First estimates of impedance issues for the FCC-e^-e^+ IR

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FCC-ee MDI meeting #3
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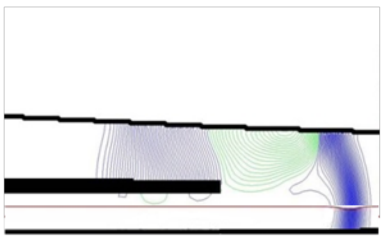
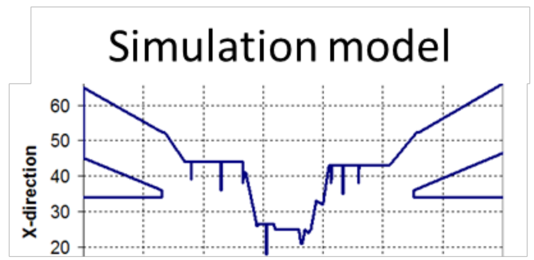
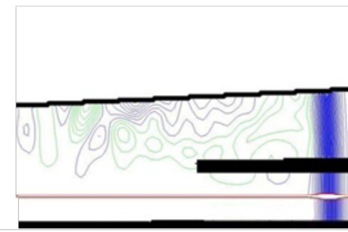
SLAC NATIONAL ACCELERATOR LABORATORY

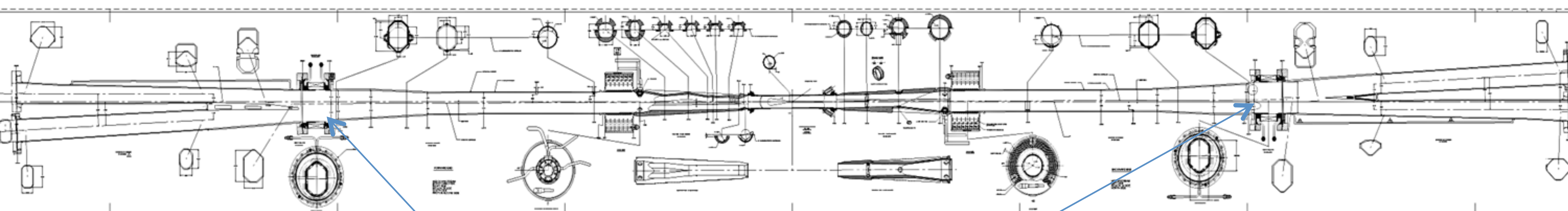
As an Introduction

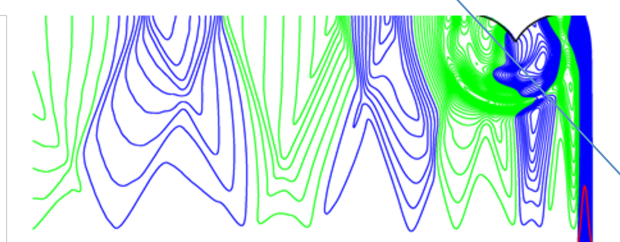
- Wake field and HOMs calculations and measurement for the PEP-II rings including interaction region.
  - *A. Novokhatski, J. Seeman, M. Sullivan*, "Analysis of the wake field effects in the PEP-II storage rings with extremely high currents", *NIM A 735 (2014)*



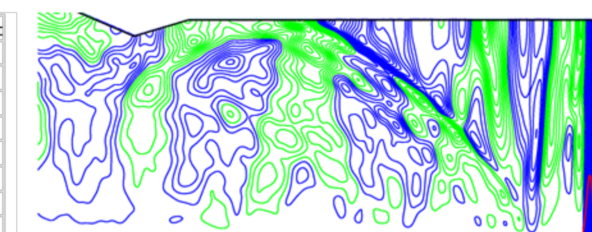








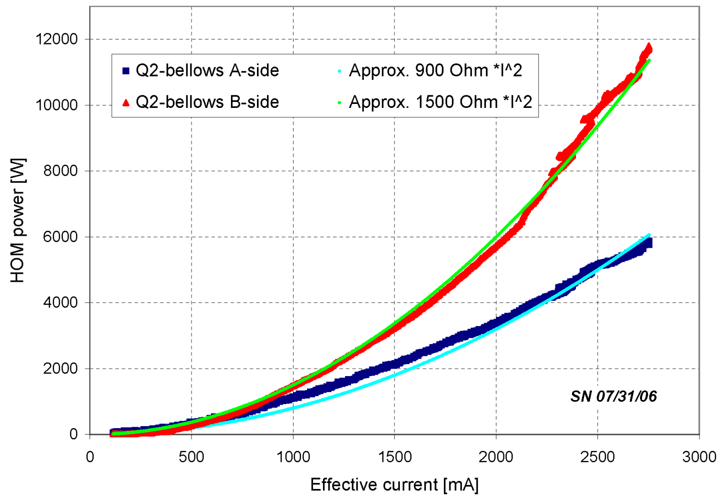
Parameters	PEP-II	PEP-II more c
Bunch length [mm] =	11.3	11.3
Loss factor [V/pC]=	0.327	0.327
LER current [A]	2.6	3
HER current [A]	1.7	1.9
Bunch spacing [nsec]	4.2	4.2
Power loss (pulse) [kW]	13.26	17.33

