Coherent Diffraction Radiation and its Application at CTF3 and CLIC

P. Karataev

John Adams Institute at Royal Holloway, University of London

Potential collaboration with:

Abstract

Development of precise diagnostics for accelerator installations of the next generation such as Linear Collider (ILC or CLIC) is very important for optimal performance of the machine. To achieve a reasonable luminosity for Linear Collider (LC) the electron beam dimensions in the Interaction Point (IP) will be reduced down to a nanometer level by reducing the beta function. If the beta function reaches the size of the bunch length, the luminosity is degraded due to a so-called “hour-glass” effect. Moreover, it was suggested that the longitudinal bunch profile should be carefully designed to optimize the luminosity enhancement. The longitudinal bunch profile in the LC IP depends on many parameters such as RF gun phase, bunch charge, longitudinal particle distribution after the beam extraction from the damping ring, injection time into the main linac, bunch compressor settings, etc. Therefore, monitoring of the longitudinal electron (positron) distribution in a bunch is very important at all stages of the beam delivery.

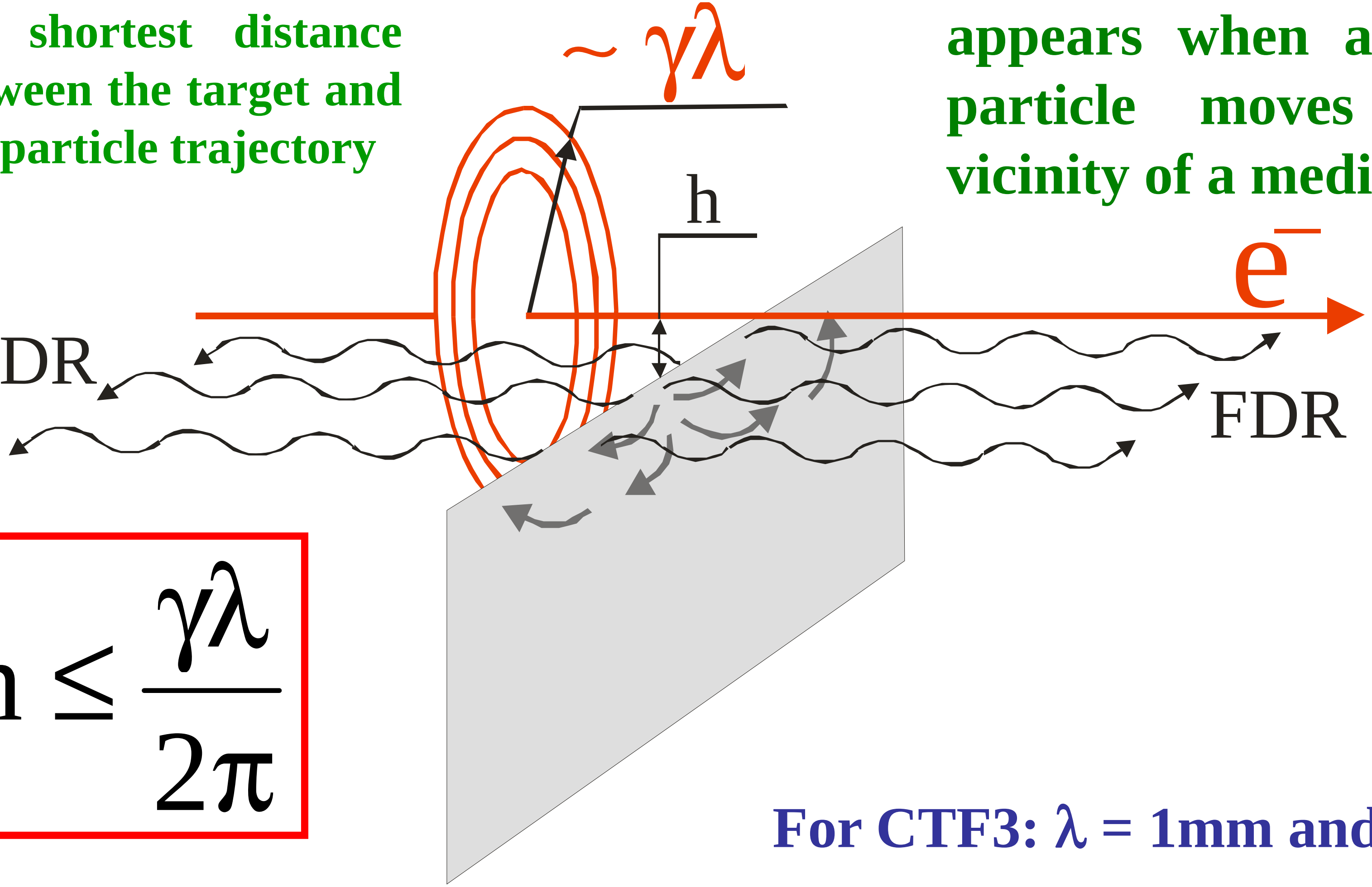
Up-to-date every accelerator machine is equipped with a set of diagnostics devises that allow the operation personnel to tune it and maintain stable high quality conditions. However, most of the reliable diagnostics methods are invasive ones. LC precludes the use of any invasive diagnostics such as, for example, transition radiation monitors or solid wire scanners due to significant electron beam charge losses. Moreover, direct interaction of the electron beam with target material results in worsening of the electron beam parameters.

