HOM heating at the IP and in QD0

Update to IRENG'07

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2011 Linear Collider Workshop of the Americas
(ALCPG11)

Eugene, Oregon , March 21, 2011

Outline

- ILC beam parameters
- ILC interaction region geometry
- Beam fields
- Wake potentials and loss power
- Trapped and propagating modes
- Frequency spectrum
- Resistive wake fields
- Total power loss

ILC beam parameters

TABLE 2.1-2
Beam and IP Parameters for 500 GeV cms.

Parameter	Symbol/Units	Nominal	Low N	Large Y	Low P
Repetition rate	f_{rep} (Hz)	5	5	5	5
Number of particles per bunch	N (10^{10})	2	1	2	2
Number of bunches per pulse	n_b	2625	5120	2625	1320
Bunch interval in the Main Linac	t_b (ns)	369.2	189.2	369.2	480.0
in units of RF buckets		480	246	480	624
Average beam current in pulse	I_{ave} (mA)	9.0	9.0	9.0	6.8
Normalized emittance at IP	$\gamma\epsilon_x^*$ (mm·mrad)	10	10	10	10
Normalized emittance at IP	$\gamma\epsilon_y^*$ (mm·mrad)	0.04	0.03	0.08	0.036
Beta function at IP	β_x^* (mm)	20	11	11	11
Beta function at IP	β_y^* (mm)	0.4	0.2	0.6	0.2
R.m.s. beam size at IP	σ_x^* (nm)	639	474	474	474
R.m.s. beam size at IP	σ_y^* (nm)	5.7	3.5	9.9	3.8
R.m.s. bunch length	σ_z (μm)	300	200	500	200
Disruption parameter	D_x	0.17	0.11	0.52	0.21
Disruption parameter	D_y	19.4	14.6	24.9	26.1
Beamstrahlung parameter	Υ_{ave}	0.048	0.050	0.038	0.097
Energy loss by beamstrahlung	δ_{BS}	0.024	0.017	0.027	0.055
Number of beamstrahlung photons	n_γ	1.32	0.91	1.77	1.72
Luminosity enhancement factor	H_D	1.71	1.48	2.18	1.64
Geometric luminosity	$\mathcal{L}_{geo}$ 10^{34}/cm^2/s	1.20	1.35	0.94	1.21
Luminosity	$\mathcal{L}$ 10^{34}/cm^2/s	2	2	2	2

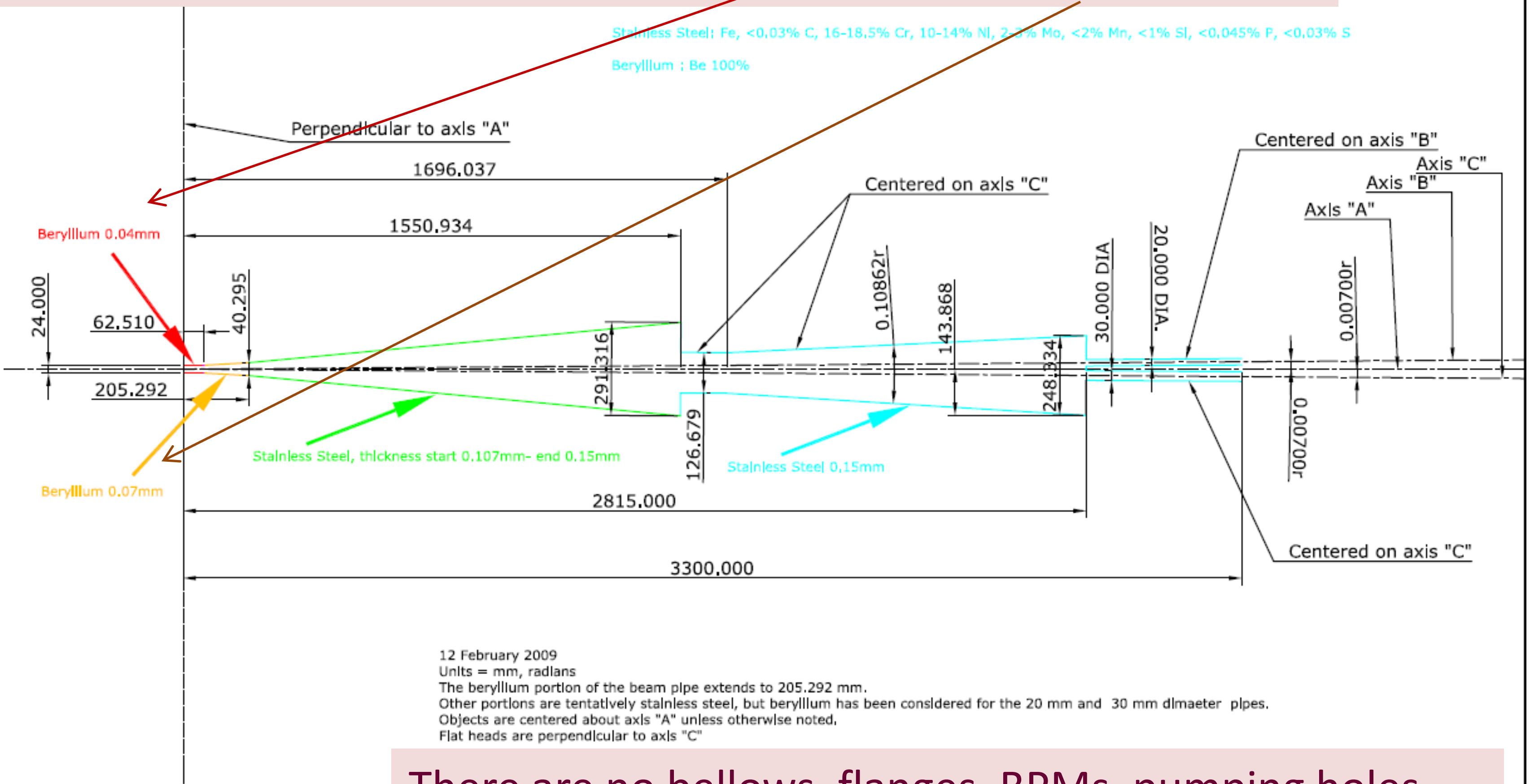
INTERNATIONAL LINEAR COLLIDER
REFERENCE DESIGN REPORT
AUGUST, 2007

- 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

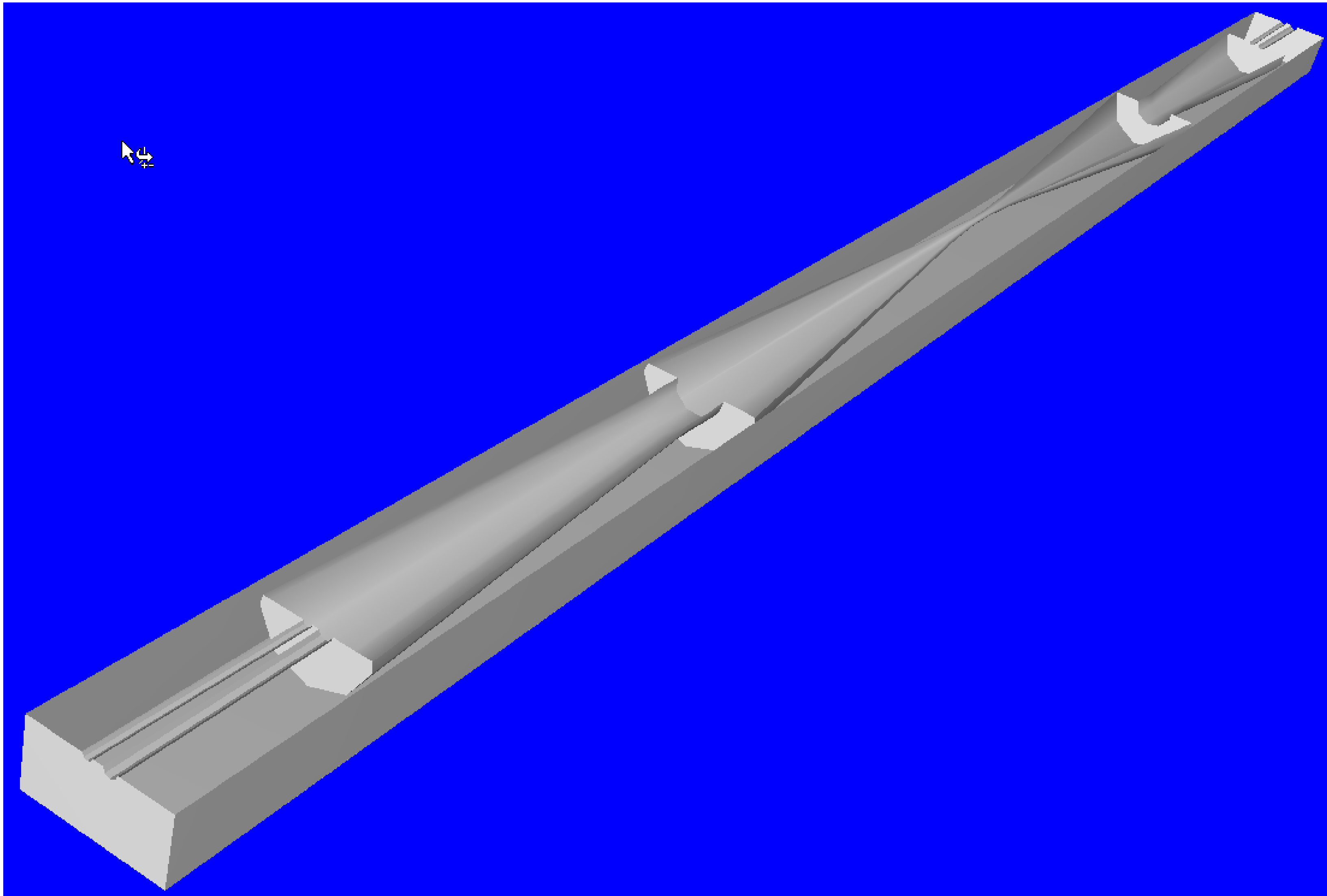
ILC IR geometry from Marco Oriunno

Comments from Takhashi Maruyama:
The thickness of the cylindrical beam pipe is 400 microns,
and of the conical section is 700 microns.

