Higher Order Modes in IR beam pipe

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Outline

I. General problems with high beam currents in storage rings
II. Beam electromagnetic interaction with IR metal vacuum chamber
III. An unavoidable trapped mode
IV. Beam electromagnetic interaction with the IR metal vacuum chamber
V. Experience from high current PEP-II B-factory
VI. Interaction Regions of other Colliders
VII. Summary

General problems with high beam currents in storage rings

I. High current beams in storage rings have a great impact on the performance of the machine.

II. An electromagnetic interaction of the beam with a metallic vacuum chamber not only changes the beam dynamics but also increases the background as a result of additional microwave heating.

III. Mainly this is an interaction with the resistive metal walls of the beam pipe (multi-bunch instability and wall heating)

IV. However any geometrical disturbance of the beam pipe (like RF seals between chamber elements joints) gives a possibility for the beam field to be scattered. In this way the beam will generate electromagnetic waves, which can propagate long distances or escape through the small electromagnetically coupled holes in the beam pipe (slots in shielded bellows, valves, pumps or ceramics in BPMs connectors)

V. Several accelerator elements (like RF cavities, kickers or Interaction Region) have trapped RF modes, which frequencies can be in resonance with the harmonics of the beam rotation frequency. As a result the accumulated electric filed of a trapped RF mode can be high enough to produce sparks and destroy good vacuum.

VI. Without a proper cooling the temperature of some vacuum elements can be very high enough to mechanically deform the element, to melt thin shielded fingers or partioly destroy the vacuum sealing

High currents notice: it must be very small impedance of the beam pipe

Heating power

$$P = \tau_b \times k \times I^2$$

Power   Bunch Spacing   Loss Factor   Current

$$P_{[kW]} = 4.2_{[n\sec]} \times 0.026_{\frac{V}{pC}} \times 3^2_{[A]}$$

Bunch pattern by 2

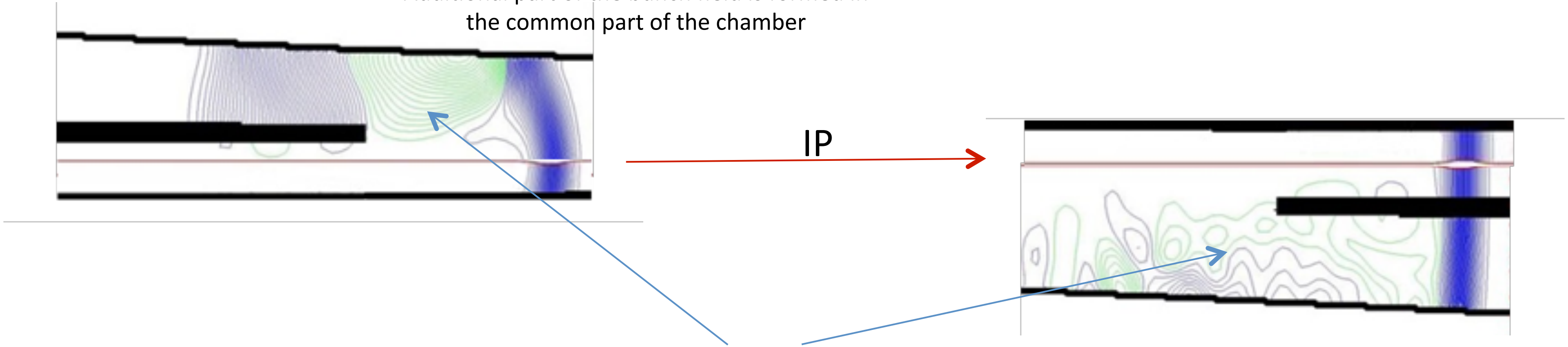
$\boxed{\text{Loss factor of only 0.026 V/pC "works" like a 1 kW microwave}}$

Every small irregularity of the vacuum chamber becomes very important

Beam electromagnetic interaction with IR metal vacuum chamber

- The geometry of the beam pipe of the interaction region (IR) is very complicated. Two pipes are merged into one central pipe and then are separated again.
- When an electron bunch travels from one pipe to another trough the central part, it excites electromagnetic fields due to diffraction of the bunch self field on the pipe connections.

Additional part of the bunch field is formed in the common part of the chamber



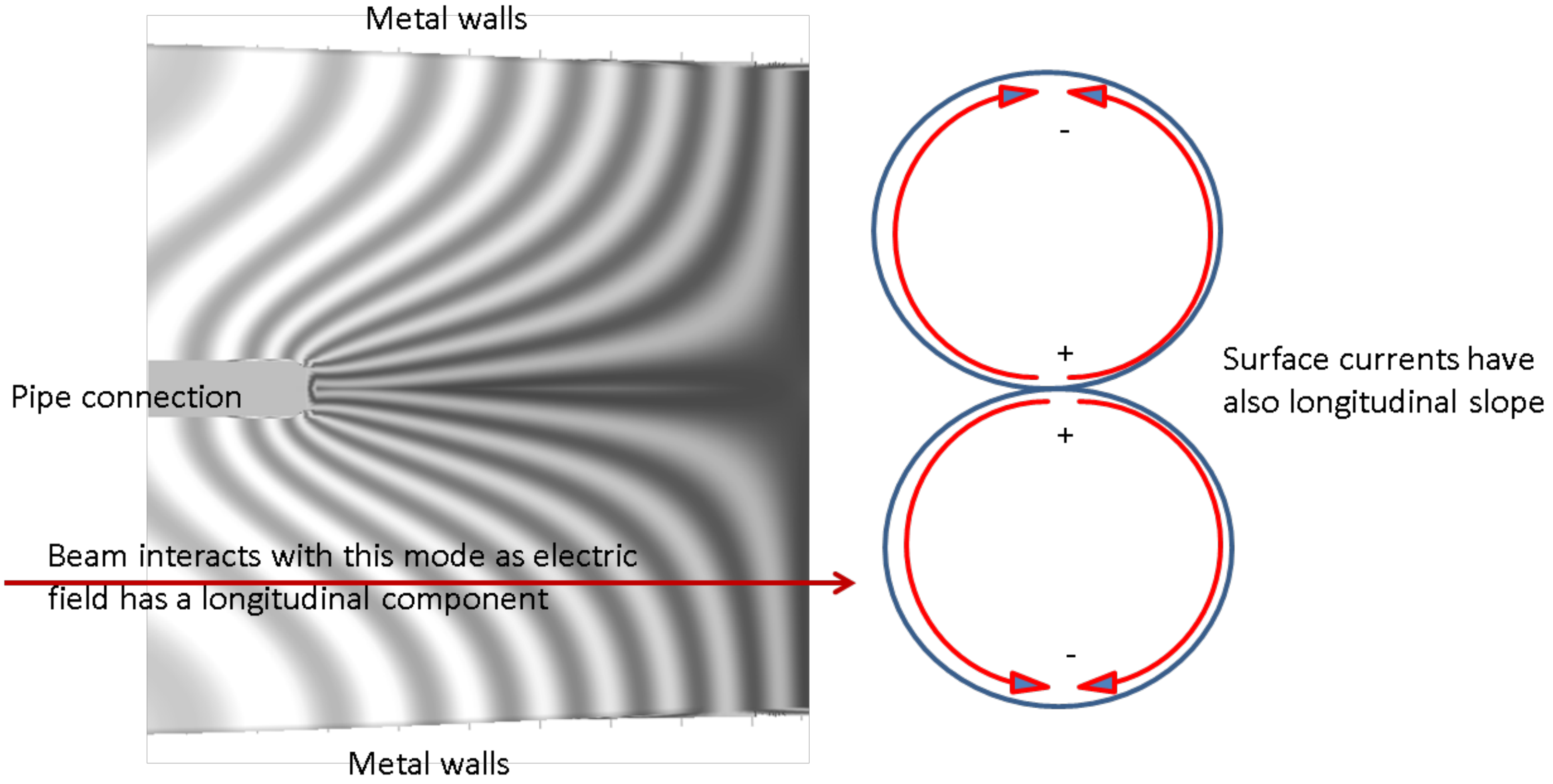
Forward and backward excited fields propagate to other pipe connections and are reflected back. In this way they form a Higher Order trapped Mode.

Some part of the bunch field is cut by the metal pipe connection

Electromagnetic fields in IR

- We may consider three types of electromagnetic fields exciting in IR
  - Resistive-wall wake fields, which are responsible for local heating, especially for NEG coating
  - Propagating wave, which may leave IR and be absorbed somewhere in the ring
  - Trapped modes, which are stay and absorbed in IR
    - Under resonant conditions trapped modes can be strongly magnified.

An unavoidable trapped mode



Importance of the IR beam chamber design

- We may minimize the effect of HOM heating by optimizing the geometry of the IR beam chamber
- For optimization a careful calculation of the HOMs and propagating waves is needed. To get best results we used high level CAD model in 3D CST and HFSS calculations
- The design of the IR HOM absorber is very important to achieve high currents in collisions.
- A proper air, water or paraffin cooling of the IR beam chamber will keep the temperature at right level

Experience from PEP-II SLAC B-factory

The SLAC PEP-II asymmetric B-factory storage ring collider nominally collides 1700 bunches of 3.0 A of 3 GeV positrons on 1.75 A of 9 GeV electrons consisting of a low energy positron storage ring (LER) situated above a high energy electron storage ring (HER).

