CAS

Bunch Length Measurements

T. Lefevre, CERN

- Longitudinal beam profile in accelerators
- Bunch compression scheme
- Bunch length measurement techniques

How to accelerate Particles

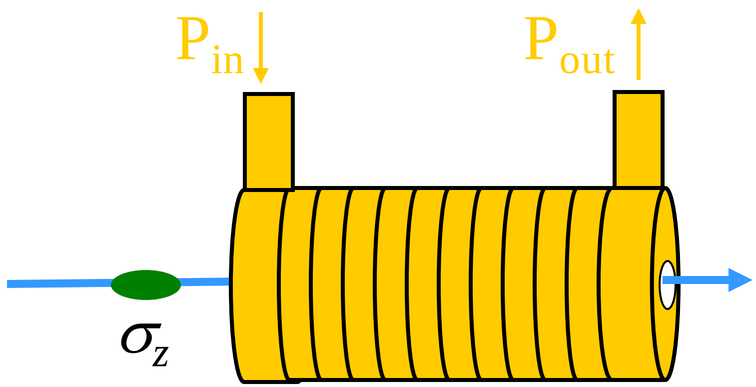
DC Accelerator

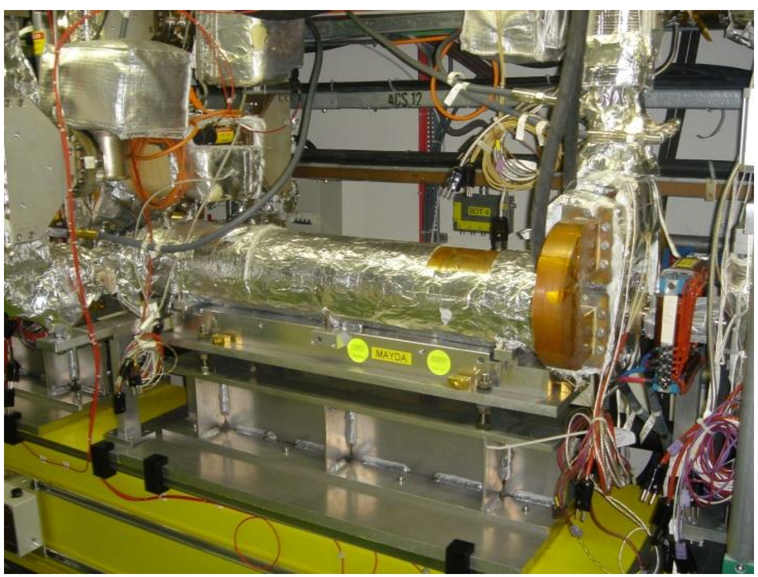
RF Accelerator

synchronizing particle
with an
electromagnetic wave!

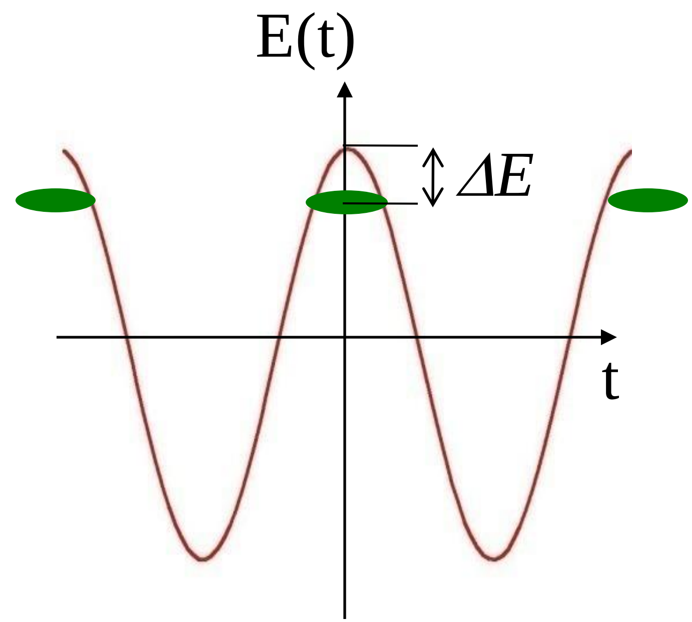
How to accelerate Particles

RF Accelerating structures





RF Accelerating Field

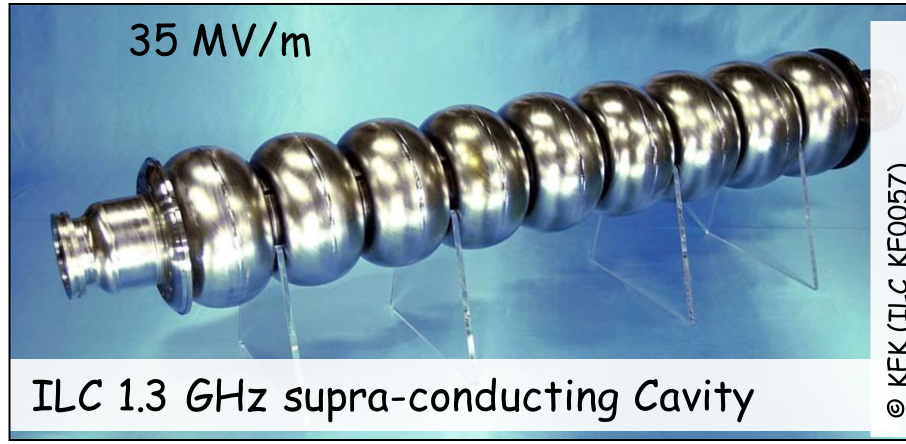


At 3GHz

1 period = 333ps : Bunch spacing
Typical bunch length : few deg ~ few ps

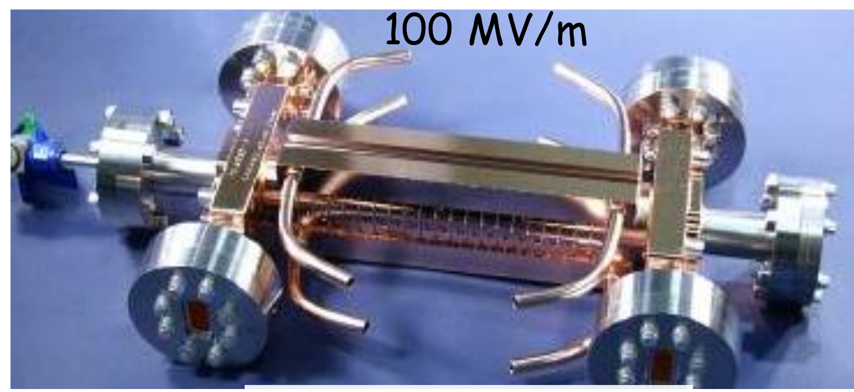
Accelerating Cavities

CERN PS 19 MHz Cavity (prototype 1966)



ILC 1.3 GHz supra-conducting Cavity

400MHz LHC Cavity in its cryo-module



CLIC 12 GHz Cavity

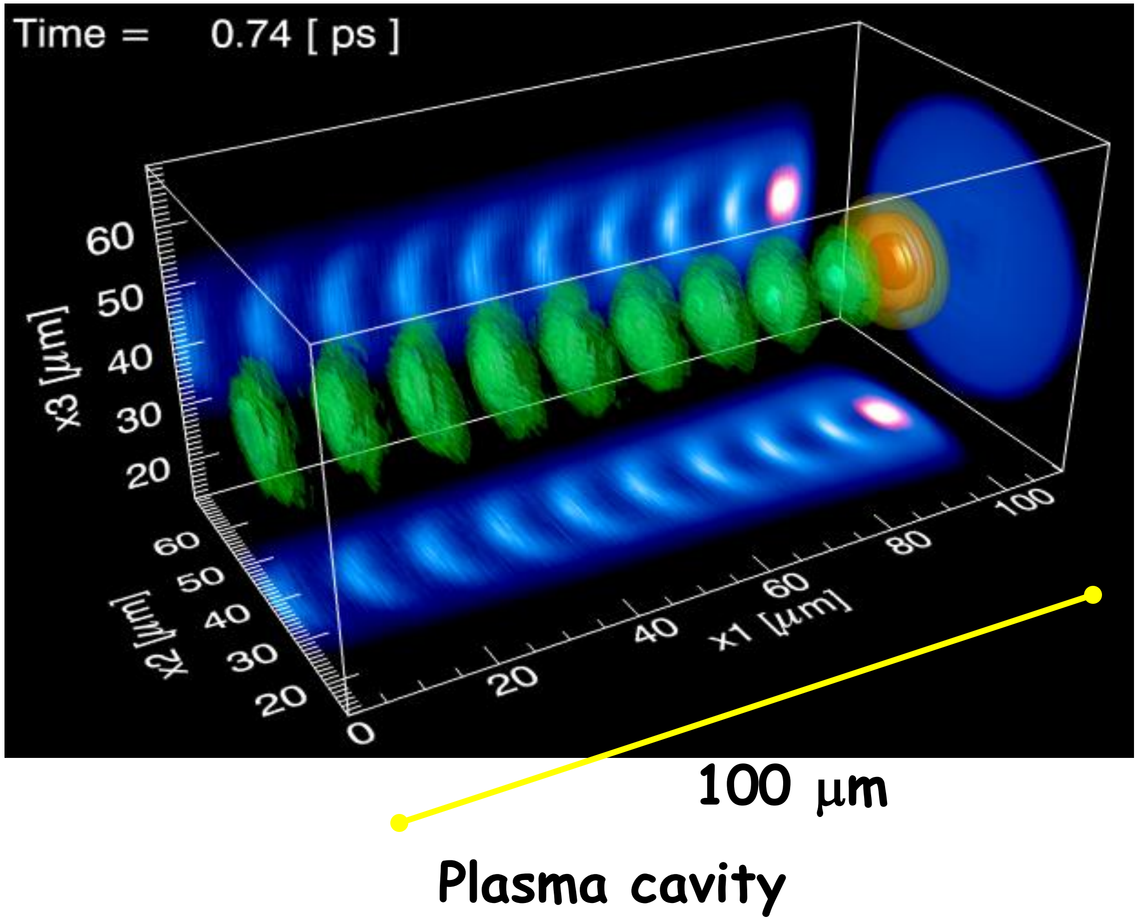
Longitudinal profile in accelerators

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

H^- @ SNS	100ps
H^+ @ LHC	230ps
e^- @ ILC	500fs
e^- @ CLIC	130fs
e^- @ XFEL	80fs
e^- @ LCLS	75fs

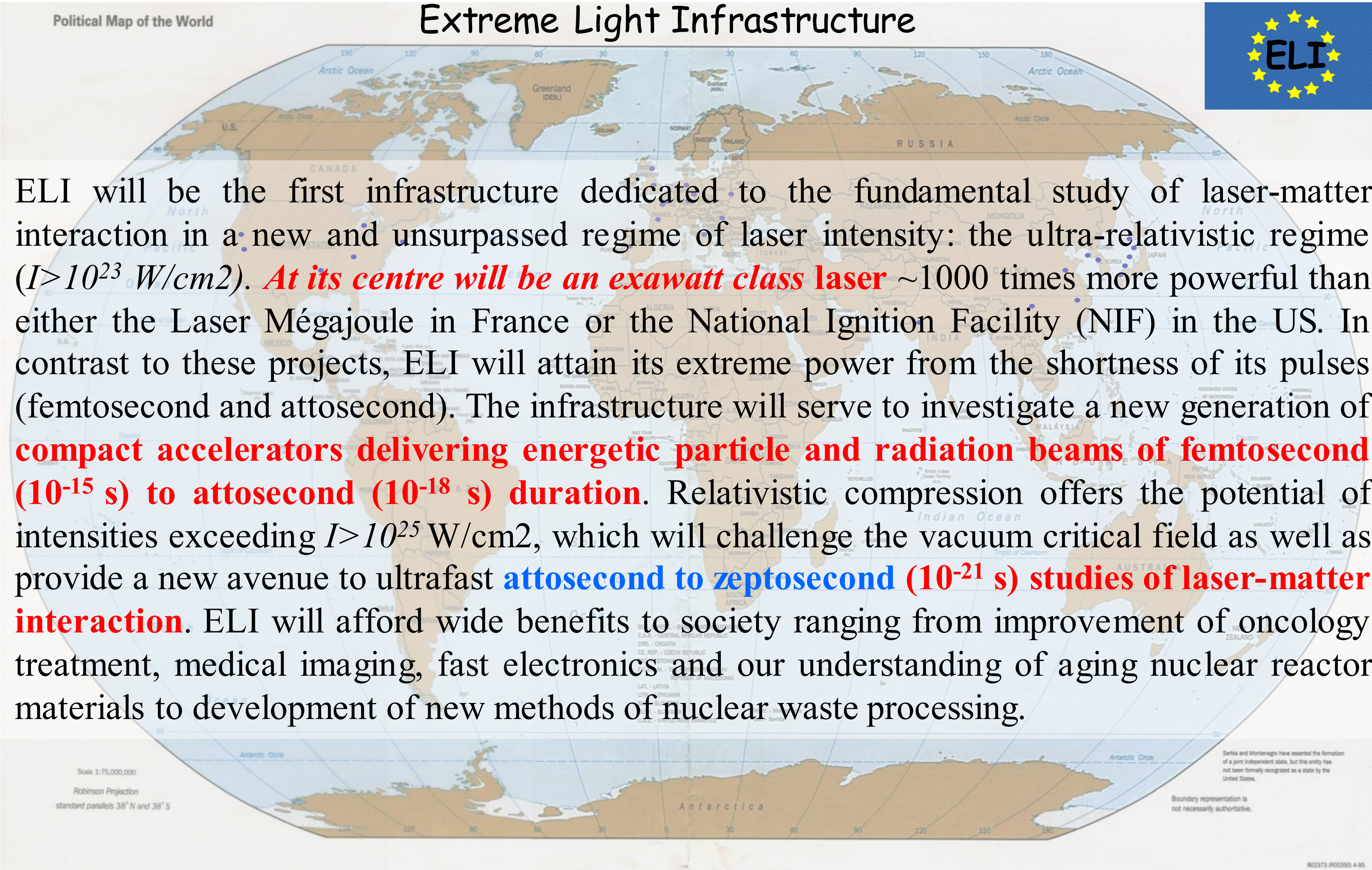
What is the next frontier ?

Courtesy of W. Mori & L. da Silva



What is the next frontier ?

Extreme Light Infrastructure

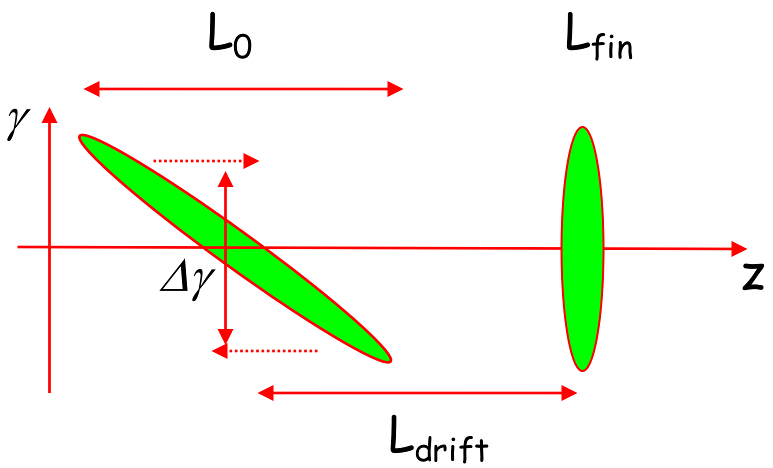


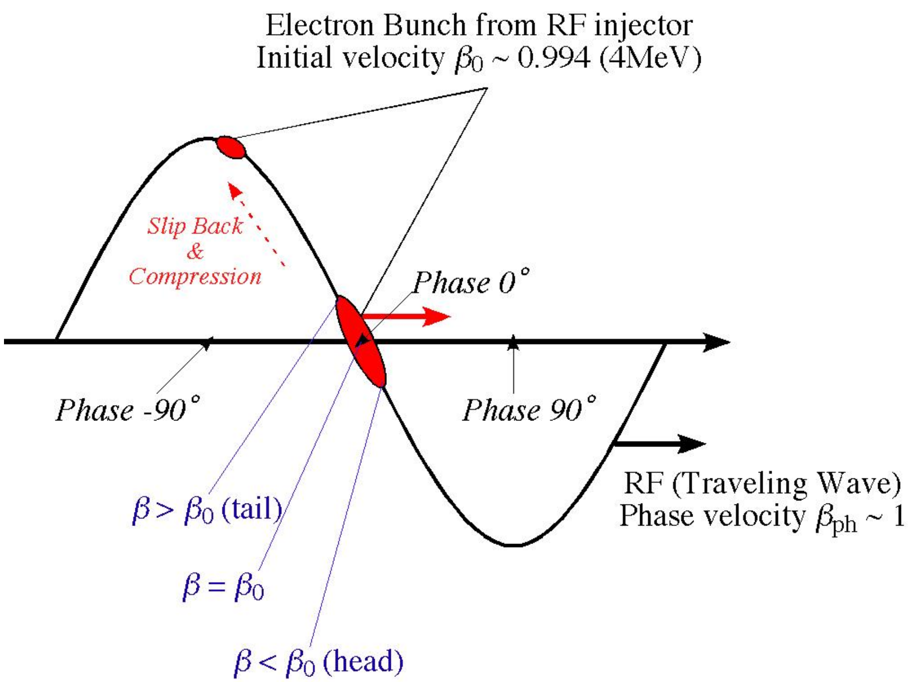
ELI will be the first infrastructure dedicated to the fundamental study of laser-matter interaction in a new and unsurpassed regime of laser intensity: the ultra-relativistic regime (*I*>10^{23} *W/cm2*). ***At its centre will be an exawatt class laser*** ~1000 times more powerful than either the Laser Mégajoule in France or the National Ignition Facility (NIF) in the US. In contrast to these projects, ELI will attain its extreme power from the shortness of its pulses (femtosecond and attosecond). The infrastructure will serve to investigate a new generation of **compact accelerators delivering energetic particle and radiation beams of femtosecond (10^{-15} s) to attosecond (10^{-18} s) duration**. Relativistic compression offers the potential of intensities exceeding *I*>10^{25} W/cm2, which will challenge the vacuum critical field as well as provide a new avenue to ultrafast **attosecond to zeptosecond (10^{-21} s) studies of laser-matter interaction**. ELI will afford wide benefits to society ranging from improvement of oncology treatment, medical imaging, fast electronics and our understanding of aging nuclear reactor materials to development of new methods of nuclear waste processing.

Bunch length manipulation

- Ballistic Compression
- Magnetic Compression

Short bunches by Ballistic/Velocity Compression





$\Delta T \rightarrow \Delta v \rightarrow \Delta L \rightarrow \Delta T$

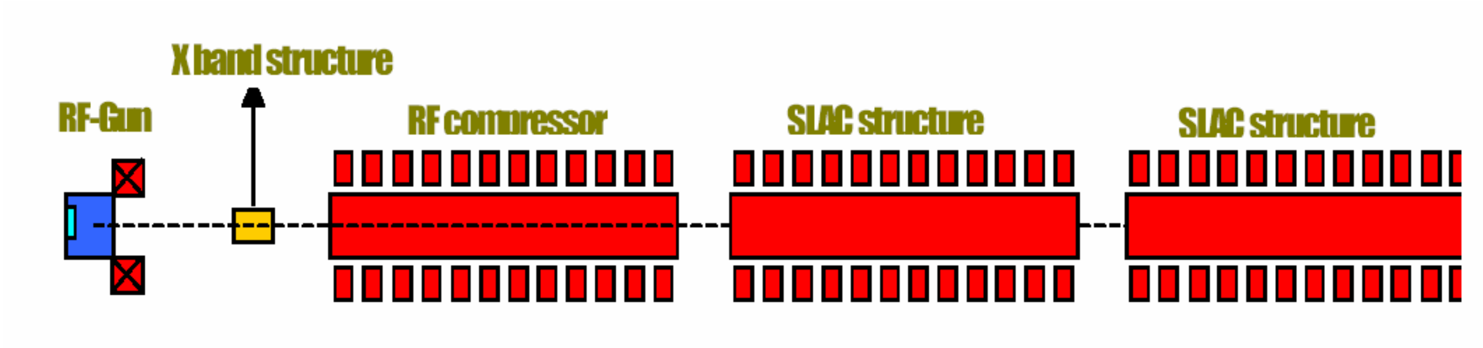
$\Delta\gamma$

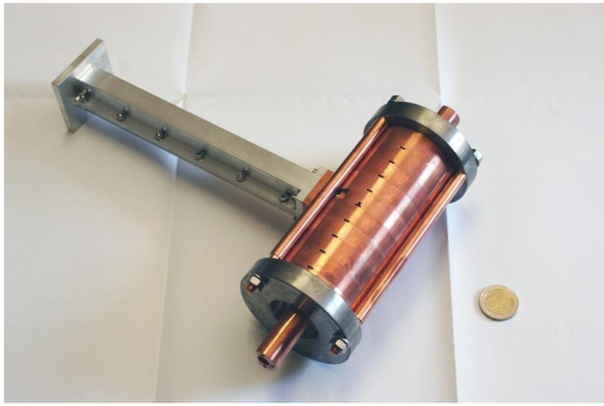
Provide a correlated velocity spread enough to produce, in a drift of length L_{drift} a *path difference* equal to ΔL

$$\Delta L = \left[\frac{L_{drift}}{\bar{\gamma}^2} \right] \frac{\Delta \gamma}{\bar{\gamma}}$$

P. Piot *et al*, PRSTAB 6 (2003) 033503
S.G. Anderson *et al*, PRSTAB 8 (2005) 014401

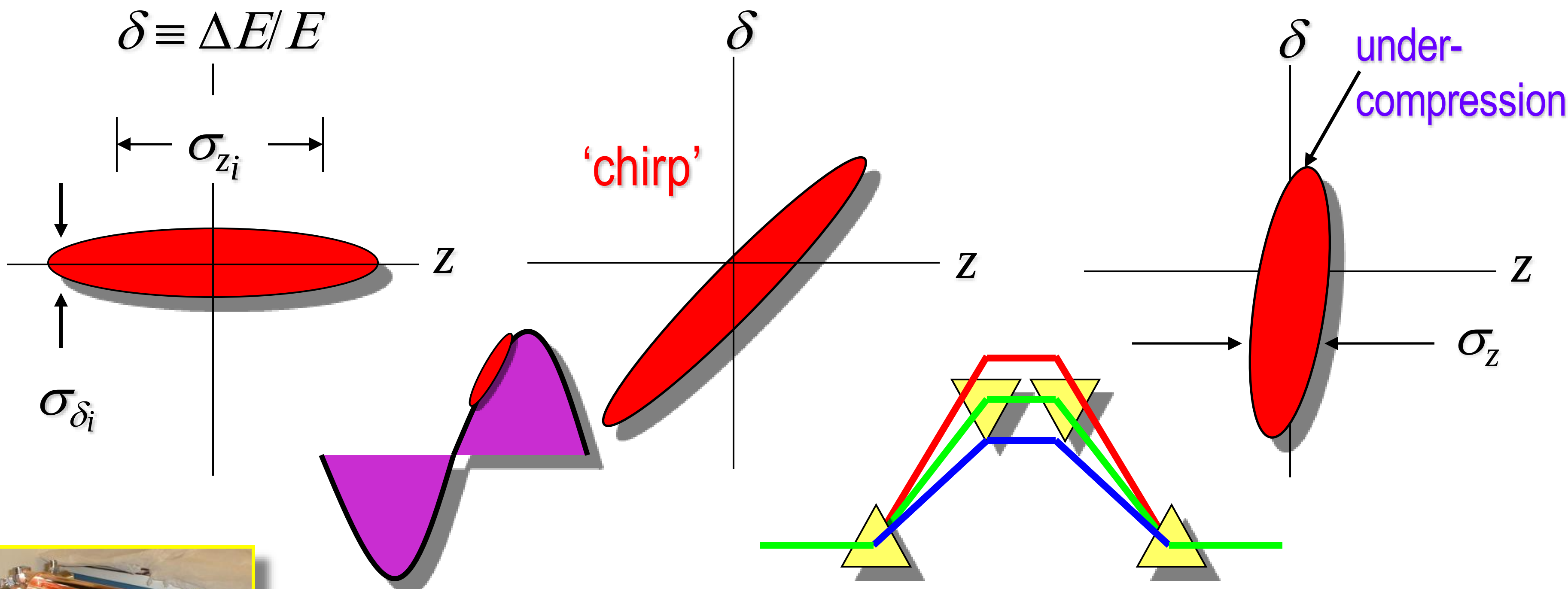
Short bunches by Ballistic Compression





- Works well for non ultra-relativistic beam energies
- no Coherent Synchrotron Radiation effect and bend-plane emittance growth
- Longitudinal emittance growth due to RF non linearities

Short bunches by Magnetic Compression



$V = V_0 \sin(kz)$ $\Delta z = R_{56}\delta$

RF Accelerating Voltage

Path-Length Energy-Dependent Beamline

ΔT → ΔE → ΔX → ΔT

Bunch length measurement techniques

Short bunch length measurements

Radiative techniques

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

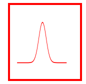
RF manipulation

Use RF techniques to convert time information into spatial information

Laser-based beam diagnostic

Using short laser pulses and sampling techniques

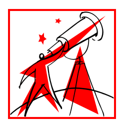
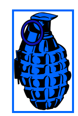
Beam instrumentation

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*
- *Beam Power : No risk of damage by the beam itself*

Simplicity and Reliability

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

A detector, what for ?

