The CERN Accelerator School

Longitudinal Beam Diagnostics

6 – 18 November 2022
Neaclub, Sévrier, France

T. Lefevre, CERN

Outline

- Longitudinal beam profile in accelerators

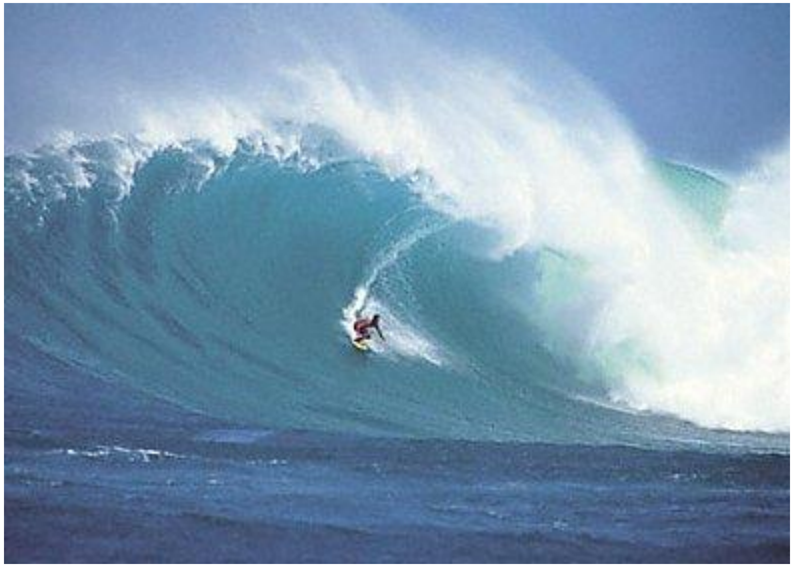
- Invasive and Non-invasive techniques
  - Explain concepts
  - Review performances and limitations

Accelerating charged particles

Acceleration techniques

DC Accelerator

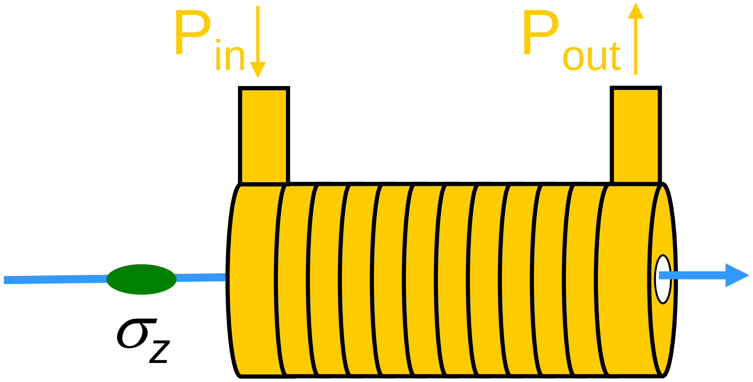
RF Accelerator

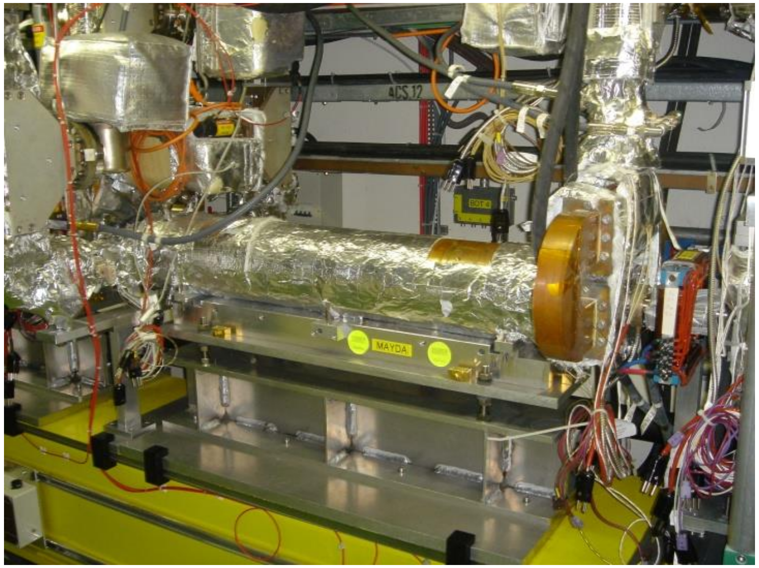


synchronizing particle
with an
electromagnetic wave!

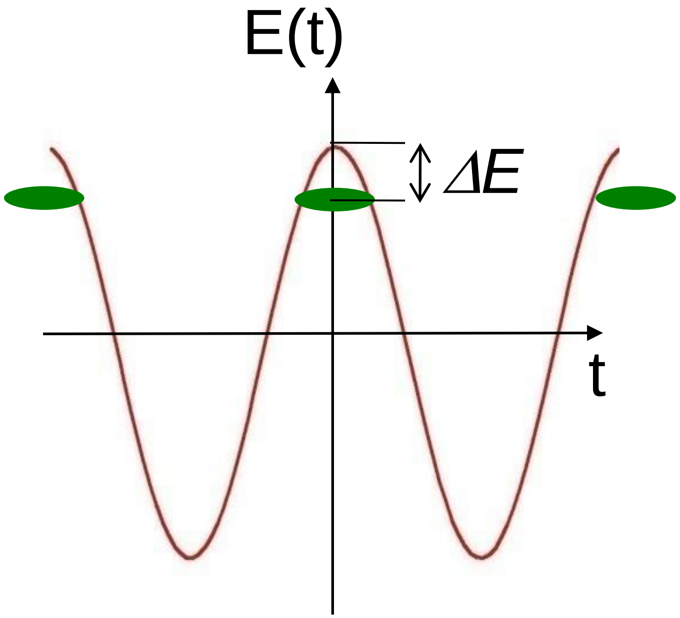
Acceleration techniques

RF Accelerating structures





RF Accelerating Field

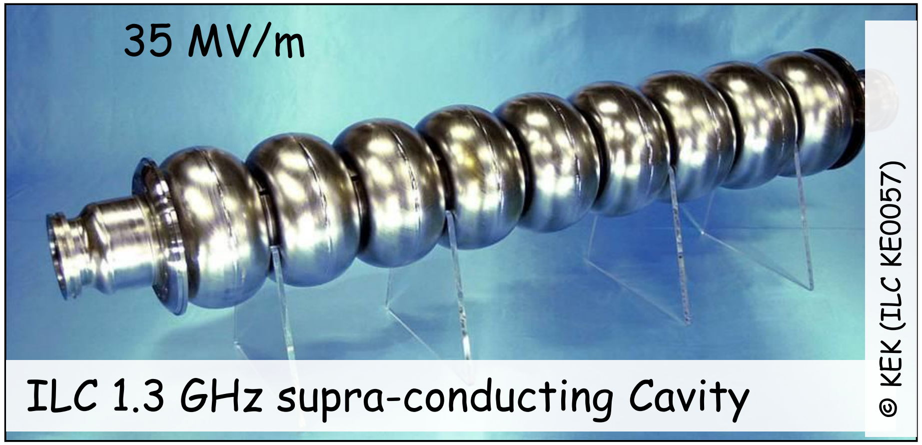


At 3GHz accelerating frequency

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

Accelerating cavities

CERN PS 19 MHz Cavity (prototype 1966)



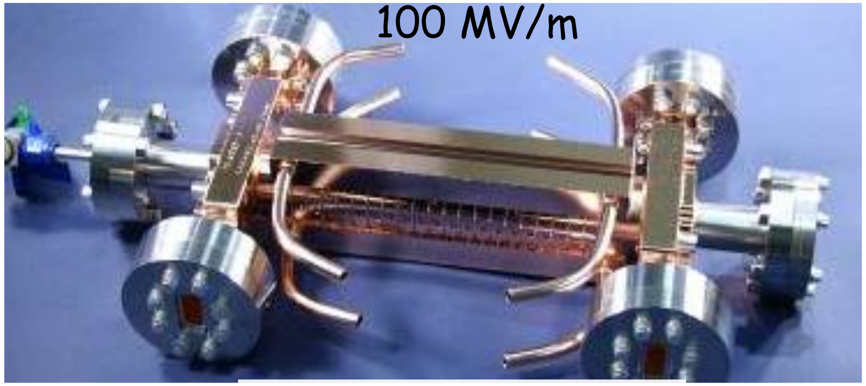
35 MV/m

ILC 1.3 GHz supra-conducting Cavity

© KEK (ILC KE0057)

5MV/m

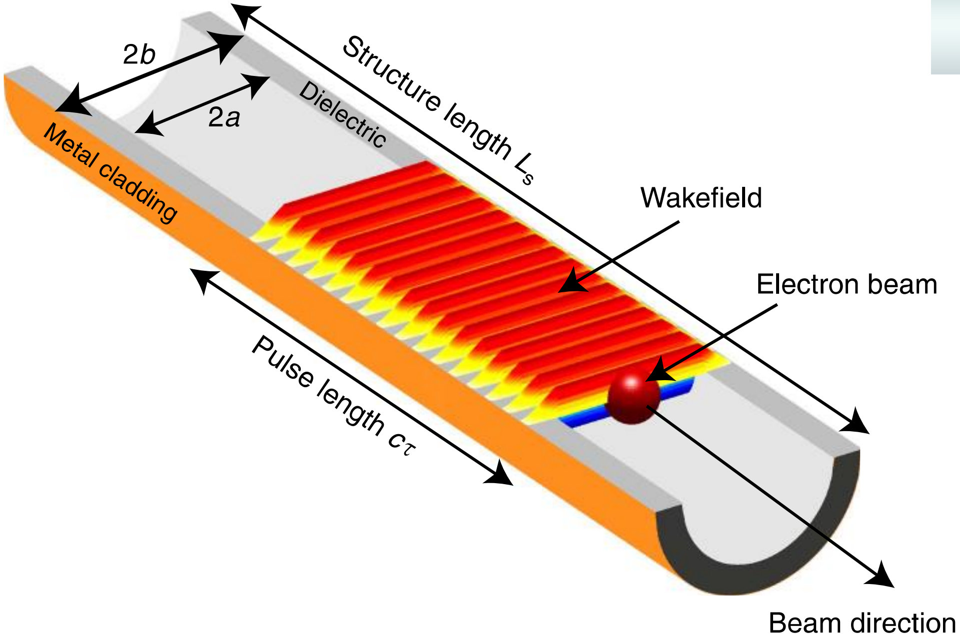
400MHz LHC Cavity in its cryo-module

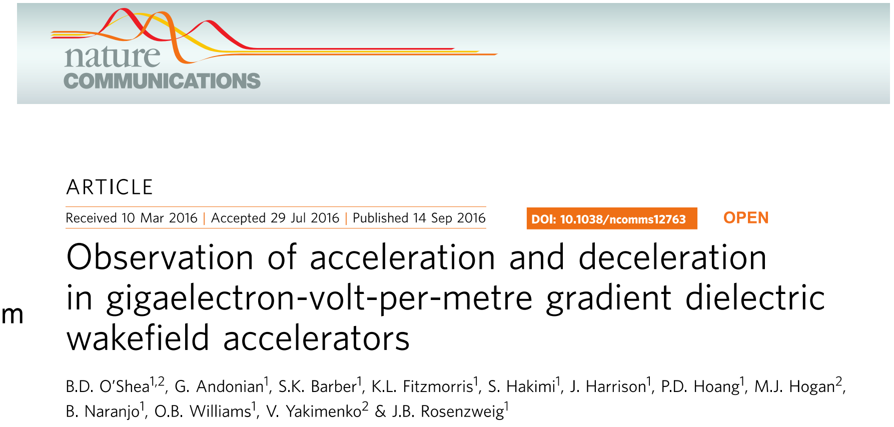


100 MV/m

CLIC 12 GHz Cavity

Dielectric Wakefield Acceleration





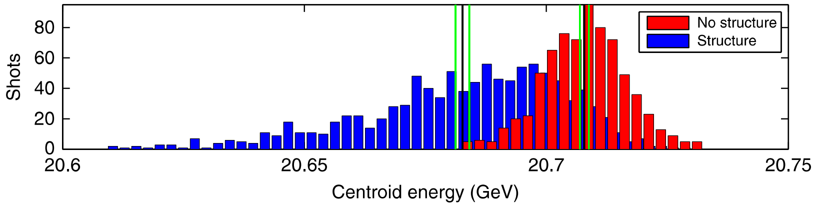
nature COMMUNICATIONS

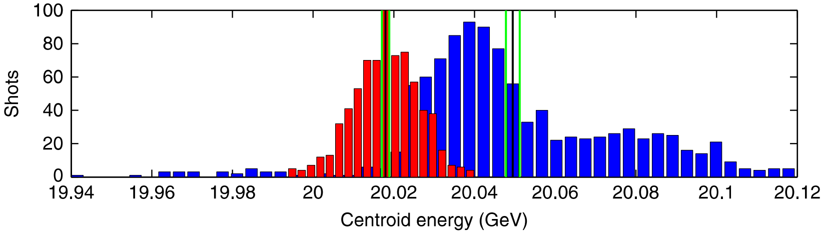
ARTICLE

Received 10 Mar 2016 | Accepted 29 Jul 2016 | Published 14 Sep 2016 DOI: 10.1038/ncomms12763 OPEN

Observation of acceleration and deceleration in gigaelectron-volt-per-metre gradient dielectric wakefield accelerators

B.D. O'Shea[1,2], G. Andonian[1], S.K. Barber[1], K.L. Fitzmorris[1], S. Hakimi[1], J. Harrison[1], P.D. Hoang[1], M.J. Hogan[2], B. Naranjo[1], O.B. Williams[1], V. Yakimenko[2] & J.B. Rosenzweig[1]





<u>SiO_2 - 15cm long dielectric</u>

Outer diameter : 2b-400um

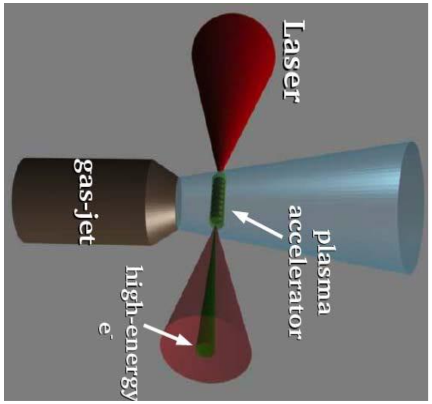
Inner diameter : 2a-300um

Beam size 30um

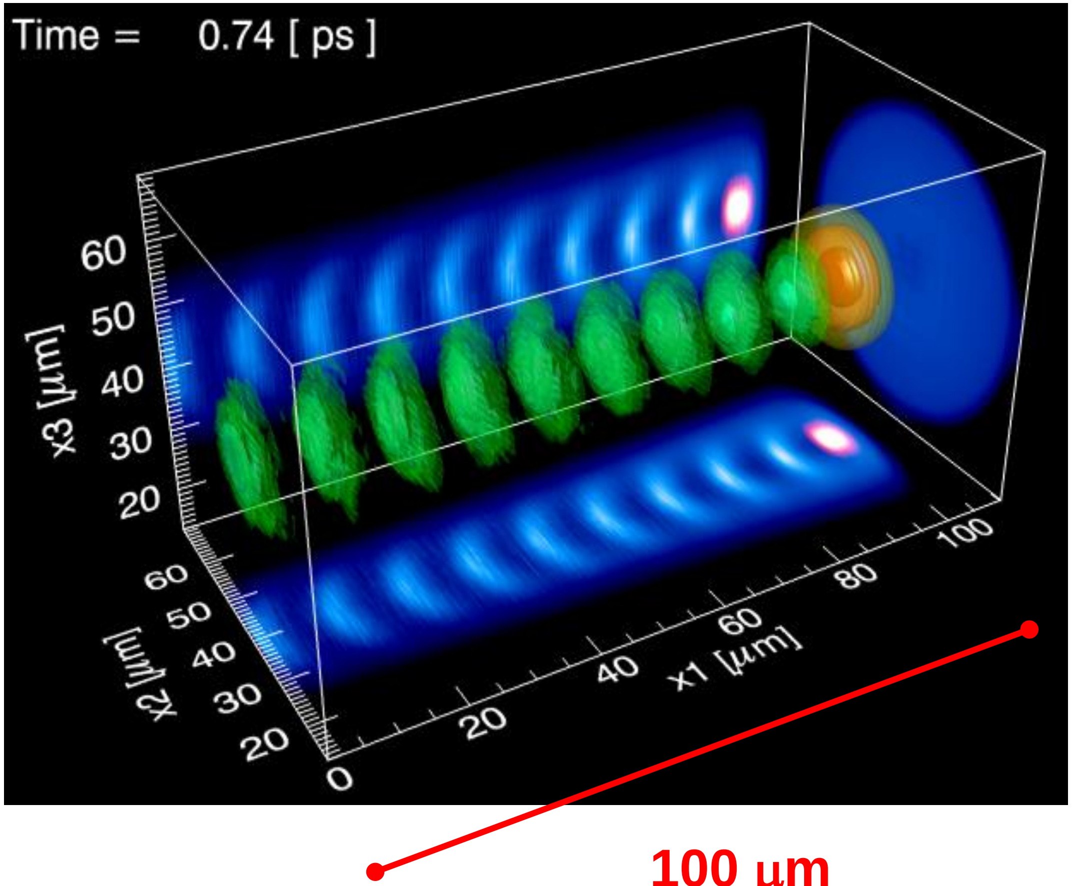
Bunch length 25um (W) and 55um (D)