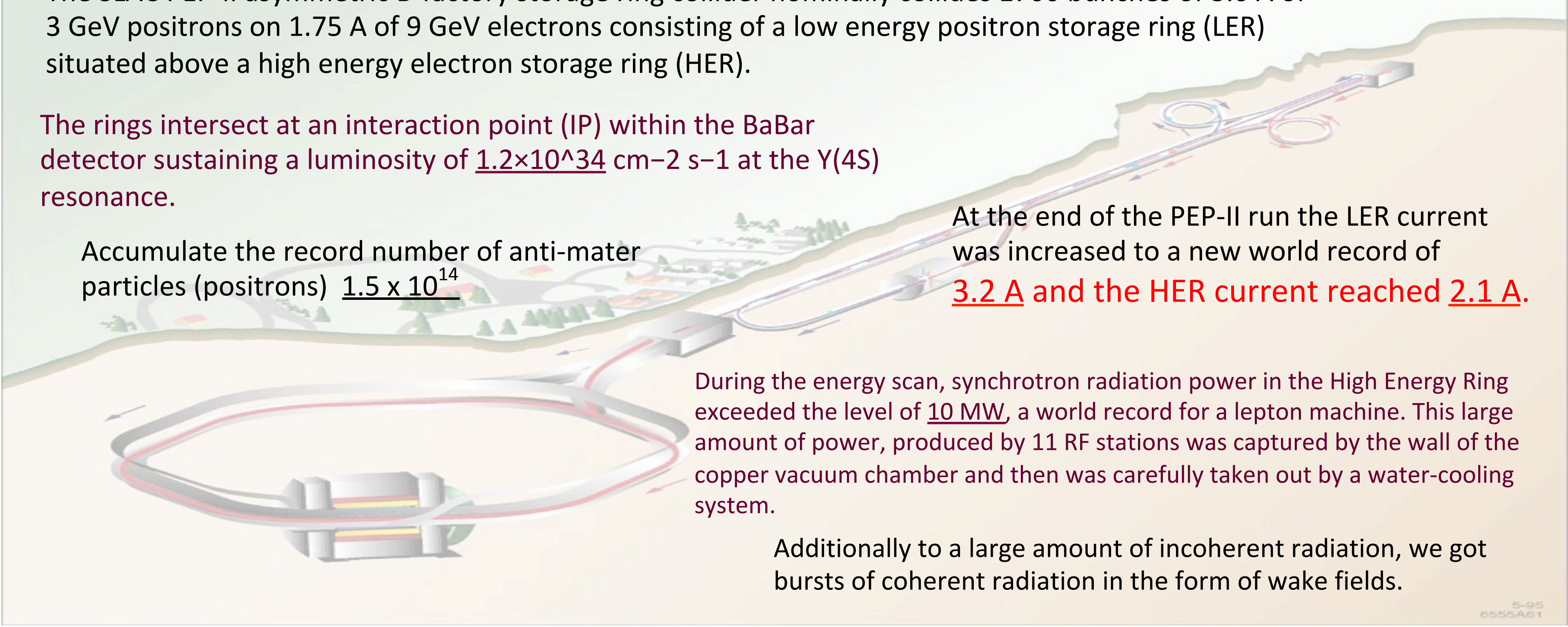
The rings intersect at an interaction point (IP) within the BaBar detector sustaining a luminosity of <u>1.2×10^34</u> cm−2 s−1 at the Y(4S) resonance.

Accumulate the record number of anti-mater particles (positrons) <u>1.5×10^{14}</u>

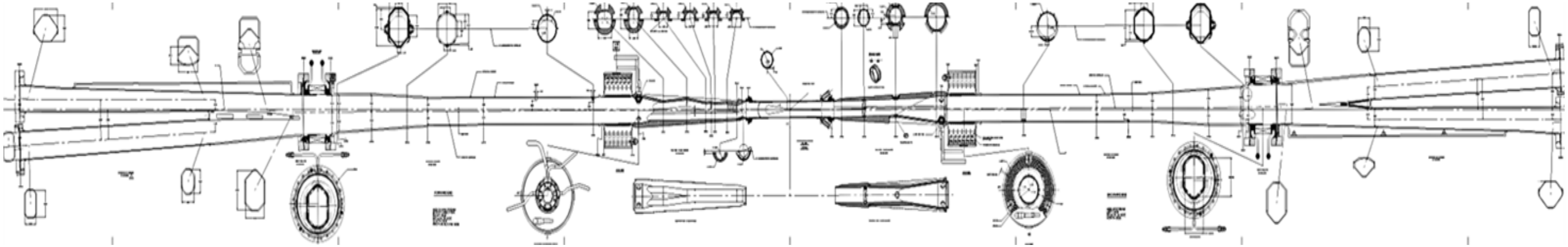
At the end of the PEP-II run the LER current was increased to a new world record of <u>3.2 A</u> and the HER current reached <u>2.1 A</u>.

During the energy scan, synchrotron radiation power in the High Energy Ring exceeded the level of <u>10 MW</u>, 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.

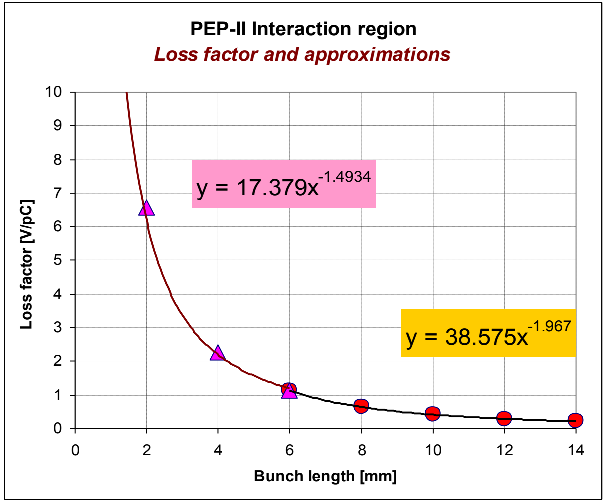
Additionally to a large amount of incoherent radiation, we got bursts of coherent radiation in the form of wake fields.



PEP-II B-factory Interaction Region.

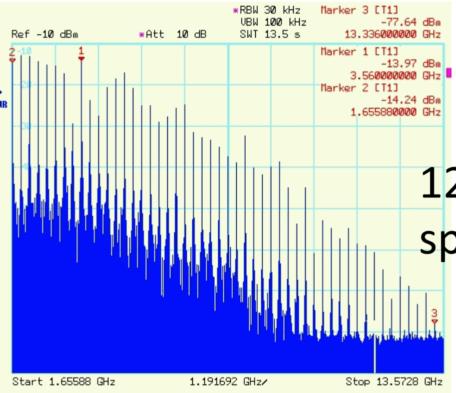


Smooth transitions from two pipes to a common pipe, but there are several unregular disturbances for synchrotron masks. Two HOMs absorbers, but with open to the beam ceramic tiles, which gives a possibility for a beam to generate addition power due to Cherenkov radiation.



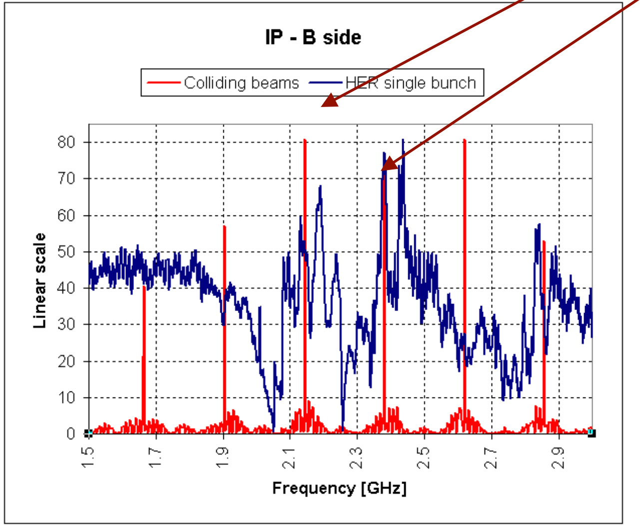
A. Novokhatski, J. Seeman, M. Sullivan, "Analysis of the wake field effects in the PEP-II storage rings with extremely high currents", *NIM A 735 (2014)*

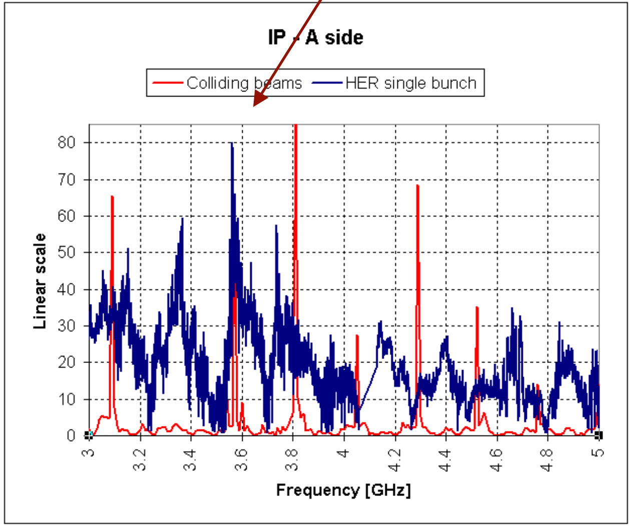
HOM spectrum and dangerous resonances of the colliding beams in IR

