Longitudinal Beam diagnostics

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CERN

The CERN Accelerator School

A big thanks to all the people who provided materials for this lecture !!

A. Gillepsie, S. Jamison, A. Cianchi, ...

Outline

- Longitudinal beam profile in accelerators

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

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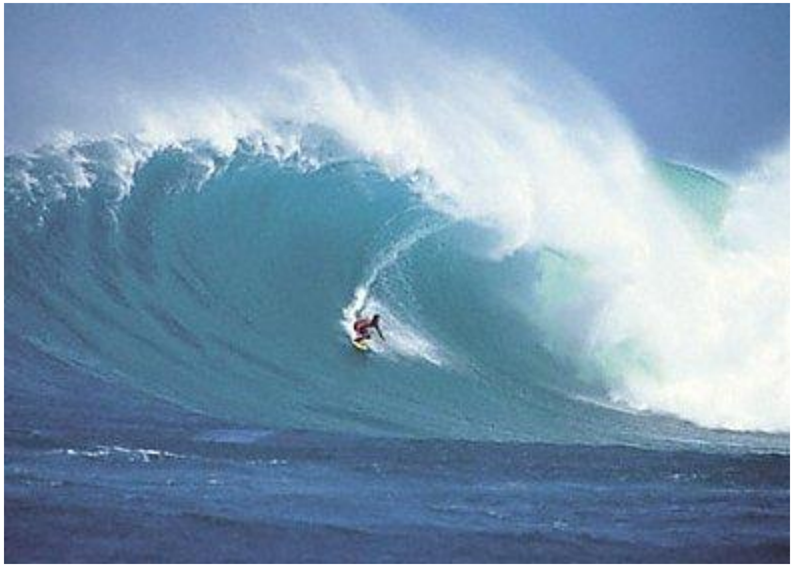
Accelerating charged particles

Acceleration techniques

DC Accelerator

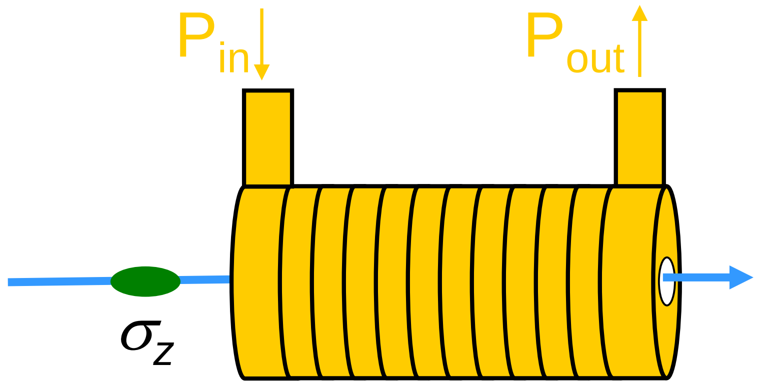
RF Accelerator

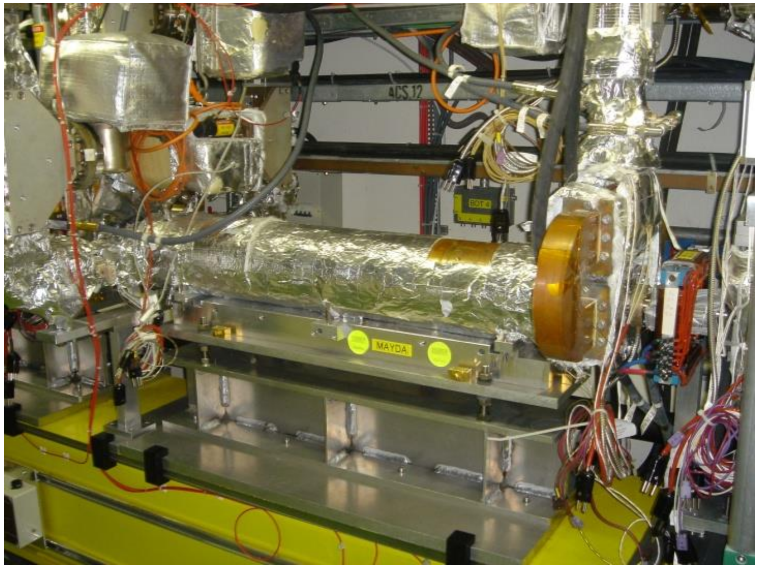


synchronizing particle
with an
electromagnetic wave!

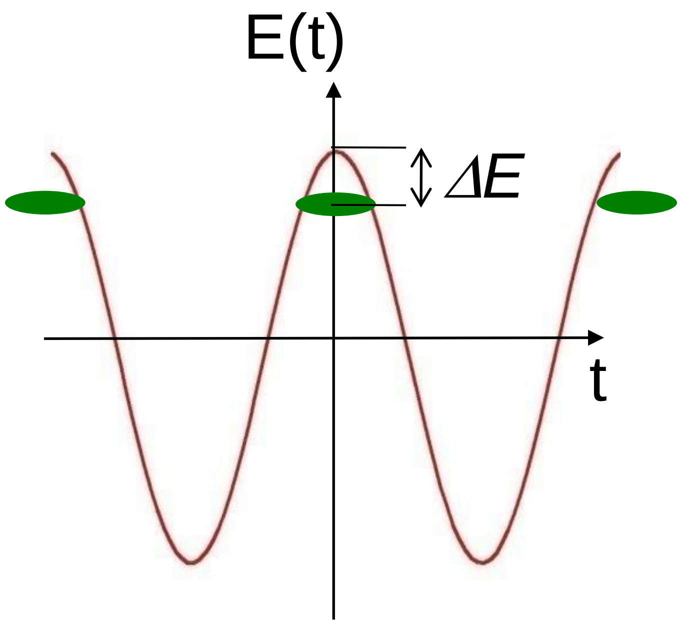
Acceleration techniques

RF Accelerating structures





RF Accelerating Field

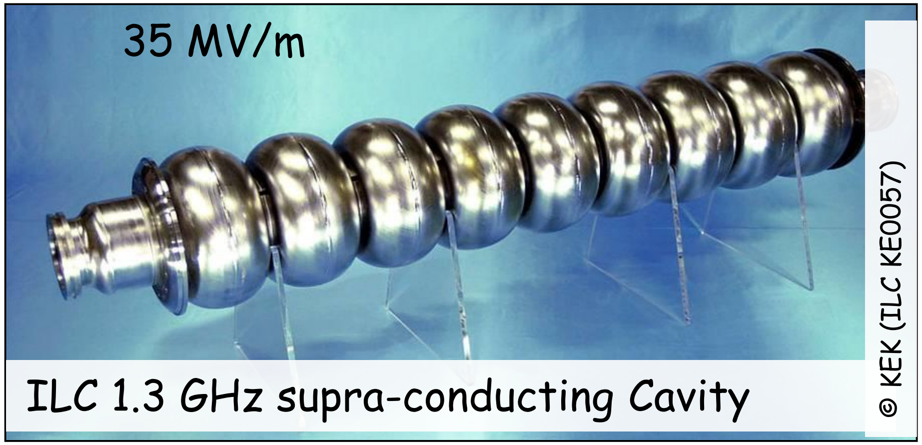


At 3GHz accelerating frequency

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

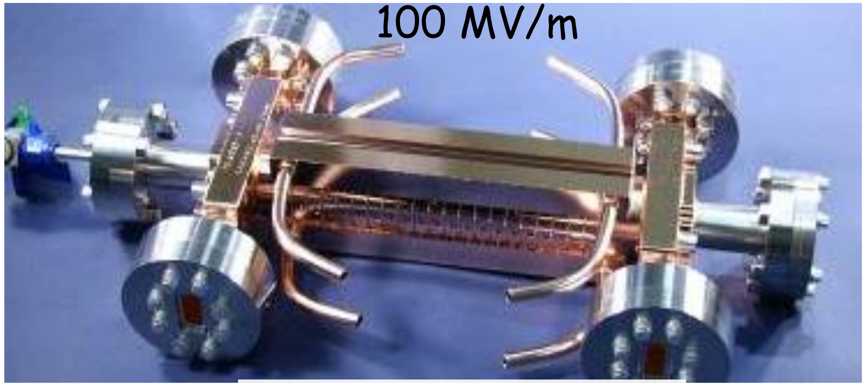
Accelerating cavities

CERN PS 19 MHz Cavity (prototype 1966)



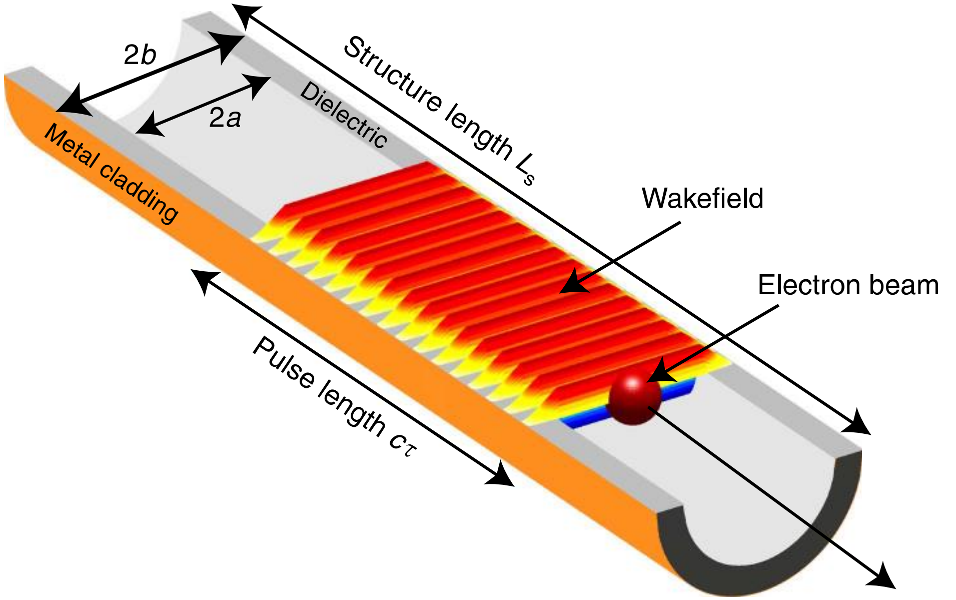
ILC 1.3 GHz supra-conducting Cavity

400MHz LHC Cavity in its cryo-module



CLIC 12 GHz Cavity

Dielectric Wakefield Acceleration



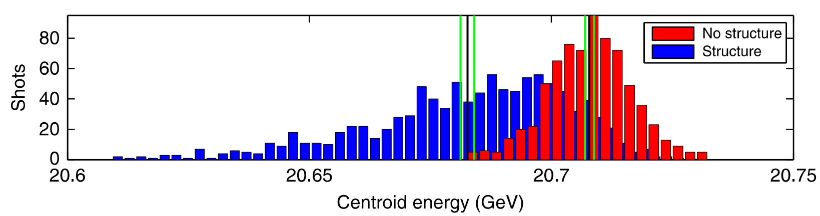
nature COMMUNICATIONS

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]



