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Role of Electromagnetic Radiation in Charged Particle Bunch Length Diagnostics

Pavel Karataev

John Adams Institute for Accelerator Science at
Royal Holloway, University of London

karataev@pp.rhul.ac.uk

Lecture content

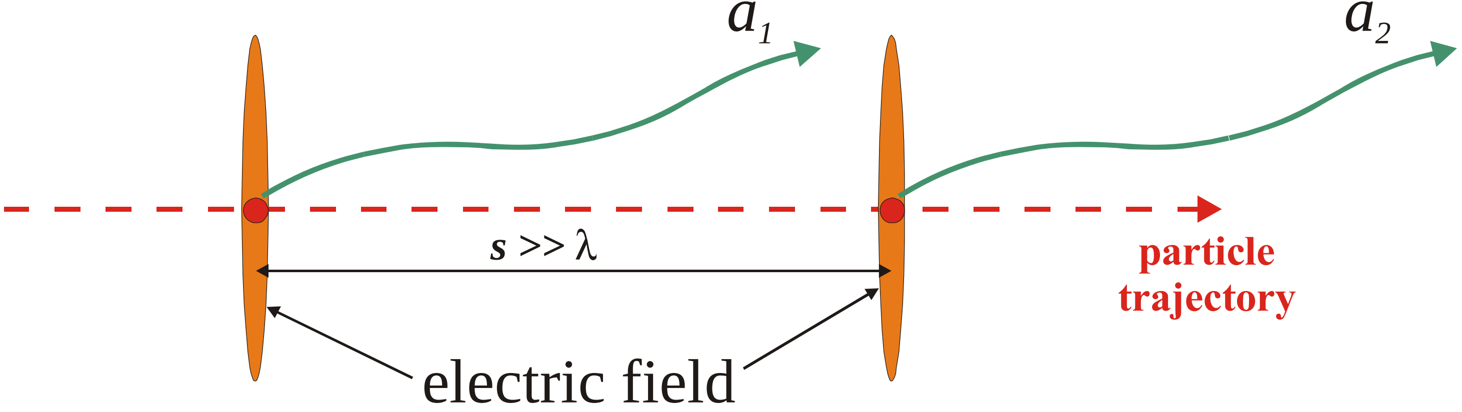
1) Introduction:
   - Incoherent and coherent emission
   - Radiation spectrum
   - Longitudinal bunch form factor

2) Radiation mechanisms:
   - Synchrotron radiation
   - Polarization Bremsstrahlung
   - Transition radiation
   - Diffraction radiation
   - Smith-Purcell radiation

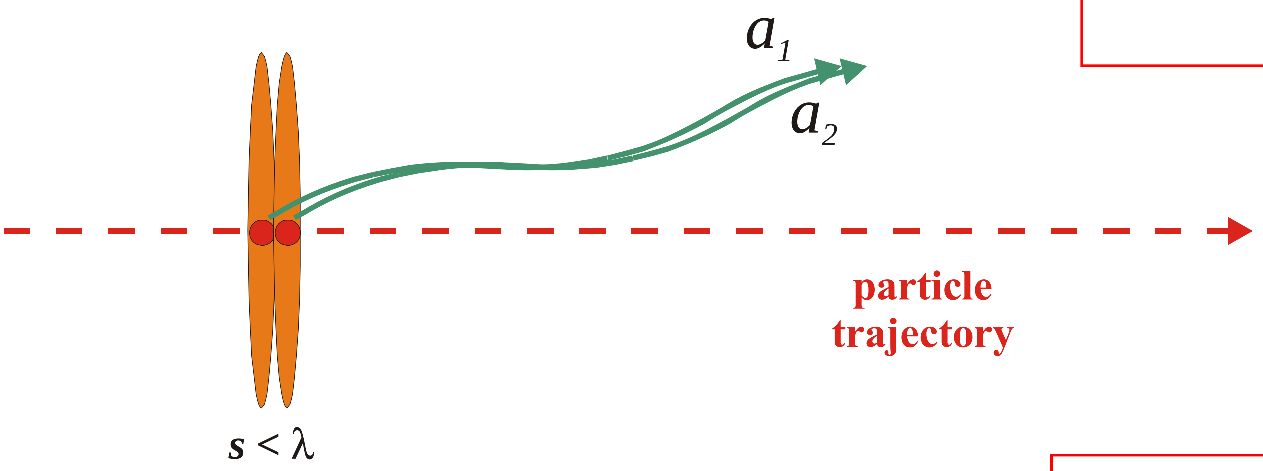
3) Kramers-Kronig method for longitudinal profile reconstruction

4) Summary

Incoherent and Coherent radiation



$$I = |a_1|^2 + |a_2|^2 = 2|a|^2 \rightarrow$$
$$N|a|^2$$



$$I = |a_1 + a_2|^2 = |2a|^2 = 4|a|^2 \rightarrow$$
$$N^2|a|^2$$

Radiation spectrum

$$\boxed{S(\omega) = S_e(\omega)\left[N + N(N-1)F(\omega)\right]}$$

$S(\omega)$ – radiation spectrum

$S_e(\omega)$ – single electron spectrum

N – number of electrons in a bunch

$F(\omega)$ – longitudinal bunch form factor

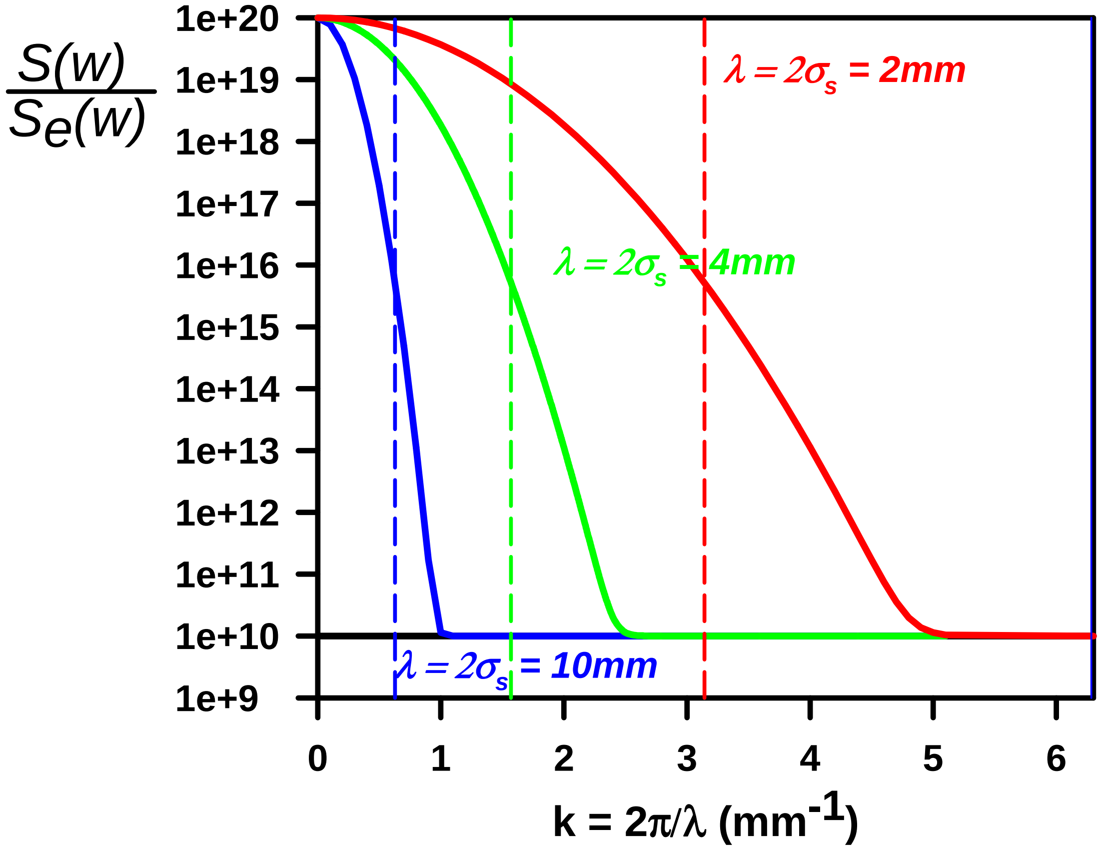
$$\boxed{F(\omega) = \left| \int_{-\infty}^{\infty} \rho(s)\, e^{-i\frac{\omega}{c}s}\, ds \right|^2}$$

$\rho(s)$ – Longitudinal particle distribution in a bunch

Gaussian beam

$$F(\omega)=\left|\frac{1}{\sigma_s\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{-\frac{s^2}{2\sigma_s^2}}\, e^{-i\frac{\omega}{c}s}\, ds\right|^2 = e^{-\frac{\omega^2\sigma_s^2}{c^2}} = e^{-k^2\sigma_s^2}$$

