Preliminary RF design studies of 1300 MHz CW buncher

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PITZ Physics Seminar
DESY-Zeuthen

Outline

- Basic design : Literature survey
- RF design of two cell buncher
- Multipacting study
- Thermal design
- RF power coupler design
- Outlook

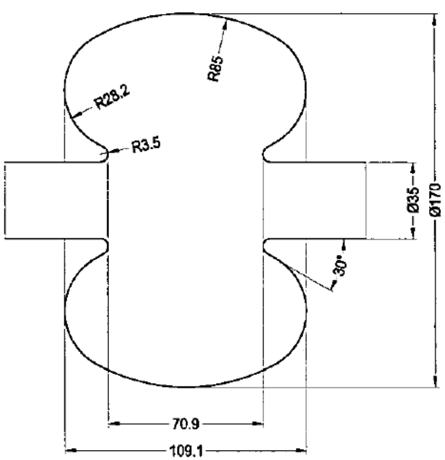
1300 MHz buncher : Literature survey

- **Single cell 1300 GHz buncher cavity: Cornell/Jlab ERL**

Proceedings of the 2003 Particle Accelerator Conference

BUNCHER CAVITY FOR ERL

V. Veshcherevich† and S. Belomestnykh
Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, NY 14853, USA



Inner shape of buncher cavity

Table 1

Energy of electrons, E	500 keV
Velocity of electrons, v/c	0.863
Beam current, I_0	100 mA
Resonance frequency, f	1300 MHz
Q	20,000
Shunt impedance, $R = V^2/2P$	2.1 MOhm
Nominal operating voltage, V	120 kV
Maximum accelerating voltage, V_m	200 kV
Maximum dissipating power, P_m	9.6 kW
Peak surface electric field, E_p	8.8 MV/m
Cavity detuning by beam current, ψ	73°

4.2 MΩ

$$R = \frac{V^2}{P_c}$$

- **Accelerating voltage of 200 kV @P~ 9.6 kW**

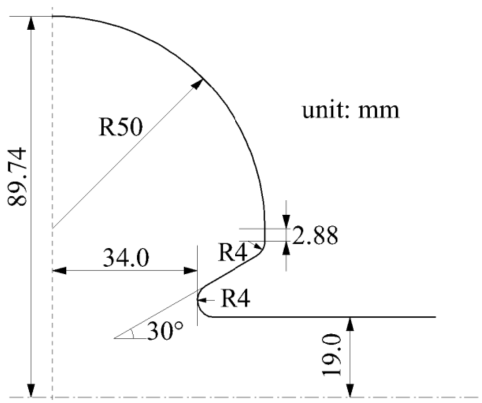
1300 MHz buncher : Literature servey

- Single cell 1300 GHz buncher cavity: KEK design

THPRI045 Proceedings of IPAC2014, Dresden, Germany

DEVELOPMENT OF A 1.3-GHZ BUNCHER CAVITY FOR THE COMPACT ERL

T. Takahashi#, Y. Honda, T. Miura, T. Miyajima, H. Sakai, S. Sakanaka, K. Shinoe, T. Uchiyama, K. Umemori, M. Yamamoto
High Energy Accelerator Research Organization (KEK), Oho, Tsukuba, Ibaraki 305-0801, Japan



Inner shape of buncher cavity

Table 1: The Principal Parameters of the Buncher Cavity (Shunt impedance is defined by $R_{sh}=(V_c)^2/P_c$)

Resonant frequency	1.300 GHz
R_{sh}/Q (for $\beta=v/c=1$)	232.8 Ω (calc.)
R_{sh}/Q (for $\beta=v/c=0.863$)	194.7 Ω (calc.)
R_{sh}/Q (for $\beta=v/c=0.824$)	181.3 Ω (calc.)
Shunt impedance R_{sh} (for $\beta=v/c=1$)	5.33 MΩ
Unloaded-Q Q_0	22900 (meas.)
External-Q of input coupler Q_{ex}	21100 (meas.)
Coupling of input coupler	1.08 (meas.)
Maximum cavity voltage (V_c) for usual operation	130 kV
Dissipated power in cavity P_c (at V_c=130 kV)	3.17 kW
Maximum cavity voltage during conditioning (at P_c=7 kW)	193 kV

At the maximum rf voltage of 130 kV, the maximum power density on the inner wall is 6.9 W/cm^2, while the maximum electric field is 4.8 MV/m. These values are well within our experience of the PF accelerating cavity.

- **Accelerating voltage of 130 kV P~ 3.17 kW**
- **Accelerating voltage of 193 kV @ 7 kW**
- **Accelerating voltage ~200kV @ 7.5 kW**

High power RF conditioned up to 7kW

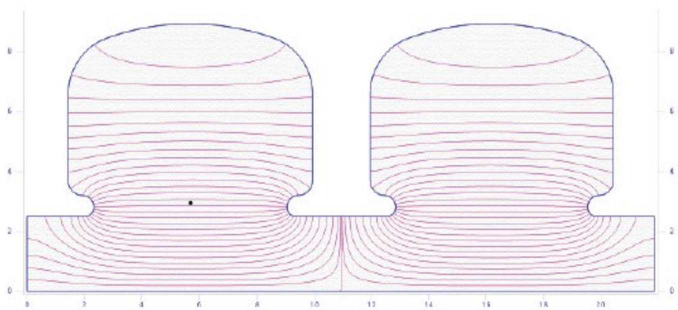
1300 MHz buncher : Literature servey

➢ Two-cell 1300 GHz buncher cavity for APEX: LBNL design

THPRI066 Proceedings of IPAC2014, Dresden, Germany

DESIGN OF A 1.3 GHZ TWO-CELL BUNCHER FOR APEX*

H. Qian#, K. Baptiste, J. Doyle, D. Filippetto, S.Kwiatkowski, C.F. Papadopoulos, D. Patino, F. Sannibale, J. Staples, S. Virostek, R. Wells, LBNL, Berkeley, CA 94720, USA



2D cavity profile

Table 1: Beam and Buncher Cavity Parameters*

	Units	Values
Beam energy	keV	750
Beam current	mA	0.3
Mode separation	MHz	0.88
PI mode frequency	MHz	1300
PI mode Q_0		2.35×10^4
Shunt impedance	MΩ	7.8
Nominal cavity voltage	kV	240
Dissipating power	kW	7.4
Peak surface electric field	MV/m	4.7
Peak surface power density	W/cm^2	5.8

* Parameters are calculated assuming 45 C wall temp.

Compared with a single cell design, the cavity power dissipation decreased from 15 kW to 7.4 kW, so the cavity can be powered by a 10 kW solid state amplifier, and both the RF source cost and the thermal power density are reduced.

➢ **Accelerating voltage of 240 kV P~ 7.4 kW**

➢ **Accelerating voltage of 400 kV @ 20.5 kW**

1300 MHz buncher : comparison

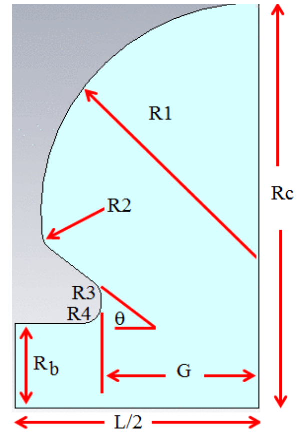
Parameter	Cornell/Jlab	KEK	LBNL	DESY (proposed)
No. of cells	1	1	2	2 or 3
Frequency (MHz)	1300	1300	1300	1300
$R_{sh} = \frac{V^2}{P_c}$	4.2	5.33	7.8	
Nominal Acc. Voltage (kV)	200	130	240	400* (study underway)
Power dissipation (kW)	3.42	3.17	7.4	

- **Proposed PITZ/DESY design: KEK design (highest shunt impedance/cell) with multiple cells**

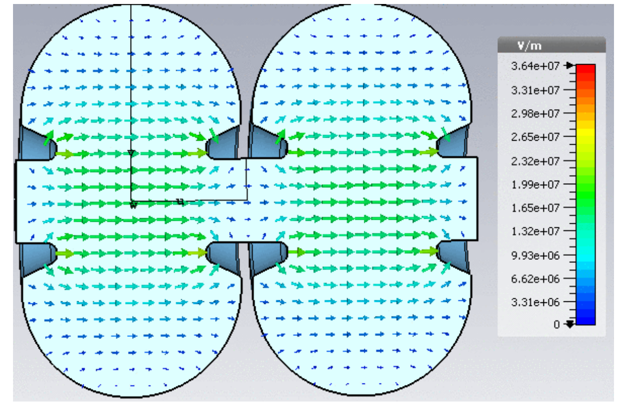
Two - cell 1300 MHz pre-buncher

Geometrical parameters
- Cell length: 105.1 mm
- Accelerating gap : 68 mm (T=0.8)
- Beam aperture: 38 mm
- R1=50 mm, R2=R3=4 mm
- Cavity radius : 89.449 mm

