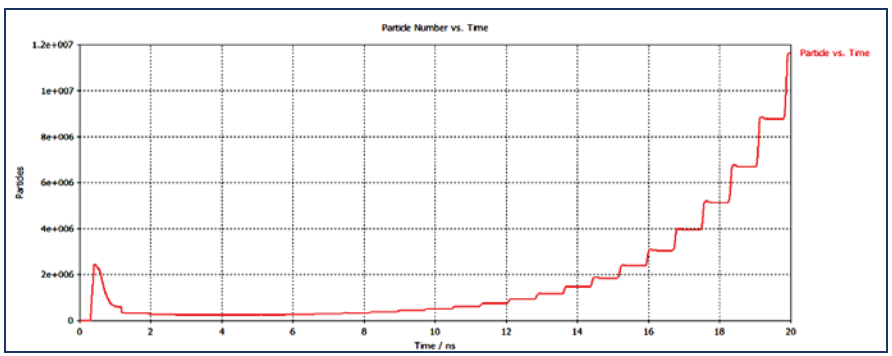
Multipacting simulation result for 650MHz, β=0.61Cavity
using CST Particle Studio



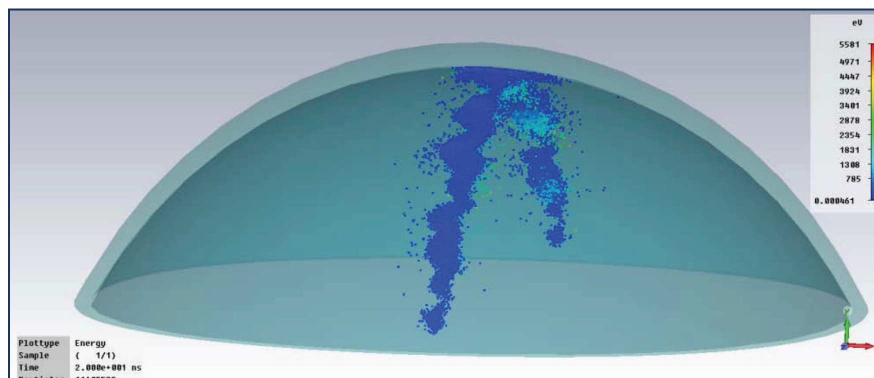
Particle Vs time(ns) at 6.8MV/m (Strong Multipacting)



Particle after 6ns at 6.8MV/m

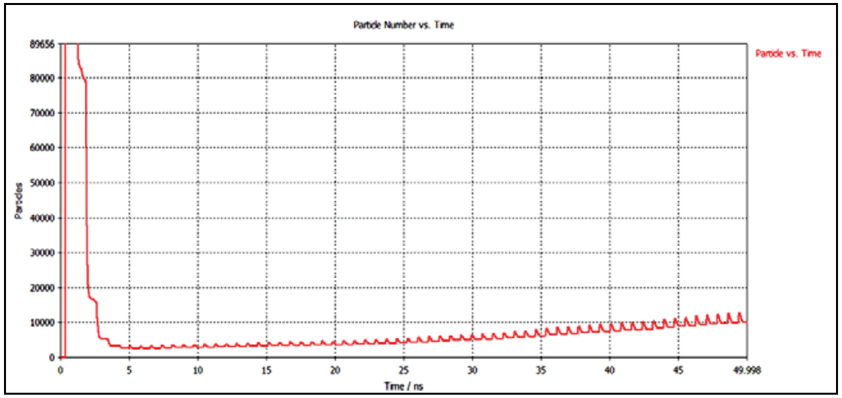


Particle Vs time(ns) at 9MV/m

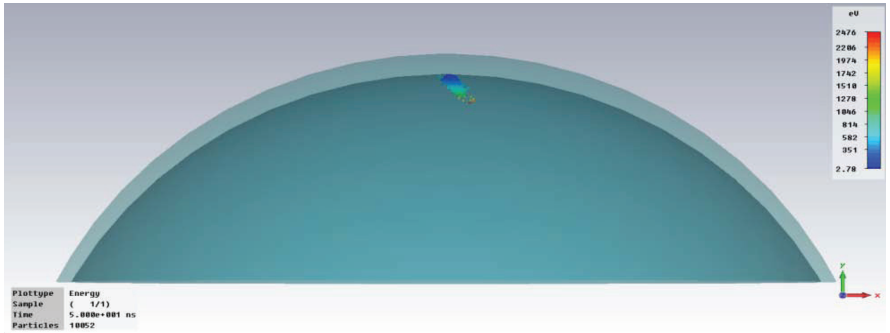


Particle after 20ns at 9MV/m

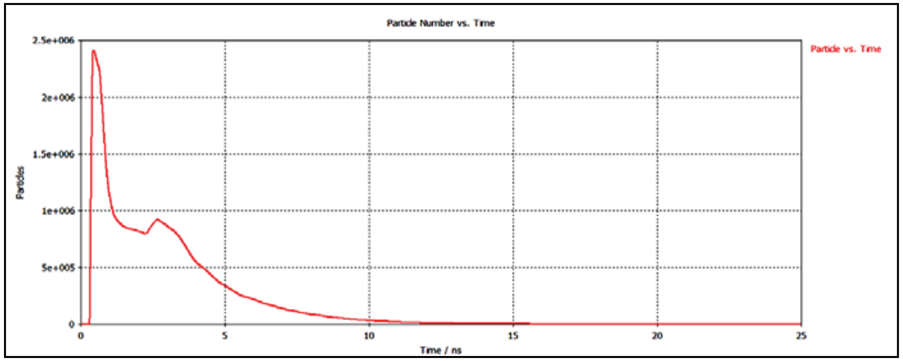
Multipacting simulation data for 650MHz, β=0.61 Cavity
using CST Particle Studio