SiO_2 - 15cm long dielectric

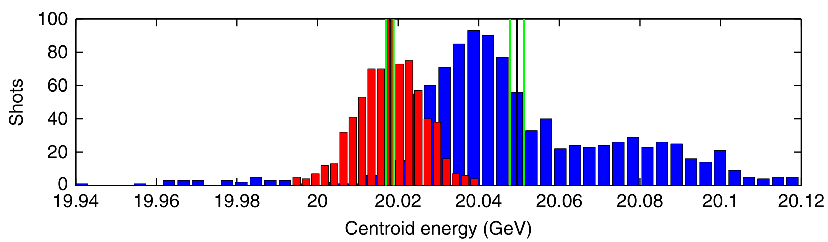
Outer diameter : 2b-400um

Inner diameter : 2a-300um

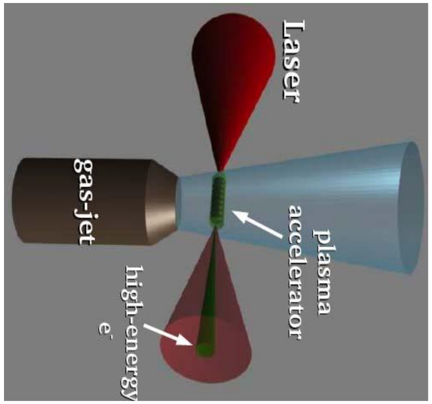
Beam size 30um

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

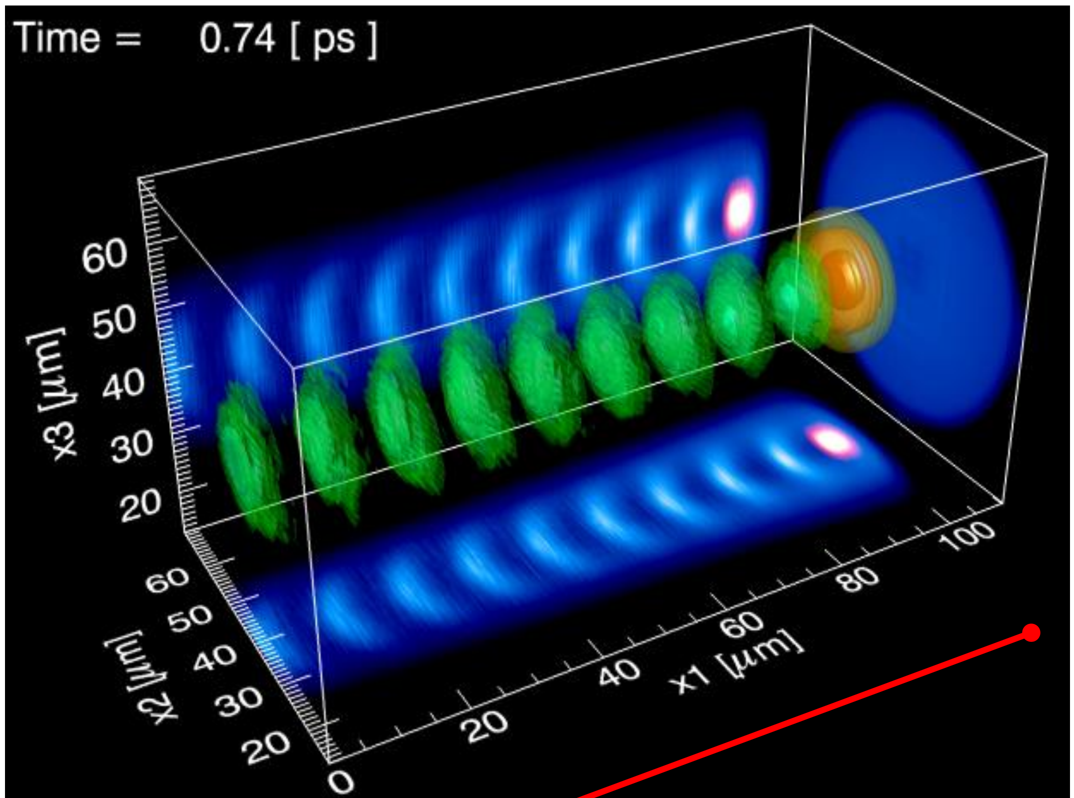
Δt (D-W) = 250um – 833fs



Laser Plasma Wakefield Acceleration



Courtesy of W. Mori & L. da Silva



100 µm

Beam Plasma Wakefield Acceleration

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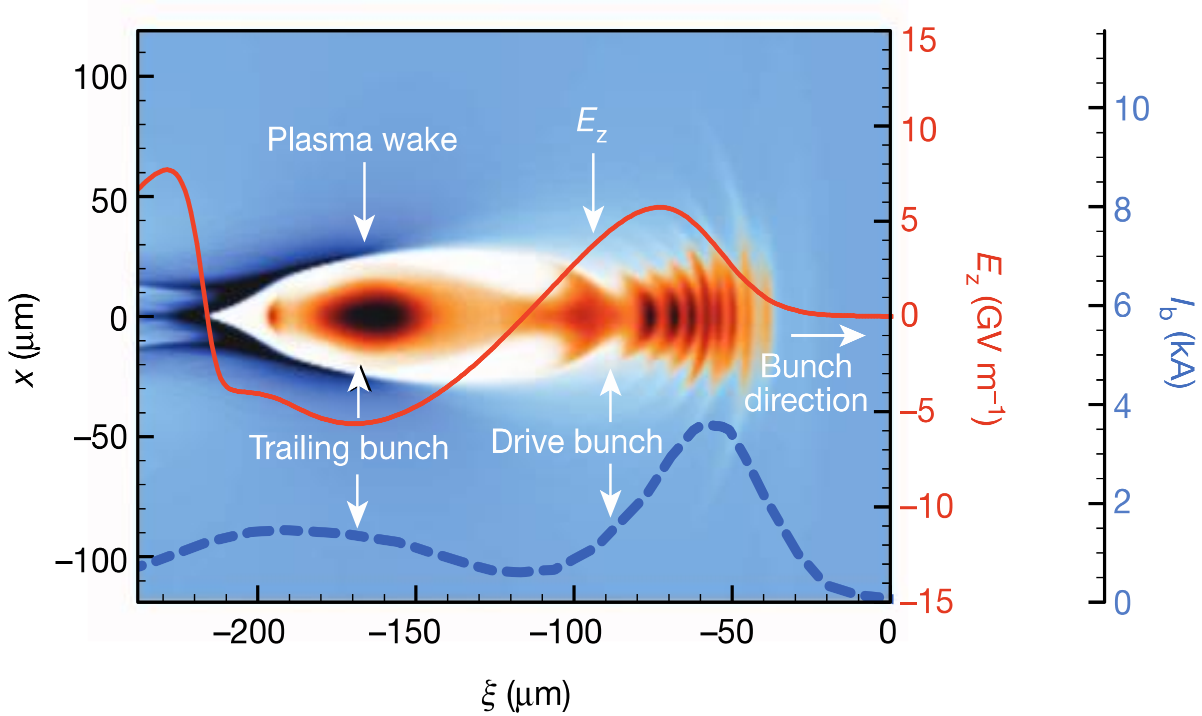
LETTER

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

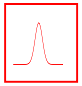
RF manipulation

Use RF techniques to convert time information into spatial information

Laser-based beam diagnostic

Using short laser pulses and sampling techniques

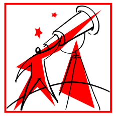
Bunch length measurement techniques

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

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Do not forget about **Simplicity and Reliability**

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

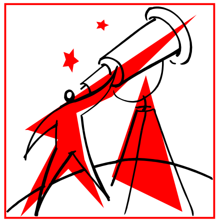
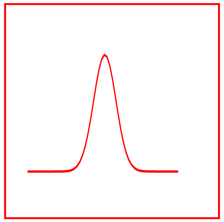
A detector, what for ?

- 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 ?

