LCLS-II Technical Note

CSR Radiation in BC2 of LCLS-II

LCLS-II TN-15-39

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G. Stupakov
SLAC, Menlo Park, CA 94025, USA

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G. Stupakov
(K. Bane, M. Dohlus, H. Loos, P. Emma, GS)

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Motivation

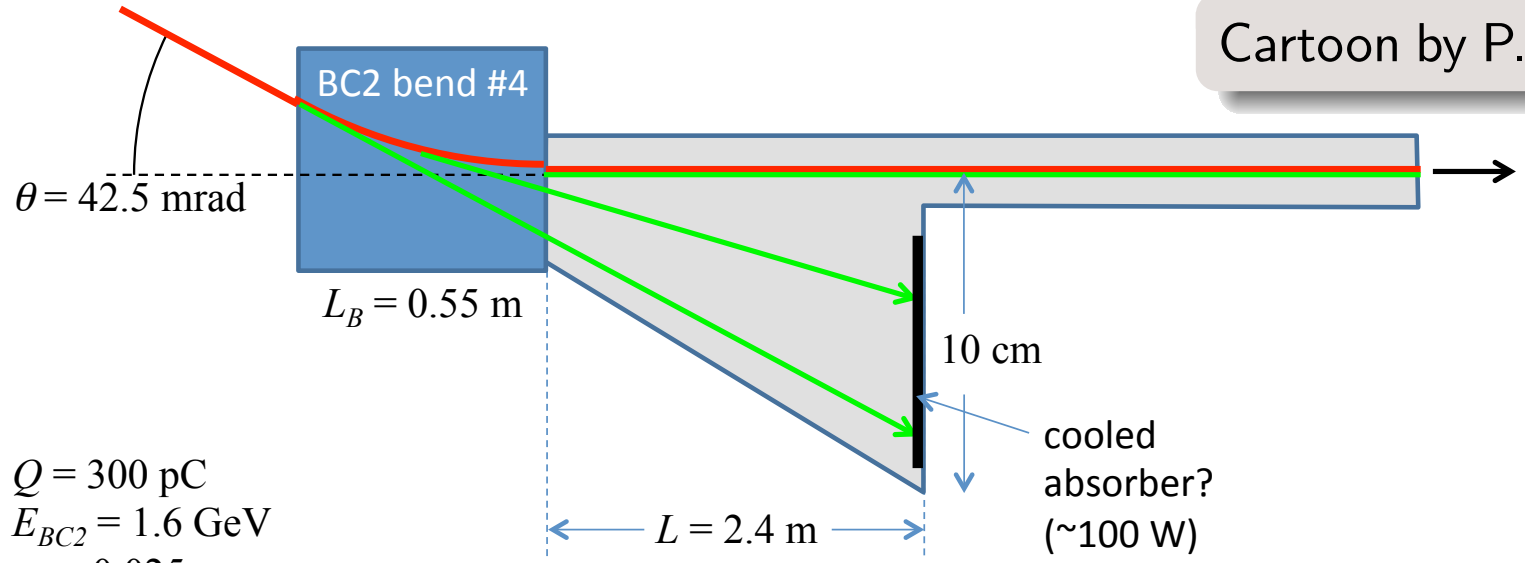
Motivation for this study:

- Calculate the energy loss of the beam due to the coherent radiation in the last bend of BC2
- Evaluate local heating of metal surfaces of the vacuum chamber caused by the CSR radiation
- Understand how much of radiated energy can propagate to the nearest cryomodule

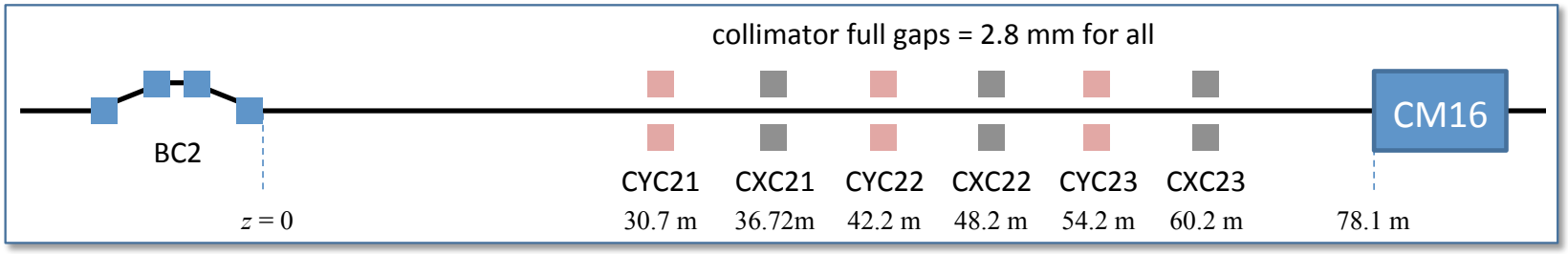
There is no code that could simulate the beam radiation at short wavelenghts that takes into account the longitudinal beam profile, the shielding effect of the metallic walls of the vacuum chamber and attenuation of the EM radiation due to ohmic losses in the walls. We used a combination of various methods. Sometimes we had to start from crude models and then tried to improve on them.

CSR Trap for BC2 ?

Cartoon by P. Emma.



