CSR radiation and wake problems in free-electron laser LCLS-II at SLAC

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Outline

- LCLS-II project at SLAC
- New issues due to CSR in LCLS-II. Simple models of CSR wakefields and using mode expansion code
- General formulation of shielded CSR impedance problem
- Dechirper experiment at LCLS

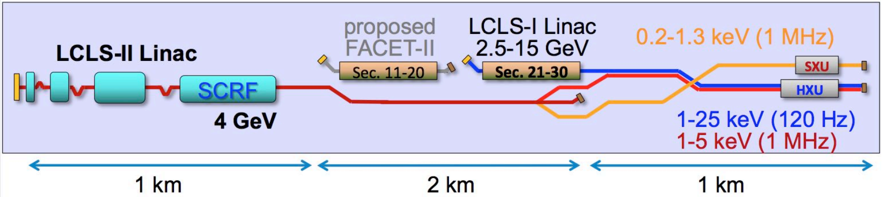
LCLS-II x-ray free electron laser at SLAC

LCLS-II Accelerator Layout

New superconducting linac $\rightarrow$ LCLS undulator hall

- Two sources: MHz rate SCRF linac and 120 Hz Cu LCLS-I linac
- Hard and Soft X-ray undulators can operate simultaneously in any mode
- SCRF beam destination controlled with fast (μs) magnetic deflector

Undulator	SC Linac (up to 1 MHz)	Cu Linac (up to 120Hz)
Soft X-ray	0.20 - 1.3 keV with >>20 Watts	
Hard X-ray	1.0 - 5.0 keV with >20 Watts	1 - 25 keV with mJ-class X-ray pulses



From T. Raubenheimer.

LCLS-II parameters

Parameter	symbol	nominal	range	units
Electron Energy	E_f	**4.0**	2.0 - 4.5	GeV
Bunch Charge	Q_b	**100**	10 - 300	pC
Bunch Repetition Rate in Linac	f_b	**0.62**	0 - 0.93	MHz
Average e^- current in linac	I_{avg}	**0.062**	0.0 - 0.3	mA
Avg. e^- beam power at linac end	P_{av}	**0.25**	0 - 1.2	MW
Norm. rms slice emittance at undulator	$\gamma\varepsilon_{\perp\text{-}s}$	**0.45**	0.2 - 0.7	µm
Final peak current (at undulator)	I_{pk}	**1000**	500 - 1500	A
Final slice E-spread (rms, w/heater)	σ_{Es}	**500**	125 - 1500	keV
RF frequency	f_{RF}	**1.3**	-	GHz
Avg. CW RF gradient (powered cavities)	E_{acc}	**16**	8 - 20	MV/m
Avg. Cavity Q0	$Q0$	**2.7e10**	1.5 - 5e10	-

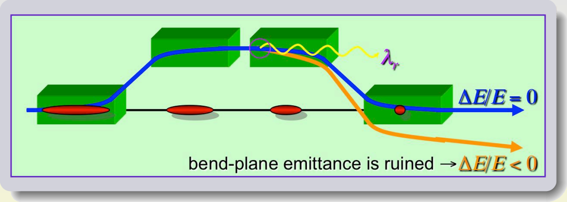
From T. Raubenheimer.

The bunch is compressed to $\sigma_z \approx 25$ µm.

CSR wake in modern FELs: emittance growth in BC

When a bunch of charged particle emits radiation, the energy of the electromagnetic field is taken from its kinetic energy. The energy balance in the process is maintained through a force that acts in the direction opposite to the velocity of the bunch. This force is called the radiation reaction force. In accelerator physics it is usually referred to as coherent synchrotron radiation, or CSR, wake.