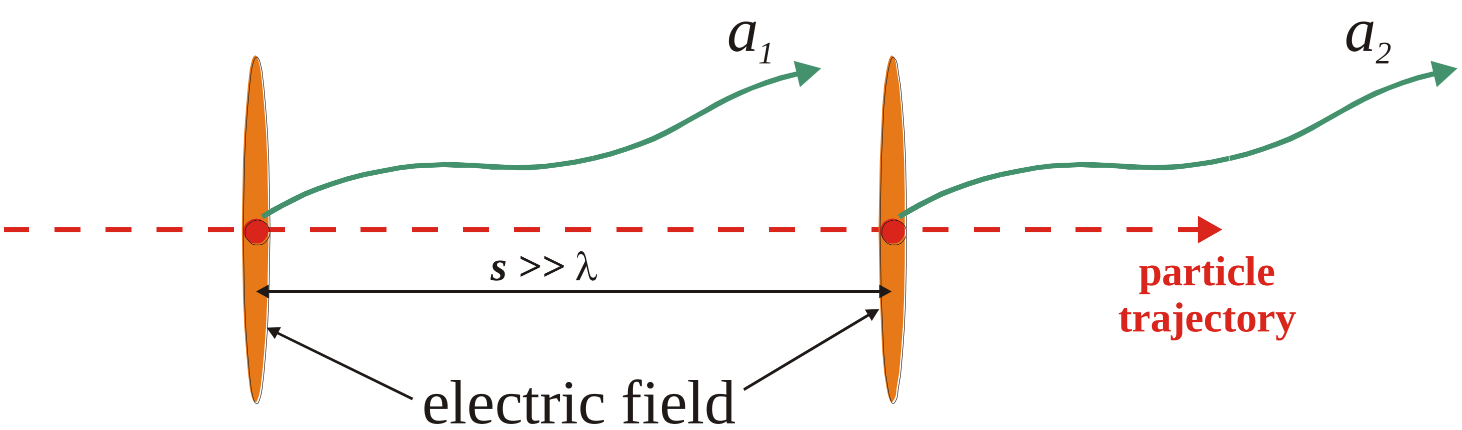
1 +  +  = 

Radiative techniques

‘How to convert 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

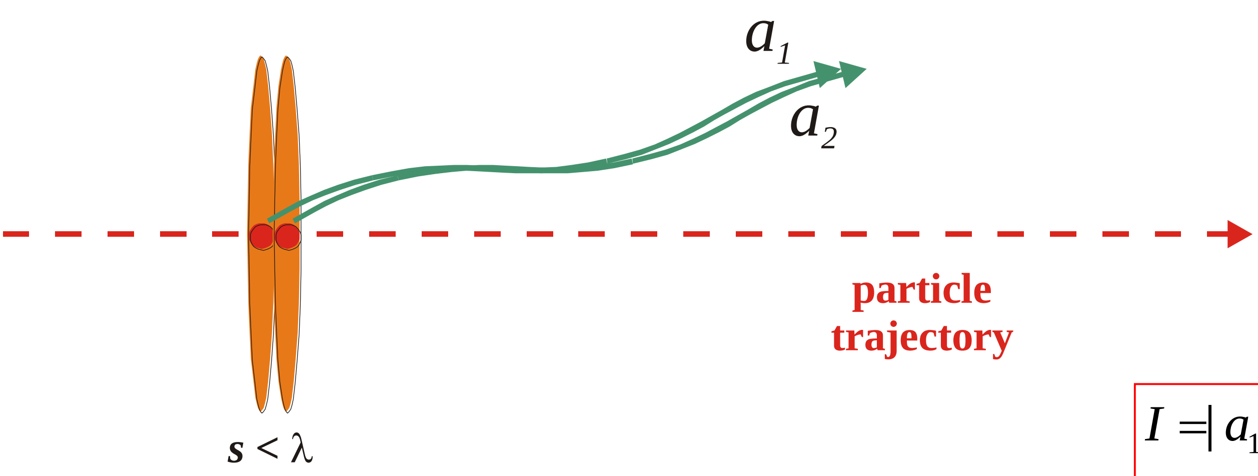


$$I = |a_1|^2 + |a_2|^2 = 2|a|^2 \rightarrow N|a|^2$$

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



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

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

Total radiation spectrum

Incoherent term   Coherent term

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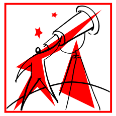
$\rho(s)$ – Longitudinal particle distribution in a bunch

Radiative processes

- Transition radiation — Better for γ >100
- Cherenkov radiation — β > 1/n



- Diffraction radiation
- Cherenkov Diffraction radiation
- Synchrotron radiation

For incoherent radiation

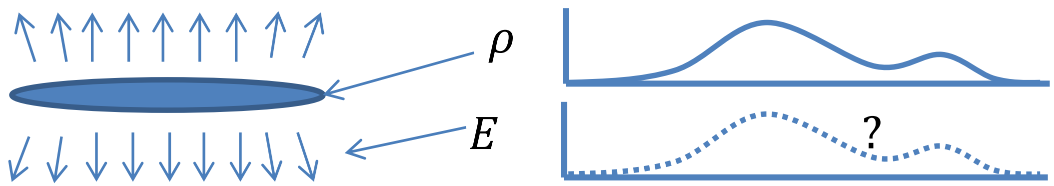
$$\gamma > 3000$$

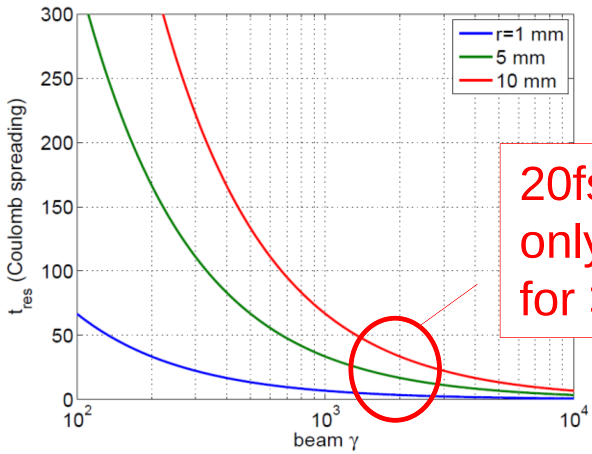
For coherent radiation

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

Radiative processes

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 :

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

$\Rightarrow$ ultrafast time resolution requires close proximity to bunch

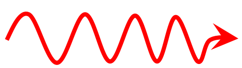
Optical method using Incoherent light

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

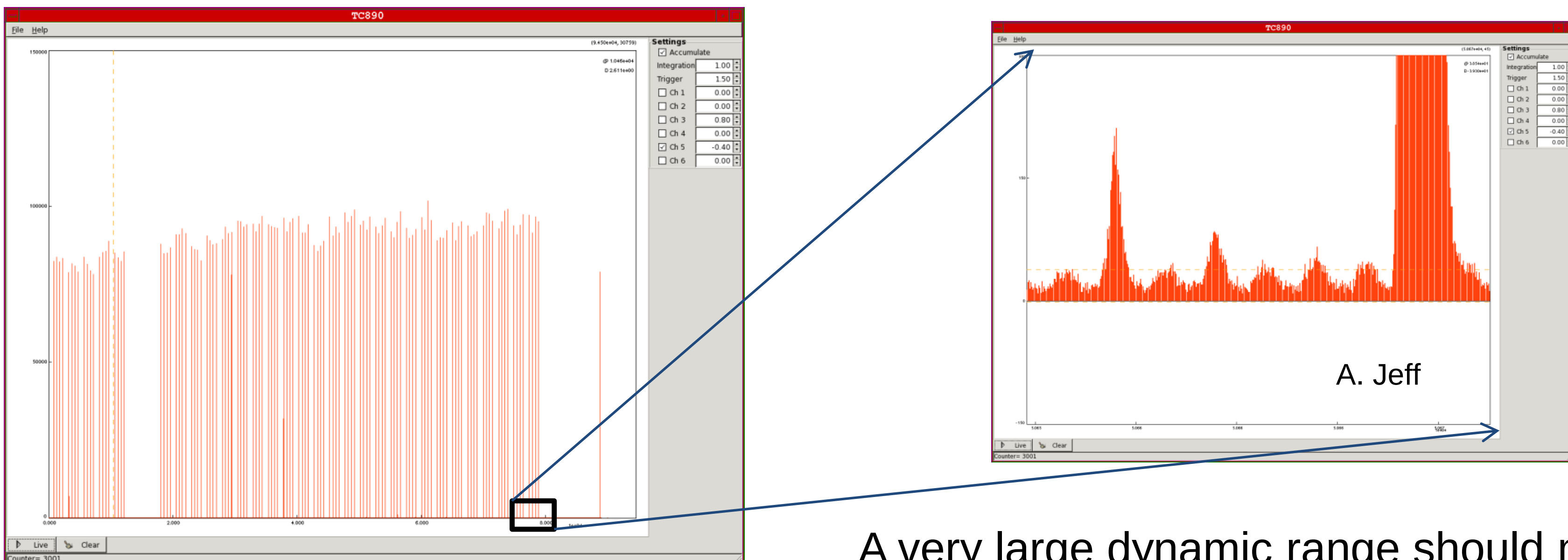
- Avalanche photodiode have deadtime and are subject to after-pulsing
- State of the art TDC typically limited to 10ps sampling

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!

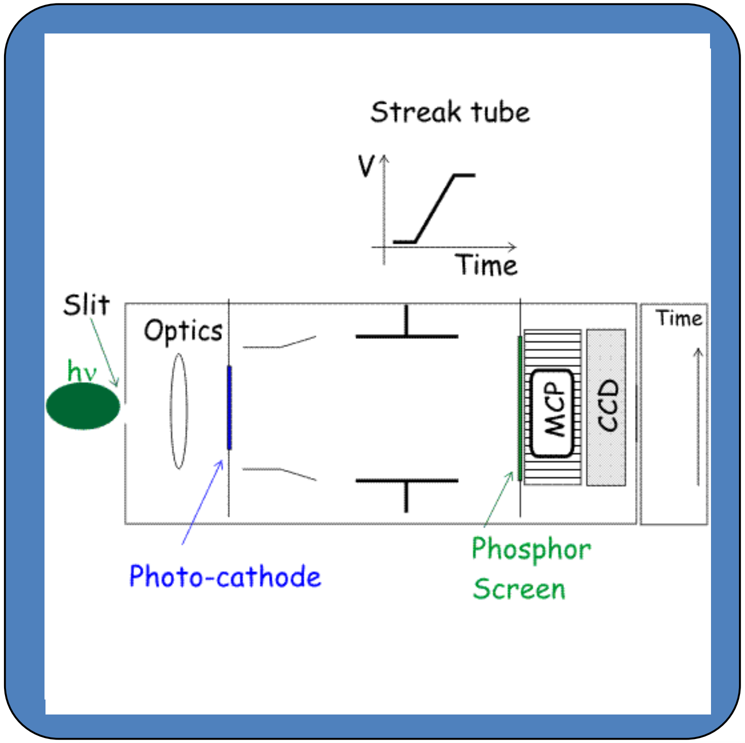
Longitudinal profile of the entire LHC ring (89us) with 50ps resolution using SR light



