

Plan for today

1. CSR effect short lecture.(20 minutes)
2. ATF in general (20 min)
3. 10 minutes break.
4. Group A will go to ATF control (~50 min)
5. Group B: Questions & Answers preparation for next week presentation (~50 min)
6. Short break for switch between lecture class and control rooms

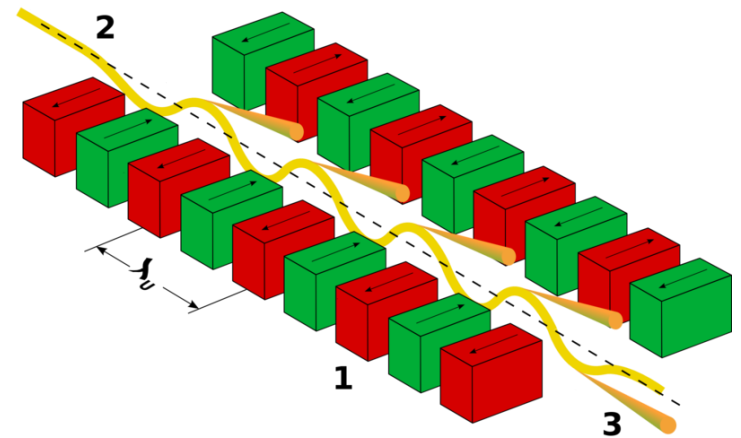
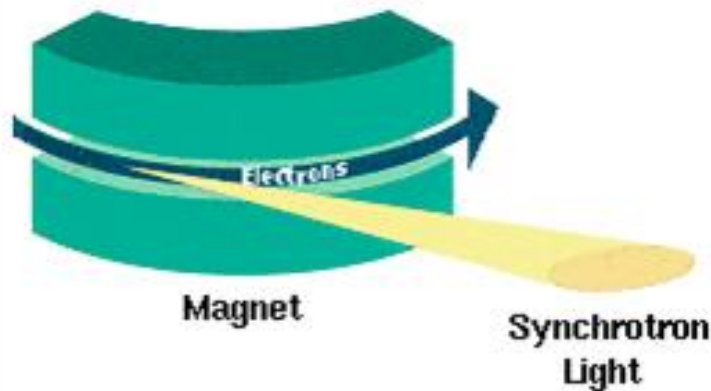
PHY542. Collective effects: CSR

D. Kayran

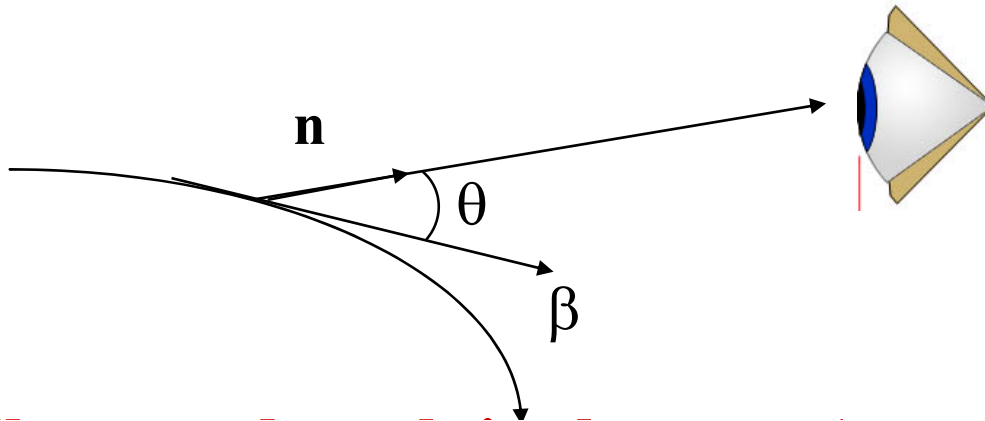
April 20, 2015

Synchrotron Radiation

- Energy emitted to infinity or other boundary condition.
 - Form: Electromagnetic wave
 - Source: the charged particles
 - Direction: Along the tangent of the beam trajectory curve.



Synchrotron Radiation (single particle effect)



The time of the emitter and the time of the observer is linked as :

$$T_{obs} = (1 - \hat{n}\vec{\beta})T_{emit}$$

The retarded scalar and vector potential is needed:

$$\phi(t) = \frac{1}{4\pi\epsilon_0} \frac{q}{r(1 - \hat{n}\vec{\beta})} \Big|_{ret}$$

$$\vec{A}(t) = \frac{q}{4\pi\epsilon_0 c^2} \frac{\vec{v}}{r(1 - \hat{n}\vec{\beta})} \Big|_{ret}$$

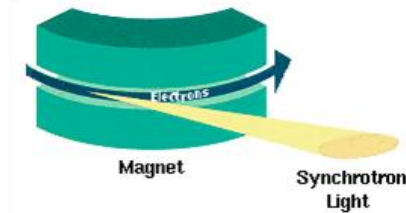
Synchrotron radiation

The power and its distribution can be calculated from the 'retarded potential'

$$P = \frac{e^2}{6\pi\epsilon_0 c} \gamma^6 \left[\left| \dot{\vec{\beta}} \right|^2 - \left| \vec{\beta} \times \dot{\vec{\beta}} \right|^2 \right]$$

Radiation due to
Acceleration
(Negligible)

Radiation due to
Bending
(Dominating)

