Analysis of the Wake Field Effects in the PEP-II SLAC B-factory

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Mini-workshop "Simulation of Power Dissipation and Heating from Wake Losses in Accelerator Structures"

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On behalf of

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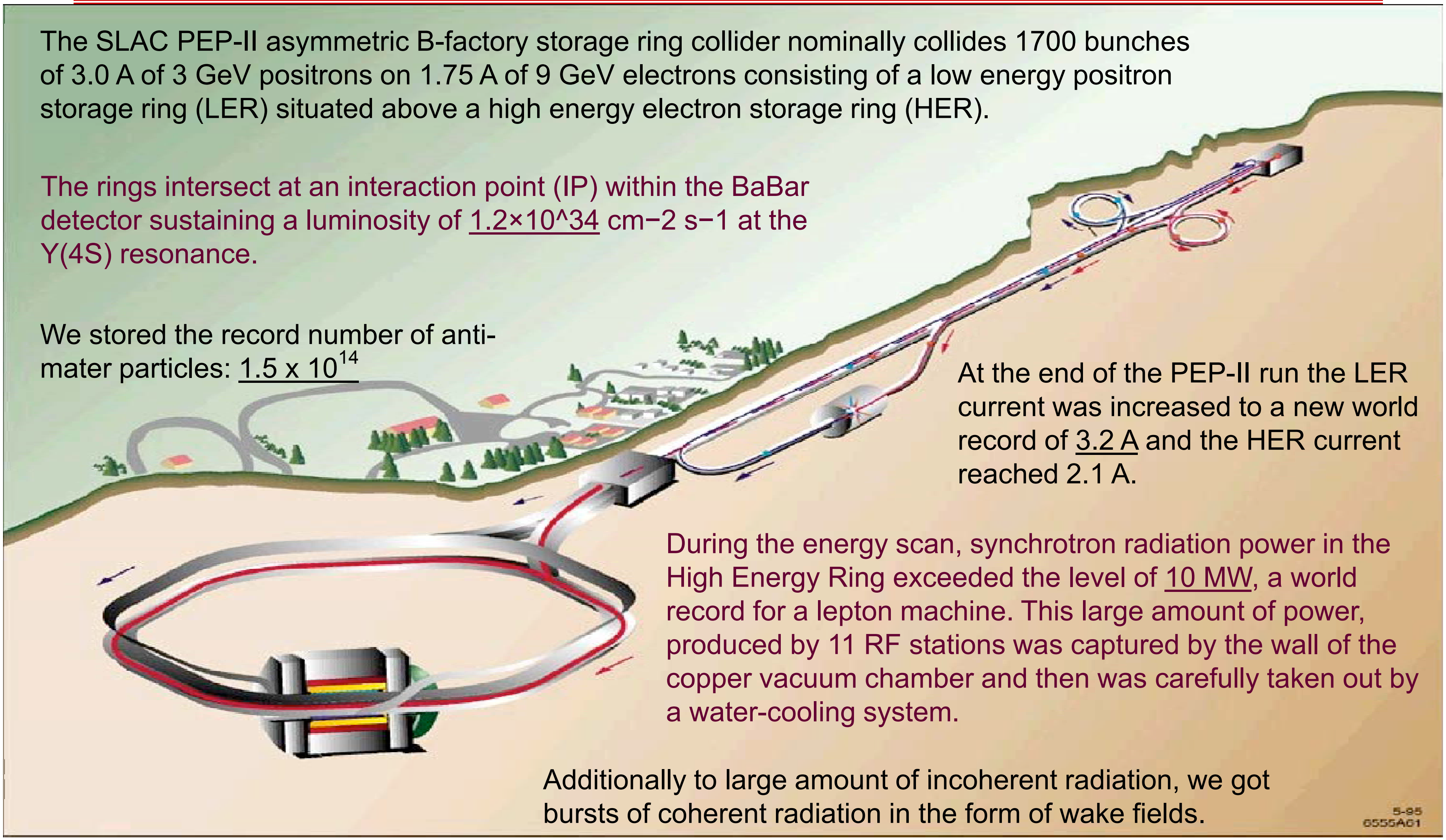
PEP-II SLAC B-factory



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 1.2×10^34 cm−2 s−1 at the Y(4S) resonance.

We stored the record number of anti-mater particles: 1.5 x 10^{14}

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.

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.

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

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Why there was a problem with wake fields?

- The design of the PEP-II beam chamber was very smooth. We used shielded bellows and shielded vacuum valves , which had water-cooled flanges. The transition from elliptical cross section to circular were long enough. Masks in the interaction region were smoothed. Collimators were designed in the way not to produce longitudinal fields.
  - A lot of calculation were done for the PEP-II project. Results can be found in SLAC publications SLAC-PUB 6989, January 1996 : "Impedance study for the PEP-II B-Factory" by S. Heifets, K. Ko, C. Ng, X. Lin, …, J. Byrd, …, T. Weiland.
- Everything worked well until we start to increase currents in order to get more luminosity.
- There were several thermocouples in the ring, but now we had to install more and more thermocouples to control the temperature of the beam chamber elements.

What effects we had to take into account

- Wake fields generated inside a beam chamber may propagate long distances but sooner or later be absorbed by the resistive walls of the chamber.
- Sometimes, because of forward and back reflections, these fields may stay in one place or in one vacuum element.
- In this case the wake field power will be concentrated and dissipated in a small region.
- Without a proper cooling the temperature of this vacuum element can be very high.
- Temperature can be high enough to mechanically deform the element, to melt thin shielded fingers or to destroy the vacuum sealing.

Wake fields effects. Cont.

- Electrical sparks, breakdowns or multipacting because of the high amplitude of electric field
  - electric component of the wake field can be much higher than the electric field of a bunch (PEP-II 30-50 kV/cm)

$$E = \frac{cZ_0}{(2\pi)^{3/2}} * \frac{eN_b}{a\sigma} \qquad E_{\left[\frac{kV}{cm}\right]} = 23. * \frac{N_b}{10^{11}} * \frac{1}{a_{cm}\sigma_{cm}}$$

- Wake fields excited due to resistivity of a vacuum chamber give an additional (to synchrotron radiation) heating.
  - The PEP-II beam chambers were water-cooled.
- RF background
  - wake fields penetrate outside the vacuum chamber though the high voltage feed-through connector of vacuum pumps or NEG heaters.

What we observed during the PEP-II operation

- heating and damage of vacuum beam chamber elements
  - RF seals: breakdowns, sparks
  - vacuum valves: melted fingers
  - shielded bellows: melted fingers
  - BPM buttons falling down
  - ceramic tiles: sparks
- vacuum rise, spikes and vacuum instabilities
  - NEGs stop pumping
  - high detector background
- beam instabilities
  - longitudinal, transverse and ion instability
- RF background
  - wake fields outside the beam chamber

High currents need small impedance beam chamber

Although the impedance of the high and low energy rings is small, the intense high current beams generated a lot of power

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

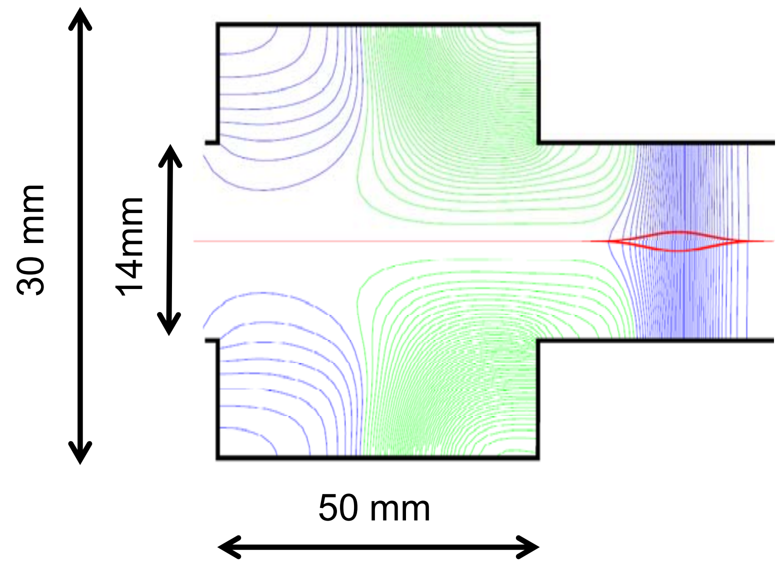
HOM Power   Bunch Spacing   Loss Factor   Current

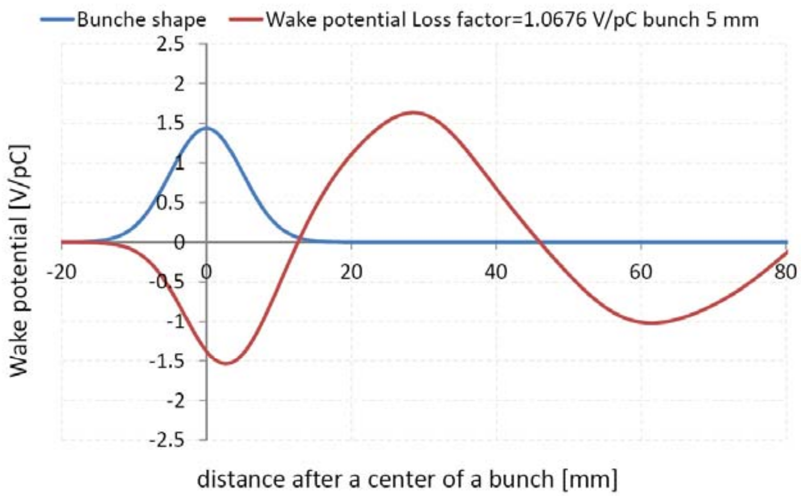
$$1_{[kW]} = 4.2_{[n\sec]} \times 0.026_{\frac{V}{pC}} \times 3^2_{[A]}$$

Loss factor of only 0.026 V/pC "works" like a microwave

Every small irregularities of the vacuum chamber become very important

Example: a pillbox





5 mm bunch
Loss factor 1.068 V/pC

PEP-II would have 30 kW HOM power with this cavity.

But if you have less current 0.5 A, then the power is about 1KW, still large

Coherent and incoherent excitation of trapped modes

Bunch spacing

$$\tau_b$$

Mode decay time (loaded)
or filling time

$$\tau_{l,n} = \frac{2Q_l}{\omega_n} = \frac{2Q_l}{2\pi f_n} = \frac{Q_l}{\pi f_n}$$

Loss factor

$$k_n = \frac{\omega_n}{2}\frac{R}{Q}$$

Incoherent	Coherent at the resonance
$\tau_{l,n} << \tau_b$	$\tau_{l,n} >> \tau_b$

Loss power

Incoherent	Coherent at the resonance
$P_n = I^2 k_n \tau_b$	$P_n = 2I^2 k_n \tau_{l,n}$

The power is twice more if the bunch spacing is equal to a mode decay time

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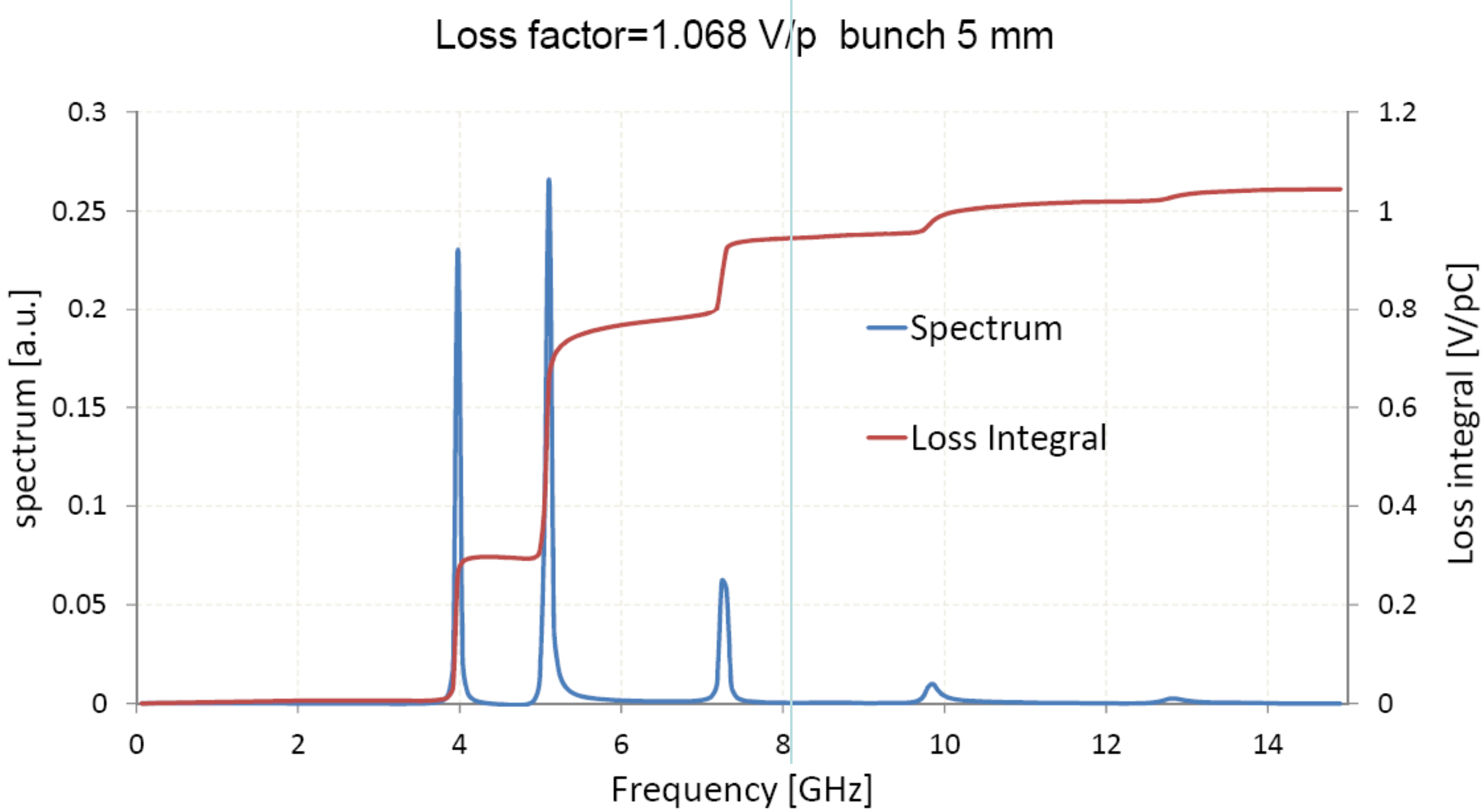
Trapped modes in the pill-box (f< 8.2 GHz)



We had to solve the wake field problem as quick as possible. How did we try do this work?

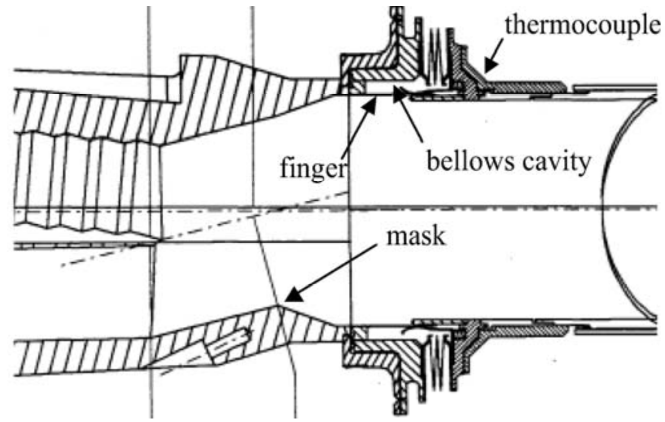
- a problem: high temperature, vacuum spikes or beam instability
- search for the source and it's location
- study the drawings (three Labs built PEP-II)
- make a computer model
  - usually engineers developed a CAD model and then saved it in an STL format
- wake field calculation
  - using MAFIA or 2d code NOVO
- analysis and search for a solution
  - add more cooling
  - take away the element
  - design a new device for damping HOMs

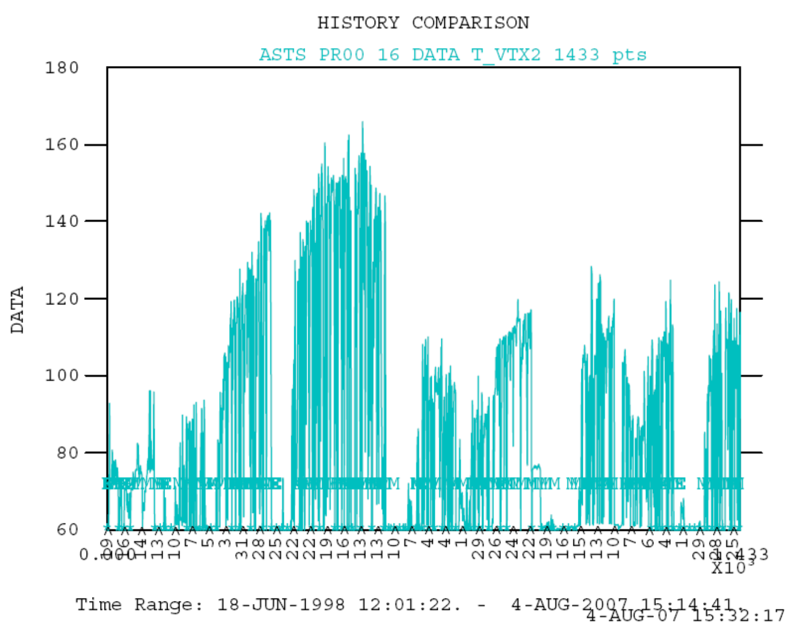
We present here some examples

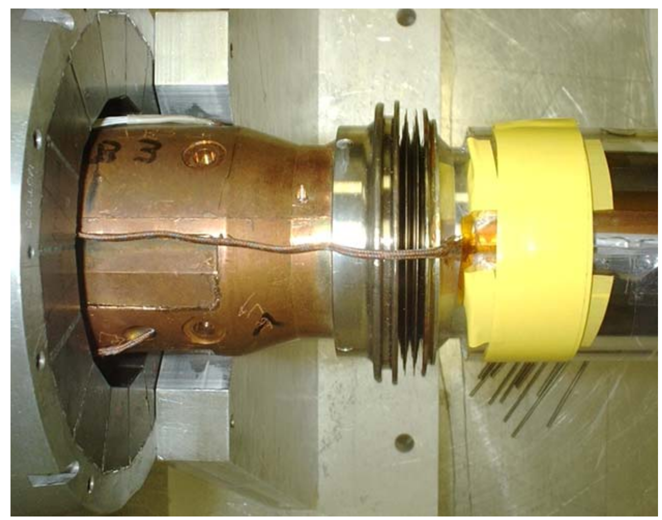
Temperature raise in IR vertex bellows

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.



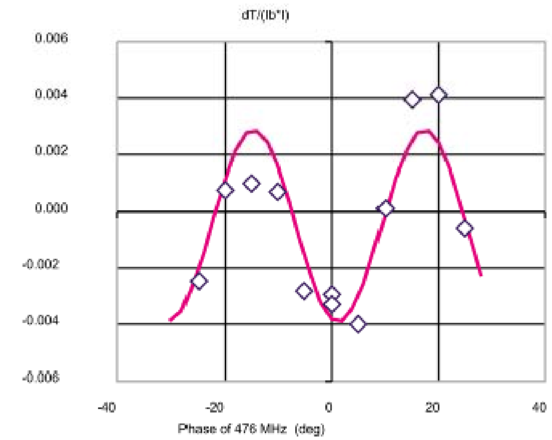




A tiny vertex bellows inside a large BaBar detector

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.

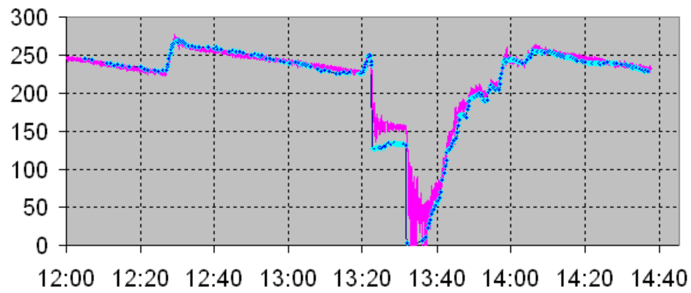
S. Ecklund et al., "High Order Mode Heating Observations", PAC'2001, p.3576.



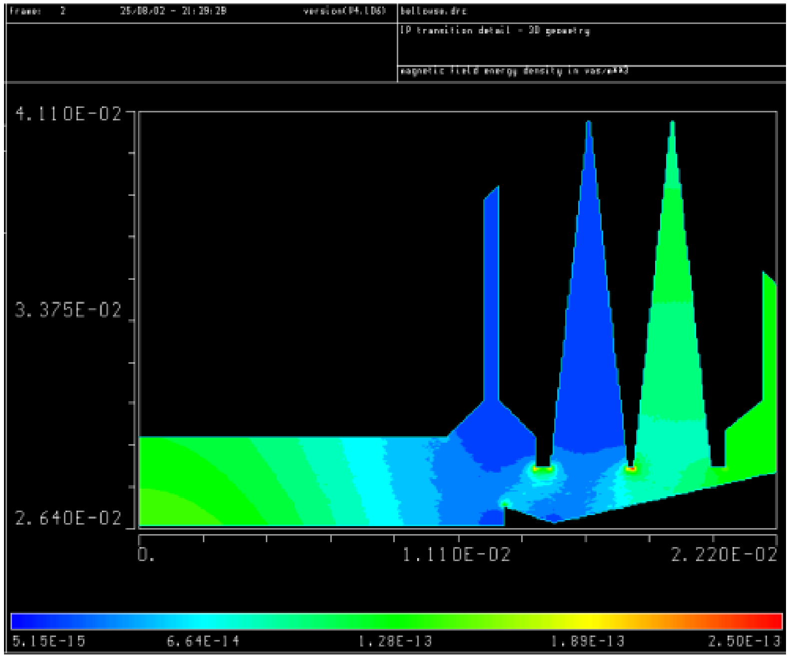
We also measured the spectrum of the fields generated in the interaction region and found one mode at the frequency of 5.59 GHz, the amplitude of which was correlated with the heating power, calculated from the bellows temperature *and* cooling time

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

A. Novokhatski "HOM effects in vacuum chamber with short bunches", PAC 2005.



Computer simulations



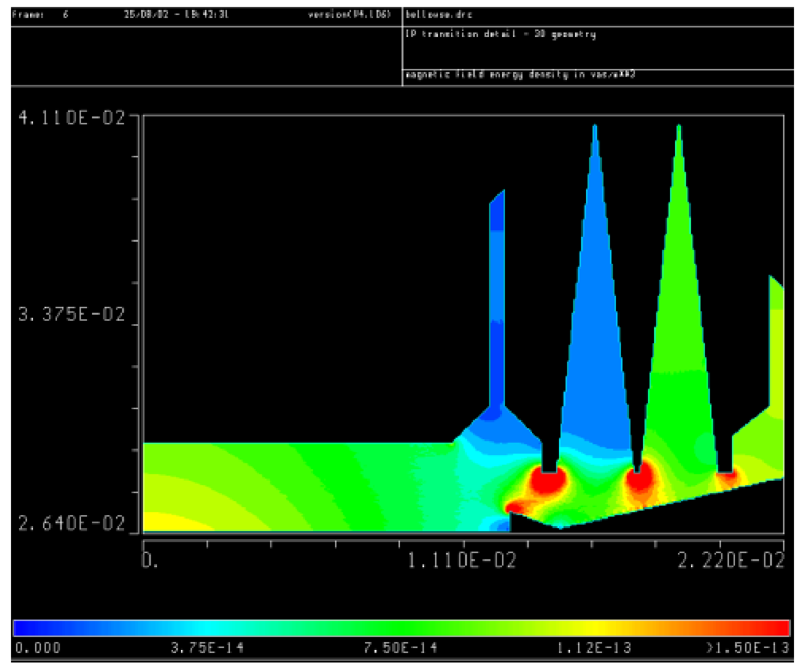
We made a computer model of the vertex bellows and did eigenmode calculations using MAFIA.