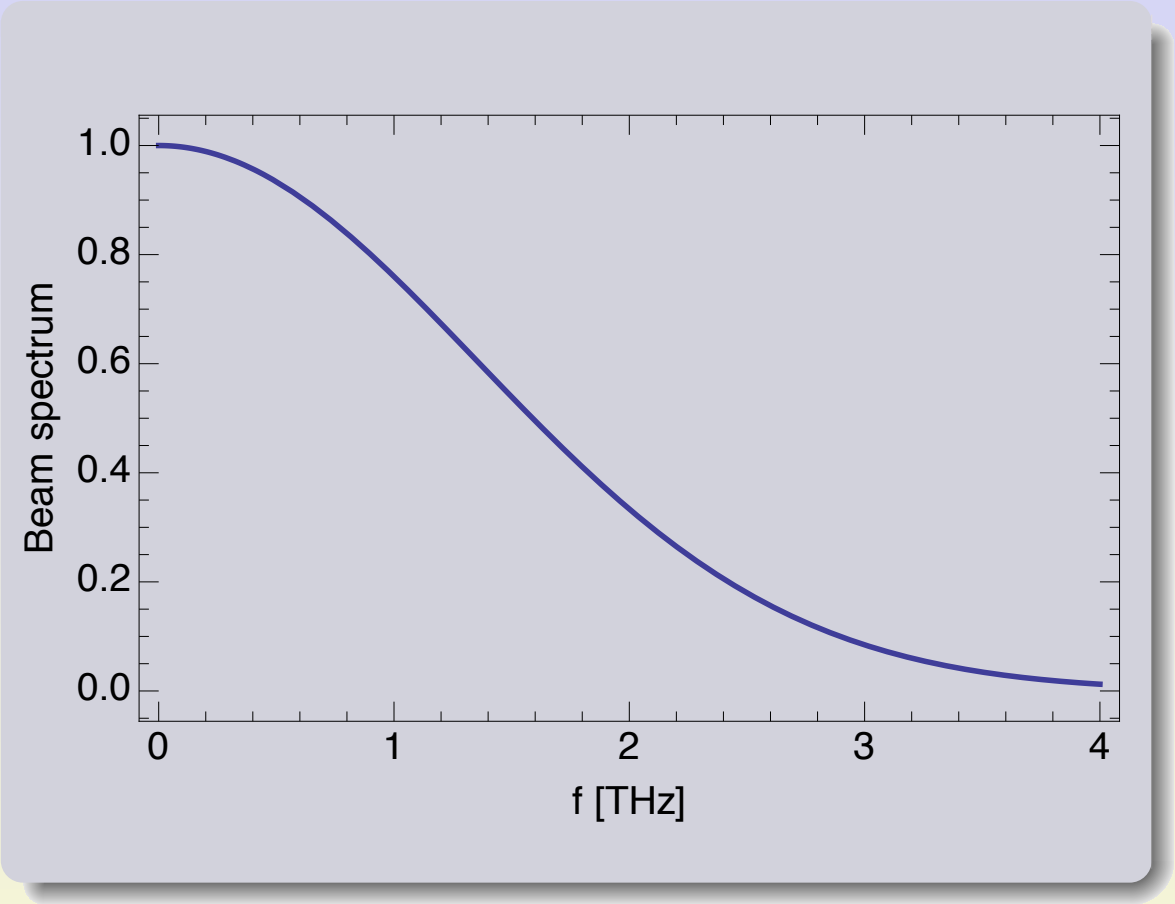
$Q = 300$ pC
$E_{BC2} = 1.6$ GeV
$\sigma_z = 0.025$ mm
$f_{max} = 0.929$ MHz
$\sigma_x = 0.020$ mm (at BC2 4th bend exit)
$\sigma_y = 0.16$ mm (at BC2 4th bend exit)



Bending radius $\rho = 12.9$ m.

Beam spectrum extends to THz frequencies

Assuming Gaussian beam distribution with $\sigma_z = 25\ \mu\text{m}$



Beam spectrum extends to 2-3 THz, the wavelengths $100 - 150\ \mu\text{m}$.

Simple estimate of CSR power

A simple estimate uses steady-state CSR radiation and neglects shielding[1]:

$$P_{CSR} = \varkappa_{CSR} L_b Q^2 f_{rep}$$

with (ρ—the bending radius, L_b—the length of the bend)

$$\varkappa_{CSR} = 0.76 \frac{Z_0 c}{2 \cdot 3^4/3\pi} \frac{1}{\rho^{2/3} \sigma_z^{4/3}}$$

Estimated radiation power: $Q = 300$ pC, repetition rate $f_{rep} = 1$ MHz.

E [GeV]	1.6
L [m]	0.55
ρ [m]	10.2
σ_z [μm]	24

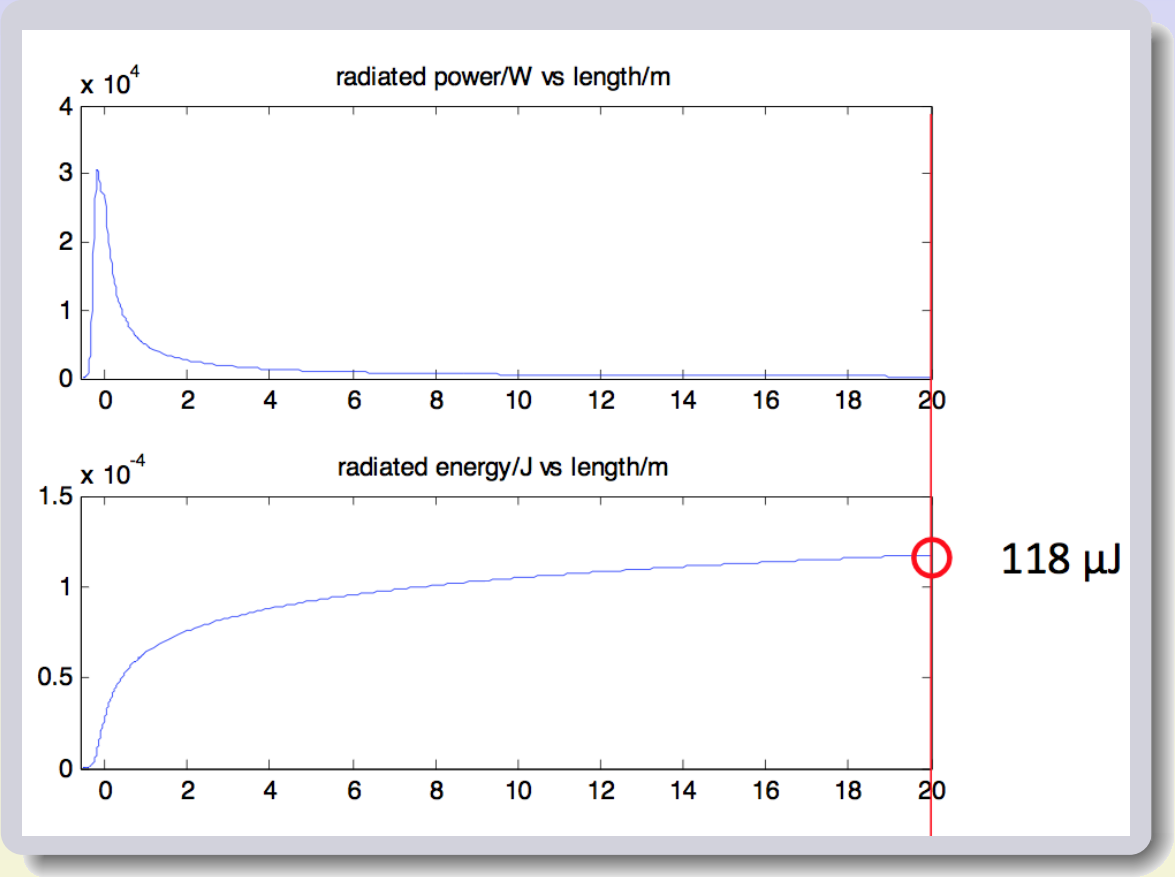
This gives $P_{CSR} = 48.5$ W.
The steady-state model is valid if $L \gg \ell$:

$$\ell = (24\sigma_z \rho^2)^{1/3} \approx 40 \text{ cm}$$

[1] K. Bane, P. Emma. Estimates of Power Radiated by the Beam in Bends of LCLS-II, LCLS-II TN-13-03.

