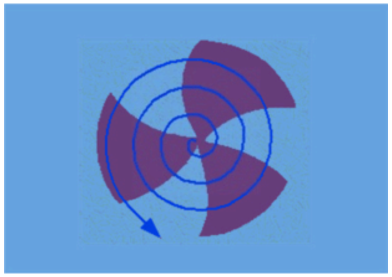
650 MHZ, β=0.61, SCRF CAVITY & ASSOCIATED ACTIVITIES AT VECC

Sumit Som
Head, RF Division

Variable Energy Cyclotron Centre
Kolkata, India



Presented in IIFC meeting at Fermilab on April 08, 2011

OUTLINE OF THIS TALK

- MOTIVATION FOR SCRF ACTIVITIES
- SCRF CAVITY DESIGN
- PROTOTYPE COPPER CAVITY AND ITS RF CHARACTERIZATION
- ELLIPTICAL CAVITY SIMULATION FOR 650 MHz, β=0.61
- TEST CRYOSTAT DESIGN
- ACTIVITIES ON HIGH POWER RF SOURCE, ASSOCIATED DC POWER SUPPLIES & LOW-LEVEL CONTROLS

MOTIVATION FOR SCRF CAVITY ACTIVITIES

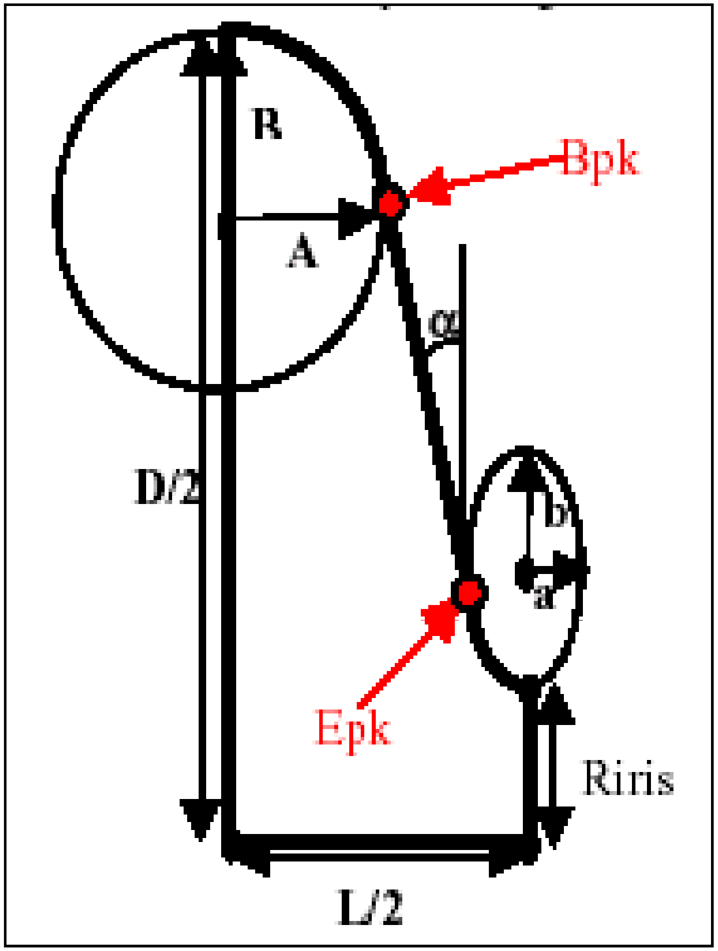
- In view of vast thorium resources in India, the concept of Accelerator Driven Subcritical System (ADSS) gained momentum – more nuclear power generation

- ADSS : high energy (~ 1 GeV), high current (>10 mA) proton beam hits the target of heavy element (such as Th, Pu or U etc.), spallation neutron is produced. Spallation target is surrounded by a blanket assembly of nuclear fuel (such as ${}_{90}Th^{232}$, a fissile isotope) which breeds to ${}_{92}U^{233}$ and sustaining fission chain reaction takes place.

- XI Plan period: Govt. has been funding for the project on "Design, Analysis and Development of multi-cell SCRF Linac Cavity" at VECC, Kolkata

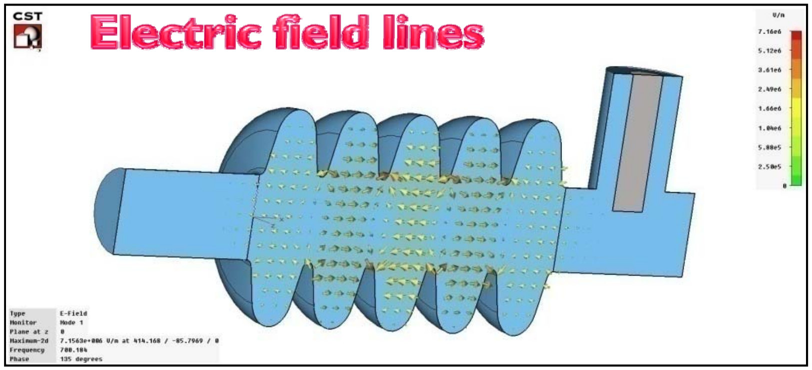
DESIGN CRITERIA FOR ELLIPTICAL CAVITY

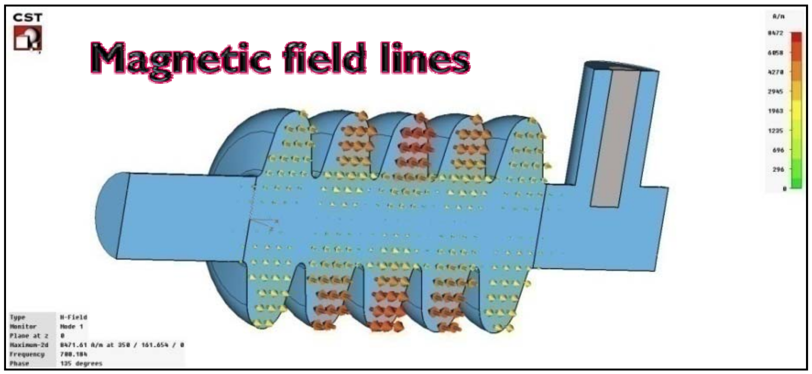
- **Elliptical structures with $\beta<0.5$ are inefficient, because of filling and transit time factors**
- **For cavity inner cell design,**
  - **Minimize E_{pk} & B_{pk}**
  - **Contradictory requirement**
  - **Provide reasonable mechanical stiffness**
  - **Maximize R/Q**
  - **Achieve a reasonable inter-cell coupling coefficient**



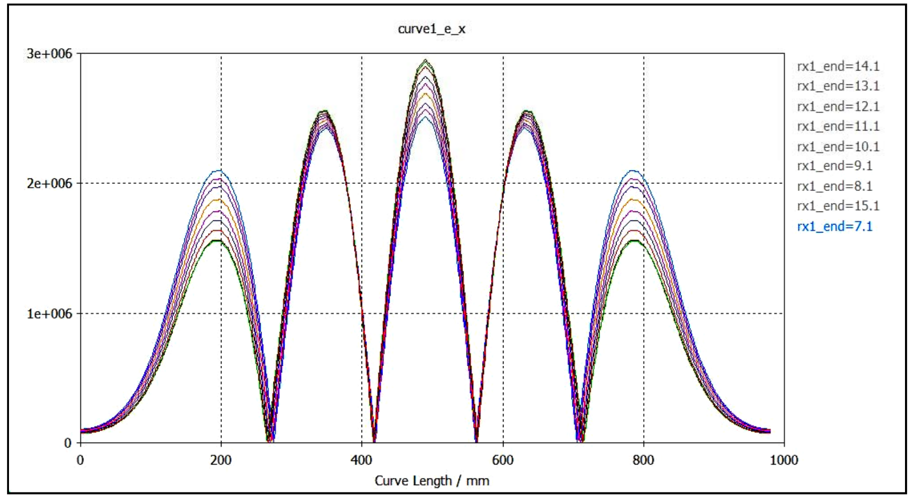
Cavity Shape Parametrization

ANALYSIS WITH CST MICROWAVE STUDIO

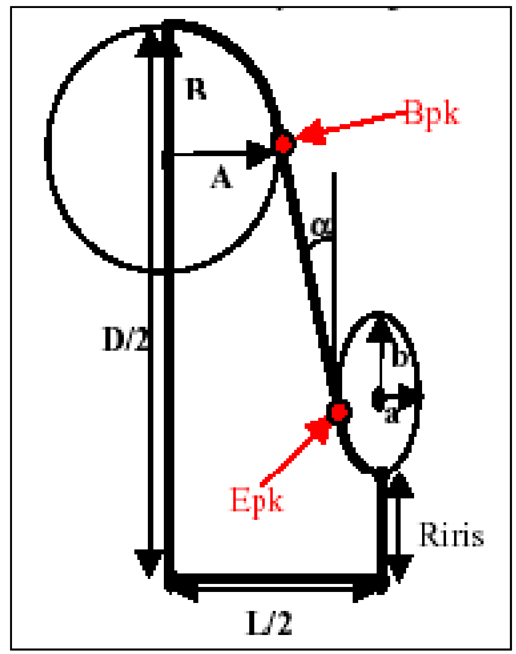




E-field profile along the axis



Frequency:
704.4 MHz



- **Length of a half-cell of the cavity =L/2 =70 mm.**
- **Iris radius = R_{iris} = 50.4 mm.**
- **Dome (equator) radius = D/2 = 188.2mm.**
- **Equator ellipse ratio = A/B = 45 mm/47 mm.**
- **Iris ellipse ratio = a/b = 12.5 mm/15 mm.**

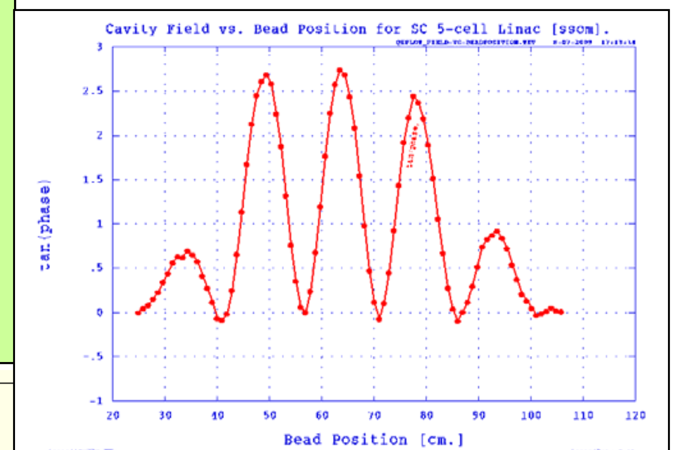
Bead-pull measurement :
Using Phase-shift technique instead of frequency-shift

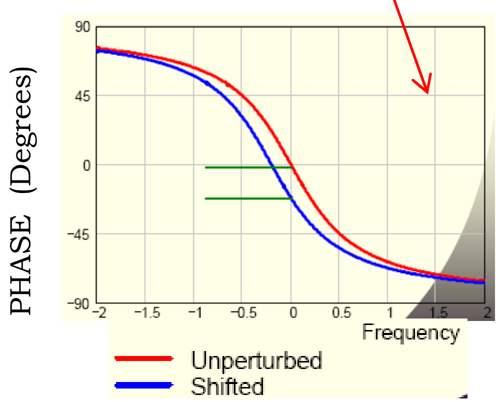
In manufacturing or tuning multi-cell cavity, it is required to investigate the field profile inside the cavity

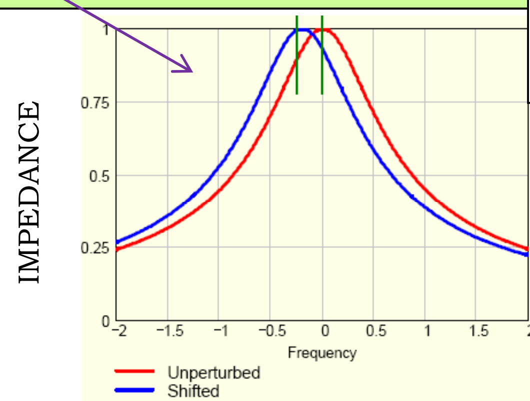
The Field can be sampled by introducing a perturbing object and measuring its change in f_0

The object must be very small so that the field does not vary significantly over its largest linear dimension: it is a perturbation method

Phase deviation is much easier to observe than frequency change especially for small perturbation.