Diffraction radiation appearing when a charged particle moves in the vicinity of a medium is a promising candidate for non-invasive electron beam diagnostics development. In this report one proposes to use coherent diffraction radiation (CDR) generated from a double target system for longitudinal bunch profile measurements.

What is Diffraction Radiation?

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

Diffraction radiation (DR) appears when a charged particle moves in the vicinity of a medium



$$\boxed{h \le \frac{\gamma\lambda}{2\pi}}$$

For CTF3: λ = 1mm and γ = 400

$$\boxed{h = 10\text{mm} << \frac{\gamma\lambda}{2\pi} = 64\text{mm}}$$

λ - observation wavelength

γ = E/mc^2 – Lorentz - factor

Advantages of the Coherent Diffraction Radiation technique

- **Non-invasive method and long distance from the beam line**

  (no beam perturbation or target destruction)

- **Instantaneous emission**

  (quick measurements)

- **Very high photon yield (proportional to N^2)**

  (easy to detect)

- **Large emission angles ($0 \sim 180^0$)**

  (good background conditions)

- **Possibility to monitor an asymmetry of the longitudinal bunch profile**

  (bunch profile optimization is possible)

Coherent Radiation Spectrum

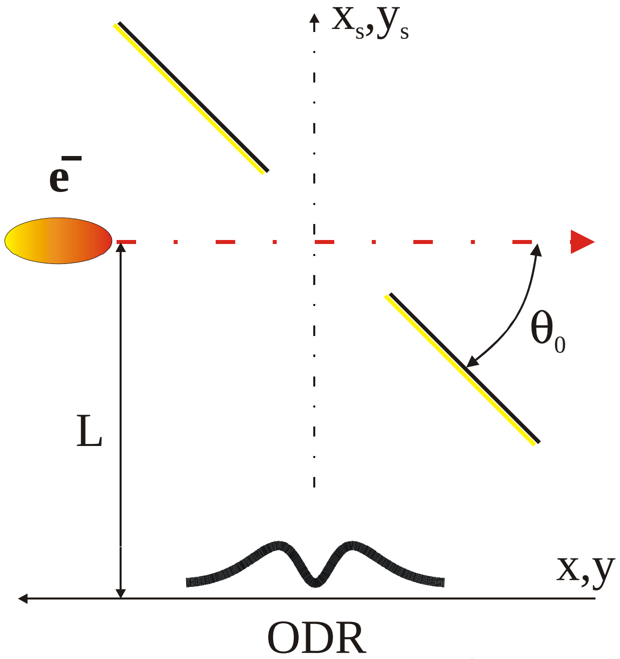
$$\boxed{S(\omega) = S_e(\omega)\left[N_b + N_b(N_b - 1)F(\omega)\right]}$$

- ✓ **$S(\omega)$ – radiation spectrum from a bunch of electrons**
  (known from experiment)
- ✓ **N_b – number of electrons in the bunch**
  (known from experiment)
- ✓ **$F(\omega)$ – bunch form function**
  (measurement purpose)
- ✓ **$S_e(\omega)$ – radiation spectrum from a single electron**
  (should be predictable)

Theory of Diffraction Radiation generated by a single electron from a single target

$$E^{DR}_{x,y} = -\frac{ekR_{x,y}}{4\pi^3\gamma L}\iint \frac{x_s, y_s}{\sqrt{x_s^2+y_s^2}} K_1\left(\frac{k}{\gamma}\sqrt{x_s^2+y_s^2}\right) e^{\left[\frac{k}{2L}\left(x_s^2+y_s^2\right)-\frac{k}{L}\left(x_s x+y_s y\right)\right]} dy_s dx_s \quad (*)$$

