Short Bunch Length Measurements

- What is short ?
- Why short Bunches ?
- How do we produce them ?
- How do we measure them ?

What is short ?

"When you are courting a nice girl an hour seems like a second. When you sit on a red-hot cinder a second seems like an hour. That's relativity. "

Albert Einstein

Why do we need short pulses ?

- Develop machine with the aim to improve luminosity for a linear collider or brightness for a radiation source

- Short pulse to resolve fast phenomenon
  - Femto Chemistry : Pump probe experiment – diffraction dynamics
  - Nanoscale Dynamics in Condensed matter : Coherent scattering at nanoscale
  - Atomic Physics : ex: photo ionization
  - Plasma and Warm dense Matter ; Astrophysical and weapons related studies
  - Structure Studies on Single Particles and Biomolecules : Xray diffraction,…

Fast Chemistry

$H_2O \rightarrow OH + H$

about **10 fs**

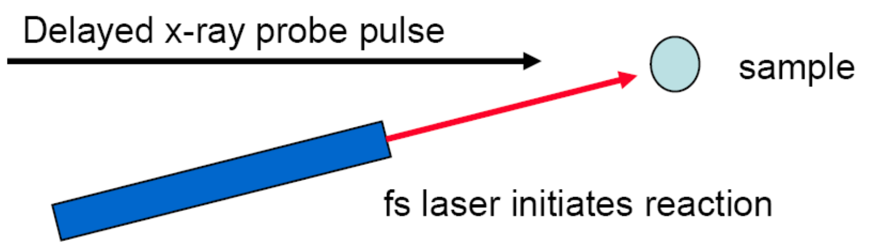
time depends on mass →

$CH_2I_2 \rightarrow CH_2I + I$

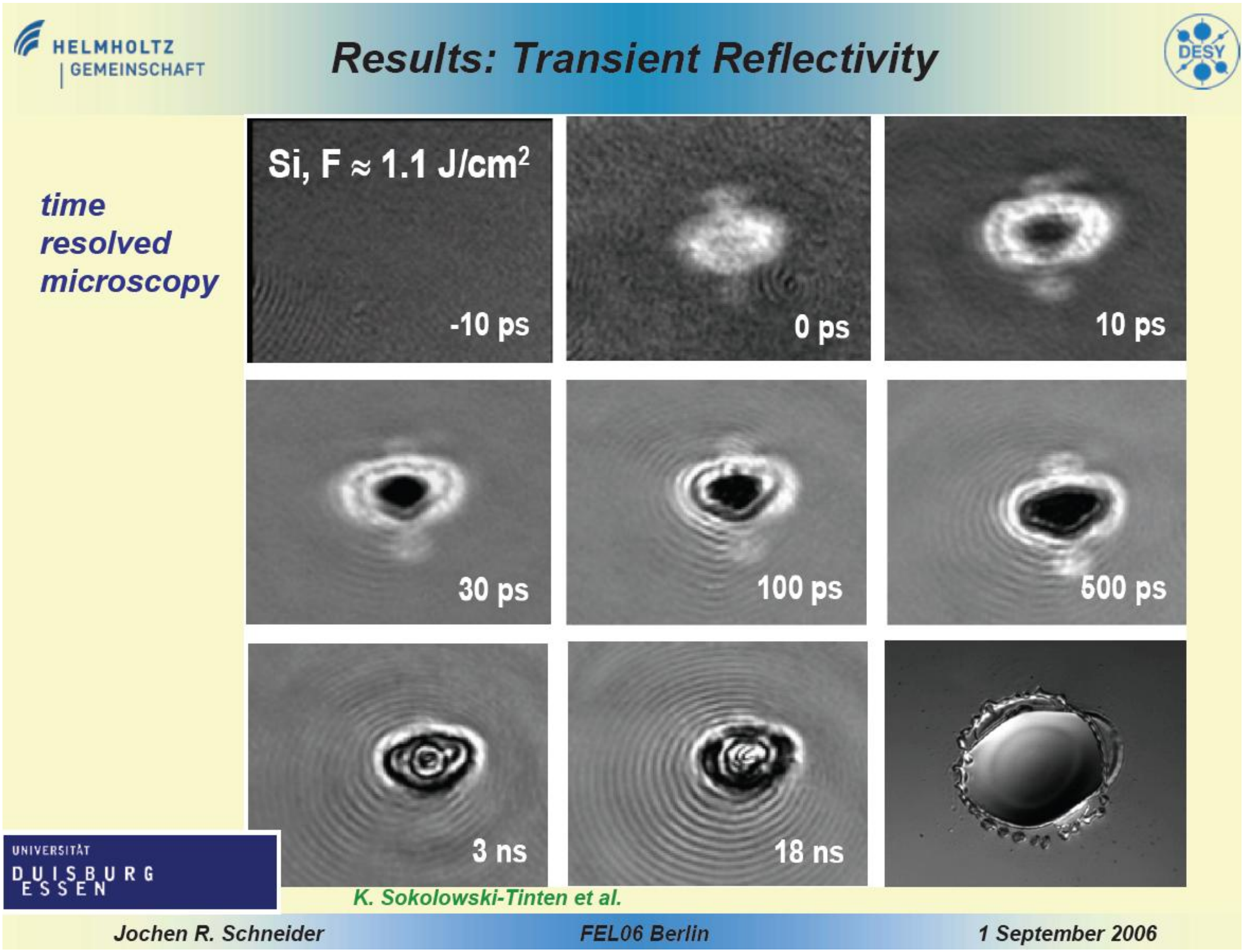
about **100 fs**

Pump-probe experiment

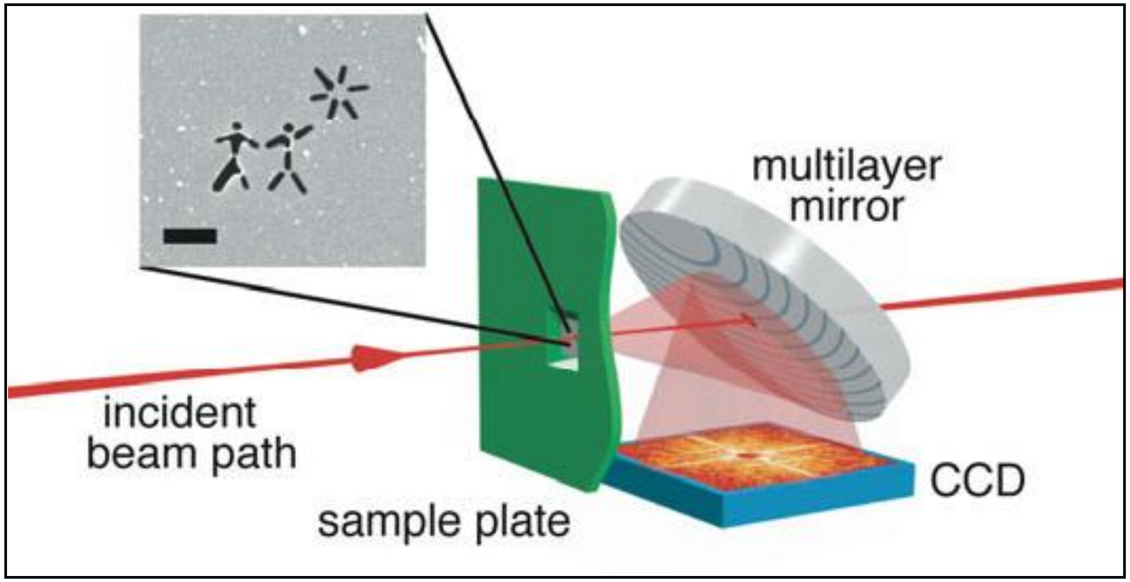
Combine single-pulse x-ray diffraction with fast laser excitation