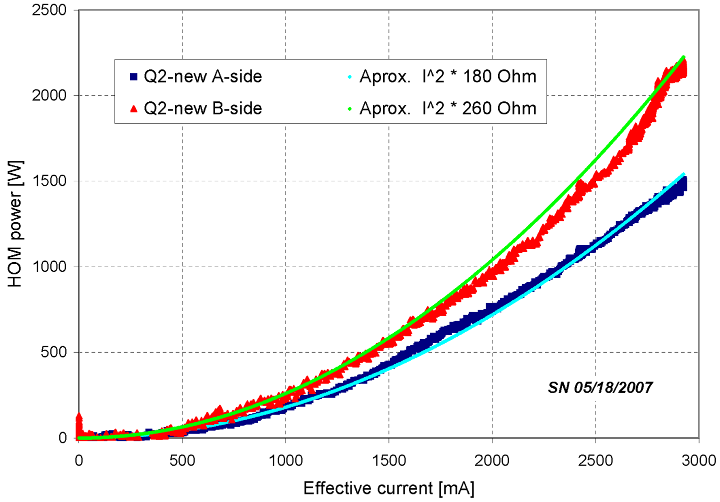


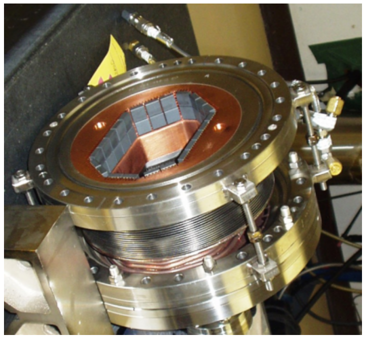
1/3 of the power is due to the the absorbing ceramic tiles being open to the beam (Cherenkov radiation)

HOMs absorbers in IR

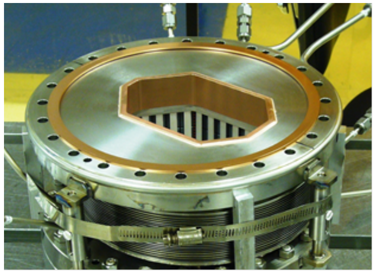
A. Novokhatski, S. DeBarger, S. Ecklund, N. Kurita, J. Seeman, M. Sullivan, S. Weathersby, U. Wienands, , “ A NEW Q2-BELLOWS ABSORBER FOR THE PEP-II SLAC B-FACTOR” *, Proc. of PAC’07 (2007)*





