RF design studies of 1300 MHz CW buncher for European X-FEL

Design study for CW upgrade of European XFEL

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

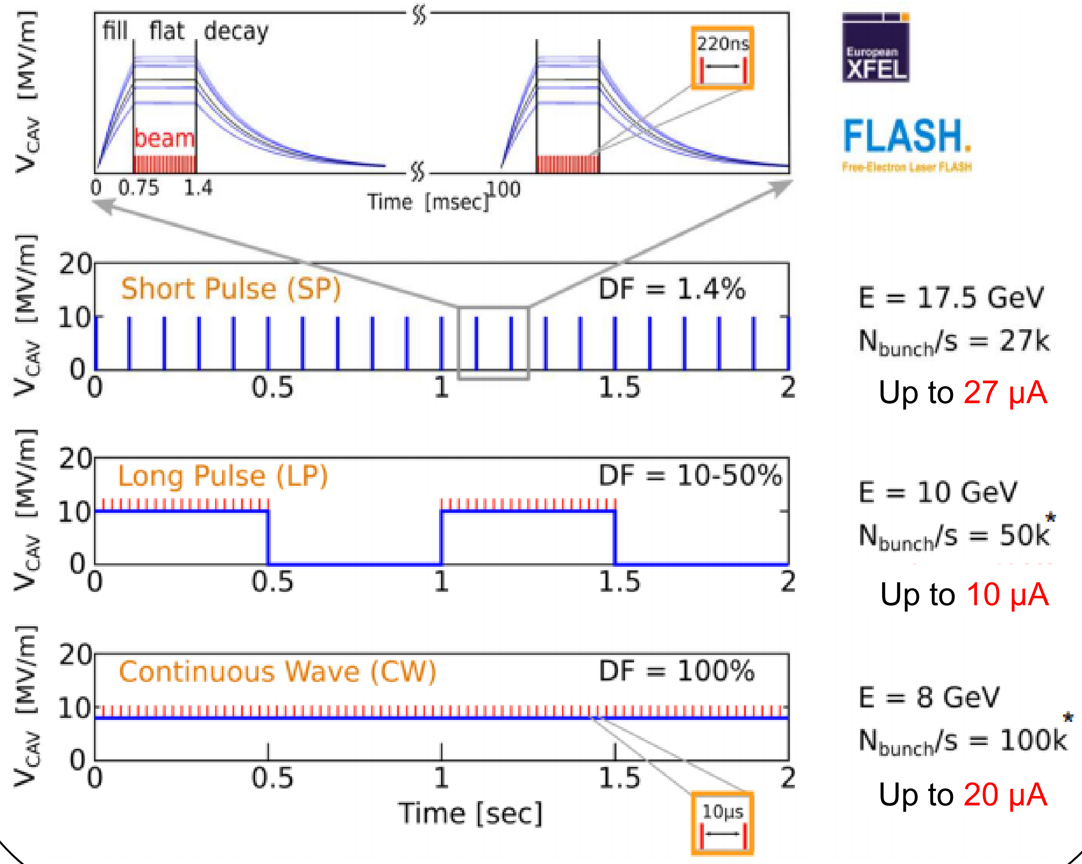
Outline

- Overview
- Two cell buncher RF design: summary
- Three-cell buncher: RF design, Multipacting, Multiphysics and RF power coupler design study
- Study of field asymmetry induced by coupler
- Summary
- Outlook

Introduction: Requirement of buncher

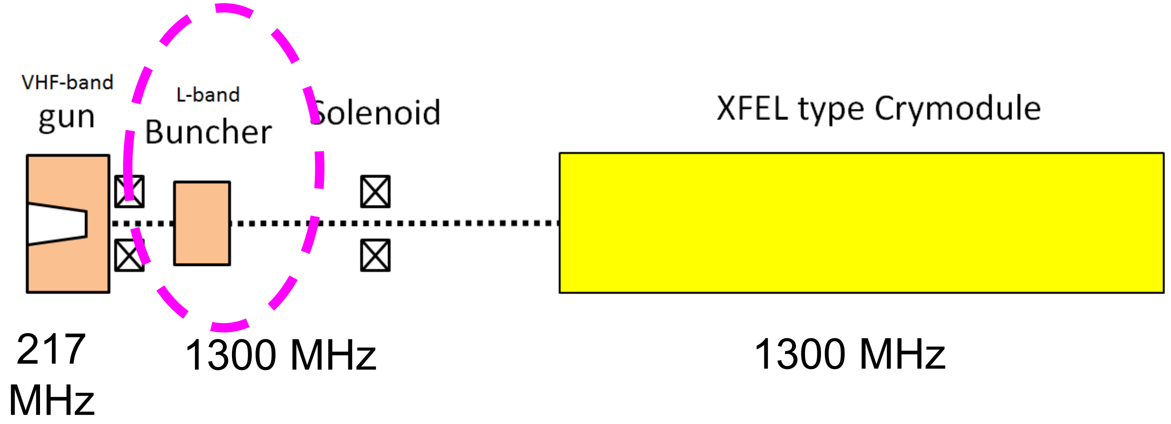
XFEL needs CW injector for future upgrade

Three operation modes envisioned for FLASH and XFEL



Possible injector systems

1. CW SC DESY gun: under experimental demonstrations
2. CW NC gun based injector system: Under design study

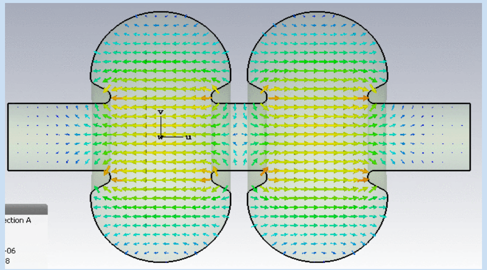
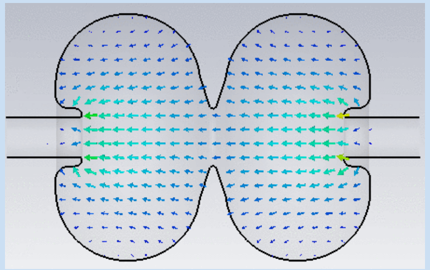
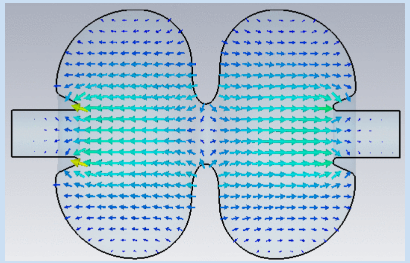
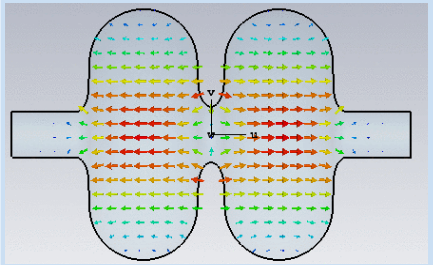


Design goal : Accelerating voltage ~400 kV (beam dynamics)

RF power <5kW/cell (APEX), Multipacting free

Borrowed from Dr. Houjun Qian, PITZ DESY

Two-cell buncher : different design options

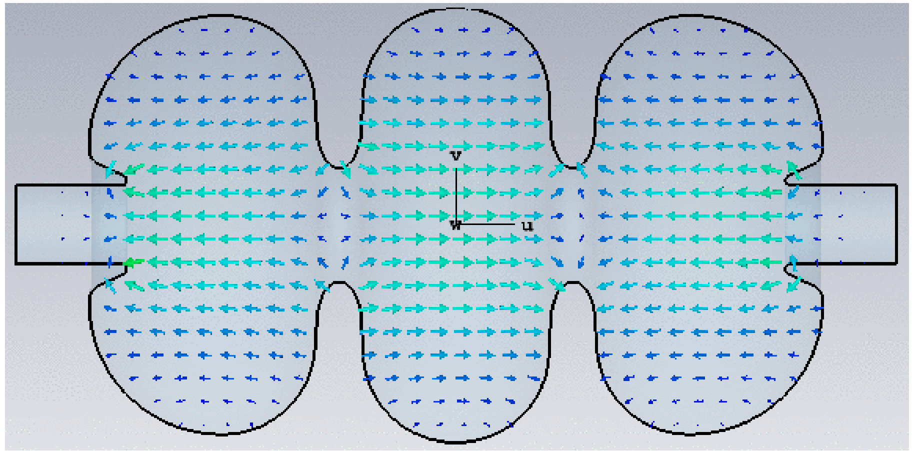
Design \Parameters	Re-entrant	Re-entrant with tapered inter-cell coupling iris	Re-entrant with elliptical inter-cell coupling iris	TESLA type
Geometry				
$R_{sh} = \frac{V^2}{P_c}$	**9.9**	8.9	9.2	7.7
Q	25316	**27206**	27819	27009
$f_\pi - f_0$ (MHz)	1.03	2.75	3.02	2.90
P_c (kW) for 400 kV	16.2	18.4	17.5	20.7
Maximum Heat location	Inter-cell coupling iris	Near beam pipe	Near beam pipe	Near equator

- Shunt impedance and Mode separation improved compared to APEX design
- Power dissipation (P_c) ~ 9 kW/cell: significantly higher compared to (~ 5 kW/cell)

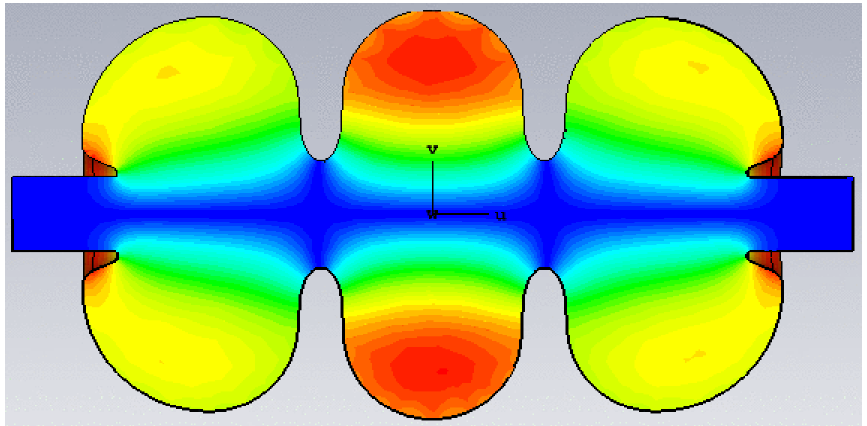
To have P_c <5kW/cell → 3-cell design

Three-cell buncher: RF design

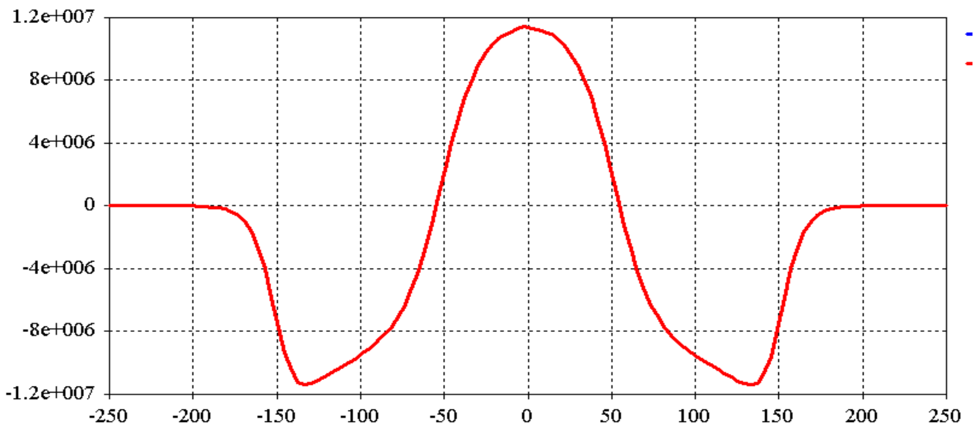
- Central geometry similar to SCRF cavities (TESLA type) with re-entrant end
- Inter-cell coupling iris 52 mm
- Mode separation (f_{π}-$f_{2\pi/3}$) ~3 MHz
- Shunt impedance ~12 MΩ
- E_{peak}/E_z ~ 3.5 , not a problem at low gradient
- RF power required for 400 kV ~13 kW (<5 kw/cell)



Electric field array plot for π mode



Magnetic field distribution



On- axis Electric field profile

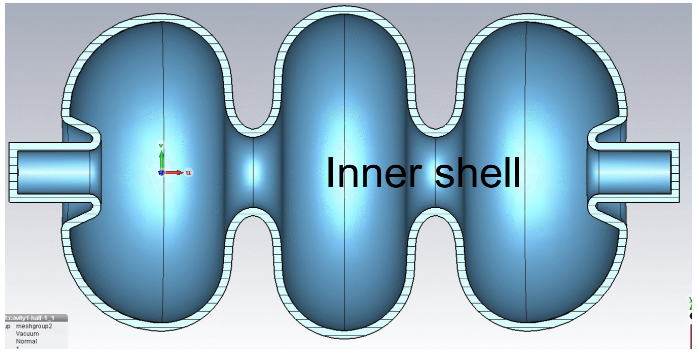
Three cell buncher: Multipacting Study

Mutipacting simulation : Issues and solutions

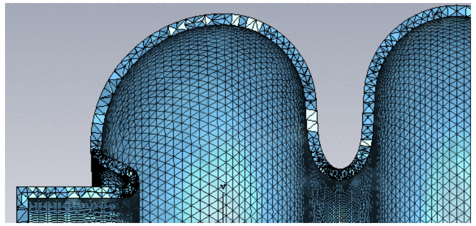
- Multipacting mostly occurs near surface (s) with small features (like iris, nose cone curvature etc.) where emitted electrons (secondary) satisfy the resonance condition with EM field: Exponential growth of electrons

$$N(t) = N_0 e^{\alpha t},\ \alpha = \frac{dN}{dt} = growth\,rate$$

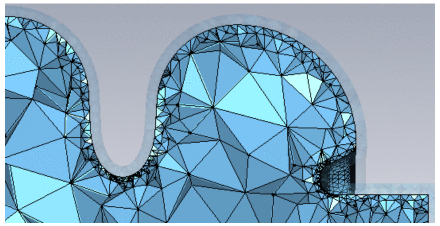
- Multipacting Simulations tools: CST Particle Studio (CSTPS) tracking & PIC
- Multipacting simulation errors: CST use "hexahedral mesh" for MP simulations, poor representation of small features.
- Approach to minimize errors:
  - Enhance mesh density → long simulation time
- Approach to improve simulation accuracy with reasonable simulation time:
  - Import RF field from Eigen mode solver with tetrahedral mesh
  - Enhanced mesh density near surface: using a two shells model (outer with fine mesh and inner with coarse mesh)[1]
  - Simulate 1/8th Model to reduce simulation time



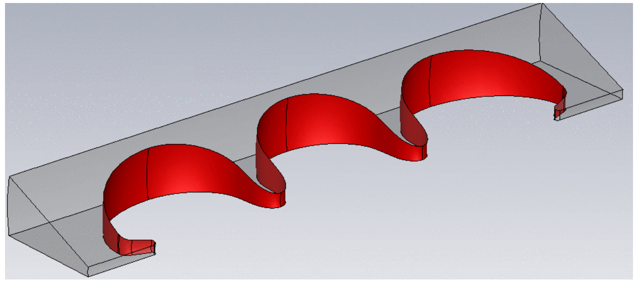
Three cell buncher mesh view



Outer mesh view



Inner mesh view



18^{th} model of three-cell buncher with emitting surface

Ref 1: P. Berutti *et al*. Technical note TD16-005, Fermilab

Multipacting study: some basics of SEY

Mutipacting " Secondary electron emission Yield"

- Multipacting strongly depends upon Secondary Electron Yield (SEY) of material
- SEY strongly depends upon : Material composition, processing (machining, cleaning, backing etc.).
- SEY data of copper : (1) CST inbuilt library (δ_{max}=2.09) and (2) CERN paper/ Valentin Paramonov (δ_{max}=1.24)[1,2]
- Higher SEY→ higher probability of multipacting

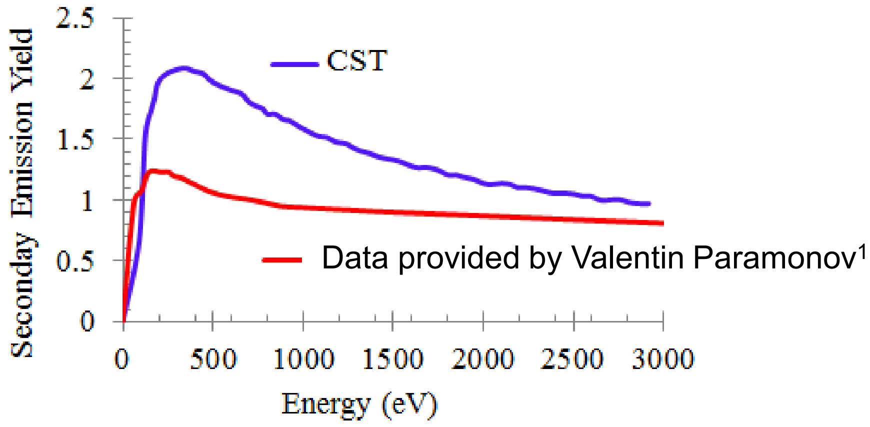


Figure.1: The comparison of SEY data to copper.

