FCC-ee IR Heat Load

(due to wake fields excited by the circulating beams)

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SLAC NATIONAL ACCELERATOR LABORATORY

FUTURE CIRCULAR COLLIDER

Outline

- Resistive-wall wake fields are very important for the circular collider operation
- Some history of the PEP-II operation with high currents
  - Unfortunately, my flight was late on last monday, and I missed the discussion about high currents. Here it is some kind of compensation
- A new CAD model for the IR heat load calculations from Francesco Fransesini
- Results for wake potentials
- Heat load distribution in FCC IR.
- Are resistive-wall wake field unavoidable?
  - Some results of our study (Pantaleo and me) for a special case
- Summary

Experience from the PEP-II SLAC B-factory

Under the leadership of John Seeman PEP-II SLAC B-factory successfully operated with record electron and positron currents, achieving very high luminosity 1.2 10^34 at that time.

PEP-II B-factory consists of a Low Energy Ring (LER) for accumulating 3 GeV positrons and a High Energy Ring (HER) for accumulating 9 GeV electrons.

At the end of the PEP-II run the LER current was increased to a new world record of 3.2 A and the HER current reached 2.1 A.

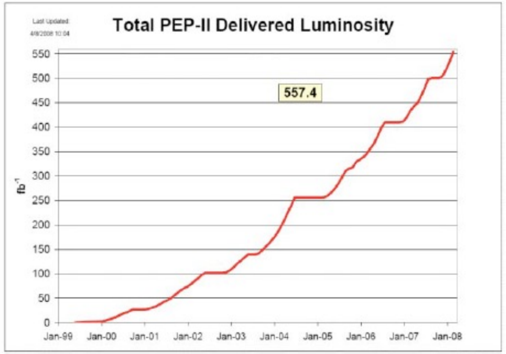


Figure 14 : Total integrated luminosity from 1999 to 2008.

During the energy scan, synchrotron radiation power in the High Energy Ring exceeded the level of 10 MW, a world record for a lepton machine. This large amount of power, produced by 11 RF stations was captured by the wall of the copper vacuum chamber and then was carefully taken out by a water-cooling system.

Wake field effects on beam dynamics at PEP-II

- Different slope for X and Y tune shift

Tunes	LER x	LER y	HER x	HER y
Tune slope [1/A]	0.0175	-0.0170	0.0145	-0.0195

Table 1: Tune shifts per current for LER and HER.

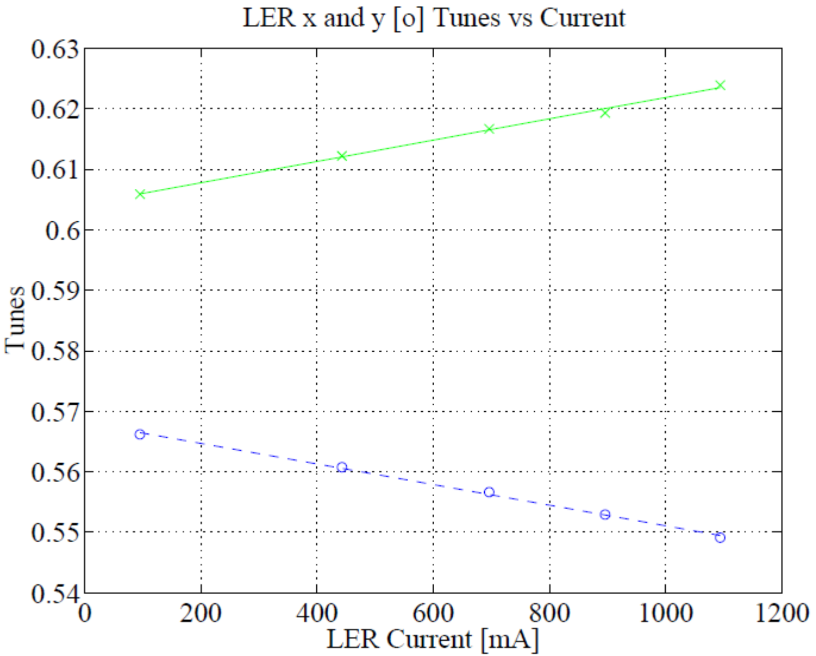


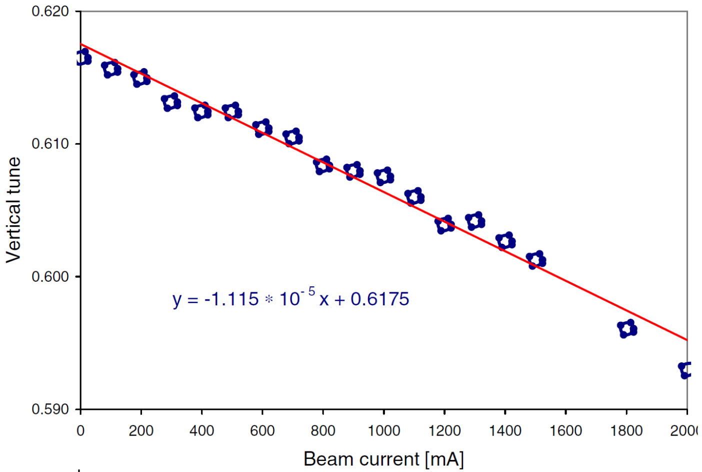
Fig. 2: LER tune variation versus current with 700 bunches in a by-4 pattern. The desired tune adjustments have nearly the same values with opposite signs.

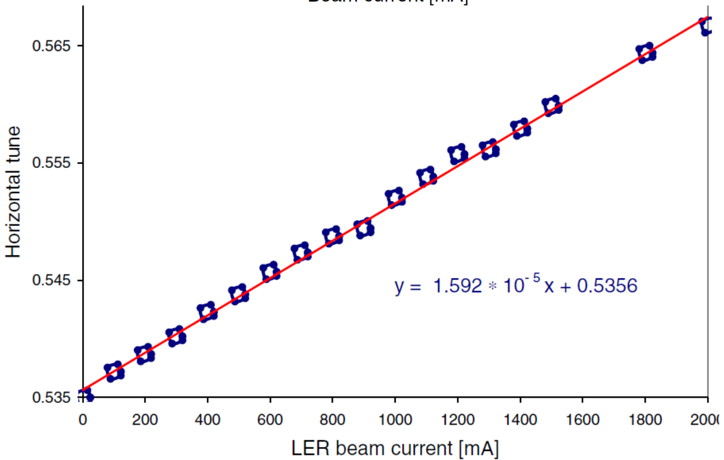
Resistive-wall wake field quadrupole component in the non round (elliptical shape) beam chamber explains this effect

Transverse fields between two metal plates bunch is in the middle (long bunches)

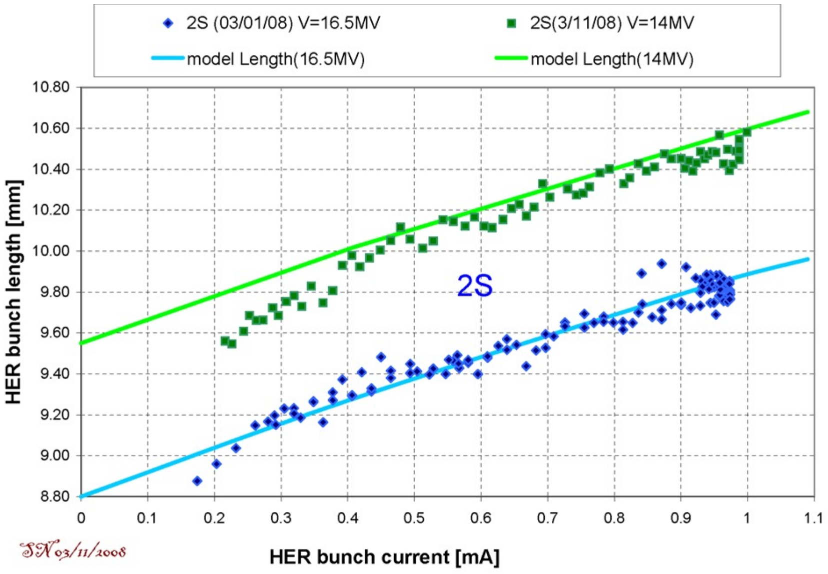
$$\frac{1}{Q}\int_{2\pi R} F_y\left(s,y,x=0\right)dz = 8\frac{QR}{b^3}\sqrt{\frac{c}{\sigma_c s}}\,y \qquad \text{defocusing}$$

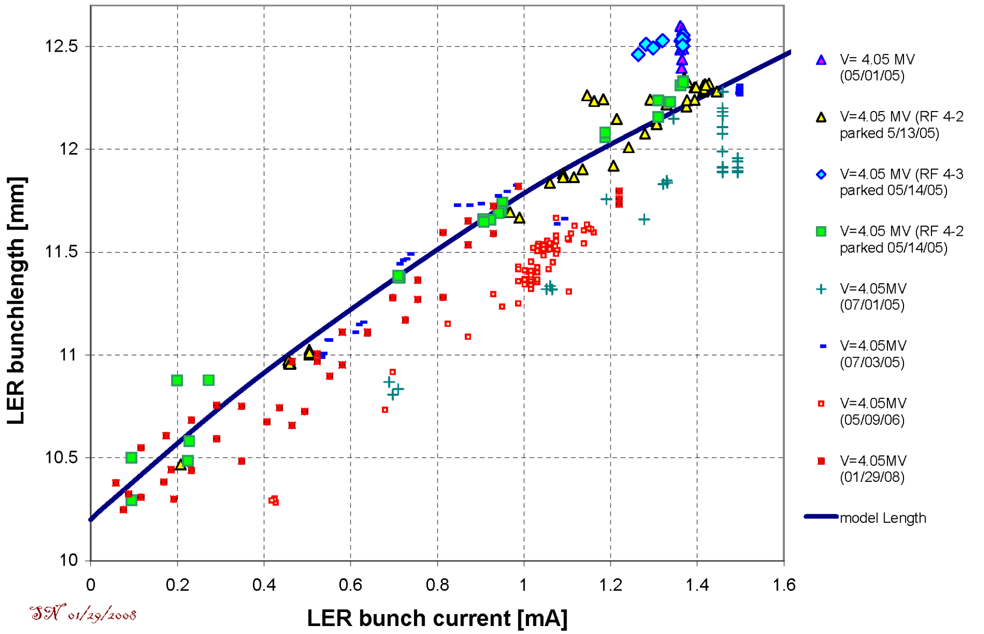
$$\frac{1}{Q}\int_{2\pi R} F_x\left(s,y=0,x\right)dz = -8\frac{QR}{b^3}\sqrt{\frac{c}{\sigma_c s}}\,x \qquad \text{focusing}$$





Bunch lengthening





Different RF voltages

Synchrotron tune shift

$$\sigma_s^2 = \left(\frac{\omega_s}{\omega_{so}}\right)^2 \sigma_0^2$$

$$\omega_s^2 = \omega_{s0}^2 + \lambda c^2 \left\langle W_{\parallel} \right\rangle$$

