Longitudinal Beam Profile part 1

T. Lefevre, CERN

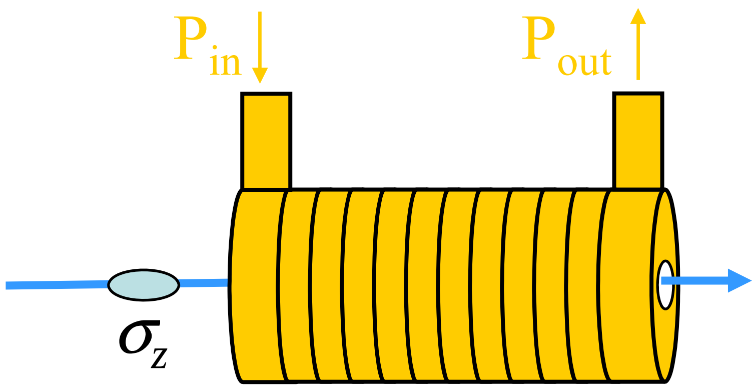
- Longitudinal beam profile in Accelerators
- Bunch compression scheme
- Bunch Length measurement techniques

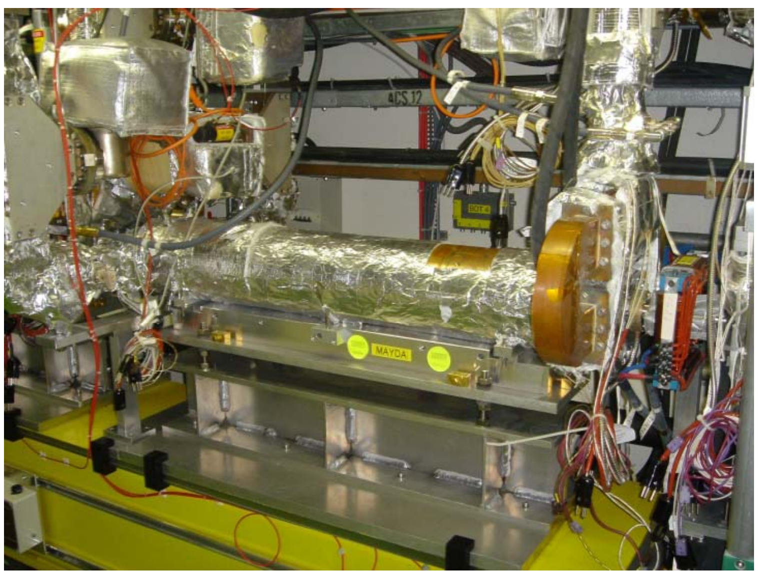
"When you are courting a nice girl an hour seems like a second. When you sit on a red-hot cinder a second seems like an hour. That's relativity. "

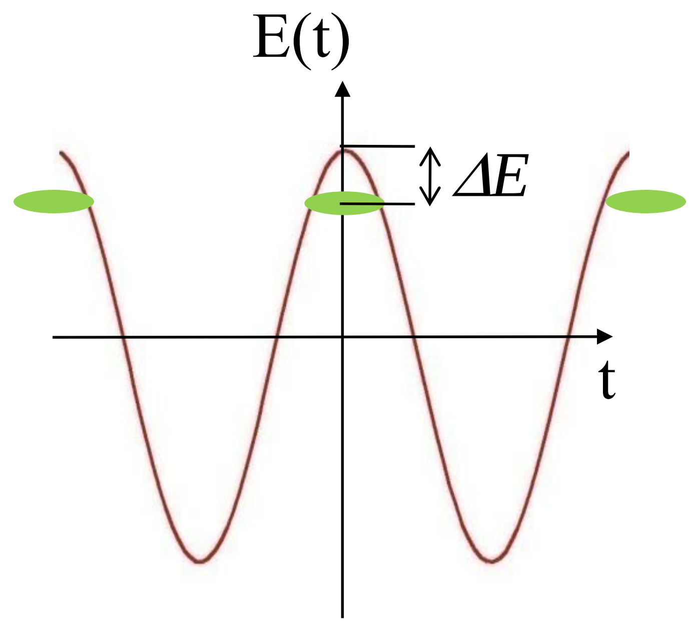
Albert Einstein

Longitudinal profile in accelerators

3GHz accelerating structures







At 3GHz

1 period = 333ps : Bunch spacing
1deg = 925fs : Bunch length

Longitudinal profile in accelerators

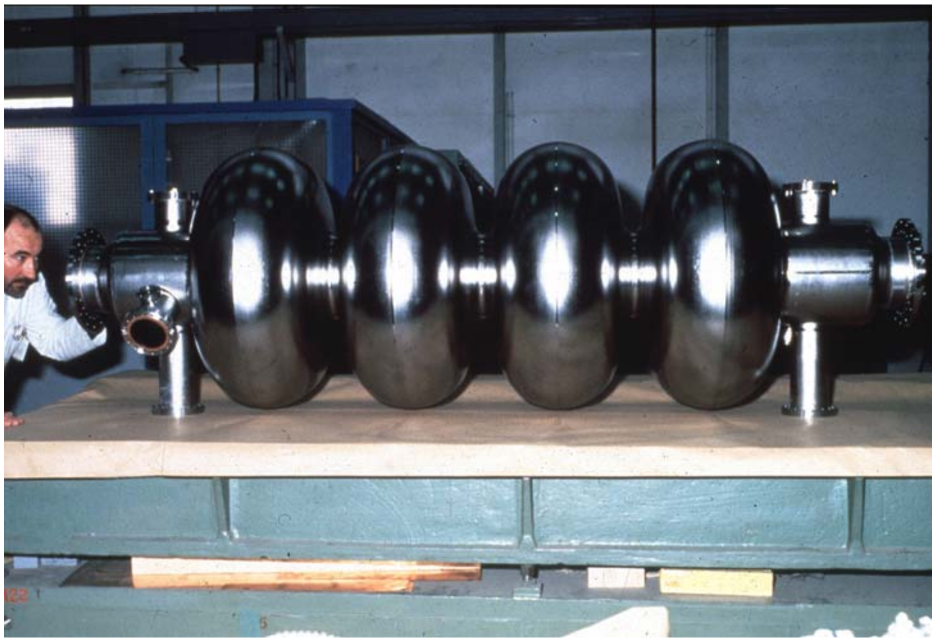
• Develop machine with the aim to improve luminosity for a linear collider or brightness for a radiation source or neutron source

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

• Short pulse to resolve fast phenomenon

- Femto Chemistry : Pump probe experiment – diffraction dynamics
- Nanoscale Dynamics in Condensed matter using Coherent scattering techniques
- Plasma and Warm dense Matter ; Astrophysical and weapons related studies
- Structure Studies on Single Particles and Biomolecules
- ….

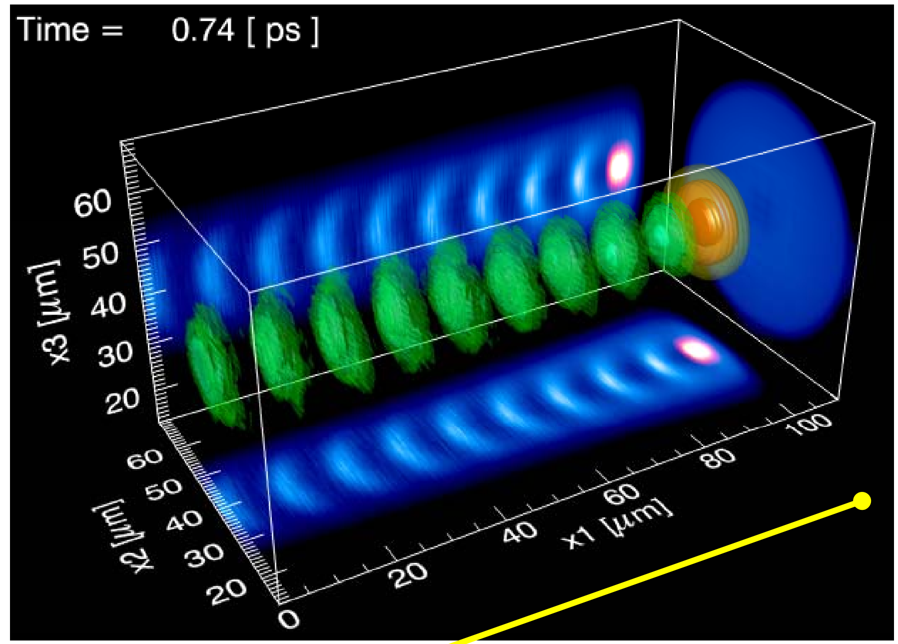
What is the next frontier ?



1 m

RF cavity

Courtesy of W. Mori & L. da Silva

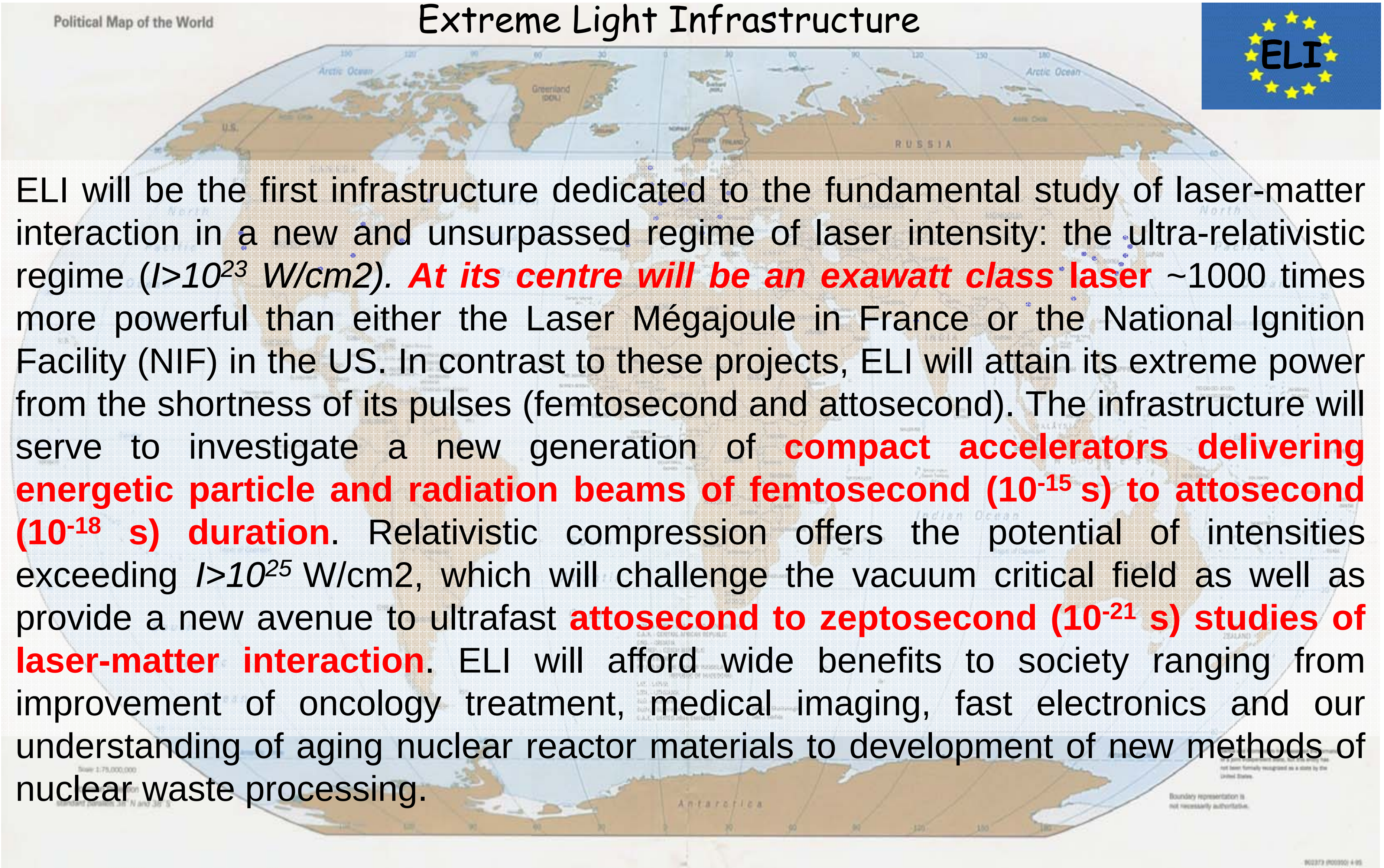


100 μm

Plasma cavity

What is the next frontier ?

Extreme Light Infrastructure

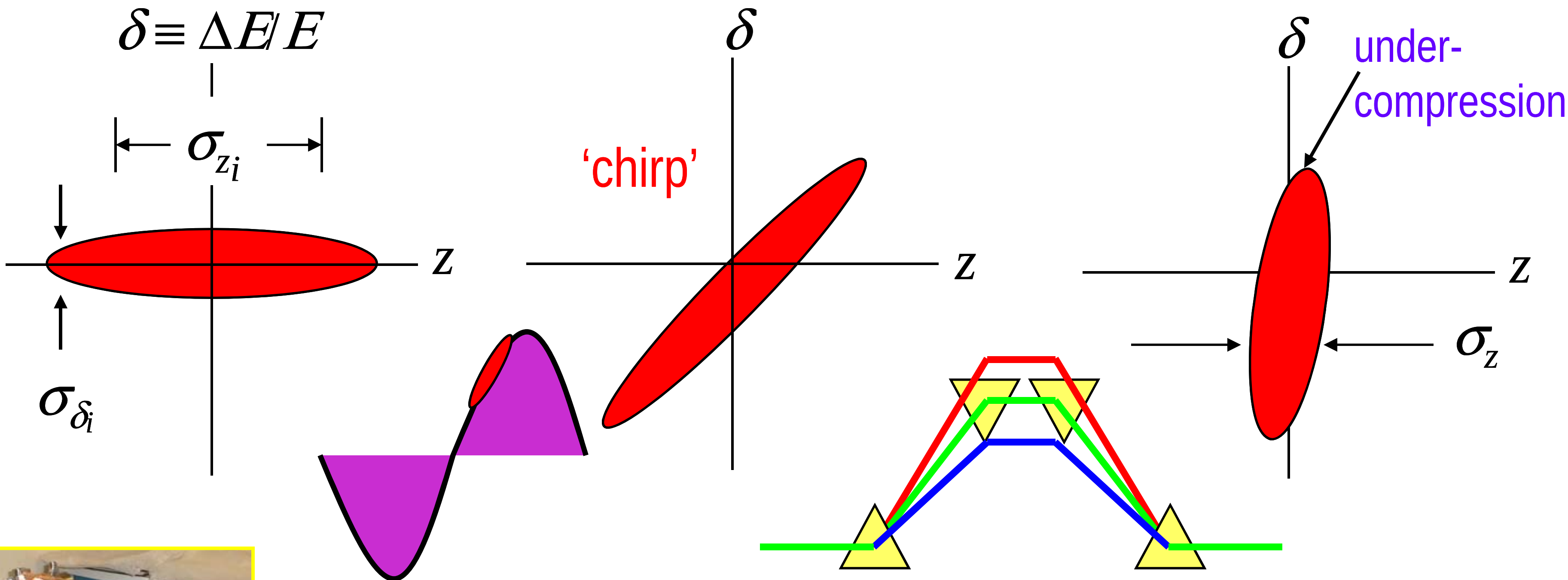


ELI will be the first infrastructure dedicated to the fundamental study of laser-matter interaction in a new and unsurpassed regime of laser intensity: the ultra-relativistic regime (*I*>10^{23} *W/cm2*). ***At its centre will be an exawatt class*** **laser** ~1000 times more powerful than either the 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