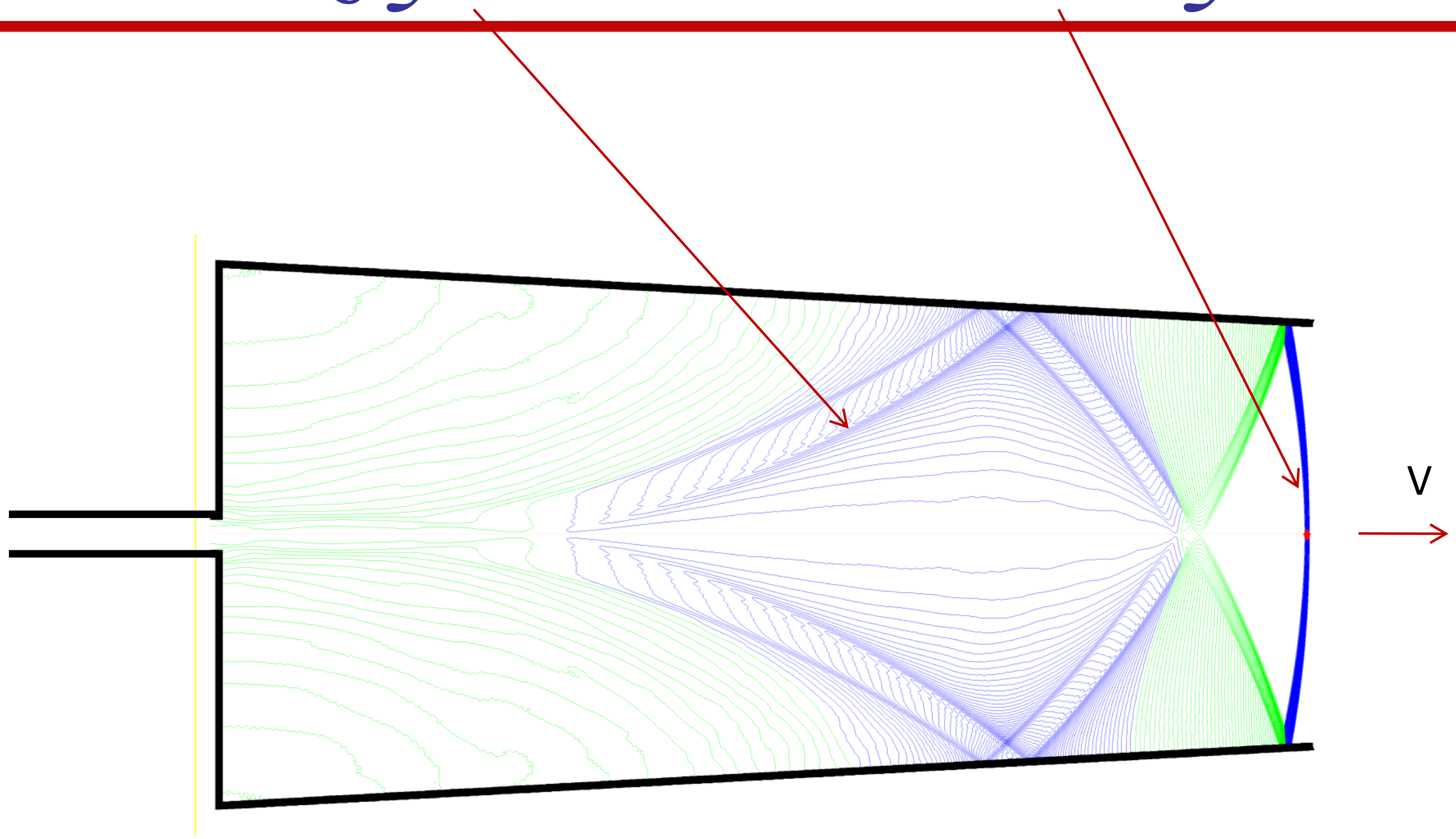


There are no bellows, flanges, BPMs, pumping holes, …

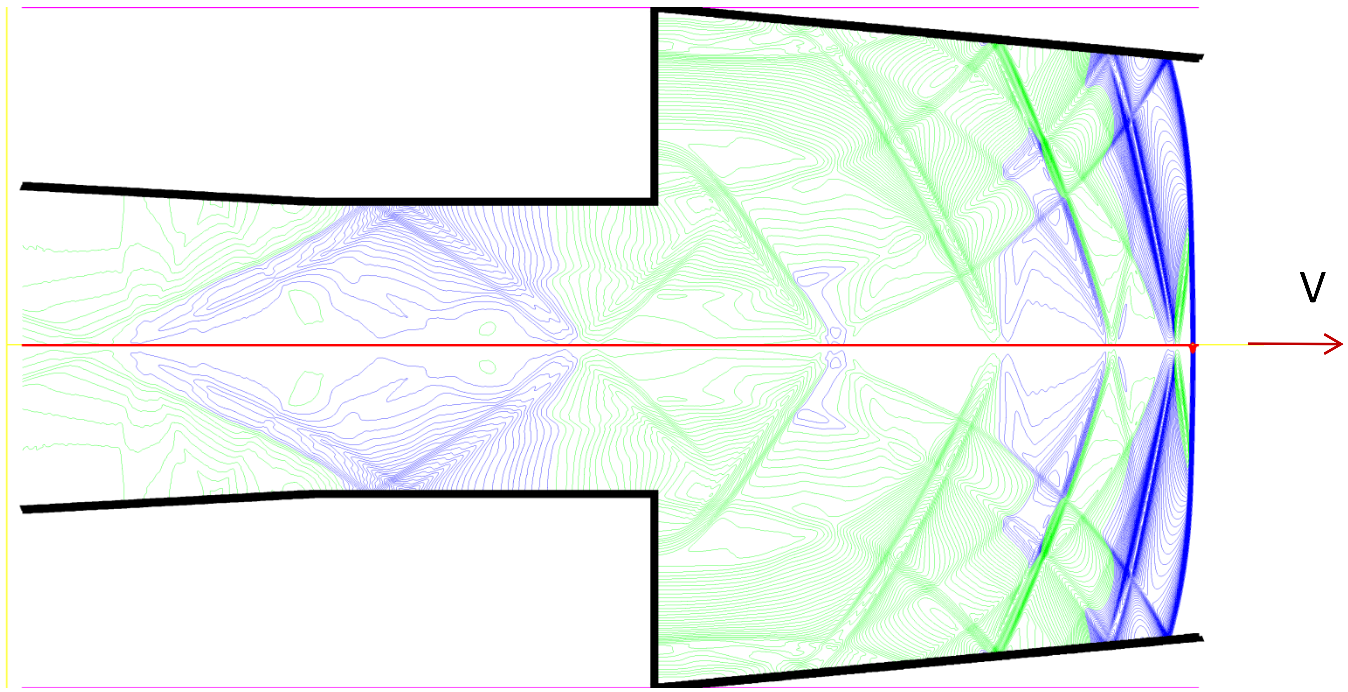
3-D stl model from Marco Oriunno



Wake fields and a bunch field



After a second chamber step



Bunch field

Electric field at the beam pipe wall

$$E = \frac{cZ_0}{(2\pi)^{3/2}} * \frac{eN_b}{a\sigma} \qquad E_{\left[\frac{kV}{cm}\right]} = 1.15 * \frac{N}{10^{10}} * \frac{1}{a_{cm}\sigma_{cm}}$$

$$a_{cm} = 1cm \qquad N = 2 \cdot 10^{10}$$

$$\sigma_{cm} = 0.03cm \qquad E = 75\frac{kV}{cm}$$

$$\sigma_{cm} = 0.02cm \qquad E = 115\frac{kV}{cm}$$

High electric field at the wall.