The theory has been used for comparison with the experiment in:
M. Castellano, et al., Physical Review E 63 (2001) 056501

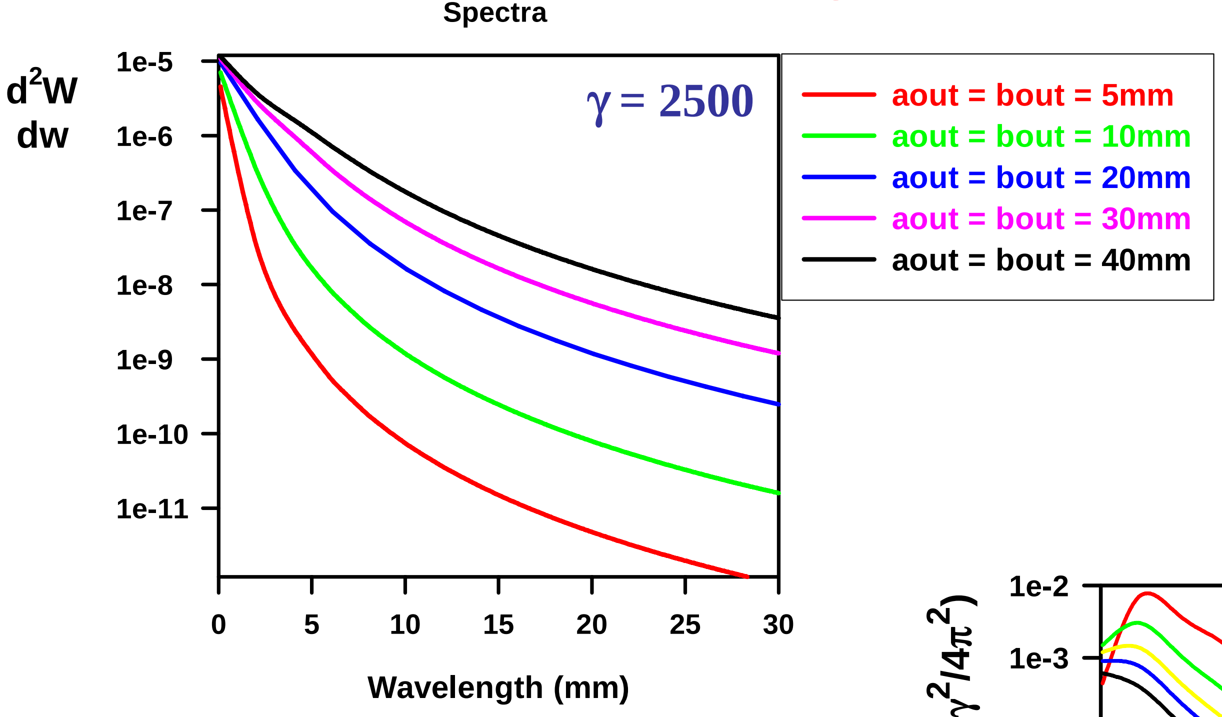


$R_{x,y}$ are the Fresnel reflection coefficients;
e is the electron charge;
γ is the charged particle Lorentz-factor;
k=2π/λ is the radiation wave number;
λ is the radiation wavelength;
L is the target-to-detector distance;
K1 is the modified Bessel (McDonald) function;
$\theta_0 = 45^0$ is the target tilt angle.

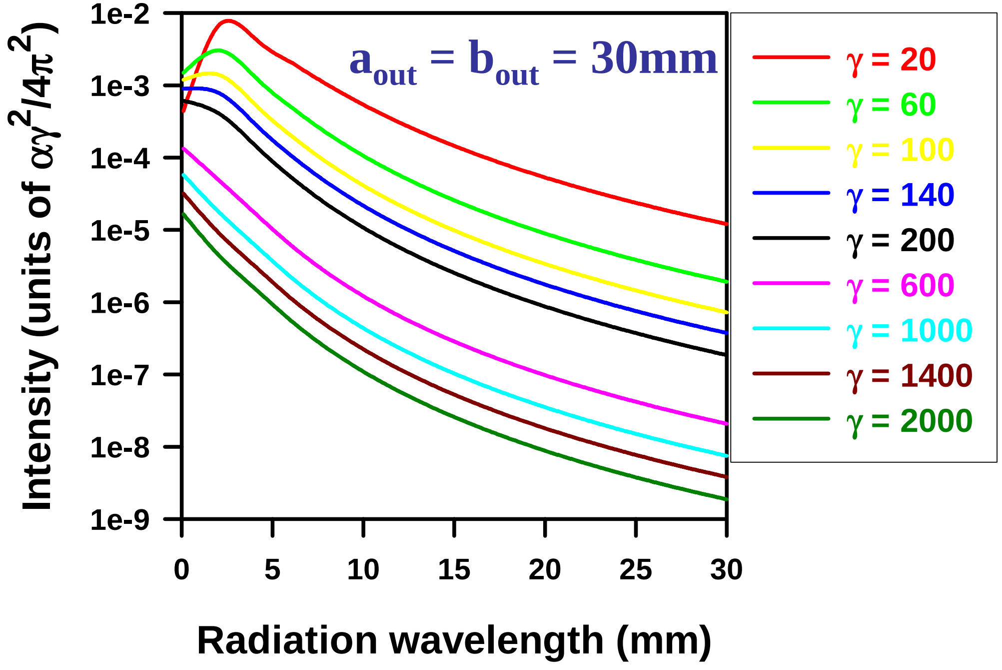
Spectral-Spatial Distribution:

$$\frac{d^2W^{DR}}{d\omega d\Omega} = 4\pi^2k^2L^2\left[\left|E^{DR}_x\right|^2 + \left|E^{DR}_y\right|^2\right]$$

CDR Spectra for different electron energies and target dimensions



The theory takes into account:
- the material of the target;
- outer target dimensions;
- finite distance from target to detector



Calculation parameters:

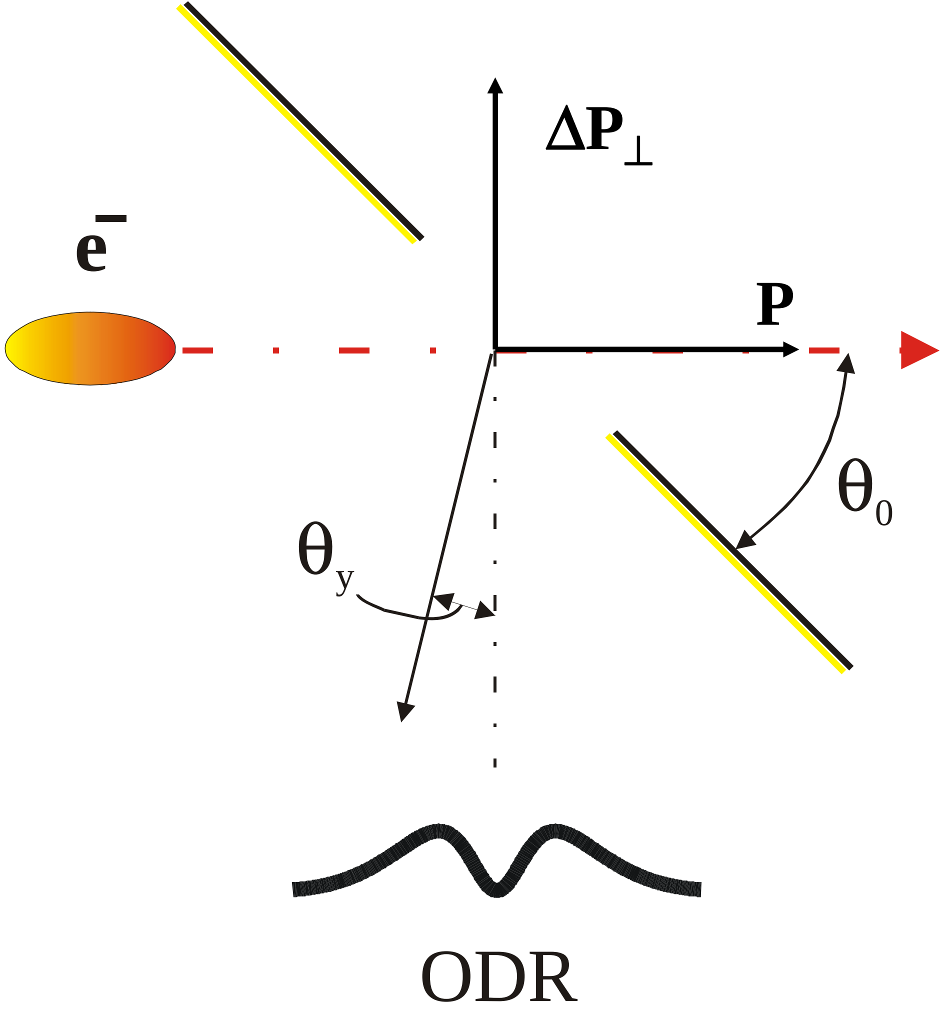
as = bs = 0

ain = bin = 1mm

l2 = 0.4m

$\Delta x/L = \Delta y/L = 0.2$rad.