- Magnetic Compression
- Ballistic Compression

Short bunches by Magnetic Compression



$$V = V_0 \sin(kz)$$

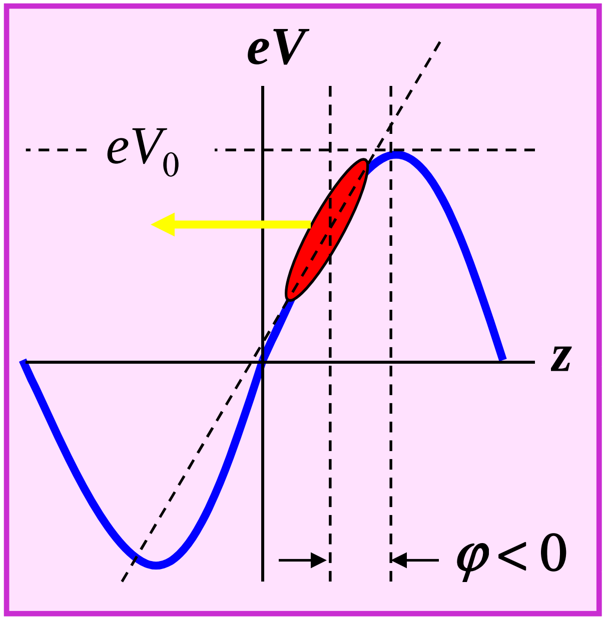
$$\Delta z = R_{56}\delta$$

RF Accelerating Voltage

Path-Length Energy-Dependent Beamline

ΔT → ΔE → ΔX → ΔT

Short bunches by Magnetic Compression



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

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

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

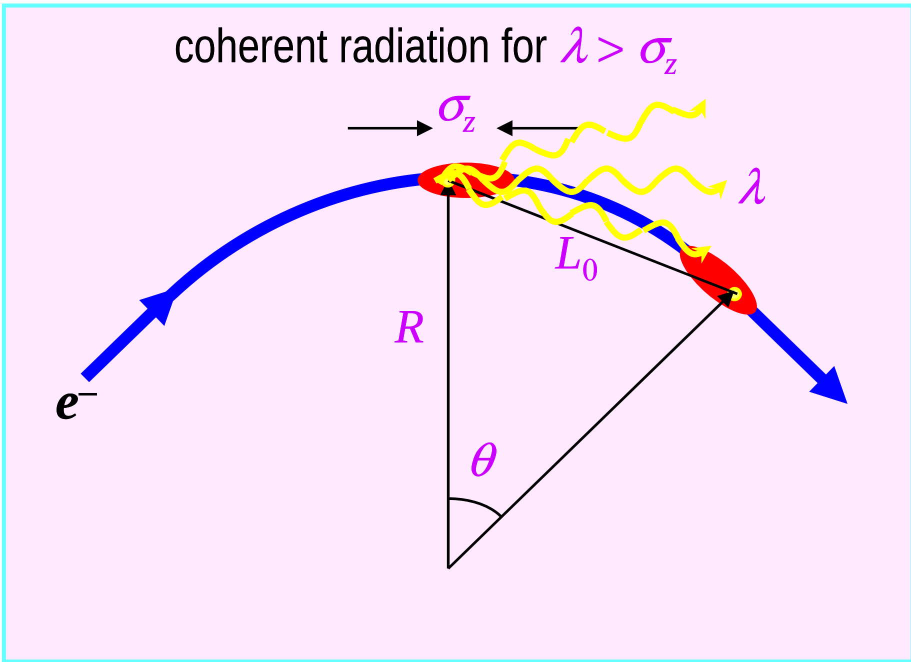
$$k(\varphi) \equiv \frac{\partial \delta}{\partial z} = -\frac{2\pi}{\lambda}\left(1 - \frac{E_0}{E}\right)\frac{\sin(\varphi+\Delta\varphi)}{\cos(\varphi)}$$ 'chirp'

final bunch length and energy spread…

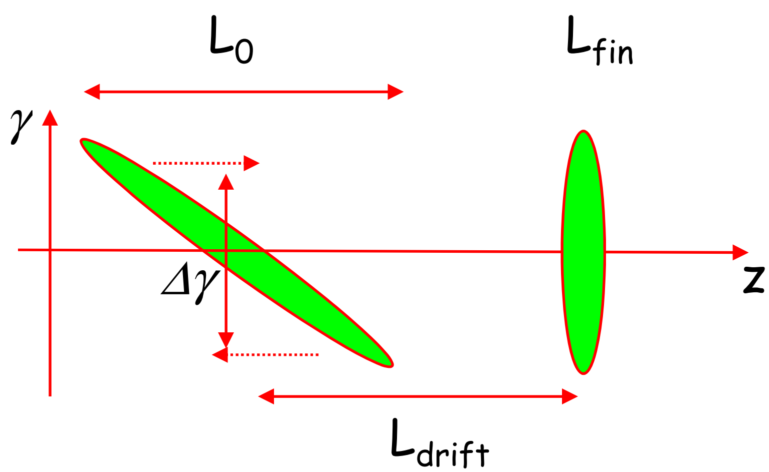
$$\sigma_z = \sqrt{(1+kR_{56})^2\sigma_{z0}^2 + R_{56}^2\sigma_{\delta 0}^2 E_0^2/E^2} \quad , \quad \sigma_\delta = \sqrt{k^2\sigma_{z0}^2 + \sigma_{\delta 0}^2 E_0^2/E^2}$$

Coherent Synchrotron Radiation in Magnetic Chicane

- Powerful radiation generates energy spread in bends (see in Pavel's talk)
- Energy spread breaks achromatic system
- Causes bend-plane emittance growth (short bunch worse)

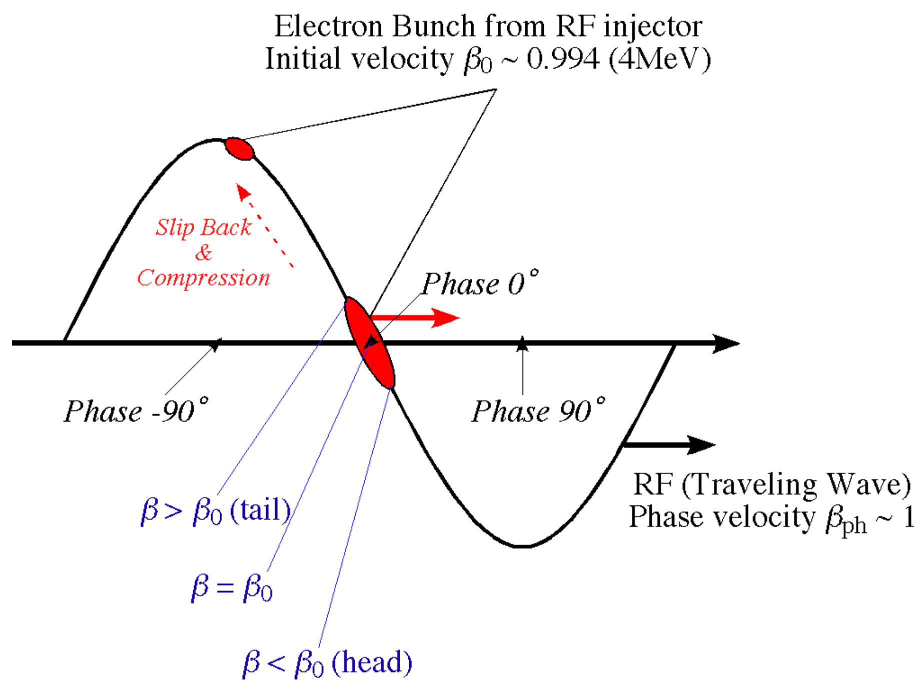


Short bunches by Ballistic/Velocity Compression



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

$\Delta\gamma$

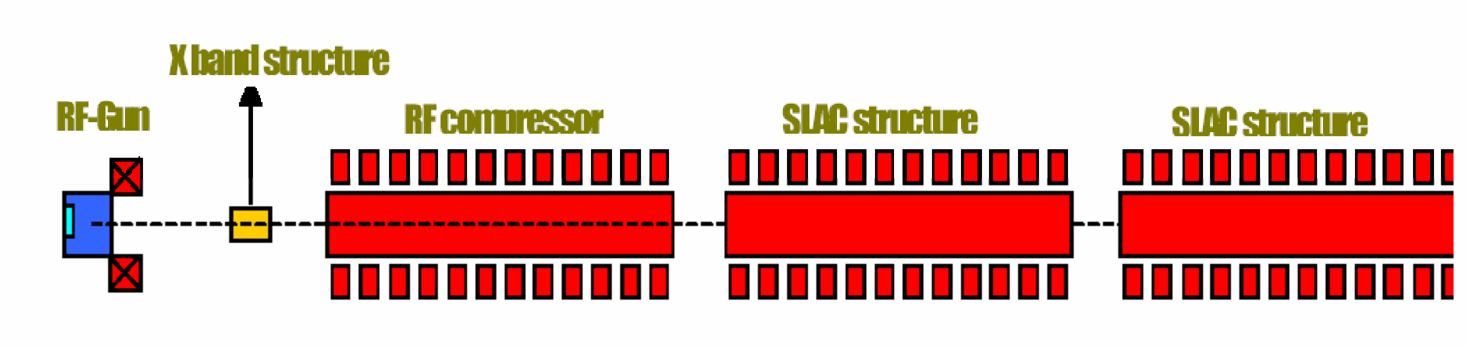


Provide a correlated velocity spread enough to produce, in a drift of length L_{drift} a *path difference* equal to ΔL

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

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

Bunch length measurement techniques

Short bunch length measurements

RF manipulation

Use RF devices to convert time information into spatial information

Laser-based beam diagnostic

Using short laser pulses and sampling techniques

Incoherent EM radiation

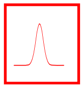
1. Produce visible light
2. Analyse the light pulse using dedicated instruments

Coherent EM Radiation

Based on the measurement of the bunch frequency spectrum

Covered by P. Karataev lectures : Longitudinal Beam profiles part 2

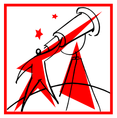
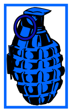
Beam instrumentation

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*

Beam instrumentation

<u>Simplicity and Reliability</u>

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

⬇

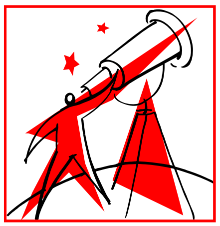
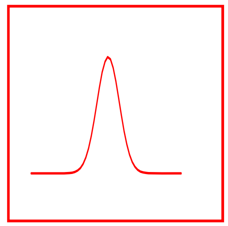
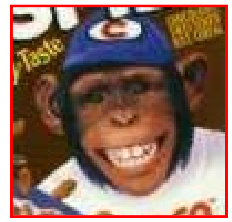
<u>A detector, what for ?</u>

• 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

Beam instrumentation

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

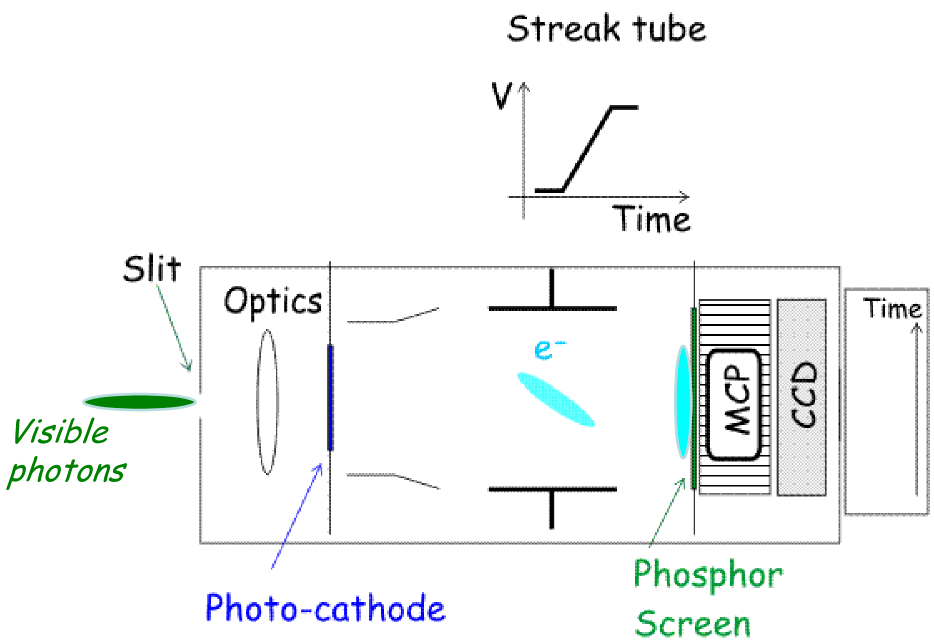
 + 1 +  = 

All in red → 'perfect system'

RF techniques

'How to transform time information into spatial information'

Optical method : Streak Camera



$\Delta T \longrightarrow \Delta X$

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

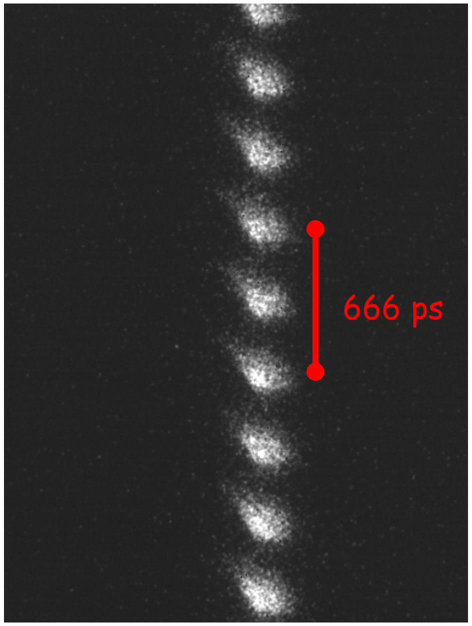
M. Uesaka *et al,* NIMA 406 (1998) 371

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 :