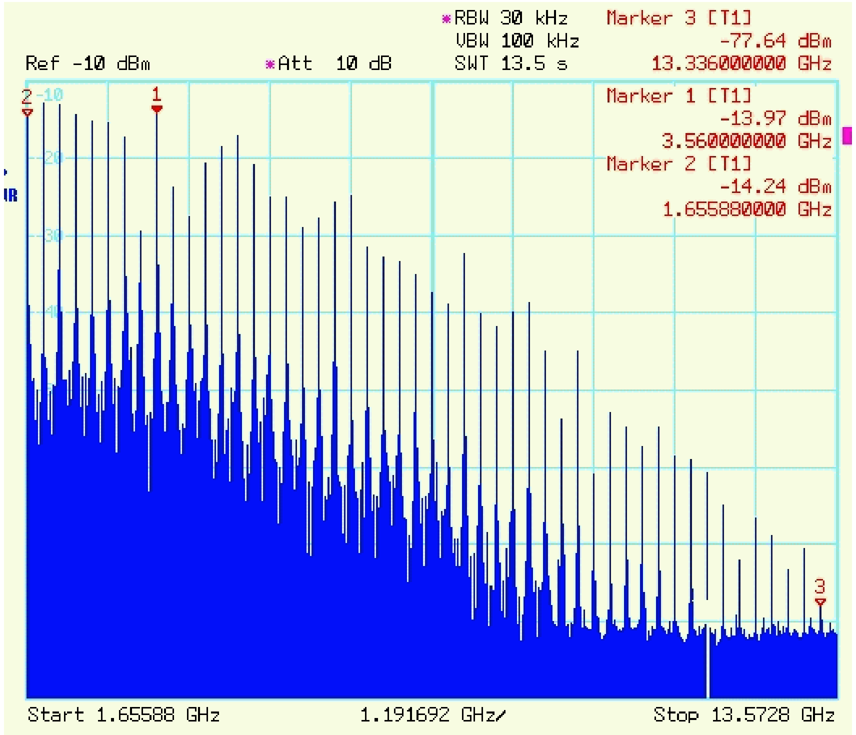
Beam spectrum

Bunch spectrum goes to higher frequency with shorter bunches

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

$$f_{\max} = \frac{c}{2\pi\sigma} = 160 - 240 \text{ GHz}$$

Example from PEP-II



Bunch spacing resonances

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

$$\frac{1}{\tau_b} = \frac{f_{RF}}{480} = 2.7 \text{ MHz}$$

Wake potentials and Green's function

Wake potential describes the integrated effect of the wake fields

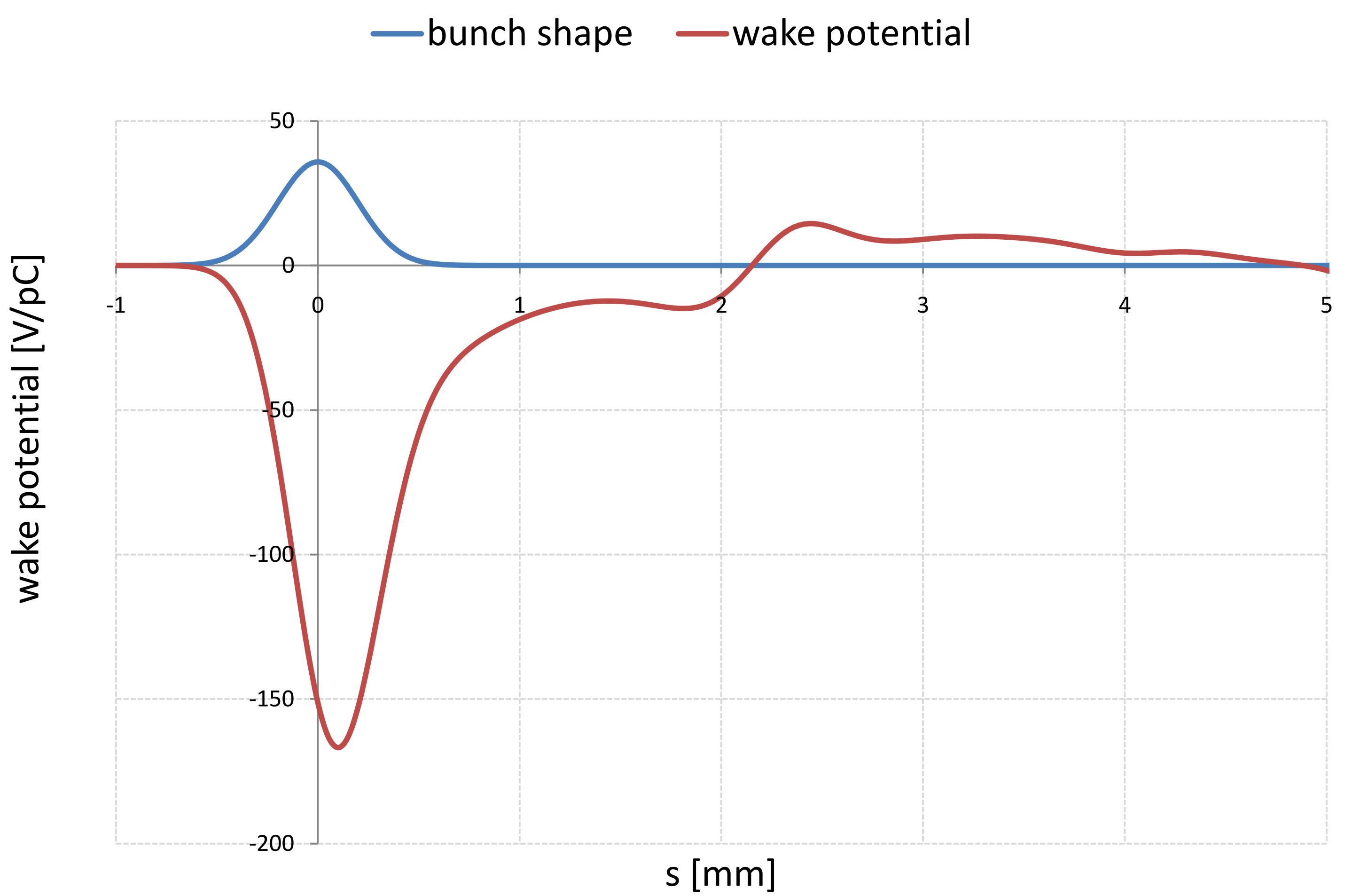
$$W(\tau) = \int_{-\infty}^{\infty} E_z(t,z)_{z=c(t-\tau)}\,dt$$

and can be calculated in the time domain by solving Maxwell's equations.

Wake potential of a point charge is a Green's function to calculate fields of any bunch distribution

$$W(\tau) = \int_{-\infty}^{\tau} \rho(\tau')G(\tau-\tau')d\tau' = \int_{0}^{\infty} \rho(\tau-\tau')G(\tau')d\tau'$$

Short range wake potential (0.2 mm bunch)



Calculated with a code "NOVO"

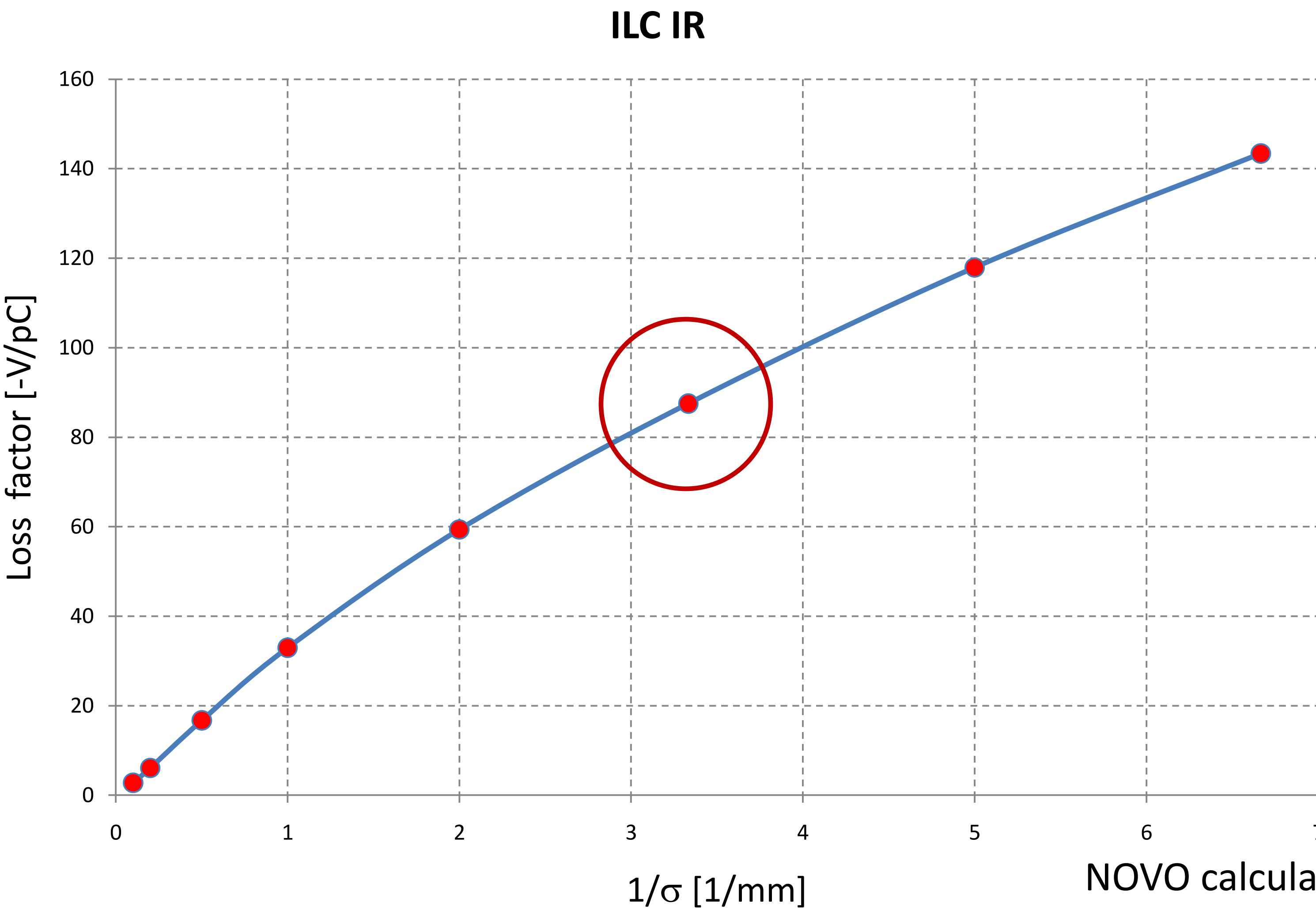
Bunch Loss Factor

- Beam energy loss is calculated by

$$k = \frac{1}{Q}\int_{-\infty}^{\infty} W(\tau)\rho(\tau)d\tau \qquad Q = \int_{-\infty}^{\infty} \rho(\tau)d\tau$$

- Single bunch loss factor is normalized to a bunch charge and usually measured in V/pC.

Loss factor of IR vs bunch length



NOVO calculations

Loss frequency integral

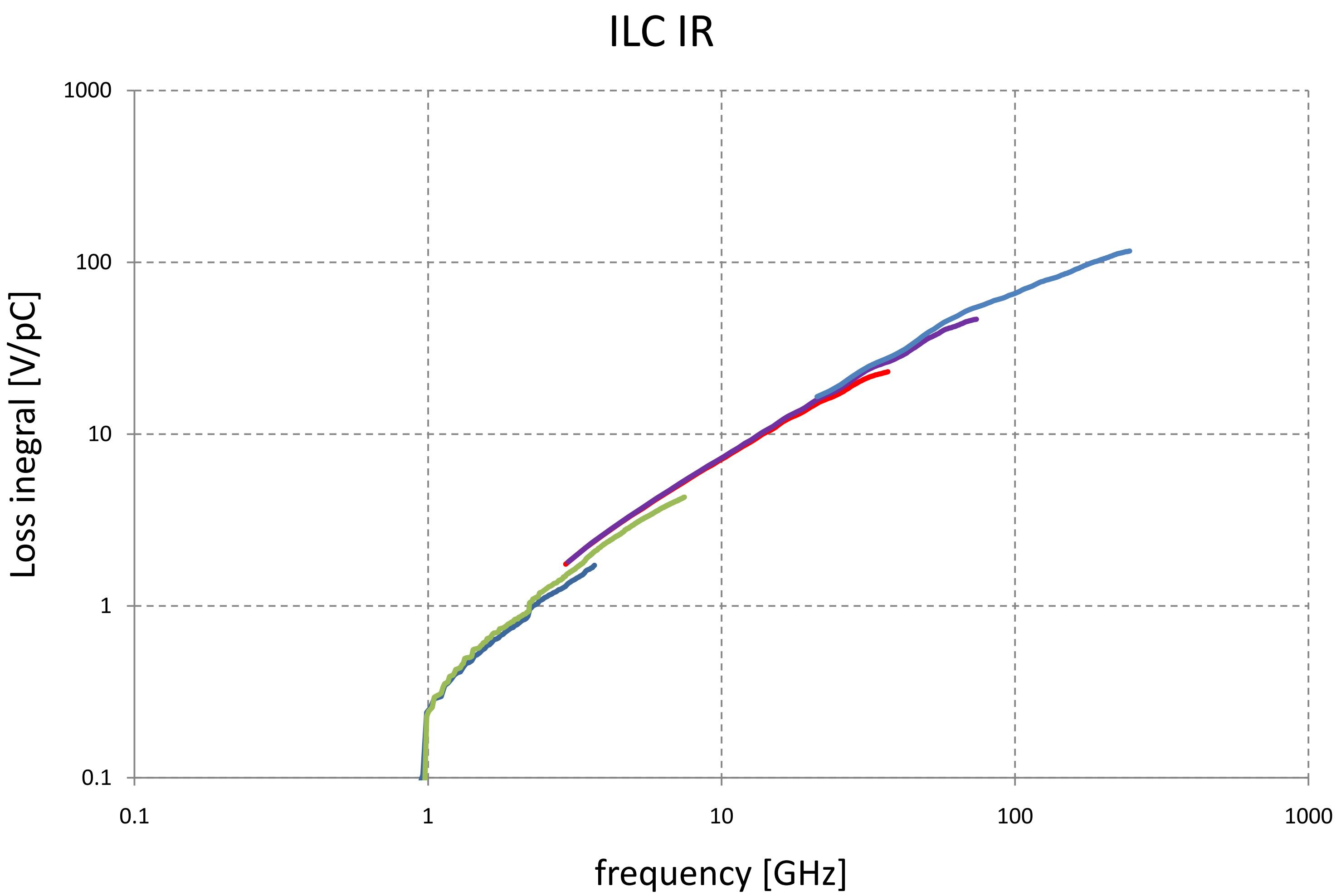
- We introduce loss frequency integral of a single bunch