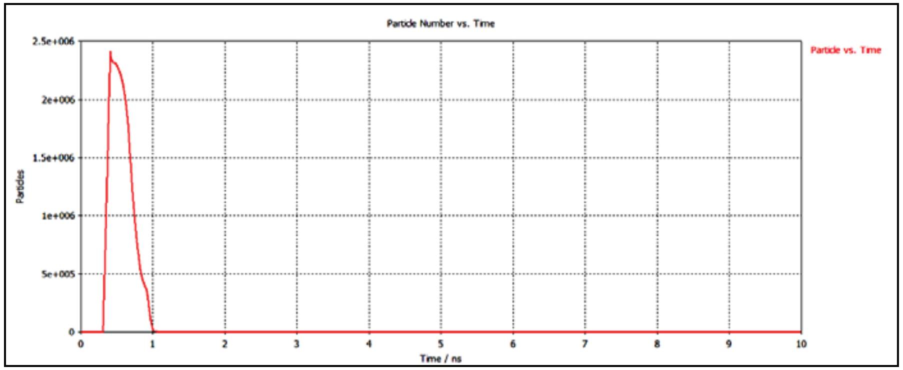
Particle Vs time(ns) at 11.5 MV/m
(slow multipacting)



Particle after 50ns at 11.5MV/m



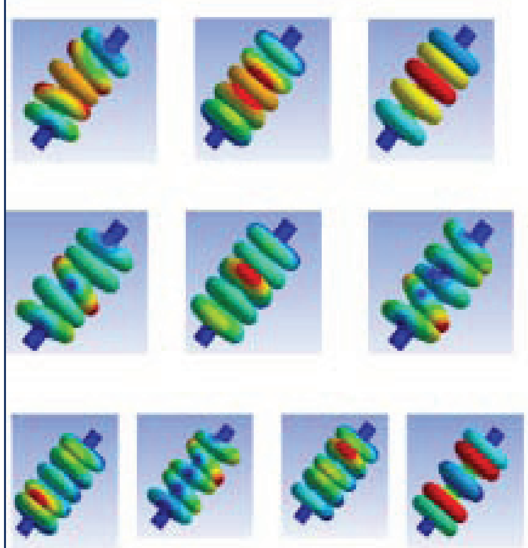
Particle Vs time(ns) at 4.5MV/m
(No Multipacting)



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

Mechanical modal analysis of 650 MHz SRF 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 (NOT desirable!)
  - ➢(with stiffener) shows frequency >100 MHz



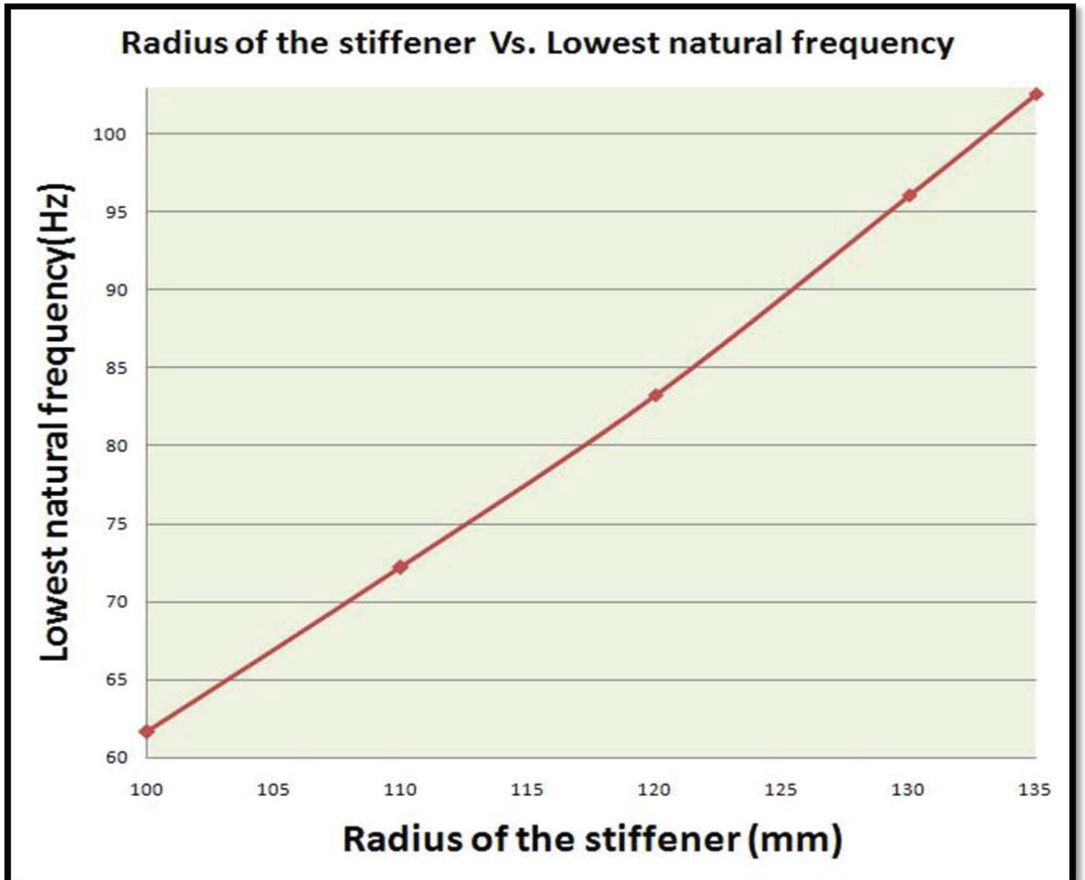
Mode	Frequency [Hz]
1.	3.0625
2.	5.9953
3.	8.6136
4.	10.776
5.	11.161
6.	24.688
7.	26.005
8.	27.449
9.	28.538
10.	57.485