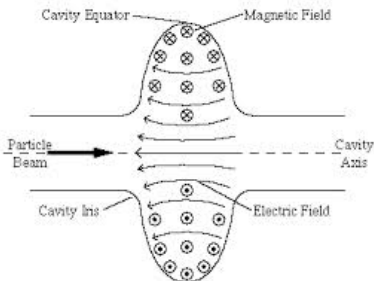


SR in storage ring

$$P = \frac{e^2 c}{6\pi\epsilon_0} \frac{\gamma^4}{\rho^2}$$

The energy loss per turn:

$$\Delta U_e(keV) = 88.46 \frac{E(GeV)^4}{\rho(m)}$$



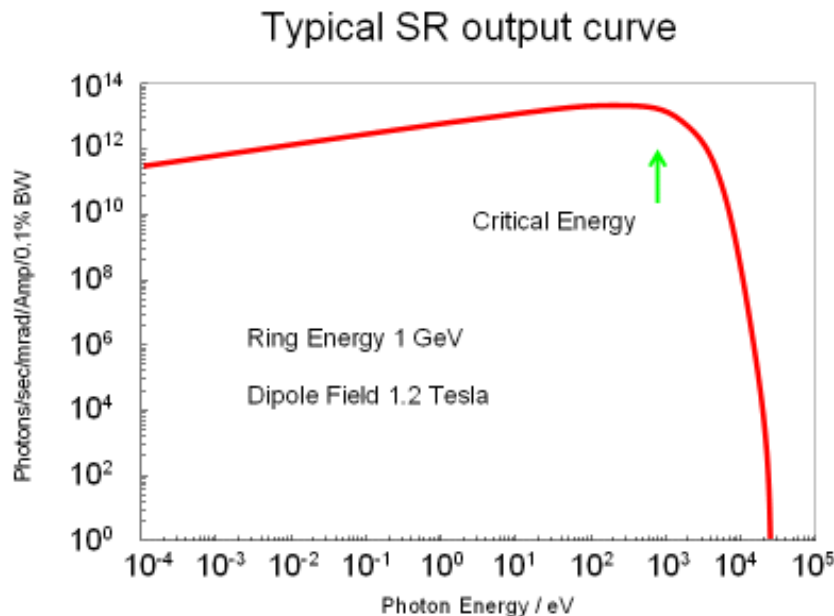
SR: Spectrum

an approximate formula [*]

$$I(\omega) = \frac{\sqrt{3}}{2\pi} \frac{\omega_0 e^2}{c} \left(\frac{E}{mc^2} \right) F\left(\frac{\omega}{\omega_c}\right) \quad F(\xi) = \xi \int_{\xi}^{\infty} K_{5/3}(\eta) d\eta$$

$\omega_0 = 2\pi f_0$ is a revolution frequency,

Where $\omega_c = \frac{3}{2} \omega_0 \left(\frac{E}{mc^2} \right)^3$ is a critical harmonic frequency,



the total power loss

$$\frac{dE}{dt} = \int_0^{\infty} I(\omega) d\omega = \frac{2}{3} \omega_0^2 \frac{e^2}{c} \left(\frac{E}{mc^2} \right)^4$$

*) G. A. Schott, Electromagnetic Radiation, Cambridge (1912).

Coherent effects

- Coherent radiation can be described as a low frequency part of the synchrotron radiation in bending magnets.
- As this part is independent of the electron energy, the fields of different electrons of a short bunch can be in phase and the total power of the radiation will be quadratic with the number of electrons.

This is Coherent Synchrotron Radiation (CSR) effect. *)

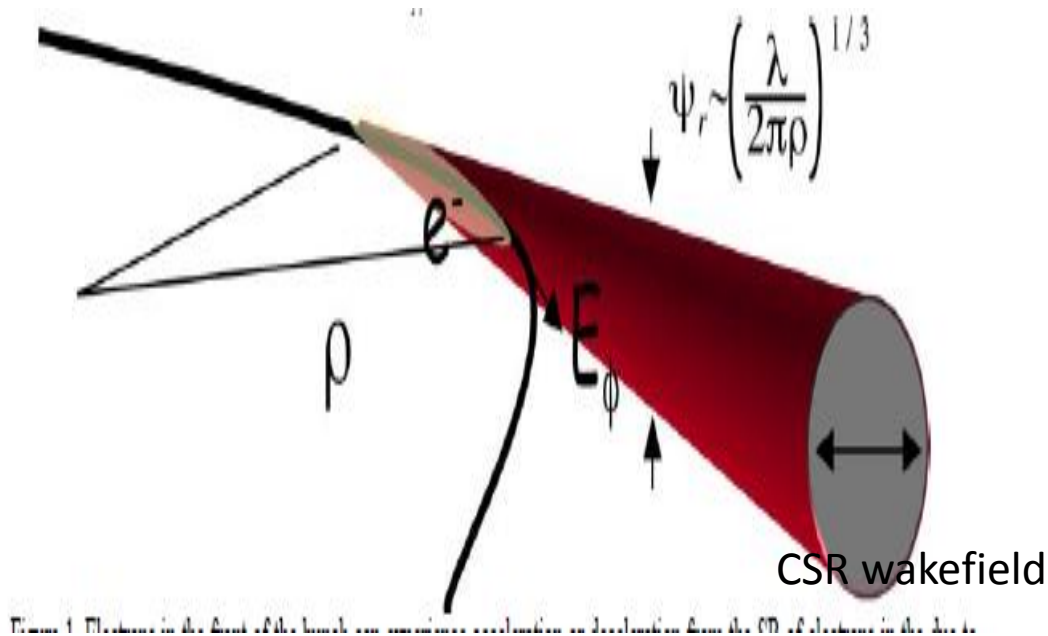
$$P_{\text{incoh.}}^{(N)} = N \frac{2}{3} \frac{\omega e^2}{R} \left(\frac{E}{mc^2} \right)^4$$

$$P_{\text{coh.}}^{(N)} = N^2 \frac{\omega e^2}{R} \left(\frac{\sqrt{3}}{\alpha} \right)^{4/3}$$

