Short Bunch Length Exercises & Solutions

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Exercise

You have just been hired to work on a 5MeV electron gun – 4ps bunch length. Your first job is dedicated to the design of a bunch length monitor using Cherenkov radiation and a streak camera.

As a reminder, Cherenkov light is emitted when a charge particle travels inside a transparent medium with a velocity higher than the speed of light in this medium. The Cherenkov photons are emitted all along the material thickness

- Speed of light inside the material : $v = \frac{c}{n}$ with n is the index of refraction of the material
- β is the relative particle velocity
- γ is the particle relativistic factor : $\gamma = \frac{1}{\sqrt{1-\beta^2}}$
- d the thickness of the Cherenkov radiator

Questions:

- What is the minimum index of refraction of the given material so that Cherenkov effect occurs?

The condition to produce Cherenkov is that β is higher than 1/n. In our case for 5MeV electron, $\gamma = 10$ and corresponds to a $\beta = 0.995$. n should be then higher than 1.005

- Assuming that you will use fused silica as a Cherenkov radiator (index of refraction is 1.46), How thick must be the crystal to keep the time resolution below 1ps?

Since the photons travel at a speed lower than the electrons, and the time resolution will correspond to the time difference between photons and electrons in order to traverse the radiator.

$$\Delta t = d\left(\frac{n}{c} - \frac{1}{\beta c}\right)$$

In the present case in order to keep the time resolution better than *1ps*, it corresponds to 660μm

Exercise

You have been promoted and are now in charge of the bunch length measurement at the end of the Linac for electrons energy of 50GeV (4ps bunch length). Your boss specifically asks for a non destructive method and you are considering Optical Diffraction Radiation.

ODR is a pure high relativistic phenomenon (contraction of length), where a charged particle emits radiation when it passes close to the edge of a dielectric medium. To produce ODR, there is a condition to fulfill between the distance from the edge to the beam (h), the beam energy (γ) and the wavelength (λ) of the radiation you like to produce.

$$h \leq \frac{\gamma\lambda}{2\pi}$$

Questions:

•What will be the required minimum distance from the edge of the slit to the beam in order to produce visible photons (550nm wavelength)

Following the mentioned formula, the limit to produce 550nm photons corresponds to 8mm

•Is that distance looks reasonable, Would you think it can be used at lower beam energies

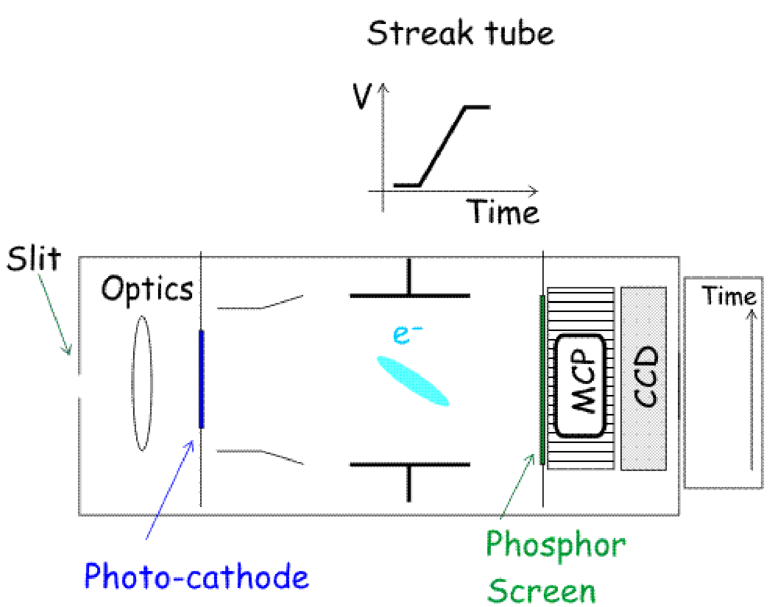
Without emittance dilution, the beam size shrinks with the beam energy and 8mm is quite large with respect to the maximum transverse beam size (some 100µm) you will find at these beam energies.

In principle, 1mm would be still good enough and it would correspond to *6.25GeV* electrons.

Exercise

You are responsible for the purchase of the streak camera and you should define what are the parameter of the streak camera to buy. You were told that you need a minimum of 2points per sigma in order to clearly measure a Gaussian bunch length.