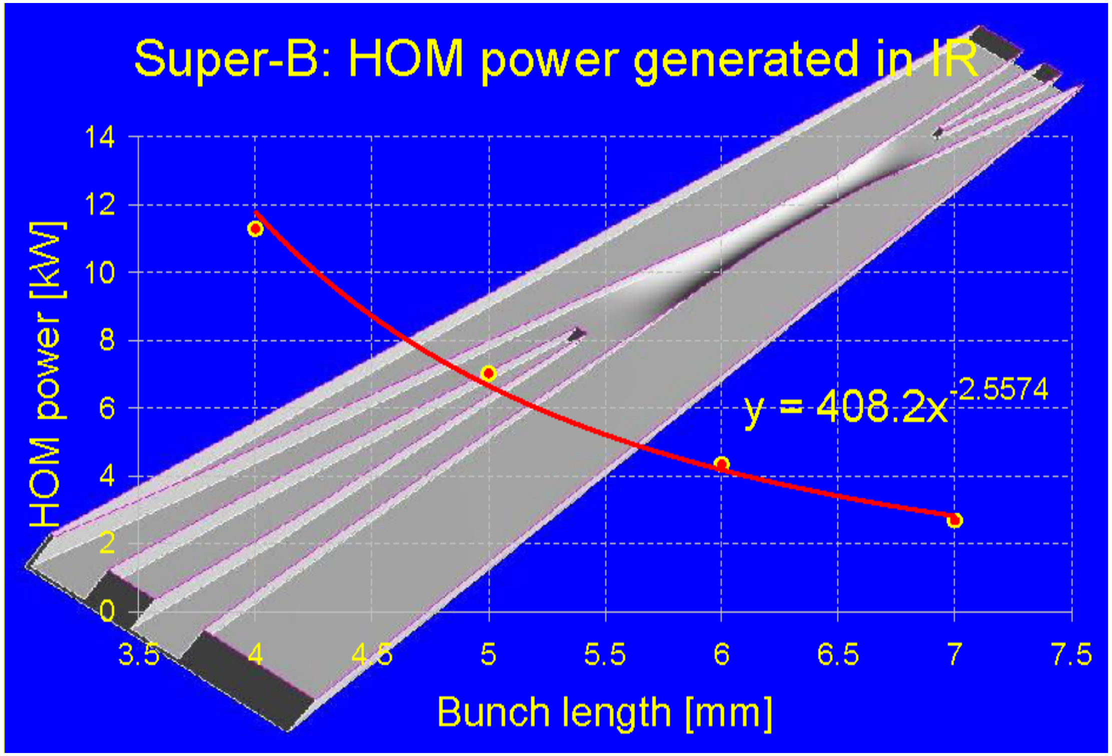


Open to the beam ceramic tiles were shielded



The 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)*



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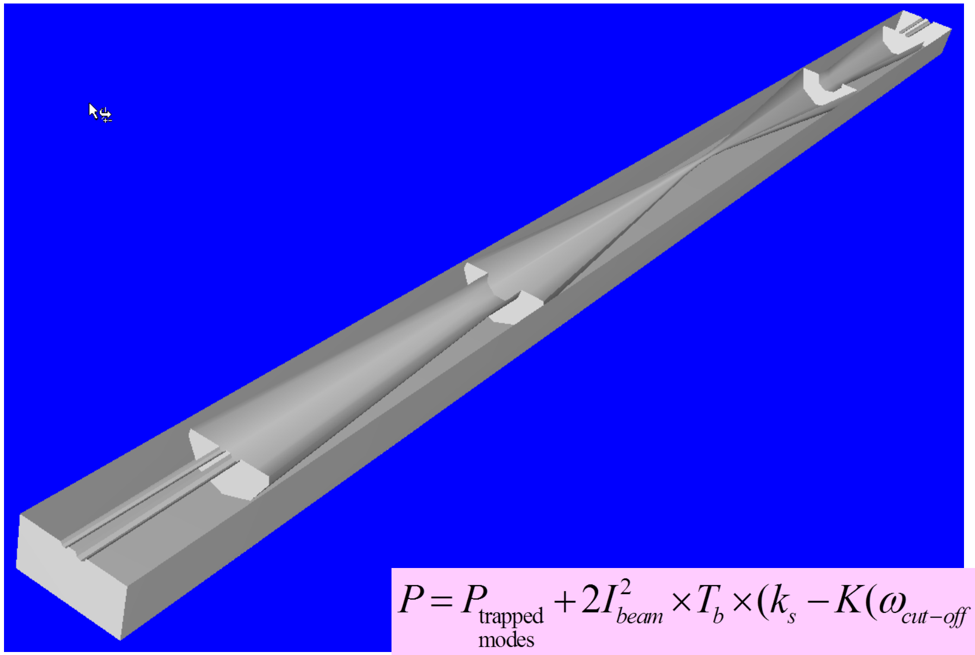
ILC Interaction Region