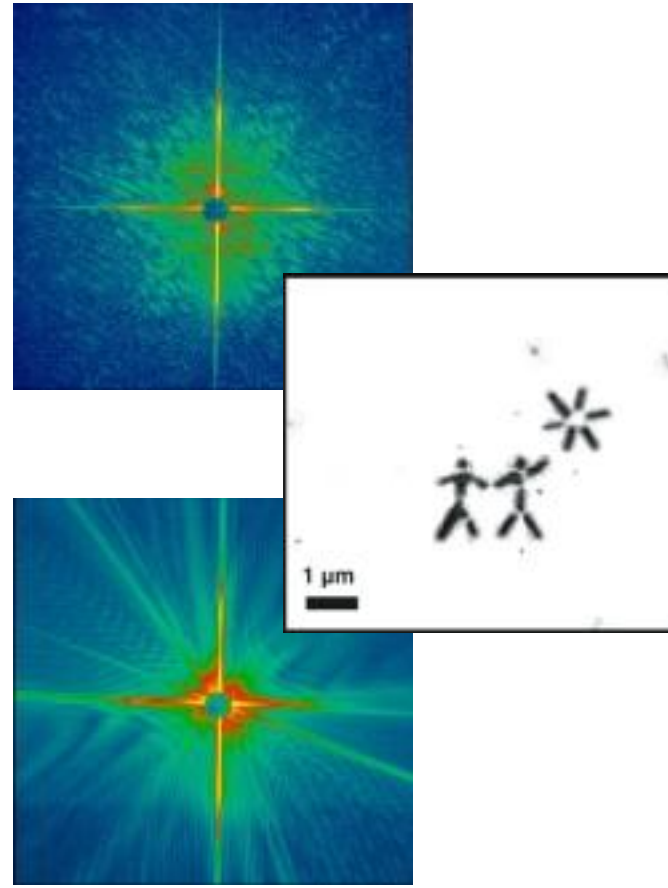


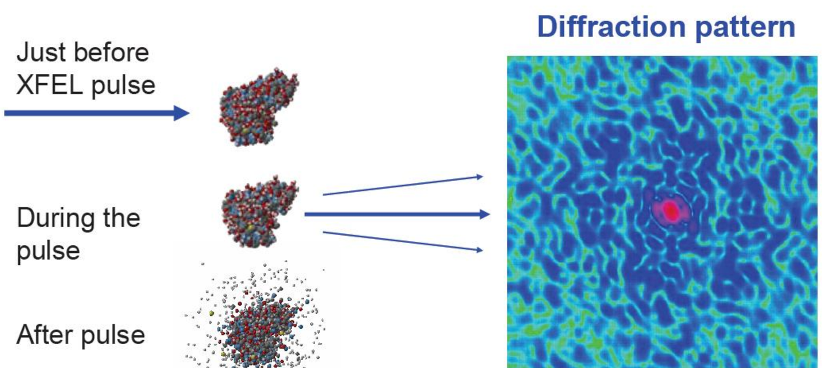
Nanoscale dynamics



Structure Analysis

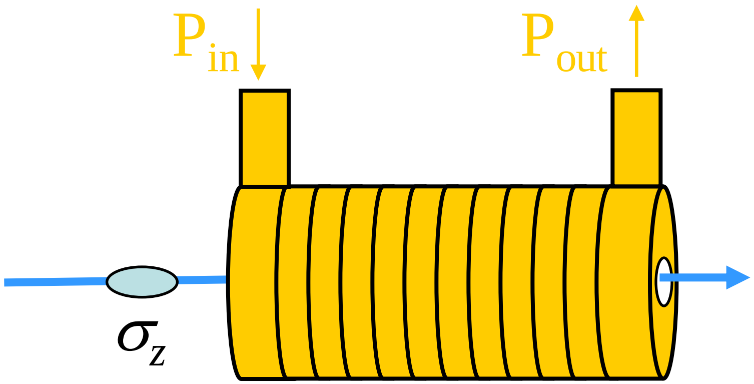


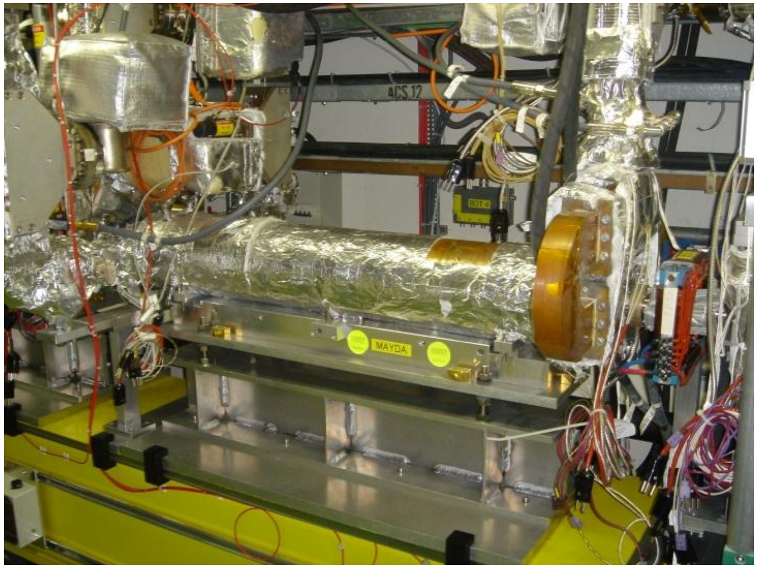


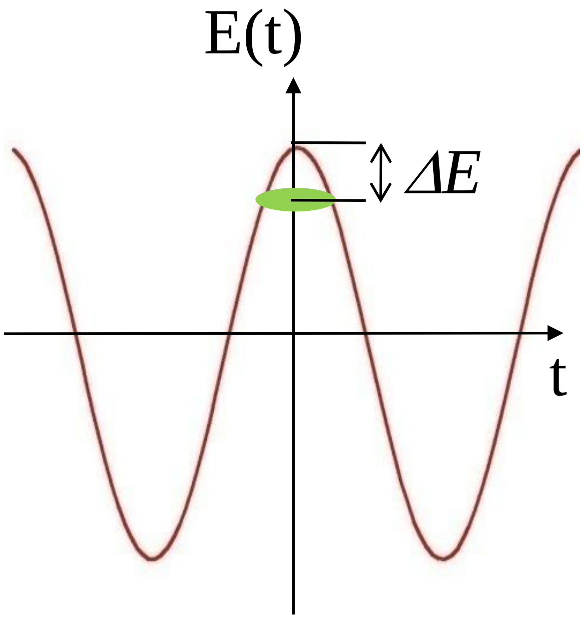


What is short in accelerators ?