Correction: beam energy loss after the exit

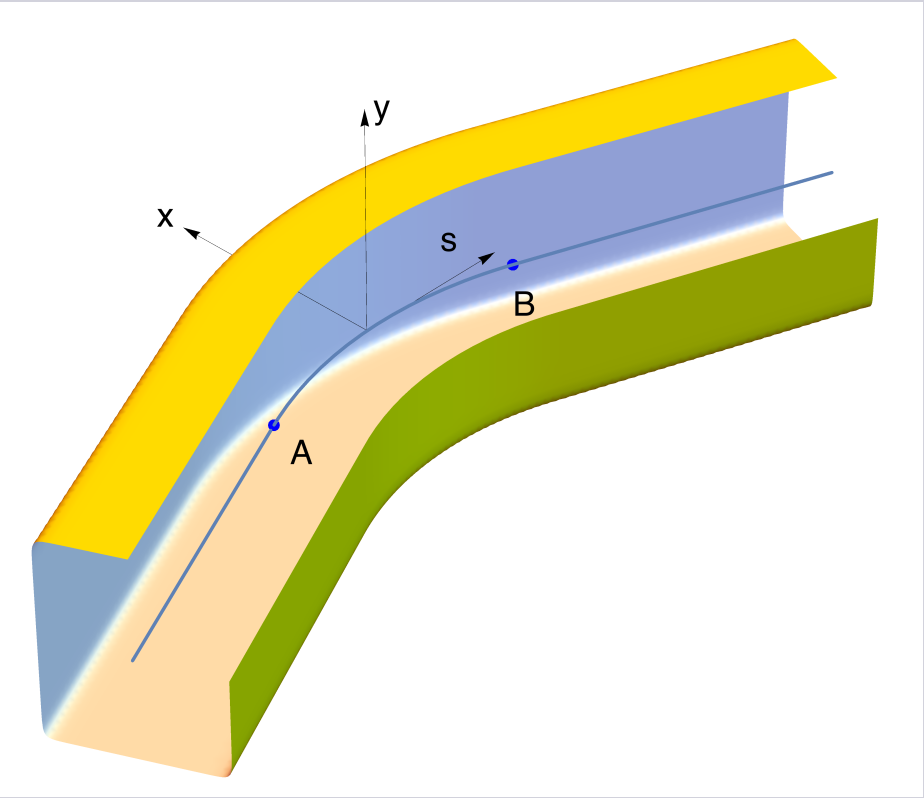
M. Dohlus: the beam keeps loosing energy after exiting the bend.
Calculation for CSR in free space:



The long tail of the wake is due to the edge radiation of the beam.
Shielding is important when $a/\sigma_z \lesssim \gamma$ where a is the pipe radius.

Calculation with account of shielding and finite bend length

I have a code which computes the CSR wakefield in a bend in a rectangular vacuum chamber[2].



Vacuum chamber: full vertical gap $2\mathfrak{h} = 3.2$ cm, and the full horizontal gap 9.6 cm. The beam radiates 113 μJ energy (113 W); this agrees with M. Dohlus's two-parallel-plates result: 120 μJ. Also, the wakefields calculated at various distances from the exit of the bend agree between the two codes.

[2] Stupakov, Kotelnikov, PRST-AB, **12**, 104401, (2009)

CSR Power in LCLS-II Bends

CSR Power in LCLS-II Bends

LCLS-II TN-15-31

9/4/2015

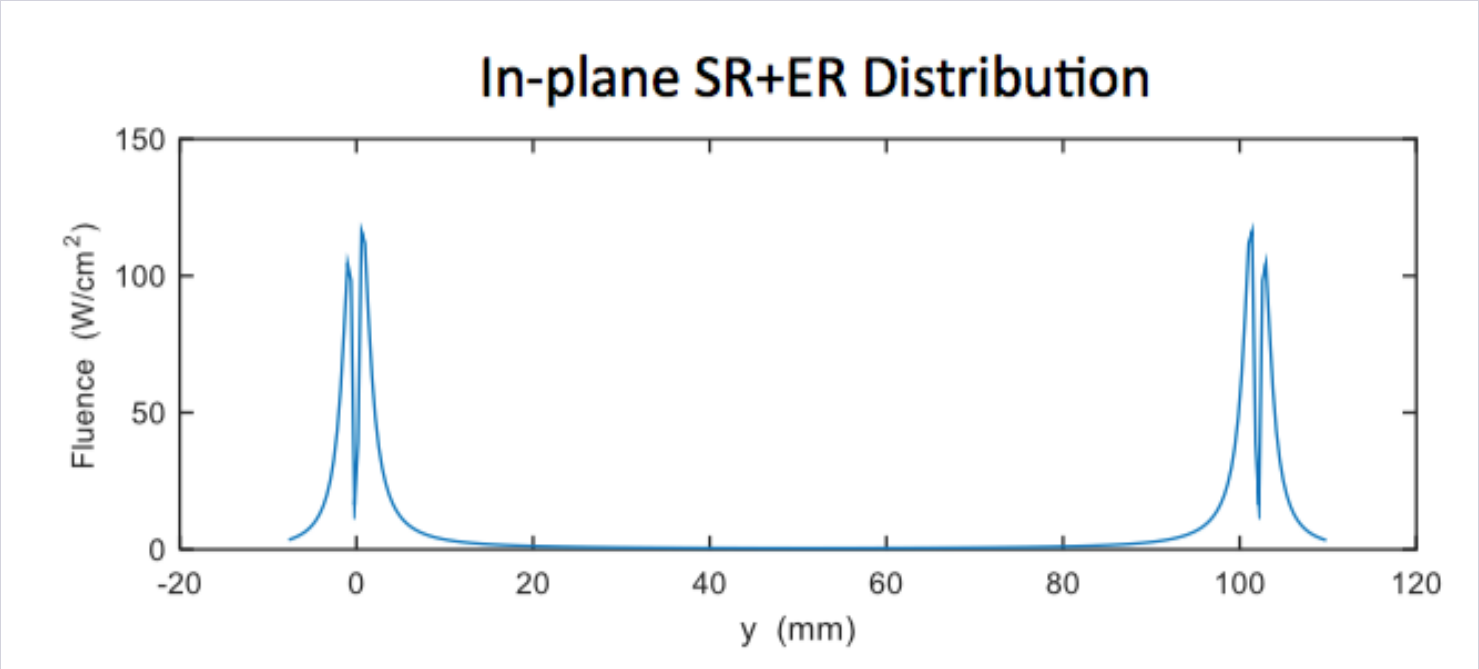
Paul Emma

Table 1: Average CSR power for each LCLS-II bend which transports the short bunch.