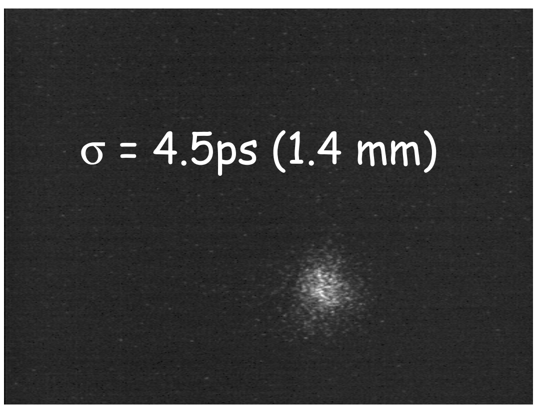
(i) Initial velocity distribution of photoelectrons : *narrow bandwidth optical filter*
(ii) Spatial spread of the slit image: *small slit width*
(iii) Dispersion in the optics

Streak camera examples

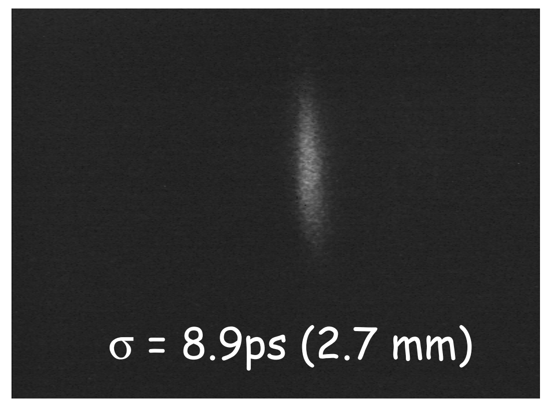


Observation of bunch train
Sweep speed of 250ps/mm

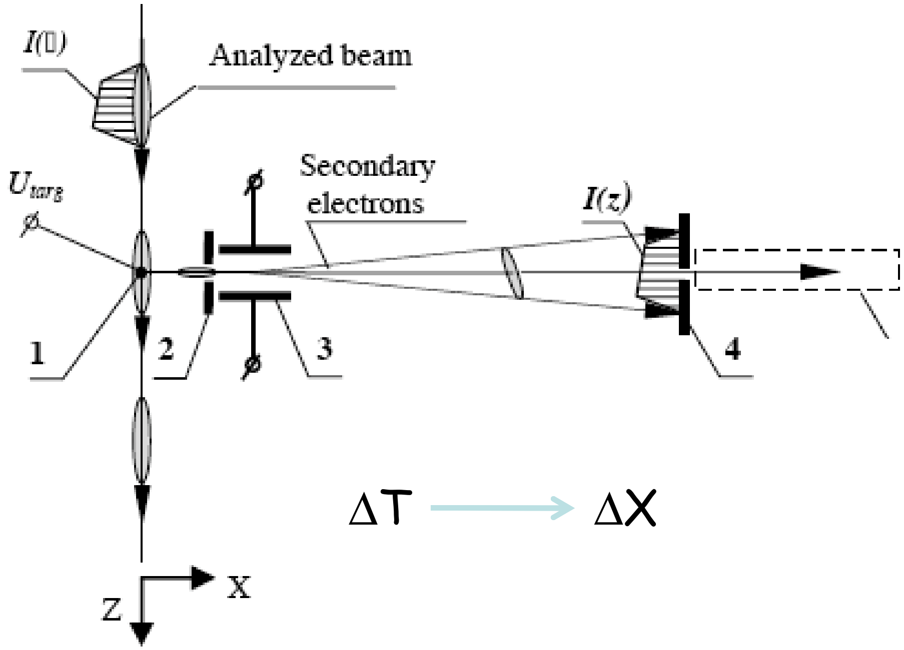
Measure of bunch length



Sweep speed of 10ps/mm



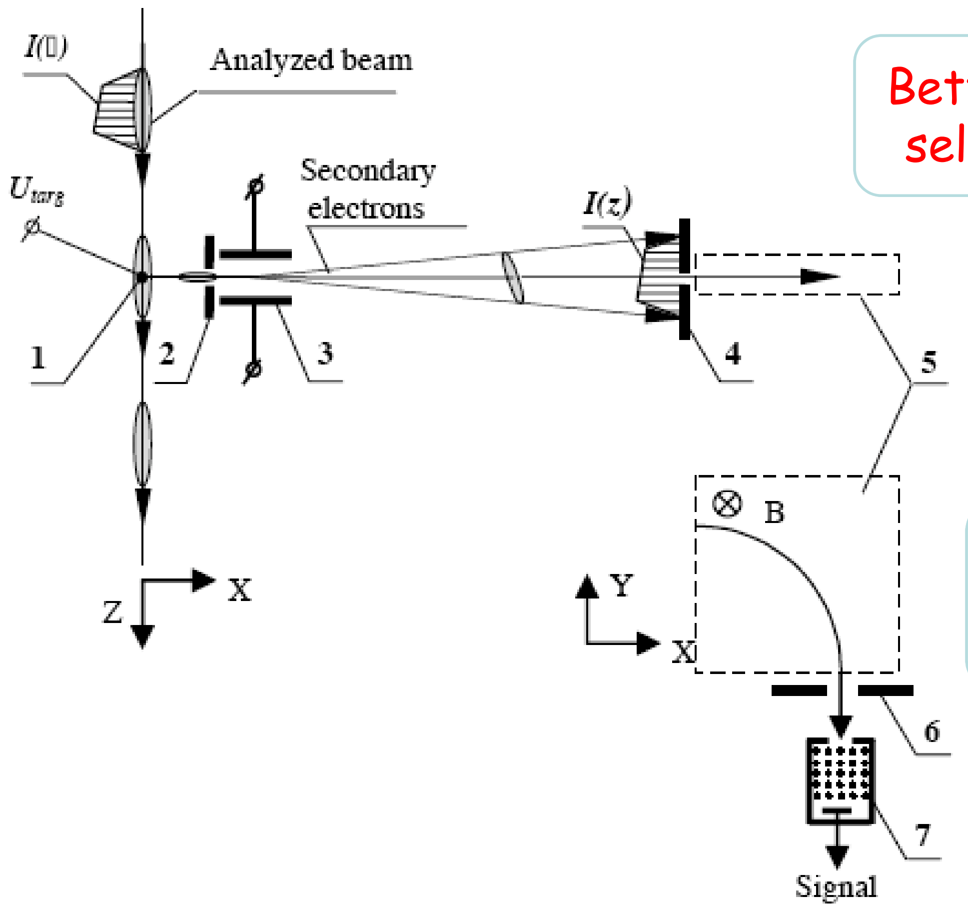
Bunch Shape Monitor - Feschenko monitor



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



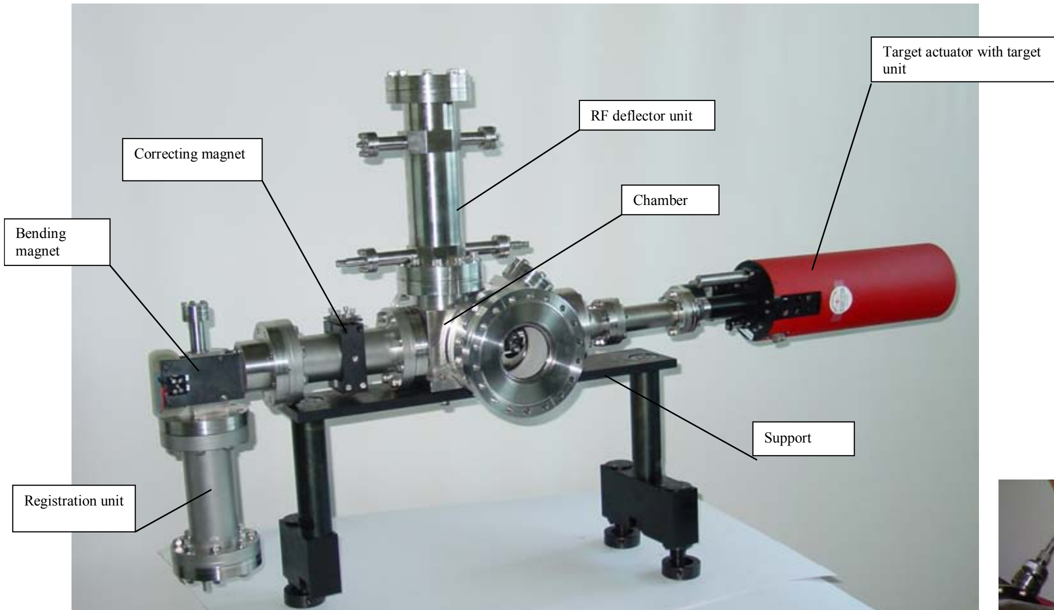
Better accuracy using slit and energy selection of the secondary electron

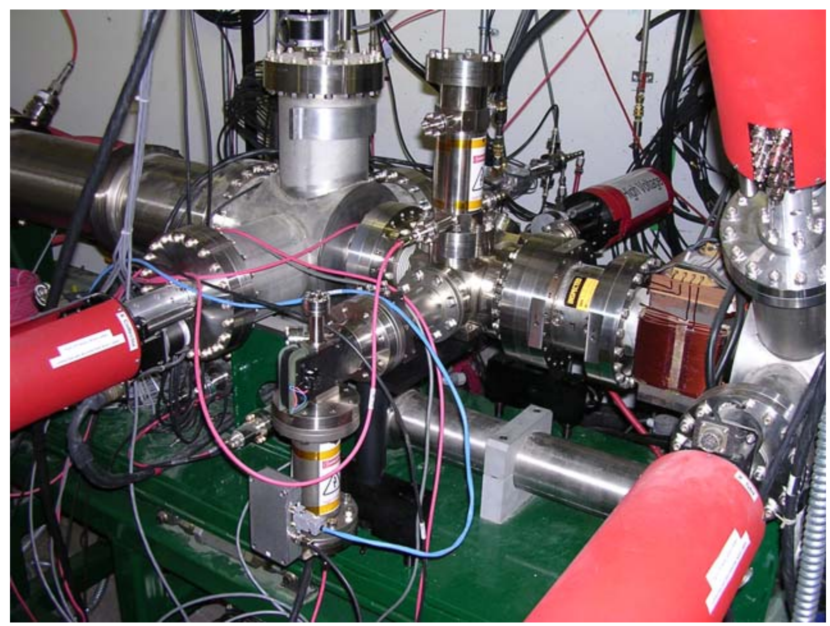
Typical resolution of 20-40ps

1 - Target (wire, screen, laser for H^-)
2 - Input collimator
3 - RF deflector (100MHz, 10kV) combined with electrostatic lens
4 - Output Collimator
5 - Bending magnet
6 - Collimator
7 - Electron Beam detector (MCP coupled to a camera, ..)

Bunch Shape Monitor - Feschenko monitor

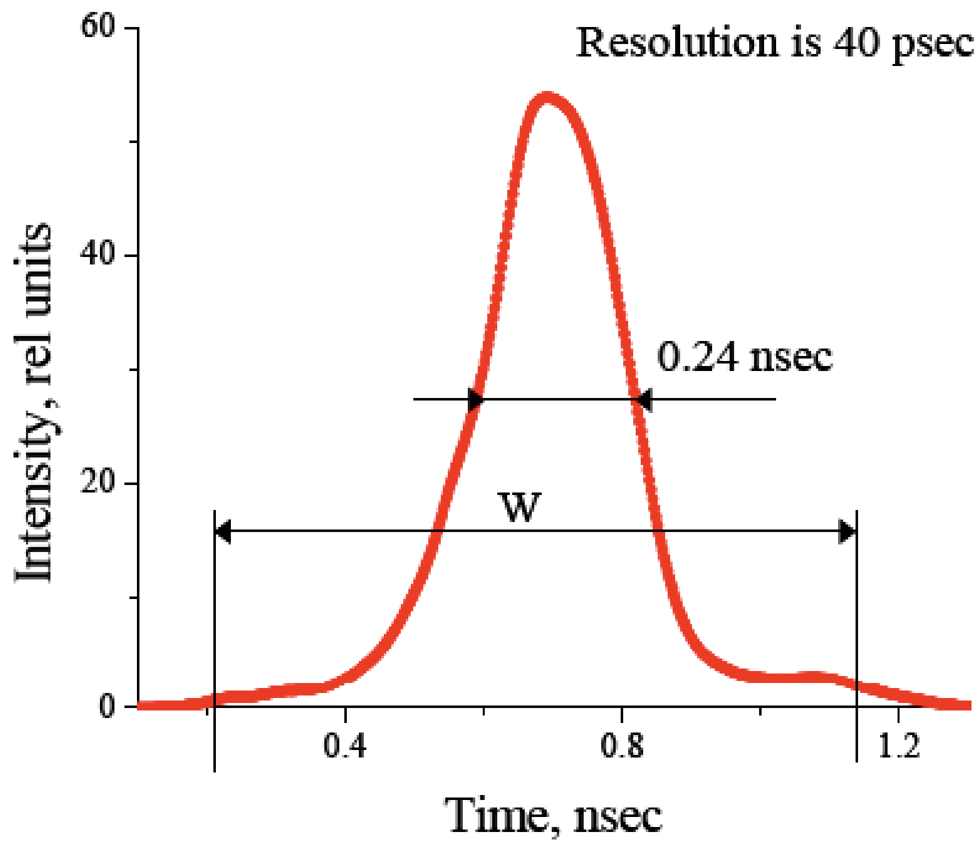
Bunch Shape Monitor @ SNS





Bunch Shape monitor - Feschenko monitor

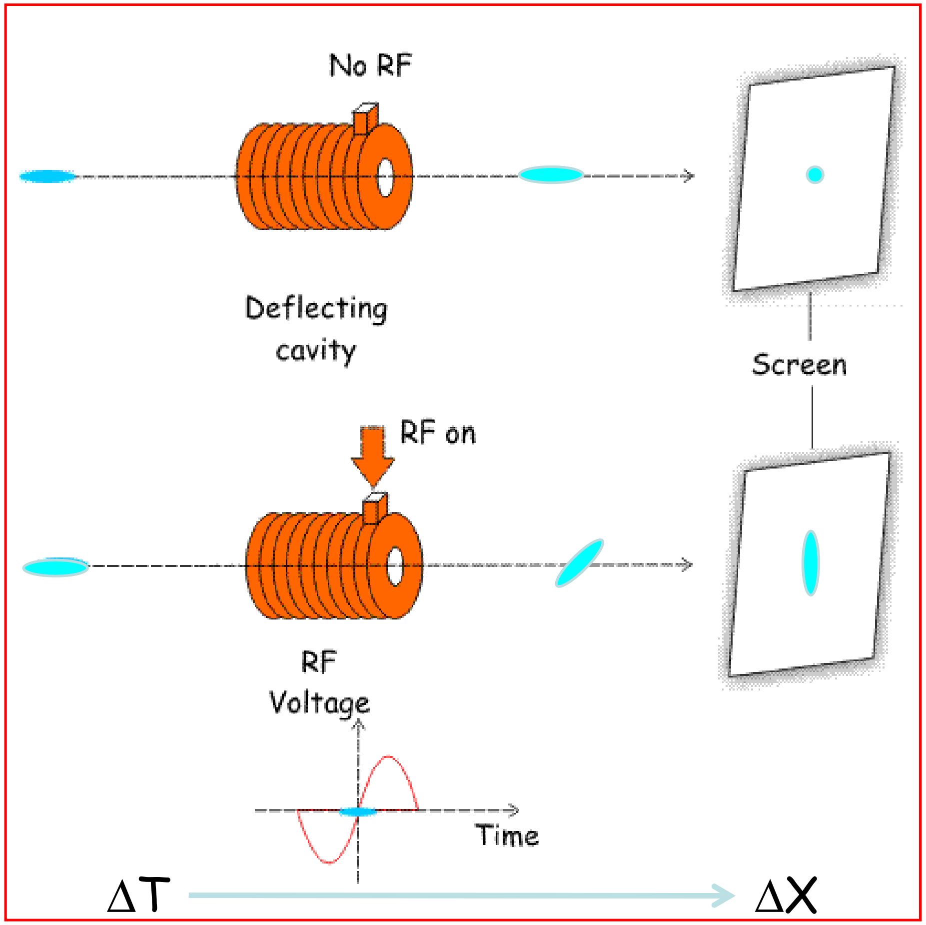
Longitudinal Bunch profile @ SNS



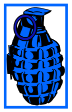
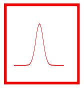
A. Feschenko *et al*, Proceedings of LINAC 2004, Lübeck, p408