Acceleration @ 3GHz

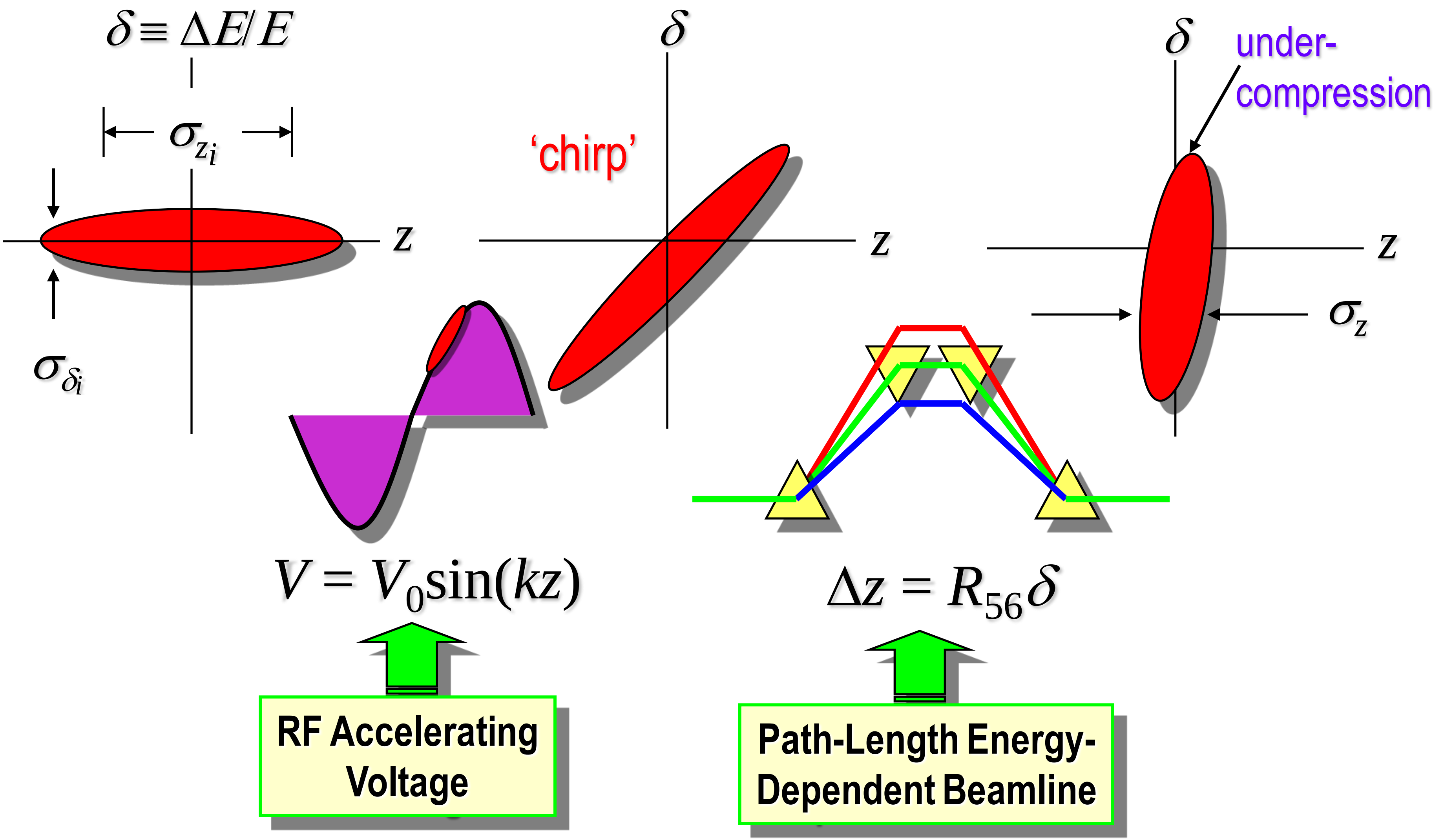






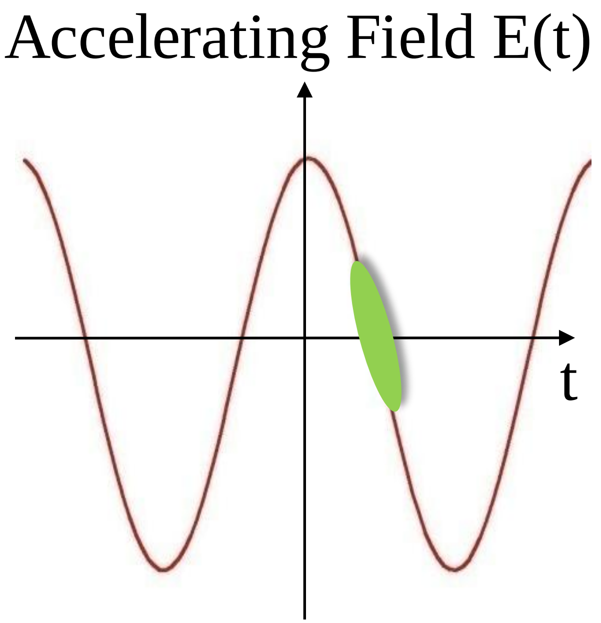
At 3GHz
1deg = 925fs

Short bunches by Magnetic Compression



Velocity Bunching

By decelerating the bunch head and accelerating the bunch tail



- Need one dedicated accelerating cavity
- No CSR effect and emittance dilution in the bends

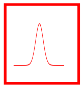
- Classical method with low energy thermoionic guns
- New concept with RF guns and emittance compensation

Short bunches around the world

ILC	500fs
CLIC	130fs
XFEL	80fs
LCLS	75fs

How do we measure short bunch length

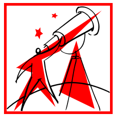
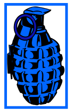
Define characteristics of beam instrumentation

1- Longitudinal Profile  ← → σ RMS or FWHM values

- *More precise information on the beam characteristic*

2- Single shot measurements 1 ← → n! Sampling measurements

- *Do not care about the beam reproducibility*
- *No additional problem due to timing jitter*

3- Non interceptive  ← →  Destructive Devices

- *Can be used for beam study and beam control for on-line monitoring*
- *No risk of damage by the beam itself*

How do we measure short bunches

Level of Difficulty and Reliability

'Beam diagnostics should help you to understand how the beam behaves, **it should not be the opposite**'

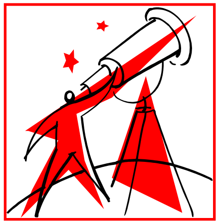
A detector, what for ?

• Online Beam stability → Non-intercepting and reliable
Only have access to a partial information (RMS values,..)

• Beam characterization and beam physics study → Full information
Complexity and time consuming

How do we measure short bunches

Can we do non intercepting, single shot, beam profile measurement in an easy way ?



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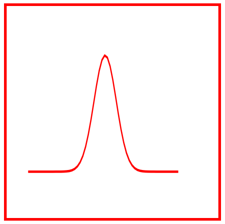

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All in red → 'perfect system'

How do we measure short bunches

Optical Method

1. Produce visible light
2. Analyse the light pulse using dedicated instruments

Bunch Frequency Spectrum

The shorter the bunches, the broader the bunch frequency spectrum

RF cavities manipulation

Use RF cavities to convert time information into spatial information

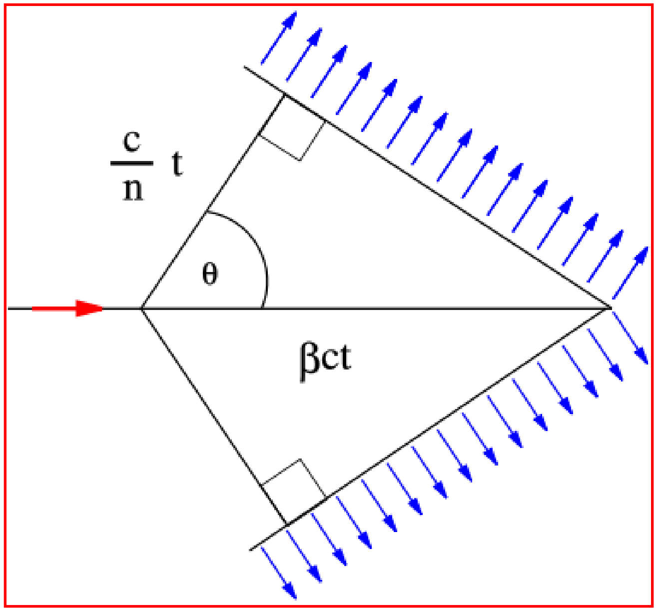
Laser-based beam diagnostic

Using short laser pulses and sampling techniques

Cherenkov radiation

'Equivalent to the supersonic boom but for photons'

Threshold process: Particles go faster than light $\beta > 1/n$



- n is the index of refraction
- β is the relative particle velocity
- γ is the particle relativistic factor

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

- θ_c is the Cherenkov light emission angle

$$\cos(\theta_c) = \frac{1}{\beta n}$$

- l the length of the cherenkov radiator

$$N_{cherenkov} = 2\pi\alpha l\left(\frac{1}{\lambda_a} - \frac{1}{\lambda_b}\right)\left(1 - \frac{1}{\beta^2 n^2}\right)$$

The total number of photons proportional to the thickness of the Cherenkov radiator

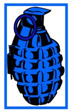
Optical Transition Radiation

Optics

Spectrum

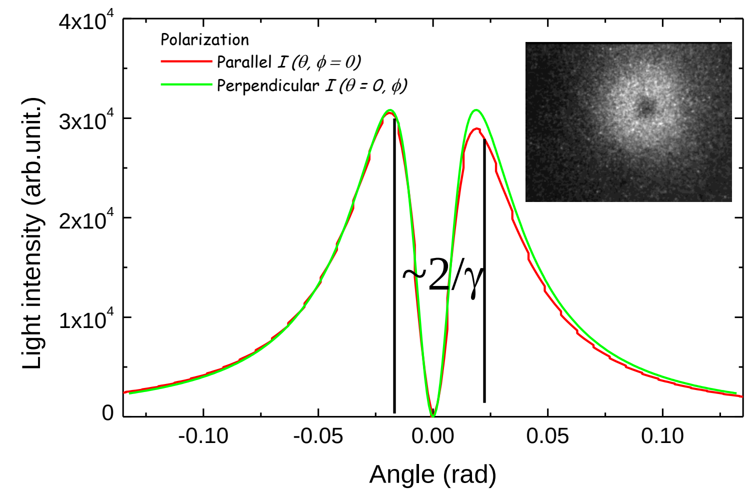
RF

Laser

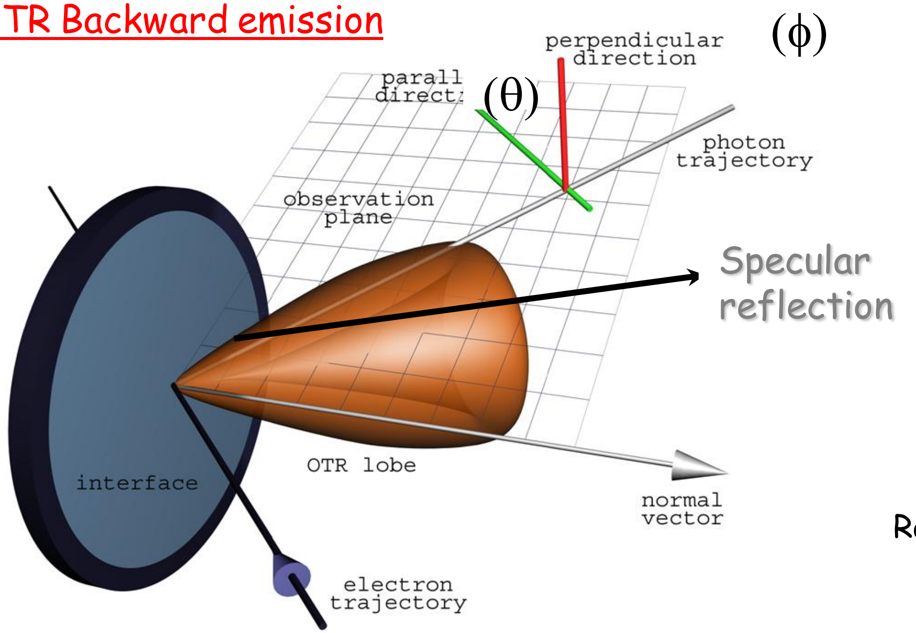


A huge amount of development for the past 30 years

'TR is generated when a charged particle passes through the interface between two materials with different permittivity (screen in vacuum)'