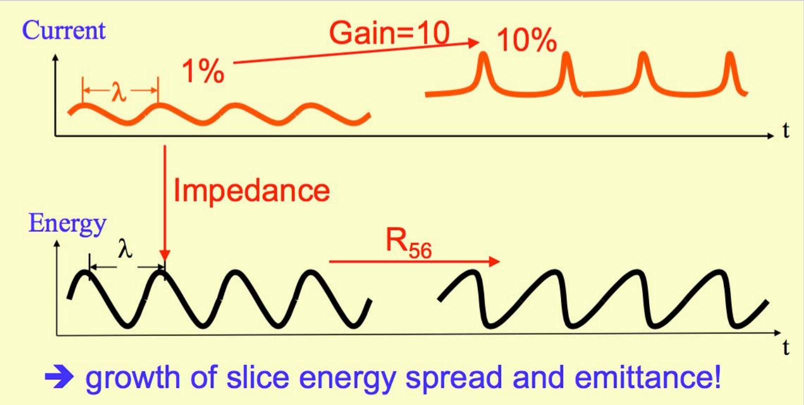
Traditionally, CSR effects in modern FELs are manifested in two areas.



Synchrotron radiation inside a bunch compressor of an FEL may lead to emittance growth of the beam.

CSR wake in modern FELs: MBI

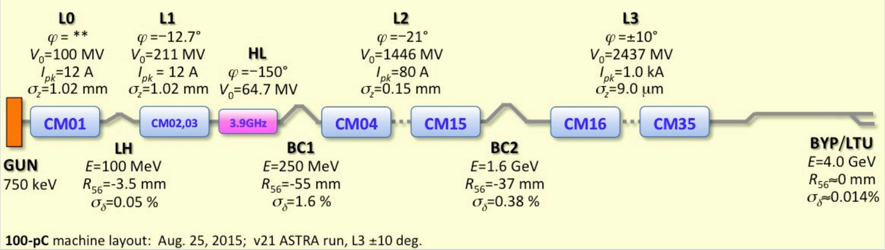
CSR wakefields in the bunch compressor contribute to the microbunching instability (MBI) of the beam.



Another driver of MBI is the longitudinal space charge wake in the linac.

New aspects of CSR in bunch compressor of LCLS-II

Because LCLS-II has superconducting RF cavities, there is a concern that CSR of the beam can reach the RF structures, get absorbed at cryogenic temperatures and lead to additional heat load.

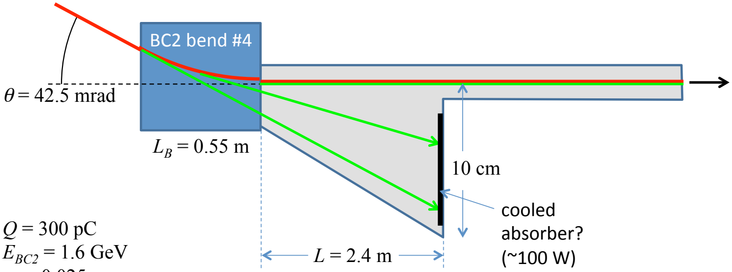


Problems

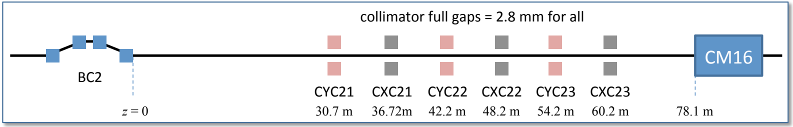
- Calculate the energy loss of the beam due to the coherent radiation in the last bend of BC2
- Evaluate local heating of metal surfaces of the vacuum chamber caused by the CSR radiation
- Understand how much of the radiated energy can propagate to the nearest cryomodule

Last magnet of BC2

CSR Trap for BC2 ?

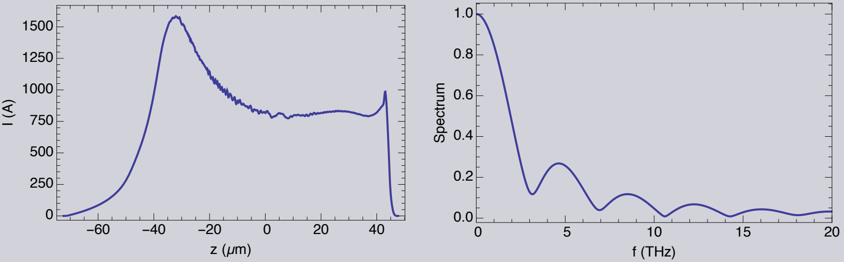


$Q = 300$ pC
$E_{BC2} = 1.6$ GeV
$\sigma_z = 0.025$ mm
$f_{max} = 0.929$ MHz
$\sigma_x = 0.020$ mm (at BC2 4th bend exit)
$\sigma_y = 0.16$ mm (at BC2 4th bend exit)



Beam spectrum extends to THz frequencies

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



Beam spectrum extends to 2-3 THz, the wavelengths $100 - 150$ μm.