RF Deflecting Cavity

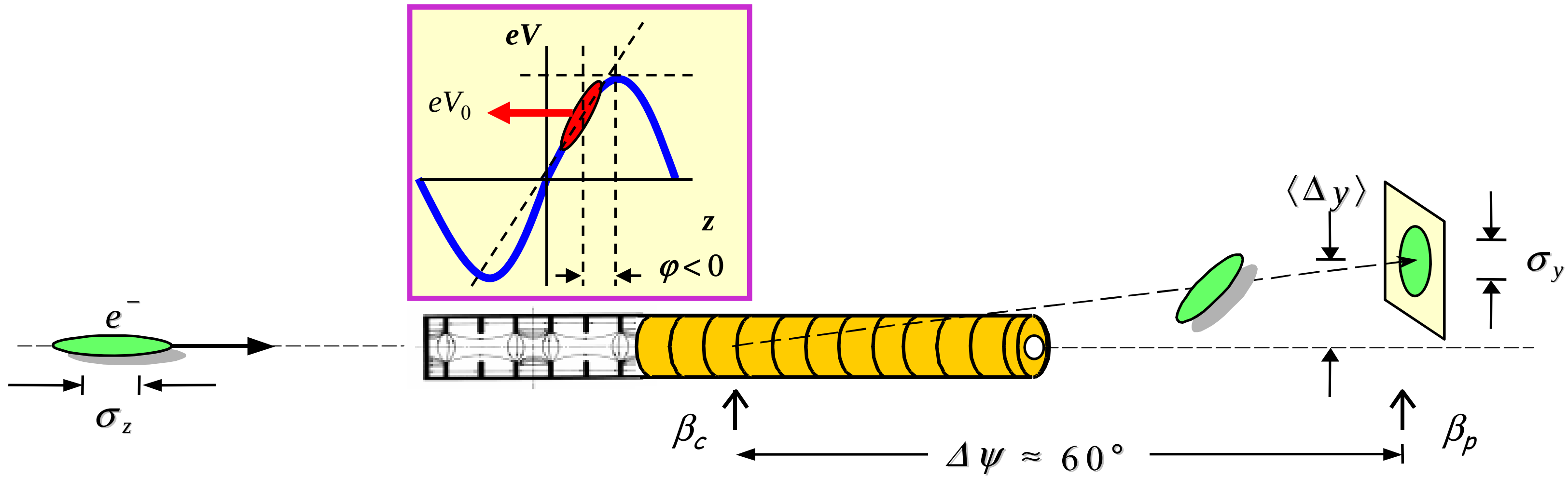
- *Old idea from the 60's*
- *The RF Deflector can be seen as a relativistic streak tube.*
- *The time varying deflecting field of the cavity transforms the time into a spatial information*
- *The bunch length is then deduced measuring the beam size at a downstream position*