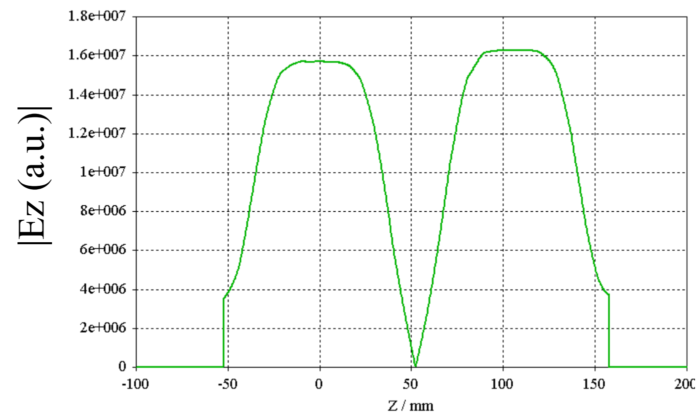
RF parameters π mode	
Parameter	value
f (MHz)	1300.01
Q	24389
R/Q	464.27
R (MΩ)	11.32
P (for 200 kV)	5.08 kW
P (for 400 kV)	14.15 kW
$f_\pi - f_0$ (MHz)	0.2



Parametric view of cavity



Electric field array plot for π mode



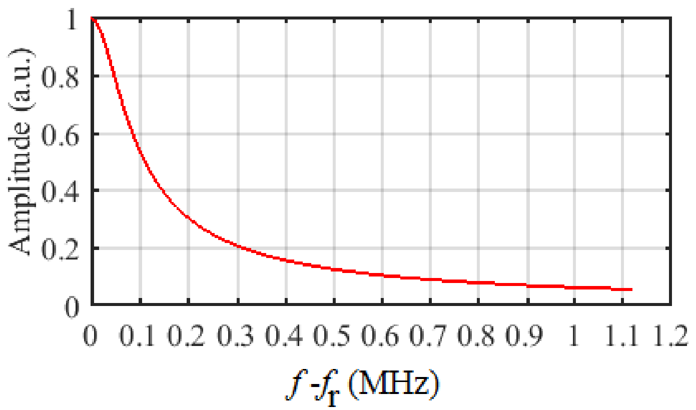
Electric field profile along cavity length for π mode

Remarks: Mode separation is very small (0.2 MHz) need to increase.

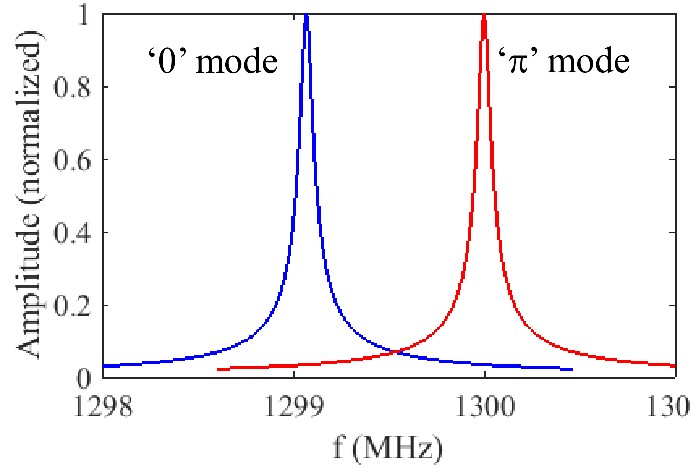
Two-cell 1300 MHz pre-buncher design : issues

Mode mixing: excitation of ‘0’ mode when RF feed for π mode

$$A \rightarrow 1\Big/\sqrt{1 + Q^2\left(\frac{f}{f_r} - \frac{f_r}{f}\right)^2}$$



Variation in amplitude of a driven harmonic oscillator with frequency

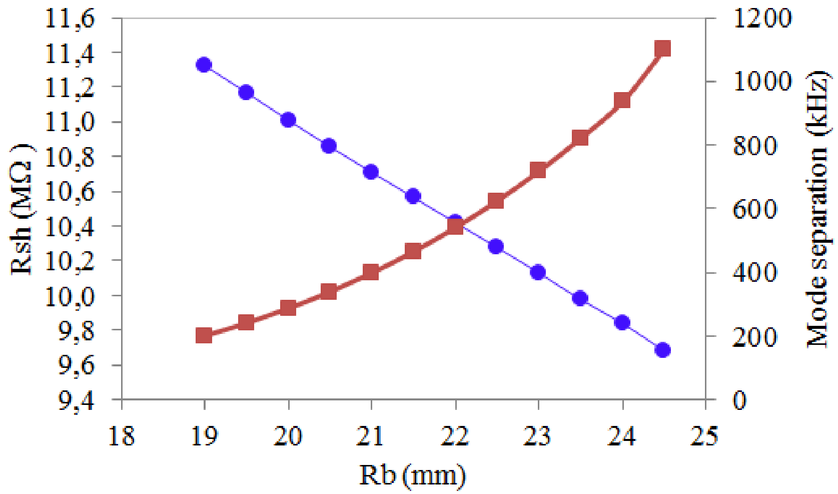


Typical frequency spectrum of two coupled cavities with quality factor of 20000 and mode separation = 0.9MHz

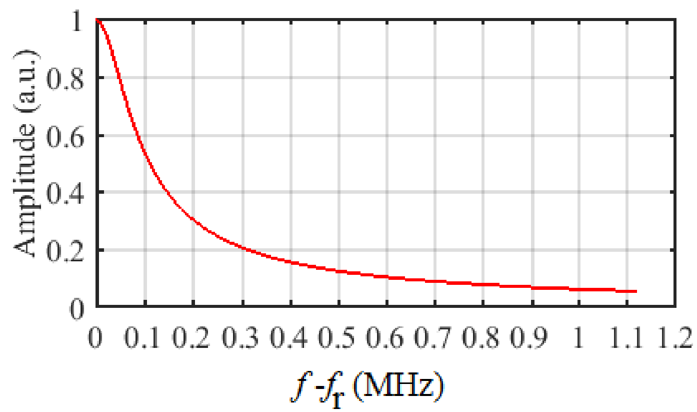
- **‘0’ mode amplitude at π mode frequency: ~30%@ 0.2 MHz and ~ 3%@ 0.9 MHz**
- **For critical coupling (β_{RF}=1) Q_L=Q_0/2**
- **‘0’ mode amplitude at π mode frequency :~7% for mode separation ~ 0.9 MHz**

Increase of mode separation

Increase the ID of inter-cell coupling iris ($2R_b$): Reduce R_{sh}



Variation in shunt impedance and mode separation with inner radius of inter-cell coupling iris



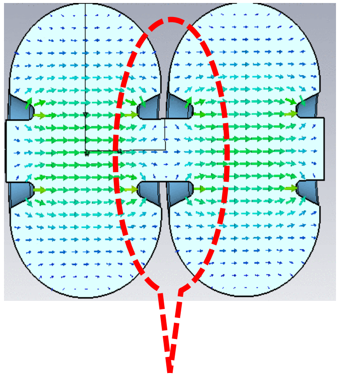
Variation in amplitude of a driven harmonic oscillator with frequency

- Mode separation increased from 0.2 MHz to 1.1 MHz for R_b increased from 19 to 24.5 mm
- Shunt impedance reduced from 11.32 to 9.6 MΩ for R_b increased from 19 to 24.5 mm
- For mode separation of > 0.9 MHz: No much reduction in ‘0’ mode field
- **Mode mixing should not be a problem for mode separation > 0.9 MHz**

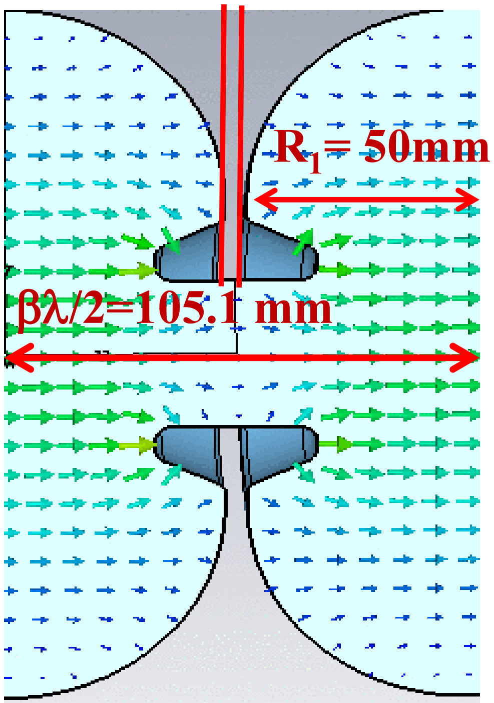
Two-cell 1300 MHz pre-buncher design : issues