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***

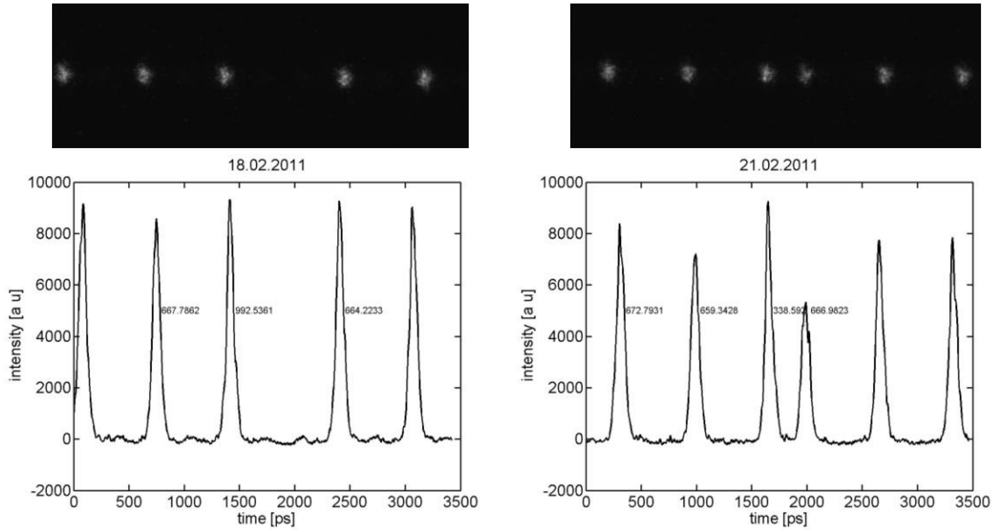
200fs time resolution obtained using reflective optics and 12.5nm bandwidth optical filter (800nm) and the Hamamatsu FESCA 200

<u>Limitations : Time resolution of the streak camera :</u>

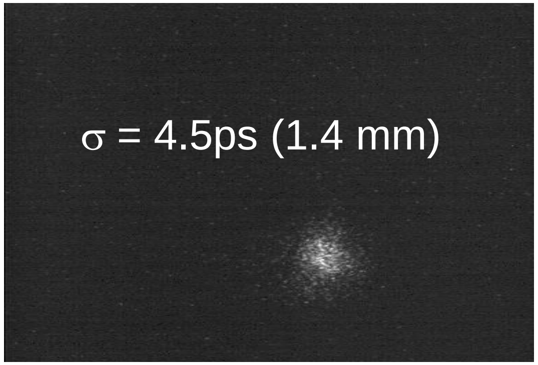
(i) Initial velocity distribution of photoelectrons : *narrow bandwidth optical filter*
(ii) Spatial spread of the slit image: *small slit width*
(iii) Dispersion in the optics

Streak Camera

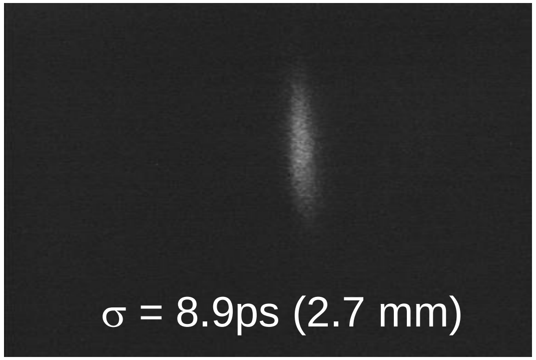
Observation of 5MeV electron bunch train using Cherenkov radiation
Sweep speed of 250ps/mm



Measure of bunch length using OTR and OSR



Sweep speed of 10ps/mm

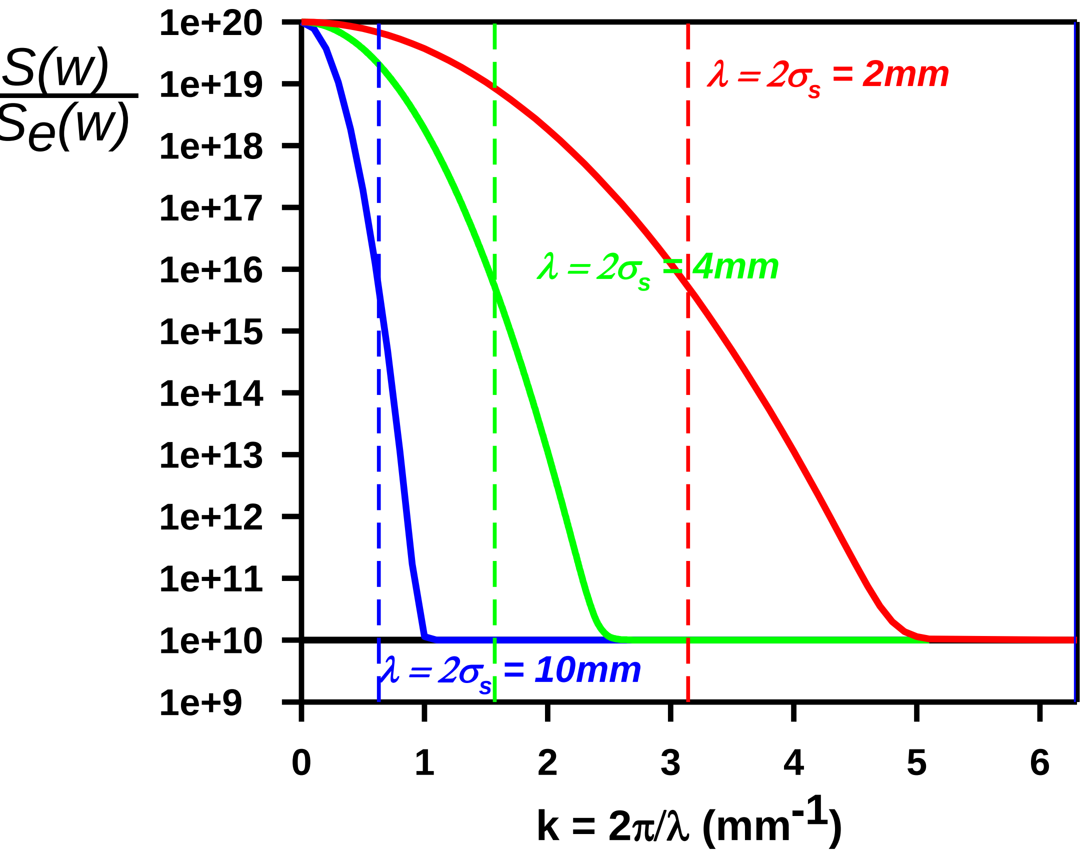


Bunch length measurement using using Coherent light

'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

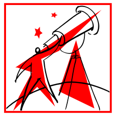
Measuring the Radiation Spectrum

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

- ✓ S(ω)– radiation spectrum (known in the experiment)
- ✓ N – number of particles s / 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, **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 $\sigma(z)$

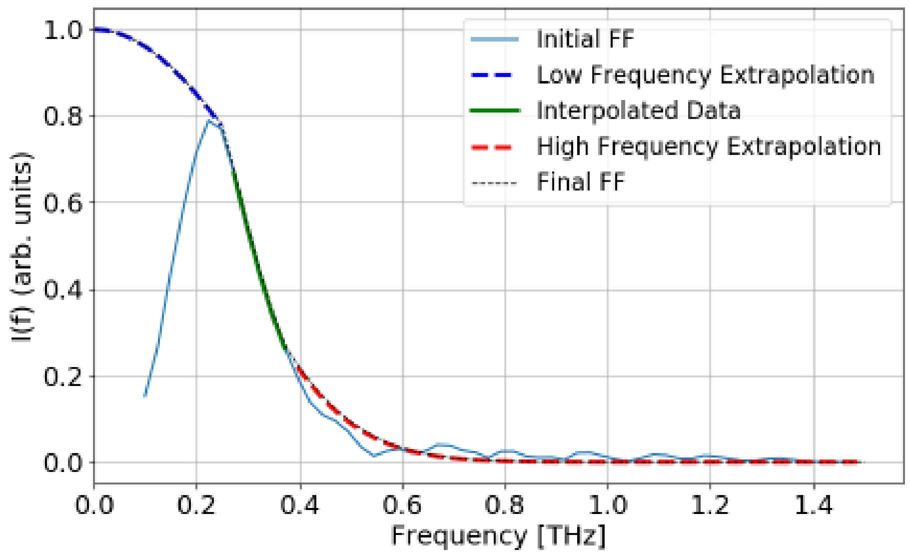
Kramers-Kronig relation
for non symmetric bunches

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

Time Domain

Measuring the Radiation Spectrum

Frequency Domain



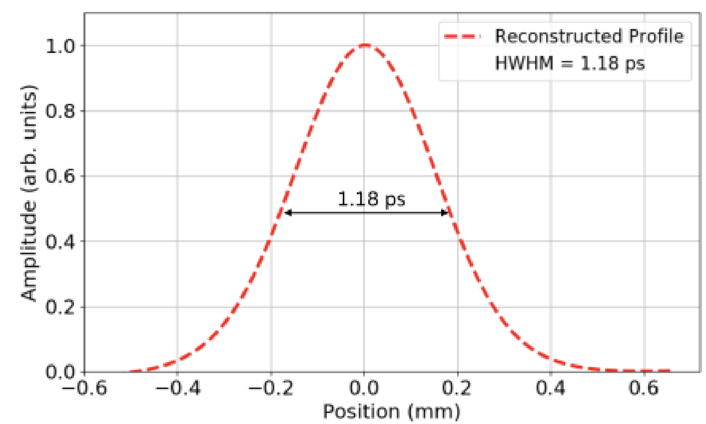
- Extrapolation

(high and low frequencies)

- Correction

(transfer function of detection system)