$$K_s(\omega) = \mathrm{Re}\{\frac{1}{\pi}\int_0^{\omega} W_s(\omega)\rho(-\omega)d\omega\} =$$
$$= \frac{1}{\pi}\int_0^{\omega} |\rho_s(\omega)|^2 \,\mathrm{Re}\{Z(\omega)\}d\omega$$

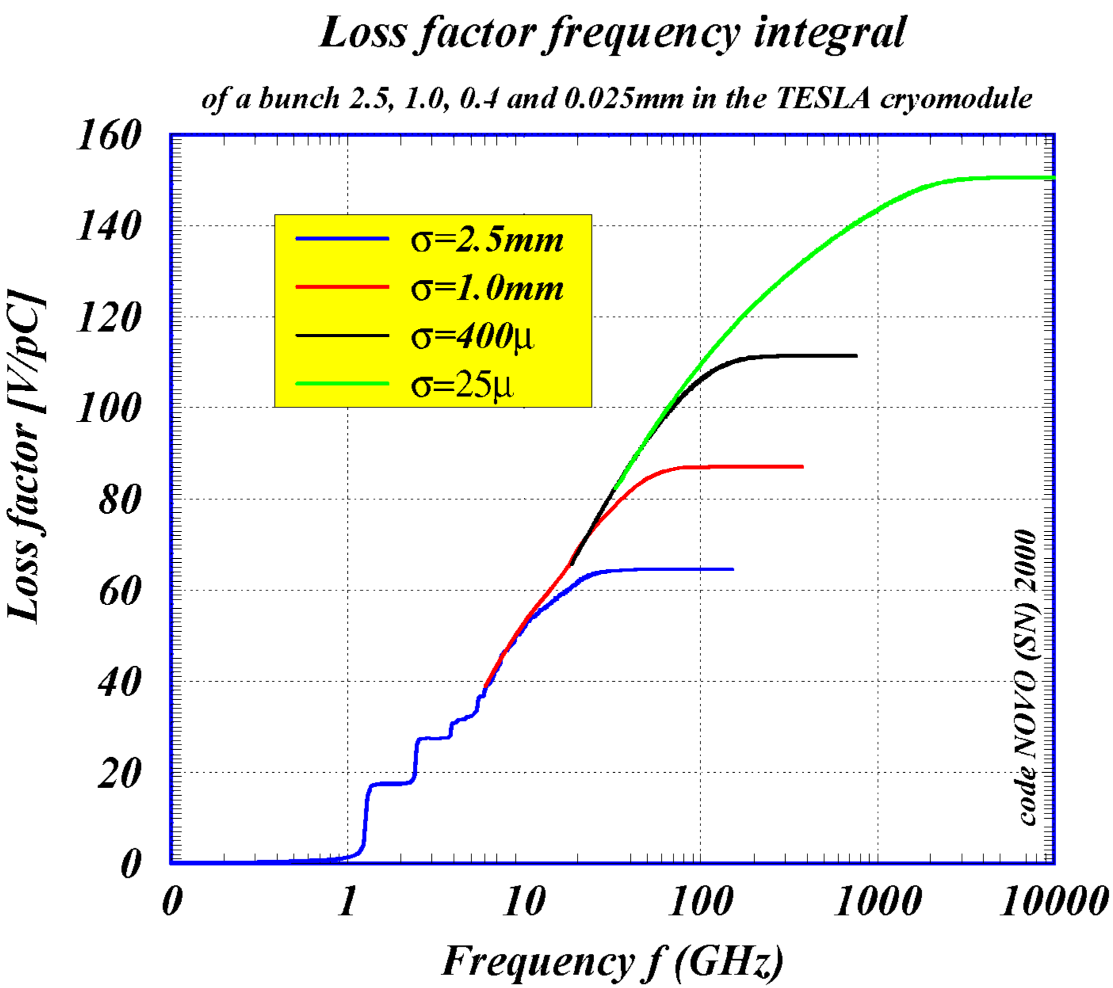
- Full integration gives the loss factor:

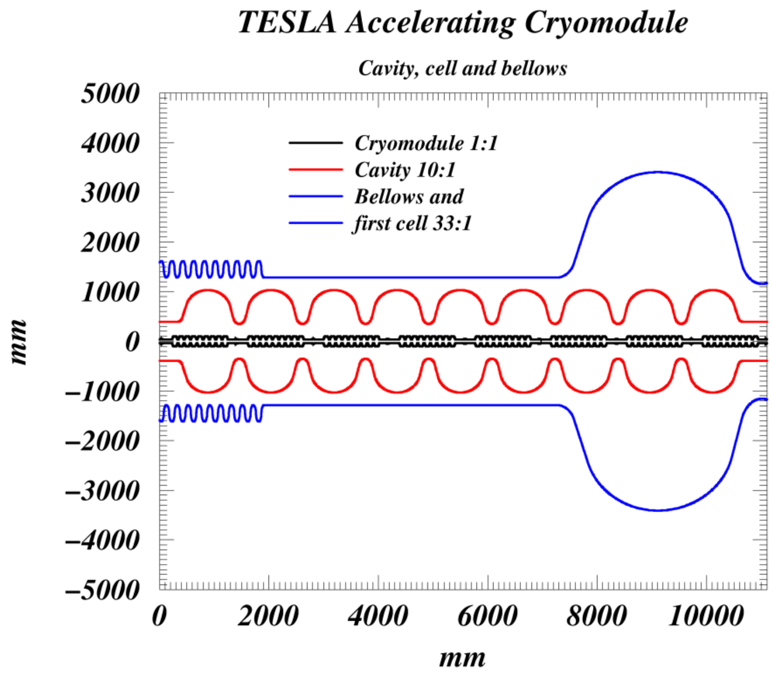
$$K_s(\omega \to \infty) = k_s$$

Loss frequency integral of IR



Comparison with loss frequency integral of the ILC (TESLA) cryo-module





IR produce almost same amount of wake fields as one cryomodule

Power loss of a train of bunches

- IR is a large "cavity".
- Some of the fields excited in the IR can be trapped and absorbed there. Other part can leave IR, travel along the beam pipes and absorbed.
- Trapped modes may have high Q-value and keep the fields from the previous bunches.
- Modes with higher frequencies can leave the region.

Longitudinal impedance

- A Fourier transform of a Green's function gives a longitudinal coupling impedance

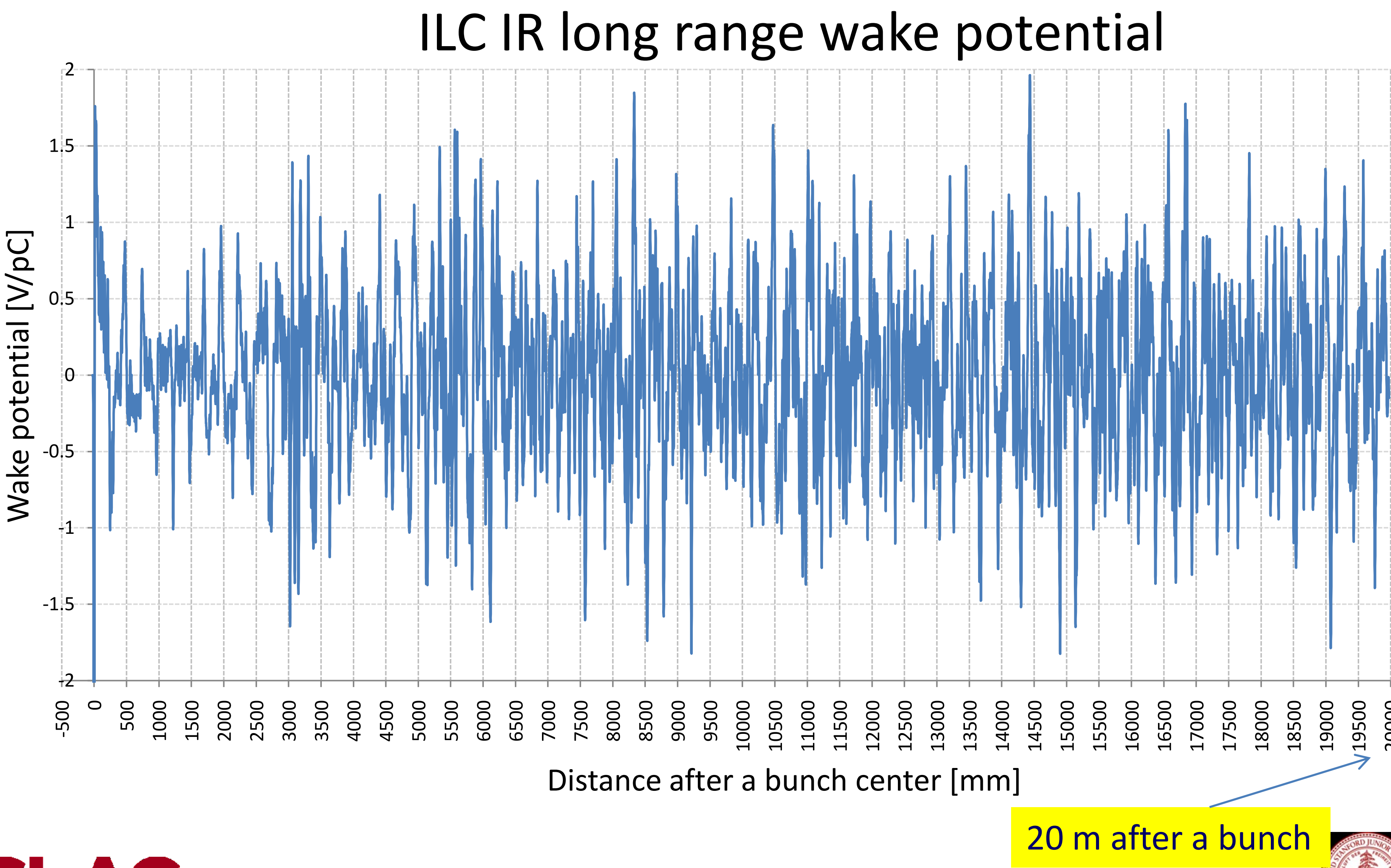
$$Z(\omega) = \int_{-\infty}^{\infty} G(\tau)\exp(-i\omega\tau)d\tau$$