- **Minimum wall thickness between two cavities is only 5.1 mm which is very small need to be increased.**
- **Can be increased by reducing radius R_1**
- **Minimum wall thickness ~10 mm (also depends upon thermal design): R_1=47 mm**

Re-optimization of geometrical dimensions to with R_1= 47 mm and mode inter-cell coupling iris = 49 mm

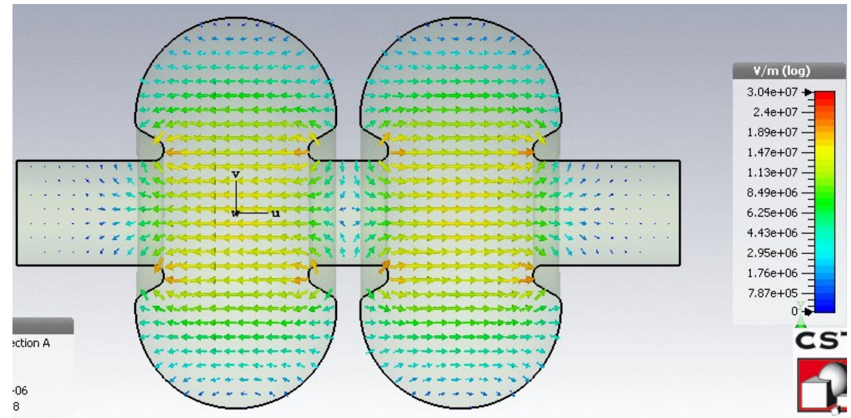


5.1 mm

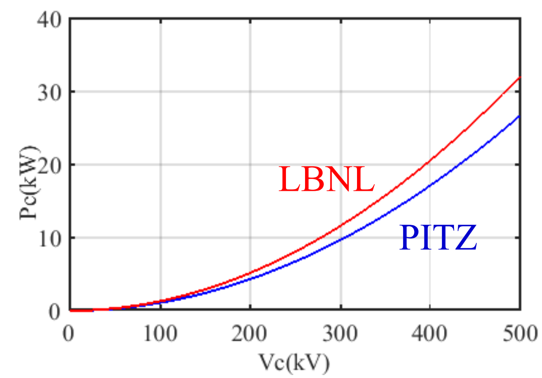


Two-cell 1300 MHz pre-buncher: First design

RF parameters of π mode	
Parameter	**Value**
f (MHz)	1300.01
Q	24452
R (MΩ)	9.35
f_{π}-f_0 (MHz)	0.96
P (for 400 kV)	17.11 kW
P (for 240 kV)	6.16 kW
E_{peak}/E_{z0}	2.02
Peak surface power density (W/cm^2)	5.62 @ 400 kV



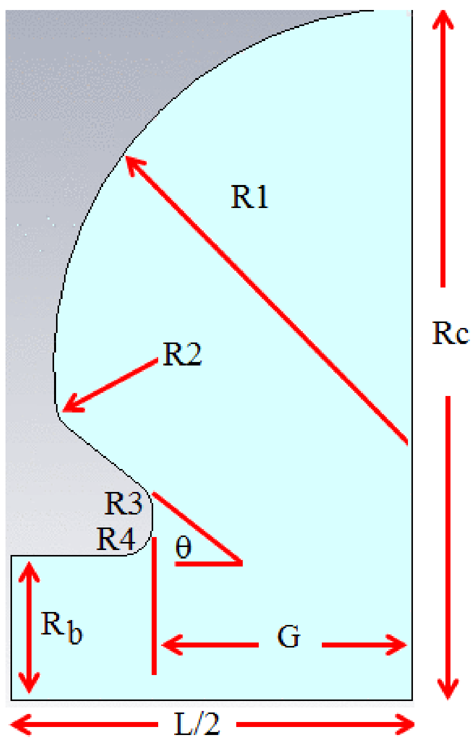
Electric field array plot for π mode



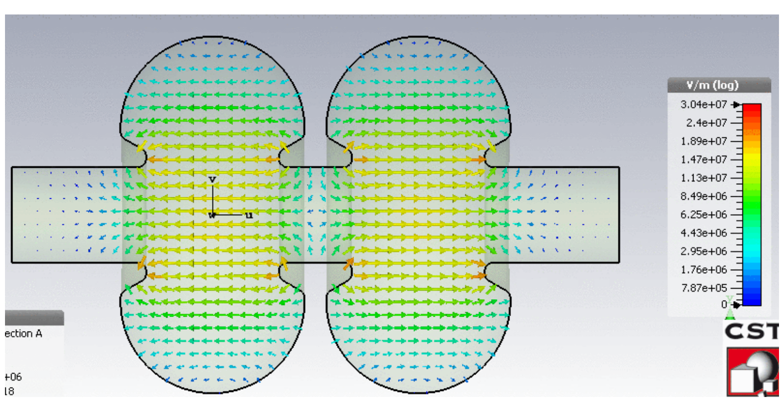
Pc with accelerating voltage

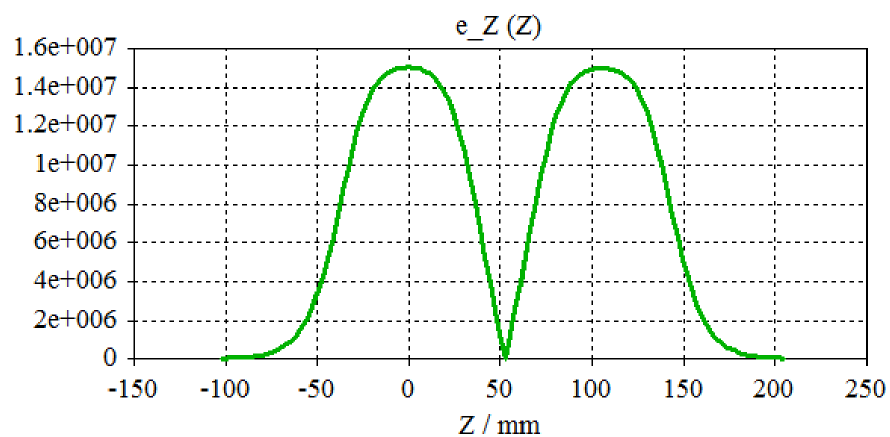
- R_{sh} is ~ 20 % higher compare to LBNL design (7.8 MΩ)
- Mode separation ~ 0.96 MHz
- RF power required to generate nominal cavity voltage (total) of 400 kV is ~ 16 kW

Two-cell 1300 MHz pre-buncher: Geometry



Geometrical parameters	
Parameter	Value
R_c (mm)	91.207
R_1 (mm)	47
R_2 (mm)	4
R_3 (mm)	4
R_b (mm)	24.5
G (mm)	68
L (mm)	105.1

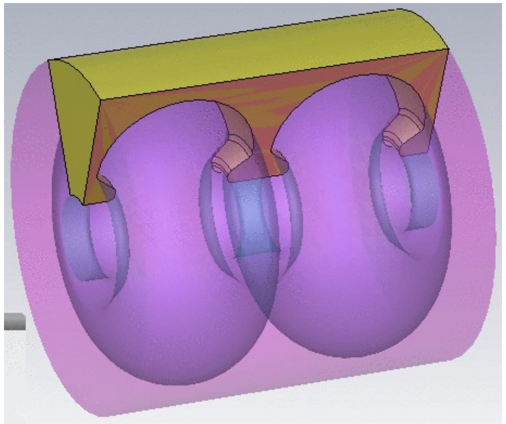




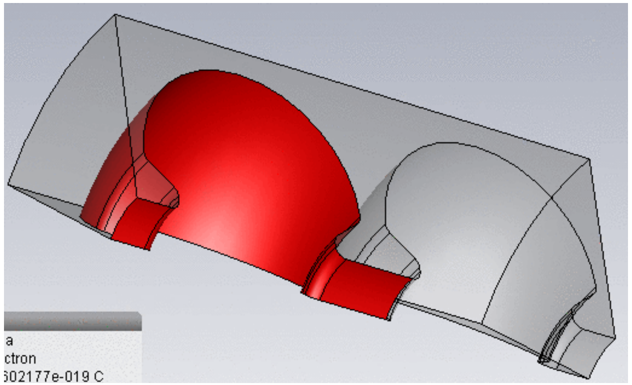
Multipacting study

Multipacting simulations using CST PIC solver

- 1/8th model simulated for minimize simulation time (1/8th model is made of copper with SEE and rest without SEE)
- Initial particles : ~ 100 to minimize the simulation time
- Particle emission time: ~ 1 ns (1RF period~ 0.76 ns) to cover all phases of RF
- Energy : 2-6 eV and angular spread ~90^{o} *
- EM fields imported from Eigen mode solver
- Simulation time 100 ns (~ 130 RF periods)