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



Bunch charge = 3.2 nC

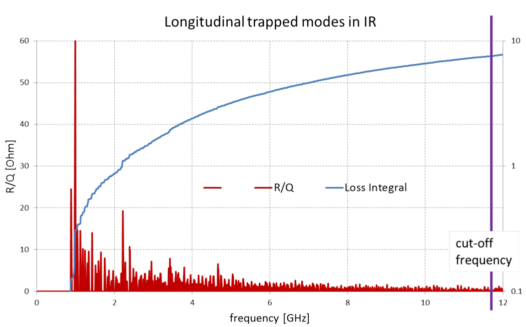
Bunch length = 0.2-0.3 mm

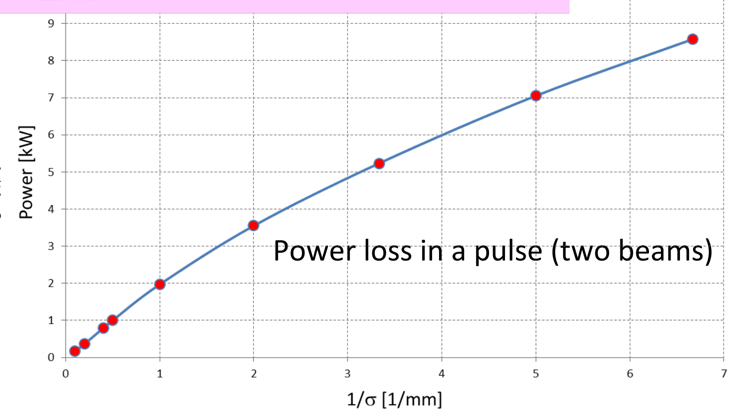
Bunch spacing = 369.2 ns

Beam current in a pulse 9 mA

Duty ratio=200

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





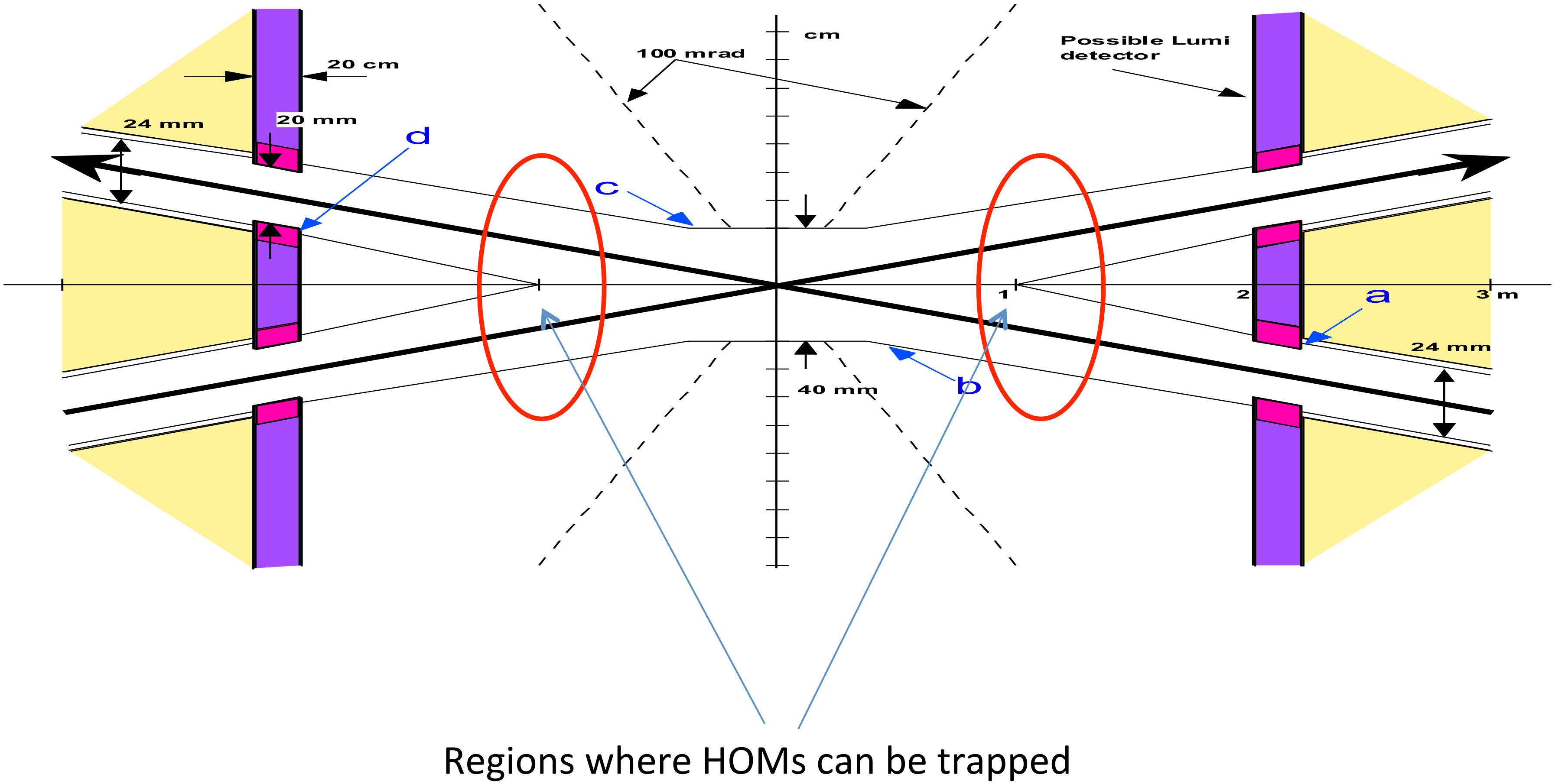
Power loss due to resistive wall.
Not so much.