Bend Magnet Name	Energy (GeV)	Bend Angle (mrad)	Bend Length (m)	Rate (Hz)	CSR Power (W)
Common Line					
BCX24	1.600	42.5	0.55	929	42.6
BCXDLU1	4.000	10.7	0.35	929	14.7
BCXDLU2	4.000	-10.7	0.35	929	14.7
BCXDLU3	4.000	-10.7	0.35	929	14.7
BCXDLU4	4.000	10.7	0.35	929	14.7
BRB1	4.000	24.5	1.00	929	36.0
BRB2	4.000	-24.5	1.00	929	36.0
BCXDLD1	4.000	10.7	0.35	929	14.7
BCXDLD2	4.000	-10.7	0.35	929	14.7
BCXDLD3	4.000	-10.7	0.35	929	14.7
BCXDLD4	4.000	10.7	0.35	929	14.7

Can edge radiation locally heat the vacuum chamber?

See cartoon, s. 3. H. Loos simulated fluence of radiation on the wall assuming free space.



The peaks are due to the edge radiation from the bend.

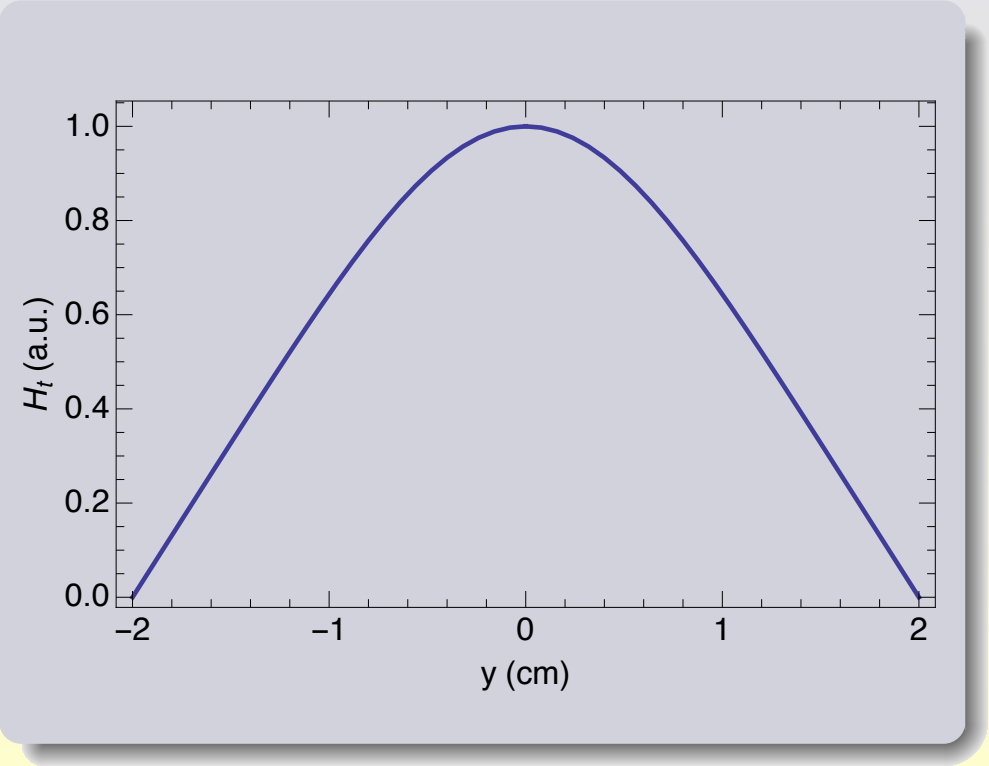
Edge radiation is the similar to the transition radiation from a metal foil, in free space it is localized at angles $\sim 1/\gamma$. It can be shielded by the parallel plates if $a \lesssim \lambda\gamma \approx 25\ \mu\text{m} \times 3200 = 8$ cm.

Can edge radiation locally heat the vacuum chamber?

Even with the incident fluence of 120 W/cm^2 only 3 W/cm^2 is absorbed in stainless steel wall [$\sigma = 1.4 \times 10^4/(\mathrm{Ohm} \cdot \mathrm{cm})$].

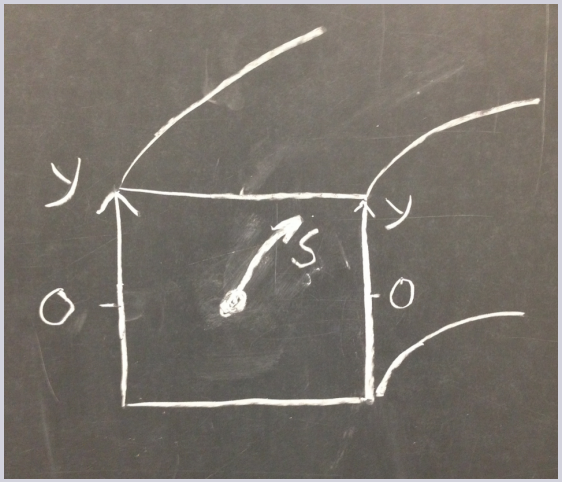
When the beam propagates in a straight round SS pipe of radius 2 cm, the heating from the image currents is ≈ 1.5 mW/cm^2.