Inverse Fourier Transform using Kramer kronig relation

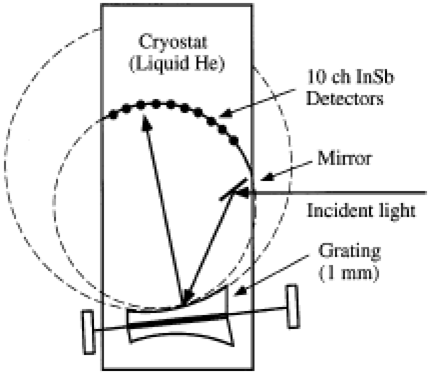


Time Domain

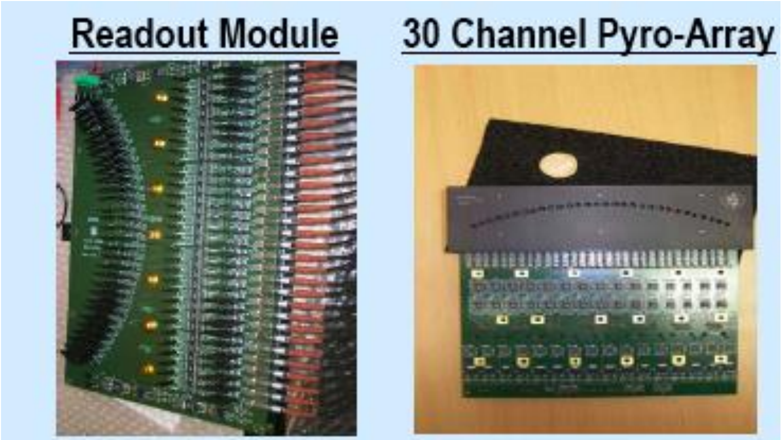
Measuring the Radiation Spectrum

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'*

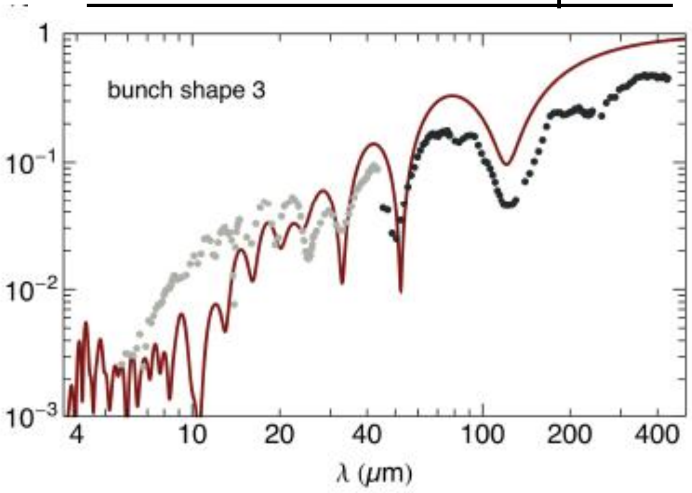


T. Wanatabe et al., NIM-A 480 (2002) 315-327
H. Delsim-Hashemiet al., Proc. FLS, Hamburg 2006, WG512



B. Schmidt, DESY

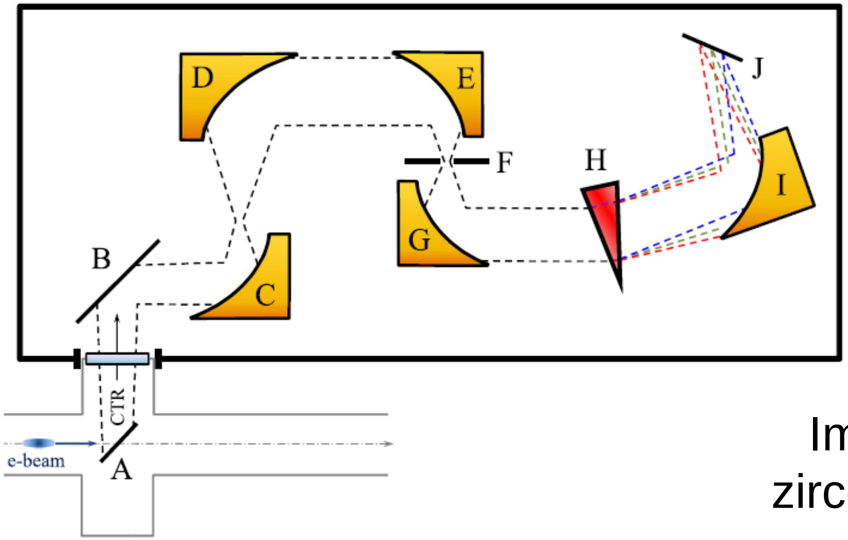
Measured & calculated spectra



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

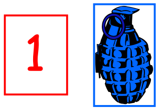
Single shot CTR measurements

- 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)

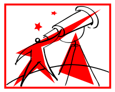


KRS-5 (thallium bromoiodide) prism based spectrometer

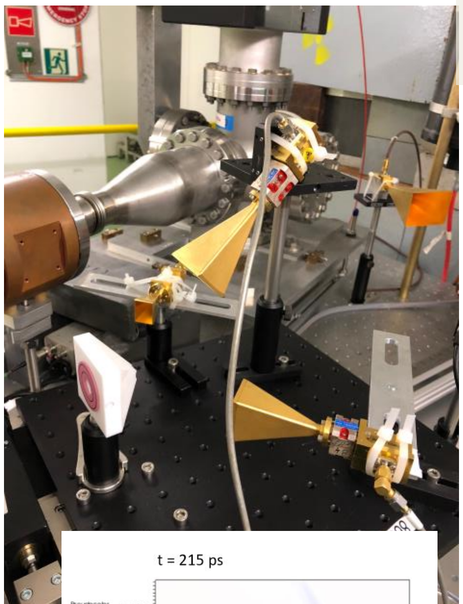
Images CTR from foil onto 128 lead zirconate titanate pyroelectric elements with 100 μm spacing line array



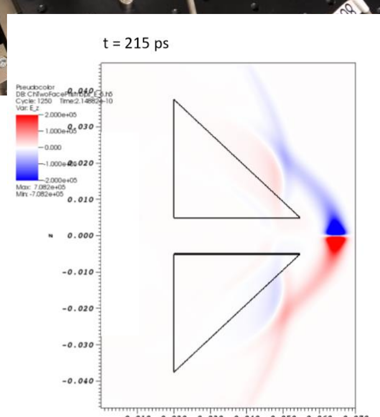
Single-shot Cherenkov diffraction measurement

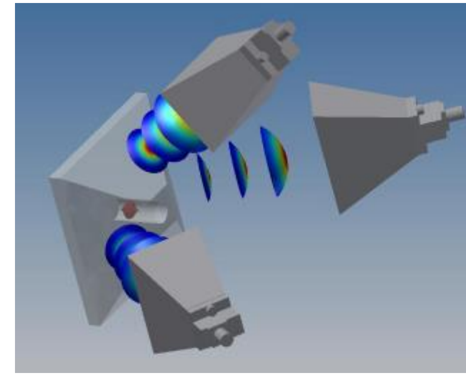
1 

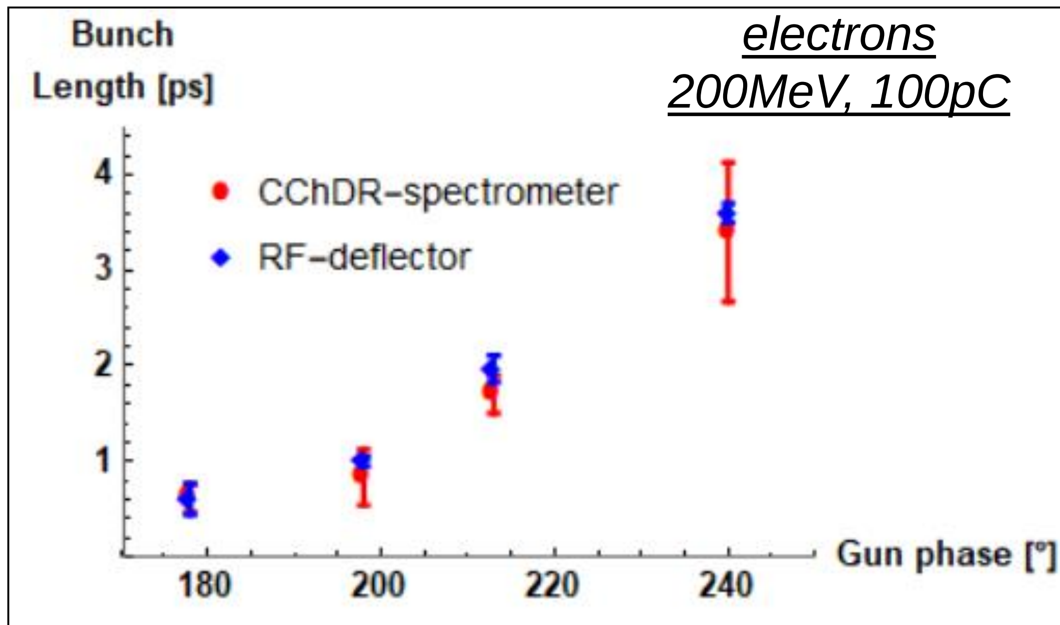
Cherenkov diffraction radiation
Measured in 3 bands (60-90-110GHz)