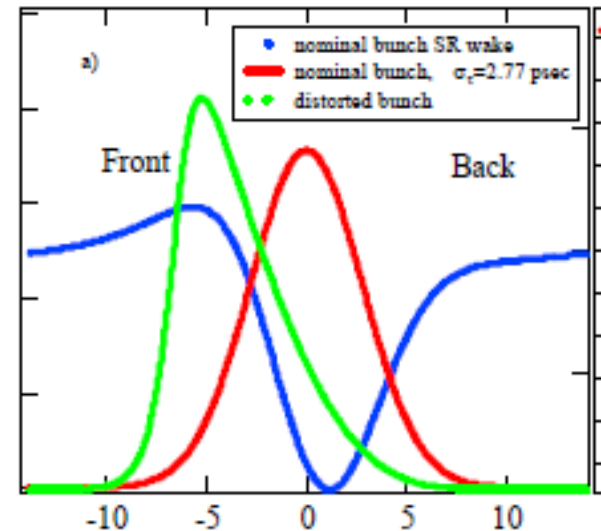
the electrons are uniformly distributed over an angular range *alpha*.

*) J. Schwinger, "On the Classical Radiation of Accelerated Electrons", Phys. Rev. 75, Num 12, p. 1912 (1949).

CSR effect



Bunching due to CSR



Electrons in the front of the bunch can experience acceleration or deceleration from the SR of electrons in the due to their bent trajectory in the SR field.

Synchrotron radiation wake (blue dashed line) for a Gaussian bunch. The wake distorts the bunch shape resulting in a sharp front leading edge.

SR+ CSR: Spectrum (free space)

Incoherent the total energy loss

$$\frac{dE}{dt} = \int_0^\infty I(\omega) d\omega = \frac{2}{3} \omega_0^2 \frac{e^2}{c} \left(\frac{E}{mc^2} \right)^4$$

$\omega_0 = 2\pi f_0$ is a revolution frequency,

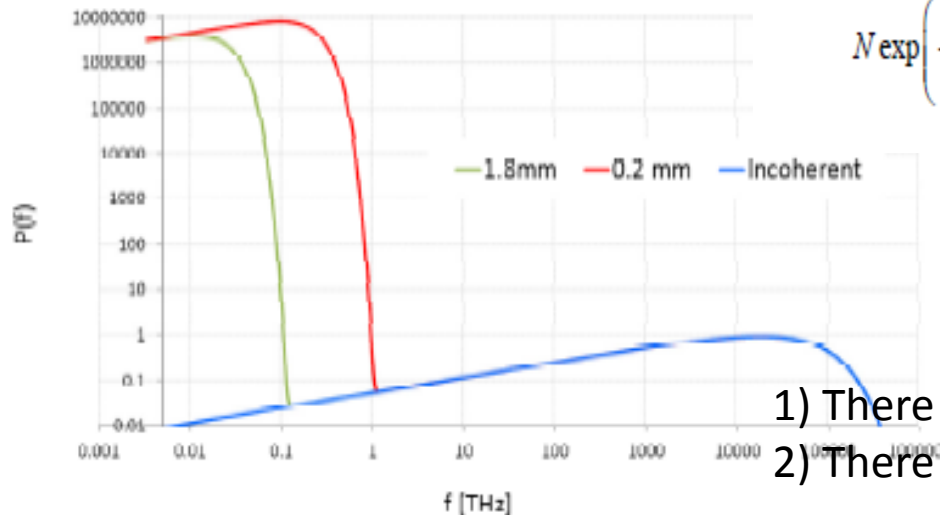
+Coherent part

$$I_b(\omega) = I(\omega) |j(\omega)|^2 = I(\omega) N \left[1 + N \exp \left(- \left(\frac{\omega \sigma}{c} \right)^2 \right) \right]$$

The coherent part of the radiation can become noticeable in some region of a spectrum if

$$N \exp \left(- \left(\frac{\omega \sigma}{c} \right)^2 \right) > 1 \quad \text{or} \quad \omega < \frac{c}{\sigma} \sqrt{\ln N} \quad \text{or} \quad f = \frac{\omega}{2\pi} < \frac{c}{2\pi \sigma} \sqrt{\ln N}$$