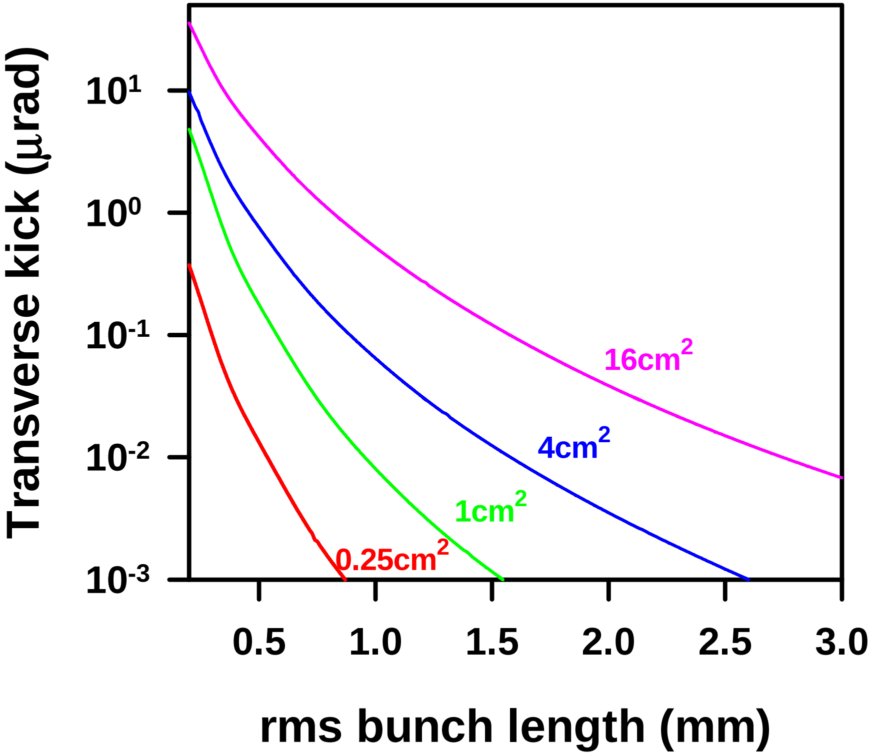
Transverse kick caused by the CDR target.



Coherent DR may cause a transverse kick

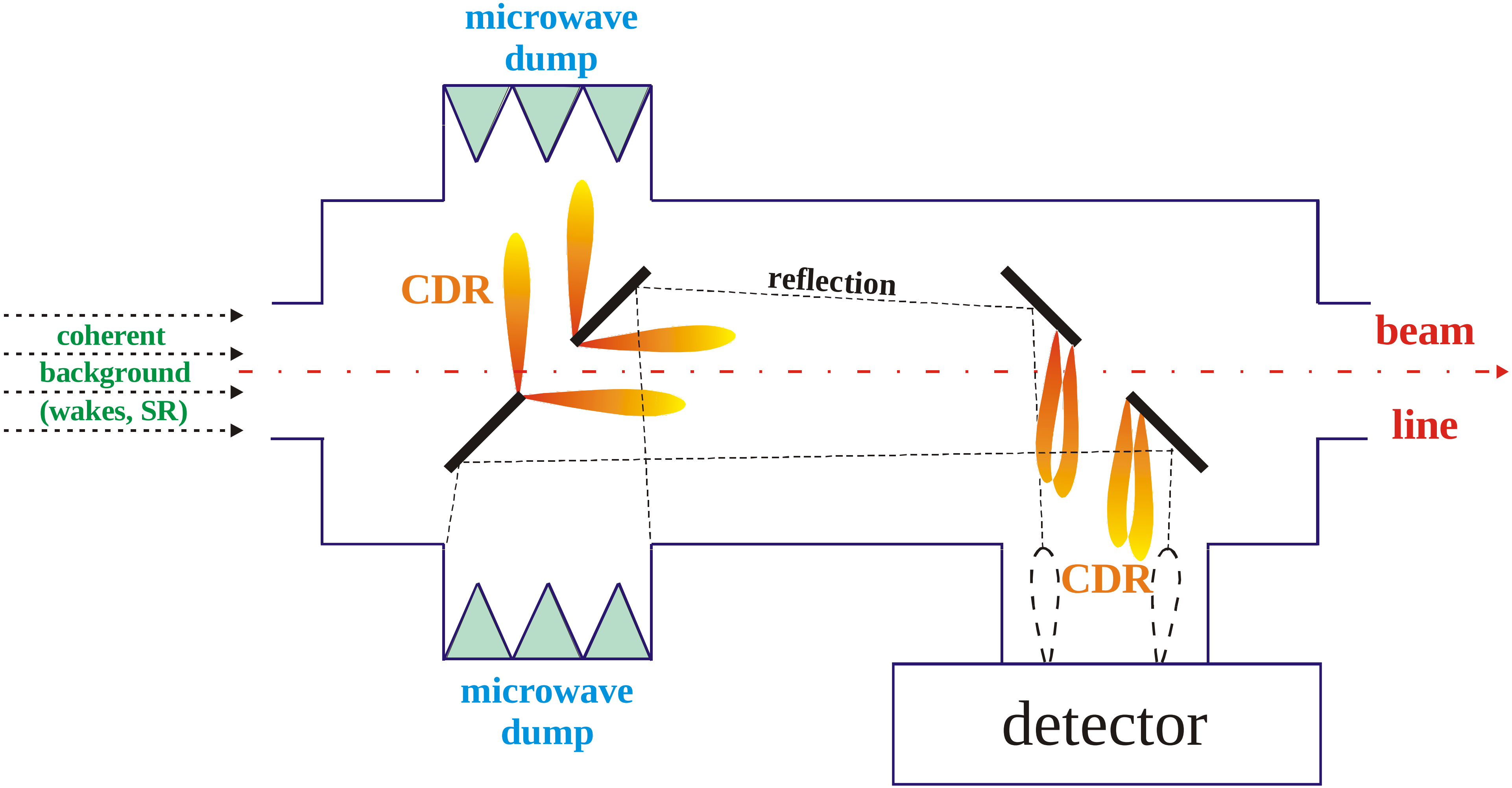
$$\Delta\theta_\perp = \frac{\Delta P_\perp}{P}$$