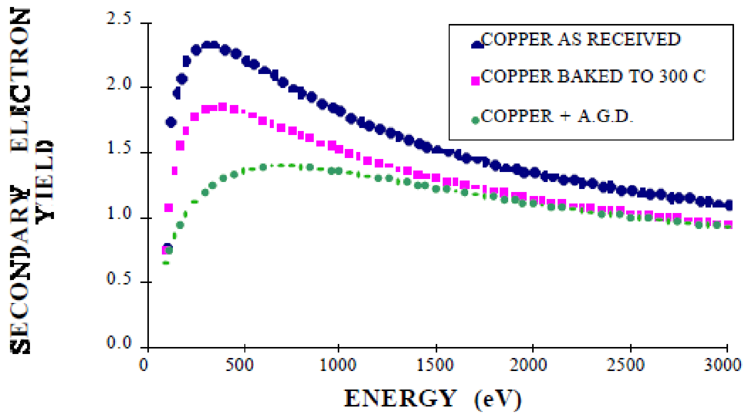


Figure 2: The S.E.Y. of copper for various surface treatments

δ (Received) >2, (300°C backed) ~1.8
δ (300° backed + Argon glow discharge)~1.3

Remarks

- Large variation in CST and CERN SEY data
- Since any structure has to be brazed (which means it is backed) CERN data may be used.
- CERN SEY data: tested on samples not on accelerator cavity
- To be on safer side also check MP with CST SEY data
- Targeted growth rate <0.06/ns[3]

Ref 1:Valentin Paramonov, Private communication; 2: V. Baglin *et al.* , "The secondary electron yield of technical materials and its variation with surface treatment", EPAC 2000, pp.217-221; 3: P. Berutti, Private communication

Three cell buncher: Multipacting study

Tool : CST Particle Studio tracking solver (2016)

- SEY data : (1) CST inbuilt library (δ_{max}=2.09) and
  (2) CERN paper/ Valentin Paramonov (δ_{max}=1.24)[1]
- Particle emission: energy 2-6 eV, phase: 0-360 ° in steps of 30°

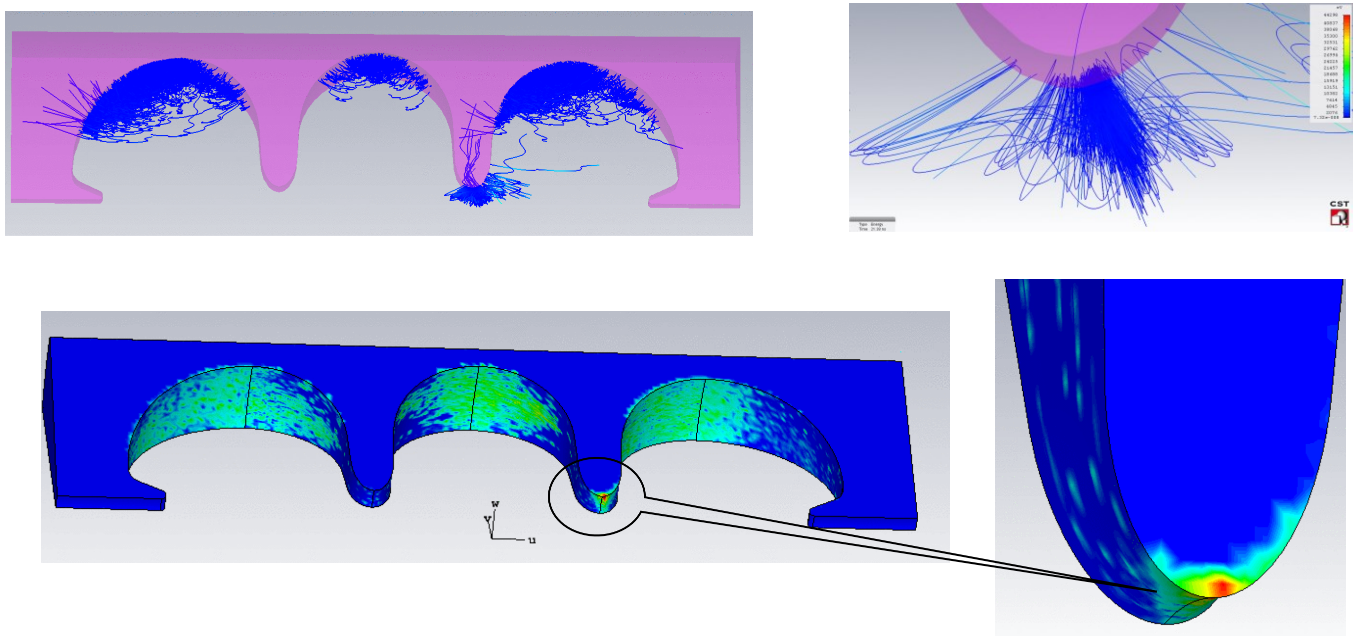


Fig. 1: A typical view of electron trajectories and current density predicted by CST PS tracking solver.

Ref 1:Valentin Paramonov, Private communication

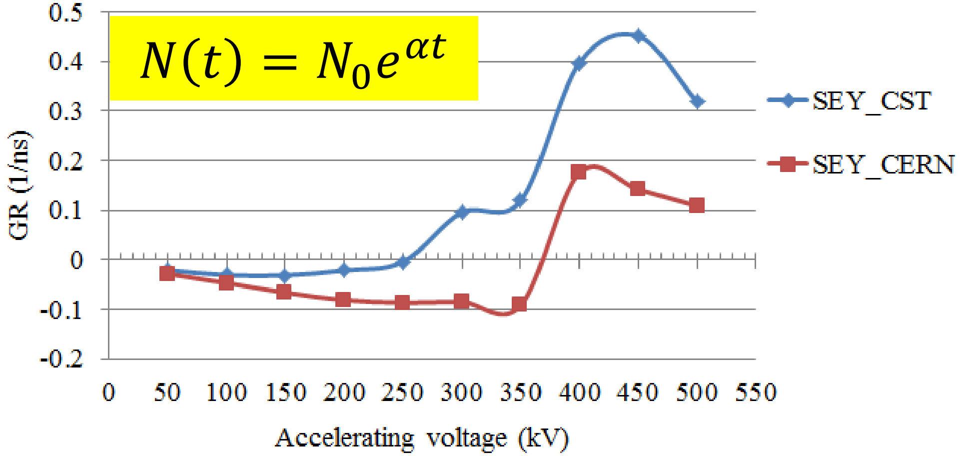


Fig. 2: Particle growth rate (GR) with accelerating voltage for different SEY data.

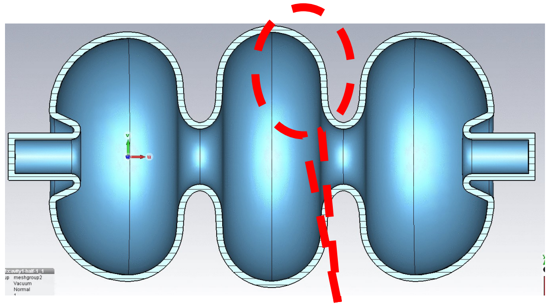
- Strong MP near inter-cell coupling iris (1st order single point)
- GR > 0.1/ns for V_{acc} > 250 KV with SEY from CST
- GR > 0.1/ns for V_{acc} >350 KV with SEY from CERN.

Mitigation of Multipacting

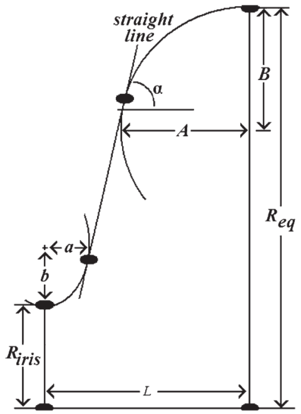
- Modification geometry near the location of MP → modify EM locally: to break resonance condition)
- Re-optimize the geometrical parameters to achieve desired RF parameters (frequency and on-axis field uniformity etc.)

Parameters	Option1	Option2	Option3
a (mm)	10	12	12
A (mm)	42	40	42
L (mm)	52.75	52.75	54.75
R_{sh} (MΩ) for β=0.91	12.5	11.7	11.5
P_c (kW) for V=400kV	12.8	13.8	13.9
GR (1/ns) (SEY CST)	>0.1 for V >250kV	< 0 for V ≤ 400 kV >0.1 for V> 400 kV	< 0 for V ≤ 400 kV < 0.03 for V up to 500 kV
GR (1/ns) (SEY CERN)	>0.1 for V >350kV	<0 for V up to 500kV	<0 for V up to 500kV

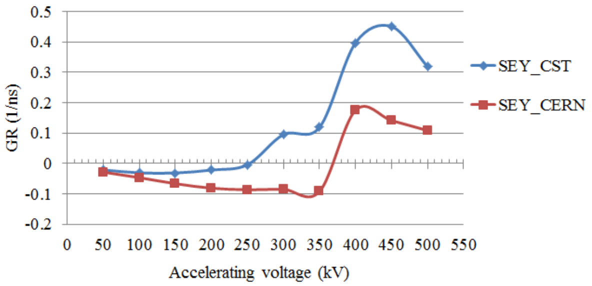
$$N(t) = N_0 e^{\alpha t}$$

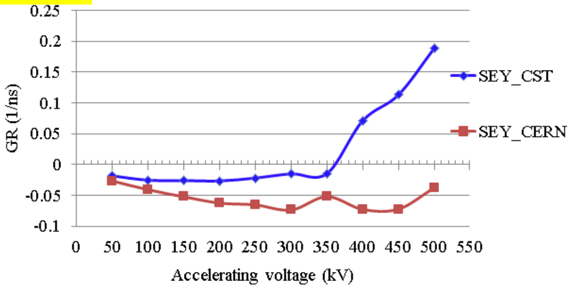


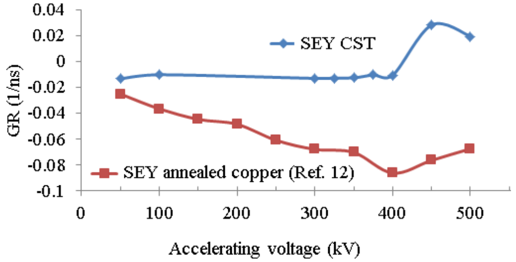
A, a→ variable



Schematic of central cell geometry







Multipacting simulation: comparison

➢ CST Particle Studio tracking solver (2016) and PIC 2017

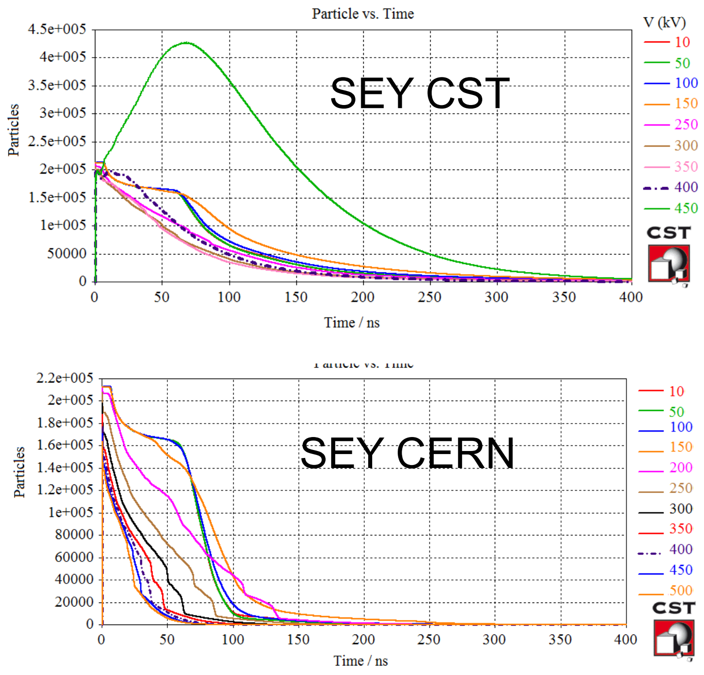


Fig.1: Typical variation in number of particles with time for different SEY data and PIC solver

$$N(t) = N_0 e^{\alpha t}, \alpha = GR$$

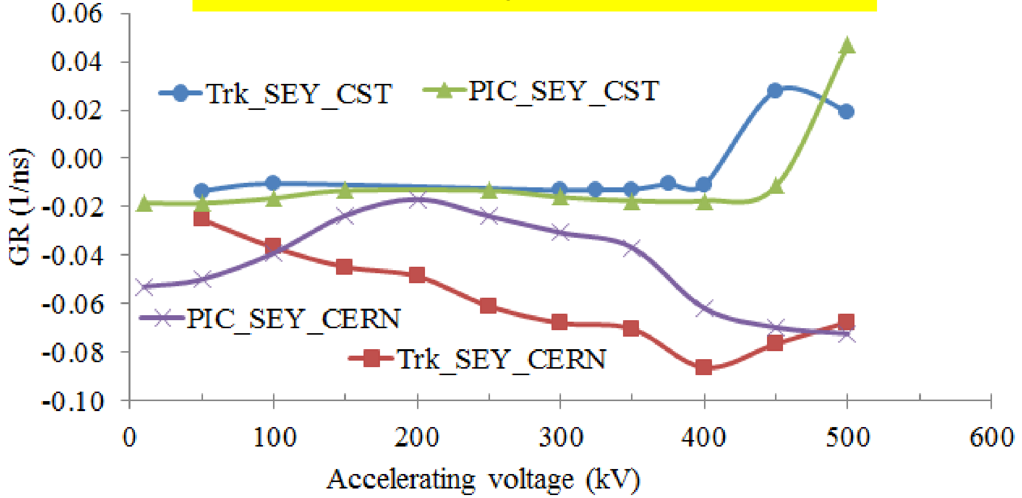
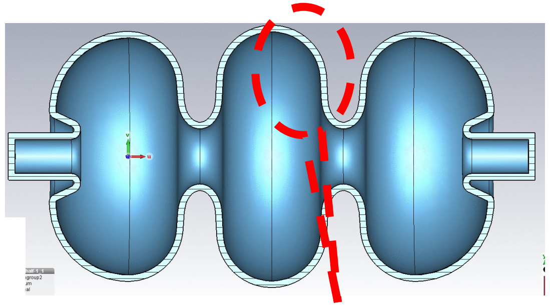
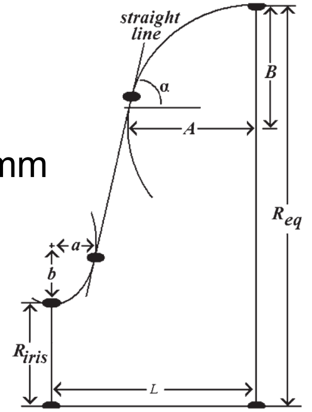


Fig.2: Comparison of the GR with accelerating voltage for different SEY data and solvers.



a=12 mm,
A=42 mm
L=54.75 mm



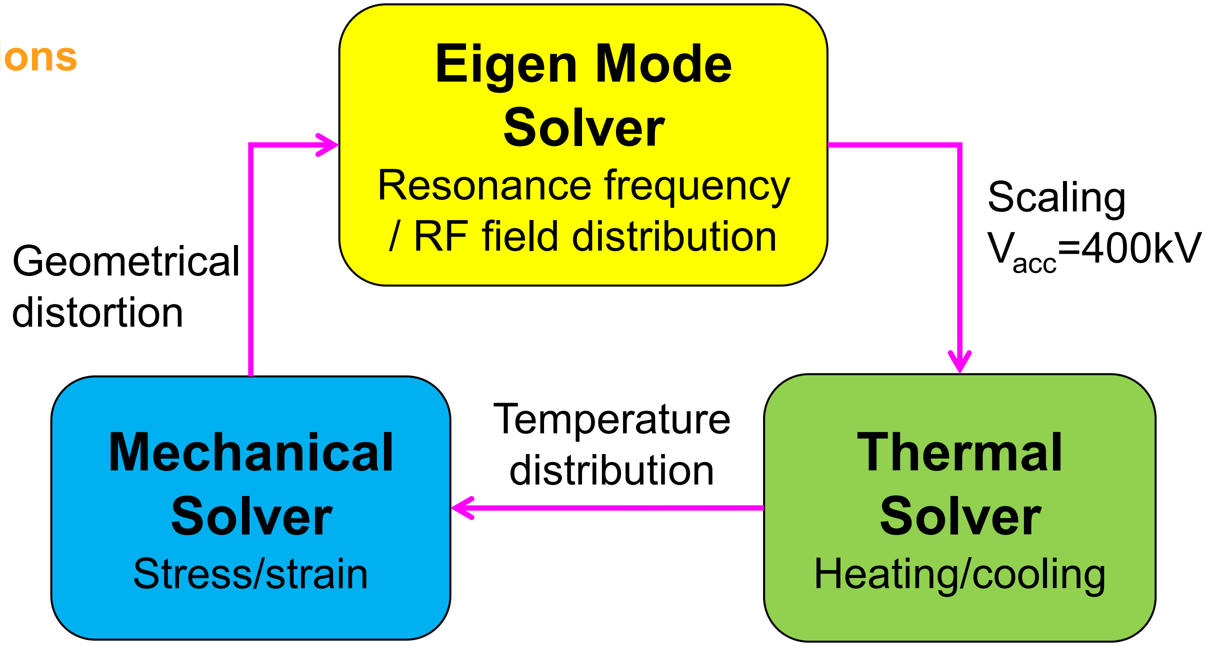
Schematic of central cell geometry

- ➢ PIC solver: emission over 360° of RF phase
- ➢ For accelerating voltage up to 400 kV no MP
- ➢ Tracking and PIC solver: results are quit similar for CST SEY data and slightly different for CERN data
- ➢ Tracking and PIC solver has similar trend

Multiphysics simulations

Electromagnetic- Thermal- Mechanical : Coupled simulations

- CST Multiphysics Solver
- Eigen mode solver :RF field distribution
- Thermal solver: Temperature distribution
- Mechanical solver: Geometrical distortion
- Eigen mode solver: RF parameters



Thermal Simulations : Analytical approach

Martial properties, heat transfer coefficient and pressure droop

Heat transfer coefficient calculation

$$h = \frac{\lambda}{D} N_u \qquad N_u = 0.023 Re^{0.8} Pr^{0.4} \qquad Re = \frac{\nu D \rho}{\mu}$$

λ= thermal conductivity of fluid (water 0.58 W/mK), ν = liquid velocity (m/s), ρ= liquid density (water1000 kg/m^3), μ= liquid viscosity (water ~0.8e-3 kg/ms), Re= reynold number, Nu= Nusselt number, Pr=Prandtl number (5.7 for copper), D= hydraulic dimeter of cooling channel (Area/ perimeter) and h= heat transfer coefficient (W/m^{2}K)

Pressure droop: Darcy Weisbach equation

$$\Delta p = f_D \frac{L}{D} \frac{\rho v^2}{2}$$

Δp= pressure droop (N/m^2), f_D= Darcy friction factor, ν = liquid velocity (m/s), ρ= liquid density (kg/m^3), D= hydraulic dimeter of cooling channel (Area/ perimeter) and L=pipe length

Table 1
Material properties used for simulations of coupled effects.