Δt (D-W) = 250um – 833fs

Laser Plasma Wakefield Acceleration

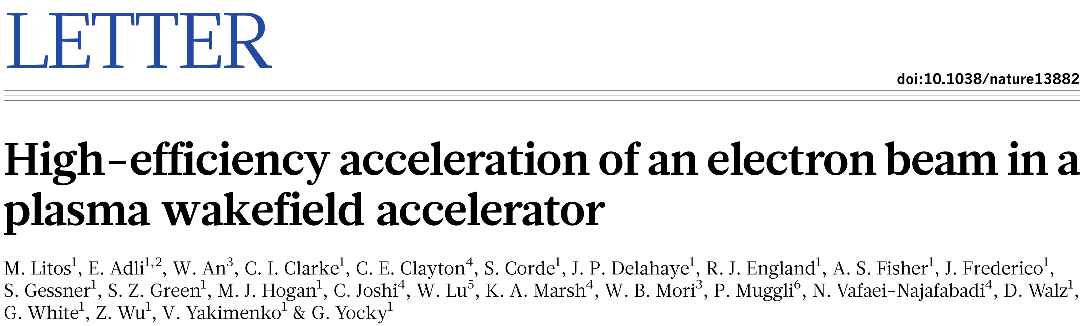


Courtesy of W. Mori & L. da Silva



100 μm

Beam Plasma Wakefield Acceleration

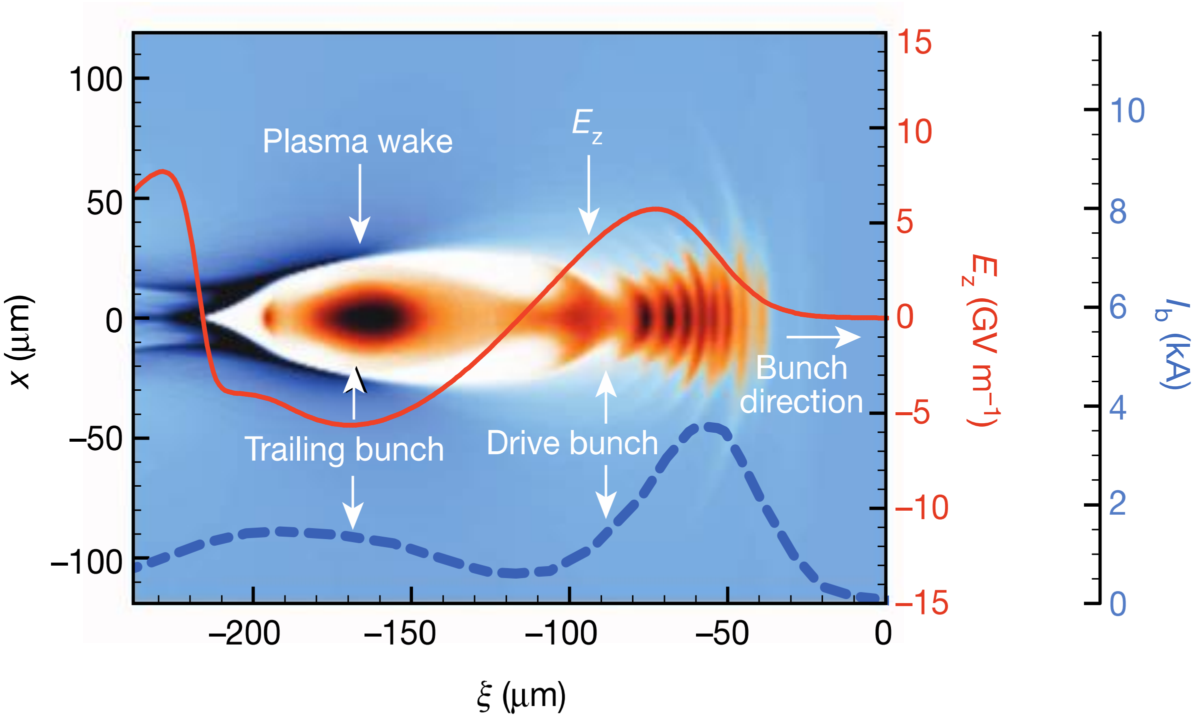


LETTER

doi:10.1038/nature13882

High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

M. Litos[1], E. Adli[1,2], W. An[3], C. I. Clarke[1], C. E. Clayton[4], S. Corde[1], J. P. Delahaye[1], R. J. England[1], A. S. Fisher[1], J. Frederico[1], S. Gessner[1], S. Z. Green[1], M. J. Hogan[1], C. Joshi[4], W. Lu[5], K. A. Marsh[4], W. B. Mori[3], P. Muggli[6], N. Vafaei-Najafabadi[4], D. Walz[1], G. White[1], Z. Wu[1], V. Yakimenko[1] & G. Yocky[1]



Typical bunch length

H^- @ SNS	100ps
H^+ @ LHC	230ps
e^- @ CLIC	130fs
e^- @ XFEL	10fs
e^- @ DWFA	<60fs
e^- @ PWFA	<30fs
e^- @ LWFA	<10fs

Bunch length measurement techniques

Bunch length measurement techniques

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

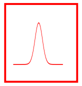
RF manipulation

Use RF techniques to convert time information into transverse information

Laser-based beam diagnostic

Using short laser pulses and sampling techniques

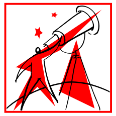
Bunch length measurement techniques

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 density : No risk of damage by the beam itself*

Bunch length measurement techniques

Do not forget about **Simplicity and Reliability**

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

⬇

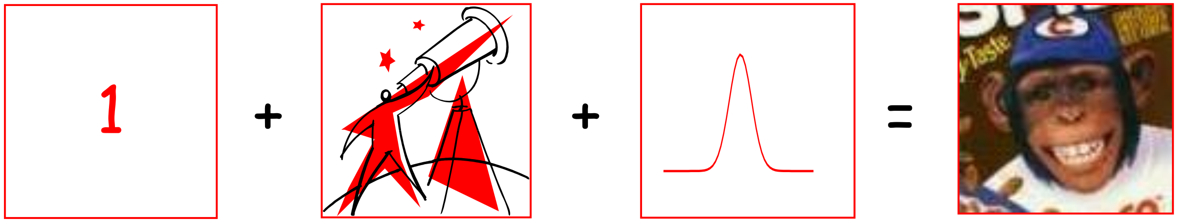
A detector, what for ?

- 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

Bunch length measurement techniques

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



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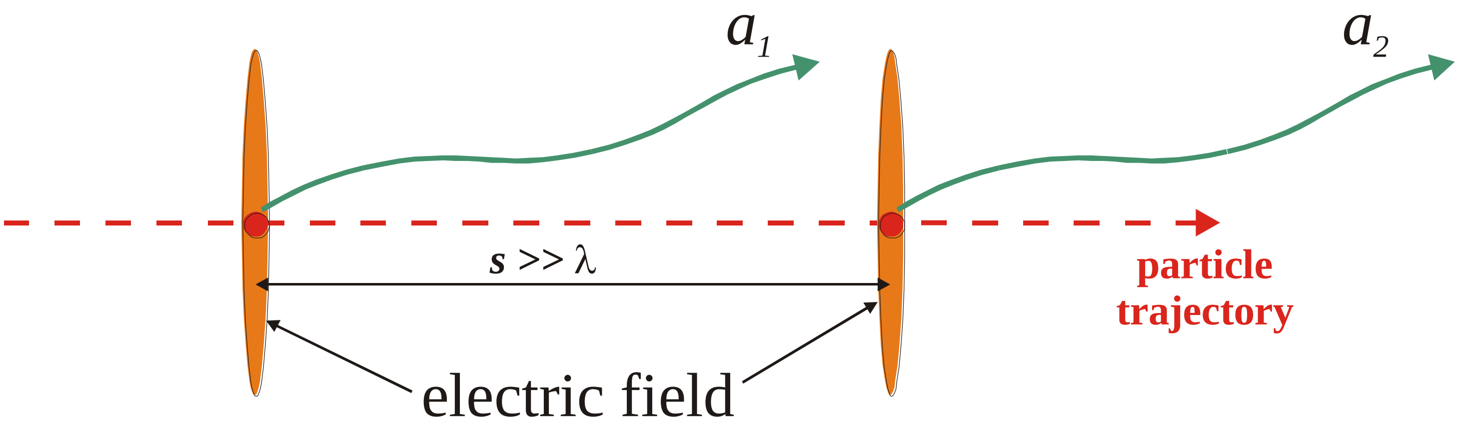
Radiative techniques

‘Converting particles into photons’

Incoherent versus Coherent Radiation

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

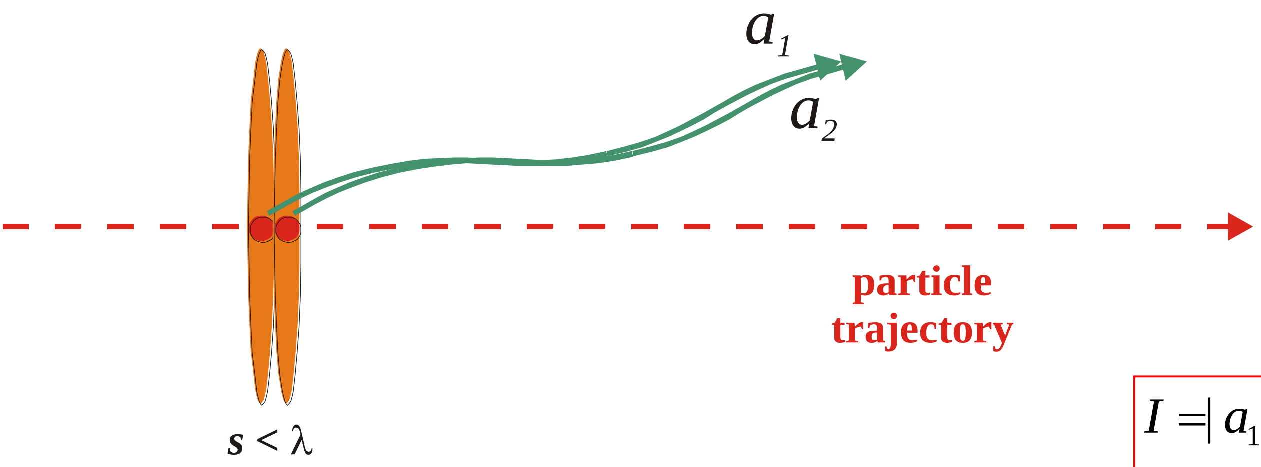


$$\boxed{I = |a_1|^2 + |a_2|^2 = 2|a|^2 \rightarrow N|a|^2}$$

Incoherent radiation

Incoherent versus Coherent Radiation

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



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

Coherent radiation

Total 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

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

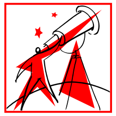
$\rho(s)$ – Longitudinal particle distribution in a bunch

Radiative processes

- Transition radiation
- Cherenkov radiation

Better for $\gamma > 100$

$\beta > 1/n$



- Diffraction radiation
- Cherenkov Diffraction radiation
- Synchrotron radiation

For incoherent radiation

$$\gamma > 3000$$

For coherent radiation

$$\gamma > \frac{0.06}{\sigma_z(m)}$$

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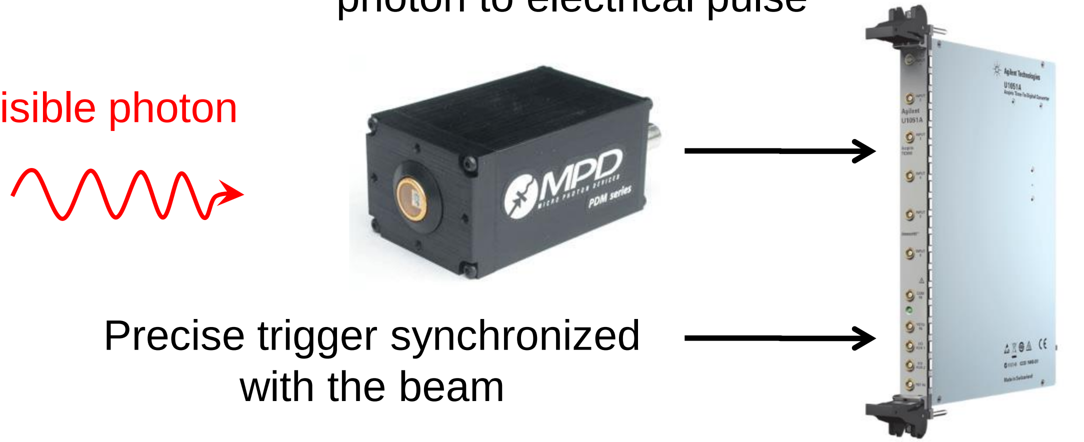
Optical method using Incoherent light

Time correlated single photon counting

n!



Geiger-mode Avalanche photodiode converts photon to electrical pulse

Visible photon

Time to Digital converter records pulse arrival time

Precise trigger synchronized with the beam

- Sampling Method allowing very high dynamic range if you measure long enough

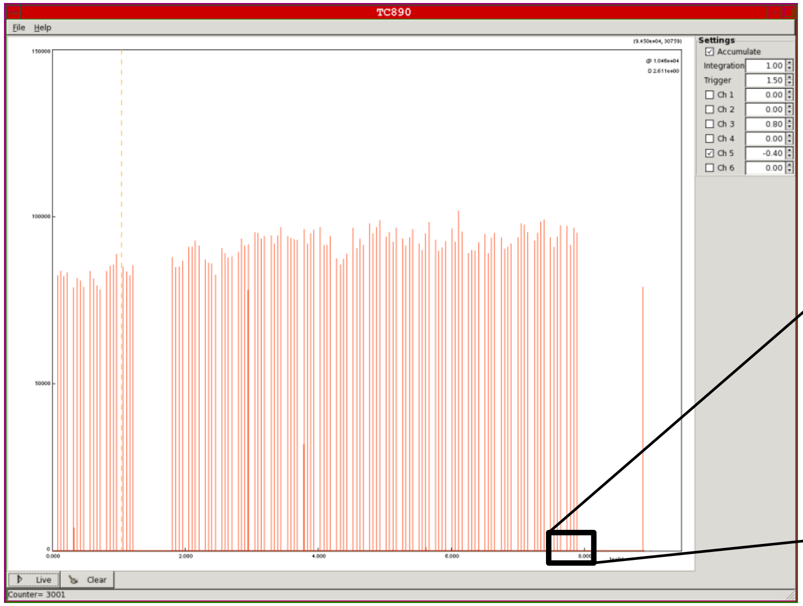
- Avalanche photodiode have deadtime and are subject to after-pulsing
- State of the art TDC typically limited to 10ps sampling

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

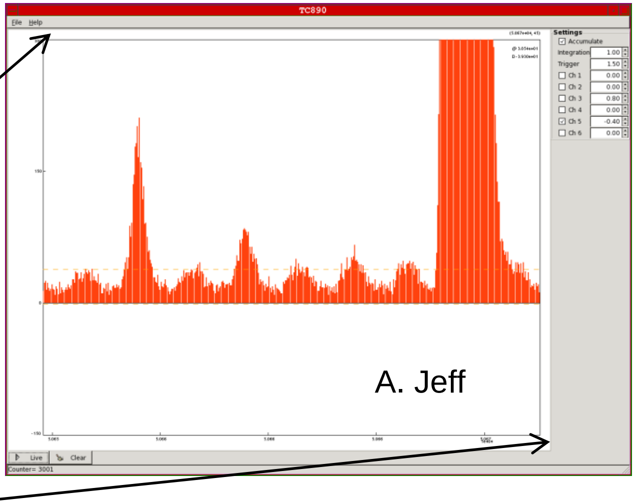
n!

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



Settings
☑ Accumulate
Integration 1.00
Trigger 1.50
☐ Ch 1 0.00
☐ Ch 2 0.00
☐ Ch 3 0.80
☐ Ch 4 0.00
☑ Ch 5 -0.40
☐ Ch 6 0.00

Counter= 3001

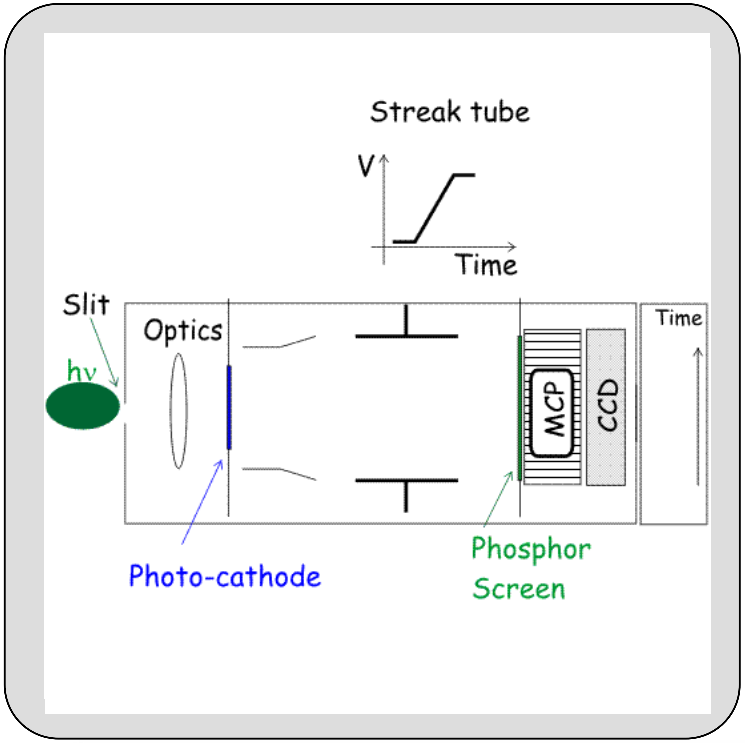


A. Jeff

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

Streak Camera

1



'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***

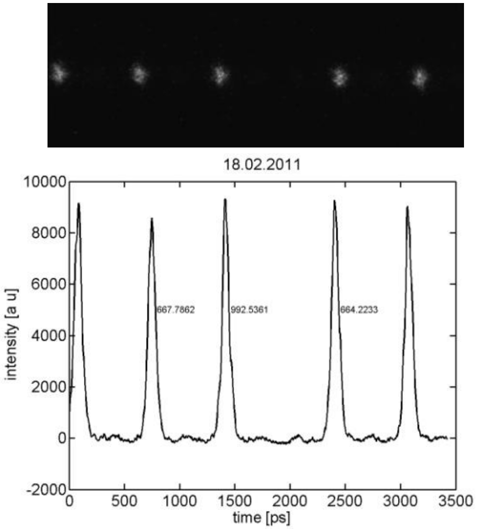
200fs time resolution obtained using reflective optics and 12.5nm bandwidth optical filter (800nm) and the Hamamatsu FESCA 200

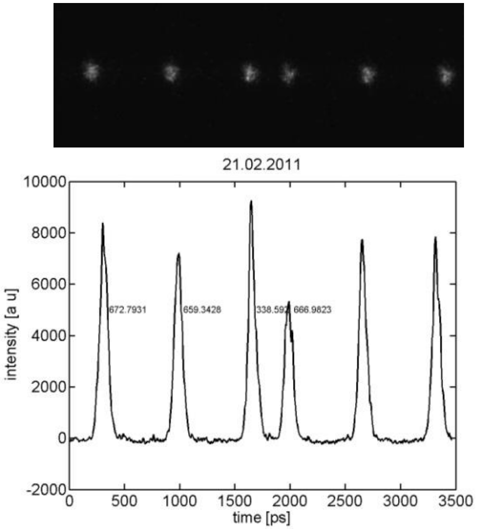
Limitations : Time resolution of the streak camera :

(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

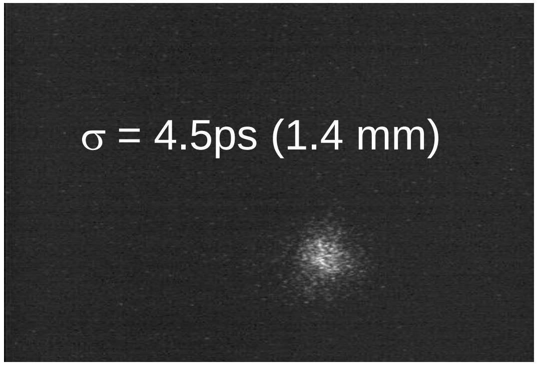
Streak Camera

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



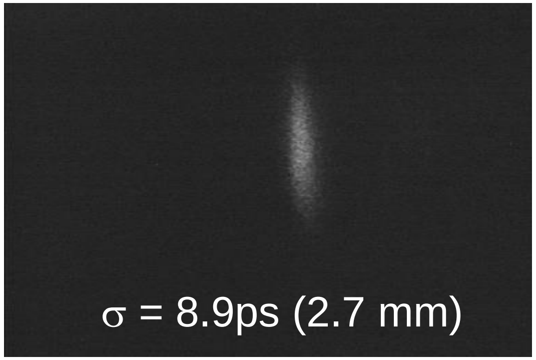


Measure of bunch length using OTR and OSR



σ = 4.5ps (1.4 mm)