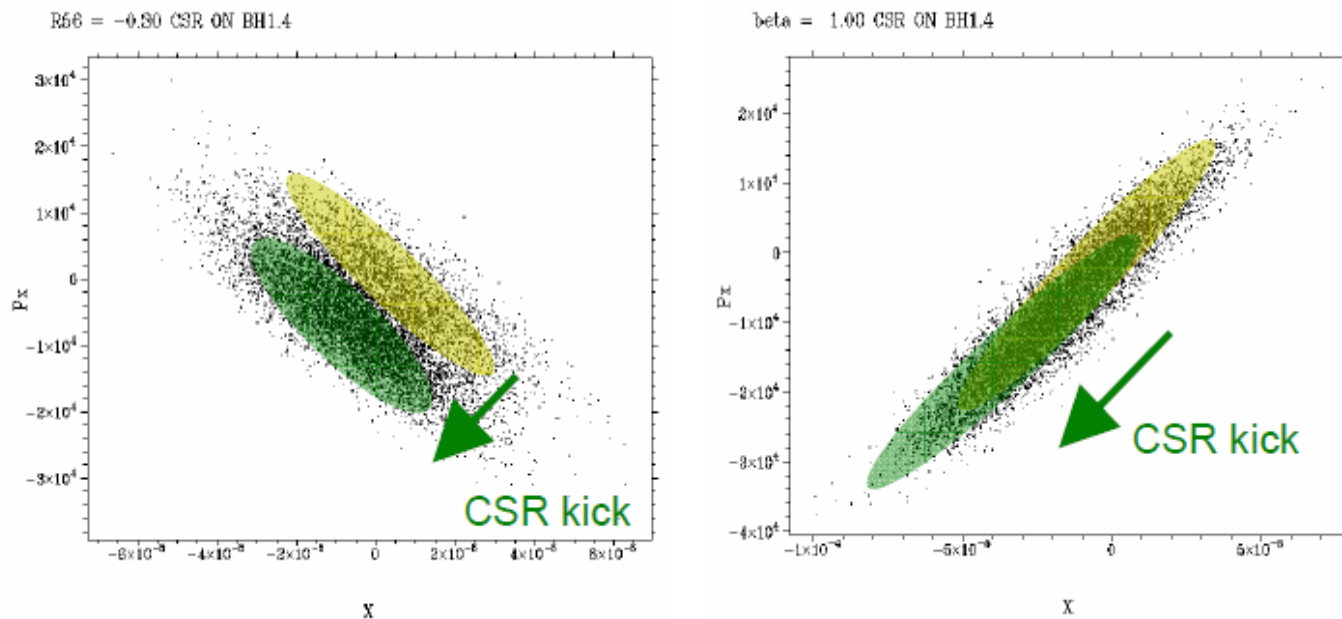
$$\frac{dE_{coh}}{dt} \approx \frac{3^{1/6}}{\pi} \Gamma^2 \left(\frac{2}{3} \right) \left(\frac{Ne}{\sigma^2} \right)^2 c \left(\frac{\sigma}{R} \right)^{2/3}$$



- 1) There bunch length dependence and radius,
- 2) There is no energy dependence,

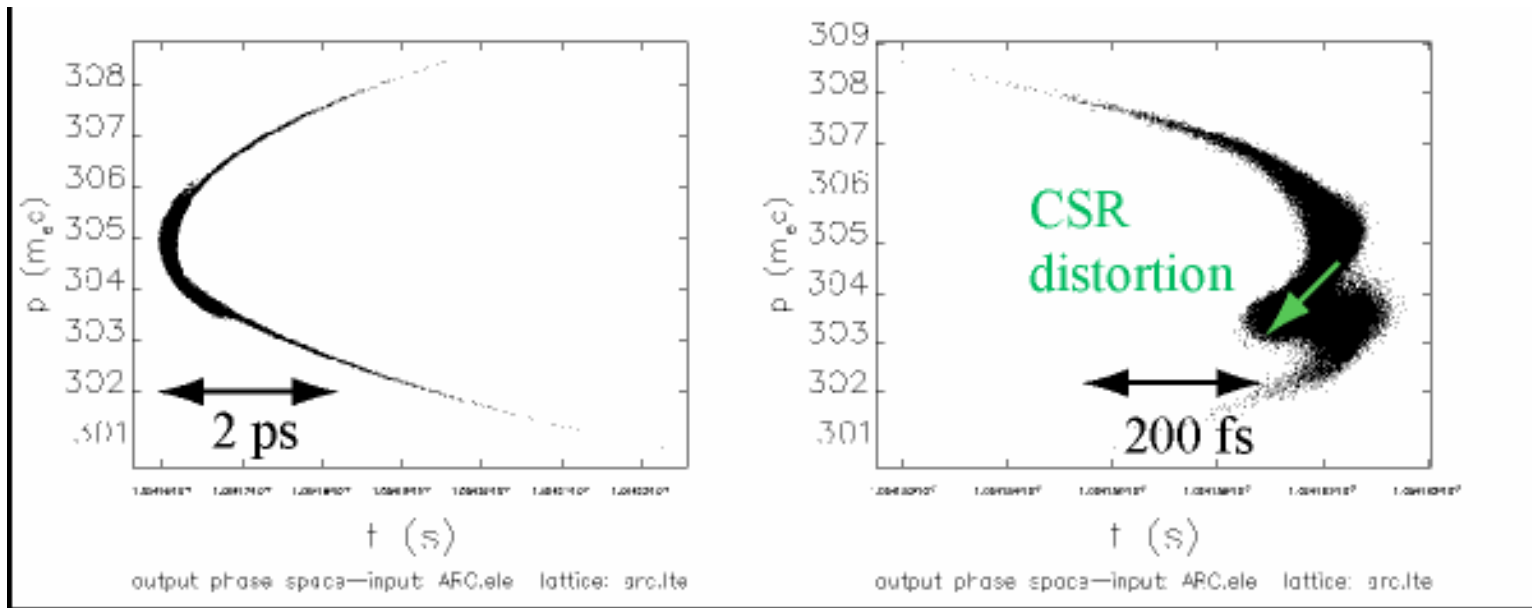
Figure 3: Power spectrum of the synchrotron radiation emitted by a 0.2 mm bunch (red line) and by a 1.8 mm bunch (green line) including incoherent radiation of a single particle (blue line).