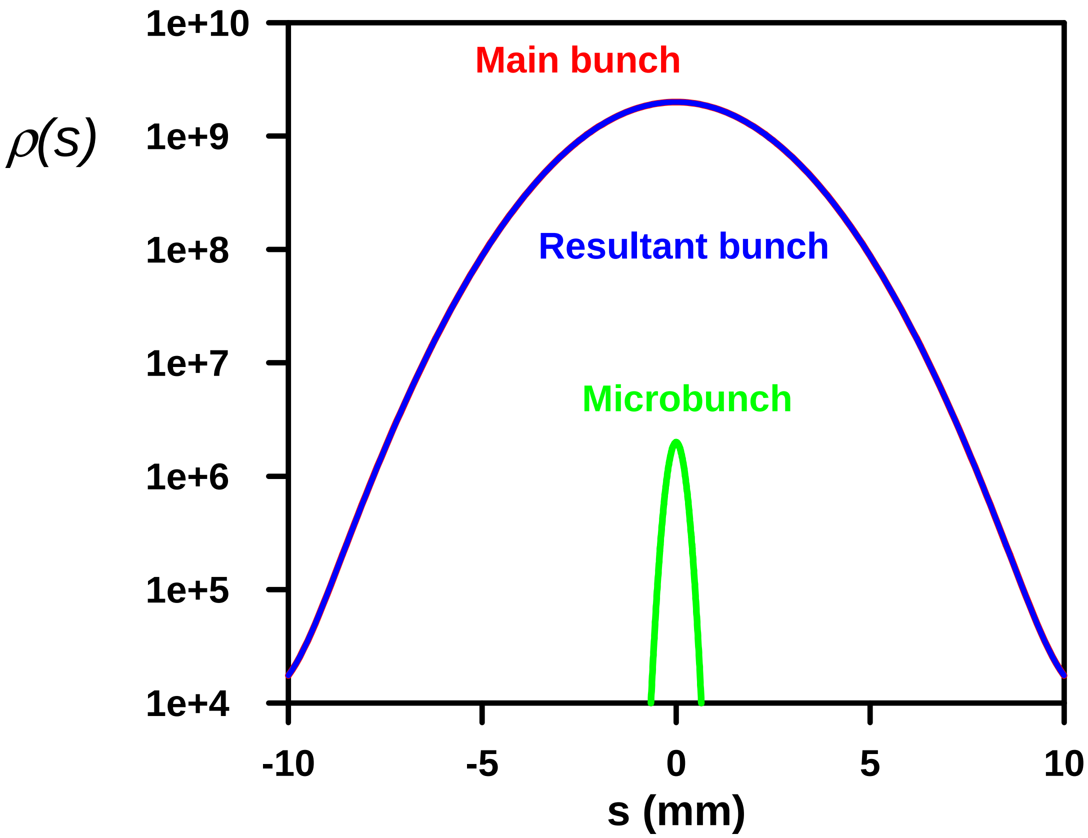
Assume $N = 10^{10}$ e/bunch



Coherent radiation appears when the bunch length is comparable to or shorter than the emitted radiation wavelength

Example 1: Two Gaussian beams

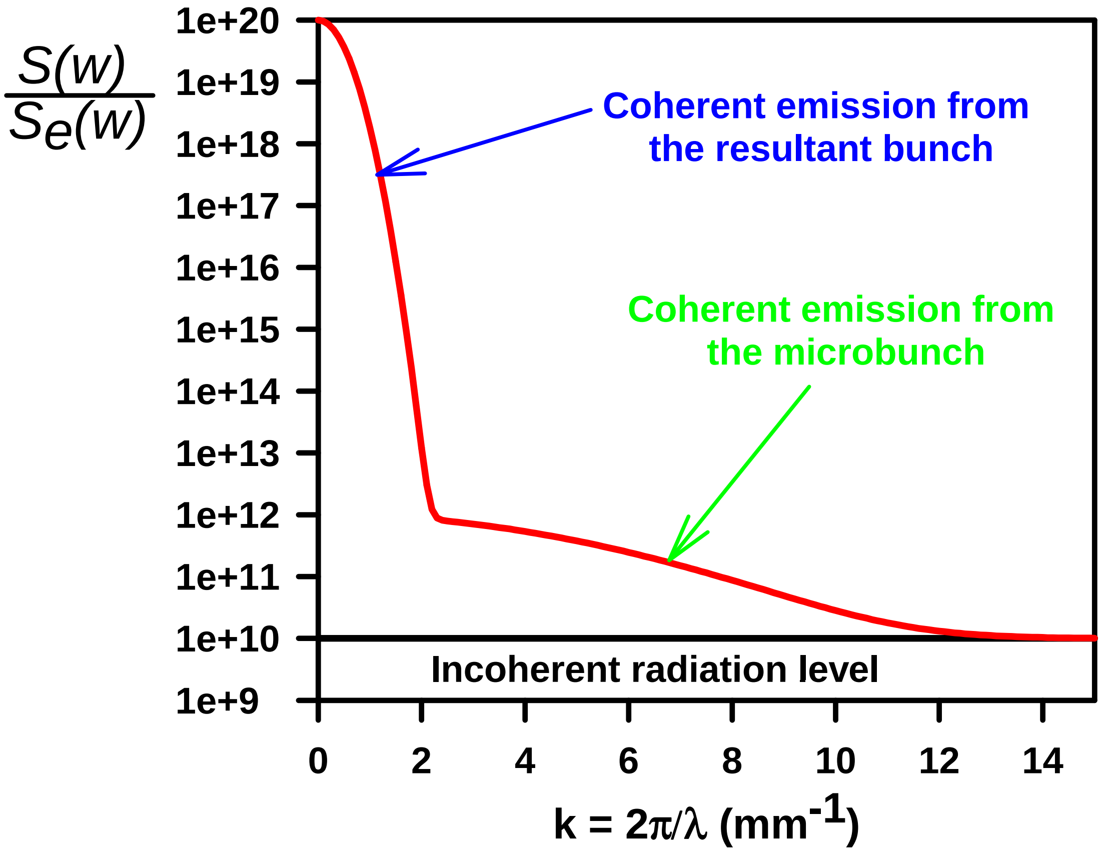
Assume we have a main bunch with σ_s = 2mm (6.7ps) and N = 10^{10}
and a microbunch in it with σ_{sm} = 0.2mm (0.67ps) and N_m = 10^6.



Example 1: Two Gaussian beams

Assume we have a main bunch with σ_s = 2mm (6.7fs) and N = 10^{10} and a microbunch in it with σ_{sm} = 0.2mm (0.67fs) and N_m = 10^6.

$$\boxed{\frac{S(\omega)}{S_e(\omega)} = \left[N + N(N-1)F(\omega)\right]}$$



Radiation spectrum

$$\boxed{S(\omega) \approx N^2 S_e(\omega) F(\omega)}$$

✓ $S(\omega)$ – radiation spectrum
(can be measured in the experiment)

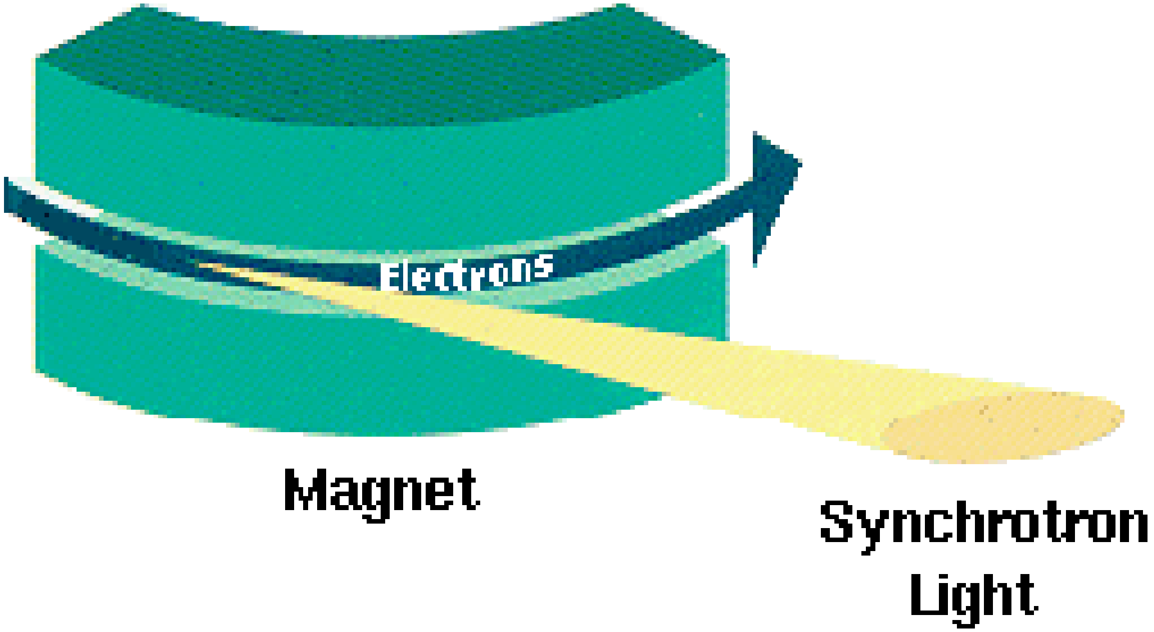
✓ N – number of electrons on the bunch
(known from the experiment)