Sweep speed of 10ps/mm



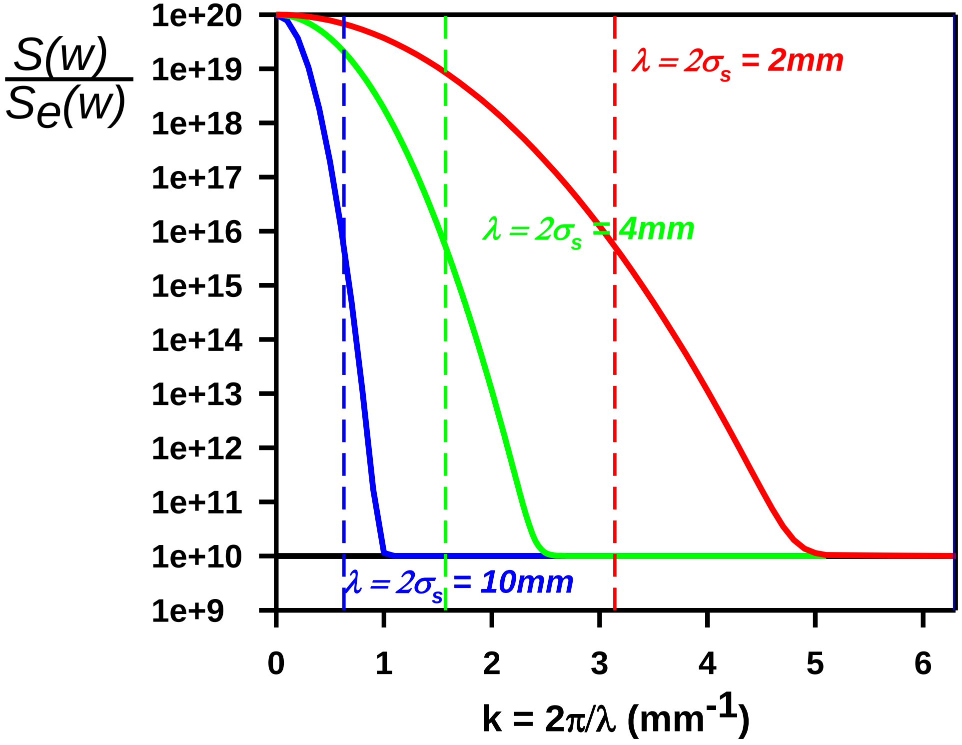
σ = 8.9ps (2.7 mm)

Bunch length measurement using using Coherent light

‘The shorter in time the broader in frequency’

Bunch form factor

$$F(\omega) = \left| \int_{-\infty}^{\infty} dz \rho(z) e^{i(\omega/c)z} \right|^2 \qquad \rho(z) = \frac{1}{\pi c} \int_0^{\infty} d\omega \sqrt{F(\omega)} \cos\left(\frac{\omega z}{c}\right)$$



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

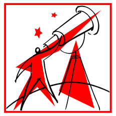
Measuring the Radiation Spectrum

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

- ✓ $S(\omega)$– radiation spectrum (known in the experiment)
- ✓ N – number of particles s / bunch (known from the experiment)
- ✓ $F(\omega)$– 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**



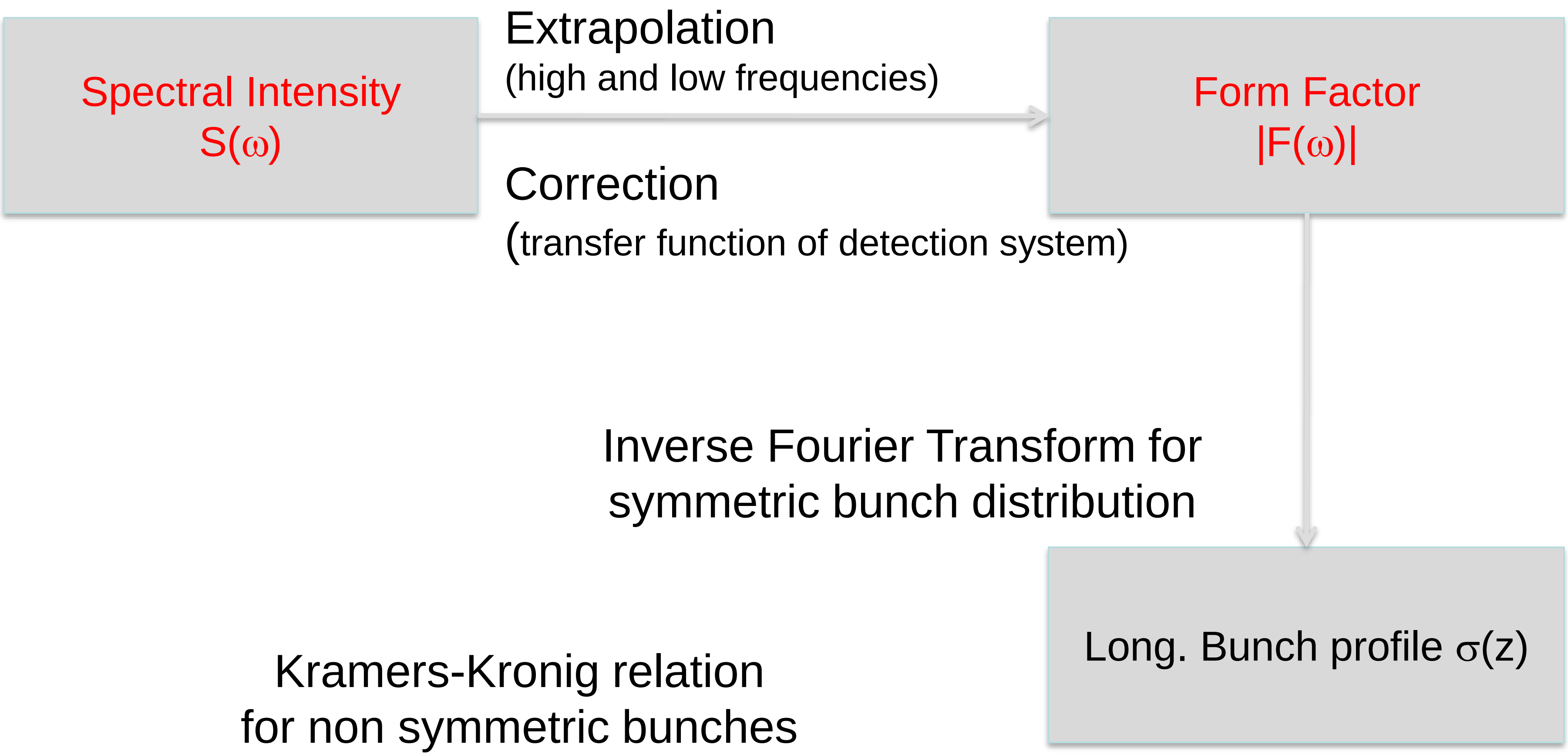
Coherent Diffraction (CDR) or Coherent Synchrotron (CSR)

B. Feng et al, **NIM A 475 (2001) 492–497 ;** A.H. Lumpkin et al, **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**

Measuring the Radiation Spectrum

Frequency Domain



Spectral Intensity
$S(\omega)$

Extrapolation
(high and low frequencies)

Correction
(transfer function of detection system)

Form Factor
$|F(\omega)|$

Inverse Fourier Transform for symmetric bunch distribution

Long. Bunch profile $\sigma(z)$

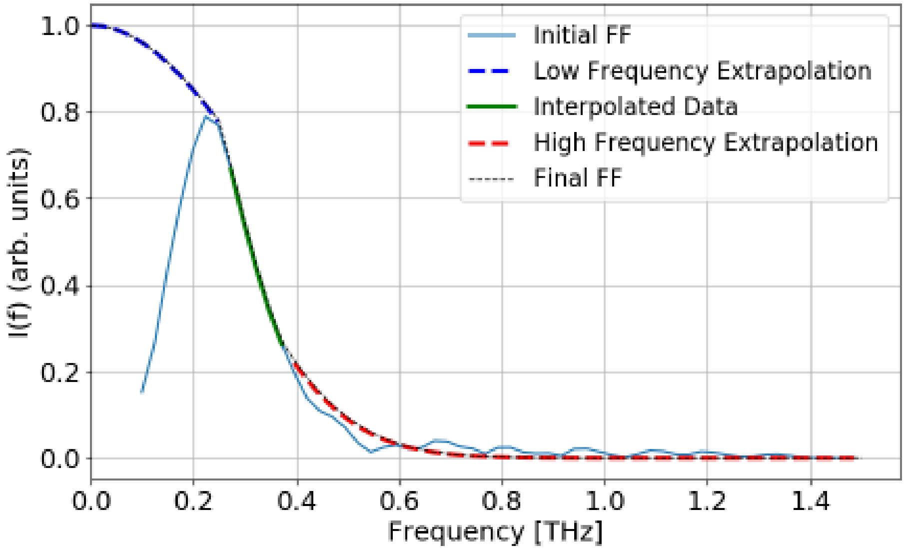
Kramers-Kronig relation
for non symmetric bunches

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

Time Domain

Measuring the Radiation Spectrum

Frequency Domain



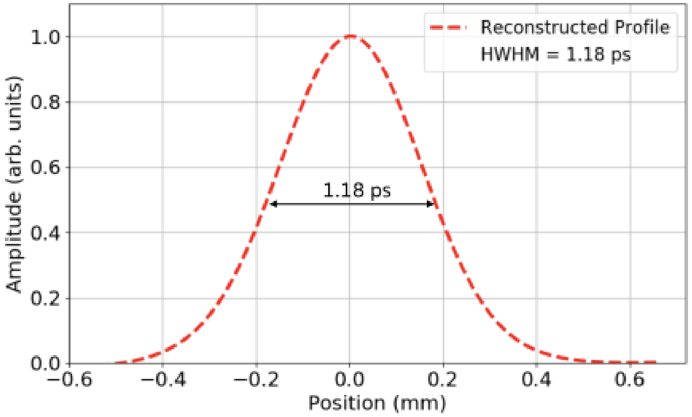
- Extrapolation

(high and low frequencies)

- Correction

(transfer function of detection system)

Inverse Fourier Transform using Kramer kronig relation



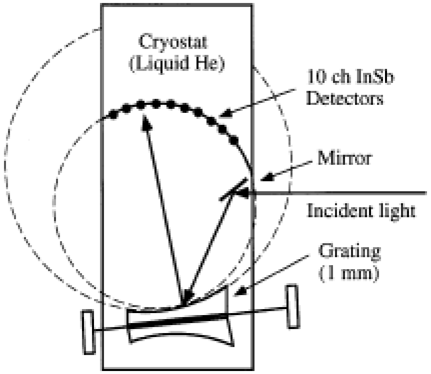
Time Domain

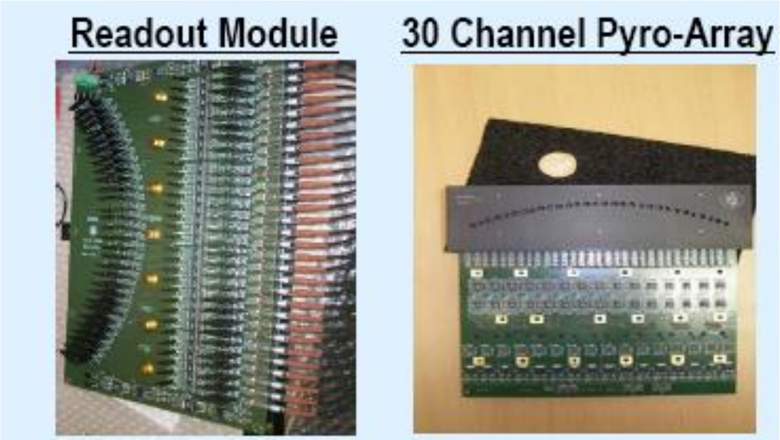
Measuring the Radiation Spectrum

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’*

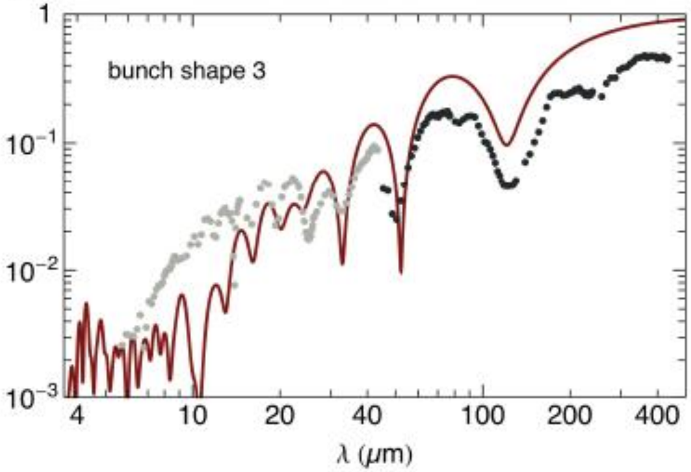
T. Wanatabe et al., NIM-A 480 (2002) 315-327
H. Delsim-Hashemiet al., Proc. FLS, Hamburg 2006, WG512





B. Schmidt, DESY

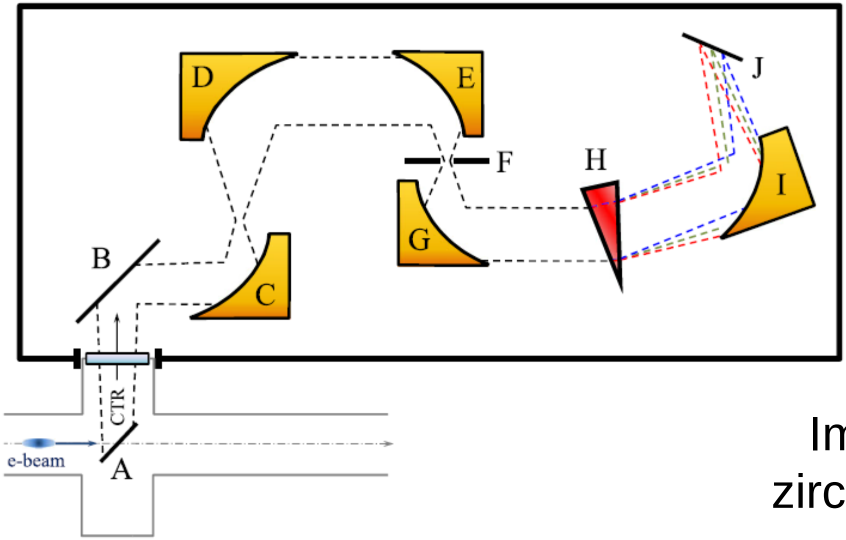
Measured & calculated spectra



(E. Hass et al., Proc. SPIE 8778, May 2013)

Single shot CTR measurements

- T. J. Maxwell et al. "Coherent-radiation spectroscopy of few-femtosecond electron bunches using a middle-infrared prism spectrometer.“ *Physical review letters* 111.18 (2013)



KRS-5 (thallium bromoiodide) prism based spectrometer

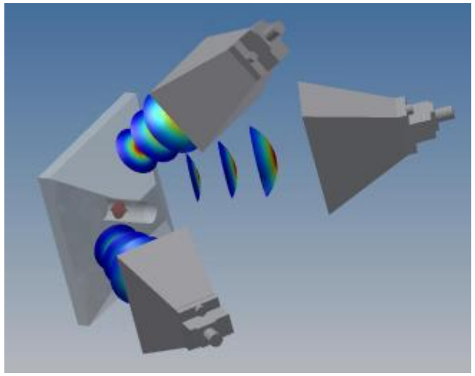
Images CTR from foil onto 128 lead zirconate titanate pyroelectric elements with 100 μm spacing line array

1

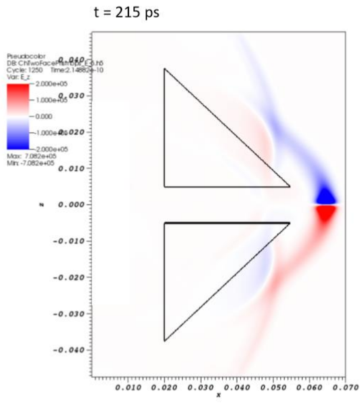
Single-shot Cherenkov diffraction measurement

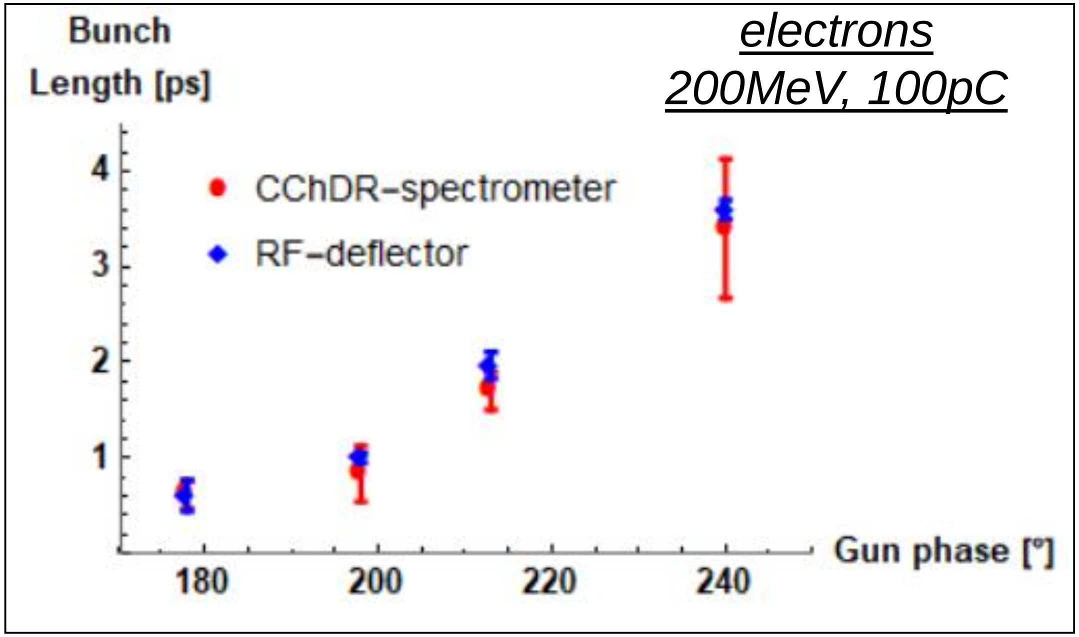
1

Cherenkov diffraction radiation
Measured in 3 bands (60-90-110GHz)