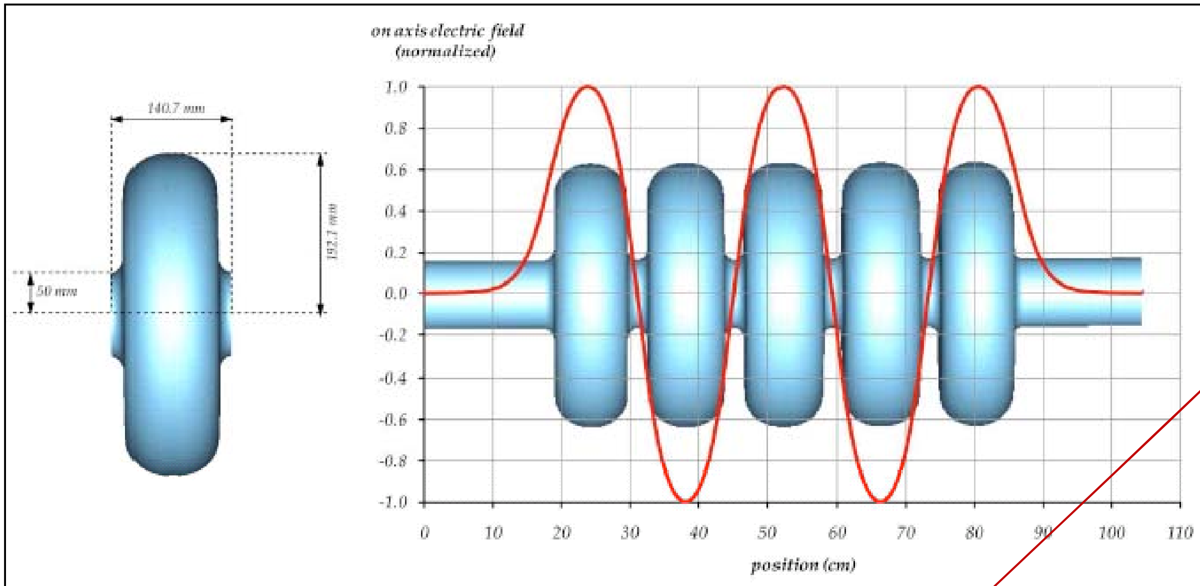




$$\frac{f_p - f_0}{f_0} = \frac{\tan\phi(f_0)}{2Q}$$

(f_p: perturbed frequency)

650 MHz, β=0.61, elliptical cavity simulation



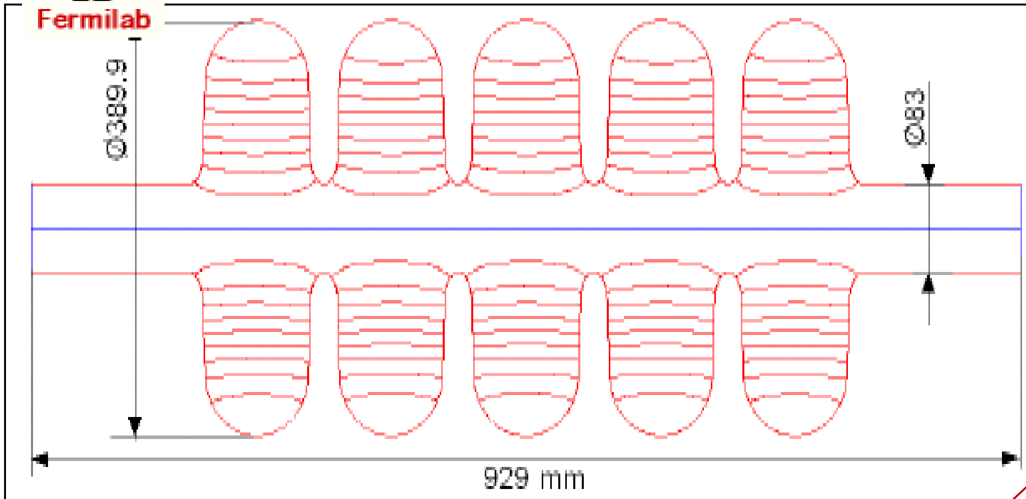
Data:
Provided from JLAB

Results:
Very Close

kc =**1.40%** **(JLAB)**
= 1.37% (VECC)

	$\frac{A}{B}$ 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	$G=Q.R_S$ Ω	E_{acc} MV/m	$\frac{E_p}{E_{acc}}$	$\frac{B_p}{E_{acc}}$	$f_{\pi-mode}$ MHz	Remarks
JLAB Design Result	$\frac{50.46}{45}$	$\frac{15}{22}$	192.1	50	65.456	297	190	17.3	2.71	4.78	650	2D SUPERFISH Equator-flat = 0.976 (mid-cell) 0.5047 (end-cell) α =0 deg Energy=118.8 J
VECC Results on JLAB Design data	$\frac{50.46}{45}$	$\frac{15}{22}$	192.1	50	65.456	297	198.2	17	2.69	4.8	649.38	2D SUPERFISH, 3D CST MWS Equator-flat = 0.976 (mid-cell) 0.5047 (end-cell) α =0 deg Energy=118.8 J Mesh size=0.05

650 MHz, β=0.61, elliptical cavity simulation

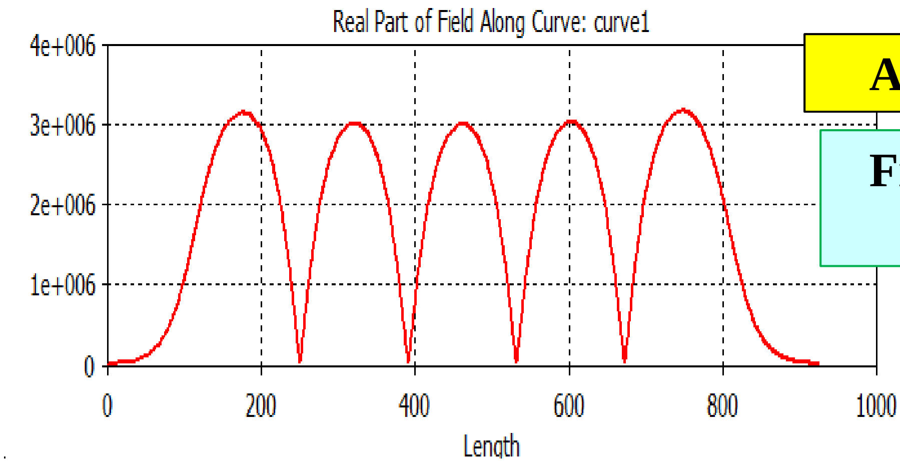


Data: Provided from FERMILAB

Results: Fairly Close

	$\frac{A}{B}$ 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.R_S Ω	E_{acc} MV/m	$\frac{E_p}{E_{acc}}$	$\frac{B_p}{E_{acc}}$	$f_{\pi-mode}$ MHz	Remarks
FERMILAB Design Result	54/58	14/25	194.95	42	70.335	378	191	17	2.26	4.21	650	2D SLANS L/2=71.385 (end-cell) α =2.0 deg (mid) =2.7 deg (end) Energy=92.7 J
VECC Results on FERMILAB Design data	54/58	14/25	194.95	42	70.335	335	239.9	15.91	2.84	5.37	650.72	2D SUPERFISH L/2=71.385 (end-cell) α =2.0 deg (mid) =2.7 deg (end) Energy=92.7 J Mesh size=0.05

650 MHz, β=0.61, elliptical cavity simulation



Accelerating mode

Field flatness: Very good!

Data: Generated by VECC

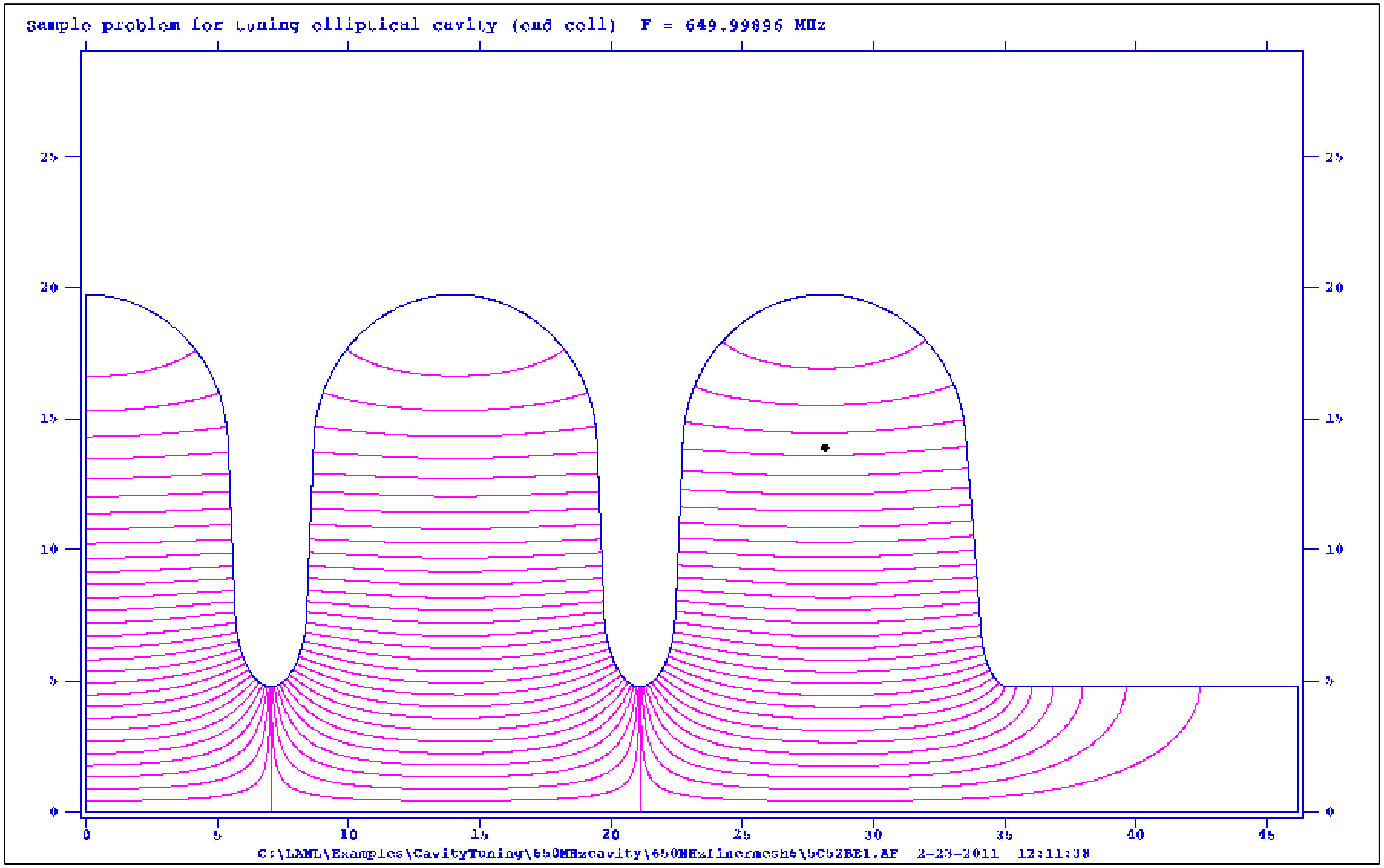
Results: Very good!

kc = 1.24% (Riris=48 mm.)

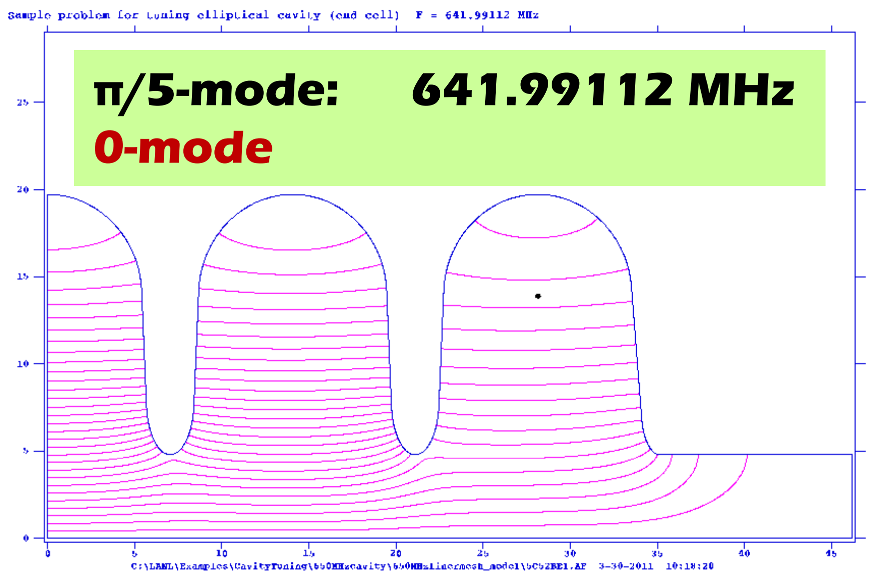
	$\frac{A}{B}$ mm./mm.	$\frac{a}{b}$ mm./mm.	Equator radius D/2 mm.	Iris radius R_{iris} mm.	Half-cell L/2 (inner) mm.	$\frac{R}{Q}$ Ω	G=Q.R_s Ω	E_{acc} MV/m	$\frac{E_p}{E_{acc}}$	$\frac{B_p}{E_{acc}}$	$f_{\pi-mode}$ MHz	Remarks
VECC Design1 Result	$\frac{54}{58}$	$\frac{11.99}{27}$	198.175	48	70.335	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

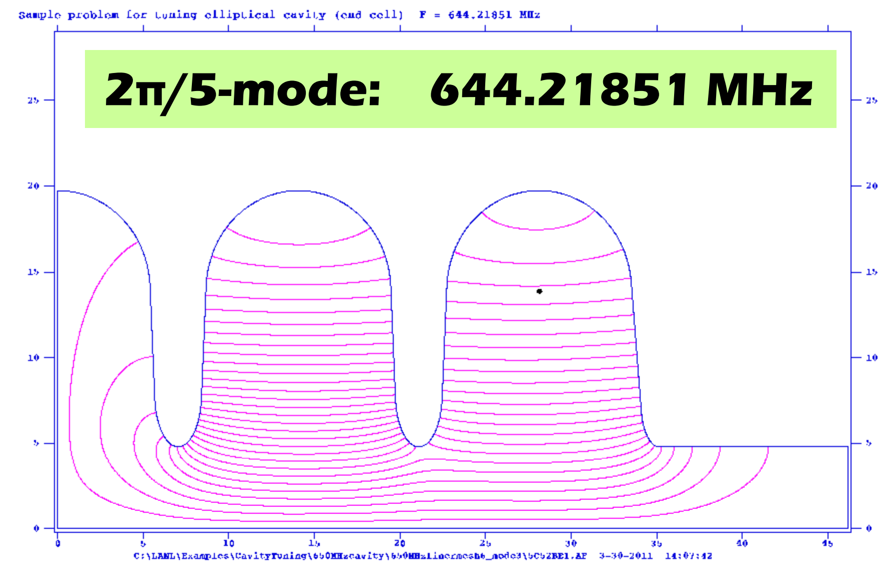
5π/5 or π -mode : 650 MHz

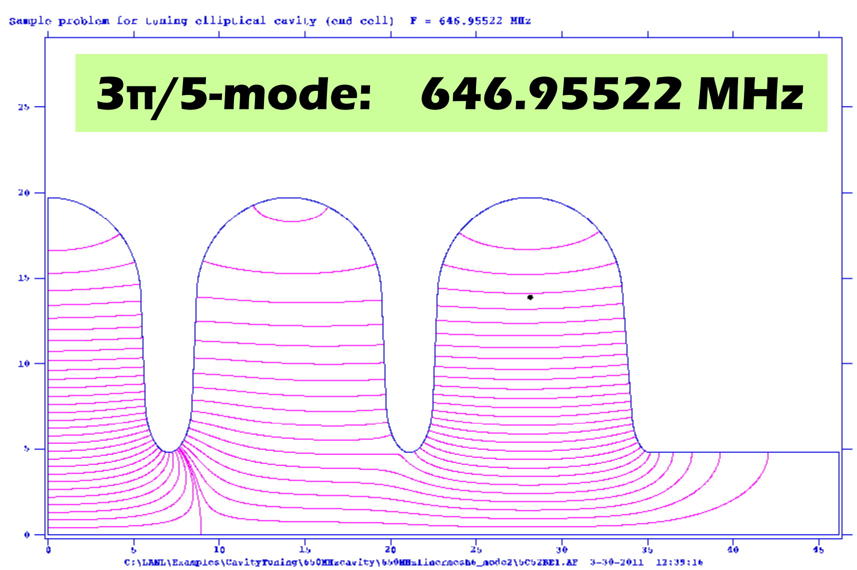
(Accelerating mode – E-field lines)