Simple estimate of CSR power

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

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

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

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

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

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

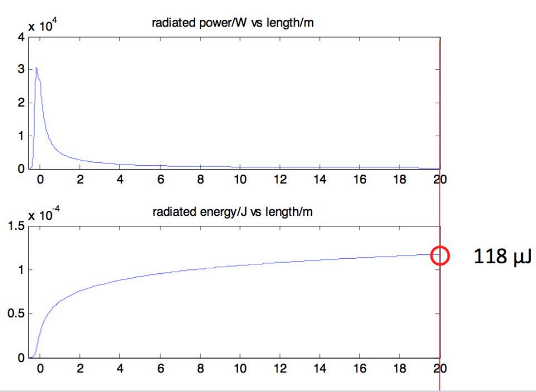
This gives $P_{\mathrm{CSR}} = 48.5$ W.
The steady-state model is valid if $L \gg \ell$:

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

[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 of CSR in free space from a bend of finite length:

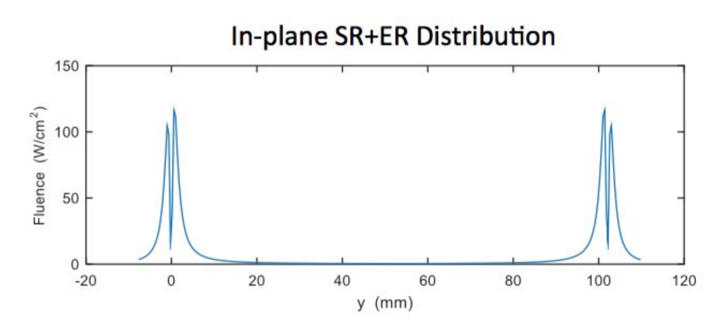


The long tail of the wake is due to the edge radiation of the beam. In the limit $\gamma \to \infty$ the total radiated energy $\to \infty$.

In reality, this radiation will be shielded by metal walls of the vacuum chamber.

Can edge radiation locally heat the vacuum chamber?

See cartoon, s. 8. H. Loos simulated fluence of radiation on the wall assuming a bend of finite length in free space.

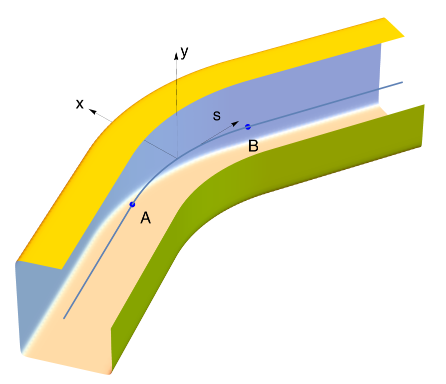


The peaks are due to the edge radiation from the bend.

Edge radiation is 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 $a \lesssim \lambda\gamma \approx 25\ \mu m \times 3200 = 8$ cm.
(Even with the incident fluence of 120 W/cm^2 only 3 W/cm^2 is absorbed in stainless steel wall $[\sigma = 1.4 \times 10^4/(\mathrm{Ohm} \cdot \mathrm{cm})]$.)

Calculation with the modified mode expansion code

We have a code that computes the CSR wakefield in a bend in a rectangular vacuum chamber[2]. The code is based on parabolic equation and uses formalism of mode expansion and matching in the toroidal and straight section.