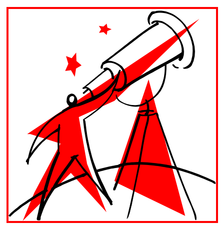
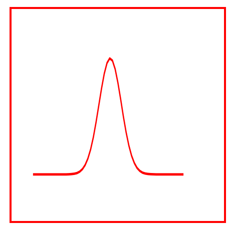
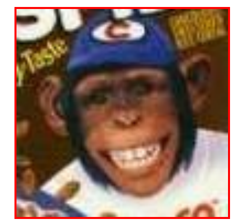
- Online Beam stability → Non-intercepting and reliable

Only have access to a partial information (RMS values,..)

- Beam characterization and beam physics study → Full information

Complexity and time consuming

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

1 +  +  = 

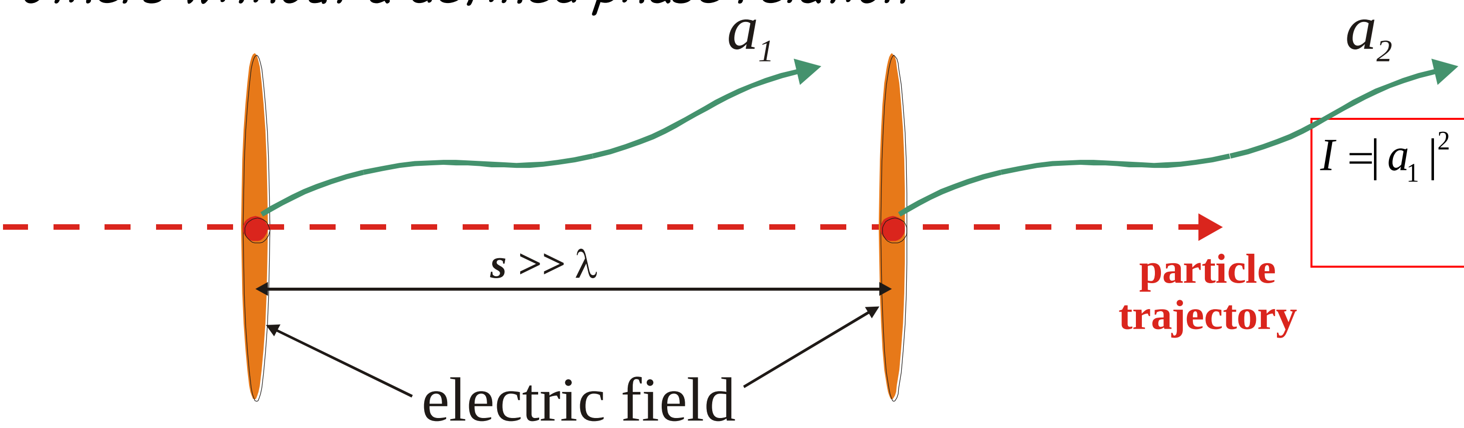
All in red → 'perfect system'

Radiative techniques

'Convert particles into photons'

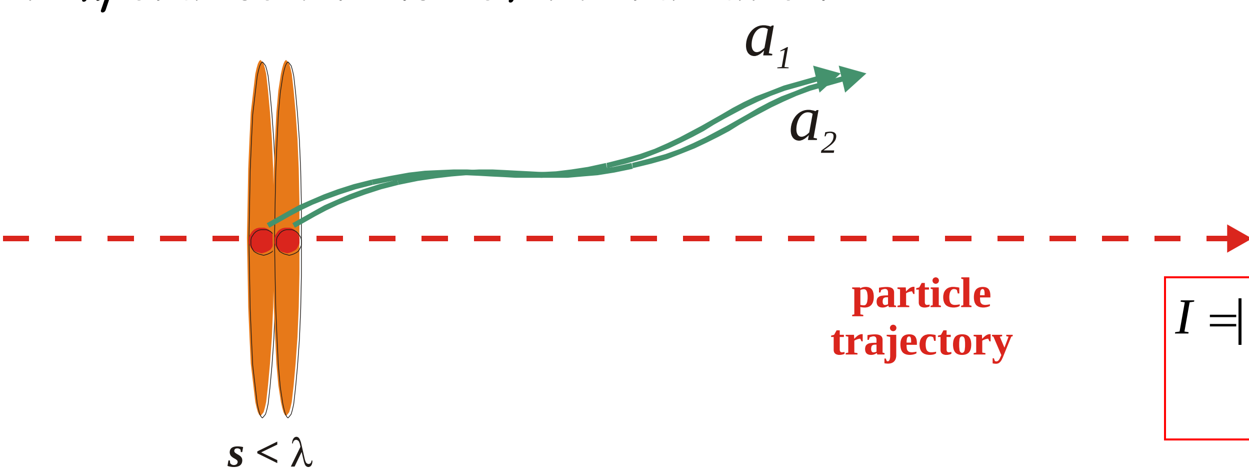
Coherent / Incoherent Radiation

- *At wavelength much shorter than the bunch length, the radiation is emitted incoherently because each electron emits its radiation independently from the others without a defined phase relation*



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

- *A coherent enhancement occurs at wavelengths which are equal to or longer than the bunch length, where fixed phase relations are existing, resulting in the temporal coherence of the radiation*



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

Radiation Spectrum

Incoherent term → Coherent term

$$S(\omega) = S_p(\omega)\left[N + N(N-1)F(\omega)\right]$$

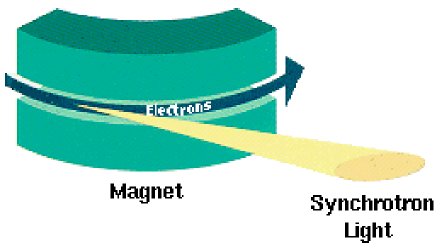
$S(\omega)$ – radiation spectrum
$S_p(\omega)$ – single particle spectrum
N – number of electrons in a bunch
$F(\omega)$ – longitudinal bunch form factor

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

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

Optical Synchrotron Radiation

SR appears when a charged particle is bent in a magnetic field



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

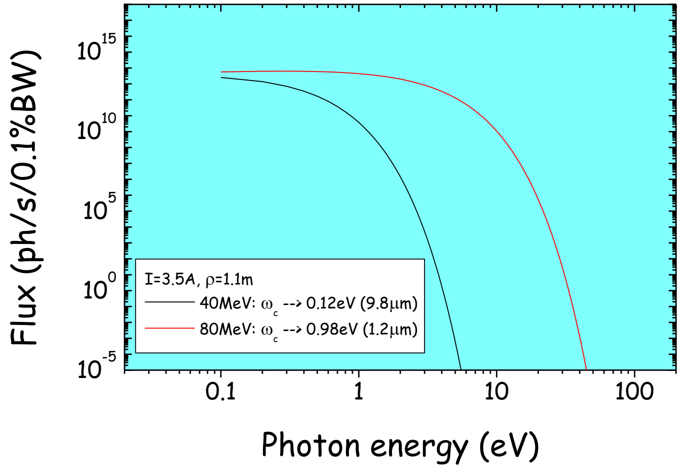
γ charged particle Lorentz-factor

ρ is the bending radius

Critical frequency :

$$\omega_c = 3\gamma^3 \frac{c}{2\rho}$$

Beam energy (γ) — Beam curvature (ρ)

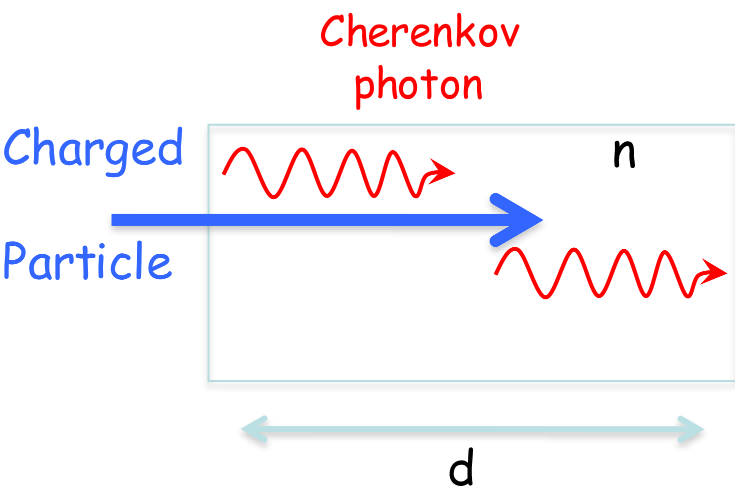


Limitations :

- Use a lot on electrons (for visible light: E > 100 MeV)
- Limited to very high energy proton or heavy ion beams

'Equivalent to the supersonic boom but for photons'

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



- n is the index of refraction (n>1)
- β is the relative particle velocity
- θ_c is the Cherenkov light emission angle

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

- d the length of the cherenkov radiator

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

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

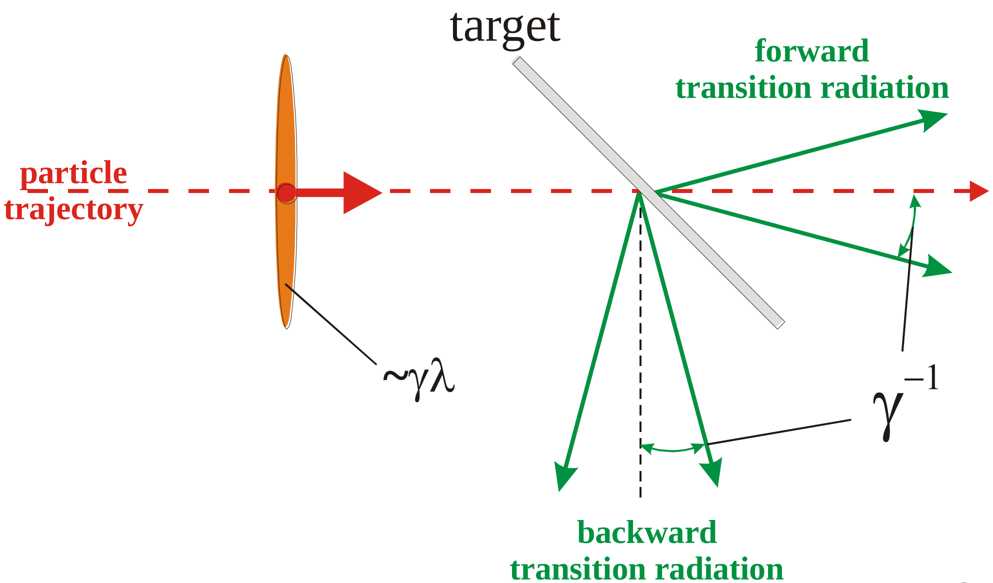
Limitations :

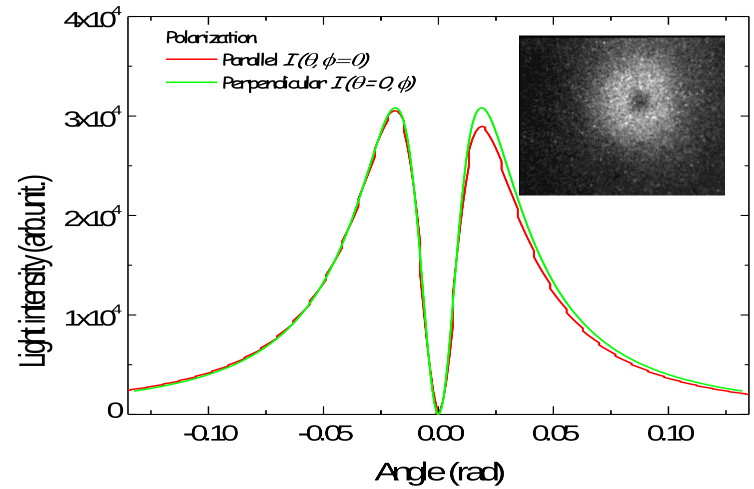
•Using transparent material (Glass n=1.46) : thermal and radiation hardenss issues

•Time resolution limited by the length of the radiator

Optical Transition Radiation

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





Number of OTR photons per charge particle

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

~ 5 10^{-3} in [400-600]nm

Radiation wavelength

Beam energy

Using good reflecting material

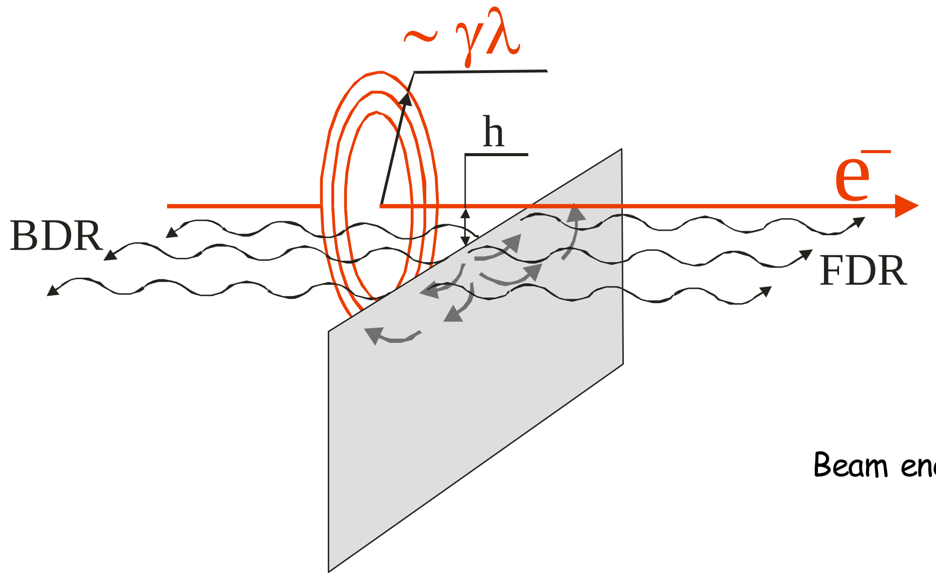
The thermal limit for 'best' screens (C, Be, SiC) is ~ 1 10^6 nC/cm^2

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

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

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

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

Limitations :

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

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

Optical method with Incoherent radiation

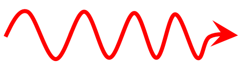
'Convert particles into visible photons'

Time Correlated Single Photon Counting

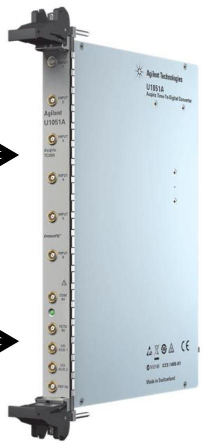
n!

Geiger-mode Avalanche photodiode converts photon to electrical pulse

Visible photon



Precise trigger synchronized with the beam



Time to Digital converter records pulse arrival time

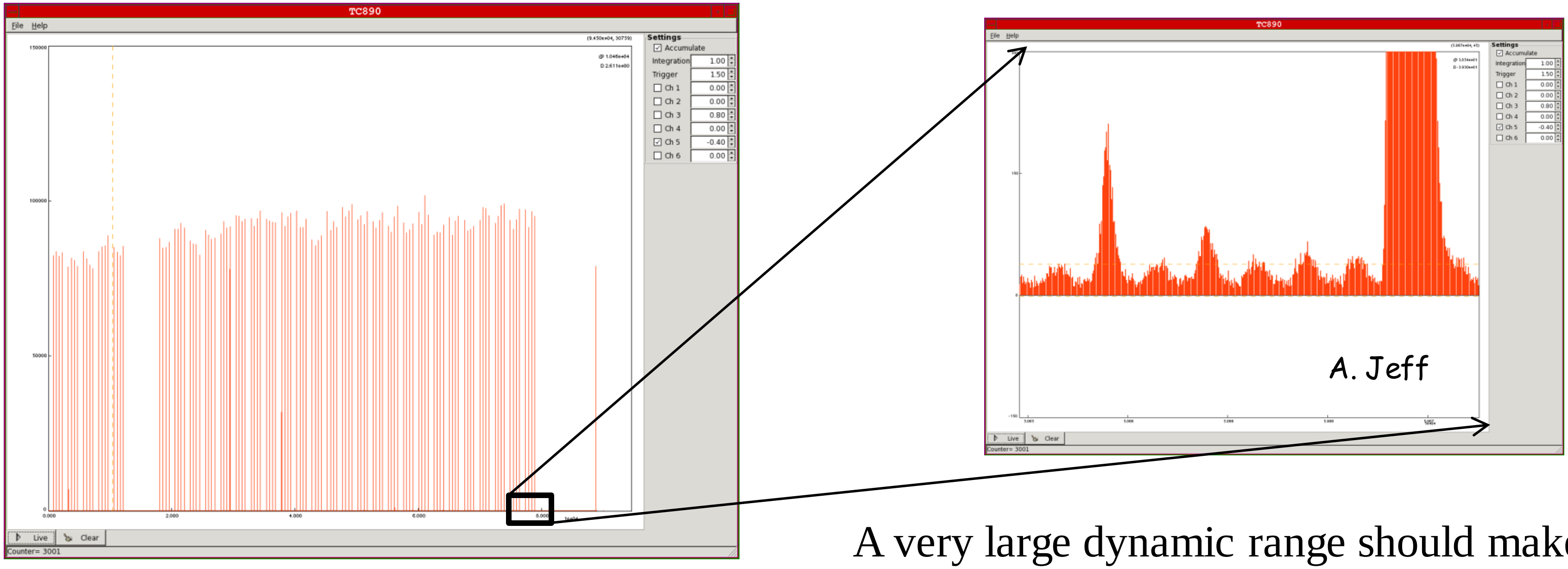
- Sampling Method allowing very high dynamic range if you measure long enough
- Avalanche photodiode have deadtime and are subject to afterpulsing
- State of the art TDC typically limited to 10ps sampling

D.V. O'Connor, D. Phillips, Time-correlated Single Photon Counting, Academic Press, London, 1984

C.A. Thomas et al., Nucl. Instr. and Meth. A566 (2006) p.762

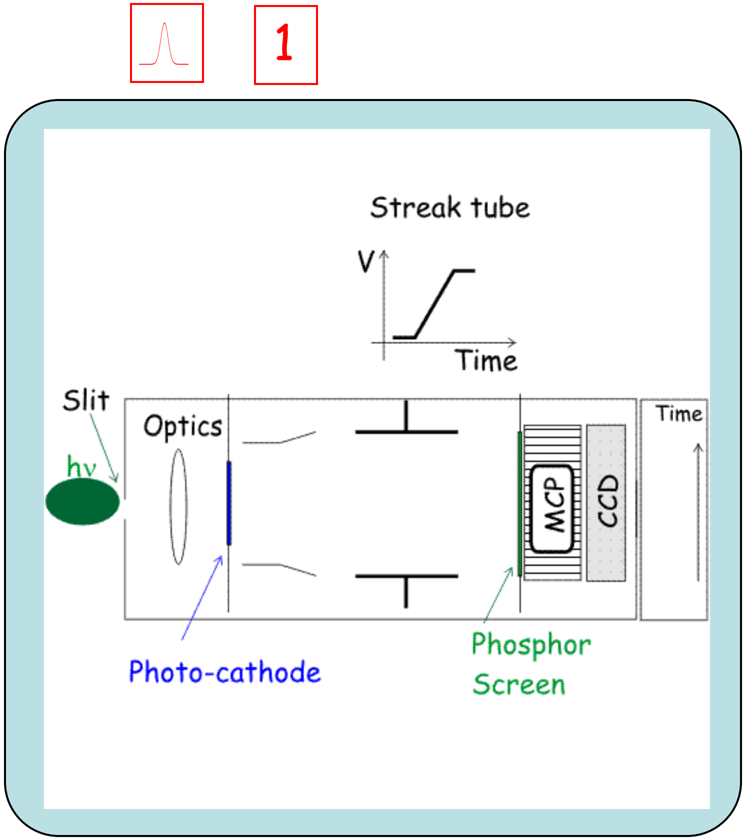
Time Correlated Single Photon Counting

Longitudinal profile of the entire LHC ring (89us)
with 50ps resolution using SR light



A very large dynamic range should make it possible to see ghost bunches as small as 5e5 protons / 50ps with long integration

Streak Camera



'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***

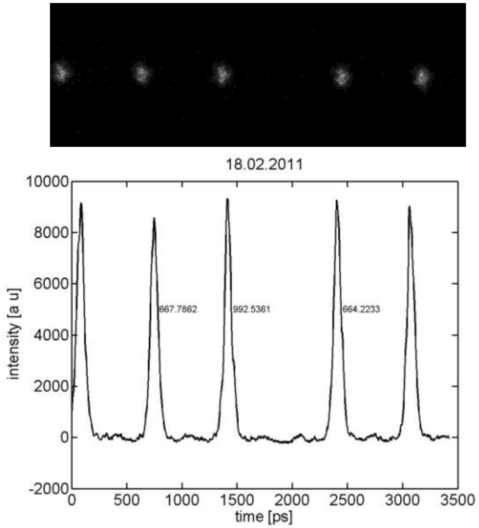
200fs time resolution obtained using reflective optics and 12.5nm bandwidth optical filter (800nm) and the Hamamatsu FESCA 200

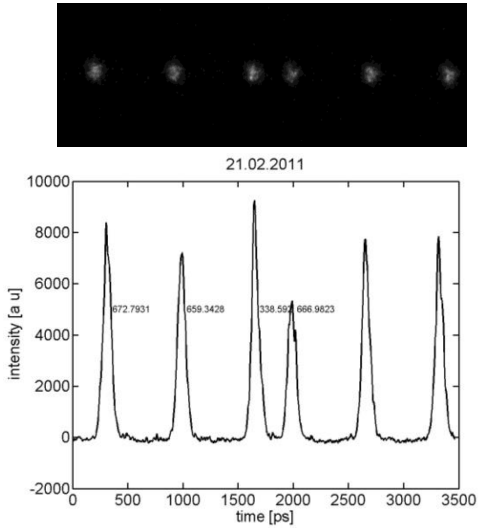
Limitations : Time resolution of the streak camera :

(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

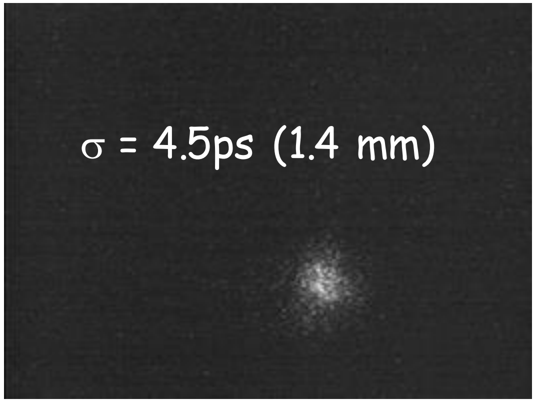
Streak camera examples

Observation of 5MeV electron bunch train using cherenkov
Sweep speed of 250ps/mm

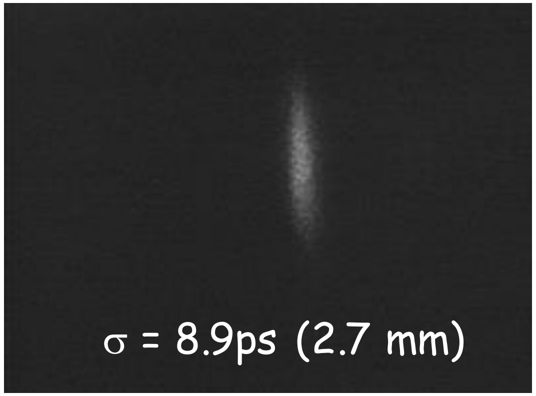




Measure of bunch length using OTR and OSR



Sweep speed of 10ps/mm



Exercise 1

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 : $g = \frac{1}{\sqrt{1 - b^2}}$
- d the thickness of the Cherenkov radiator

Questions:

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

- 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, neglecting multiple scattering of particle in the crystal and light dispersion in the crystal?

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- 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. Θc=46.5 degrees

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

In the present case in order to keep the time resolution better than *1ps*, it corresponds to 270μm

Exercise 2

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)

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

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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.