Pyramidal cone
with 1cm aperture





electrons
200MeV, 100pC

A. Curcio et al, PRAB 23 (2018) 022802

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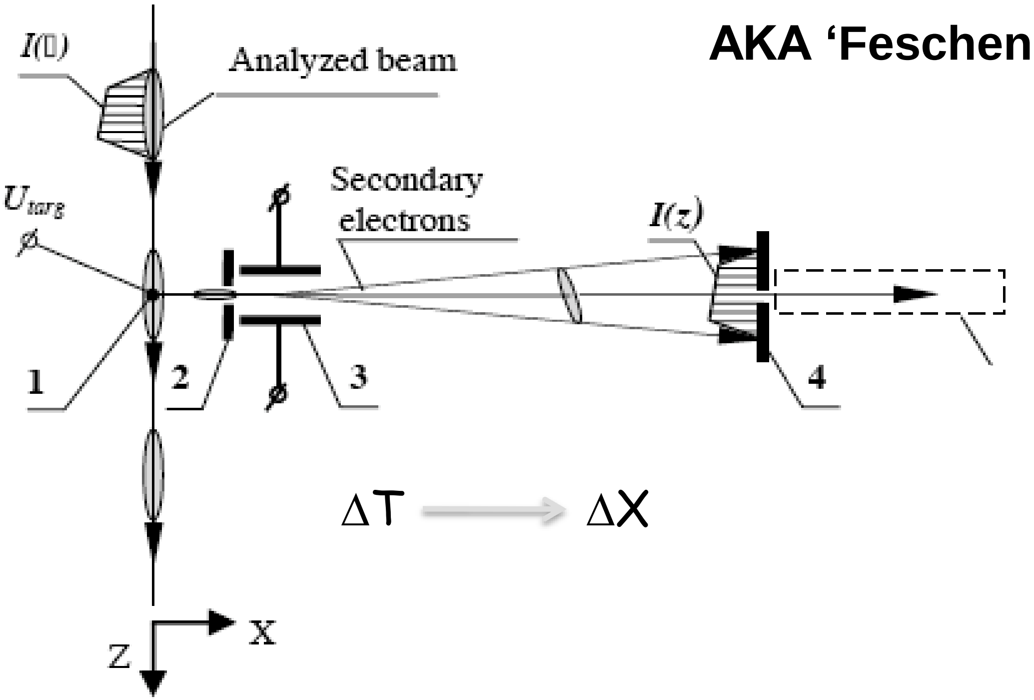
Radiofrequency manipulation

‘How to transform time information into spatial information’

Bunch shape monitor

1

AKA ‘Feschenko monitor’

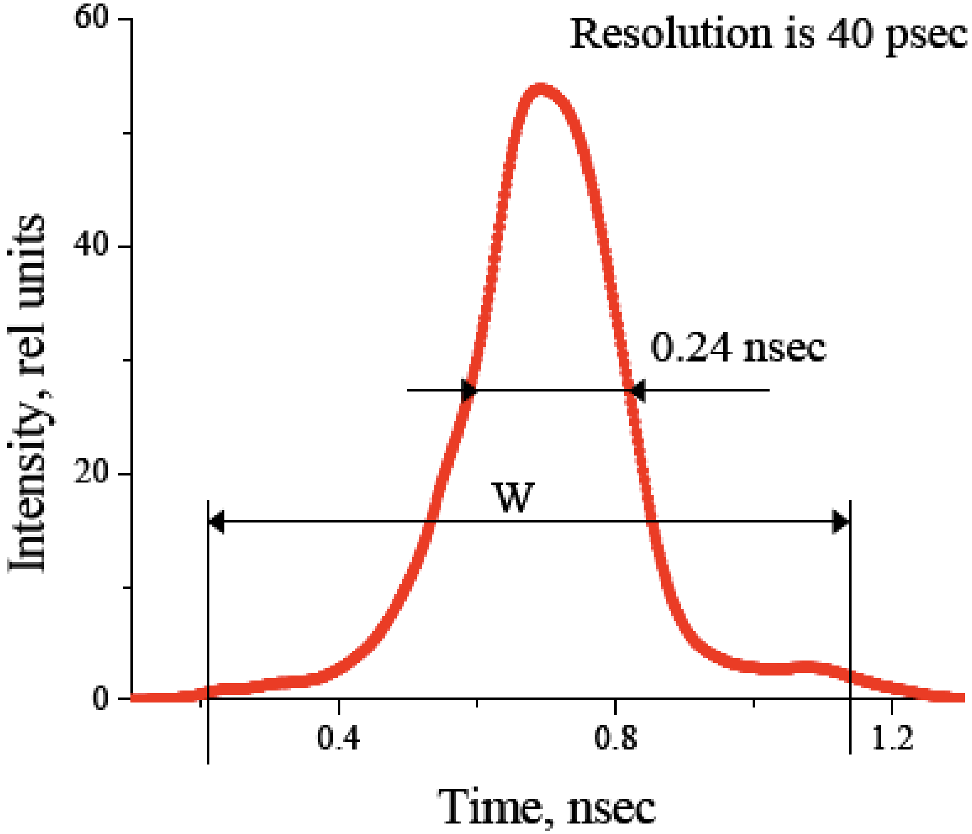


1 - Target (wire, screen, laser for H^-) : Source of secondary electrons
2 - Input collimator
3 - RF deflector (100MHz, 10kV) combined with electrostatic lens
4 - Electron Beam detector (electron multiplier, ..)

Bunch shape monitor

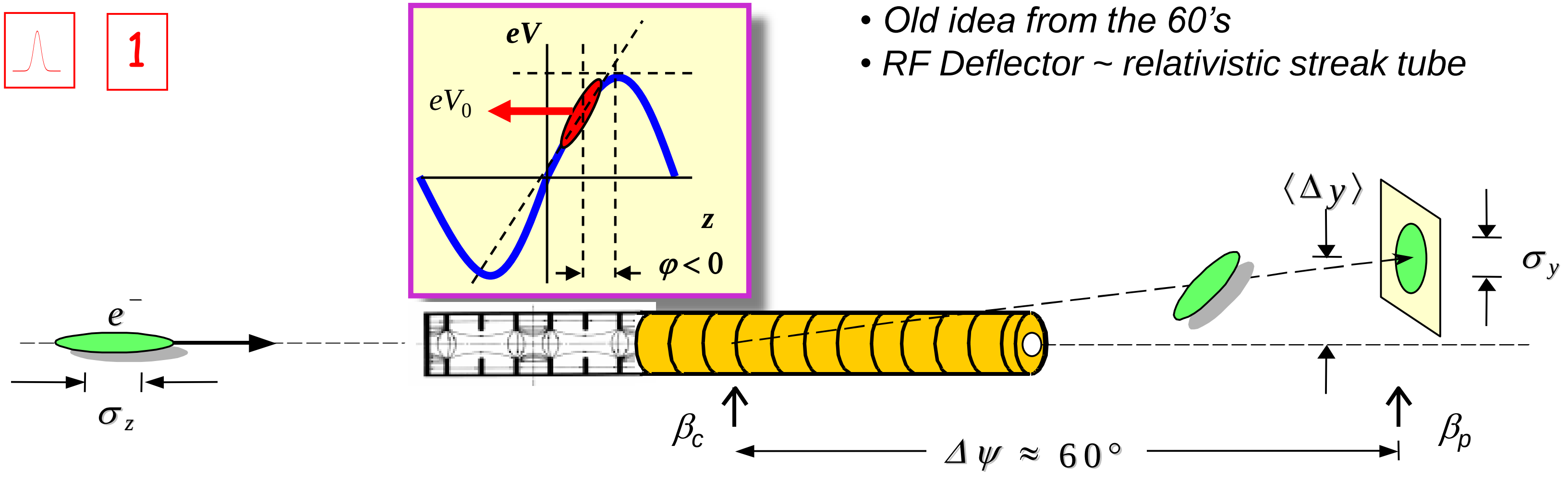
Longitudinal Bunch profile @ SNS

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



RF Deflecting cavities

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



Beam profile RF off

Deflecting Voltage

<u>Beam profile RF on</u>

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

Bunch length

Beta function at cavity and profile monitor

RF deflector wavelength

Beam energy

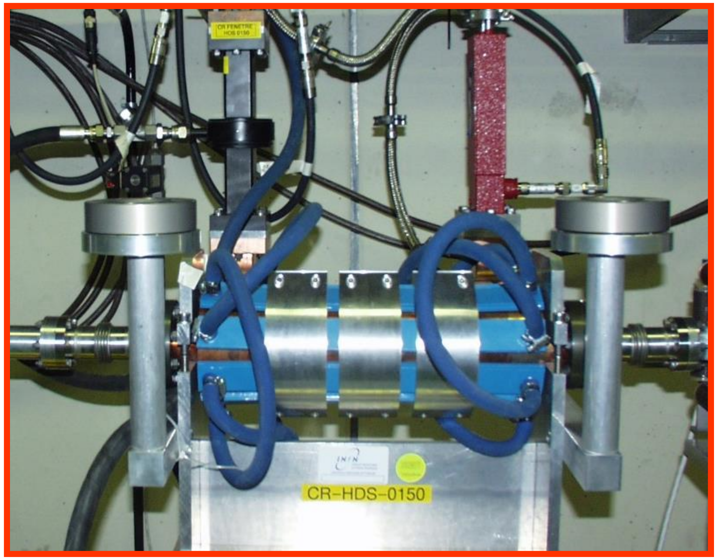
Betatron phase advance (cavity-profile monitor)

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

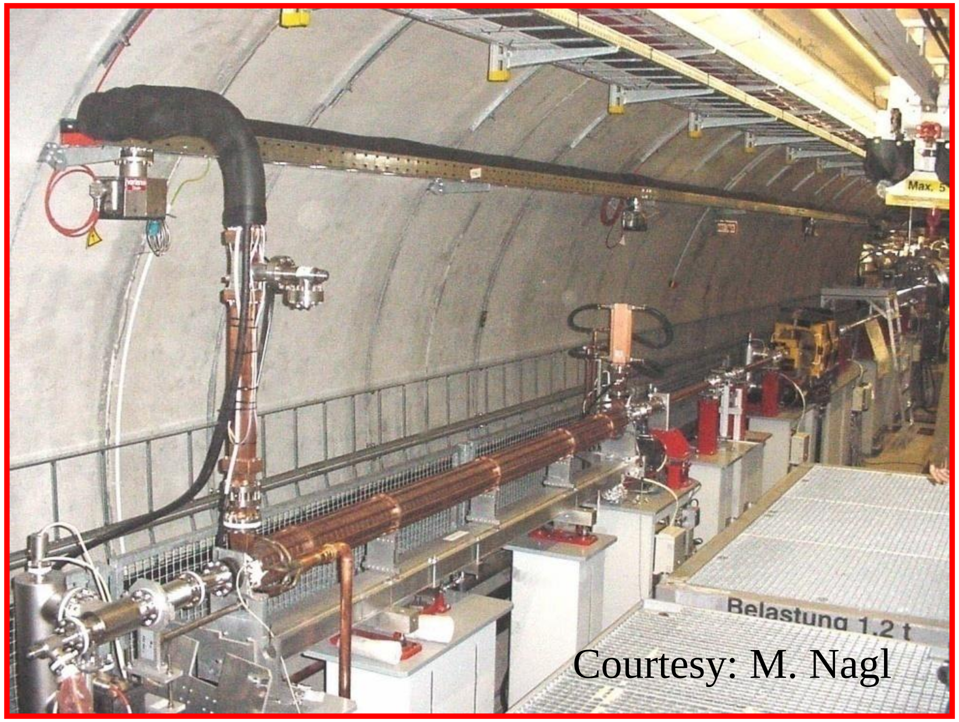
P. Emma et al, LCLS note LCLS-TN-00-12, (2000)

RF Deflecting cavities

CTF3



LOLA @ Flash



Courtesy: M. Nagl

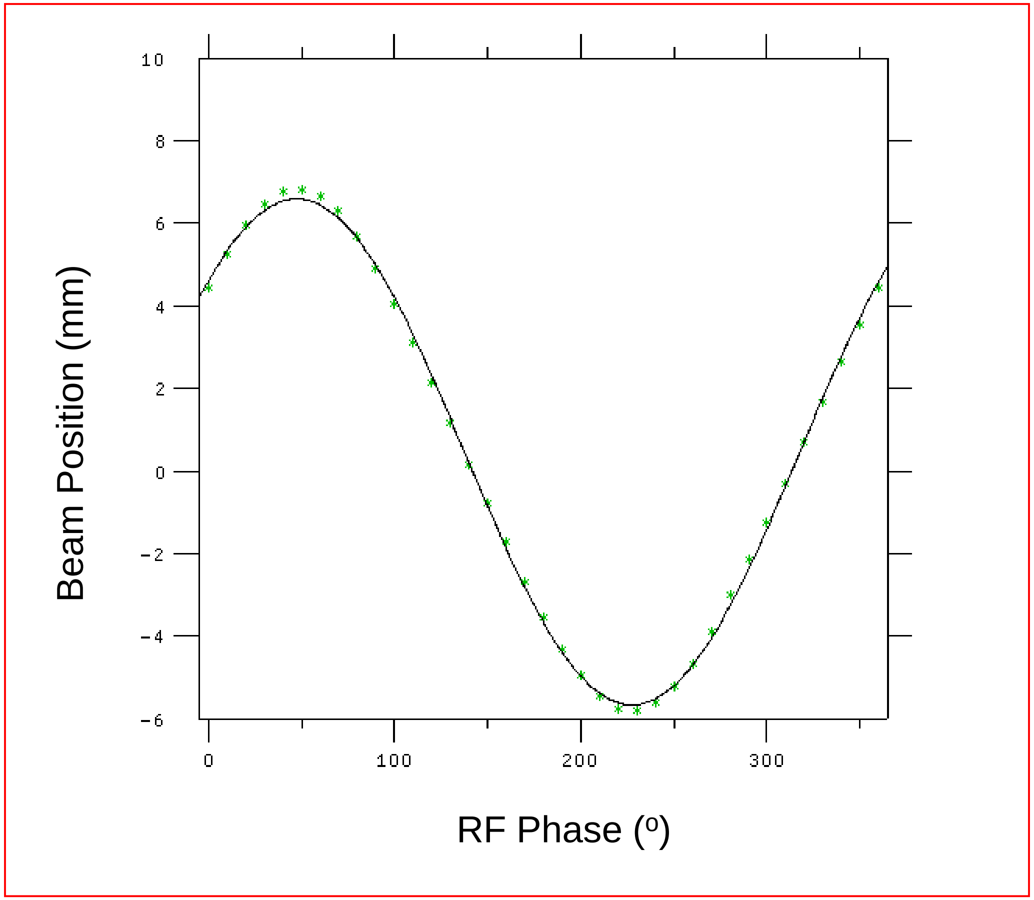
RF Deflecting cavities

Calibration of RF Deflector

$\Delta X(\text{mm}) \rightarrow \Delta\varphi(°)$

$\Delta T(\text{ps})$

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

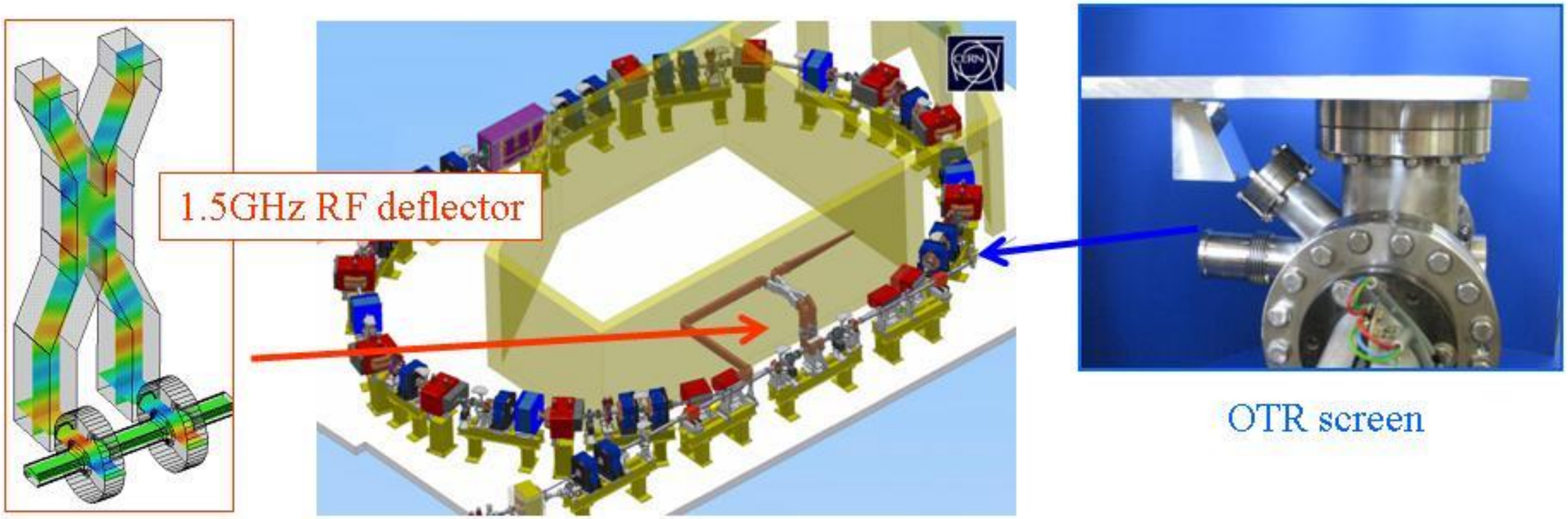


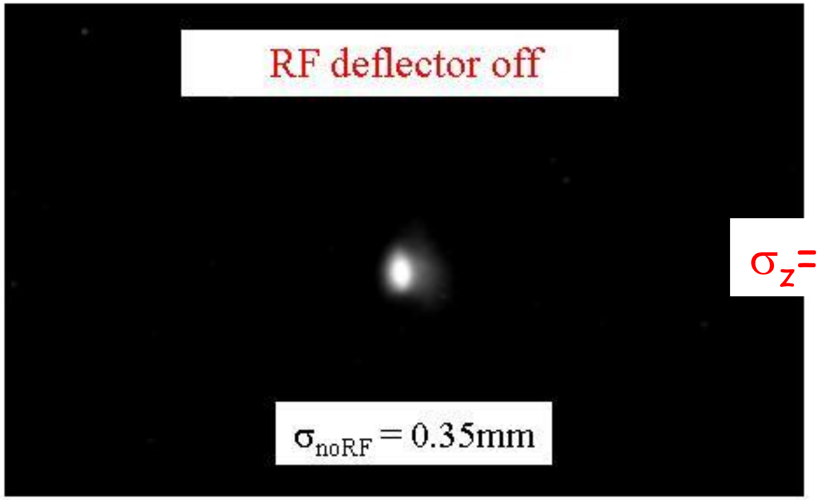
Beam offset on the screen

RF deflector phase

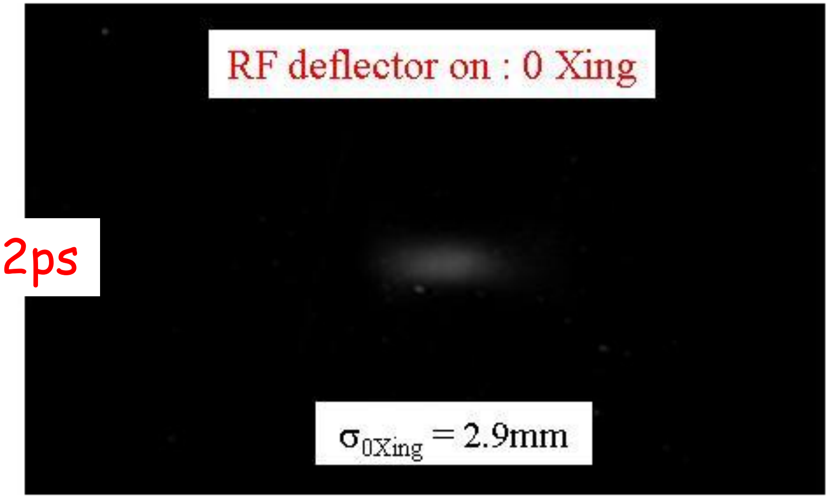
$$\Delta y(z) \approx \frac{eV_0}{E_0} \cdot \sqrt{\beta_c \beta_p}\, \sin(\Delta\Psi)\left(\frac{2\pi}{\lambda} - z\cos(\varphi) + \sin(\varphi)\right)$$