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		

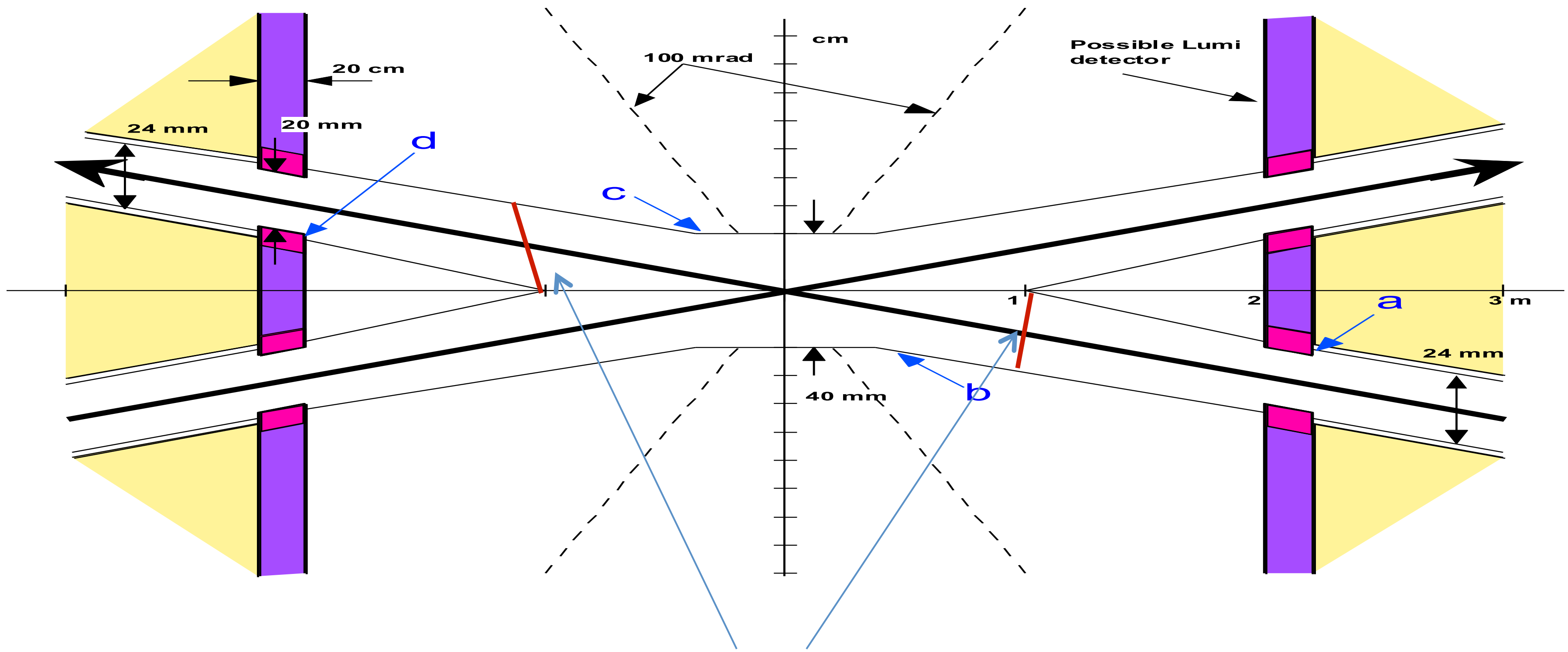
FCC-ee baseline parameters

	Z	Z	W	H	tt
Circumference [km]	100				
Bending radius [km]	11				
Beam energy [GeV]	45.6		80	120	175
Beam current [mA]	1450		152	30	6.6
Bunches / beam	30180	91500	5260	780	81
Bunch spacing [ns]	7.5	2.5	50	400	4000
Bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7
Horizontal emittance ε [nm] Vertical emittance ε [pm]	0.2 1	0.09 1	0.26 1	0.61 1.2	1.3 2.5
Momentum comp. [10^{-5}]	0.7	0.7	0.7	0.7	0.7
Betatron function at IP β^* - Horizontal [m] - Vertical [mm]	0.5 1	1 2	1 2	1 2	1 2
Horizontal beam size at IP σ^* [μm] Vertical beam size at IP σ^* [pm]	10 32	9.5 45	16 45	25 49	36 70
Crossing angle at IP [mrad]	30				
Energy spread [%] - Synchrotron radiation - Total (including BS)	0.04 0.22	0.04 0.09	0.07 0.10	0.10 0.12	0.14 0.17
Bunch length [mm] - Synchrotron radiation - Total	0.9 6.7	1.6 3.8	2.0 3.1	2.0 2.4	2.1 2.5
Energy loss / turn [GeV]	0.03		0.33	1.67	7.55
SR power / beam [MW]	50				
Total RF voltage [GV]	0.4	0.2	0.8	3	10
RF frequency [MHz]	400				
Longitudinal damping time τ_E [turns]	1320		243	72	23
Energy acceptance RF [%]	7.2	4.7	5.5	7.0	6.7
Synchrotron tune Q_s	0.036	0.025	0.037	0.056	0.075
Polarization time τ_p [min]	11200		672	89	13
Interaction region length L_i [mm]	0.66	0.62	1.02	1.35	1.74
Hourglass factor $H(L_i)$	0.92	0.98	0.95	0.92	0.88
Luminosity/IP for 2IPs [10^{34} cm^{-2}s^{-1}]	207	89.4	19.1	5.1	1.3
Beam-beam parameter - Horizontal - Vertical	0.025 0.16	0.05 0.13	0.07 0.16	0.08 0.14	0.08 0.12
Luminosity lifetime [min]	94	185	90	67	57
Beamstrahlung critical	No/Yes	No	No	No	Yes

FCC ee IR. Thanks to Mike.