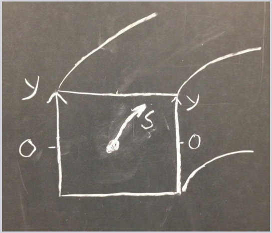


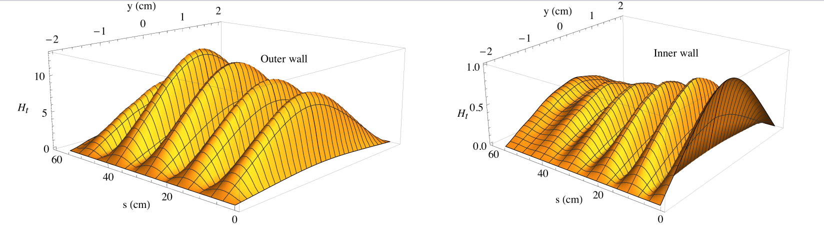
Vacuum chamber: full vertical gap $2h = 3.2$ cm, and the full horizontal gap 9.6 cm. The beam radiates 113 μJ energy (113 W); this agrees with M. Dohlus's two-parallel-plates result: 120 μJ. Also, the wakefields calculated at various distances from the exit of the bend agree between the two codes.

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

Magnetic field in toroidal section of the pipe

The modified code calculates H_t and the heating of the walls in the toroidal part of the vacuum chamber. Pipe cross section of 4 cm$\times$ 4 cm was assumed, $\rho = 12.9$ m. Calculation were done for one frequency, $f = c/(2\pi\sigma_z) = 1.9$ THz.





The unit of H is the magnetic field in the straight pipe (the heating from the image currents is ≈ 1.5 mW/cm^2). We estimate the energy deposition on the outer wall of the toroid ~ 0.2 W/cm^2.

Attenuation of waveguide modes in straight waveguide

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 $\propto 1/\sqrt{\omega}$)

$$\alpha = \frac{\omega^2\delta}{2c^2 a k_z}$$

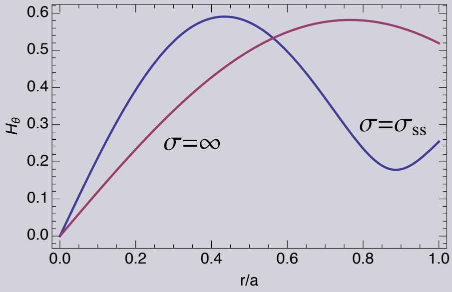
Assuming $k_z \approx \omega/c$, $\omega_0 = 2\pi \times 1.9$ THz, stainless steel pipe of radius 2 cm,

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

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

Do not blindly trust textbooks!

The formula $\alpha = \frac{\omega^2\delta}{2c^2 a k_z}$ 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?

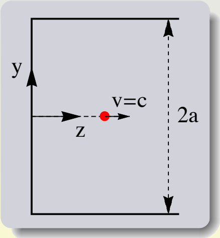
The perturbation theory (textbook formulas for the field attenuation) is valid if[4]

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

We know this condition from the theory of the resistive wall wakefields. For $a = 2$ cm, SS pipe, $s_0 = 90\ \mu\text{m}$. We expect that the deviation from the standard attenuation theory should not be large.

The beam radiates into many transverse modes.

Model problem[5] : beam passing through a foil and generating transition radiation inside a round pipe. Replace the edge radiation coming out of the bend by the transition radiation of the bunch entering a conducting pipe through a thin foil.

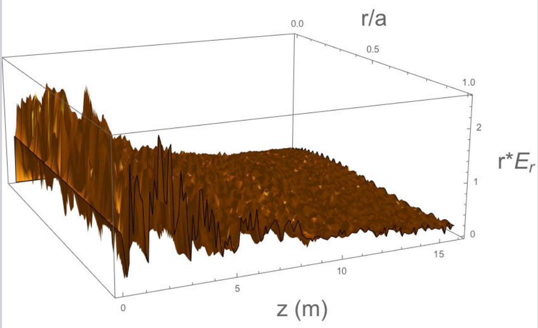


[4] Kotelnikov. Technical Physics, **49**, 1196 (2004).

[5] Bane, Stupakov. PRST-AB, **7**, 064401 (2004)

Parabolic equation solution

The problem was solved for a round pipe using the parabolic equation[5] with the boundary condition corresponding to the finite resistivity of the wall.