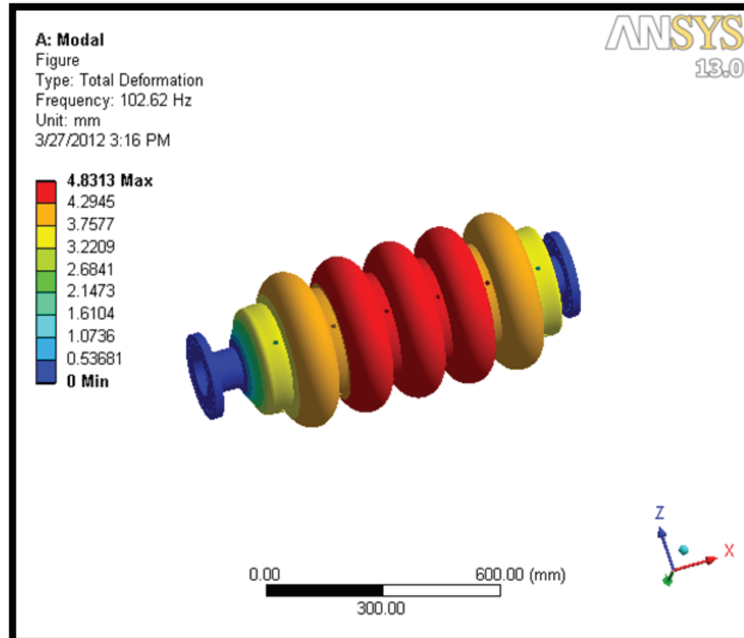
Mechanical modal analysis
(without stiffener)

	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

Mechanical modal analysis
(with stiffener)