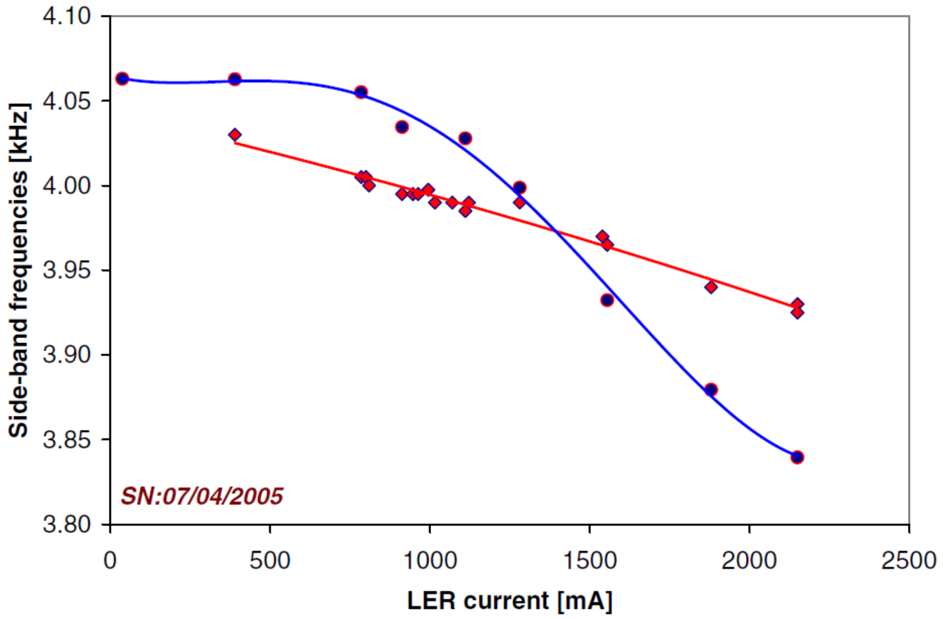
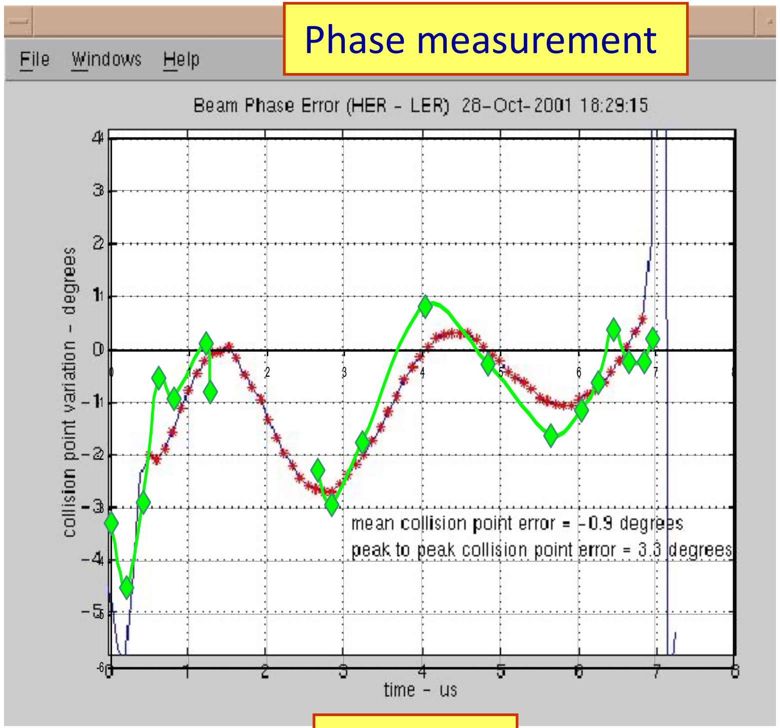


FIG. 6. (Color) Synchrotron frequency measured from the first (blue) and the second sideband (red) in the beam spectrum.

Gap transient. Excitation of the main RF mode due to a gap in the bunch spacing for the ion cleaning

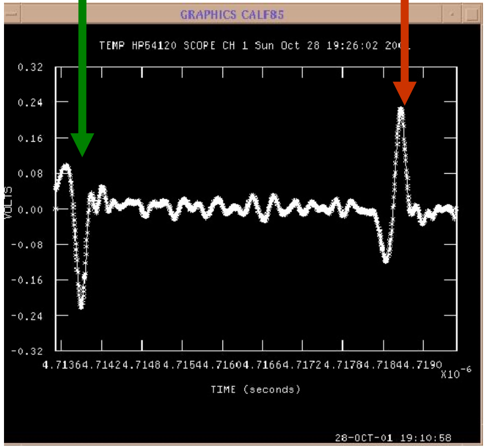
Phase measurement



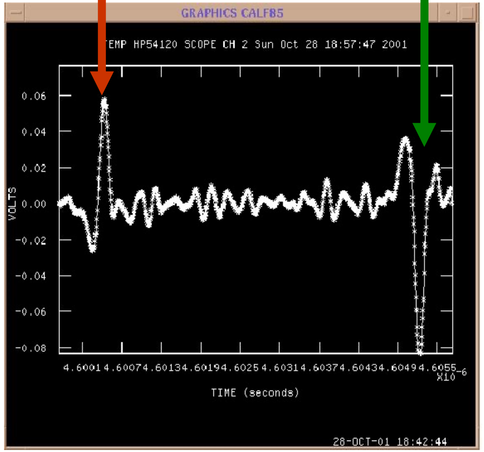
One turn

Time arrival measurement

Positrons Electrons Electrons Positrons



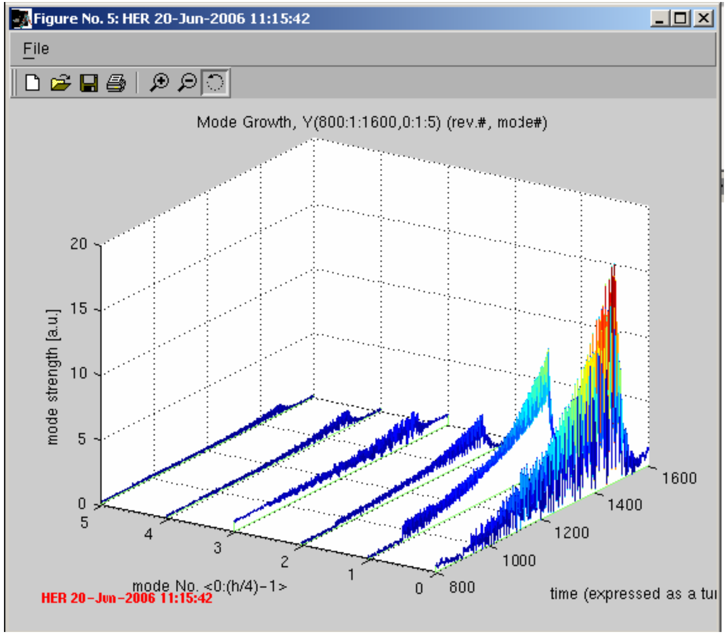
B-side BPM

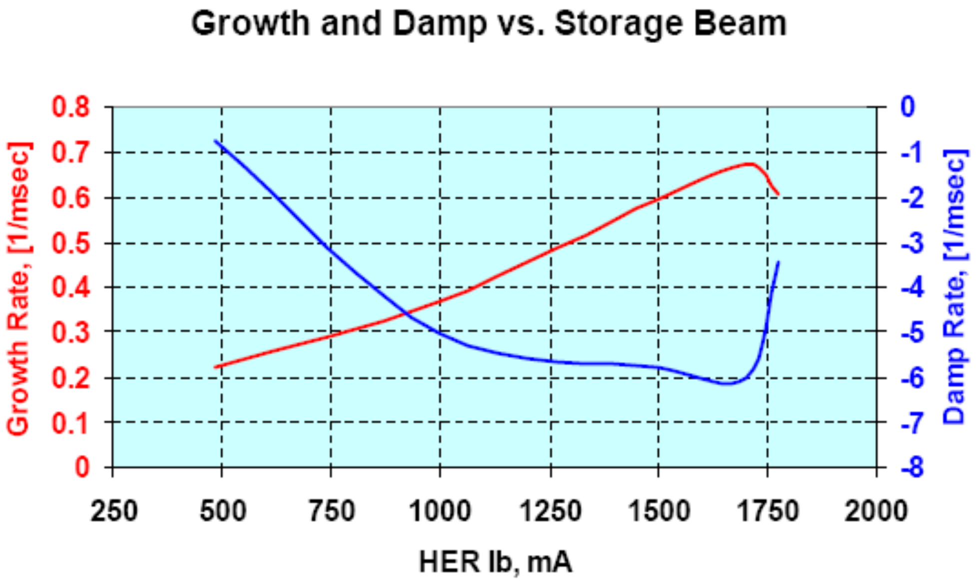


A-side BPM

Distance to a collision point from BPM = $(\Delta t^* c)/2$

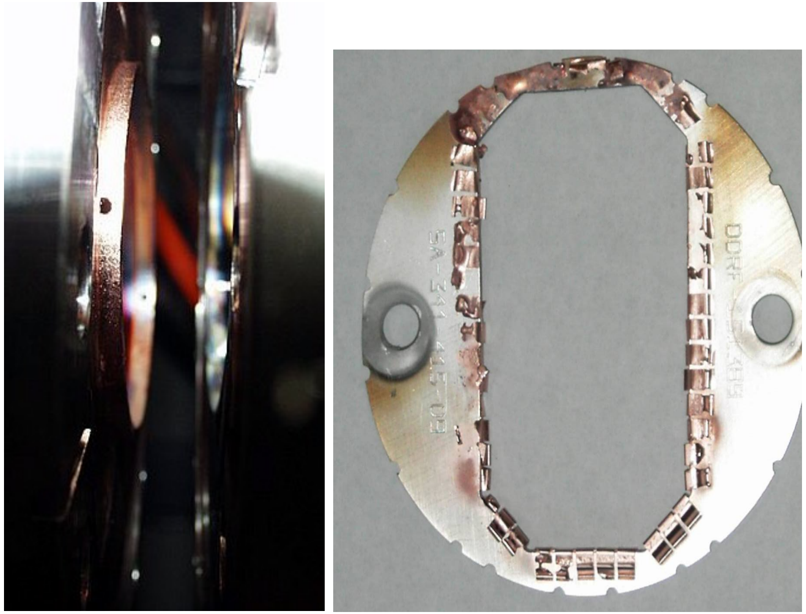
Feedback system helped a lot for damping longitudinal and transverse instabilities at higher currents





R. Akre, William Colocho, A. KrasnykhV. Pacak, D. Teytelman, U. Wienands, A. Young, 2006

However, we experienced more heating effects or breakdowns leading sometimes to beam instability



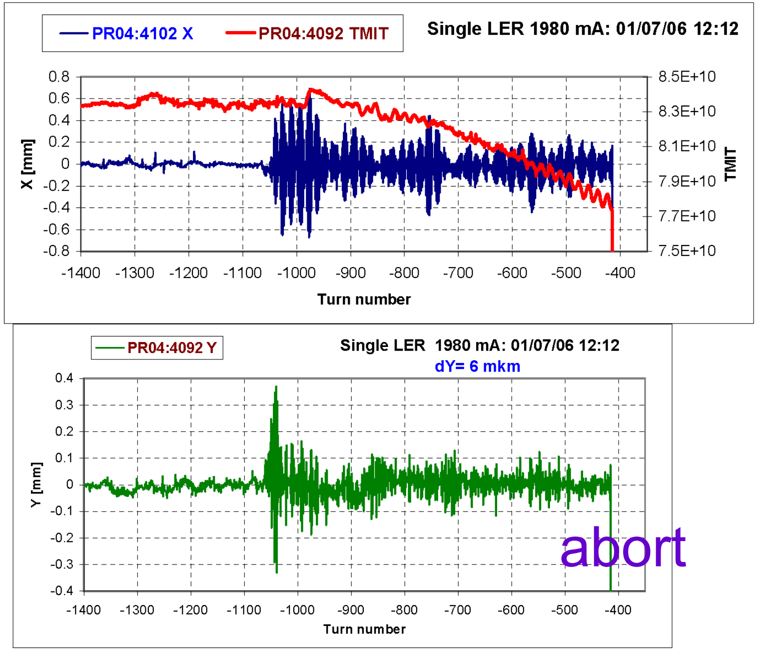
RF seals

Vacuum valves

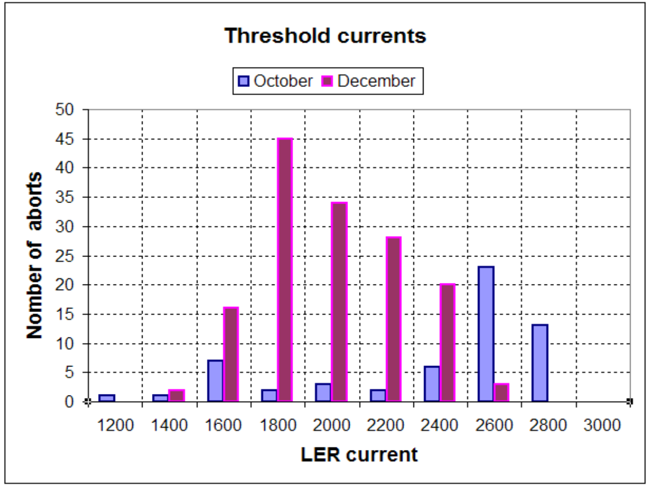
BPMs

A very strong fast instability was due to the wrong installation of the RF gasket

At the end of 2005, the beam in the PEP-II Low Energy Ring became affected by an instability with a very fast growth rate, but with a varying threshold.