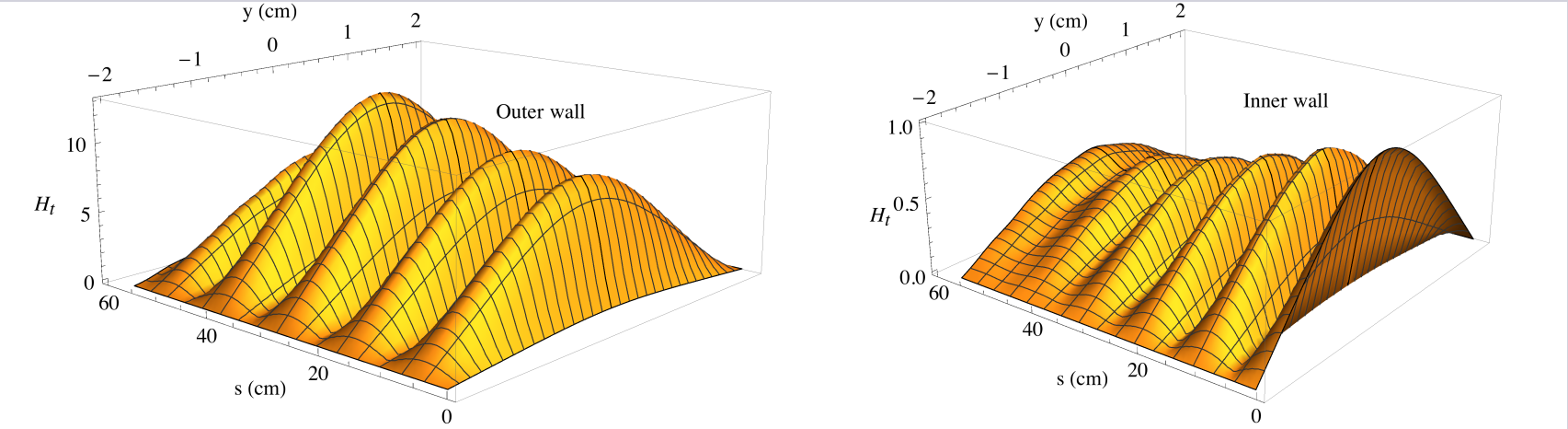
For a square cross section of the vacuum straight pipe (see s. 7), 4 cm$\times$ 4 cm, the tangential magnetic field distribution on the wall is shown below. Heating $\propto |\mathrm{H_t}|^2$.



Magnetic field in toroidal pipe

We can also calculate H_t and the heating of the walls in the toroidal part of the vacuum chamber. In calculations I assumed 4 cm$\times$ 4 cm cross section, $\rho = 12.9$ m. Calculation were done for one frequency, $f = c/(2\pi\sigma_z) = 1.9$ THz.





We estimate the energy deposition on the outer wall of the toroid ~ 0.2 W/cm^2.

Attenuation of waveguide modes in straight waveguide

See cartoon, s. 3. From Landau&Lifshitz, "Electrodynamics of Continuous Media": attenuation of waveguide modes in a round pipe of radius a.

PROBLEM 2. The same as Problem 1, but for a waveguide whose cross-section is a circle with radius a.

SOLUTION. Solving the wave equation in polar coordinates r, ϕ, we have for E waves

$$E_z = \text{constant} \times J_n(\kappa r) \begin{matrix} \sin \\ \cos \end{matrix} n\phi$$

with the condition $J_n(\kappa a) = 0$, which gives the values of κ. In H waves the value of H_z is given by the same formula, but κ is determined by the condition $J_n'(\kappa a) = 0$. The smallest value of κ occurs for the H_1 wave, and is $\kappa_{\min} = 1.84/a$.

The damping coefficient is calculated from formulae (91.12)–(91.14). For E waves it is $\alpha = \omega\zeta'/cak_z$, and for H waves

$$\alpha = \frac{c\zeta'\kappa^2}{\omega k_z a}\left[1 + \frac{n^2\omega^2}{c^2\kappa^2(a^2\kappa^2 - n^2)}\right].$$

For TM modes (δ is the skin depth $\propto 1/\sqrt{\omega}$)

$$\alpha = \frac{\omega k \delta}{2cak_z}$$

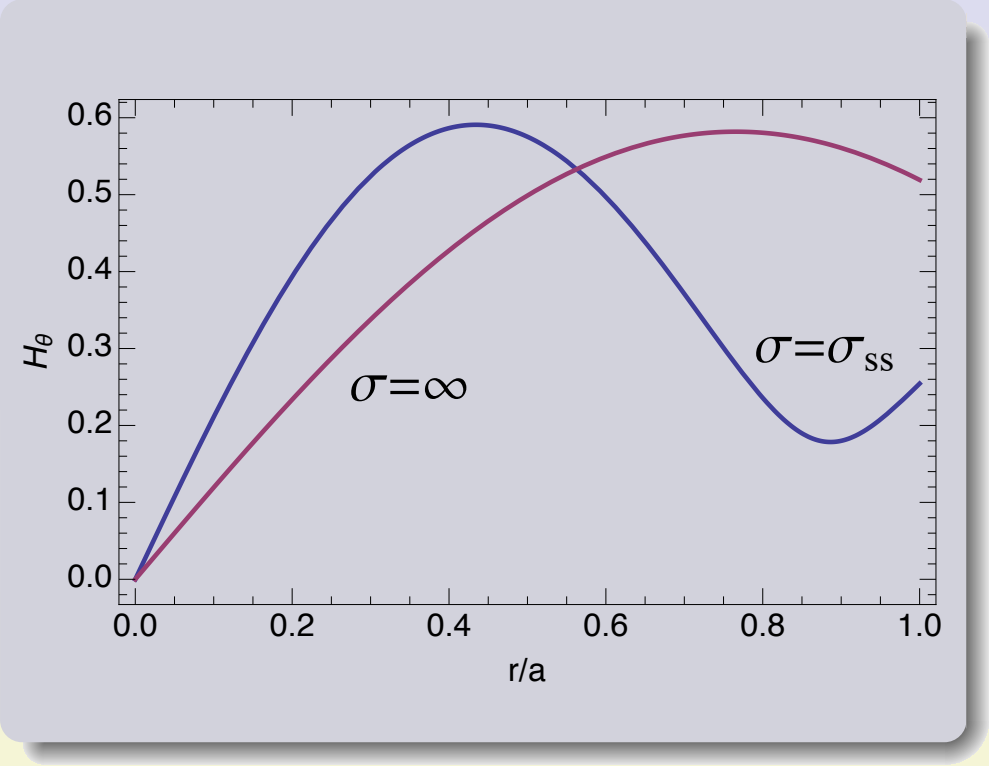
Assuming $k_z \approx k$, $\omega_0 = 2\pi \times 1.9$ THz,

$$\alpha(\omega_0) = 0.31\ \mathrm{m}^{-1}$$

The scaling $\alpha(\omega) \propto \omega^{1/2}$. Energy attenuation length $-1/2\alpha = 1.6$ m.

Do not trust textbooks!