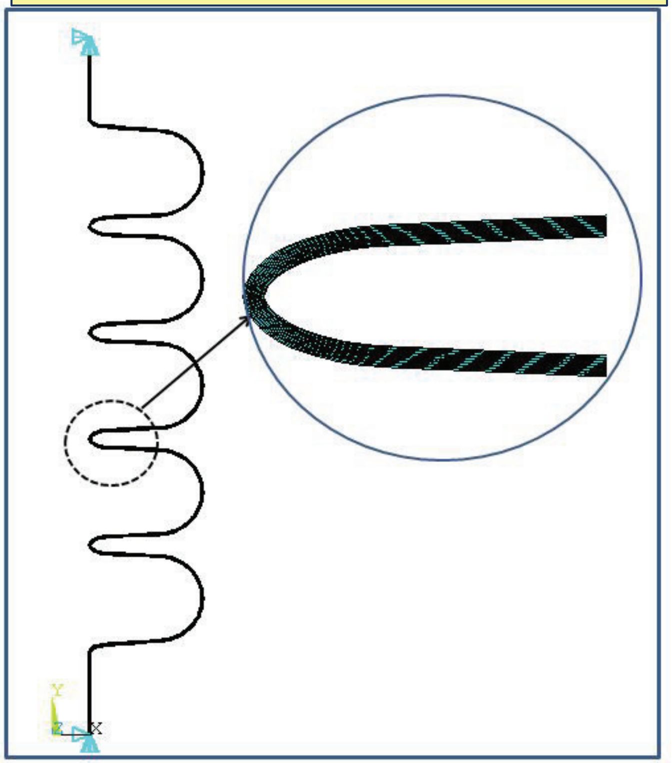
Stiffened cavity modal analysis



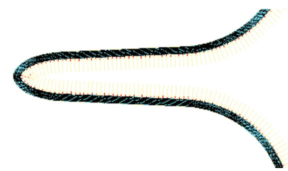


Cavity structural analysis: formulation detail

Model: Axi-symmetric

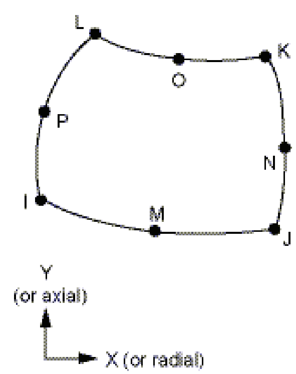


Loading:
- ✓Uniform Temperature=2K
- ✓External Pressure=3 atm

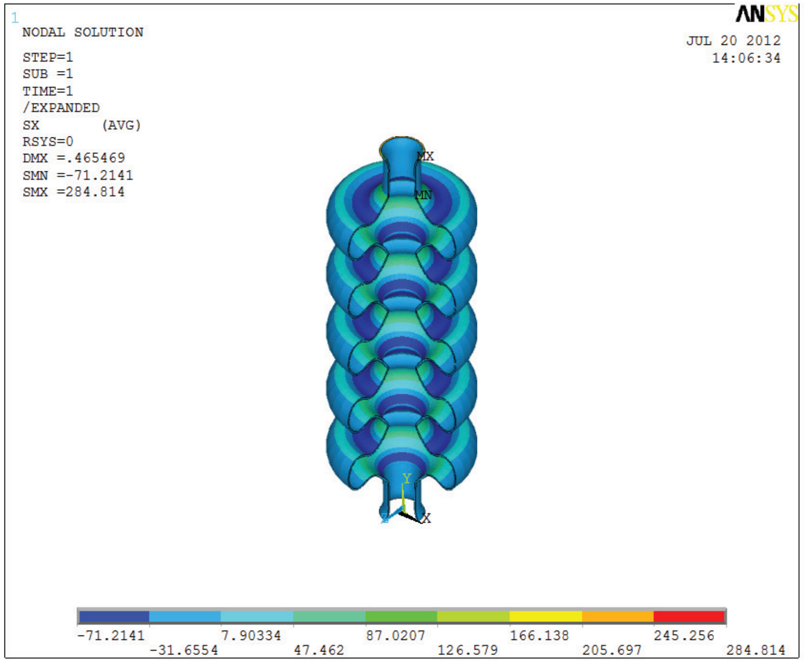


Boundary Condition: Both end fixed

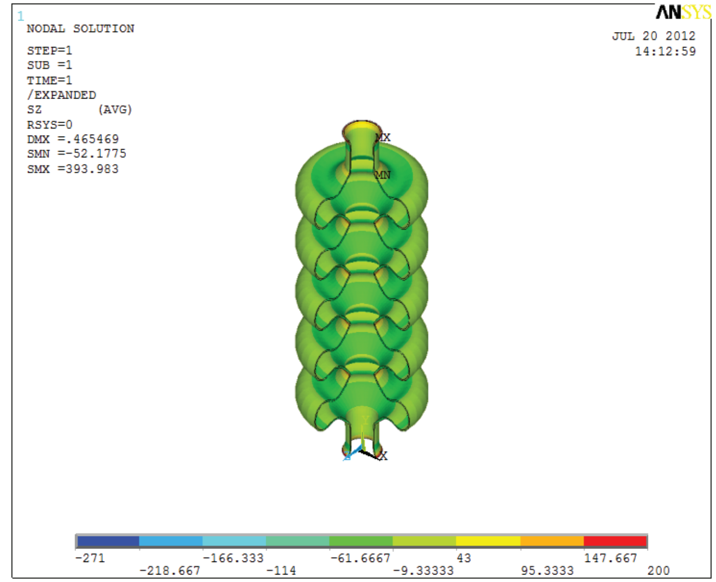
Element: Plane 183



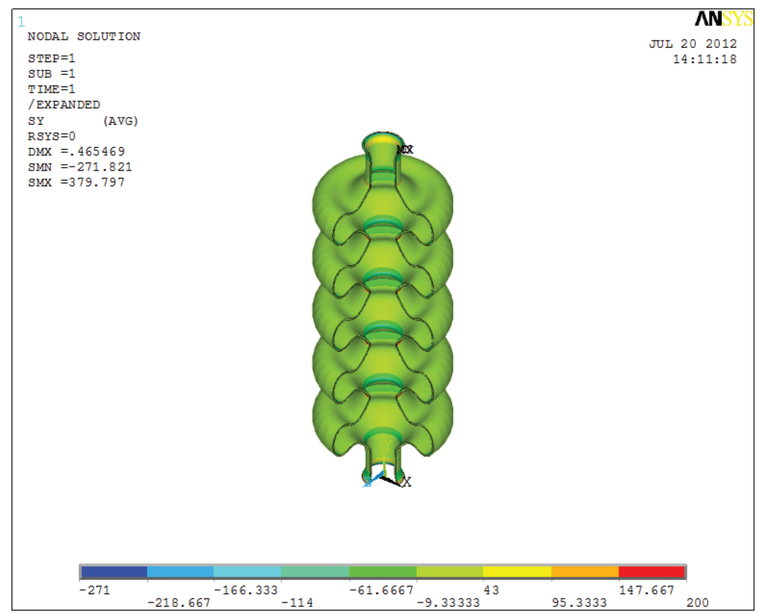
Results :Different Stress Plot



Radial stress



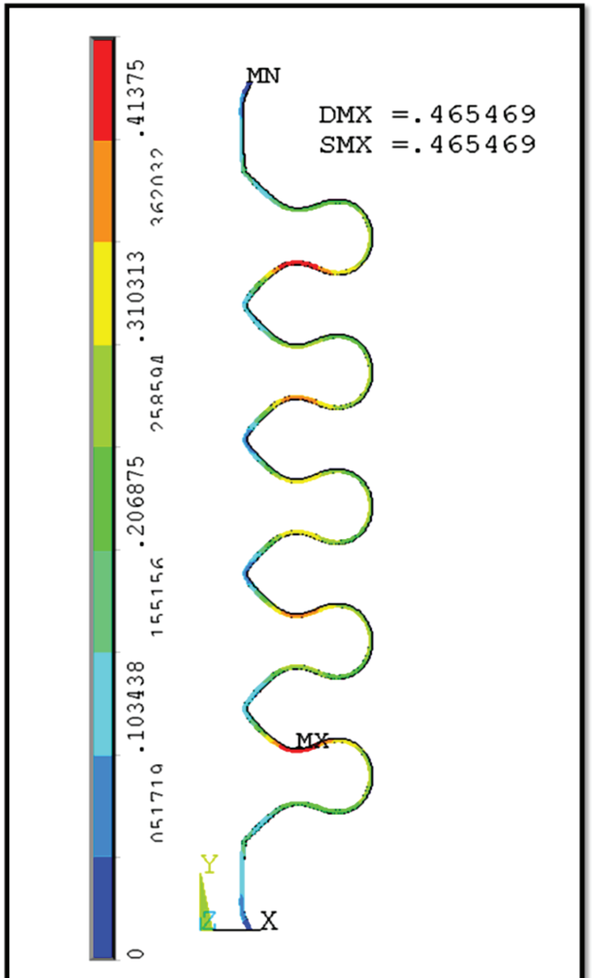
Hoop Stress



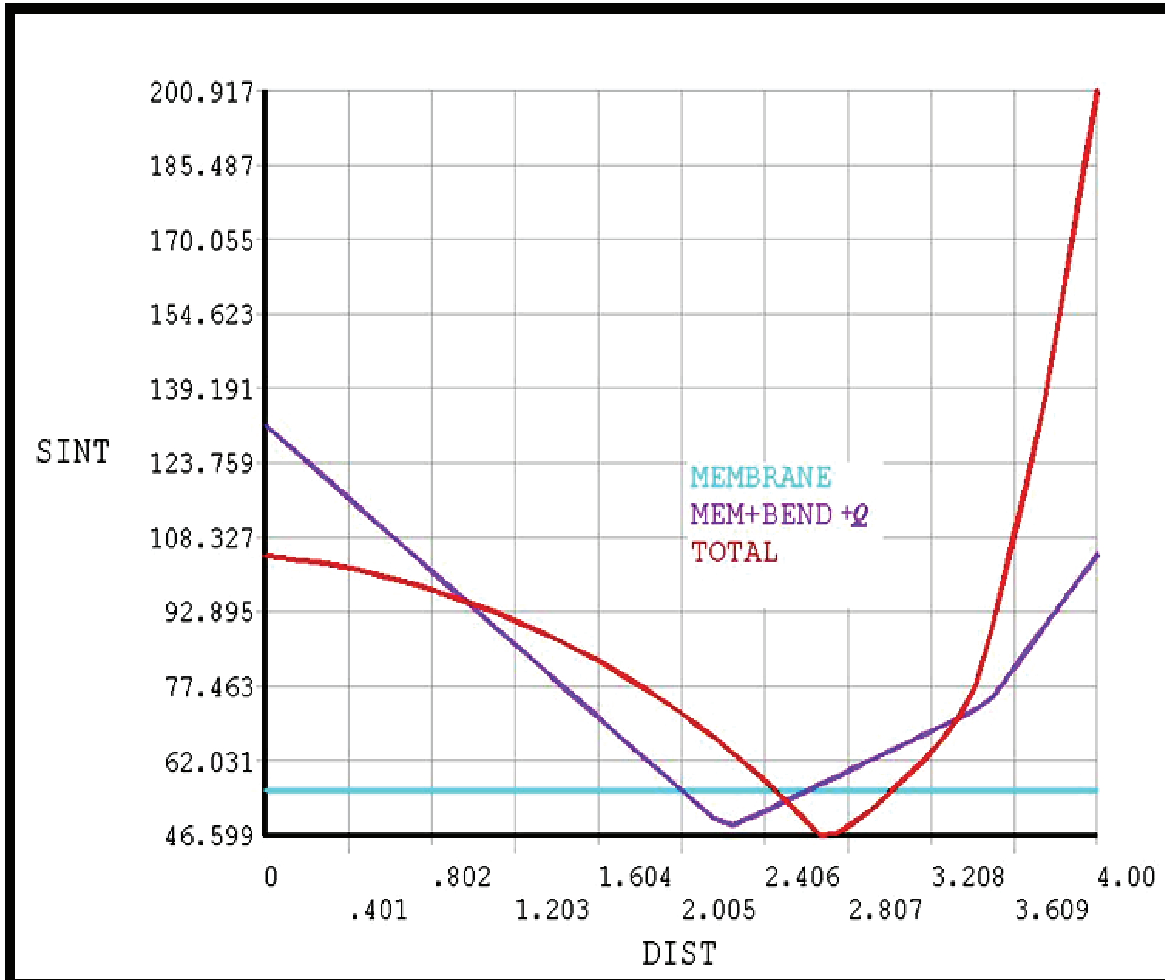
Longitudinal stress

