Wake field potentials of the ILC Interaction Region

Summary

Sasha Novokhatski

ARD MDI Meeting, SLAC
January 20, 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

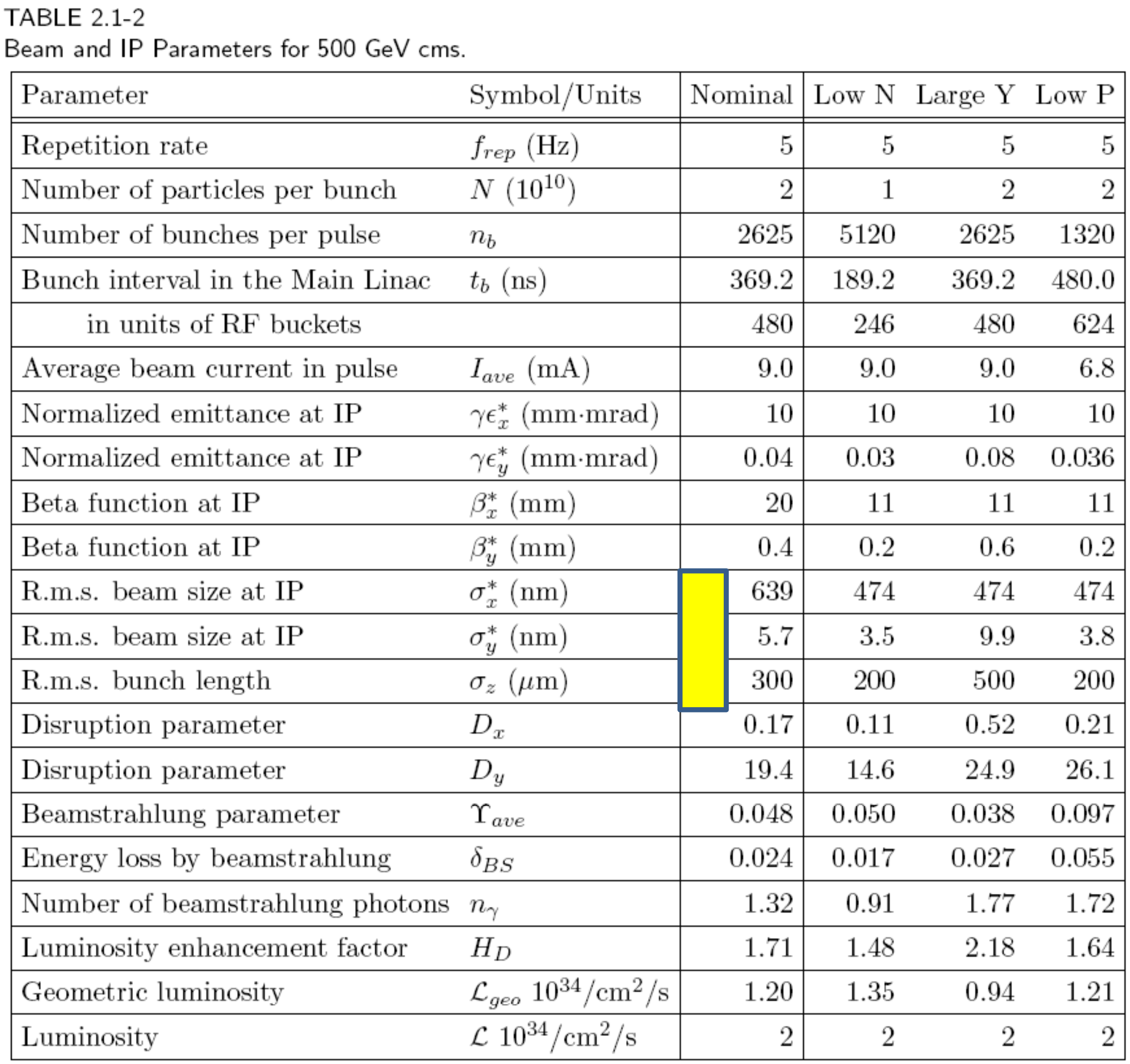


TABLE 2.1-2
Beam and IP Parameters for 500 GeV cms.

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

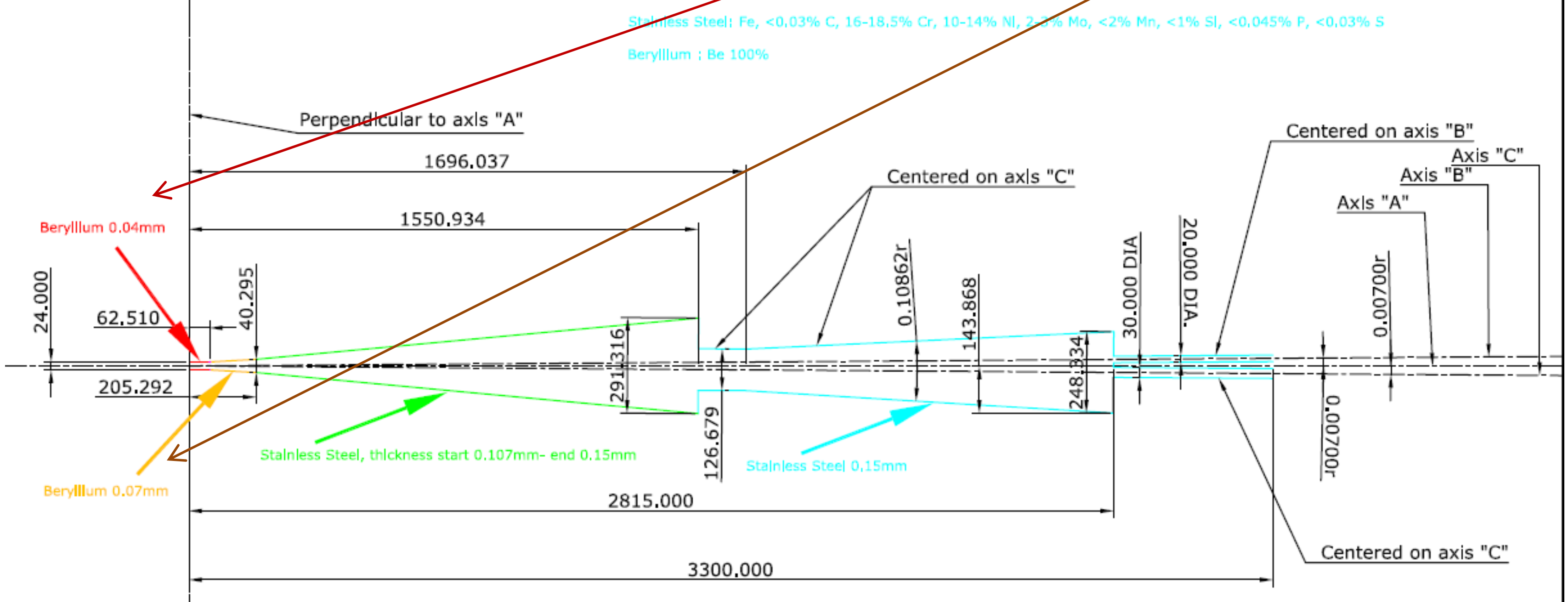
INTERNATIONAL LINEAR COLLIDER
REFERENCE DESIGN REPORT
AUGUST, 2007

- 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.



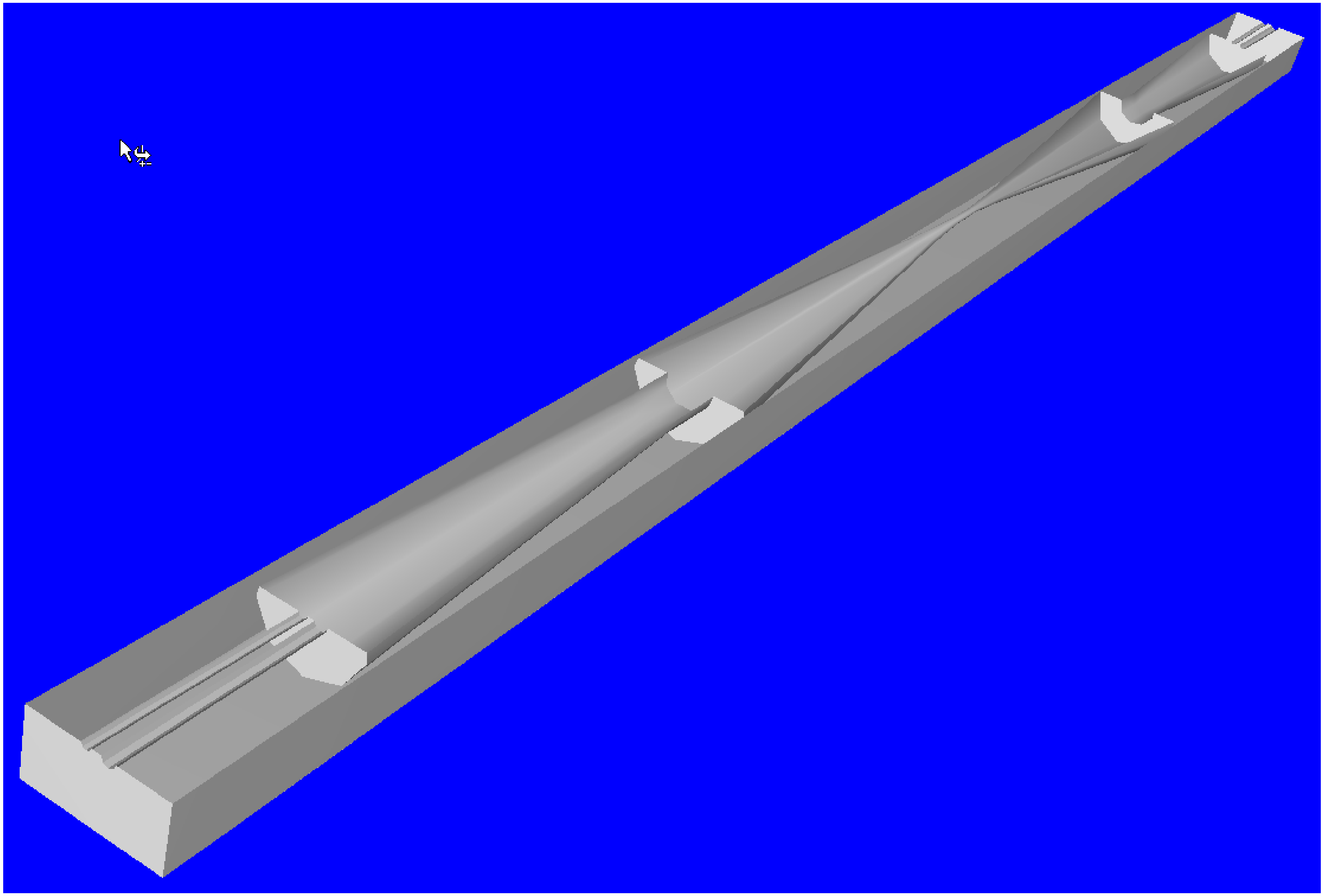
Stainless Steel: Fe, <0,03% C, 16-18,5% Cr, 10-14% Ni, 2-3% Mo, <2% Mn, <1% Si, <0,045% P, <0,03% S