Parameter	Units	OFHC,annealed, [10]	Steel AISI 316	Molybdenum
Density, ρ	$\frac{kg}{m^3}$	8950	8000	10200
Specific heat, C_p	$\frac{J}{kg\,K}$	385	460	256
Heat conductivity, k_c	$\frac{W}{m\,K}$	391	16.3	14.2
Thermal expansion, α	$\frac{1}{K}$	1.67×10^{-5}	1.59×10^{-5}	4.9×10^{-6}
Elastic modulus, E_{Ym}	GPa	123	193	336.3
Poisson's ratio, ν		0.345	0.28	0.3
Yield stress, σ_Y	MPa	62		
Electric conductivity, σ	$\frac{S}{m}$	5.8×10^7		1.73×10^7

Ref 1. V. Paramonov et al., NIMA 854 (2017) 113-126
2. S.V. Kutsaev et al., PRSTAB 17, 072001 (2014)
3.https://ncalculator.com/image/formulas/pressure-loss-darcy-weisbach-equation.jpg

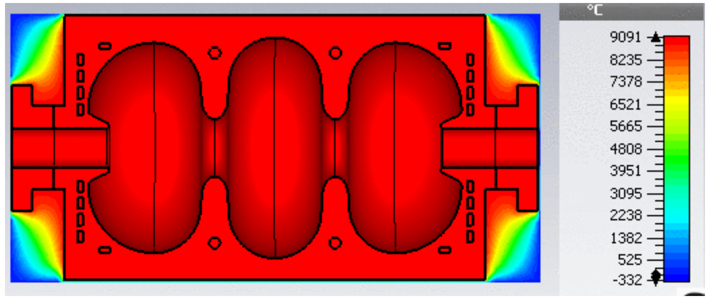
Cooling pipe shape	Size (mm)	Water flow (m/s)	Water flow (liter/s)	Re	H (W/m^{2}K)	Δp (kPa)
Circular	10 (diameter)	3	0.23	29441	10062	0.31
Square	10 x 5	3	0.15	19627	10912	0.17

Thermal-Mechanical-RF Simulations

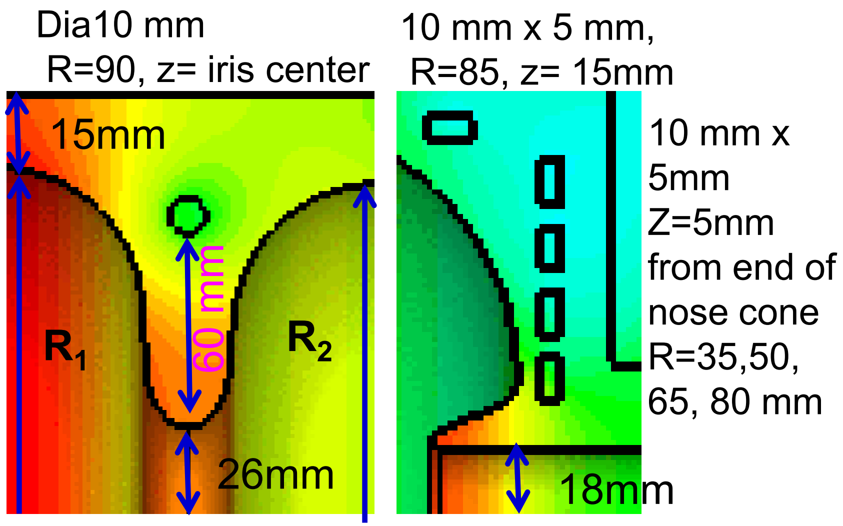
CST Multiphysics solver

Input parameters

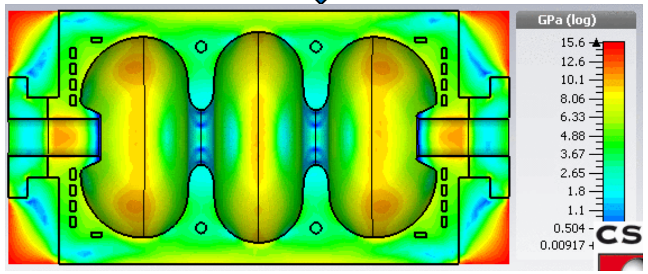
- Ambient temperature:25°C
- Input power: 14 kW (V_{acc}=400kV)
- Background material: Air
- No cooling



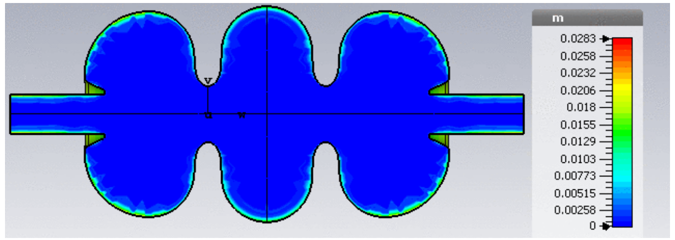
Thermal simulation: T distribution



- Maximum temperature :~9000°C
- Maximum stress ~ 15 GPa
- Maximum displacement~30 mm
- Change in f_{π} ~200 MHz



Mechanical simulation: Stress distribution



RF simulation: Eigen mode

- Temperature > melting of copper
- Cooling is necessary

Mode	*Original Frequency* (MHz)	Modified frequency (MHz)
π	1300.157	1097.295

Thermal-Mechanical-RF Simulations

CST Multiphysics solver

Input parameters

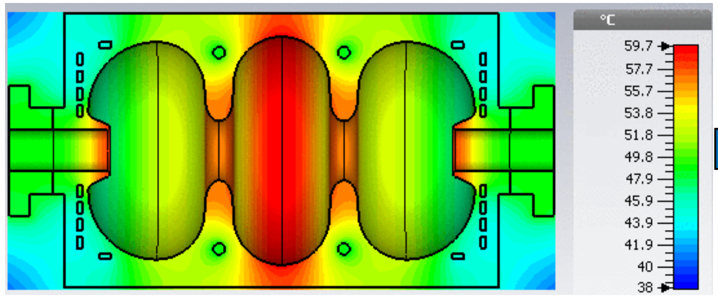
- Ambient temperature: 25°C
- Water temperature: 25°C
- Water flow 3 m/s (analytical)
- Input power: 14 kW (V_{acc}=400kV)
- Heat transfer coefficient:

(a) circular pipe =10062 W/m^{2}K
(b) square pipe = 10911 W/m^{2}K

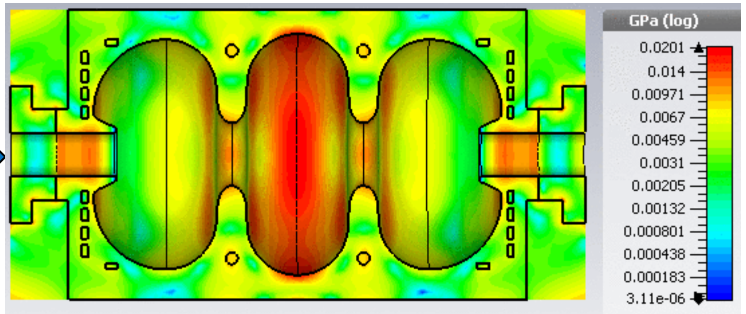
- Maximum temperature :~60°C (inter-cell equator and nose cone)
- Maximum stress ~ 20 MPa
- Maximum displacement~80 μm
- Change in f_π ~0.53 MHz

(APEX ~0.68 MHz, at 8kW RF power)

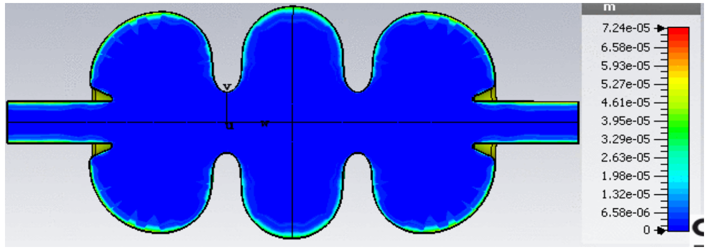
- Cell ID's re-optimized to compensate thermal effect
- R_1=99.9 →99.87 mm
- R_2 =95.225→95.205 mm



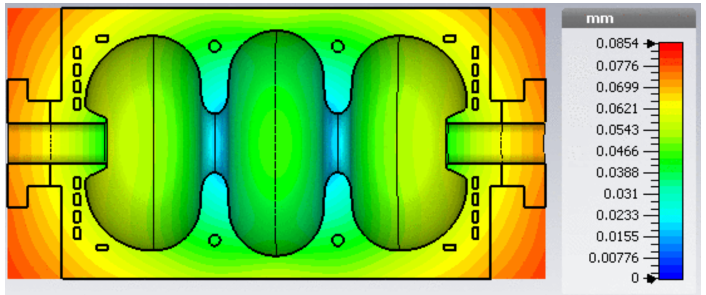
Thermal simulation: T distribution



Mechanical simulation: Stress distribution



RF simulation: Eigen mode



Mechanical simulation: displacement

Design	Mode	*Original Frequency* (MHz)	Modified frequency (MHz)
Before compensation	π	1300.196	1299.667
After compensation	π	1300.552	1300.022

RF power coupler: Waveguide & Coaxial

Literature survey

Table : Pros and cons of waveguide (hole coupling) and coaxial (loop/ antenna) couplers

	Pros	Cons
Waveguide	• Simpler design • Better power handling • Easier to cool • Higher pumping speed	• Larger size • Bigger heat leak • More difficult to make variable
Coaxial	• More compact • Smaller heat leak • Easier to make variable • Easy to modify multipacting power levels	• More complicated design • Worse power handling • Require active cooling • Smaller pumping speed

Ref: S. Belomenstnykh et.al. ERL 02-8

RF power coupler: Waveguide & Coaxial

Literature survey

Table 2: Fundamental RF power couplers and windows.

Ref: S. Belomenstnykh et.al. ERL 02-8

Facility	Frequency	Coupler type	RF window	Max. power	Comments
LHC [4]	400 MHz	Coax variable (60 mm stroke)	Cylindrical	Test: 500 kWCW 300 kWCW	Traveling wave Standing wave
PEP-II [5]	476 MHz	WG fixed	Disk WG	Test: 500 kWCW Oper: 225 kWCW	RF window test Forward power, HER [6]
CESR [7] (B-cell)	500 MHz	WG fixed	Disk WG	Test: 450 kWCW Oper: 300 kWCW 360 kWCW	RF window test Beam power Forward power
KEK-B [8] (SC cavity)	509 MHz	Coax fixed	Disk coax	Test: 800 kWCW Oper: 380 kWCW	
LEDA [9]	700 MHz	-	Disk WG	Test: 800 kWCW	Similar to PEP-II window
APT [10] (SC cavity)	700 MHz	Coax variable (±5 mm stroke, 2×10^5 to 6×10^5)	Disk coax	Test: 1 MWCW 850 kWCW	Traveling wave Standing wave (fixed coupler)
SNS [11, 3] (SC cavity)	805 MHz	Coax fixed	Disk coax	Test: 2 MW peak 22 kW average	similar to KEK-B 720 kW @ 1 ms, 30 pps
JLab FEL [12]	1500 MHz	WG fixed	Planar WG	Test: 50 kWCW Oper: 30 kWCW	RF window test, very low ΔT
TESLA [13] (TTF2 & TTF3)	1300 MHz	Coax variable (17 mm stroke, factor of 20: 10^6 to 2×10^7)	Cylindrical	Test: 1.8 MW peak (4.68 kW average) 250 kW peak (3.3 kW average)	TW, 1.3 ms pulse @2 Hz @10 Hz

Selection of RF power coupler

- Available resources and expertise
- DESY/PITZ : Waveguide is a good option (spare window and RF components of gun can be used)

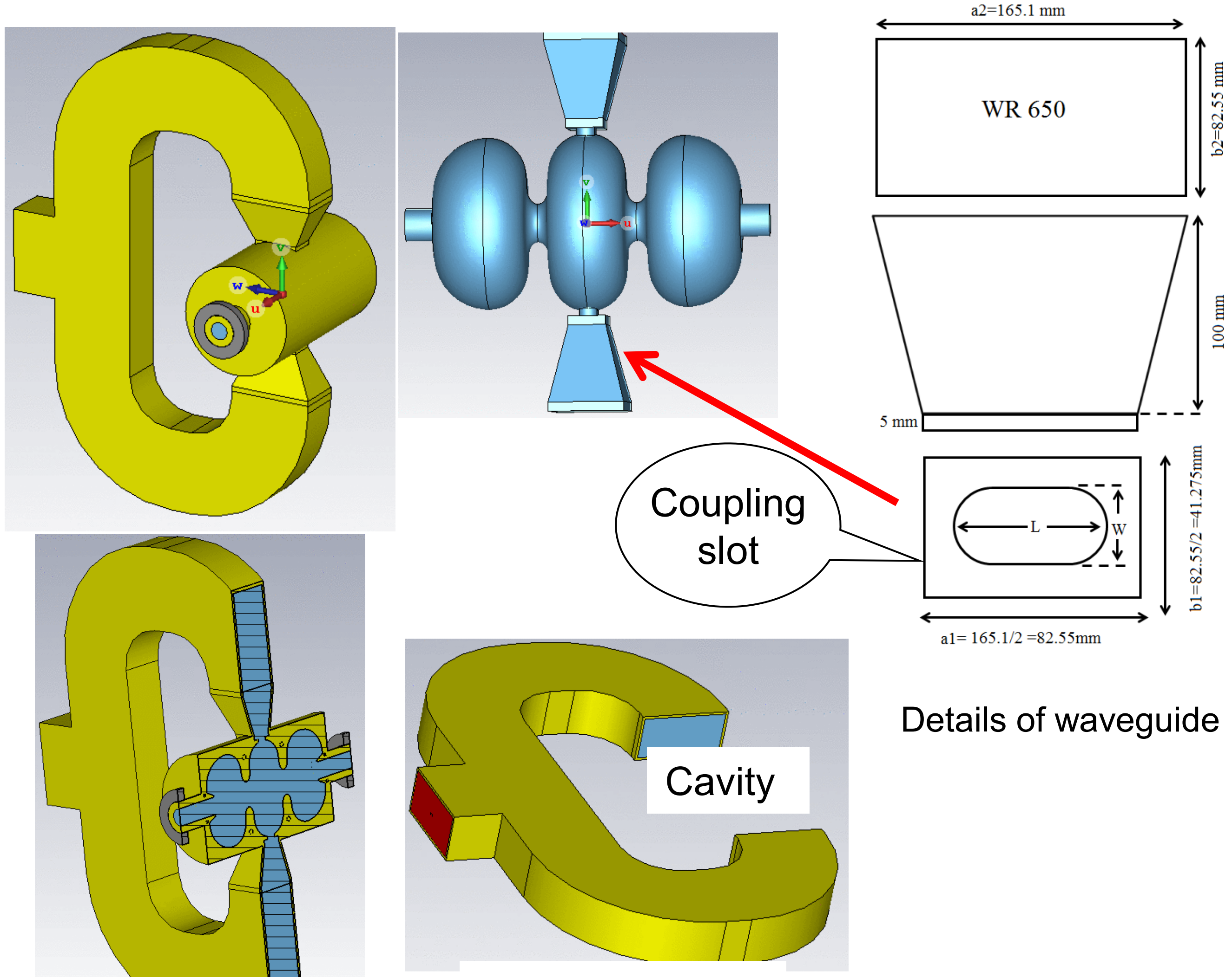
RF power coupler design: Dual feed

Design tool: CST Eigen solver

- Power feed at central cell
- Hole coupling
- Tapered waveguide
- Symmetric dual feed (to avoid dipole mode)