Deformation & Stress comparison

SRF 2013: Paris, France



Deformation Plot



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

Primary Membrane + Bending+ Secondary Stress

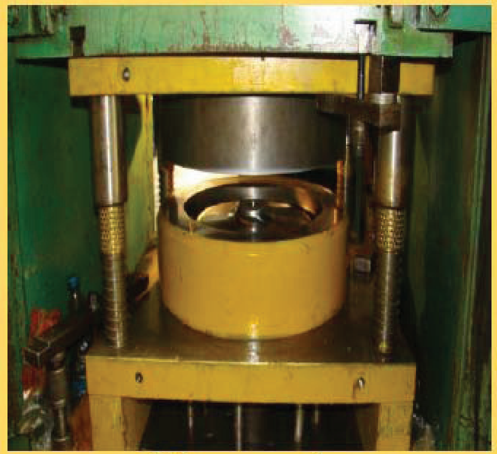
(P_m+P_b+Q < 3Sm)

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

PROTOTYPE CAVITY FABRICATION & CMM MEASUREMENT

- Fabrication of prototype aluminum cavity half-cells for 1-cell & 5-cell (Full scale) done
- Die/Punch assembly developed.
- CMM laser Faro inspection successfully done.
- Low power RF test on half-cell using VNA done & Bead-pull measurement on single-cell cavity is being carried out.