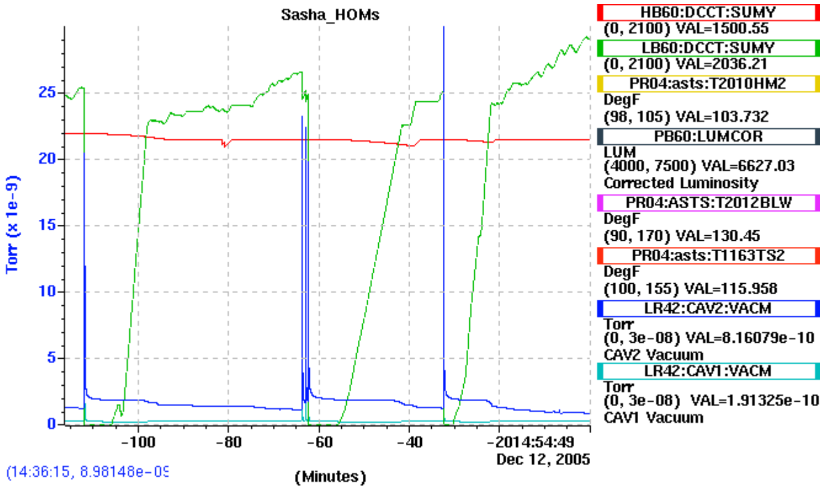


X and Y position of the beam during this instability

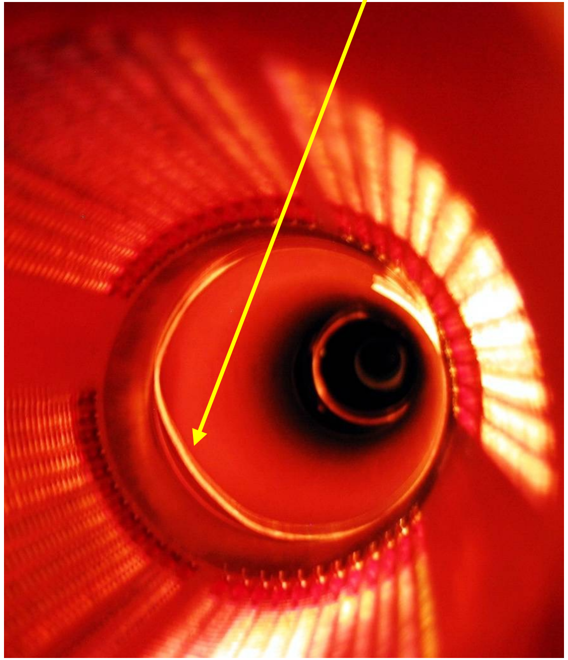


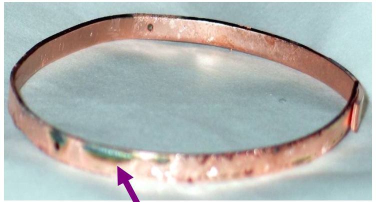
Instability study

- Instability was correlated with vacuum spikes, which happened near one of the new RF cavities. Vacuum spikes happened every time with each abort.



When we open the vacuum chamber at that location we found that RF seal (a gap ring with a cut) was not well installed



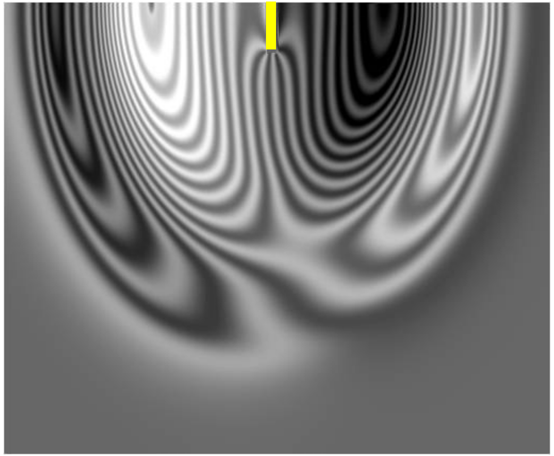


Breakdowns traces

How instability happened

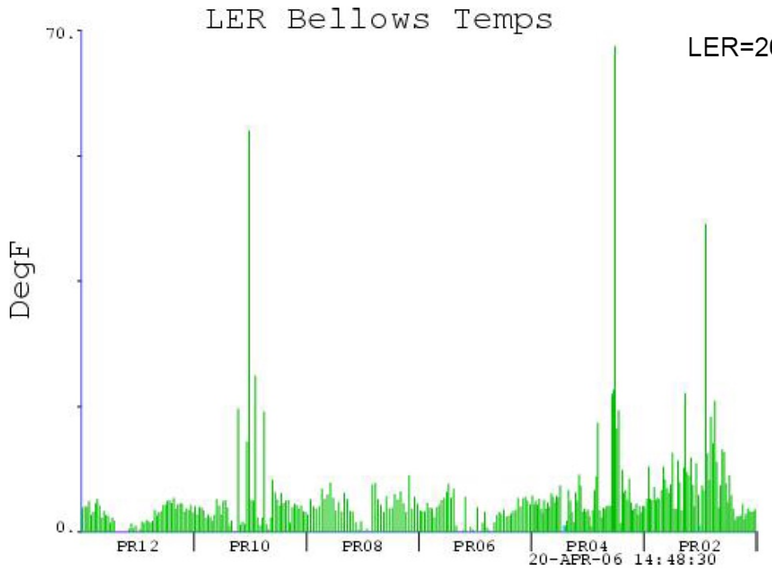
The beam excites one or several trapped modes at the place near the RF seal. At some LER current the electric field of this mode reaches the level of the breakdown threshold. When a breakdown happens, it produces a vacuum spike and a large high frequency signal, which propagates through the cavity to the RF feedback system. The disruption of the feedback system was so high, that cavity RF fields get large modulation in amplitude and phase, which destroyed the beam stability conditions and led to the beam abort.

We solved the problem by properly installing of a new gap ring. After that we no longer saw this kind of instability.

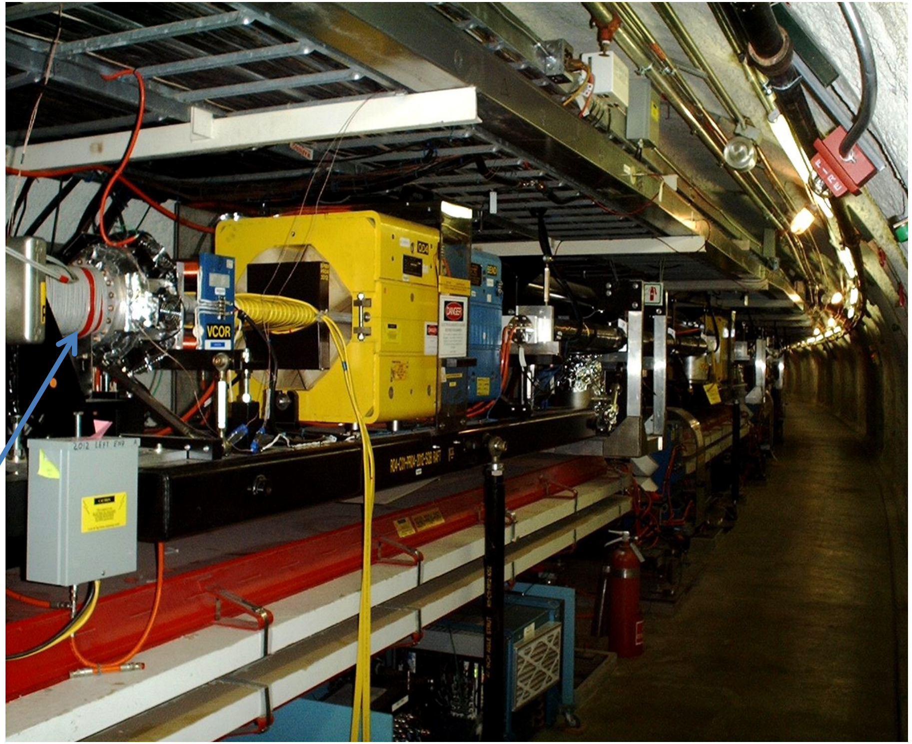


Electric field lines in a beam pipe after a bunch has passed a small bump. The electric field is concentrated at the edge of a bump.

Important problem was temperature raise in shielded bellows



LER=2600 mA

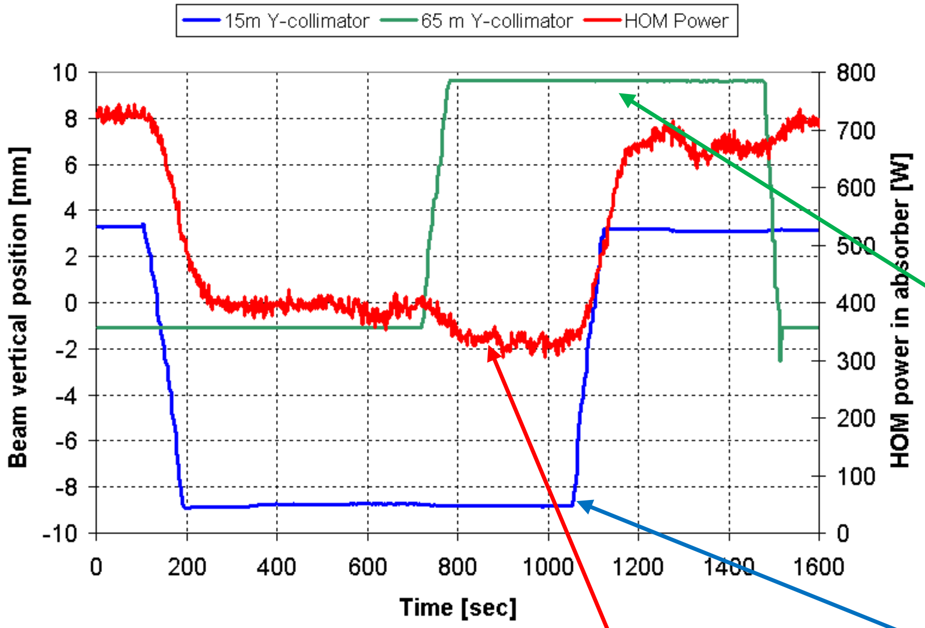


The hottest
Bellows
Region 4

Search for a source of wake fields

- We did not find any correlation between the temperature and the beam position near these elements: bellows and beam pipe ante-chambers also.
- So, we suggested that the wake fields can be generated in some other places. These fields have high frequency and may propagate long distances.
- These fields must have a transverse electric component and a longitudinal magnetic component in order to penetrate through the shielded fingers or longitudinal slots.
- An ante-chamber HOM absorber helped to find the source of these fields.