Beryllium : Be 100%

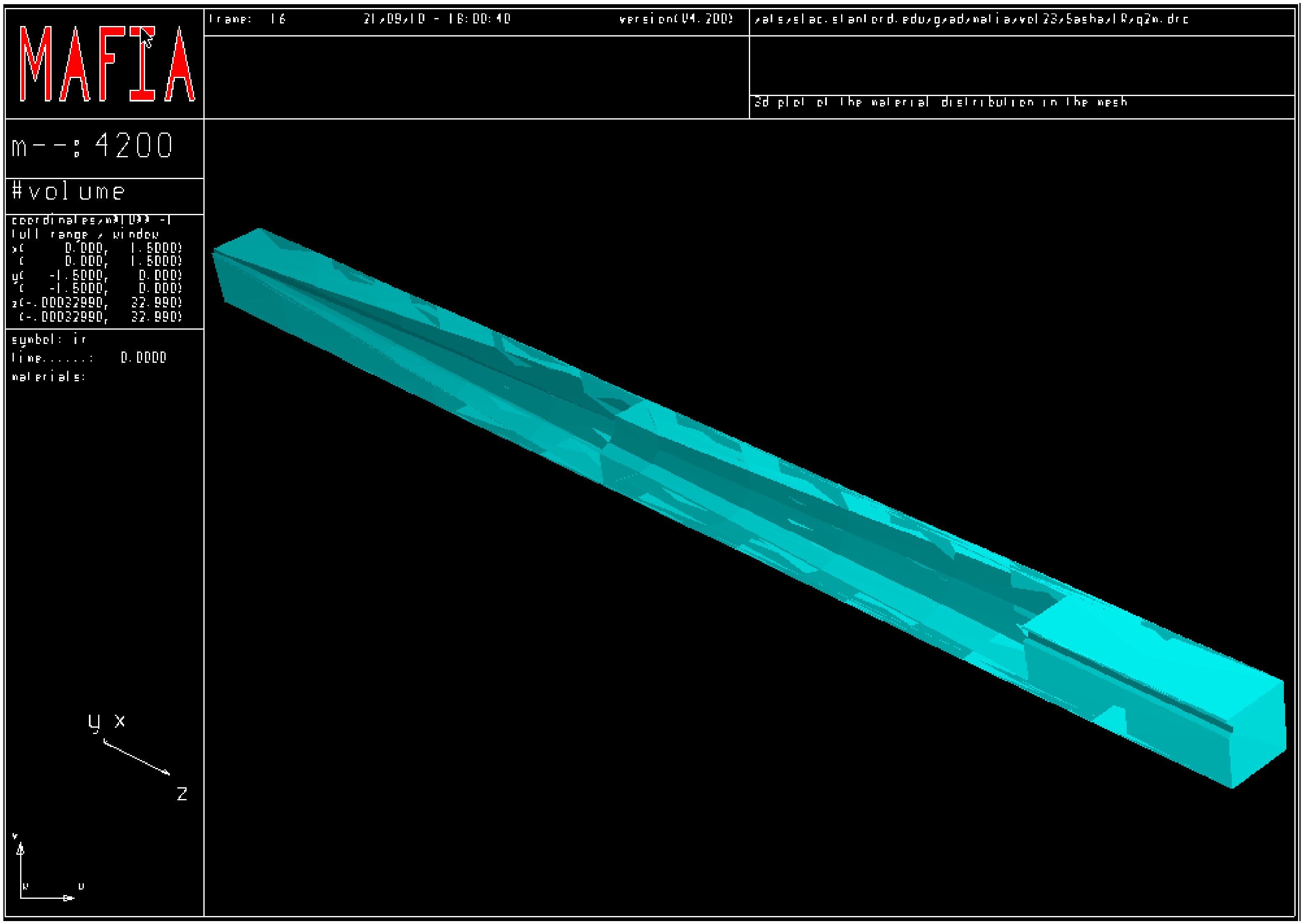
12 February 2009
Units = mm, radians
The beryllium portion of the beam pipe extends to 205.292 mm.
Other portions are tentatively stainless steel, but beryllium has been considered for the 20 mm and 30 mm dimaeter pipes.
Objects are centered about axis "A" unless otherwise noted.
Flat heads are perpendicular to axis "C"

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

3-D stl model from Marco Oriunno

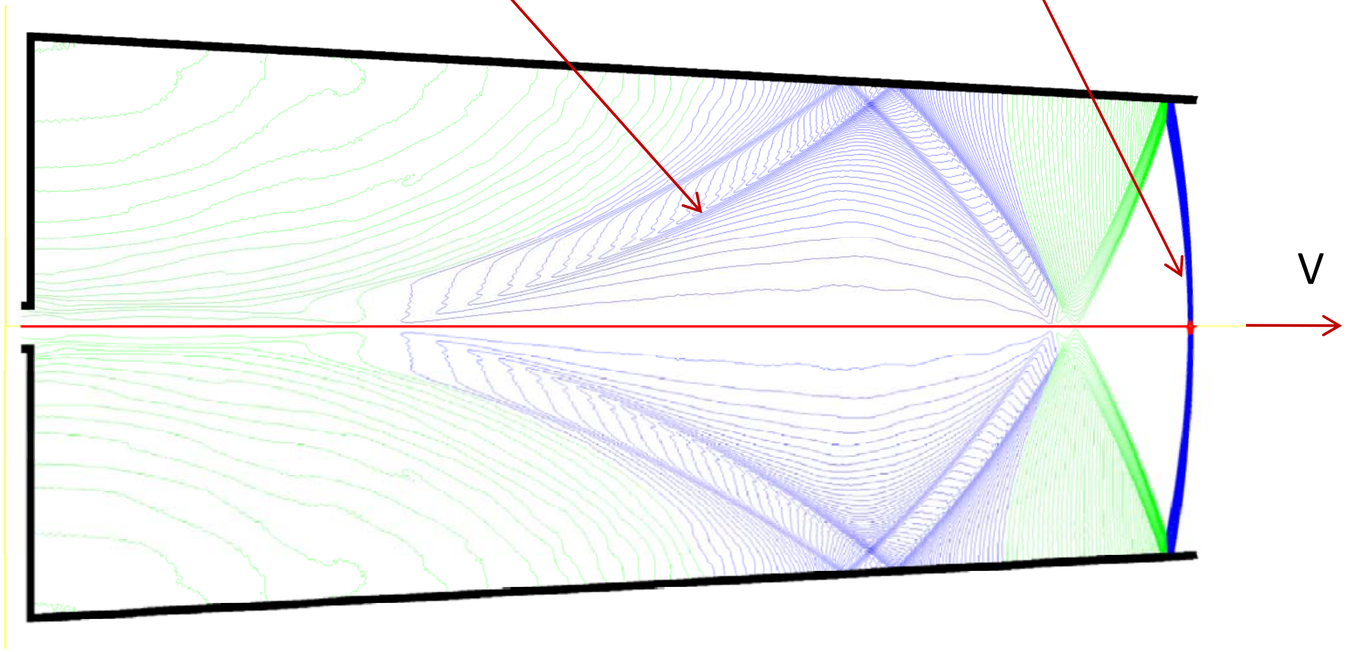


½ * ½ * ½

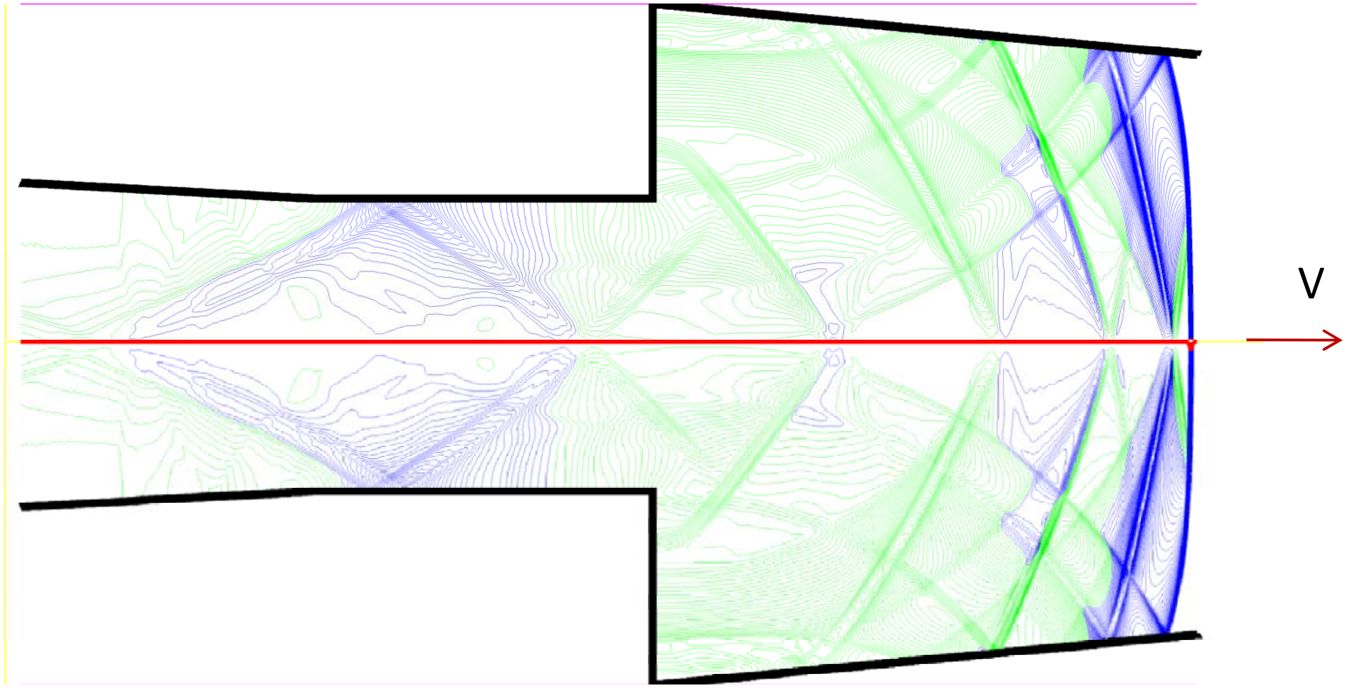


```
frame:  16          21/09/10 - 18:00:40          version(V4.200)
/afs/slac.stanford.edu/g/ad/mafia/vol23/Sasha/IR/q2m.drc
3d plot of the material distribution in the mesh

m--: 4200
#volume
coordinates/m*10** -1
full range / window
x(      0.000,   1.5000)
 (      0.000,   1.5000)
y(    -1.5000,    0.000)
 (    -1.5000,    0.000)
z(-.00032990,   32.990)
 (-.00032990,   32.990)
symbol: ir
time......:   0.0000
materials:
```

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. Possible electron current from the wall due to auto emission and even breakdowns at the metal edges.

Comparison with a bunch in the LCLS undulator chamber

$$a_{cm} = 0.25cm \qquad N = 0.156 \cdot 10^{10} (250\, pC)$$

$$\sigma_{cm} = 10^{-3} cm \ (10\mu) \qquad E = 700 \frac{kV}{cm} = 70 \frac{MV}{m}$$

Rectangular chamber gives increase by π/2, so electric field reaches level of 100 MV/m .