The formula $\alpha = \frac{\omega k \delta}{2 c a k_z}$ is not valid for our parameters. It is obtained using a perturbation theory and assuming that the field distribution in the mode is the same as in the case of a perfectly conducting wall. See detailed analysis is in[3].



Radial dependence of the magnetic field in TM_{01} for a perfectly conducting and ss pipe ($f = 1.9$ THz, $a = 2$ cm). The attenuation is actually $\alpha = 0.13\ \mathrm{m}^{-1}$.

[3] I. A. Kotelnikov. Technical Physics, **49**, 1196 (2004)

When is the perturbation theory valid?

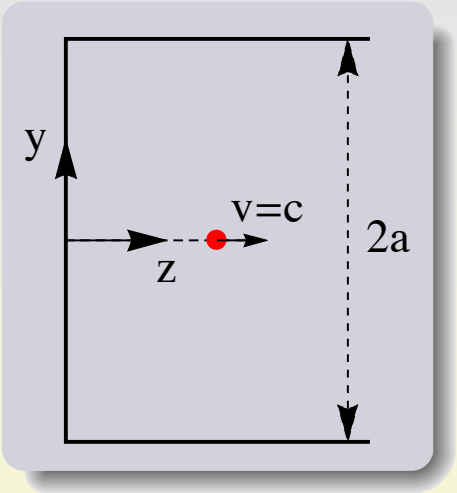
The perturbation theory (textbook formulas for field attenuation) is valid if[4]

$$\lambda \gg s_0 \equiv \left(\frac{ca^2}{4\pi\sigma}\right)^{1/3}$$

We know this condition from the theory of resistive wall wakefields.

The beam radiates into many transverse modes, so the deviation from the standard attenuation theory may not be large.

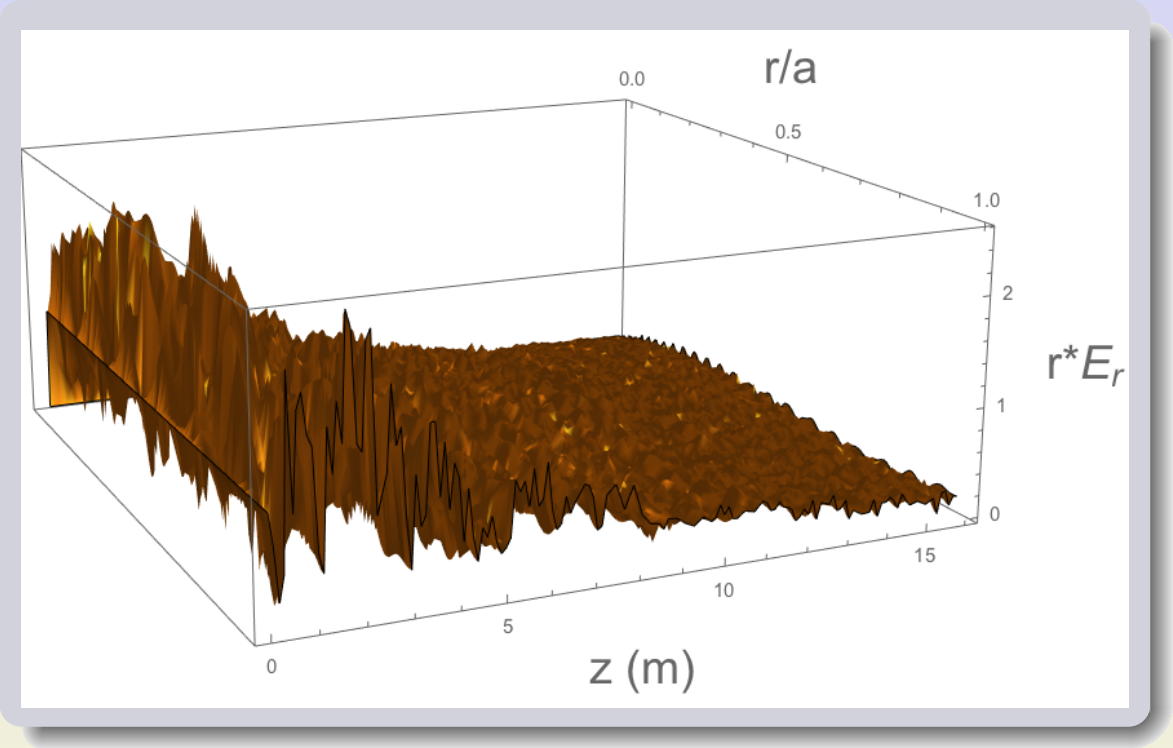
Model problem from PRST-AB, vol. 7, 064401 (2004): beam passing through a foil and generating transition radiation inside a round pipe.



[4] I. A. Kotelnikov. Technical Physics, **49**, 1196 (2004)

Parabolic equation solution

The problem was solved using the parabolic equation [5] with the correct boundary condition on the wall.