RF Deflecting cavities





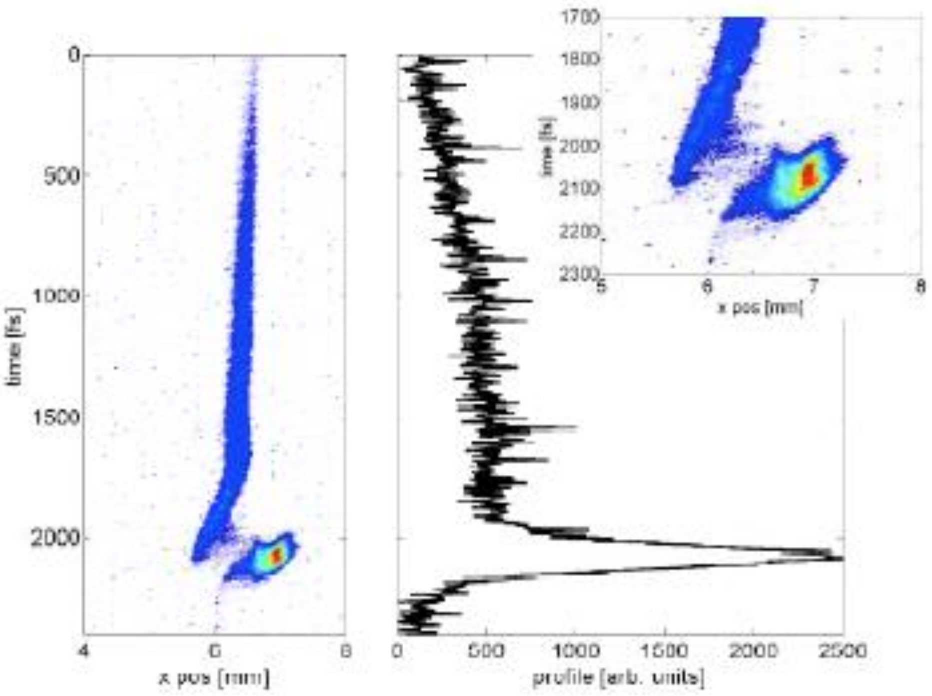
σ_z=2ps



RF Deflecting cavities

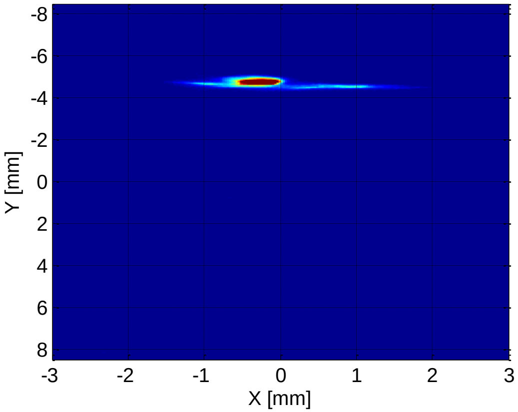
Bunch length measurement @ Flash

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

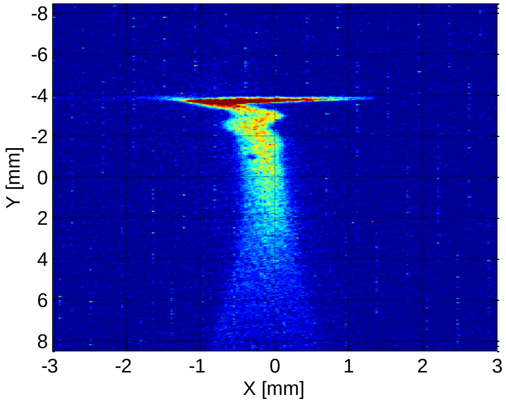


→ Resolution of 4fs/pixels

LOLA off:

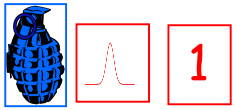


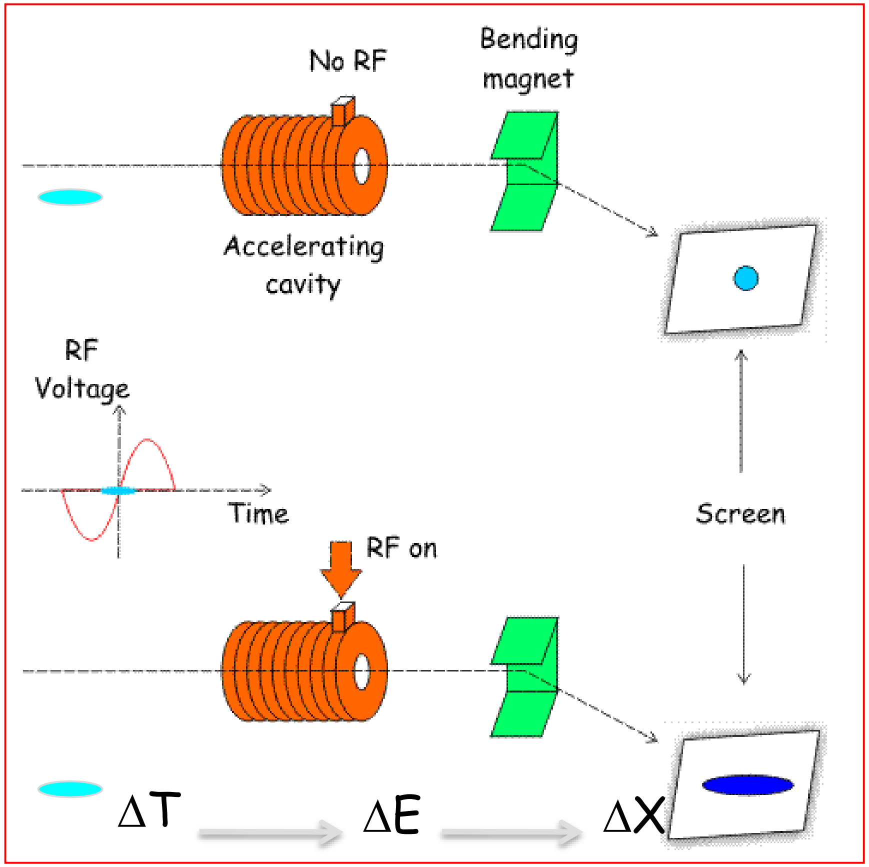
LOLA on:



RF Accelerating cavities

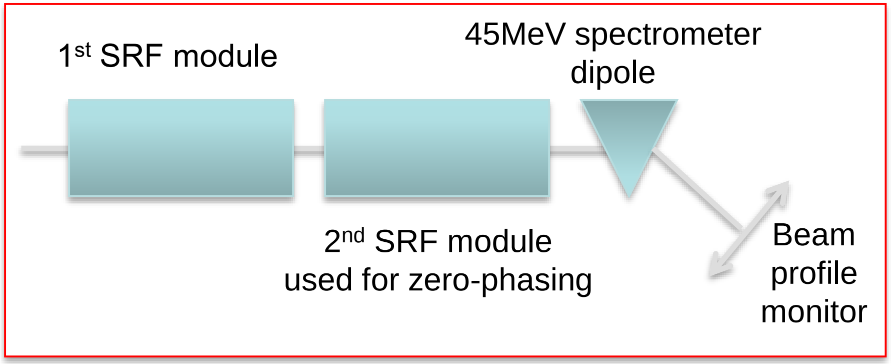
‘The electron energy is modulated by the **zero-phasing** RF accelerating field and the bunch distribution is deduced from the **energy dispersion** measured downstream using a spectrometer line’





RF Accelerating cavities

CEBAF injector, Newport News


1st SRF module

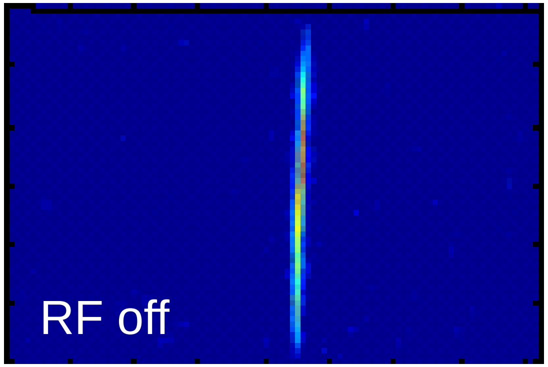
45MeV spectrometer dipole

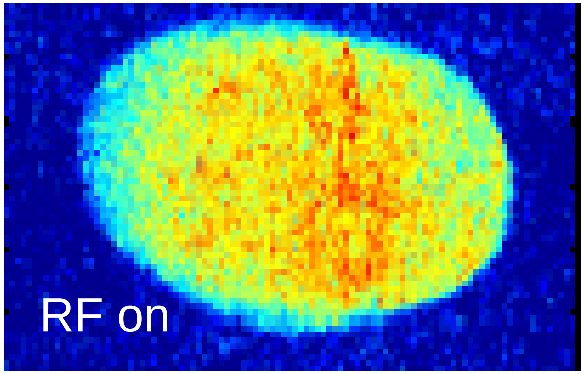
2nd SRF module used for zero-phasing

Beam profile monitor

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

84fs, 45MeV beam but low charge beam





Limitations

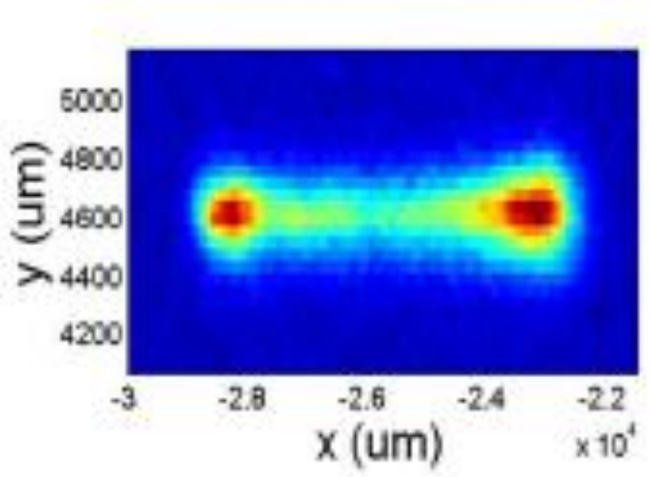
RF non linearities

Beam loading and wakefield for high charge beam

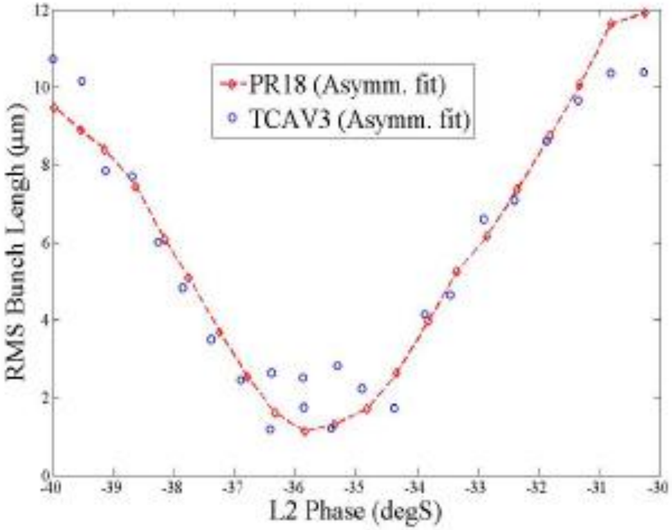
RF Accelerating cavities

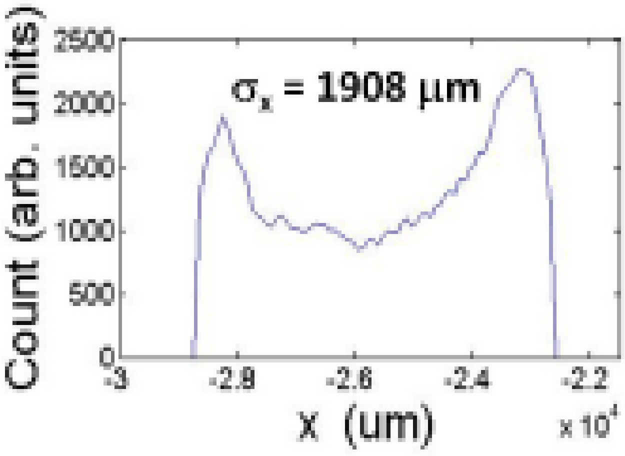
SLAC LCLS: at 4.7 GeV

- 550m of linac at RF zero crossing!
- 6m dispersion in spectrometer line



Z. Huang et al. PAC 2011, FEL2013





TCAV3

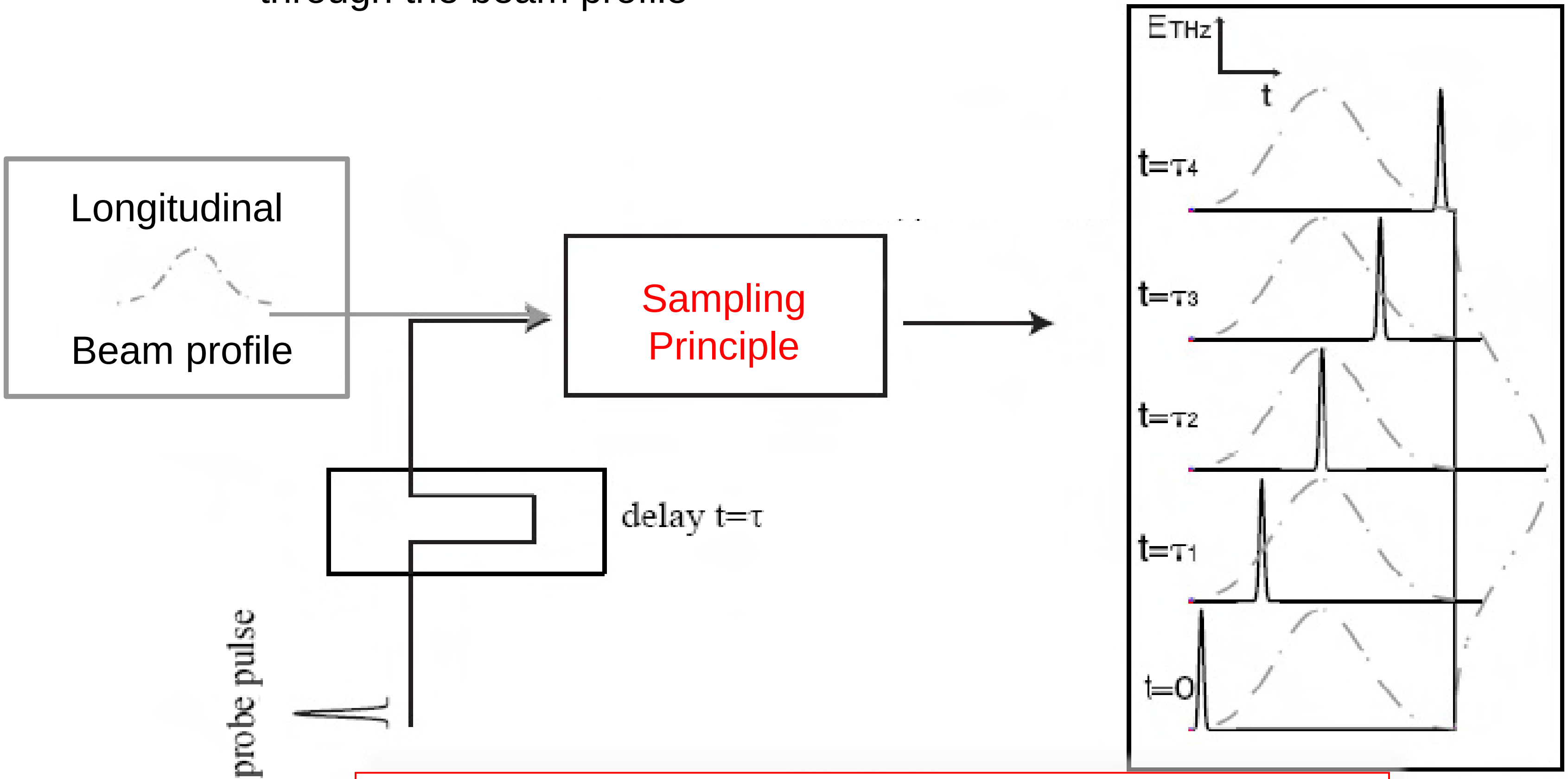
~ 1 fs rms bunch length at 4.7 GeV

The CERN Accelerator School

Laser-based diagnostics

Sampling techniques

Using a short laser pulse to scan through the beam profile



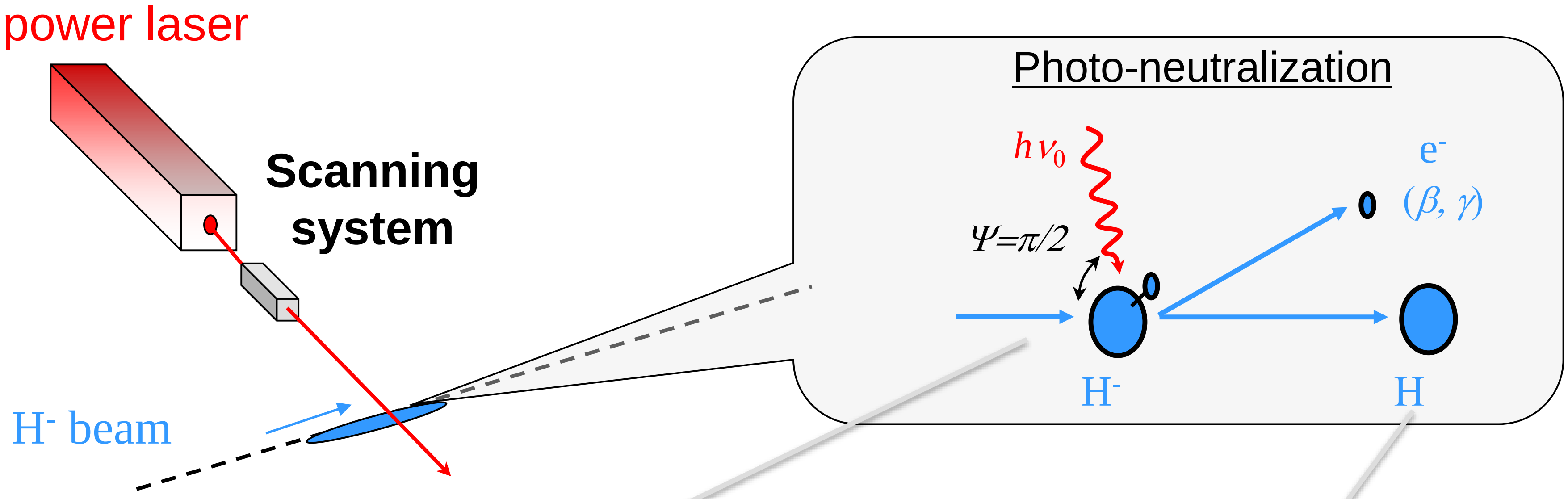
Longitudinal Beam profile

Sampling Principle

Limitation

Laser-beam synchronization jitter should be smaller than the bunch length to measure