OTR Backward emission



Number of OTR photons per charge particle

$$N_{OTR} = \frac{2\alpha}{\pi}\ln\left(\frac{\lambda_b}{\lambda_a}\right)\left(\ln(2\gamma)-\frac{1}{2}\right)$$

~ 5 10⁻³ in [400-600]nm

Radiation wavelength

Beam energy

Limitations :

The thermal limit for 'best' screens (C, Be, SiC) is ~ 1 10^6 nC/cm²

$$\Delta T(r) = \frac{dE}{dx}\frac{N_{tot}}{2\pi\sigma^2 c_p \rho}e^{-\frac{r^2}{2\sigma^2}}$$

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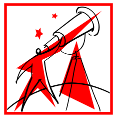
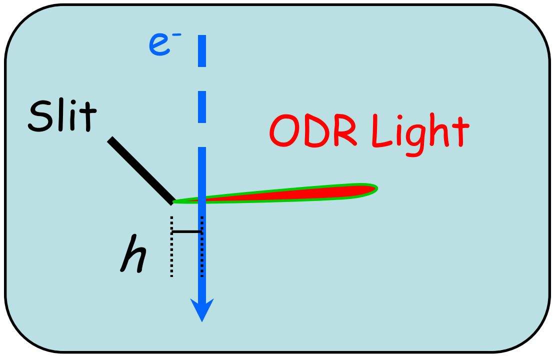
Optical Diffraction Radiation



'DR is generated when a charged particle passes through an aperture or near an edge of dielectric materials, if the distance to the target h (impact parameter) satisfies the condition :



Beam energy — Radiation wavelength

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

A lot of activities on ODR, but only one measurement up to now :

T. Muto et al, ***Physical Review Letters 90 (2003) 104801***

Limitations :

- Not enough photons in the visible for low energy particles : E < 1 GeV for a decent impact parameter (100μm)

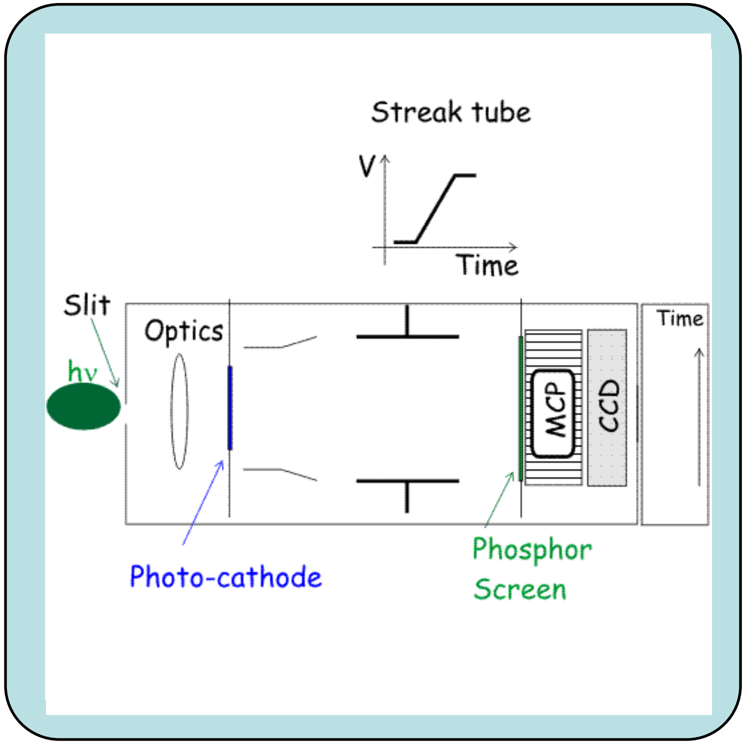
Optical method : Streak Camera

Optics

Spectrum

RF

Laser



'Streak cameras uses a time dependent deflecting electric field to convert time information in spatial information on a CCD'

Mitsuru Uesaka et al, ***NIMA 406 (1998) 371***

200fs time resolution obtained using reflective optics and 12.5nm bandwidth optical filter (800nm) and the Hamamatsu FESCA 200

Limitations : Time resolution of the streak camera :

(i) Initial velocity distribution of photoelectrons : *narrow bandwidth optical filter*
(ii) Spatial spread of the slit image: *small slit width*
(iii) Dispersion in the optics

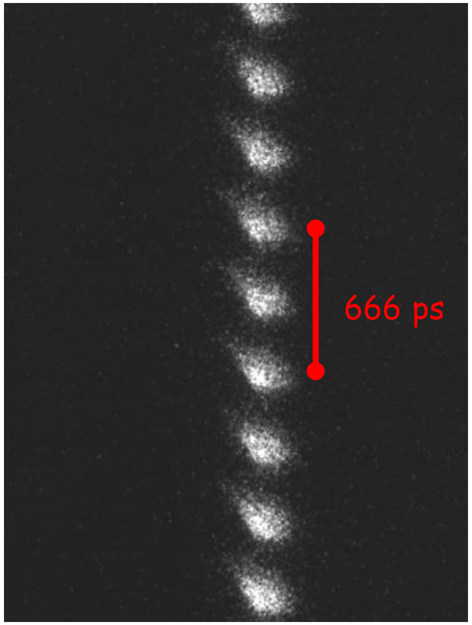
Streak camera examples

Optics

Spectrum

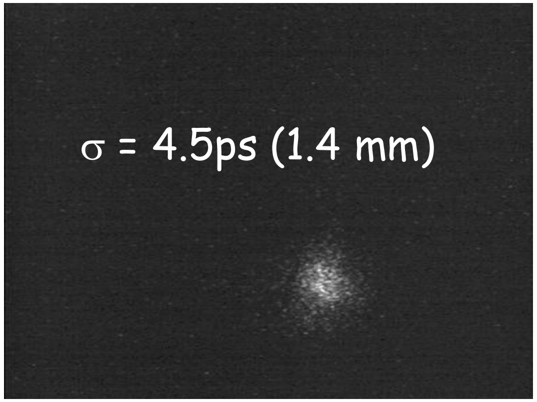
RF

Laser

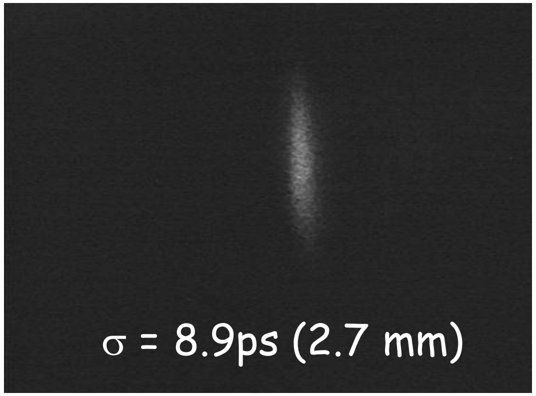


Observation of bunch train
Sweep speed of 250ps/mm

Measure of bunch length



Sweep speed of 10ps/mm



Optics

Spectrum

RF

Laser

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 660 μm

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

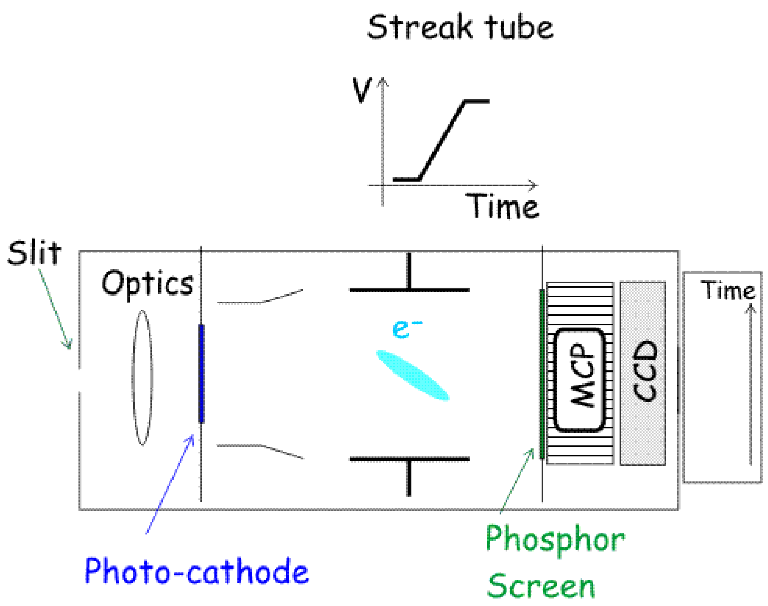
Without emittance dilution, the beam size shrinks with the beam energy and 8mm is quite large with respect to the maximum transverse beam size (some 100μm) you will find at these beam energies.