1/8th model (yellow) of two cell buncher cavity used for MP study



Particle emission surface (red)

*Berrutti et al. "Multipacting simulations of SSR2cavity at FNAL",FERMILAB-Conf-13-404-TD

Benchmarking of simulation procedure (coaxial cable)

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journal homepage: www.elsevier.com/locate/nima

Prediction and suppression of two-point 1st order multipacting

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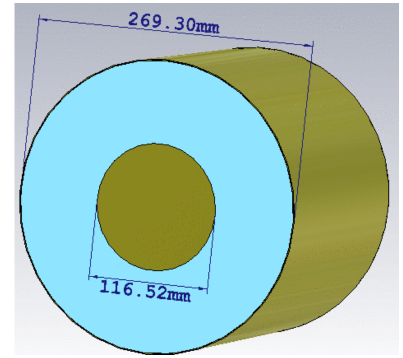
[b] Tsinghua University of Beijing, Beijing 100084, China
[c] INFN – Laboratori Nazionali di Legnaro, Padova, Italy



Resonance condition for MP in Coaxial cable

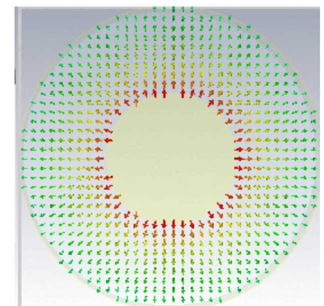
$$E_r = \frac{(r_2 - r_1)\omega^2 m}{(2n-1)\pi e}$$

r_1 and r_2 : Radius of inner and outer conductor

ω = RF angular frequency(= $2\pi f$)

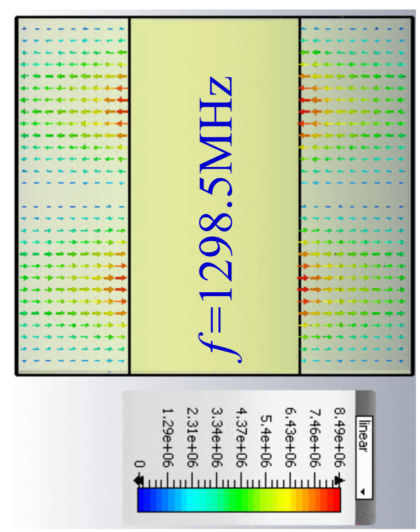
m = electron mass, e = electron charge

n = order of MP



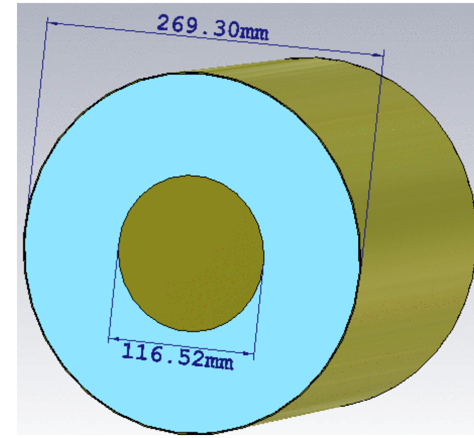
For f =1298.5 MHz

Two point first order MP : E_r=9.145MV/m

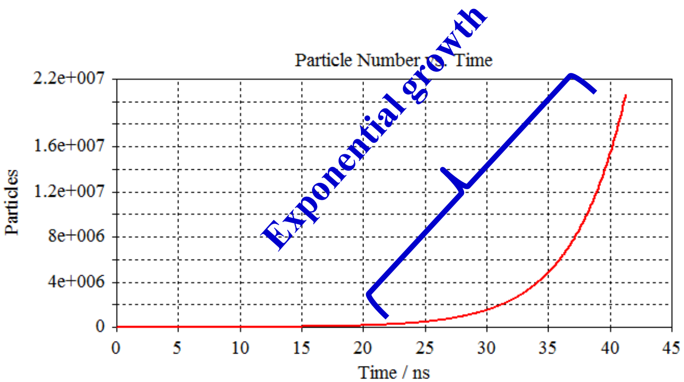


Benchmarking of simulation procedure (coaxial cable)

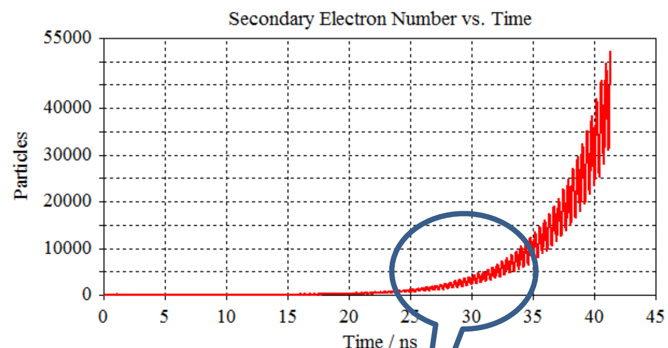
- EM fields imported from CSTMWS Eigen mode solver
- Field scaled to E_r=9.156 MV/m
- Two point 1st order MP observed
- Simulation agree with analytical prediction (E_r=9.145MV/m)



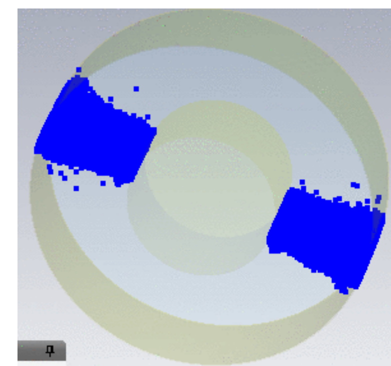
Coaxial cable



Number of particles with time



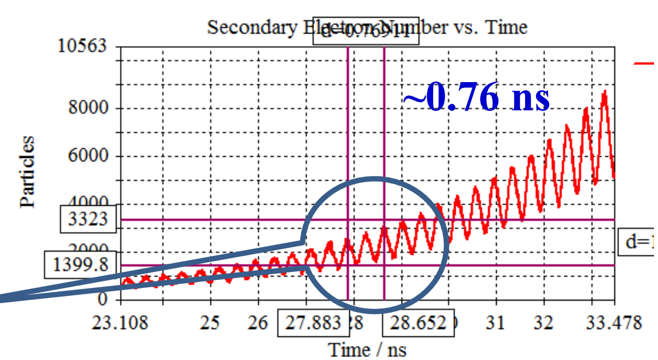
Number of secondary electrons with time



Particle view at 40 ns

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

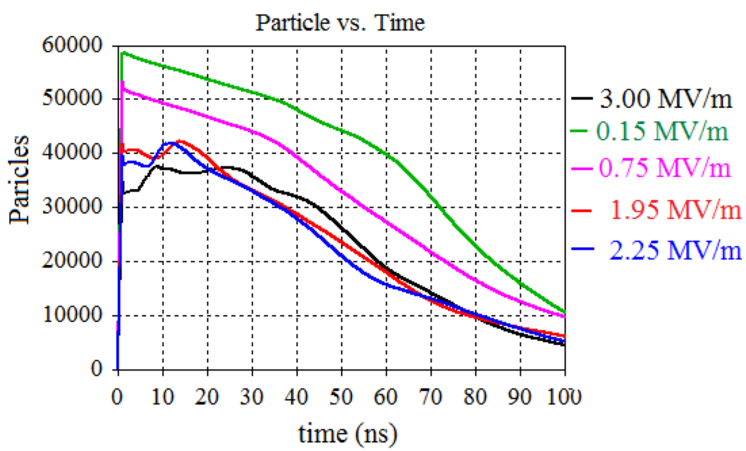
$$\alpha = \frac{1}{N}\frac{dN}{dt} = 0.29$$