Calculations for different outer target dimensions



The transverse kick depends on the outer target dimensions and the longitudinal bunch size. In some cases it might reach a microscopic values. Therefore, CDR method may not be a non-invasive one already!

Double target system as a new CDR generator



As a detector module one might use an interferometer system for the beginning to be able to develop the bunch diagnostics method. A single shot grating type spectrometer system is also considered.

Advantages of the proposed scheme

1) Single electron spectrum is predictable.

Recent progress in the DR and TR theory allows us to predict the single electron spectrum with proper accuracy. The model is described later.

2) No coherent radiation background.

Electron beam generates coherent radiation in many different ways, i.e. Coherent Synchrotron Radiation in the bending or steering magnets or wake field radiation form the accelerator chamber itself. It is very difficult to separate the CDR and other radiation types. The first target will play the role of the mask in the ODR experiment and cut off the coherent radiation background from upstream.

3) No beam distortion due to the transverse kick.

Two identical targets placed at 90^0 wrt to each other will compensate the transverse kick caused by each other. In other words both targets will cause the transverse kick but with opposite signs.

4) Higher photon yield.

Since the passing particle will generate CDR at both targets the total photon yield will be higher.

5) No CDR distortion due to backward reflection.

Any backward reflected photons coming from the detector module might be terminated in the microwave dump.

Theory of the CDR generated by a single electron moving through a double target system