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

Bunch Frequency Spectrum

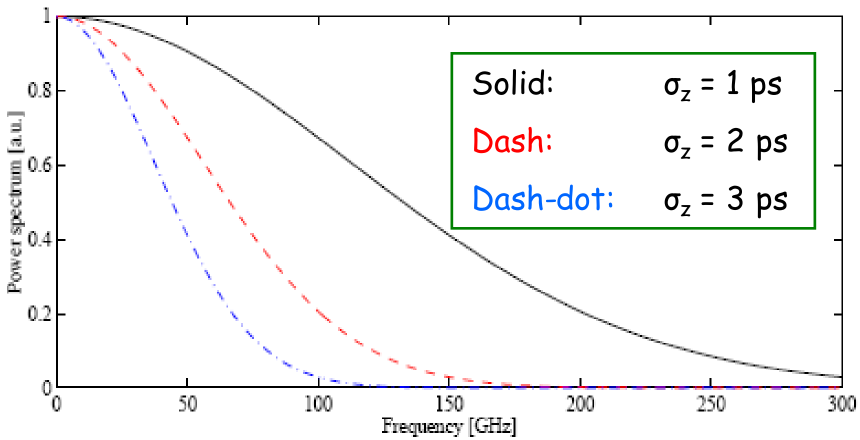
Optics

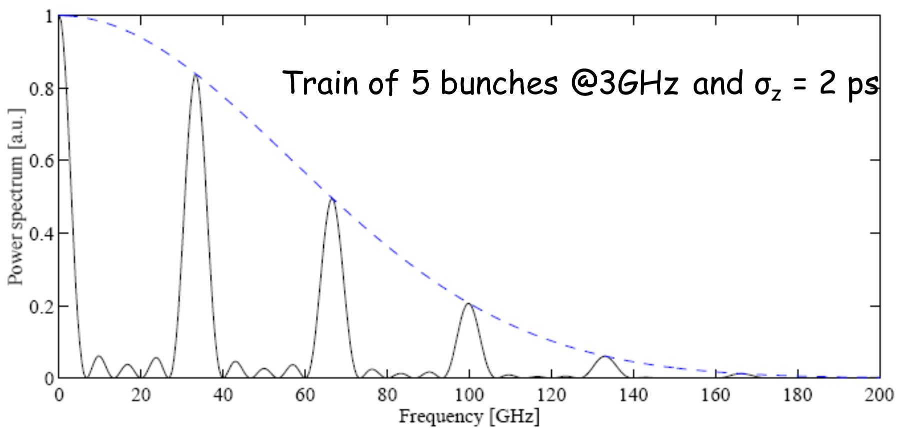
Spectrum

RF

Laser

For a given beam intensity, The shorter the bunch, the broader the bunch frequency spectrum





•The bandwidth of radiation produced from a Gaussian bunch, given by its Fourier transform, extends into the terahertz region for the ultra-short bunches

10 microns ~ 33.3femtoseconds ~ 30 THz

From the measured frequency spectrum you can reconstructed the bunch length

more

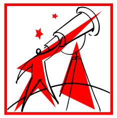
Bunch Frequency Spectrum by Coherent Radiation

- *When the wavelength of the radiation is longer than the bunch length, it is known that the coherent effect occurs inside the bunch*
- *For a given beam intensity, the shorter the bunch, the broader the bunch frequency spectrum*
- *The longitudinal shapes of the electron bunch can be extracted by analyzing the power spectrum of the radiation'*
- *Intensity of coherent radiation* $\propto N^2$

Coherent Transition Radiation (CTR)

P. Kung et al, **Physical review Letters 73 (1994) 96**

- 90fs, 32MeV beam



Coherent Diffraction (CDR)

B. Feng et al, **NIM A 475 (2001) 492-497** ; A.H. Lumpkin et al, **NIM A 475 (2001) 470-475** ; C. Castellano et al, **Physical Review E 63 (2001) 056501**

T. Watanabe et al, **NIM A 437 (1999) 1-11 & NIM A 480 (2002) 315-327**

- 700fs, 35MeV beam
- 470fs, 150MeV beam

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Bunch Frequency Spectrum by Coherent Radiation

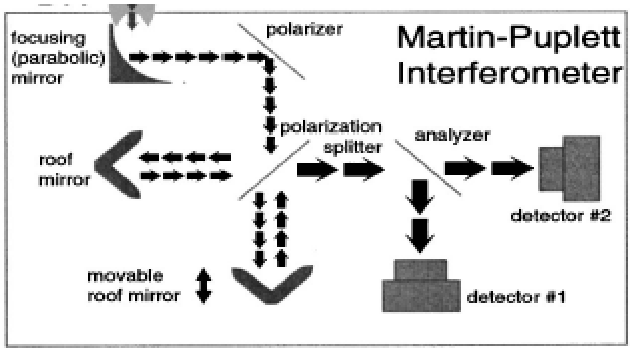
Optics

Spectrum

RF

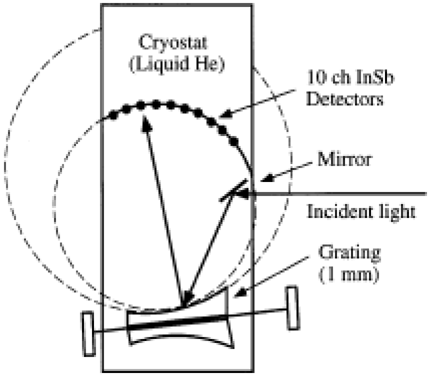
Laser

n! *'Michelson or Martin-Pupplet interferometer :*



• The radiation is split in two bunches, one is delayed by a linear stage and the intensity of the recombined bunch is measured by two detectors (one for each polarization)
• The spectrum is obtained from the Fourier transform of the interferometer function'

1 *'The **polychromator** enables to get the spectrum directly by a single shot. The radiation is deflected by a grating and resolved by the xx-channels-detector array'*



Limitations :

• Narrow dynamic range limited by the small bandwidth sensitivity of the system element (Grating, Beam splitter, …)

• Need cross calibrations

• Resolution depends on the number of detectors (**polychromator**)

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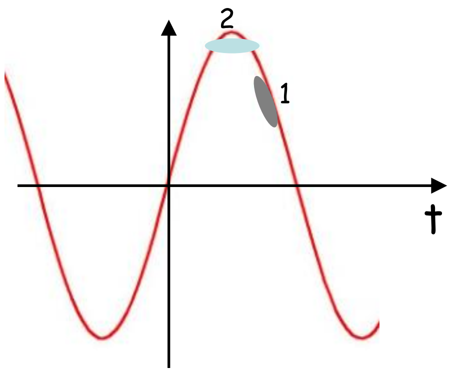
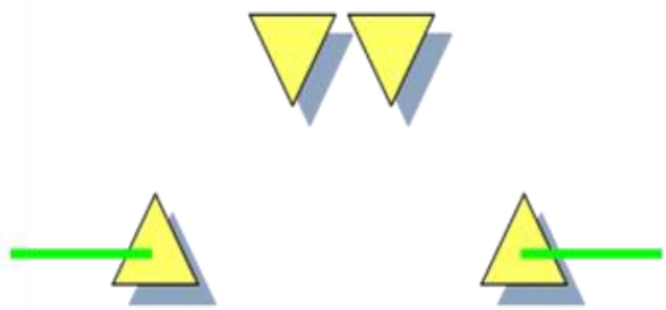
Exercise

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.