- We can use wake potential to calculate longitudinal impedance

$$W(\omega) = \int_{-\infty}^{\infty} W(\tau)\exp(-i\omega\tau)d\tau =$$

$$= \rho(\omega)\times\int_{0}^{\infty} G(\tau')\exp(i\omega\tau')d\tau' = \rho(\omega)\times Z(-\omega)$$

Long-range wake potential



Cut-off frequency

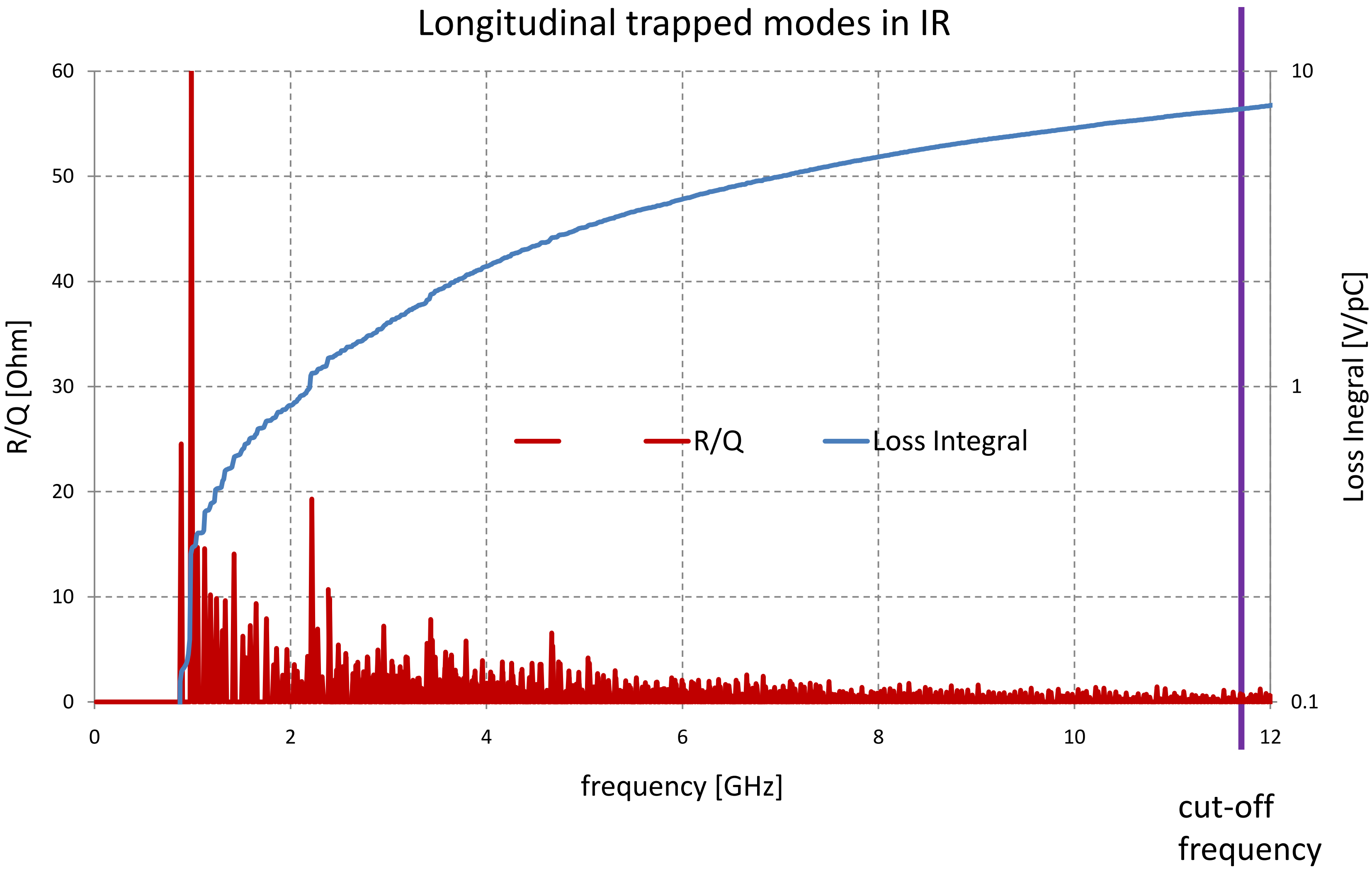
- Cut-off frequency is the maximum frequency of captured modes in a cavity.
- It is determined by the size of a beam pipe.
- For E01 mode