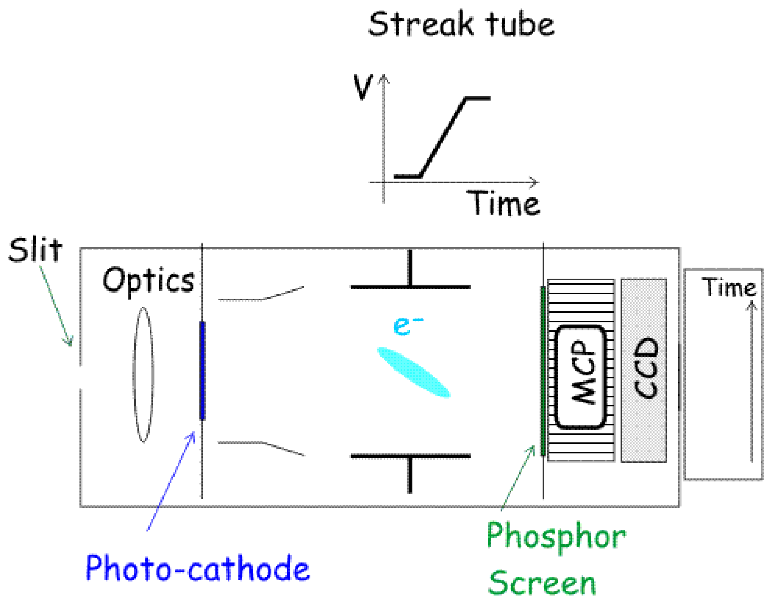
In principle, 1mm would be still good enough and it would correspond to *6.25GeV* electrons.

Exercise 3

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



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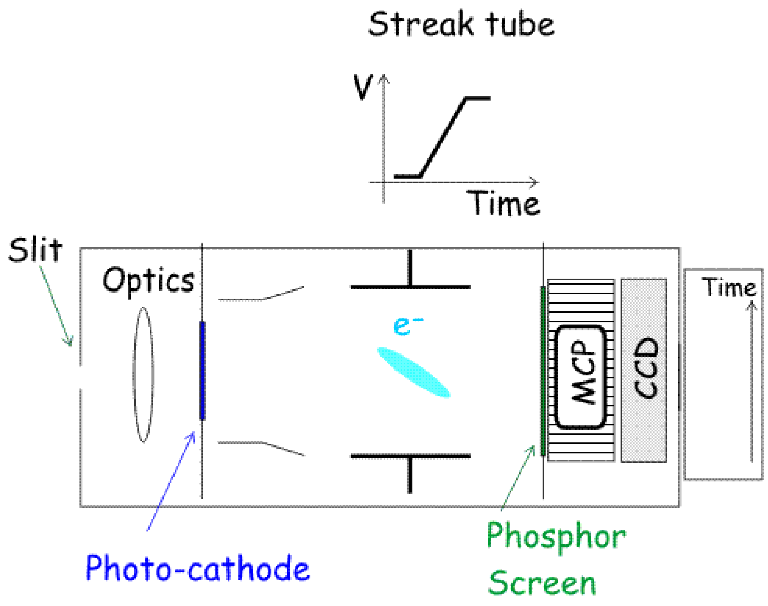


The spatial resolution of the MCP-CCD system corresponds to 1/500 = 20 µm per pixel.

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

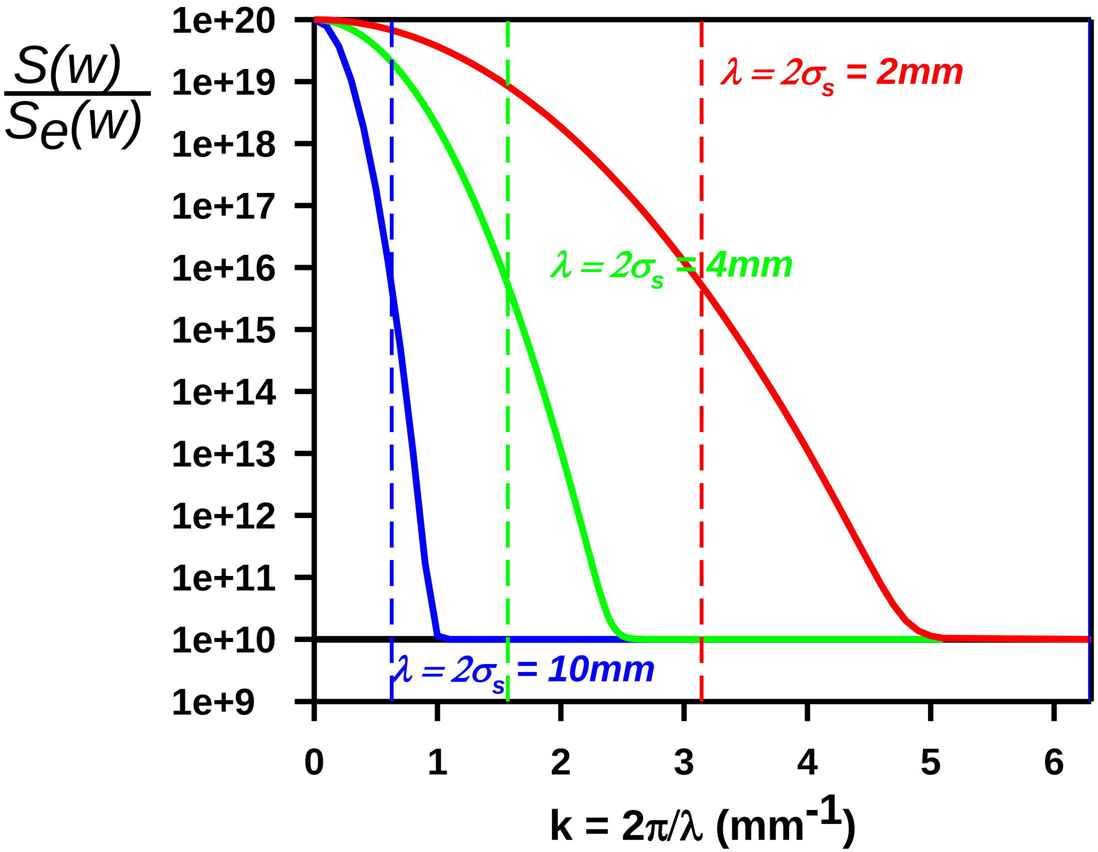
Bunch Length measurement with Coherent Radiation

'The shorter in time, The broader in frequency'

Bunch Form Factor for Gaussian distribution

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

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



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

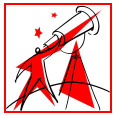
Measuring Radiation Spectrum

$$S(\omega) \approx N^2 S_p(\omega) F(\omega)$$

- ✓ S(ω)– radiation spectrum ((known in the experiment)
- ✓ N – number of electrons on the bunch (known from the experiment)
- ✓ F(ω) – bunch form factor (what you want to find out)
- ✓ $S_p(\omega)$ – single particle spectrum (should be known)

Coherent Transition Radiation (CTR)

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



Coherent Diffraction (CDR) or Coherent Synchrotron (CSR)

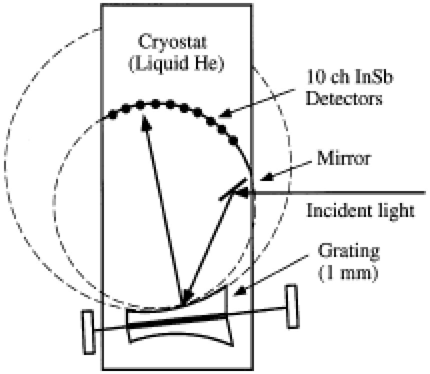
B. Feng et al, **NIM A 475 (2001) 492-497** ; A.H. Lumpkin et al, **A 475 (2001) 470-475** ; C. Castellano et al, **Physical Review E 63 (2001) 056501**

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

Bunch Frequency Spectrum by Coherent Radiation

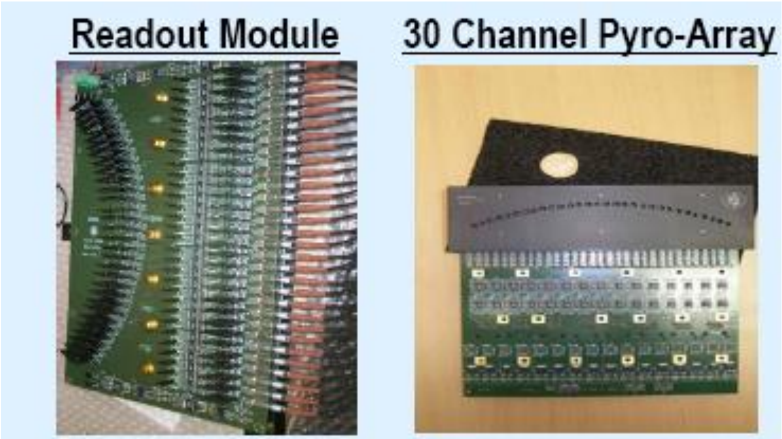
1

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



T. Wanatabe et al., NIM-A 480 (2002) 315-327

H. Delsim-Hashemiet al., Proc. FLS, Hamburg 2006, WG512



B. Schmidt, DESY

Bunch Frequency Spectrum by Coherent Radiation

Frequency Domain

Spectral Intensity
$A(\omega)$

Extrapolation
(high and low frequencies)

Correction
(transfer function of detection system)

Long Form Factor
$|F(\omega)|$

Inverse Fourier Transform for
symmetric bunch distribution

Long. Bunch profile
$S(z)$

Time Domain

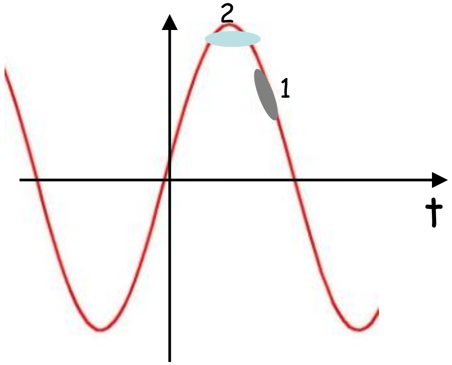
Kramers-Kronig relation
for non symmetric bunches

R. Lai and A.J. Sievers, NIM-A 397 (1997) 221 -231

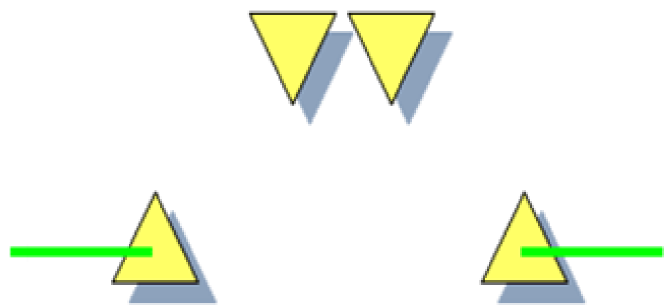
Exercise 4

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.

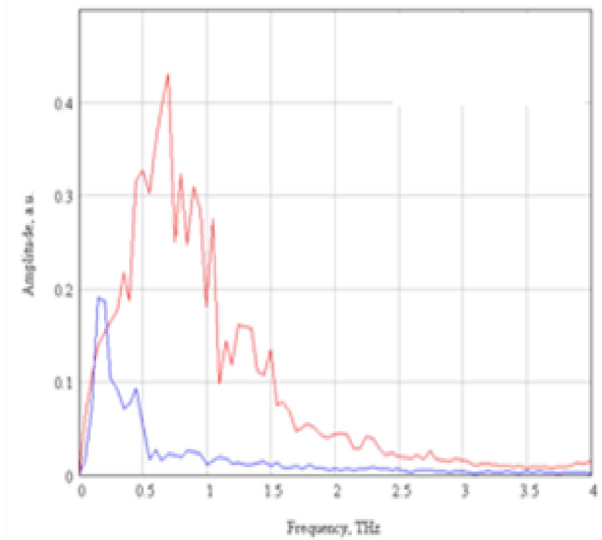
Accelerating Field E(t)



Magnetic chicane



CDR monitor



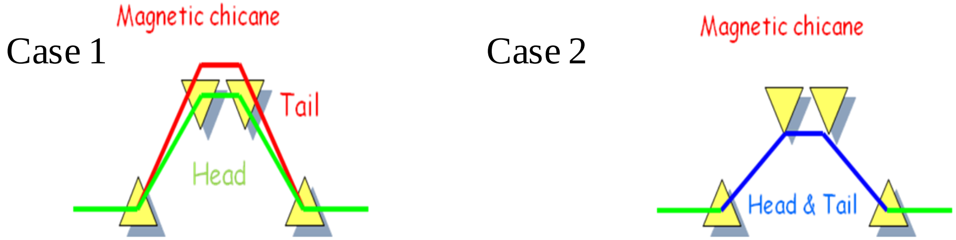
Questions:

- On the figure, there are two different settings of the accelerating structure 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

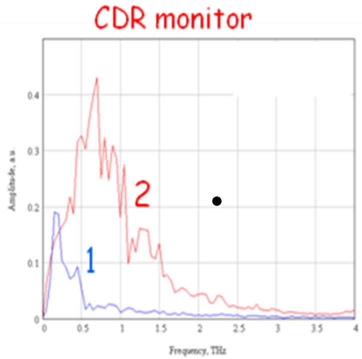
Exercise 4

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 ?



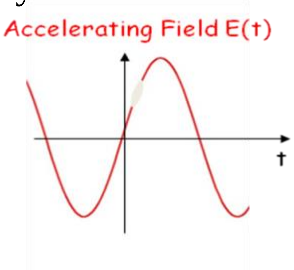
• On the CDR monitor, two different bunch frequency spectra have been measured. Choose which spectra corresponds to which phase settings



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 modifv to have a better result

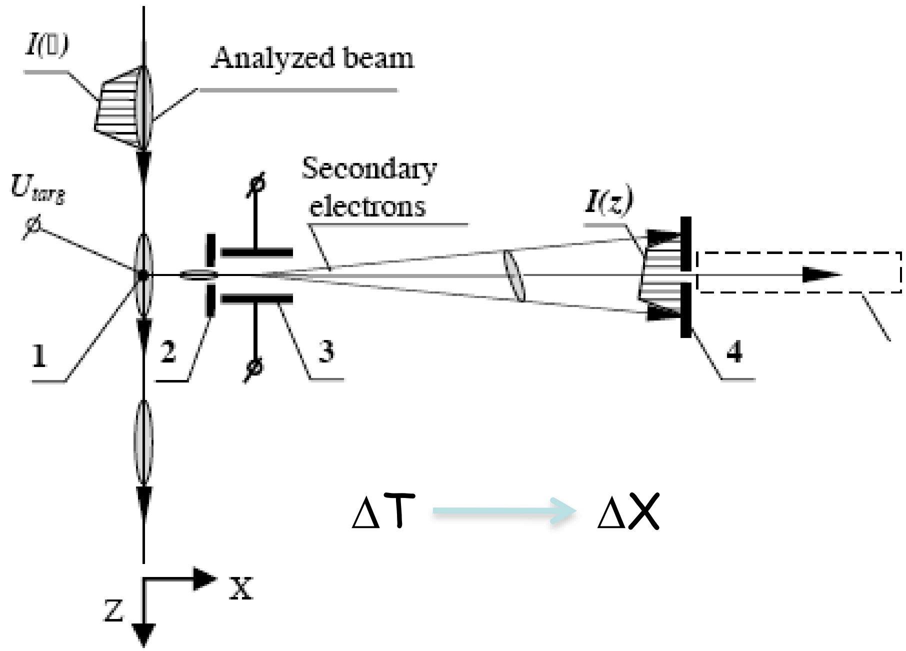


The bunch compressor is stretching the bunch at the moment and you are not satisfied, you suggest then to change the phase of the klystron in order to bring the bunch on the negative slope of the RF. This will correspond to bunch compression, accelerating more the tail than the head of the bunch.

RF techniques

'How to transform time information into spatial information'

Bunch Shape Monitor - Feschenko monitor

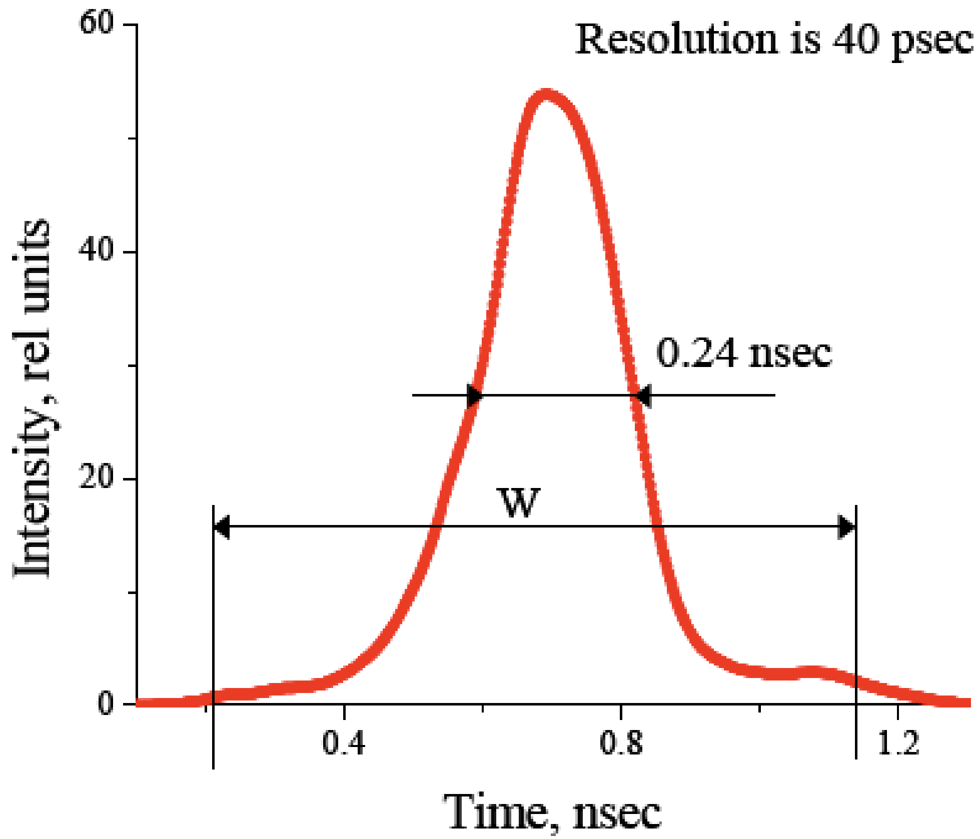


1 - Target (wire, screen, laser for H^-) : Source of secondary electrons
2 - Input collimator
3 - RF deflector (100MHz, 10kV) combined with electrostatic lens
4 - Electron Beam detector (electron multiplier, ..)

1

Bunch Shape monitor - Feschenko monitor

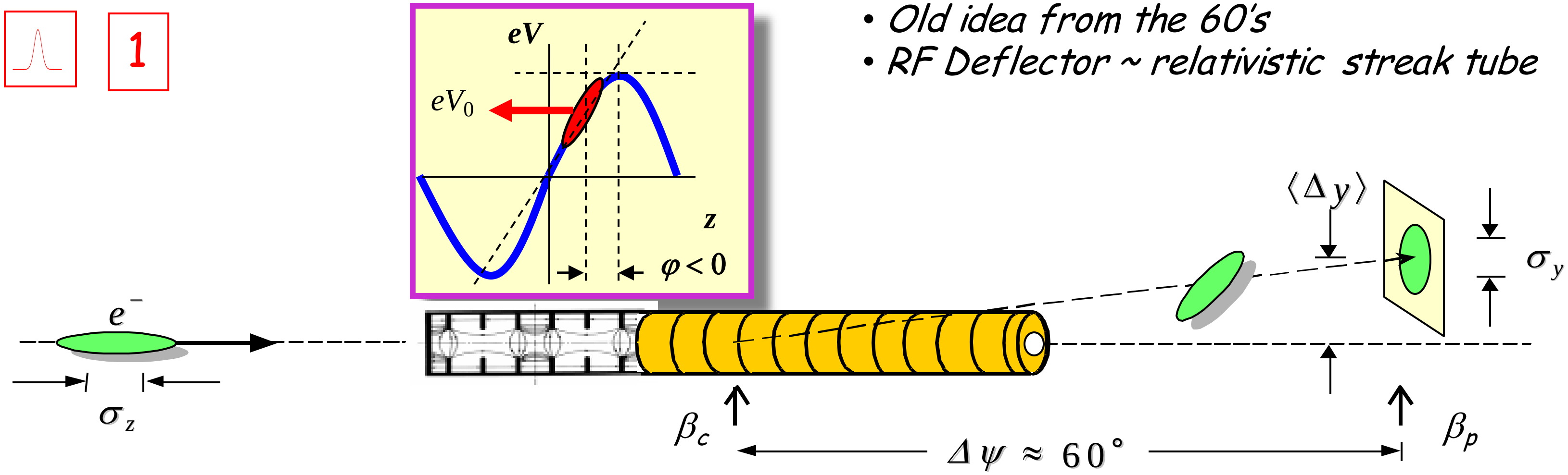
Longitudinal Bunch profile @ SNS



A. Feschenko *et al*, Proceedings of LINAC 2004, Lubeck, p408

RF Deflecting Cavity

- *Old idea from the 60's*
- *RF Deflector ~ relativistic streak tube*



<u>Beam profile RF on</u>

$$\sigma_y = \sqrt{\sigma_{y_0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi}{\lambda} \frac{eV_0}{E_0} \sin(\Delta\Psi) \cos(\varphi) \right)^2}$$

Beam profile RF off

Deflecting Voltage

Bunch length

Beta function at cavity and profile monitor

RF deflector wavelength

Beam energy

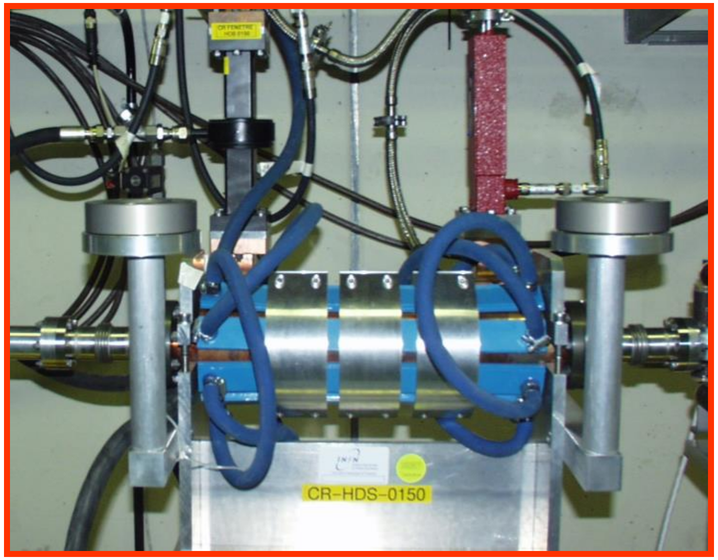
Betatron phase advance (cavity-profile monitor)

$\sin\Delta\psi = 1$, β_p small
Make β_c large

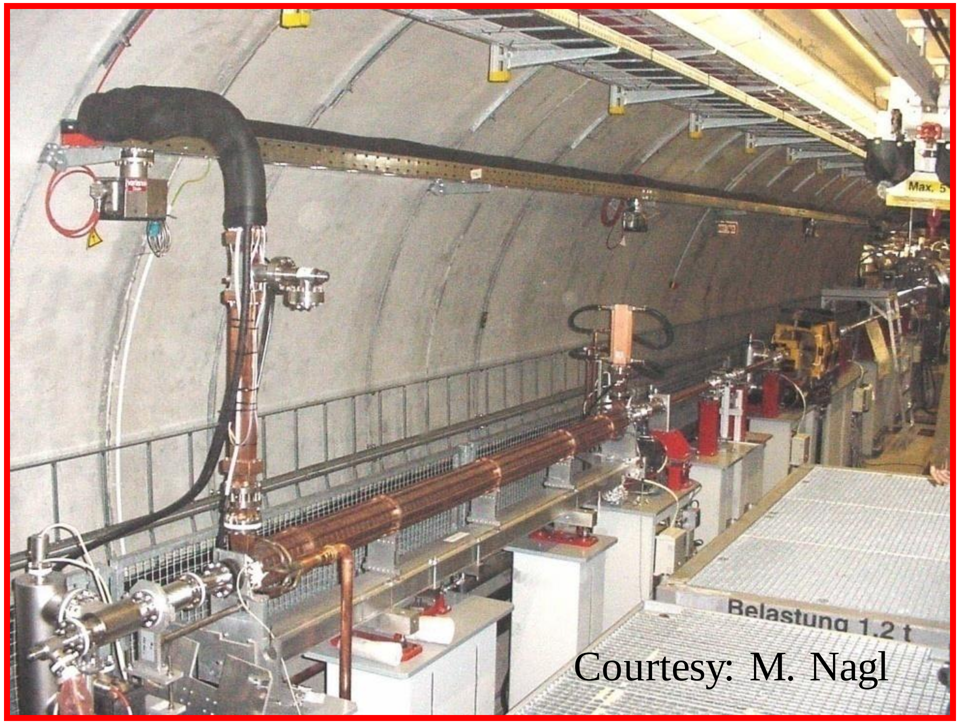
P. Emma et al, LCLS note LCLS-TN-00-12, (2000)