CSR effect to emittance



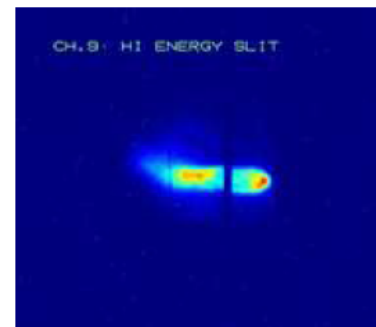
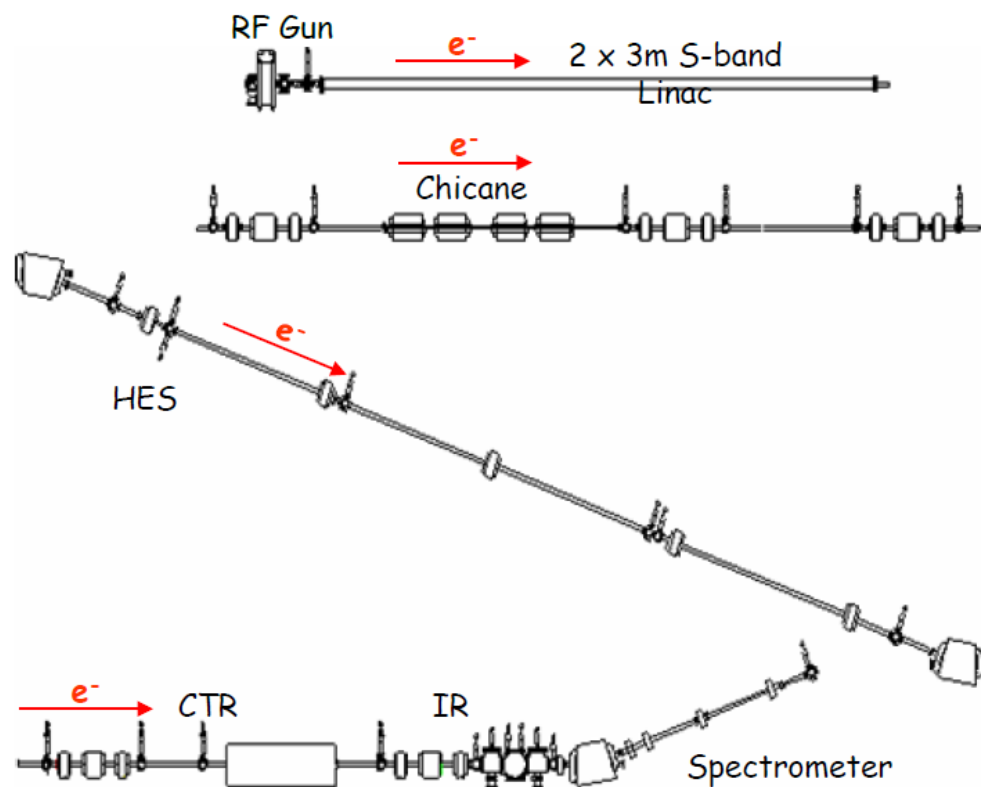
Transverse phase space at the end of arc without envelope optimization (left) and with the optimization (right). Bunch charge is 7.7 pC.

Longitudinal phase space distortion

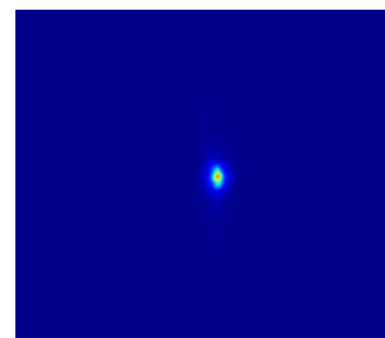


Longitudinal phase space at the end of arc with bunch before and after compression charge is 77 pC