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

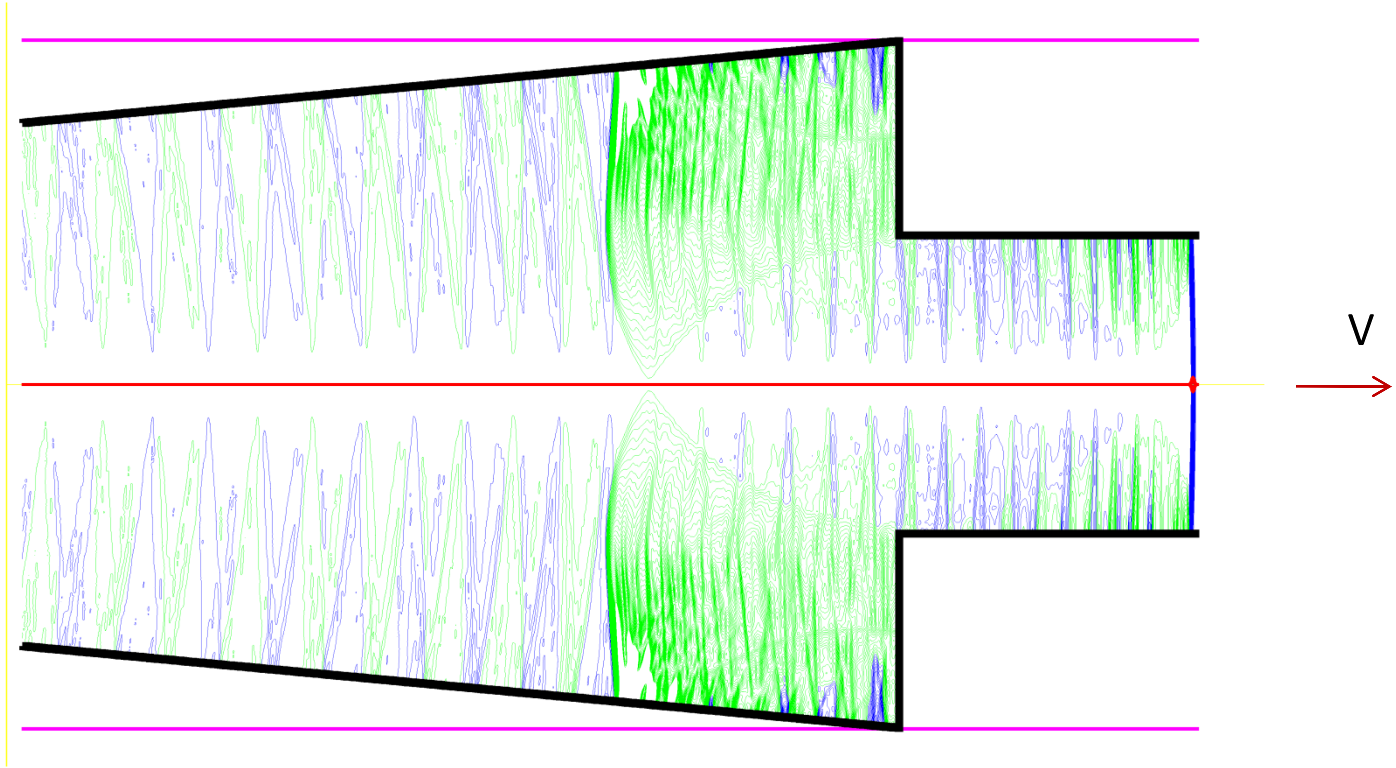
ILC IR: a=10mm=0.01m

f=11.47 GHz

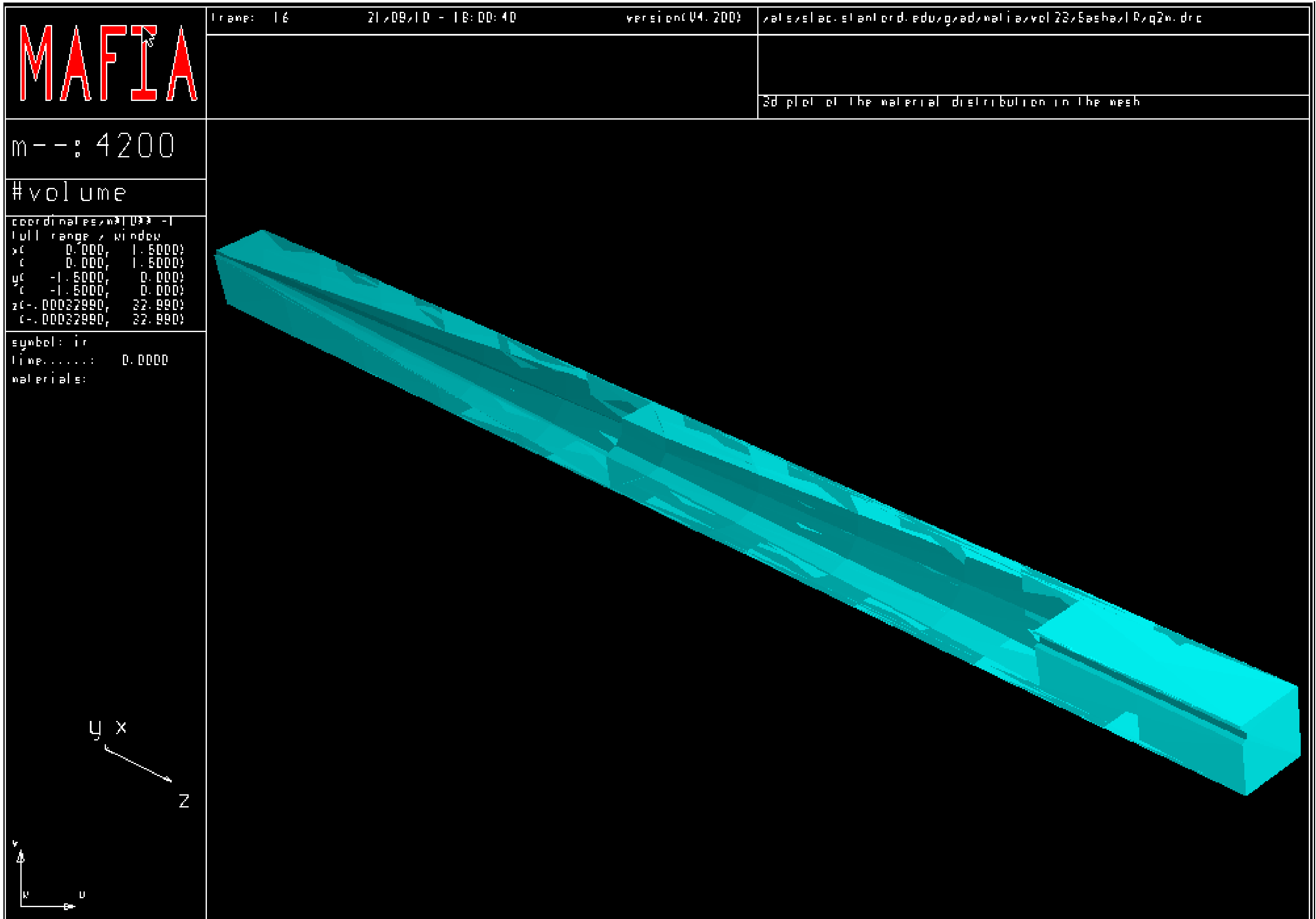
Trapped modes of IR



Wake fields in the corner



½ * ½ * ½ model for MAFIA simulations



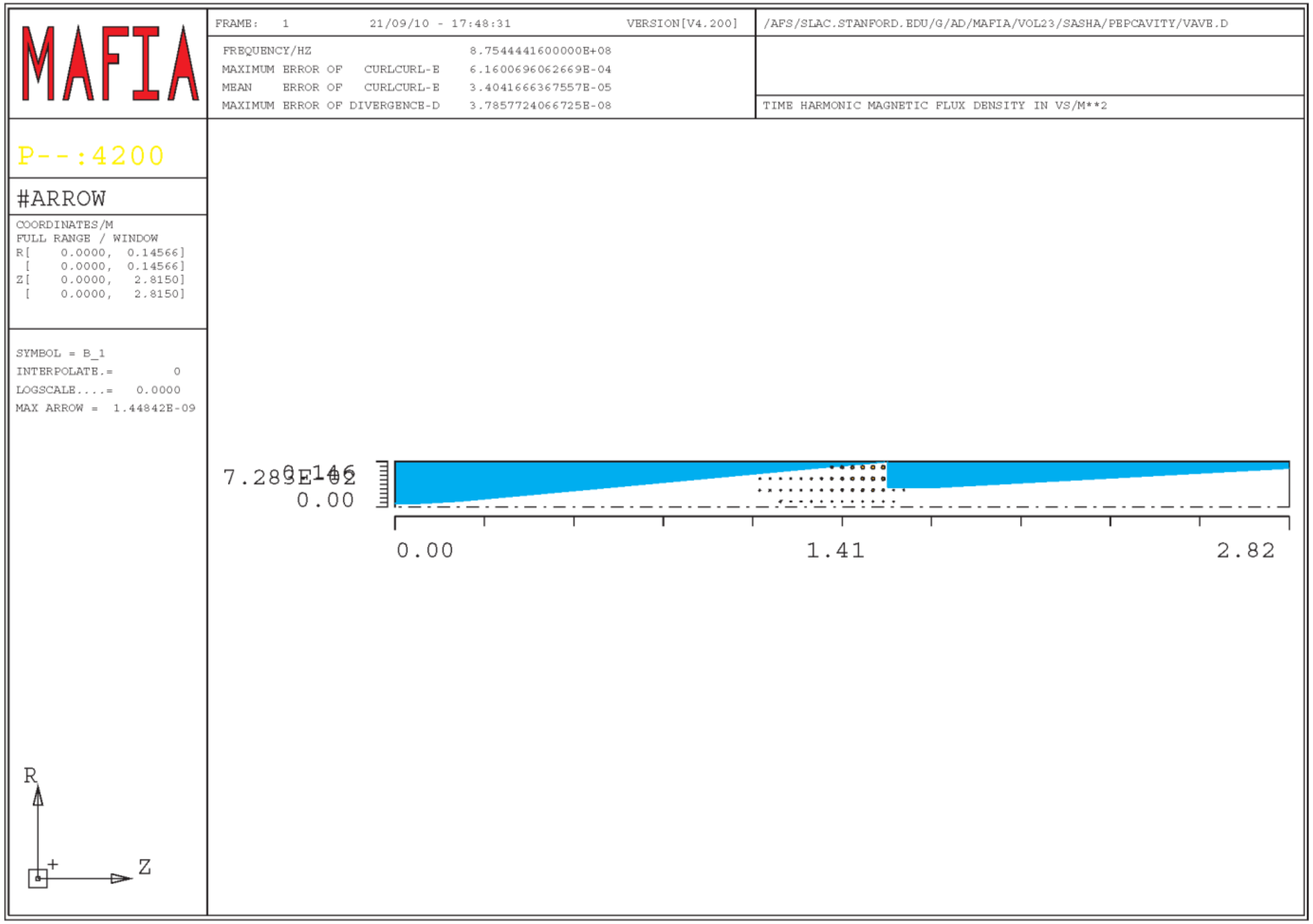
MAFIA simulations

```
************************************************************************
*                                                                      *
*                                                                      *
*            M       M    AAAAAAA    FFFFFFF   IIIIIII   AAAAAAA       *
*            MM     MM    A     A    F            I      A     A       *
*            M M   M M    A     A    F            I      A     A       *
*            M  M M  M    A     A    F            I      A     A       *
*            M   M   M    AAAAAAA    FFFFFF       I      AAAAAAA       *
*            M       M    A     A    F            I      A     A       *
*            M       M    A     A    F            I      A     A       *
*            M       M    A     A    F         IIIIIII   A     A       *
*                                                                      *
*                                                                      *
************************************************************************
```