RF power coupler design goal

- Waveguide to cavity coupling coefficient (β_{RF}) ~ 1 (critical coupling, maximum power coupling) with π mode frequency of 1300 MHz with equal on-axis field amplitude in all cells (Field Flatness ~100%)
- R_1=99.87→99.468 mm
- RF coupling coefficient (β_{RF}) =Q_0/Q_{ext}
- Shut impedance reduced from 11.5MΩ → 9.97 MΩ (RF power requirement for 400 kV increase from 14kW→16kW (~5.3kW/cell)



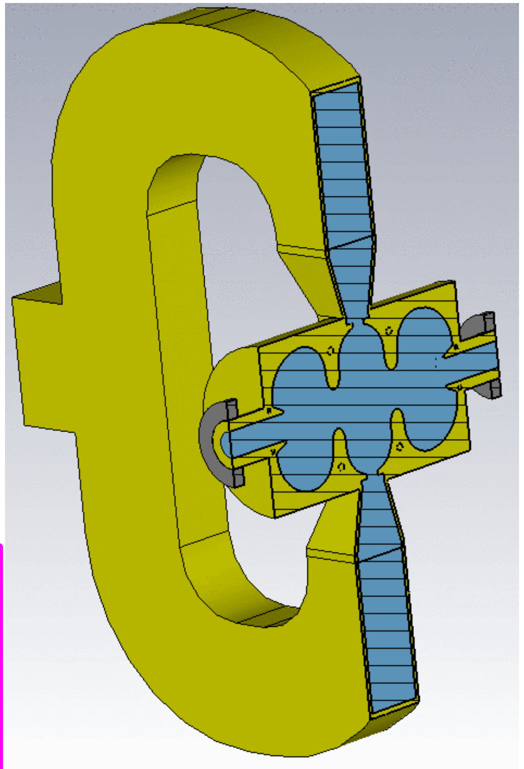
1:1 RF divider

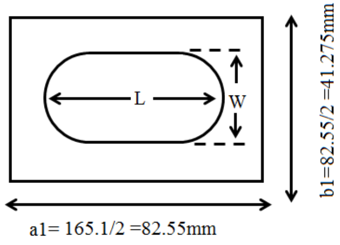
Different views of three cell buncher with RF power coupler

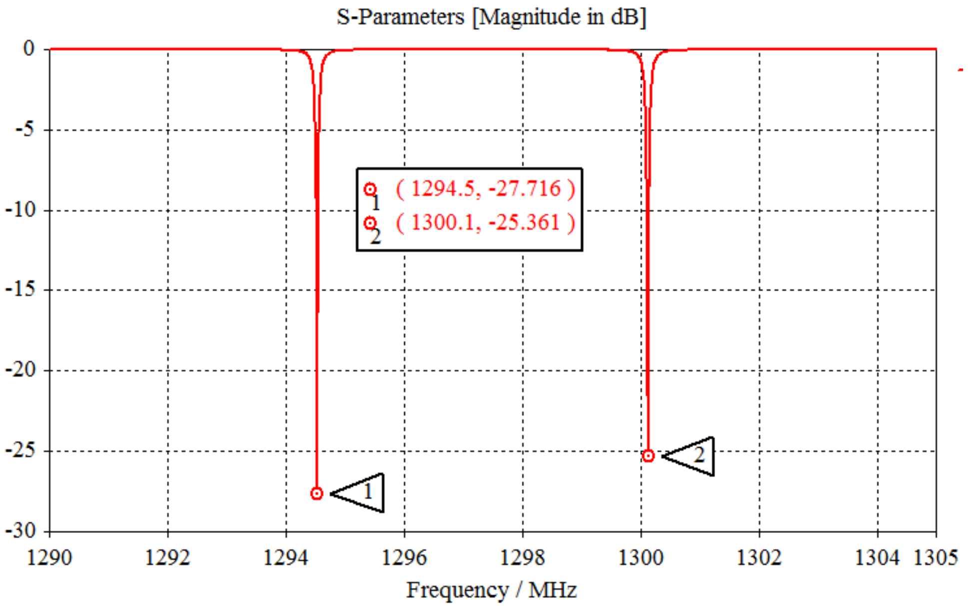
RF power coupler design: dual feed

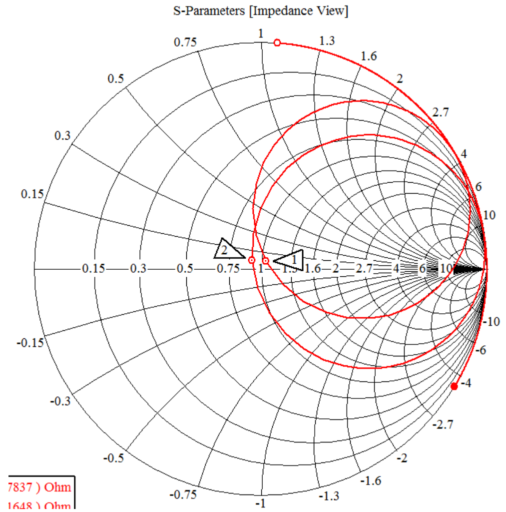
Design tool: Frequency domain solver

- ➢ Power feed at central cell
- ➢ Hole coupling
- ➢ Tapered waveguide
- ➢ Symmetric dual feed









- ➢ Frequency domain solver: S11
- ➢ Only two modes
  f_1=1294.5 MHz, f_2=1300.1 MHz
- ➢ Do not excite second mode: May be due to zero field in central cell
- ➢ Coupling coefficient :~ 1.1
- ➢ L=46.4 mm, W=20 mm

Fundamental coupler: Field asymmetry study

- Presence of RF power coupler: Break azimuthal symmetry
- Asymmetric structure : multiple modes→ emittance growth
- Study of multiple modes: Eigen mode solver CST MWS 2016
- Local mesh refinement near center of the structure

$$E_z = E_0 \sum_{m=0}^{\infty} A_m J_m\left(\frac{x_{m1}\rho}{R}\right) cosm(\theta-\theta_0)$$

$$E_z = E_{cavity} + E_{port}$$

$$E_z = E_0 \begin{bmatrix} Dcos(\theta-\theta_0) + Qcos2(\theta-\theta_0) \\ +Scos3(\theta-\theta_0) + Ocos4(\theta-\theta_0) \end{bmatrix}$$

From Ref. 1

$$Beam\ energy = \int_{-L/2}^{L/2} Re(eEz)dz = \frac{1}{2} eE_0 Lcos\overline{\varphi_0}$$

Maximum Energy $\langle\varphi_0\rangle=0$

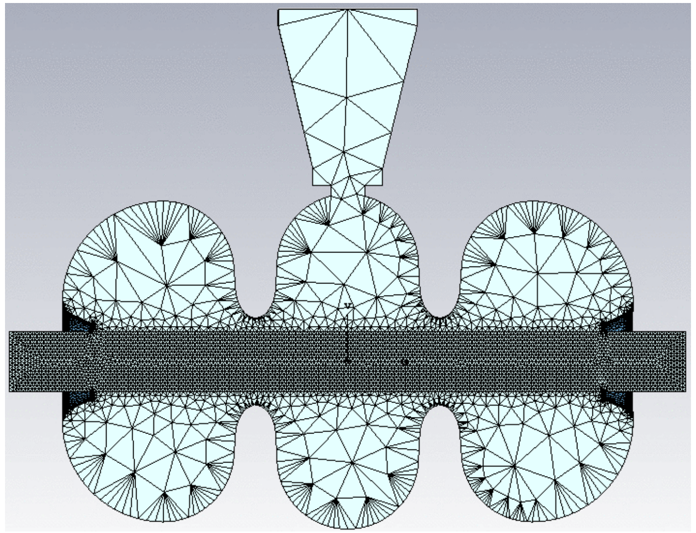


Fig.1: Mesh view showing local meshing in center

Field asymmetry: Emittance growth

$$Monopole\ \varepsilon_{n,x}^{010} = \frac{k_c^2}{2} \alpha\ Lcos\overline{\varphi_0}\sigma_x^2\sigma_\varphi, \varepsilon_{n,y}^{010} = \frac{k_c^2}{2} \alpha\ Lcos\overline{\varphi_0}\sigma_y^2\sigma_\varphi$$

$$Dipole\ \varepsilon_{n,y}^{110} = a_1 \alpha Lcos\overline{\varphi_0}\sigma_y\sigma_\varphi, coupler\ in\ y\ direction\ (\theta_0 = \frac{\pi}{2})$$

$$Quadrupole\ \varepsilon_{n,x}^{210} = 2a_2\alpha Lcos\overline{\varphi_0}\sigma_x^2\sigma_\varphi, \varepsilon_{n,y}^{210} = 2a_2\alpha Lcos\overline{\varphi_0}\sigma_y^2\sigma_\varphi$$

Maximum for $\langle\varphi_0\rangle=0$

Zero for bunching phase

Ref: 1. Juho Hong and Yong Woon PARC, Reduction of higher-order field distribution in a photocathode rf gun for the X-ray Free electron Laser", Journal of the Korean Physical Society, Vol 65, No 12, December 2014, pp. 2023-2032

2. M.S. Chae *et al*., "Emittance growth due to multipole transverse magnetic mode in an rf gun", PRSTAB 14,104203 (2011)

Fundamental coupler: Field asymmetry study

- Coupler + dummy ports of same shapes and size

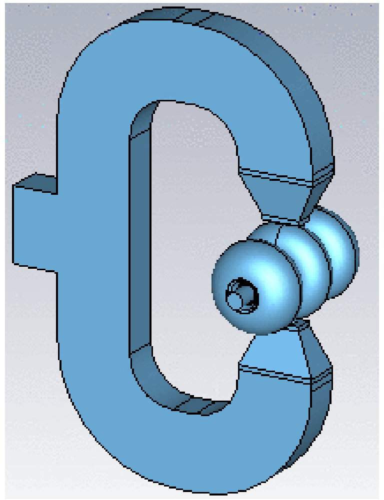


Fig.1: cavity with dual feed.

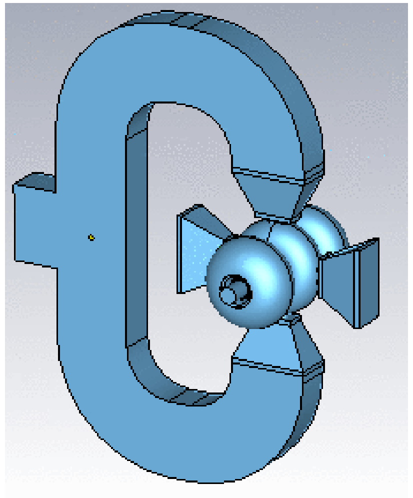


Fig.3: Cavity with dual feed and dummy ports.

Table: Normalized Fourier coefficients ($r=7\sigma_r=17.5$ mm)

Feed type	Dipole	Quadrupole	Sextupole	Octupole
No feed	3.03e-8	6.32e-8	3.47e-8	7.80e-8
Single feed	1.47e-3	1.90e-4	4.02e-5	8.71e-6
Dual feed	1.10e-5	4.24e-4	6.39e-6	1.33e-5
Dual feed with two dummy ports	7.83e-7	1.28e-7	9.8e-7	2.00e-5

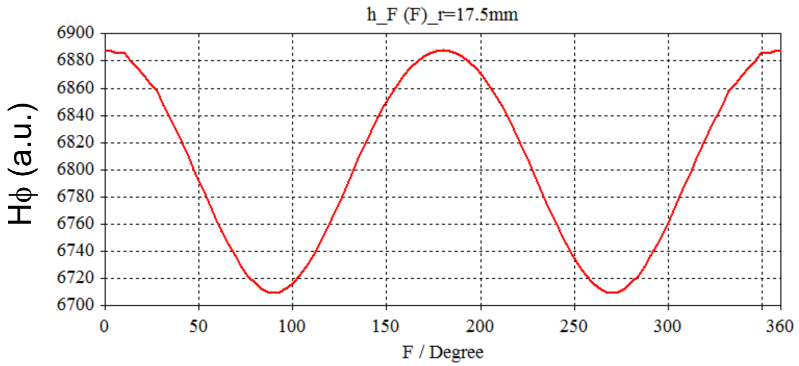


Fig.2: Variation in H_ϕ with ϕ for dual feed as shown in Fig.1.

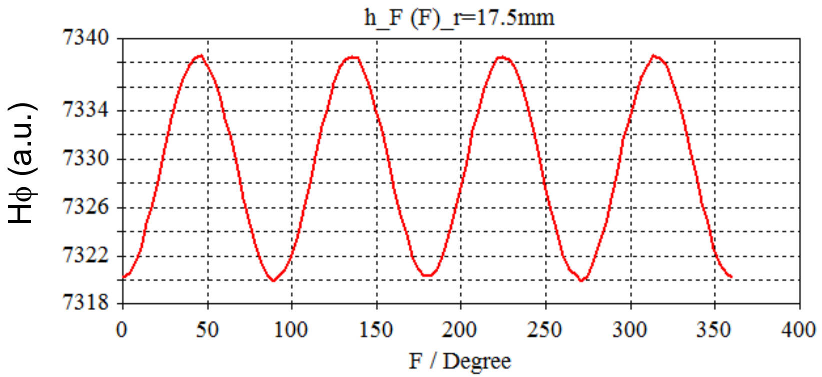


Fig.4: Variation in H_ϕ with ϕ for dual feed with two dummy ports as shown in Fig.3.

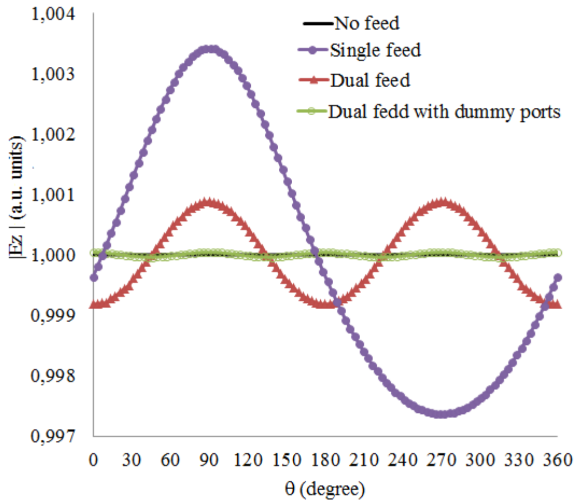
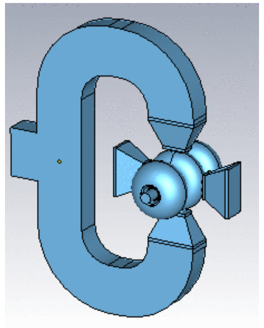


Fig.5: Variation in Ez with ϕ for different options.

Fundamental coupler→ Field asymmetry study → re-tuning

- **Presence of RF feeding ports and dummy ports: change RF properties of cavity (resonance frequency, coupling coefficient and field uniformity)→ re-optimization for the π mode at 1300 MHz with β_{RF}~1 and FF~100%**
- **Tool: Frequency domain solver CST MWS 2016**



Coupling slot : Length =46.4 mm, Width = 20mm,

Dummy slots for multipole mode elimination: Length =46.4 mm, Width = 20mm,

Central cavity radius: changed from 99.468 mm → 99.16mm

RF coupling coefficient: ~ 0.91

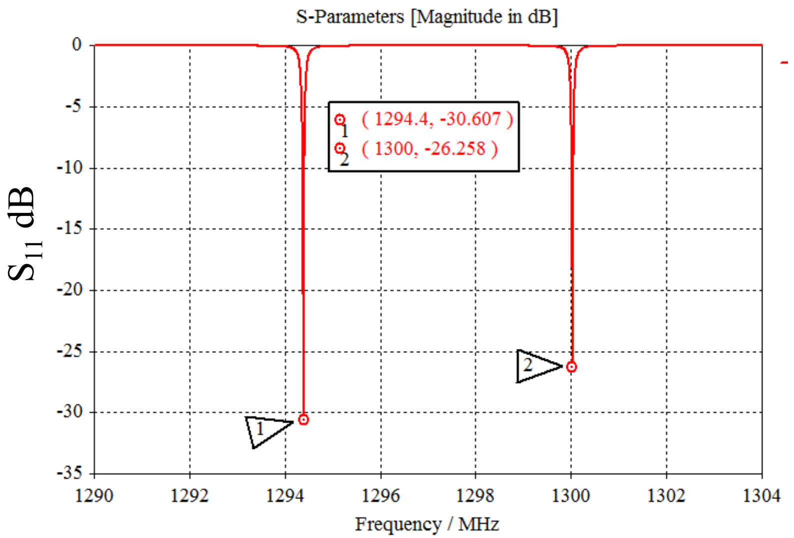


Fig.1: Frequency spectrum of cavity after tuning.

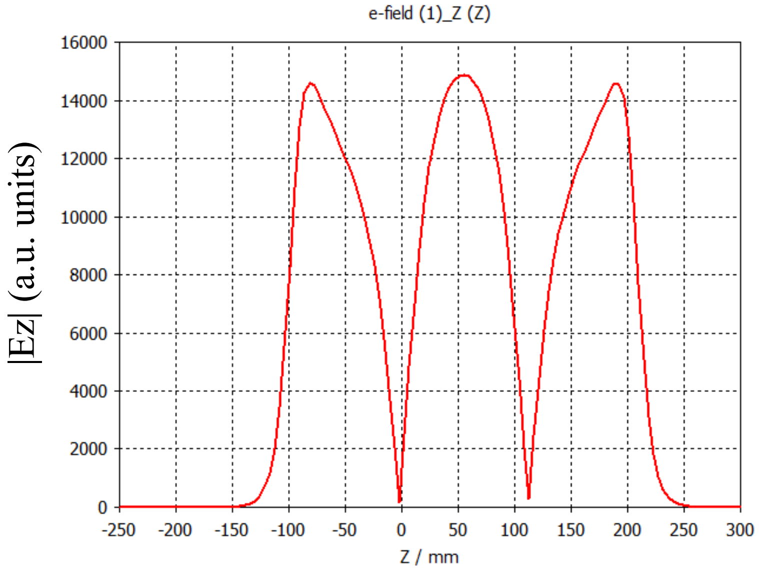


Fig.2: On-axis accelerating field profile after tuning of cavity.