More than ten times higher field. May be they have such a problem. The field in the LCLS RF BPMs is around 35 MV/m

Magnetic field near a center of a bunch

$$\sigma_y << \sigma_x$$

$$E_y(y) = E_{\max}\sqrt{\frac{2}{\pi}}\int_0^{y/\sigma_y} e^{-\frac{\eta^2}{2}}\,d\eta$$

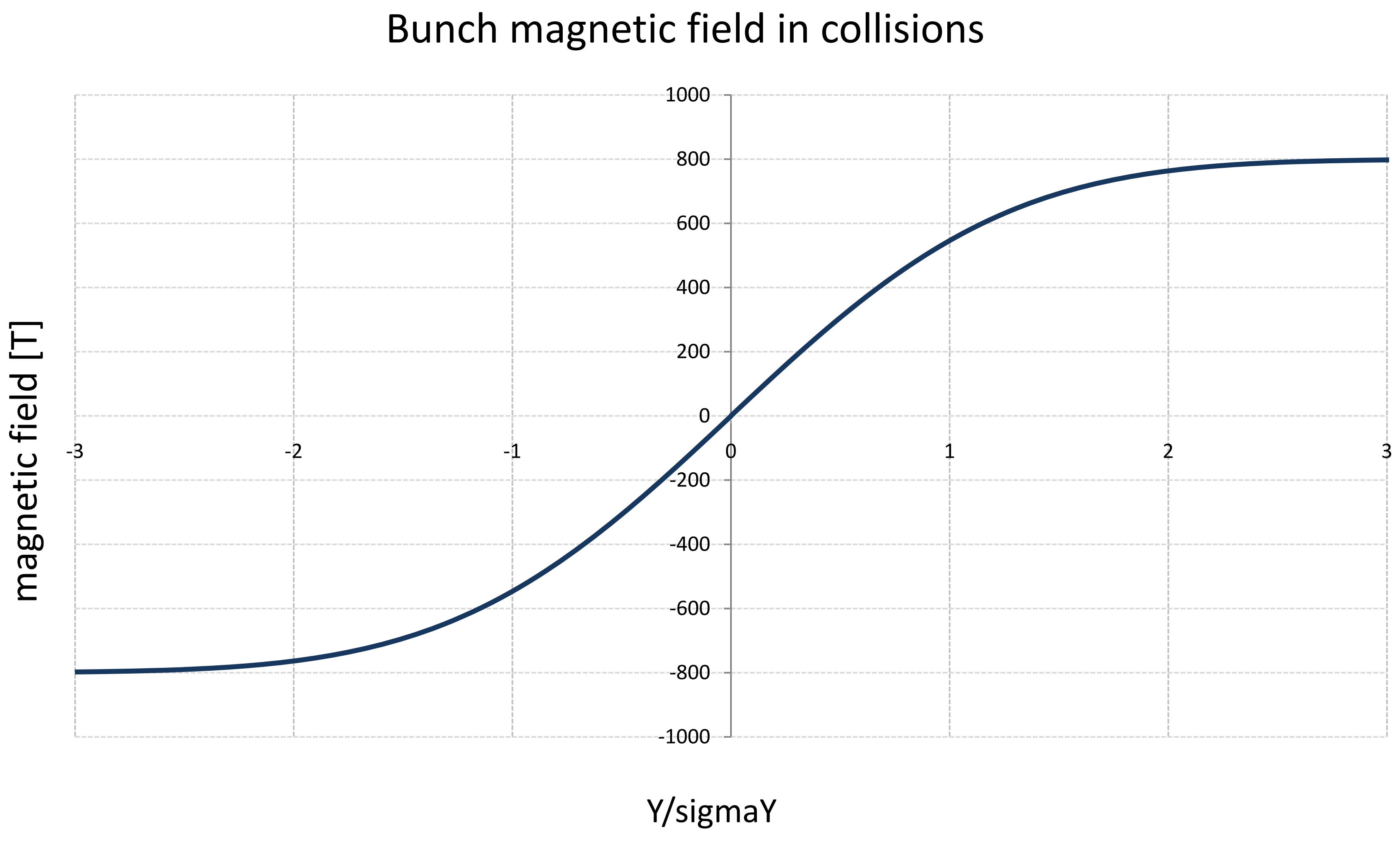
$$\boxed{E_{\max} = \frac{cZ_0}{(2\pi)^{3/2}} * \frac{eN}{\sigma_x\sigma_z}}$$

$$E_{\left[\frac{MV}{cm}\right]} = 115 * \frac{N}{10^{10}} * \frac{1}{\sigma_{x[\mu]}\sigma_{z[mm]}} = 1200\frac{MV}{cm} = 1.2\frac{GV}{cm}$$

$H_{x[MG]} = \frac{1}{300}E_{\left[\frac{MV}{cm}\right]} * 2$ (in the collision) $H^{\max} = 8$ MG=800T

bending radius = 1m

Field vertical distribution - quad



Beam spectrum

Bunch spectrum goes to higher frequency with shorter bunches

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

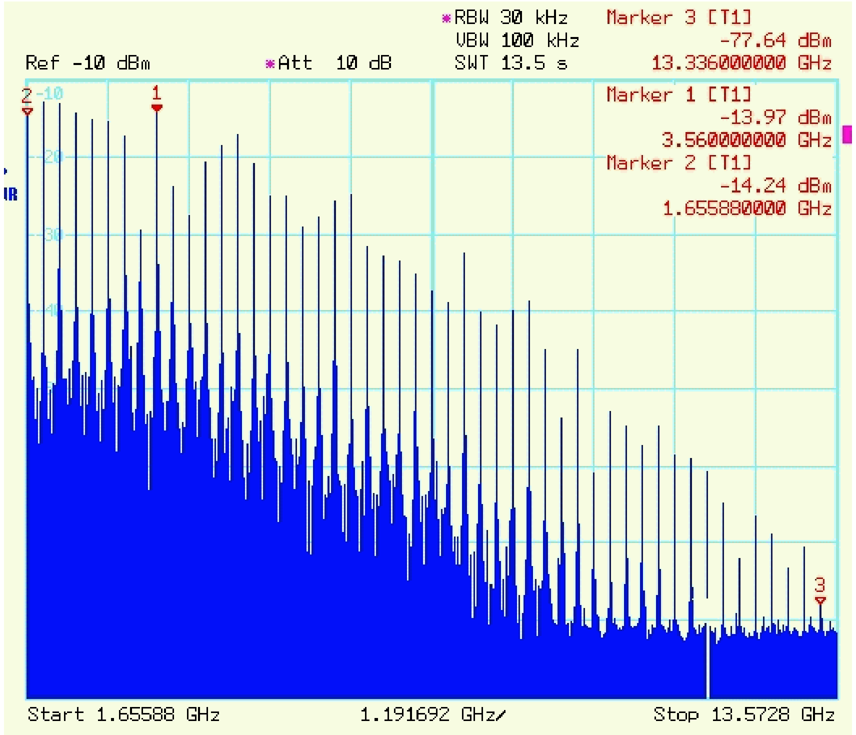
$$f = \frac{c}{2\pi\sigma} = 160 - 240 \text{ GHz}$$

Bunch spacing resonances

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

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

Example from PEP-II



Ref -10 dBm

*Att 10 dB

*RBW 30 kHz

VBW 100 kHz

SWT 13.5 s

Marker 3 [T1]
-77.64 dBm
13.336000000 GHz

Marker 1 [T1]
-13.97 dBm
3.560000000 GHz

Marker 2 [T1]
-14.24 dBm
1.655880000 GHz

Start 1.65588 GHz

1.191692 GHz/

Stop 13.5728 GHz

Wake potentials and Green's function

- Wake potential describes the integral effect of the wake fields

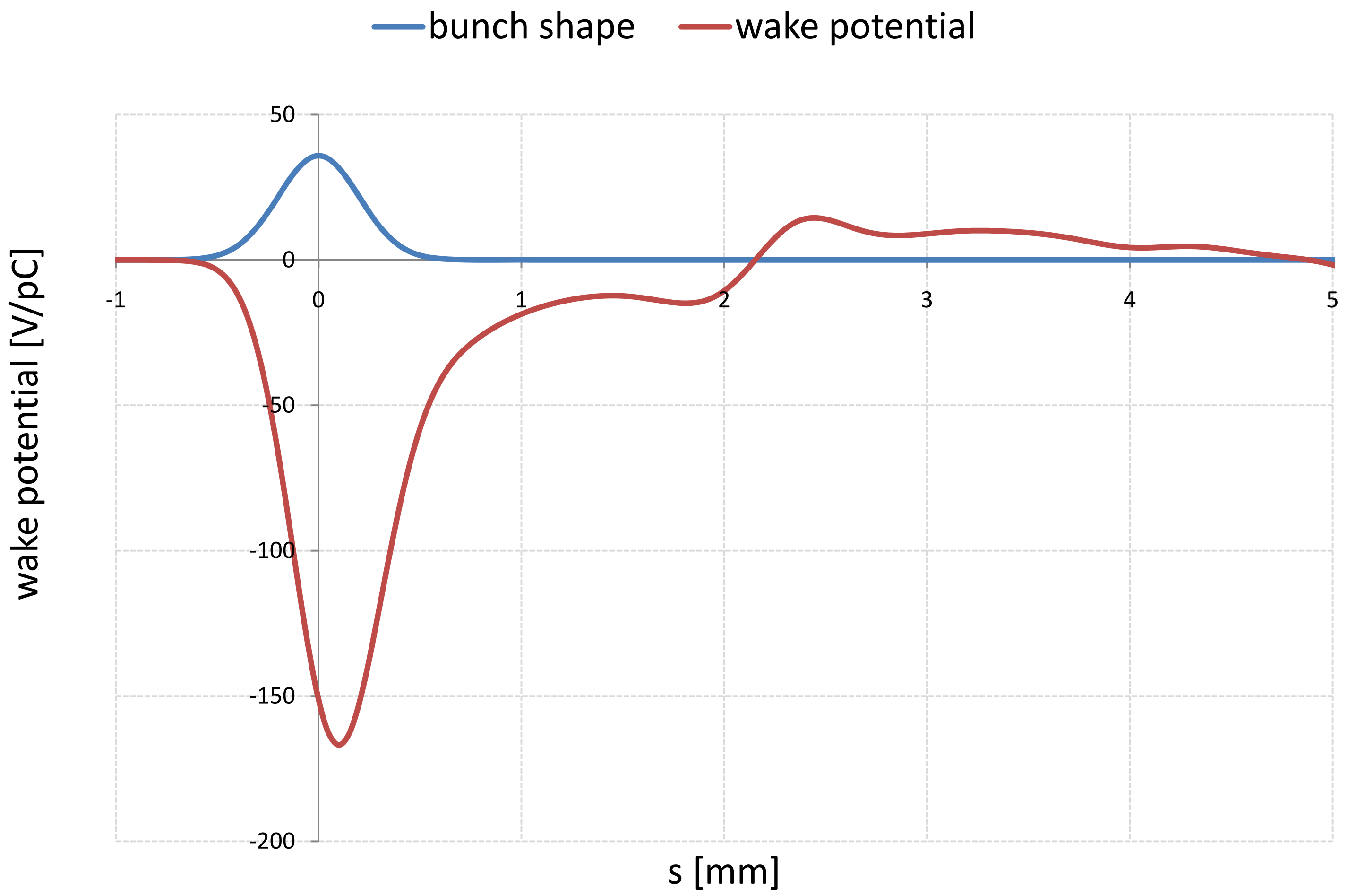
$$W(\tau) = \int_{-\infty}^{\infty} E_z(t, z)_{z=c(t-\tau)}\, dt$$

and can be calculated in the time domain by solving the 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"