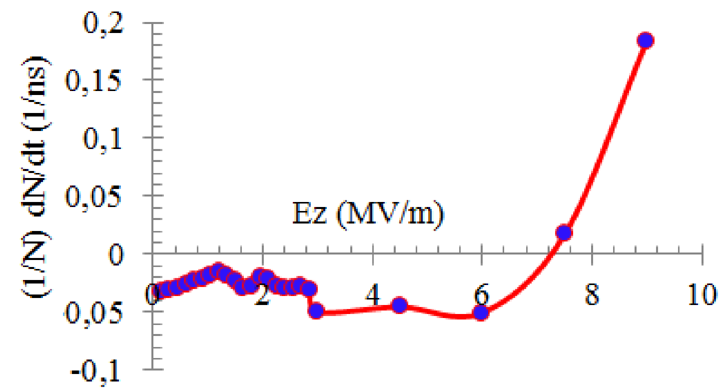
- Number of particles increase every half RF period
- 1st order two point MP

Two-cell 1300 MHz pre-buncher: Multipacting study

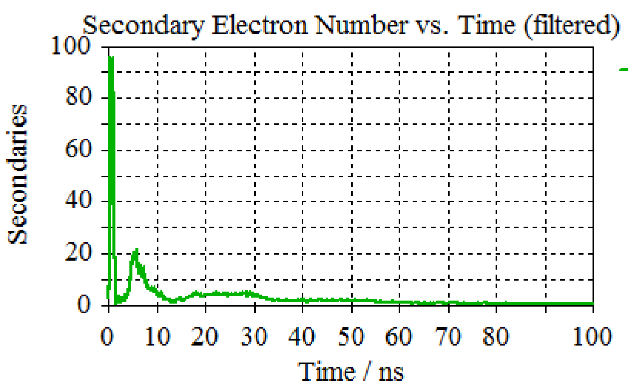
- **No MP for accelerating field gradient < 7 MV/m (total gap voltage =1.4 MV)**
- **Operating accelerating gradient Ez =1.95 MV/m (total cavity voltage 410 kV)**



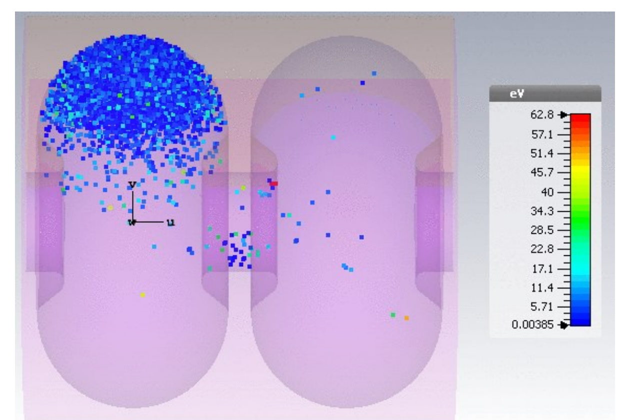
Particles with time



Growth rate with accelerating field



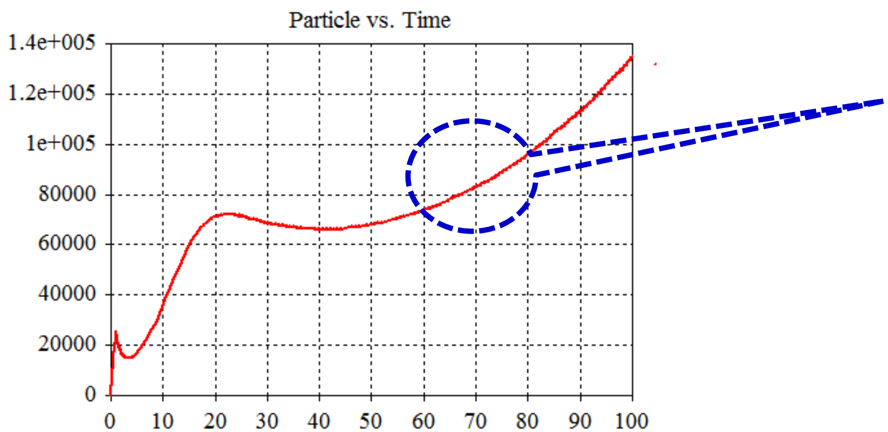
SE with time for Ez =1.95 MV/m



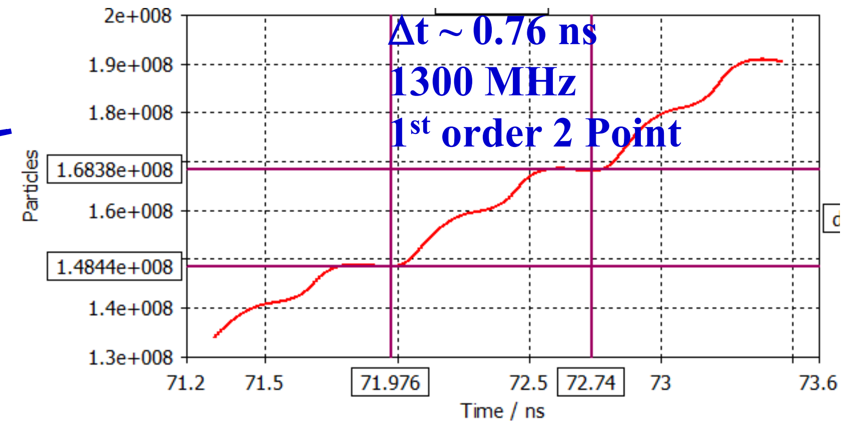
Particle distribution for Ez = 1.95 MV/m

Multipacting study at higher field

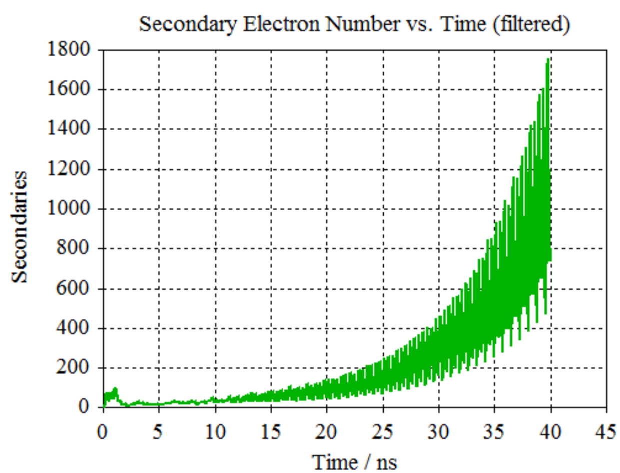
- **MP study at Ez~ 9 MV/m (total gap voltage 1.89 MV)**
- **Strong MP observed after 7.5 MV/m**



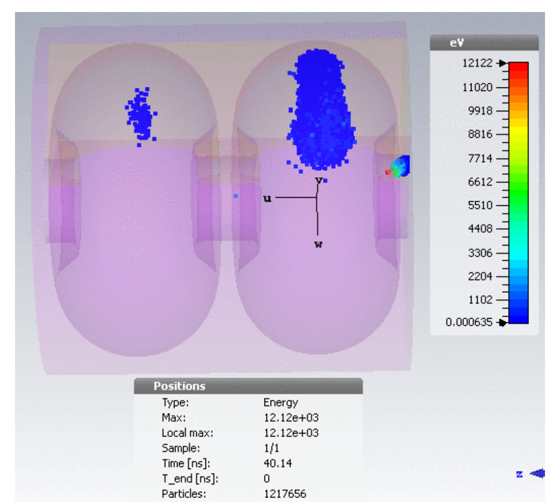
Number of particle with time for Ez =7.5 MV/m



Number of particle with time



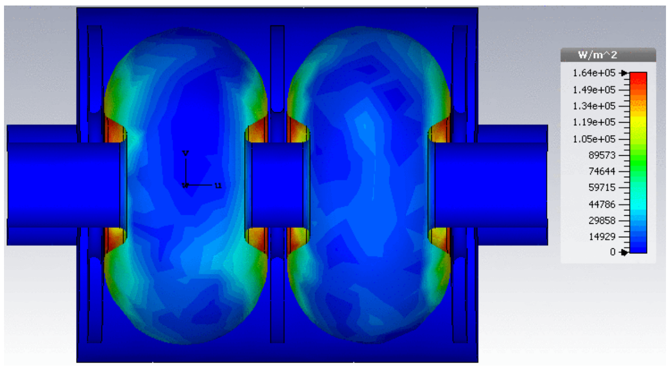
Number of Secondary Electrons with time



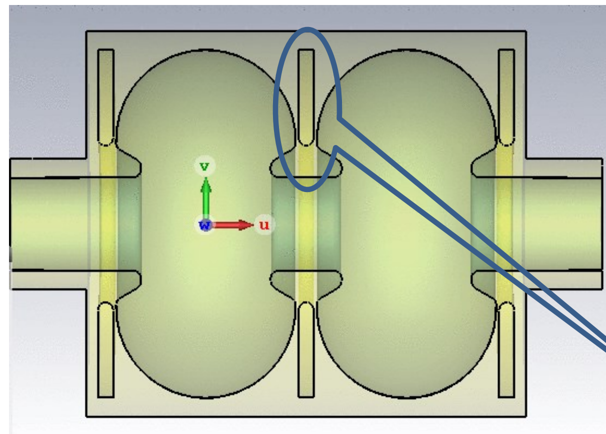
Particle distribution for Ez = 7.5 MV/m

Two-cell 1300 MHz pre-buncher: Thermal study

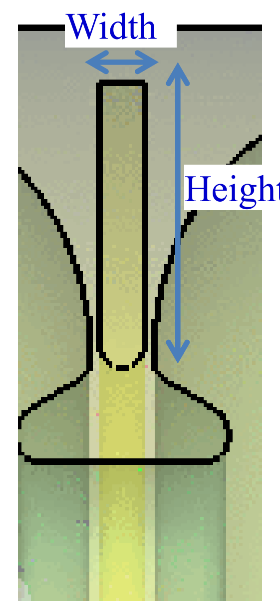
- CST Thermal solver (steady state) is used
- RF field imported from Eigen mode solver
- Oblong cooling channels near nose cone (initial design) with heat transfer coefficient