We found a dipole mode with a frequency 5.46 GHz, which is very close to a measurement value.

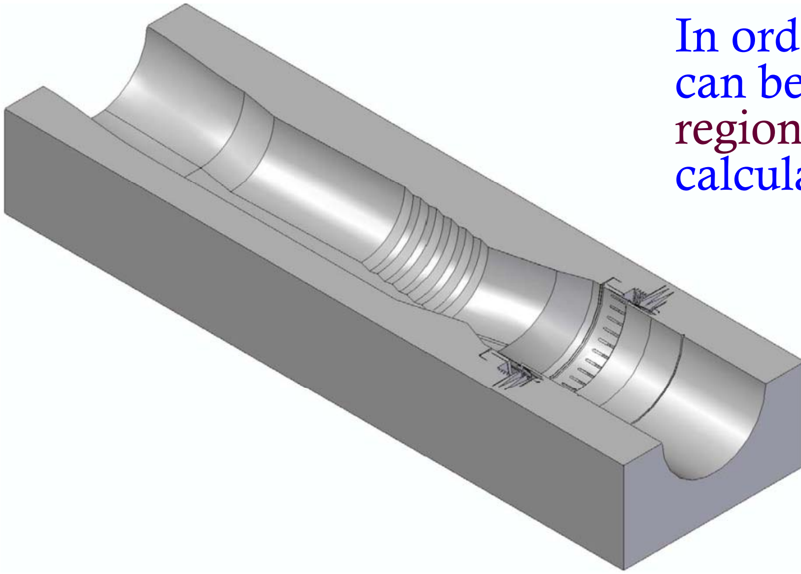
Maximum heating (red color) was at the convolutions.

We also found a quadrupole mode with a frequency of 6.19 GHz, which produce more heating at the convolutions

A. Novokhatski and S. Weathersby., “RF Modes in the PEP-II Shielded Vertex Bellows”, ICAP’2002, PAC’2003.



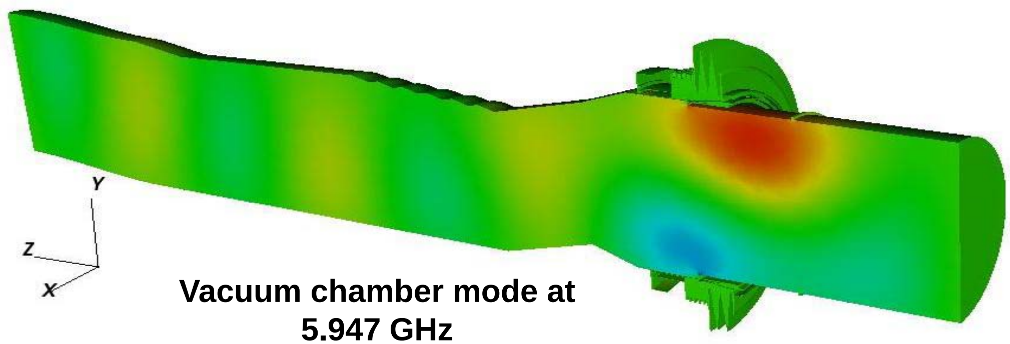
Excitation of the vertex bellows cavity



In order to understand how the vertex bellows cavity can be excited we made a model of the interaction region, which was used in MAFIA and Omeg3P calculations.

C.-K. Ng, N. Folwell, L. Ge, J. Langton, L.-Q. Lee, A. Novokhatski "Simulation of HOM leakage in the PEP-II bellows" PAC 2003

Synchrotron radiation mask (grooves) worked like a mode transformer of the symmetric bunch field into dipole, quadrupole and other azimuthal harmonics. Some trapped modes in the beam chamber were observed in Omeg3P calculations

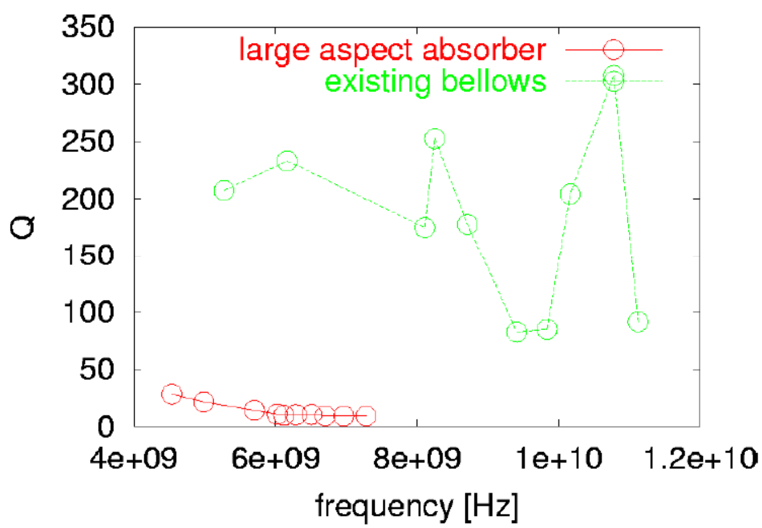


Vacuum chamber mode at 5.947 GHz

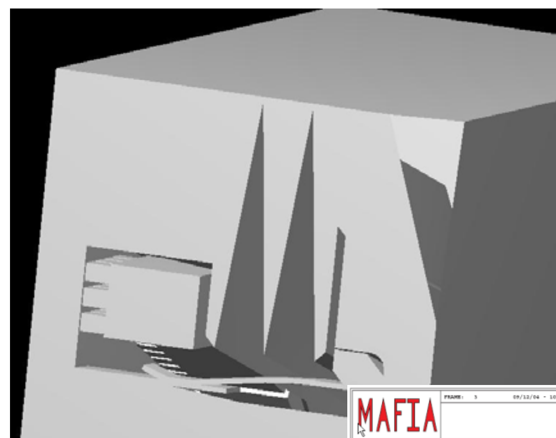
A vertex bellows with ceramic tiles

In 2003 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.

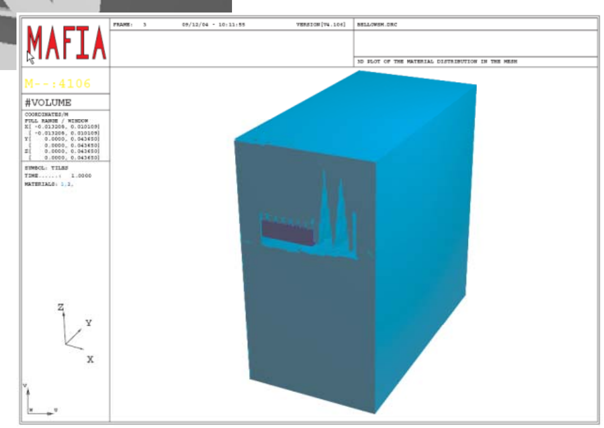
However, we had designed a bellows, which can survive much more higher currents. This bellows contains water-cooled absorbing ceramic tiles.



Q values of the bellows cavity modes are reduced more than 20 times



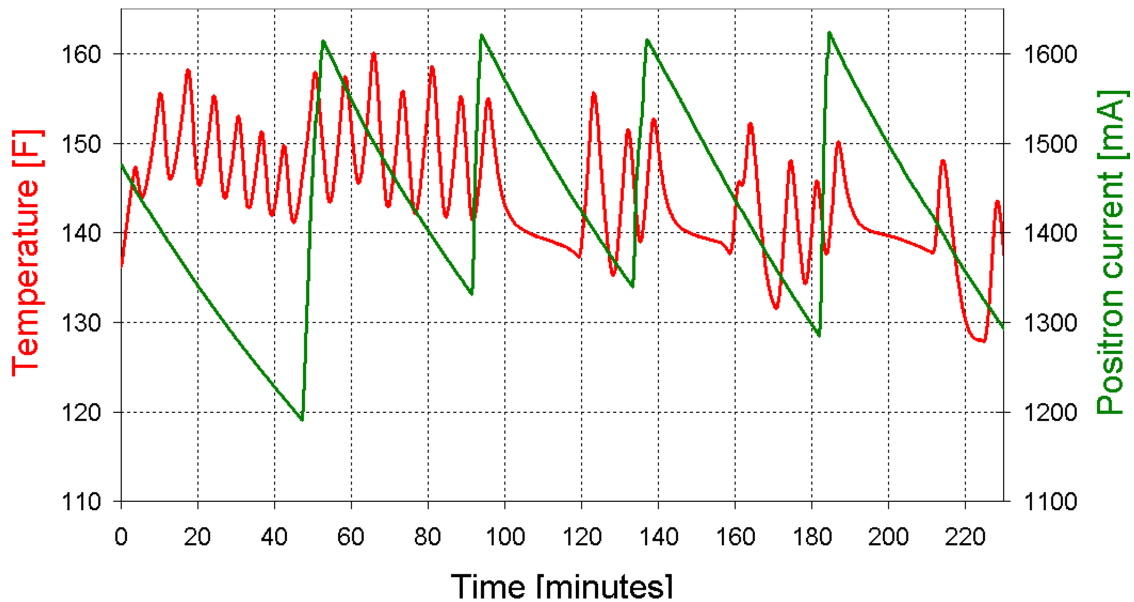
stl-model



DAMPING HIGHER ORDER MODES IN THE PEP-II B-FACTORY VERTEX BELLOWS∗ S. Weathersby, J. Langton, A. Novokhatski, J. Seeman, PAC 2005

Temperature oscillations

During the 2001 PEP-II run an unusual behaviour of a valve body temperature was observed in the low energy (positron) ring. A high positron current elevated the temperatures on different vacuum chamber elements like bellows and vacuum valves. The temperatures, measured by thermocouples, generally varied monotonically in accordance with the positron current. However, thermocouples placed on vacuum valve 2175 showed oscillations of temperature with a period of 3-8 minutes. The amplitude of the oscillations was of the order 5–20 F. The oscillations happened from time to time, when the positron current reached 1000 mA and more.



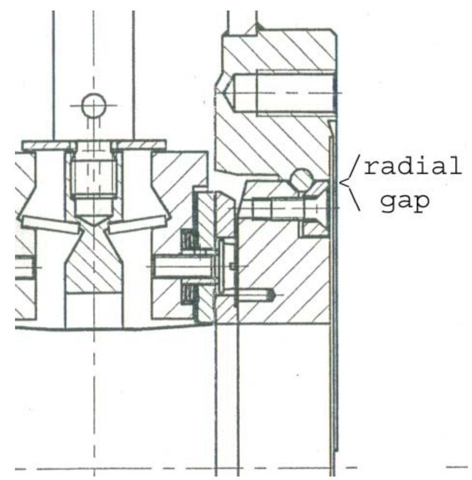
A. Novokhatski, J.Seeman, M.Sullivan, "RF Heating and Temperature Oscillations due to a small Gap in a PEP-II vacuum Chamber, PAC 2003

Vacuum valve

* Simultaneously a vacuum valve was destroyed by breakdowns of intensive HOMs excited in it's very large "inside cavity"

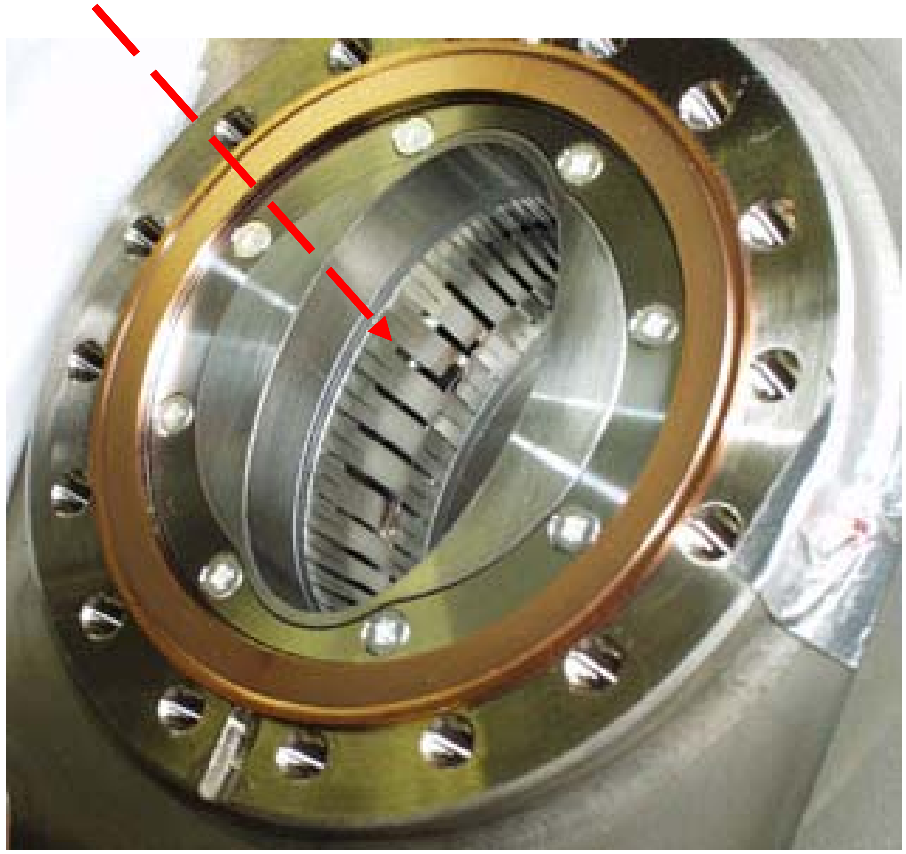
* We have studied different models to understand how the temperature oscillations could occur. Here we discuss one model.

* A vacuum valve flange consists of two stainless steel parts. Parts are connected through a circular ring and radial gaps could be from both sides of the ring. When the inner part of the flange is heated, the size of these gaps decreases with the temperature and thermal contact is improved. The heat energy flows to the outer flange part, which is cooled though with a fan and a copper water-cooled disk. The temperature then goes down and the radial gap opens up once again.



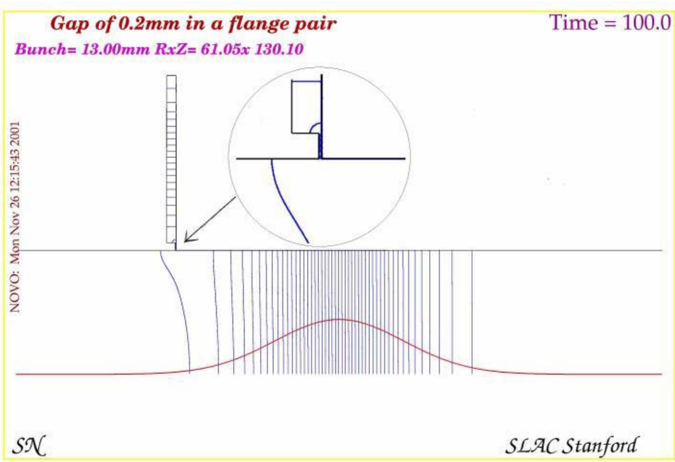
We had such a problem with several vacuum valves

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

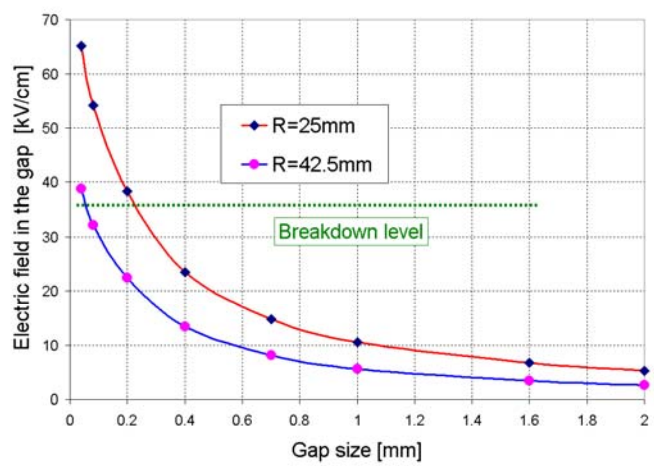


Breakdowns

- We suggested that the gasket (RF gap ring), which is placed in the joint between the vacuum valve and the vacuum chamber, could have dimensions that are incorrect thereby producing a very small gap. We suspected that the gap size could be of order 100 microns.
- The positron beam through this size of a small gap could excite a cavity formed by the flange sides and the gaskets. Maximum electric field is in the gap and reach breakdown limits.
- When we opened the vacuum chamber we found traces of breakdowns.
- We cured this effect with a better design of the gap ring



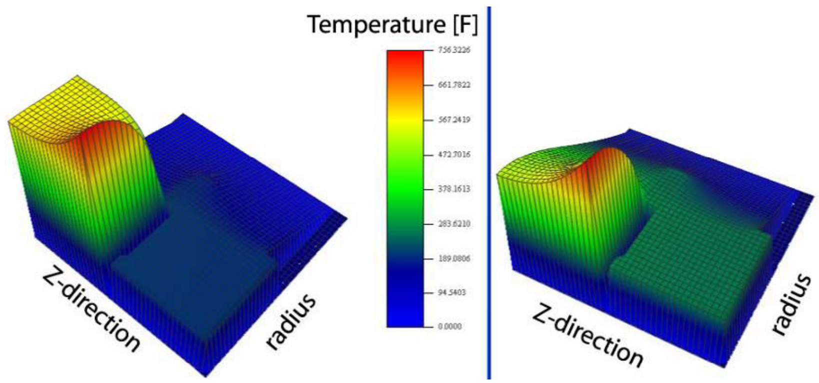
Wake fields due to a small 0.2 mm gap in a flange connection



Electric field in the gap

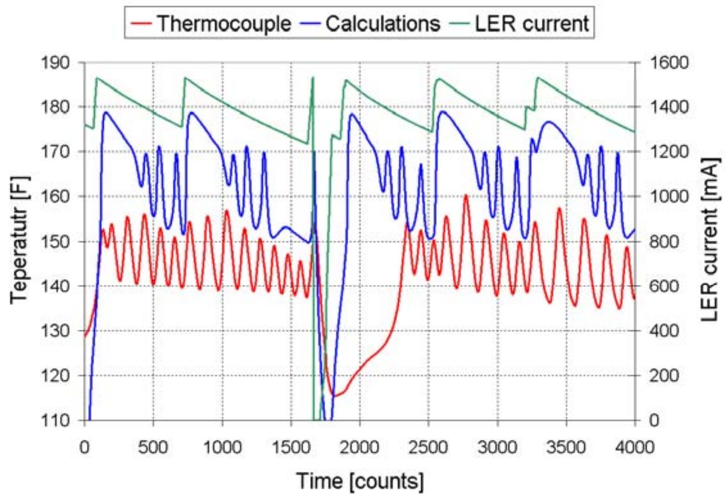
Simulations

* The left figure shows the temperature distribution at the time when the gap size is large and the thermal contact is small.
* The right figure shows the temperature distribution at the time when the gap size is small.



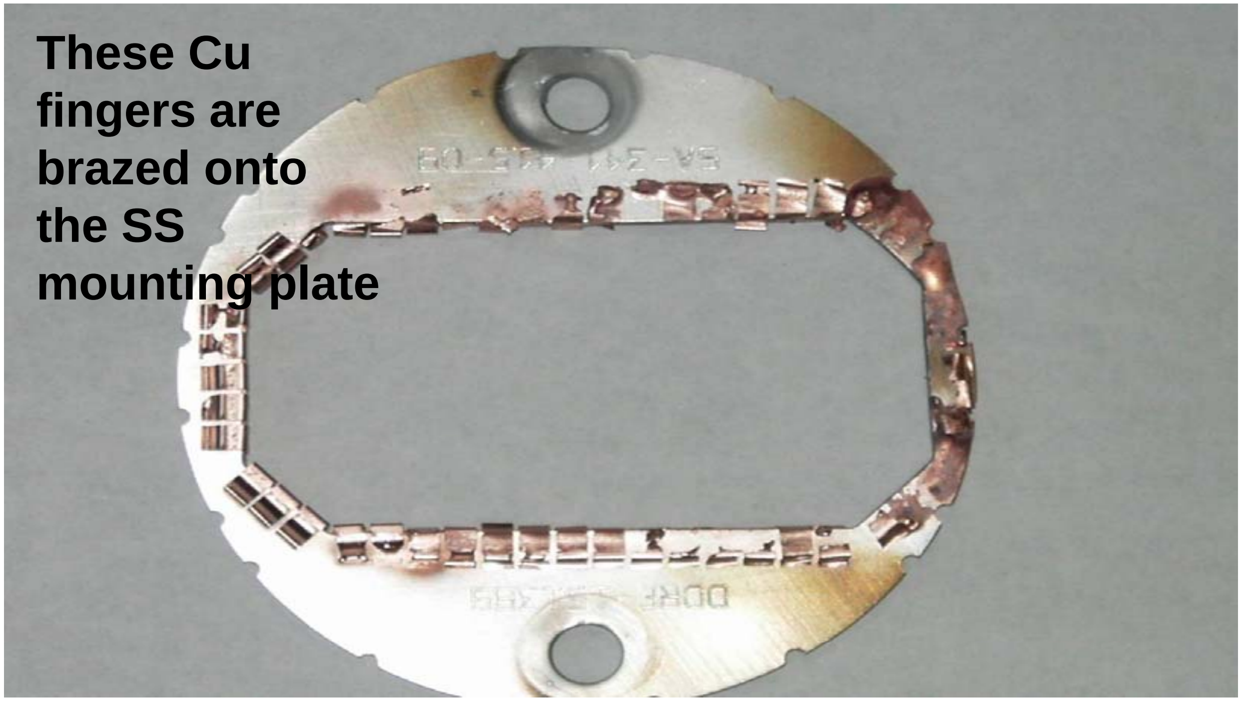
* Comparison of the simulated and measured temperatures.

* Solution: improve thermo contact and place a water-cooled absorber inside the valve (It was planned, but never done).



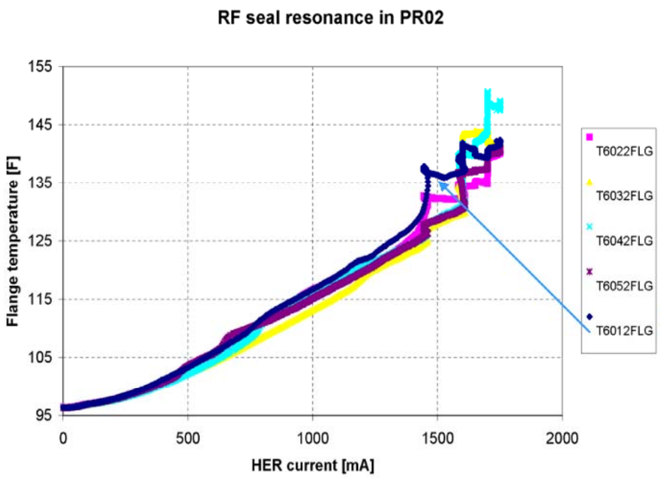
RF seal design is very important!

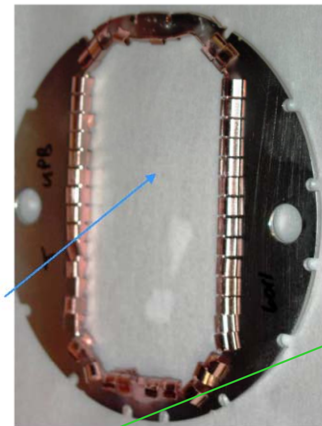
Almost the same happened later with arc RF Seals in the High Energy Ring when increase HER current to 2 A.