✓ $F(\omega)$ – bunch form function
(measurement purpose)

✓ $S_e(\omega)$ – single electron spectrum
(should be known)

Synchrotron radiation

Synchrotron radiation appears when a charged particle beam is bent in a magnetic field



$$\boxed{P_\gamma = \frac{1}{6\pi\varepsilon_0}\frac{q^2c}{\rho^2}\gamma^4}$$

$\gamma = \frac{E}{m_0c^2}$ **is the charged particle Lorentz-factor**

ρ **is the bending radius**

Synchrotron radiation

Advantages for diagnostics:

- in circular accelerators it is just generated
- in linear accelerators it might exist in magnet chicanes and bunch compressors
- no need for any special insertion devices

Disadvantages for diagnostics:

- very difficult to predict (spectrum might be distorted while propagating through the vacuum chamber)
- impossible to separate from background (e.g. wakefield radiation)

Example 2: Microbinch Instabilities in Storage Rings

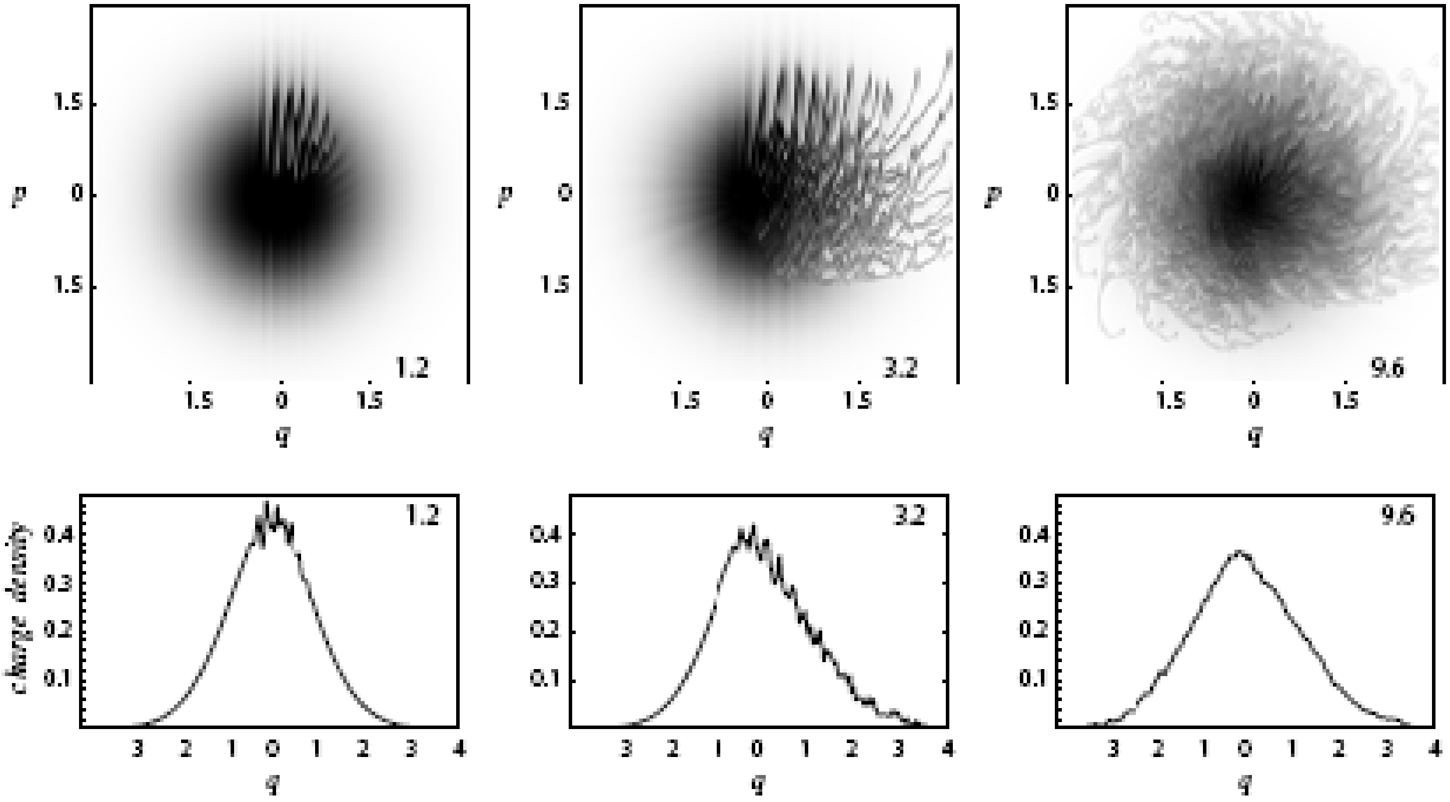


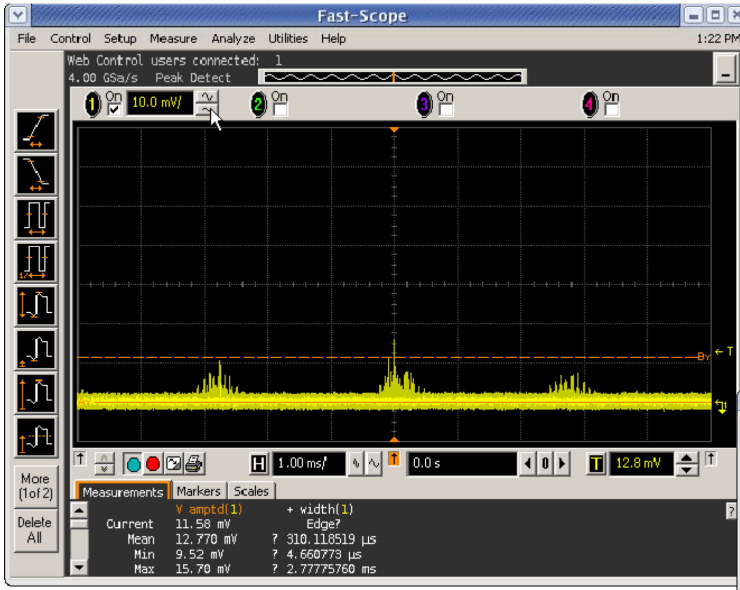
FIG. 6: Time evolution of bunch under effect of CSR in a compact storage ring. Density plots in phase space (top row) and charge density (second row). Pictures are taken at (normalized) time $\tau = 1.2, 3.2$, and 9.6. Instability initiated by a small perturbation with mode number $n = 702$ (wavelength $\lambda = 2.2$ mm). A unit of q corresponds to 1 cm.

M. Venturini, et al., PR ST-AB 8, 014202 (2005)

Example 2: Microbinch Instabilities in Diamond LS

Schottky Barrier Diode was used as a detector sensitive to 3.33 – 5mm radiation wavelength

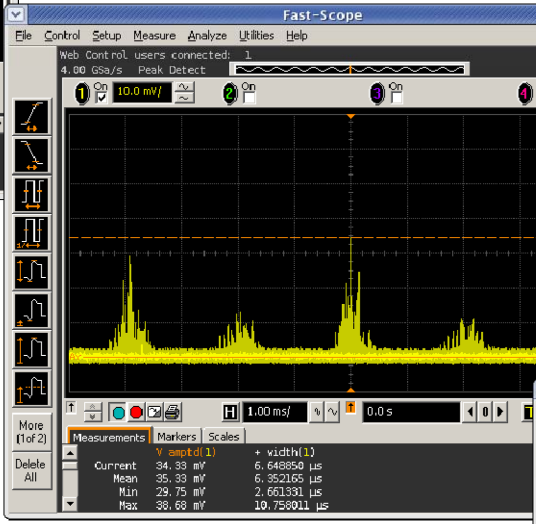
1.9 mA



```
Web Control users connected:  1
4.00 GSa/s   Peak Detect

           V amptd(1)       + width(1)
  Current  11.58 mV           Edge?
     Mean  12.770 mV      ? 310.118519 µs
      Min  9.52 mV        ? 4.660773 µs
      Max  15.70 mV       ? 2.77775760 ms
```