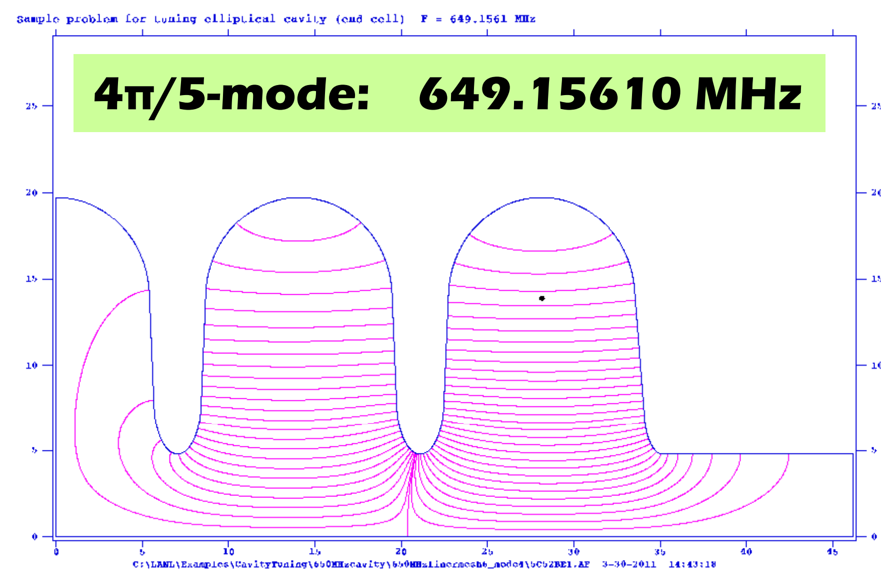


5-cell, 650 MHz, β=0.61, elliptical cavity modes

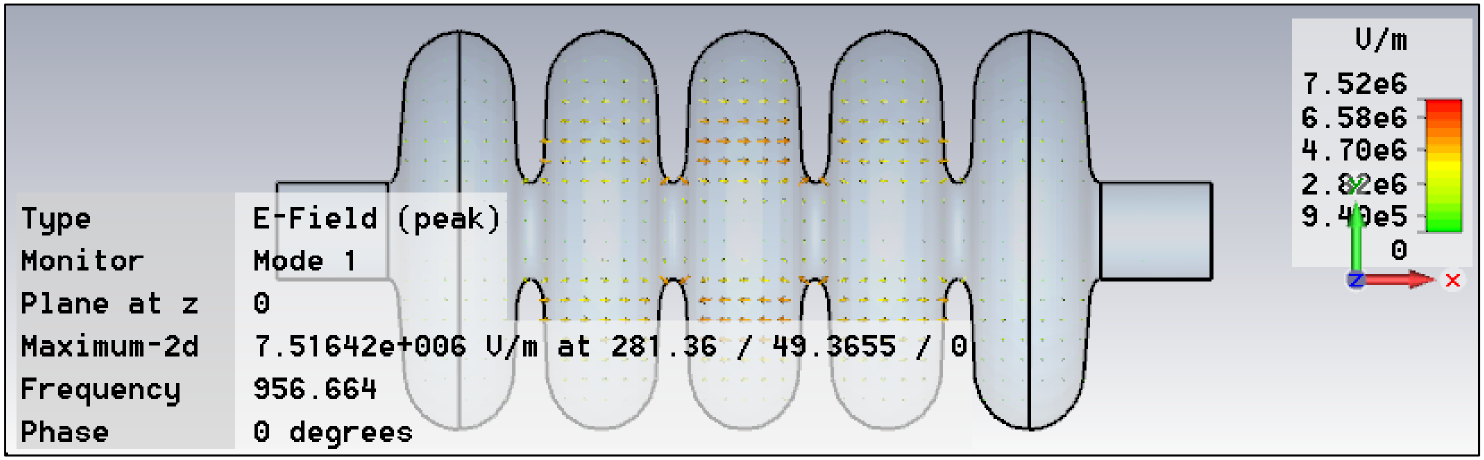


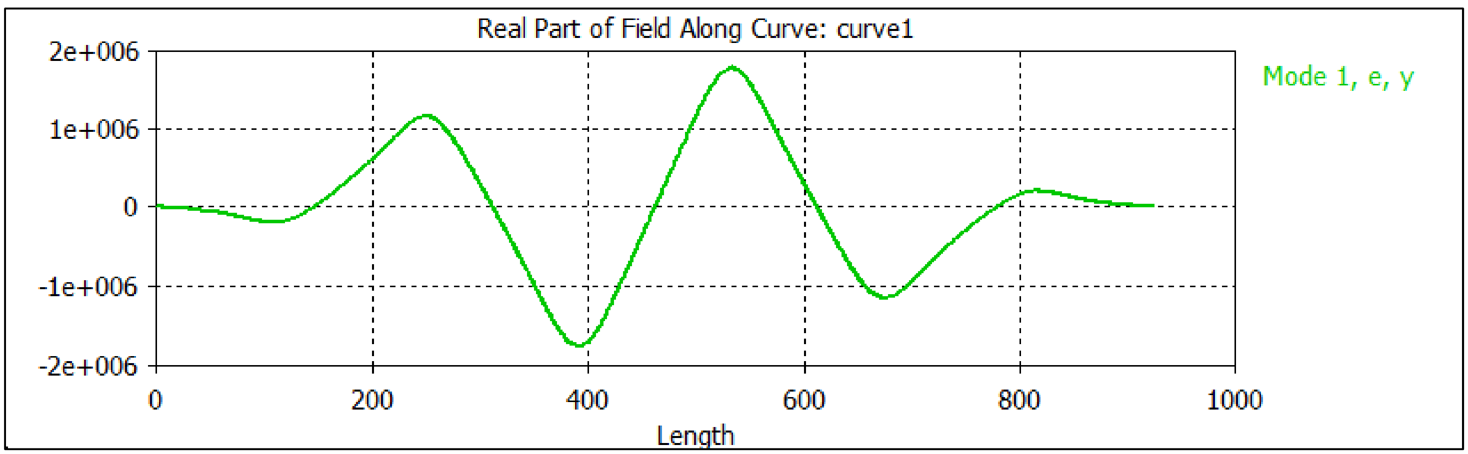






Transverse Higher Order Mode (HOM)



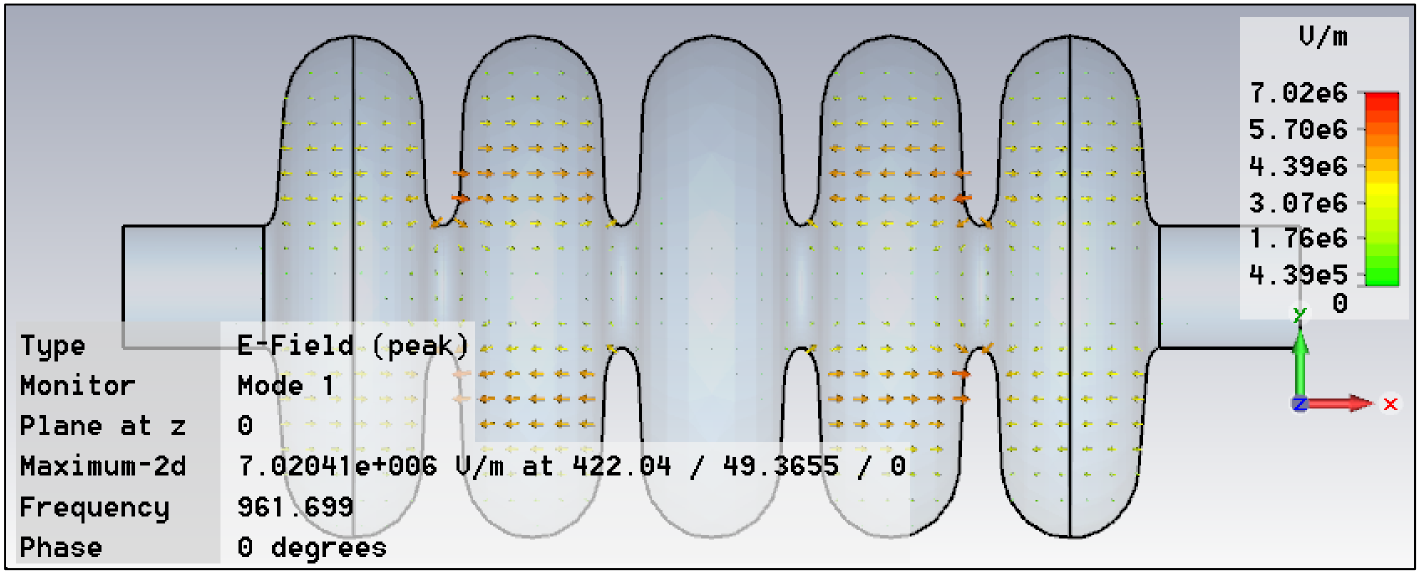


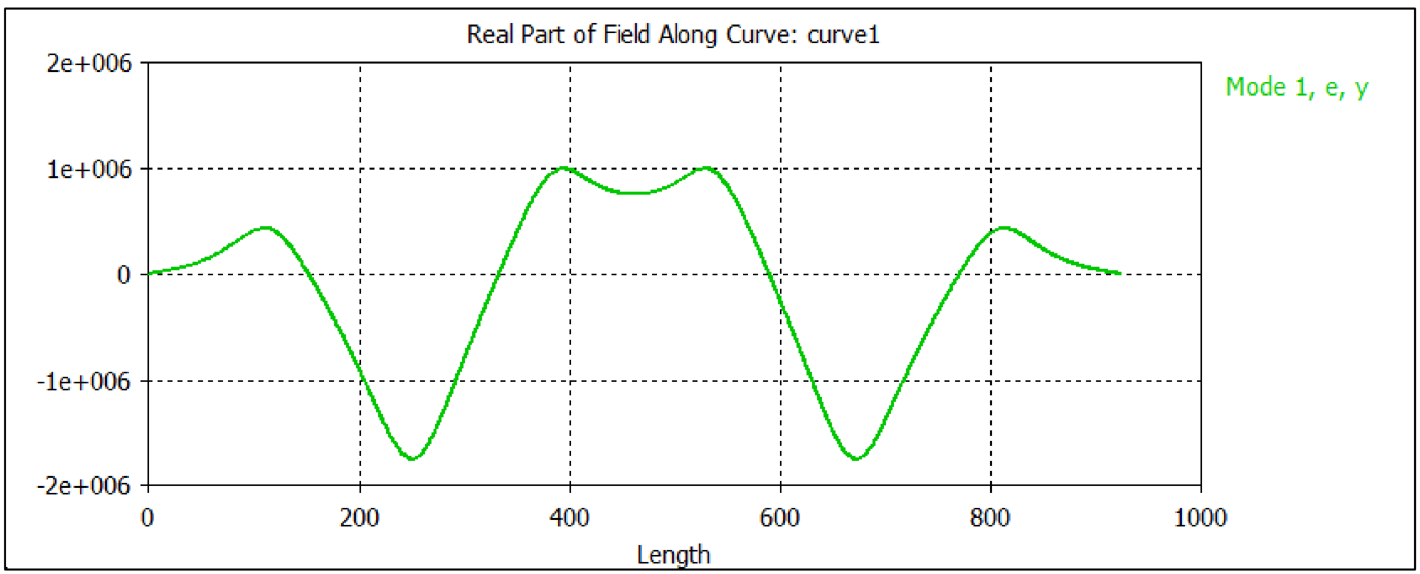
CST MWS RESULTS

Frequency: 956.664 MHz

Effective Transverse impedance: 0.035434 $\Omega.cm^{-2}$

Transverse Higher Order Mode (HOM)





CST MWS RESULTS

Frequency:

961.669

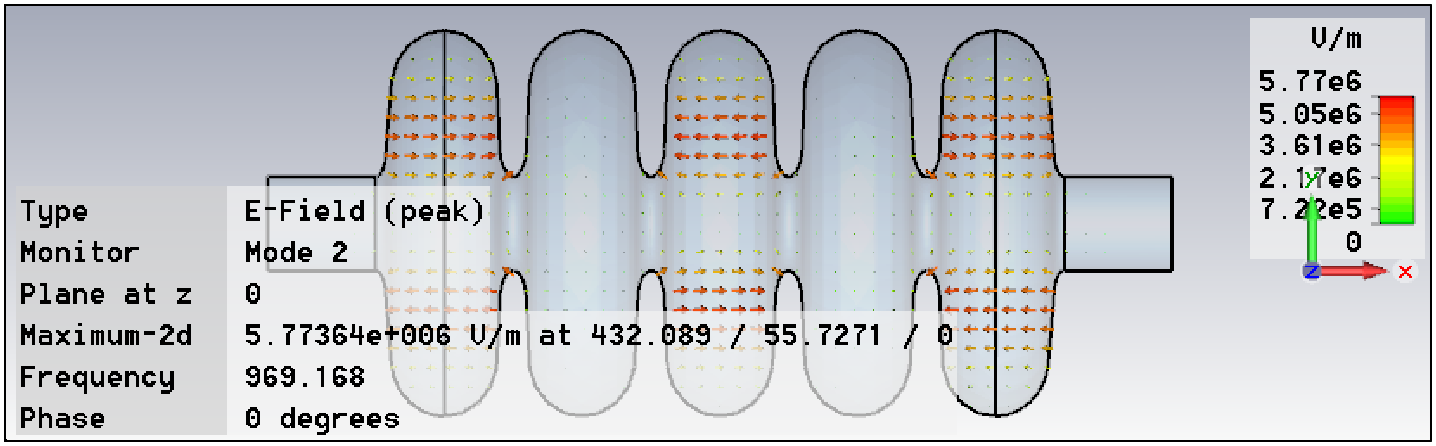
MHz

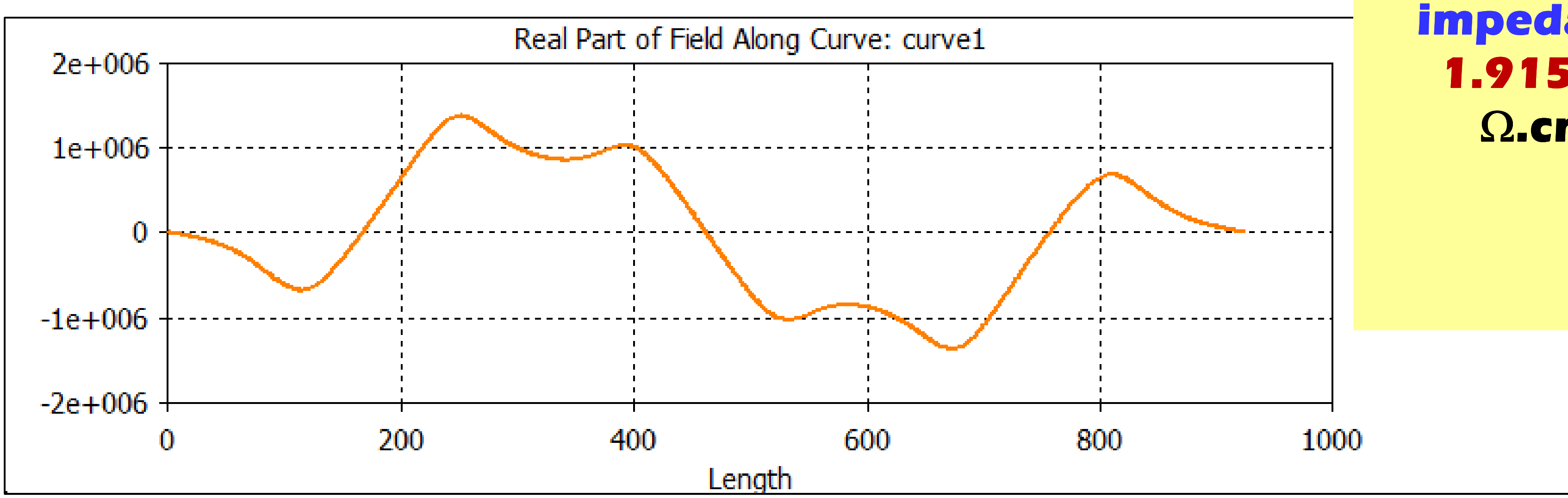
Effective Transverse impedance:

1.02762

Ω.cm^{-2}

Transverse Higher Order Mode (HOM)



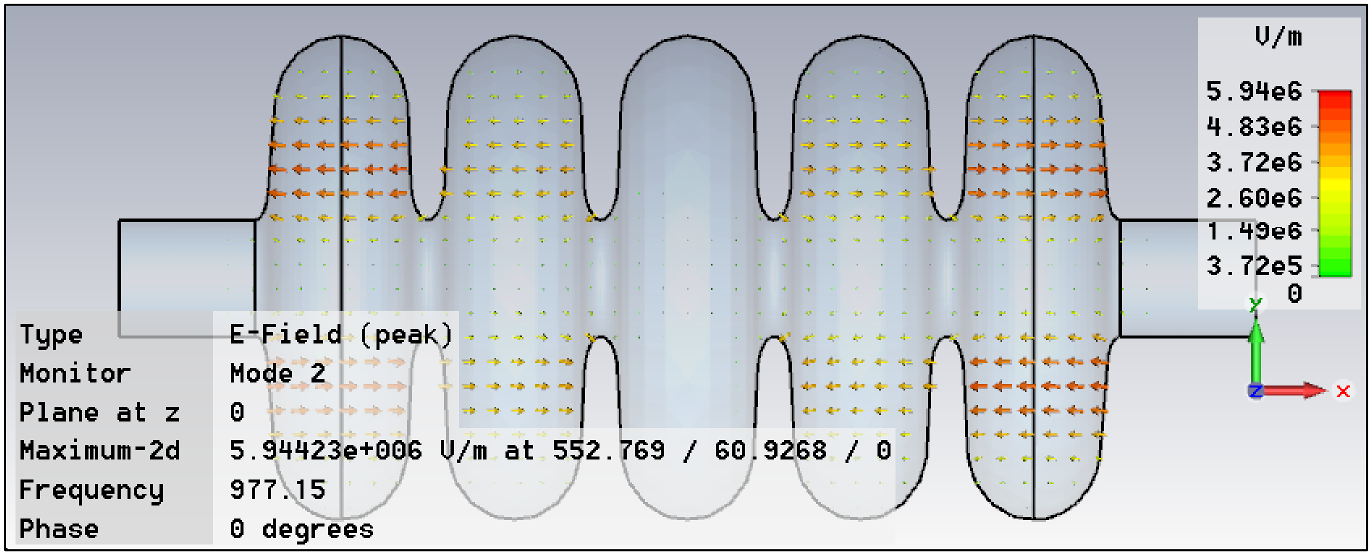


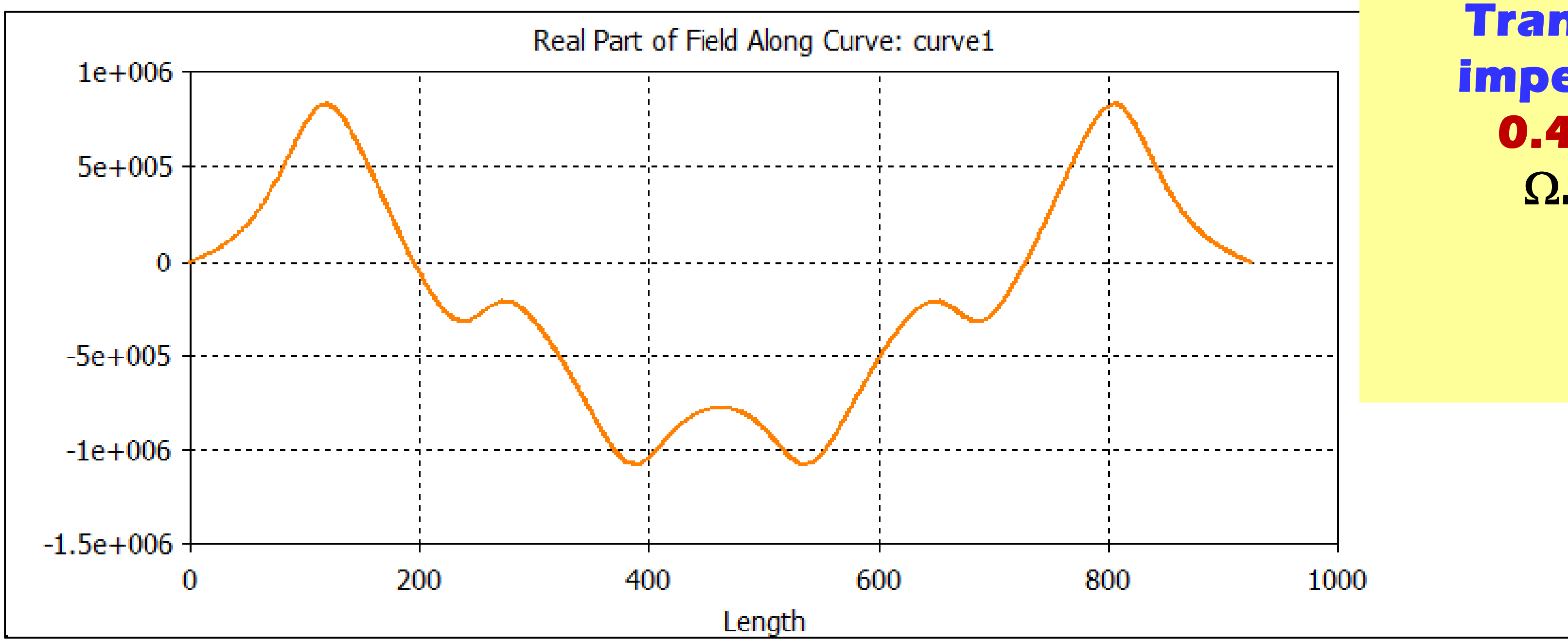
CST MWS RESULTS

Frequency: 969.168 MHz

Effective Transverse impedance: 1.915332 Ω.cm^{-2}

Transverse Higher Order Mode (HOM)



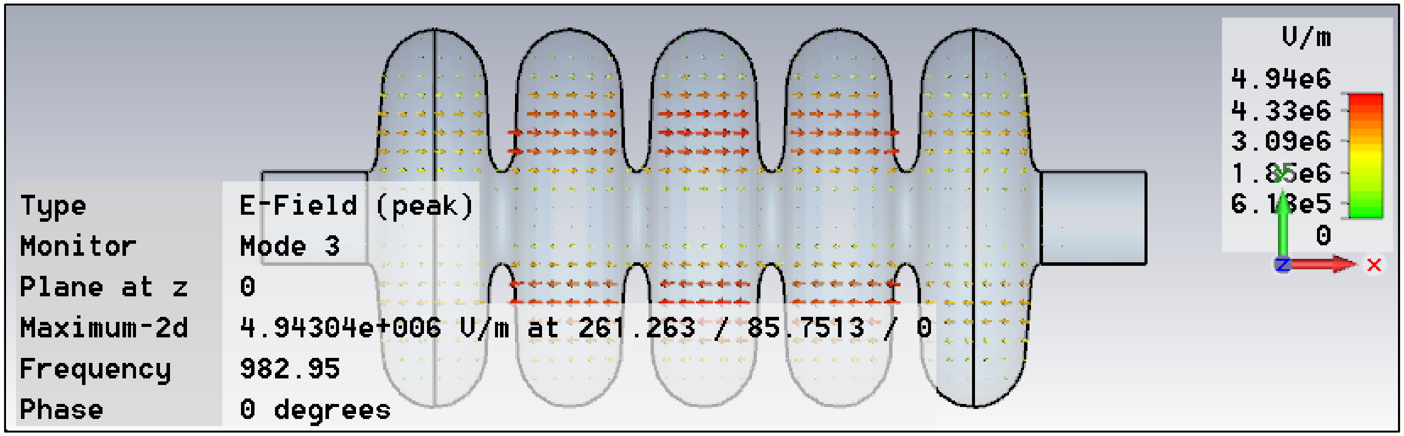


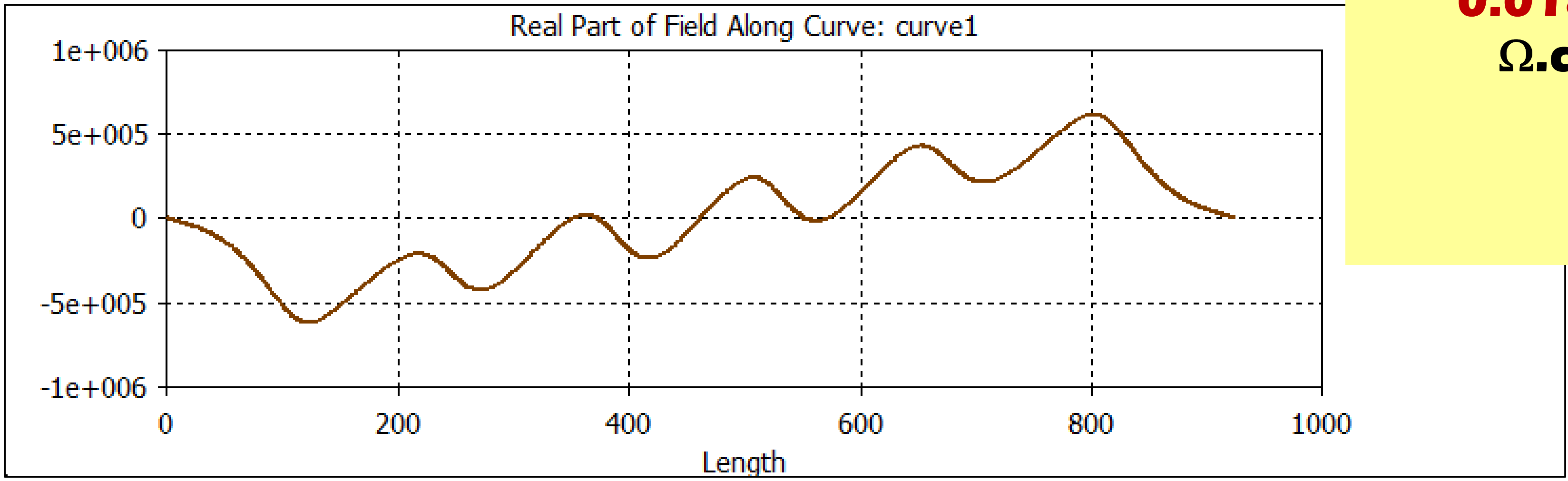
CST MWS RESULTS

Frequency:
977.15
MHz

Effective Transverse impedance:
0.43999
Ω.cm^{-2}

Transverse Higher Order Mode (HOM)