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

RF Deflecting Cavity



Beam profile RF off

Deflecting Voltage

Beam profile RF on

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

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

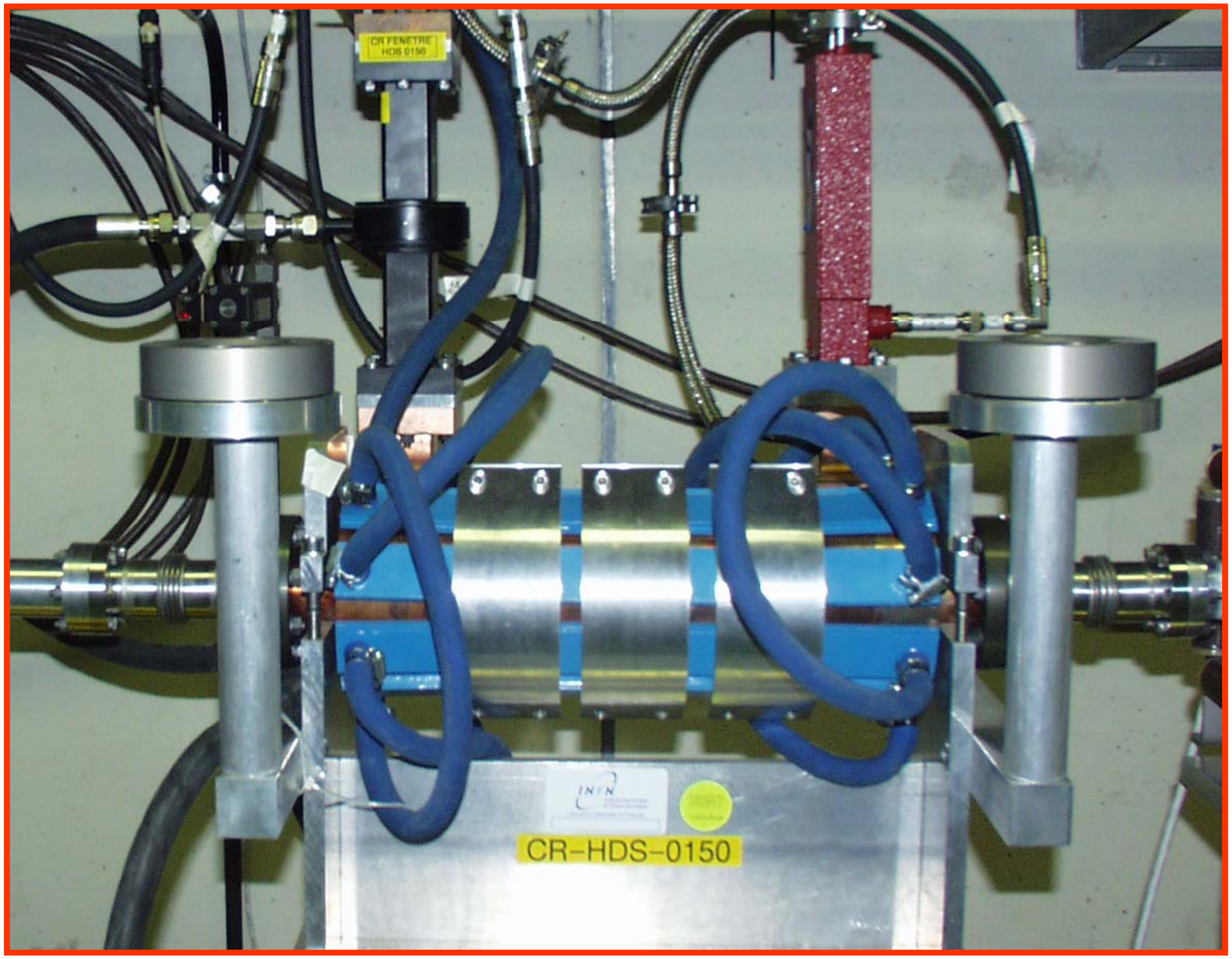
RF deflector phase

Beam offset on the screen

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

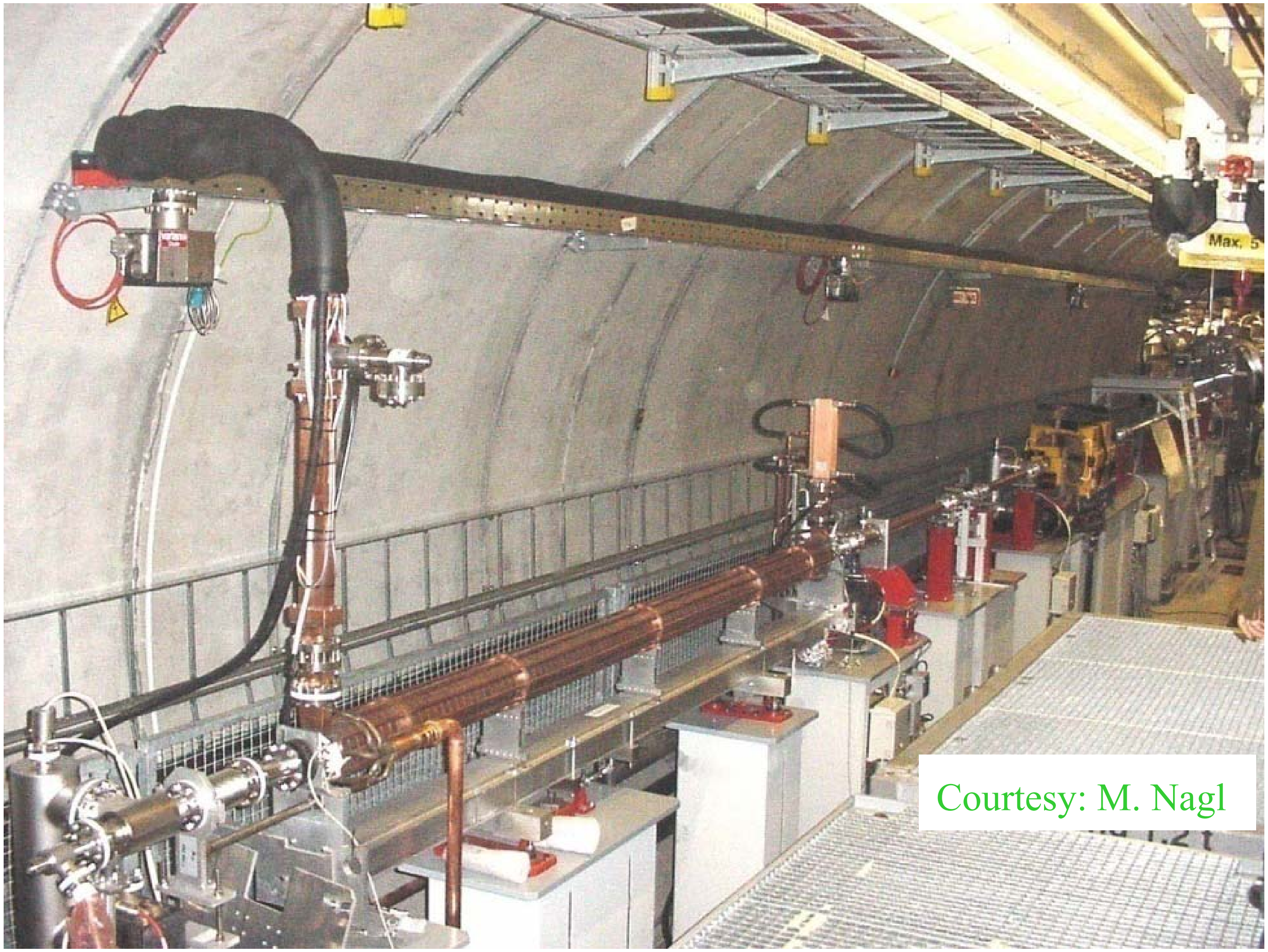
RF Deflecting Cavity

CTF3



RF Deflecting Cavity

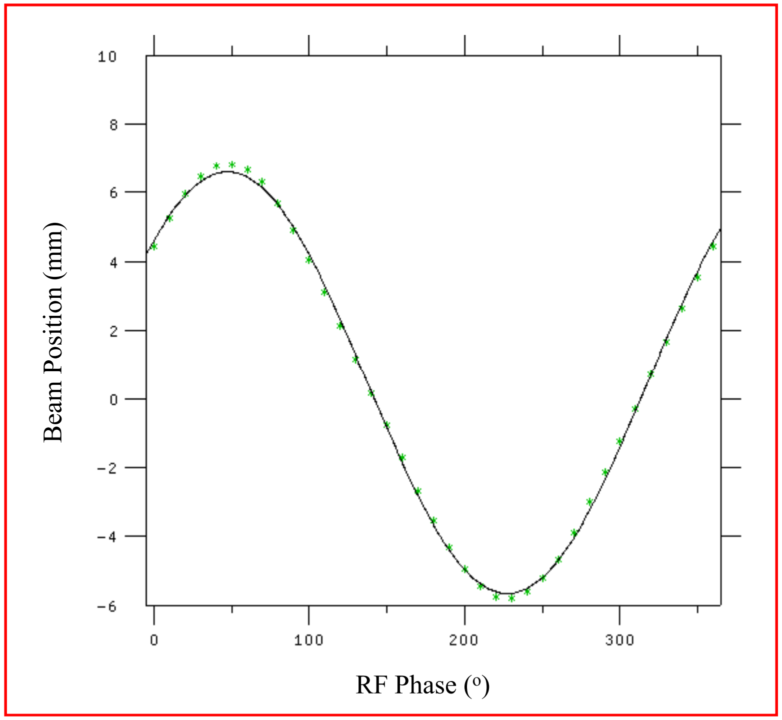
LOLA @ Flash

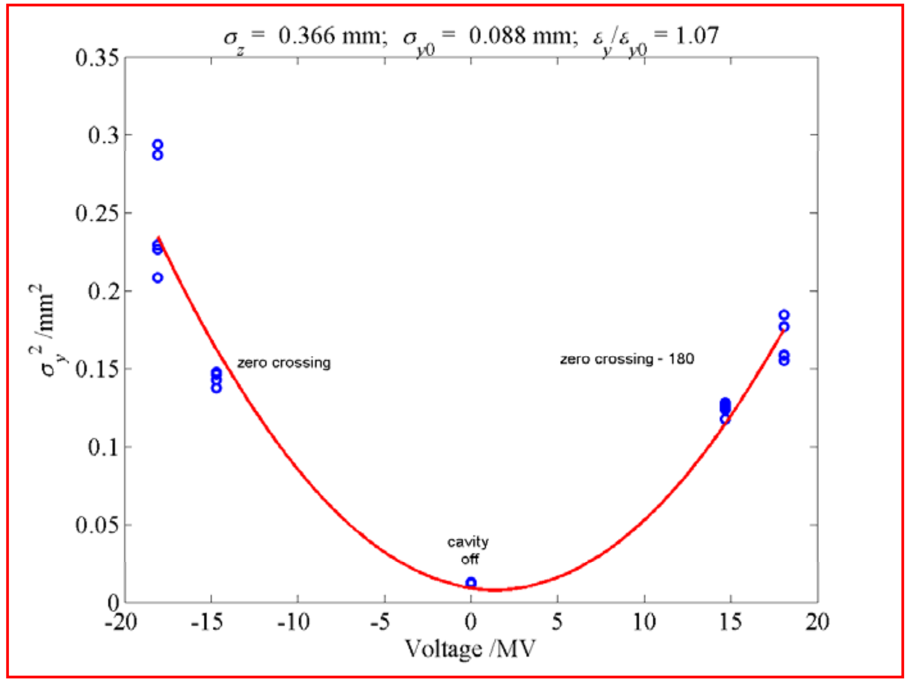


Courtesy: M. Nagl

RF Deflecting Cavity

Calibration of RF Deflector





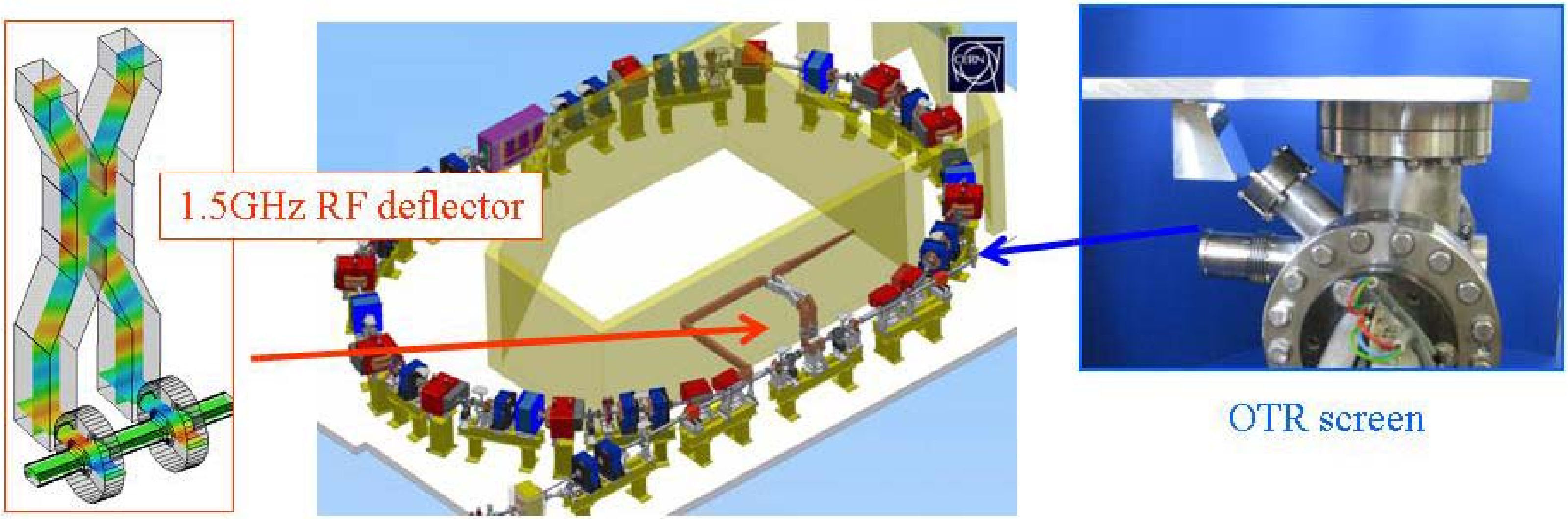
Use a Beam Position Monitor close to the Profile monitor to calibrate the deflection angle

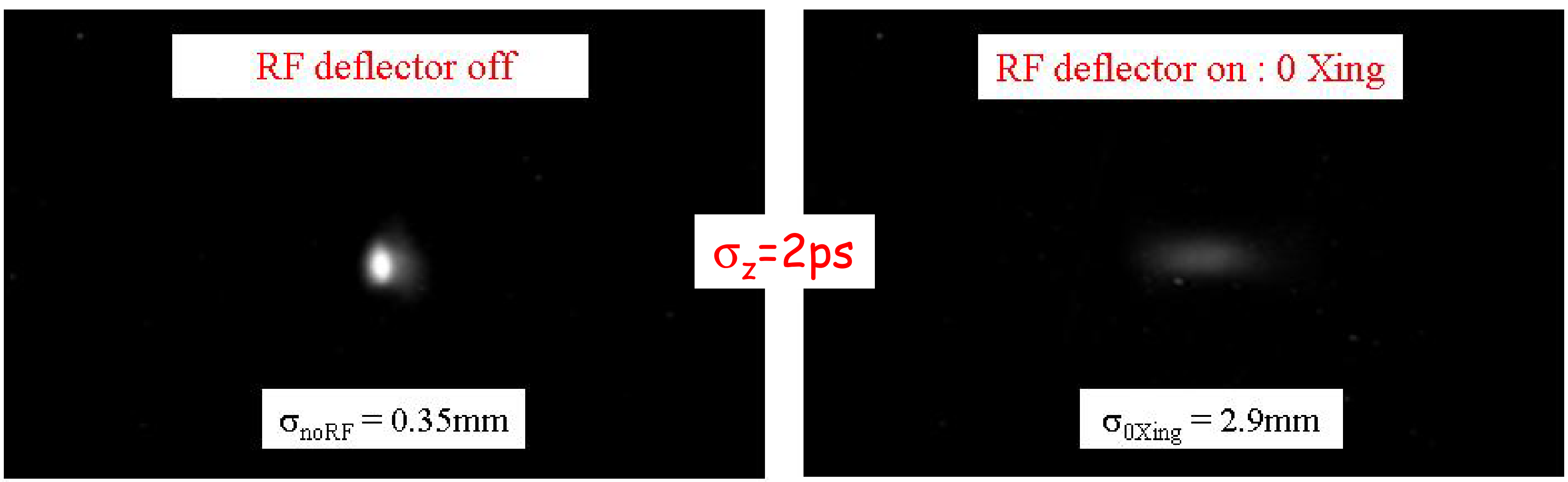
Make a power scan at zero crossing and (zero crossing – 180°) to check if there is no perturbation from linac wakefields

ΔX(mm) → $\Delta\varphi$(°)

ΔT(ps)

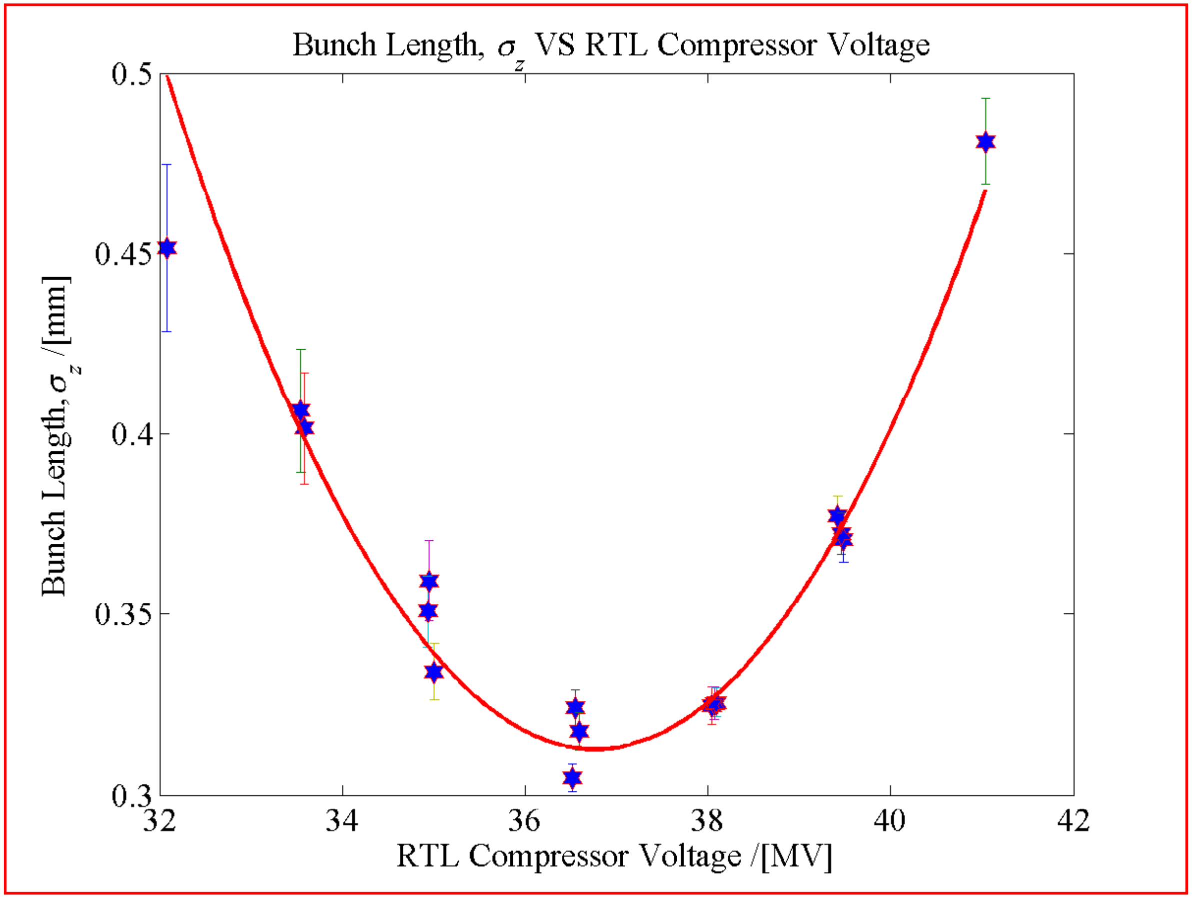
RF by Deflecting Cavity





RF by Deflecting Cavity

Measuring bunch compression curve

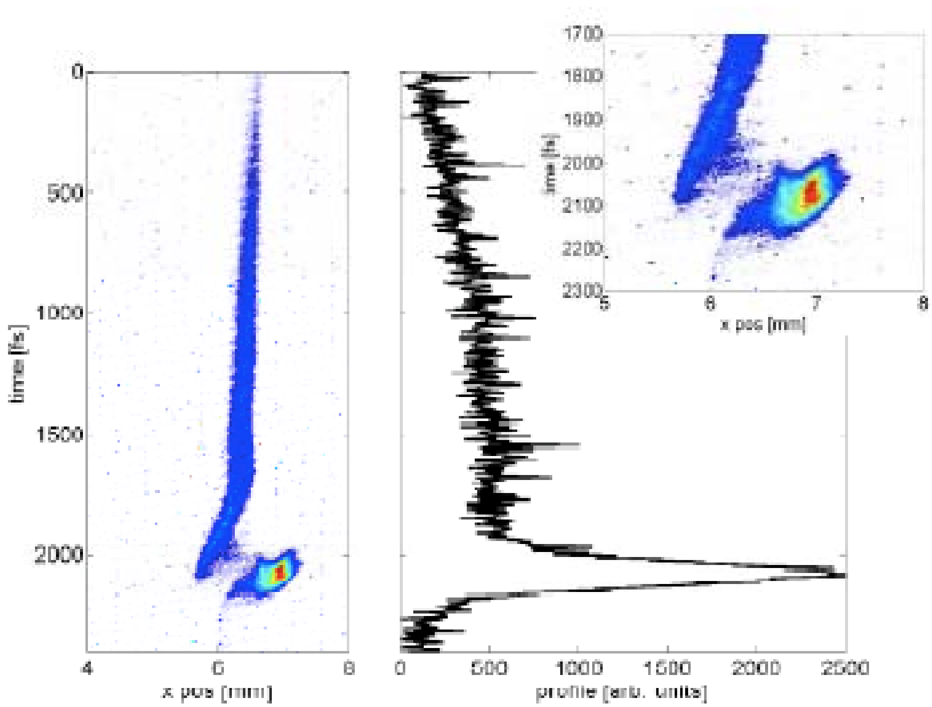


σ_z = 300μm @ SLAC in 2002

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

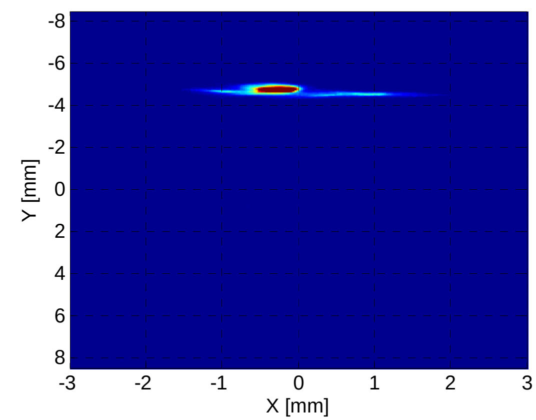
RF by Deflecting Cavity

Bunch length measurement @ Flash

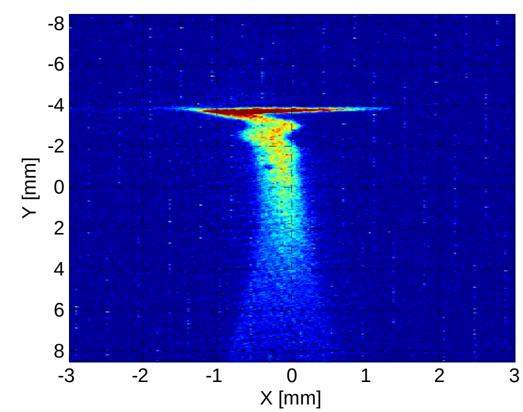


→ Resolution of 4fs/pixels

LOLA off:



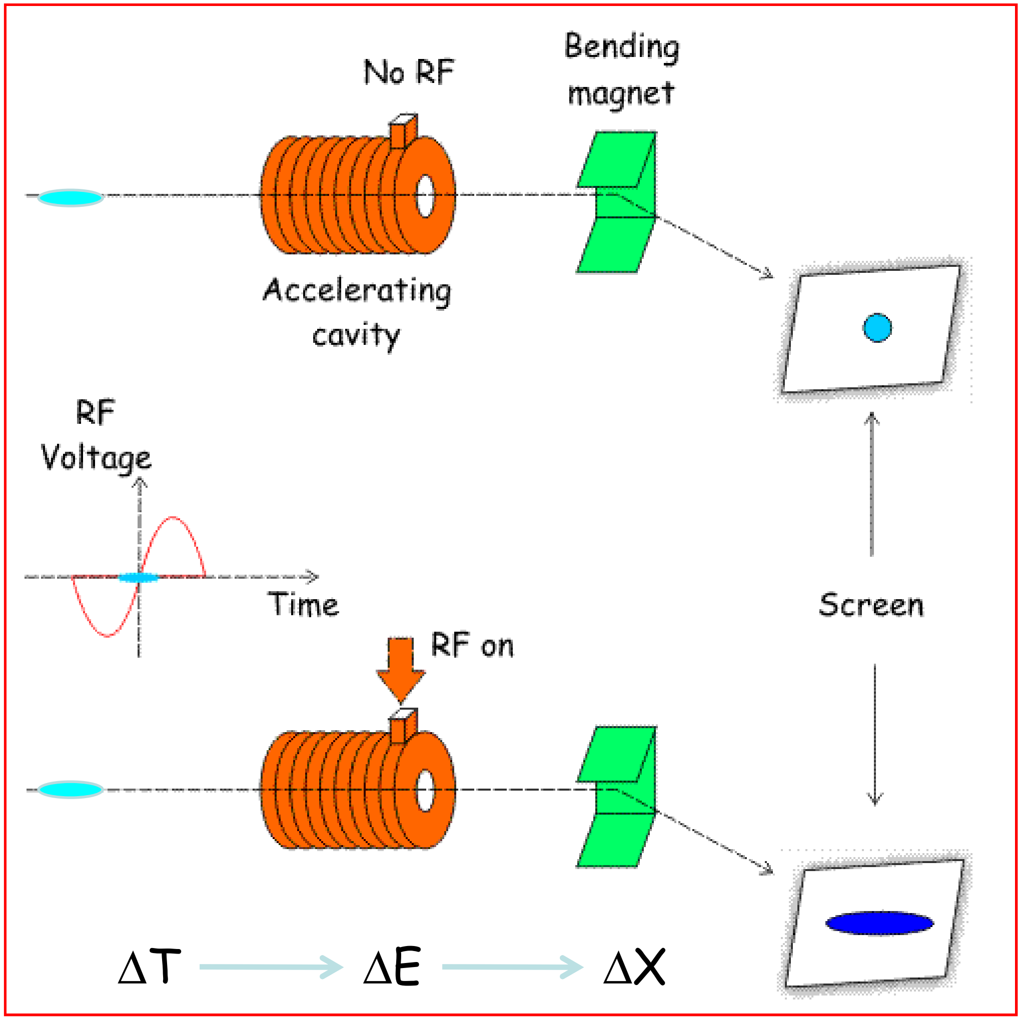
LOLA on:



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

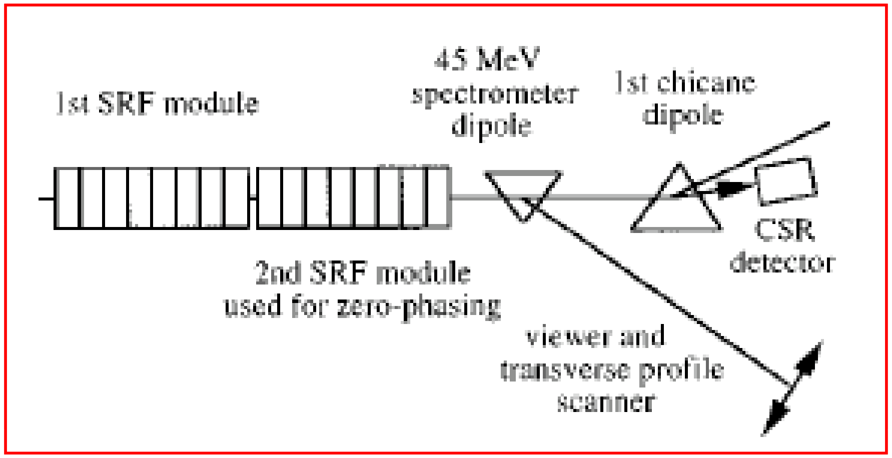
RF accelerating structures

'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'



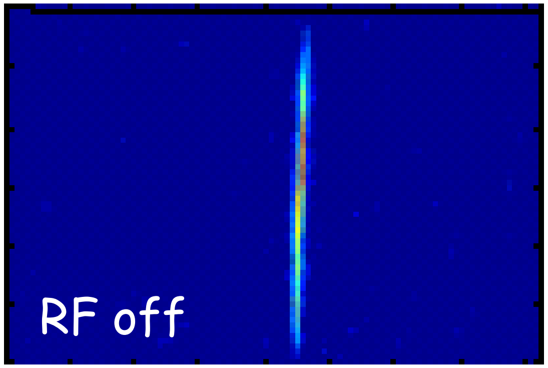
RF accelerating structures

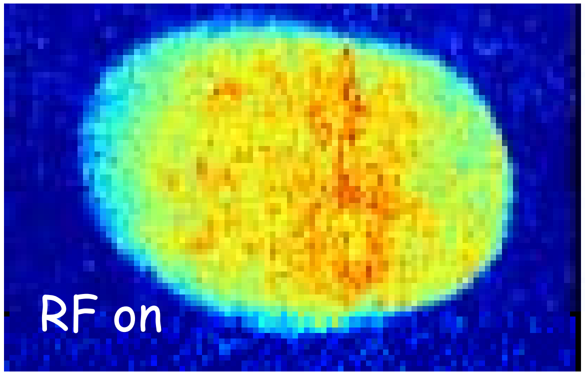
CEBAF injector, Newport News



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

84fs, 45MeV beam but low charge beam





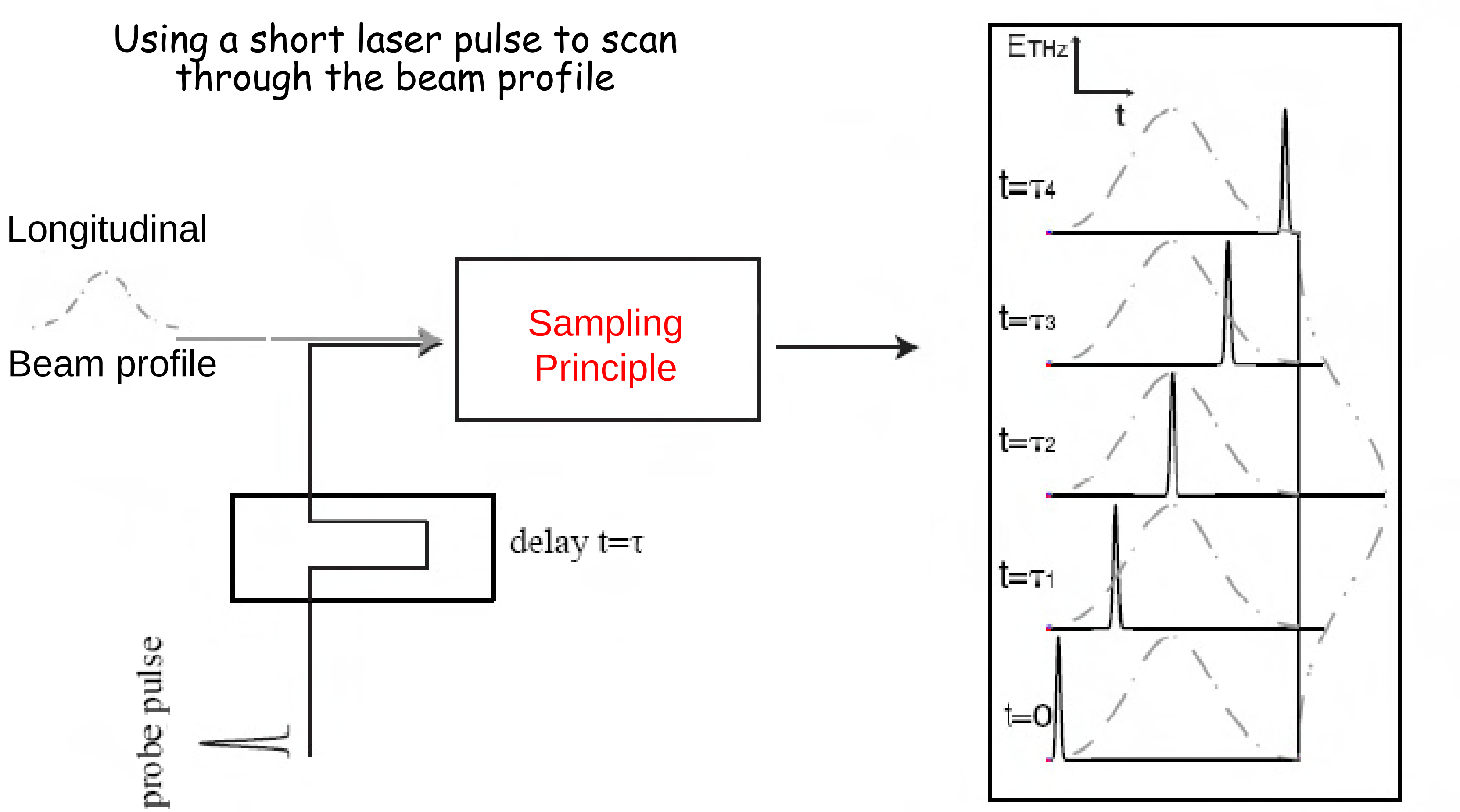
Limitations

RF non linearities
Beam loading and wakefield for high charge beam

Laser-based Techniques

Sampling Techniques

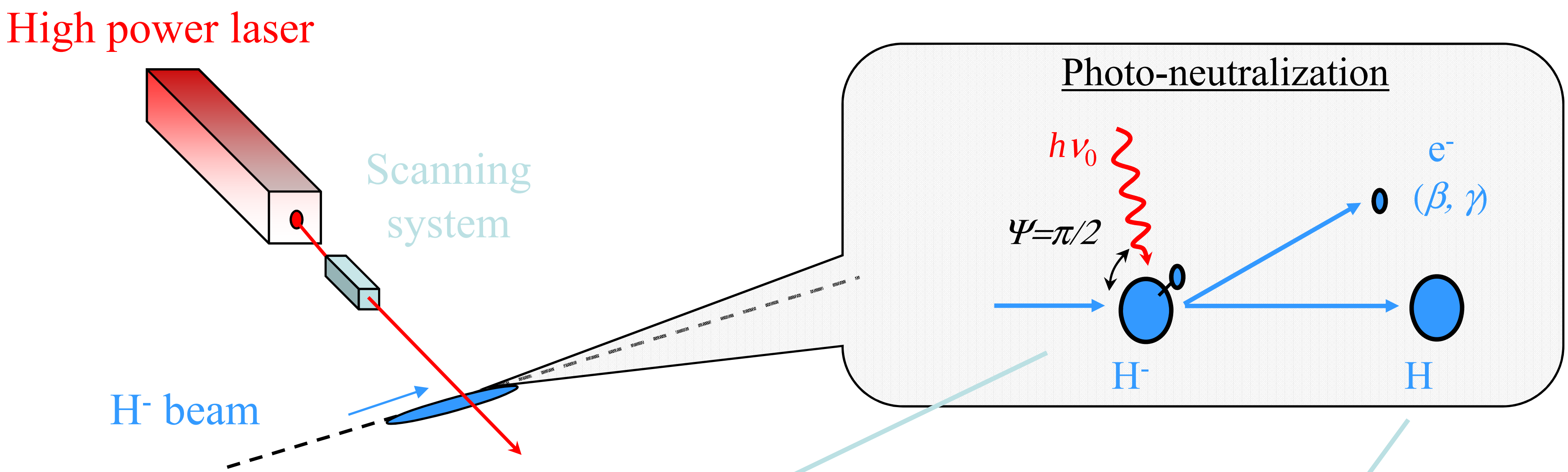
Using a short laser pulse to scan through the beam profile



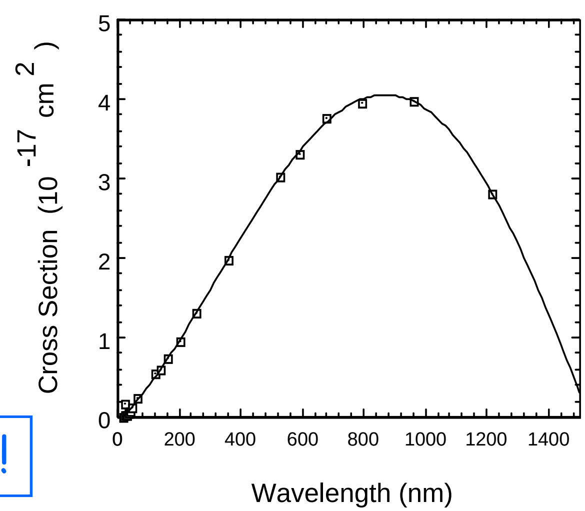
Limitation

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

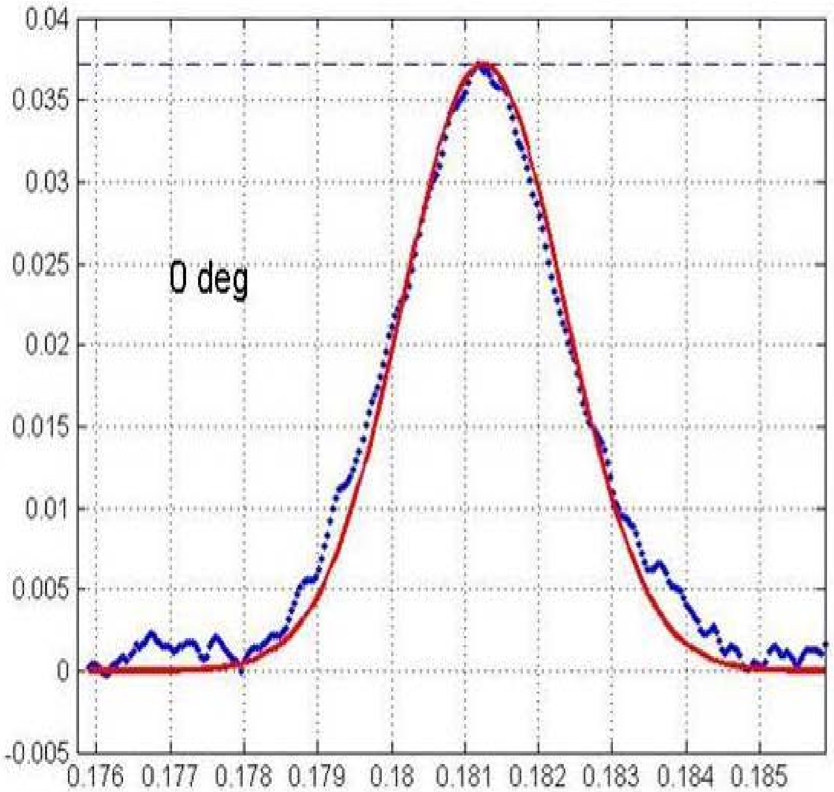
- The measurement of released electrons using a magnet and a collector (faraday cup, MCP,..)