Laser Wire Scanner

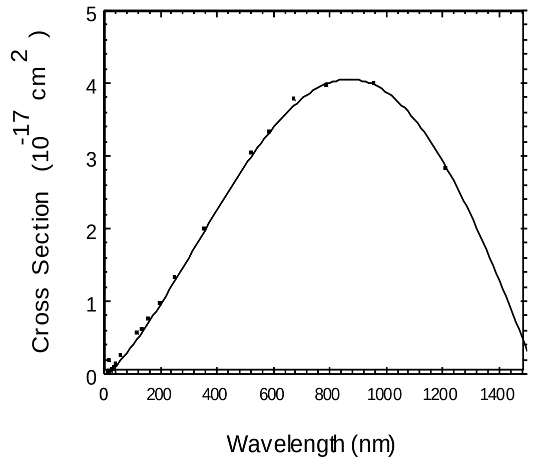


High power laser

Scanning system

Photo-neutralization

- First ionization potential for H^- ions is 0.75eV
- Photo-neutralization cross section : $\sigma \sim 4.10^{-17}$ *cm²*



Detection system based on

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

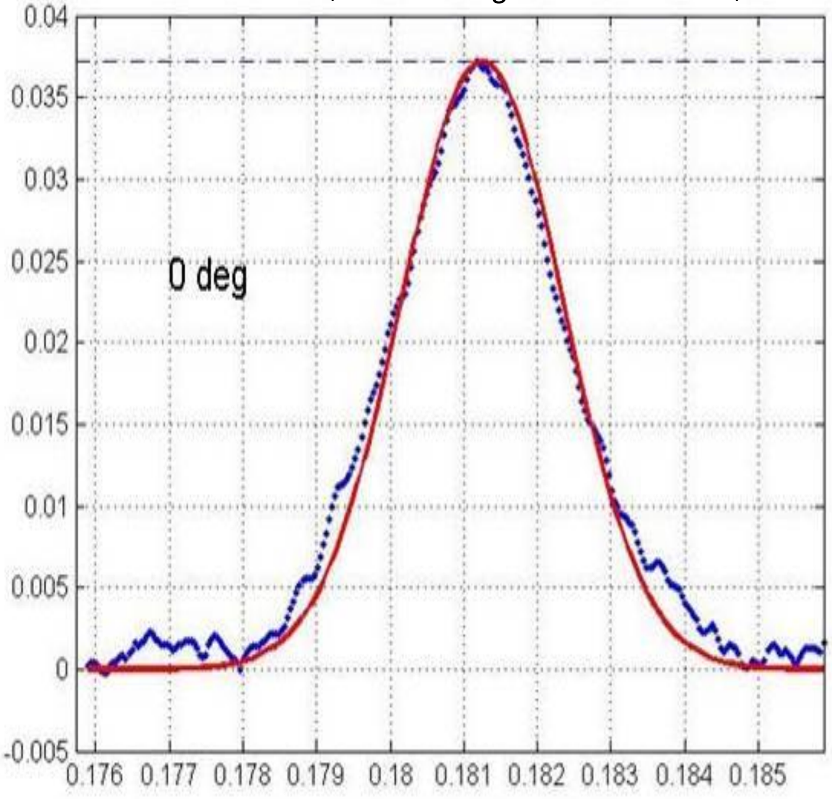
- *Measured the conversion of H^- into H with a current monitor*

Laser Wire Scanner

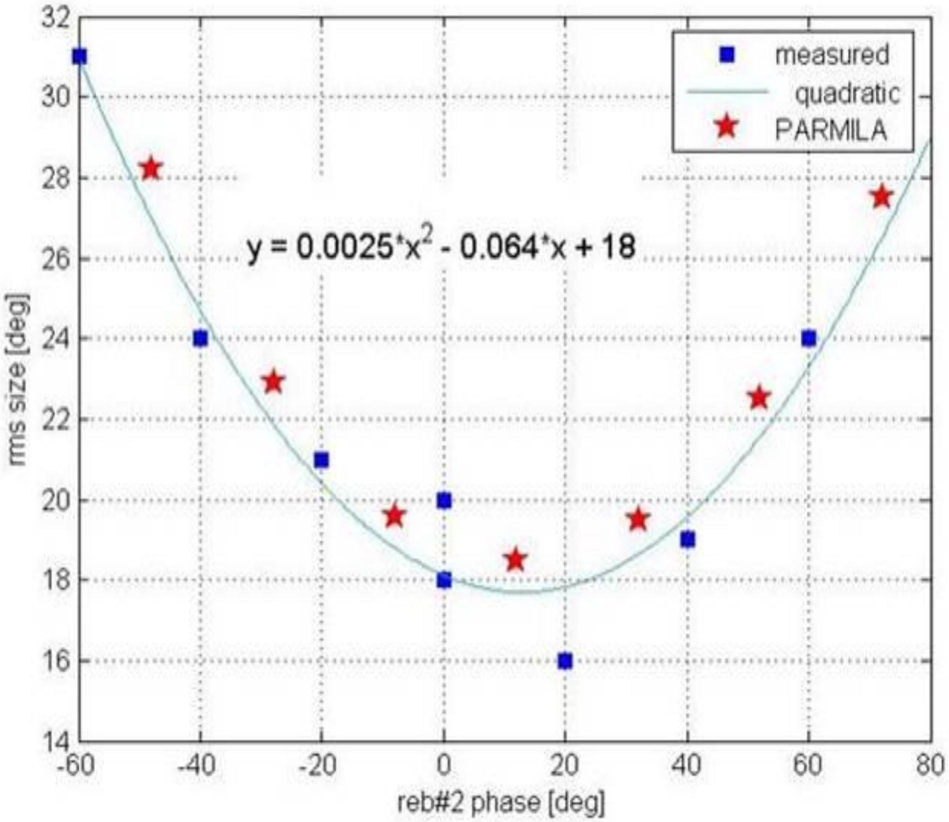
Longitudinal Measurements @ SNS

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

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

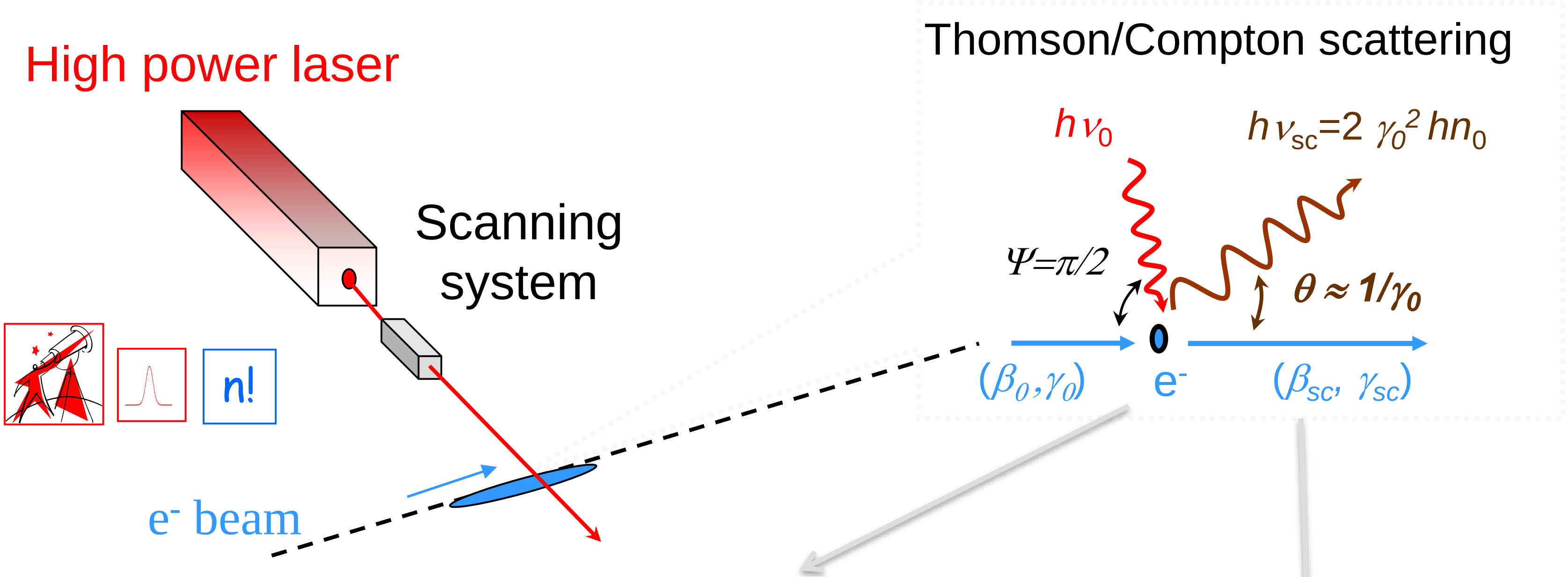


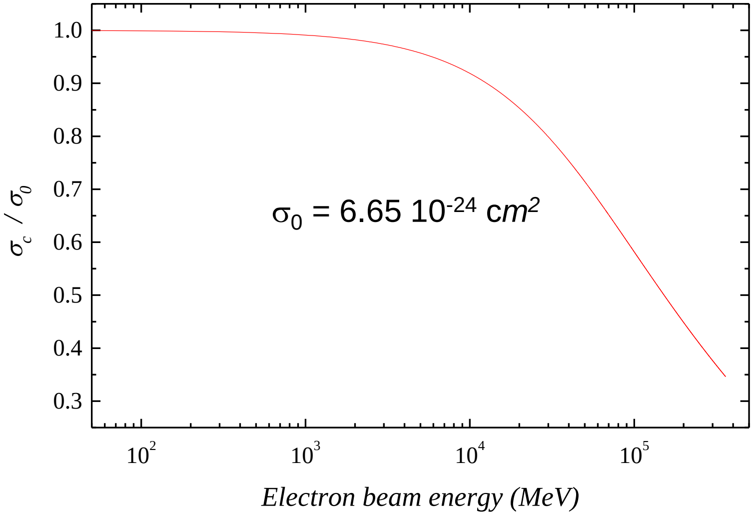
Collected electron signal plotted vs. phase



Measured and predicted bunch length vs. cavity phase setting

Laser Wire Scanner



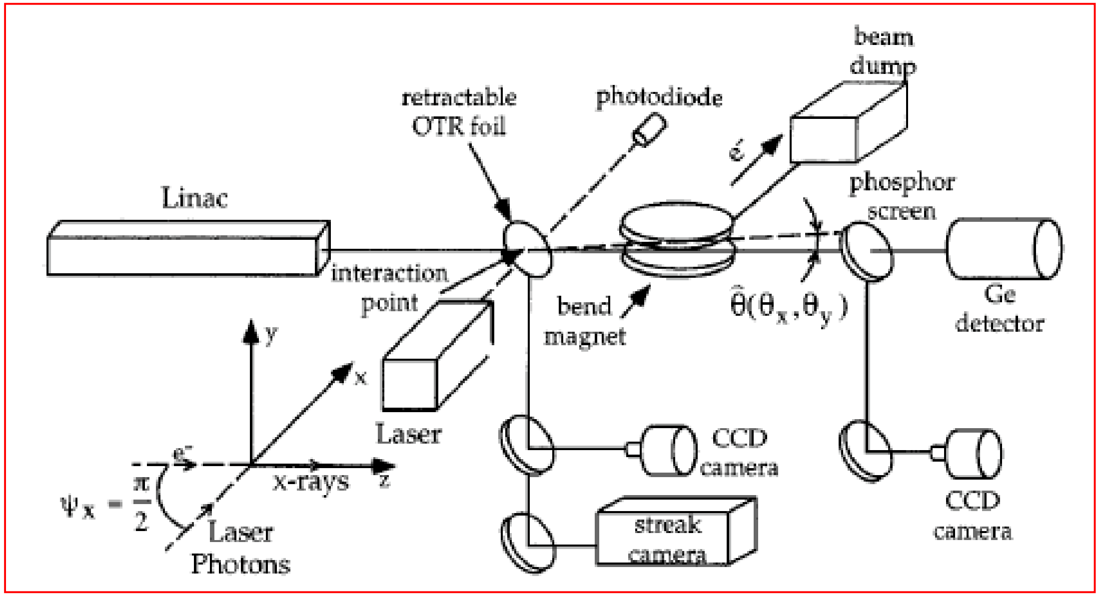


Detection system based on

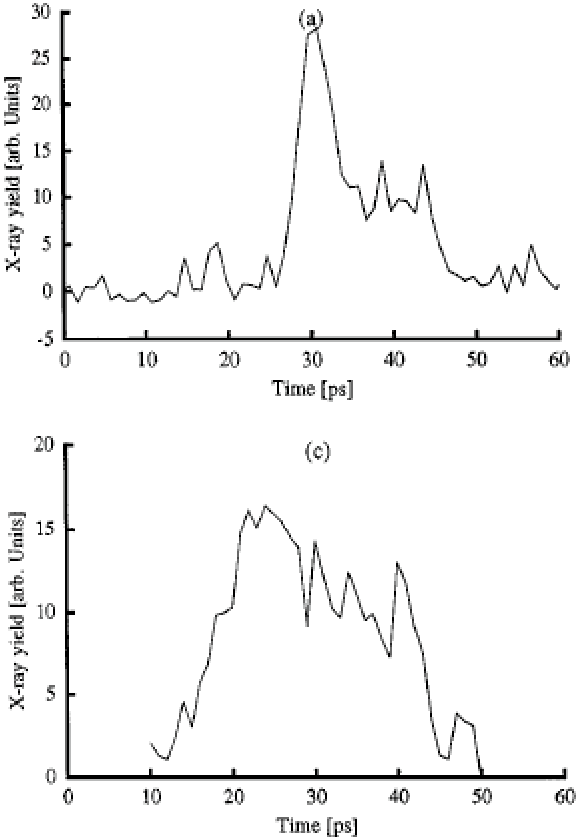
- The measurement of the scattered photons
- The measurement of degraded electrons

Laser Wire Scanner

ALS @ LBNL



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

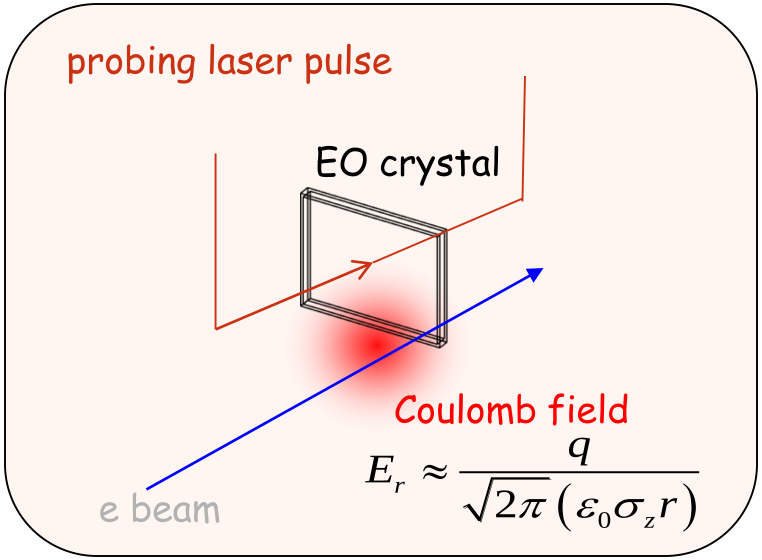


Using a 10TW Ti:Al_2O_3 laser system. Detecting 5.10^4 10-40 keV X-rays using either an X-ray CCD and Ge detector.

Electro-optical techniques

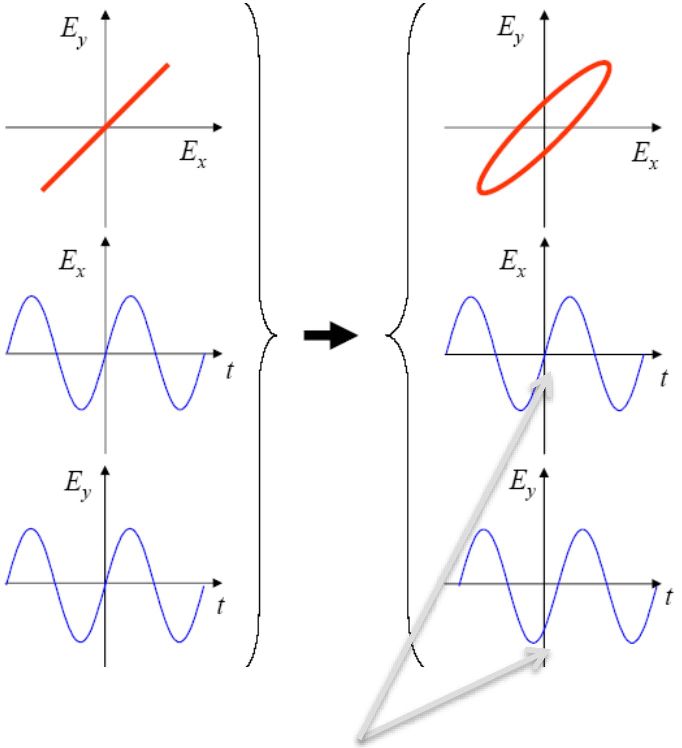
'This method is based on the polarization change of a laser beam which passes through a crystal itself polarized by the electrons electric field'

E-field induced birefringence in EO-crystal : Pockel/Kerr effect



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

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

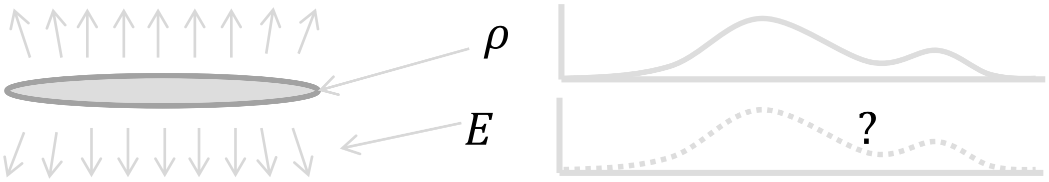


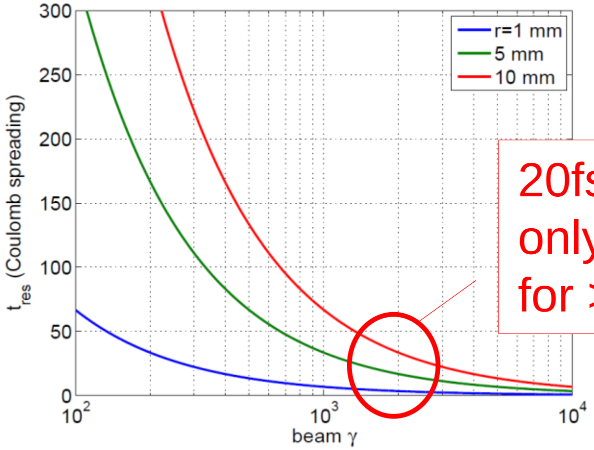
$$\Gamma = \frac{2\pi d}{\lambda_0}\left(n_x - n_y\right) = \frac{2\pi d}{\lambda_0} n_0^3 r_{41} E_r$$

Relative phase shift between polarizations increases with the beam electric field

Bunch length and bunch field

Field radiated or probed is related to Coulomb field near the electron bunch





20fs resolution only obtainable for >1GeV beam

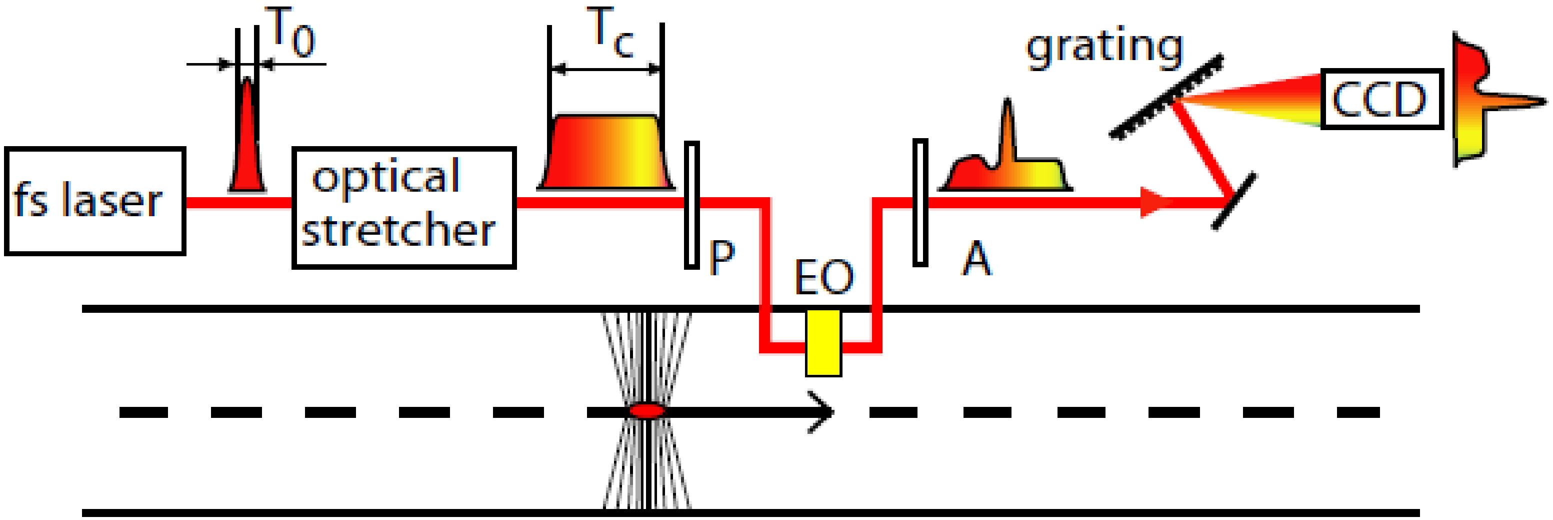
High γ is an advantage!