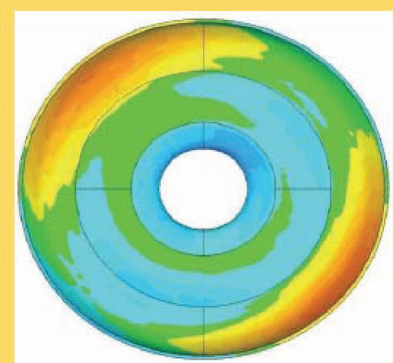
RF Test on Half Cell using VNA

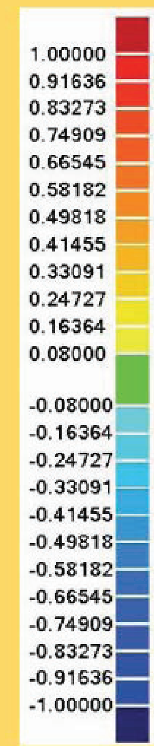


Die-punch

Formed dummy cavity

CMM inspection





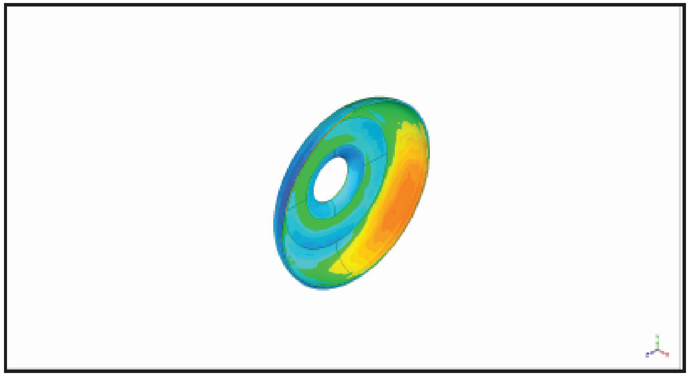
measured deviations

3D Comparison Results

Reference Model	Cavity
Test Model	rf cavity
	models/export.u3d
No. of Data Points	931018
# Outliers	340

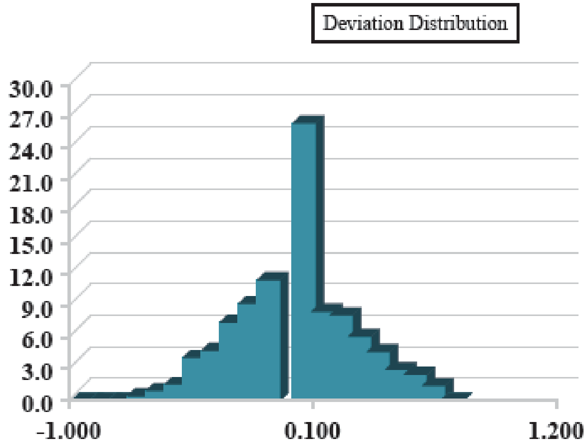
Tolerance Type	3D Deviation
Units	mm
Max. Critical	1.00000
Max. Nominal	0.08000
Min. Nominal	-0.08000
Min. Critical	-1.00000

Deviation	
Max. Upper Dev.	0.72803
Max. Lower Dev.	-1.16984
Average Deviation	0.21875 /-0.20639
Standard Deviation	0.26688



Deviation Distribution

>=Min	<Max	# Points	%
-1.00000	-0.91636	2	0.00021
-0.91636	-0.83273	24	0.00258
-0.83273	-0.74909	105	0.01128
-0.74909	-0.66545	3700	0.39741
-0.66545	-0.58182	8303	0.89182
-0.58182	-0.49818	13964	1.49986
-0.49818	-0.41455	37864	4.06695
-0.41455	-0.33091	44072	4.73374
-0.33091	-0.24727	69118	7.42392
-0.24727	-0.16364	85585	9.19263
-0.16364	-0.08000	106685	11.45896
-0.08000	0.08000	245775	26.39852
0.08000	0.16364	78602	8.44259
0.16364	0.24727	75330	8.09114
0.24727	0.33091	56466	6.06497
0.33091	0.41455	42797	4.59680
0.41455	0.49818	26980	2.89790
0.49818	0.58182	22668	2.43475
0.58182	0.66545	12844	1.37957



2D Comparison Results

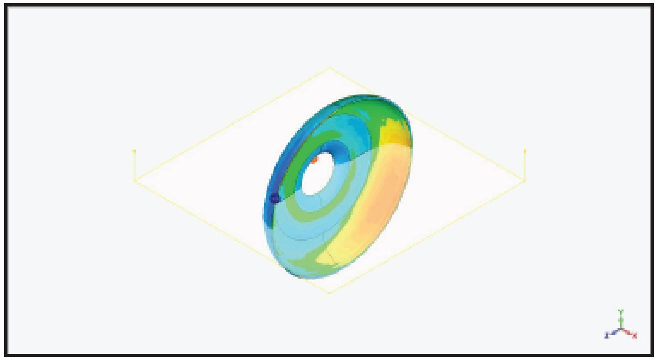
CSYS: World CSYS

Reference Model	Cavity
Test Model	rf cavity
	models/export.u3d

Name	2D Comparison 4
Location	Y = 1264.90521 mm
No. of Data Points	642

Units	mm
Max. Critical	1.00000
Max. Nominal	0.08000
Min. Nominal	-0.08000
Min. Critical	-1.00000