Pyramidal cone
with 1cm aperture

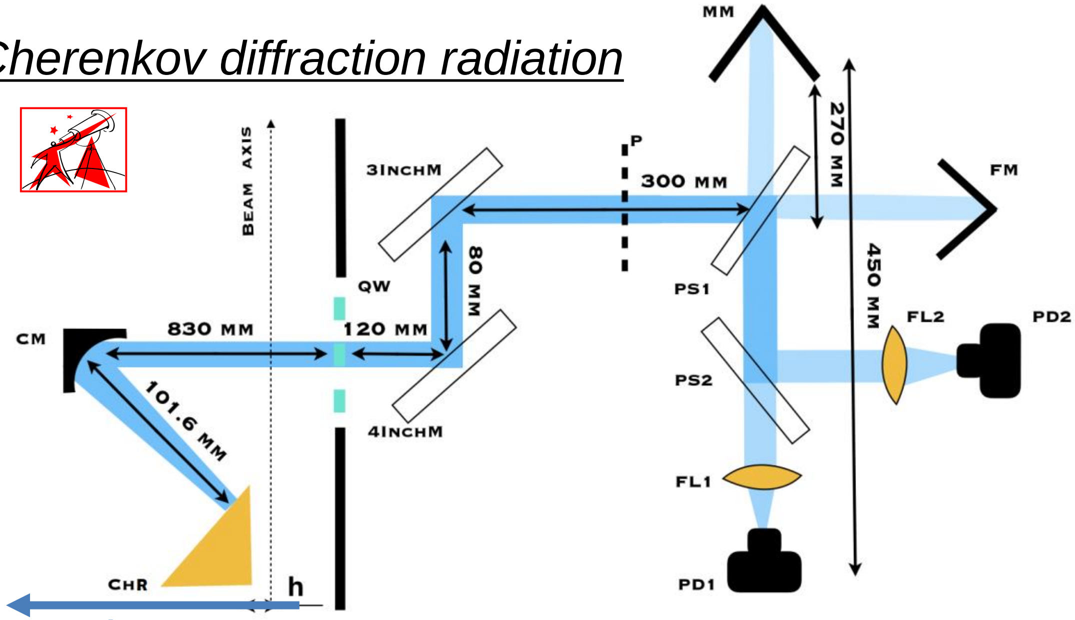






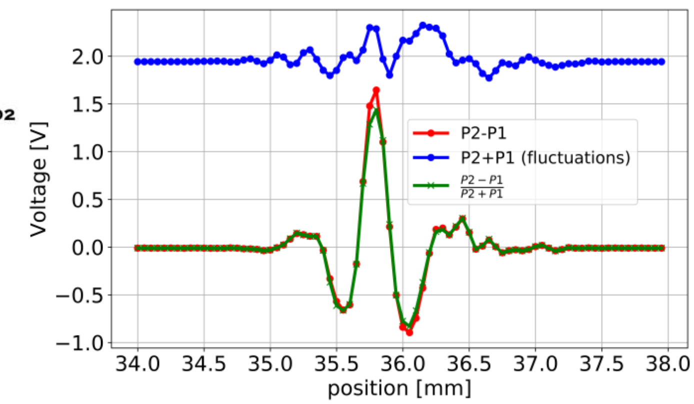
Martin-Puplett Interferometer

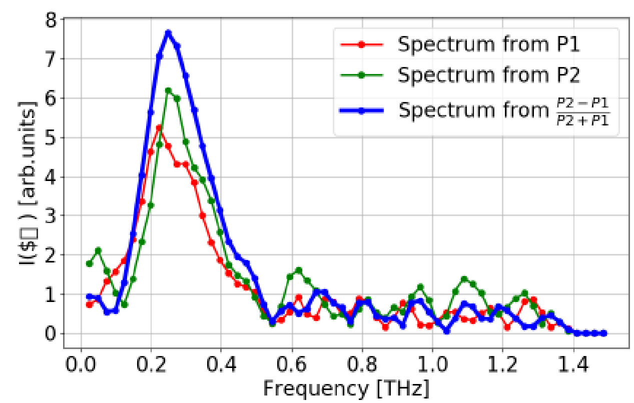
Cherenkov diffraction radiation



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"

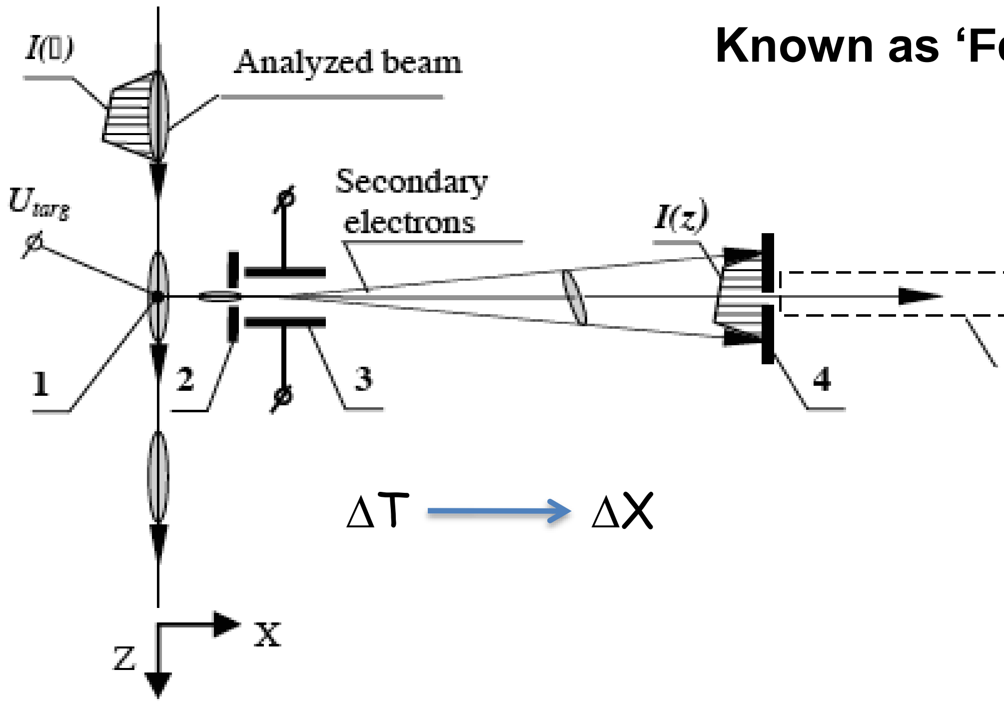
$$I(\omega) \propto \int_{-\infty}^{\infty} I(\delta) \cos\left(\frac{\omega\delta}{c}\right) d\delta$$

Radiofrequency manipulation

‘How to transform time information into spatial information’

Bunch shape monitor

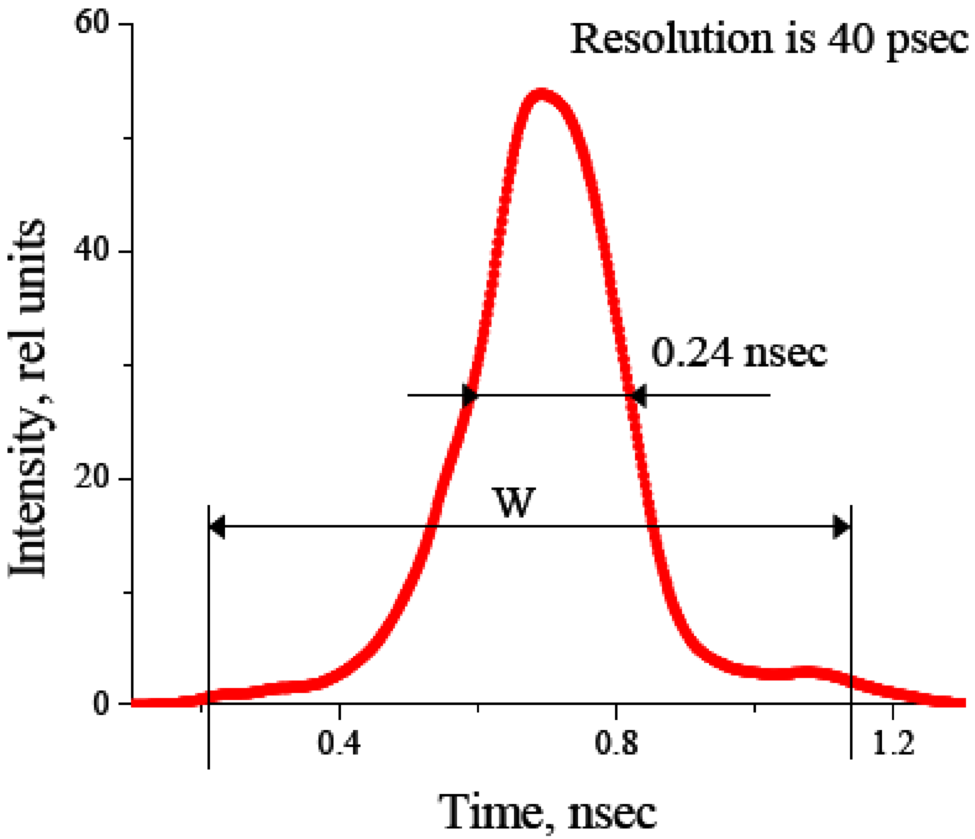
Known as ‘Feschenko monitor’