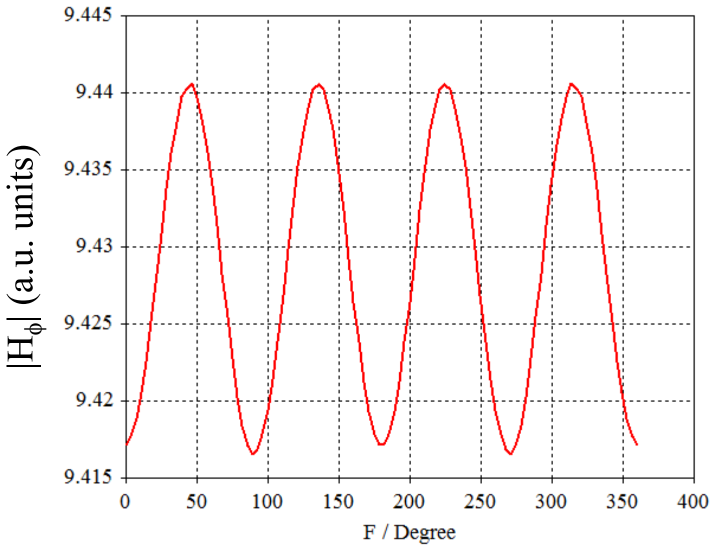
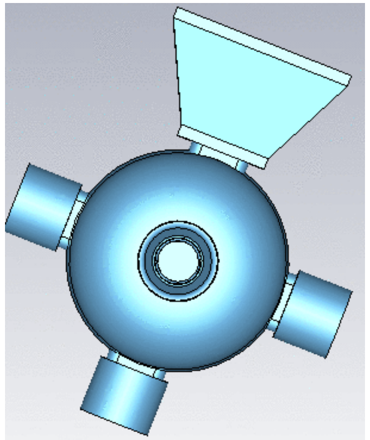
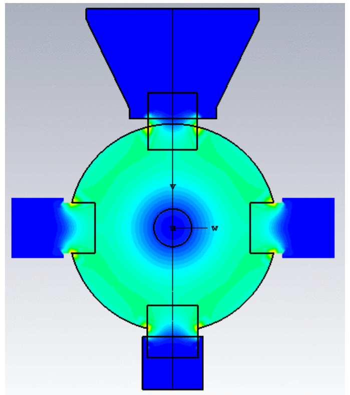


Fig.3: Variation in H_ϕ with ϕ after tuning of cavity.

Single Feed coupler: Field asymmetry study

- Tool : Frequency domain CST MWS 2016
- Single feed + (vacuum + two dummy) ports of cylindrical shape





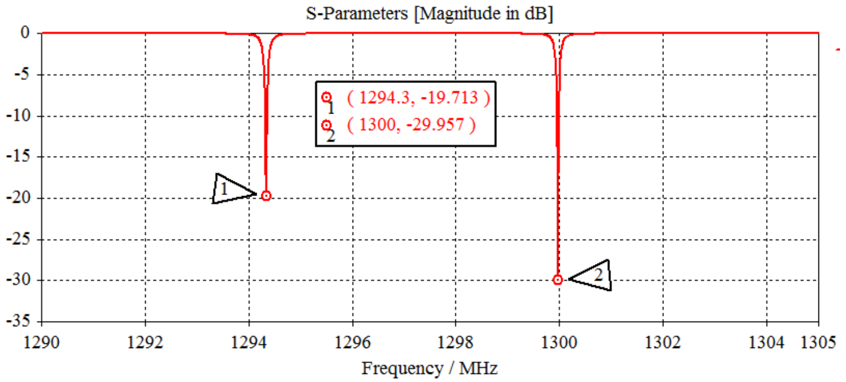


Fig. 1: S11 with frequency

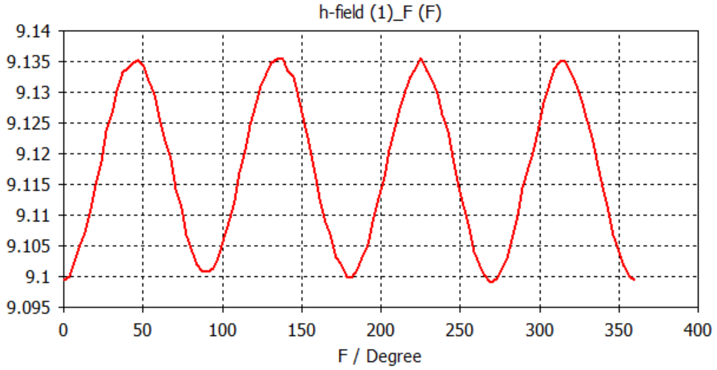


Fig. 2 : $|H_\phi|$ with ϕ at r=17.5 mm and z = center of coupler cavity center

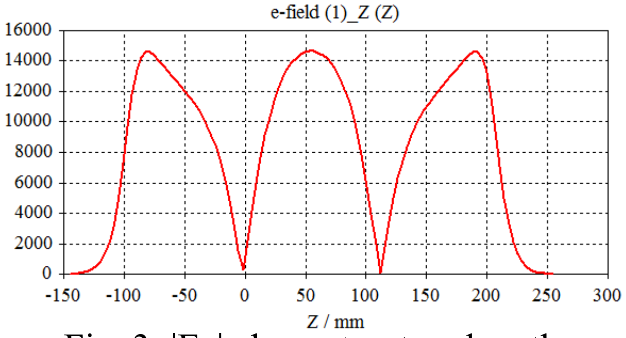


Fig. 3: |Ez| along structure length

- Coupling slot (oblong shape) : L=54.5 mm, W = 20mm (coupler slot length changed to make β_{RF}~1)
- Vacuum / dummy slot (oblong shape): L=55.4 mm, W =20 mm
- Center cell ID changed to make |Ez| uniform.
- Center cell ID: 98.75mm

Table: Normalized Fourier coefficients ($r=7\sigma_r$ =17.5 mm)

Feed /multiple modes	D	Q	S	O
RF port (Single)	1.47e-3	1.90e-4	4.02e-5	8.71e-6
All port (RF+ vac+2 dummy) same size	2.60e-4	3.31e-5	7.58e-6	3.01e-5
Vacuum/dummy ports optimized	9.20e-7	9.04e-7	1.30e-6	3.24e-5

Fundamental coupler: Field asymmetry study→ comparison

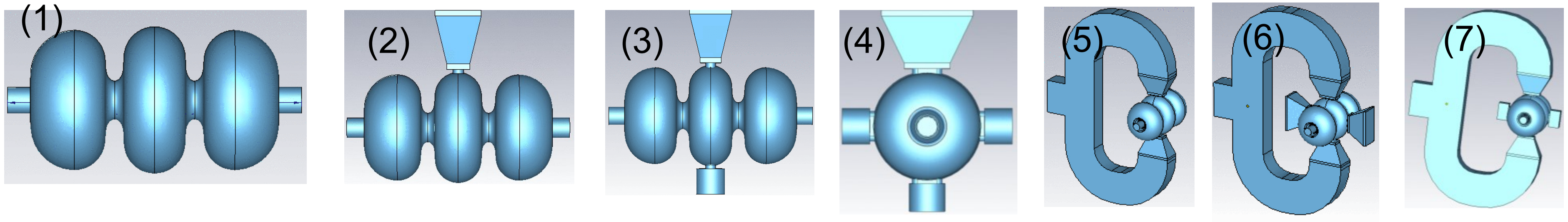
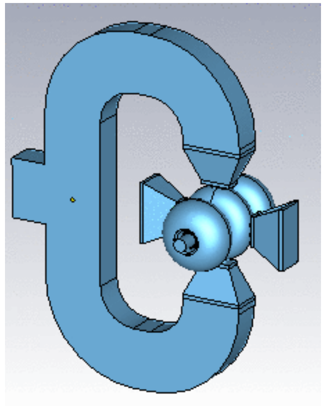


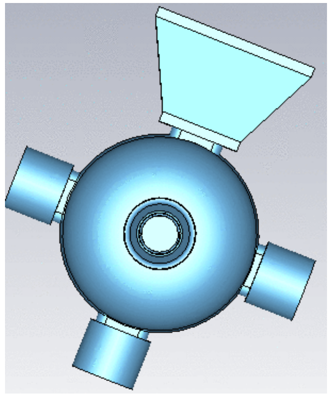
Table: Normalized Fourier coefficients (r=7σ_r =17.5 mm)

	Feed type	Dipole	Quadrupole	Sextupole	Octupole
(1)	No feed	3.03e-8	6.32e-8	3.46e-8	7.80e-8
(2)	Single feed (tapered WG)	1.47e-3	1.90e-4	4.02e-5	8.71e-6
(3)	Single feed (tapered WG) + Vacuum port (dimension optimized)	9.45e-6	3.91e-4	6.42e-6	1.26e-5
(4)	**Single feed (tapered WG) + Vacuum +2 dummy ports (dimension optimized)**	**9.20e-7**	**9.04e-7**	**1.30e-6**	**3.24e-5**
(5)	Dual feed (tapered WG)	1.10e-5	4.24e-4	6.39e-6	1.33e-5
(6)	**Dual feed (tapered WG) +2 dummy ports of same size and shape**	**7.83e-7**	**1.282e-7**	**9.83e-7**	**2.00e-5**
(7)	**Dual feed (tapered WG) +2 dummy ports of rectangular shape**	**4.91e-7**	**7.34e-7**	**9.51e-7**	**1.96e-5**

Fundamental coupler: variation in phase

- Presence of RF port gives a variation in phase → emittance growth



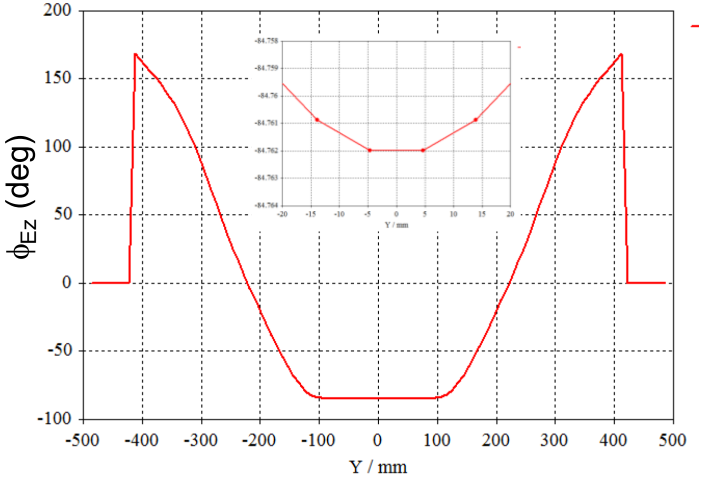


$$E_z = E_0 e^{i(\omega t + \sum \varphi(\theta-\theta_0) + \sum \varphi(y))} \sum_{m=0}^{\infty} A_m J_m\left(\frac{x_{m1}\rho}{R}\right) cosm(\theta-\theta_0)$$

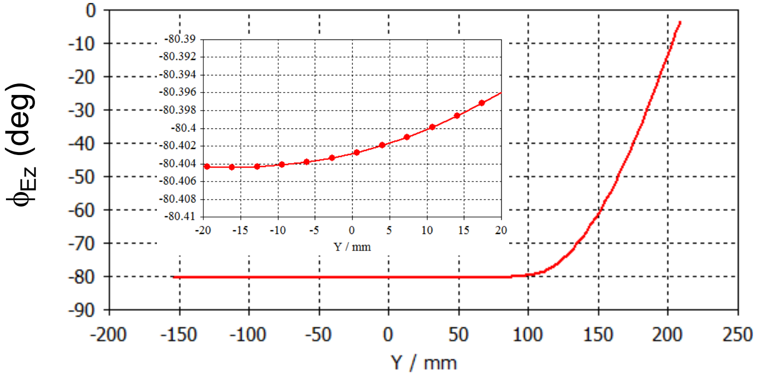
$$\varphi(\theta-\theta_0) = \cos M(\theta-\theta_0)$$
$$\varphi(y) = a_0 + a_1 y + a_2 y^2 + \cdots$$

For linear term in ‘y’

$$\varepsilon_{ny} = \frac{1}{2}\alpha a_1 \lambda \sigma_y \sigma_\varphi sin\varphi_0$$ (Ref. 1)



Dual feed + two dummy



single feed + two dummy

Feed type / emittance	a_0	a_1/ mm	a_2 /mm^2
Dual + 2 dummy Emittance (mm mrad)	-84.8	2.53e-14 ~1e-12	6.06e-6
Single+3 dummy Emittance (mm mrad)	-80.4	2.09e-4 9.7e-3	6.65e-6

- Emittance growth ~0.01 << required value 0.1
- To be checked by beam dynamics simulations

Ref. 1 : H. J. Qian et al. FEL2012 (MOPD55)

Summary

- RF design of a three-cell 1300 MHz buncher is carried out
- Multipacting is studies and mitigated by suitable geometrical modifications.
- Multiphysics (RF, thermal and mechanical) coupled analysis has been carried out and a suitable cooling scheme has been devised to compensate the thermal effects.
- WR650 waveguide (tapered) based RF power coupler is designed.
- Study of multipole modes induced due to presence of RF power coupler is studied. The amplitude of dipole, quadrupole and sextupole modes are minimized by adding additional ports.

Out look

- Study of variation in RF parameters with geometrical dimensions (determination of geometrical tolerances)
- Study of RF power pick ups
- Design of RF tuners
- Study of loop based RF power coupler ???

Acknowledgments

I would like to thanks Dr. Houjun Qian, Dr. Guan Shu, Dr. Hamed Shaker, Dr. Frank Stephan and all PITZ team members for useful discussions and critical feedback.

I would also like to thanks Dr. Valentin Paramonov from *Institute for Nuclear Research of Russian Academy of Sciences, Moscow, Russia* for his feedback on thermal design issues.

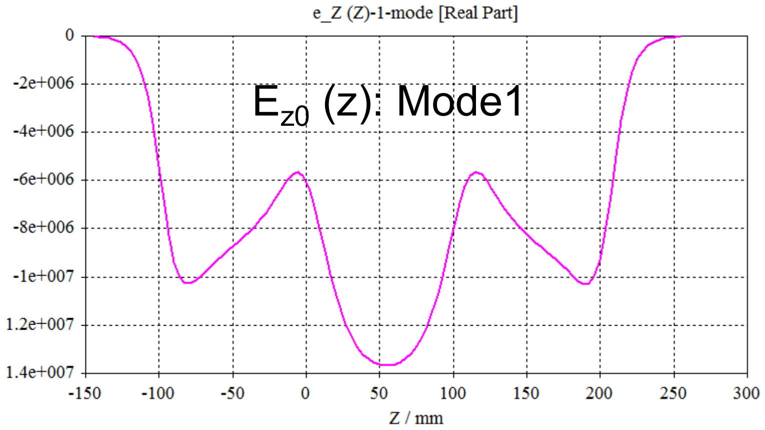
Thank you for your attention

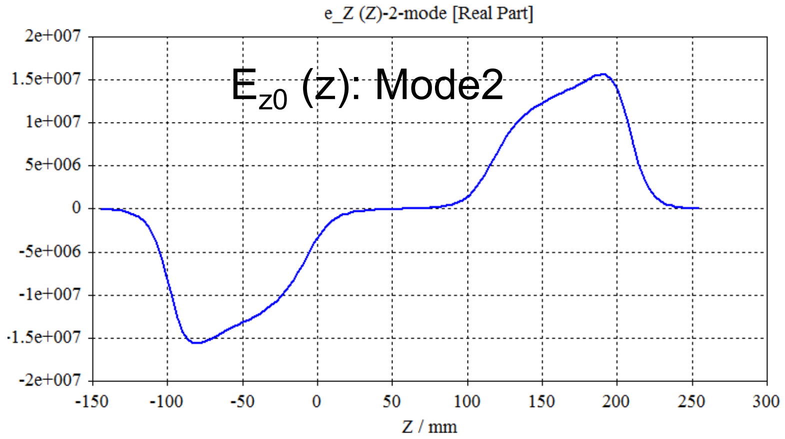
Give your feedback and comments

Backup slides

Three-cell buncher: Eigen modes

- Central geometry similar to SCRF cavities (TESLA type) with re-entrant end
- Three modes : last mode is π, first 2 either π/3, 2π/3 or 0, π/2 (see table)