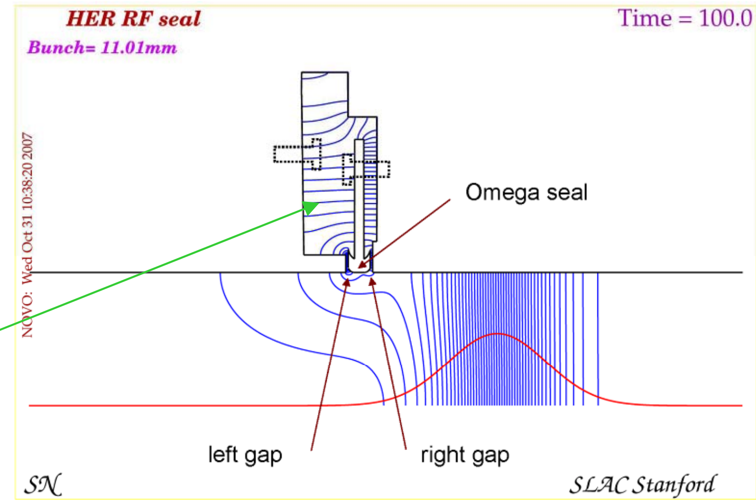


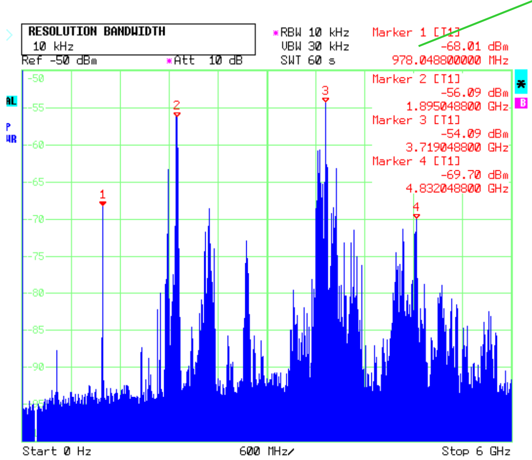
A MODEL OF AN ELECTRICAL DISCHARGE IN THE FLANGE CONTACTS WITH OMEGA SEALS AT HIGH CURRENTS IN PEP-II. A. Novokhatski **, J.Seeman, M.Sullivan EPAC 2008**

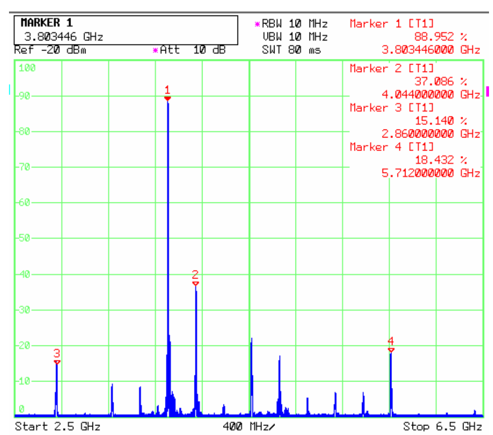
RF seal temperature jumps and an outer cavity excitation

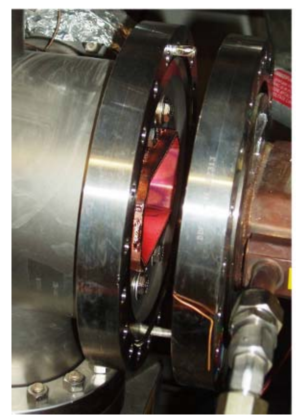








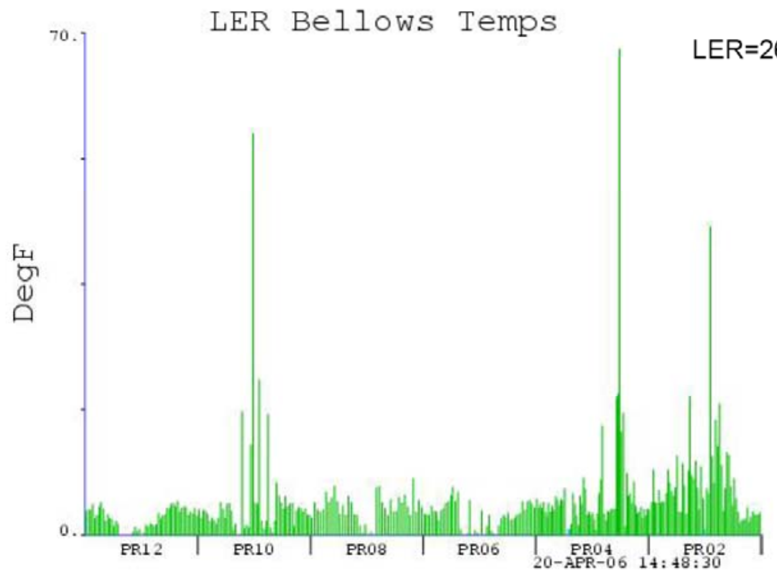




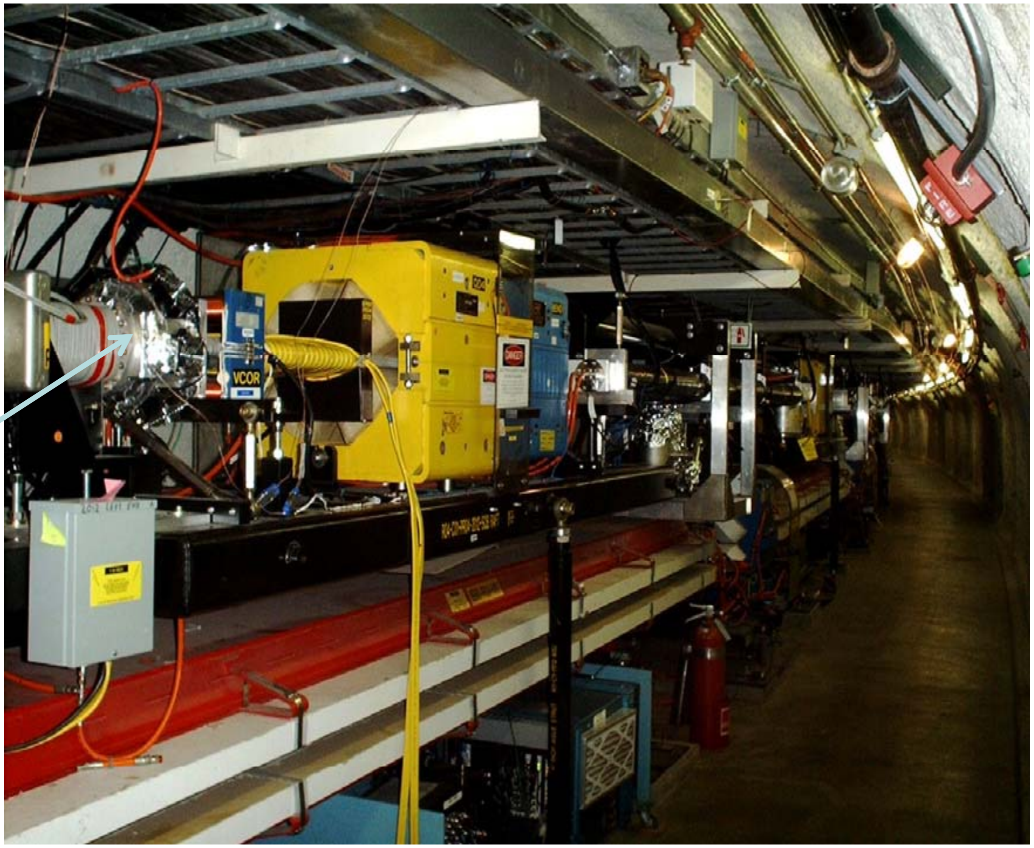
Measured single bunch and multi bunch spectrum

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

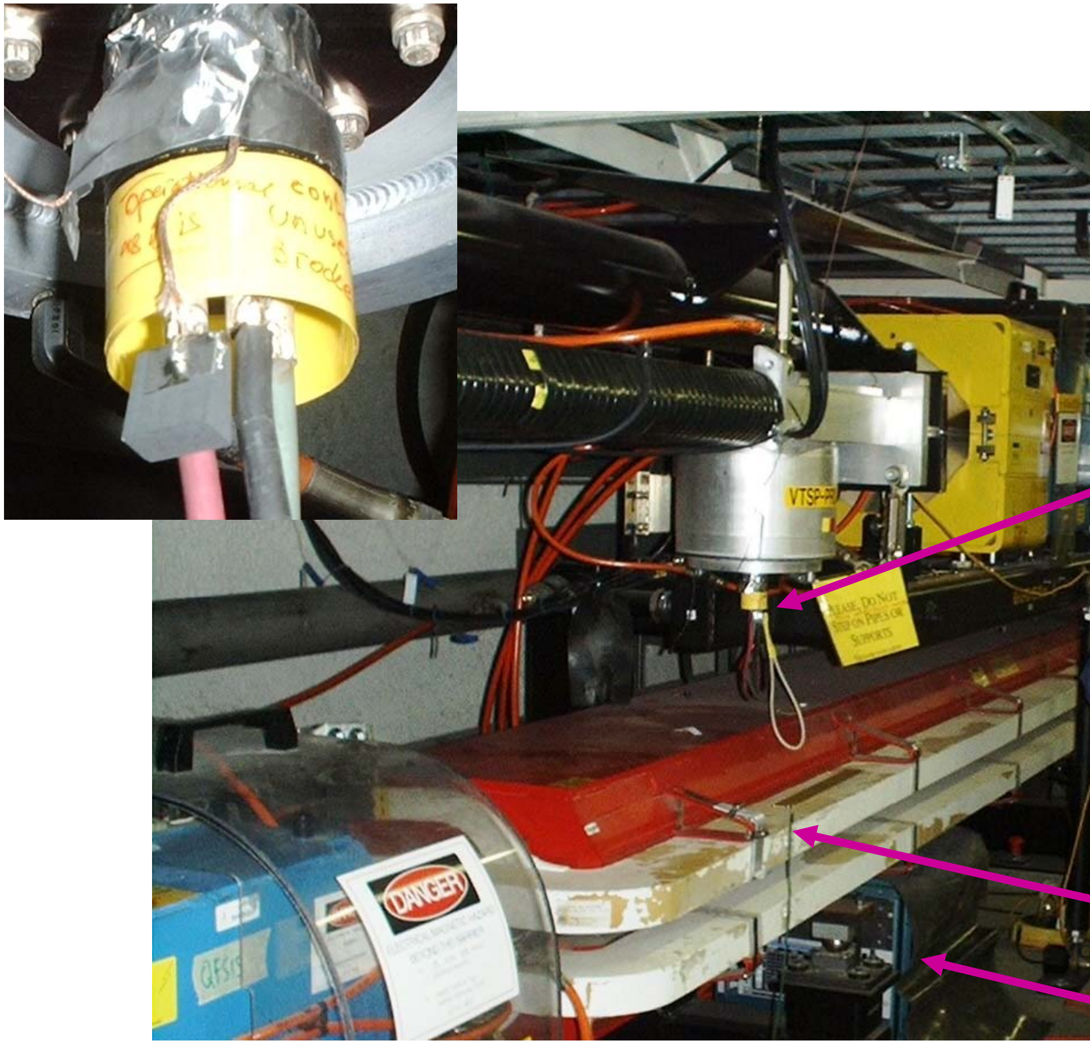
Temperature raise in shielded bellows



The hottest
Bellows
Region 4

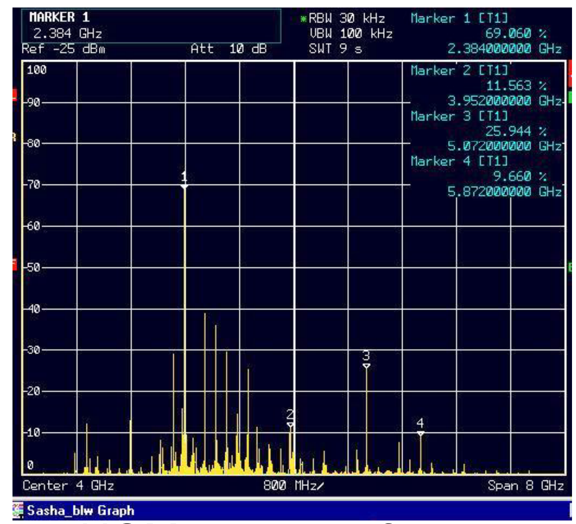


In the same region we found HOM leaking from TSP heater connector



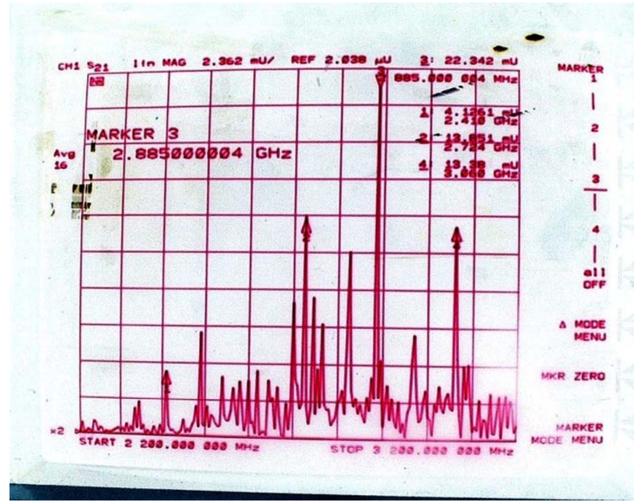
The power in the wake fields was high enough to char beyond use the feed-through for the titanium sublimation pump (TSP).

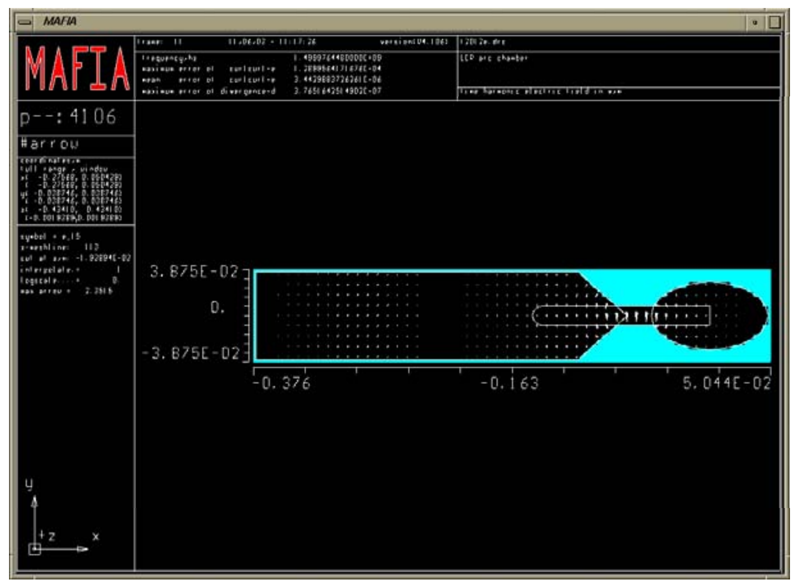
antenna



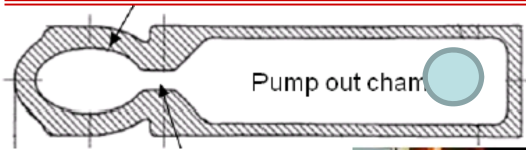
HOM spectrum from Spectrum analyzer

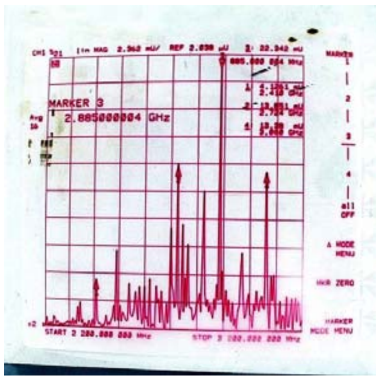
Measurement and simulations



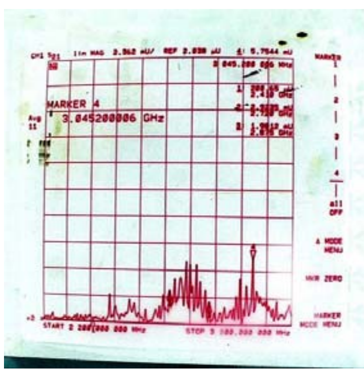


Solution: a HOM absorber in the ante-chamber

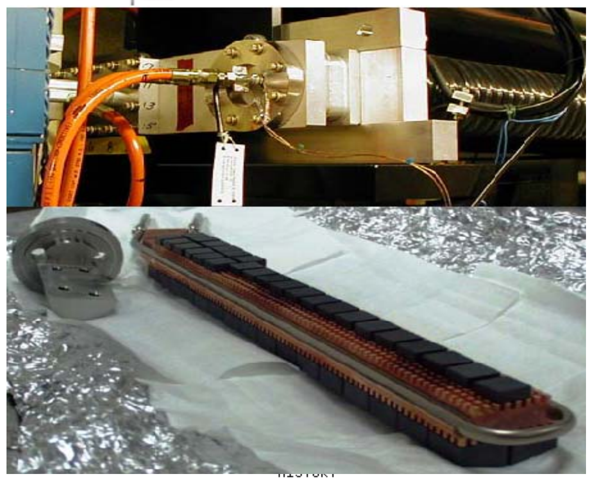


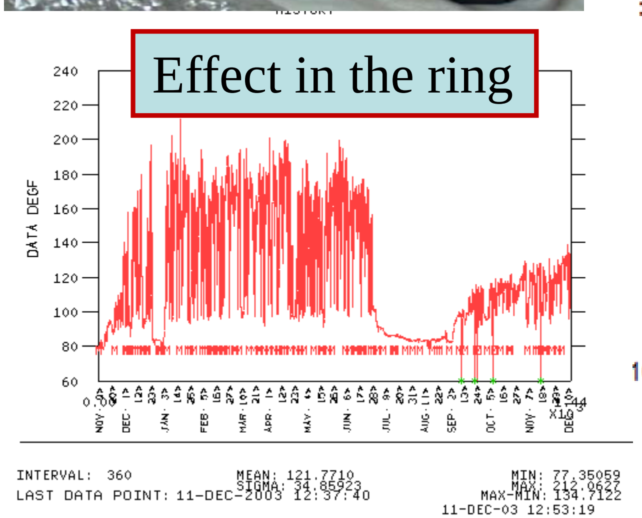


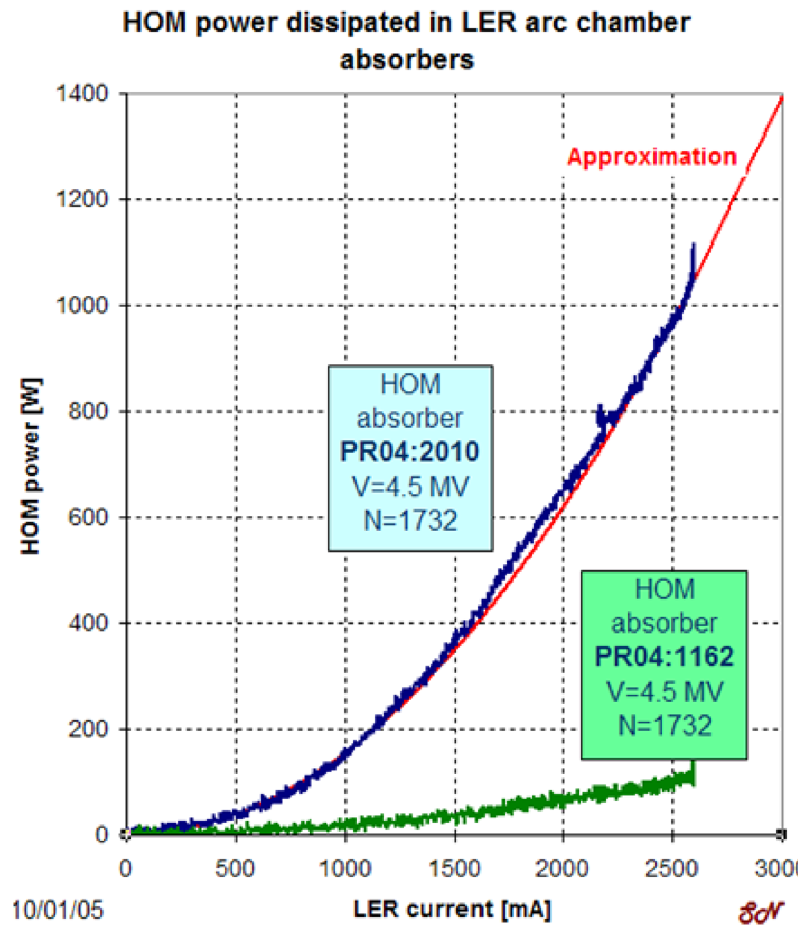
No absorber



With absorber



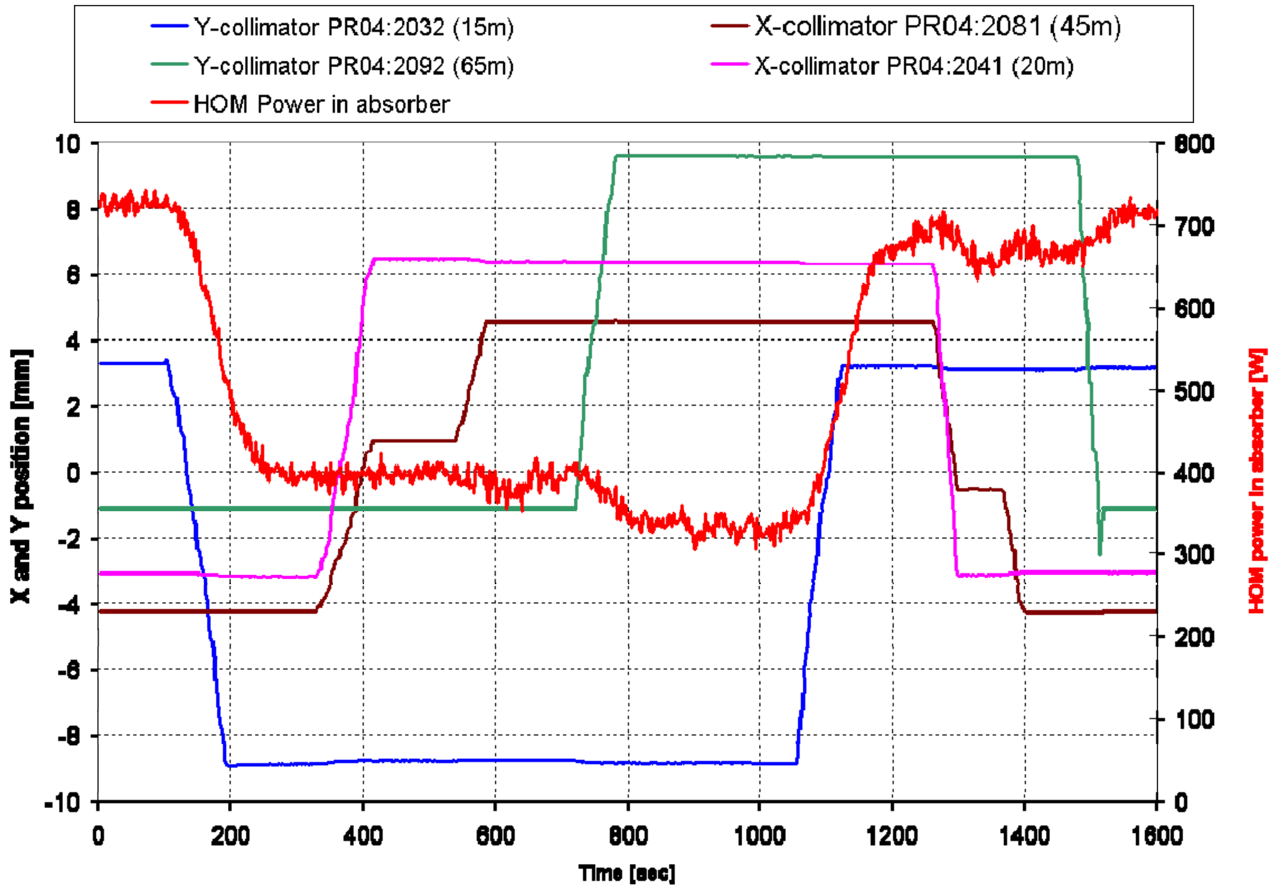




Search for a source of wake field

* We did not find correlation between the temperature and the beam position at the elements: bellows and ante-chambers.
* We suggested that the wake fields are generated in some other place. These fields have high frequency and may travel long distances.
* Also these fields have a transverse electric component or a longitudinal magnetic component and may penetrate through the shielded fingers or longitudinal slots.
* An ante-chamber HOM absorber helped to find the source of these fields.