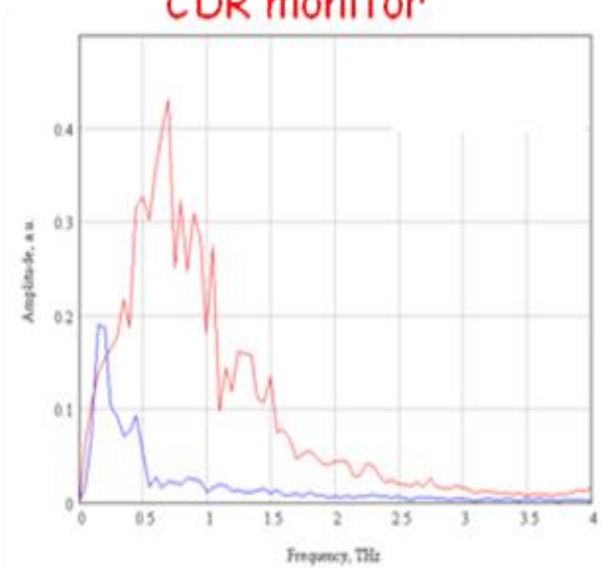
Accelerating Field E(t)



Magnetic chicane



CDR monitor



Questions:

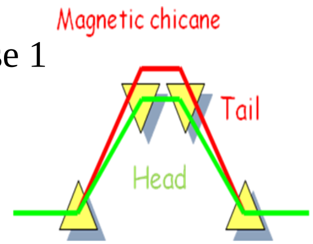
- On the figure, there are two different settings of the klystron phase. For these two cases, draw what will be the trajectory of electrons sitting at the head and at the tail of the bunch for each case?
- On the CDR monitor, two different bunch frequency spectra have been measured. Choose which spectra 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

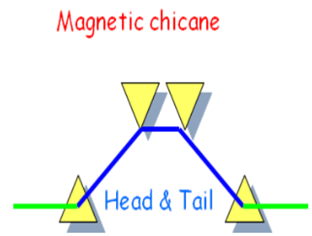
Questions:

• 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?

Case 1



Case 2



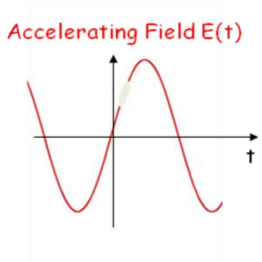
• On the CDR monitor, two different bunch frequency spectra have been measured. Choose which spectra corresponds to which phase settings

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.

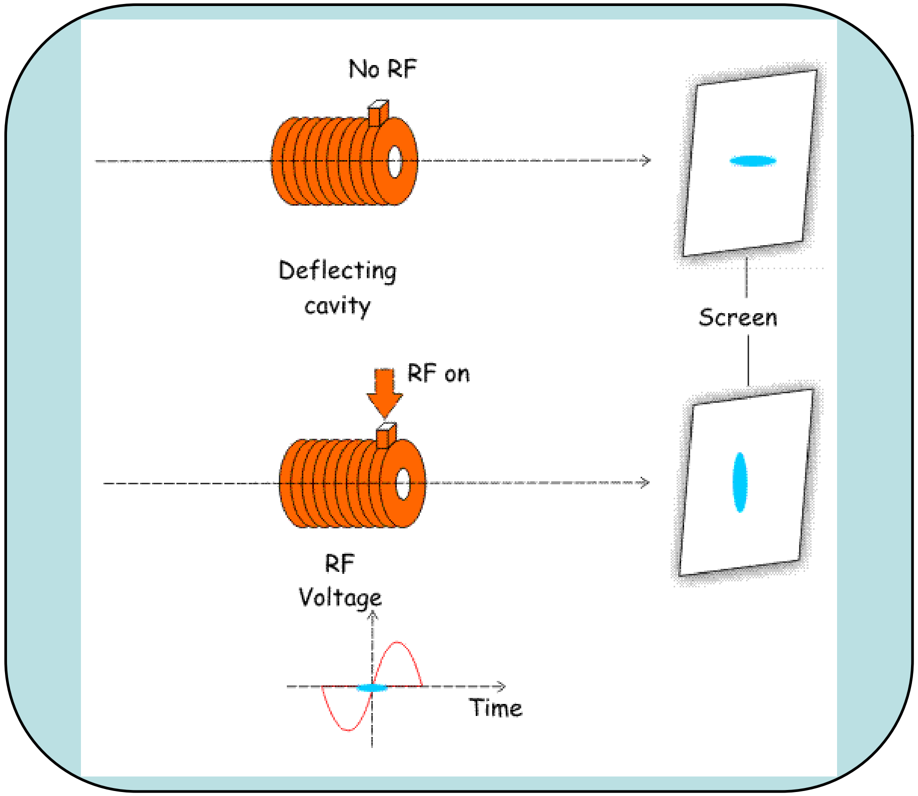
•Are you happy with the performance of the bunch compressor? if not what will you modify to have a better result

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.



RF by Deflecting Cavity

'The RF Deflector can be seen as a relativistic streak tube. The time varying deflecting field of the cavity transforms the time information into a spatial information
The bunch length is then deduced measuring the beam size at a downstream position using a screen or (LWS)



R. Akre et al, **SLAC-PUB-8864, SLAC-PUB-9241, 2002**

- 300μm, 28GeV beam using a S-band RF deflector

- Can extract even more information than the bunch length
- ex: slice emittance and intra bunch energy spread

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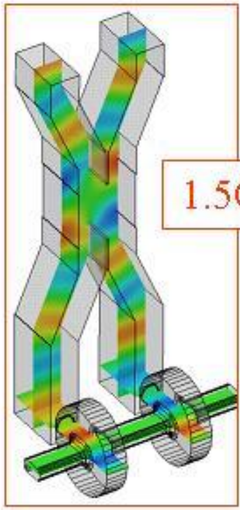
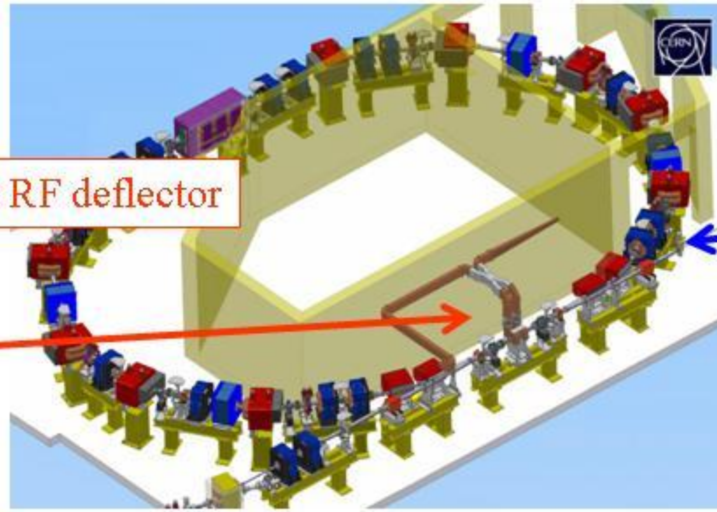
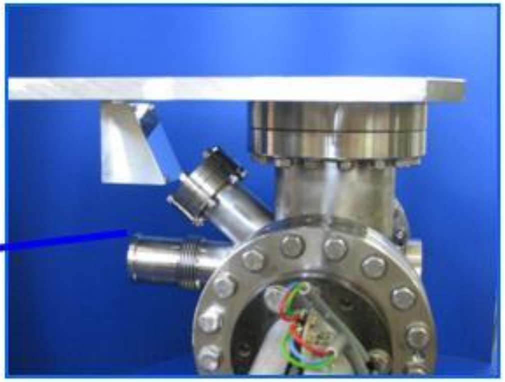
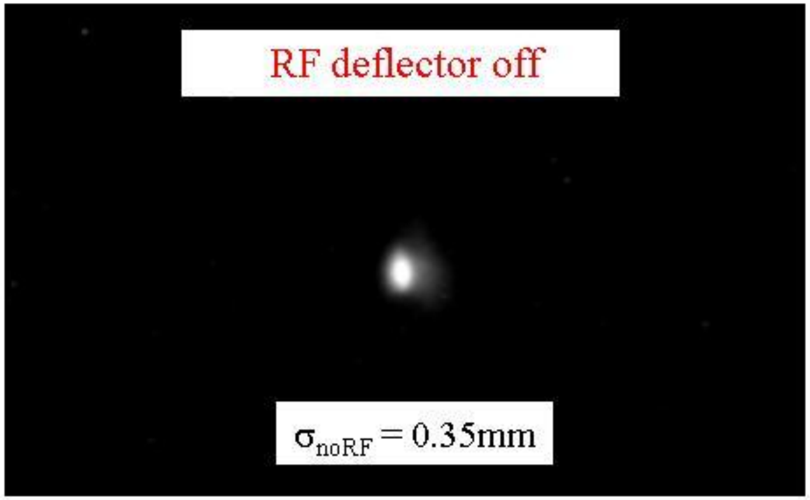
RF by Deflecting Cavity