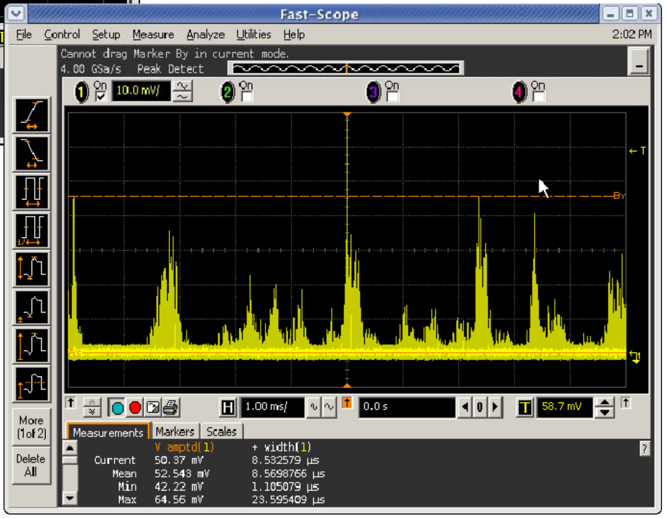
3.0 mA



```
Web Control users connected:  1
4.00 GSa/s   Peak Detect

           V amptd(1)       + width(1)
  Current  34.33 mV         6.648850 µs
     Mean  35.33 mV         6.352165 µs
      Min  29.75 mV         2.661331 µs
      Max  38.68 mV         10.758011 µs
```

5.2 mA

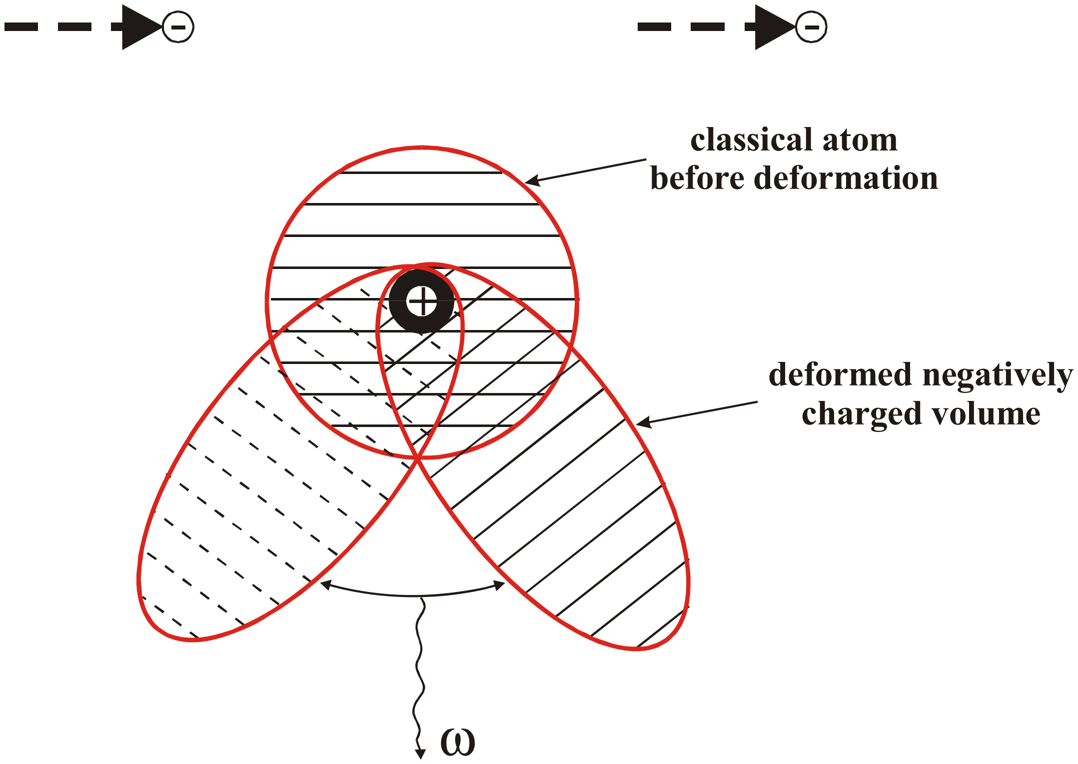


```
Cannot drag Marker By in current mode.
4.00 GSa/s   Peak Detect

           V amptd(1)       + width(1)
  Current  50.37 mV         8.532579 µs
     Mean  52.543 mV        8.5698766 µs
      Min  42.22 mV         1.105079 µs
      Max  64.56 mV         23.595409 µs
```

Polarization Bremsstrahlung

A charged particle moving in condensed matter approaches the atom polarizing it

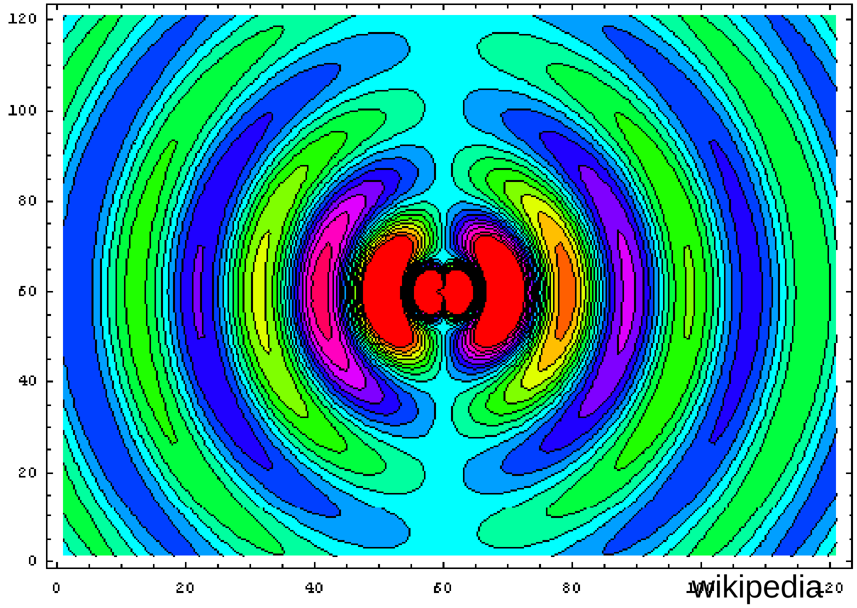


classical atom
before deformation

deformed negatively
charged volume

Polarization Bremsstrahlung

A charged particle moving in condensed matter approaches the atom polarizing it



wikipedia

i) Radiation is defined by the electrons of medium

ii) The energy loss due to the process is so small that the particle is assumed to be moving rectilinearly and with constant velocity

iii) There is no dependence on the particle mass (it depends on particle energy and its charge)

Polarization Bremsstrahlung

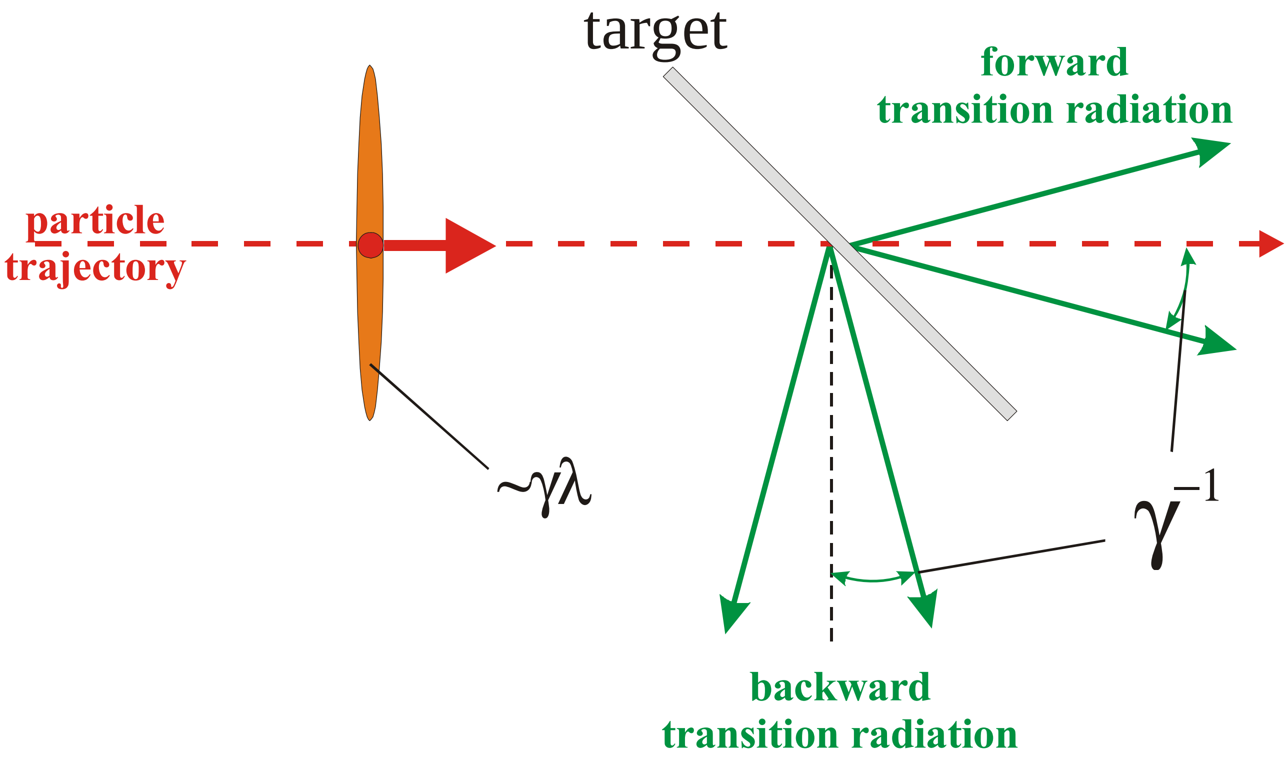
- **Cherenkov radiation**
- **Transition radiation**
- **Diffraction radiation**
- **Smith-Purcell radiation**
- **Parametric X-ray radiation in crystals**