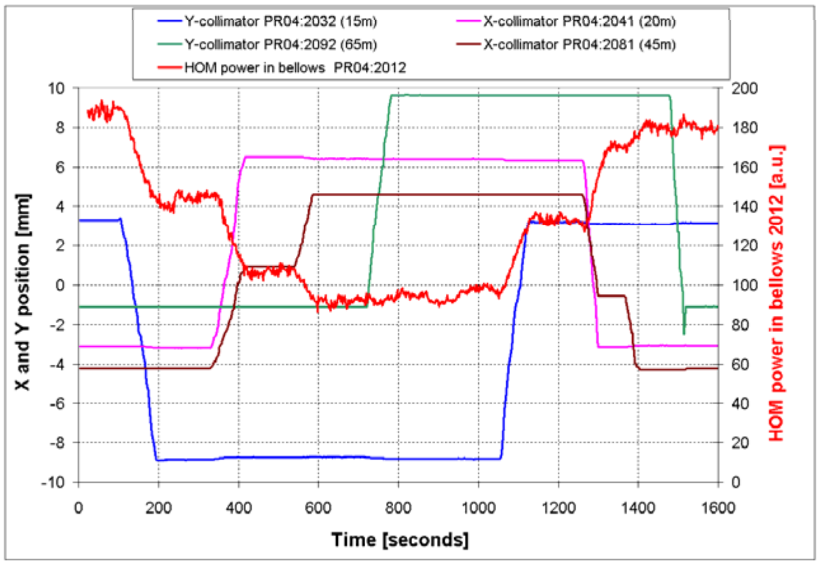
We found the Source for the HOM power - collimators



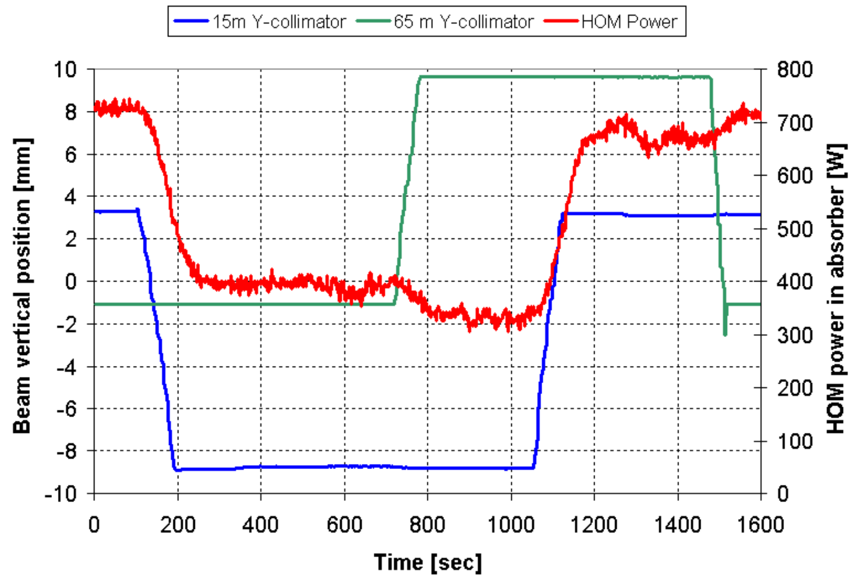
HOM power in absorber (red line) and vertical beam position near 15m collimator (blue line) and 65m collimator (green line).

HOM Source: collimators 20m and 45 m away

HOM power in bellows



HOM power in absorber

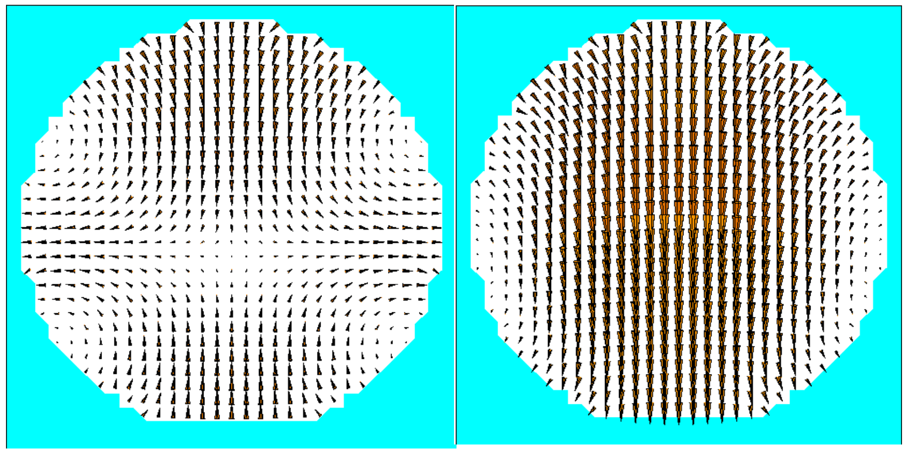


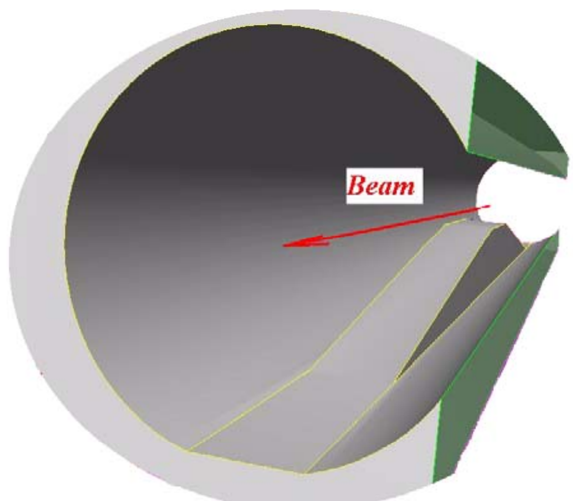
We found a strong correlation with the beam position near collimators which are far away from the bellows and arc chamber.

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

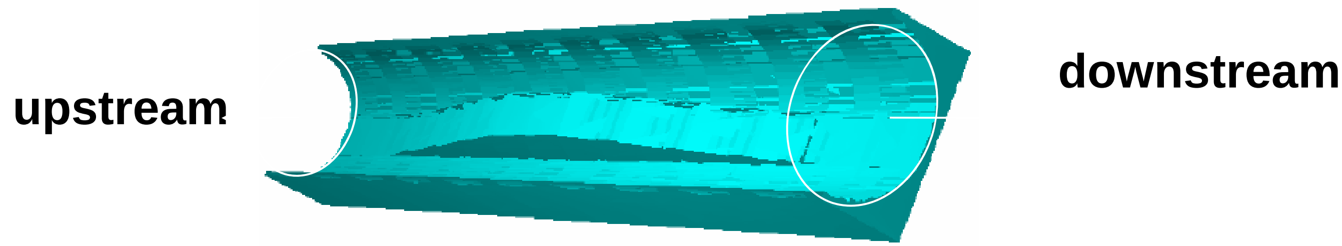
Simulations of collimator wake fields

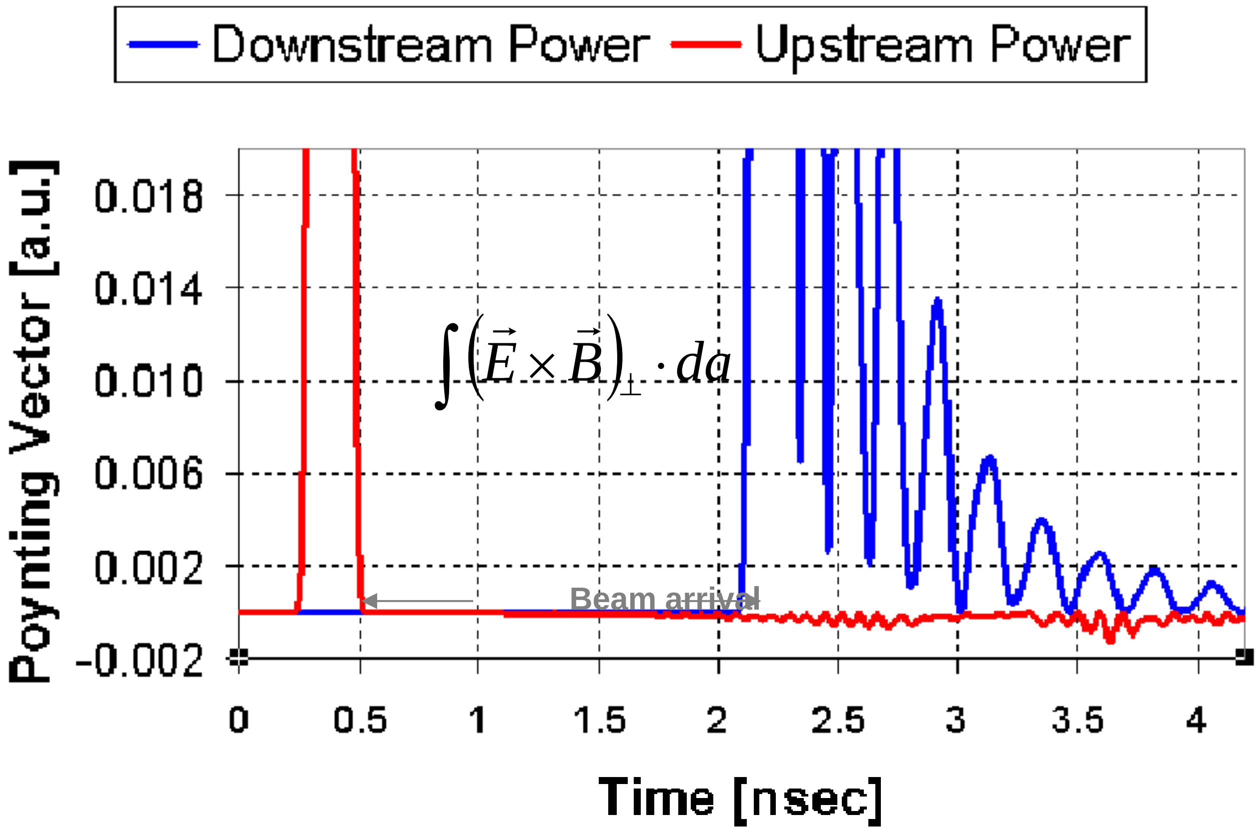
Main component: dipole and quadrupole



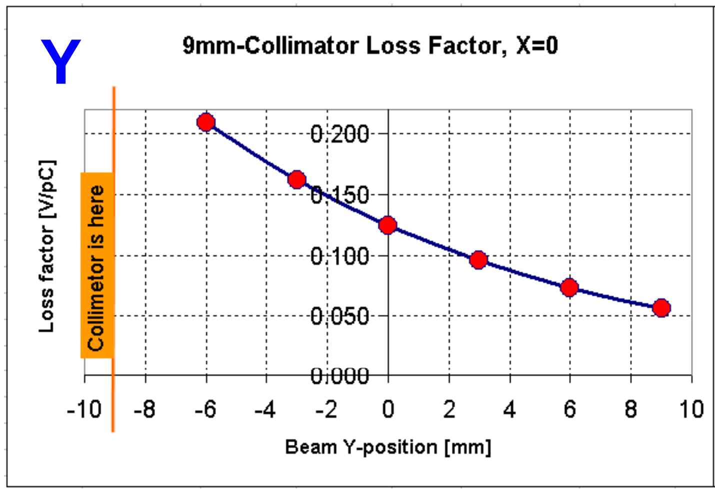


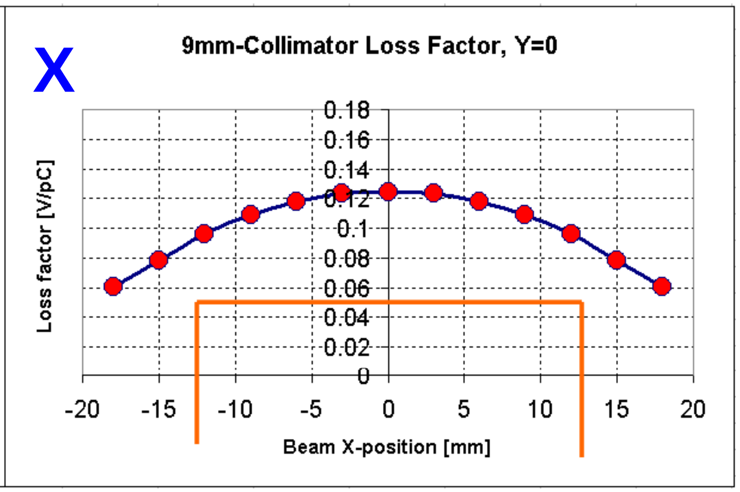
Power propagation follows bunch

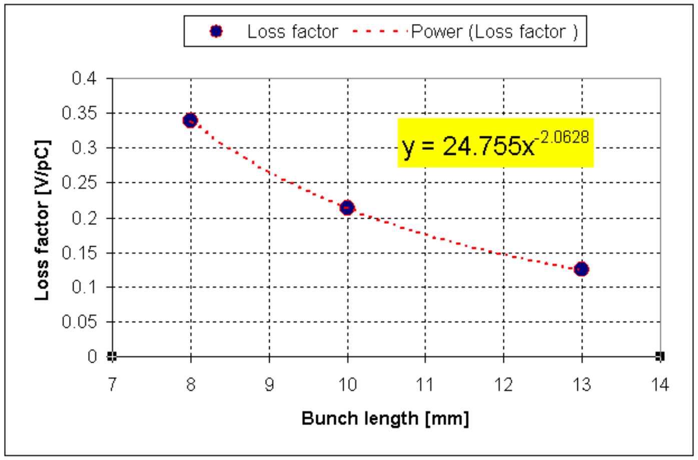




Collimator loss factor calculation



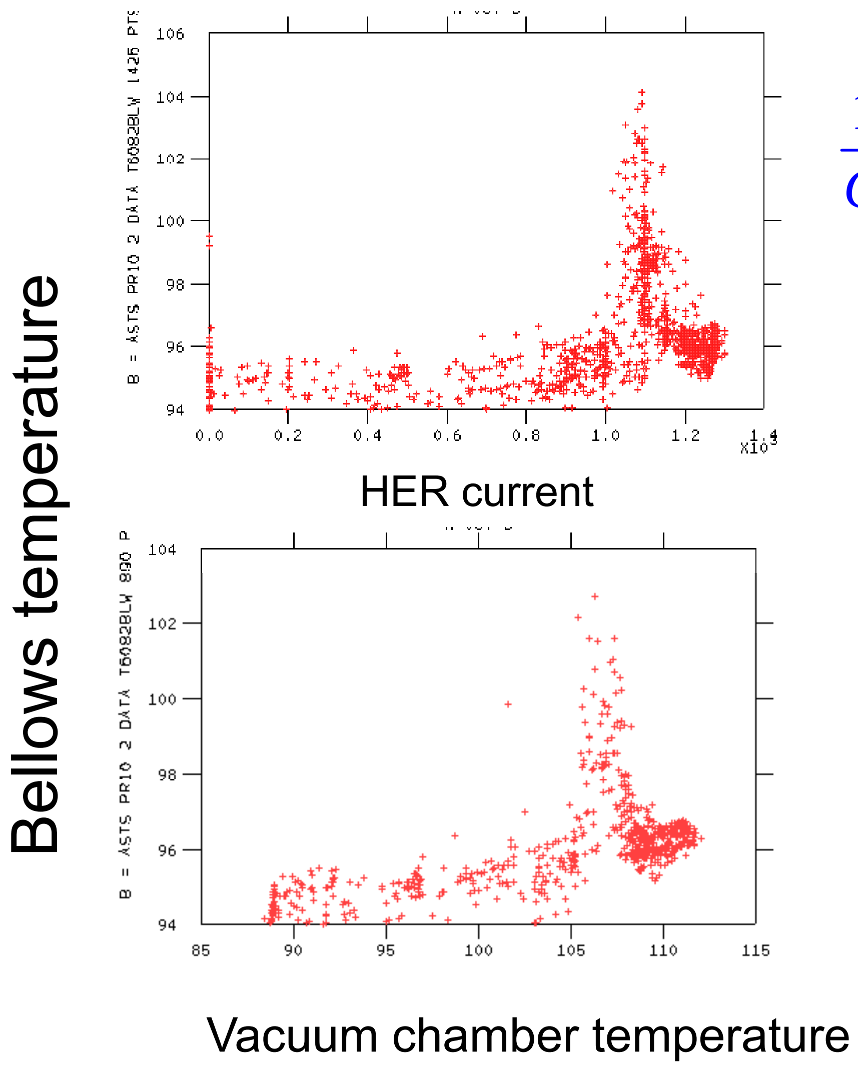




S. Weathersby.

Bunch length

Bunch-spacing resonance in HER bellows, which had short shielded fingers



$$\frac{1}{Q} = \frac{\Delta f}{f} \sim \frac{\Delta l_{bellows}}{l_{bellows}} = \frac{\alpha l_{chamber} \times \Delta T_{chamber}}{l_{bellows}} \sim 10^{-3}$$

Beam spectrum

Bunch spacing

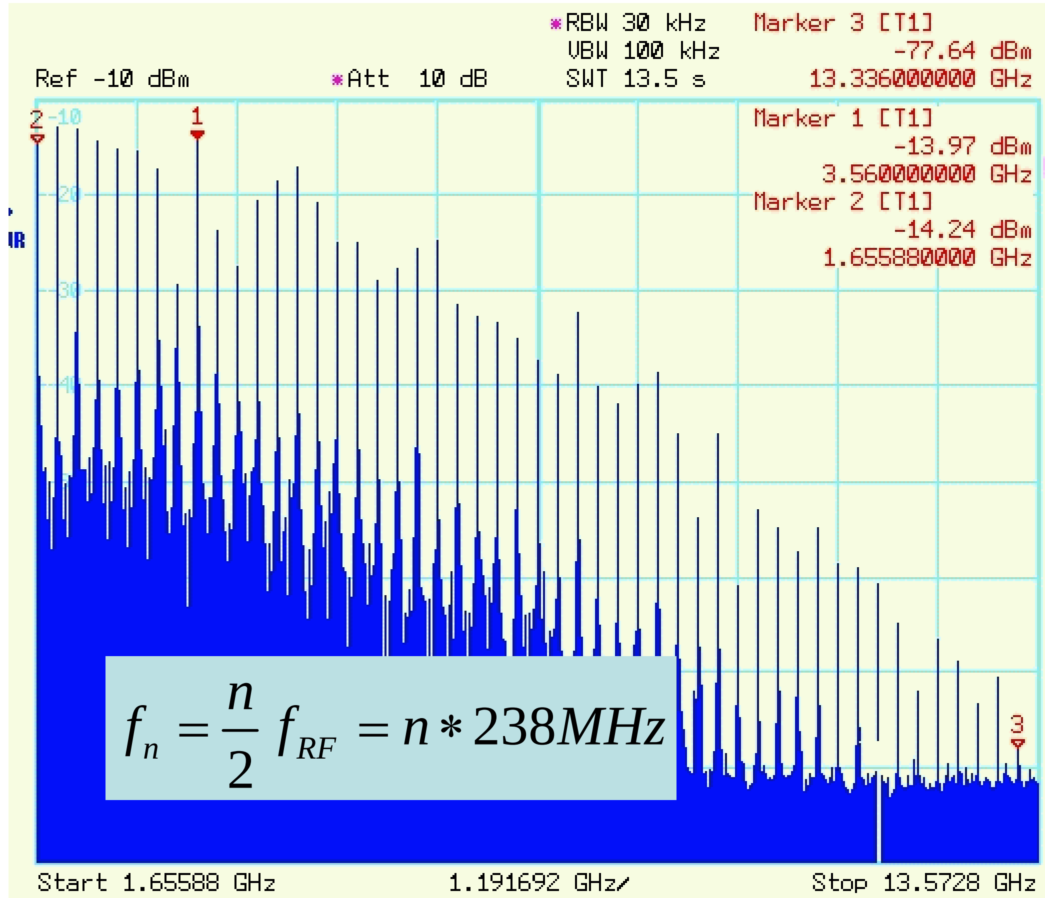
$$\tau_b = \frac{m}{f_{RF}} \qquad m = 1, 2, 3, \ldots$$

Main spectrum lines

$$f_n = \frac{n}{\tau_b} = \frac{n}{m} f_{RF} \qquad n = 1, 2, 3, \ldots$$

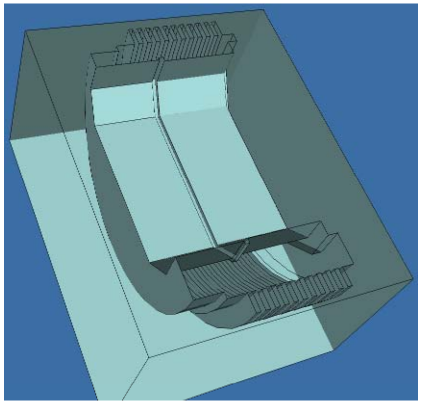
•Field spectrum goes to higher frequency with shorter bunches exponentially

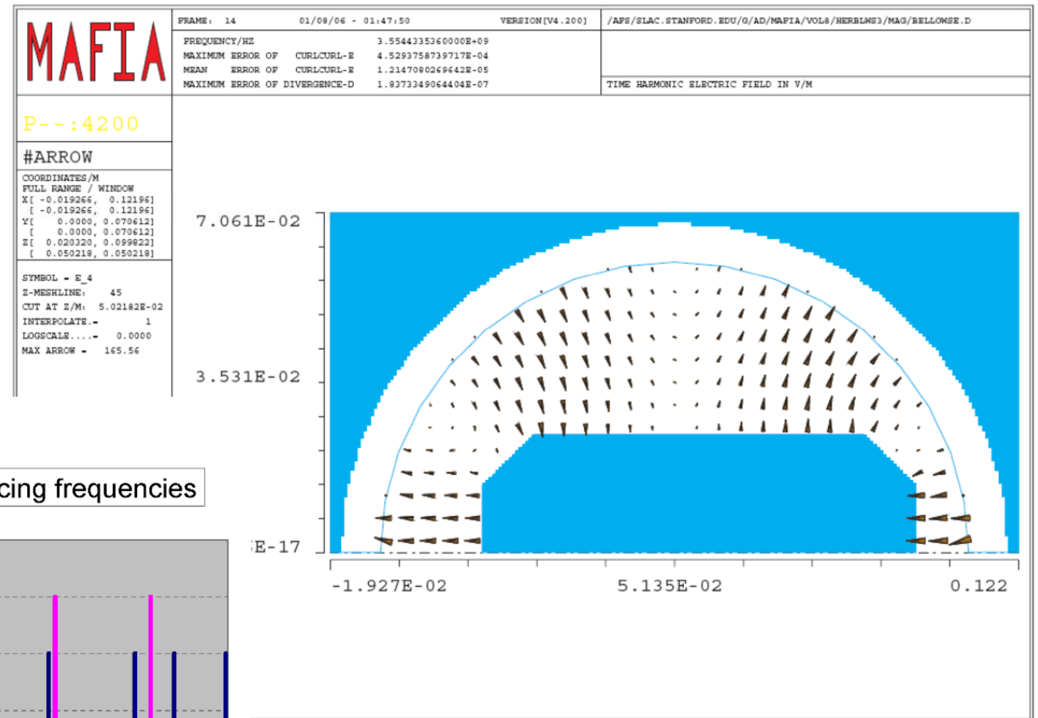
$$A(\omega) \sim e^{-\left(\frac{\omega}{c}\sigma\right)^2}$$