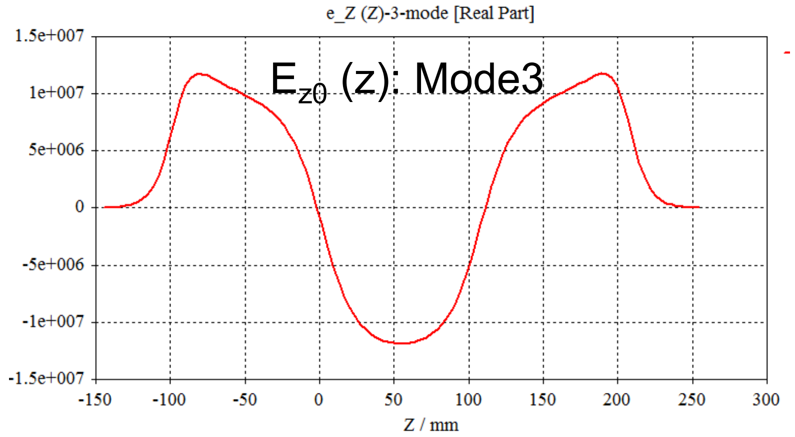


Table 1: 'Flat-Field' Cavity Phase Values and Amplitudes

End Termination	Mode ϕ_q	End Cell Detune	Field Amplitudes	Phase Values	Mode Numbering
Full	0	$f_{end}=f_0\sqrt{1-k/2}$	$i_n \sim \cos[(n-1/2)\phi_q]$	$\phi_q=\frac{\pi(q-1)}{N}$	$q=1,2,3,\cdots,N$
Full	$\pi/3$ $\pi/2$ $2\pi/3$	$f_{end}=f_0$	$i_n \sim \sin(n\phi_q)$	$\phi_q=\frac{\pi q}{(N+1)}$	$q=1,2,3,\cdots,N$
Full	π	$f_{end}=f_0\sqrt{1+k/2}$	$i_n \sim \sin[(n-1/2)\phi_q]$	$\phi_q=\frac{\pi q}{N}$	$q=1,2,3,\cdots,N$
Half	0 $\pi/2$ π	$f_{end}=f_0$	$i_n \sim \cos[(n-1)\phi_q]$	$\phi_q=\pi\frac{(q-1)}{(N-1)}$	$q=1,2,3,\cdots,N$

- Structure has full cells at end
- Cells are tuned to have equal field amplitude for π mode
- Three cells: N=3

Mode/ Cell	1	2	3	Mode type
Mode 1	0.5	1	0.5	π/3
Mode 2	0.866	~0	-0.866	2π/3
Mode 3	1	-1	1	π

Ref : Stan O. Schiber, " To be π or not to be π: that is the dilemma", EPAC02

Methods to decrease the SEY

- Changing the surface composition
- Changing the surface roughness
- The “dose” effect
- Photon dose effect

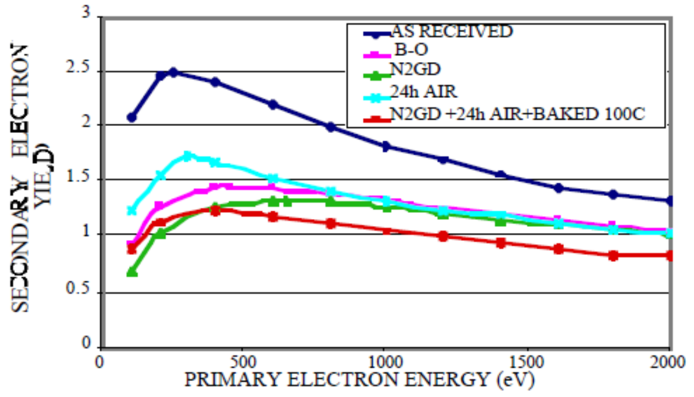


Figure 7: S.E.Y. of copper after various surface treatments

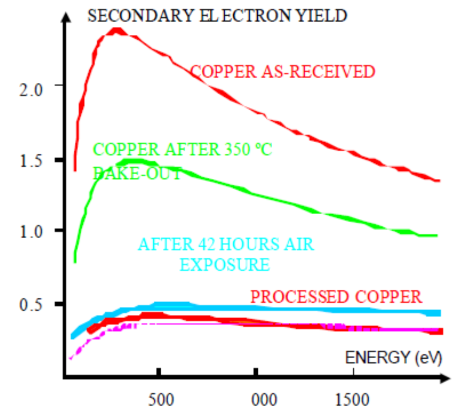


Figure 11: Secondary electron yield of a textured copper surface

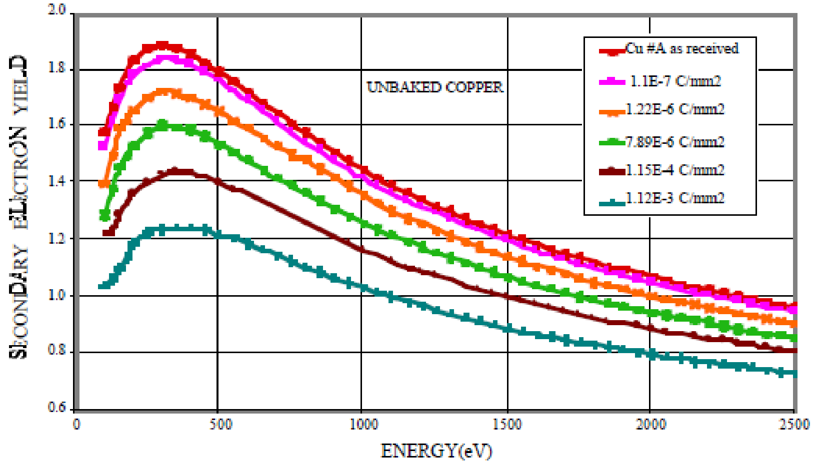


Figure 12: Variation of the S.E.Y. of copper with the incident electron dose

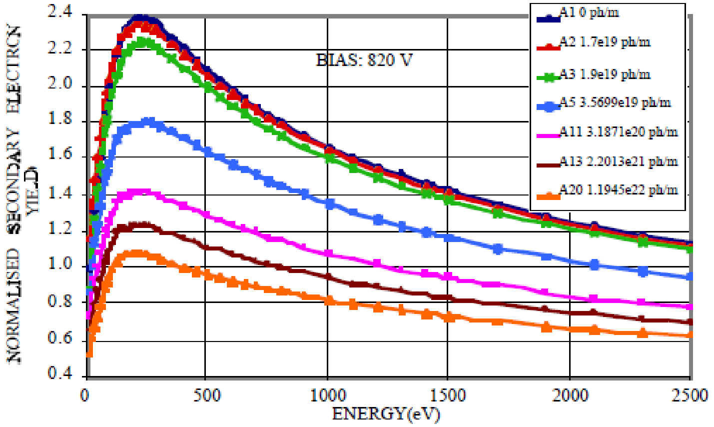


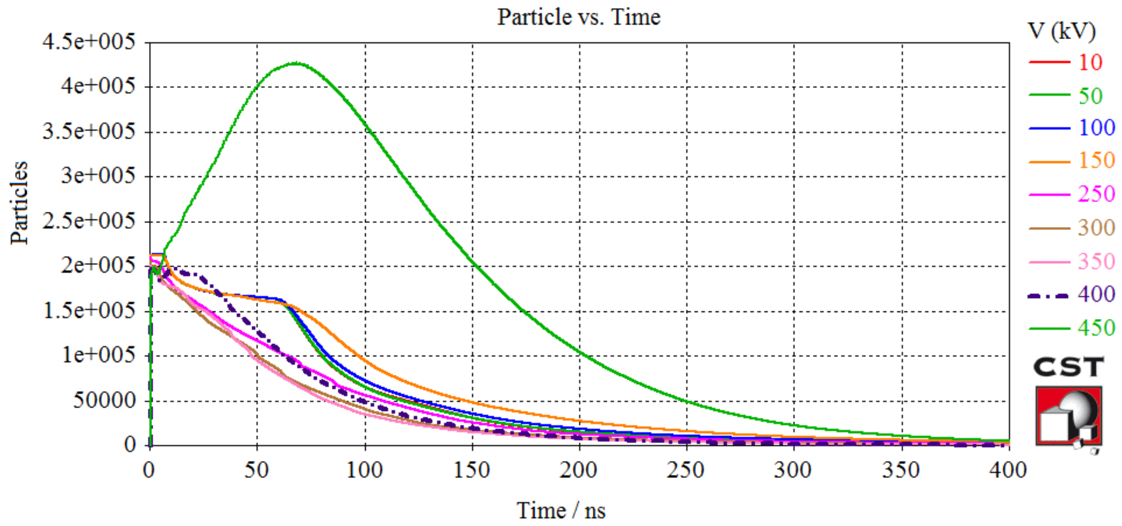
Figure 14: Variation of the S.E.Y. of with the photon dose

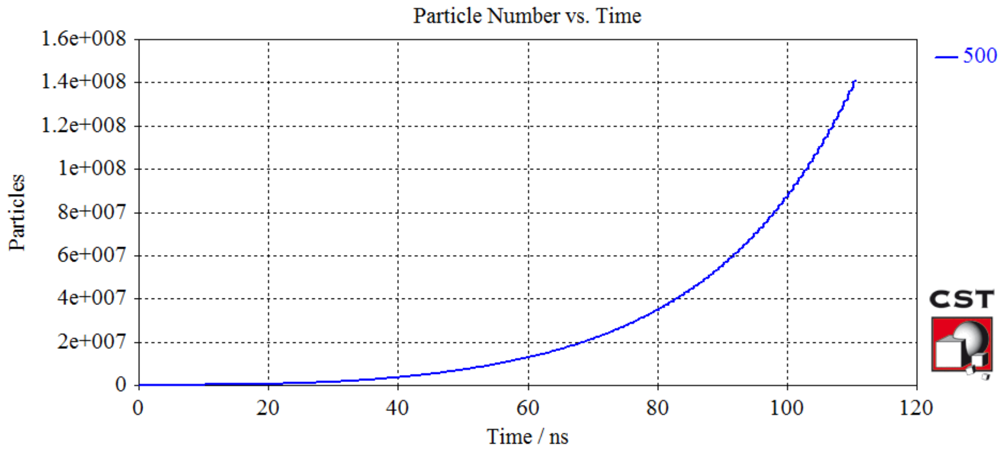
Ref V. Baglin *et al.* , “The secondary electron yield of technical materials and its variation with surface treatment”, EPAC 2000, pp.217-221;

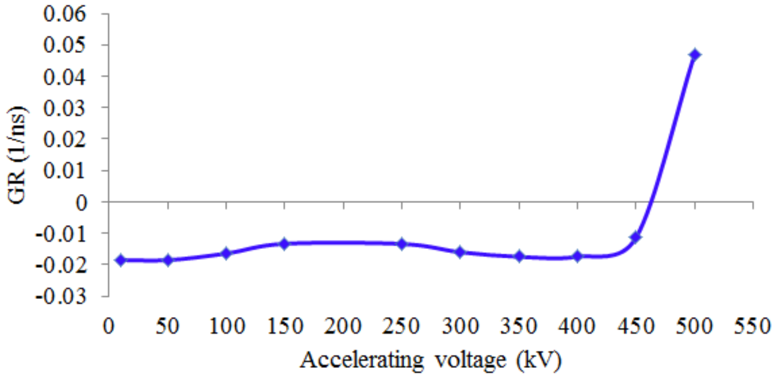
Multipacting simulation: comparison

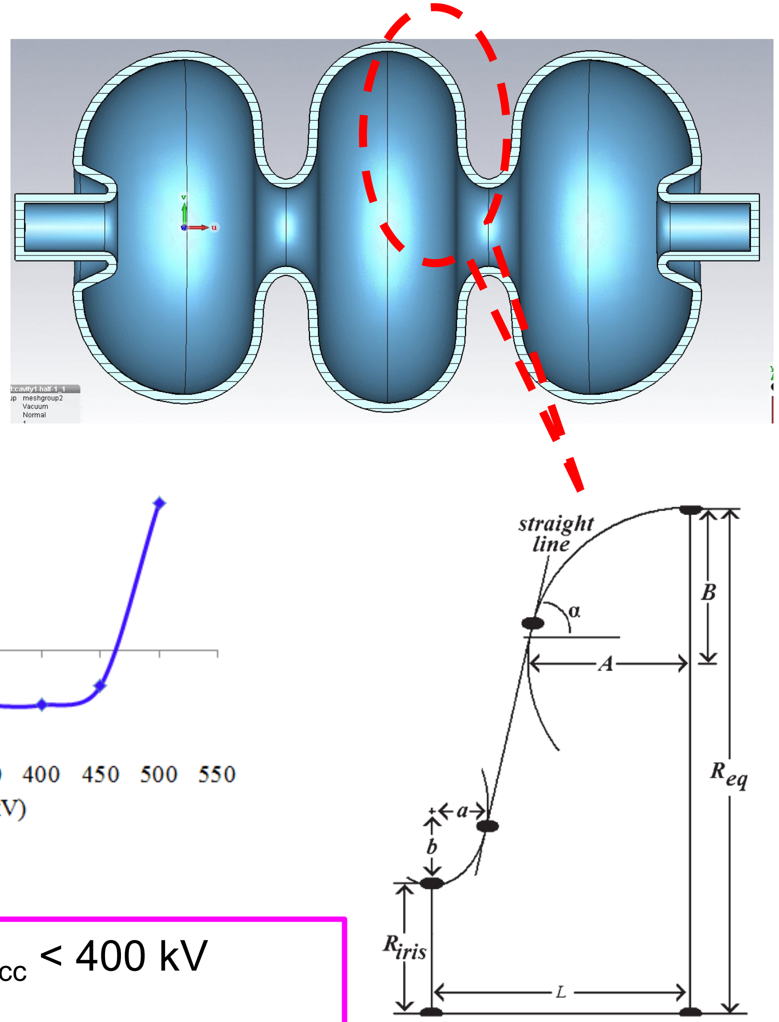
CST Particle Studio PIC solver (2017): emission cover 360 RF Phase

CST SEY data





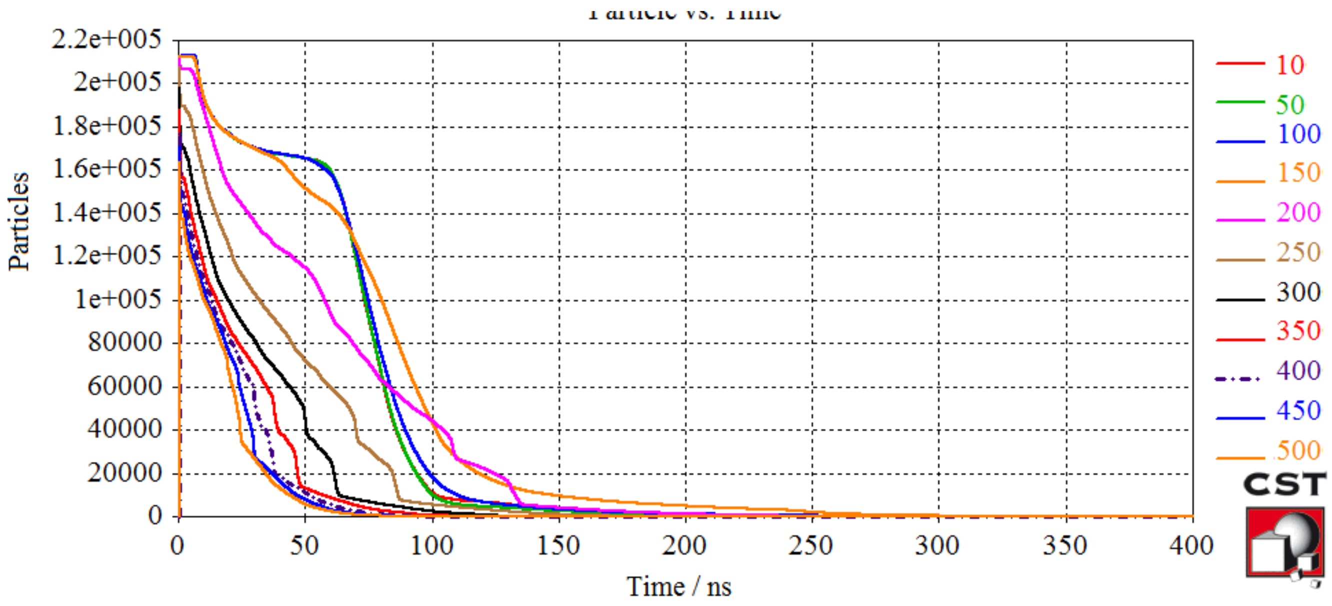


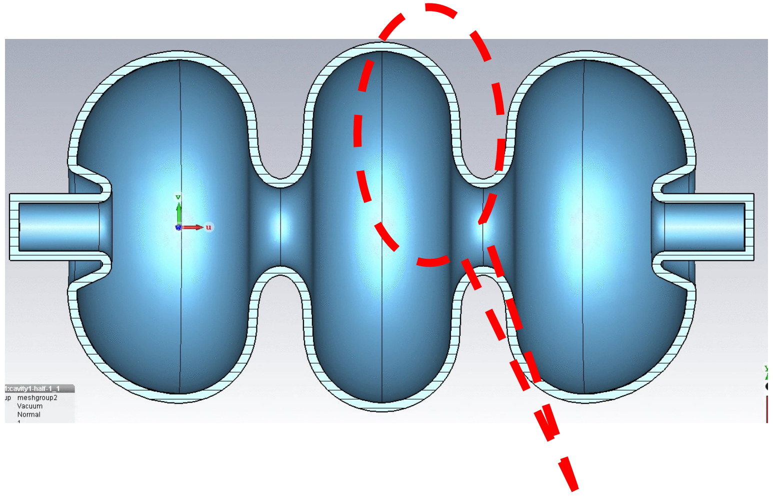


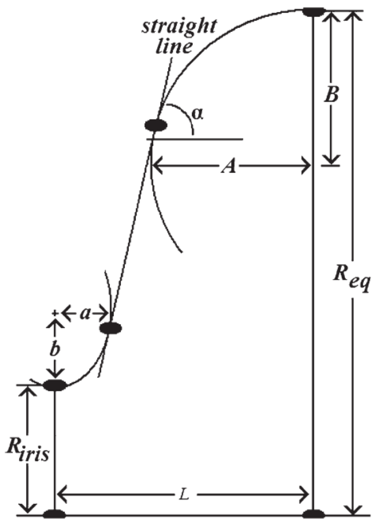
- Growth rate (GR) < 0 for V_{acc} < 400 kV
- Growth rate (GR) = 0.04/ns for V_{acc} 500 kV