RF Deflecting Cavity

CTF3



LOLA @ Flash



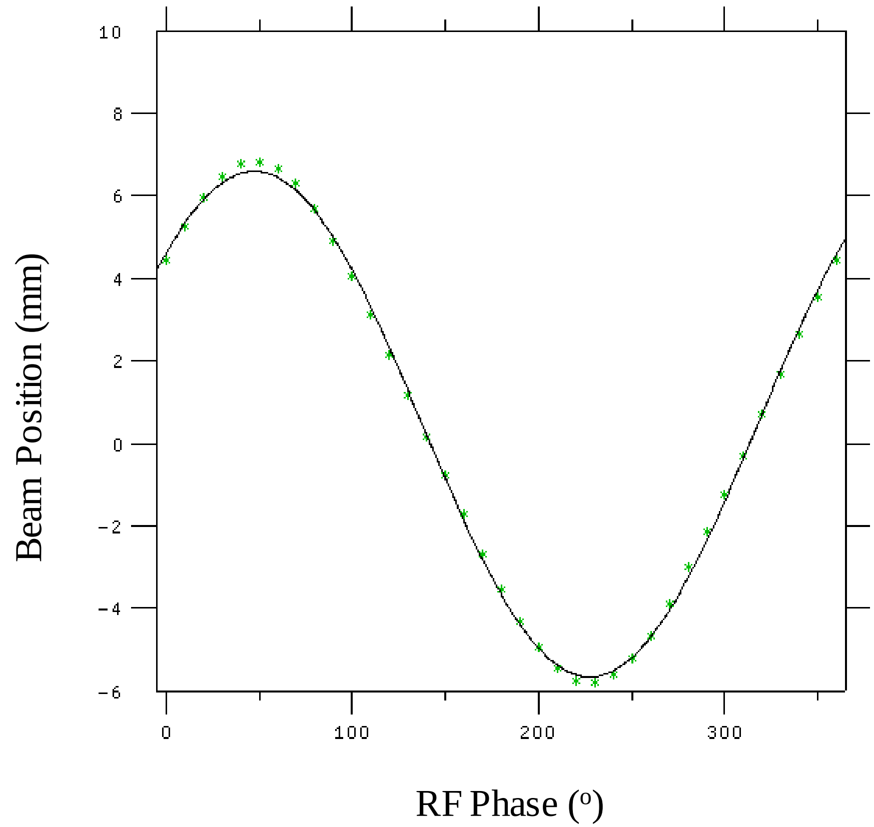
Courtesy: M. Nagl

RF Deflecting Cavity

Calibration of RF Deflector

ΔX(mm) → $\Delta\varphi$(°) ΔT(ps)

Monitor the Beam Position on (or close to) the Profile monitor to calibrate the deflection angle

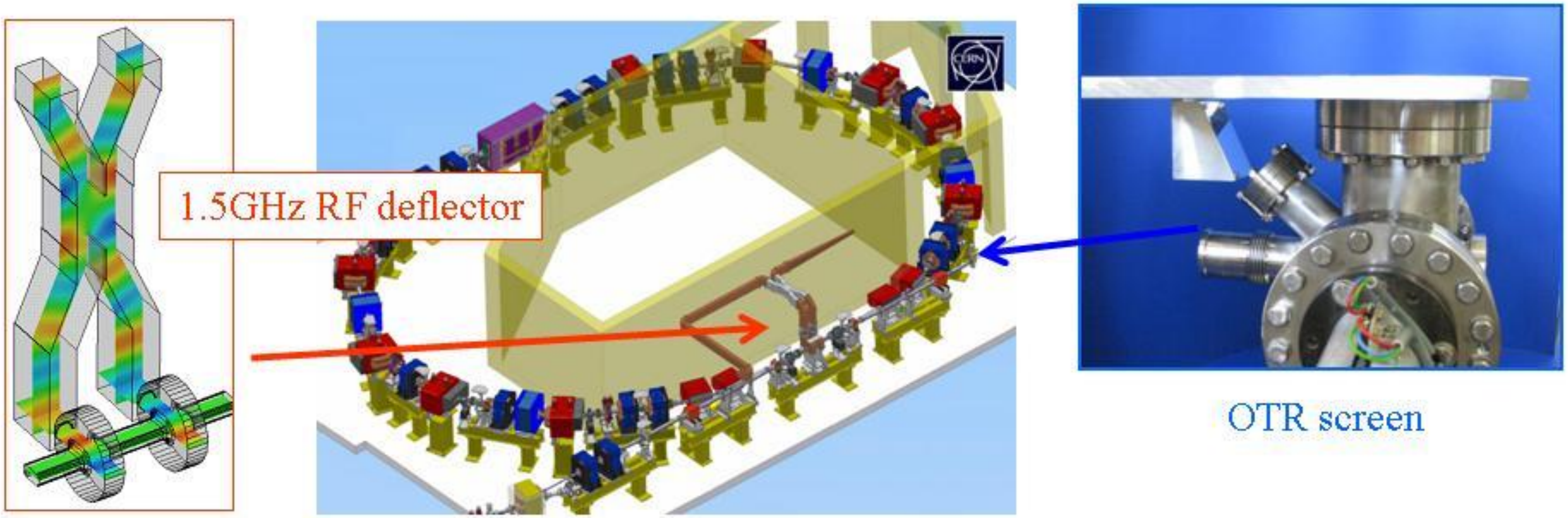


Beam offset on the screen

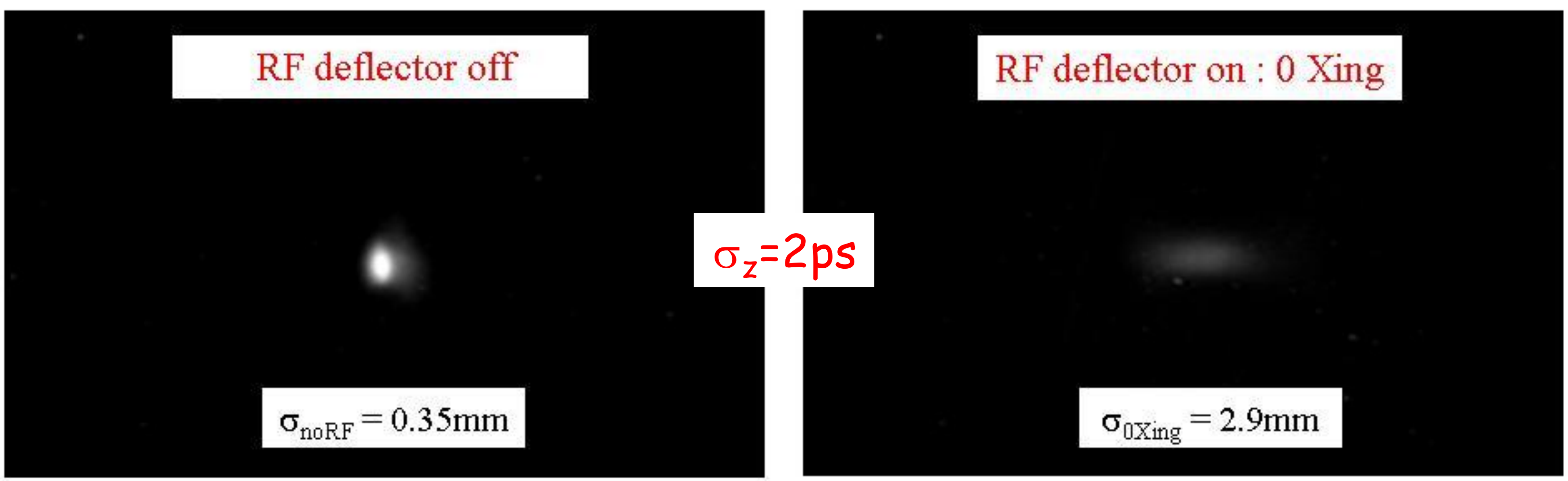
$$\Delta y(z) \approx \frac{eV_0}{E_0} \cdot \sqrt{\beta_c \beta_p} \sin(\Delta\Psi)\left(\frac{2\pi}{\lambda} - z\cos(\varphi) + \sin(\varphi)\right)$$

RF deflector phase

RF by Deflecting Cavity

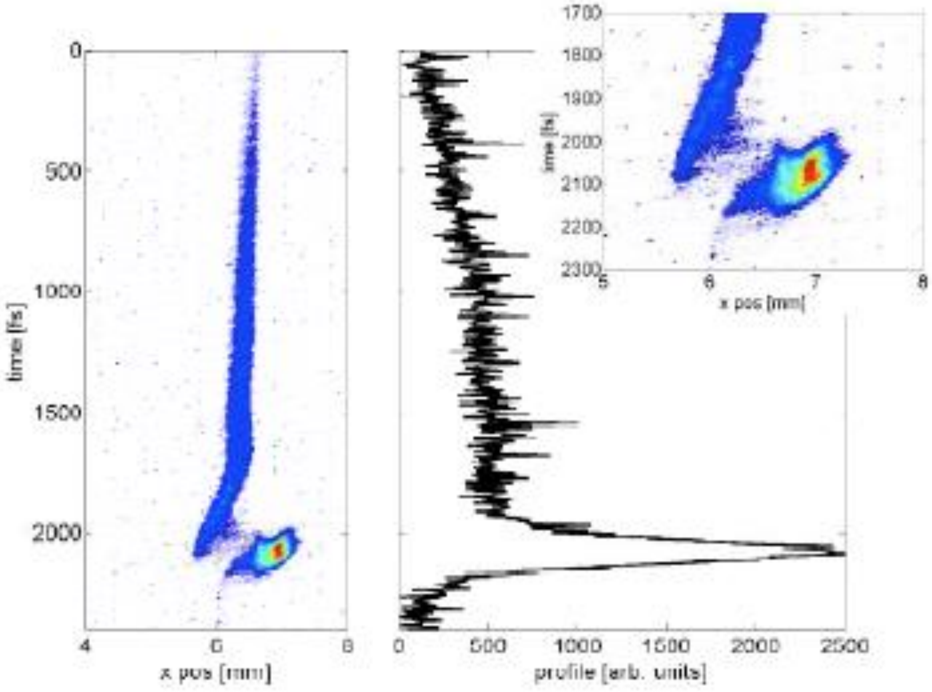


OTR screen

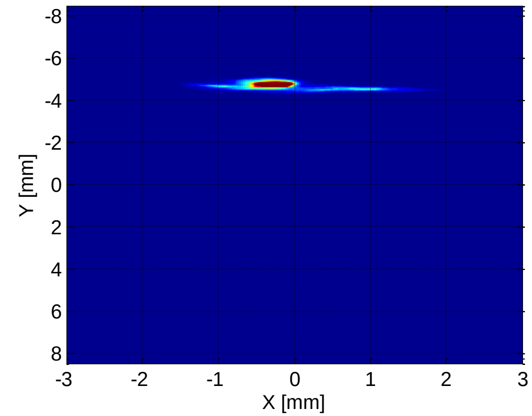


RF by Deflecting Cavity

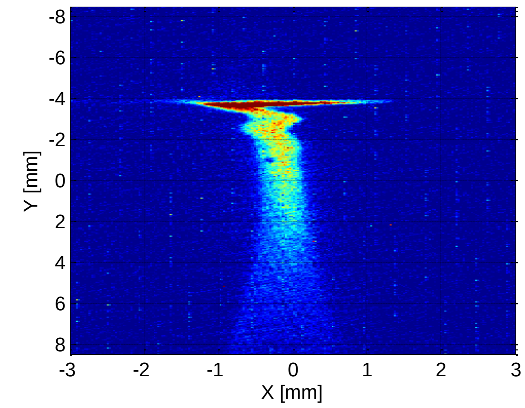
Bunch length measurement @ Flash



LOLA off:



LOLA on:

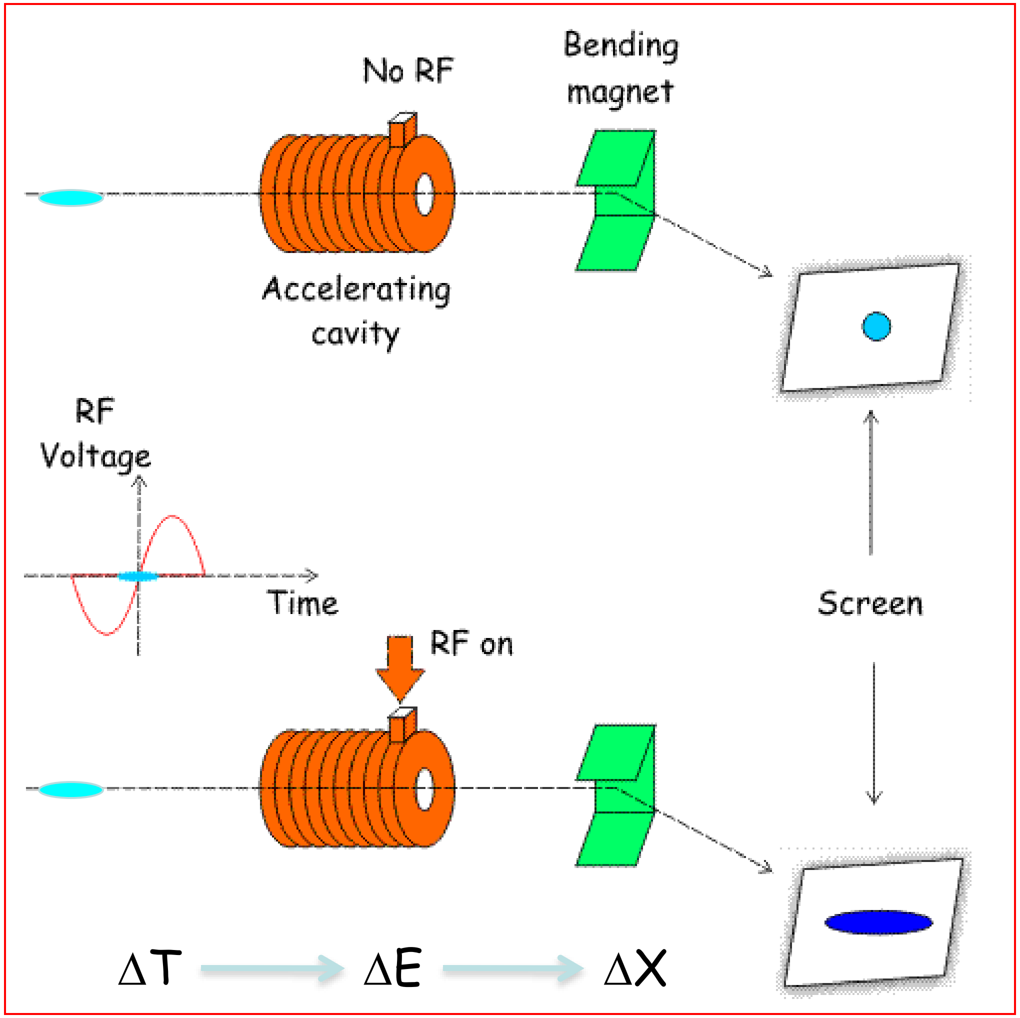


→ Resolution of 4fs/pixels

M. Hüning *et al*, Proceeding of the27th FEL conference, Stanford, 2005, pp538

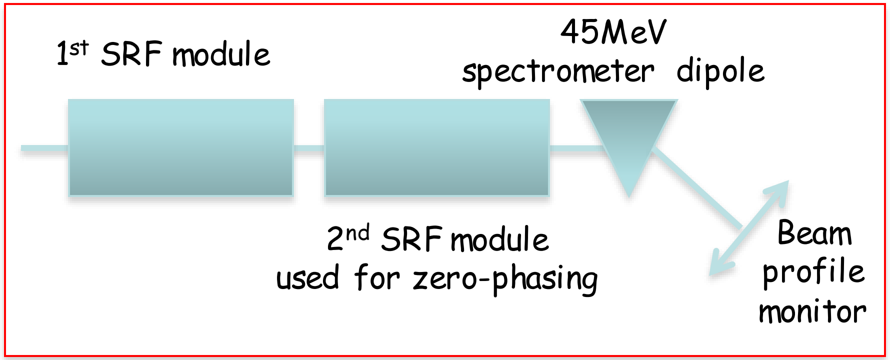
RF accelerating structures

'The electron energy is modulated by the zero-phasing RF accelerating field and the bunch distribution is deduced from the energy dispersion measured downstream using a spectrometer line'



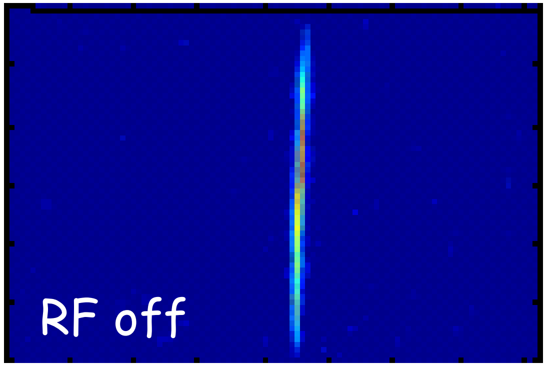
RF accelerating structures

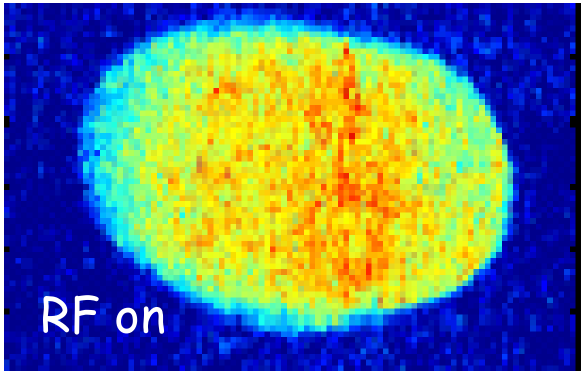
CEBAF injector, Newport News



D. X. Wang *et al*, Physical Review E57 (1998) 2283

84fs, 45MeV beam but low charge beam





Limitations

RF non linearities

Beam loading and wakefield for high charge beam

Exercise 5

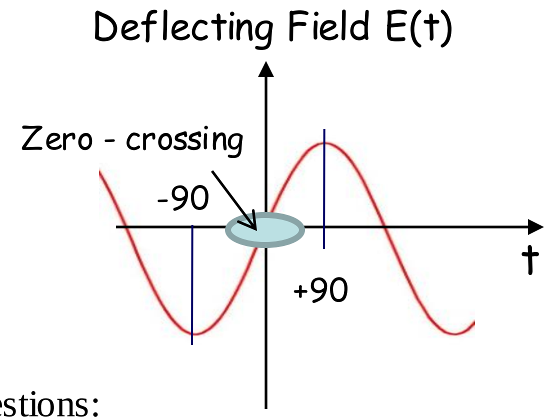
Optics

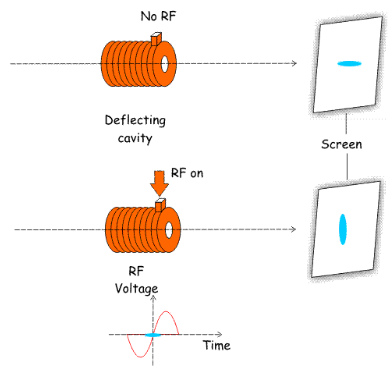
Spectrum

RF

Laser

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.





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

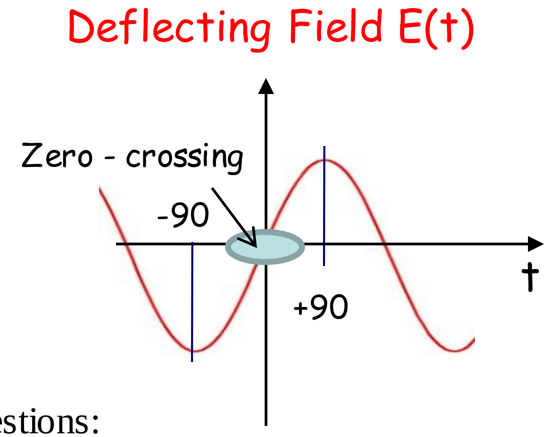
Questions:

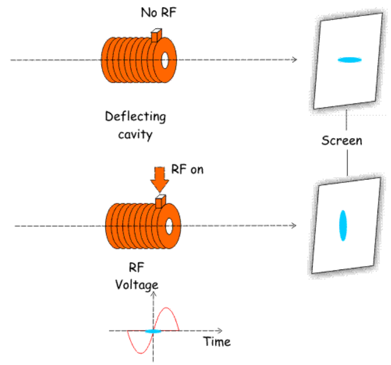
- If the bunch is placed at the zero-crossing of the RF deflector. What happens to the beam position and to the beam size?

- 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.

Exercise 5

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.





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

Questions:

• If the bunch is placed at the zero-crossing of the RF deflector. What happens 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.

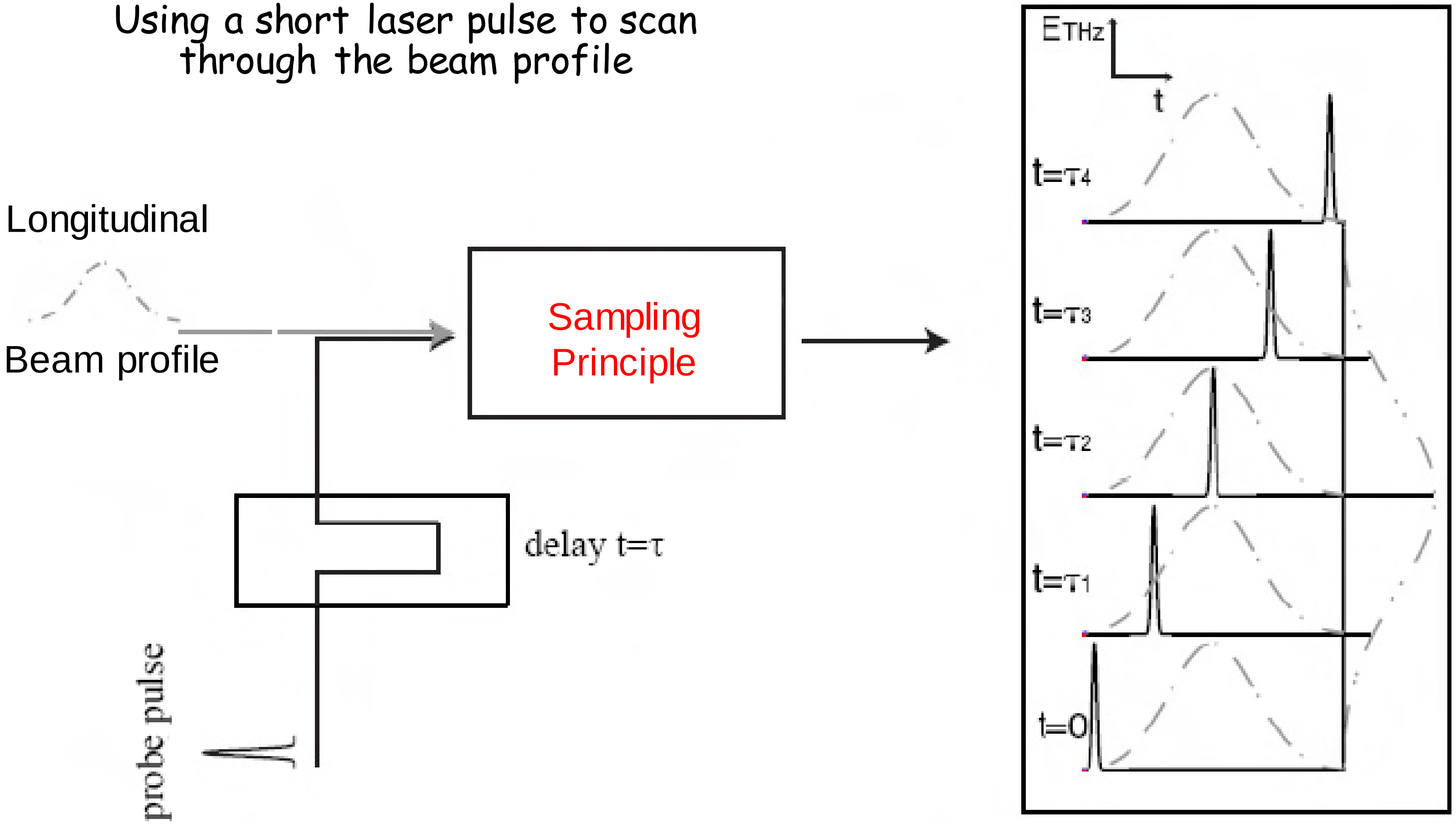
•The beam is moved by 5mm on the screen for a 90degrees klystron phase and would correspond to a time delay corresponding to 83.25ps