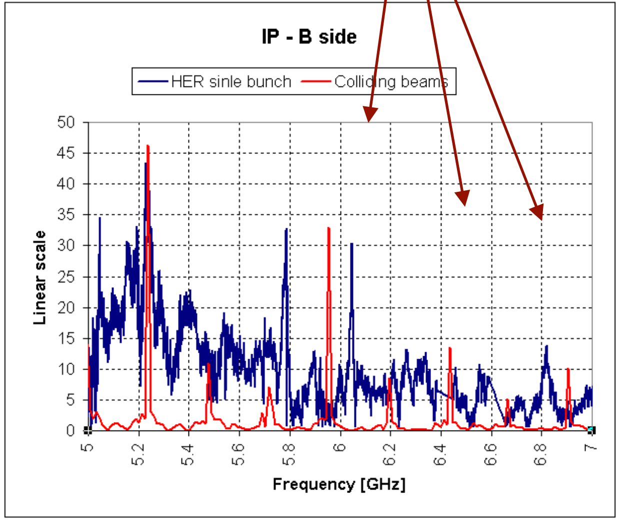


12 mm bunch spectrum

Vertex bellows modes



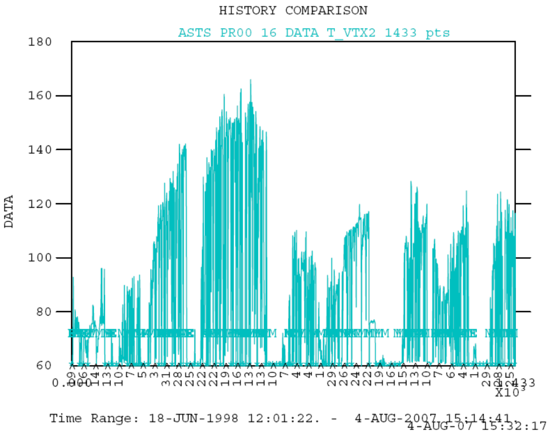


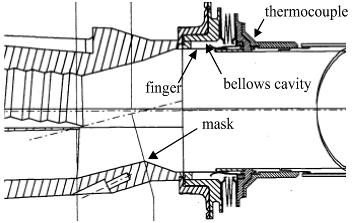


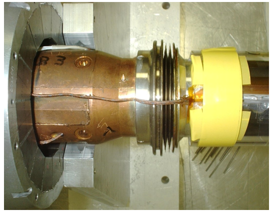
Temperature raise in a tiny IR vertex bellows

One thermocouple, located near the shielded vertex bellows, showed higher readings than expected. With beam currents of 0.8 A on 1.5 A at this time, it typically read 150 F, a rise of 90 F above the cooling water temperature.

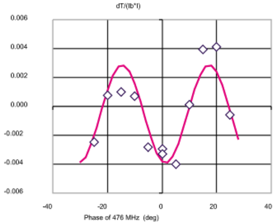
It was a real danger to damage the tiny convolutions of this bellows.







To determine if any single HOM resonance was responsible for the heating, the RF phase of the HER was then moved relative to the LER and a modulation of the temperature was measured. The resonance was around 5.4 GHz. *S. Ecklund et al., "High Order Mode Heating Observations", PAC'2001, p.3576*.



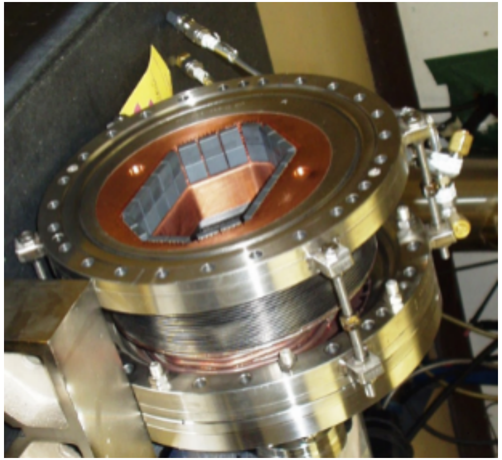
We also measured the spectrum of the fields generated in the interaction region and found one mode at the frequency of 5.59 GHz, the amplitude of which was correlated with the heating power, calculated from the bellows temperature nd cooling time. *A. Novokhatski "HOM effects in vacuum chamber with short bunches", PAC 2005.*

$$P \approx K*(T - T_{cool} + \frac{\tau_c}{2}\frac{\partial}{\partial t}T)$$

Finally we opened the BaBar detector and installed more cooling around the vertex bellows. This helped and we did not have further problems in this location at higher currents.

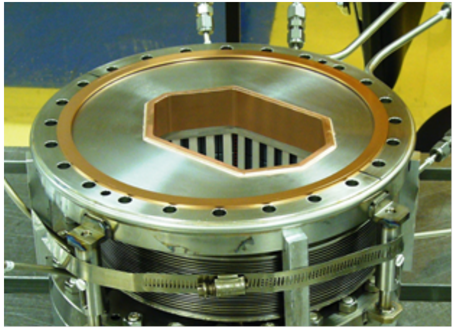
We also designed a new bellows, which can survive much more higher currents. This bellows contains water-cooled absorbing ceramic tiles. *DAMPING HIGHER ORDER MODES IN THE PEP-II B-FACTORY VERTEX BELLOWS∗ S. Weathersby, J. Langton, A. Novokhatski, J. Seeman, PAC 2005*

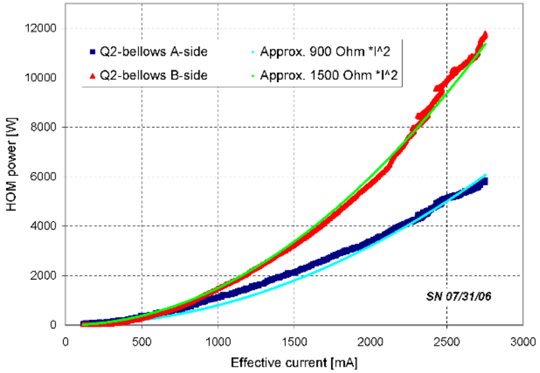
PEP-II IR HOM absorber

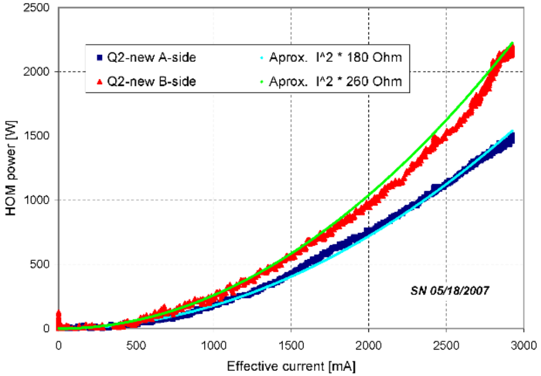


A. Novokhatski, S. DeBarger, S. Ecklund, N. Kurita, J. Seeman, M. Sullivan, S. Weathersby, U. Wienands, , " A NEW Q2-BELLOWS ABSORBER FOR THE PEP-II SLAC B-FACTOR" *, Proc. of PAC'07 (2007)*

Open to the beam ceramic tiles were shielded

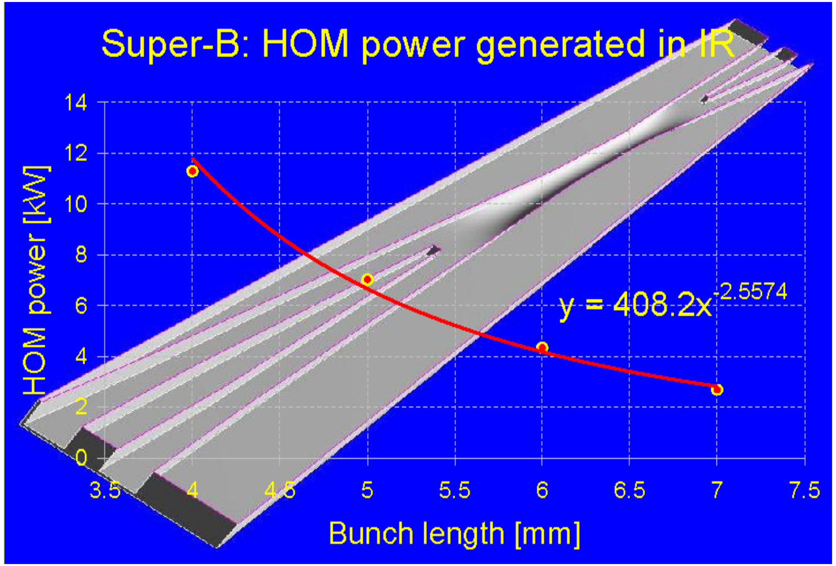






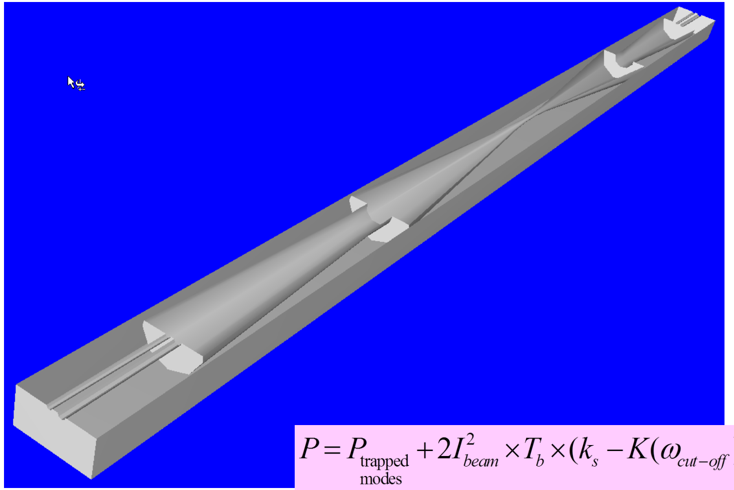
The future Italian Super-B Interaction Region

- *M. Sullivan, M. Donald, S. Ecklund, A. Novokhatski , J. Seeman, U. Wienands*, "A preliminary interaction region design for a Super-B factory", *Proc. Of PAC'05 (2005)*
- *S. Weathersby and A. Novokhatski*, "Wake fields in the Super-B interaction region", *Proc. of IPAC'10 (2010)*
- *A. Novokhatski and M. Sullivan*, "Beam fields and energy dissipation inside the BE pipe of the Super-B detector", *Proc. Of IPAC'10 (2010)*



ILC Interaction Region

– *A. Novokhatski*, "Wake potentials in the ILC Interaction Region", *Proc. Of PAC'11 (2011)*