Experimental Layout



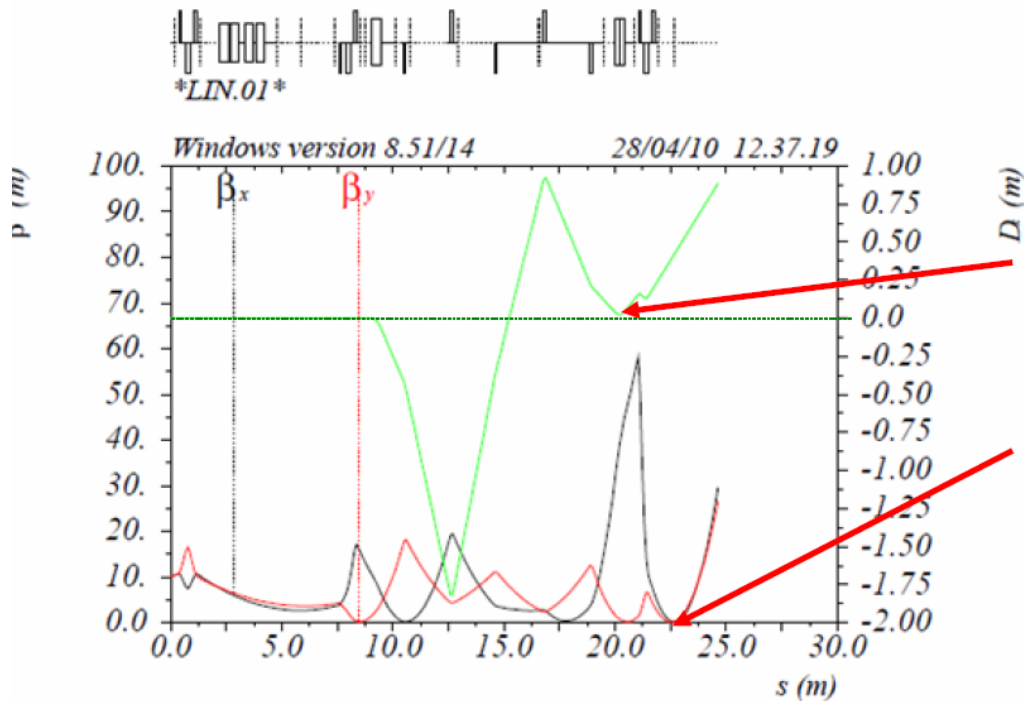
HES image



BPM/flag image

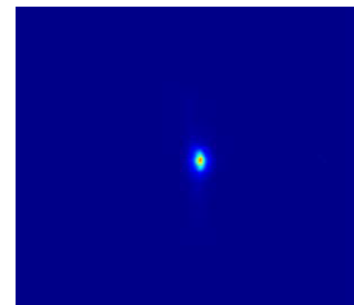
Photocathode gun, solenoid lens, accelerating section, dogleg with energy defining slit, beam position monitor (flag) together with distributed quadrupole triplets are

Optic functions configuration



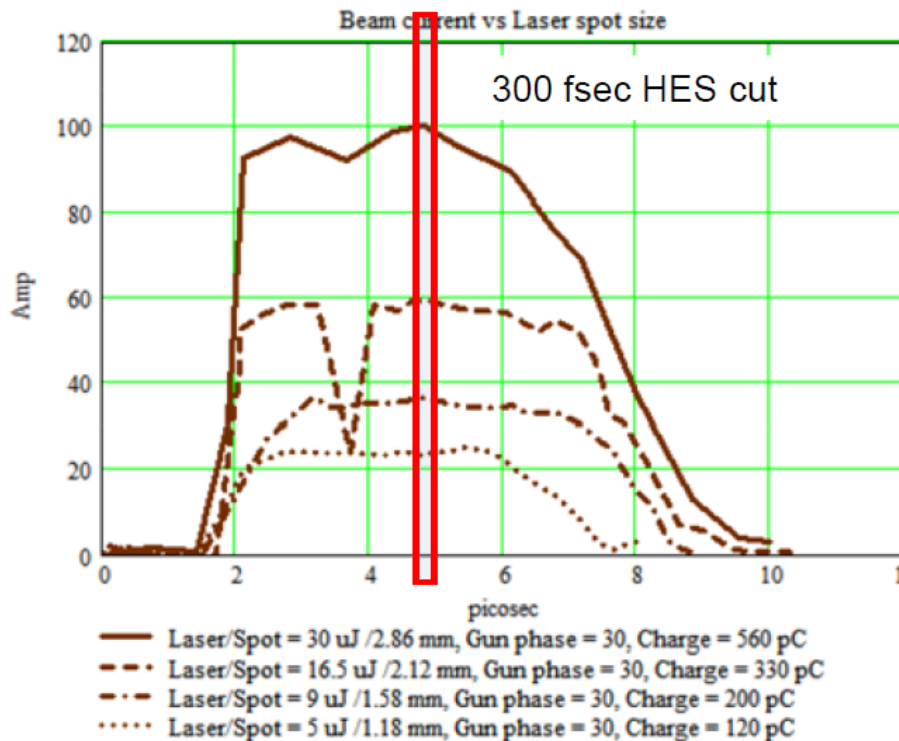
Dispersion function minimized in the dipole where shielding plates are installed.

Horizontal and vertical beta-functions minimized at the observation BPM where CSR and Resistive Wakes effects are measured.