Multipacting simulation: comparison

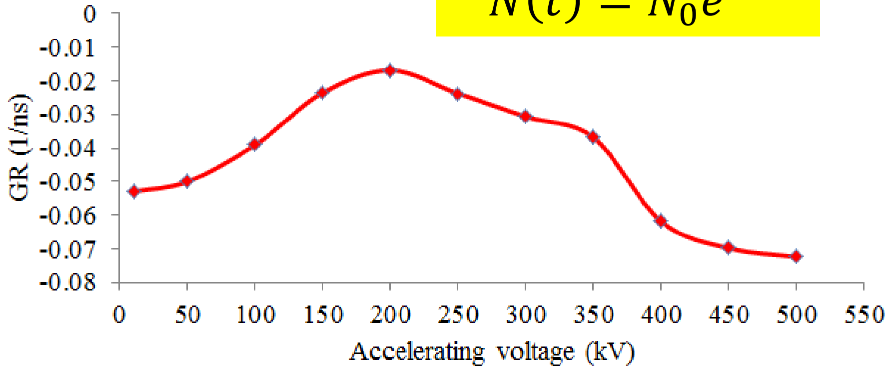
CST Particle Studio PIC solver (2017): emission cover 360 RF Phase
CERN SEY data







$$N(t) = N_0 e^{\alpha t}$$



- Growth rate (GR) < 0 for V_{acc} up to < 500 kV

Thermal Simulations : Analytical approach

Estimation of change in frequency with temperature : pill box approximation

$$Resonance\ frequency\ of\ pill\ box = f = \frac{2.404c}{2\pi R}, R = radius\ of\ cavity$$

- Change in frequency with temperature: Linear approximation

$$L = L_0[1 + \alpha\Delta T] \rightarrow 2\pi R = 2\pi R_0[1 + \alpha\Delta T]$$

α = thermal expansion coefficient ~16.7µm for copper
ΔT = temperature change

$$f = \frac{2.404c}{2\pi R_0[1 + \alpha\Delta T]} \approx f_0[1 + \alpha\Delta T]^{-1} \approx f_0[1 - \alpha\Delta T] = f_0 - f_0\alpha\Delta T$$

$\Delta f \approx -f_0\alpha\Delta T \rightarrow 21.71\ kHz/°C$ (for 1.3 GHz cavity)

Assumptions: Uniform surface temperature
Actual cavity under operating condition : non uniform change in temperature

Mechanical Simulations : Analytical approach

Estimation of change in frequency with radius : pill box approximation

$$Resonance\ frequency\ of\ pill\ box = f = \frac{2.404c}{2\pi R}, R = radius\ of\ cavity$$

- ❑ Change in frequency with radius

$$R = R_0 + \Delta, \qquad \Delta \ll R_0 \rightarrow R = R_0\left(1 + \frac{\Delta}{R_0}\right)$$

$$f = \frac{2.404c}{2\pi R} = \frac{f_0}{\left(1 + \frac{\Delta}{R_0}\right)} \approx f_0\left(1 - \frac{\Delta}{R_0}\right) \rightarrow f - f_0 = f_0\frac{\Delta}{R_0}$$

$\Delta f \approx f_0\frac{\Delta}{R_0} \rightarrow -14.72\frac{kHz}{\mu m}$ (for 1.3 GHz cavity R_0=88.294 mm)

Assumptions: Uniform change in radius
Actual cavity under stress: non uniform change in radius

RF power coupler

Literature survey

APEX

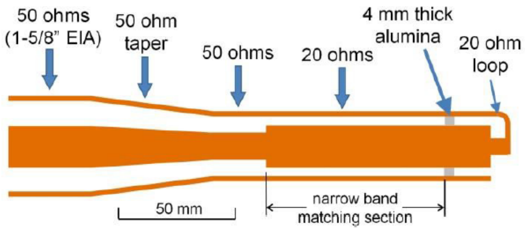
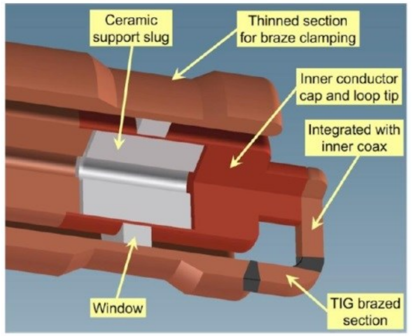
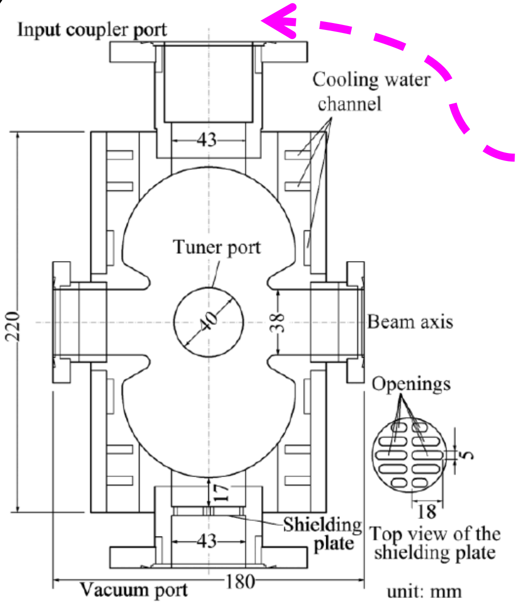


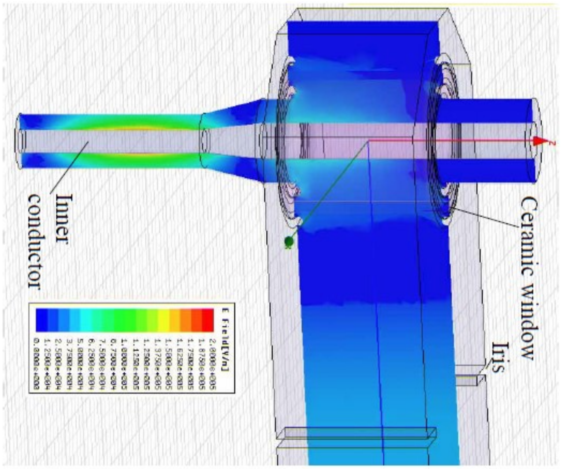
Figure 3: Internal geometry of the RF loop coupler.



- Coaxial loop couplers
- Customized design
- Each cavity 2 couplers(symmetric feed)
- 5/8" coaxial semi-rigid transmission line
- Each coupler ~2.5 kW
- TiN coating to eliminate MP

Ref: S. P. Virostek et al., IPAC2017





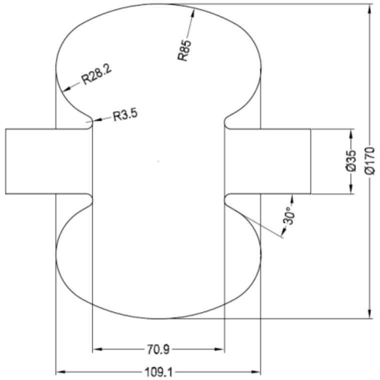
- Coaxial loop couplers (asymmetric feed)
- Cylindrical ceramic window
- Vacuum port with RF shielding
- RF conditioning up to 7 kW

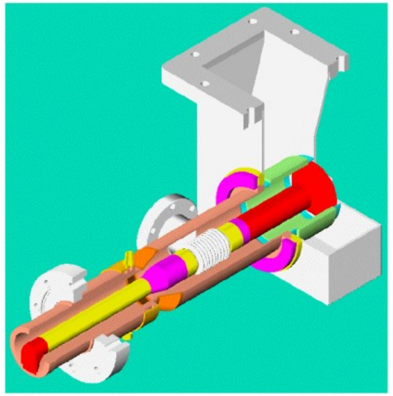
Ref: T. Takahasi et al., IPAC2014

RF power coupler

Literature survey

Cornell/Jlab ERL

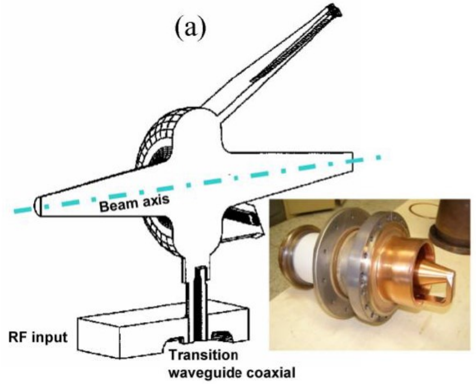


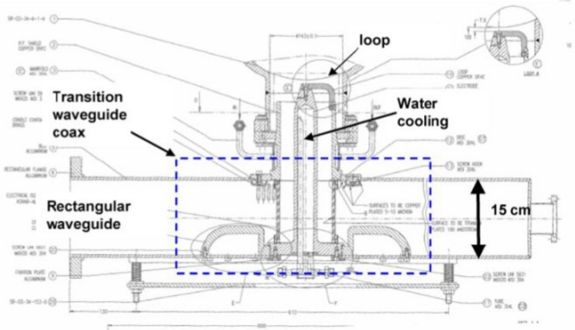


- Coaxial loop couplers (asymmetric feed)
- Cylindrical ceramic window (similar to warm window of TESLA
- RF conditioning up to 9.6 kW

Ref: V. Veshcherevich et al., PAC02, ERL03-2 and SRF 03506

DAΦNE (LNF-INFN)





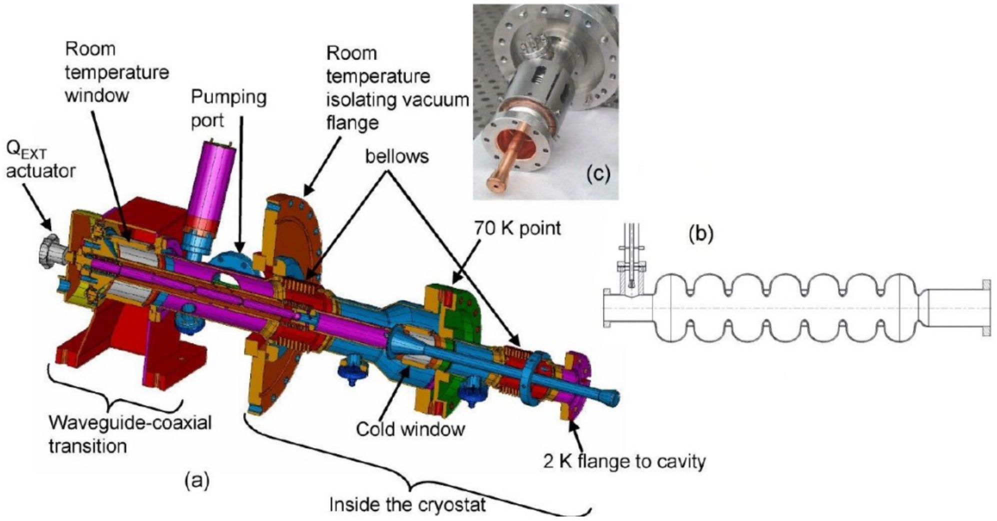
- Frequency 368 MHz
- Coaxial loop couplers (asymmetric feed)
- Cylindrical ceramic window
- RF conditioning up to 100 kW

Ref: S.Bratucci et al., PAC 1993

RF power coupler

Literature survey

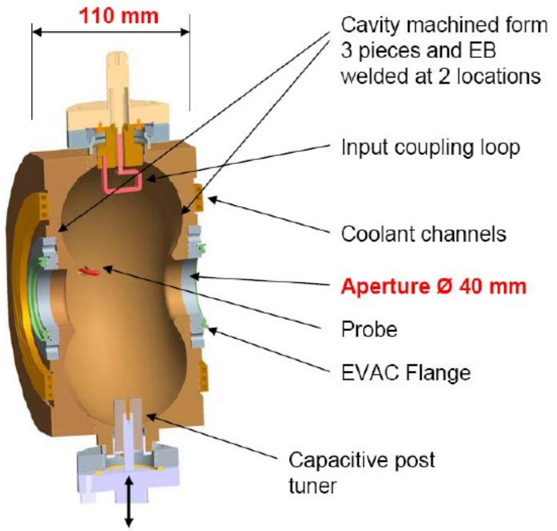
TESLA

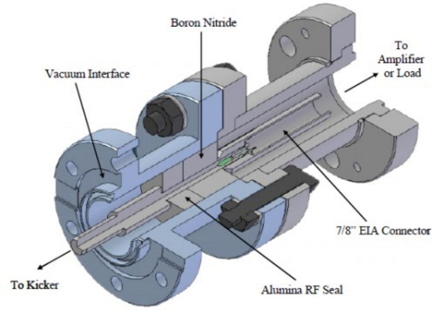


- Frequency 1300 MHz (SCRF)
- Coaxial antenna (asymmetric feed)
- Cylindrical ceramic window
- RF power > 200 kW

Ref: A. Aune PRSTAB 3 (2000) 092001

EMMA @ Daresbury



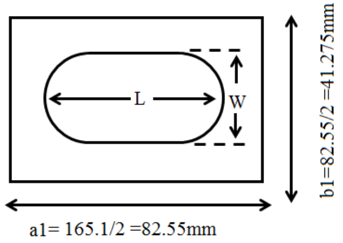


- Frequency 1300 MHz
- Coaxial loop
- Feed 7/8" EIA type transmission line (SLAC)
- RF power 8.1 kW (design/testing ??)

Ref: C.D. Beard et al. EPAC08

Fundamental coupler (dual feed): Field asymmetry study

- **Tool : Eigen mode solver CST MWS 2016:**
- **Local mesh refinement near center of the structure**
- **Dual feed + two dummy ports of rectangular shapes**



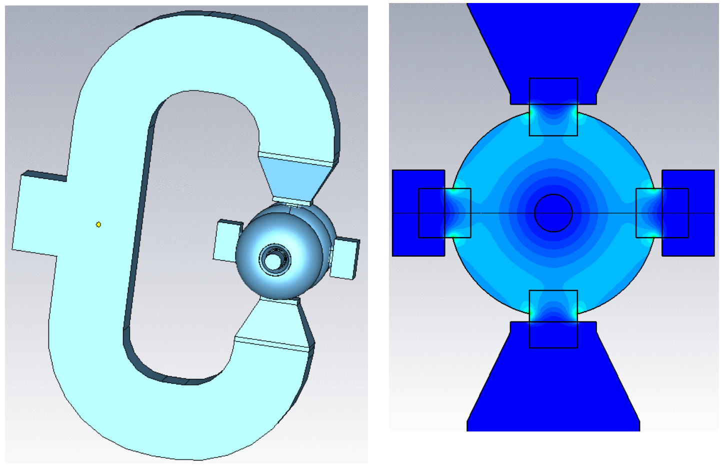


Fig.1: Structure with coupling and dummy ports

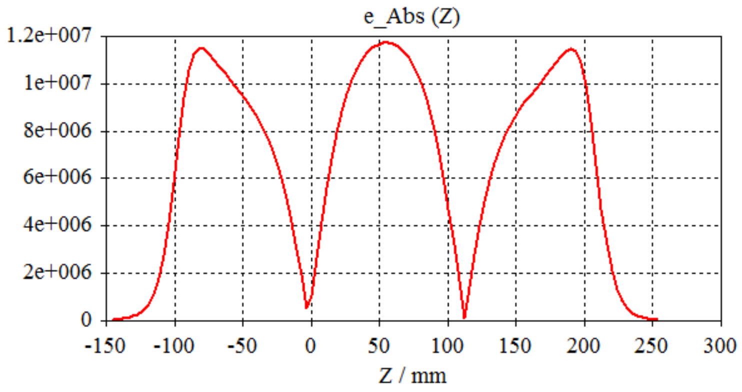


Fig.2: Variation in Ez with z .