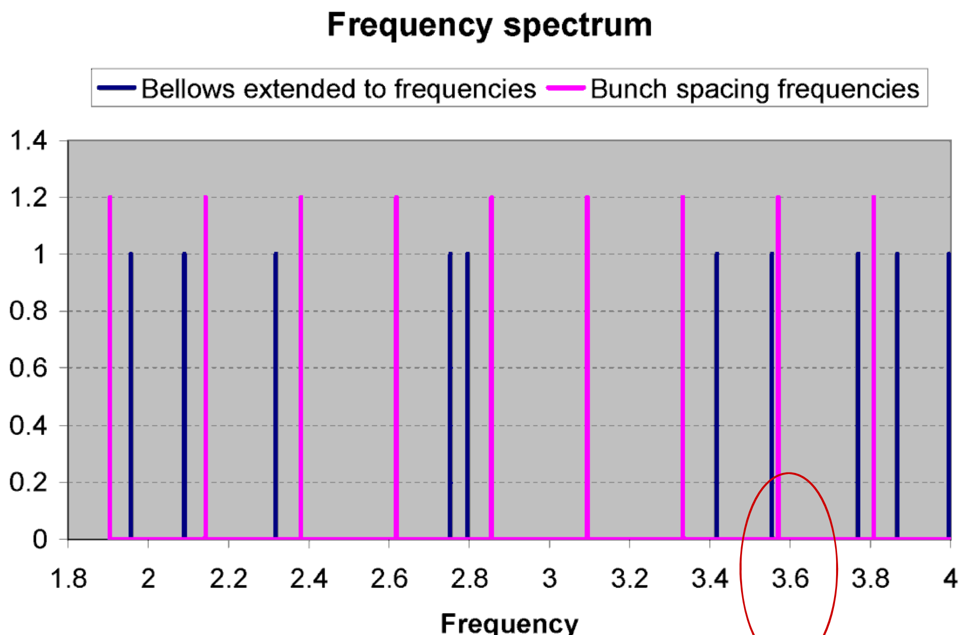


Spectrum from a BPM signal of a train of 12 mm bunches

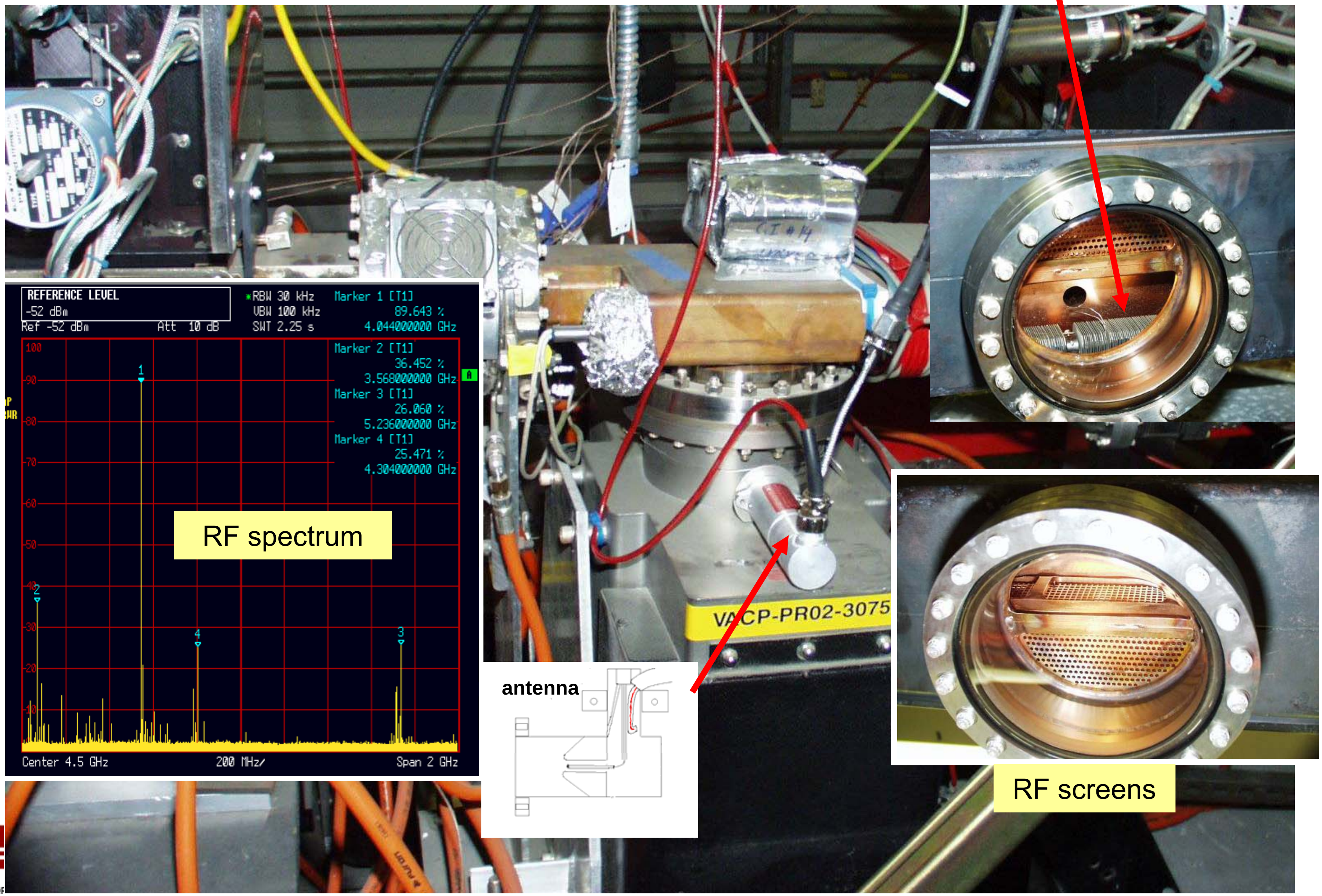
Simulations







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

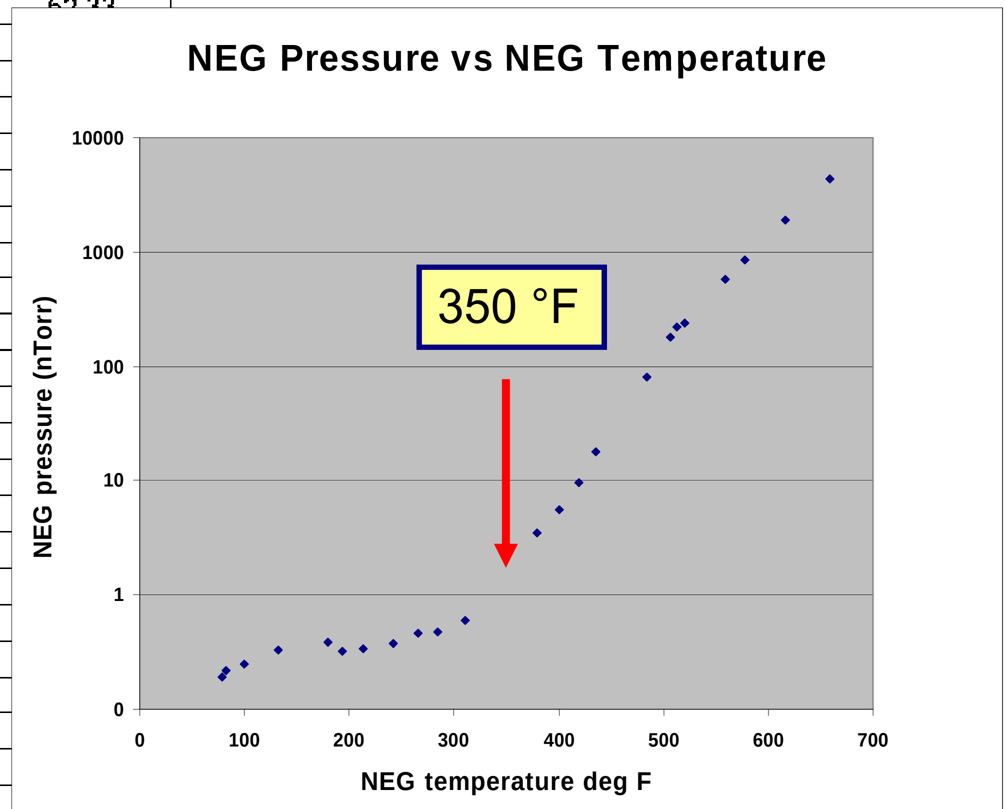


LER NEG Pump Temperatures

M.Sullivan

NEG #	Chamber	Screen type	Temperature	Location (m)	Location (feet)
3022A/B	Q2	A	82	3.4	11.25
3023	QD4	B	465	5.5	18.00
3025	QF5	B	300	7.8	25.75
3042	BV1B	C	750	9.8	32.25
3043	Coll 3043	B	425	12.4	40.67
3052	QDCX21	C	600	14.6	47.83
3053	QDCX21	B	130	16.0	[illegible]
3061	BCX21A	B	110	16.3	
3062	BCX21B	C	500	18.6	
3063	BCX22	B	120	20.8	
3066	QDCX2A	B	100	22.3	
3072	QDCX2B	C	775	22.5	
3074	QDCX2B	B	150	24.3	
3076	Coll 3076	B	725	25.5	
3082	QFCX1	C	425	26.6	
3101	SCX2	C	600	26.7	
3102	BCC1	B	140	30.4	
3112	QDCY21	C	425	32.2	
3114	Drift 32 (right)	D	90	32.3	
3115	Drift 32 (left)	D	90	37.0	
3116	Drift 38 (right)	D	90	37.3	
3118	Drift 38 (left)	D	90	42.0	
3132	QDCY22	D	90	44.8	
3141	BCC4	D	95	45.7	
3142	BV2	C	825	47.7	
3149	QFBM1	C	850	51.3	
3165	QFBM2	D	90	54.4	
3174	QFBM4A	D	90	56.2	
4011	BBM1B	D	90	63.1	
4012	B	D	95	65.5	214.83

Upstream LER side



Lab test data of NEG outgassing as a function of temperature

Design of a HOM absorber

We took a decision to design a new HOM absorber to damp electromagnetic fields that may propagate through the slots in bellows, vacuum valves and pump screens.

At the same time absorber must not disturb much the beam image current on the chamber wall.

We plan to install an absorber after each collimator and everywhere we have HOM heating

A new absorber combines bellows functions.

A new absorber contains ceramic tiles, which were used already in the PEP-II RF system.

We choose ceramics: AlN-SiC Ceralloy 13740Y.

ceradyne, inc.
ADVANCED TECHNICAL CERAMICS

3169 Redhill Avenue • Costa Mesa, CA 92626
Phone: 714-549-0421 • Fax: 714-549-5787
email: sales@ceradyne.com
internet: www.ceradyne.com

Properties of Ceradyne's Advanced Technical Ceramics for Microwave Applications

Property	Ceramic Composition							
	Al_2O_3-SiC	MgO-SiC		AlN-SiC		AlN-Composite		BeO-
GRADE	Ceralloy® 7712	Ceralloy® 6703	Ceralloy® 6705	Ceralloy® 13740	Ceralloy® 13740Y*	Ceralloy® 137 CA*	Ceralloy® 137 CB*	Cera 27
Composition	Al_2O_3+60%SiC	MgO+2%SiC	MgO+5%SiC	AlN+40%SiC	AlN+40%SiC	AlN Composite	AlN Composite	BeO+
Tailored Compositions Available	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Y
Processing Route	Hot Pressing	Hot Pressing	Hot Pressing	Hot Pressing	Hot Pressing	Hot Pressing	Hot Pressing	Hot P
Density (g/cc)	3.36	3.50	3.48	3.19	3.19	2.99	2.99	3
Outgassing	No	No	No	No	No	No	No	N
Thermal Conductivity (W/m°K) (RT)		30	30	30	53	85	95-105	1
Dielectric Constant								
@ 1.0 GHz				22	30	28	40	
@ 8.0 GHz	130	11.2	12.8	15	22	18	30	
@10.0 GHz	83	11.1	12.7	15	21	18	28	
@12.0 GHz	69	10.9	12.6					
Loss Tangent								
@ 1.0 GHz				0.11	0.11	0.20	0.15	0
@ 8.0 GHz	0.40	0.02	0.03	0.30	0.30	0.20	0.30	0
@10.0 GHz	0.57	0.02	0.03	0.28	0.28	0.20	0.30	0
@12.0 GHz	0.53	0.02	0.03					
Thermal Expansion Coefficient x10⁻⁶/°C; (RT-1000°C)		15.4	14.8	5.1	5.1	5.0	5.0	7
Flexural Strength (MPa)	530	200	200	300	300			
Key Features						Dielectric Loss Independent of Temperature (to 3°K)	Higher Thermal Conductivity than Ceralloy® 2710 @ Temps. >150°C. Close Match in Electrical Properties	Former I Standar Terminat
Applications	Slot Mode Absorbers	Absorbers, Buttons	Absorbers, Buttons	Replacement for Ceralloy® 2710 BeO-SiC, Terminations, Sever Wedges, Load Pellets, Absorbers	Replacement for Ceralloy® 2710 BeO-SiC, Terminations, Sever Wedges, Load Pellets, Absorbers	Terminations, Sever Wedges, Load Pellets, Absorbers, Cryogenic Environment Applications	Replacement for Ceralloy® 2710 BeO-SiC, Terminations, Sever Wedges, Load Pellets, Absorbers	Terminat Sever W Load Pe Absorbe

NOTE: Properties are typical and should not be considered as specifications.

* Patent Pending ** BeO and BeO-SiC ceramics are no longer manufactured by Ceradyne. Data is included for reference only.

A.Novokhatski, J. Seeman and S. Weathersby, "High efficiency absorber for damping transverse fields" Phys. Rev. ST Accel. Beams **10**, 042003 (2007).

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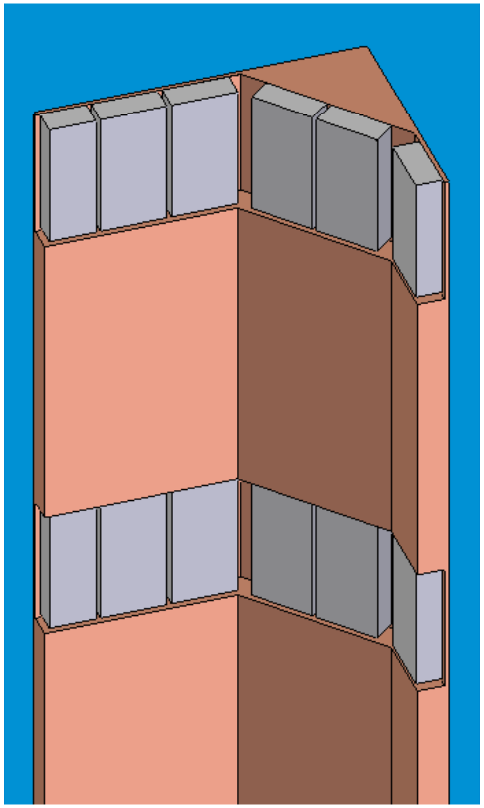
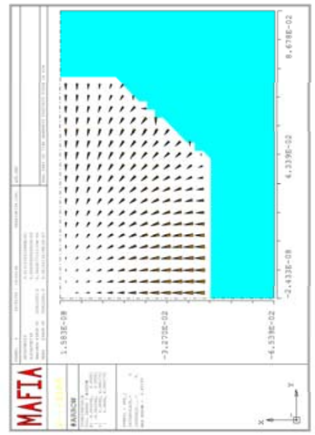
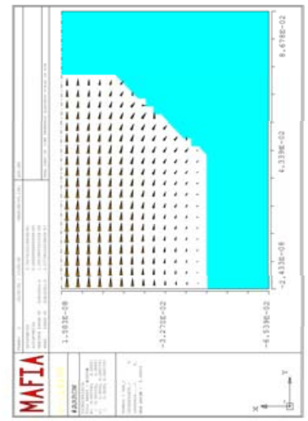
Simulation of absorption: mode scattering.



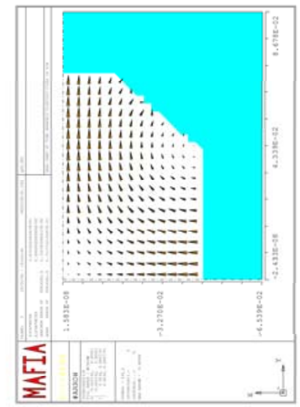
Input waves:



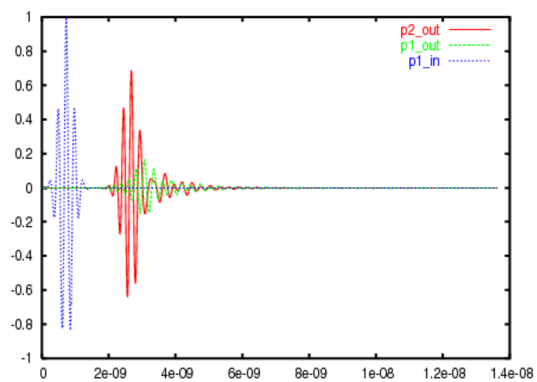
mono



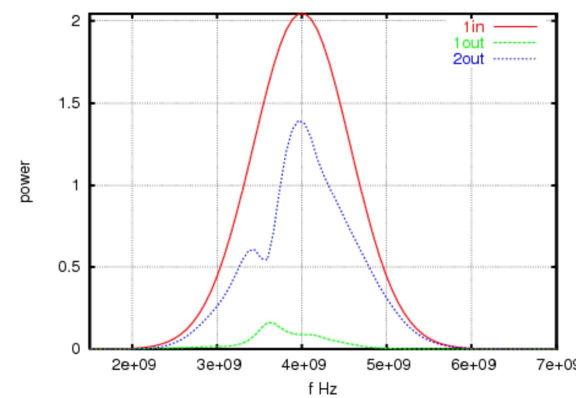
dipole



quad

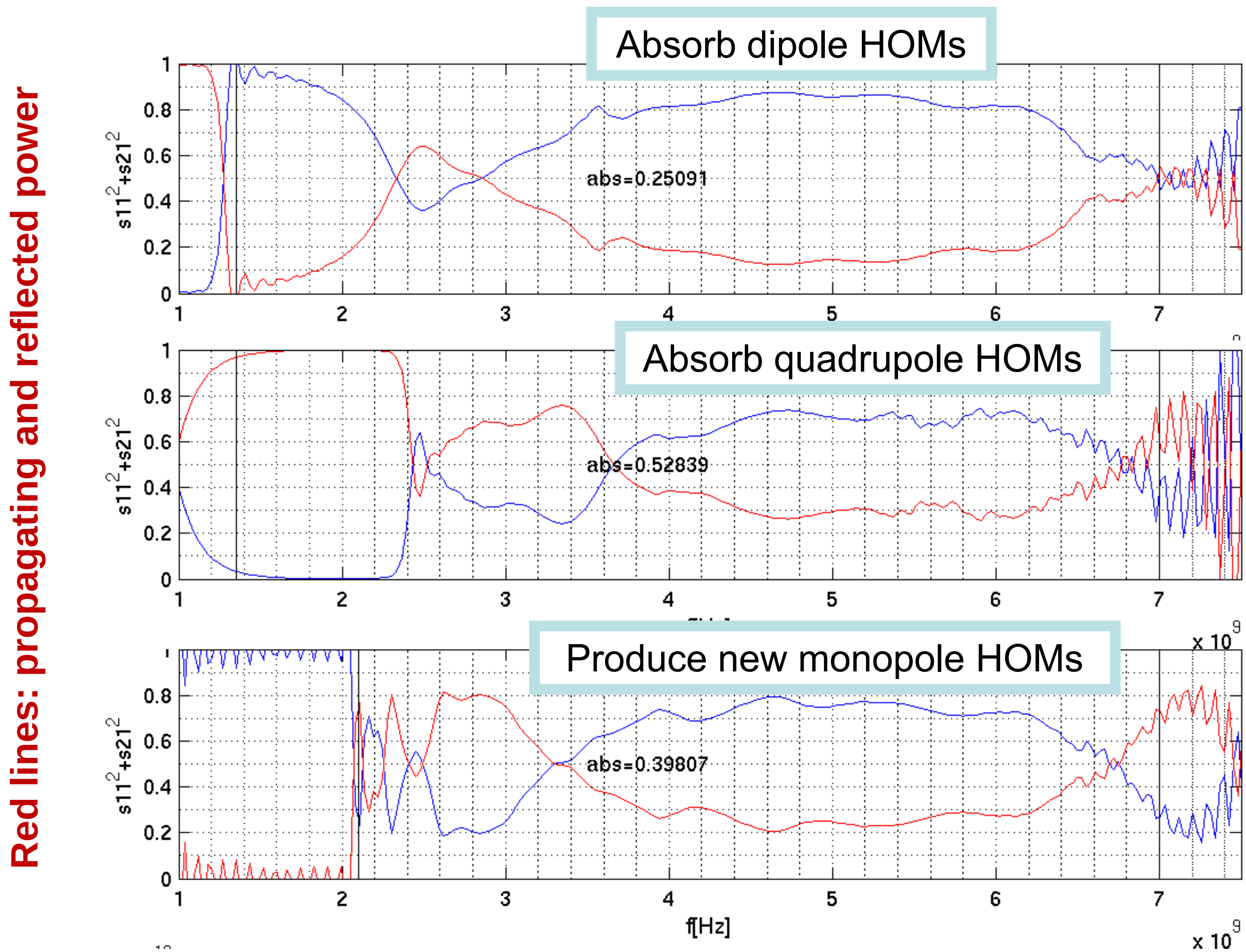


Input, propagated and reflected signals

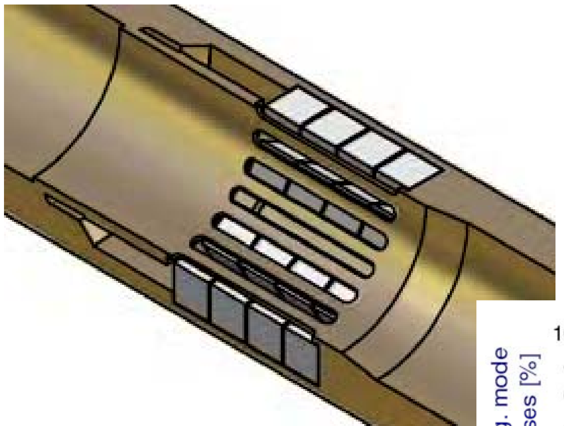


Furrier transformation

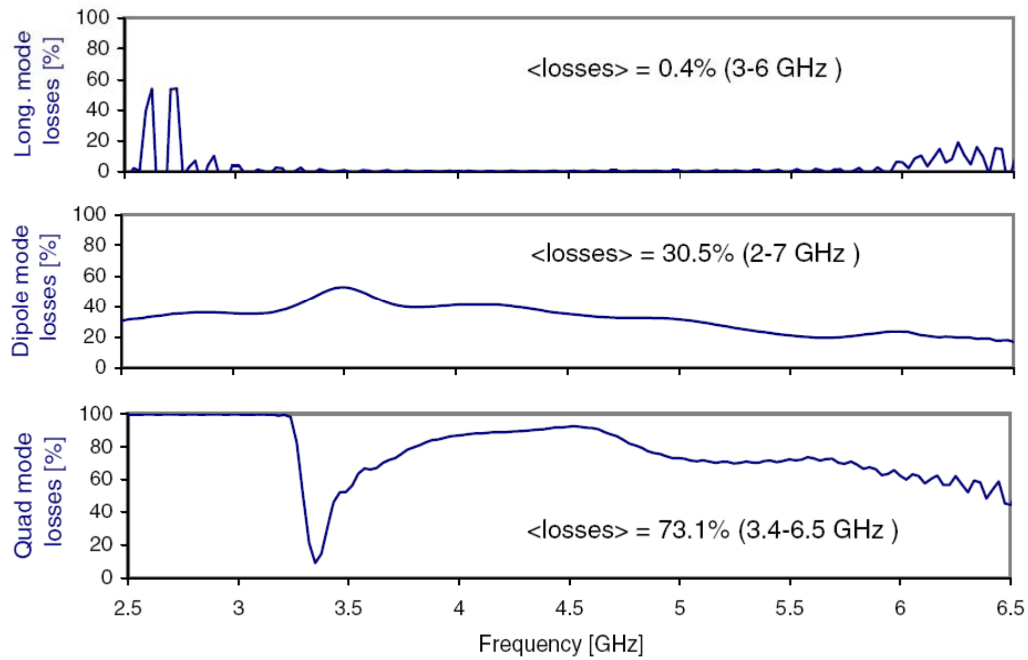
Adsorbed power in the ceramic tiles



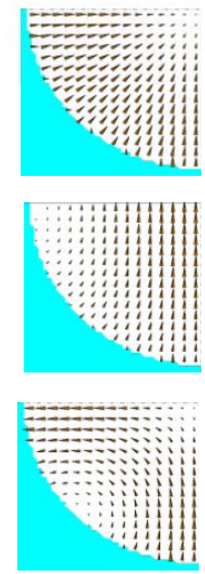
Mode scattering in a round pipe with shielding fingers.