Finally, we found the source of the wake fields

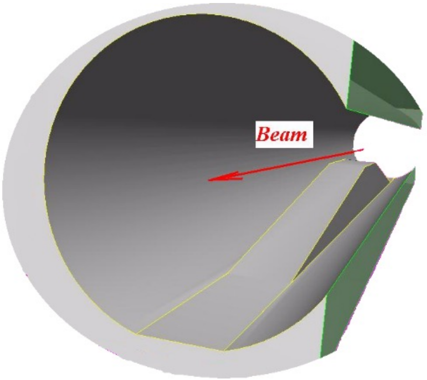


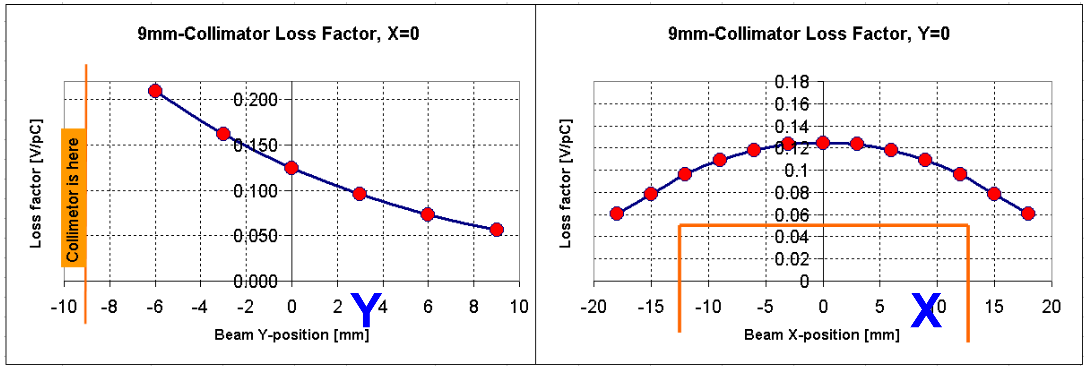
We found a strong correlation of the power in the HOM absorber with the beam position near collimators at 15 m and 65 m.

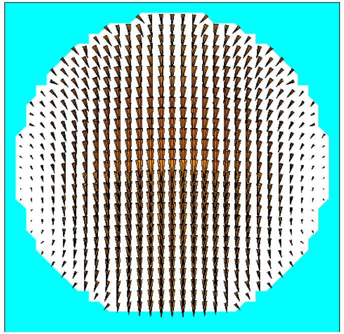
A. Novokhatski et al, "Damping the higher order modes in the pumping chamber of the PEP-II low energy ring", EPAC 2004,

Power in HOM absorber (red line) and when taking away the beam from collimators: vertical beam position near the collimator at 15 m (blue line) and at 65 m (green line)

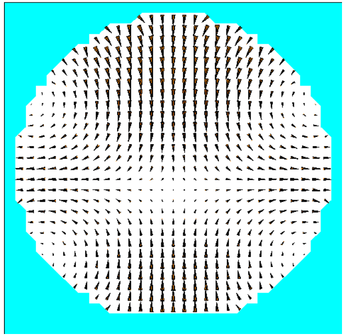
We did wake field simulations for the PEP-II collimators and found that they are really generate a lot of power in dipole and quadrupole modes



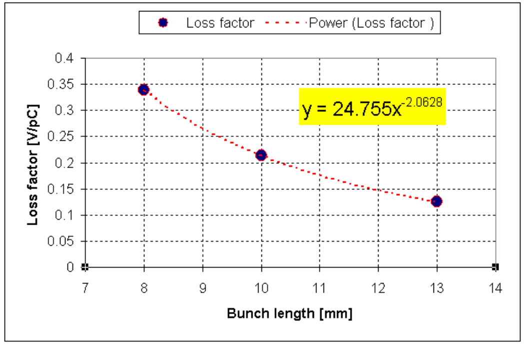




Dipole mode

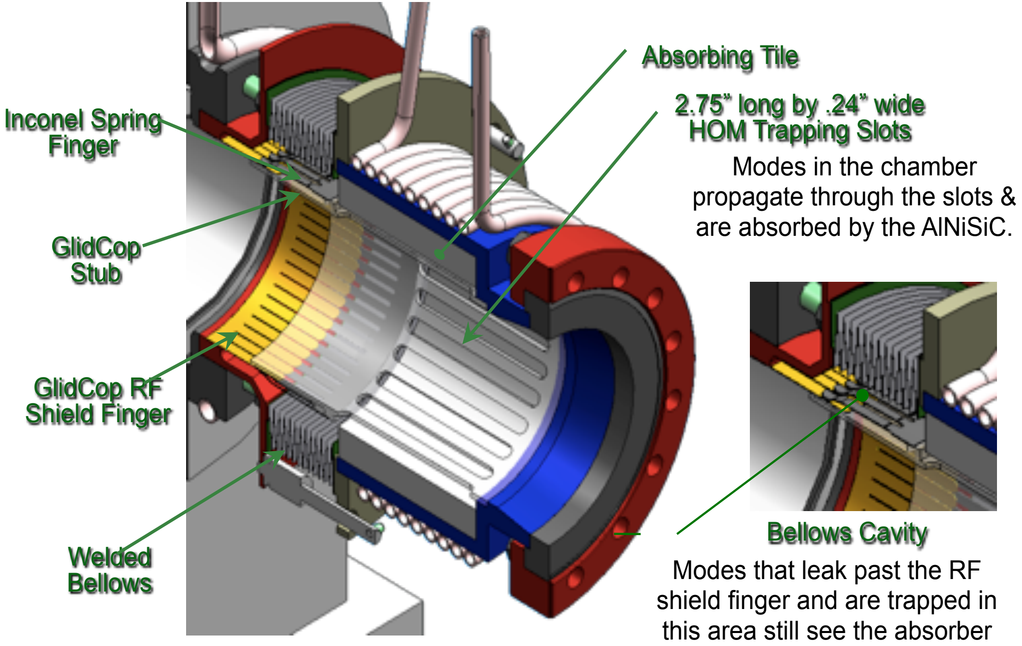


Quad mode



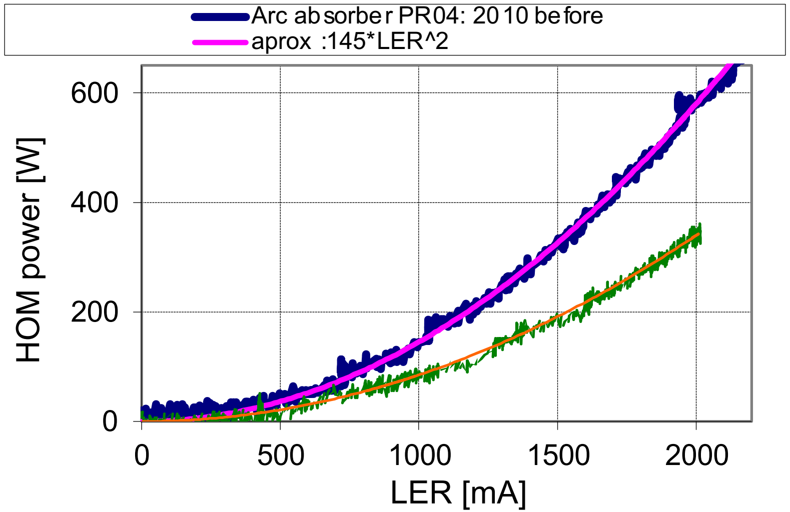
Bunch length

We designed a special HOM absorber, installed after each collimator and solved the problem.



>2 kW absorbed power at 3 A

HOM power in Arc absorber before and after installation of the straight HOM absorber



$$\eta = \frac{P_{before} - P_{after}}{P_{before}} \times 100\% = \frac{145-85}{145} \times 100\% = 41\%$$

As we have designed!

More information on the PEP-II bellows will be on Wednesday.

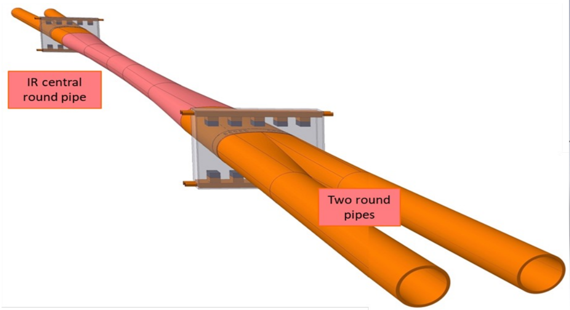
Now FCC IR beam pipe

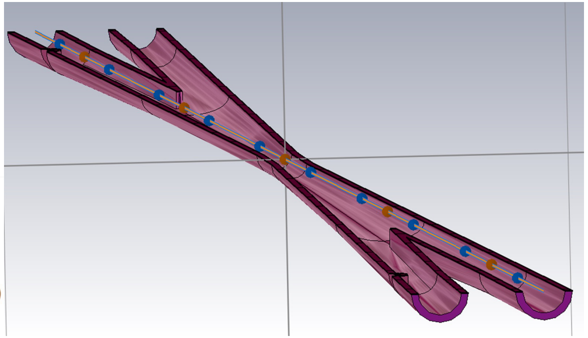
Historically the FCC IR beam pipe got several modifications. Precise wake field simulations using the CST code were impossible without CAD models, developed by

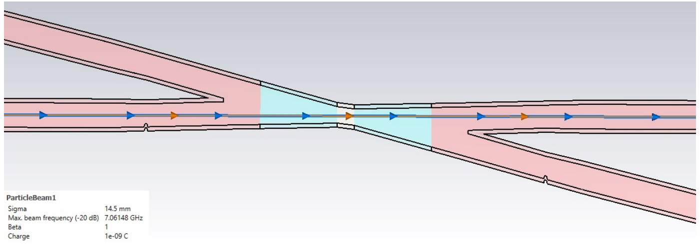
Miguel Gil Costa

Luigi Pellegrino

Francesco Fransesini

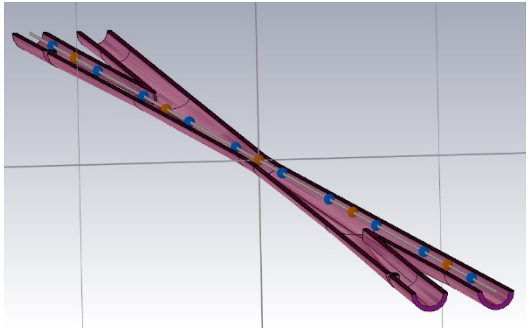




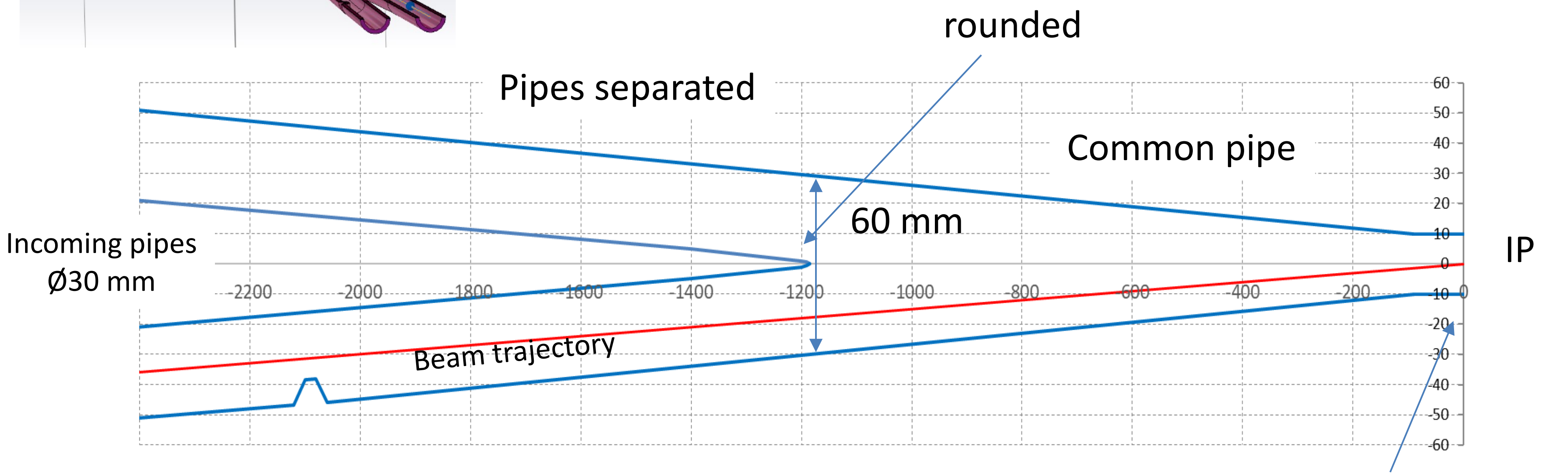


Many thanks !!!