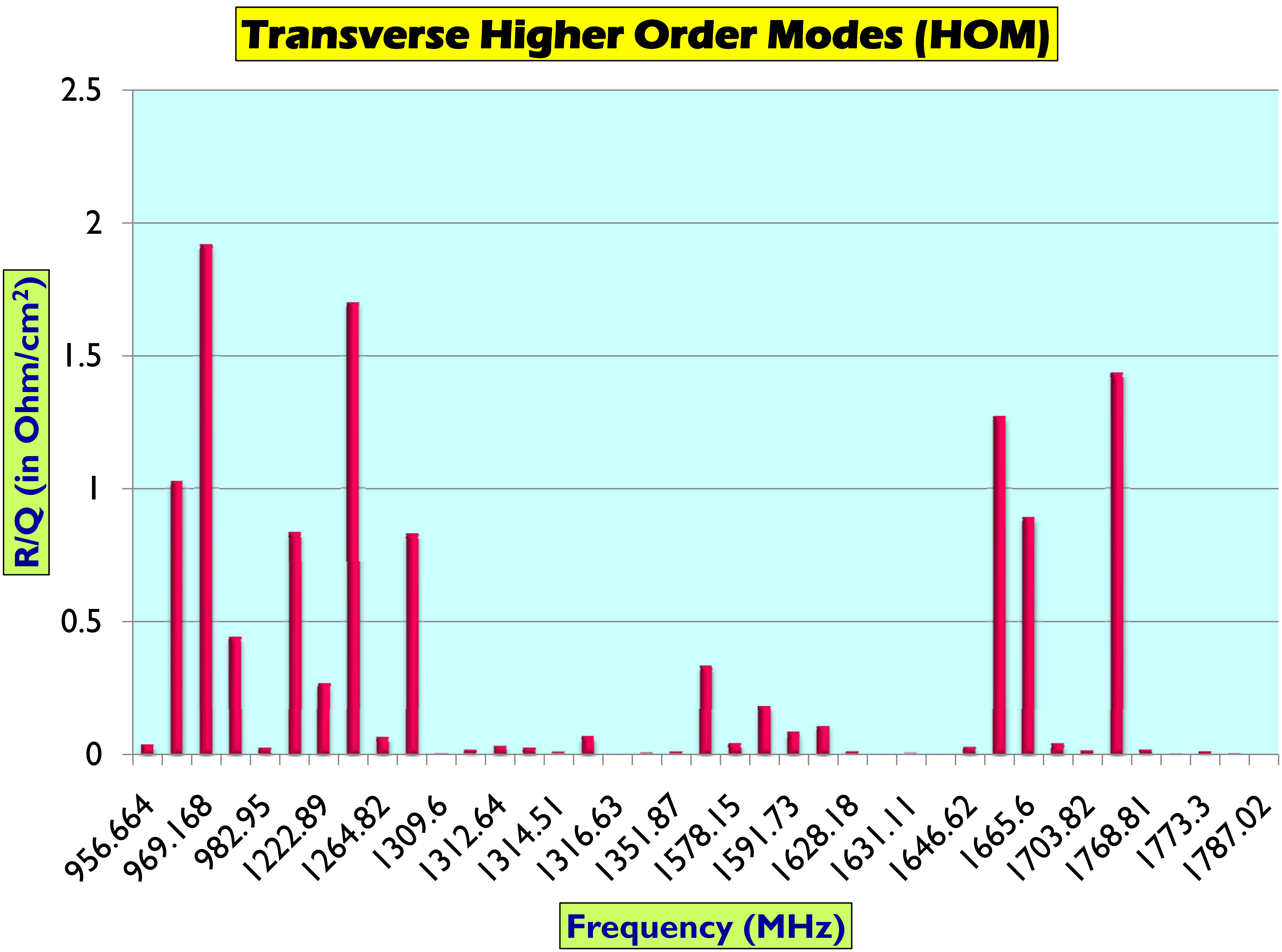




CST MWS RESULTS

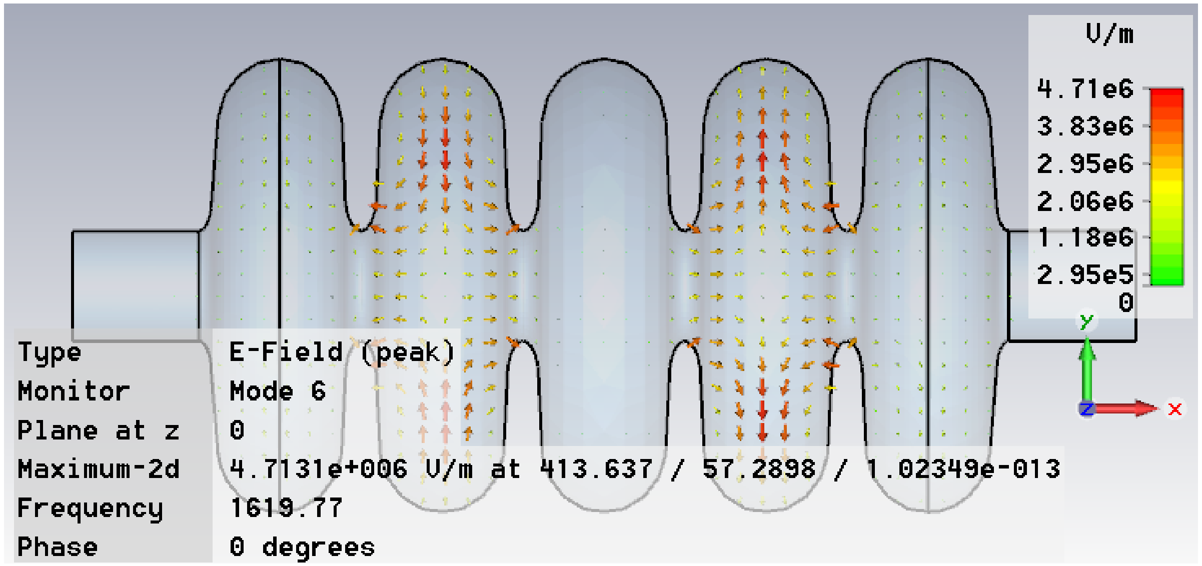
Frequency:
982.95
MHz

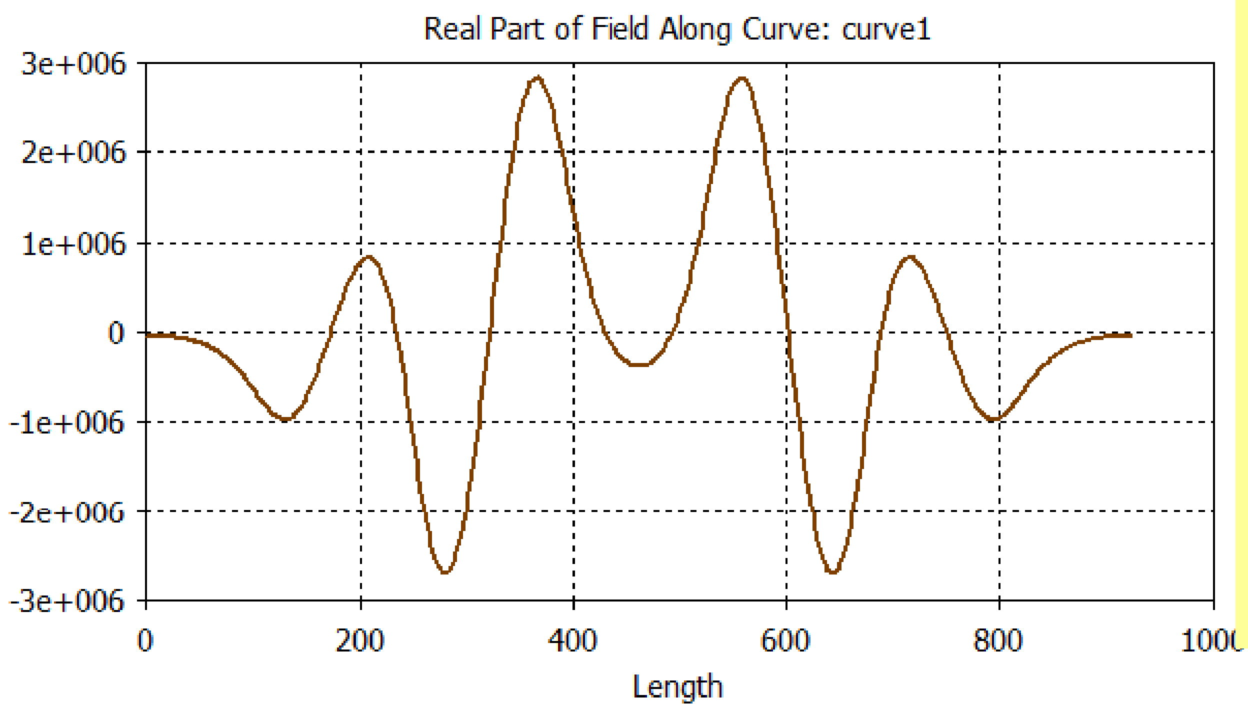
Effective Transverse impedance:
0.018686
Ω.cm^{-2}



Transverse Higher Order Modes (HOM)
R/Q (in Ohm/cm²)
2.5
2
1.5
1
0.5
0
956.664
969.168
982.95
1222.89
1264.82
1309.6
1312.64
1314.51
1316.63
1351.87
1578.15
1591.73
1628.18
1631.11
1646.62
1665.6
1703.82
1768.81
1773.3
1787.02
Frequency (MHz)

Longitudinal Higher Order Mode (HOM)





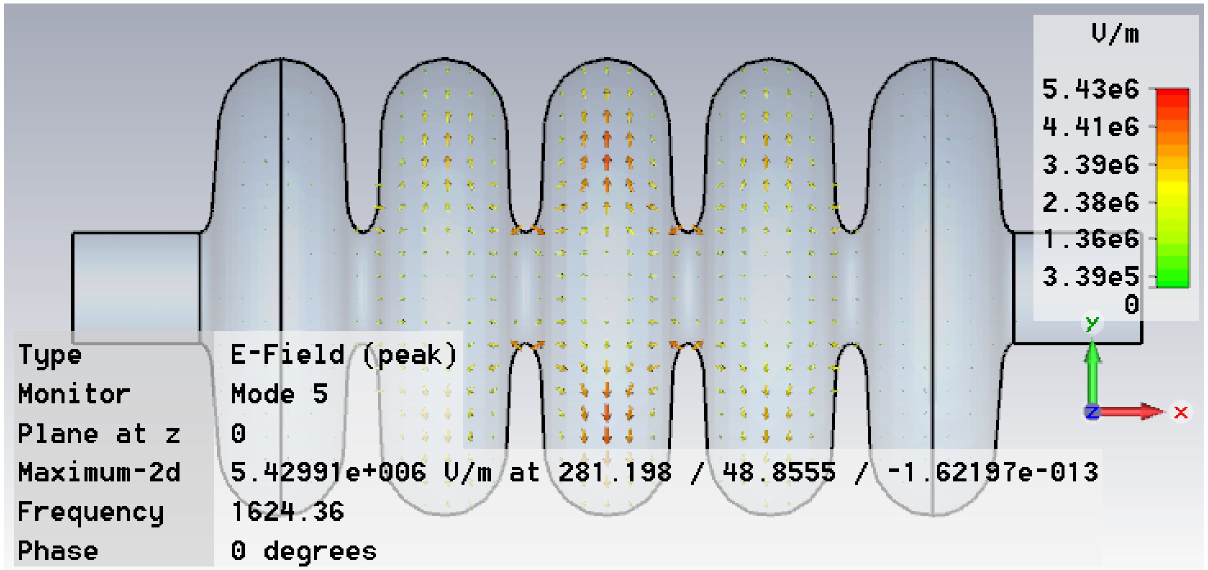
CST MWS RESULTS

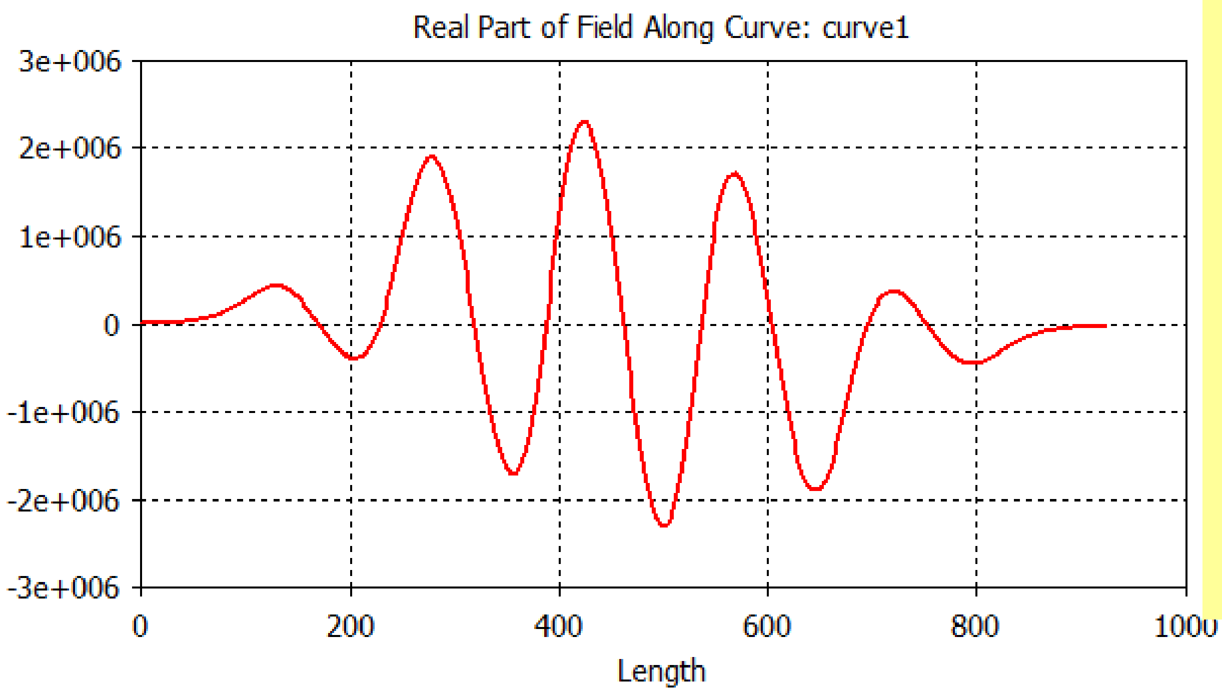
Frequency:
1619.77
MHz

Effective Longitudinal impedance:

1.66 Ω (β=0.61)
0.135 Ω (β=0.75)

Longitudinal Higher Order Mode (HOM)