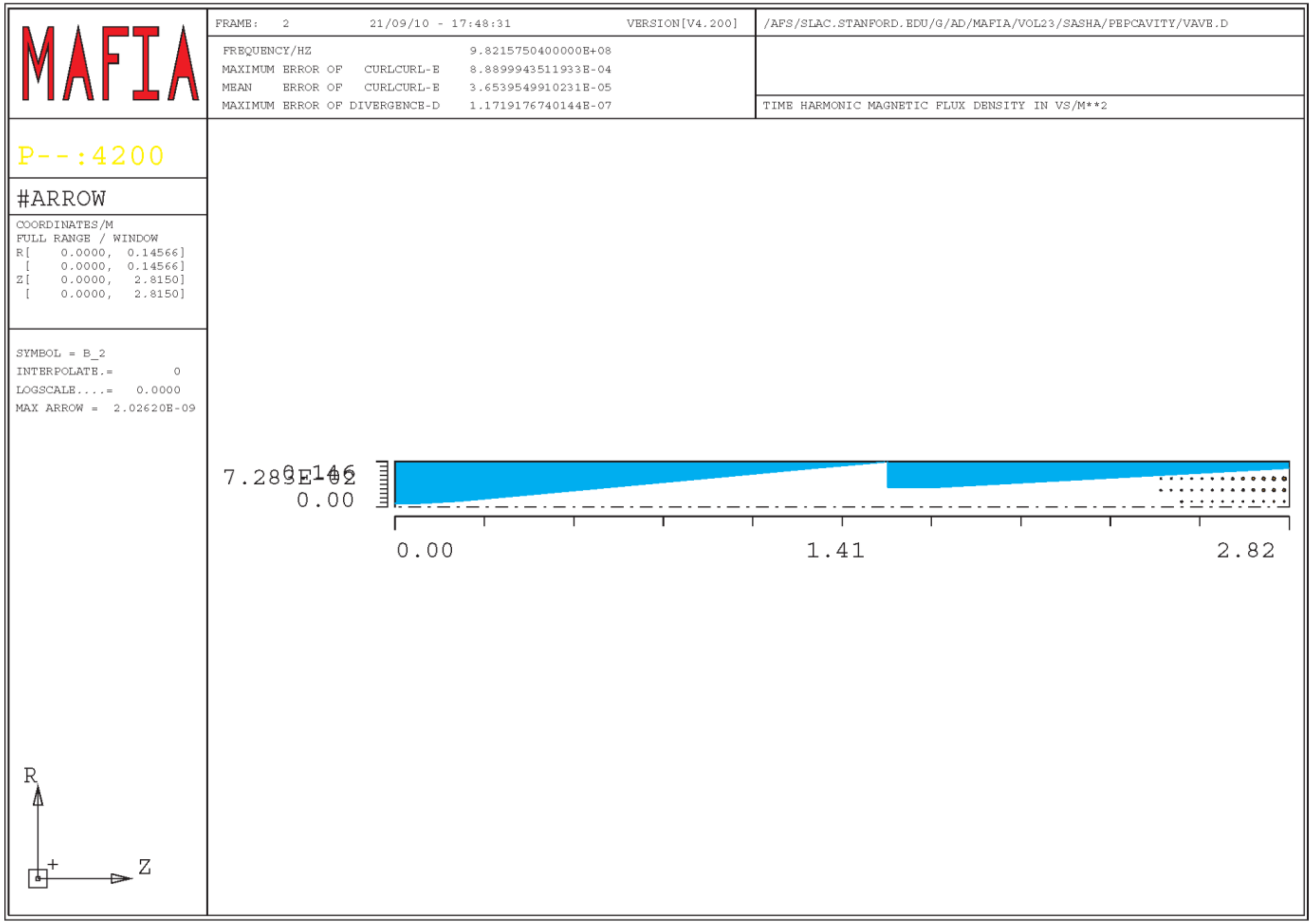
summary of all modes found

mode	frequency/hz	maxwell's laws =div(d)= max norm	maxwell's laws =div(b)= max norm	maxwell's laws =curlcurl(e)= max norm	maxwell's laws =curlcurl(e)= l2 norm	solver accuracy /Ax-lx/ /Ax/
1	8.754444E+08	3.8E-08	0.0E+00	6.2E-04	3.4E-05	1.6E-04
2	9.821575E+08	1.2E-07	0.0E+00	8.9E-04	3.7E-05	2.1E-04
3	1.044301E+09	5.4E-08	0.0E+00	5.9E-04	4.6E-05	2.0E-04
4	1.125241E+09	1.1E-07	0.0E+00	7.5E-04	7.3E-05	2.9E-04
5	1.179520E+09	7.0E-08	0.0E+00	7.5E-04	1.1E-04	4.0E-04
6	1.231551E+09	8.7E-08	0.0E+00	6.2E-04	5.3E-05	2.3E-04
7	1.302785E+09	6.8E-08	0.0E+00	4.3E-04	3.6E-05	1.7E-04
8	1.326441E+09	8.5E-08	0.0E+00	5.8E-04	9.8E-05	3.9E-04
9	1.415353E+09	8.0E-08	0.0E+00	5.6E-04	6.4E-05	2.8E-04
10	1.419791E+09	7.3E-08	0.0E+00	4.8E-04	5.5E-05	2.5E-04
11	1.500033E+09	7.6E-08	0.0E+00	4.3E-04	5.9E-05	2.7E-04
12	1.532397E+09	6.9E-08	0.0E+00	4.3E-04	3.4E-05	1.7E-04
13	1.581816E+09	7.6E-08	0.0E+00	3.8E-04	5.3E-05	2.6E-04
14	1.641874E+09	6.2E-08	0.0E+00	3.8E-04	5.3E-05	2.7E-04
15	1.661642E+09	8.4E-08	0.0E+00	4.0E-04	2.4E-05	1.2E-04
16	1.738912E+09	7.3E-08	0.0E+00	3.2E-04	3.5E-05	1.8E-04
17	1.749572E+09	7.7E-08	0.0E+00	3.3E-04	1.9E-05	1.1E-04
18	1.812262E+09	7.9E-08	0.0E+00	3.5E-04	3.1E-05	1.5E-04
19	1.854955E+09	6.1E-08	0.0E+00	3.4E-04	3.0E-05	1.8E-04
20	1.868092E+09	1.3E-07	0.0E+00	3.2E-04	3.2E-05	1.9E-04
21	1.910781E+09	1.1E-07	0.0E+00	4.3E-04	7.2E-05	3.5E-04
22	1.956755E+09	6.5E-08	0.0E+00	4.8E-04	6.6E-05	3.3E-04
23	1.970687E+09	9.1E-08	0.0E+00	4.5E-04	7.4E-05	3.2E-04
24	2.029463E+09	5.1E-08	0.0E+00	4.5E-04	7.9E-05	4.1E-04
25	2.064812E+09	6.2E-08	0.0E+00	5.1E-04	4.8E-05	2.8E-04
26	2.097944E+09	8.4E-08	0.0E+00	7.7E-04	1.1E-04	4.5E-04
27	2.143732E+09	1.3E-07	0.0E+00	2.4E-04	3.3E-05	1.6E-04
28	2.167004E+09	7.7E-08	0.0E+00	3.0E-04	2.6E-05	1.7E-04
29	2.197244E+09	1.0E-07	0.0E+00	2.9E-04	3.3E-05	3.1E-04
30	2.205334E+09	5.4E-08	0.0E+00	3.6E-04	5.6E-05	2.5E-04

Second mode


MAFIA
FRAME: 1 21/09/10 - 17:48:31 VERSION[V4.200]
/AFS/SLAC.STANFORD.EDU/G/AD/MAFIA/VOL23/SASHA/PEPCAVITY/VAVE.D
FREQUENCY/HZ 8.7544441600000E+08
MAXIMUM ERROR OF CURLCURL-E 6.1600696062669E-04
MEAN ERROR OF CURLCURL-E 3.4041666367557E-05
MAXIMUM ERROR OF DIVERGENCE-D 3.7857724066725E-08
TIME HARMONIC MAGNETIC FLUX DENSITY IN VS/M**2
P--:4200
#ARROW
COORDINATES/M
FULL RANGE / WINDOW
R[0.0000, 0.14566]
[0.0000, 0.14566]
Z[0.0000, 2.8150]
[0.0000, 2.8150]
SYMBOL = B_1
INTERPOLATE.= 0
LOGSCALE....= 0.0000
MAX ARROW = 1.44842E-09
0.146
7.283E-02
0.00
0.00
1.41
2.82
R
Z

Other mode



MAFIA
FRAME: 2 21/09/10 - 17:48:31 VERSION[V4.200]
/AFS/SLAC.STANFORD.EDU/G/AD/MAFIA/VOL23/SASHA/PEPCAVITY/VAVE.D
FREQUENCY/HZ 9.8215750400000E+08
MAXIMUM ERROR OF CURLCURL-E 8.8899943511933E-04
MEAN ERROR OF CURLCURL-E 3.6539549910231E-05
MAXIMUM ERROR OF DIVERGENCE-D 1.1719176740144E-07
TIME HARMONIC MAGNETIC FLUX DENSITY IN VS/M**2
P--:4200
#ARROW
COORDINATES/M
FULL RANGE / WINDOW
R[0.0000, 0.14566]
[0.0000, 0.14566]
Z[0.0000, 2.8150]
[0.0000, 2.8150]
SYMBOL = B_2
INTERPOLATE.= 0
LOGSCALE....= 0.0000
MAX ARROW = 2.02620E-09
0.146
7.283E-02
0.00
0.00
1.41
2.82
R
Z

Interaction with one mode

Mode voltage decay $V(t) = V(o)\, e^{-\frac{t}{\tau_{l,n}}}$

Loaded time decay or filling time $\tau_{l,n} = \dfrac{2Q_l}{\omega_n} = \dfrac{2Q_l}{2\pi f_n} = \dfrac{Q_l}{\pi f_n}$

Loaded Q-value which includes coupling Q_l

Bunch spacing τ_b

Mode **survives** to the next bunch if $\dfrac{\tau_b}{\tau_{l,n}} << 1$

and loaded Q $Q_l >> \dfrac{\omega_n \tau_b}{2} = \pi f_n \tau_b$

Coherent and incoherent excitation

	Incoherent	Coherent at resonance
condition	$Q_l \ll \pi f_n \tau_b$	$Q_l \gg \pi f_n \tau_b$
Loss power	$P_n = I^2 \frac{\omega_n}{2} \frac{R}{Q} \tau_b$	$P_n = I^2 \frac{R}{Q} Q_l$
	$P_n = I^2 k_n \tau_b$	$P_n = 2 I^2 k_n \tau_{l,n}$

Loss factor

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

If the bunch spacing is equal to mode decay time the coherent power is only two times larger than incoherent power

Total loss power (all trapped modes)

Total power $$P_{incoh.} = I^2 \tau_b \sum_n k_n \qquad P_{coh.} = 2I^2 \sum_n k_n \tau_{l,n}$$