The last CAD file is based on this geometry



Different metal part around the beam trajectory

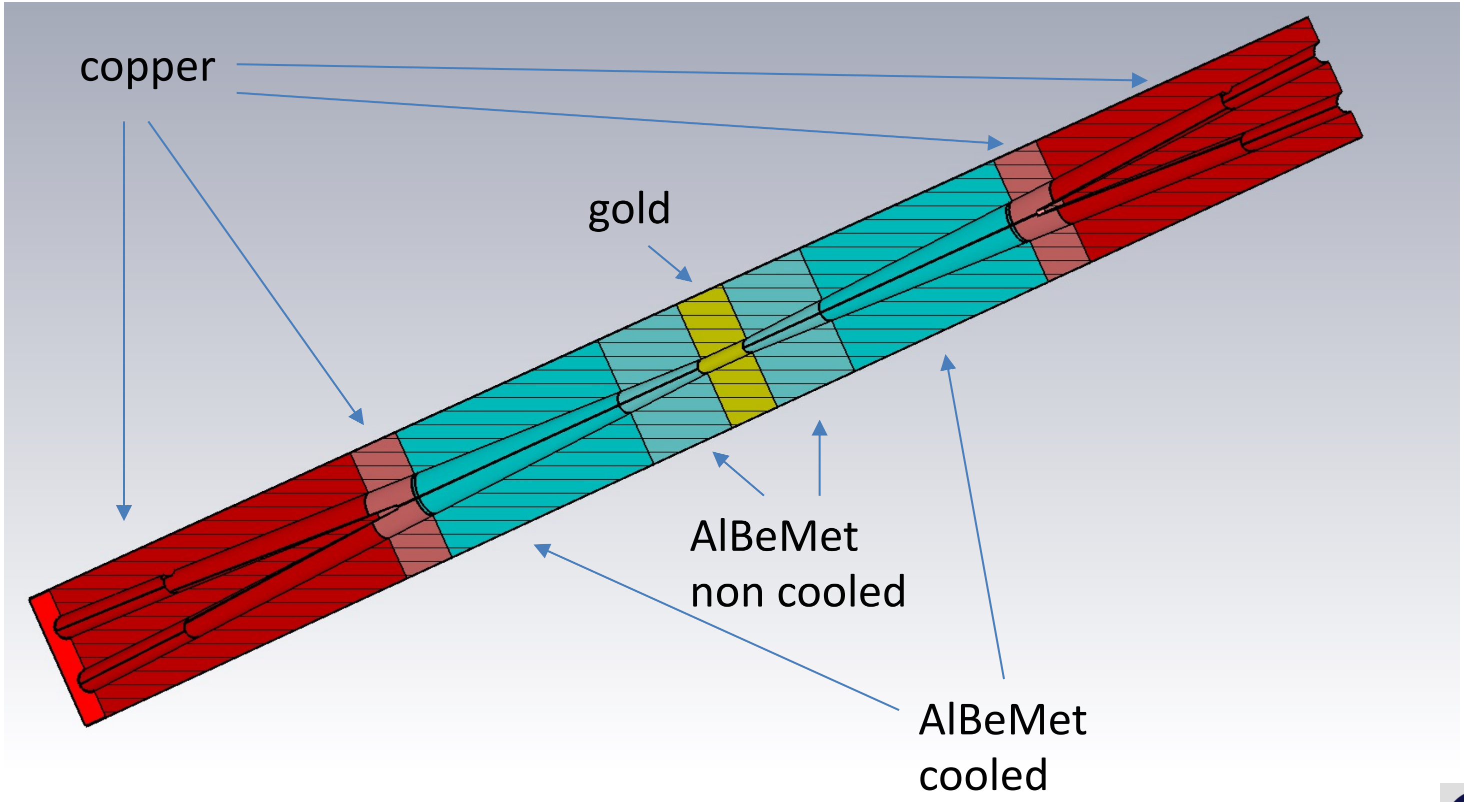


7 mm SR mask

Maximum transverse common pipe size

Ø20 mm x 2 x 90 mm IP round Be pipe

A new CAD model from Francesco Fransesini with special requirements for the heat load distribution simulation using the CST code



Calculation of the heat load distribution

- To find the heat load in some part of IR, we do the following calculations:
  - At first, we do wake field calculations, assuming that all materials have infinite conductivity
  - Then we do wake filed calculations, also assuming that all materials have infinite conductivity, except the material of the interested part of IR
  - Finally, we take the difference
- Naturally, it needs a lot of calculations, but the result is important for the cooling system design.

Heat load: electromagnetic power of wake fields

All electromagnetic waves, exciting by the beam will be absorbed by the beam pipe walls or inside some accelerating components.

Here is a general formula to estimate the heat load from one beam

$$P = k\tau I^2$$

Power = Loss factor x bunch spacing x Current^2

$k\tau$ can be consider as an overall resistance of the beam pipe

For two colliding beams the power is usually doubled

I checked this formula practically during PEP-II operation. It really works.

Last week beam parameters from K. Oida

"latest" parameters

FUTURE CIRCULAR COLLIDER

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.95 / 2.75
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.5 / 8.8
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	399.994581		399.994627	
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.0
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y[a]		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.093 / 0.140
Luminosity / IP	[10^{34}/cm^{2}s]	182	19.4	7.26	1.25
Lifetime (q + BS + lattice)	[sec]	840	–	< 1065	< 4062
Lifetime (lum)	[sec]	1129	1070	596	744

[a]incl. hourglass.

K. Oide, Oct. 17, 2022 5

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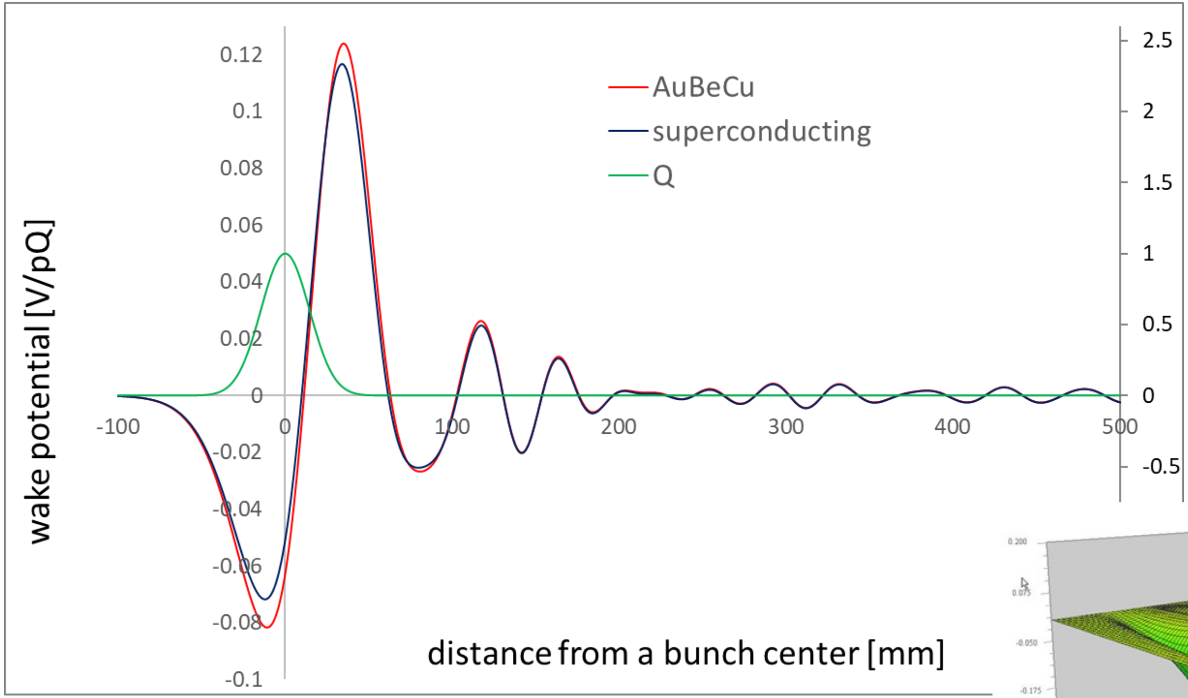
Comparison of the wake potentials (with/out materials)



Heat load

with without

4.0 2.7

kW

In the IR walls

1.3 kW

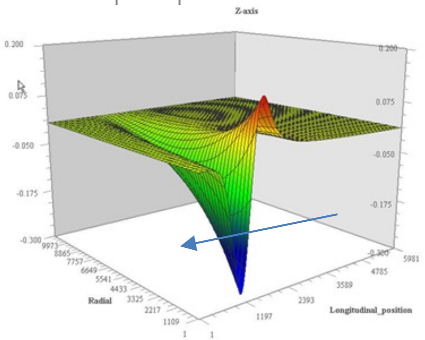
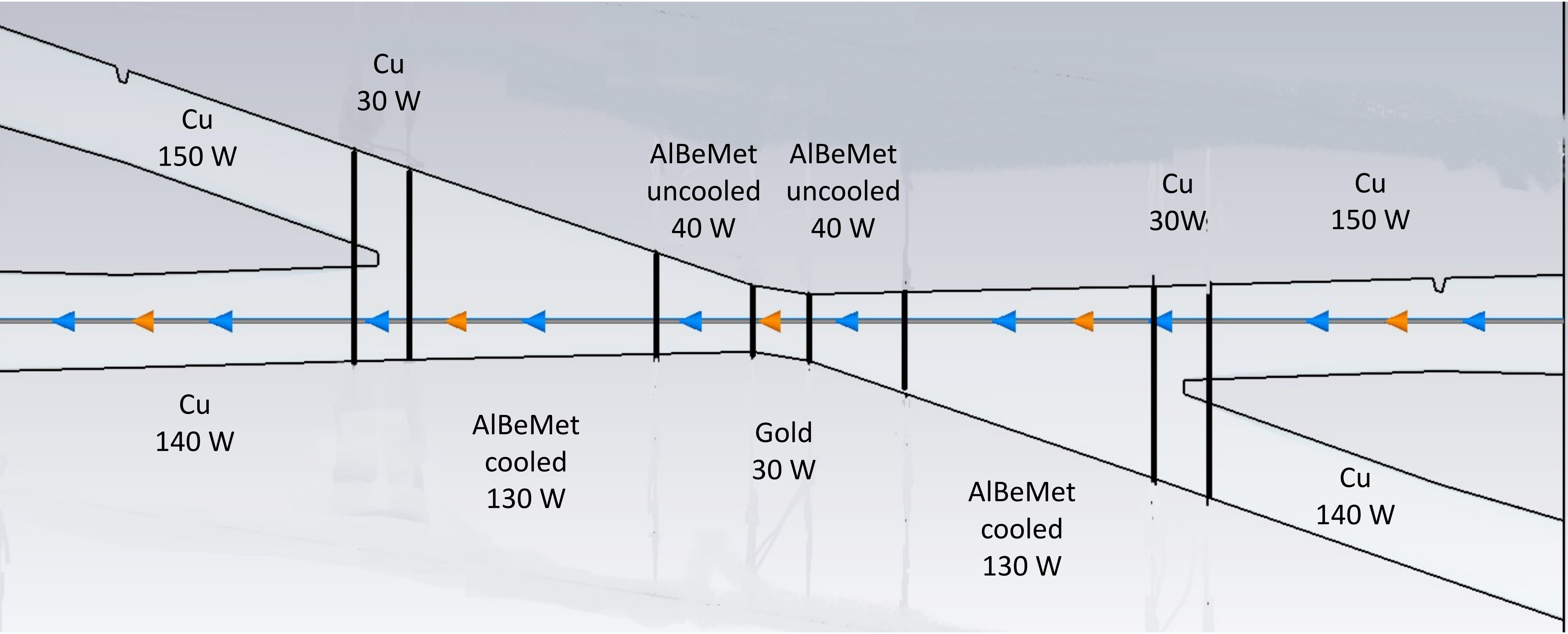