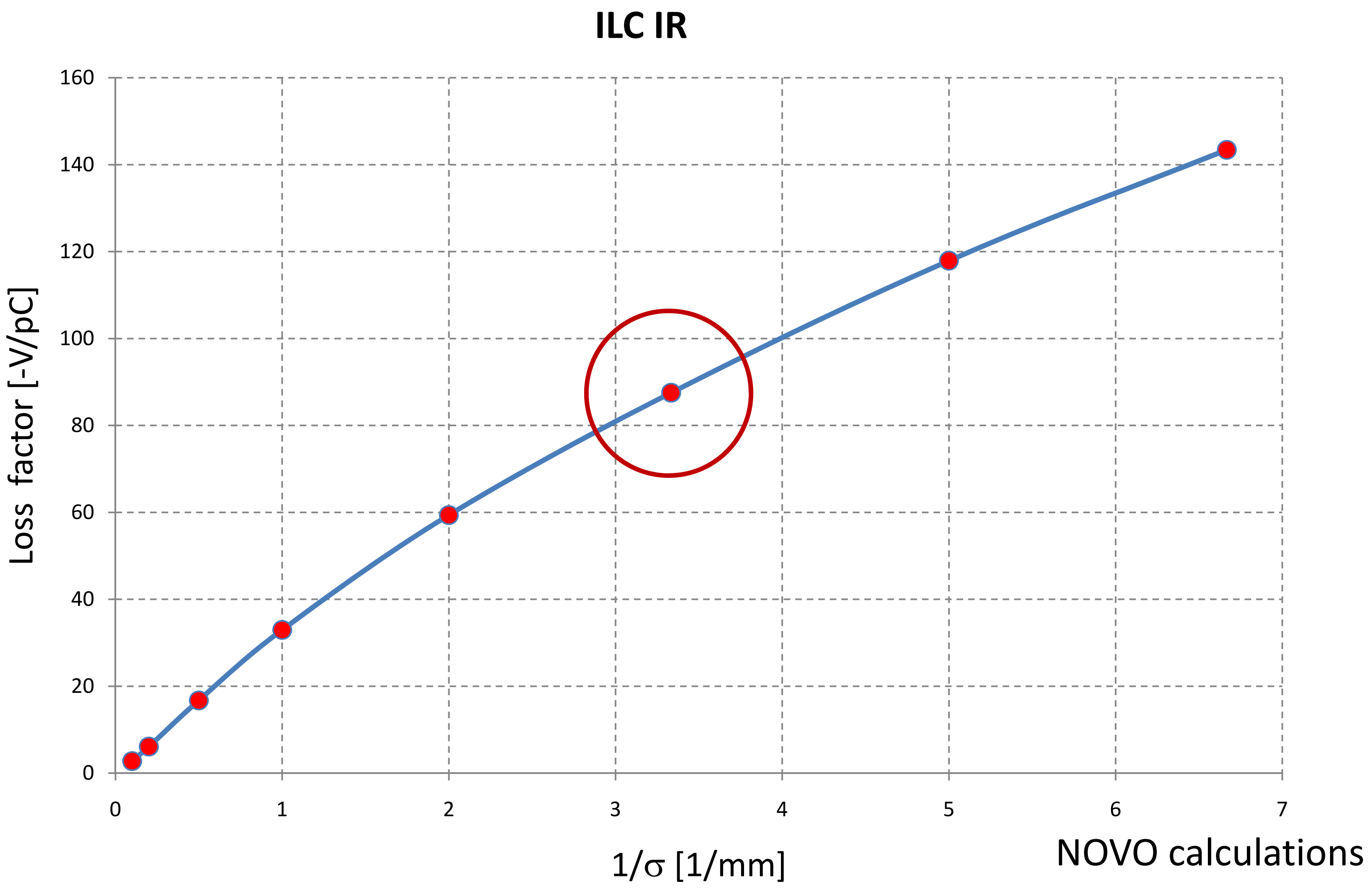
Bunch Loss Factor

- Beam energy loss is calculated by

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

- 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

Longitudinal impedance

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

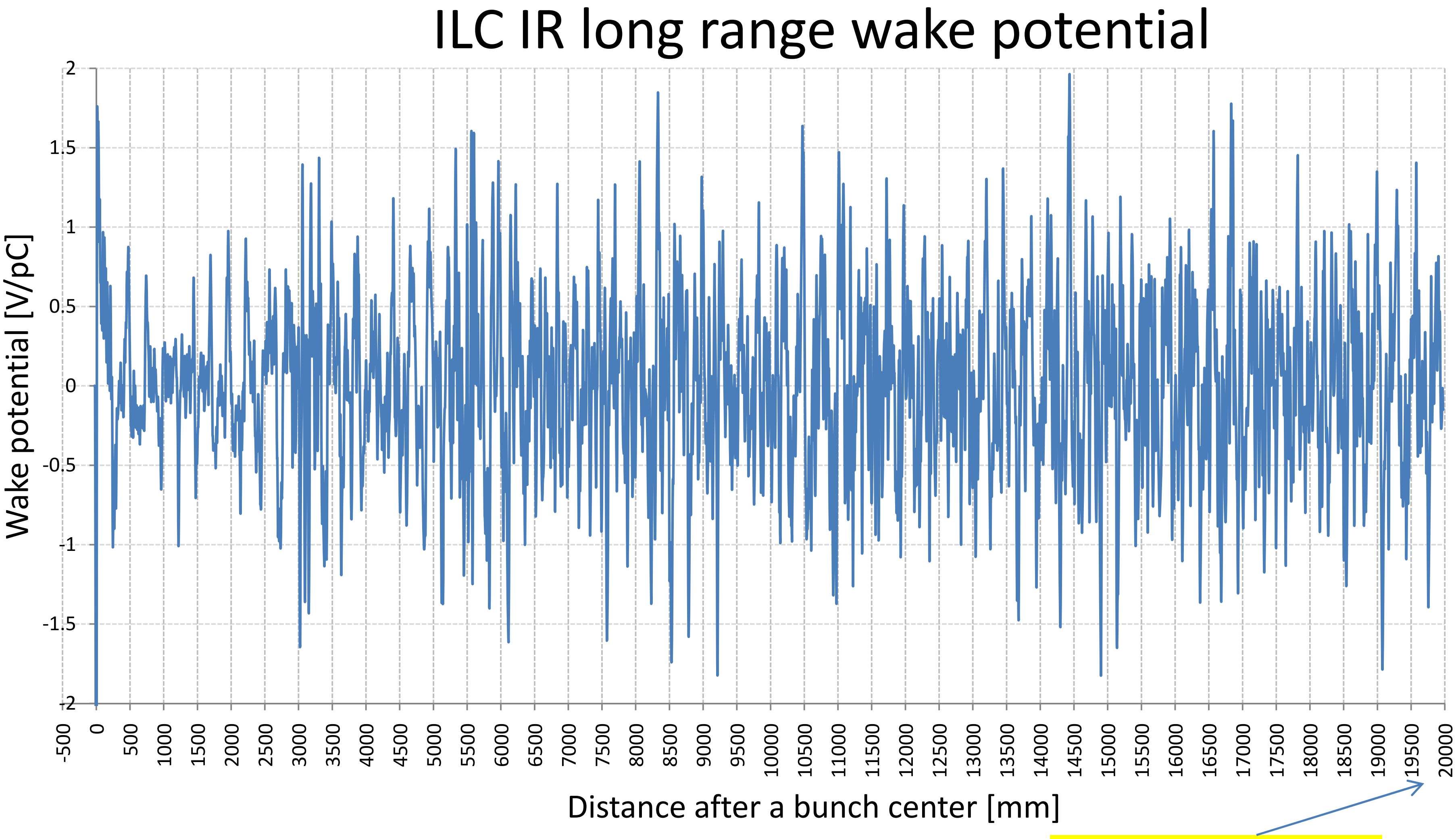
$$Z(\omega) = \int_{-\infty}^{\infty} G(\tau)\exp(-i\omega\tau)d\tau$$

- And frequency spectrum of the wake potential

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

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

Long range wake potential



20 m after a bunch

Loss integral

- We introduce loss integral for a single bunch

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

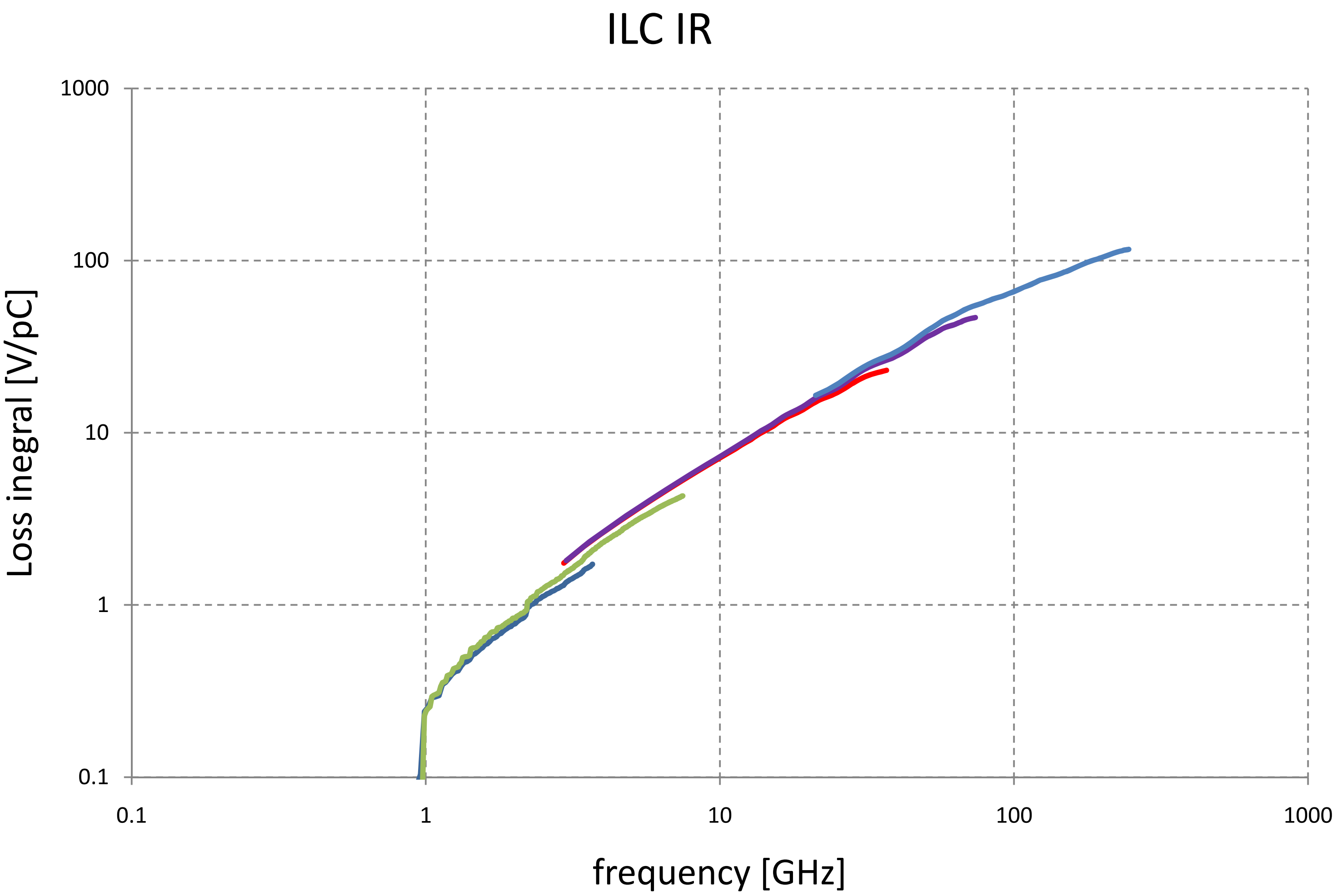
$$= \frac{1}{\pi}\int_0^{\omega} \left|\rho_s(\omega)\right|^2 \mathrm{Re}\{Z(\omega)\}d\omega$$