- *Measured the conversion of H^- into H with a current monitor*

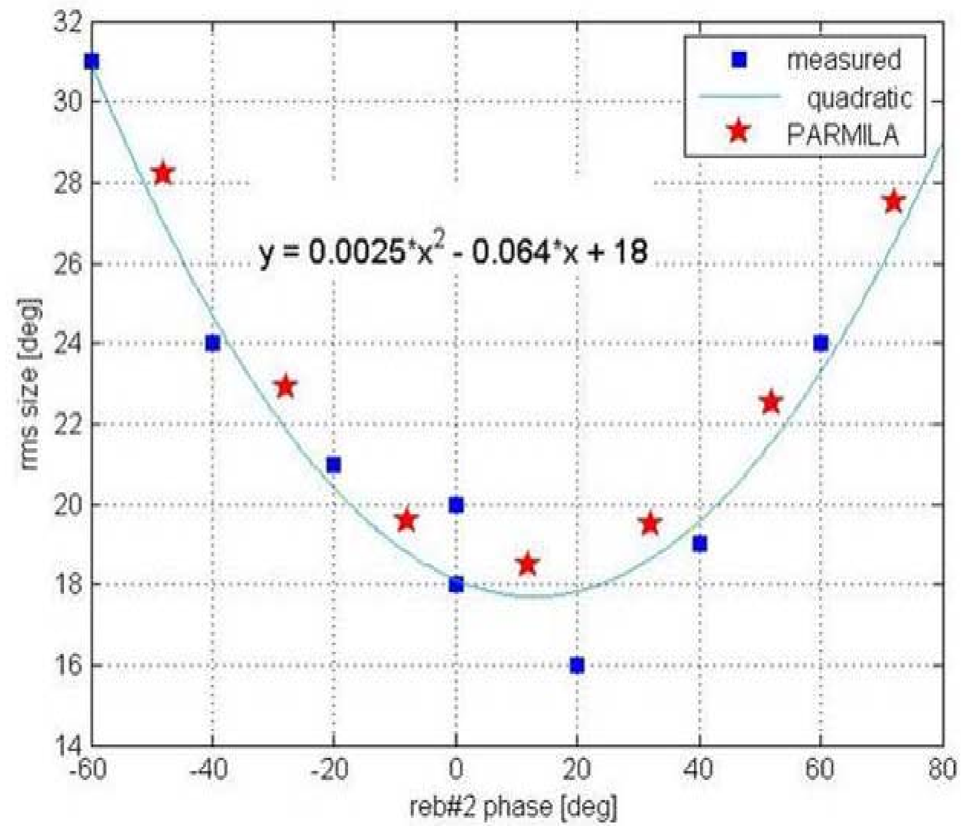
Laser Wire Scanner : Photo-neutralization

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



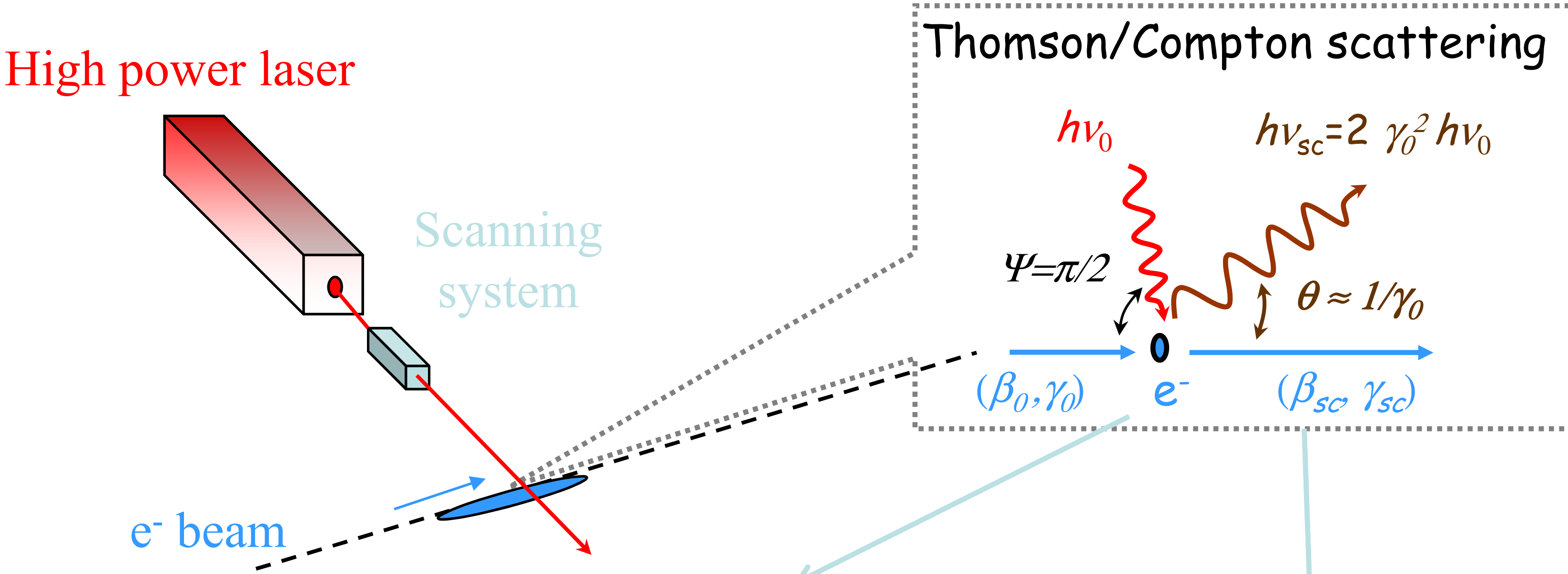
Collected electron signal plotted vs. phase

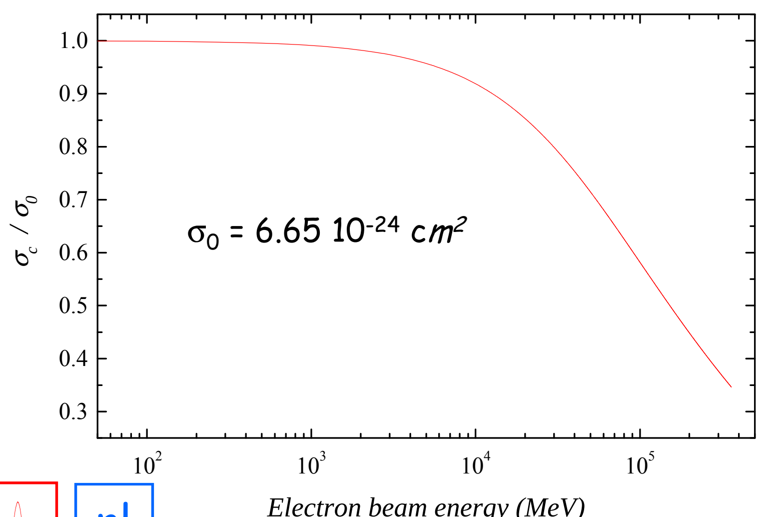


Measured and predicted bunch length
vs. cavity phase setting

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

Laser Wire Scanner – Compton scattering





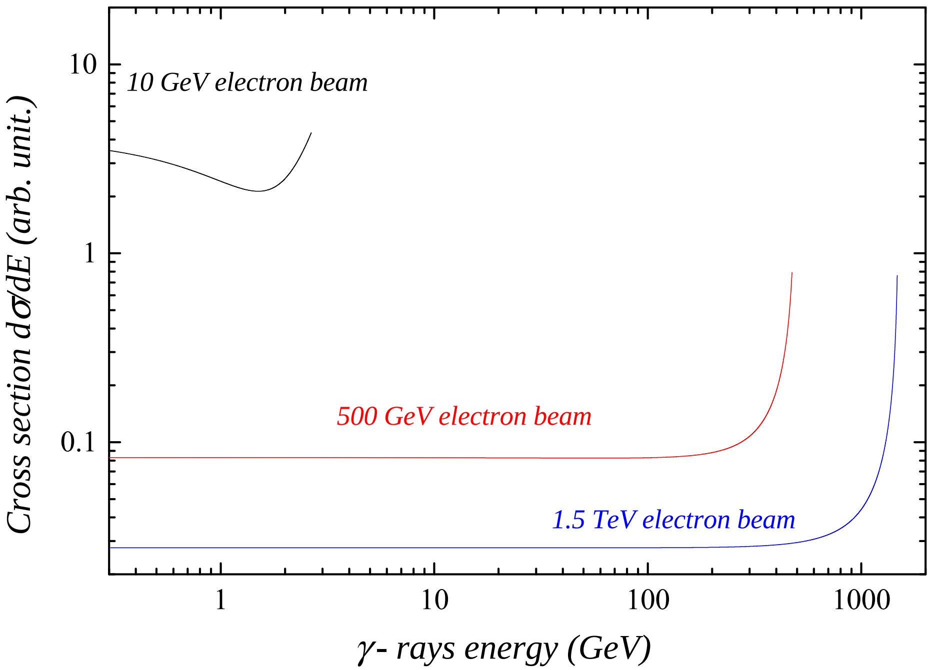
Detection system based on

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

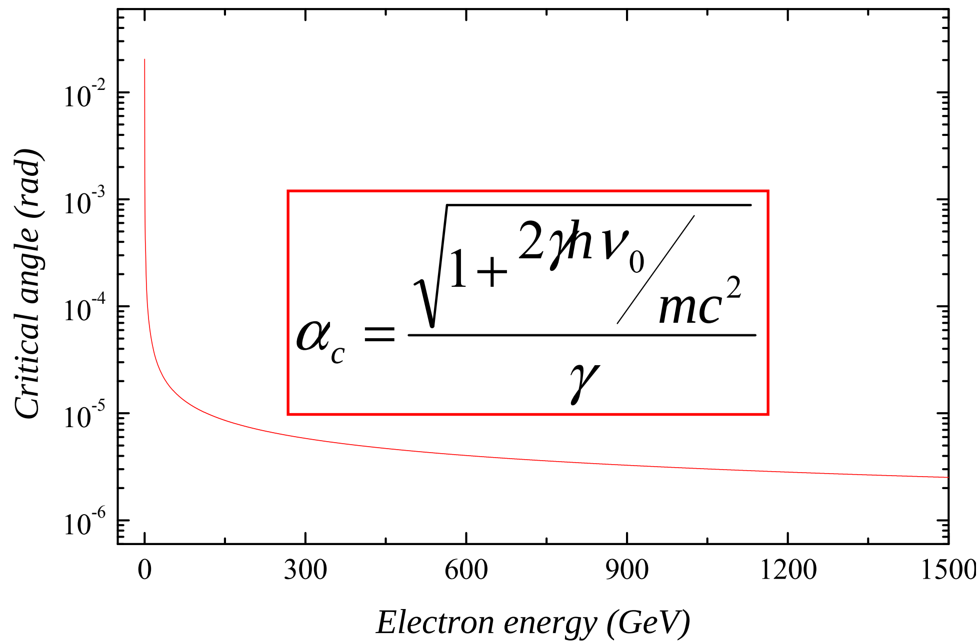
Laser Wire Scanner – Compton scattering

Energy spectrum of scattered photons

Using a 266nm wavelength laser



Emission angle of the scattered photons



$$\alpha_c = \frac{\sqrt{1+\frac{2\gamma h\nu_0}{mc^2}}}{\gamma}$$

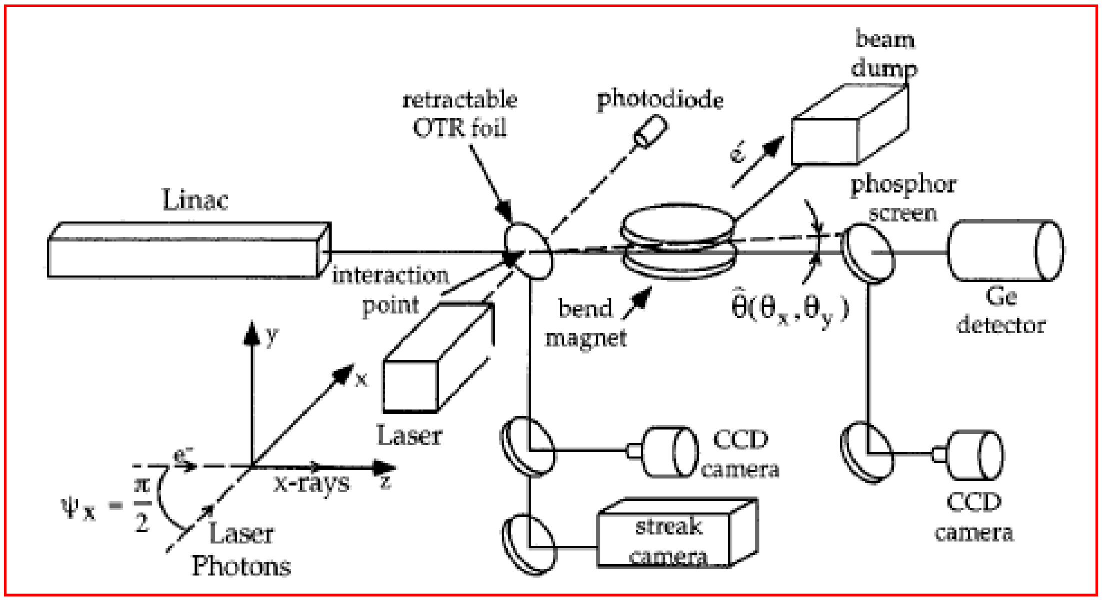
At very high energy

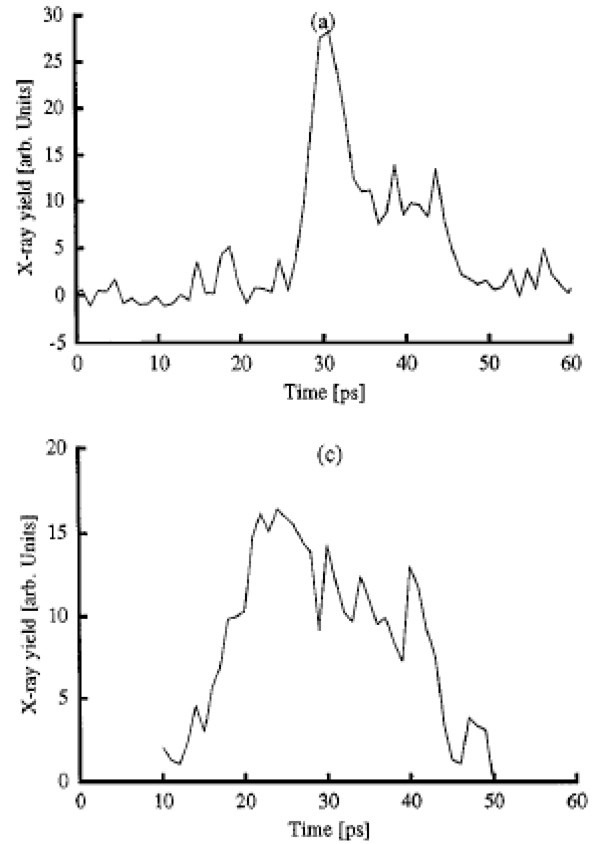
- The photons steal most of the electron energy *(electron recoil becomes extremely important)*
- The photons are emitted within a very small angle (a few μrad) in the forward direction