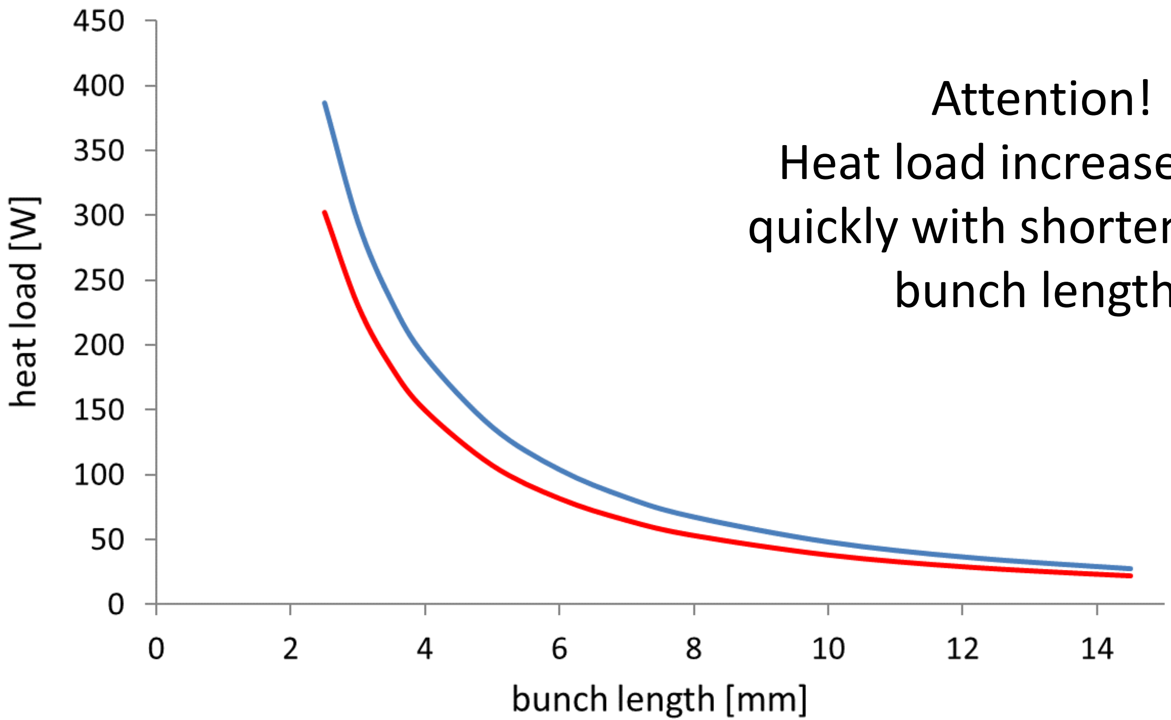
Image current fields follows the bunch

Heat load distribution



Scale is distorted

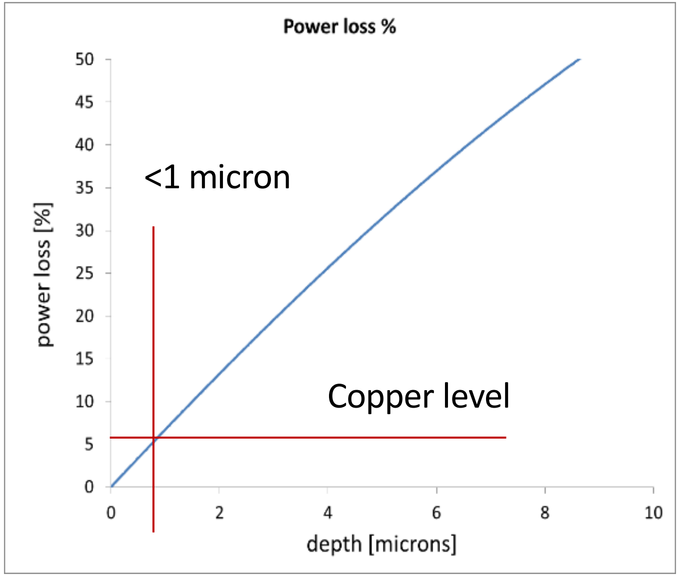
Heat load in the central part (180 mm) vs bunch length



Attention!
Heat load increases very quickly with shortening the bunch length.

We are keeping in mind that the NEG coating can be used sometime in IR

Just for this case we did wake field calculation for the NEG with a conductivity of 100 Ohm/mm



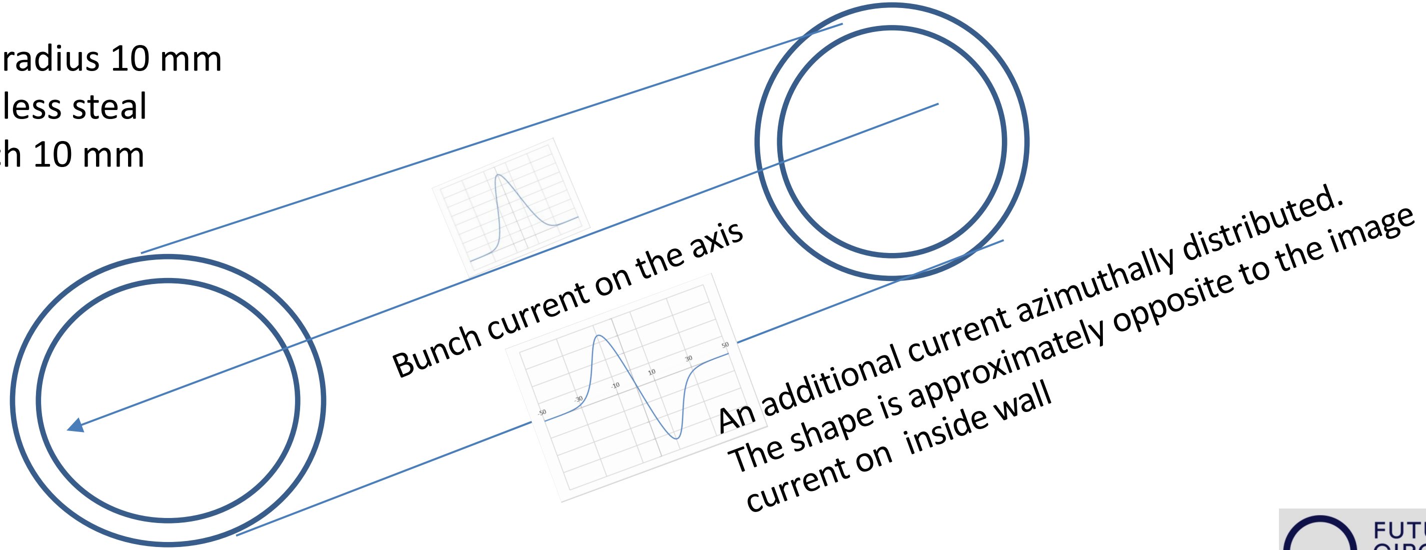
NEG coating must be less than 1 micron to have the same heat load as copper walls.

Are resistive-wall wake fields unavoidable?

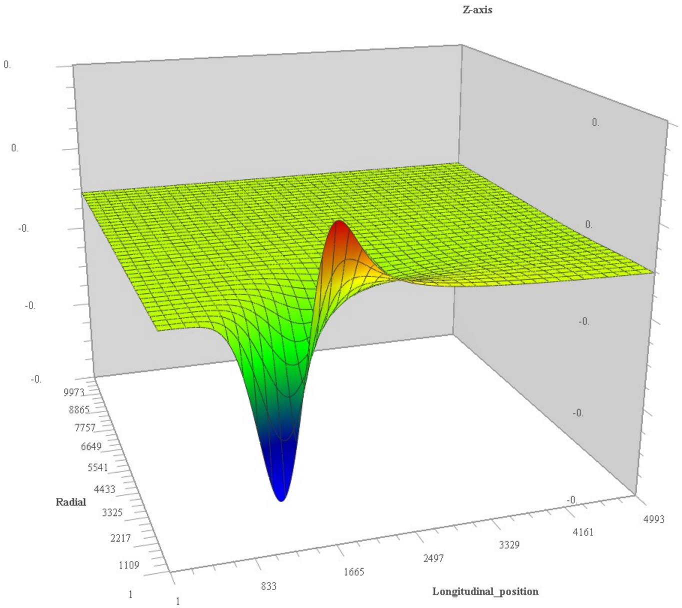
Is it possible to partially compensate the resistive losses?

Here are some results our study (Pantaleo Raimondi and me), considering a possibility for potential use on specialized chambers (eg. kickers or ultra small gap devices).

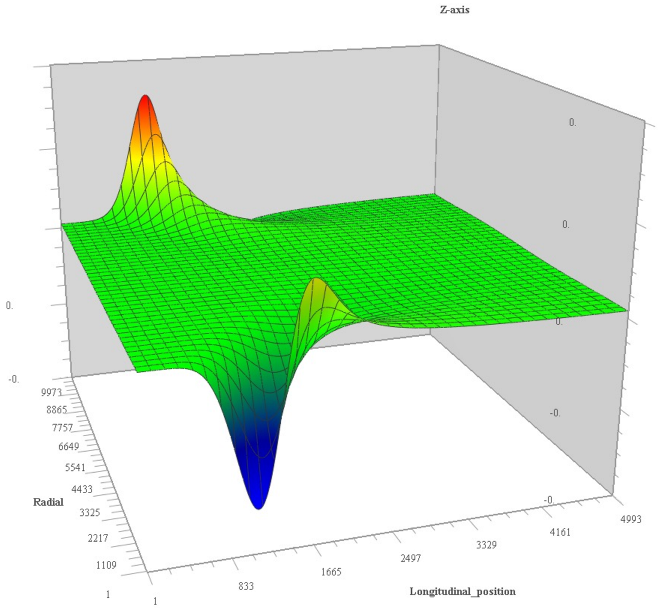
Pipe radius 10 mm
Stainless steal
Bunch 10 mm



100-micron beam pipe thickness
Longitudinal current inside a metal part of the beam pipe