Bunch charge = 3.2 nC

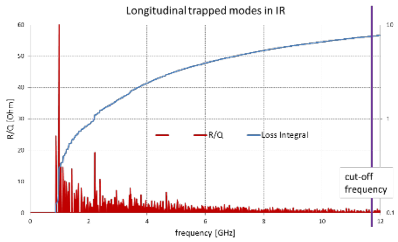
Bunch length = 0.2-0.3 mm

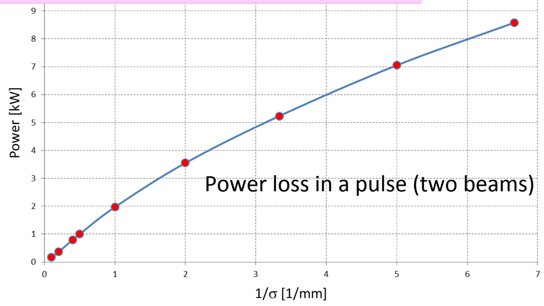
Bunch spacing = 369.2 ns

Beam current in a pulse 9 mA

Duty ratio=200

$$P = P_{\substack{\text{trapped}\\\text{modes}}} + 2I_{beam}^2 \times T_b \times (k_s - K(\omega_{cut-off}))$$

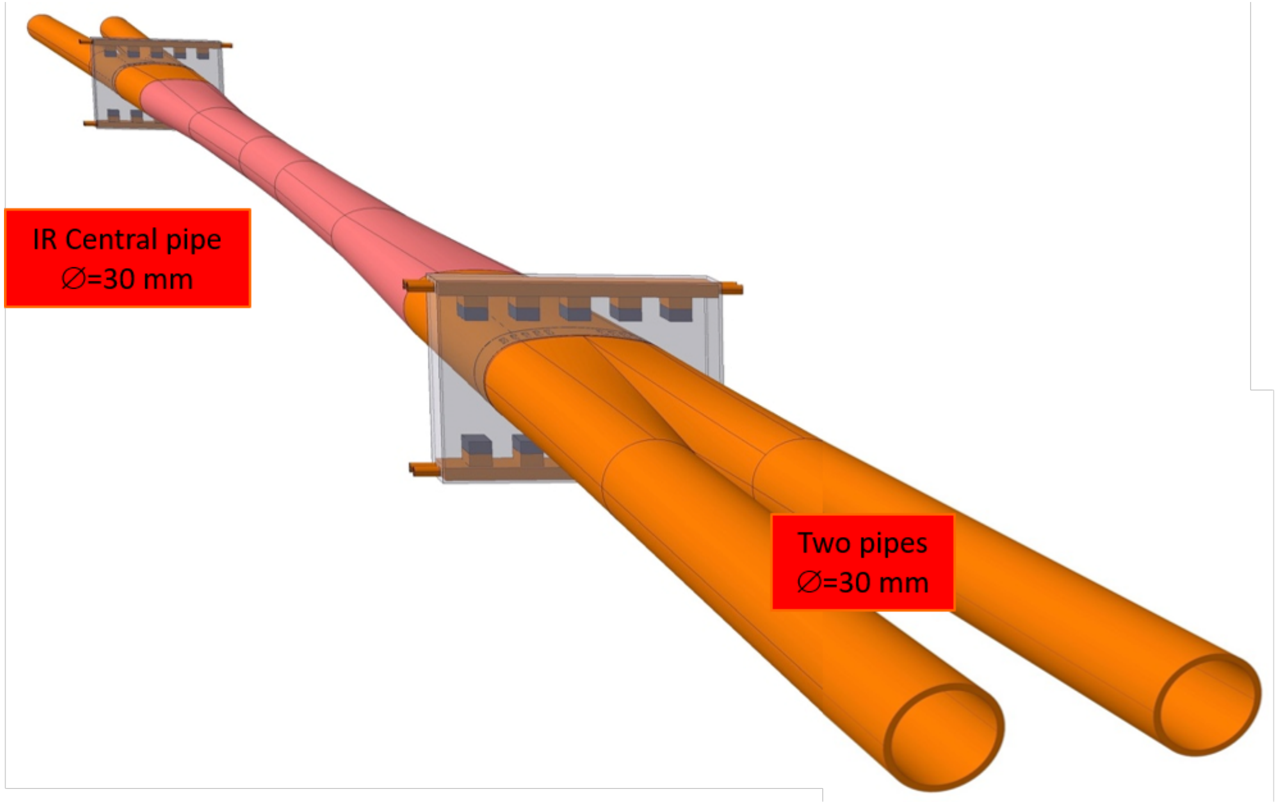




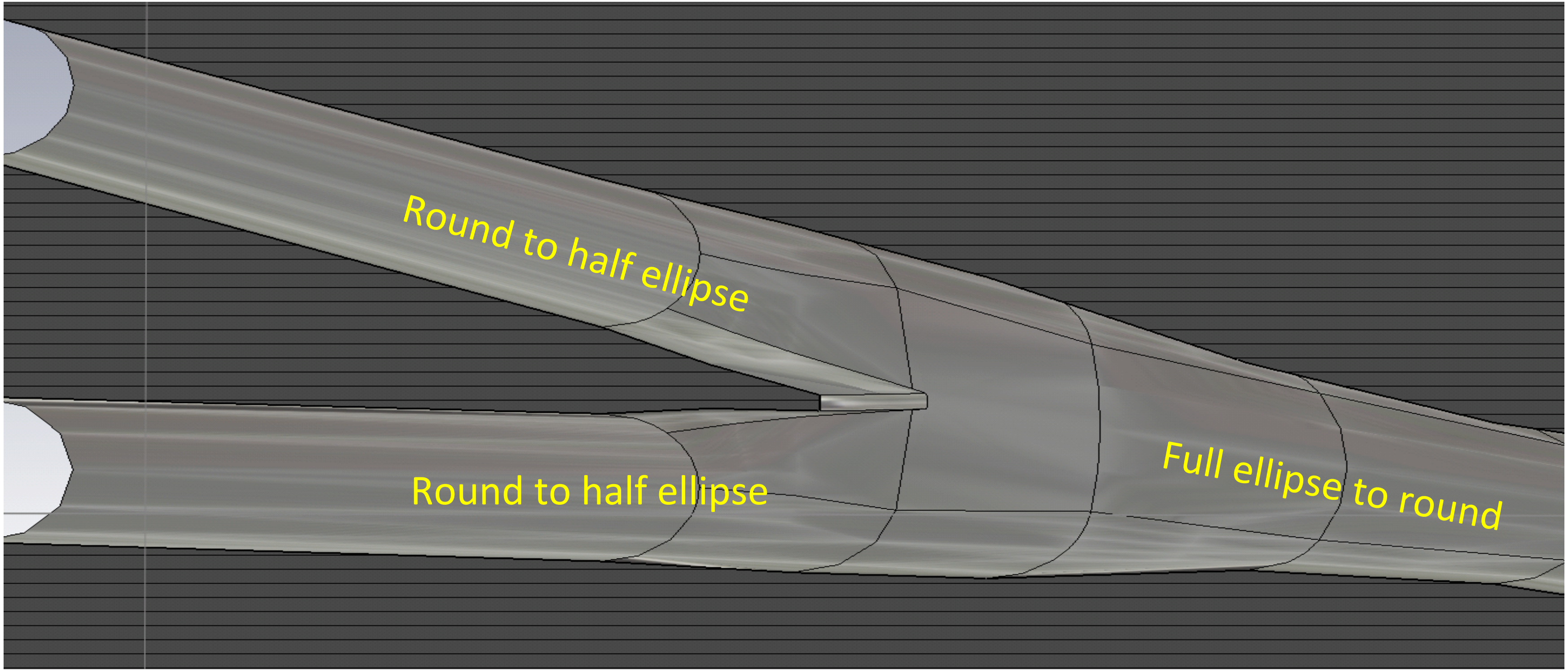
Power loss due to resistive wall. Not so much.

Resistive wall wakes		Be 40 mu	a [mm]	L/2 [m]		Total resistive	Power [W]
			12	0.0625			
bunch [mm]	f bunch	1/mm	V/pC/m		Power [W]		
0.2	238.7324146	5	0.7710933		5.764924839		224.4359994
0.3	159.1549431	3.333333333	0.4153219		3.105071121		114.3046605
0.5	95.49296586	2	0.1917086		1.433271006		45.96733098
Resistive wall wakes		Be 70 mu	a [mm]	L/2 [m]			
			16	0.14279			
bunch [mm]	f bunch	1/mm	V/pC/m		Power [W]		
0.2	238.7324146	5	0.5829		9.956313235		
0.3	159.1549431	3.333333333	0.3127758		5.342415229		
0.5	95.49296586	2	0.1440609		2.460654392		
Resistive wall wakes		SS 150 mu	a [mm]	L/2 [m]			
			82.81	1.345644			
bunch [mm]	f bunch	1/mm	V/pC/m		Power [W]		
0.2	238.7324146	5	0.6931		111.5662359		
0.3	159.1549431	3.333333333	0.3488		56.14529371		
0.5	95.49296586	2	0.1386		22.31002783		
Resistive wall wakes		SS 150 mu	a [mm]	L/2 [m]			
			63.3485	0.145			
bunch [mm]	f bunch	1/mm	V/pC/m		Power [W]		
0.2	238.7324146	5	0.8888		15.41625022		
0.3	159.1549431	3.333333333	0.4305		7.467029388		
0.5	95.49296586	2	0.174		3.018032784		
Resistive wall wakes		SS 150 mu	a [mm]	L/2 [m]			
			93.8	1.119			
bunch [mm]	f bunch	1/mm	V/pC/m		Power [W]		
0.2	238.7324146	5	0.6106		81.73227528		
0.3	159.1549431	3.333333333	0.3156		42.24485109		
0.5	95.49296586	2	0.1251		16.74534497		