Surface loss density



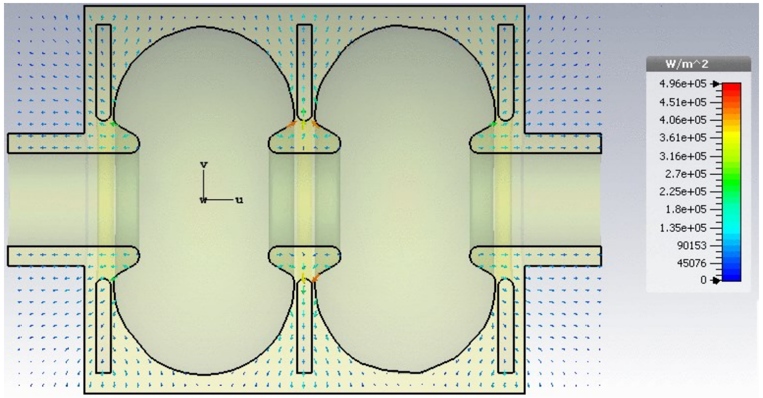
Cooling channels geometry



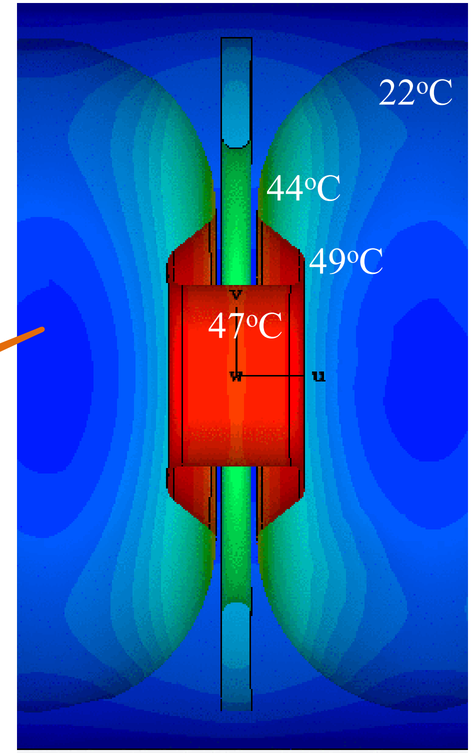
- Cooling channel : width = 8 mm, height = 30 mm
- 35 mm way from beam port ID
- Heat transfer coefficient : 2 W/cm^2K*
- Cooling water temperature : 30^oC

*H.Qian et al. "Design of a 1.3 GHz two-cell buncher for APEX, IPAC 2014.

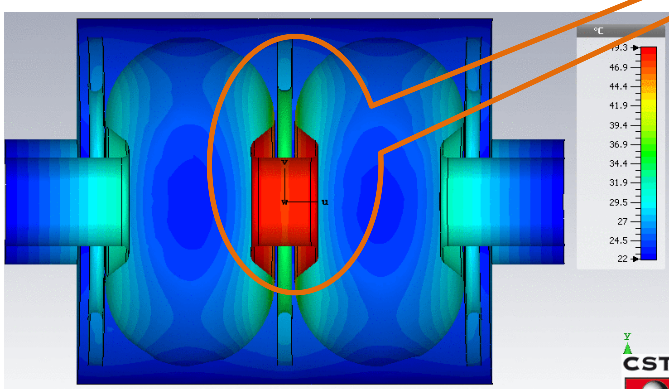
Two-cell 1300 MHz pre-buncher: Thermal study



Heat flow density



Temperature distribution



Steady state temperature distribution

- Maximum temperature at central iris ~50°C
- Temperature of end iris ~ 45°C

- **Wall thickness at the end of cooling pipe is ~ 4 mm**

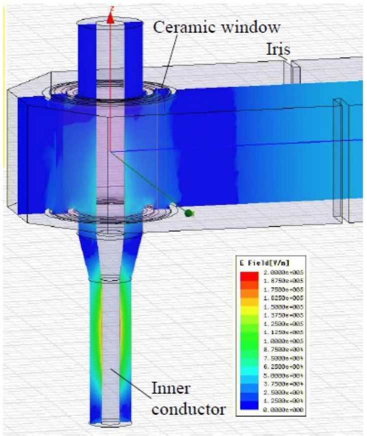
RF power coupler: Options

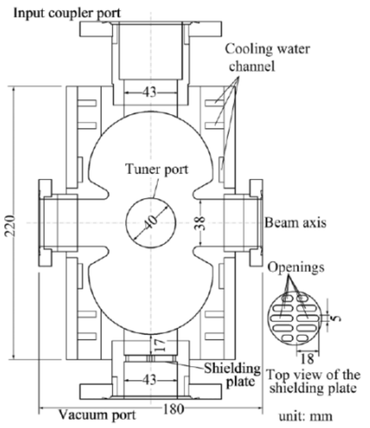
APEX design

- Coaxial loop coupler
- 2 couplers to each cavity
- 4 kW power to each port
- 1-5/8 EIA 50 Ω coaxial line

KEK design

- Coaxial loop coupler
- Cylindrical ceramic window
- Coaxial-to-waveguide transformer





Other possibility

- On-axis PITZ type coupler
- Rectangular ceramic window

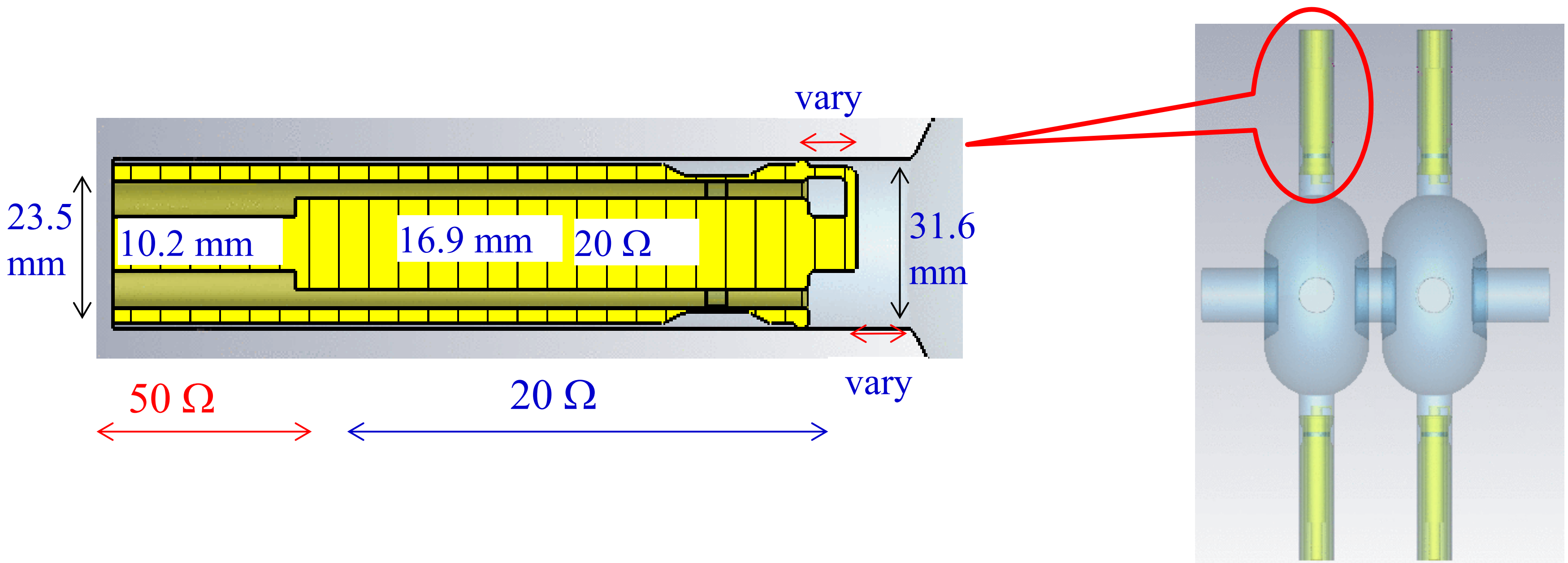
Comparison of different RF power coupler schemes