○

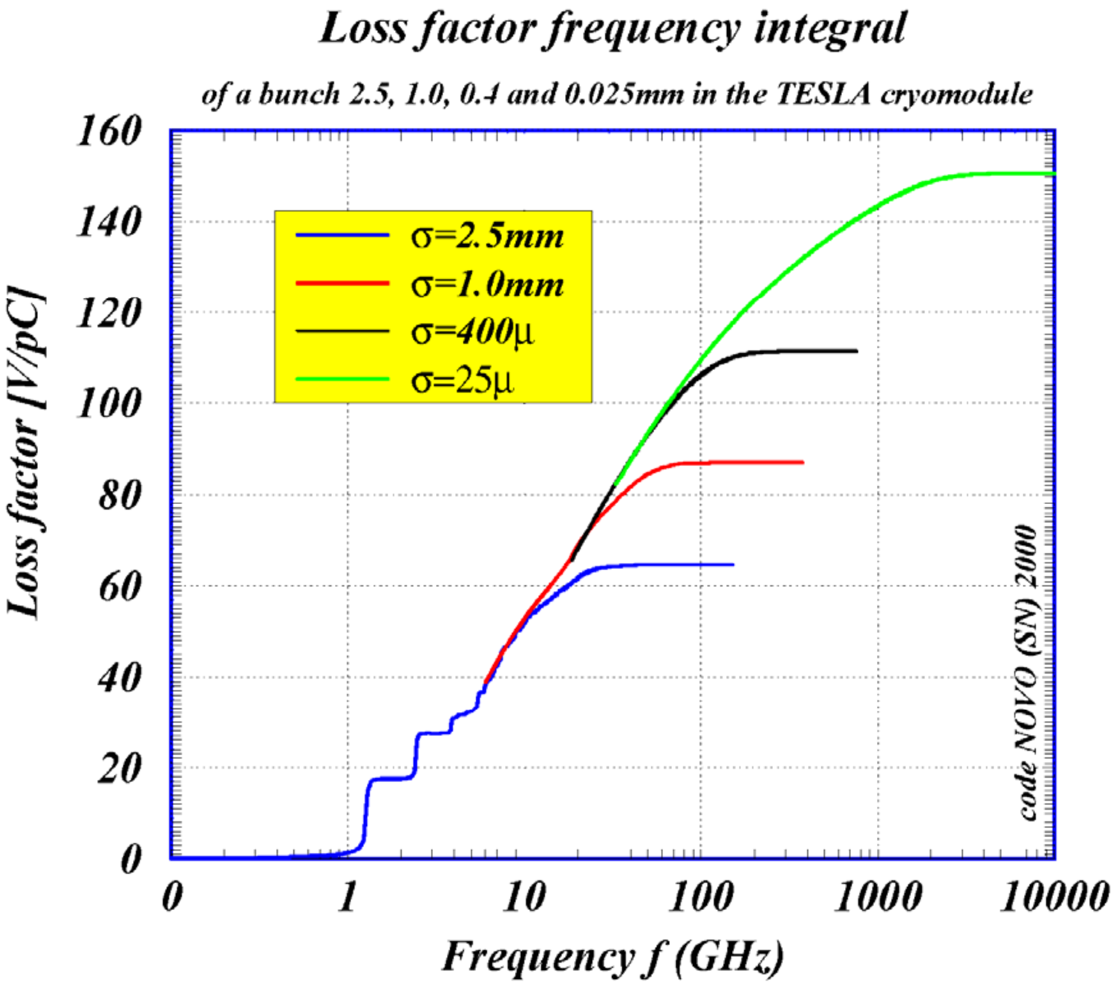
- Full integration gives the loss factor:

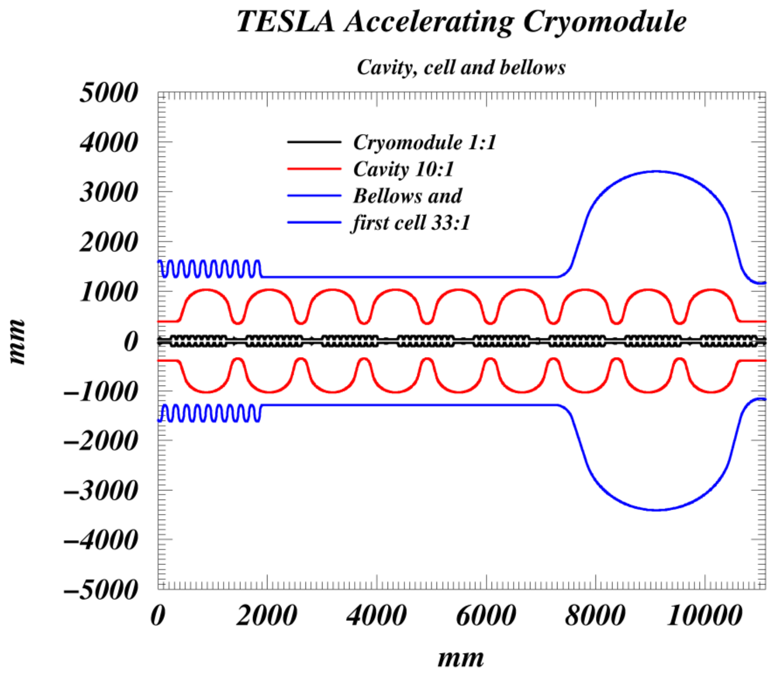
$$K_s(\omega \to \infty) = k_s$$

Loss integral of IR



Comparison with loss integral of the TESLA cryomodule





IR produce almost same amount of wake fields as one cryomodule

Power loss of a train of bunches

- Because of superposition of electromagnetic fields, the total field is a linear sum of fields of each charge. If we have a train of equal bunches spaced in time by T_b , then wake potential for the N-th bunch is a sum of wake potentials of previous bunches

$$W_N(\tau) = \sum_{m=0}^{N} W_s(mT_b + \tau)$$

Power loss

- Energy loss of *N* bunches

$$k_N = \frac{1}{\pi}\int_0^{\infty} \left|\rho_N(\omega)\right|^2 \operatorname{Re}\{Z(\omega)\}d\omega$$

- Power loss

$$P_N = \frac{k_{N+1} - k_N}{T_b} =$$

$$\frac{1}{\pi}\int_0^{\infty} \frac{\left|\rho_{N+1}(\omega)\right|^2 - \left|\rho_N(\omega)\right|^2}{T_b} \operatorname{Re}\{Z(\omega)\}d\omega$$

$$\rho_N(\omega) = \rho_s(\omega) \times \sum_{m=0}^{N} \exp(im\omega T_b) = \rho_s(\omega) \times \frac{1 - \exp(iN\omega T_b)}{1 - \exp(i\omega T_b)}$$

Some mathematics

- In case of a long bunch train

$$\lim_{N\to\infty}\frac{1}{\pi}\frac{\sin\omega T_b(N+\frac{1}{2})}{\sin\frac{\omega T_b}{2}}\to\frac{2}{T_b}\sum_{m=1}^{\infty}\delta(\omega-\omega_m)$$

- After integration we get final result

$$P=\sum_{m=1}^{\infty}\frac{2}{T_b^2}\left|\rho_s(\omega_m)\right|^2\mathrm{Re}\{Z(\omega_m)\}$$

Cut-off frequency

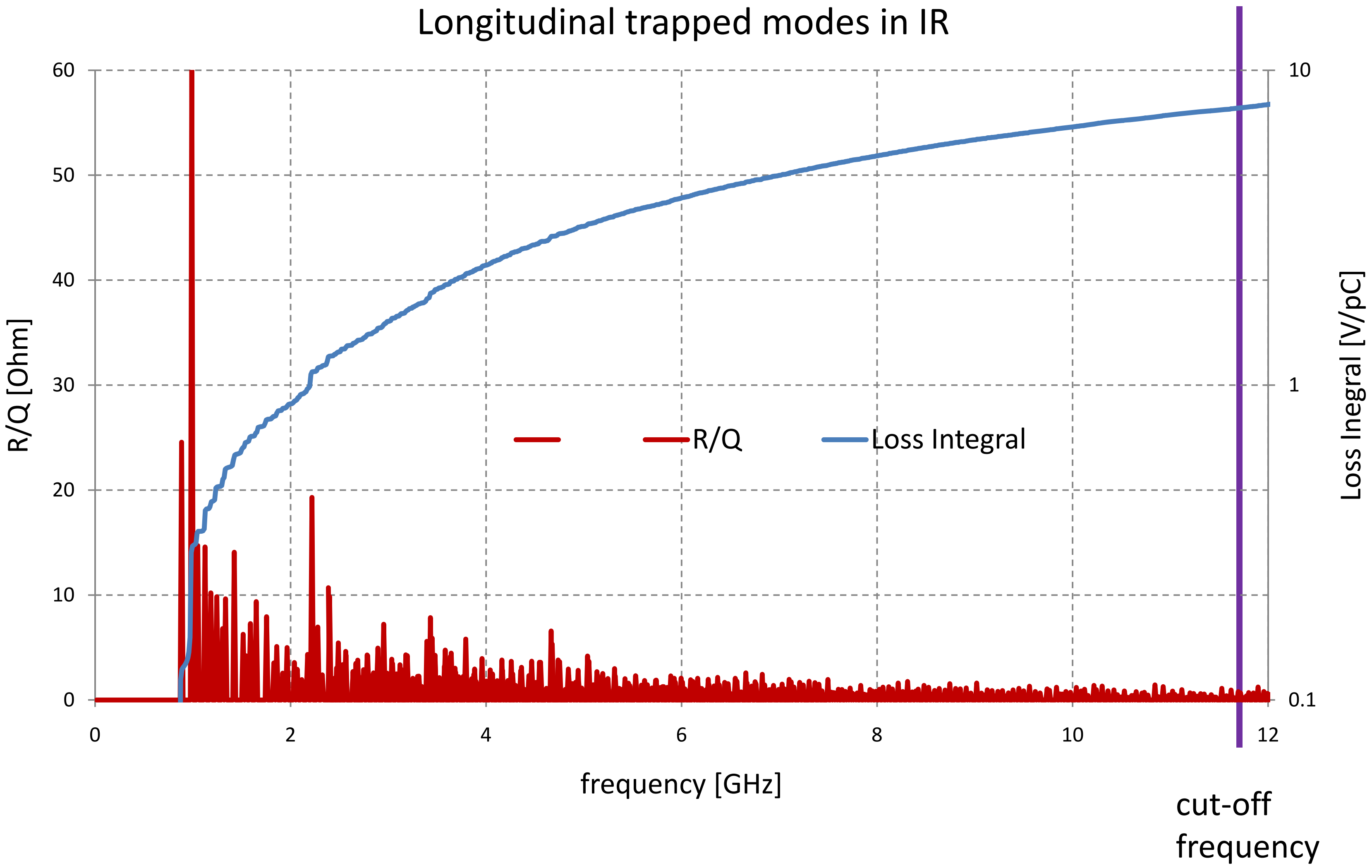
- Cut-off frequency is the maximum frequency of captured modes in a cavity.
- It is determined by the size of a beam pipe.
- For E01 mode