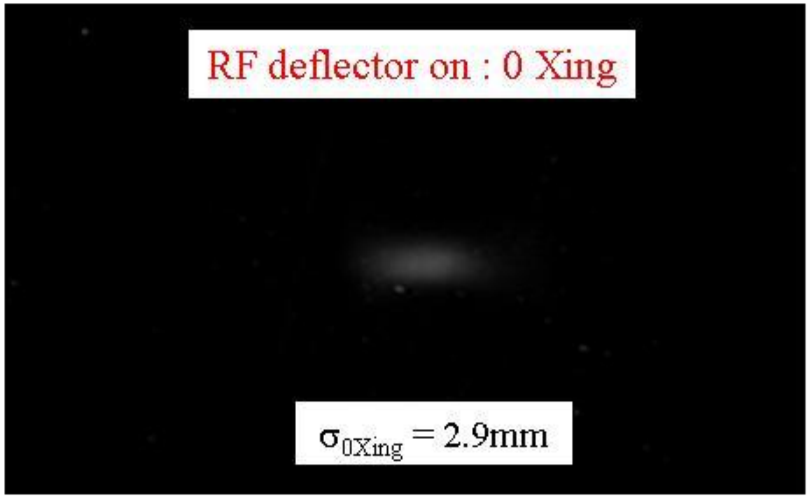






OTR screen





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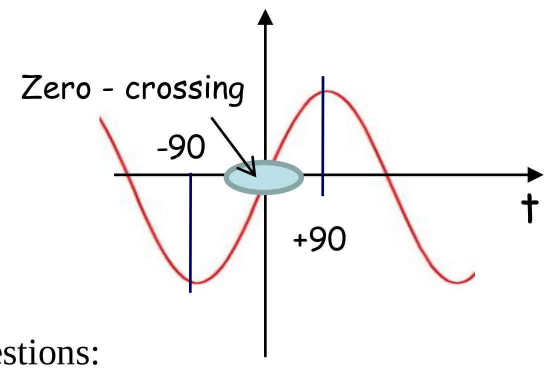
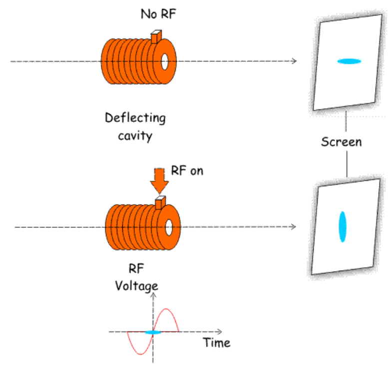
Exercise

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)





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

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.

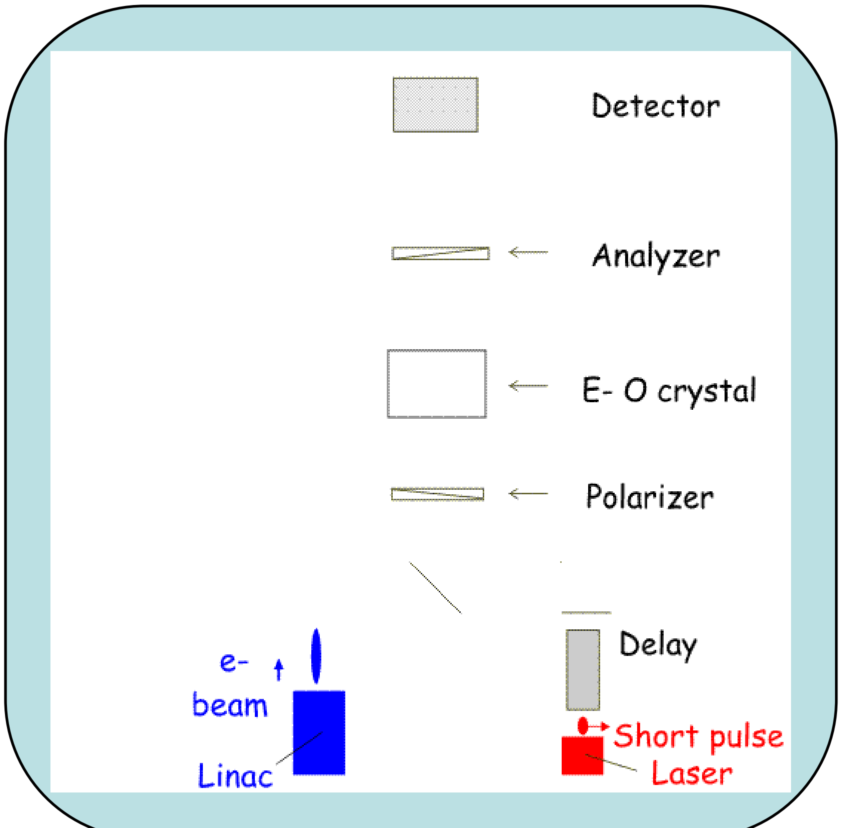
•The beam is moved by 5mm on the screen for a 90degrees klystron phase and would correspond to a time delay corresponding to 83.25ps

•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

Electro Optic Sampling

'This method is based on the polarization change of a laser beam which passes through a crystal itself polarized by the electrons electric field'

n! *Bunch length is reconstructed by measuring the intensity of the polarization change as a function of laser timing*



A. M. MacLeod et al, **Physical Review Letters 85 (2000) 3404**

Using 12fs Ti:Al2O3 laser at 800nm and ZnTe crystal 0.5mm thick and a beam of 46MeV, 200pC, 2ps.

Limitations :

- Presence of phonon (5.3THz for ZnTe) can distort the measurement for bunch length < 200fs
- Radiation hardness (no problem observed up to now)
- Jitter of the laser-RF synchronization

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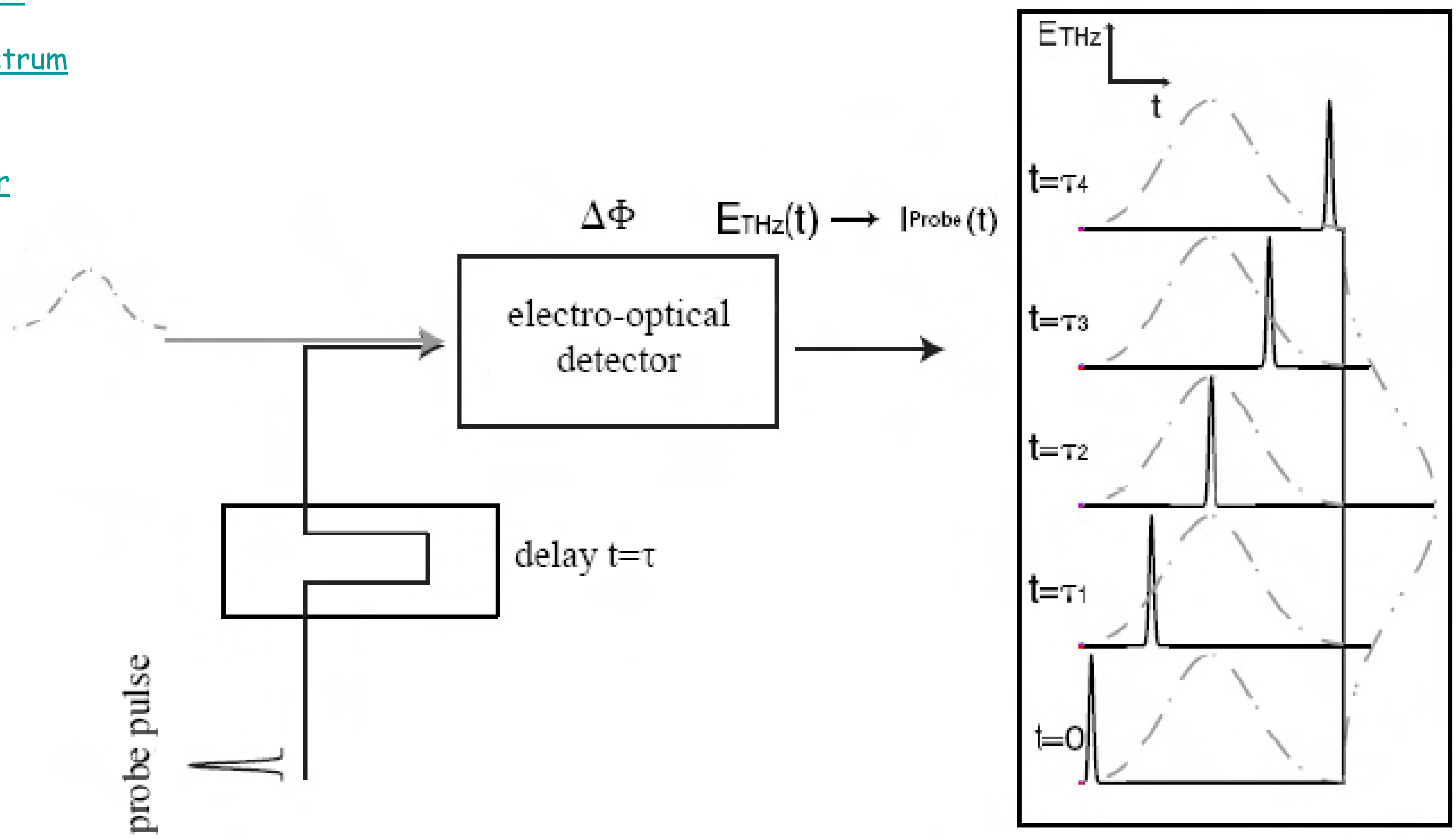
Sampling Techniques