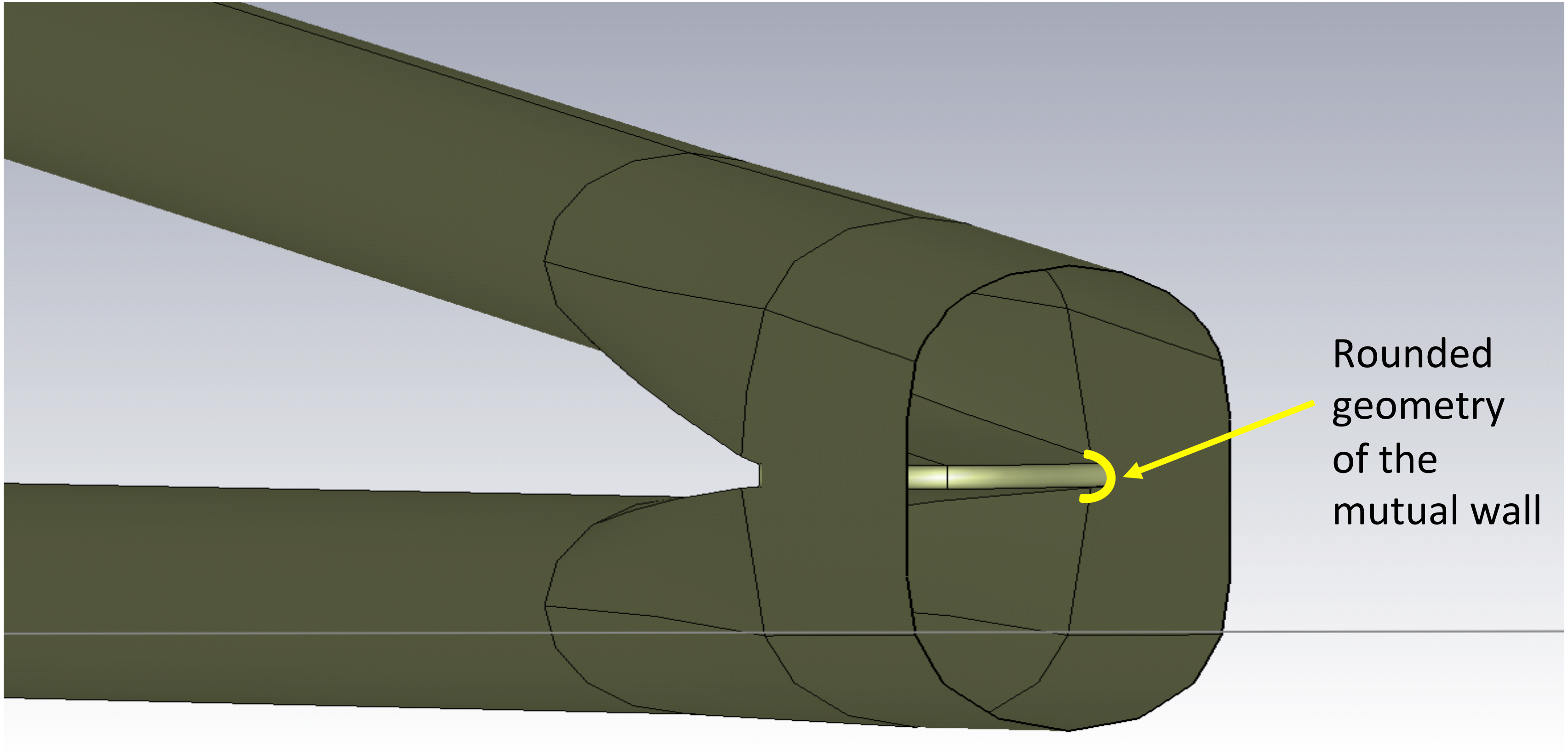
FCC IR beam pipe geometry



All smooth geometrical transitions.

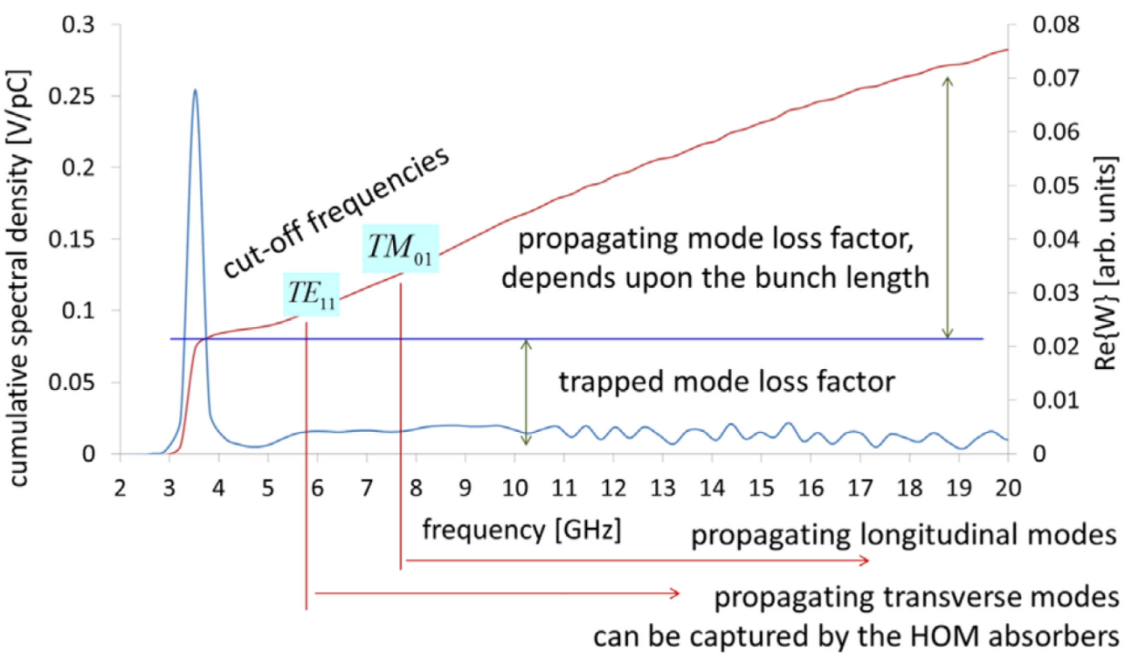


Inner view



Rounded geometry of the mutual wall

Spectrum and cumulative spectral density of the energy losses



PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 111005 (2017)

Unavoidable trapped mode in the interaction region of colliding beams

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Eleonora Belli, Miguel Gil Costa, and Roberto Kersevan
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$$P_{prop} = I^2\left(k - k_{HOM}\right)\times\tau_b$$

$$P_{HOM} = 2I^2 k_{HOM}\tau_{l,HOM}$$

Each beam will produce electromagnetic power of approximately 5 KW from both connections.

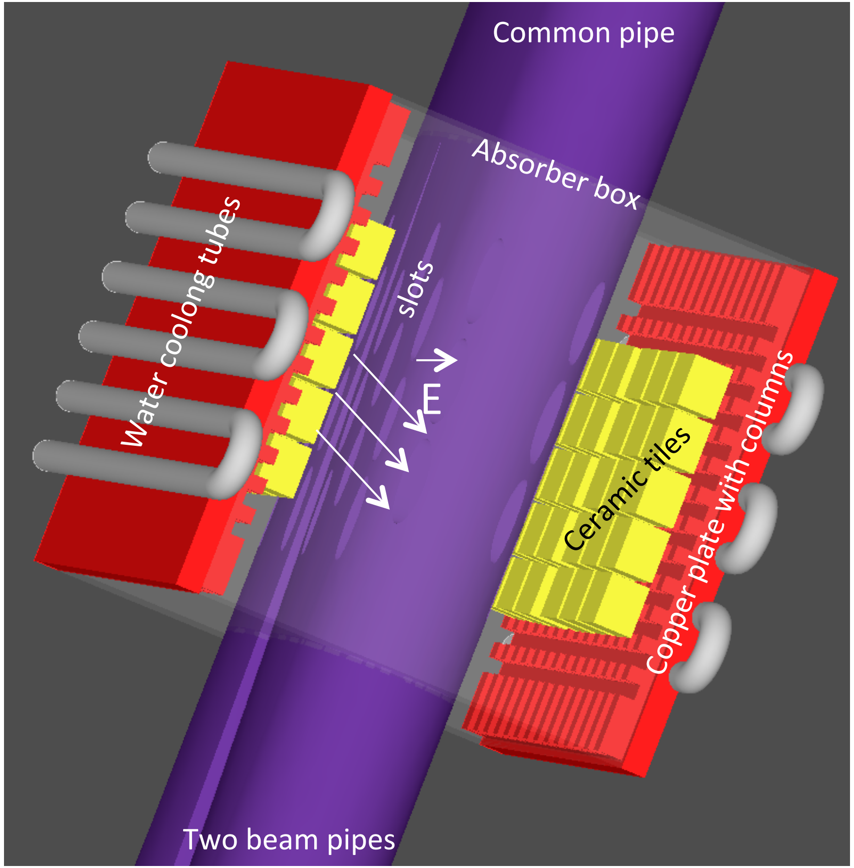
Primary concept of the HOM absorber for FCC ee

The absorber vacuum box is situated near (around) beam pipe connection. Inside the box we have ceramic absorbing tiles and copper plates (walls). The beam pipe in this place have longitudinal slots, which connect the beam pipe and the absorber box. Outside the box we have stainless steel water-cooling tubes, braised to the copper plates.

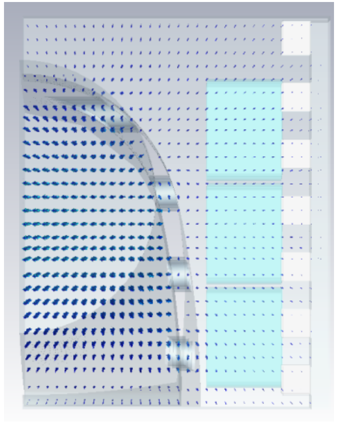
HOM fields, which are generating by the beam in the IR have a transverse electrical component and can pass through the longitudinal slots in the beam pipe.

Inside the absorber box these fields are absorbed by ceramic tiles, which have high value of the loss tangent.