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

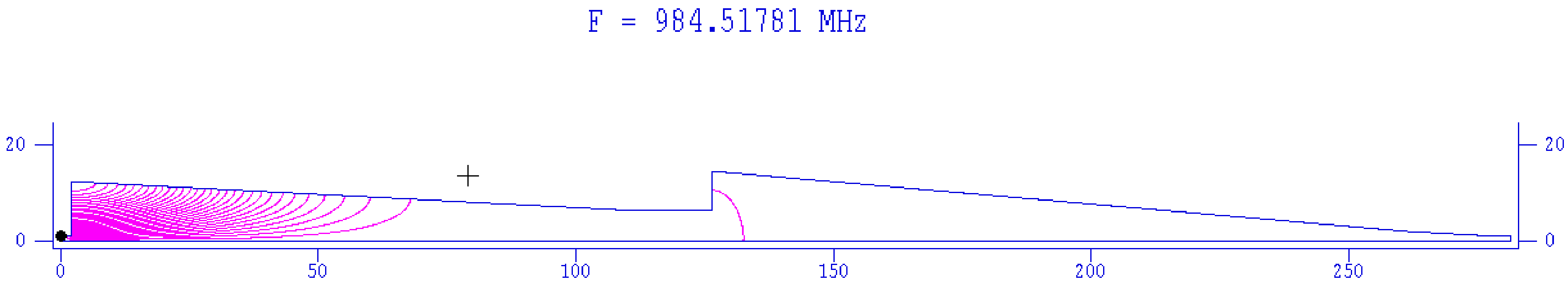
ILC IR: a=10mm=0.01m

f=11.47 GHz

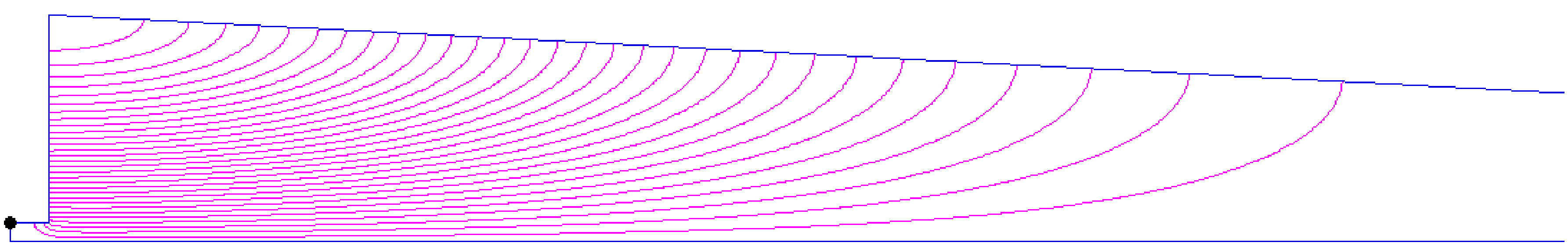
Trapped modes of IR



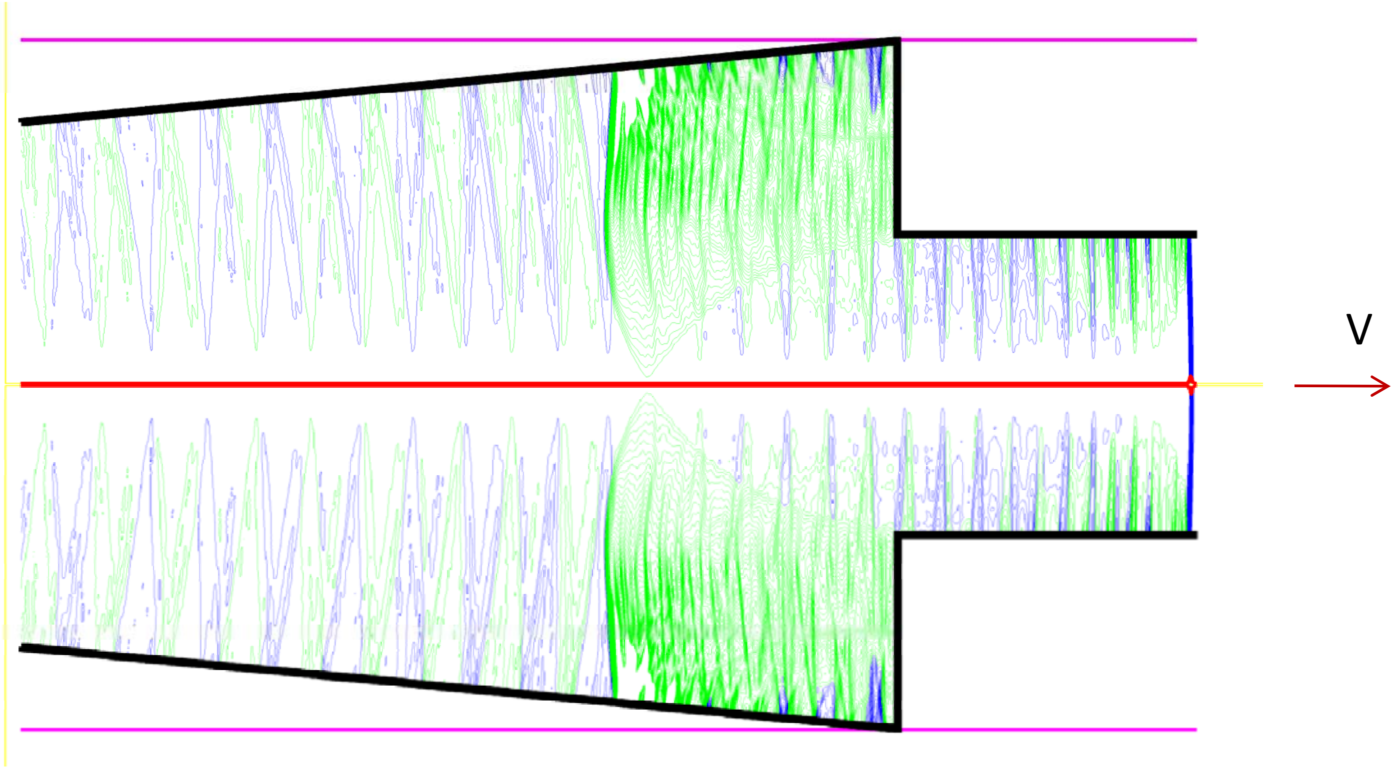
Second mode(363 harmonics): maximum R/Q



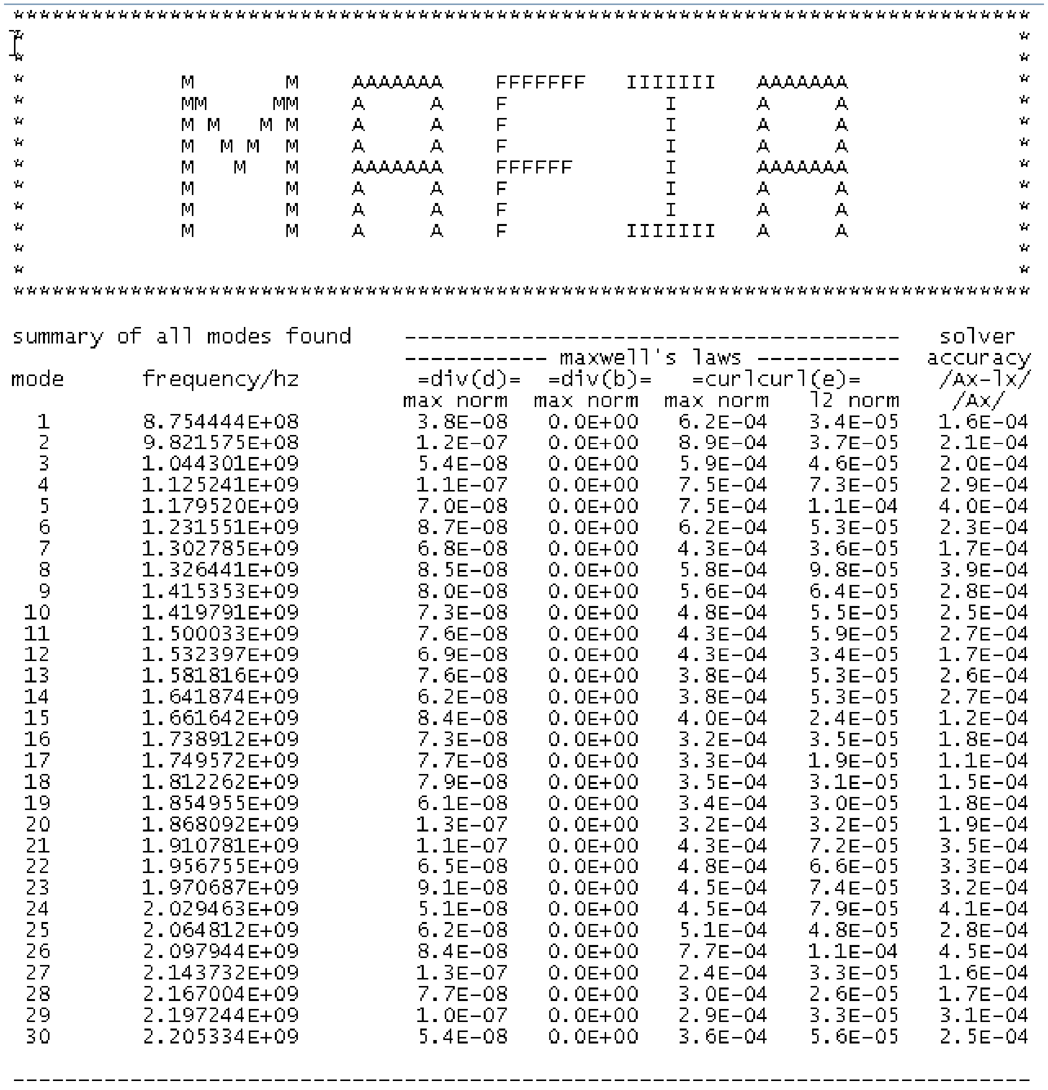
zoomed



Wake fields in the corner

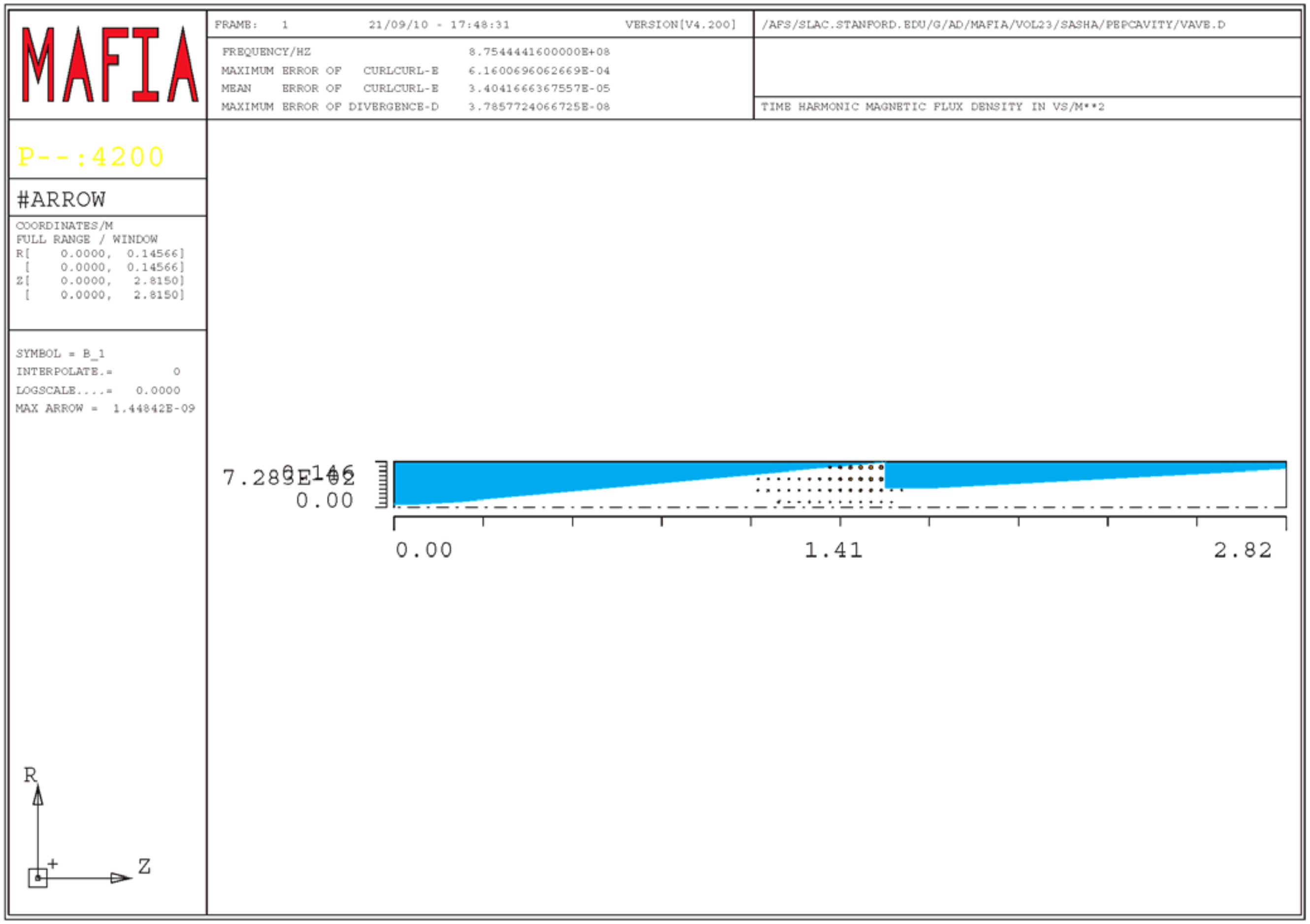


MAFIA simulations



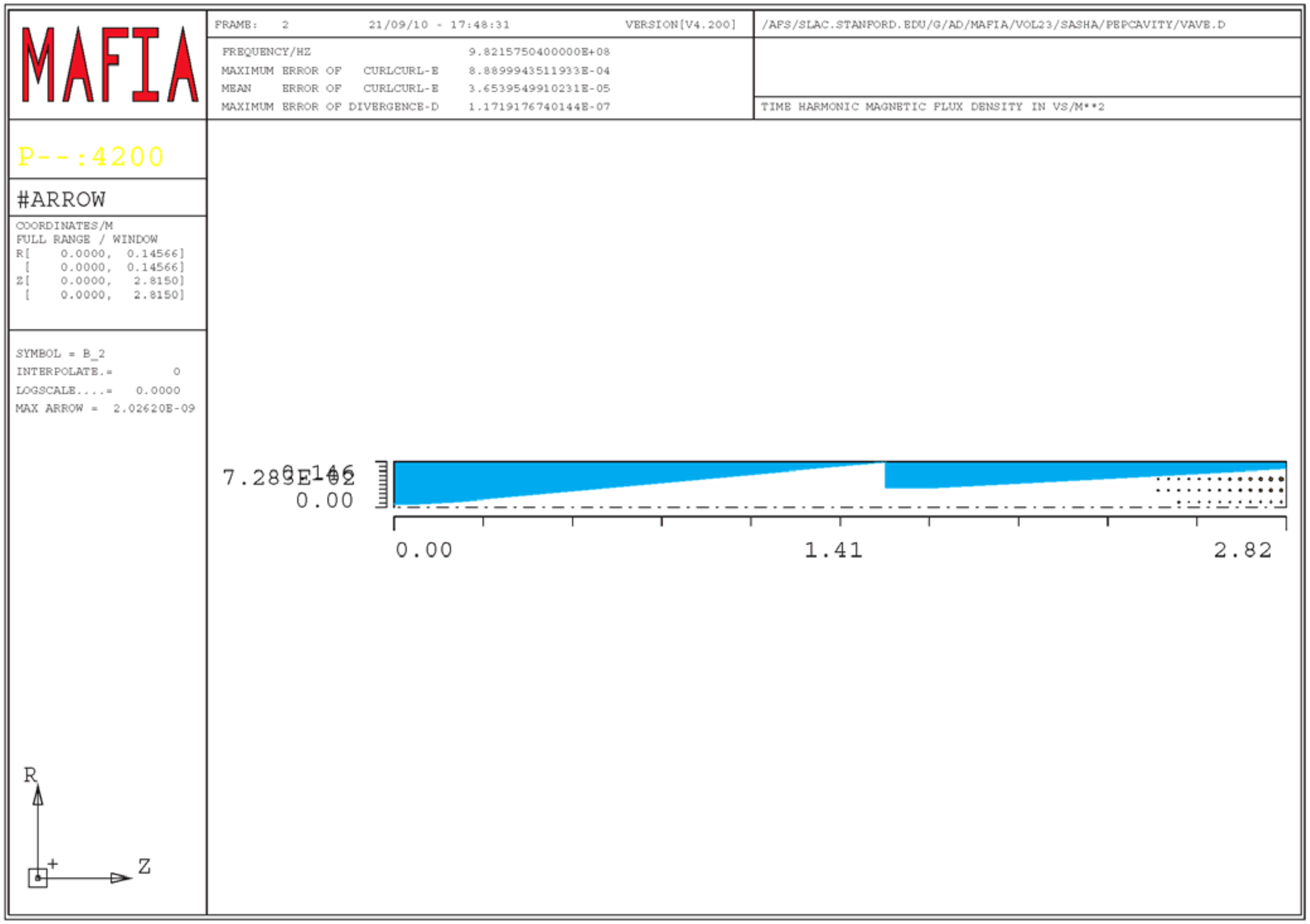
```
******************************************************************************
*                                                                            *
*                                                                            *
*            M       M    AAAAAAA    FFFFFFF   IIIIIII   AAAAAAA             *
*            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    --------------------------------------   solver
                              ----------- maxwell's laws -----------  accuracy
mode      frequency/hz         =div(d)=  =div(b)=   =curlcurl(e)=      /Ax-lx/
                              max norm  max norm  max norm   l2 norm    /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
```