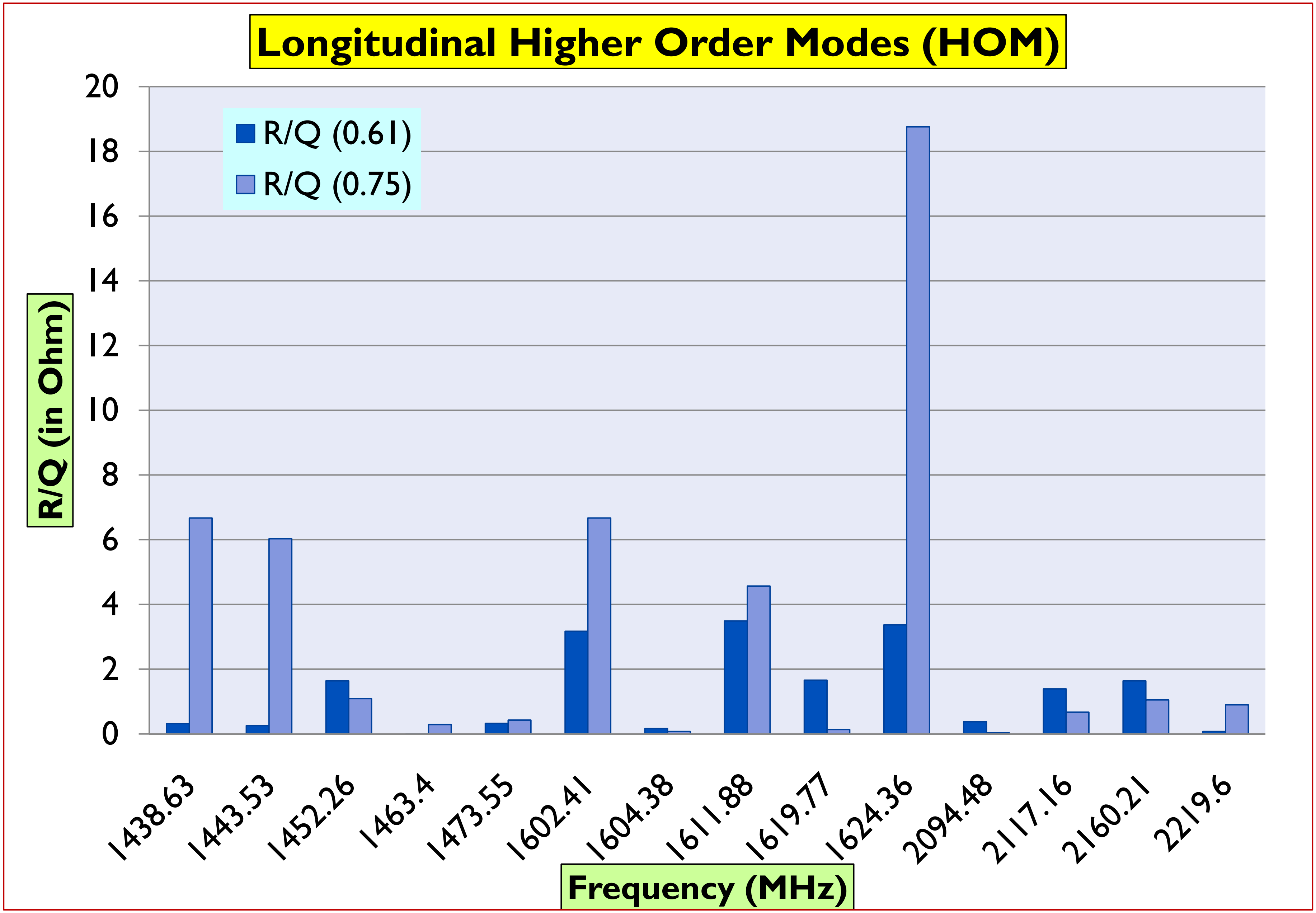
CST MWS RESULTS

Frequency:
1624.36
MHz

Effective Longitudinal impedance:

3.370 Ω (β=0.61)

18.756 Ω (β=0.75)



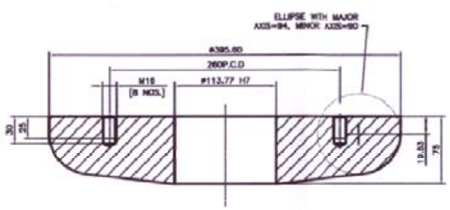
Longitudinal Higher Order Modes (HOM)
R/Q (in Ohm)
20
18
16
14
12
10
8
6
4
2
0
R/Q (0.61)
R/Q (0.75)
1438.63
1443.53
1452.26
1463.4
1473.55
1602.41
1604.38
1611.88
1619.77
1624.36
2094.48
2117.16
2160.21
2219.6
Frequency (MHz)

Longitudinal & Transverse Higher Order Modes (HOMs)

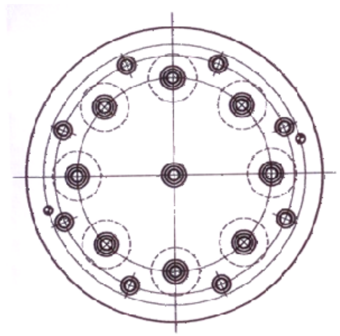
- Transverse and longitudinal HOMs for the cavity at 650 MHz, β=0.61, has been studied.

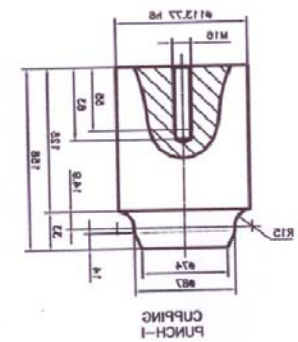
- There is no trapped mode with high effective impedance.

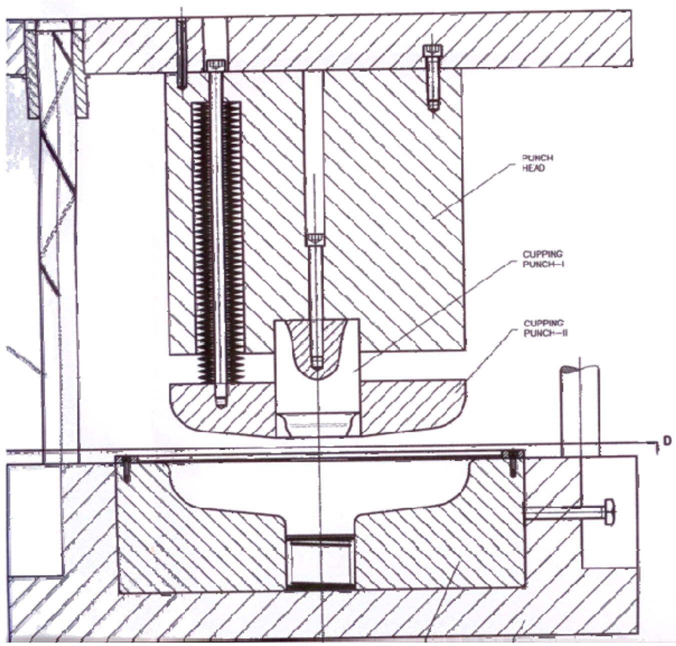
DIE DRAWING FOR HALF-CELL CAVITY

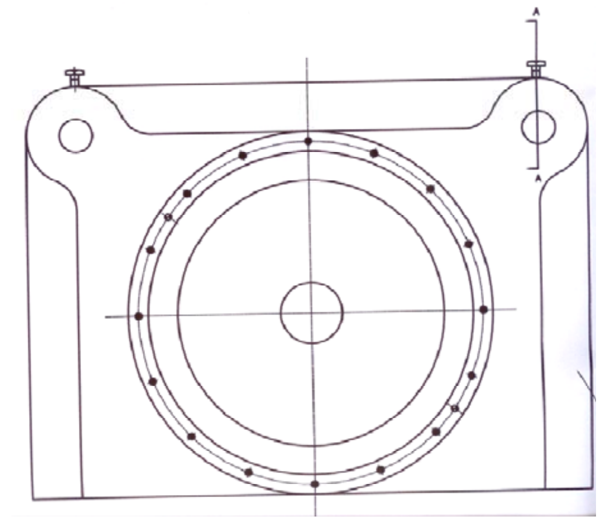


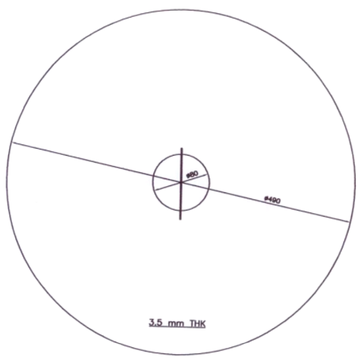
CUPPING PUNCH–II











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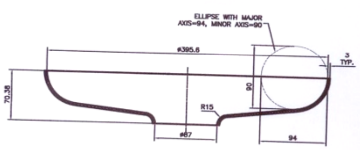
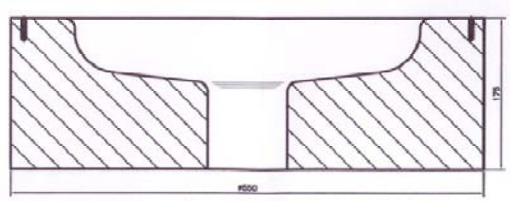
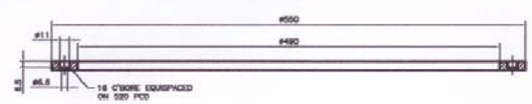


COMPONENT



DIE

DIE CLEARANCE : 3 mm



NIOBIUM SHEET

- Dimension: 600 mm. x 600 mm. x 4 mm.
- Tolerances: ±1.5 mm. x ±1.5 mm. x ±0.125 mm.
- RRR value: 300 or better
- Surface texture: better than 3.175 μm finish
- Surface roughness: better than 1.6 μm
- Deep drawing quality, grain size ASTM#5 or finer, local grain sizes ASTM#4 allowable, min. 90% recrystallized
- Grain size: Typically 50 μm
- Yield strength > 50 N/mm^2
- Tensile strength > 100 N/mm^2
- Elongation > 30%,
- Vicker Hardness < 50 N/mm^2
- ATI Wah Chang, USA.
- Received in March, 2011.

Impurities:

$H_2 \leq 2$ Wt. ppm	W ≤0.007%
C ≤ 10 Wt. ppm	Ti ≤0.005%
$N_2 \leq 10$ Wt. ppm	Fe ≤0.003%
$O_2 \leq 10$ Wt. ppm	Si ≤0.003%
Ta ≤ 500 Wt. ppm	Mo ≤0.005%
	Ni ≤0.003%

DESIGN OF TEST CRYOSTAT

- Overall design has been done for Test Cryostat that can accommodate the 5-cell elliptical shape

  650 MHz, β=0.61 cavity
- Dimension of the Test Cryostat:

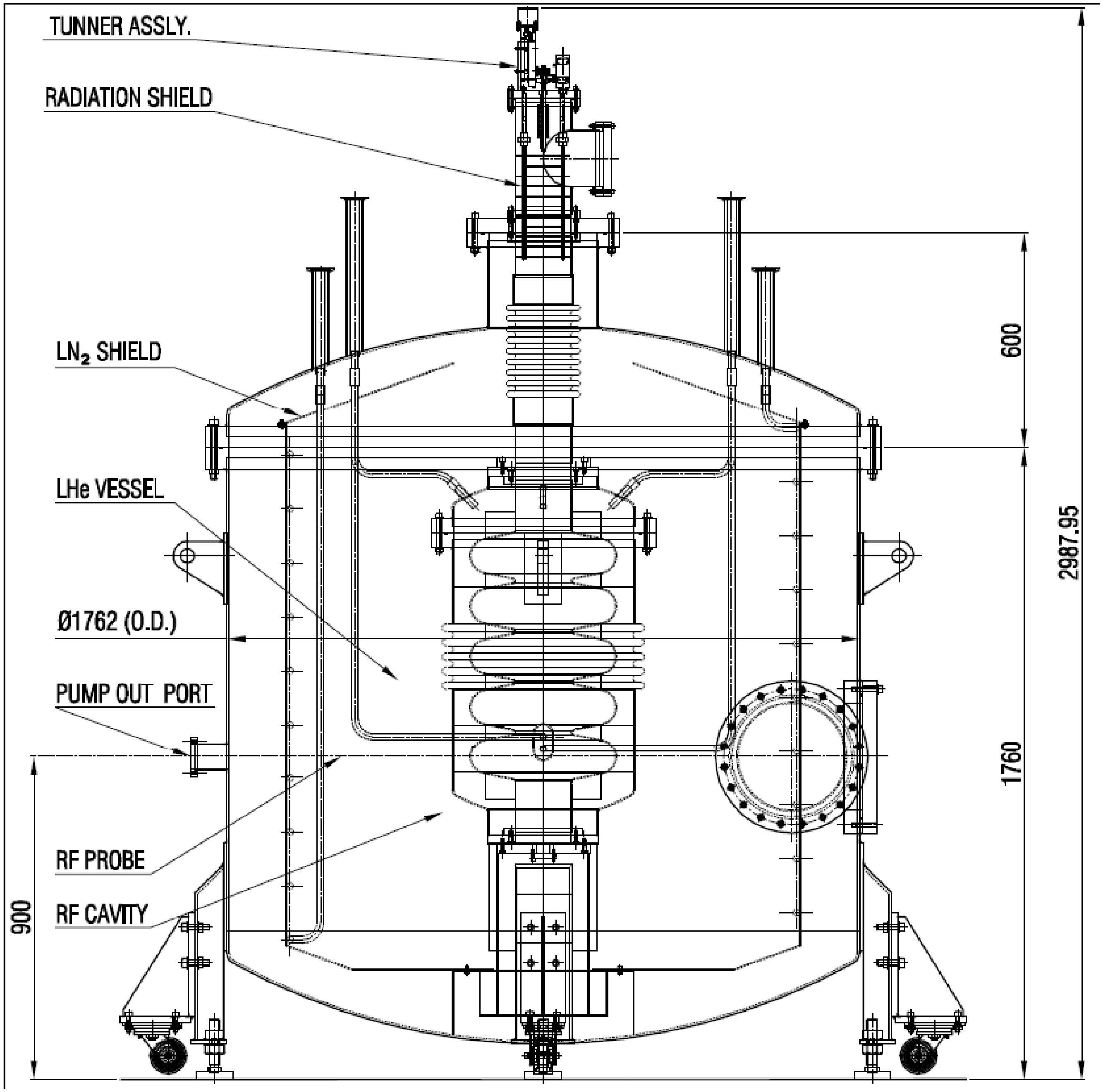
  2360 mm. Height x 1762 mm. Diameter
- LHe vessel dimension of the Test Cryostat:

  1050 mm. Length x 512 mm. Diameter
- Cryostat consists of:
  - LHe vessel, LN2 shield
  - Internal & external magnetic shielding
  - Pump out port
  - LN2/LHe in, LN2/LHe gas out, Safety port
  - LN2/LHe instrumentations
  - RF probe in/out --- adjustable from outside
  - RF power coupler arrangement etc.