Coupler type	LBNL	KEK	PITZ
RF Coupling type	Magnetic (Loop)	Magnetic (Loop)	Electric (Antenna)
Number of couplers	4	2	1
Tuning of coupling	By rotation of loop	By rotation of loop	Moving antenna ??
RF windows	4 (cylindrical)	2(cylindrical)	1 (rectangular)
RF coupler geometry	Coaxial 20Ω to 50Ω transition	Coaxial-to-waveguide transformer	Coaxial-to-waveguide transformer
High power test	4 kW	Tested up to 7 kW	Tested up ~10 MW
Additional requirement	RF phase between 4 ports	RF phase between 2 ports	

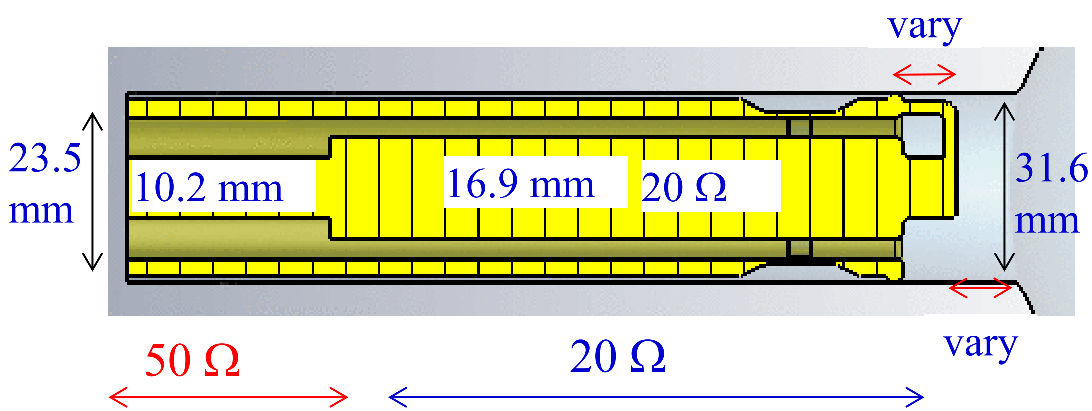
Two-cell 1300 MHz pre-buncher: RF power coupler

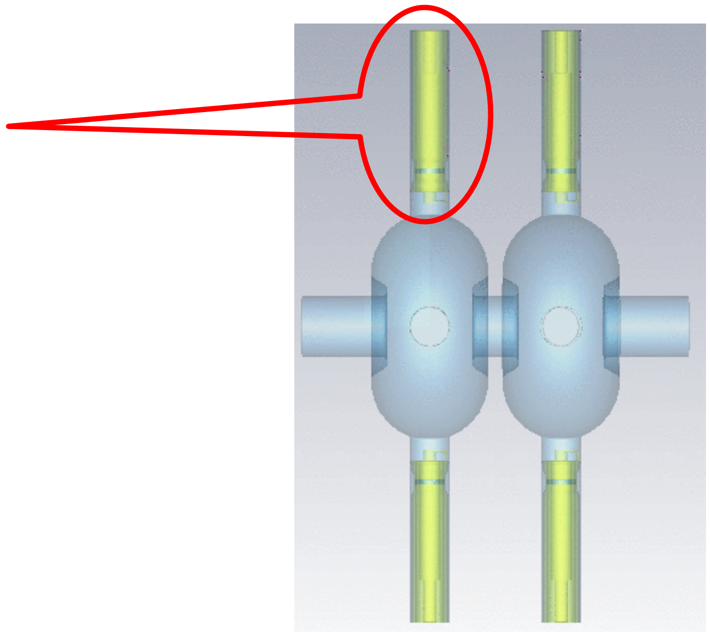
Follow APEX design

- **CSTMWS Frequency Domain Solver**
- **Two ports (diagonally opposite) each cavity**
- **One pickup & one pumping port**
- **Each port ~1/4 power**

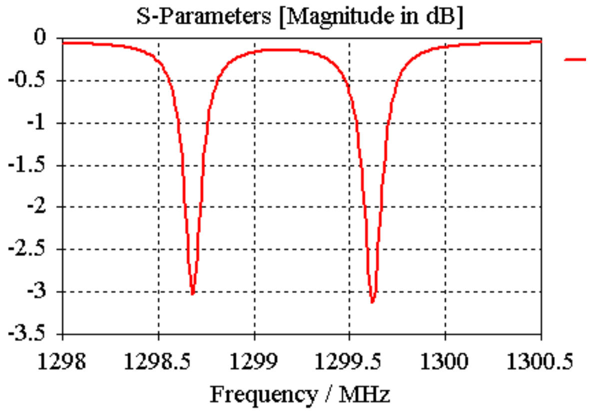


Two-cell 1300 MHz pre-buncher: RF power coupler

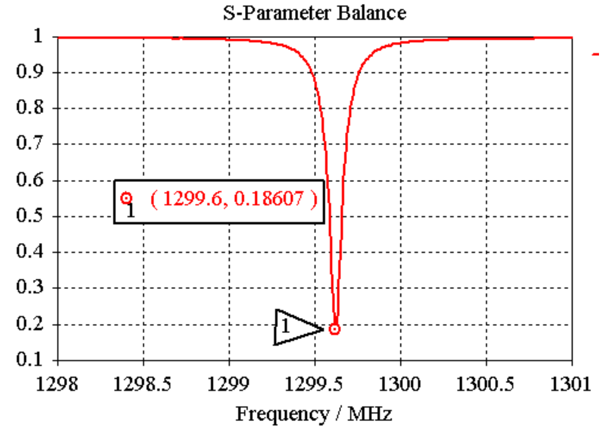




- **All power coupler ports are identical**
- **Phase between two cavities :180**



S11 for port 1



S parameter all ports combine

- VSWR= 0.7 for parameters as per LBNL design
- Optimization under way

Summary

- First RF design of two-cell 1300 MHz buncher is carried out
- Proposed design has ~ 20 % higher shunt impedance compared to LBNL design
- Simulations predict no MP for operating voltage of 400 kV
- LBNL based loop type RF power coupler is designed. Each cavity has two RF power couplers. Each coupler need to feed RF power of ~ 4 kW for desired operating voltage of 400 kV.
- Thermal simulations predict temperature raise of ~ 20^{o}C near nose cone.

Out look

- Study of variation in RF parameters with geometrical dimensions
- Study other options of RF power coupling like on-axis PITZ type coupler and compare the with present design.
- Design of RF pickup loop
- Study of Multipacting in RF power coupler
- Design of RF tuners
- RF design of 3 cell: higher shunt impedance (~12 MΩ) lower RF power (~12 kW for 400 kW)