Polarization Bremsstrahlung

- ☐ Cherenkov radiation
- ☐ **Transition radiation**
- ☐ **Diffraction radiation**
- ☐ **Smith-Purcell radiation**
- ☐ Parametric X-ray radiation in crystals

Transition Radiation

It appears when a charged particle crosses a boundary between two media with different dielectric properties



Transition Radiation

Advantages for diagnostics:

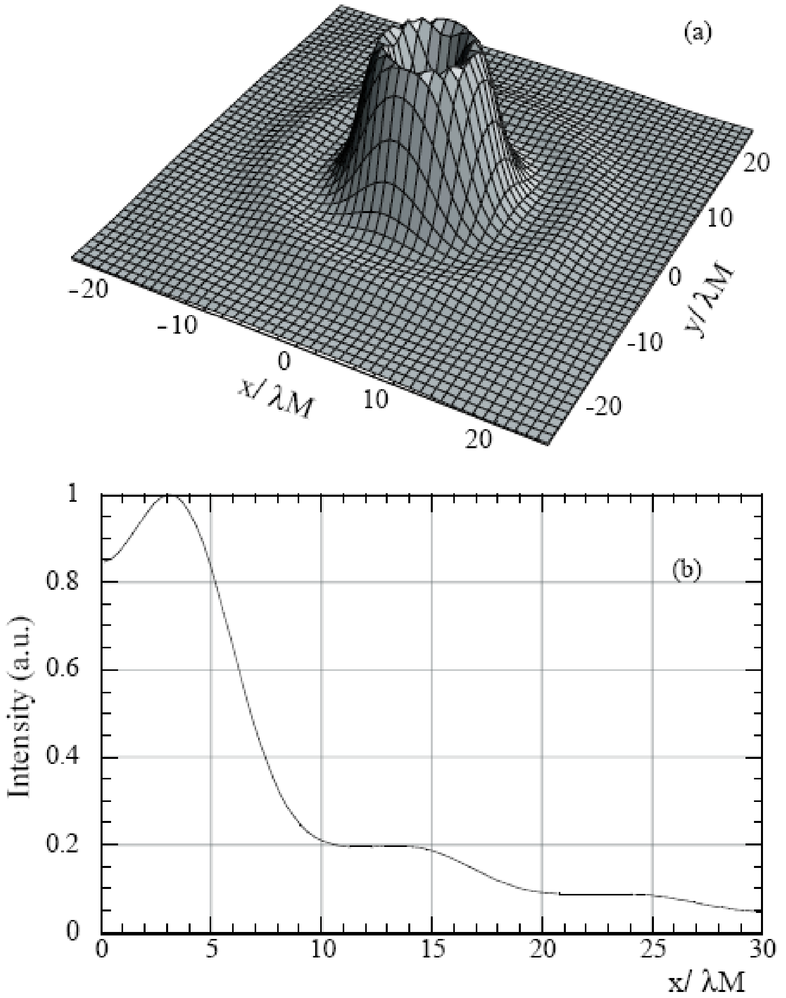
- Instantaneous emission
- Large emission angles
- High intensity, i.e. single shot measurements are possible
- Spectrum can be predicted with proper accuracy

Disadvantages for diagnostics:

- Invasive mechanism (can not be used in rings)
- High brightness beam might destroy the target
- The target can change the beam parameters

Example 3: OTR beam profile monitor

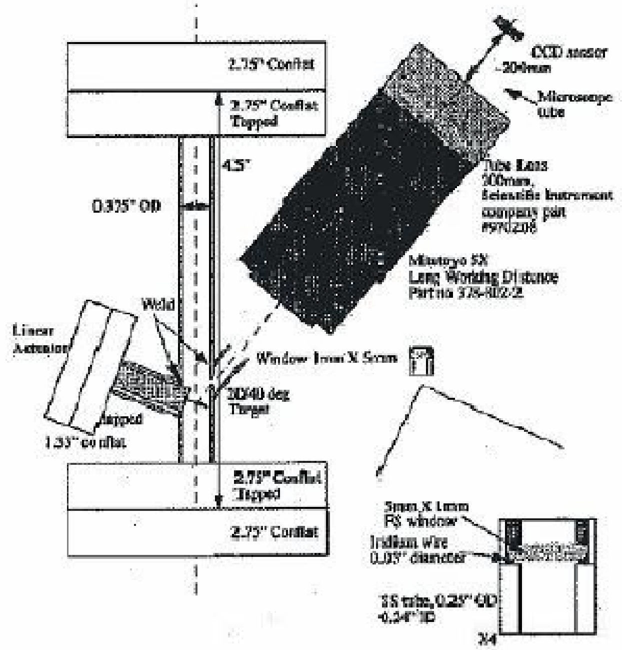
Single particle distribution at the target surface
(Half Width at Half Maximum, HWHM is a couple of wavelengths)

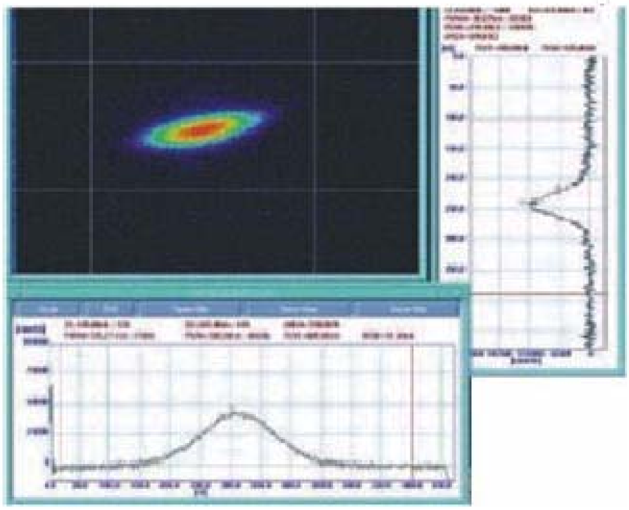


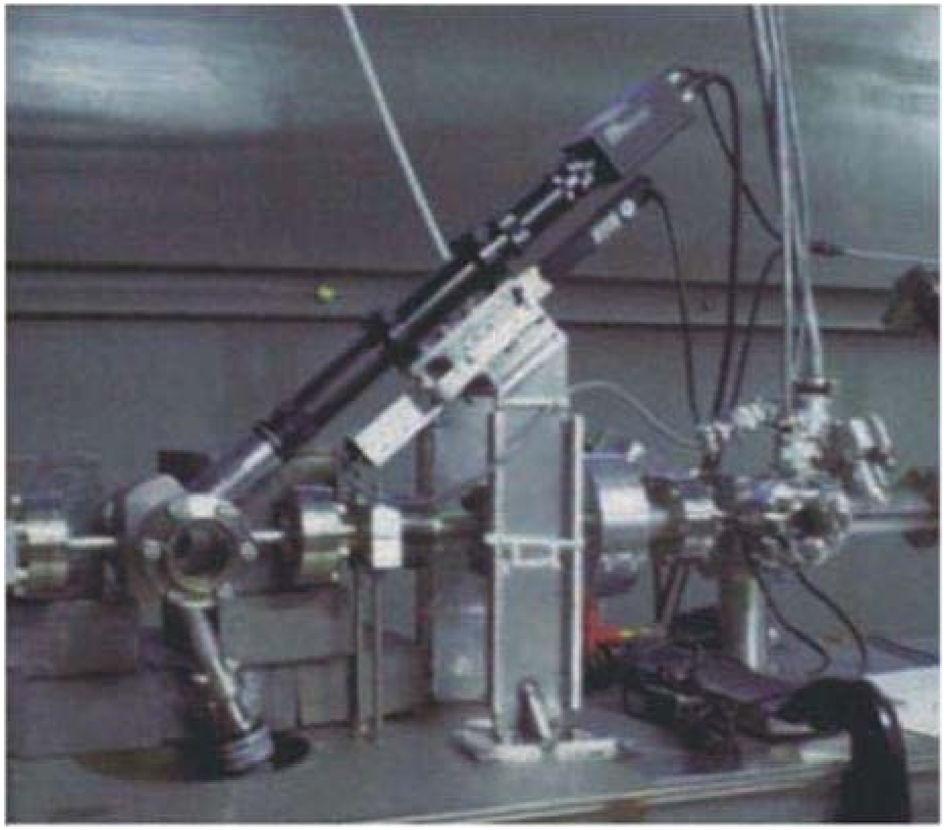
M. Castellano and V. Verzilov,
Phys. Rev. ST-AB 1, 062801 (1998)