Absorbed power in the tiles

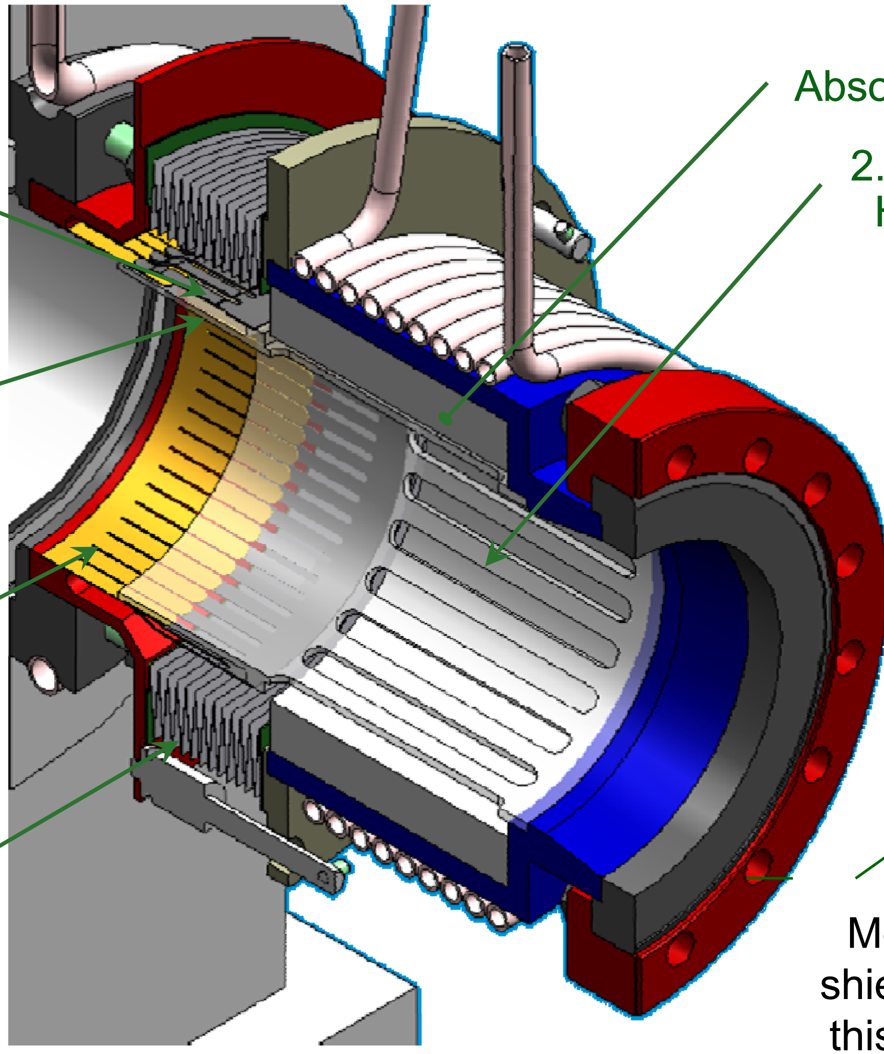


Input waves



optimizing geometry for the absorption to get 40% absorption level of dipole modes

Straight HOM Bellows -design details



Inconel Spring Finger

GlidCop Stub

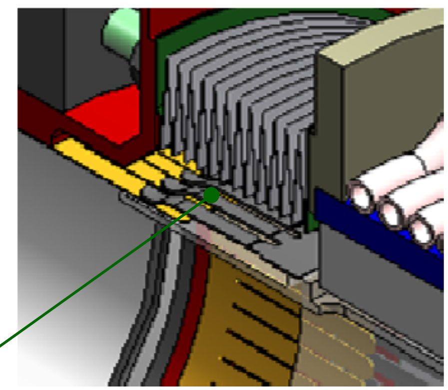
GlidCop RF Shield Finger

Welded Bellows

Absorbing Tile

2.75” long by .24” wide HOM Trapping Slots

Modes in the chamber propagate through the slots & are absorbed by the AlNiSiC.



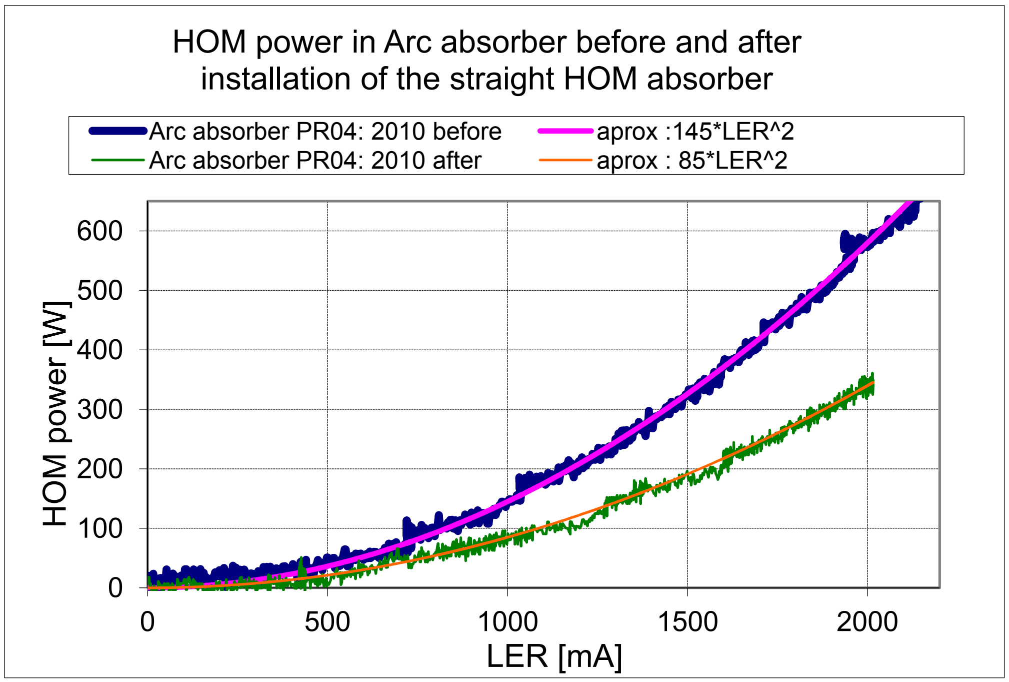
Bellows Cavity

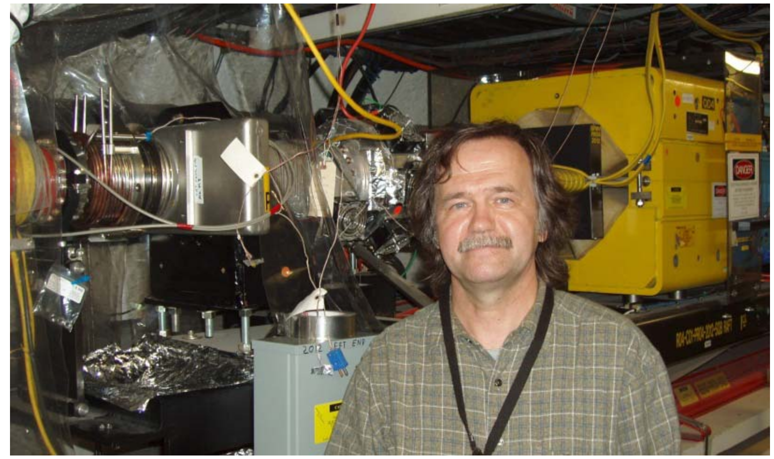
Modes that leak past the RF shield finger and are trapped in this area still see the absorber

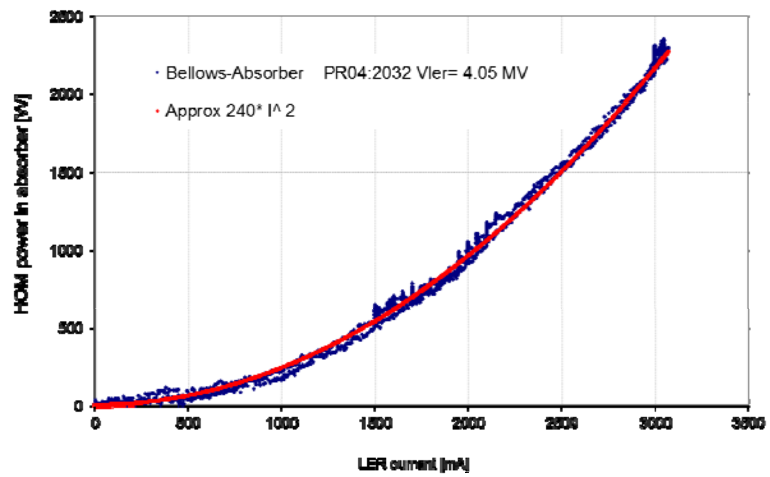
Efficiency of the absorber

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

As it was designed!







>2 kW absorbed power at 3 A

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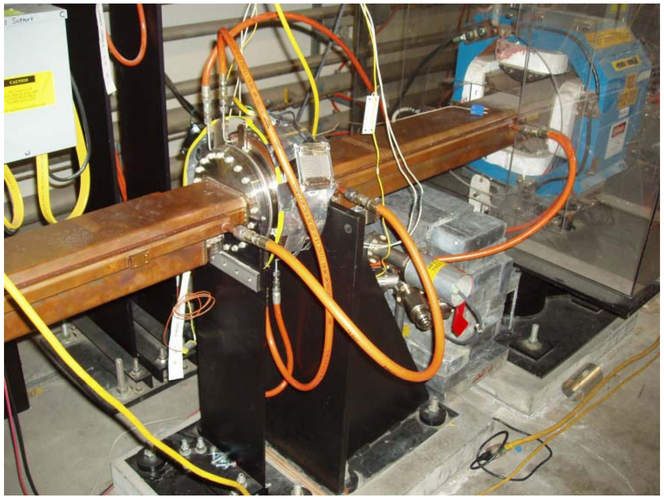
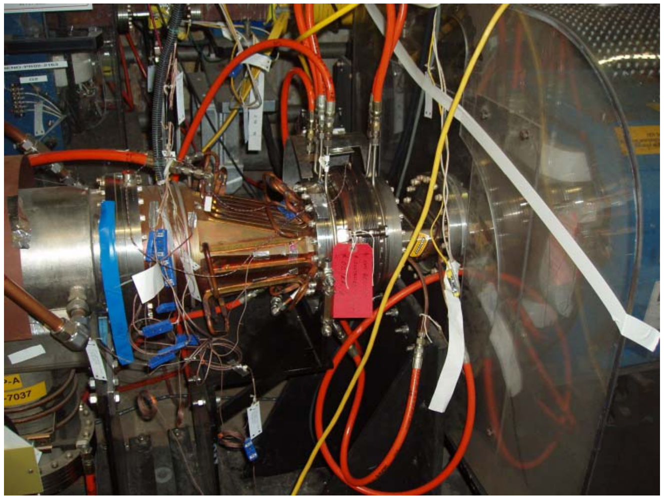
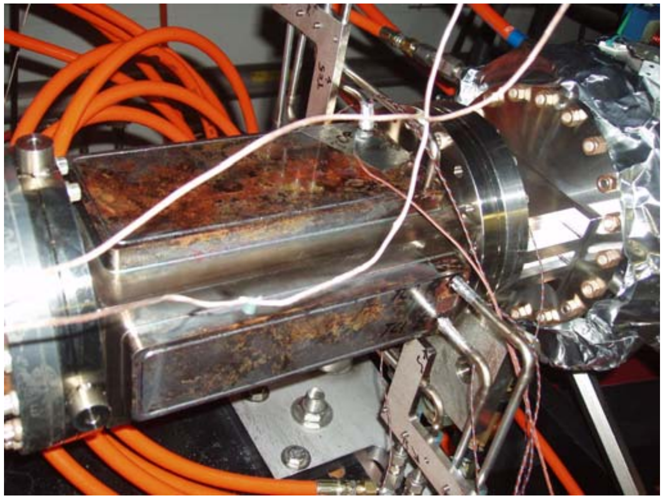
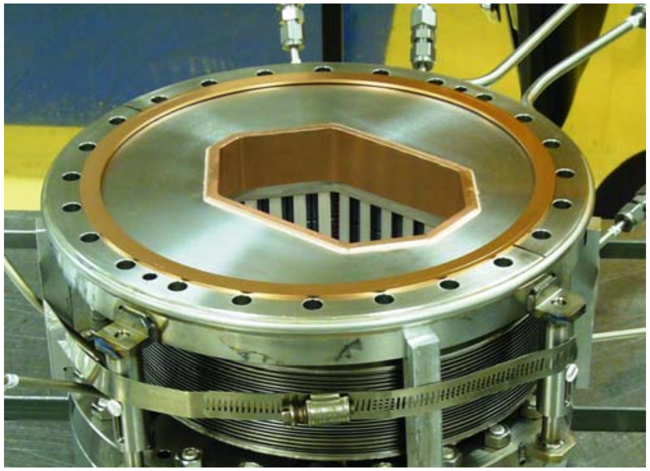
SLAC has developed high efficiency HOMs absorbers for different cross-sections and installed 25 in the rings



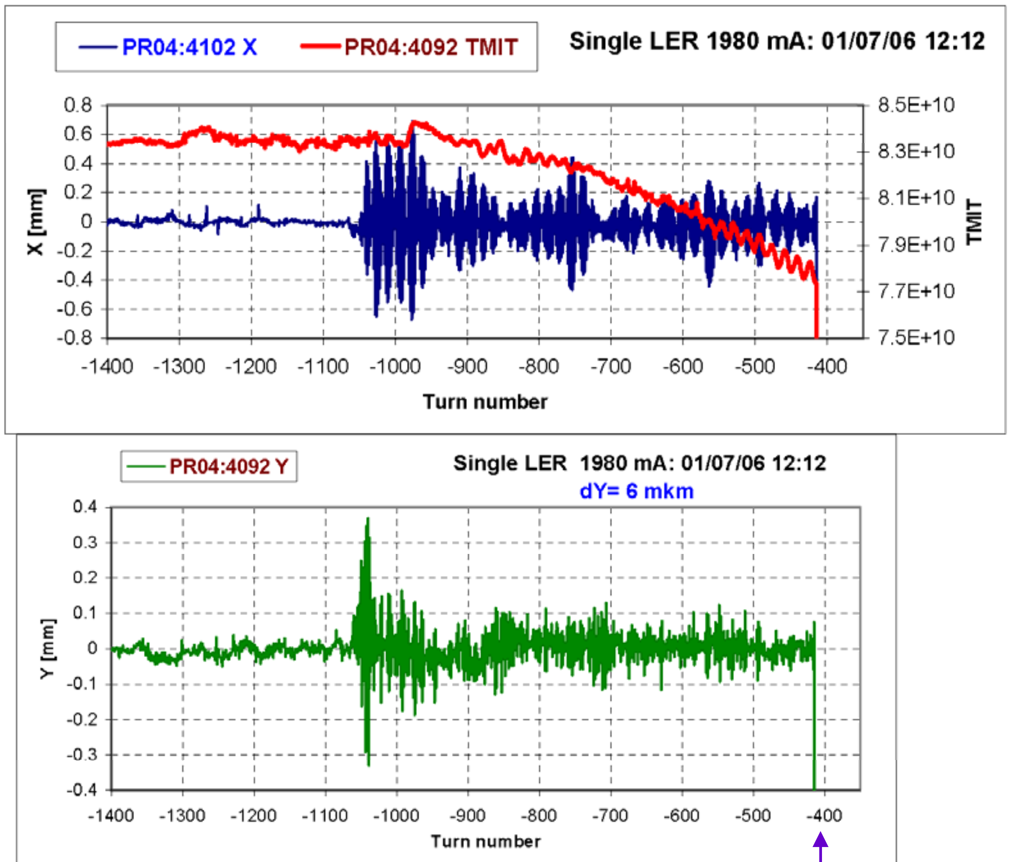






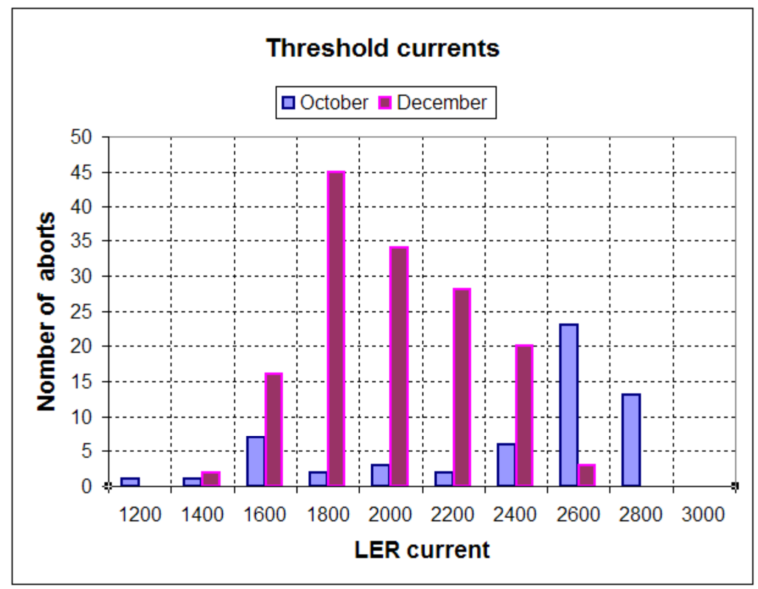
Trapped modes. Fast Instability

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

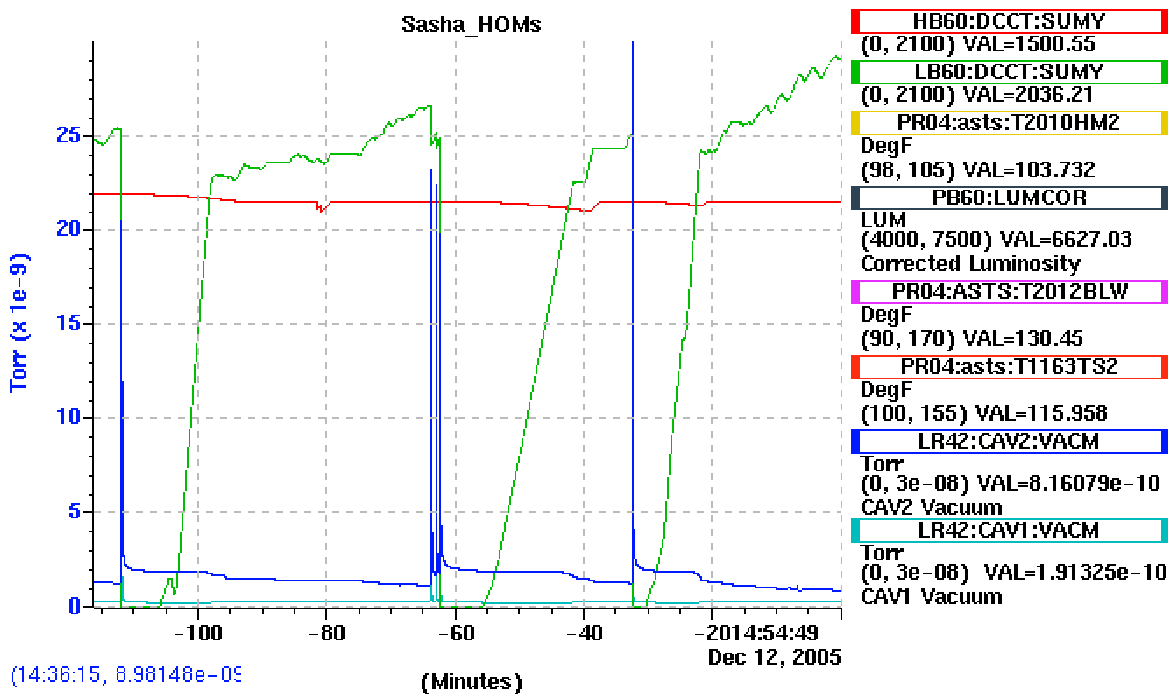
abort



Instability study

* It was two month of study of this instability. Many people were involved. Different kind of complicated theories were suggested, but …

… it was very simple. We found perfect correlations between aborts and vacuum spikes near one of RF cavities. Vacuum spikes happened every time with each abort.