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
```

Interaction with one mode

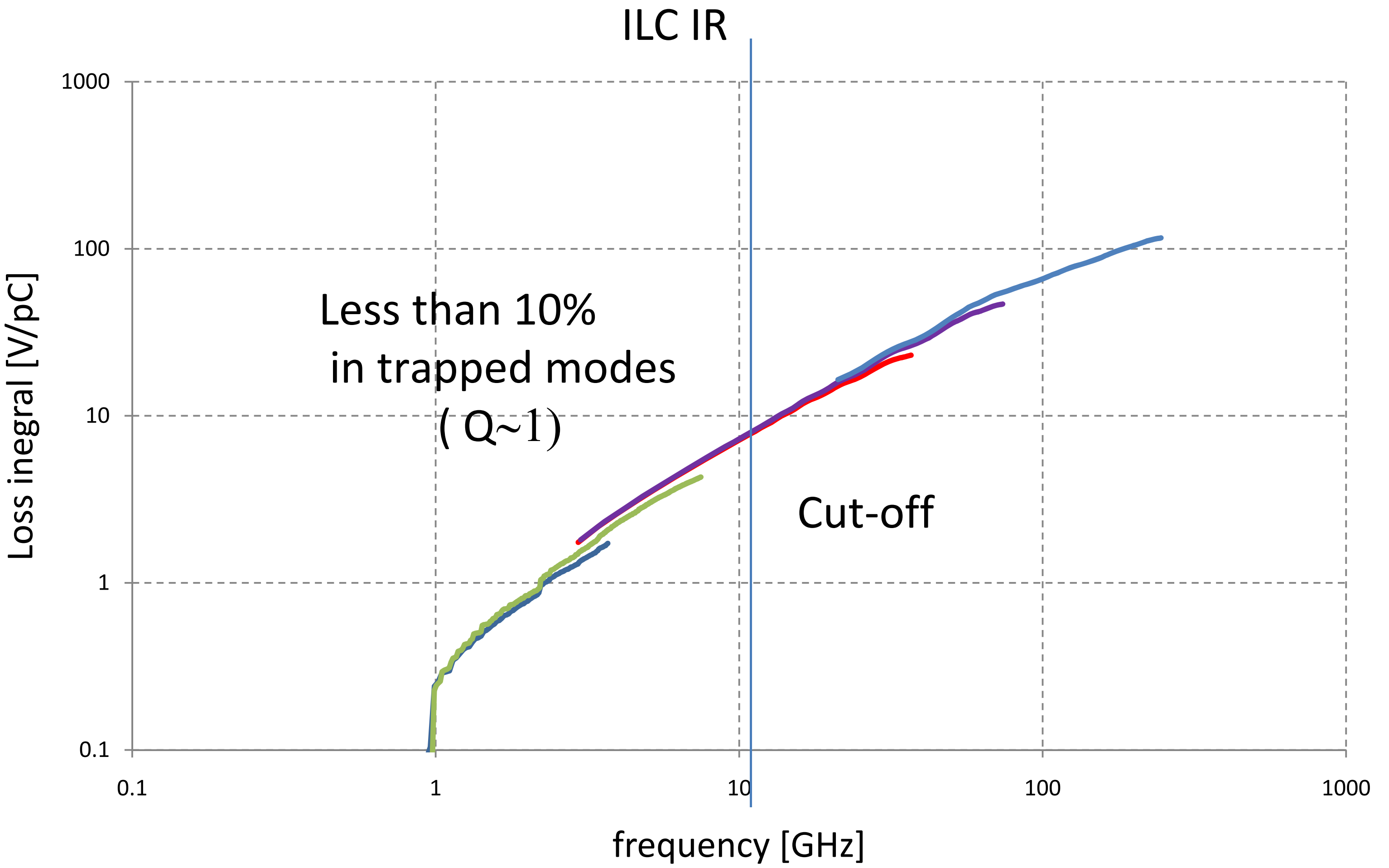
Mode voltage decay	$V(t)=V(o)\,e^{-\frac{t}{\tau_{l,n}}}$
Loaded time decay or filling time	$\tau_{l,n}=\frac{2Q_l}{\omega_n}=\frac{2Q_l}{2\pi f_n}=\frac{Q_l}{\pi f_n}$
Loaded Q-value which includes coupling	Q_l
Bunch spacing	τ_b
Mode **survives** to the next bunch if	$\frac{\tau_b}{\tau_{l,n}}<<1$
and loaded Q	$Q_l>>\frac{\omega_n\tau_b}{2}=\pi f_n\tau_b$

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	$P_n = I^2 \frac{\omega_n}{2} \frac{R}{Q} \tau_b$	$P_n = I^2 \frac{R}{Q} Q_l$
Loss factor $k_n = \frac{\omega_n}{2} \frac{R}{Q}$	$P_n = I^2 k_n \tau_b$	$P_n = 2I^2 k_n \tau_{l,n}$

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

Loss integral and cut-off frequency



Total loss power (all trapped modes)

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

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

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

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

Average power is 200 times smaller

Power loss above cut-off frequency

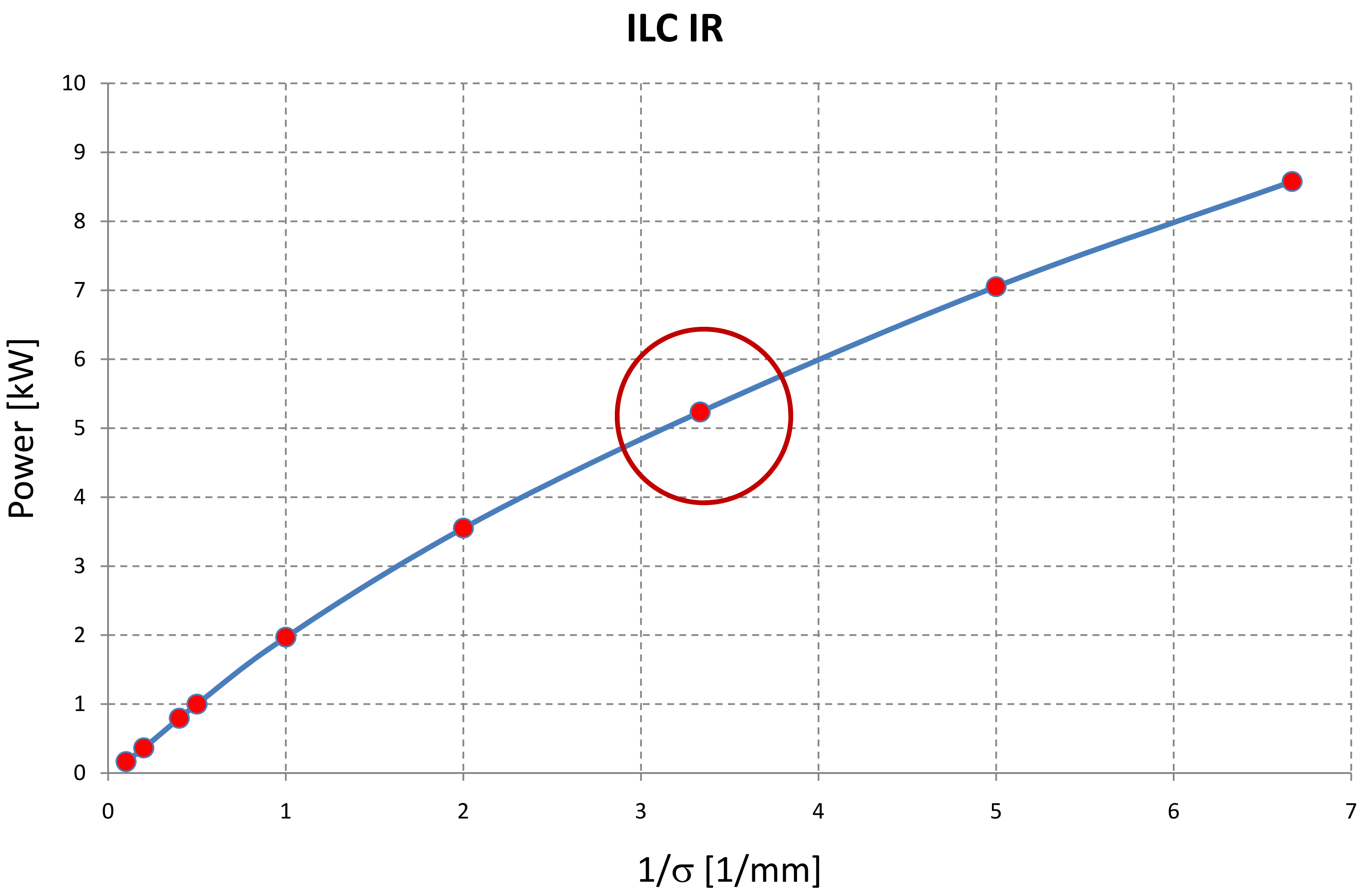
- The spectrum here is more or less smooth function of frequency and we can change the sum of series back to integral

$$P = \sum_{m=1}^{\infty} \frac{2}{T_b^2} \left|\rho_s(\omega_m)\right|^2 \mathrm{Re}\{Z(\omega_m)\} \approx \int_{\omega_{cut-off}}^{\infty} \frac{1}{\pi T_b} \left|\rho_s(\omega_m)\right|^2 \mathrm{Re}\{Z(\omega_m)\} d\omega$$

- The beam power loss above cut-off frequency

$$P = I_{beam}^2 \times T_b \times (k_s - K(\omega_{cut-off}))$$

Power in a pulse (two beams)

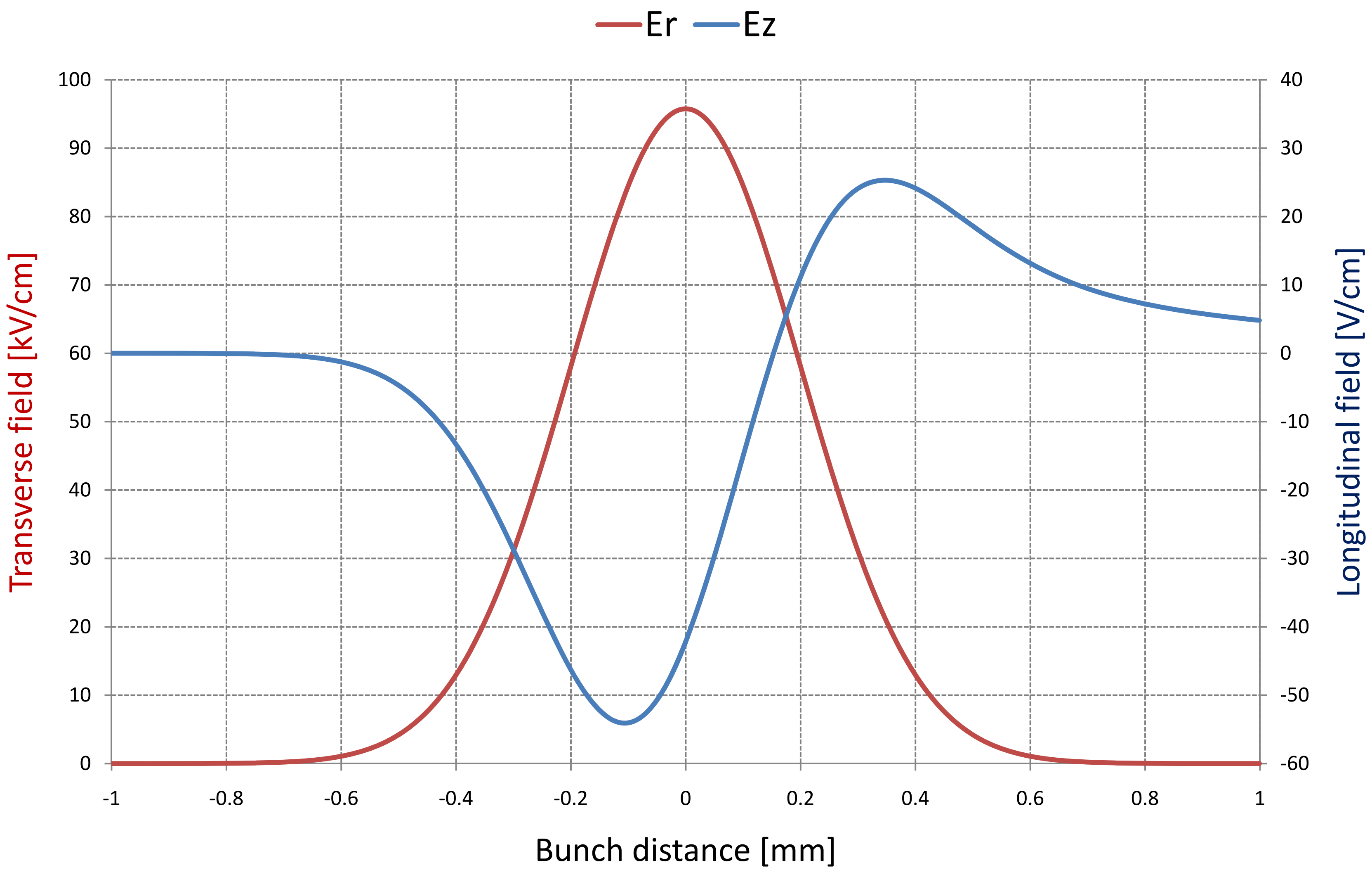


Resistive-wall wake fields

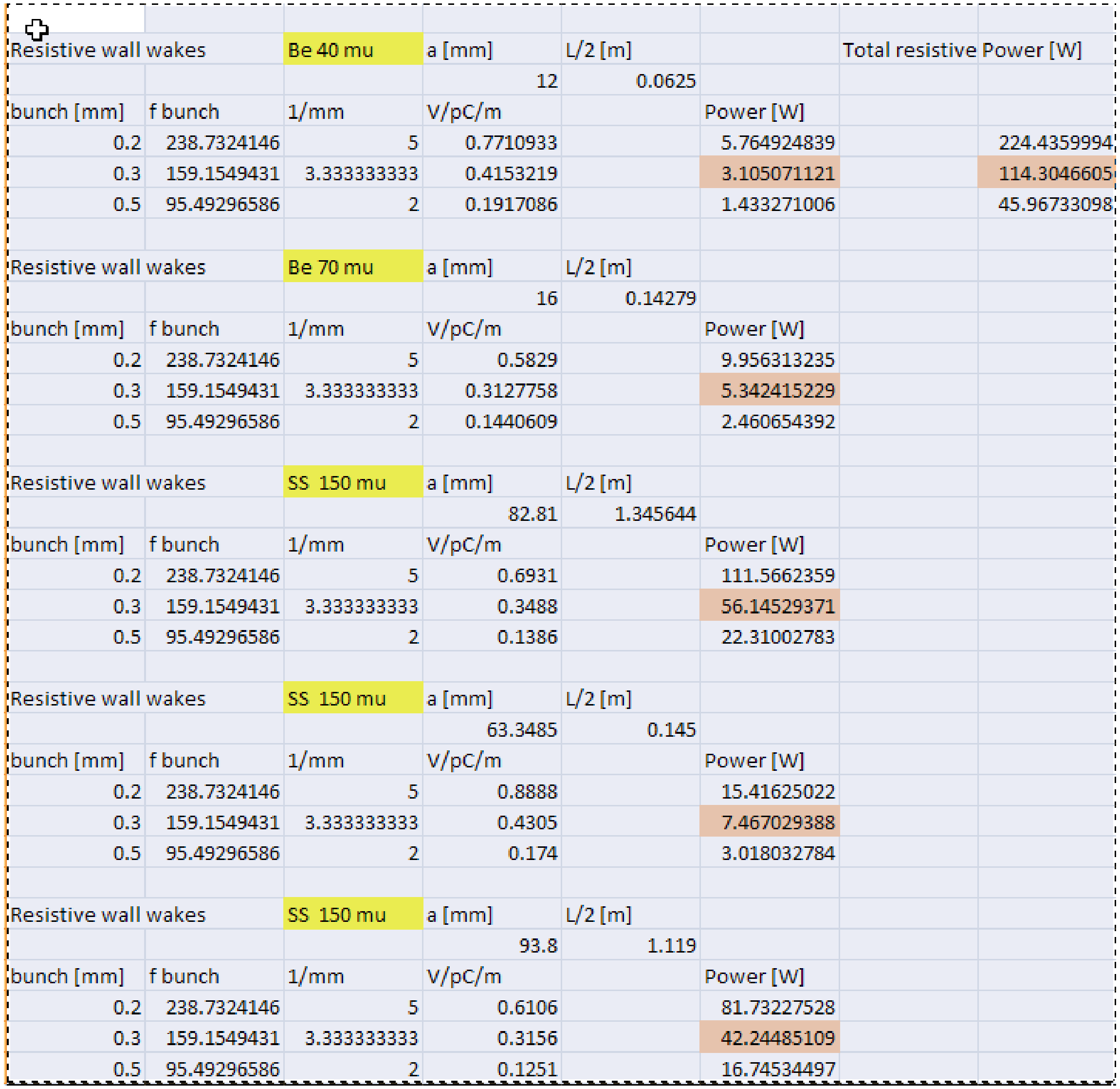
(Losses of image currents)

conductivity	/Ohm/mm		
Al	35000		
Cu	58000		
SS	1400		
Au	48800		
Be	25000		
Ni	14600		
NEG	55	???	To be checked

Fields at the Be chamber wall. Bunch 0.2 mm



Power loss due to resist 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 energy loss in IR is almost the same as energy loss in one accelerating cryo-module.
- Addition energy spread at IR is not more than 0.2 MeV
- Average power of IR wake fields is of order of 30 W, when pulse power is of order of several of kilowatts.
- The spectrum of the wake fields is bounded by 300 GHz
- Transverse wake fields may travel long distance and penetrate inside bellows, pumps and vacuum valves and may interfere with sensitive electronics.