Simplified model of IR



Additional boundaries

Cut-off frequency

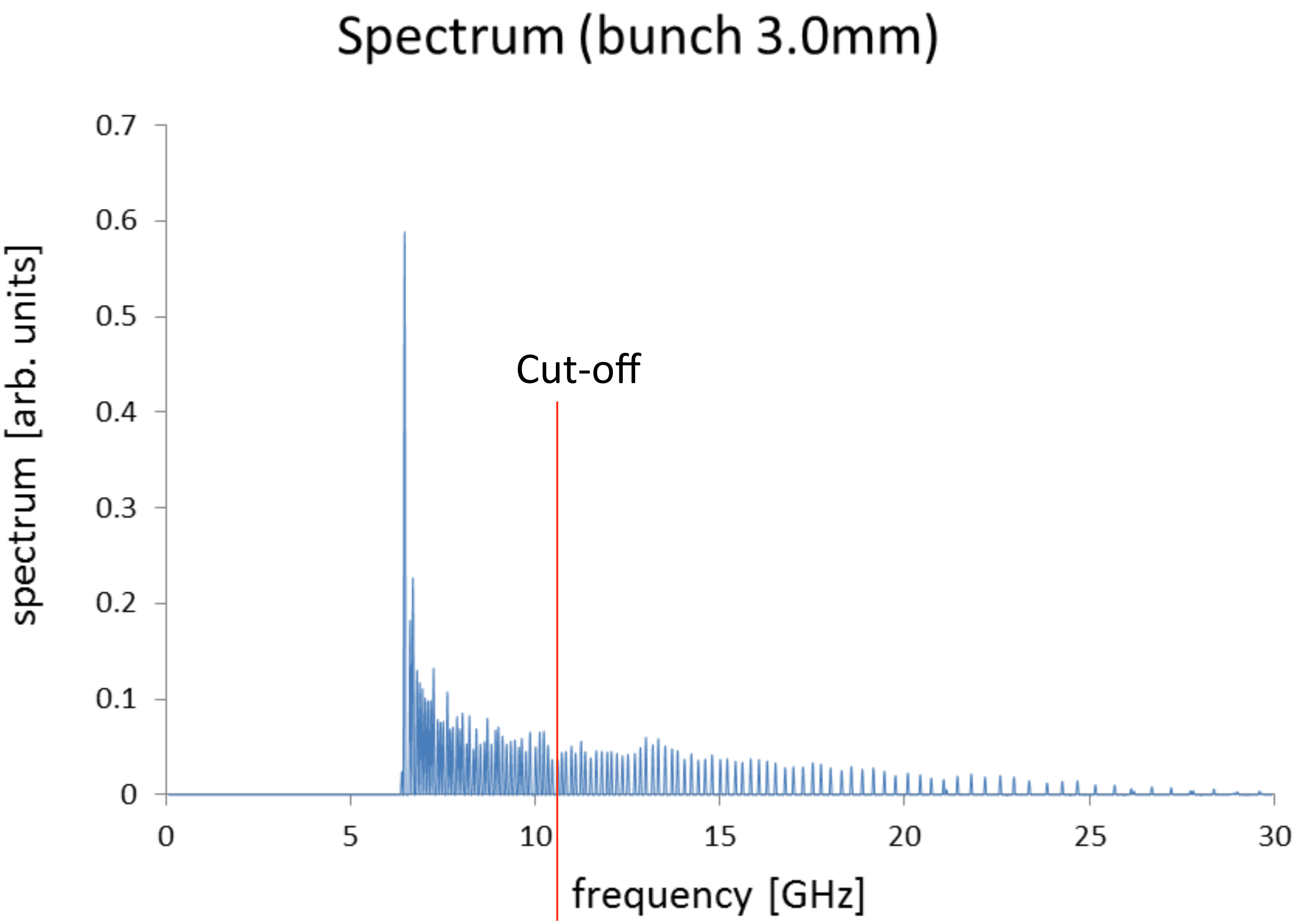
- Cut-off frequency is the maximum frequency of captured modes in a cavity.
- It is determined by the size of the beam pipe.
- For E01 mode

$$f_{[GHz]}^{cut-off} = \frac{c}{a} \times \frac{\nu_{01}}{2\pi} = \frac{0.11474}{a_{[m]}}$$

a=10mm=0.01m

f=11.47 GHz

Spectrum


Spectrum (bunch 3.0mm)
spectrum [arb. units]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cut-off
0
5
10
15
20
25
30
frequency [GHz]

Beam spectrum

Bunch spacing

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

Main spectrum lines

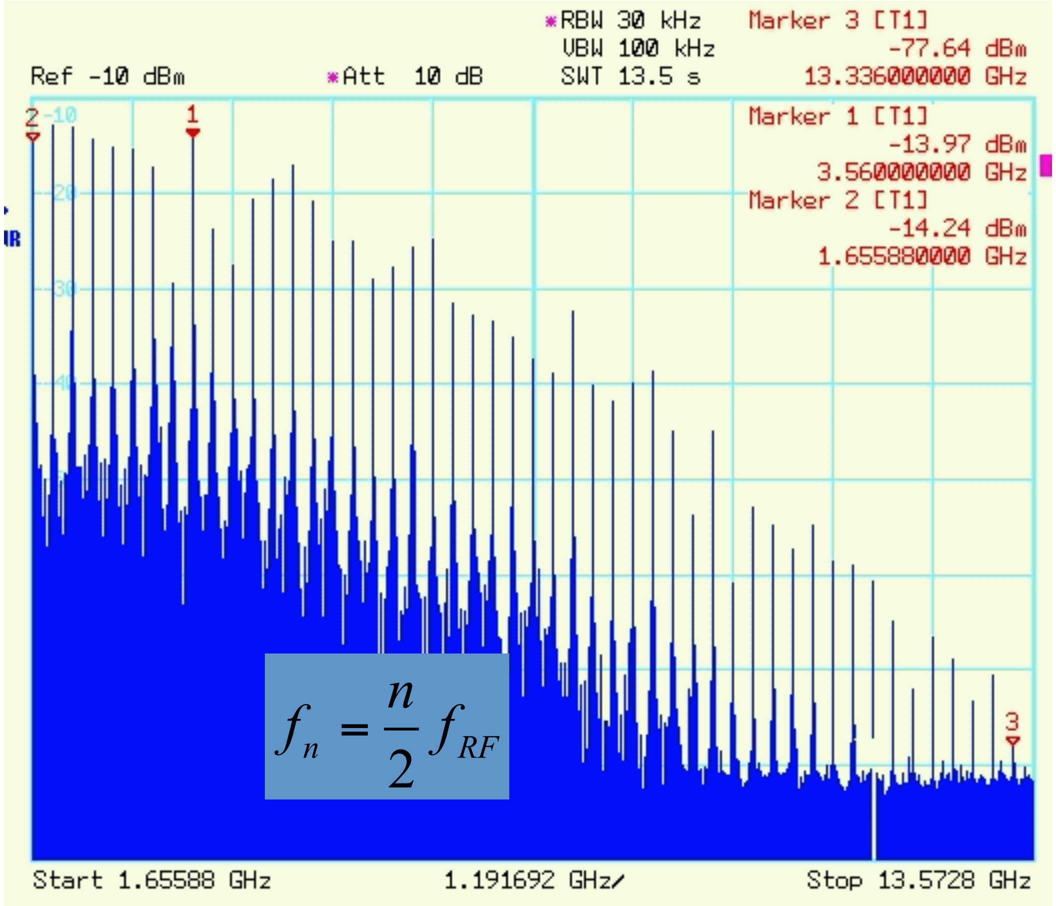
$$f_n = \frac{n}{\tau_b} = \frac{n}{m} f_{RF} \qquad n = 1, 2, 3, \ldots$$