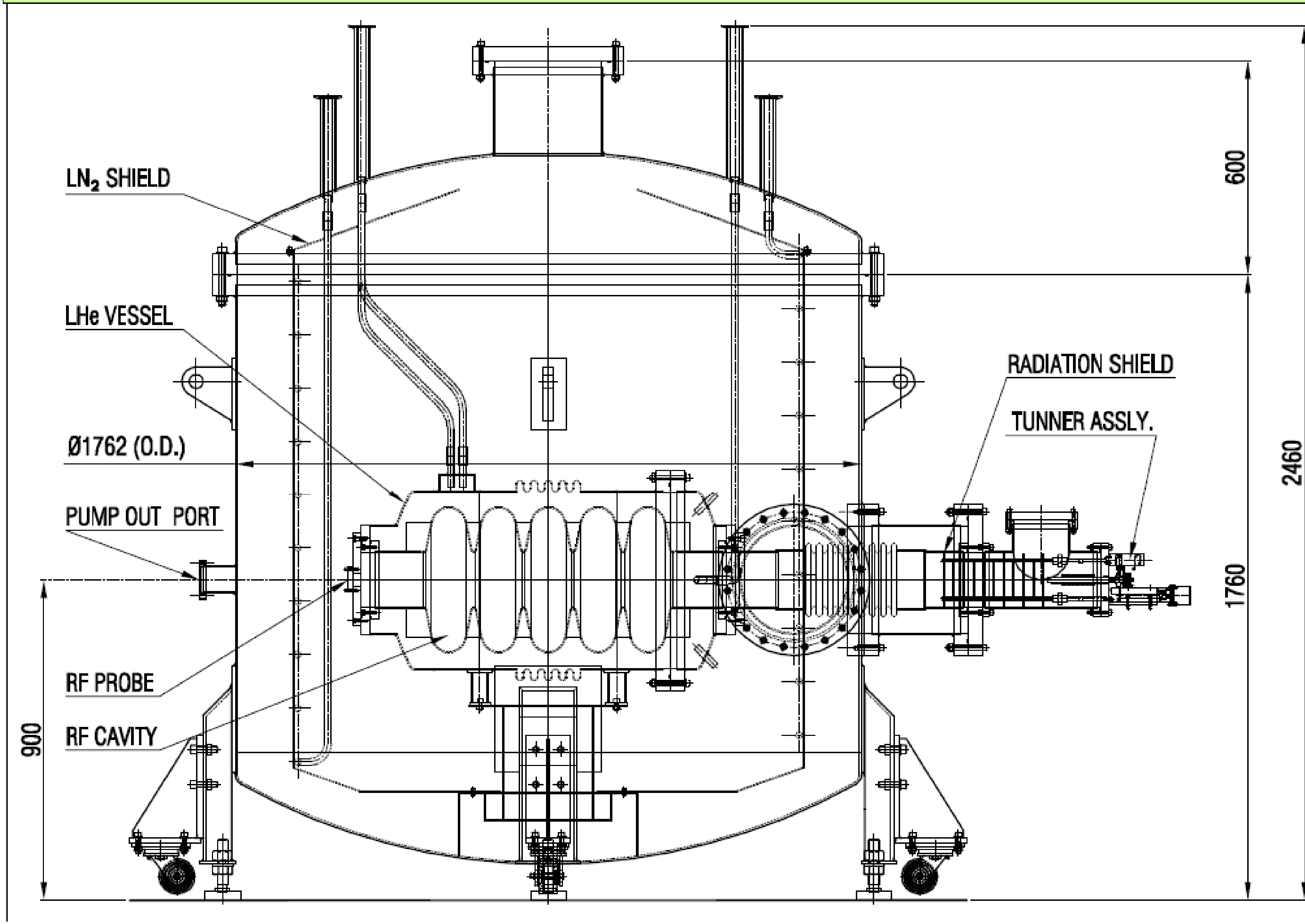
CAVITY PLACED VERTICALLY IN CRYOSTAT

- SCRF cavity can be placed in the same CRYOSTAT in two possible ways
  - Vertically
  - Horizontally

- Future modification: CRYOSTAT can be operated at 2K (for cavity placed horizontally) adding components (Heat Exchanger, JT valve etc.) – provision for space



CAVITY HORIZONTALLY PLACED INSIDE CRYOSTAT



Mechanical Design

- Volume of inner helium vessels ~ 216 lts.
- Overall diameter of the cryostat has been increased to accommodate the cavity in horizontal as well as in vertical condition.
- The cryostat has provision for operation of the cavity at 2K also.
- Conductive Heat load to the liquid helium vessels from top support is < 4 watt.
- Heat load to the helium vessels due to radiation using the10 layers of MLI on helium vessels is 0.05W.

Table 1: Design details for inner and outer vessels

		Thickness (mm.)	External Pressure (PSI)	Internal Stress (PSI)
Inner Vessel	Cylindrical Shell	2	17.00	8789.00
	Torispherical head		21.20	15646.00
	Cylindrical Shell	3	42.00	5823.00
	Torispherical head		40.90	10344.00
	Cylindrical Shell	4	73.50	4387.00
	Torispherical head		60.60	7776.00
Outer Vessel	Cylindrical Shell	5	10.00	11349.00
	Torispherical head		12.20	19368.00
	Cylindrical Shell	6	15.30	943.00
	Torispherical head		16.20	1674.00
	Cylindrical Shell	8	29.50	7077.00
	Torispherical head		24.00	12550.00

Table 2 : Design details for Main Flanges inner and outer vessels

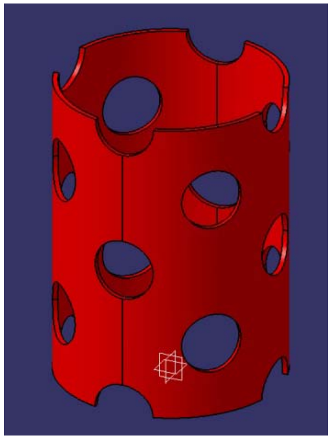
Flange	Thickness (mm.)	Int. stress (UG-34)* (PSI)	Ext. pressure (Apx-2) (PSI)	Int. stress (Apx-2) (PSI)
Inner Vessel	30	11392	556	10953
	39	6790	331	6527
Outer Vessel	55	21365	3888	15879
	60	17953	3267	13342

* ASME BOILER & PRESSURE VESSEL CODE, SECTION VIII Div. 1 & 2.

Thermal Design

To reduce the heat load on liquid helium system:

- The liquid helium 4.5 K vessel is shielded with the liquid nitrogen 77 K shell made of OFHC Copper.
- The liquid helium vessel and liquid nitrogen vessel is covered by reflective multi-layer insulation.
- The annular space between the outer vessels and helium vessels is evacuated to reduce the heat leak.
- Liquid helium vessel is supported from top using thin bellows
- Bottom support is optimally designed glass epoxy Cylinder (G-10).
- The heat load of the bottom support to the 4.5 K system has been evaluated by using ANSYS.



- Total Heat Load : 0.0918 watt
- Hole Size : Diameter 100 mm
- Vertical Distance Between two hole : 175 mm
- No. of holes in a plane : 4 Nos in 90º
- No. of plane : 5 Nos
- Vertical Distance Between two Plane : 75 mm
- Angular rotation between two plane : 45º

Support structure

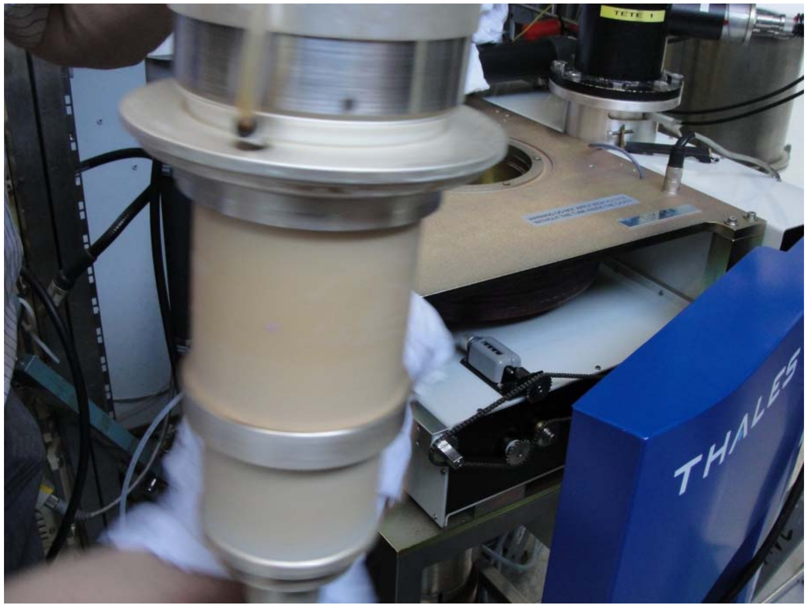
- The whole cryostat is supported on four legs with jack
- Four caster wheel mounted on the legs for the easy handling and movement of cryostat.
- The S.S.304 Channel 160 mm X 80 mm X 8 mm has been used with the 6 mm reinforcement plate.
- Maximum general longitudinal stress is 3547 psi
- Maximum localized stress to cause buckling above the leg top is 632 psi.
- Three lifting hook welded with reinforcement plate in the outer vessels for the lifting and handling of whole assembly.
- The lifting hook is 20 mm thick S.S. 304 plate with 6 mm. thick reinforcement plate. The maximum stress is 5425 psi.

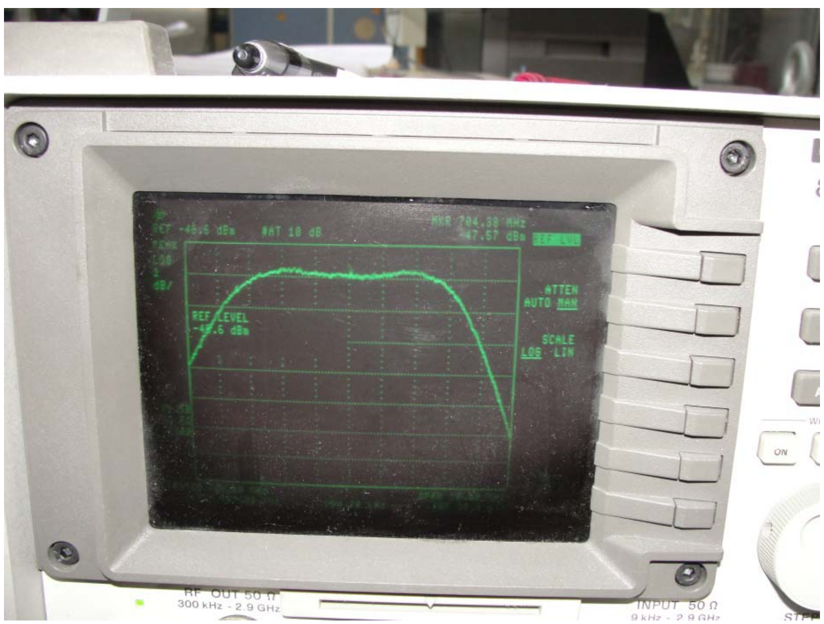
High power RF Source development

IOT based RF Amplifier, 60 kW at 704.4 MHz

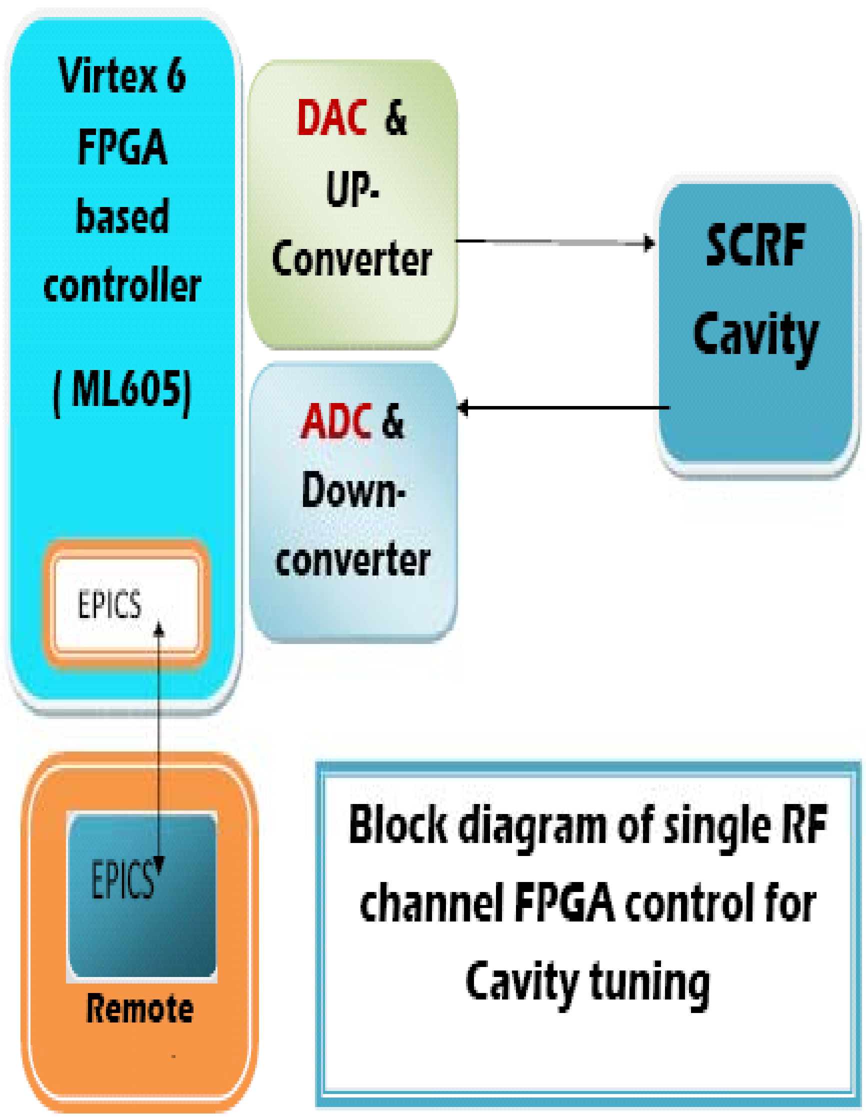
- **Compared to klystrons, IOTs exhibits very interesting characteristics in terms of efficiency (> 65% is usually reached), linearity and compactness.**
- **operating at 460-800 MHz, with powers up to 60 kW CW , compatible with our requirement.**
- **We have selected TH 793 IOT for 704.4 MHz and also for 650 MHz operation**
- **Maintenance is simpler -- replacement of the tube only**
- **IOT can be re-gunned twice, at about 60% cost of a new IOT**
- **Output RF cavities are external to tube.**

IOT amplifier cavity





FPGA based control



Block diagram of single RF channel FPGA control for Cavity tuning

Cavity Field Control Objectives

- Amplitude: 0.01% pp
- Phase : 0.05 degree rms
- User Interface and Diagnostic Data –
  - Digital IQ based Amplitude and FPGA based systems
  - Amplitude and Phase stabilization via control loop
- RF DACs are 16 bit, 800 MSPS, 1 GHz analog BW
- IF 100MHz
- Commercially available The Virtex®-6 FPGA ML605 carrier board with FMC (FPGA Mezzanine Card) adapter has following features:
  - Commercially available FMC
  - Daughter Modules :16 Bit D/A 1GSPS
  - Daughter modules : 14 Bit 250MSPS A/D
  - Conversion, 700MHz analog input BW
  - Communications: Ethernet and optical fibre