Measuring the incoherent part of radiation spectrum we do not have to care about single particle distribution as long as the transverse beam size is much larger it

Example 3: SLAC OTR monitor at KEK-ATF

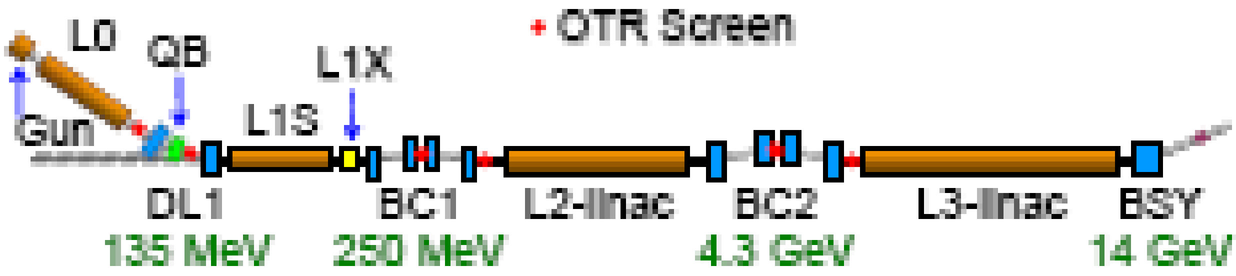






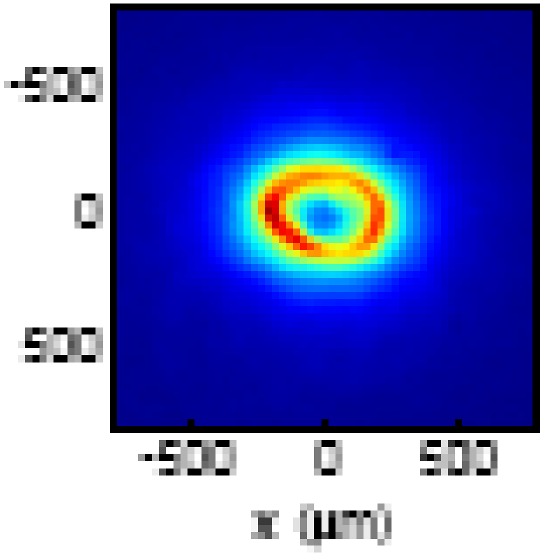
Very high resolution for an OTR monitor (~2μm) predicted by the theory but only ~5.5μm spot was actually measured.

Example 3: Linac Coherent Light Source



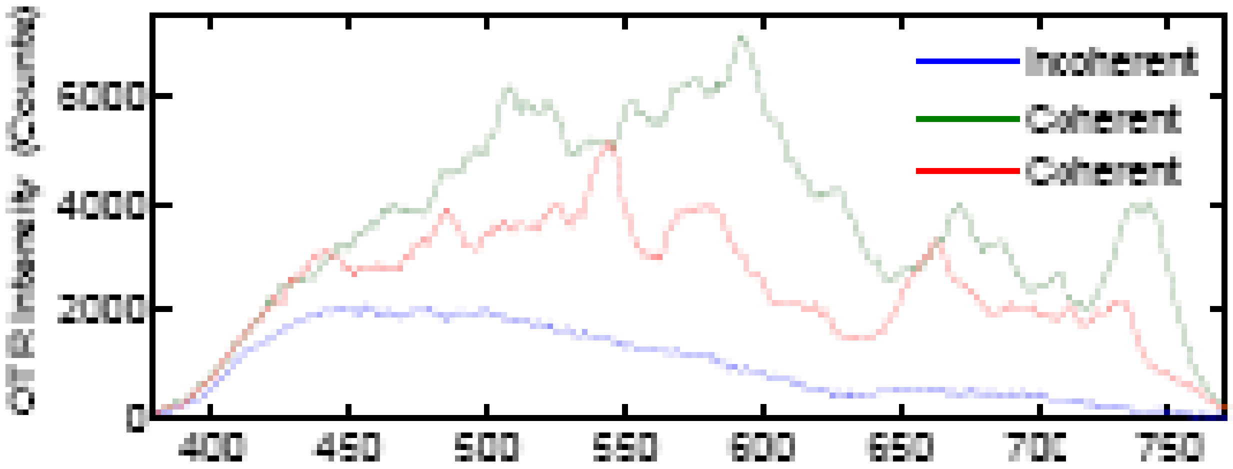
200fs (0.06mm)

25fs (0.0075mm)



H. Loos, et al., SLAC-pub-13395

Example 3: OTR spectrum at LCLS

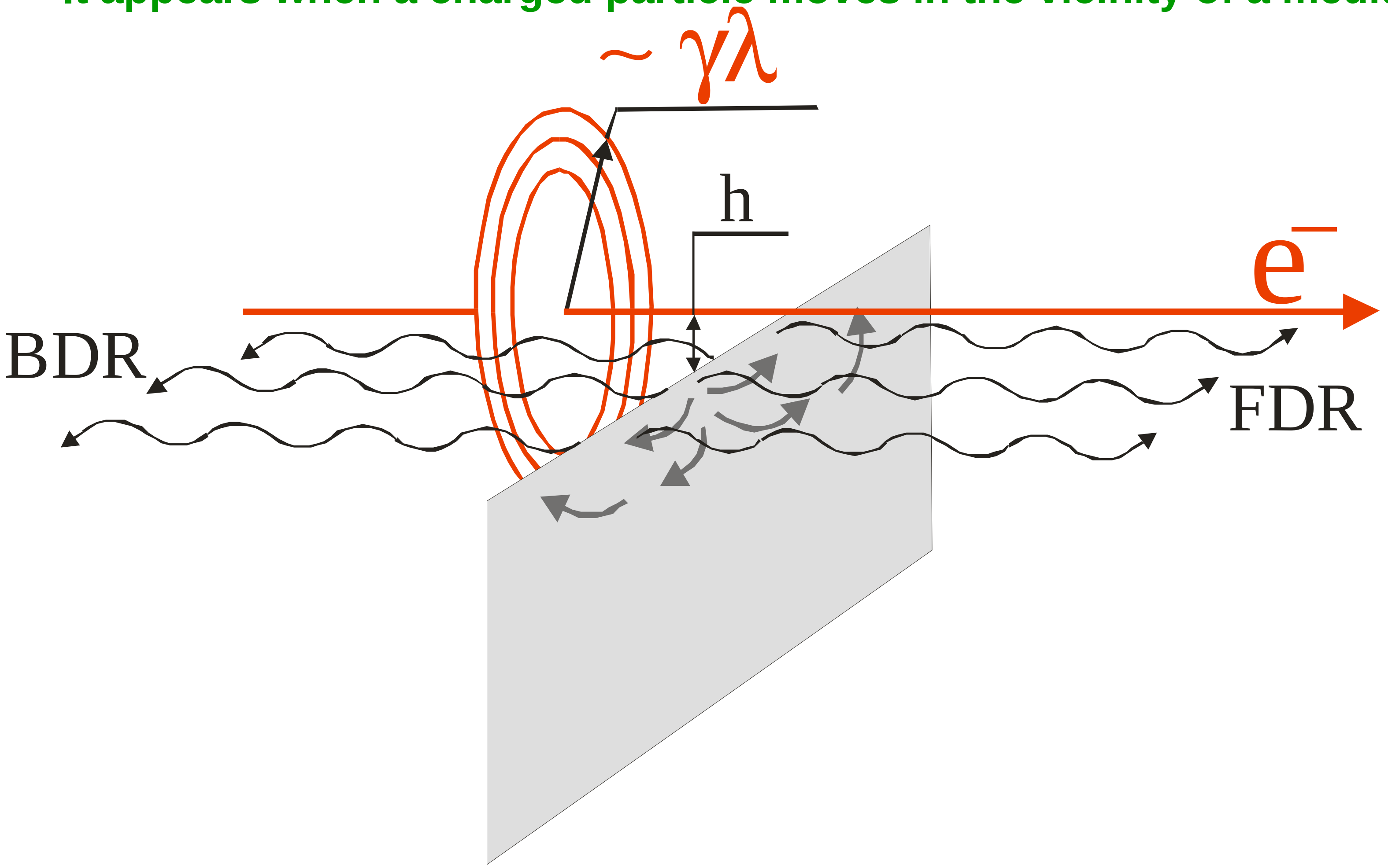


- The form of the coherent spectrum fluctuates from shot to short
- Existence of spikes in the spectrum suggests that there are a few microbunches in the longitudinal particle distribution
- The coherent part of the OTR intensity could be much higher than the incoherent one