FCC: $m = 1 \qquad f_{RF} = 400\text{MHz}$

$f_n = 400 \times n \quad [MHz]$

approx 10 modes

Spectrum for two beams is different



Beam spectrum goes to higher frequency with shorter bunches exponentially

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

Spectrum of the PEP-II BPM signal
12 mm bunch

Coherent and incoherent excitation of trapped modes

Bunch spacing

τ_b

Mode decay time (loaded) or filling time

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

FCC:

$$\tau_{l,n} = \frac{Q_l}{\pi f_n} = \frac{1000}{3.14 * 6_{GHz}} = 60\ ns$$

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

Incoherent

$$\tau_{l,n} << \tau_b$$

Coherent at the resonance

$$\tau_{l,n} >> \tau_b$$

Loss power

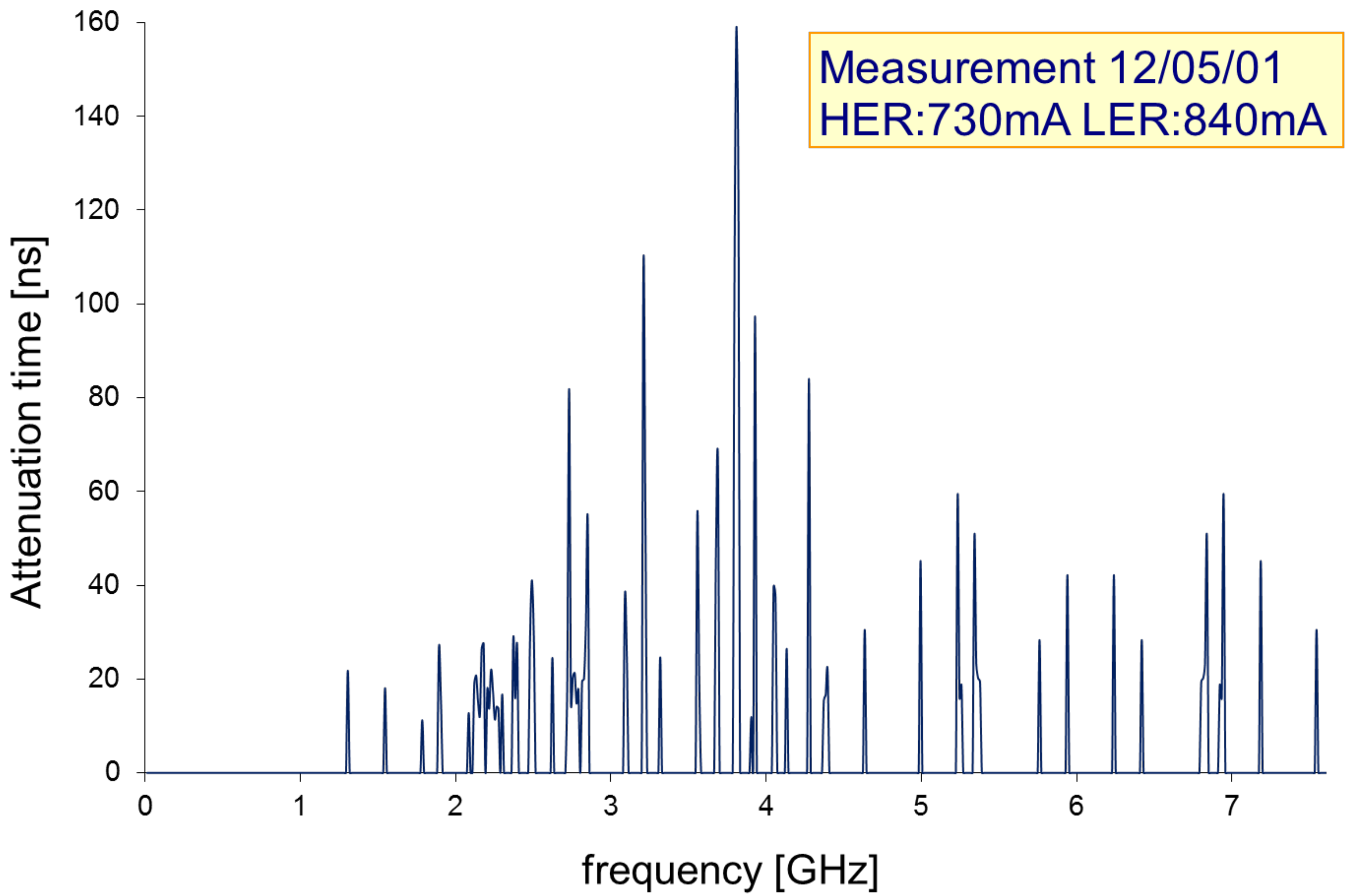
$$P_{in} = I^2 \sum k_n \tau_b \qquad P_{coh} = 2I^2 \sum k_n \tau_{l,n}$$