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

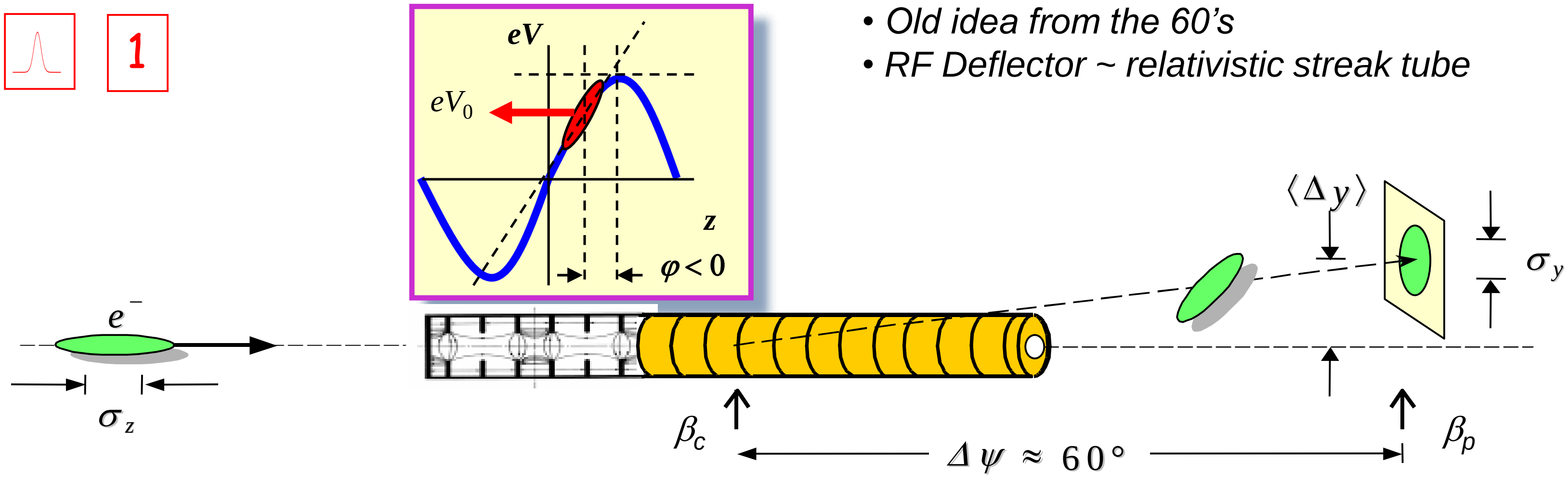
Longitudinal Bunch profile @ SNS



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 on

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

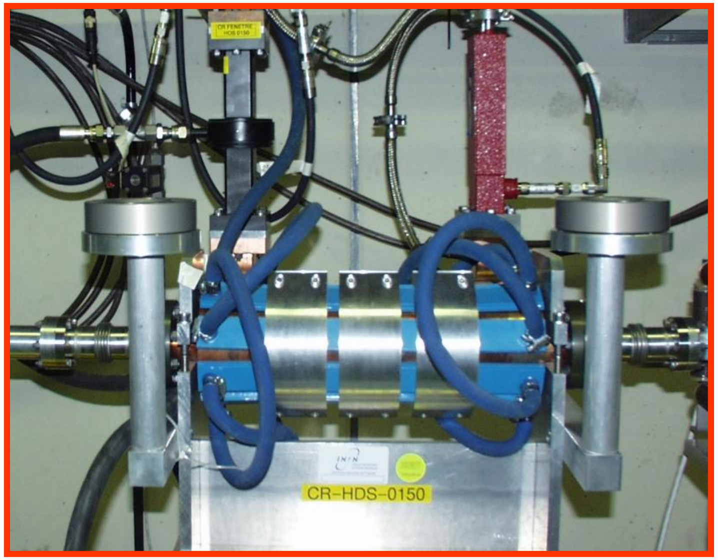
- Beam profile RF off: $\sigma_{y_0}^2$
- Deflecting Voltage: eV_0
- Bunch length: σ_z^2
- Beta function at cavity and profile monitor: $\beta_c \beta_p$
- RF deflector wavelength: λ
- Beam energy: E_0
- Betatron phase advance (cavity-profile monitor): $\Delta\Psi$

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

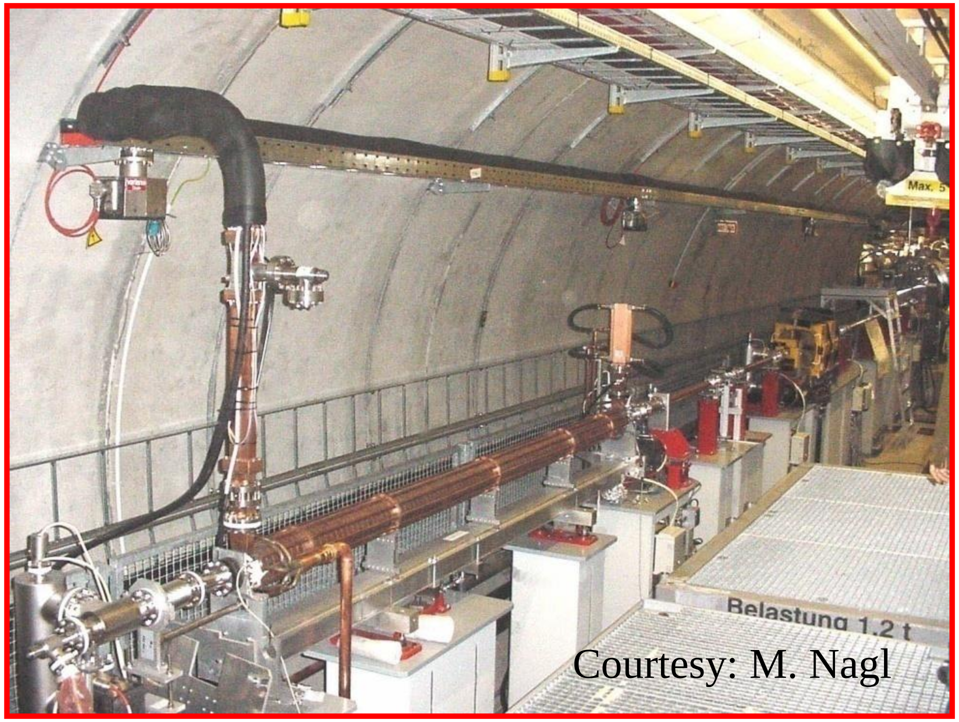
P. Emma et al, LCLS note LCLS-TN-00-12, (2000)

RF Deflecting cavities

CTF3



LOLA @ Flash



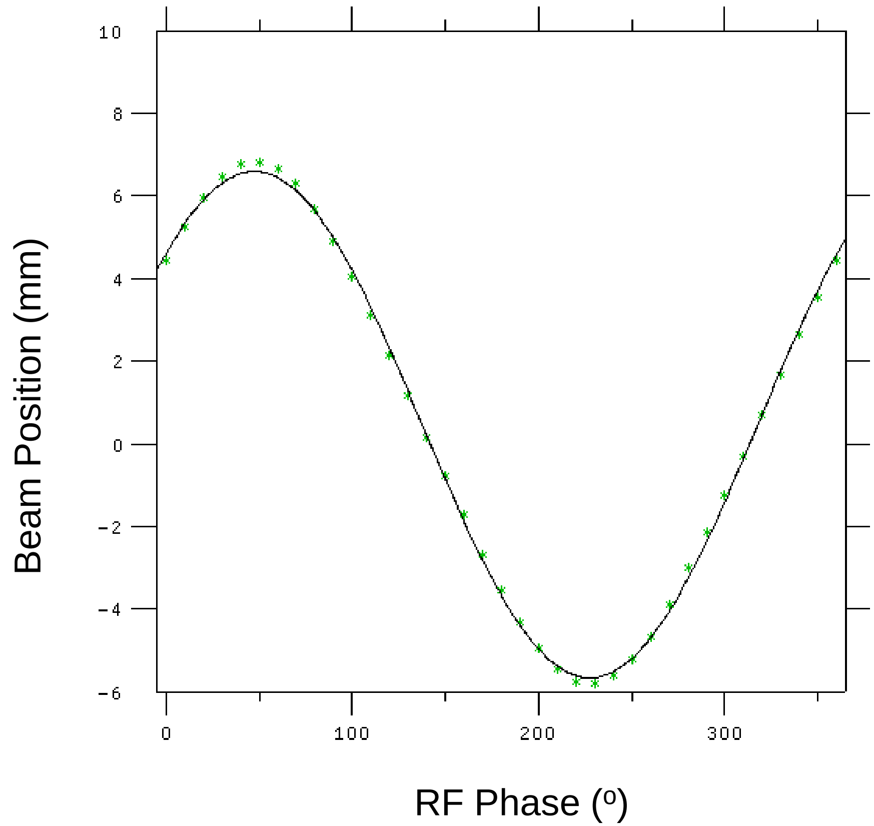
Courtesy: M. Nagl

RF Deflecting cavities

Calibration of RF Deflector

ΔX(mm) → Δφ(°) ΔT(ps)