•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

Laser based techniques

Sampling Techniques

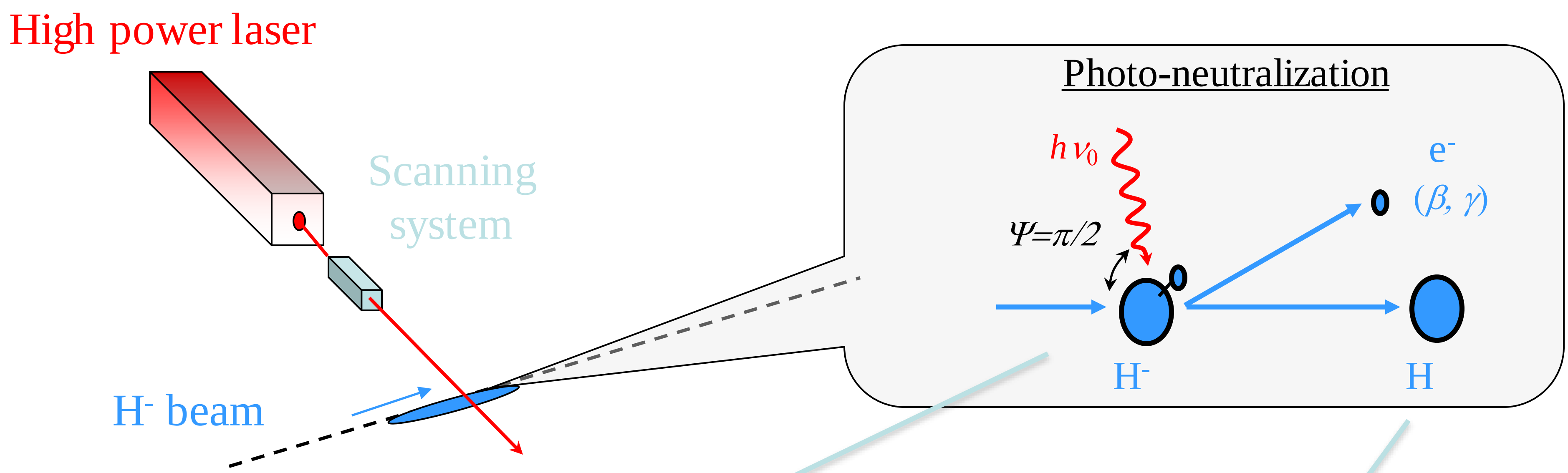
Using a short laser pulse to scan through the beam profile



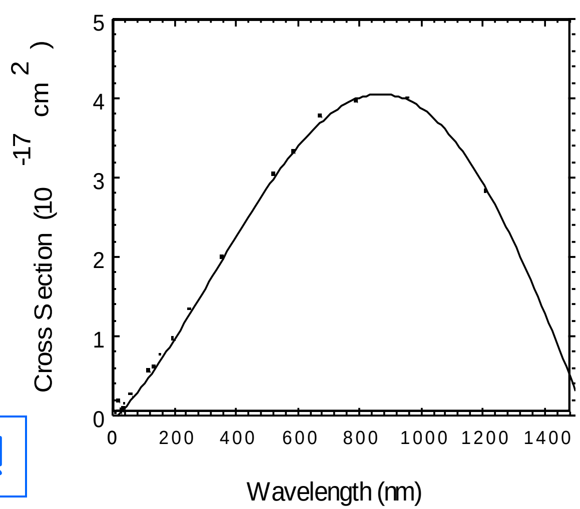
Limitation

Laser-beam synchronization jitter (50fs)

Laser Wire Scanner : Photo-neutralization



- First ionization potential for H^- ions is 0.75eV
- Photo-neutralization cross section : $\sigma \sim 4.10^{-17}\ cm^2$



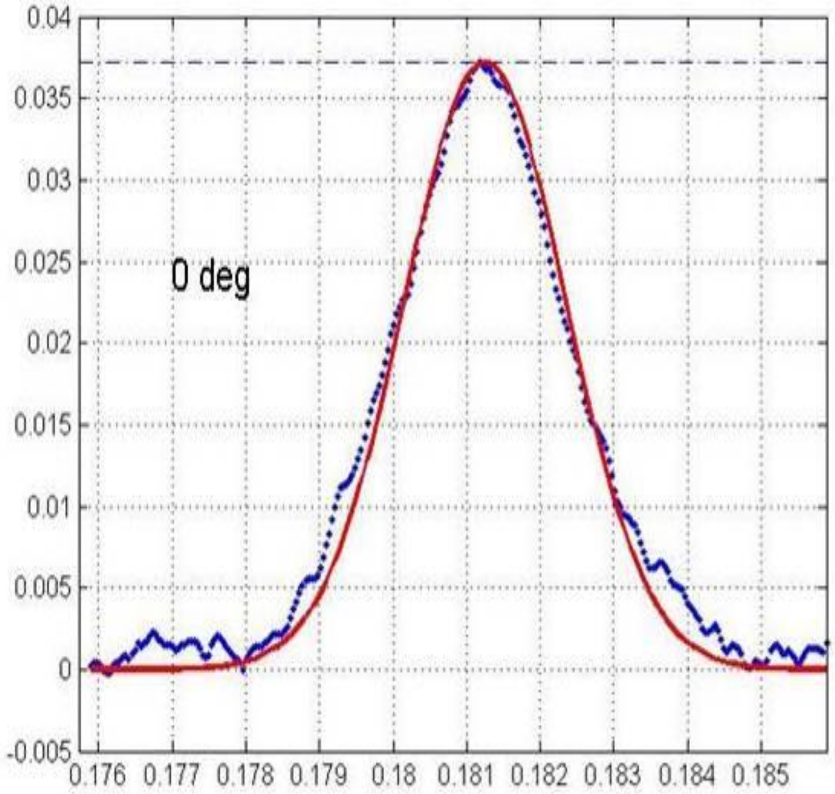
Detection system based on

- The measurement of released electrons using a magnet and a collector (faraday cup, MCP,..)
- *Measured the conversion of H^- into H with a current monitor*

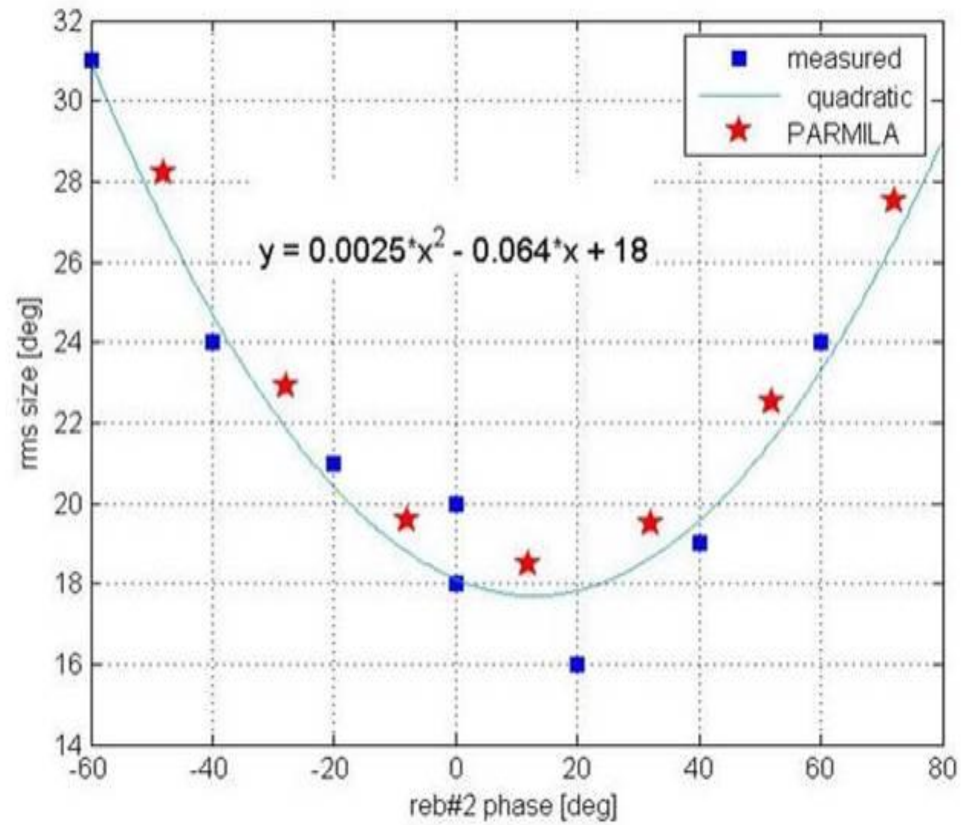
Laser Wire Scanner : Photo-neutralization

Mode Locked Laser Longitudinal Measurements @ SNS

2.5 MeV H^-, 402.5 MHz bunching freq, Ti-Sapphire laser phase-locked @ $1/5^{th}$ bunching frequency



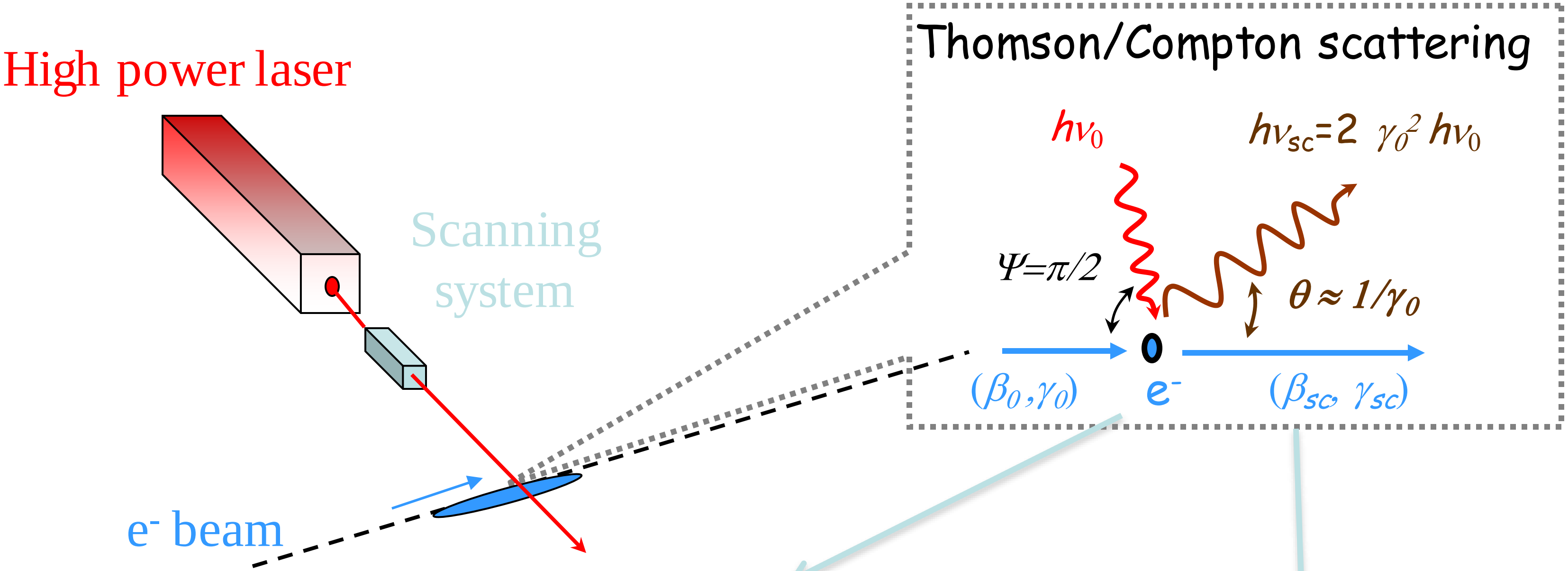
Collected electron signal plotted vs. phase

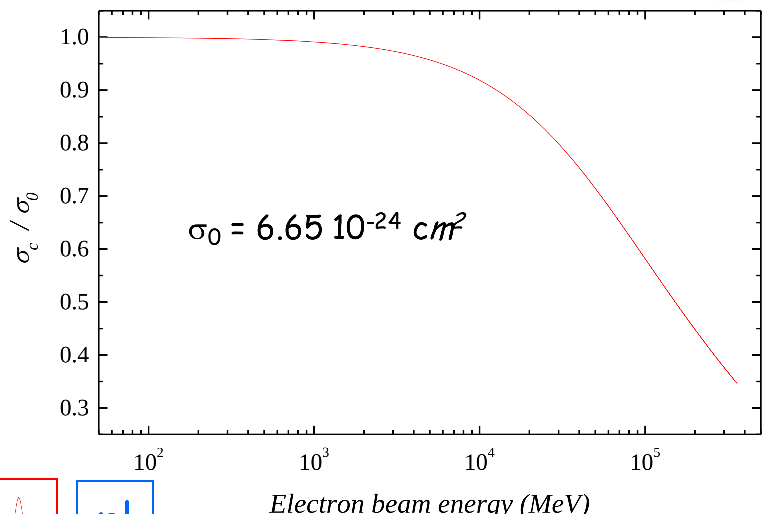


Measured and predicted bunch length vs. cavity phase setting

S. Assadi *et al*, Proceedings of EPAC 2006, Edinburgh, pp 3161

Laser Wire Scanner - Compton scattering



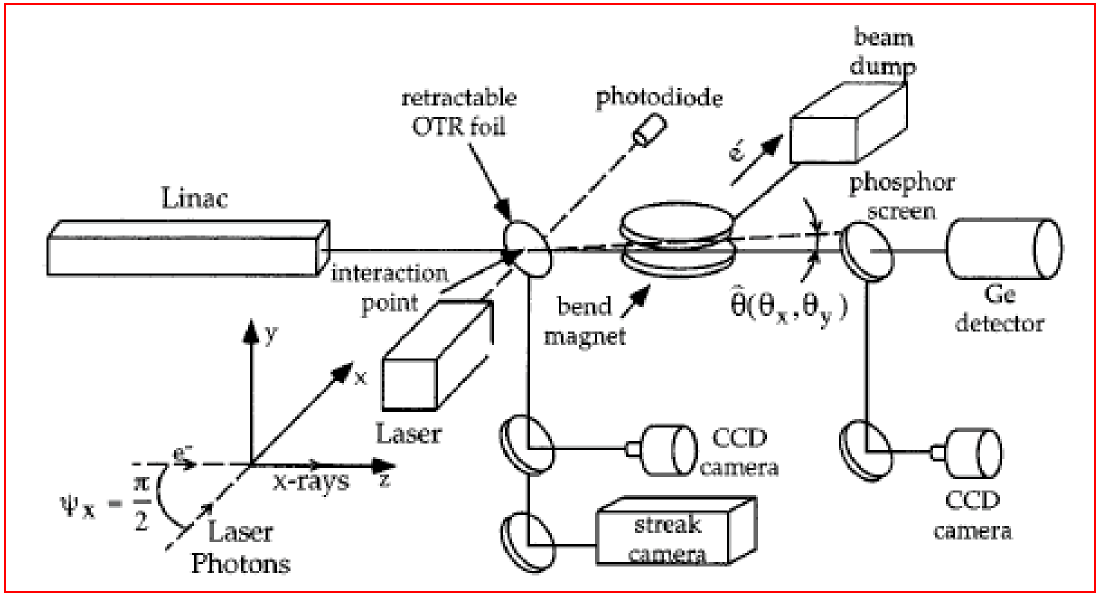


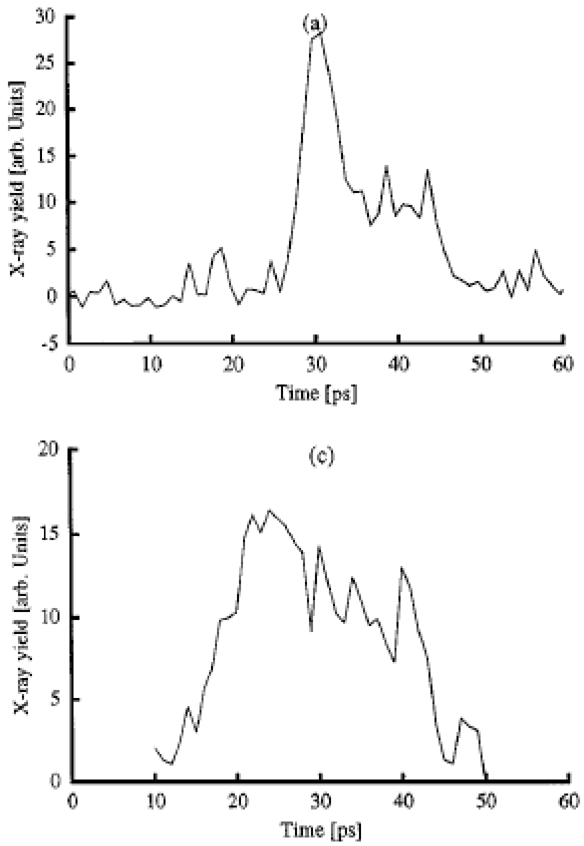
Detection system based on

- The measurement of the scattered photons
- The measurement of degraded electrons

Laser Wire Scanner – Compton scattering

ALS @ LBNL



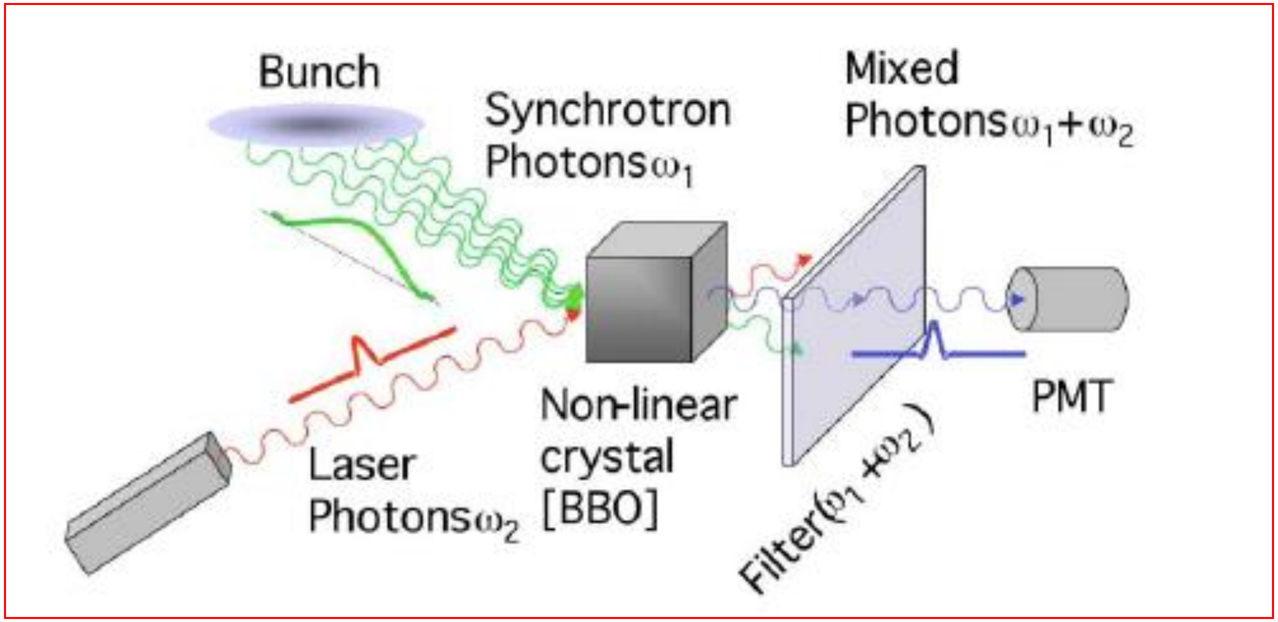


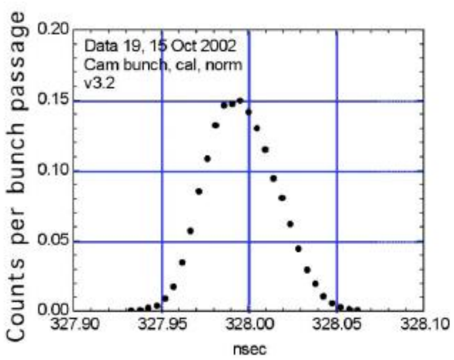
Using a 10TW Ti:Al_2O_3 laser system. Detecting 5.10^4 10-40 keV X-rays using either an X-ray CCD and Ge detector.

W.P. Leemans *et al*, PRL 77 (1996) 4182

Non linear mixing

'Non linear mixing uses beam induced radiation, which is mixed with a short laser pulse in a doubling non linear crystal (BBO,..). The resulting up frequency converted photons are then isolated and measured'





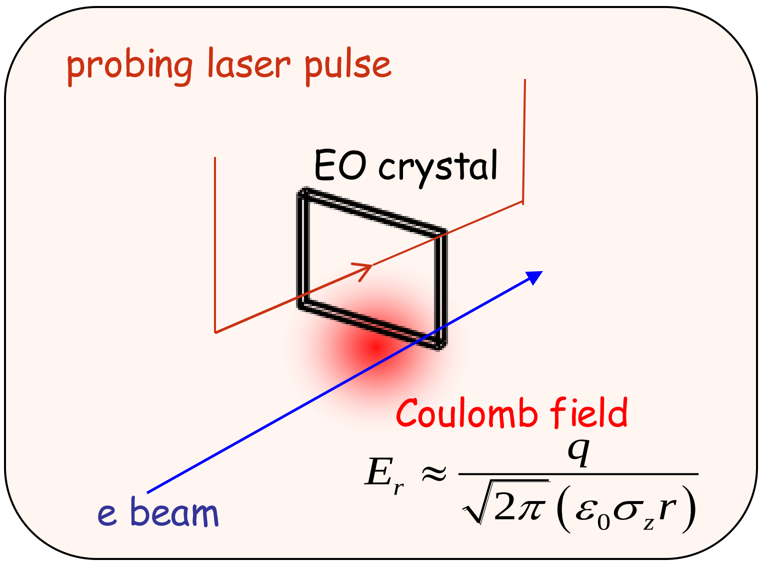
M. Zolotorev *et al*, **Proceeding of the PAC 2003, pp.2530**

15-30ps electron bunches (ALS, LBNL) scanned by a 50fs Ti:Al_2O_3 laser

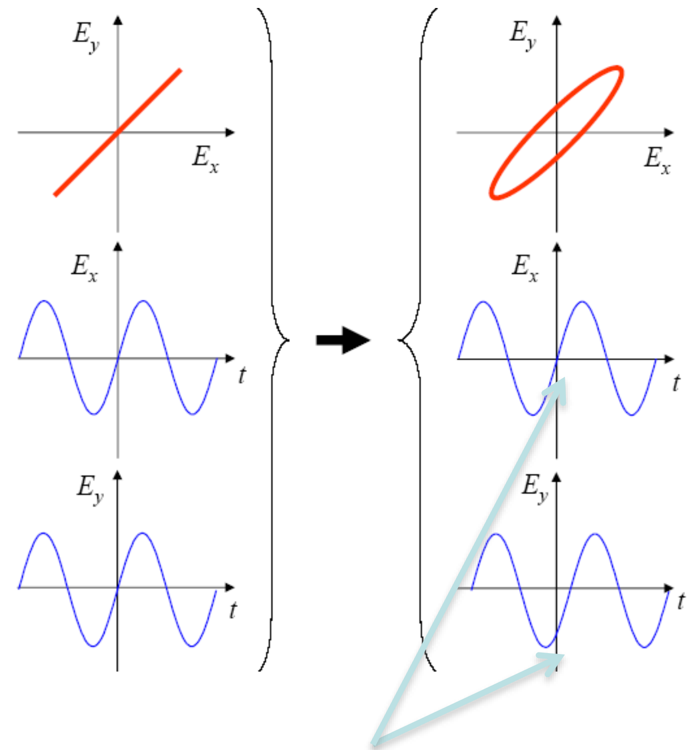
Electro Optic Sampling

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

E-field induced birefringence in EO-crystal : Pockels effect



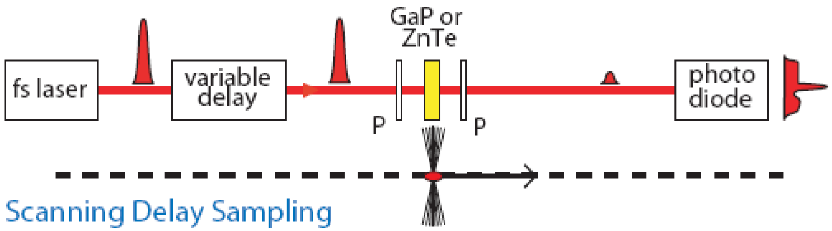
- Polarization diagram
- electric field of the horizontal polarization
- electric field of the vertical polarization



$$\Gamma = \frac{2\pi d}{\lambda_0}\left(n_x - n_y\right) = \frac{2\pi d}{\lambda_0} n_0^3 r_{41} E_r$$

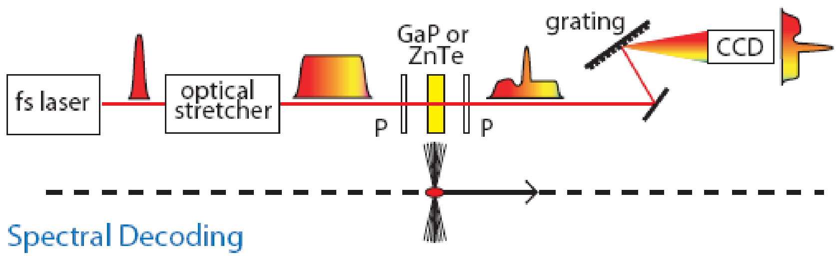
Relative phase shift between polarizations increases with the beam electric field