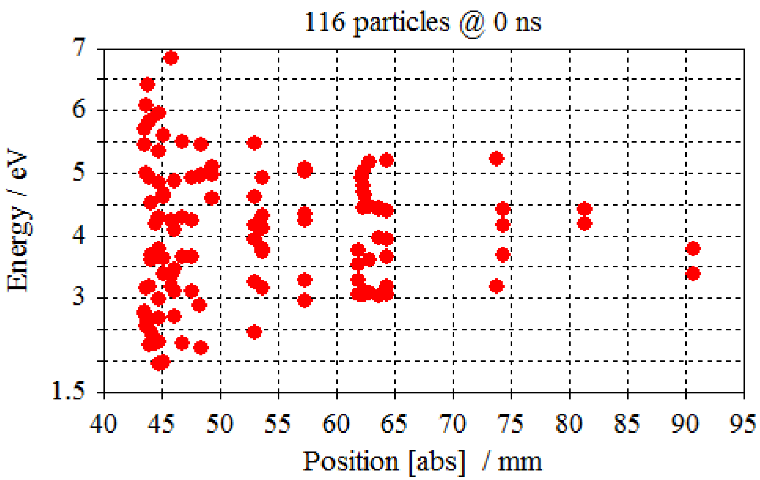
Thank you for your attention

If you are still alive…

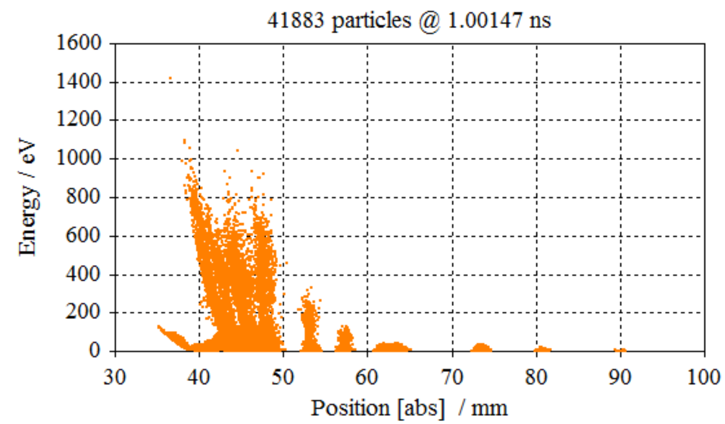
Give your feedback and comments

Two-cell 1300 MHz pre-buncher: Multipacting study

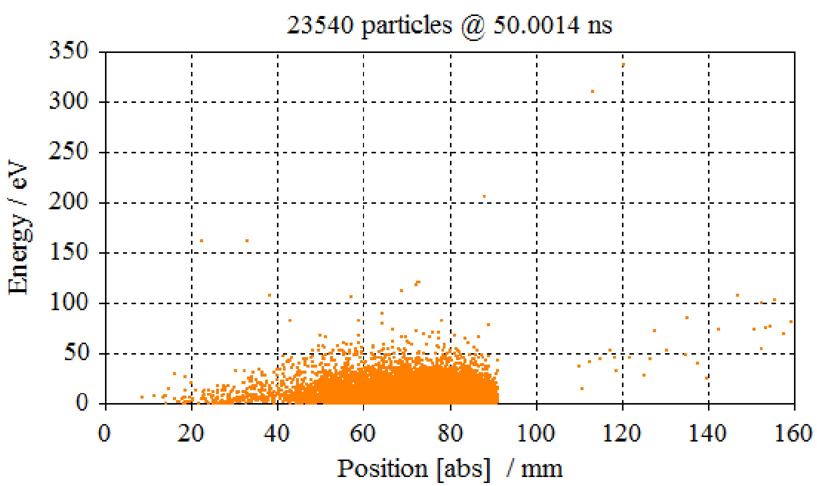
- Particle distribution with time for Ez=1.95 MV/m (total gap voltage 205 kV)



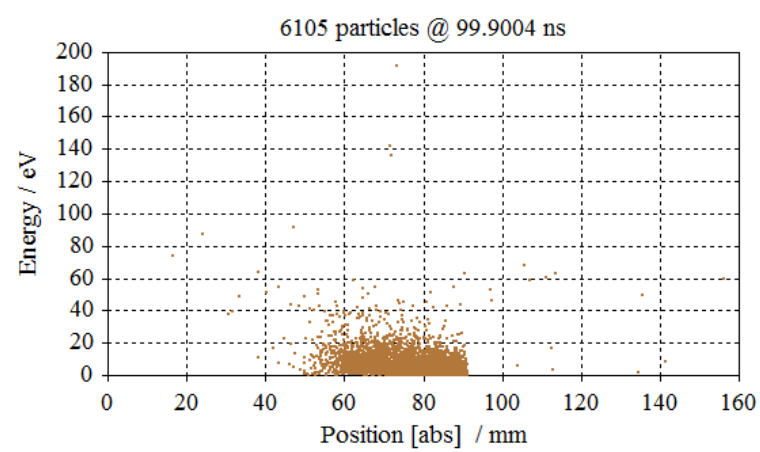
Particle at start of emission (0 ns)



Particle at end of emission (1ns)



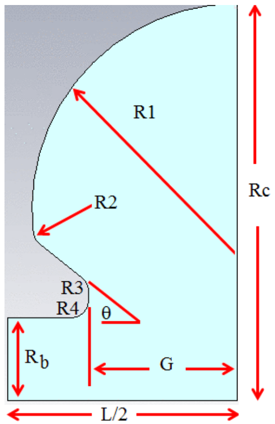
Particle at 50 ns



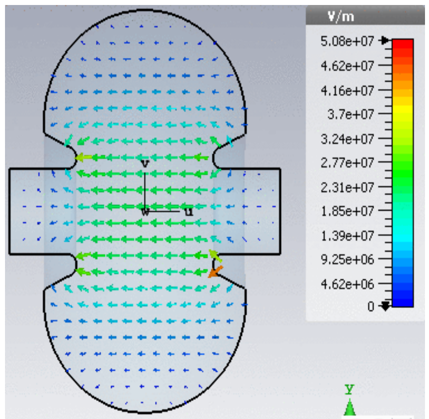
Particle at end of simulation (100 ns)

Single-cell 1300 MHz pre-buncher

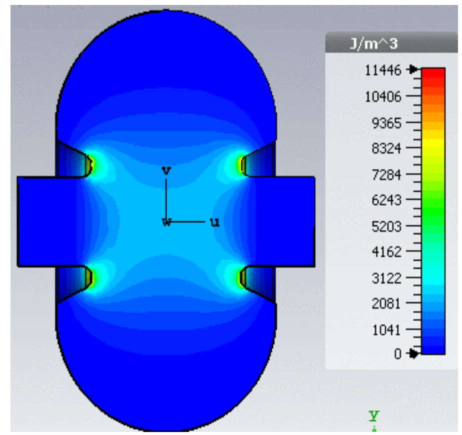
➢ Parametric model based upon KEK design



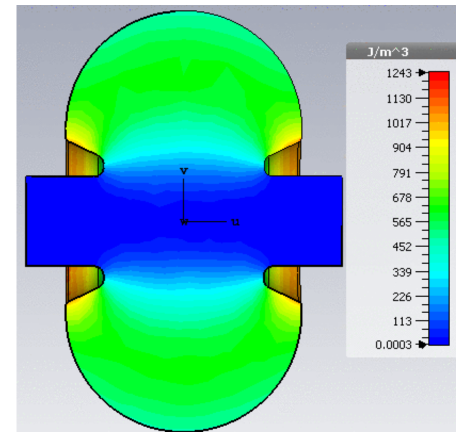
Parametric view of cavity



Electric field array plot

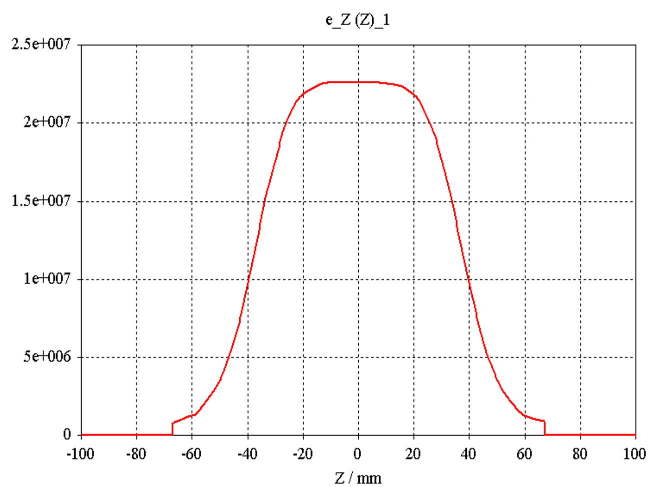


Electric energy density

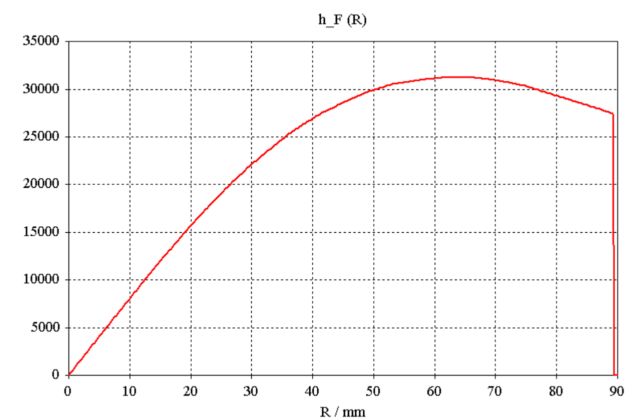


Magnetic energy density

RF parameters	
f (MHz)	1300.01
Q	2.438e4
R (MΩ)	5.71
Ez (r = 0) (MV/m) For U=1 J	2.26e7
P_c (kW)	335
E max	5.05e7
Pc for 200kV	10.1 kW



Ez profile along cavity length



Magnetic field profile along radius of cavity (z= cavity center)