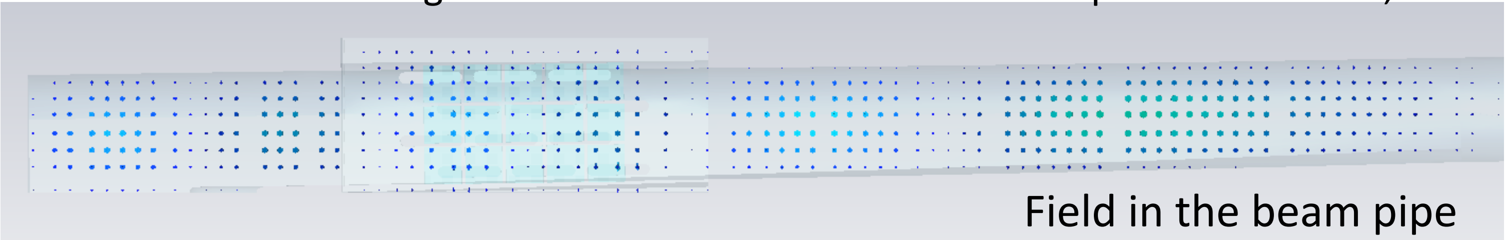
Ceramic tiles are braised to copper plates with columns. The heat from ceramic tiles is transported through the copper plates to water cooling tubes.



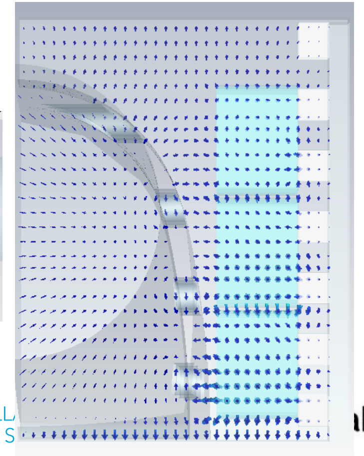
To show the how HOM absorber works we simulate two cases when ceramic tiles do not absorb HOM power (loss tangent is zero) and absorb the power.



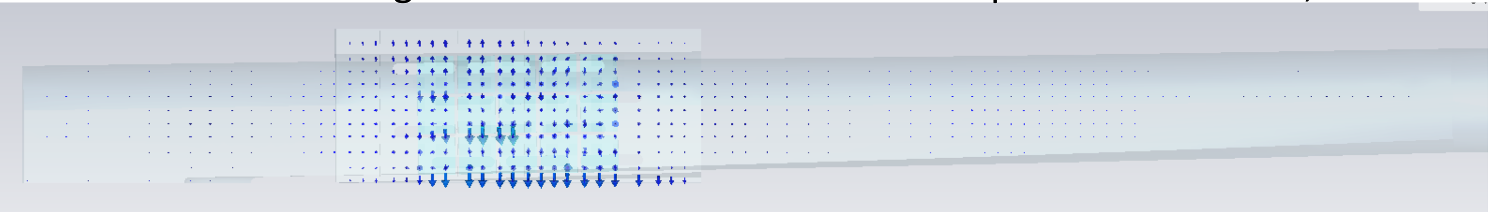
HOM mode in the IR region when ceramic tiles have vacuum parameters : ε=1, δ=0



Field in the beam pipe

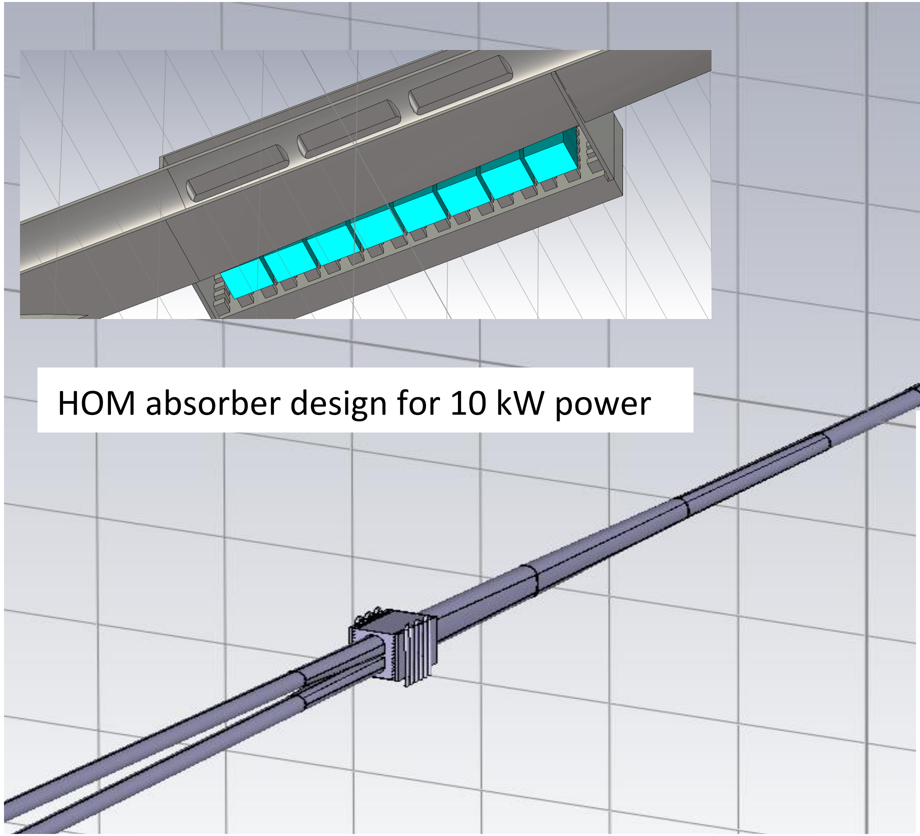


HOM mode in the IR region when ceramic tiles have real parameters : ε=22, δ=0.1



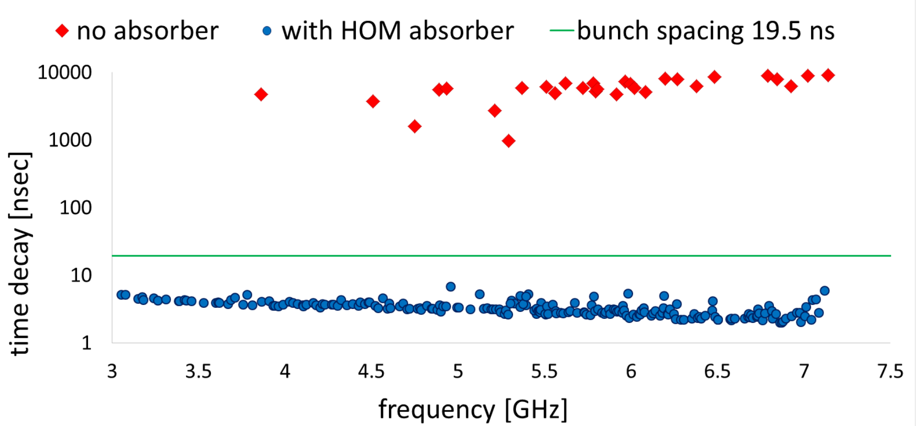
The field concentrated in the absorber region and in the ceramic tiles

Efficiency of the FCC ee HOM absorbers



HOM absorber design for 10 kW power

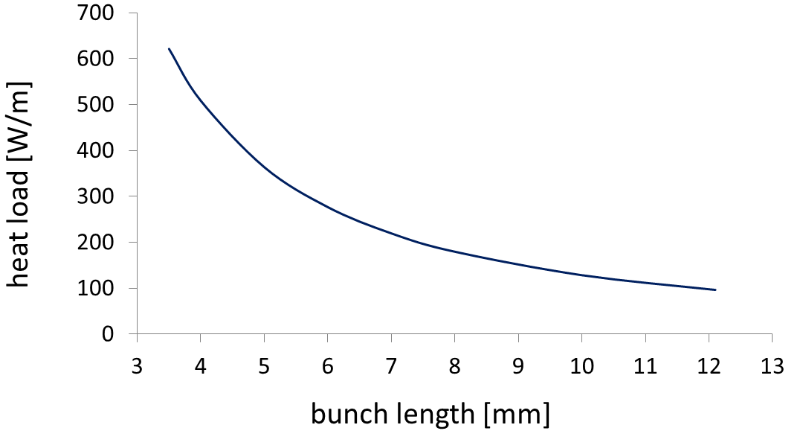
Efficiency of Damping Trapped and Propagating Modes



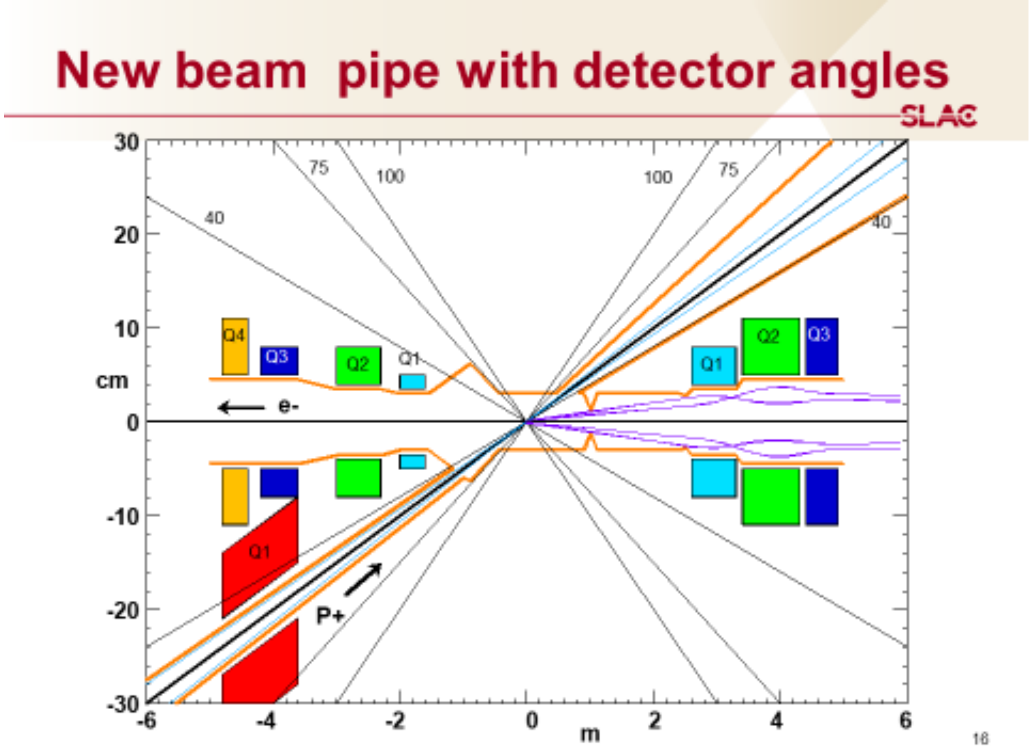
Resistive wall heat load for FCC ee IR central pipe

bunch length [mm]	HEAT LOAD Two beams [W/m]				current [A]	Bunch spacing [ns]	
					2 x 1.39	19.50	
12.10	63.45	69.18	81.68	96.57	125.23	349.64	1473.91
Material	Cu	Au	Al	Be	Ni	SS	NEG