H. Loos, et al., SLAC-pub-13395

Diffraction Radiation

It appears when a charged particle moves in the vicinity of a medium



Impact parameter, h, – the shortest distance between the target and the particle trajectory

$$h \leq \gamma\lambda$$

λ - observation wavelength

$\gamma = E/mc^2$ – Lorentz - factor

Diffraction Radiation Advantages

- **Non-invasive method**

  (no beam perturbation or target destruction)

- **Instantaneous emission**

  (quick measurements)

- **Single shot measurements**

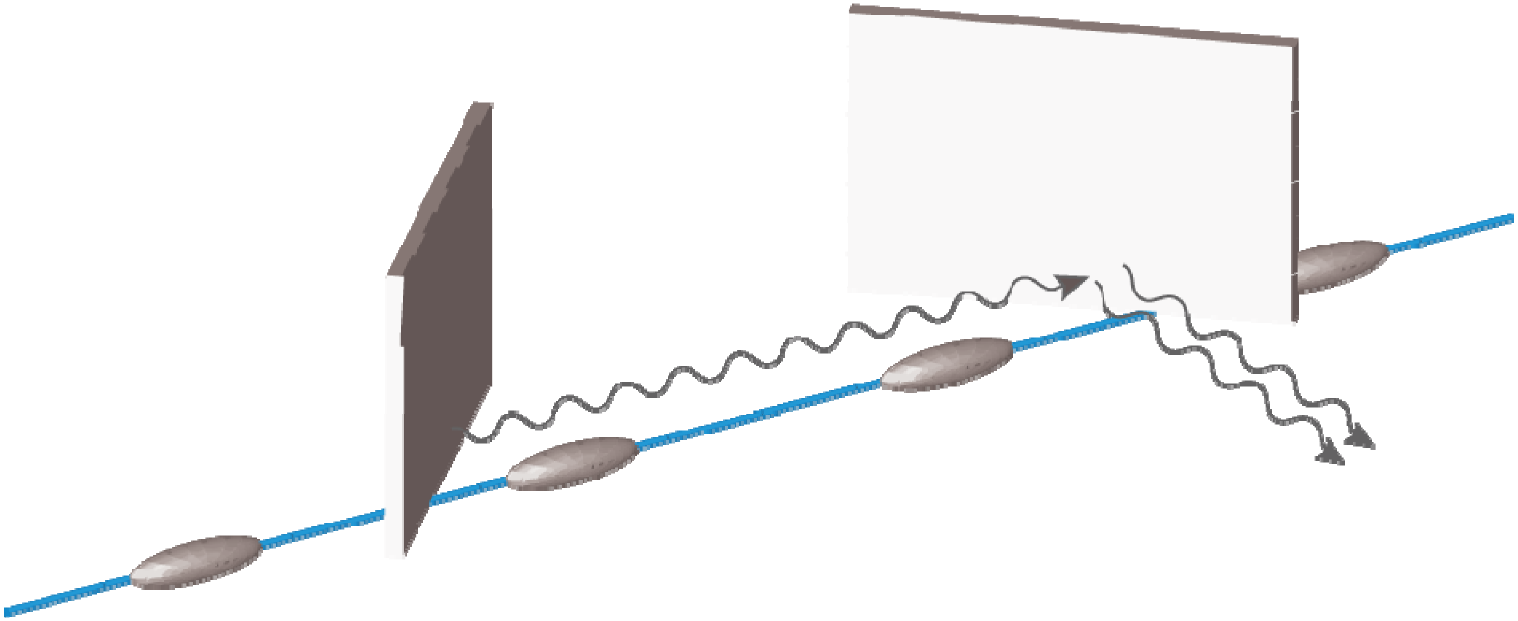
  (no additional error from shot-by-shot instabilities)

- **Large emission angles (0 ~ 180^0)**

  (good background conditions)

- **Single electron spectrum is predictable**

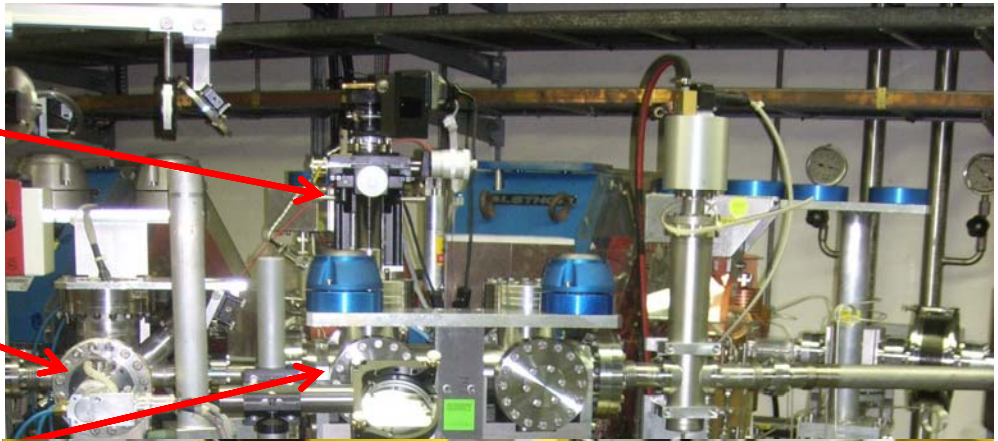
Coherent Diffraction Radiation experiment at CTF3 in CERN

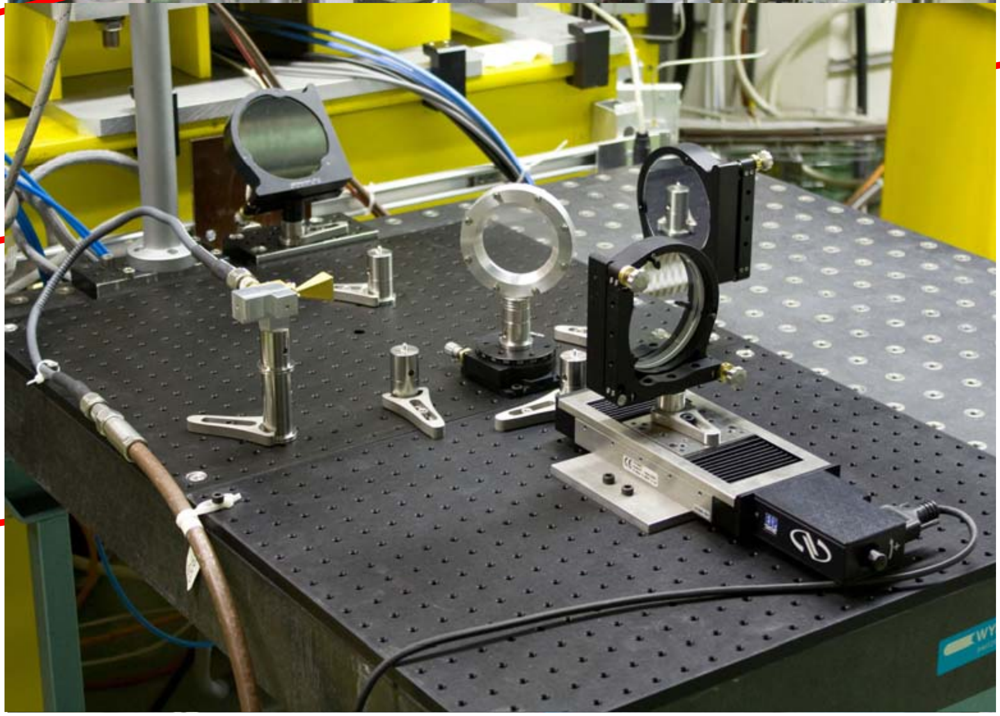


- ☐ For our setup at CTF3, h ≈ 15 mm ≤ γλ = 1175 for γ = 235 and λ = 5mm;
- ☐ SR background will be blocked by the first target;
- ☐ Ultra-fast Schottky Barrier Diode detector (time response <250ps) is used