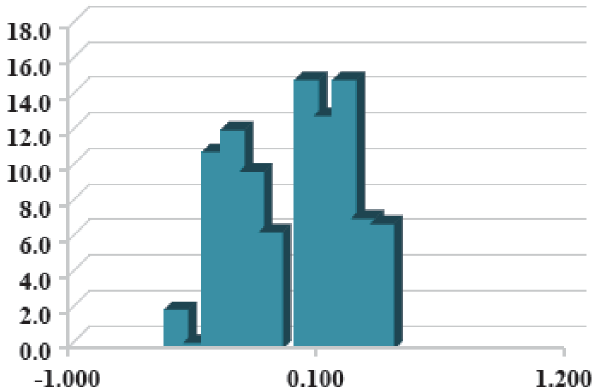
Deviation	
Max Dev +	0.38653
Max Dev -	-0.53125
Standard Deviation	0.24558



Percentage Deviations

>=Min	<Max	# Points	%
-1.00000	-0.91636	0	0.00000
-0.91636	-0.83273	0	0.00000
-0.83273	-0.74909	0	0.00000
-0.74909	-0.66545	0	0.00000
-0.66545	-0.58182	0	0.00000
-0.58182	-0.49818	14	2.18069
-0.49818	-0.41455	2	0.31153
-0.41455	-0.33091	71	11.05919
-0.33091	-0.24727	79	12.30530
-0.24727	-0.16364	64	9.96885
-0.16364	-0.08000	42	6.54206

Deviation Distribution



SCRF CAVITY MATERIAL - PURE NIOBIUM

- Niobium is the elemental superconductor with highest T_c (9.25 K) and H_c (190 mT)
- Formability like OFHC Copper
- Readily available in different grades of purity (RRR > 300)

- High affinity to interstitial impurities like H,C,N,O (in Air T<150 ºC)
- Joining by EB welding Technique
- Hydrogen can readily be absorbed – lead to Q degradation in cavities

SCRF CAVITY MATERIAL - PURE NIOBIUM

- $RRR = R(300)/[R(10) + \sum \delta R_i/\delta C_i]$

- $\delta R_i/\delta C_i$: Contributions by interstitial impurities
- H: 0.8×10^{-10} Ω-Cm/wt. ppm
- C: 4.3 x 10-10 Ω-Cm/wt. ppm
- N: 5.2 x 10-10 Ω-Cm/wt. ppm
- O: 4.5 x 10-10 Ω-Cm/wt. ppm
- Ta: 0.25 x 10-10 Ω-Cm/wt. ppm

*** K. Schulze, Journal of Metals 33 (1981)*

Some Manufacturers in the world:
Wah Chang (USA), Cabot (USA),
Tokyo Denkai (Japan),
Heraeus (Germany),
Ningxia (China),
CBMM (Brazil).

Typical Specification for impurities (Wt. ppm):