Electro Optic based bunch length monitors



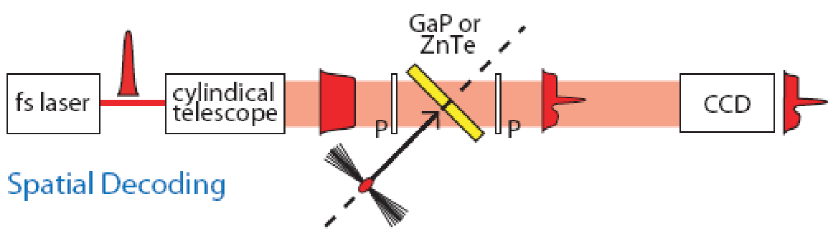
1. Sampling:
- multi-shot method
- arbitrary time window possible

1



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

Wilke *et.al*., PRL 88 (2002) 124801

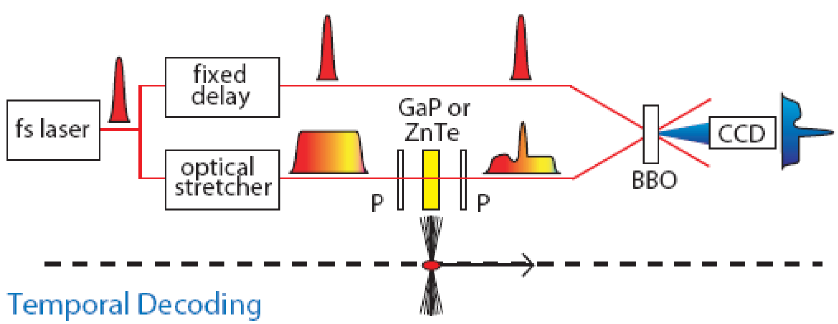


3. Spatial encoding:
- imaging limitation ~ 30-50 fs

Cavalieri *et. al*, PRL 94 (2005) 114801

Jamison *et. al*, Opt. Lett. 28 (2003) 1710

Van Tilborg *et. al*, Opt. Lett. 32 (2007) 313



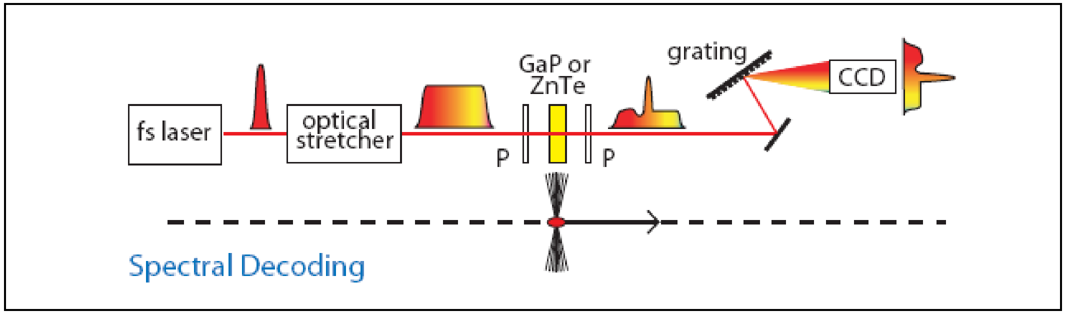
4. Temporal decoding:
- laser pulse length limited ~ 30fs

Berden *et.al*, PRL 93 (2004) 114802

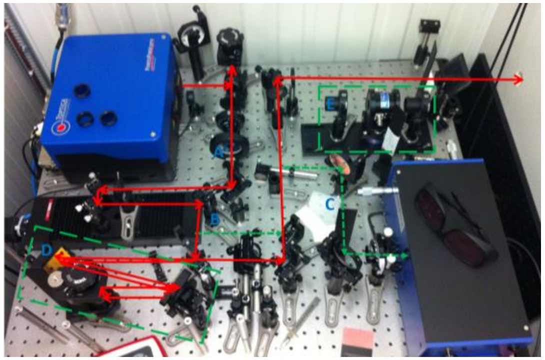
Electro Optic based bunch length monitors

Electro-**O**ptical **S**pectral **D**ecoding Technique

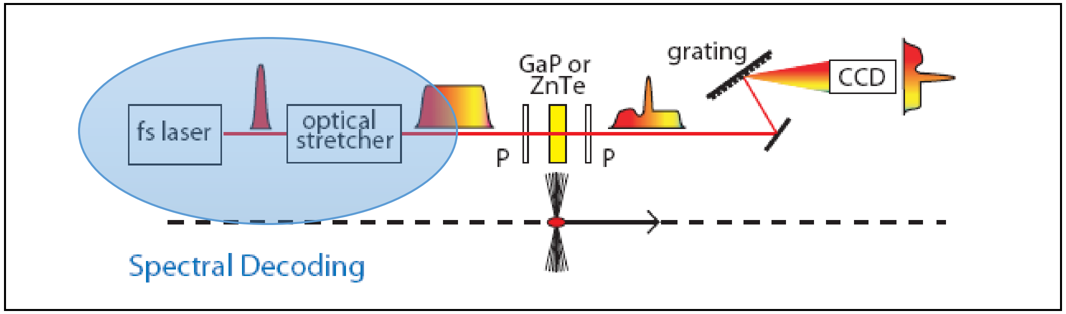
Single shot bunch length measurement



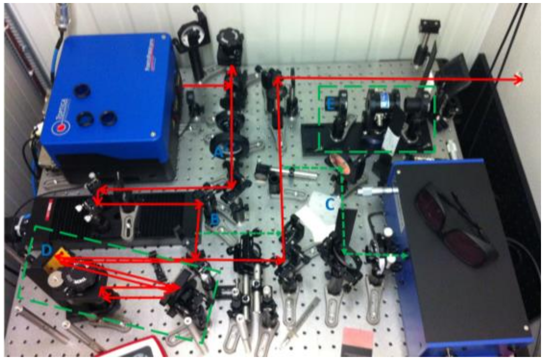
Electro Optic based bunch length monitors



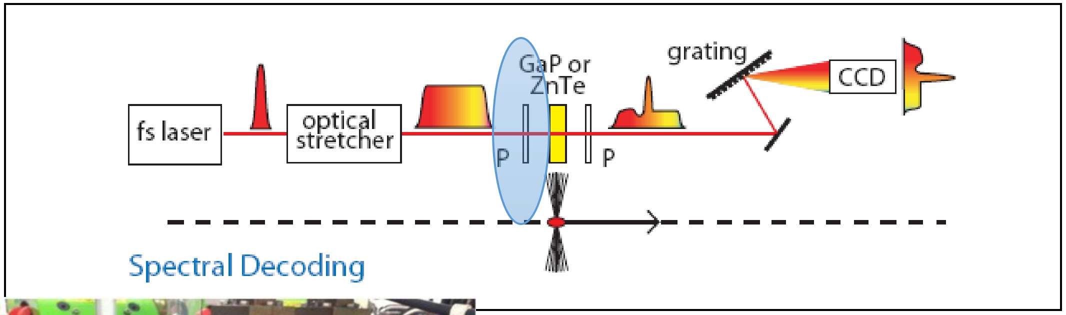
Er laser
780nm
150fs – 12ps

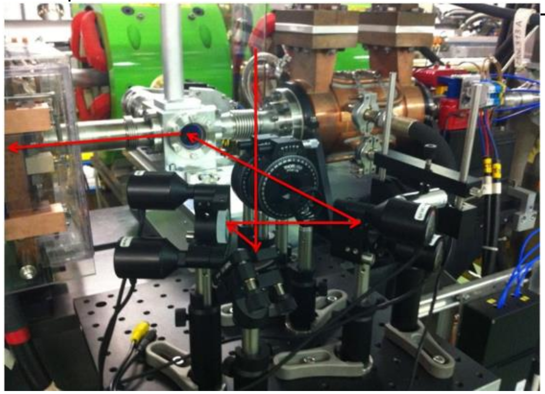


Electro Optic based bunch length monitors



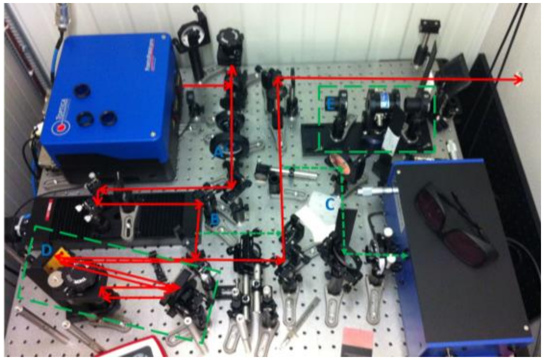
Er laser
780nm
150fs – 12ps





First polariser and Laser injection Chamber

Electro Optic based bunch length monitors



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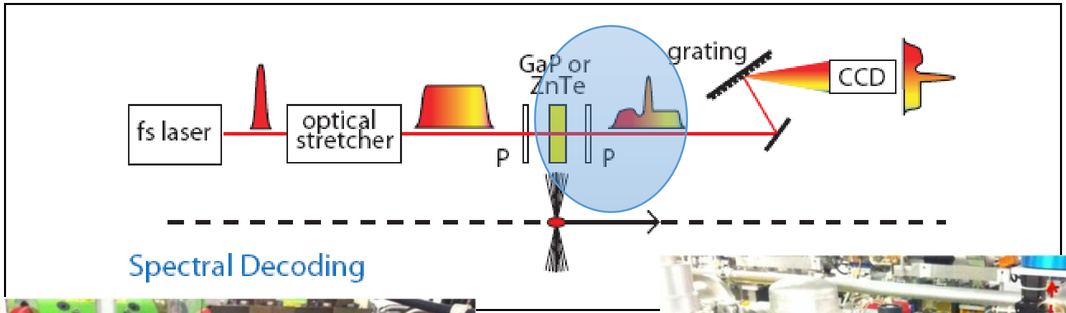

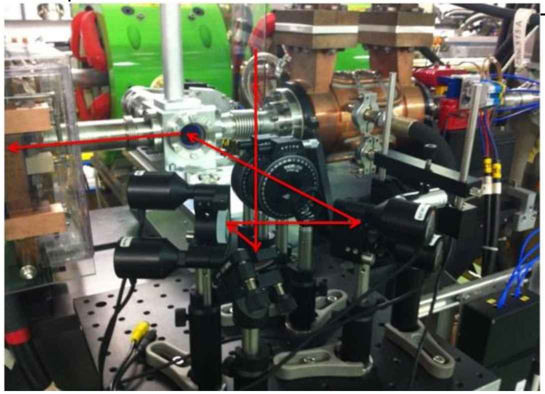

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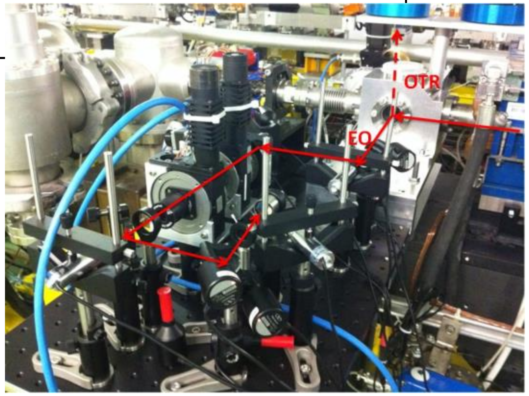
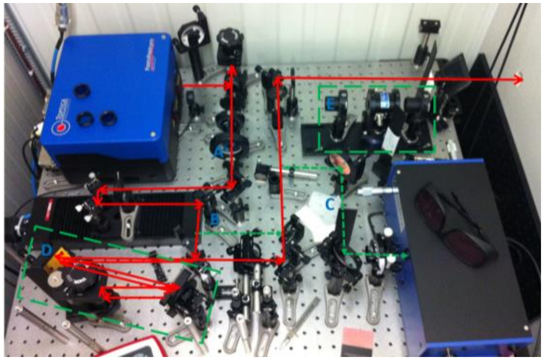


Crystal chamber (4mm ZnTe), crossed polariser and fiber coupling

Electro Optic based bunch length monitors



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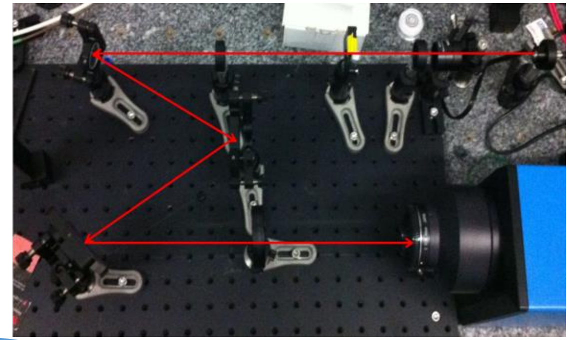
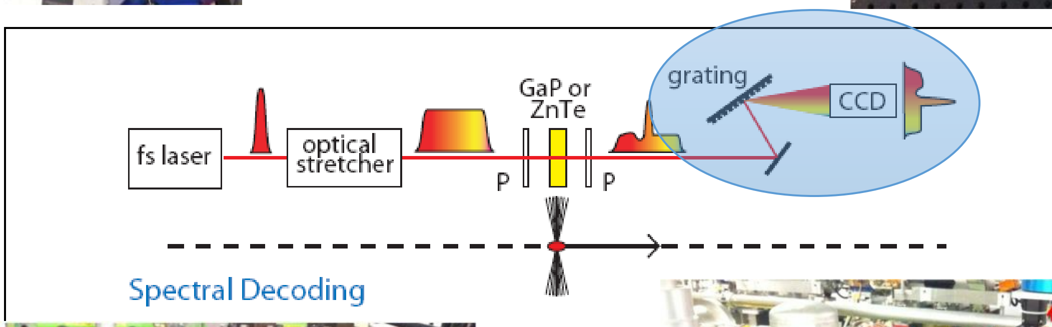
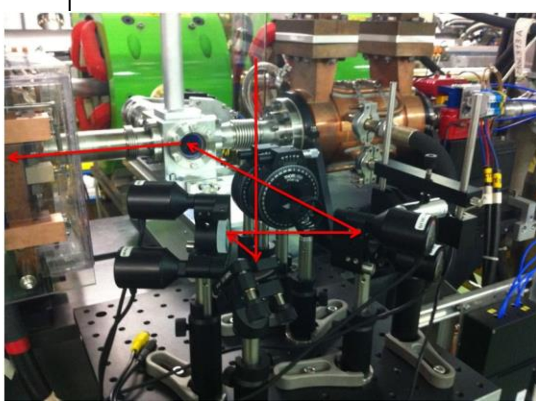
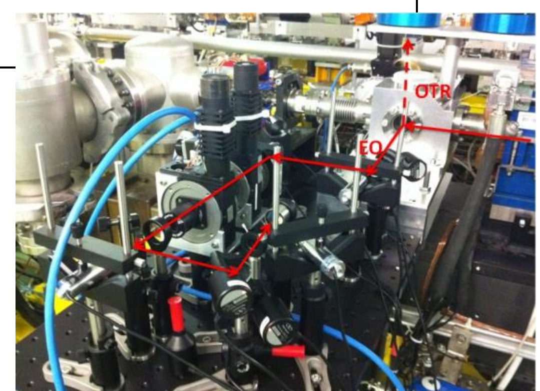


Spectrometer with grating and intensiifed gated CCD camera





First polariser and Laser injection Chamber



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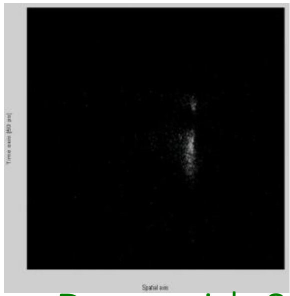
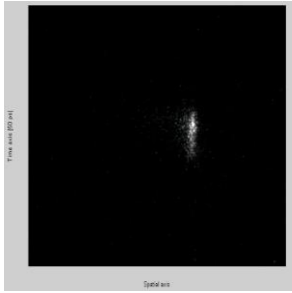
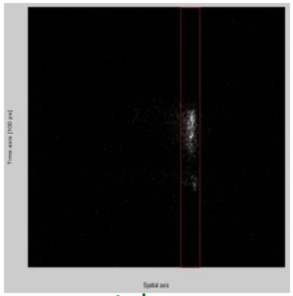
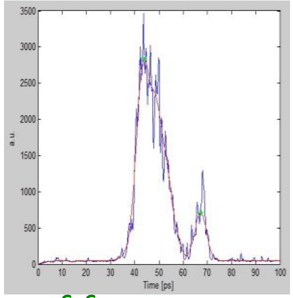
Electro Optic based bunch length monitors

1 – Laser-electron beam synchronization





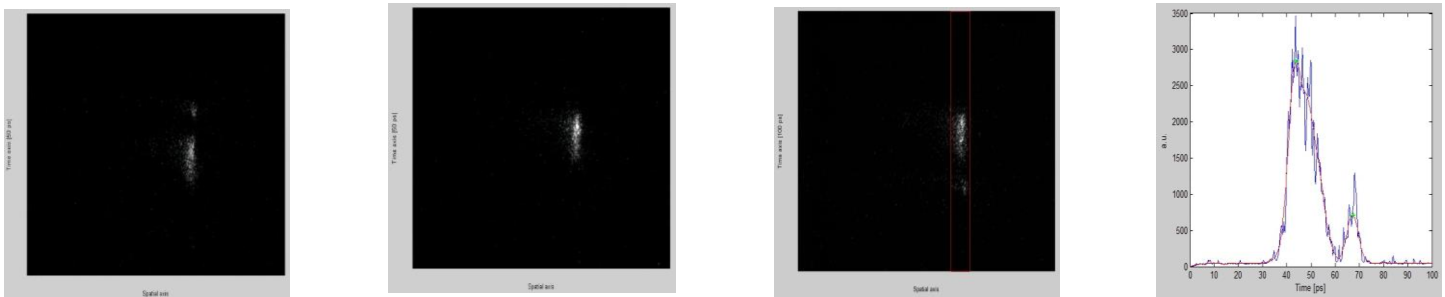




Done with Streak camera measurements with an accuracy of few ps

Electro Optic based bunch length monitors

1 – Laser-electron beam synchronization



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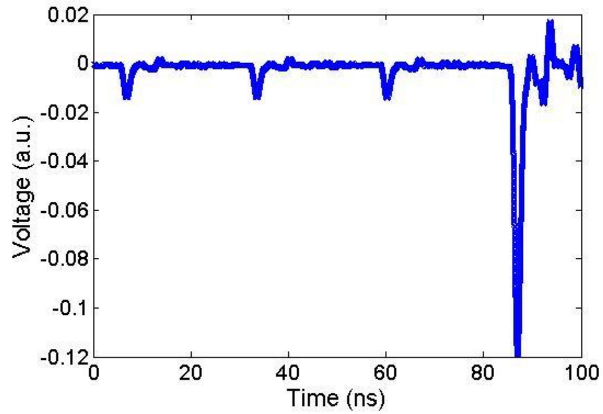
2 – EO measurements

- First optimizing the EO signal intensity using a PMT and scope

  The laser is pulsed every 26ns



Electro Optic based bunch length monitors

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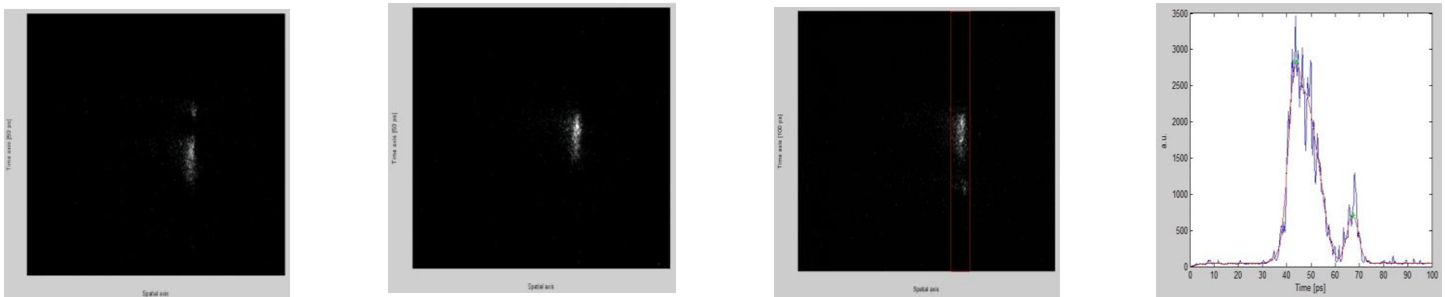

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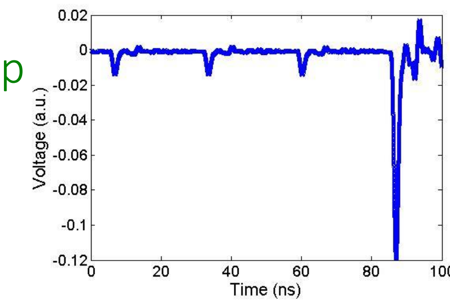
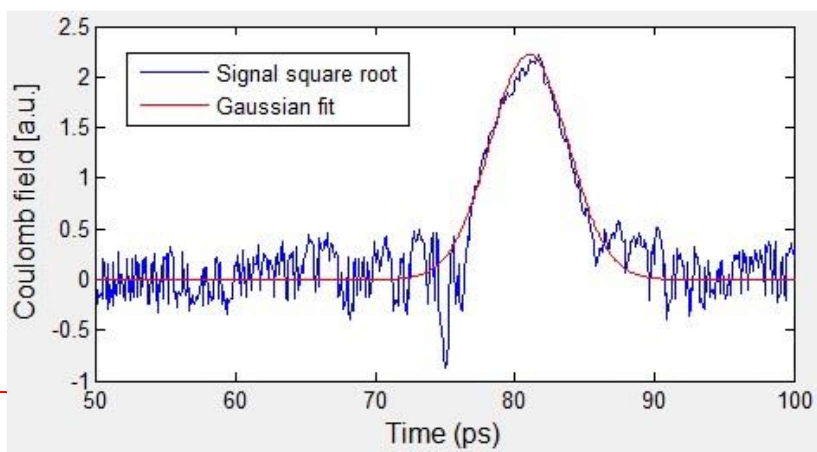
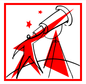
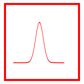


- Then measuring bunch length with spectrometer



- 6.6ps FWHM, 0.35nC bunch charge

Summary

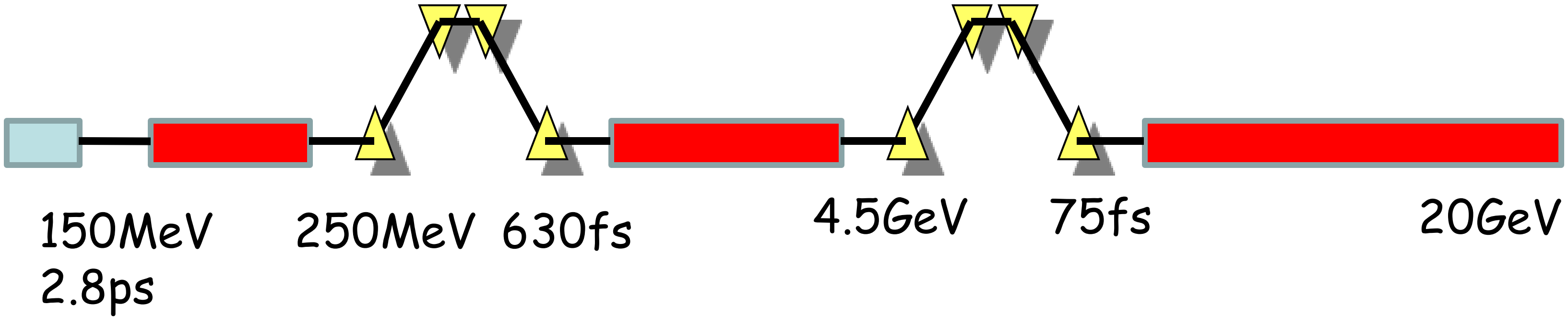
				σ	1	n!	Limitations
• Optical radiation							
• Cherenkov / OTR radiation		X					
• ODR / OSR Radiation	X						
• Streak camera			X				200fs
• Coherent radiation : Bunch spectrum							
• Interferometry				X		X	
• Polychromator				X	X		
• RF techniques							
• 'Feschenko' monitor	X		X		X		Hadron, 20ps
• RF Deflector		X	X		X		10fs
• Zero phasing techniques		X	X		X		10fs
• Laser based Method							
• Sampling						X	Jitter (50fs)
• Non linear mixing			X				
• Thomson/Compton scattering	X		X				Electron
• Photo-neutralization	X		X				H^-
• Electro-Optic Sampling	X		X				
• E-O Spectral decoding	X		X		X		~ 200fs
• E-O Spatial decoding	X		X		X		~ 50fs
• E-O Temporal decoding	X		X		X		~ 50fs