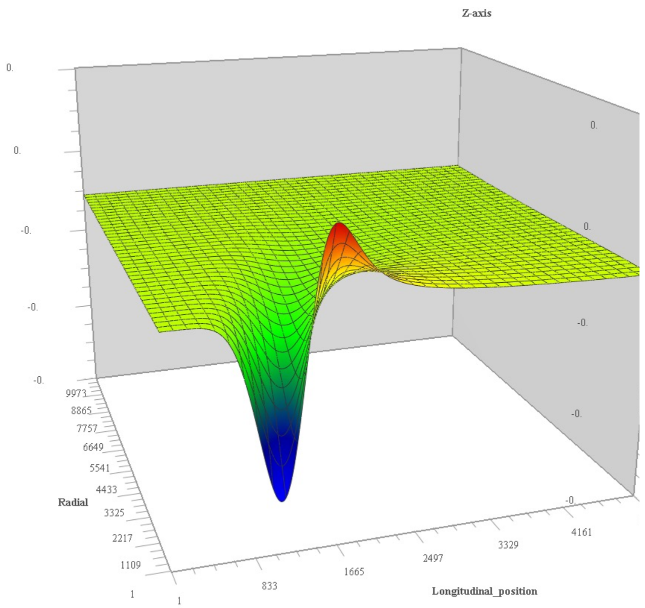


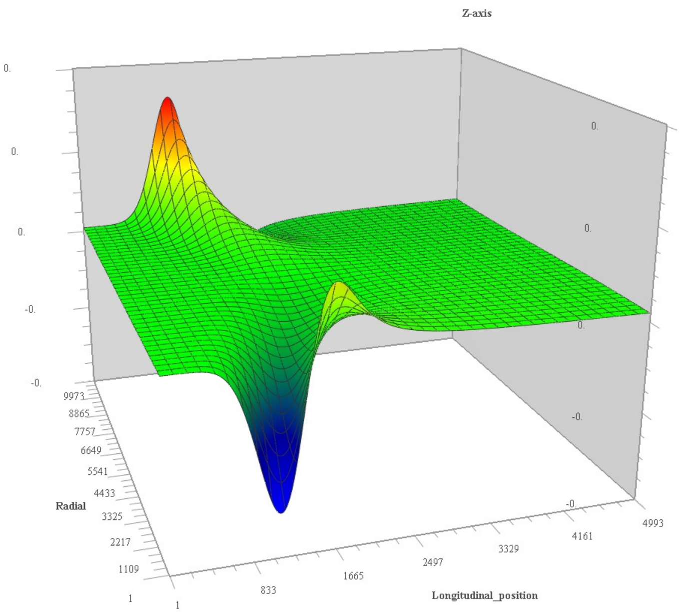
Current excited by a moving bunch



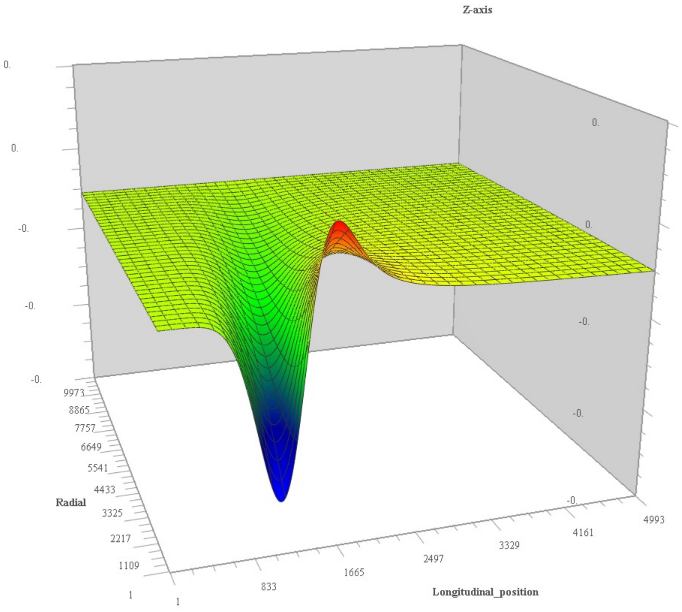
+ additional opposite current

50-micron


Z-axis
Radial
Longitudinal_position
9973
8865
7757
6649
5541
4433
3325
2217
1109
1
833
1665
2497
3329
4161


Z-axis
Radial
Longitudinal_position
9973
8865
7757
6649
5541
4433
3325
2217
1109
1
833
1665
2497
3329
4161
4993

25 micron



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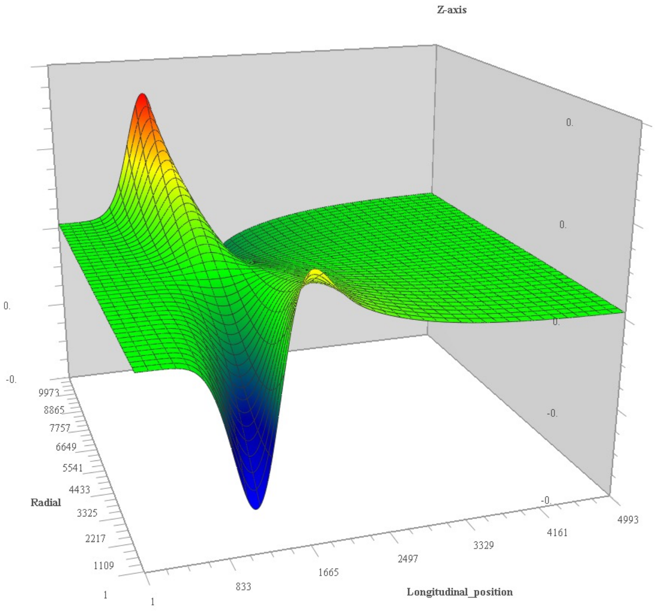
0.
-0.
-0.
-0.
0.
0.
-0.
-0.
-0.
9973
8865
7757
6649
5541
4433
Radial
3325
2217
1109
1
1
833
1665
2497
3329
4161
4993
Longitudinal_position



Z-axis
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0.
-0.
0.
-0.
-0.
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Radial
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1
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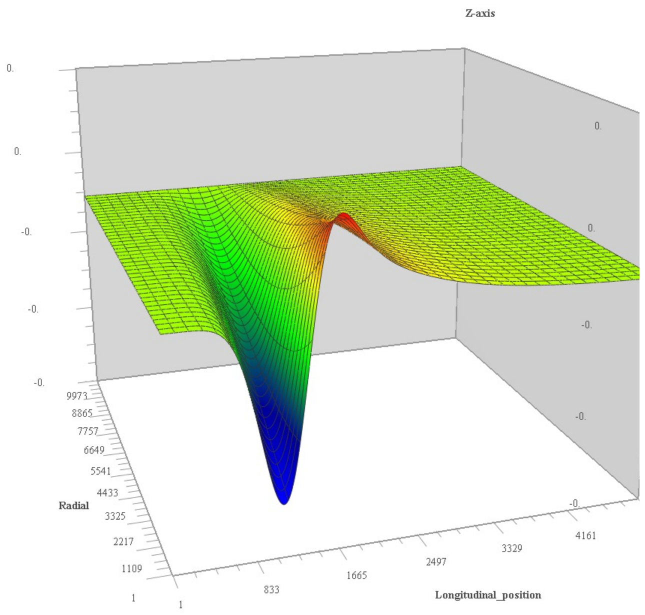
2497
3329
4161
4993
Longitudinal_position

12.5 micron



Z-axis
Radial
Longitudinal_position
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1
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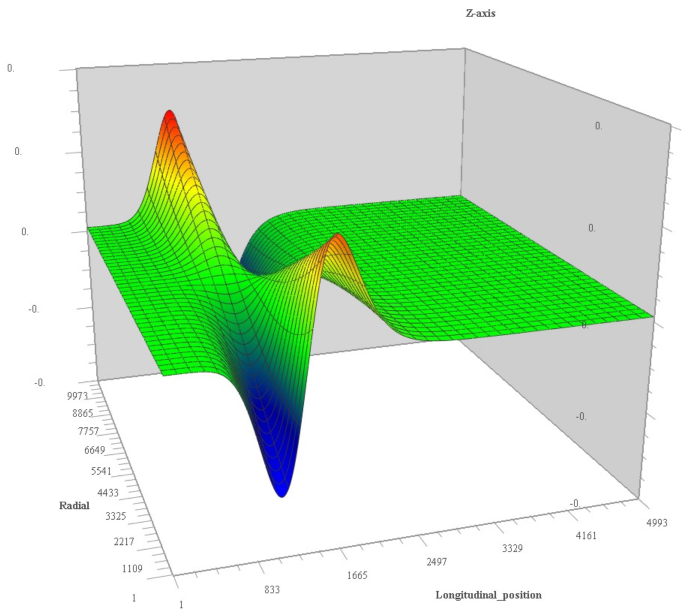

Z-axis
Radial
Longitudinal_position
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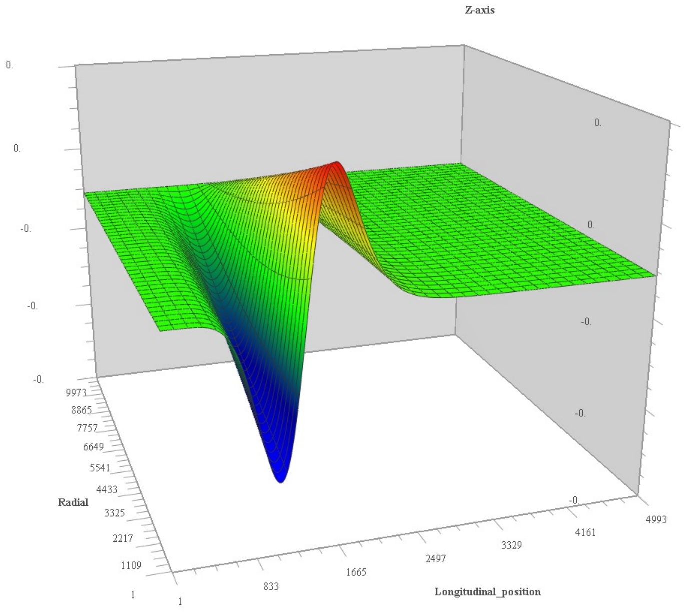
4433
3325
2217
1109
1
833
1665
2497
3329
4161
4993