H < 2

C < 10

N < 10

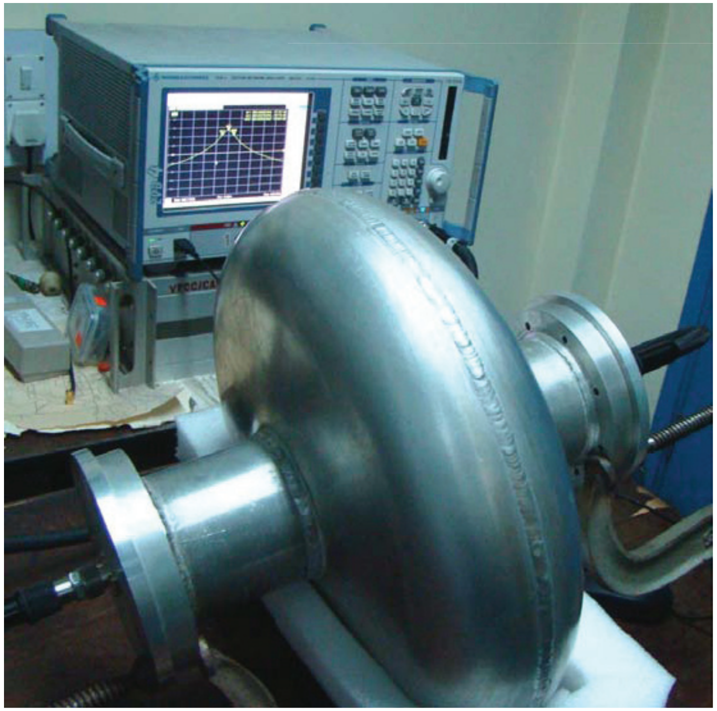
O < 10

Ta < 500

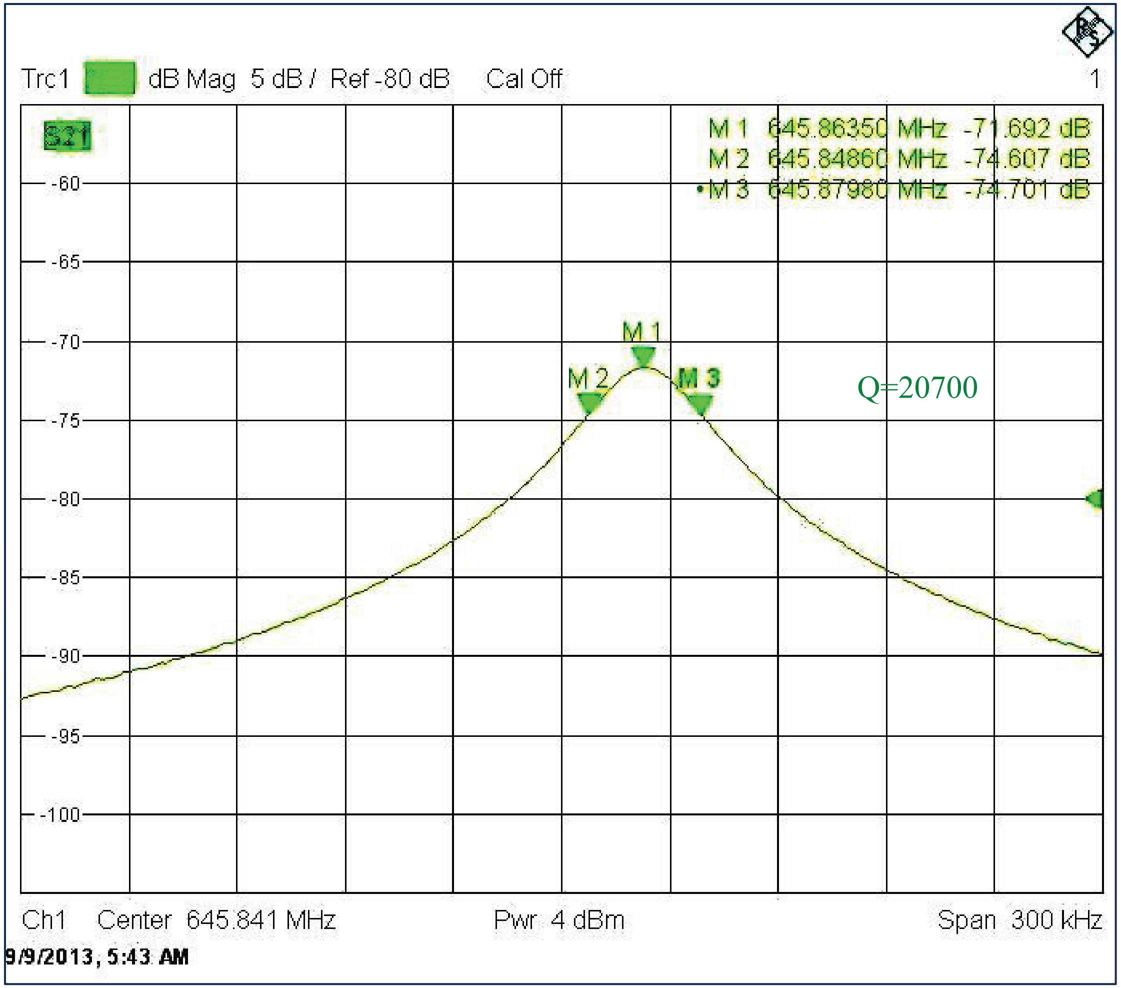
- RRR > 250
- Grain Size: 50 μm
- Yield strength > 50 MPa
- Tensile Strength > 100 MPa
- Elongation > 30%
- VH < 50
- Thermal Conductivity (4.2k):

  λ (4.2k) ~ RRR /4

Single cell prototype cavity-- VNA measurement



Resonant frequency, f_0 = 645.86350 MHz



Half power (–3dB) Bandwidth,
$\Delta f = f_2 - f_1 = 31.2$ kHz.

[f_1 = 645.84860 MHz;
f_2 = 645.87980 MHz]

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

SUMMARY

- EM design and analysis, Structural analysis, Mechanical modal analysis of the 5-cell 650 MHz, β=0.61, SCRF cavity has been carried out.
- No trapped HOMs with high effective impedance present. So, HOM dampers are NOT required for 1 mA beam current.
- Multipacting analysis carried out with: 2D MultiPact code (No multipacting) and 3D CST Particle Studio code (Multipacting occurs).
- Mechanical modal analysis, preliminary structural analysis of the cavity done.
- Fabrication of die has been done and deep drawing of prototype aluminum half-cell has been carried out by local vendor.
- Single cell prototype cavity measurement with VNA done and Bead-pull measurement is in progress.
- After successful completion of aluminum prototype, fabrication of Niobium cavity will start with available niobium sheets.
- 600 x 600 x 4 mm. Nb sheet (RRR > 300) already procured from ATI Wah Chang.

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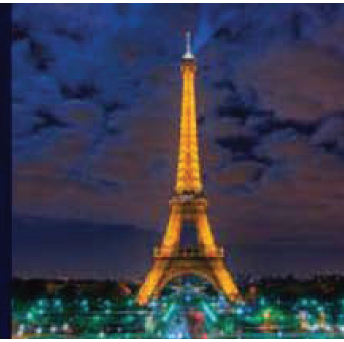

September 23-27, 2013

Cité Internationale Universitaire, PARIS

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धन्यवाद

Thank You

Grazie