Exercise 6

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



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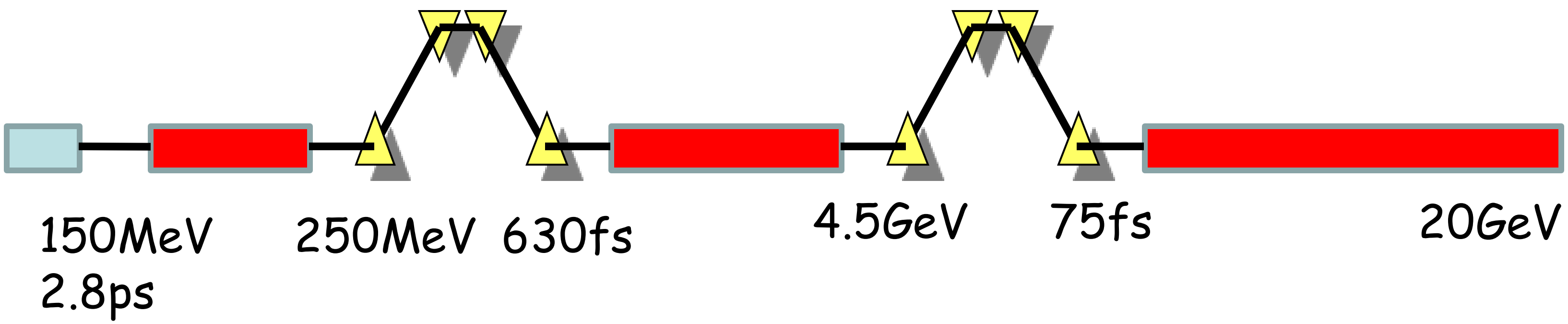
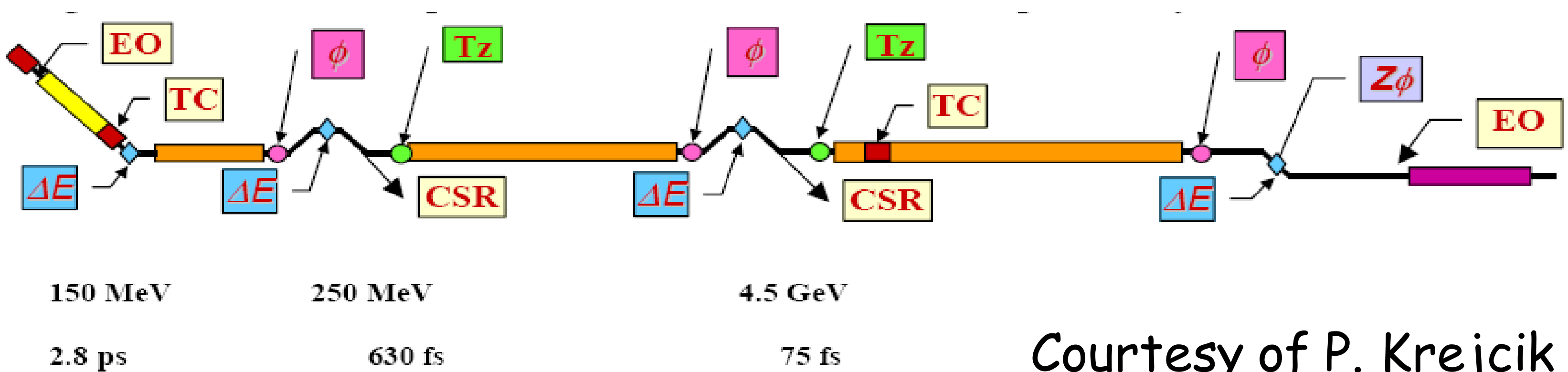


The streak camera works in the visible range and is limited to some 200fs. ODR requires high energy (some GeV) in order to be useful in the visible range (see Problem 2). So basically the ODR used with a streak camera is completely useless. You are fired !!

Exercise 6

LCLS Machine Schematic

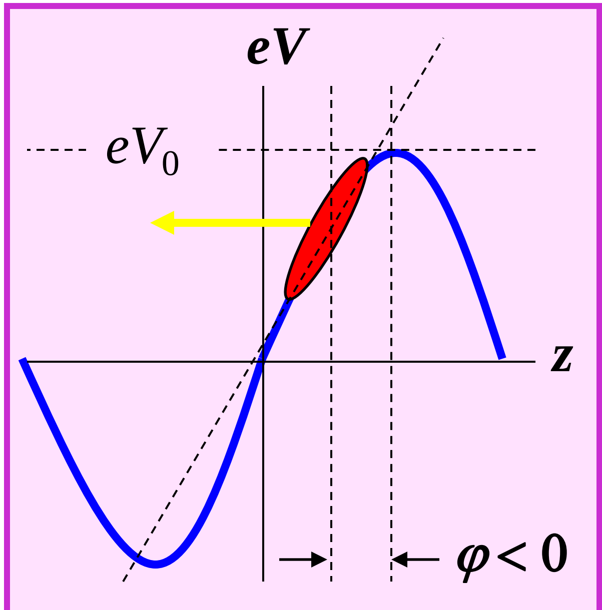


Courtesy of P. Krejcik

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).

Reserved Slides

Short bunches by Magnetic Compression



$$E(z) = E_0 + eV_0 \cos(\varphi + 2\pi z/\lambda)$$

$$\delta \equiv \frac{\Delta E}{E} \approx \quad \ldots$$

$$\delta_0 \frac{E_0}{E} + \left(1 - \frac{E_0}{E}\right)\left[\frac{\cos(\varphi + \Delta\varphi) - (2\pi z/\lambda)\sin(\varphi + \Delta\varphi)}{\cos(\varphi)} - 1\right]$$

$$k(\varphi) \equiv \frac{\partial \delta}{\partial z} = -\frac{2\pi}{\lambda}\left(1 - \frac{E_0}{E}\right)\frac{\sin(\varphi + \Delta\varphi)}{\cos(\varphi)} \qquad \text{'chirp'}$$

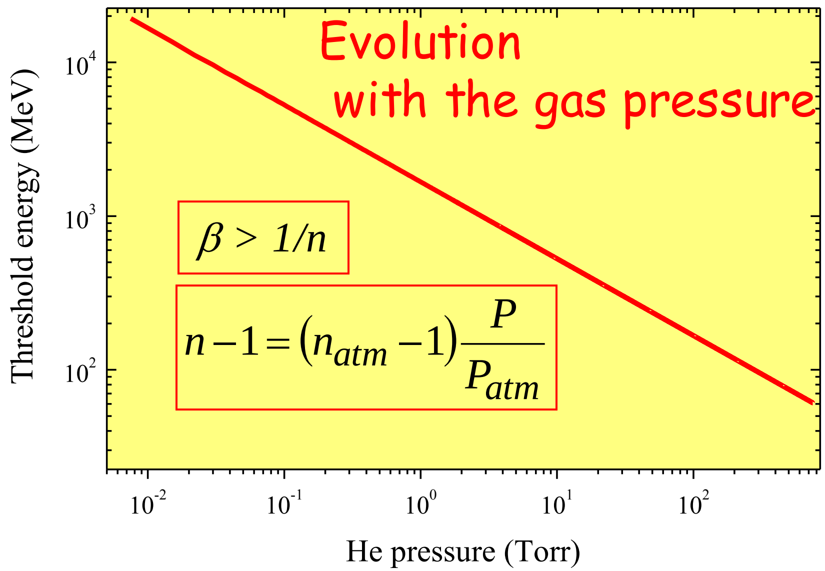
final bunch length and energy spread…

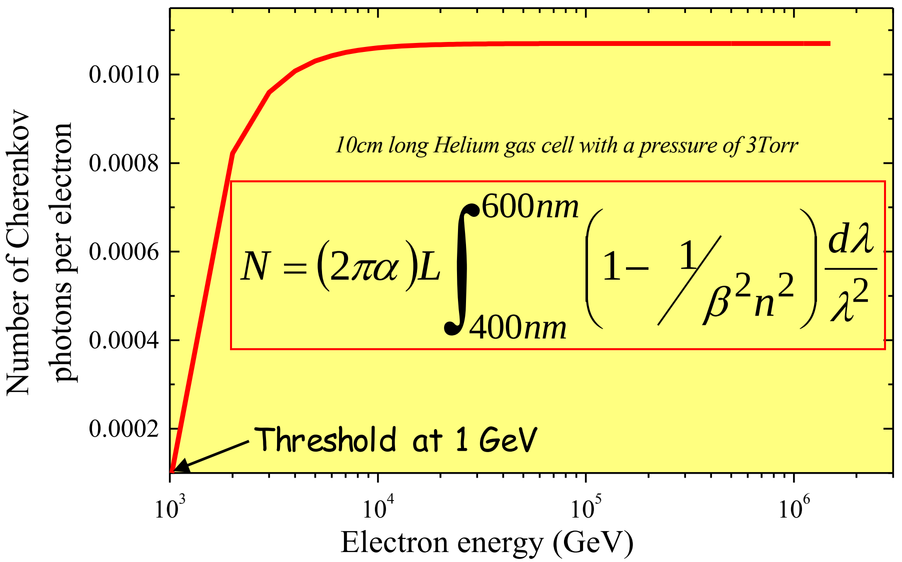
$$\sigma_z = \sqrt{(1 + kR_{56})^2 \sigma_{z0}^2 + R_{56}^2 \sigma_{\delta 0}^2 E_0^2/E^2} \quad , \quad \sigma_\delta = \sqrt{k^2 \sigma_{z0}^2 + \sigma_{\delta 0}^2 E_0^2/E^2}$$

Cherenkov in gases

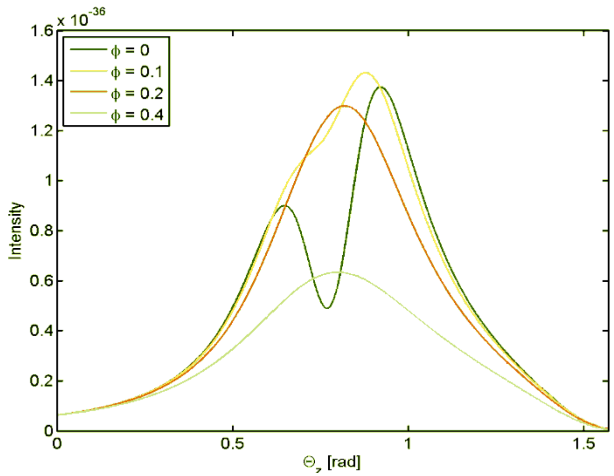
<u>Threshold Cherenkov detector :</u> $\beta > 1/n$

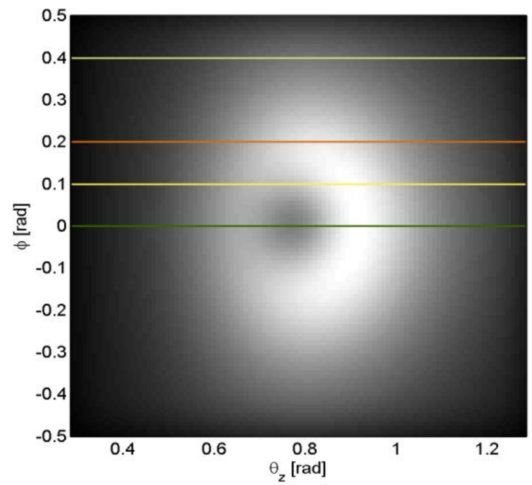
Cherenkov radiator (1atm)	Silica aerogel	Pentane C_5H_{12}	Ethane C_2H_6	Argon Ar	Neon Ne	Helium He
Index of refraction (n-1)	$8.4\ 10^{-3}$	$1.7\ 10^{-3}$	$7.1\ 10^{-4}$	$2.8\ 10^{-4}$	$6.7\ 10^{-5}$	$3.5\ 10^{-5}$
Cherenkov threshold (MeV)	3.5	8.2	13.1	20.9	43.5	60.4





Optical Transition Radiation





The angular intensity distribution is given by:

$$I_{//}=\frac{q^2}{\pi^2 c}\frac{\beta_z^2\cos^2\theta_z\left|1-\varepsilon\right|^2}{\left[(1-\beta_x\cos\theta_x)^2-\beta_z^2\cos^2\theta_z\right]^2\sin^2\theta_z}$$

$$\times\left|\frac{(1+\beta_z\sqrt{1-\sin^2\theta_z}-\beta_z^2-\beta_x\cos\theta_x)\sin^2\theta_z-\beta_x\beta_z\cos\theta_x\sqrt{1-\sin^2\theta_z}}{(1-\beta_x\cos\theta_x+\beta_z\sqrt{1-\sin^2\theta_z})(\sqrt{1-\sin^2\theta_z}+\varepsilon\cos\theta_z)}\right|^2$$

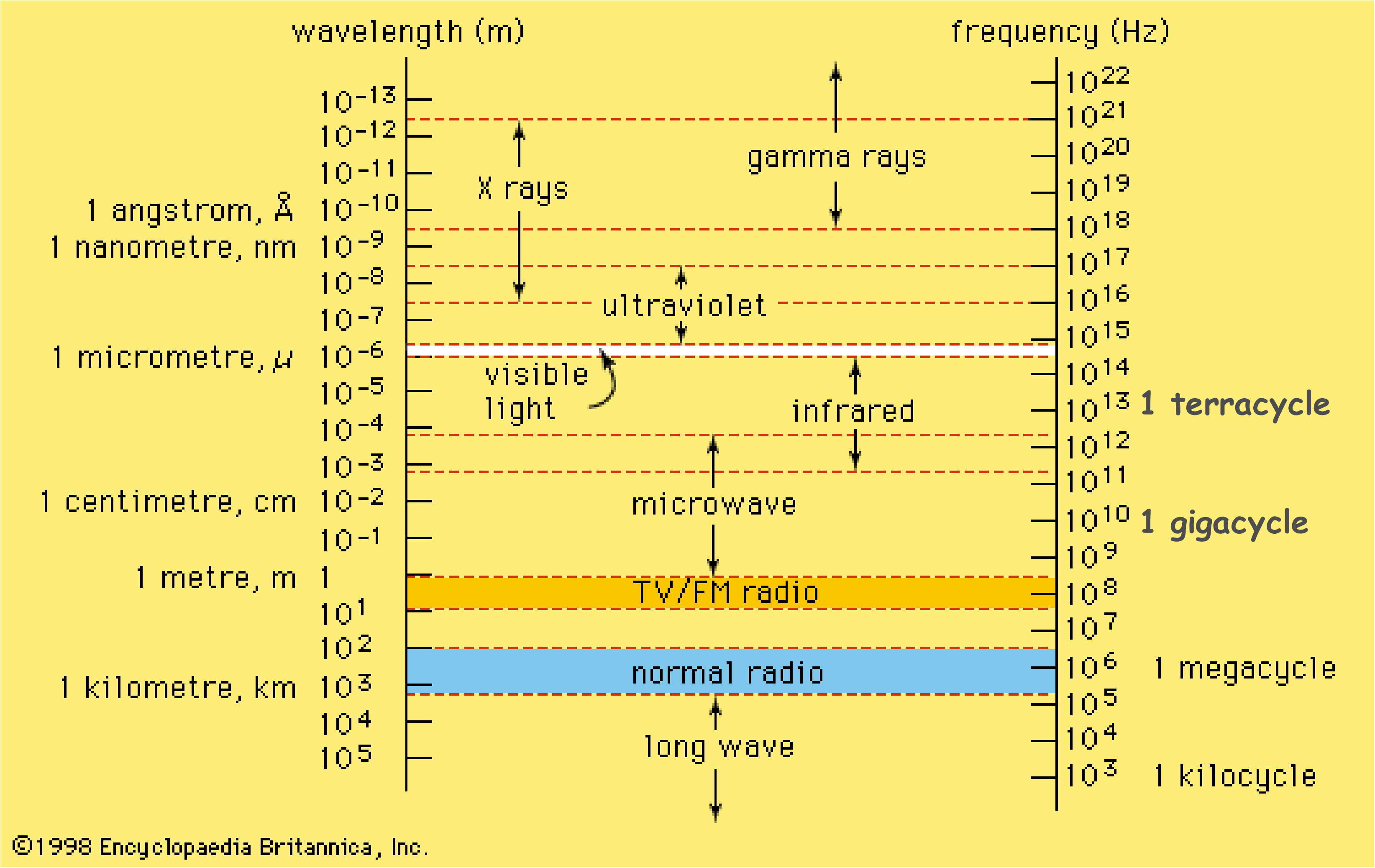
$$I_{\perp}=\frac{q^2}{\pi^2 c}\frac{\beta_x^2\beta_z^4\cos^2\theta_y\cos^2\theta_z\left|1-\varepsilon\right|^2}{\left[(1-\beta_x\cos\theta_x)^2-\beta_z^2\cos^2\theta_z\right]^2\sin^2\theta_z}$$

$$\times\frac{1}{\left|(1-\beta_x\cos\theta_x+\beta_z\sqrt{1-\sin^2\theta_z})(\sqrt{1-\sin^2\theta_z}+\cos\theta_z)\right|^2}$$

The actual angular intensity distribution becomes:

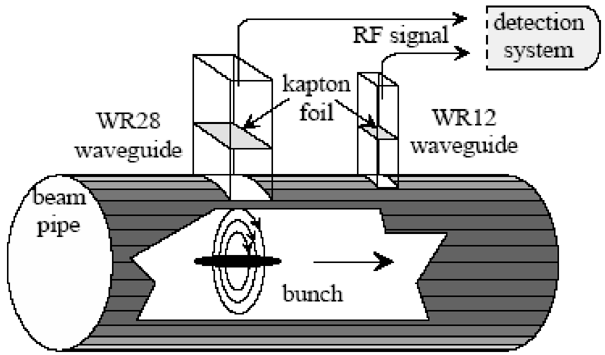
$$I(\theta_z,\phi)=\iint I_{OTR}(\theta_z-\alpha_1,\phi-\alpha_2)I_{beam}(\alpha_1,\alpha_2)d\alpha_1 d\alpha_2$$

Bunch Frequency Spectrum



Bunch frequency spectrum by RF Pick-up

σ



'Based on the measurement of the bunch spectrum which is picked-up by a rectangular waveguide coupled to the beam pipe'

1

• Simple diode detectors and fixed frequency filters

n!

• Use of RF mixers with a sweeping oscillator

By sweeping over some given frequency range, the frequency spectrum amplitude is measured

C. Martinez et al, **CLIC note 2000-020**

700fs bunch length on a 40MeV beam

Limitations :

• Sensitive to beam position and beam charge

• Limited to some 300-500fs bunch length (>170GHz)

Bunch frequency spectrum by RF Pick-up

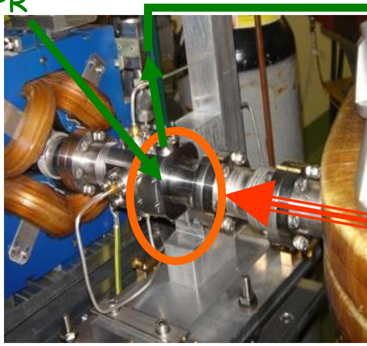
Filters, Horns and mixers

- Reflecting low pass filter - **4** frequency-band detection stages
- Series of 2 down mixing stages at each detection station.

Acqiris DC282 Compact PCI Digitizer

4 channels, 2 GHz bandwidth, 2-8 GS/s sampling rate

BPR



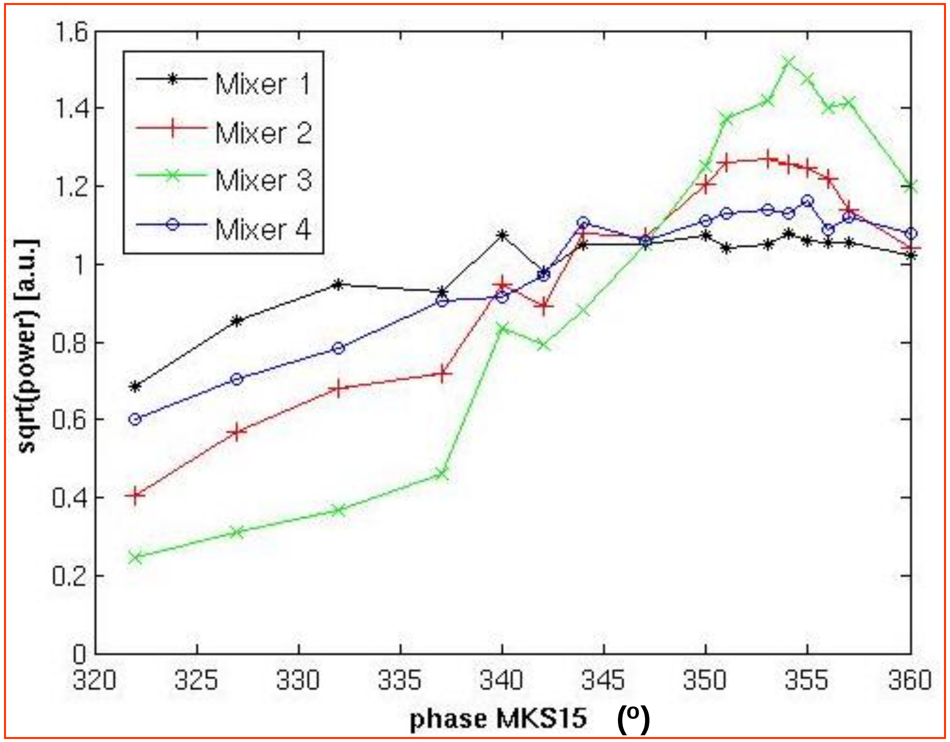
WR-28 Waveguide ~20m long

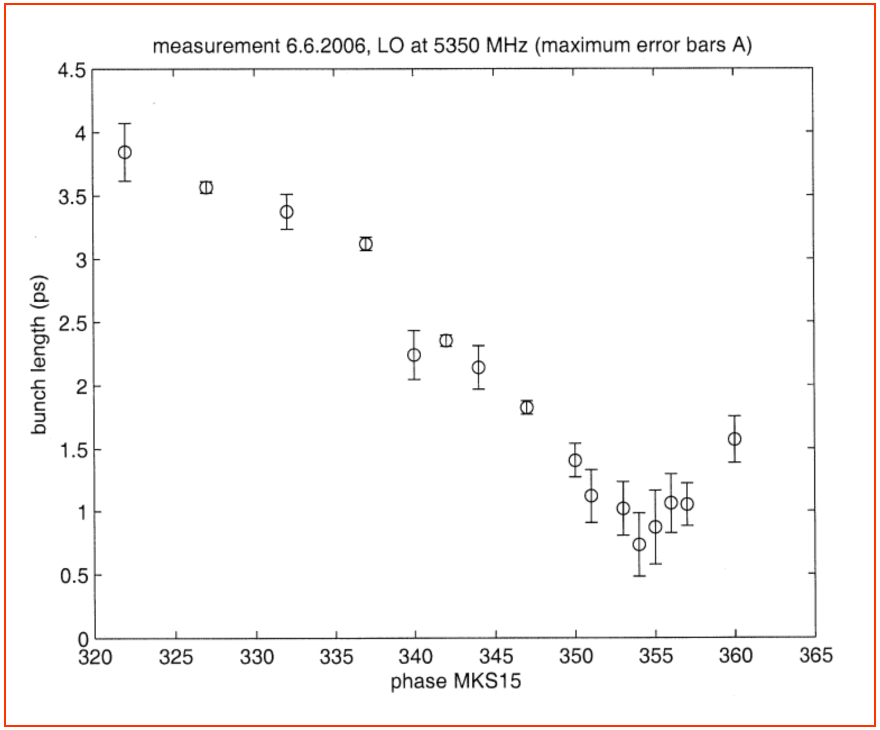
Beam

Data acquisition controlled by a Labview program, with built in Matlab FFT analysis routine