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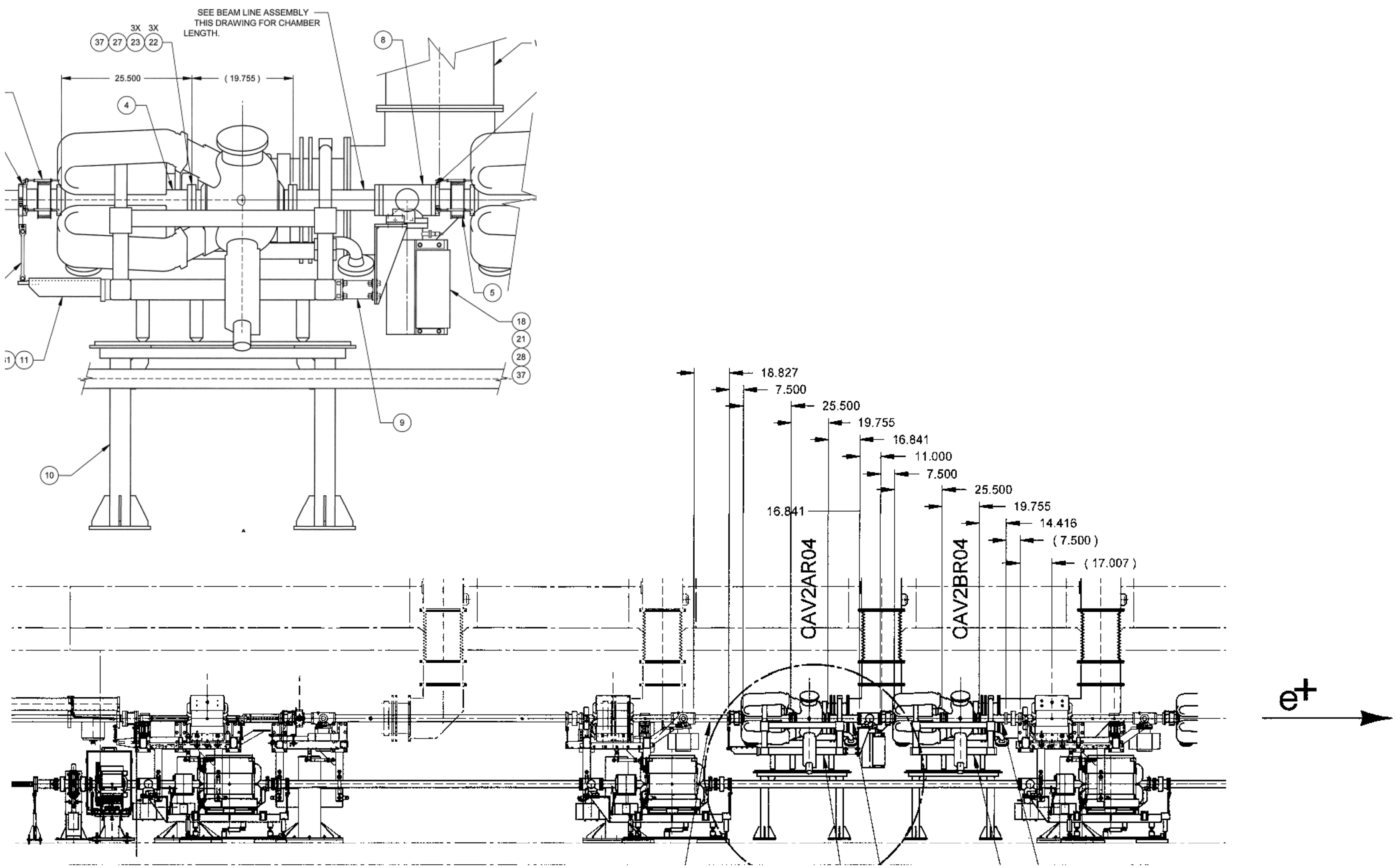
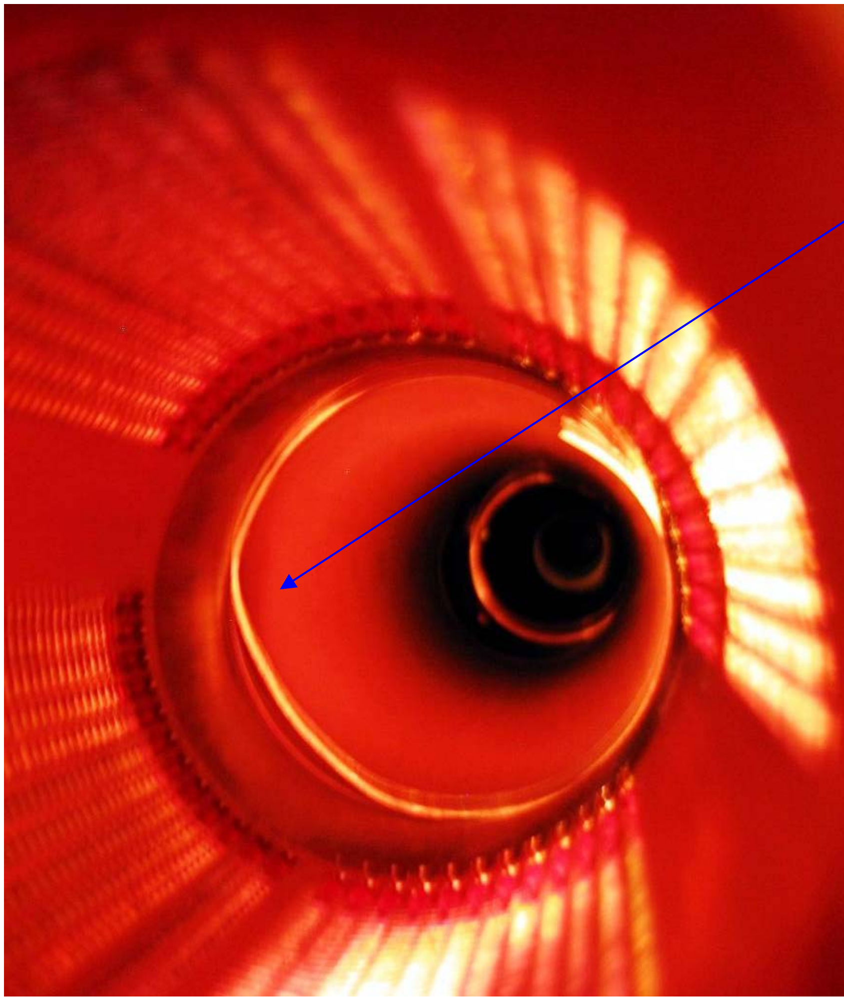
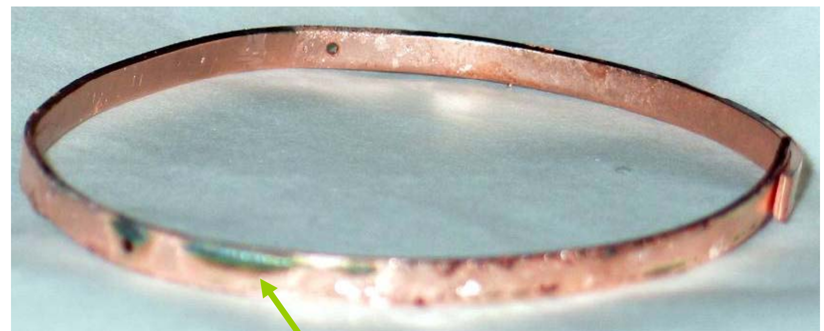
Vacuum spikes location



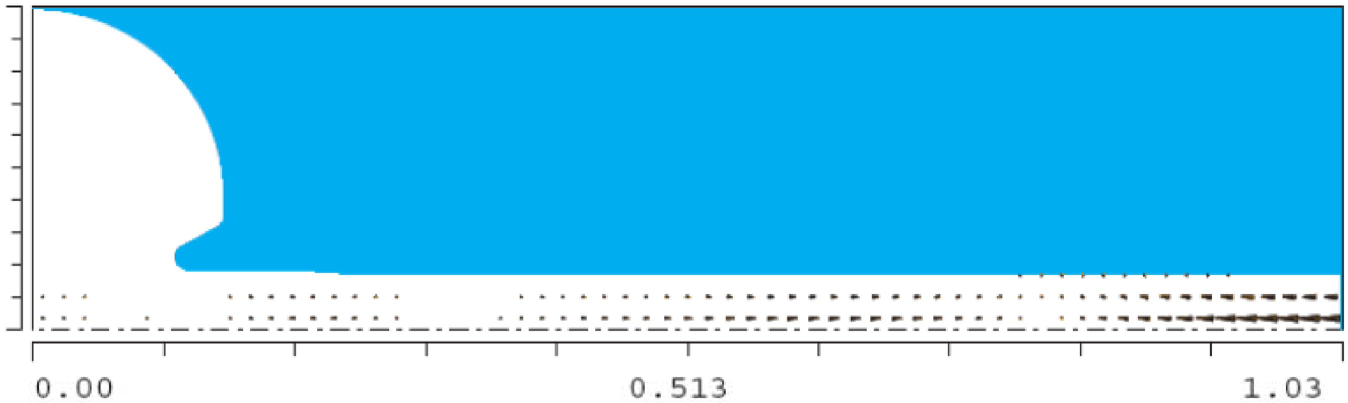
When we open the vacuum chamber at that location we found that RF seal (a gap ring with a cut) was not well installed



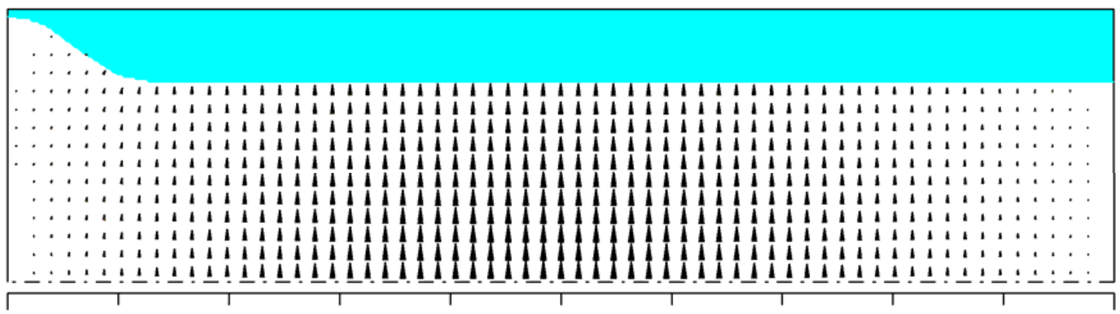


Modes between cavities which may couple to the beam because of the bad installation of the gap ring

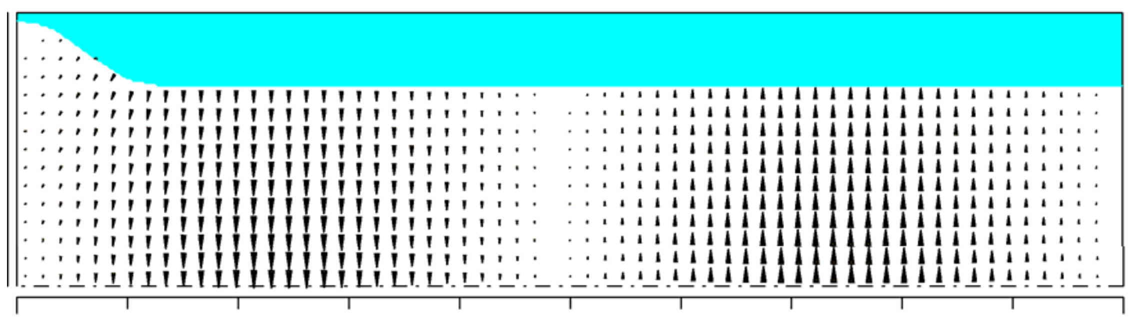
TM



TE



TE



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Higher Order Modes between cavities and bunch spacing harmonics

Cut-off frequencies

number	mode	frequency [GHz]
1	TE 1 1	1.976377976
2	TM 0 1	2.581356534
3	TE 2 1	3.278434447
4	TM 1 1	4.113017427
5	TE 0 1	4.113017427
6	TE 3 1	4.509645447
7	TM 2 1	5.5126477
8	TE 4 1	5.707902536
9	TE 1 2	5.722822841
10	TM 0 2	5.925377109
11	TE 5 1	6.886622983
12	TE 2 2	7.198451208
13	TM 3 1	7.301392097
14	TE 0 2	7.53067444
15	TM 1 2	7.53067444
16	TM 4 1	8.145421191
17	TE 3 2	8.603662903
18	TM 2 2	9.035177564
19	TE 1 3	9.163021286
20	TM 0 3	9.28904079
21	TM 5 1	9.41548922
22	TE 4 2	9.963899221

Beam frequencies

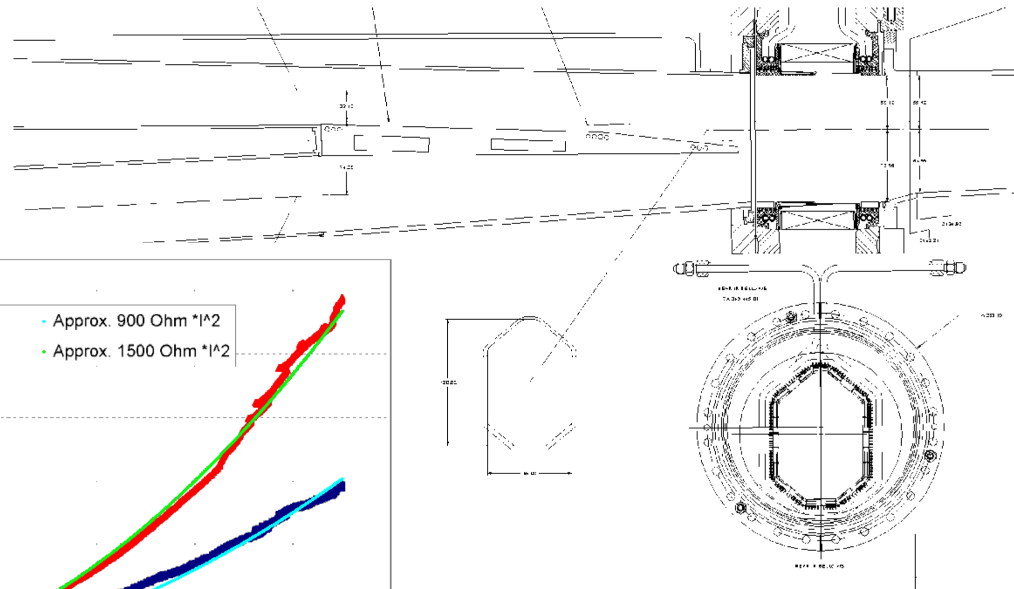
N	by 2	by 3	by 4
8	**1.90400**	1.2693333	0.952
9	2.14200	1.428	1.071
10	2.38000	1.5866667	1.19
11	**2.61800**	1.7453333	1.309
13	3.09400	2.0626667	1.547
14	**3.33200**	2.2213333	1.666
15	3.57000	2.38	1.785
16	3.80800	2.5386667	**1.904**
17	4.04600	2.6973333	2.023
18	4.28400	2.856	2.142
19	4.52200	3.0146667	2.261
20	4.76000	3.1733333	2.38
21	4.99800	3.332	2.499
22	5.23600	3.4906667	2.618
23	5.47400	3.6493333	2.737
24	5.71200	3.808	2.856
25	5.95000	3.9666667	2.975
26	6.18800	4.1253333	3.094
27	6.42600	4.284	3.213
28	6.66400	4.4426667	3.332
28	6.66400	4.4426667	3.332
29	6.90200	4.6013333	3.451
30	7.14000	4.76	3.57

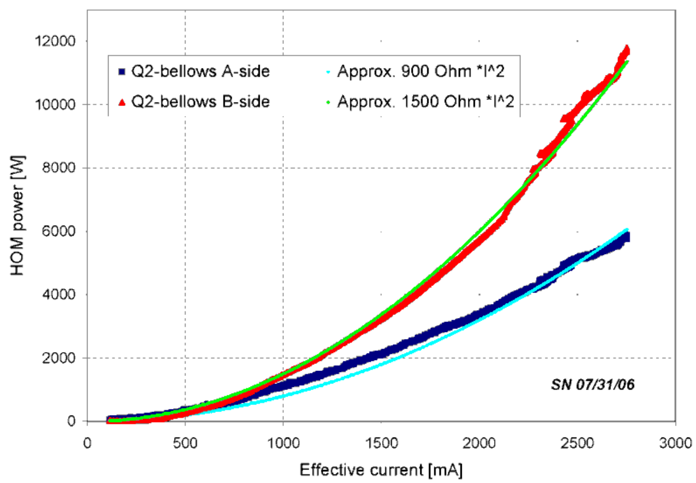
How instability happens

* The beam excites one or several trapped modes at the place near the RF seal. At some LER current electric field 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 is so high, that cavity RF fields get large modulation in amplitude and phase, which destroy the beam stability conditions.
* We solved the problem by properly installing of a new gap ring. After that we no longer saw this kind of instability.

Q2-problem

The HOM absorbing tiles located in the Q2-bellows had always been considered suspect. Q2-bellows is situated at a distance of 2.2 m from IP. The ceramic tiles absorb HOM power of over 10 kW. We considered that the tiles got very hot and perhaps outgassed because of breakdowns due to the high electric fields initiated by the high LER and HER currents.





In addition to the geometrical wake (because of the very complicated geometry of the interaction region) the Q2-bellows also produces Cherenkov radiation. The reason for this is the high permittivity of the tiles. The ceramic tiles are open to the beam, so they capture and store some part of the beam field and then these fields are radiated.

Open to the beam absorber ceramic tiles produce more HOMs
Cherenkov radiation

* Loss factor

A.Burov and A.Novokhatski
Wake Potential of a dielectric canal,
in Proceedings of HEACC'92,
p.537, Hamburg, Germany, 1992.

$$when \quad \sigma > s = \frac{a\sqrt{\varepsilon - 1}}{2\varepsilon} \approx \frac{a}{2\sqrt{\varepsilon}}$$

$$k = \frac{Z_0 L}{2\pi a^2} \times \frac{s}{\sqrt{\pi}\sigma} = \frac{Z_0 L}{4\pi a} \times \frac{1}{\sqrt{\pi\varepsilon}\sigma}$$

- For Q2-bellows parameters

$$L = 4 \times 28mm \qquad k = 0.13 \div 0.16 \quad V/pC$$

$$a = 60mm$$

$$\sigma = 13mm$$

$$\varepsilon = 30 \div 21 \quad (1 - 10GHz)$$

Additional 150% power loss!!!

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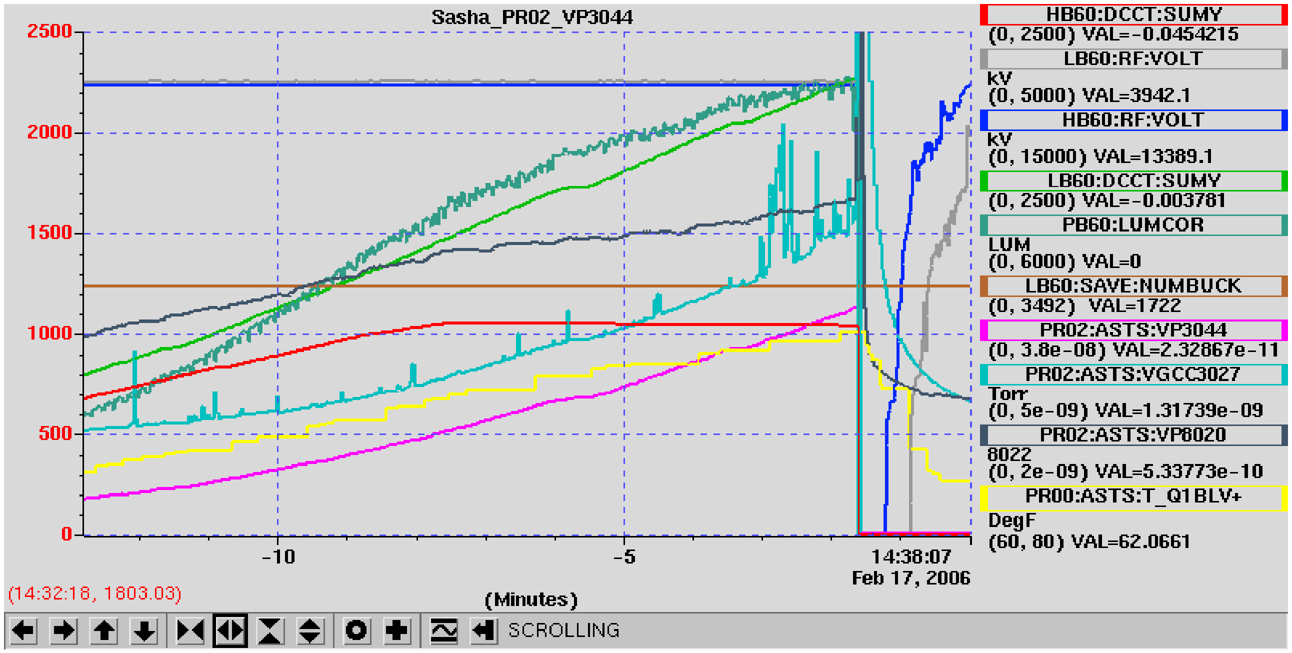
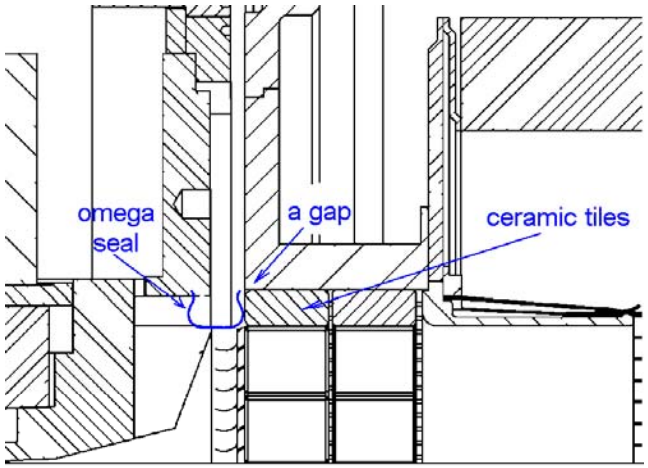
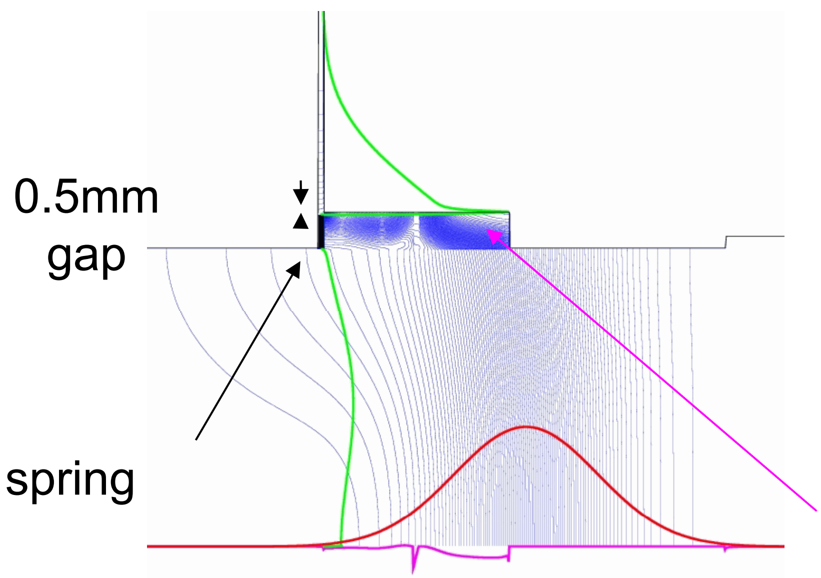
Aborts and vacuum spikes in interaction region



In 2005 PEP-II achieved a peak luminosity of 10^34 cm-2 sec-1 with beam currents of 2.94 A in LER and 1.74 A in HER. After shutting down for a month, we discovered we were unable to sustain LER currents much above 2 A without an abort occurring due to high radiation levels in the detector. The problem was the occurrence of very fast, very high pressure spikes in the vacuum chamber just upstream of the detector. The radiation levels in the detector caused by these gas events were too high and the beam had to be aborted. This problem has quickly became chronic. A wide variety of experiments were conducted to isolate the source of the problem or eliminate possible causes.