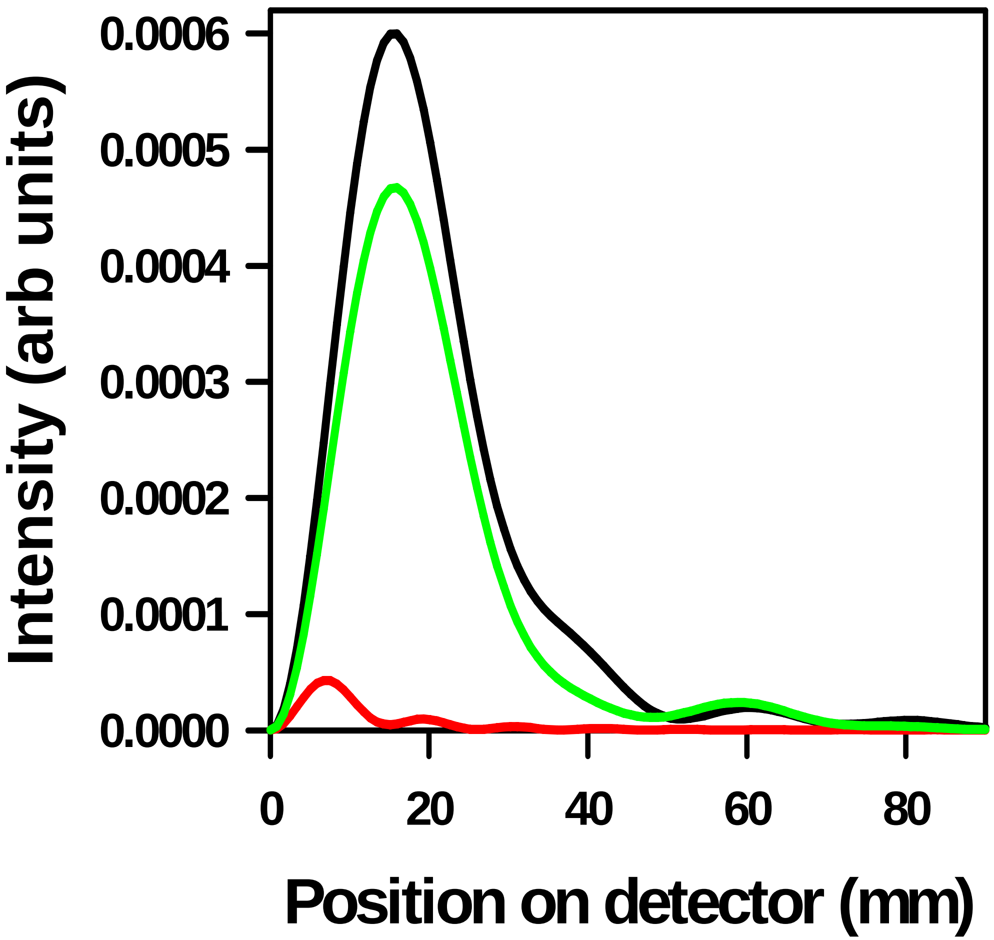
$$E_{double}(a_{out},b_{out},a_{in},b_{in}) = E1(a_{out},b_{out},a_{in},b_{in})_{x,y}\, e^{i\frac{kL_1}{\beta}} + E2(a_{out},b_{out},a_{in},b_{in})_{x,y}$$

Here:

$E2(a_{out},b_{out},a_{in},b_{in})_{x,y}$	**is the electric field of the CDR generated from the second target and determined by the Eq. (*)**
$E1(a_{out},b_{out},a_{in},b_{in})_{x,y}$	**is the electric field of the CDR generated from the first target and reflected from the first one (the model can be easily derived from the classical theory of the propagation and diffraction of light)**

a_{in} and b_{in} are the dimensions of the holes in both targets;
a_{out} and b_{out} are the outer target dimensions;
L_1 is the distance between the targets;
$k = 2\pi/\lambda$ is the CDR photon wavenumber;
λ is the radiation wavelength;
$\beta = \sqrt{1-\gamma^{-2}}$ is the particle velocity in units of light velocity;
γ is the charged particle Lorentz factor.

Simulation results



- ☐ Green line - Backward Diffraction Radiation produced at the second target;
- ☐ Red line - Forward Diffraction Radiation produced at the first target and reflected from the second one (including the diffraction effect);
- ☐ Black line - Interference of the FDR from the first target and BDR from the second one.

Calculation parameters for two identical targets:

$a_{in} = b_{in} = 1mm$

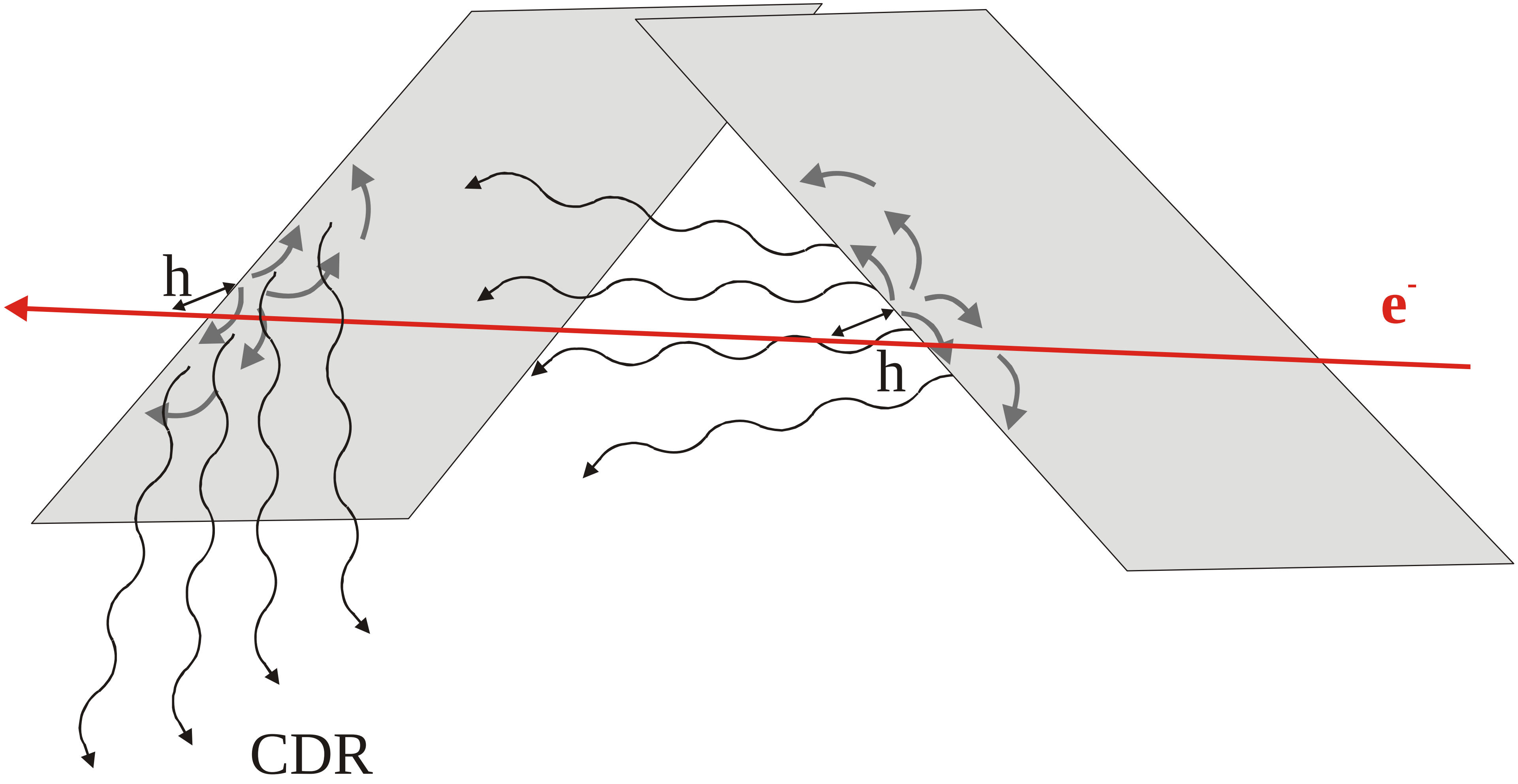
$a_{out} = b_{out} = 20mm$

$L_1 = L_2 = 0.42m$

$\gamma = 2500$

$\lambda = 1mm$

CDR generator made of two plates



An electron beam passes by two screens with h being the impact parameter.
Advantage is that much less exclusive beam time is required.

Summary

❖ Here one proposes to use a double target system as a CDR generator for application in the modern and future high energy machines for longitudinal bunch profile diagnostics.

❖ The theoretical approach has been developed;

❖ Such scheme allows us to eliminate the transverse kick, avoid large coherent radiation background contribution, and predict the single electron spectrum, which is a quite important issue for bunch length diagnostics with coherent radiation.

Future plans:

❖ simulate the CDR spectra for different target geometries for CTF3 beam parameters;

❖ optimize the configuration of the experimental installation (target dimensions, distance between target, angular acceptance of the output window, etc.);

❖ design of the CDR bunch profile monitor prototype for CTF3.

Resources and Man-power

- ❑ A few academics: Prof. G. Blair, Dr. S. Boogert, and Dr. P. Karataev

- ❑ PhD student has begun his study at RHUL from September this year (1.0FTE) Maximilian Micheler;

- ❑ A Post-Doc position funded by JAI has been offered recently (we do not know if the offer is accepted or not) (0.5 FTE);

- ❑ We are also involved in a few proposals. Potentially we can have another PhD for working on the CDR project at CTF3;

- ❑ We have a close contact with the Russian team from Tomsk Polytechnic University, with whom we achieved a success in our Optical Diffraction Radiation project in Japan. We have a plan to perform a few tests of a new detection system for CDR experiment at Tomsk 6MeV microtron that has the bunch time structure close to the CTF3 one.

- ➢ We are setting up a new Accelerator Physics lab at RHUL (80m^2); We will be able to test the measurement system before shipping it to CERN

- ➢ We already have a start up funds for equipment (detector, DAQ electronics,etc.)