Question:
Assuming that your MCP-CCD system is 1cm wide in vertical and have 500pixels, what will be the minimum sweep speed (in ps/mm) of the streak tube in order to measure the bunch length in your linac



The spatial resolution of the MCP-CCD system corresponds to 1/500 = 20 µm per pixel.

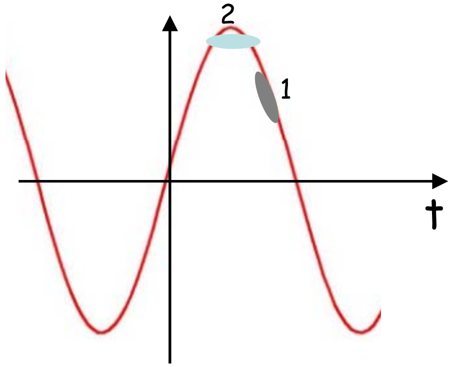
Your bunch length is 4ps sigma. Assuming that you need 2 pixels per sigma to measure the bunch length, you will need a sweep speed equivalent to 4ps/2pixels = 4ps/40µm = 100ps/mm

The required sweep speed is 100ps/mm

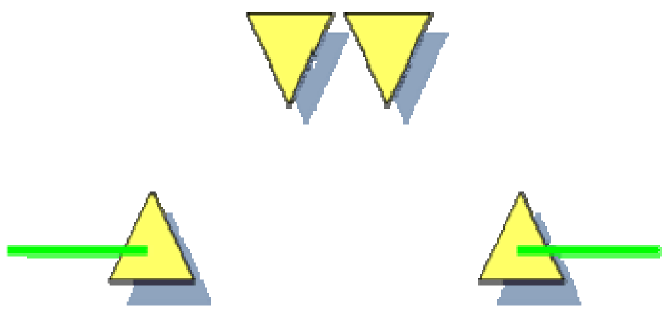
Exercise

You did so well for the bunch length measurement in the linac that you are asked to provide some support to operate of the bunch compressors. The bunch compression is done using an accelerating structure and a magnetic chicane. A coherent diffraction radiation monitor is measuring the bunch frequency spectrum just downstream of the chicane. Coherent radiation monitor relies on the fact that the shorter the bunch the broader the bunch frequency spectrum.

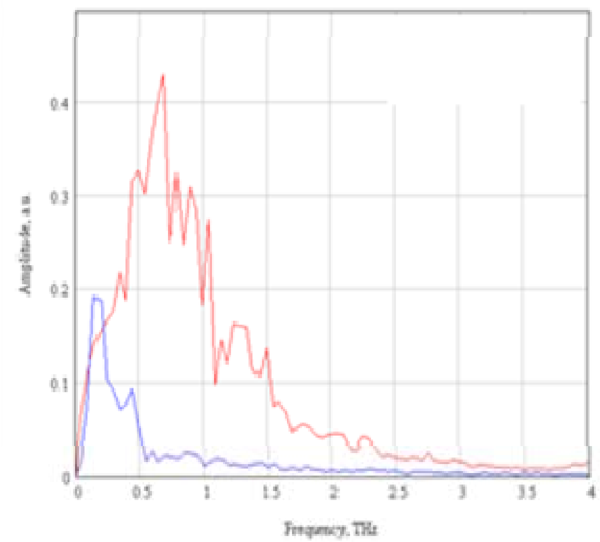
Accelerating Field E(t)



Magnetic chicane



CDR monitor



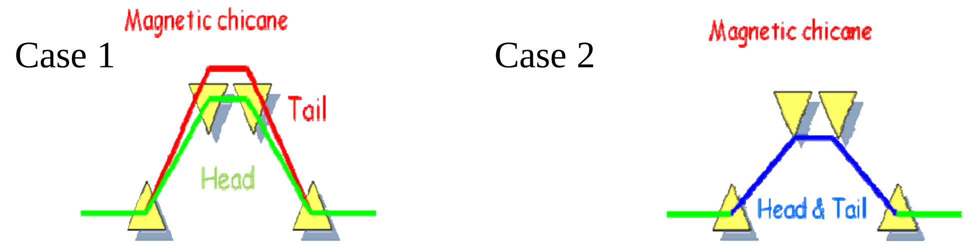
Questions:

- On the figure, there are two different settings of the klystron phase. For these two cases, draw what will be the trajectory of electrons sitting at the head and at the tail of the bunch for each case?
- On the CDR monitor, two different bunch frequency spectra have been measured. Choose which spectra corresponds to which phase settings
- Are you happy with the performance of the bunch compressor? if not what will you modify to have a better result

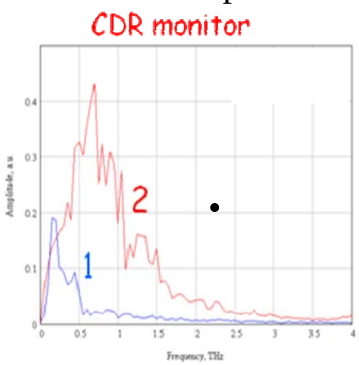
Exercise

Questions:

• On the figure, there are two different settings of the klystron phase. For these two cases, draw what will be the trajectory of electrons sitting at the head and at the tail of the bunch for each case?



• On the CDR monitor, two different bunch frequency spectra have been measured. Choose which spectra corresponds to which phase settings

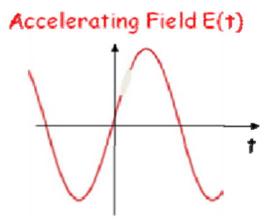


In case 1, the beam head is accelerated more than the tail such that it experiences a short trajectory than the tail in the chicane. Therefore the bunch gets longer. In case 2, the beam head and tail have the same energy so they will also have the same trajectory, the bunch length will remain the same.

On the CDR you will measure a broader spectrum for the shortest bunch, which will be with the present setting for case 2.

•Are you happy with the performance of the bunch compressor? if not what will you modify to have a better result

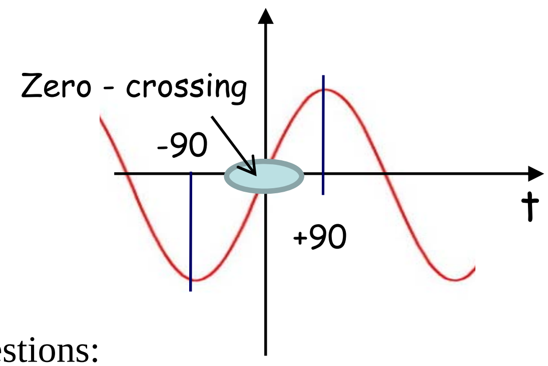
The bunch compressor is stretching the bunch at the moment and you are not satisfied, you suggest then to change the phase of the klystron in order to bring the bunch on the negative slope of the RF. This will correspond to bunch compression, accelerating more the tail than the head of the bunch.

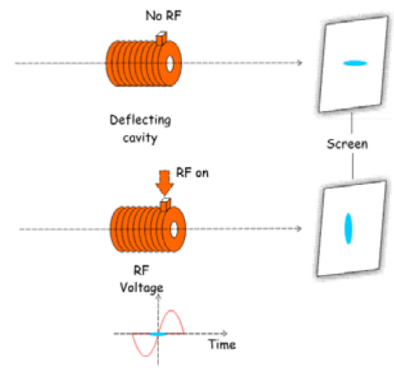


Exercise

With your new success, you really become an well recognized expert and the calibration of the RF deflector has been modified. You have been asked to calibrate the monitor. The RF deflector is working at 3GHz and for a maximum deflection (+/-90degree phase difference) the beam position on the screen changes by 5mm.

Deflecting Field E(t)





$$\sigma_y^2 = \sqrt{\sigma_{y_0}^2 + A\sigma_z^2}$$

Questions:

• If the bunch is placed at the zero-crossing of the RF deflector. What happen to the beam position and to the beam size?

The beam position remains unchanged but the beam size increases

• If the natural beam size (no RF) on the screen is 10µm, what will be approximately the size increase for zero-crossing if the bunch is 1ps long. The relation between the bunch length the beam size on the screen with and without RF power is given by the following expression.

•3 GHz RF frequency corresponds to 333ps time period. The RF period corresponds to 360degrees of phase variation such that 90degrees @ 3GHz is equivalent to 83.25ps.