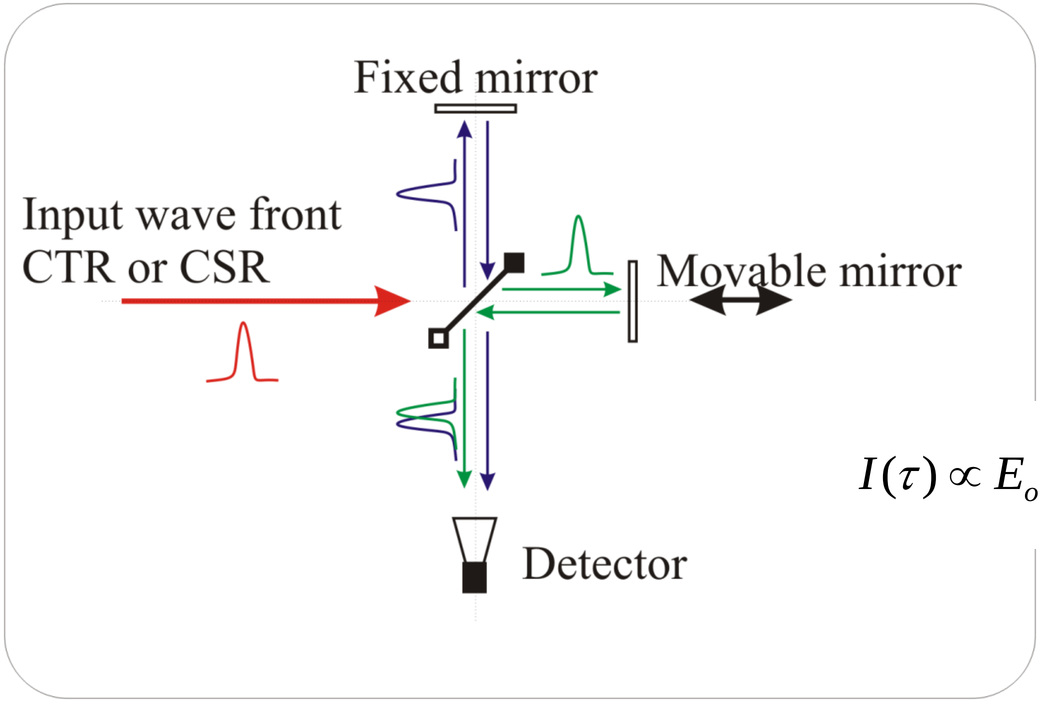
Bunch Frequency Spectrum by RF Pick-up

' Changing the phase of a klystron and measuring bunch compression on the pick-up '





Bunch Frequency Spectrum by Coherent Radiation



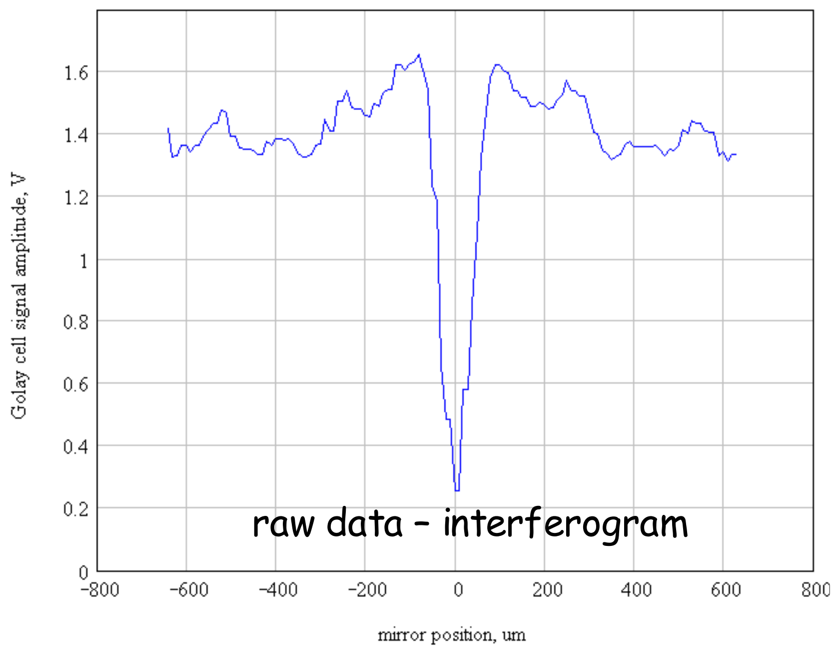
detectors measure intensity $I \propto E^2$

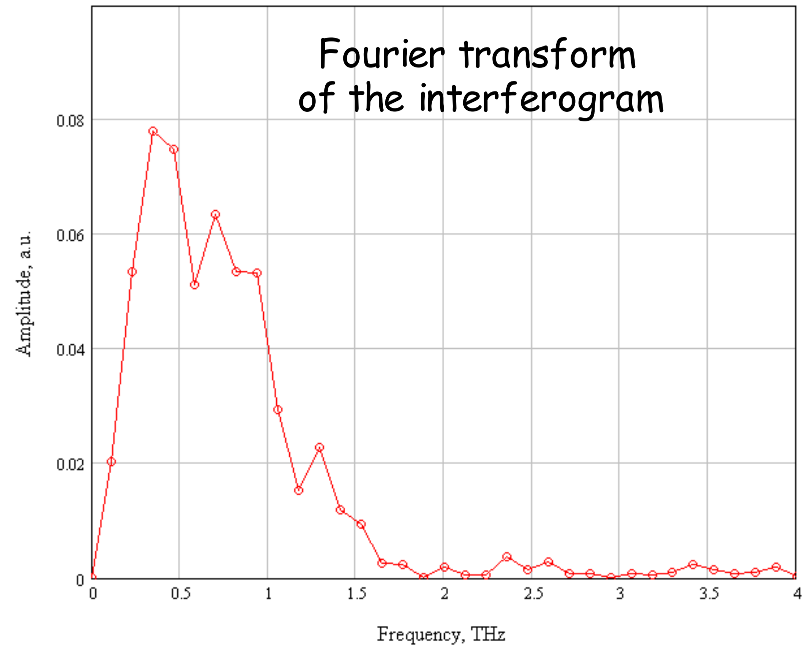
$$I(\tau) \propto E_o^{\ 2} T_\perp R_\parallel \int_{-\infty}^{+\infty} \left((g(t))^2 + g(t) g(t-\tau) \right) dt$$

the autocorrelation function is measured with the help of an interferometer

The Wiener-Khintchine theorem says:
"the Fourier transform of the autocorrelation function is the power spectrum".

Bunch Frequency Spectrum by Coherent Radiation





- the Gaussian shape of the bunch is assumed

$$n(t) = \frac{Q}{c\sigma_t\sqrt{2\pi}} e^{-\left(\frac{t}{\sigma_t\sqrt{2}}\right)^2}$$

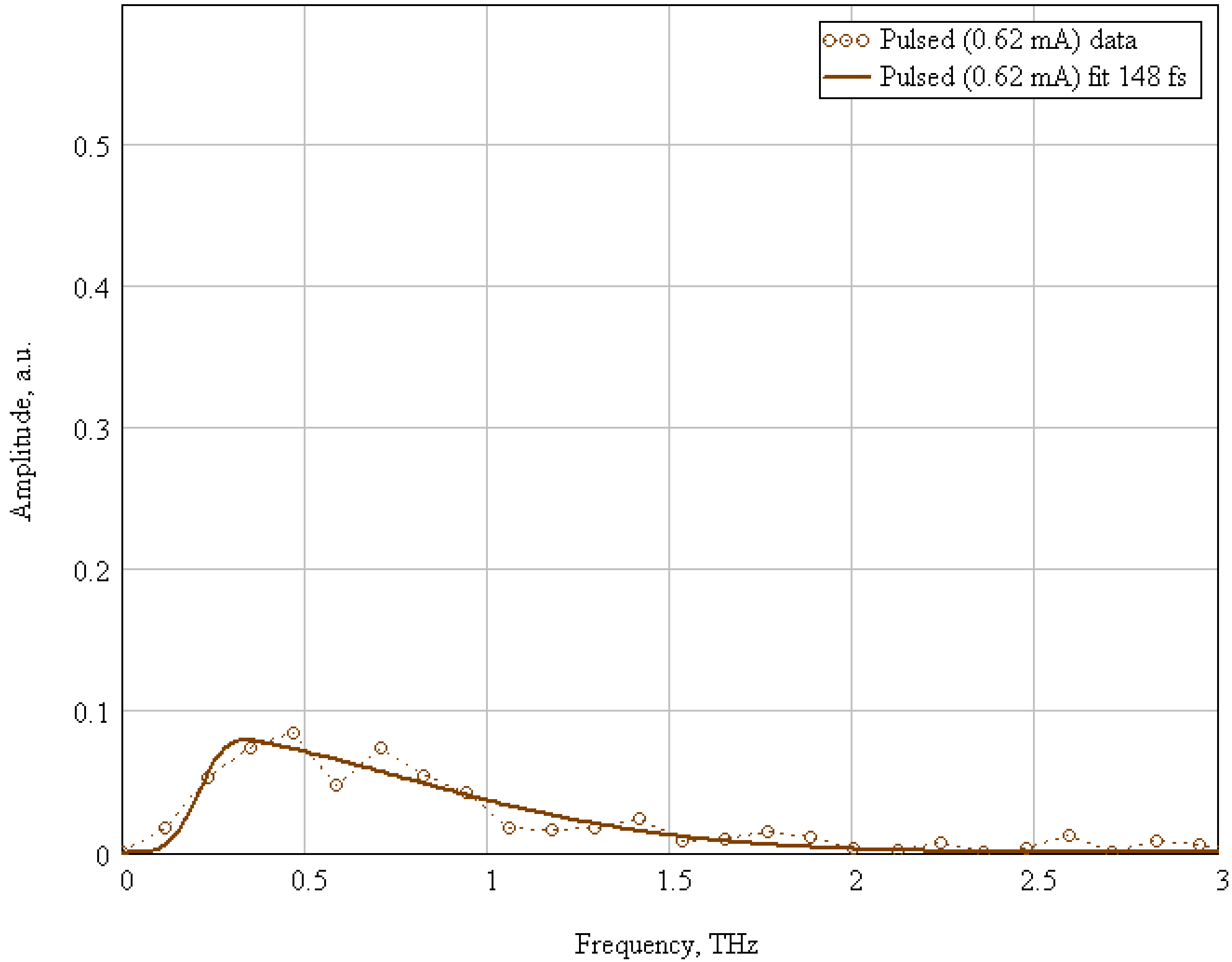
- its power spectrum is also Gaussian

$$\tilde{P}(\omega) = C\, e^{-(\omega\sigma_t)^2}$$

- The fit function is used

$$f_{fit}(\omega) = \left(1 - e^{-(\omega/\omega_0)^4}\right) C\, e^{-(\omega\sigma_t)^2}$$

Bunch Frequency Spectrum by Coherent Radiation



RF by Deflecting Cavity

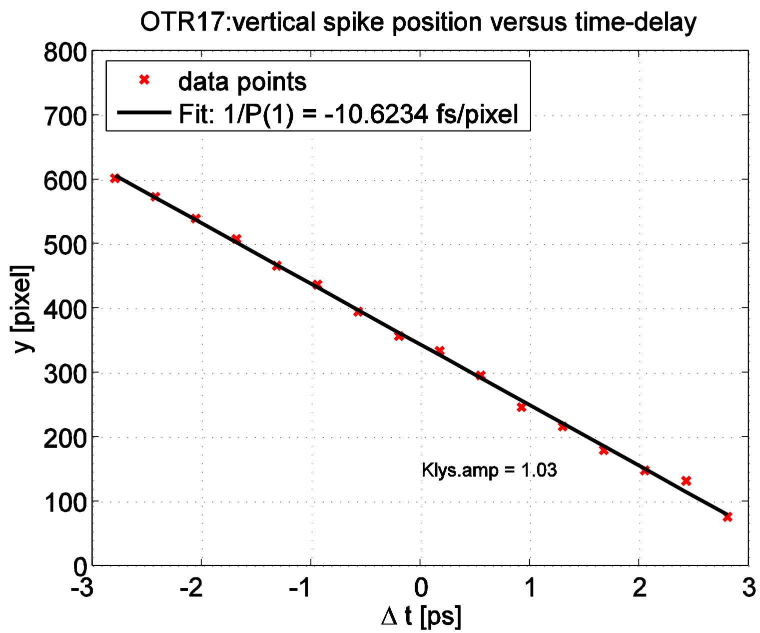
Calibration curves @ Flash

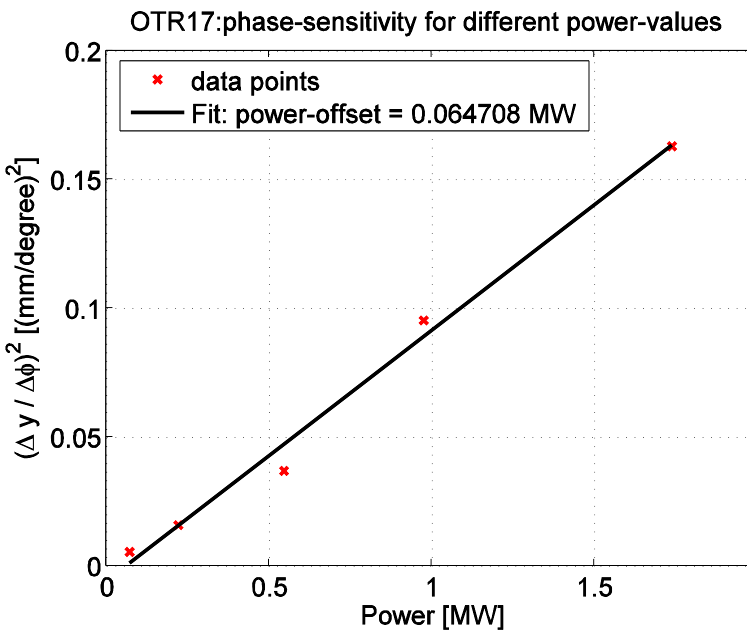
- For fixed power: measurement of the vertical beam position for different phases ϕ

$$\Delta y \approx const \cdot \phi, \quad \phi = \omega_{LOLA} \cdot \Delta t$$

- For arbitrary power:

$$\frac{\Delta y}{\Delta t} = const \cdot \sqrt{P_0}$$



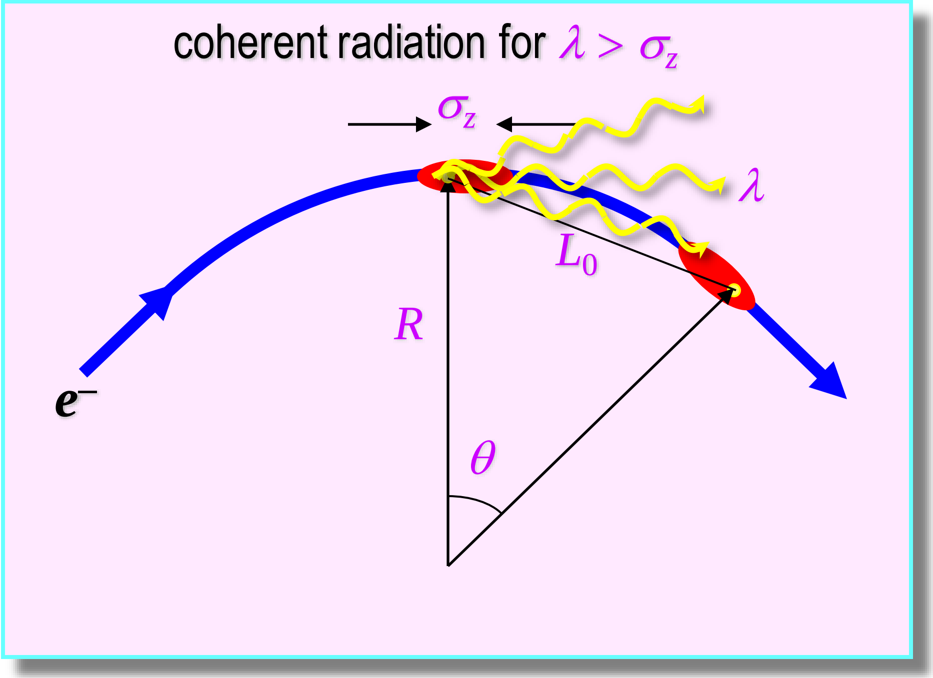


“When you are courting a nice girl an hour seems like a second. When you sit on a red-hot cinder a second seems like an hour. That's relativity. “

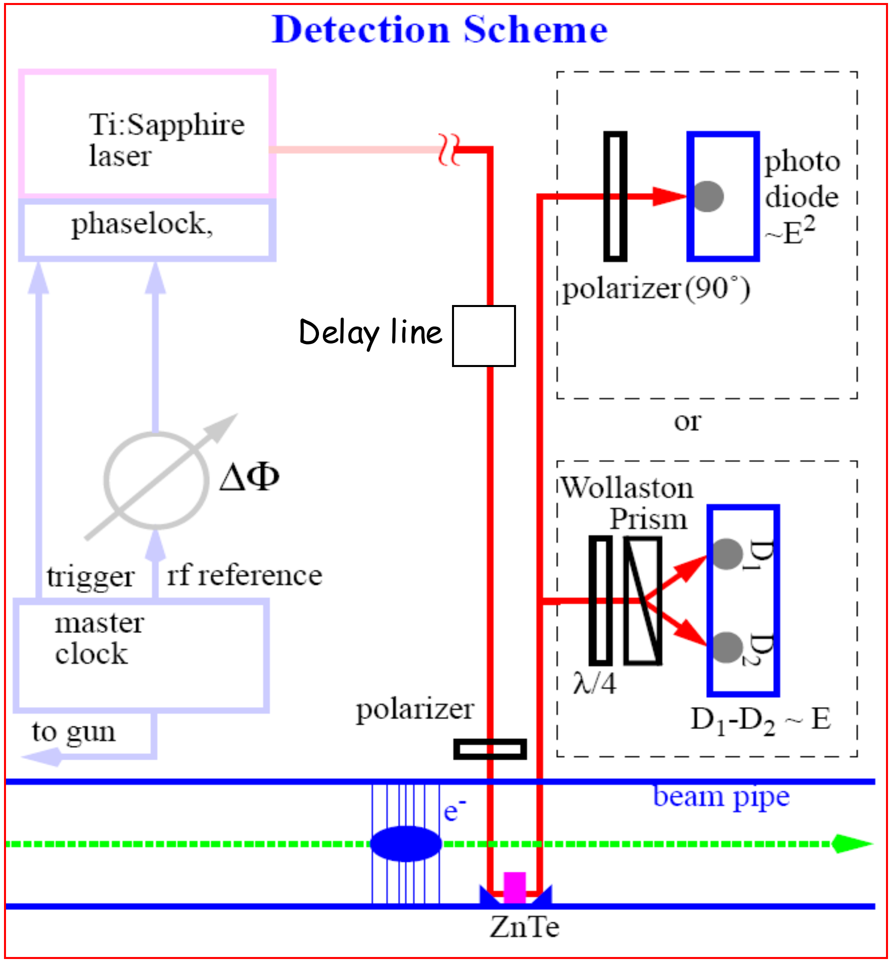
Albert Einstein

Coherent Synchrotron Radiation in Magnetic Chicane

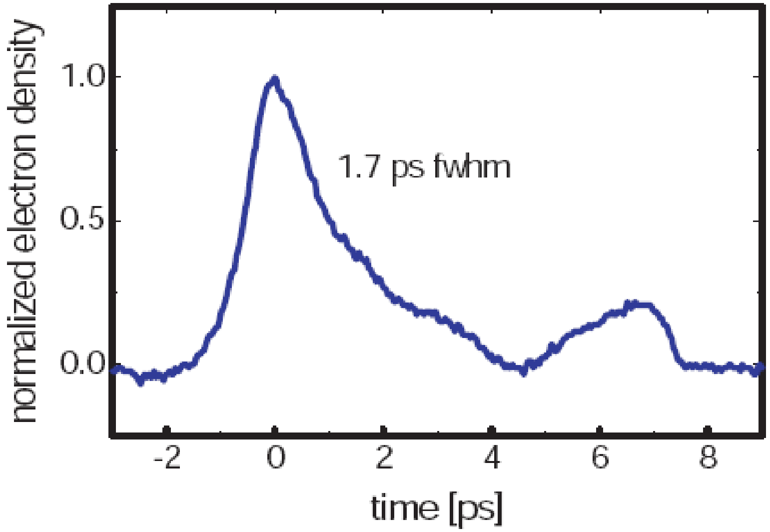
- Powerful radiation generates energy spread in bends
- Energy spread breaks achromatic system
- Causes emittance growth (short bunch worse)



Electro Optic Sampling



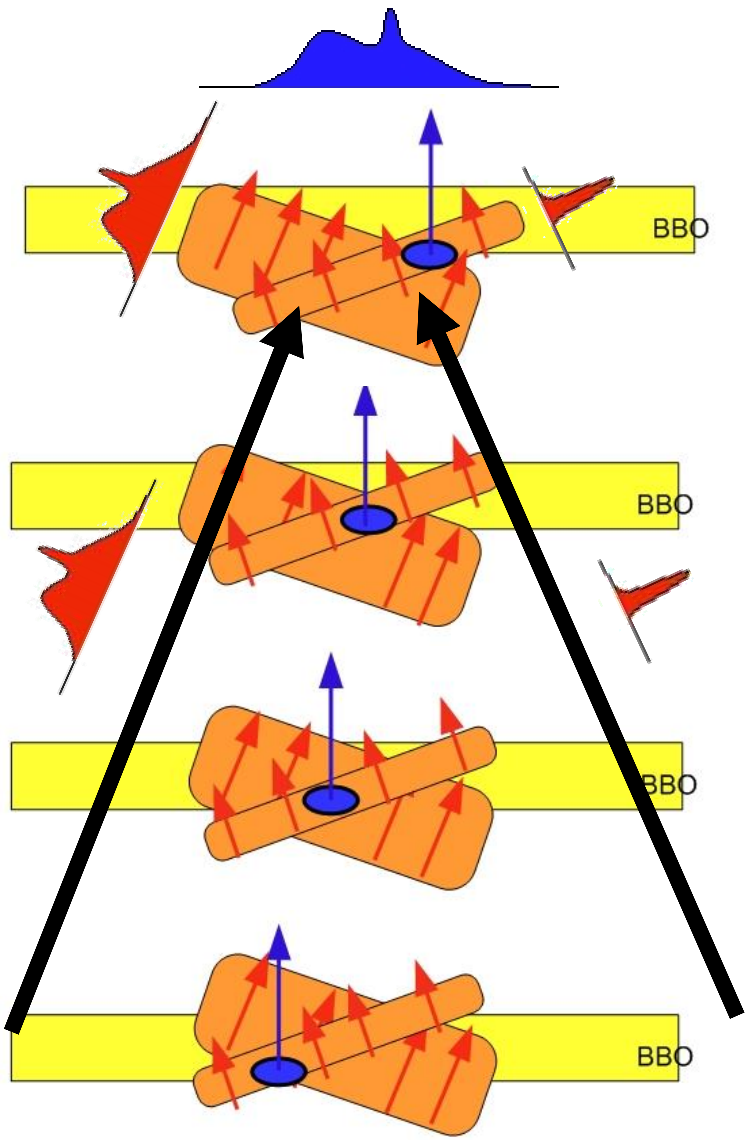
EOS @ FELIX

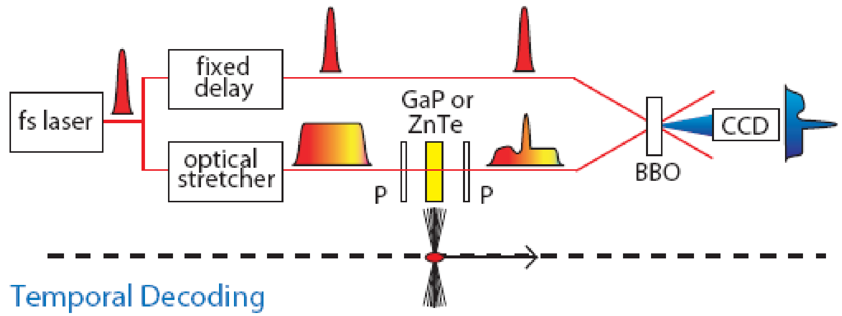


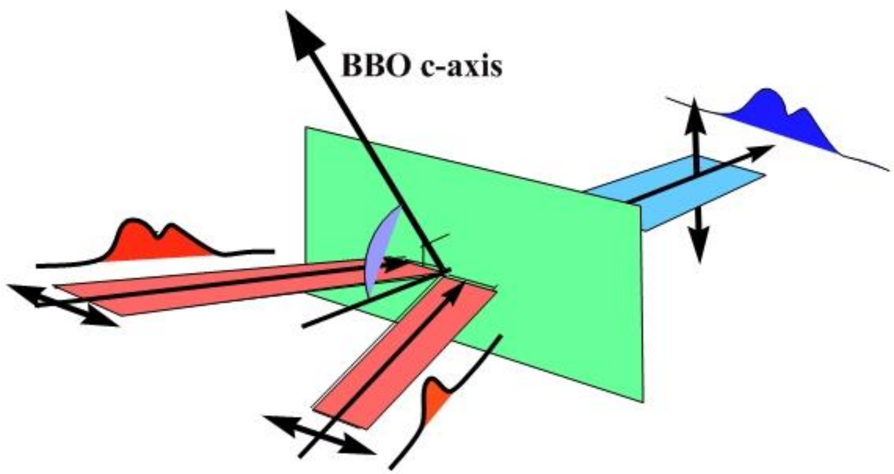
Using 12fs Ti:Al2O3 laser at 800nm and ZnTe crystal 0.5mm thick and a beam of 46MeV, 200pC, 2ps.

X. Yan *et al*, PRL 85, 3404 (2000)

Electro Optic Temporal decoding







Courtesy: S. Jamison et al.