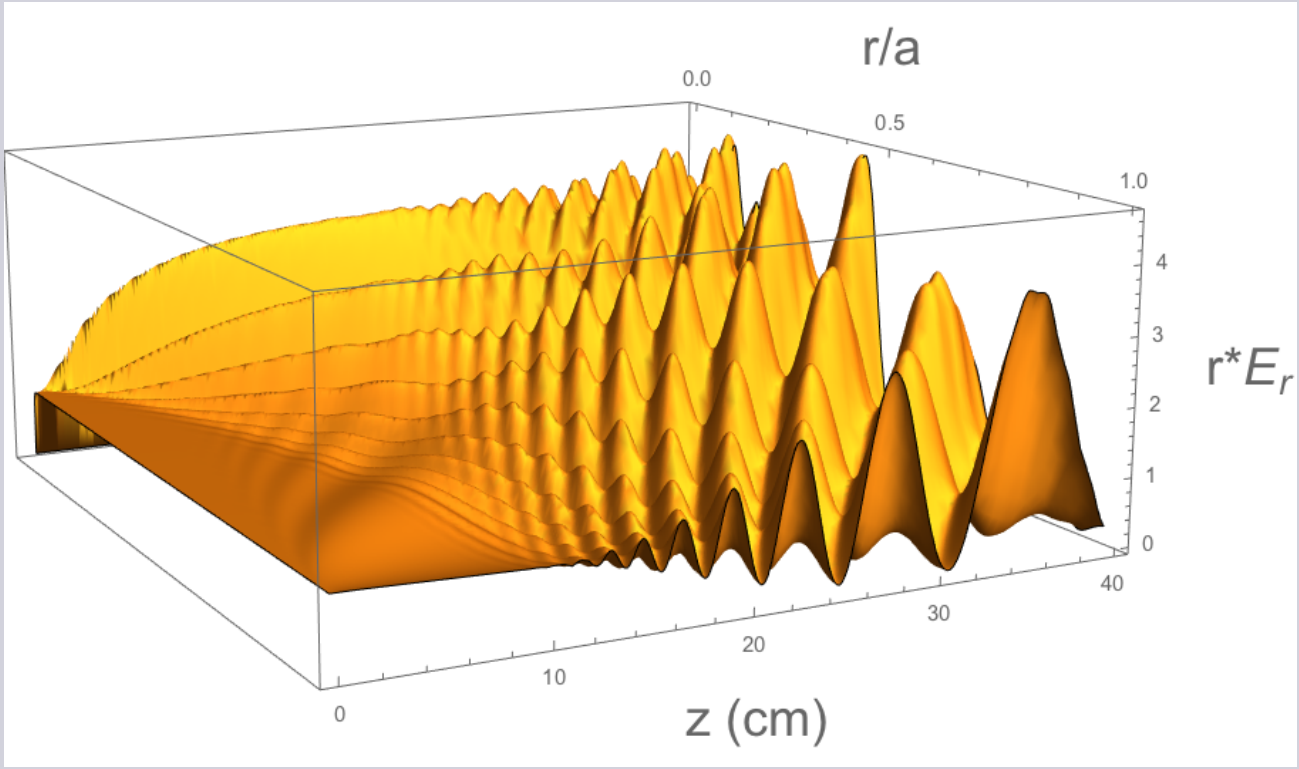


Distribution of $r|E_r(r,z)|$ for the radiation field in the pipe excited by the beam at 2.4 THz (the total field is the radiation field plus the Coulomb field of the beam).

[5] G. Stupakov, New Journal of Physics, **8**, 280 (2006).

Parabolic equation solution

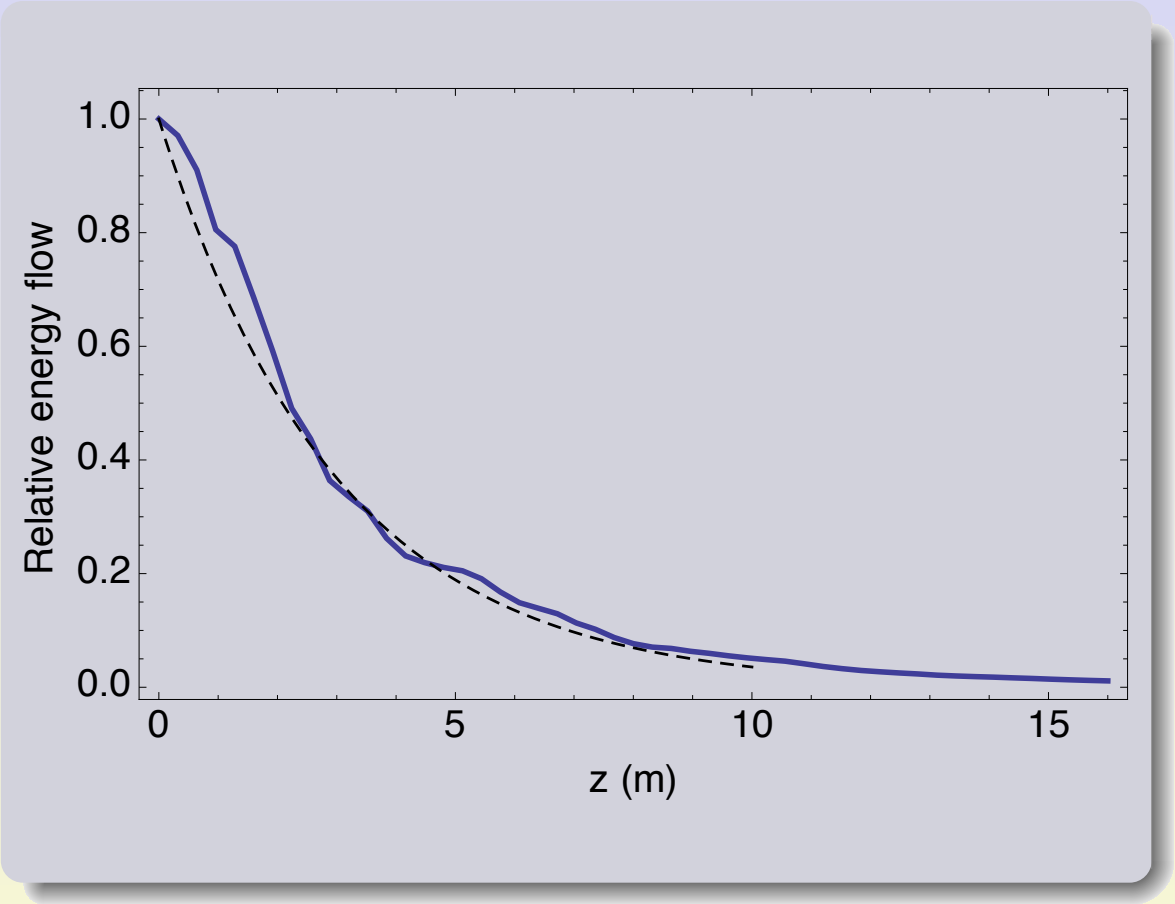
Small values of z



High frequency components diffract out from the axes to the wall.

Parabolic equation solution

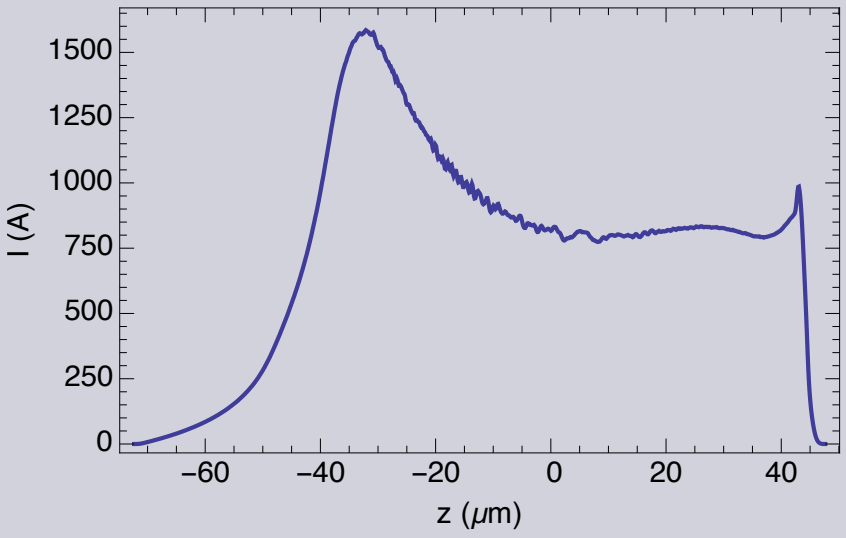
Energy flow in the EM field decays with z due to the absorption in the walls.