6.25 mikron


Z-axis
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Longitudinal_position
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1
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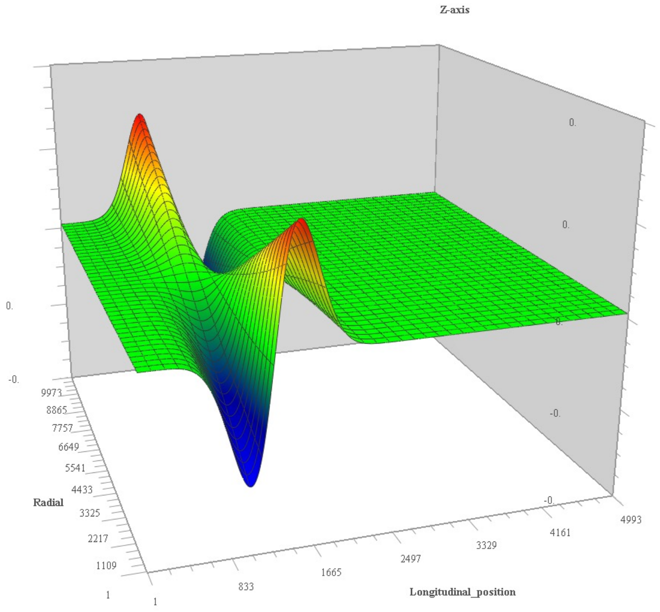
Z-axis
Radial
Longitudinal_position
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1
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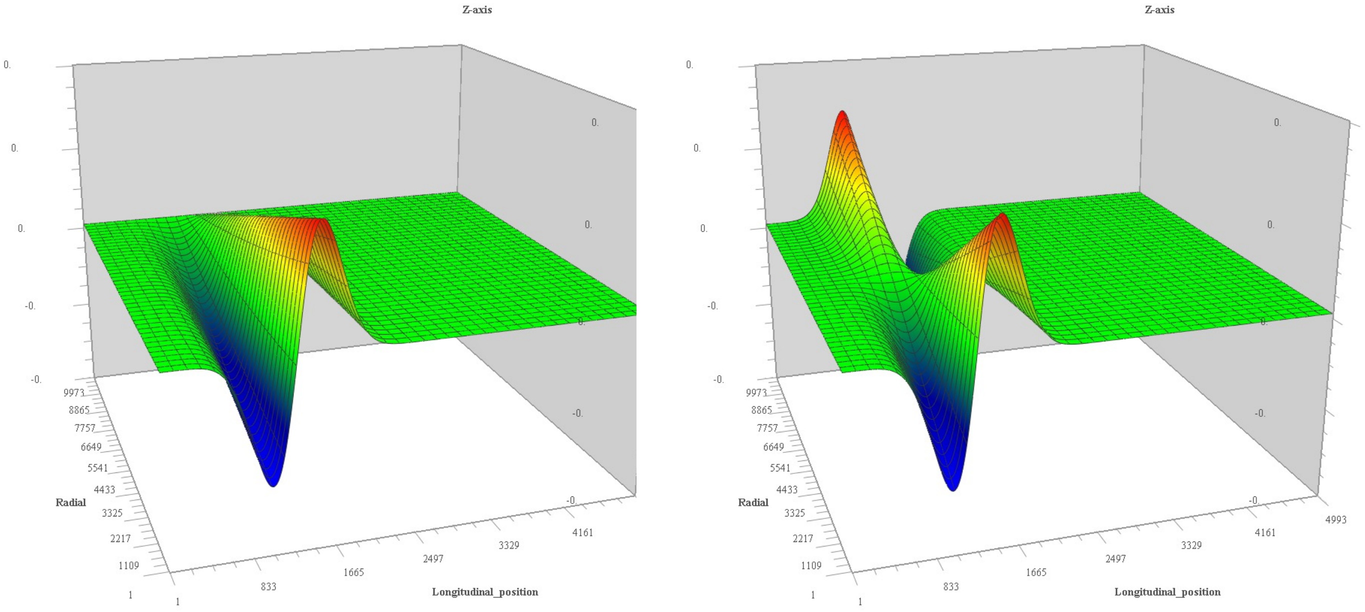
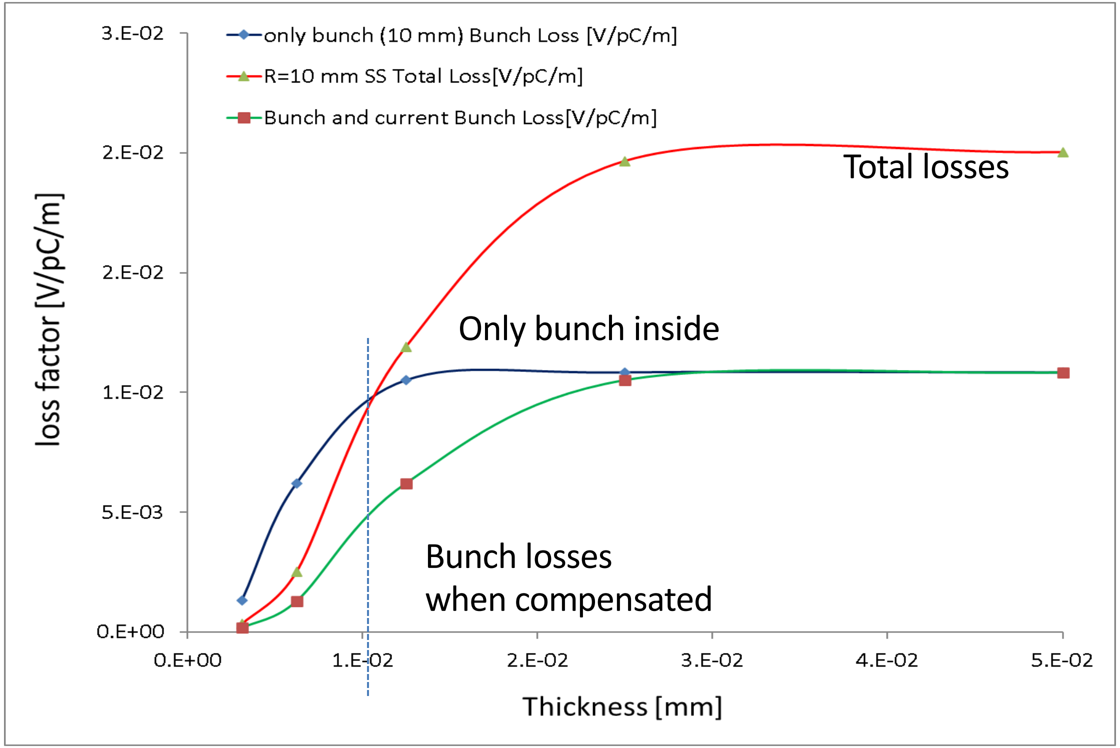
2497
3329
4161
4993

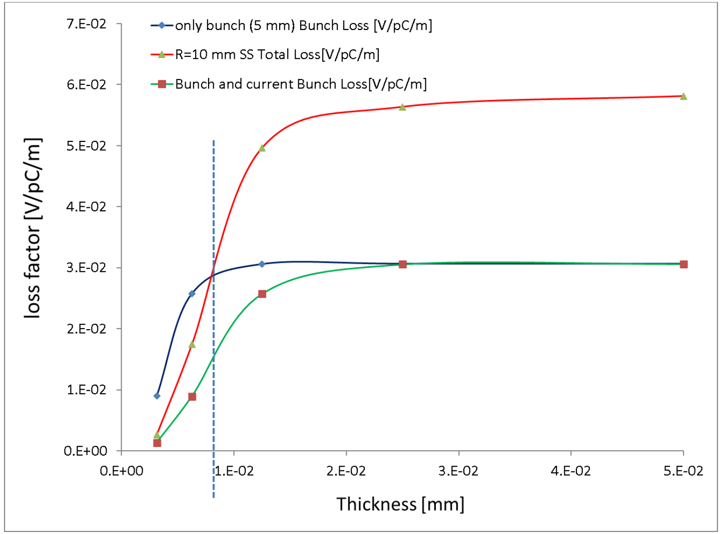
3.125 micron


Z-axis
Radial
Longitudinal_position
Z-axis
Radial
Longitudinal_position

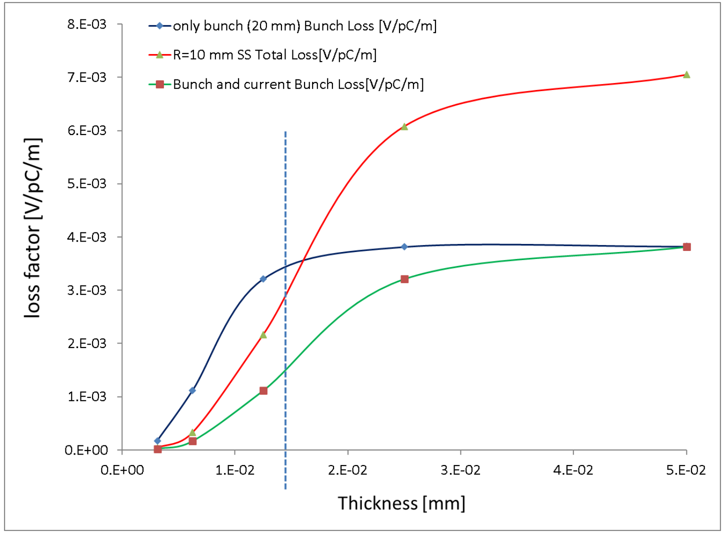
Effect of an additional current for less than 10-micron thickness (define as threshold thickness)



The threshold thickness ~ square root of the bunch length

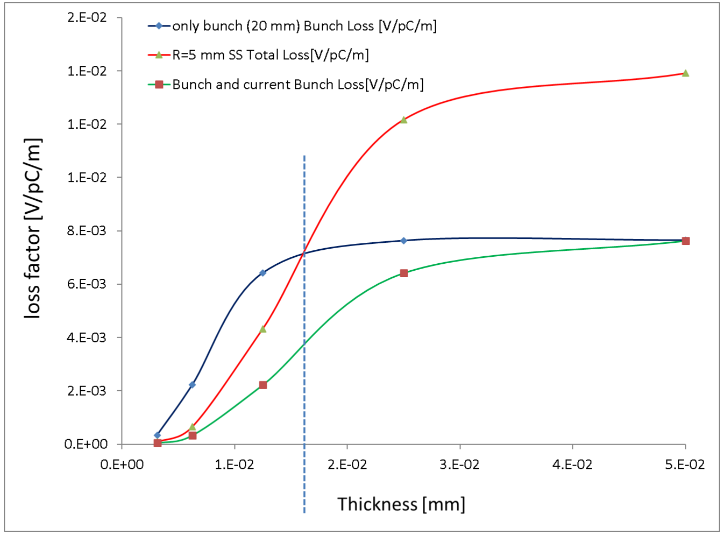


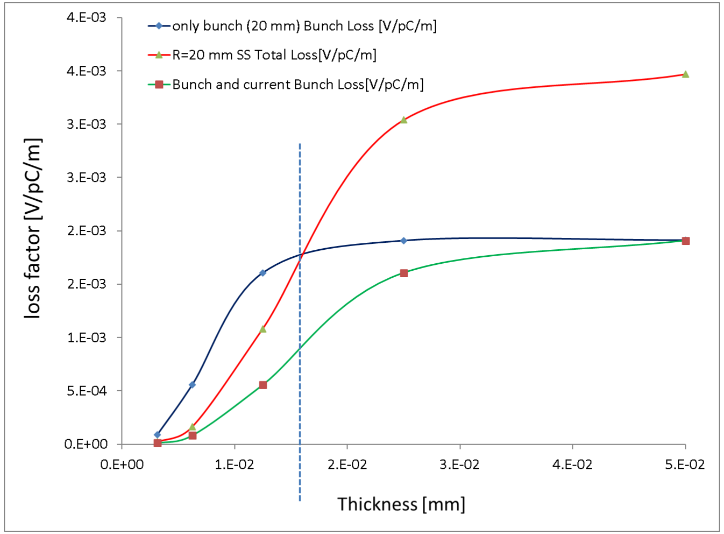
5mm bunch



20mm bunch

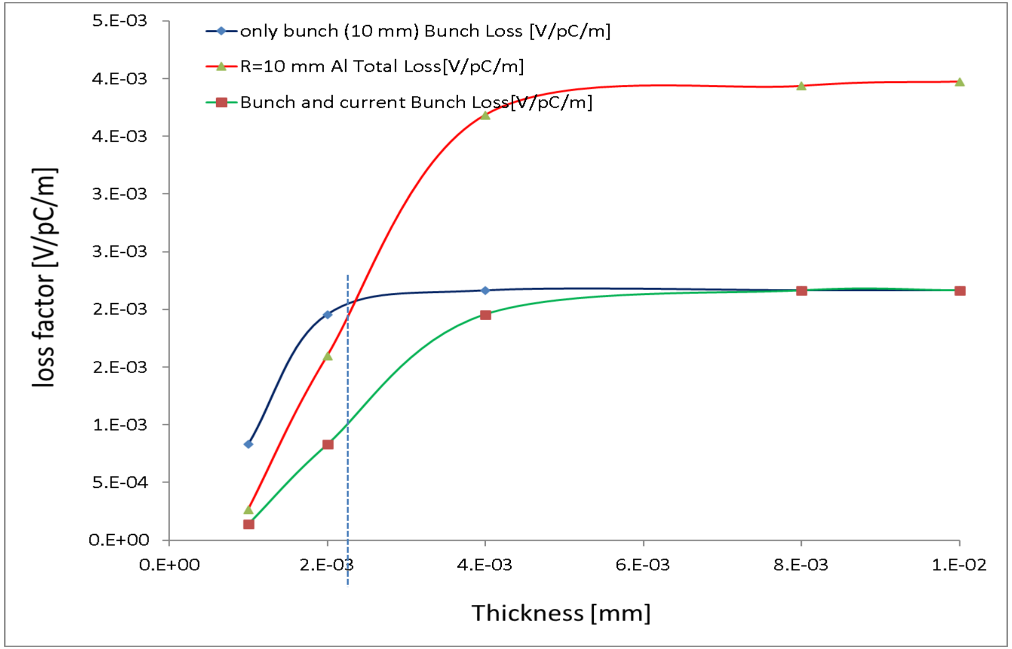
The threshold thickness does not depend on the radius of the beam pipe





R=5mm R=20mm

The threshold thickness is inversely proportional to the square root of conductivity



Conductivity of Al is 25 times higher than SS

Conclusions

- PEP-II experience with high currents can be vey useful for the FCC design
- Calculations showed that in the FCC IR region (+-4 m) approximately 1.3 kw power is dissipated in the pipe walls
- Necessary cooling is needed
- Still no sing of a strong trapped mode because of the special shape of the IR beam chamber
- However almost 2.7 kW power, which is generated in IR will go out in four pipes and will be dissipated somewhere in the rings.
- Finally, the resistive-wall wake field losses can be compensated in some cases

Acknowledgement

I would like to thank Frank Zimmermann, and Michael Benedikt for their great support of this work.

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