Time response & spectrum of field is dependent on spatial position, r :

$\delta t \sim 2r / c\gamma$

⇒ ultrafast time resolution requires close proximity to bunch

Spectral decoding



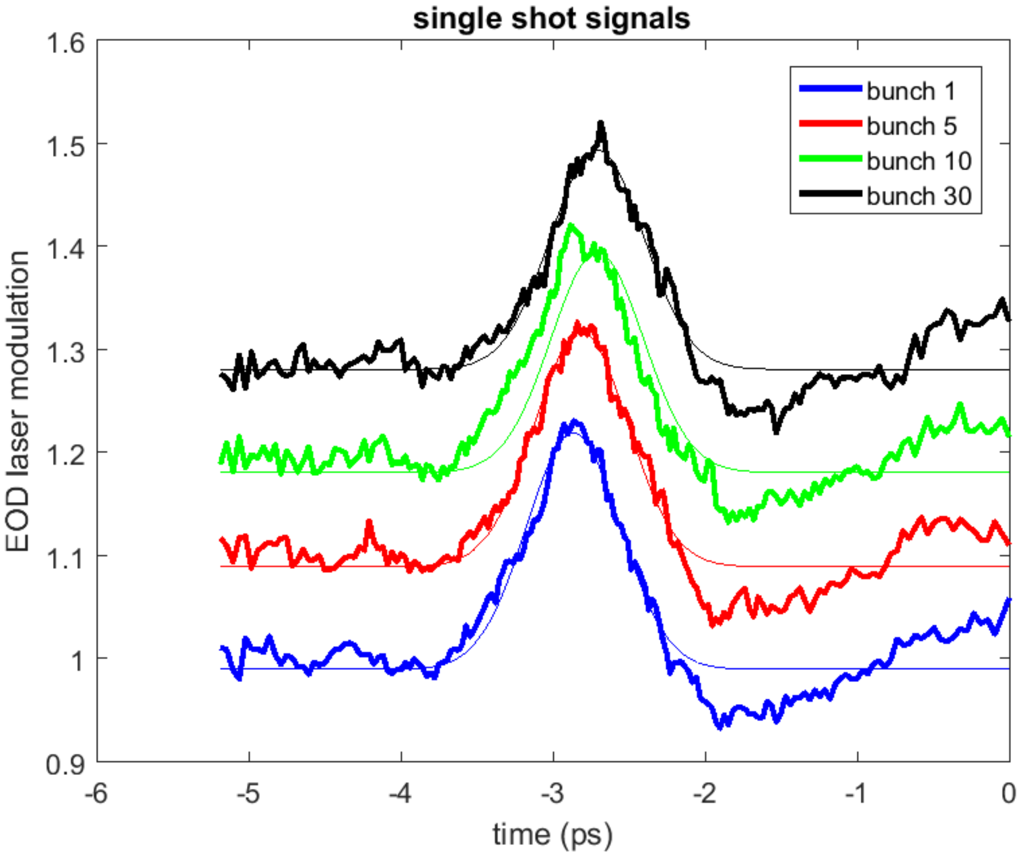
Wilke et.al., PRL 88 (2002) 124801

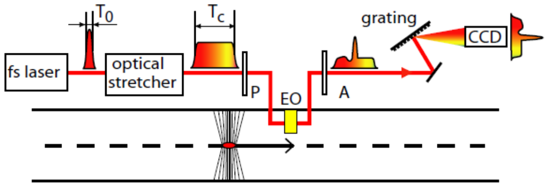
Single bunch measurements by detection the wavelength spectrum in spectrometer (position vs wavelength) of a chirped laser pulse (time vs wavelength)

- Artifacts due to frequency mixing
- Minimum resolution in the order $T_{\mathrm{lim}} \approx 2.6\,\sqrt{T_0 T_c}$

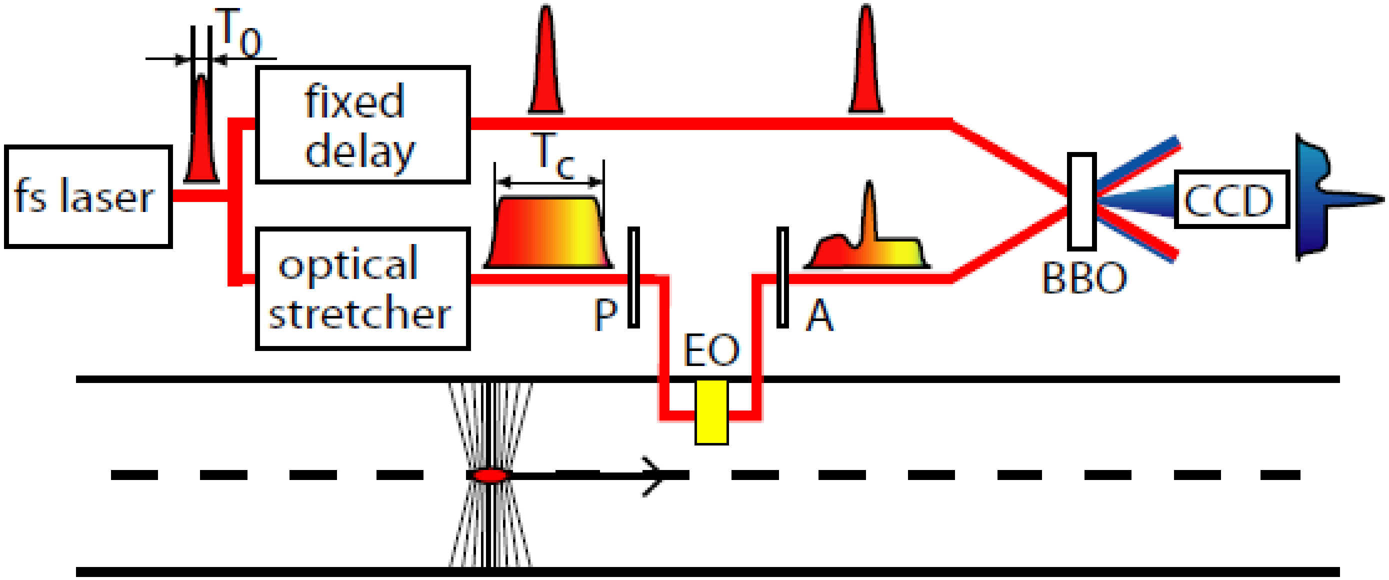
Spectral decoding

Single shot measurements at the XFEL bunch compressor 1





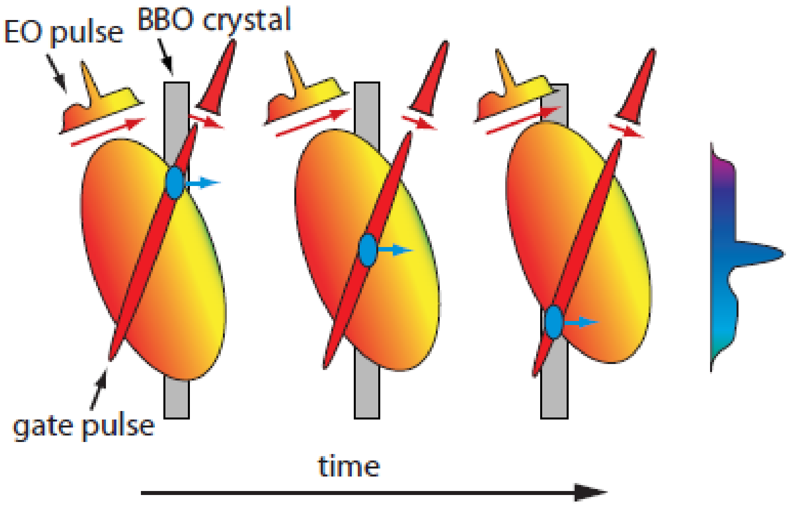
Temporal decoding



Berden et.al, PRL 93 (2004) 114802

- low efficiency of Second Harmonic Generation process, approx. 1mJ laser pulse energy necessary
- Resolution : duration of the gate beam, thickness of the SHG crystal
  - 50 fs or slightly better

Temporal decoding

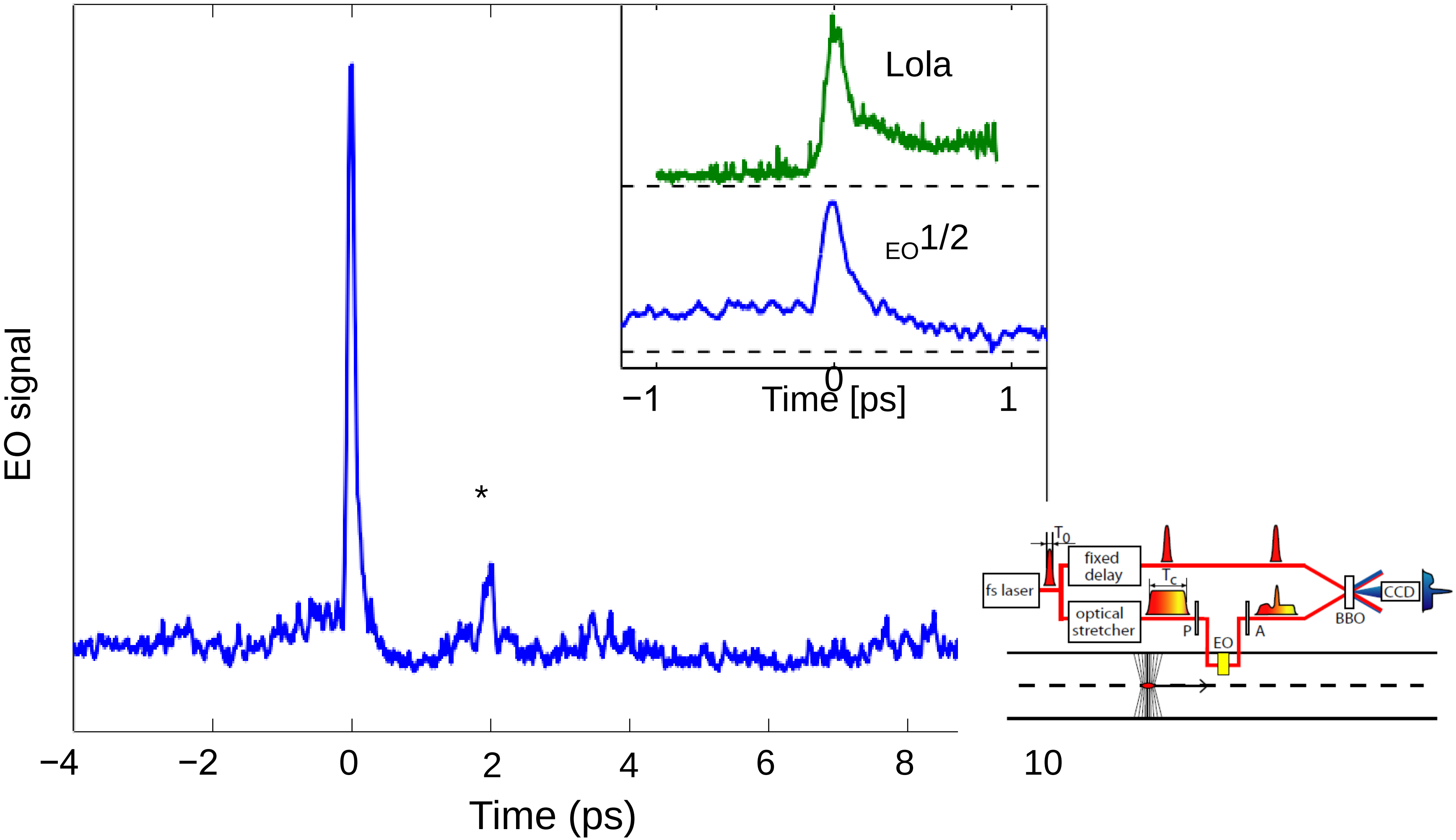


- The short gate pulse overlaps with different temporal slices of the EO pulse at different spatial positions of the BBO crystal.

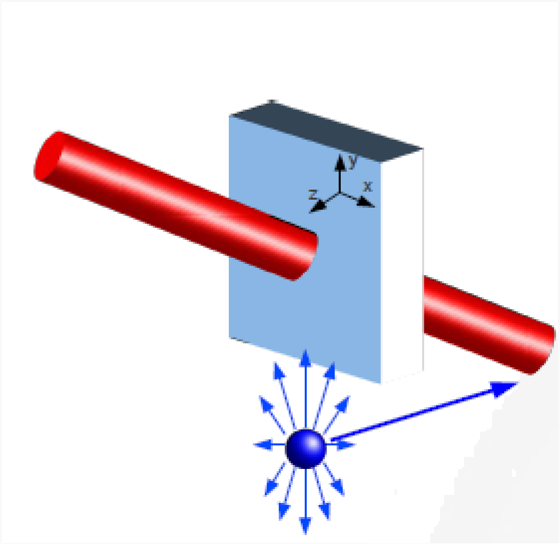
- Thus the temporal modulation of the EO pulse is transferred to spatial distribution of the SHG laser beam.

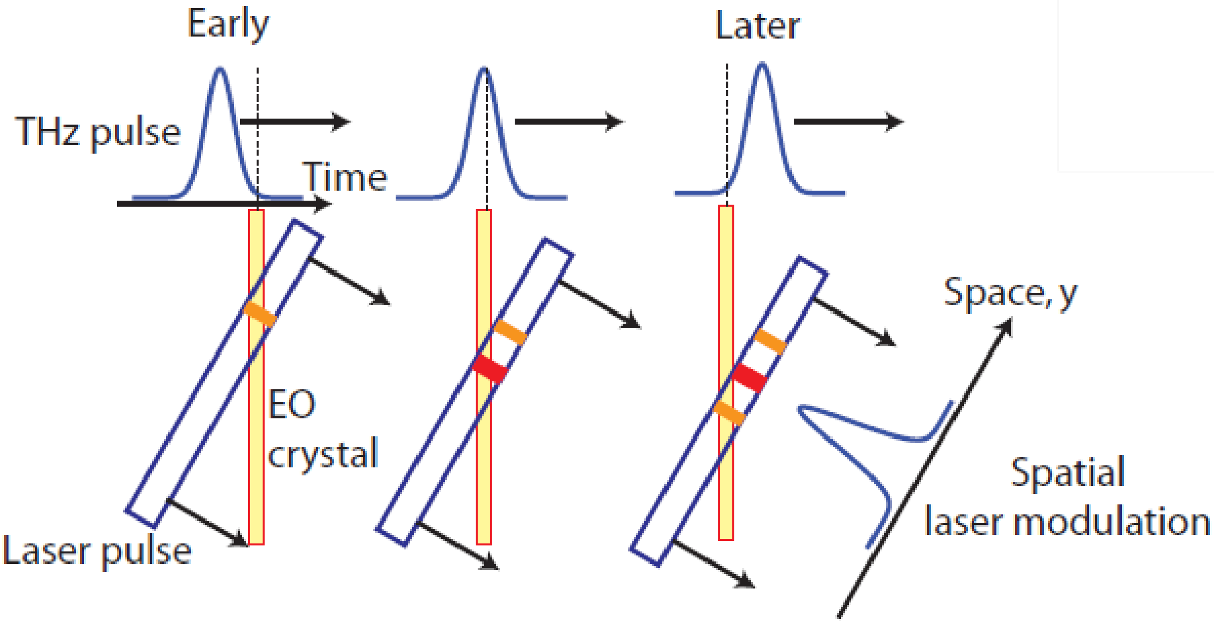
Temporal decoding

Measurement performed at FLASH/DESY



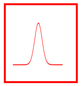
Spatial decoding





Cavalieri *et. al*, PRL 94 (2005) 114801
Jamison *et. al*, Opt. Lett. 28 (2003) 1710
Van Tilborg *et. al*, Opt. Lett. 32 (2007) 313

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		1fs
• Zero phasing techniques		X	X		X		10fs
• Laser based Method							
• Sampling						X	Jitter (10fs)
• 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

Conclusions

- Short bunch length measurements are challenging
- Resolution of few fs achieved operationally
- Field in constant move driven by the advances in FELs and novel accelerating technologies
- Another exciting field of R&D !