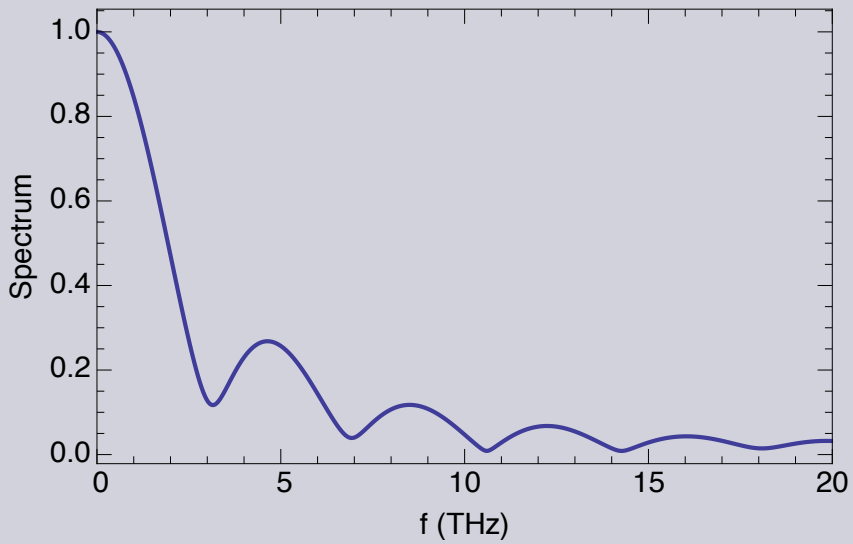


The dashed line is $e^{-z/(3\ \mathrm{m})}$

Simulated beam profile from Ji Qiang

LCLS-II beam profile after BC2, $Q = 300$ pC.



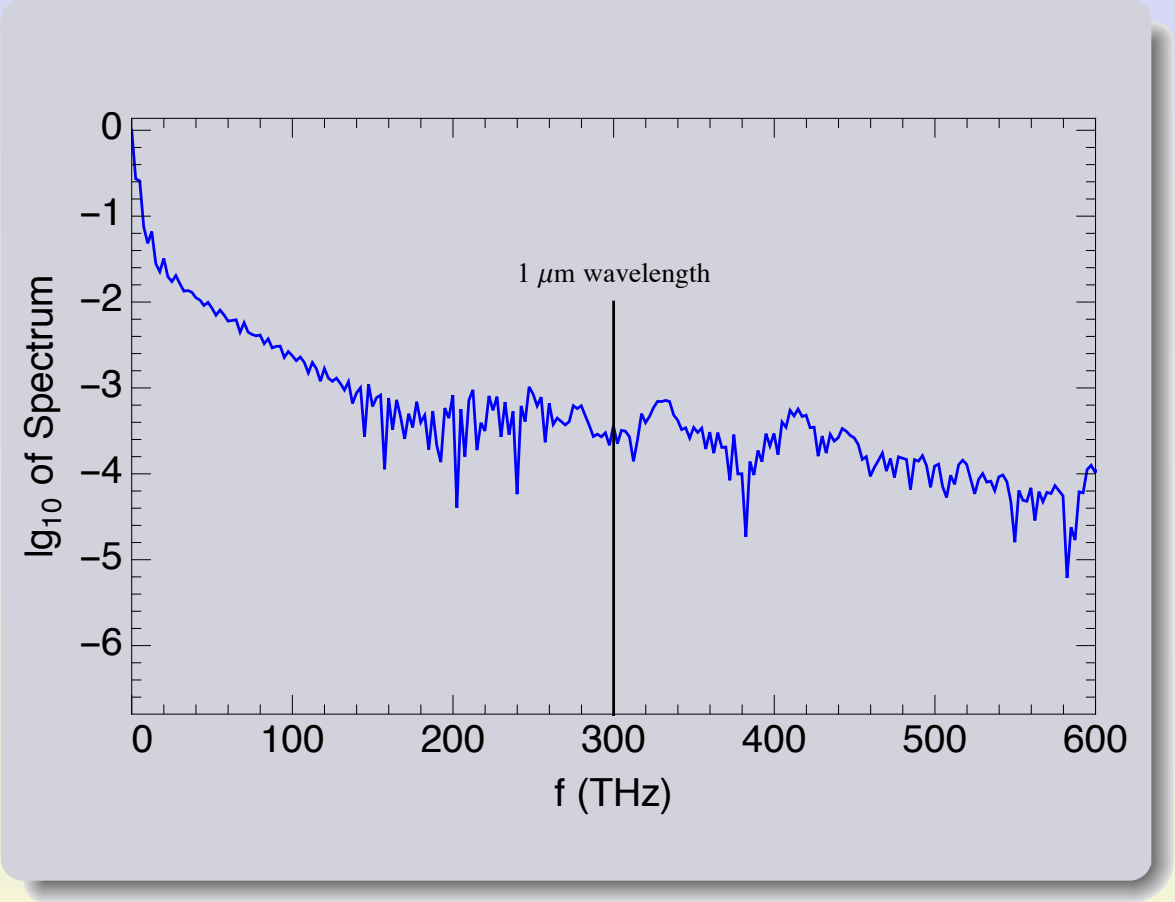


Compare the spectrum with the Gaussian, s. 4.

Tor: can we calculate the contribution to the radiation from the microbunching?

Simulated beam profile from Ji Qiang

Microbunching is not discernible in the spectrum of the beam.



Conclusions

- CSR radiation power from the last bend of BC2 is about 100-150 W (100-150 μJ/bunch).
- Wall heating in the toroidal section of the pipe as at the level of a fraction of W/cm^2 (assuming square or round pipe, SS).
- High-frequency content of the beam radiation coming our from BC2 will be absorbed in the walls of the stainless steel pipe ($a = 2$ cm) with the attenuation length of $\sim 2 - 3$ m. [This conclusion is based on the assumption that the radiation goes to TM modes of a circular waveguide. Care should be taken that it is not converted into TE modes. TE modes in a round pipe have much longer attenuation length.]
- Microbunching does not seem to add noticeably to the CSR radiation power.