•Measurement of degraded electrons only feasible at high energies

Laser Wire Scanner – Compton scattering

ALS @ LBNL



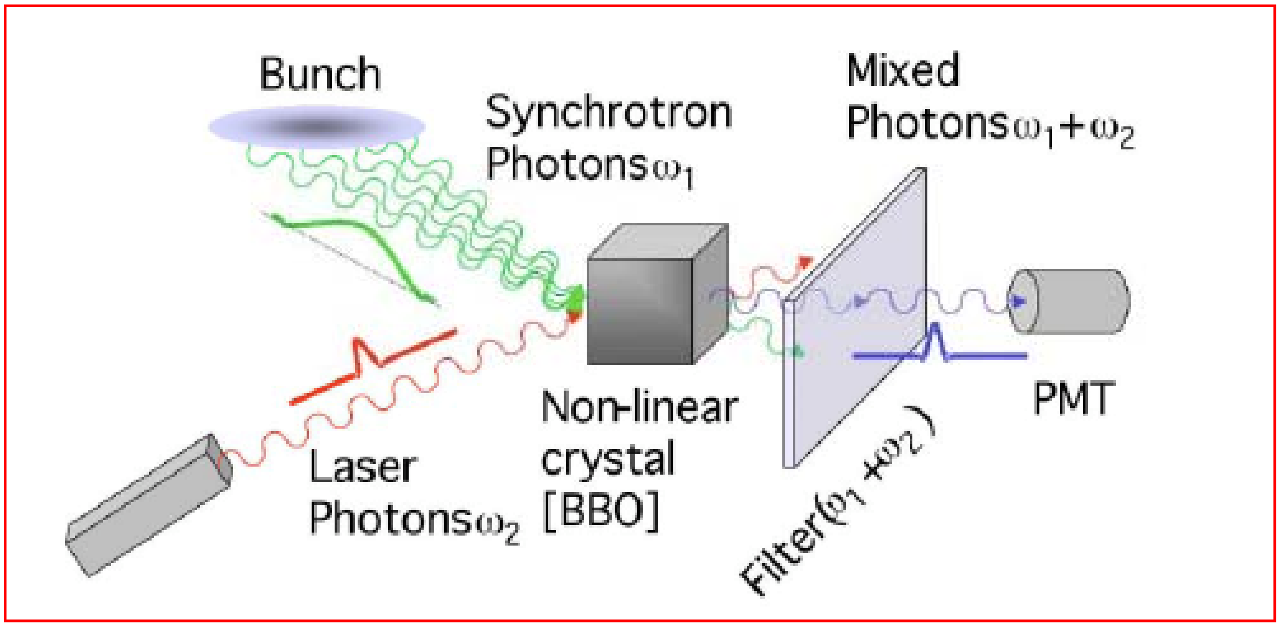


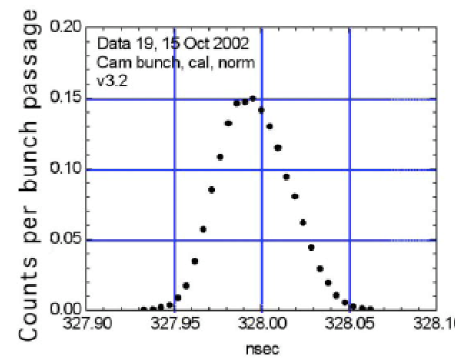
Using a 10TW Ti:Al_2O_3 laser system. Detecting 5.10^4 10-40 keV X-rays using either an X-ray CCD and Ge detector.

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'





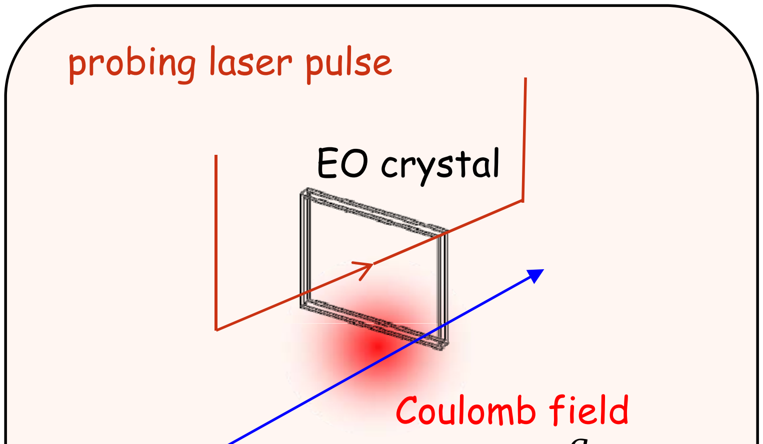
M. Zolotorev *et al*, **Proceeding of the PAC 2003, pp.2530**

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

Electro Optic Sampling

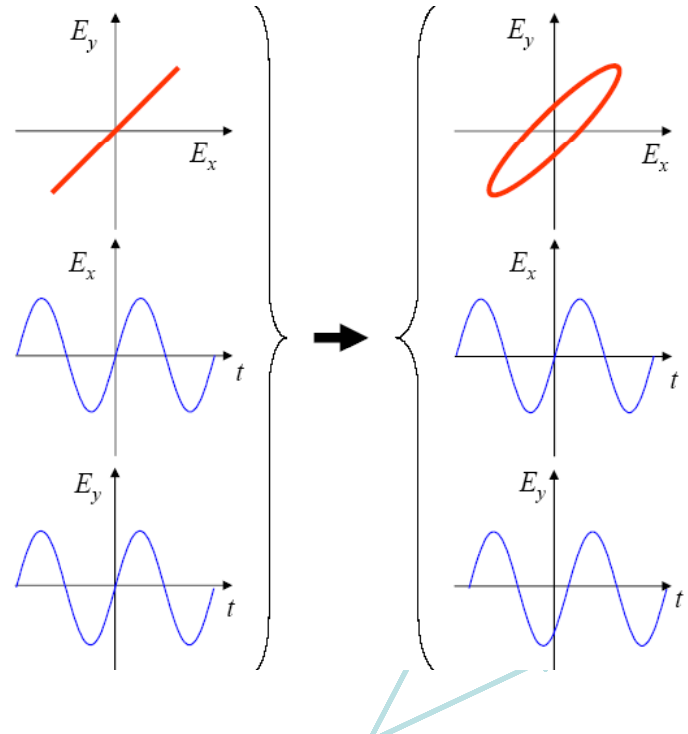
'This method is based on the polarization change of a laser beam which passes through a crystal itself polarized by the electrons electric field'

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



$$E_r \approx \frac{q}{\sqrt{2\pi}\,(\varepsilon_0 \sigma_z r)}$$

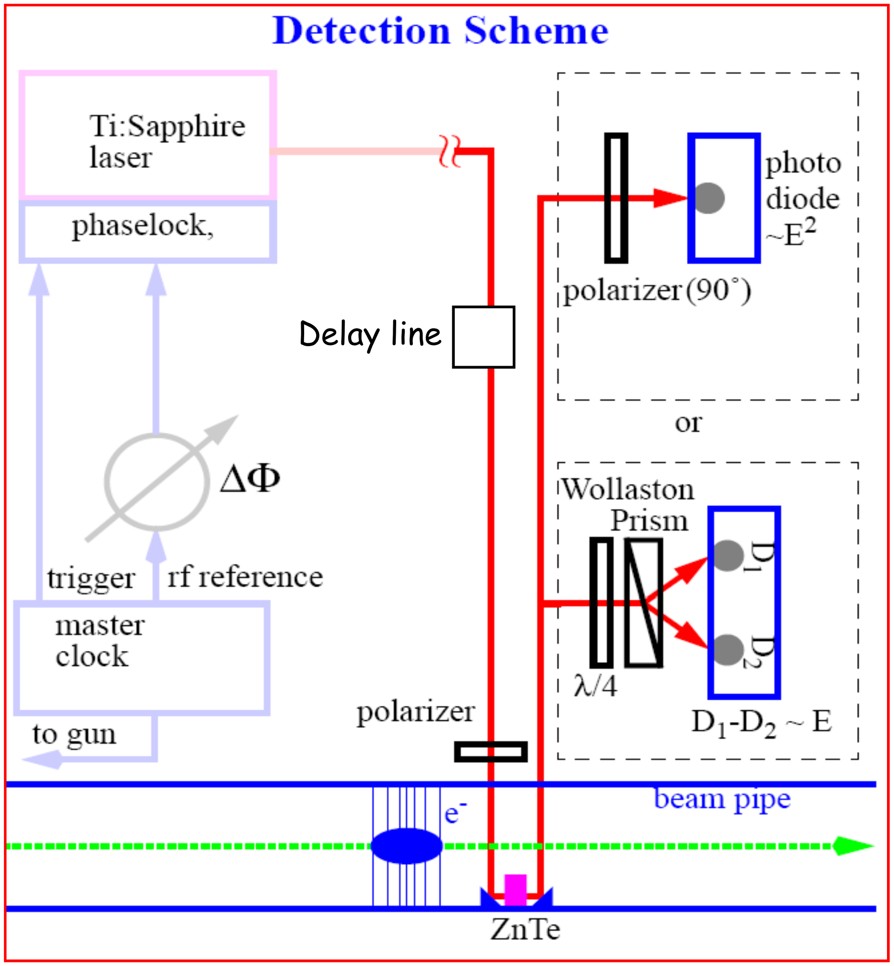
- Polarization diagram
- electric field of the horizontal polarization
- electric field of the vertical polarization



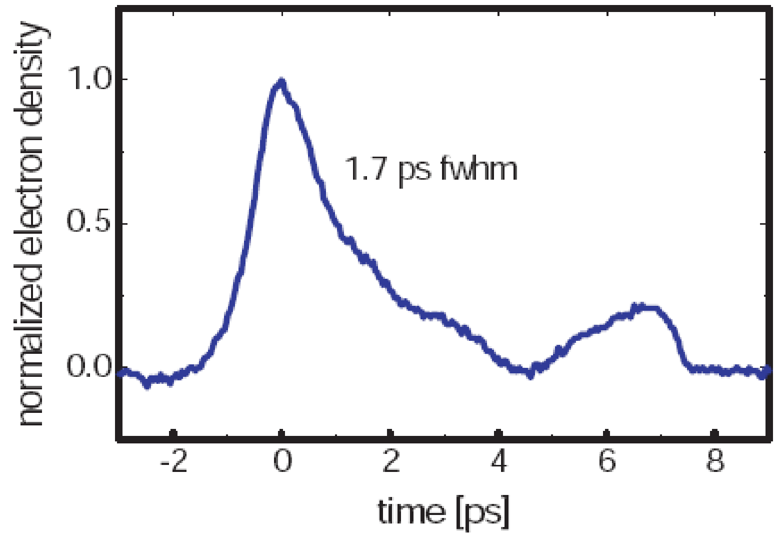
$$\Gamma = \frac{2\pi d}{\lambda_0}(n_x - n_y) = \frac{2\pi d}{\lambda_0} n_0^3 r_{41} E_r$$

Relative phase shift between polarizations increases with the beam electric field

Electro Optic Sampling



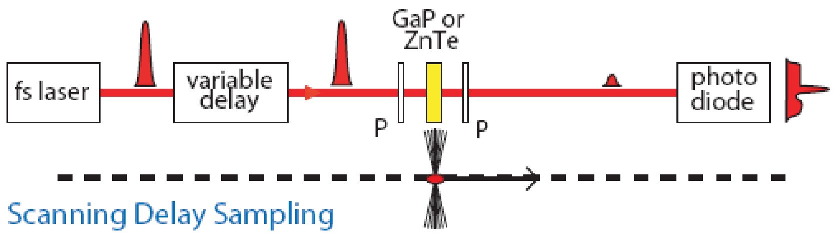
EOS @ FELIX



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

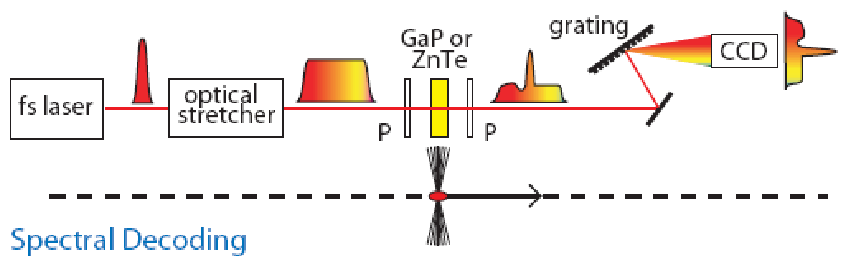
X. Yan *et al*, PRL 85, 3404 (2000)

Electro Optic based bunch length monitors



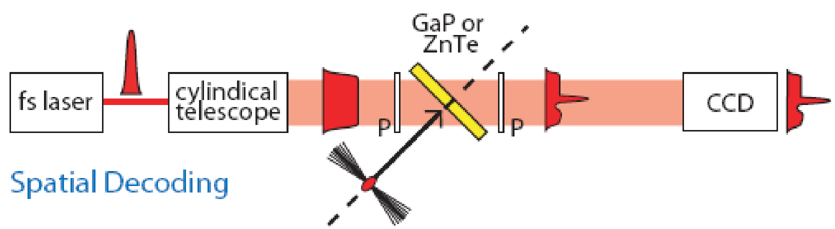
1. Sampling:
- multi-shot method
- arbitrary time window possible

1



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

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

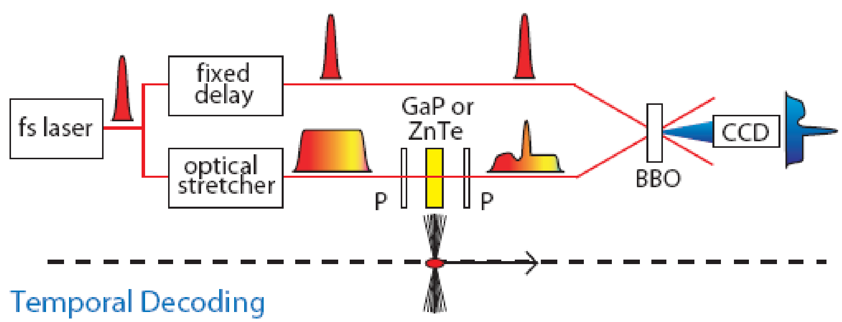


3. Spatial encoding:
- imaging limitation ~ 30-50 fs

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

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

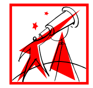
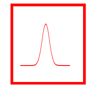
Van Tilborg *et. al*, Opt. Lett. 32 (2007) 313



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

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

Classification and Summary

	 	 σ	1 n!	Limitations
• 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				Jitter (50fs)
• Non linear mixing		X	X	
• Thomson/Compton scattering	X	X	X	Electron
• Photo-neutralisation	X	X	X	H^-
• Electro-Optic Sampling				
• E-O Spectral decoding	X	X	X	~ 200fs
• E-O Spatial decoding	X	X	X	~ 50fs
• E-O Temporal decoding	X	X	X	~ 50fs

To be continued..

Longitudinal Beam Profile part 2
by P. Karataev