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

FCC:

$$P_{incoh} = 0.3 \quad kW \qquad P_{coh} = 12 \quad kW$$

Attenuation time of the Higher Order Modes measured in the PEP-II IR using the ion gap



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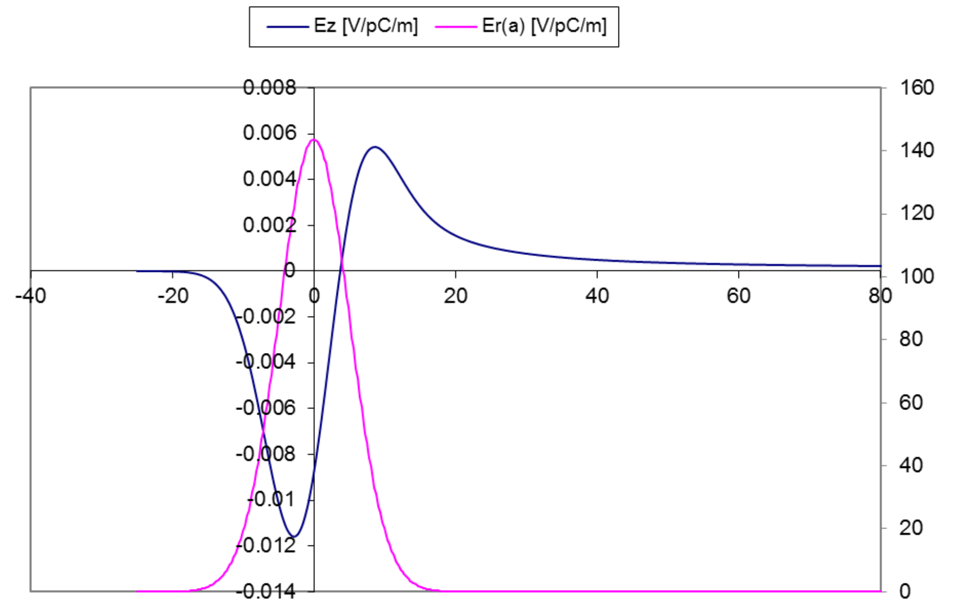
Resistive-wall wake fields

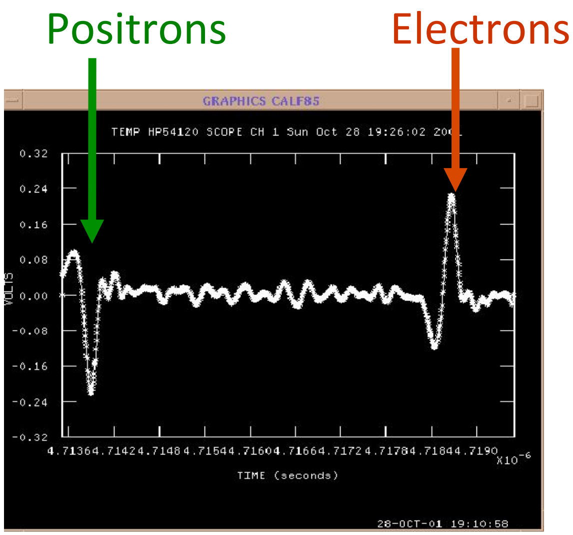
(Losses of image currents)

conductivity	/Ohm/mm
Al	35000
Cu	58000
SS	1400
Au	48800
Ag	62900
Be	25000
Ni	14600
NEG	55-1000



IR power loss (two beams)

Excitation of a cavity by electron and positron currents depends upon the difference in the arrival time and frequency of the cavity.
The power may vary from 0 to 4.
In average we assume to be 2.



B-side BPM

$$P = 2 \times \left(P_{\substack{\text{trapped} \\ \text{modes}}} + P_{RW} + P_{propag} \right) = (2.4 - 25.8) \quad kW$$

A good HOMs absorber in IP will solve the problem with resonant modes.

Summary

- The amount of beam energy loss in IR may reach 26 kW in the worst case. This is a first estimate.
- To make a more precise estimate it is necessary to make a mechanical model of the IR in the form of a CAD (STL) file.
- Then we can use this file for Eigen mode calculations with available codes.
- After we understand the structure of the trapped modes we can design HOMs absorbers.