DC POWER SUPPLIES FOR IOT

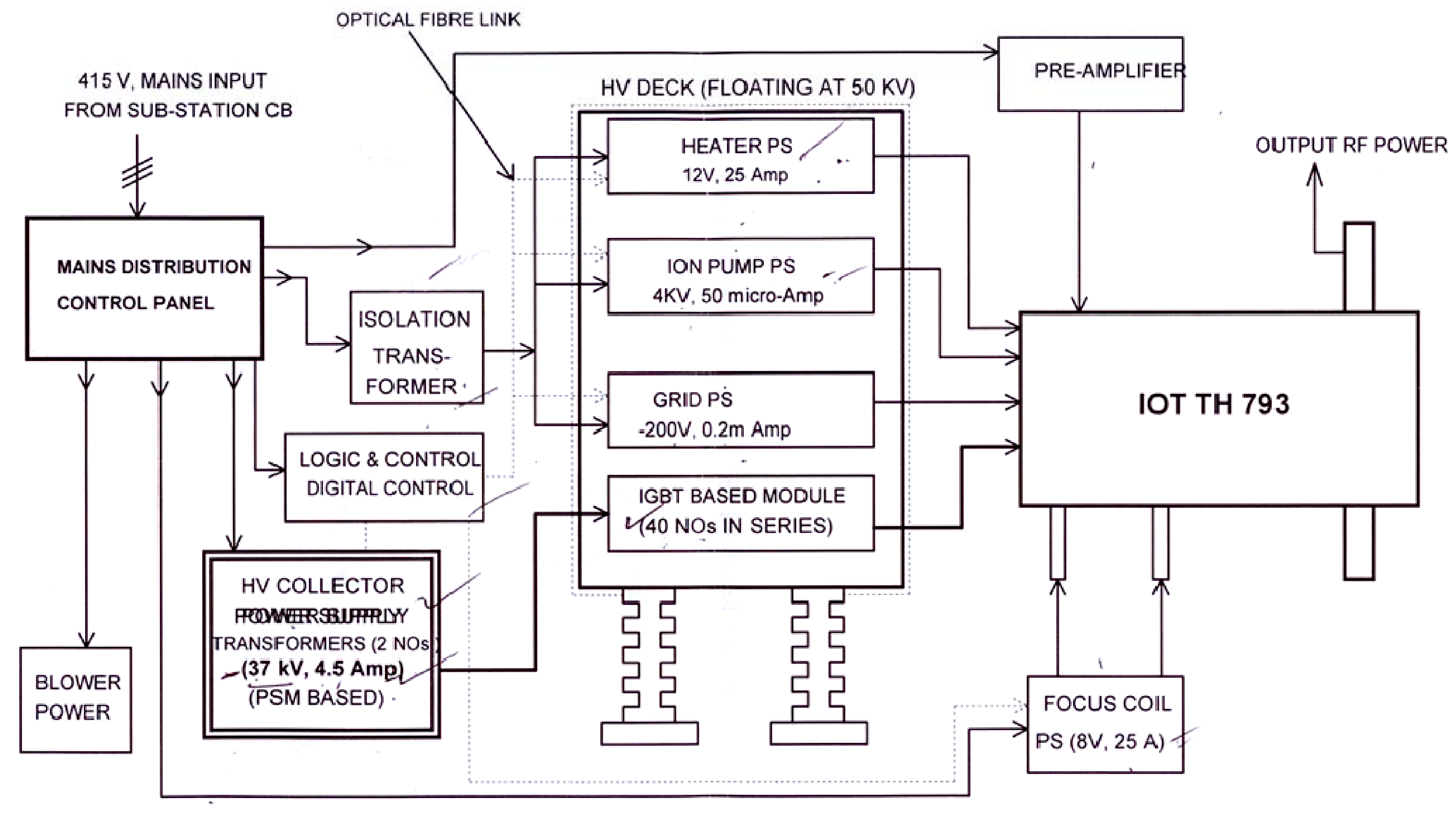
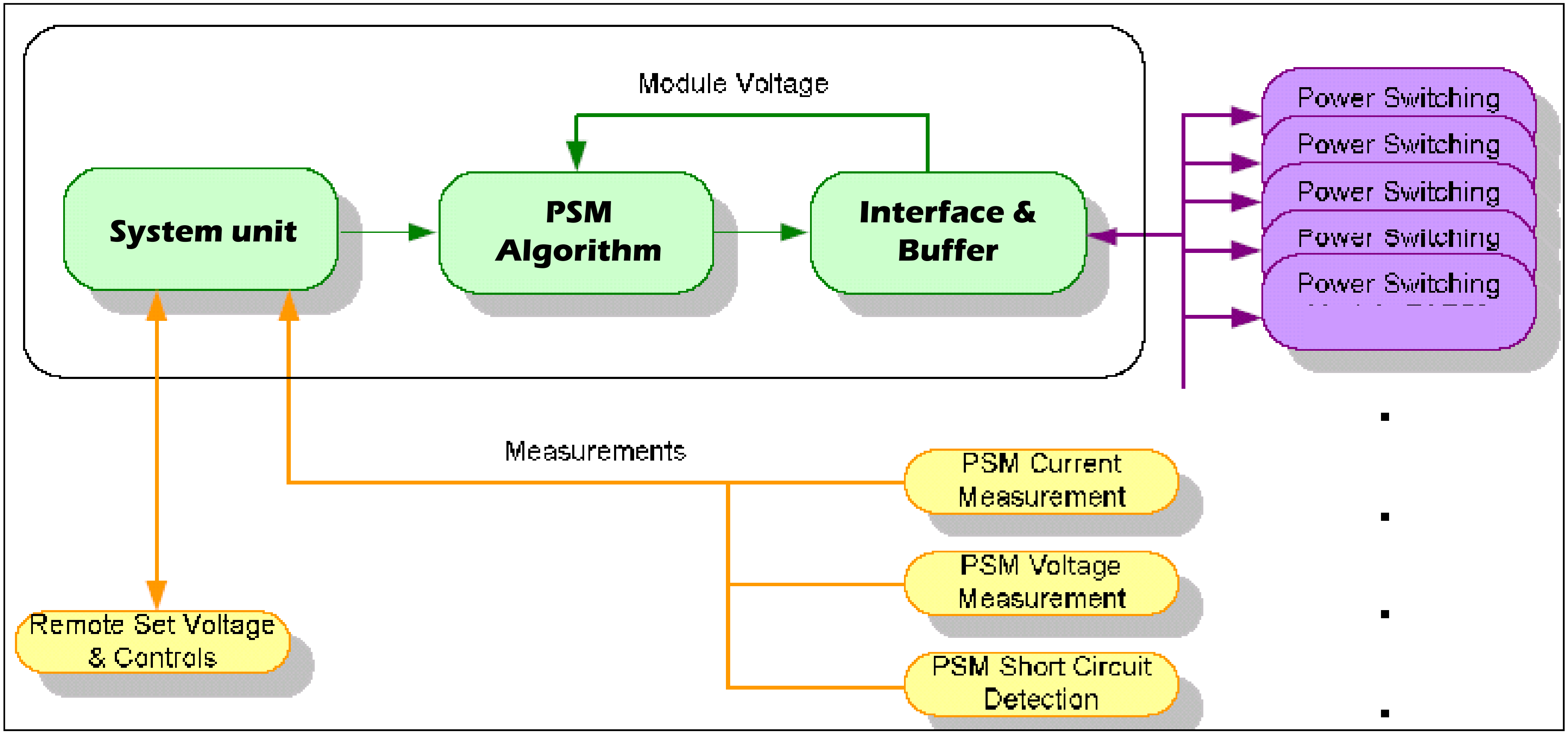


FIGURE-1:- TOTAL SCHEMATIC DIAGRAM OF IOT ASSEMBLY

Pulse-Step-Modulation (PSM) Control scheme



- Pulse step technology is recommended for RF amplifier kind of load where high efficiency, regulation speed and accuracy, and compatibility with large variation of the load impedance.
- Modular concept with high redundancy (up to 10% defective modules without performance degradation) makes it very reliable, easy to maintain and avoiding of HV crowbar tubes.

HV DC POWER SUPPLY FOR IOT

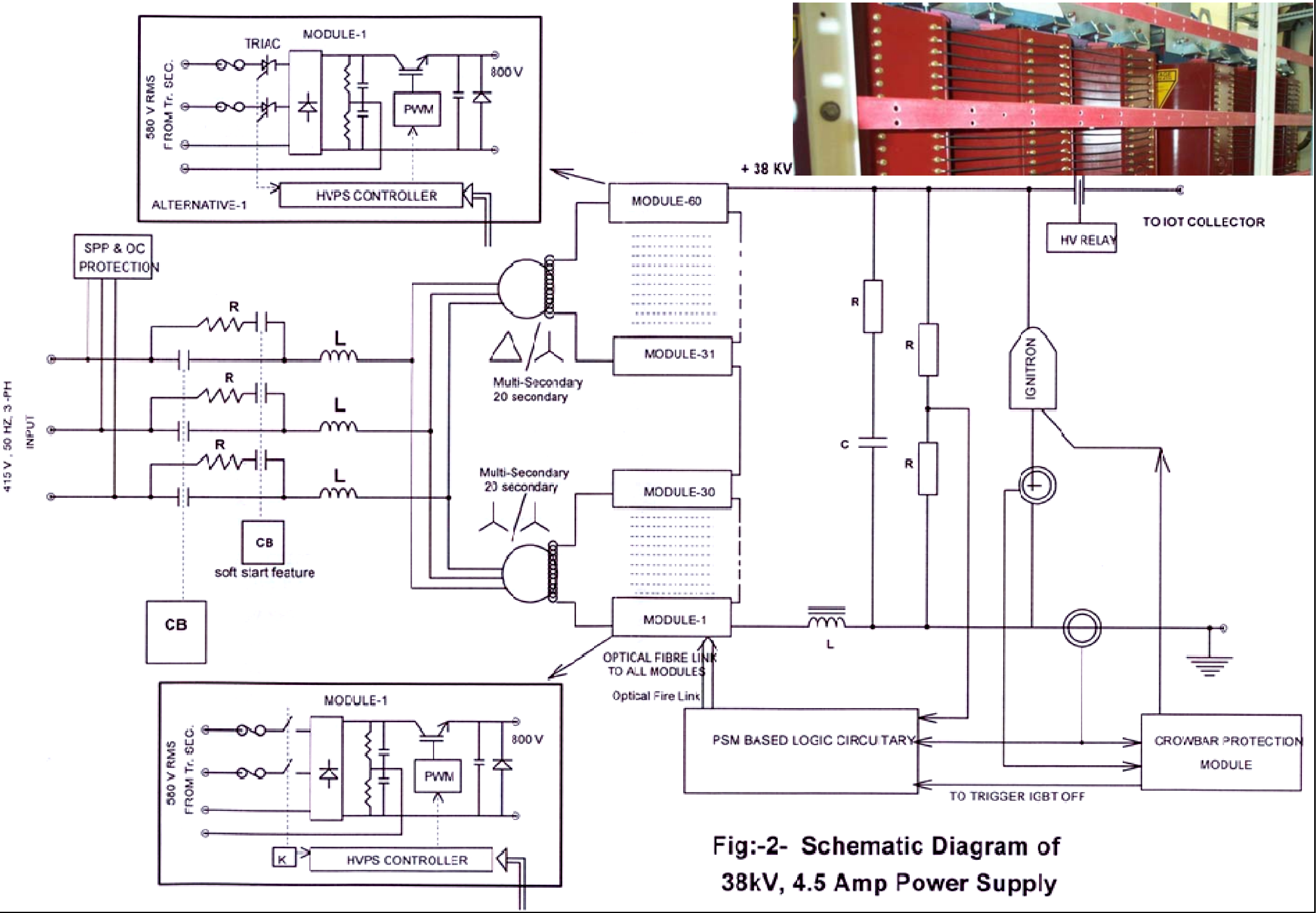


Fig:-2- Schematic Diagram of 38kV, 4.5 Amp Power Supply

OTHER DC POWER SUPPLIES

FILAMENT P/S

Switched Mode Power Supply	
Mains Input	200-250 V / 47 - 63 Hz
Current and voltage regulation	
Control voltage setting	0 .. 10 V
Output voltage	0 .. 20 V
Output voltage stability (typ.)	0.05% of V_{max}
Output current	0 .. 50 A
Output current stability (typ.)	0.05% of I_{max}
Output current accuracy	0.5 %
Output current ripple	<0.5%

CONTROL GRID P/S

Switched Mode Power Supply	
Mains Input	180 – 264 V, 47 - 63 Hz
voltage regulation	
Control voltage setting	0 .. 10 V
Output voltage	0 .. 300 V
Output voltage stability (typ.)	<0.5% of V_{max}
Output voltage ripple	<0.5% pp
Output current	0 .. ±300mA
Output current ripple	<1 % pp

ION PUMP P/S

Mains input:	210 - 250 V, 48 - 63 Hz
Output Voltage	0 – 5 kV
Output Current	0 – 240 mA
Control Voltage	0 – 10 V
Voltage and current regulation	
Output Voltage Ripple Output Voltage Accuracy	< 0.1% (RMS) < 1 %
Current Monitor accuracy	< 1 %
Voltage Monitor accuracy	< 1%

FOCUS COIL P/S

Switched mode power supply	
Mains input:	180 – 264 V, 47 - 63 Hz
Output Voltage	0 – 20 V
Output Current	0 – 50 A
Voltage and current regulation	
Output current ripple	< 1 % p-p
Output current accuracy	< 1 %
Current monitor accuracy	< 1%
Voltage monitor accuracy	< 0.5%

SUMMARY

- 650 MHz, β=0.61 elliptical SCRF cavity design is in final stage.
- Niobium sheet (RRR>300, 600 x 600 x 4 mm) has been received.
- Half-cell die design is also in the final stage. Discussion with the potential local vendor is in progress for die manufacturing.
- Cavity fabrication will be done with the help of Indian Institutions.
- Procurement of Test Cryostat (as per our design) is being initiated in April, 2011 through global tender. Expected delivery will be about 18 months from now (Fermilab help may be needed for testing the cavity before that).
- Thales # TH-793 IOT based 60 kW amplifier and Solid-state RF amplifier (80 – 1000 MHz, 500 W) are already available with us.
- Design & development of FPGA based low-level RF controls, HV DC power supplies for IOT are in progress.

धन्यवाद

Thank You

Grazie