•The beam is moved by 5mm on the screen for a 90degrees klystron phase and would correspond to a time delay corresponding to 83.25ps

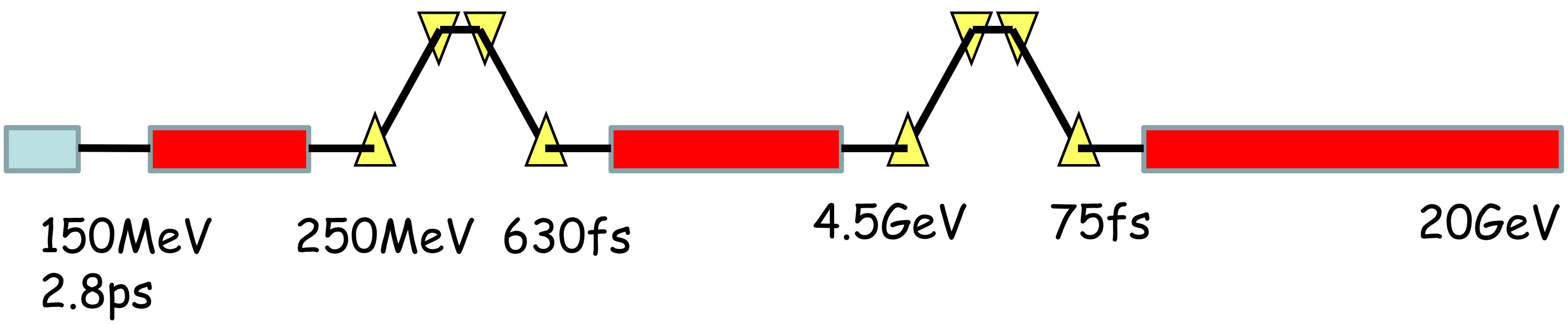
•1ps is then equivalent to 60µm that will be added in quadrature to the 10µm of the original beam size. So the beam size will be then 60.8microns

Exercise

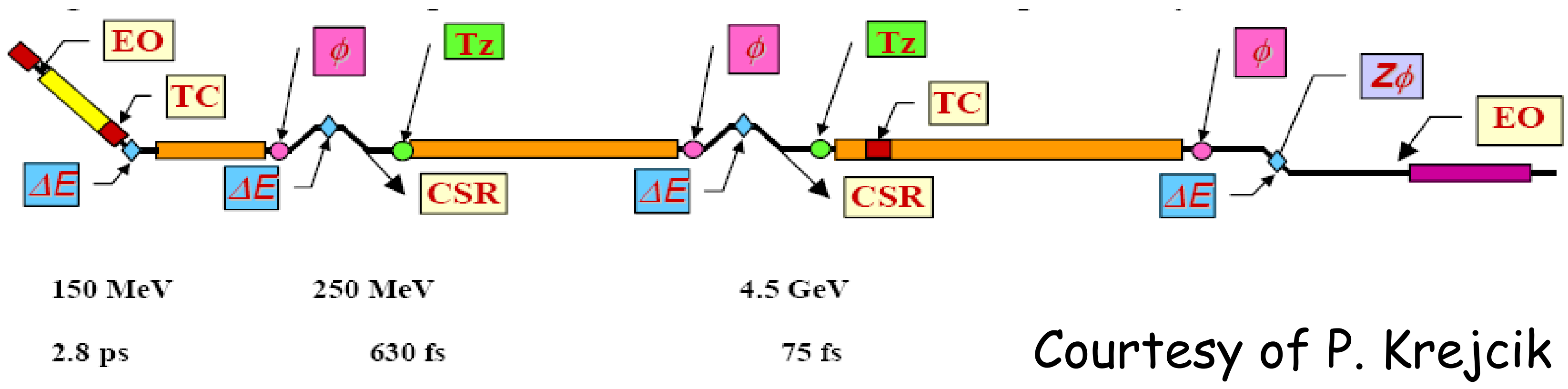
You are now working on the design of 4th generation light source and you have been asked to define the several techniques to measure bunch length all along the machine.

Choose at least one location where the following detector could be used along the machine.

- ODR with a streak camera
- RF deflector
- Coherent diffraction radiation
- EO spatial decoding



LCLS Machine Schematic



Courtesy of P. Krejcik

FIGURE 2. A schematic layout of the LCLS accelerator and bunch compressor system showing the types and locations of the various diagnostics to measure bunch length and characterize the longitudinal phase space of the beam: Electo-Optics (EO), Transverse Cavity (TC), Terahertz power monitors (Tz), Coherent Synchrotron Radiation monitors (CSR), Energy spread monitors (ΔE), Beam Phase monitors (ϕ),and Zero-phase measurement locations (Z ϕ).