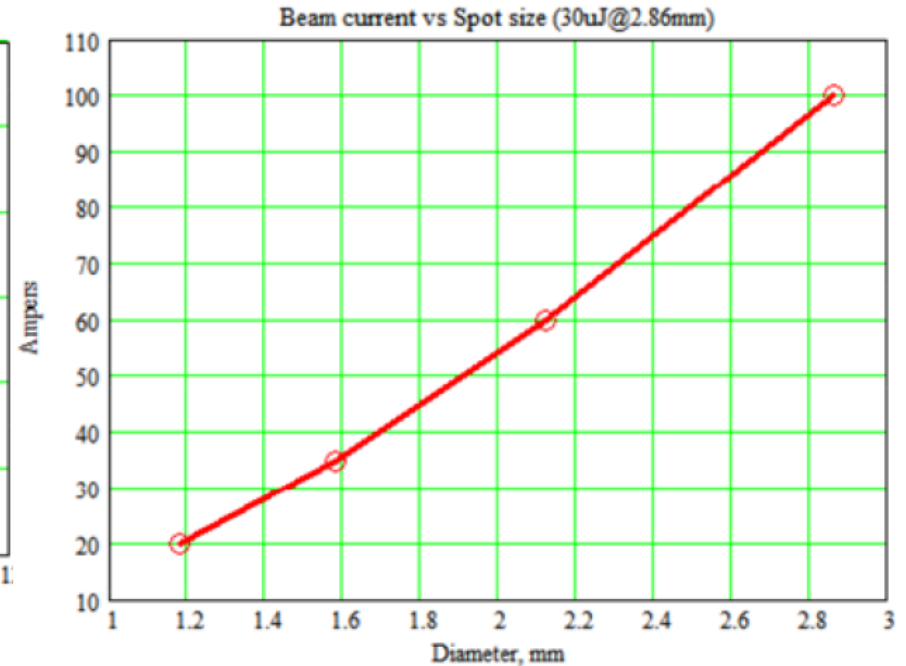


BPM/flag image

Charge per bunch and peak current controlled by changing the laser spot size



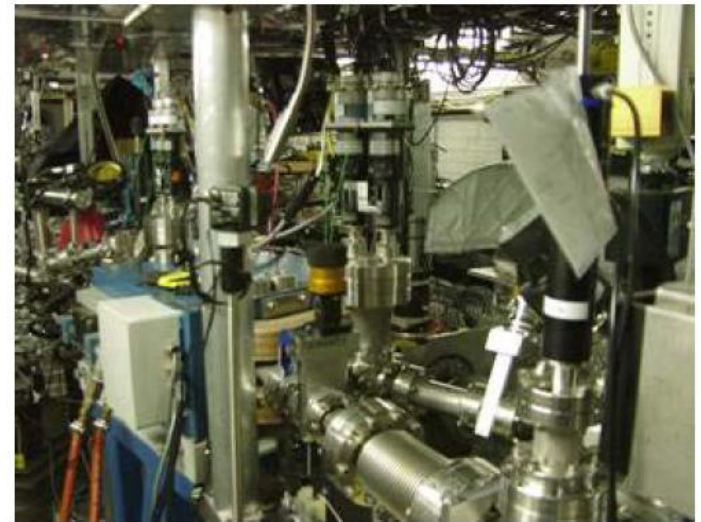
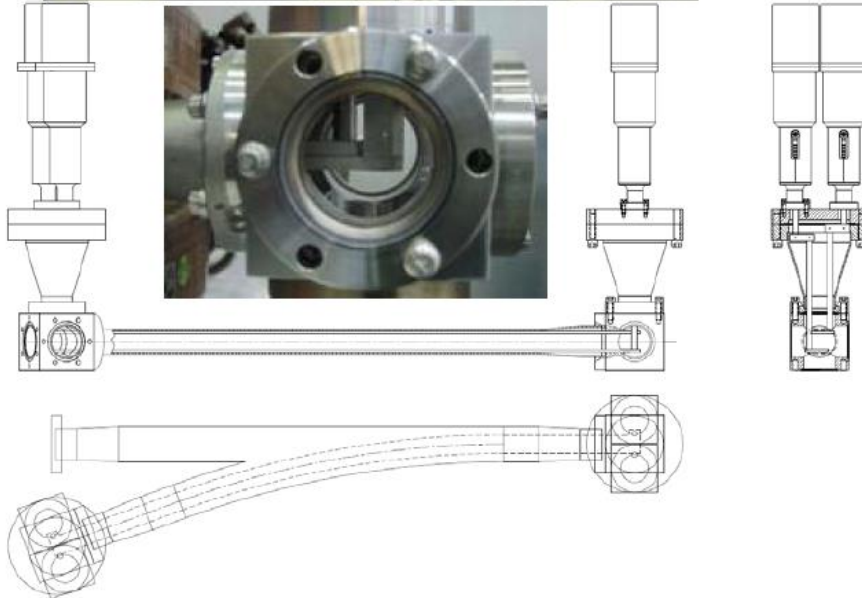
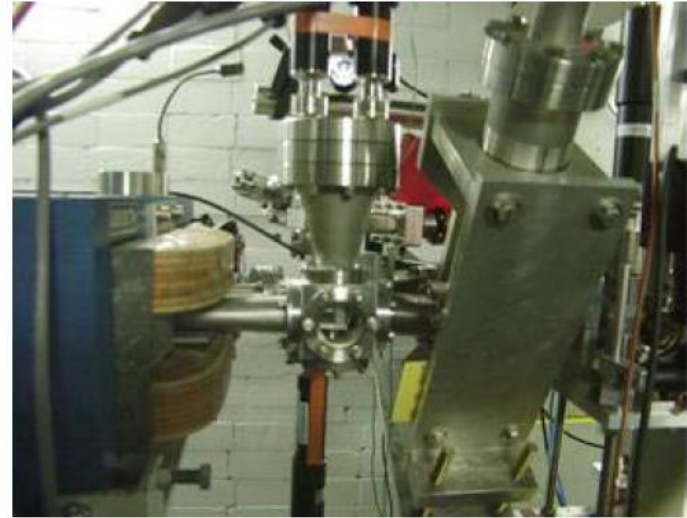
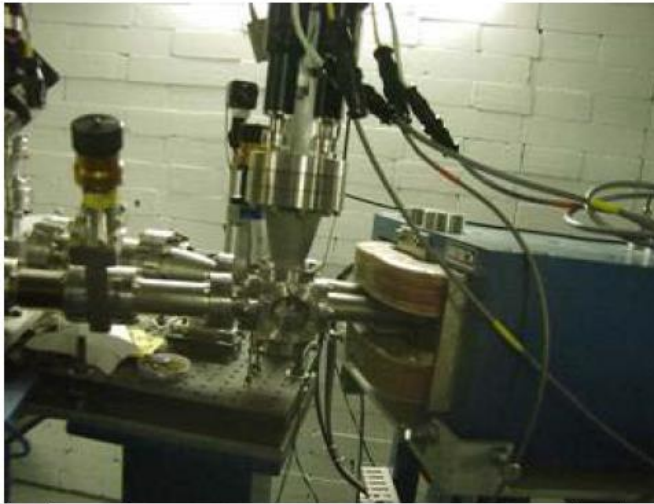
Longitudinal bunch profile for different laser spot size (charge per bunch, current)