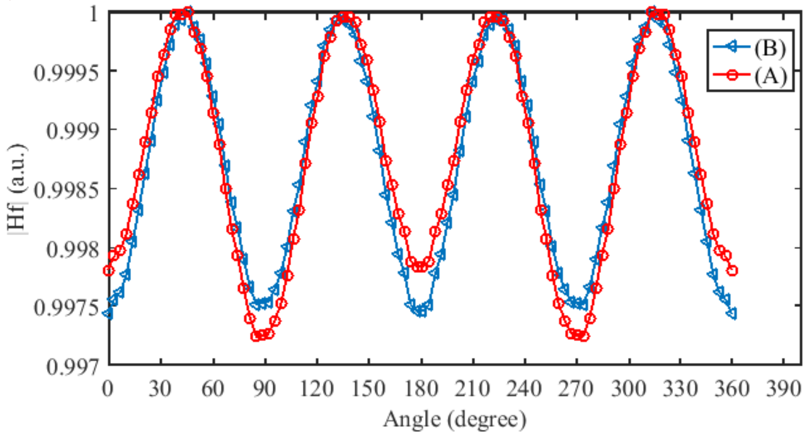


Fig .3 :Variation in H_ϕ with azimuthal angle for structure shown in Fig.1.: (A) coupling and dummy slots of same size (L=46.4mm, W=20 mm) and (B) coupling and dummy slots of different size (L= 46.9 mm, W=20 mm for dummy slots)

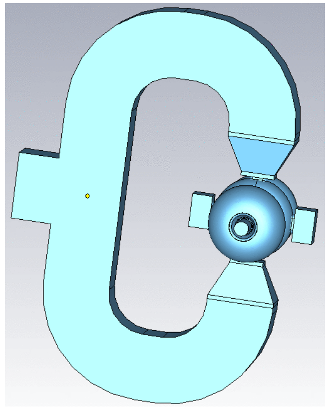
- Coupling slot (oblong shape) : Length =46.4 mm, Width = 20mm
- Dummy ports : Rectangular (41.275 mm x 82.55 mm) dummy
- Dummy slots (oblong shape): Length =46.9 mm, Width = 20mm

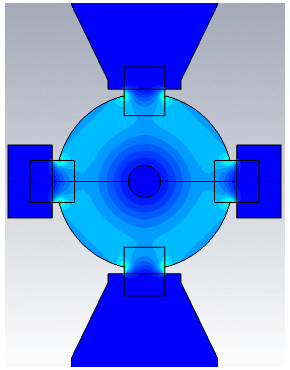
Table: Normalized Fourier coefficients (r=17.5 mm)

Feed	Dipole	Quadrupole	Sextupole	Octupole
Case (A)	4.43e-7	9.70e-6	1.12e-6	1.94e-5
Case (B)	4.91e-7	7.34e-7	9.51e-7	1.96e-5

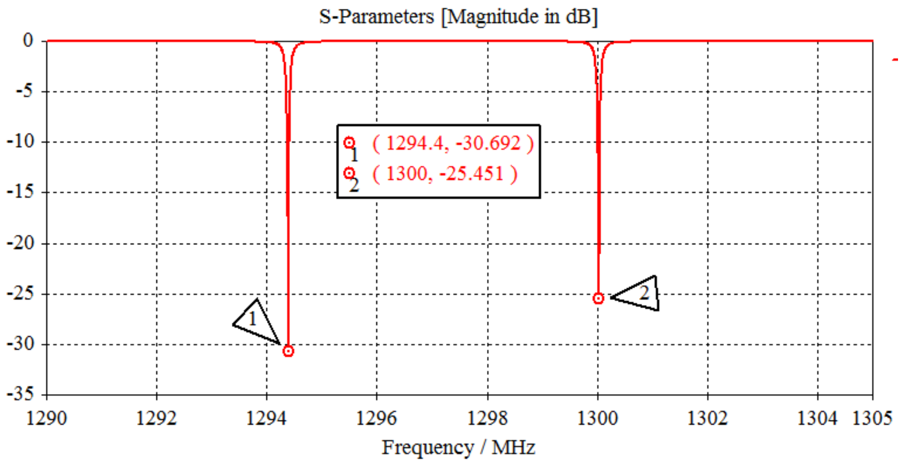
Fundamental coupler: Field asymmetry study

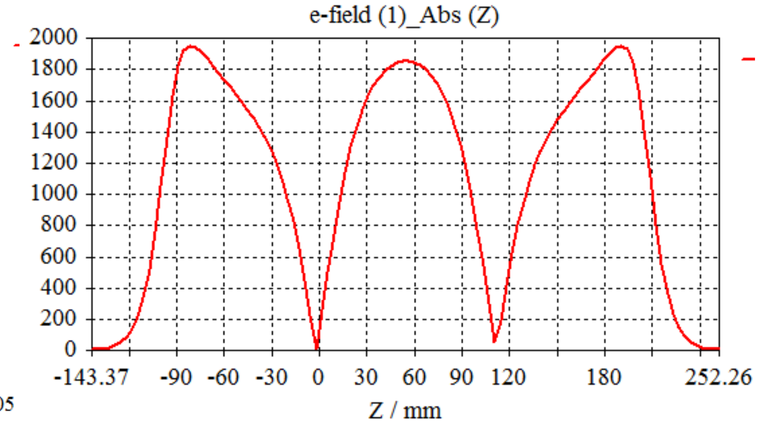
- **Tool : Frequency solver CST MWS 2016**
- **Local mesh refinement near center of the structure**
- **Dual feed + two dummy ports of rectangular shapes**

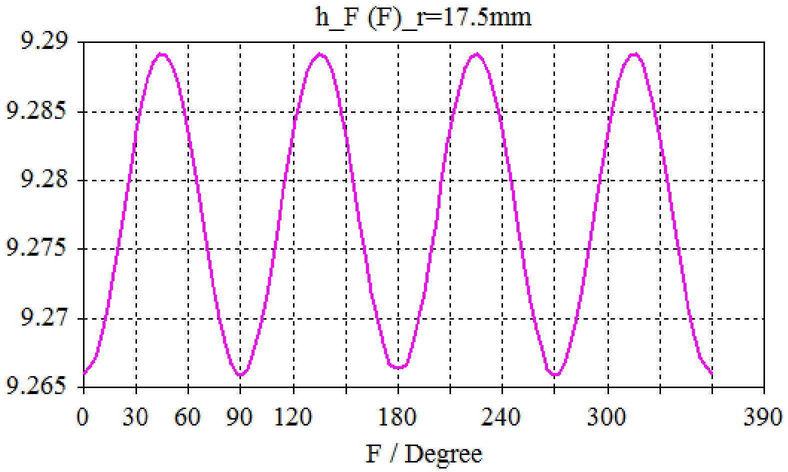




- Coupling slot (oblong shape) : Length =46.4 mm, Width = 20mm
- Dummy ports : Rectangular (41.275 mm x 82.55 mm) (WR650/2 dimensions)
- Dummy slots (oblong shape): Length =46.9 mm, Width = 20mm
- RF Coupling coefficient : ~0.91







Fundamental coupler: Field asymmetry study

- **Tool : Eigen mode solver CST MWS 2016:**
- **Local mesh refinement near center of the structure**
- **Single feed + vacuum port cylindrical shape**

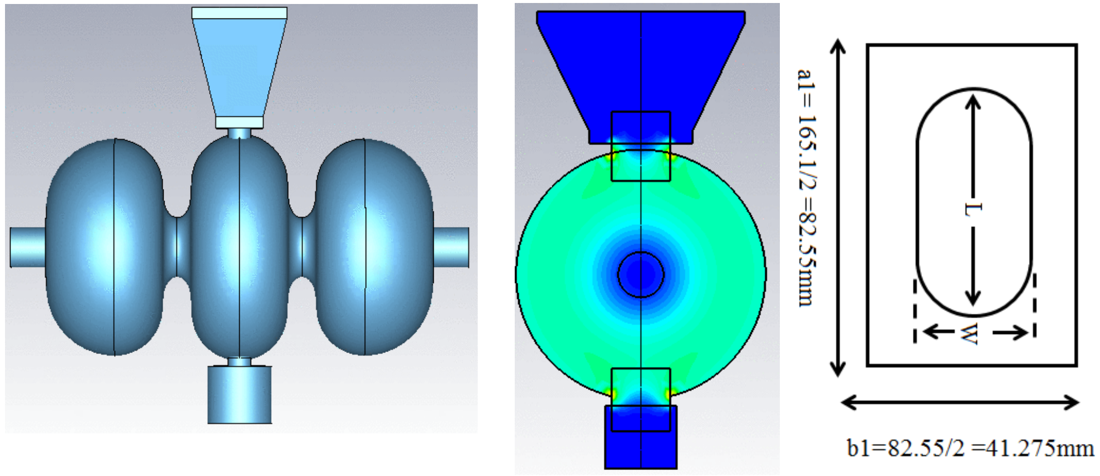


Fig.1: Structure with coupling and vacuum port

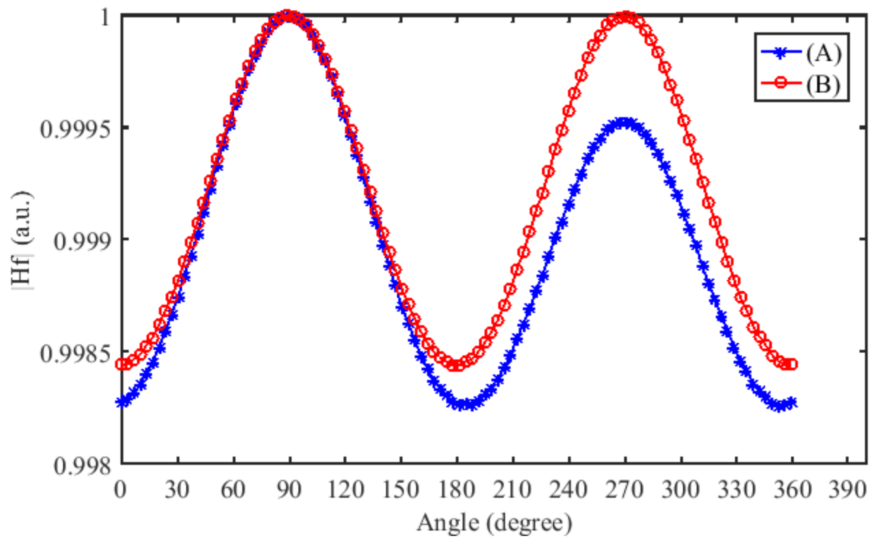


Fig .2 :Variation in H_ϕ with azimuthal angle for structure shown in Fig.1.: (A) coupling and vacuum slots of same size (L=46.4mm, W=20 mm) and (B) coupling and vacuum slots of different size (L= 47.8 mm, W=20 mm for vacuum slots)

- Coupling slot (oblong shape) : Length =46.4 mm, Width = 20mm
- Coupling port: tapered WR650 waveguide
- Vacuum slot (oblong shape)
- Vacuum port: Cylindrical (ID L_vac_slot+10mm)

Table: Normalized Fourier coefficients (r=17.5 mm)

Feed	Dipole	Quadrupole	Sextupole	Octupole
No vacuum port	1.47e-3	1.90e-4	4.02e-5	8.71e-6
Case (A)	1.15e-4	3.75e-4	6.80e-6	1.20e-5
Case (B)	9.45e-6	3.91e-4	6.42e-6	1.26e-5

Fundamental coupler: Field asymmetry study

- **Tool : Eigen mode solver CST MWS 2016**
- **Local mesh refinement near center of the structure**
- **Single feed + (vacuum + two dummy) ports of cylindrical shape**

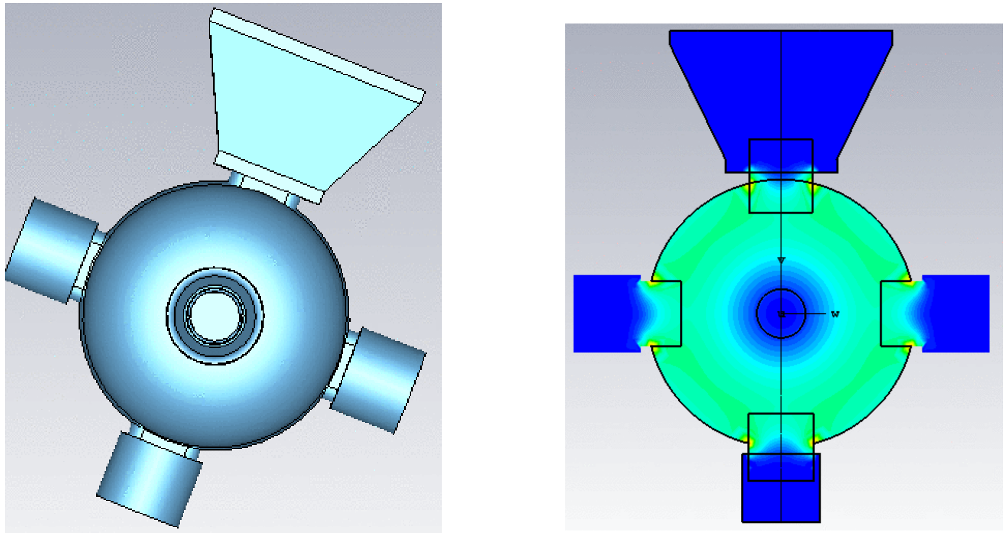


Fig.1: Structure with coupling, vacuum and dummy ports

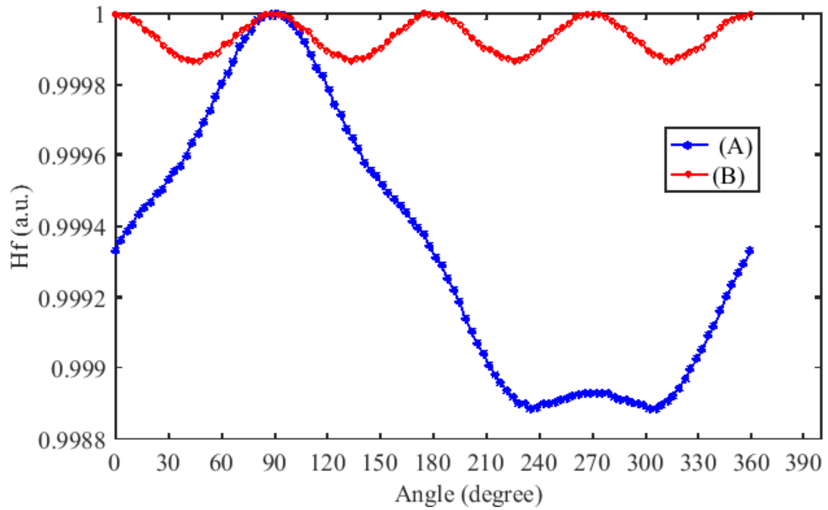


Fig .2 :Variation in H_ϕ with azimuthal angle for structure shown in Fig.1.: (A) coupling, vacuum and dummy slots of same size (L=54.5 mm, W=20 mm) and (B) coupling, vacuum and dummy slots of different size (L=56.75 mm, W=20 mm for vacuum slots)

- Coupling slot (oblong shape) : Length =54.5 mm, Width = 20mm (coupler slot length changed to make β_{RF}~1)
- Coupling port: tapered WR650 waveguide
- Vacuum slot (oblong shape)
- Vacuum port: Cylindrical (ID L_vac_slot+10mm)

Table: Normalized Fourier coefficients (r=17.5 mm)

Feed	Dipole	Quadrupole	Sextupole	Octupole
No vacuum port	1.47e-3	1.90e-4	4.02e-5	8.71e-6
Case (A)	2.60e-4	3.31e-5	7.58e-6	3.01e-5
Case (B)	9.20e-7	9.04e-7	1.30e-6	3.24e-5

RF power coupler kick

Literature

- Asymmetry of RF power coupler (fundamental/HOM): Non-zero transverse electric and magnetic field on cavity axis (in principle any features which break the azimuthal /transverse symmetry of cavity like : vacuum port , pickup, tuner etc.)

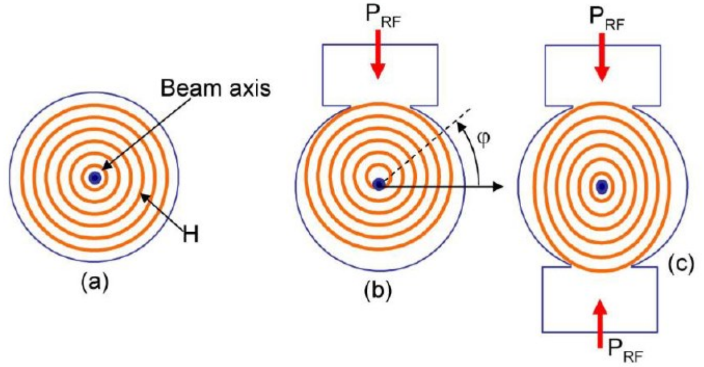


Fig. 9: Sketch of the magnetic field lines in a pure pillbox cavity (a), in a cavity with single input coupler (b), and in a cavity with double input coupler (c)

Ref: David Alesini, CAS 2010

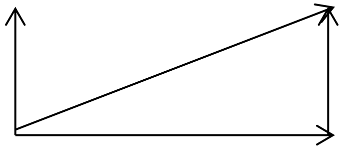
$$kick = \frac{V_t}{V_{acc}} = \frac{\int \{ \vec{E}_\perp(z,t) + \vec{v} \times \vec{B}_\perp(z,t) \} dz}{\int E_z(z,t) dz}$$

for beam with $v_\perp \to 0$

$$kick = \frac{V_t}{V_{acc}} = \frac{\int \{ \vec{E}_\perp(z,t) + v_z \times \vec{B}_\perp(z,t) \} dz}{\int E_z(z,t) dz}$$

for synchronized case

$$kick = \frac{V_t}{V_{acc}} = \frac{\int \{ \vec{E}_\perp(z) + v_z \times \vec{B}_\perp(z) \} dz}{\int E_z(z) dz}$$



Ref: S. Belomestnykh et al. ERL 02-8

- For symmetric feed: Transverse components of field on-axis is ~0
- Transverse and longitudinal field integrals can be determined by CSTMWS post processing