Principle of electro-optic sampling

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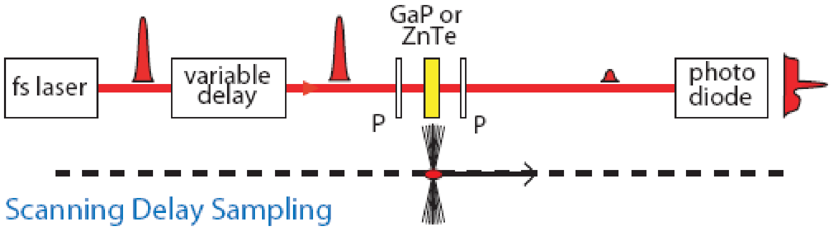
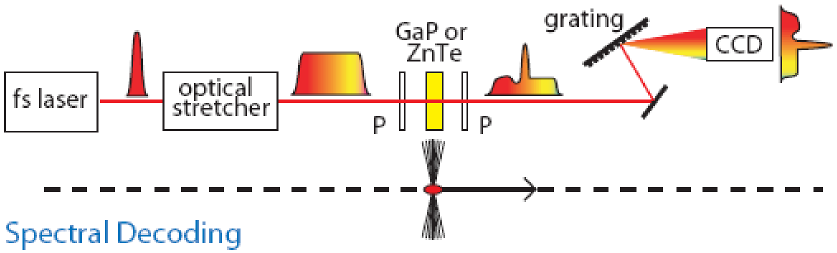
Electro Optic based bunch length monitors

Optics
Spectrum
RF
Laser

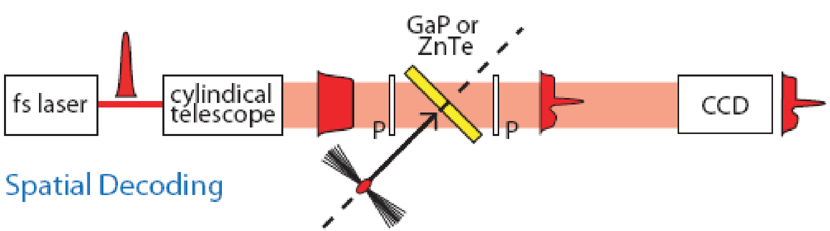


1. Sampling:
- multi-shot method
- arbitrary time window possible



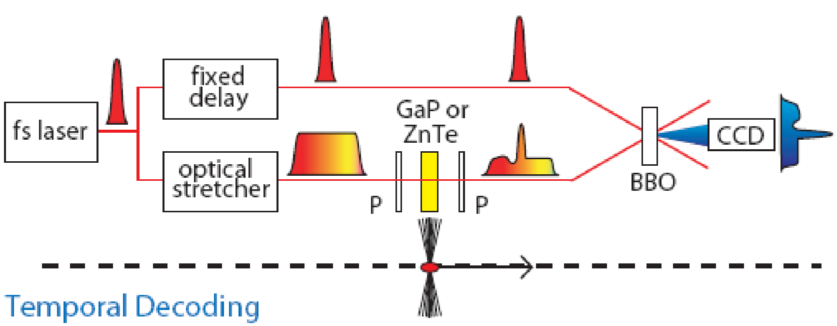
2. Chirp laser method, spectral encoding):
- laser bandwidth limited~ 250fs

I. Wilke et.al., PRL Vol.88, No.12



3. Spatial encoding:
- imaging limitation ~ 30-50 fs

A. Cavalieri, et. al., PRL. 94, 114801



4. Temporal decoding:
- laser pulse length limited ~ 30fs

S.P. Jamison, et.al., PRL Vol.93, No.11

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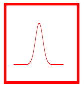
How do we measure short bunches

				σ	1	n!	Limitations
• Optical radiation							
• Cherenkov radiation		X					
• Optical Transition Radiation		X					
• Optical Diffraction Radiation	X						
• Streak camera			X		X		> 200fs
• Coherent radiation							
• Interferometry				X		X	
• Polychromator				X	X		
• RF Deflector		X	X		X		
• Electro Optic Method							
• Sampling	X		X			X	Jitter
• Spectral decoding	X		X		X		> 200fs
• Spatial decoding	X		X		X		> 50fs
• Temporal decoding	X		X		X		> 50fs

Exercise

Optics

Spectrum

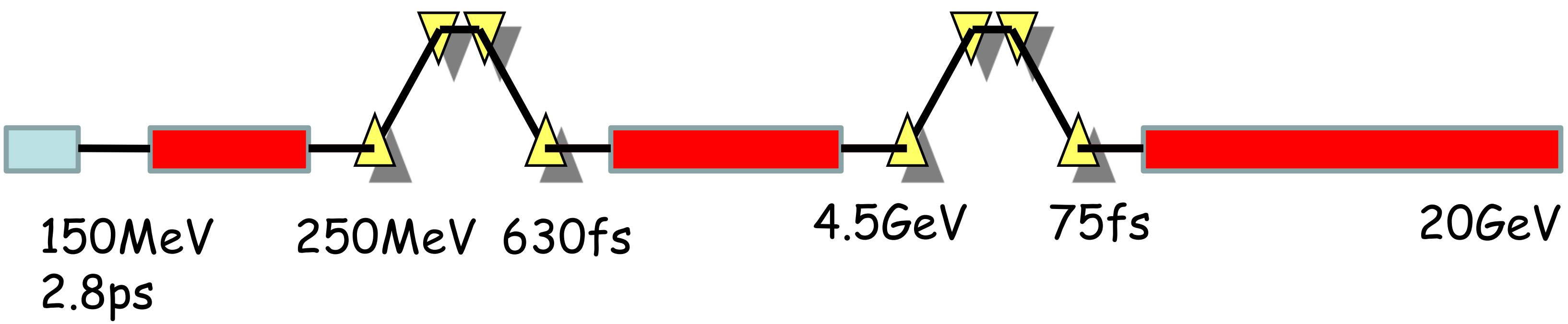
RF

Laser

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



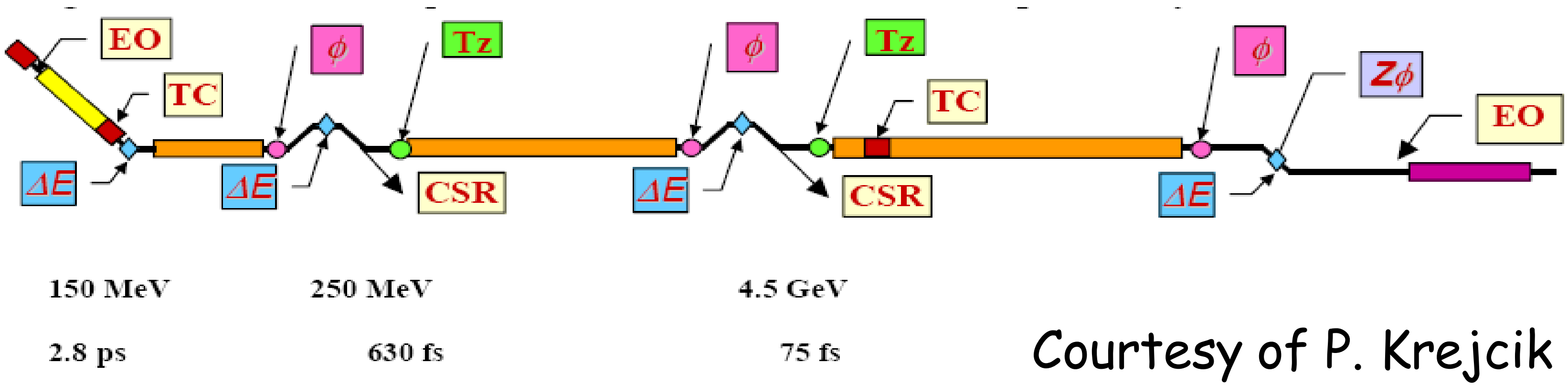
LCLS Machine Schematic

Optics

Spectrum

RF

Laser



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).