Beam current vs laser spot size

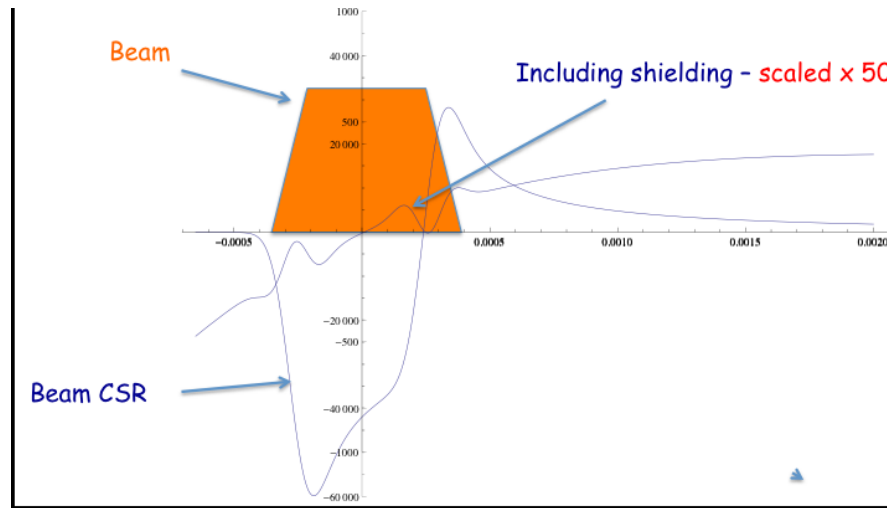
Bunch longitudinal profile stays the same for current from 20A to 100A

CSR shielding experiment plates

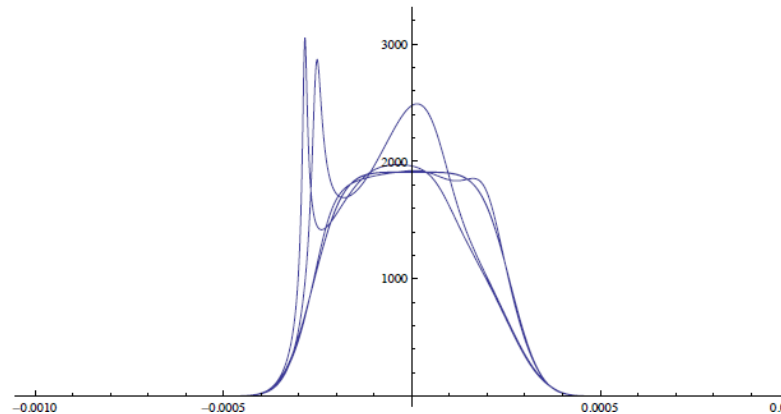


- Two plates with adjustable gap were installed into dipole vacuum chamber

CSR can be suppressed by shielding



Calculated CSR wake-fields for the unshielded and shielded case with 1 mm gap.



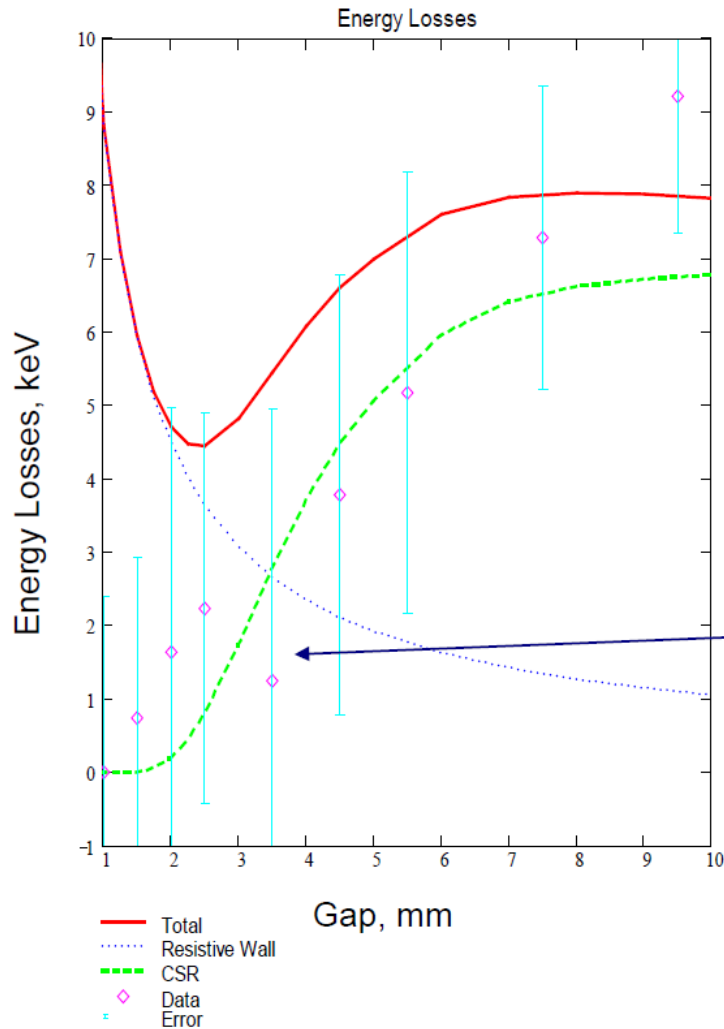
Simulations of the beam energy spectrum dependence on the gap between the plates: the two distributions with “horns” are for 12 and 8 mm gaps. The two others are for 1 and 2 mm gaps.

Observation

Vacuum chamber gap effect to the energy losses

300fs FWHM Gaussian, 40A

$$I = 40 \text{ A} \quad Q = 1.2 \times 10^{-11} \text{ C} \quad \frac{\sigma_s}{c \cdot 10^{-15} \text{ sec}} = 179.524$$



300fs FWHM "Square", 100A

$$I = 100 \text{ A} \quad Q = 3 \times 10^{-11} \text{ C} \quad \frac{dT}{10^{-15} \text{ sec}} = 300$$