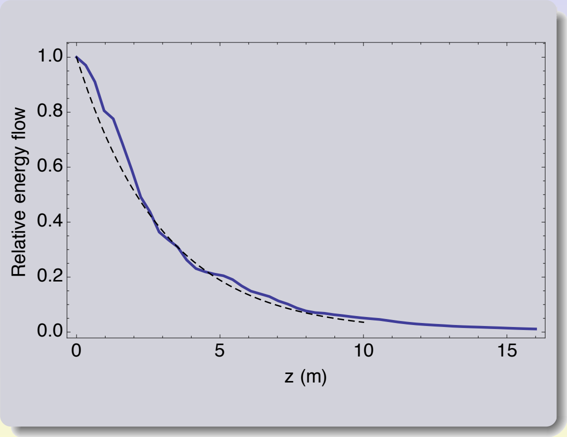


Distribution of $r|E_r(r,z)|$ for the radiation field in the pipe excited by the beam at 2.4 THz (the total field is the radiation field plus the Coulomb field of the beam).

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

Parabolic equation solution

Energy flow in the parabolic equation solution decays with z due to the absorption in the walls.



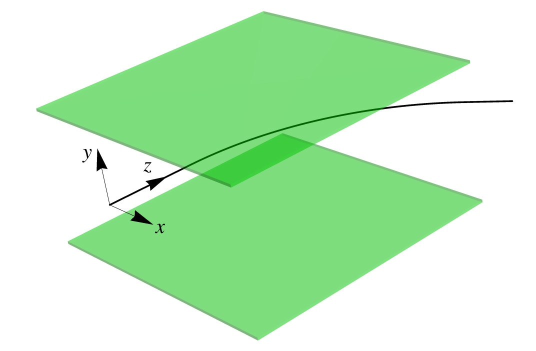
The dashed line is $e^{-z/(3\ \mathrm{m})}$

Conclusions on CSR issues in LCLS-II

- 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 is 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.]

CSR impedance shielded by conducting parallel plates

Some results obtained over the last two weeks with D. Zhou.

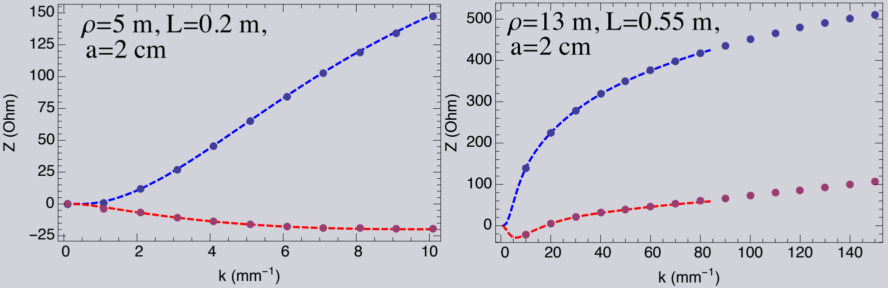


We assume $v = c$. For arbitrary plane orbit in the midplane, $\vec{r} = \vec{r}_0(s)$, the impedance is given by the following formula ($\vec{\beta} = \vec{v}/c$):

$$Z_{\mathrm{CSR}}(k) = \frac{ik}{c} \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\infty} ds \int_{-\infty}^{s} ds' \sum_{m=-\infty}^{\infty} (-1)^m \frac{1 - \vec{\beta}(s) \cdot \vec{\beta}(s')}{|\vec{r}_0(s) - \vec{r}_0(s')|} \times e^{-ik(s-s'-|\vec{r}_0(s)-\vec{r}_0(s')|}$$

Comparison with Demin's code

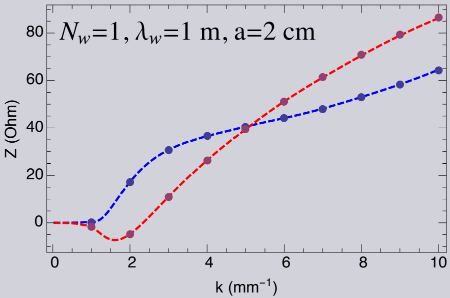
Real and imaginary parts of the longitudinal impedance for short bends. The code uses a rectangular cross section of the vacuum chamber with the aspect ratio 3-5.



Lines—the code, dots—analytical theory.

Wiggler impedance

Real and imaginary parts of the impedance for a one-period wiggler.



Remarkably, the parallel plate model agrees well with the rectangular cross section impedance with the aspect ratio $b/a \gtrsim 2 - 3$.