- Beryllium pipe takes 100 W/m for a 12 mm bunch but strongly increasing with shortening the bunch length.
- This power push the temperature up to 100 C in the center of Be pipe in the case of no cooling



First estimate for the power loss for possible JLEIC IR



Power loss: 5-10 KW
Half in propagating waves
Half in one or two trapped modes, depends upon the vertical size of the chamber

Mike Sullivan "JLEIC MDI Update" Apr 4, 2017

Summary

- A smooth transition from two incoming pipes to a common IP pipe is needed to minimize the impedance of the Interaction Region.
- Special HOM absorber must be developed and optimized for required beam parameters.
- The heat load coming from the resistive–wall wake fields needs more attention:
  - Air, water or paraffin cooling for the beryllium pipe
  - Cooling for the other (copper, titanium) part of the IR beam pipe.
  - Thin Gold coating can be also used, but needs additional study.

Acknowledgement

I would like to thank Yuhong Zhang for the invitation to present my favorite physics subject at the Meeting on the fantastic accelerator project JLEIC.

Also I would like to thank Frank Zimmermann, Oide Katsunobu, and especially Michael Benedikt for their great support of this activity.

Thank you!

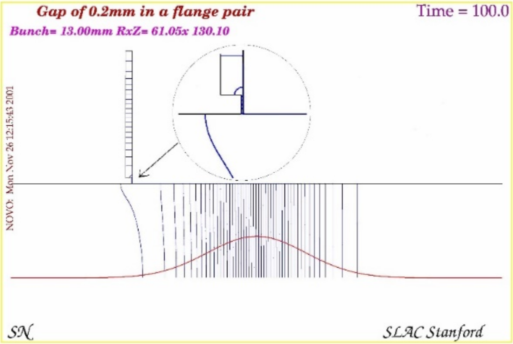
Additional slides about not very good high current effects, which must be very carefully mitigated

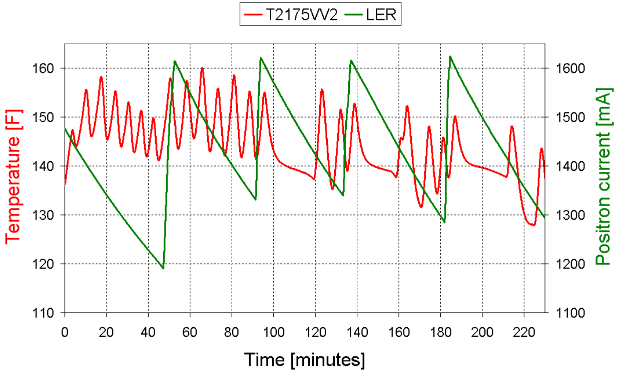
Experience from high current PEP-II B-factory

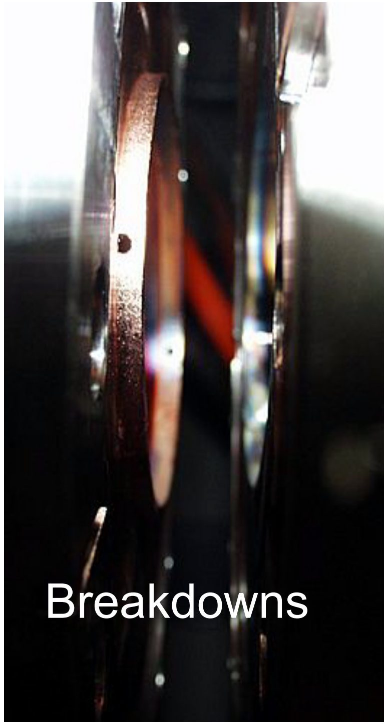
- Heating and damage of vacuum beam chamber elements
  - RF seals: breakdowns, sparks
  - vacuum valves: melted fingers
  - shielded bellows: melted fingers
  - BPM buttons feedthrough
  - ceramic or ferrite tiles: sparks
- Vacuum rise, spikes and vacuum instabilities
  - NEGs stop pumping
  - high detector background
- RF background
  - wake fields outside the beam chamber

Small Gap, Breakdowns and Temperature Oscillations

Wake fields due to a small (0.2 mm) gap in the flange RF seals

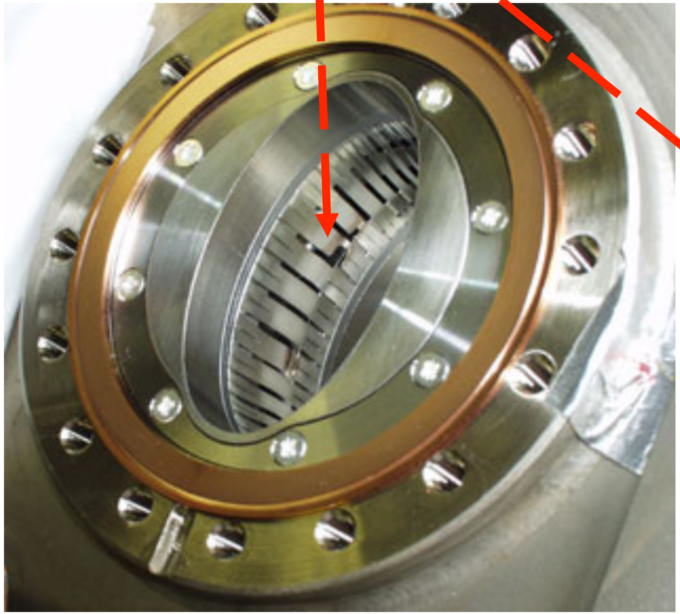




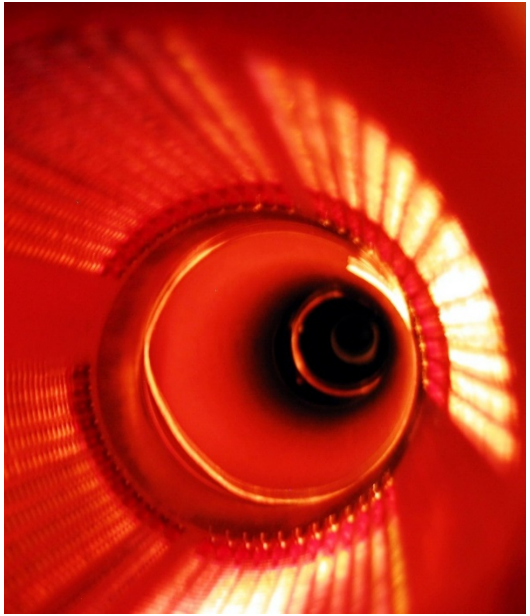


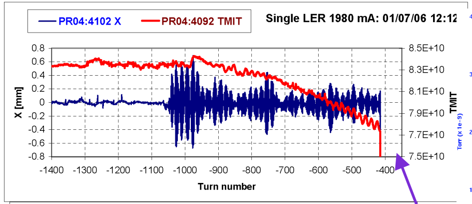
Wake fields discharge in shielded fingers of vacuum valves

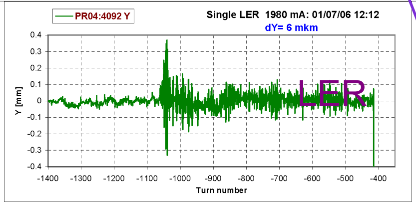
- Shielded fingers of some vacuum valves were destroyed by breakdowns of intensive HOMs excited in the valve cavity.