DITANET

CDR setup at CTF3





Vacuum manipulator for target rotation and translation

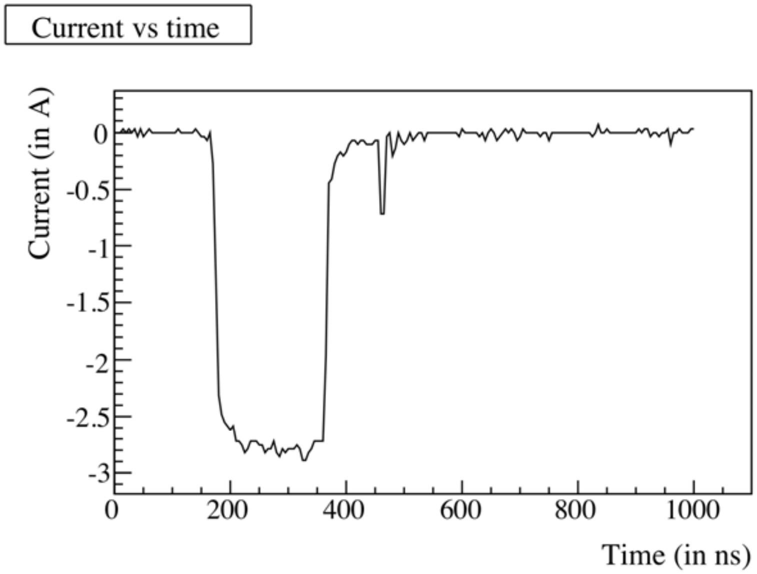
CRM.MTV0210 for target reference position

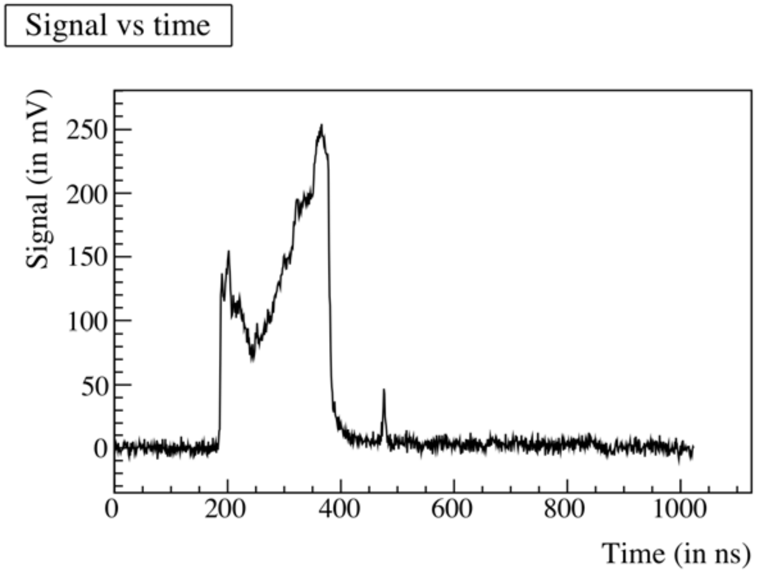
CDR target within six-way cross

CR.SVBPM0195 (not shown in picture) for beam position and charge readings

SBD detector connected to DAQ

CDR signal

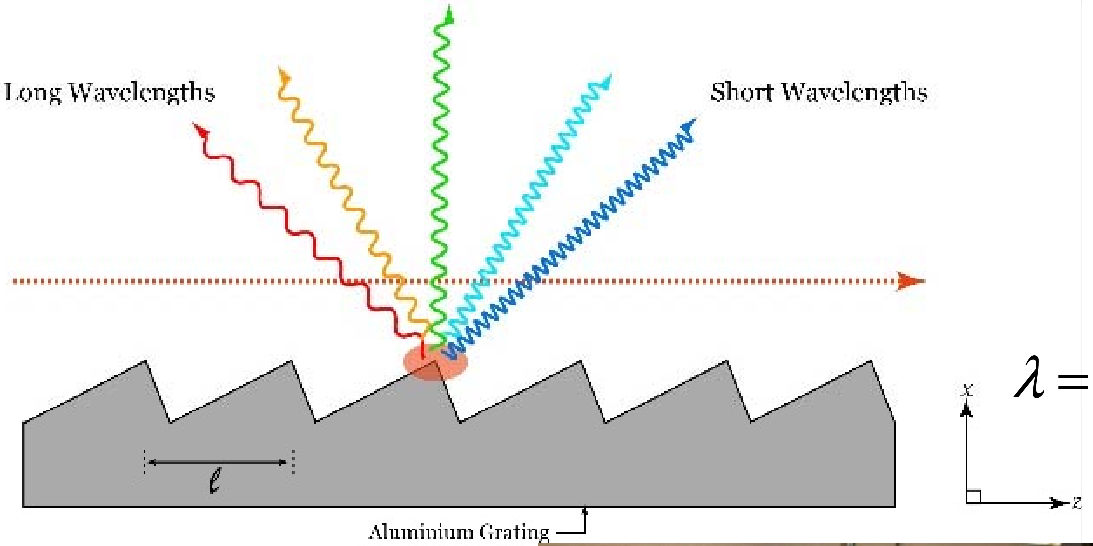

Current vs time


Signal vs time

- **Current was measured with a BPM**
- **Signal acquired by a digitizer (4Gs/s)**
- **3GHz bunch sequence rate (0.33ns)**
- **Train length is 200ns (~600 bunches)**

Smith-Purcell Radiation

Emission from blazed grating



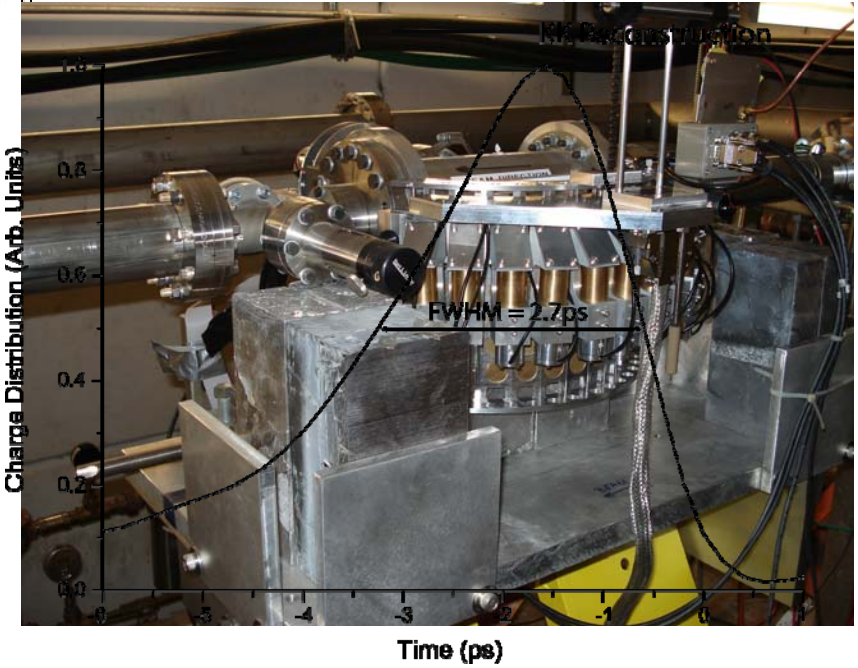
e^- beam

blazed grating

$$\lambda = \frac{l}{n}\left(\frac{1}{\beta} - \cos\theta\right)$$

- Beam test at SLAC End station A (28.5 GeV)

V. Blackmore, G. Doucas, et al., Physical Review ST-AB 12, 032803 (2009)



Smith-Purcell Radiation

Advantages:

- **Non-invasive method**
- **Instantaneous emission**
- **Single shot measurements**
- **Large emission angles (0 ~ 180^0)**

Disadvantages:

- **Smith-Purcell theory is not as advanced as for DR. Prediction of a single electron spectrum is a challenging task, but not impossible**

Kramers - Kronig method

$$\rho(s)=\frac{1}{\pi c}\int_0^{\infty}\sqrt{F(\omega)}\cos\left[\psi(\omega)-\frac{\omega s}{c}\right]d\omega$$

Here:

c is the speed of light;
s is the longitudinal coordinate;
ψ(ω) is the initial phase.

$$\psi(\omega)=\frac{2\omega}{\pi}\int_0^{\infty}\frac{\ln\left[F(\omega')\big/F(\omega)\right]}{\omega^2-\omega'^2}d\omega'$$

Summary

- ❑ **Tools based on coherent radiation are certainly useful for longitudinal charged particle beam diagnostics in modern and future accelerator machines as:**
  - ❖ **it does not have any theoretical resolution limit**
  - ❖ **it gives information about longitudinal dimensions and structure**

- ❑ **There is a set of problems which still need to be resolved:**
  - ❖ **Coherent radiation backgrounds;**
  - ❖ **Precise prediction of a single electron spectrum;**
  - ❖ **Precise extrapolation method for phase reconstruction;**
  - ❖ **The method should be robust and simple in use;**
  - ❖ **The hardware should be relatively inexpensive.**

- ❑ **Modern accelerators have a lot of surprises which need to be identified and resolved**