Trapped mode frequency range 0.85 – 11.5 GHz

Bunch spacing 369.2 ns

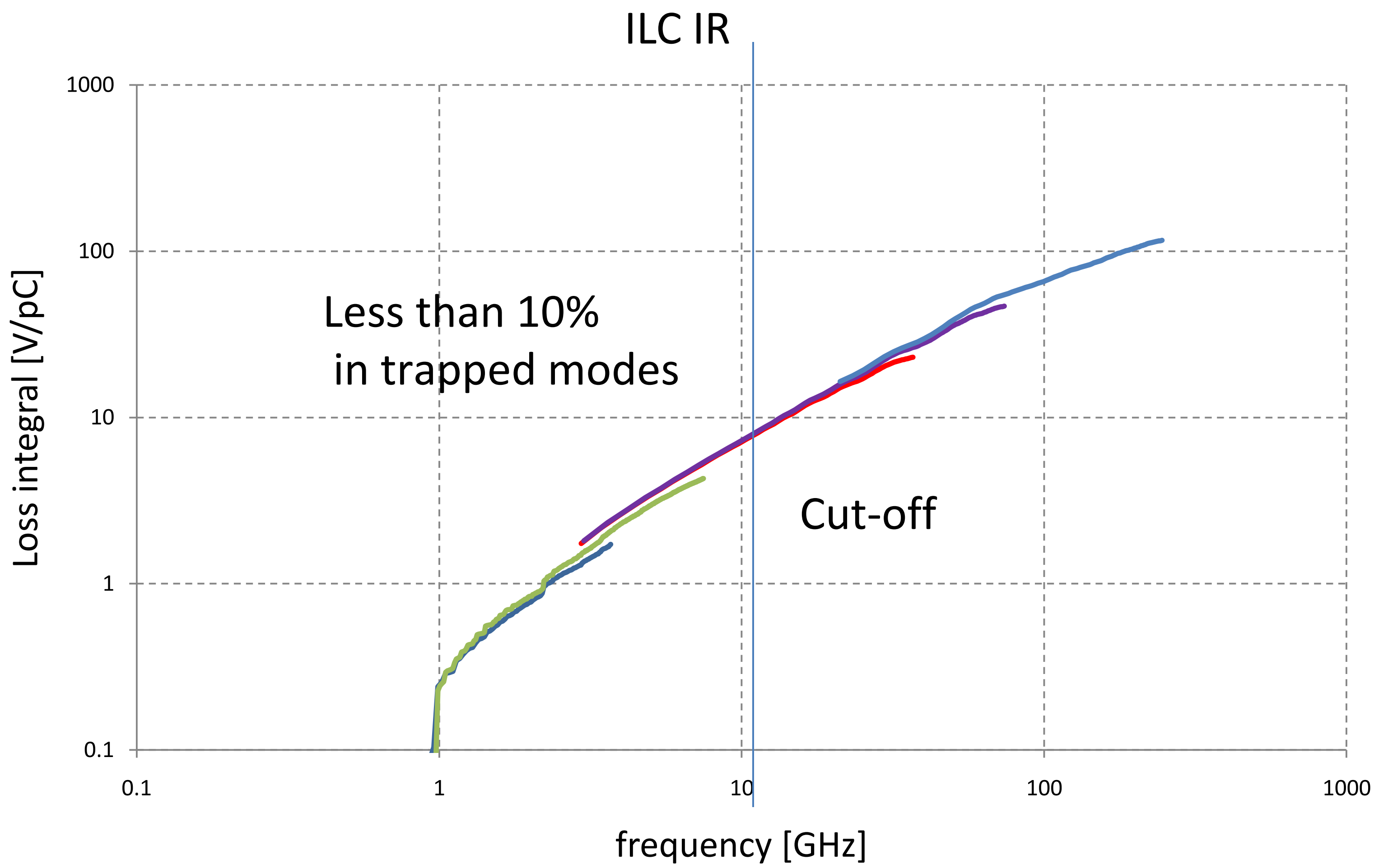
Loaded Q $Q_l = \pi f_n \tau_b$ 990 - 13300

$$\sum_n k_n = 7.3 \text{ V/pC}$$

$$P_{incoh.} = 440 \text{ W} \qquad P_{coh.} = 880 \text{ W}$$

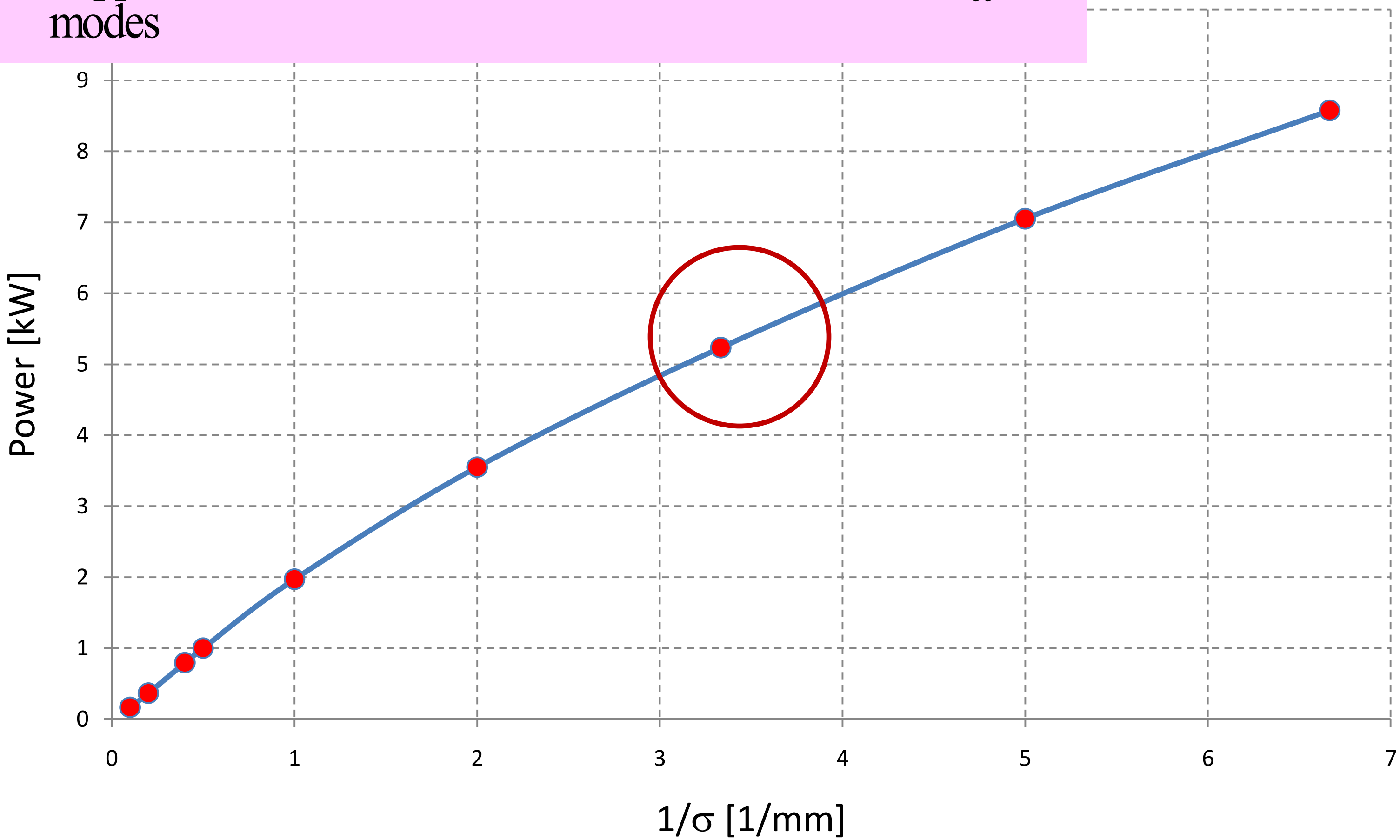
Average power is 200 times smaller

Loss integral and cut-off frequency



Power loss in a pulse (two beams)

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

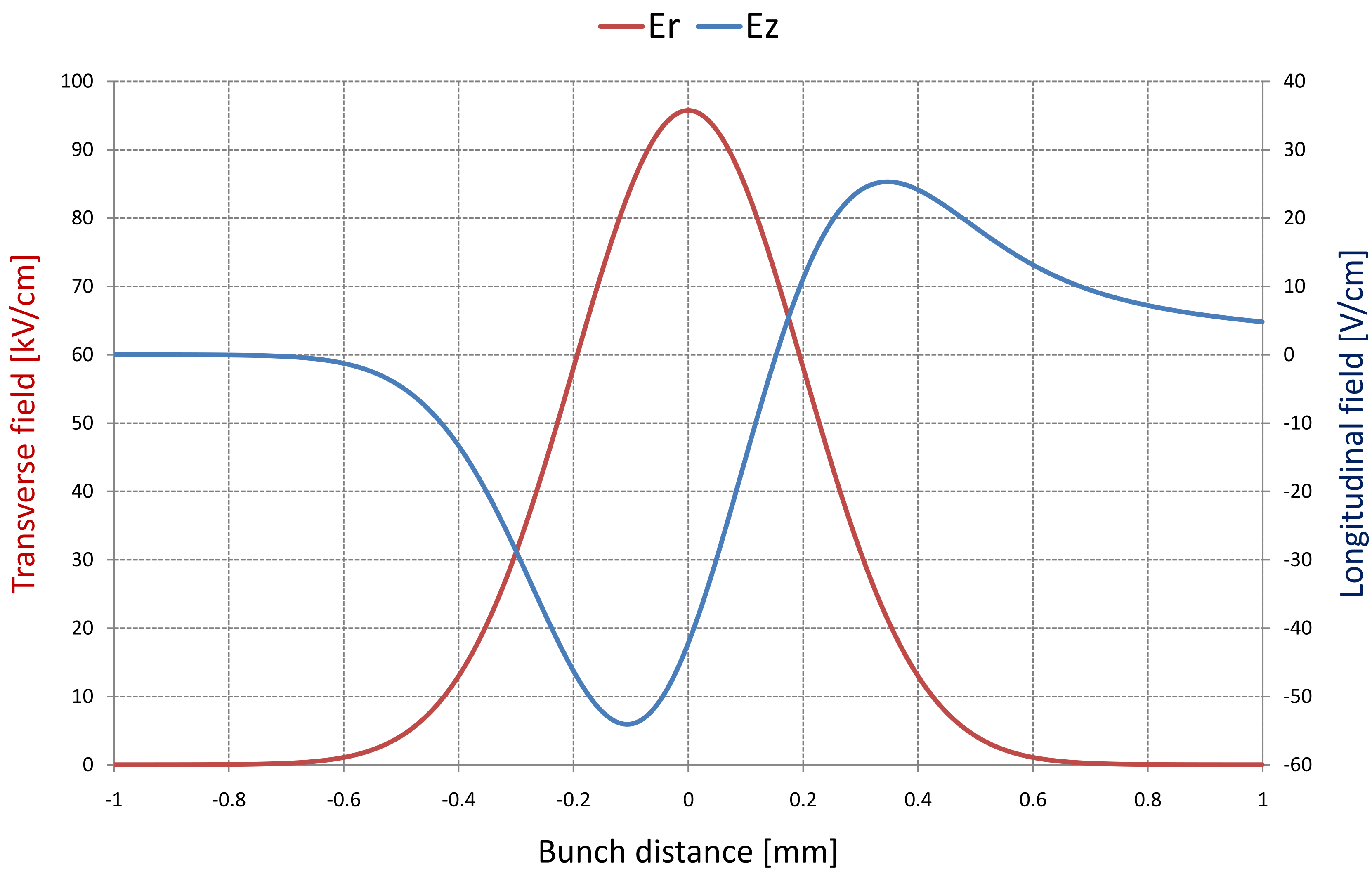


Resistive-wall wake fields

(Losses of image currents)

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

Fields in Be chamber. Bunch 0.2 mm



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		

X 5 (NEG) =600 W

Summary

- The amount of beam energy loss in IR is almost equal to the energy loss in one accelerating cryo-module.
- Additional energy spread accumulated in the IR is very small.
- Spectrum of the wake fields is limited to 300 GHz
- Average power of the wake fields excited in IR is around 30 W for nominal parameters.
- Pulse power in this case is 6 kilowatts.