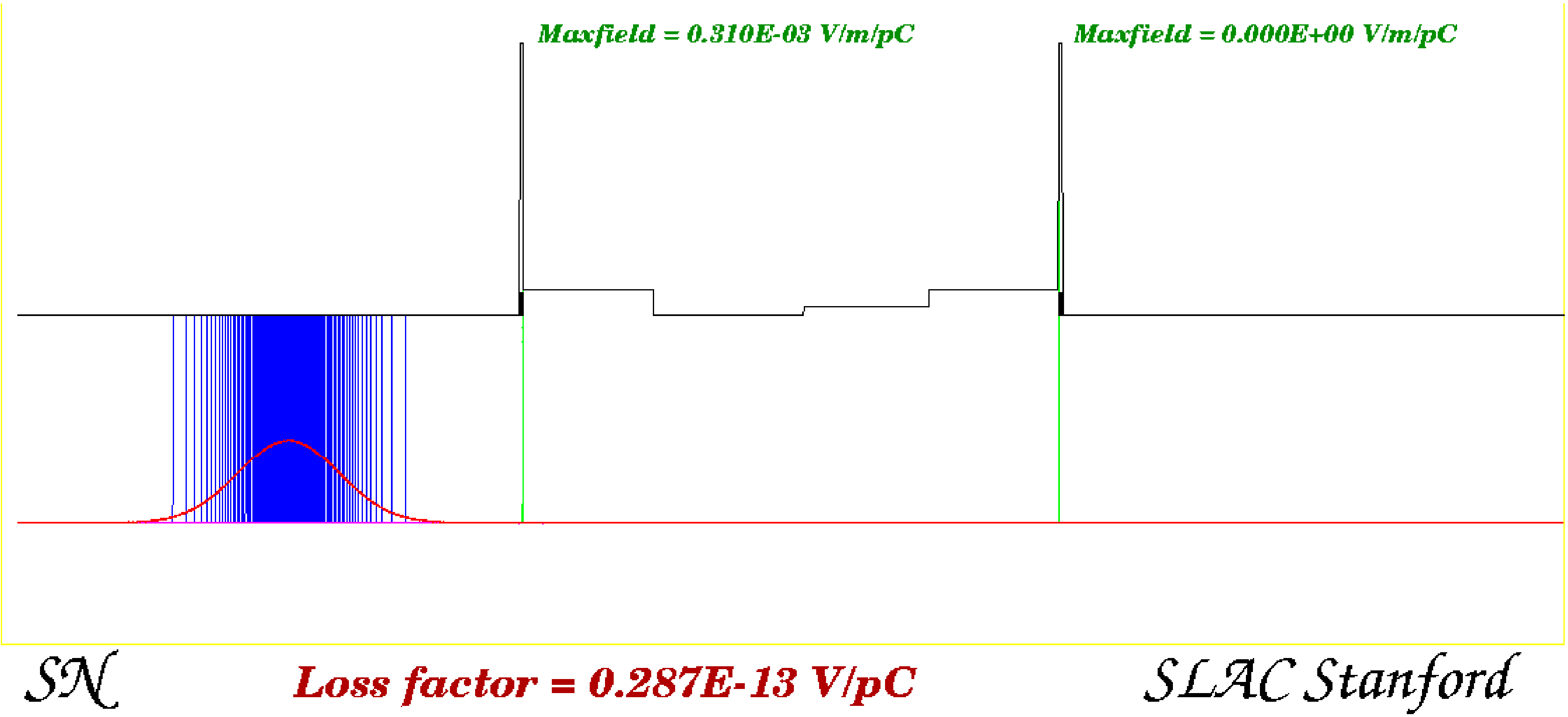
Geometry and simulation model



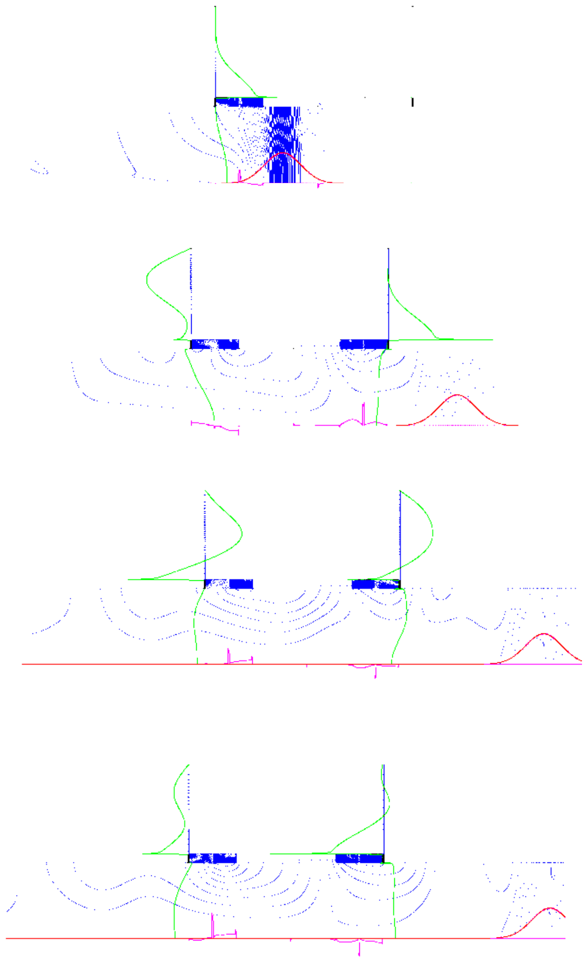


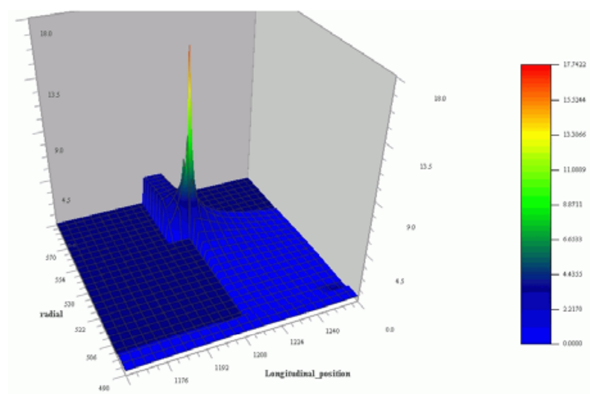
After we have checked the bellows drawings it became clear that the omega seal that is next to the tiles had been designed incorrectly. The metal seals were touching the tiles (which are insulators) instead of touching the metal surface under the tiles. Any sharp edge of a seal, which is very close to a ceramic tile may strengthen the electric field many times causing sparking or breakdowns. Then very fast high pressure spikes can be easily explained by these stochastic breakdowns.

Electromagnetic fields in ceramic tiles

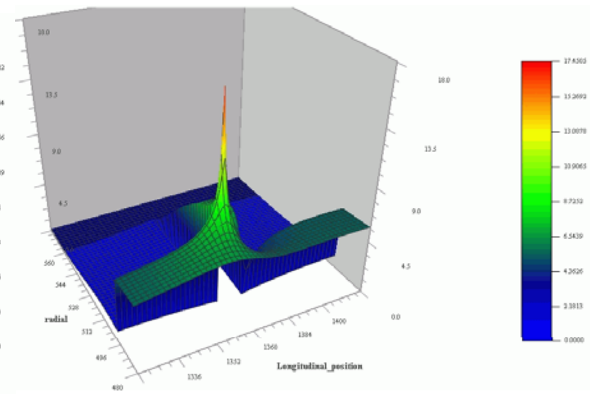


Snapshots of the electric displacement force lines at different times. Maximum electric fields

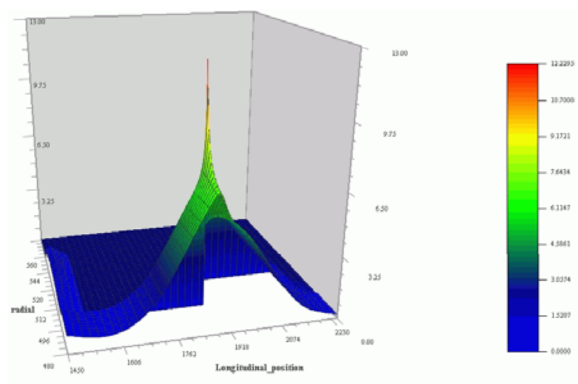




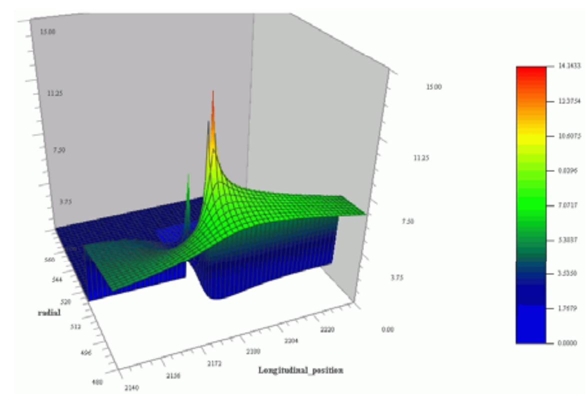
Left spring corner



First tiles gap



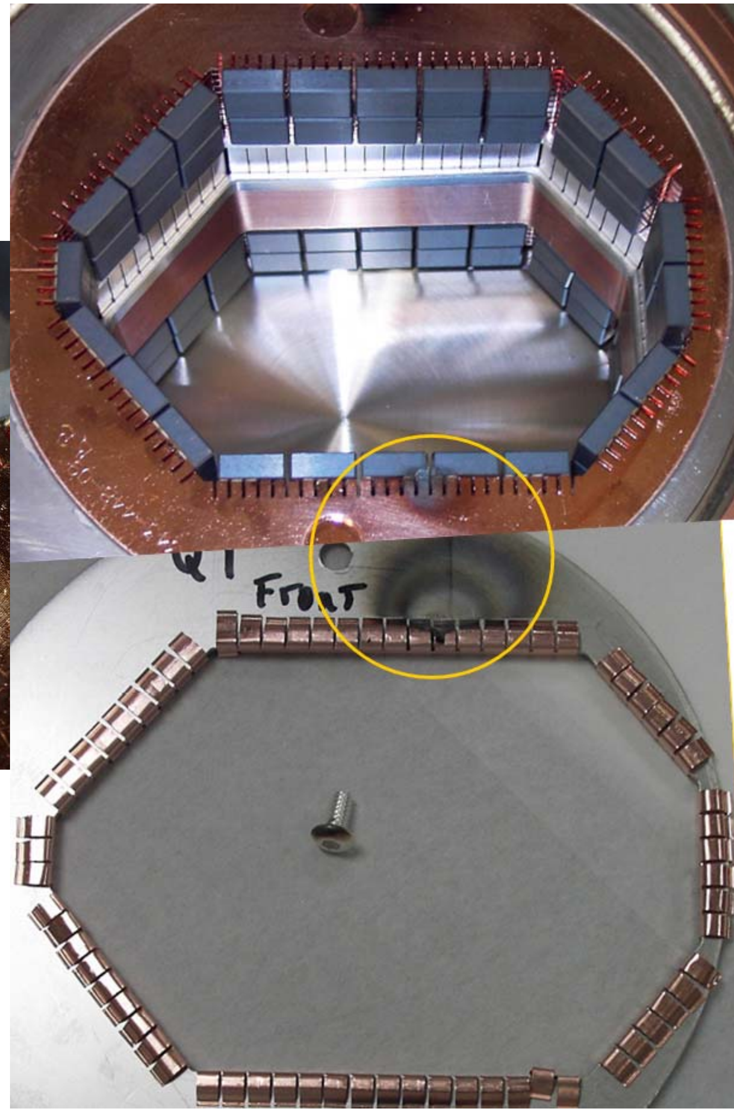
Metal corner



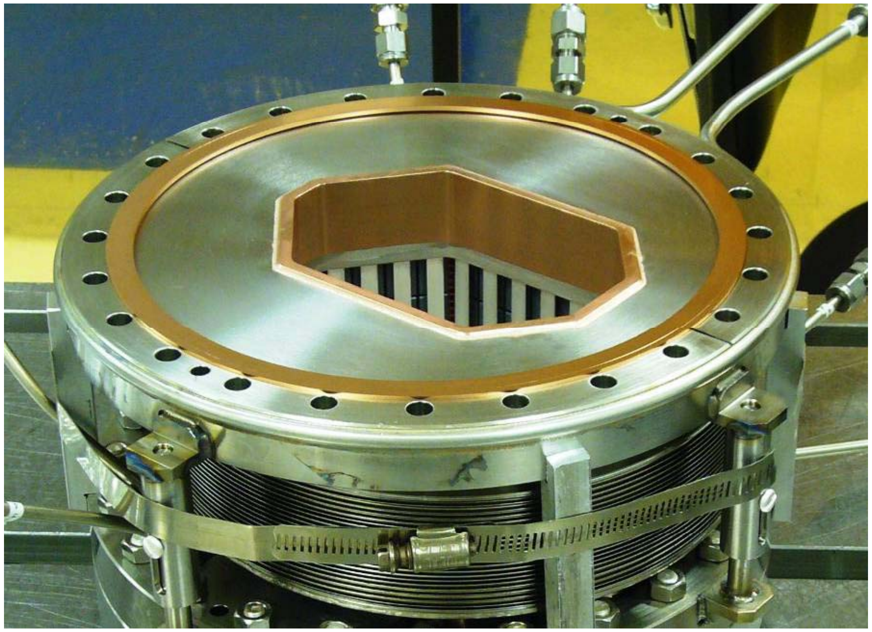
Tile corner

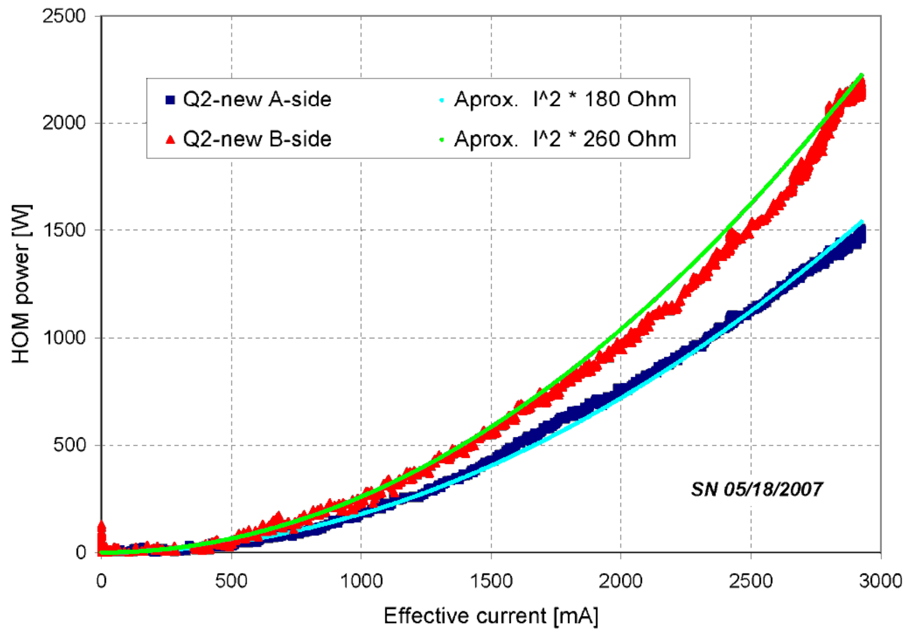
MODELING OF THE SPARKS IN Q2-BELLOWS OF THE PEP-II SLAC BFACTORY A. Novokhatski#, J. Seeman and M. Sullivan, PAC'2007

What we found when we open the beam chamber



A new Q2-bellows





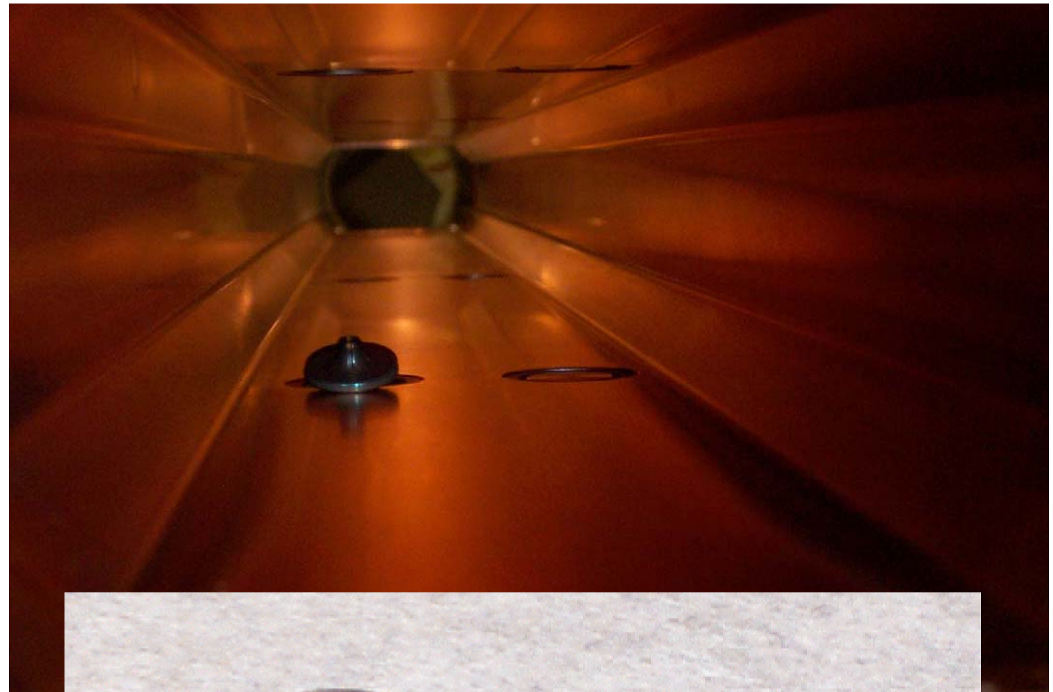
It is very important to note that we did not observe any dramatic temperature change in the vertex bellows, which are situated between the Q2-bellows. This means that Q2-bellows absorb transverse fields well, not allowing them to propagate inside the IR.

A NEW Q2-BELLOWS ABSORBER FOR THE PEP-II SLAC B-FACTORY
A. Novokhatski#, S.DeBarger, S. Eckland, N.Kurita, J.Seeman, M.Sullivan, S.Weathersby, U.Wienands, PAC'07

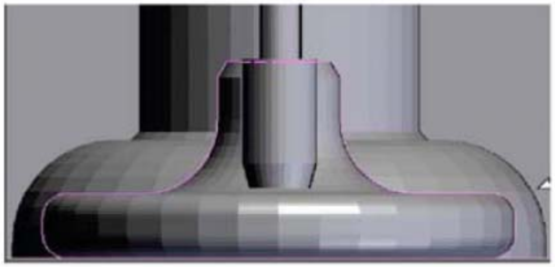
BPMs

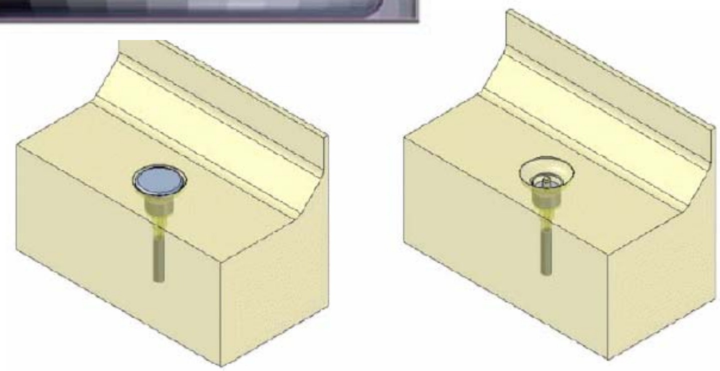
* The last PEP-II run concluded with an energy scan encompassing several of the energy states in which the HER energy was varied from 8 to 10 GeV. The energy scan was implemented entirely through varying HER magnet strengths.
* While transitioning to a lower energy at the 2S resonance (HER energy 8 GeV) from a higher energy 3S resonance (HER energy 8.6 GeV), a vacuum breach occurred caused by an overheated beam position monitoring (BPM) electrode at 1500 mA of beam current.
* The origin of the heating is determined to be higher order modes (HOMs) caused by a shortened bunch. The bunch length change is a consequence of the energy change with constant RF gap voltage and frequency. Subsequently, the RF gap voltage was reduced by 15% from 16.5 to 14 MV in order to lengthen the bunch and prevent excessive HOM heating, allowing 2S runs to continue at nominal currents. The HER energy and gap voltage were later restored to (4S) running with energy scans up to 10 GeV at the (5S) resonance.

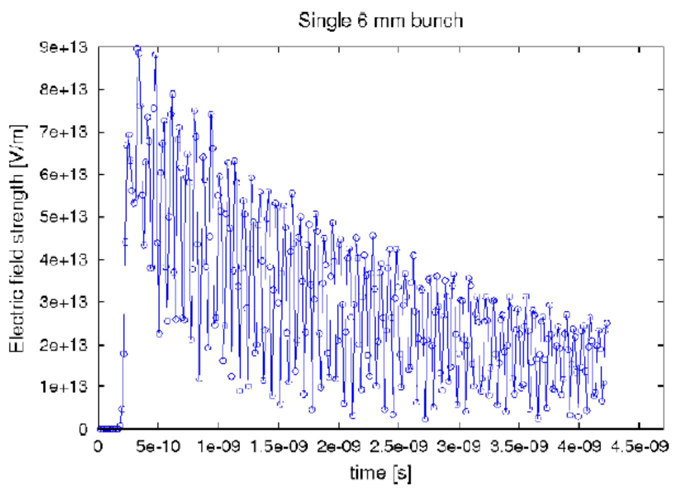
Everybody knows about "falling" BPMs



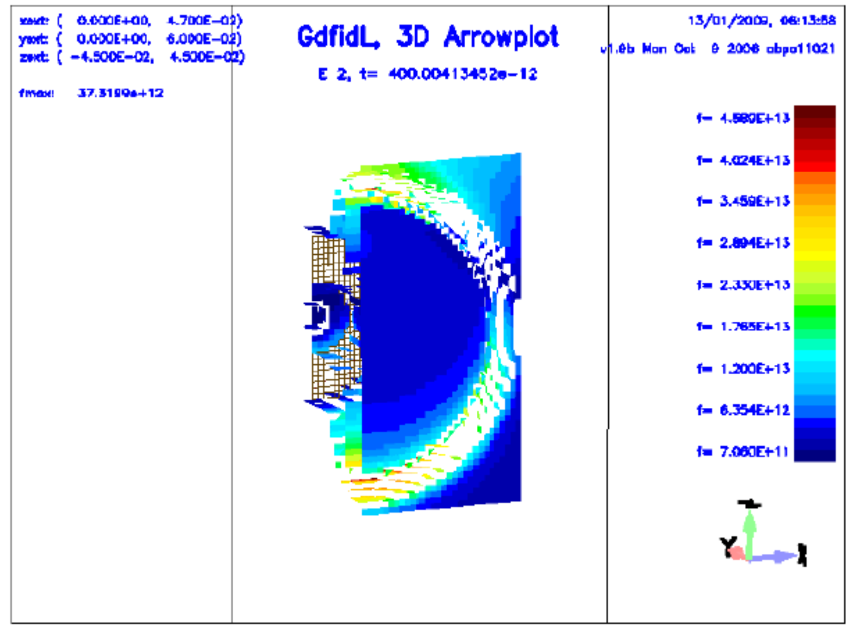
Simulations







Maximum electric field strength at the BPM as a function of time for one 6 mm Gaussian 1 C bunch. The 14 GHz oscillation correlates with a 7 GHz half cycle of electric field maximum at two ends of the button.



Electric field strength at the button as a function of time just after the arrival of one 9 mm 1 C bunch as computed with Gdfidl. Maximum field strength is 4.59×*1013* V/m near the gap between the button and vacuum chamber interior to the button housing.

BPM BREAKDOWN POTENTIAL IN THE PEP-II B-FACTORY STORAGE RING COLLIDERS. Weathersby, Al. Novokhatski, ICAP '2009

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Recommendations

- Electron and positron bunches generate electromagnetic fields at any discontinuity of the vacuum chamber
- These fields can travel long distance and penetrate inside bellows, pumps and vacuum valves.
- Vacuum chamber must be very smooth.
- HOM absorbers must be installed in every region that has unavoidable discontinuity of the vacuum chamber
- Maximum attention to the RF seal designs
- Better design of a BPM button
- No open (to the beam) ceramic or ferrite tiles