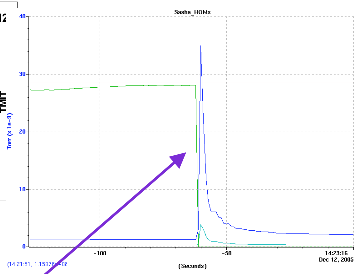


Not well installed gap ring may be a reason for the beam instability









Vacuum bursts

Abor
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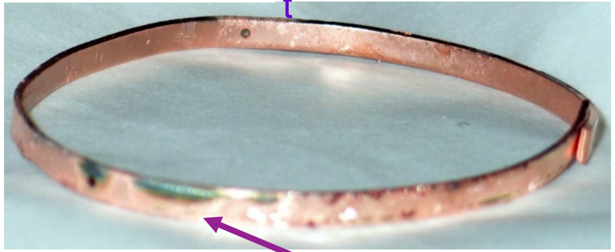
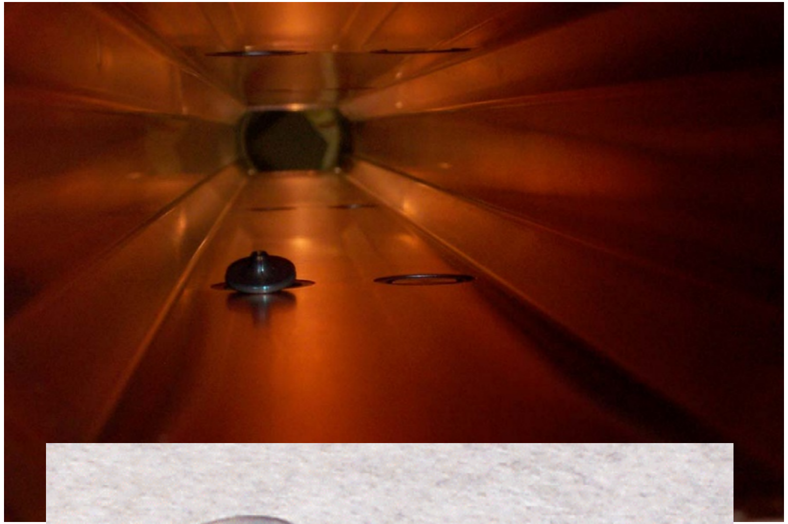
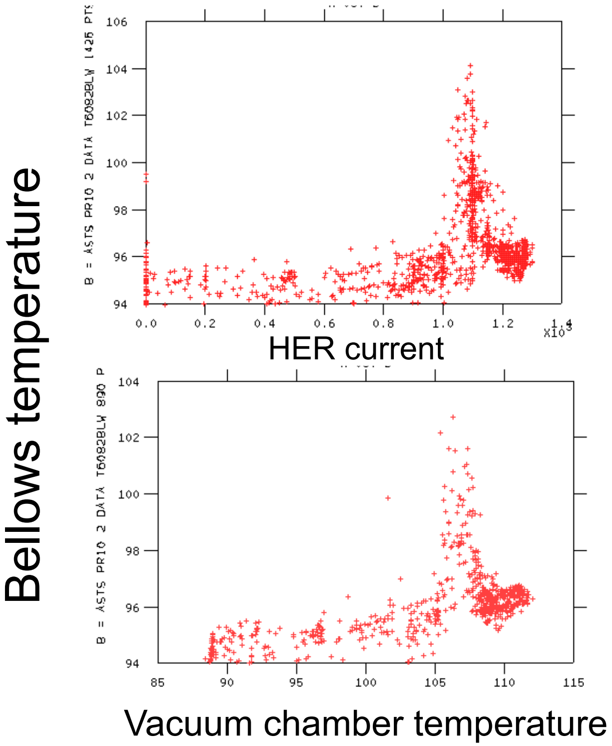


Breakdowns traces

Temperature raise in a BPM feed-through



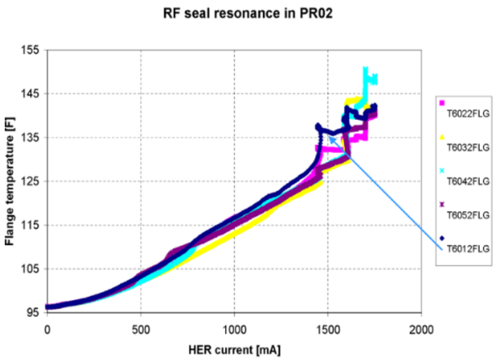
Bunch-spacing resonances in HER bellows

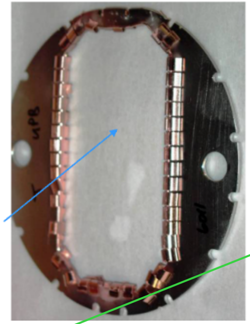


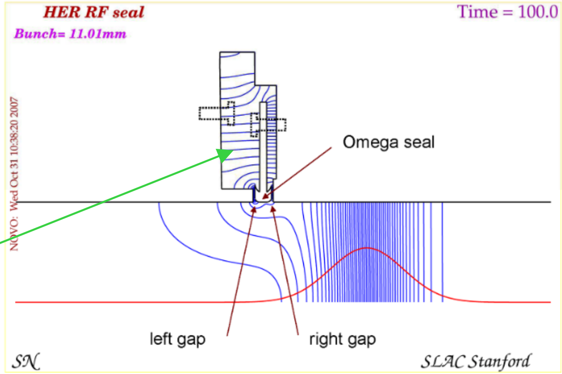
$$\frac{1}{Q} = \frac{\Delta f}{f} \sim \frac{\Delta l_{bellows}}{l_{bellows}} =$$

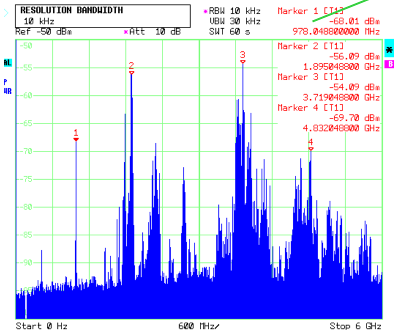
$$= \frac{\alpha l_{chamber} \times \Delta T_{chamber}}{l_{bellows}} \sim 10^{-3}$$

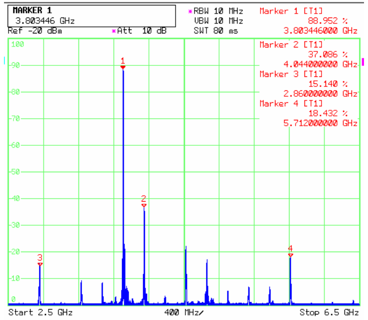
RF seal temperature jumps and an outer cavity excitation



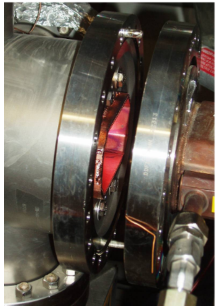


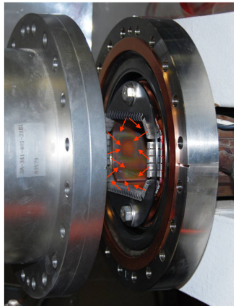






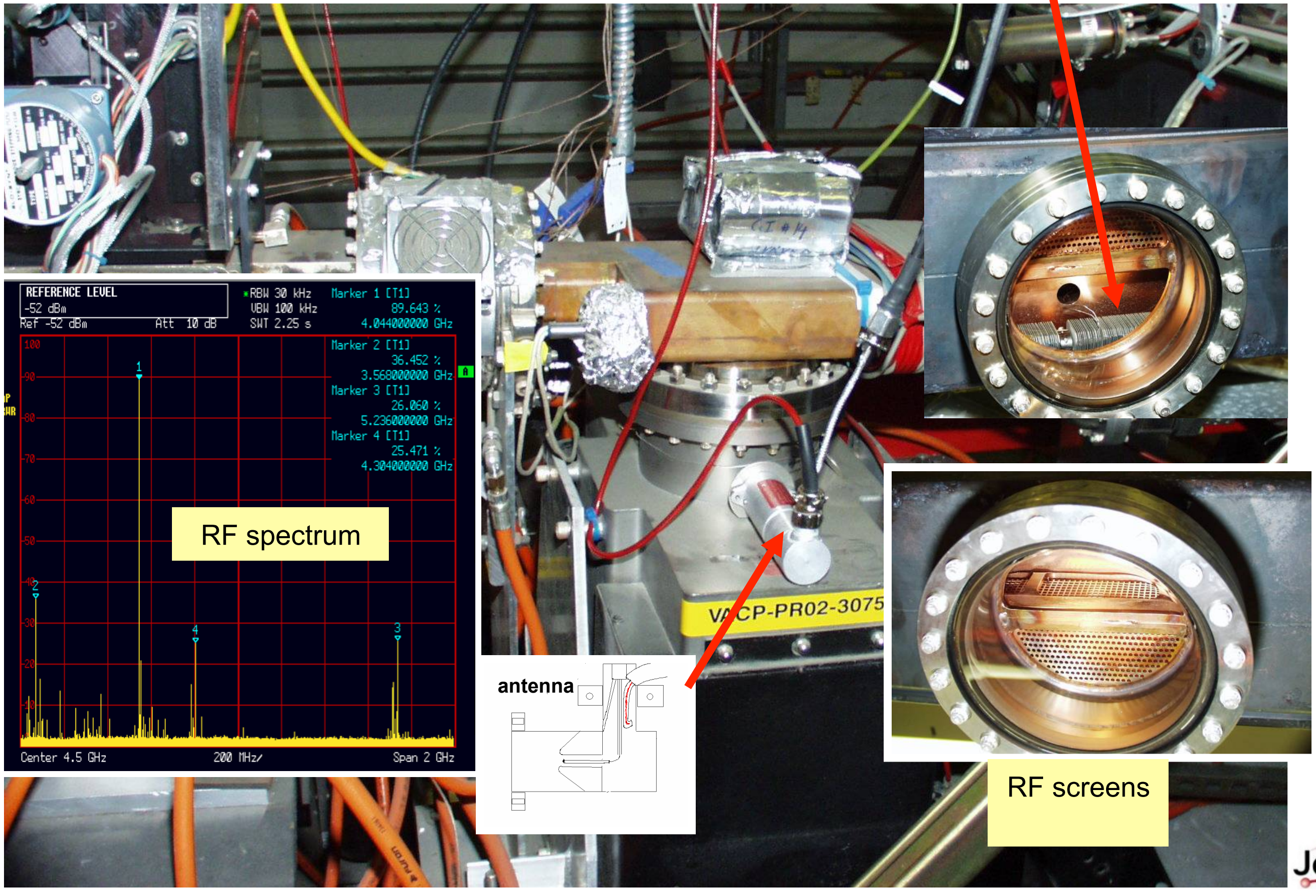
Measured single bunch and multi bunch spectrum





HER flanges and flexible omega seal. Red arrows show thermal radiation

HOMs go through RF screen into the NEG chamber, heat it to high temperature and destroy the pumping.



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Jefferson Lab

HOM absorber for IR of PEP-II