The CERN Accelerator School

Thank you for your attention

The CERN Accelerator School

Advanced Accelerator Physics

The CERN Accelerator School

Extra slides

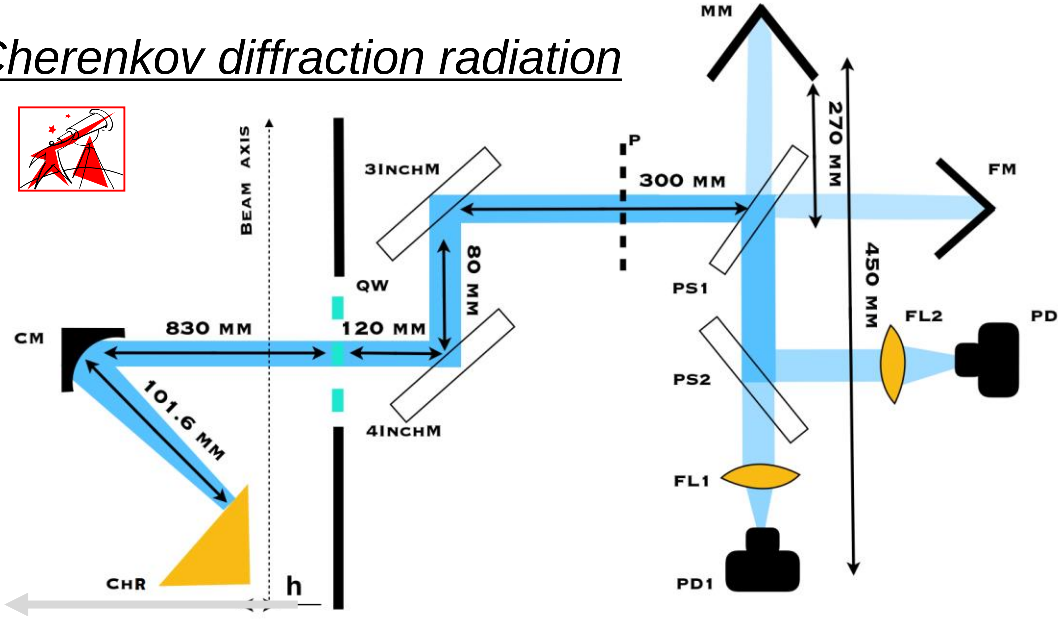
“When you are courting a nice girl an hour seems like a second. When you sit on a red-hot cinder a second seems like an hour. That's relativity. “

Albert Einstein

Martin-Puplett Interferometer

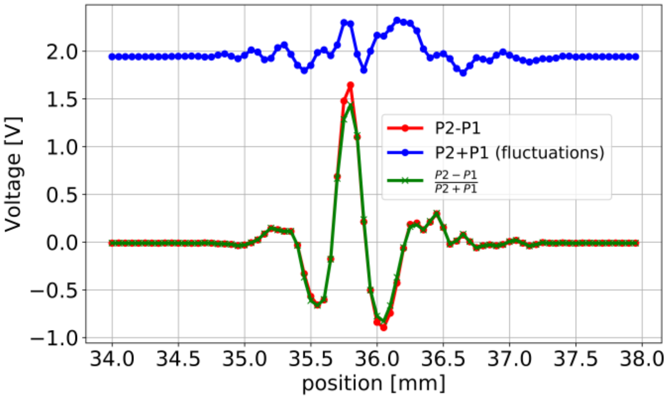
Cherenkov diffraction radiation

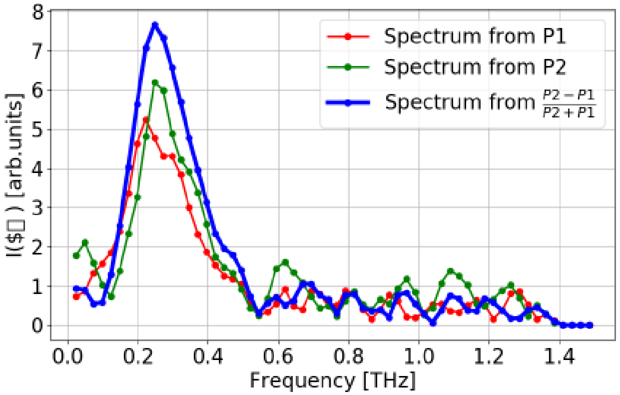
n!



electrons
35MeV, 70pC

$$I(\delta) \propto \int_{-\infty}^{\infty} \left| E(t) + E(t+\delta/c) \right|^2 dt$$





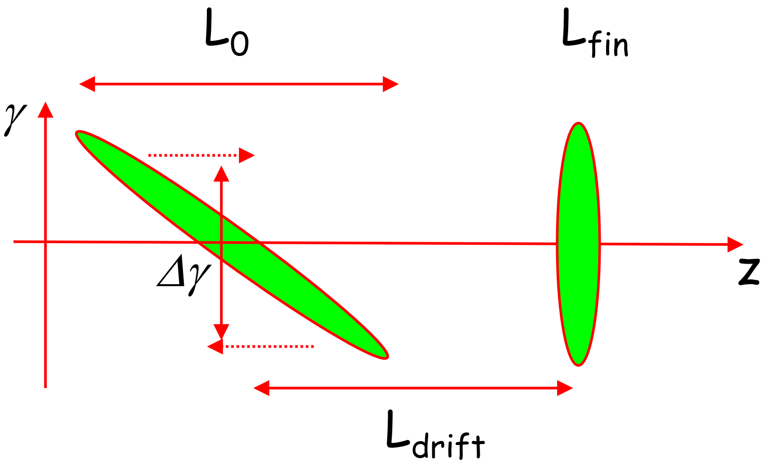
"the Fourier transform of the autocorrelation function is the power spectrum"

$$I(\omega) \propto \int_{-\infty}^{\infty} I(\delta)\cos\left(\frac{\omega\delta}{c}\right) d\delta$$

Bunch length manipulation

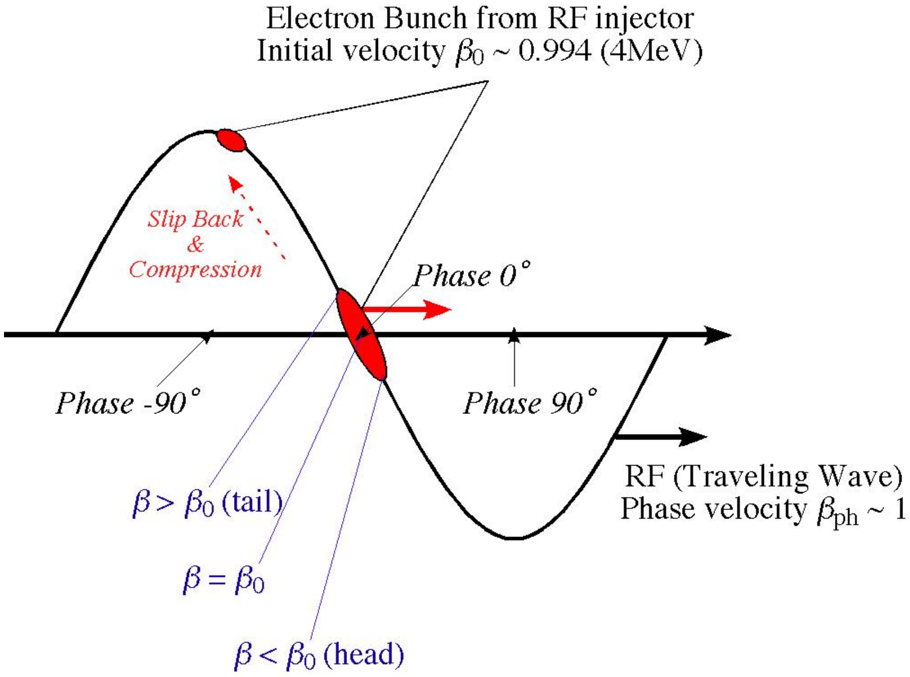
- Ballistic Compression
- Magnetic Compression

Short bunches by Ballistic/Velocity Compression



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

$\Delta\gamma$

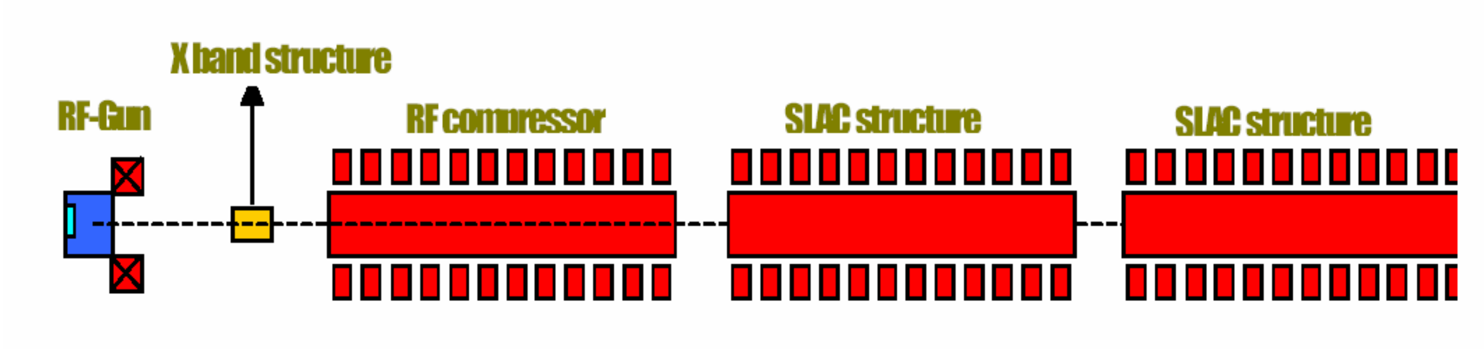


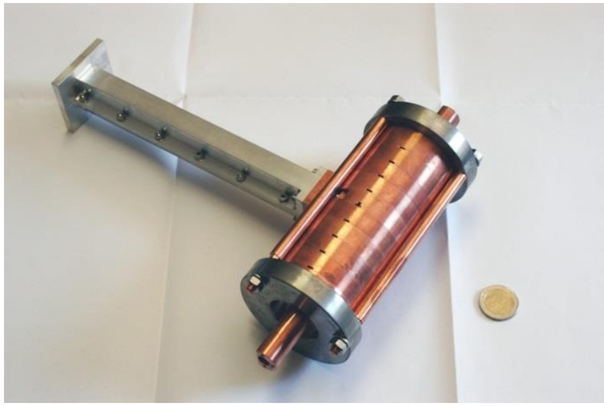
Provide a correlated velocity spread enough to produce, in a drift of length L_{drift} a *path difference* equal to ΔL

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

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

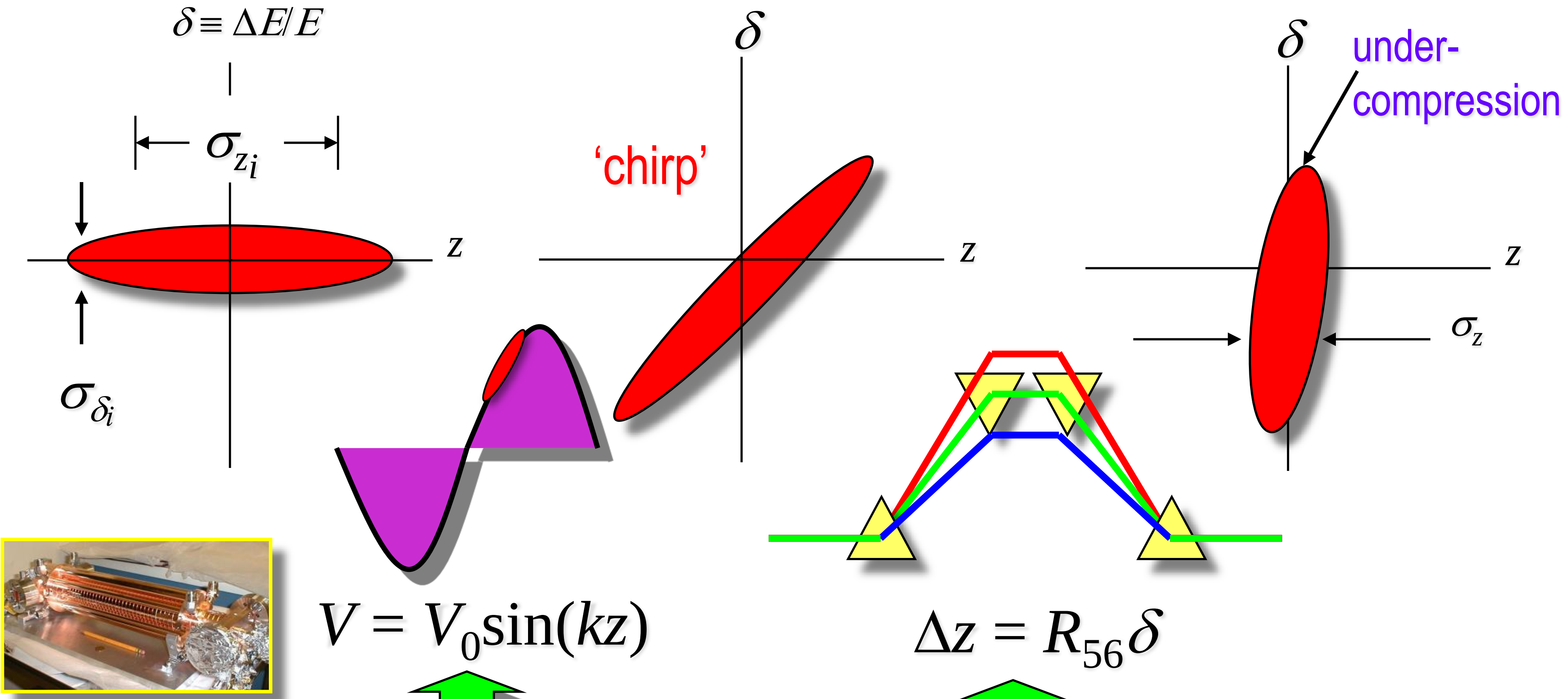
Short bunches by Ballistic Compression





- 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



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

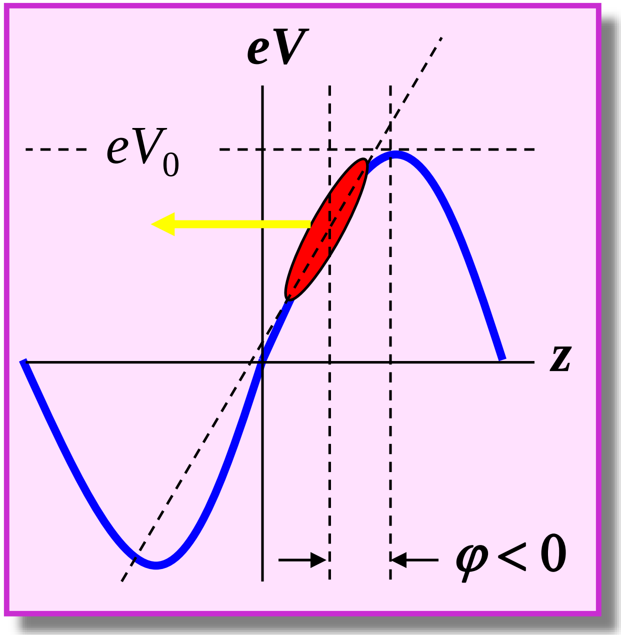
$$\Delta z = R_{56}\,\delta$$

RF Accelerating Voltage

Path-Length Energy-Dependent Beamline

$\Delta T \rightarrow \Delta E \rightarrow \Delta X \rightarrow \Delta T$

Short bunches by Magnetic Compression



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

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

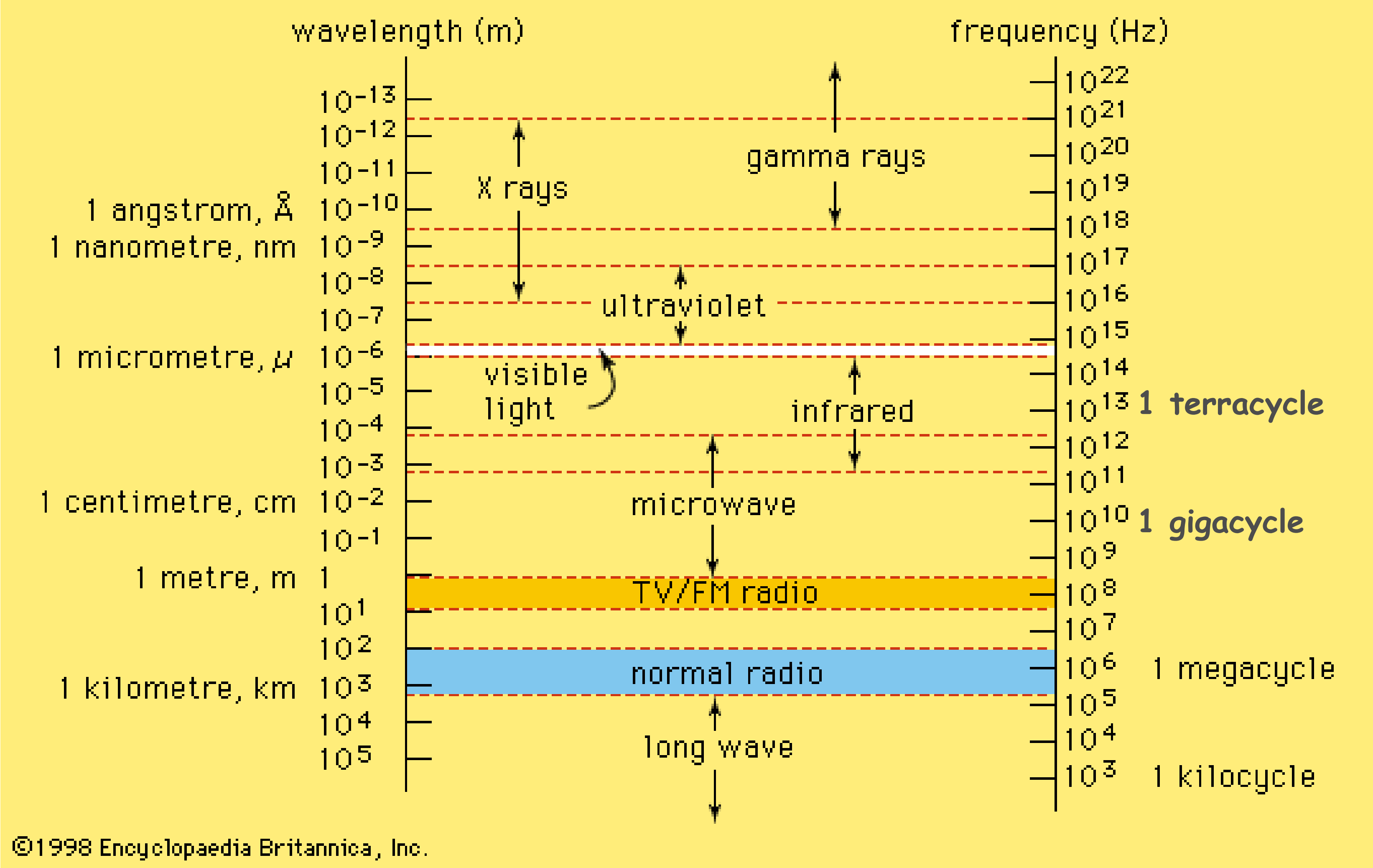
$$\delta_0 \frac{E_0}{E} + \left(1 - \frac{E_0}{E}\right)\left[\frac{\cos(\varphi + \Delta\varphi) - (2\pi z/\lambda)\sin(\varphi + \Delta\varphi)}{\cos(\varphi)} - 1\right]$$

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

final bunch length and energy spread…

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

Bunch Frequency Spectrum



1 terracycle

1 gigacycle

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Coherent Synchrotron Radiation in Magnetic Chicane

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