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

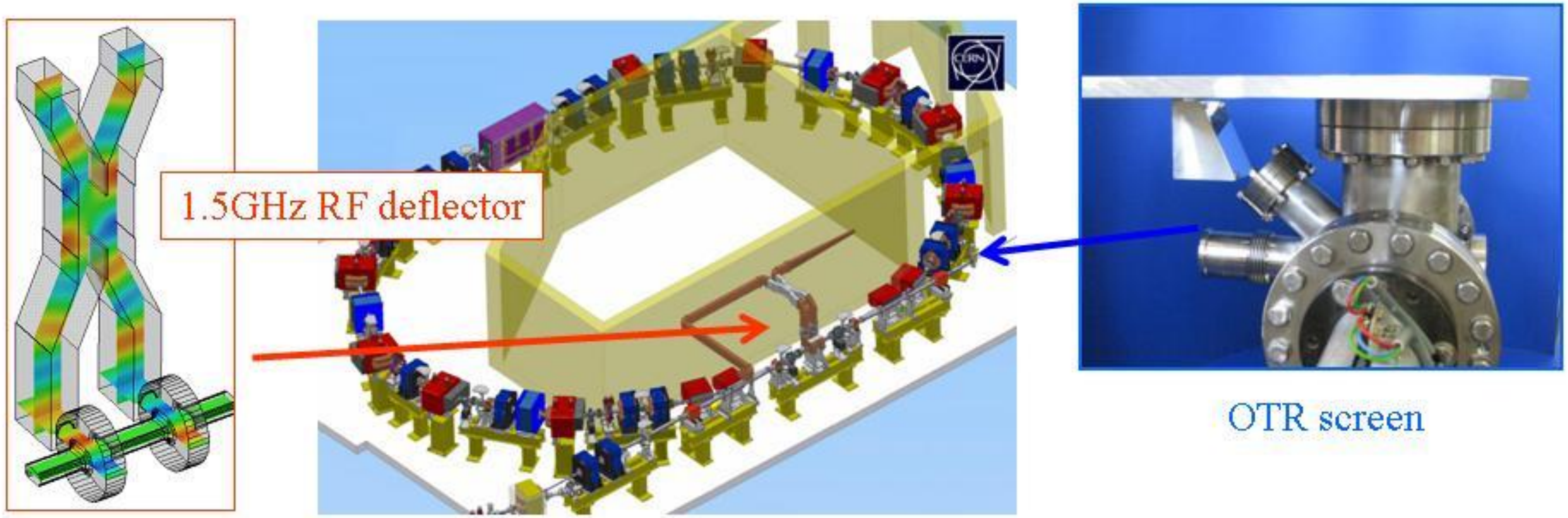


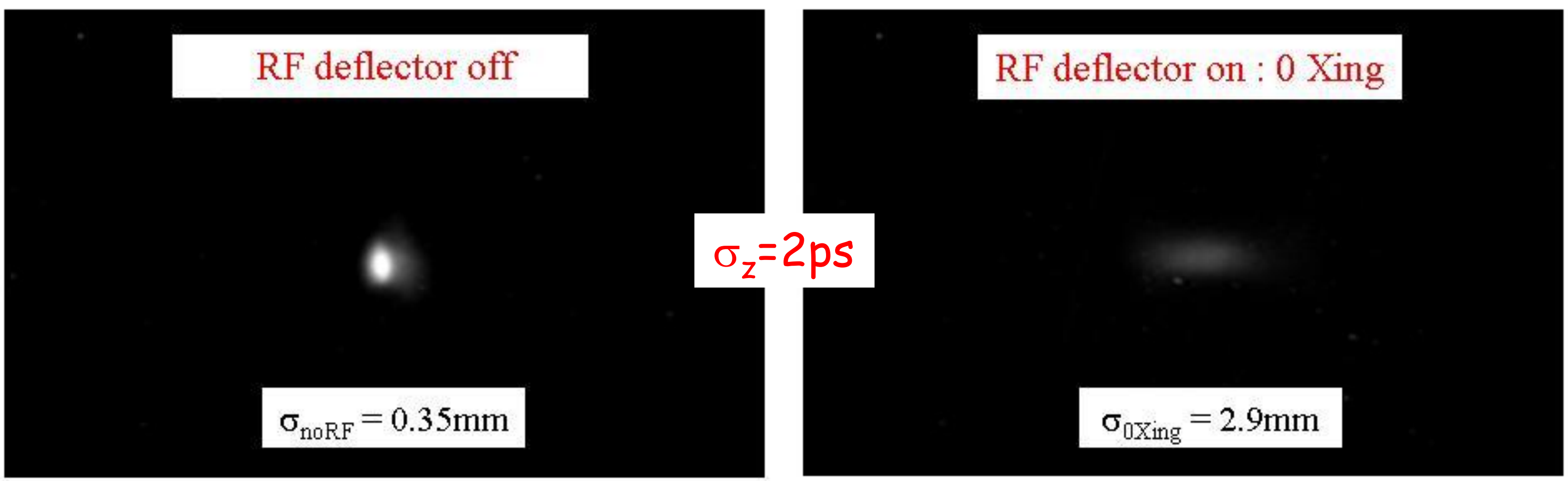
Beam offset on the screen

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

RF deflector phase

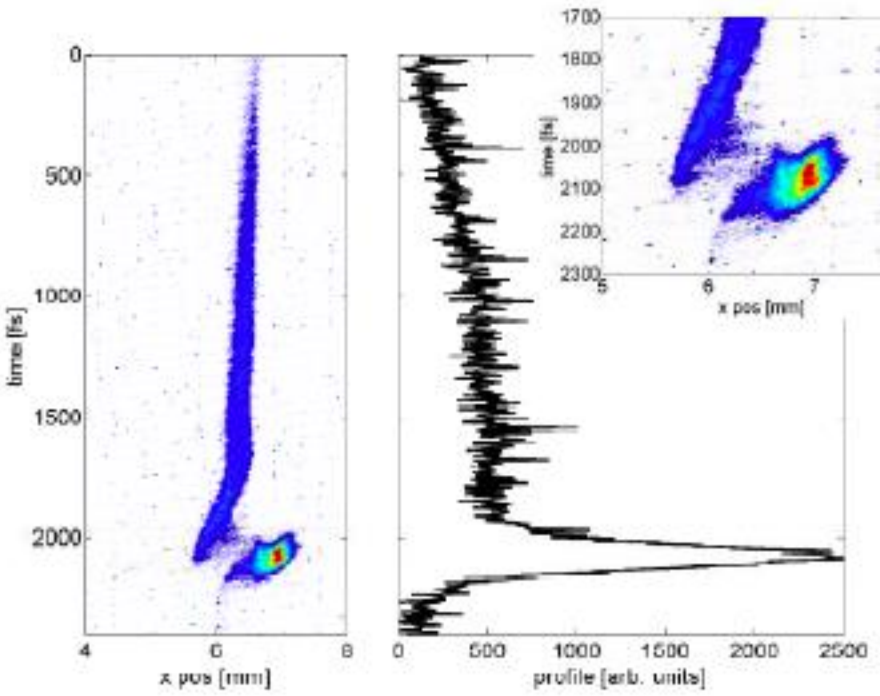
RF Deflecting cavities





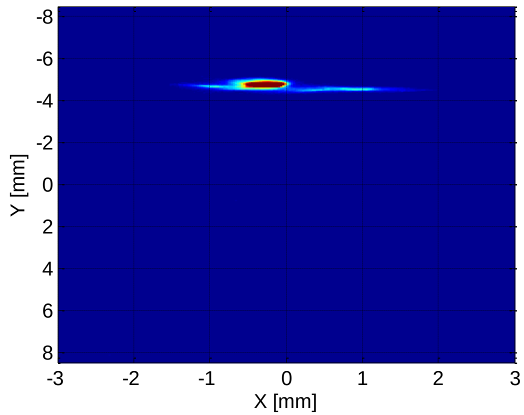
RF Deflecting cavities

Bunch length measurement @ Flash

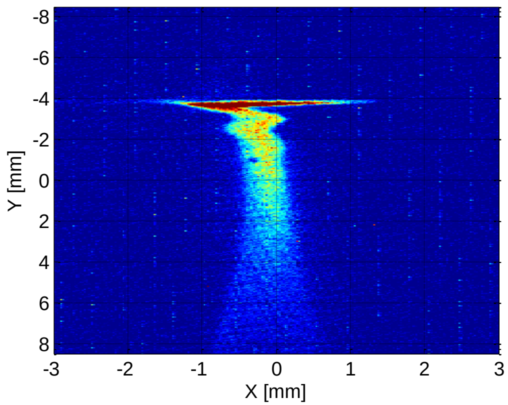


→ Resolution of 4fs/pixels

LOLA off:



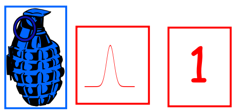
LOLA on:

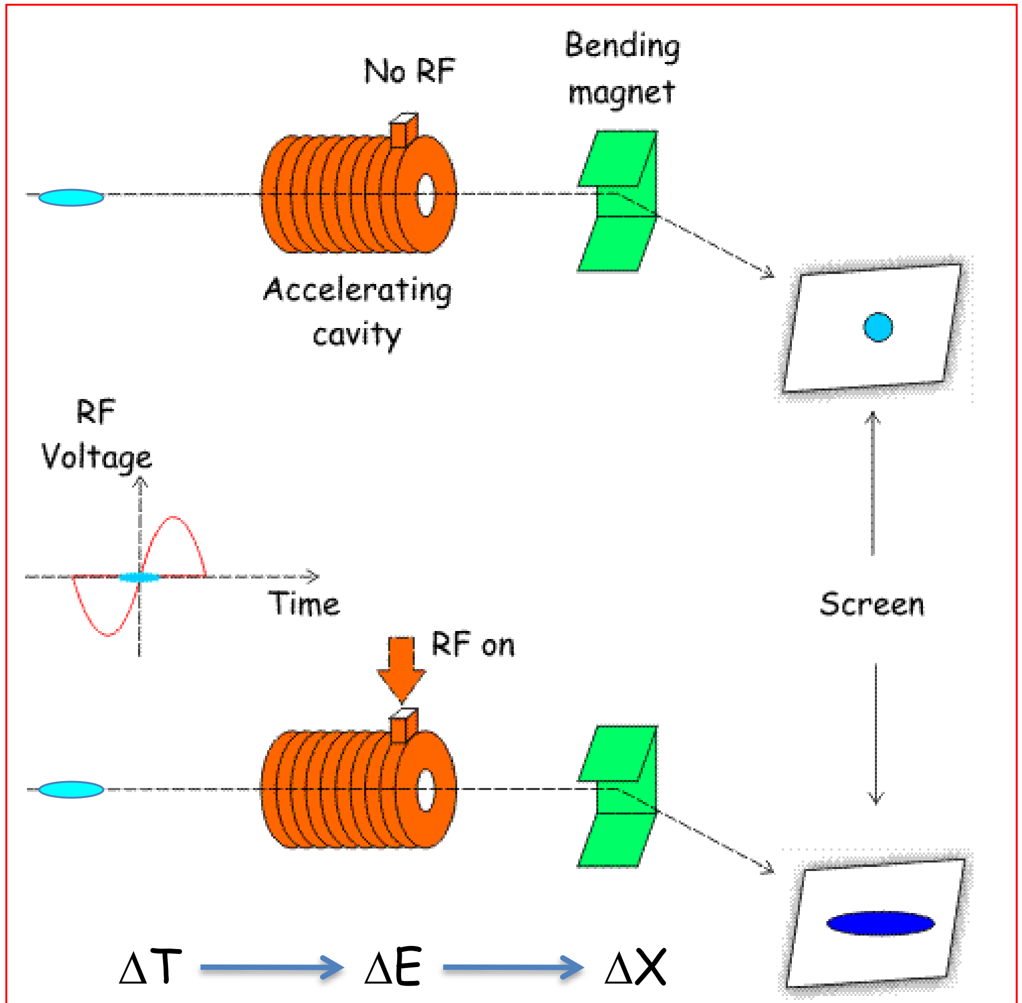


M. Hüning *et al*, Proceeding of the27th FEL conference, Stanford, 2005, pp538

RF Accelerating cavities

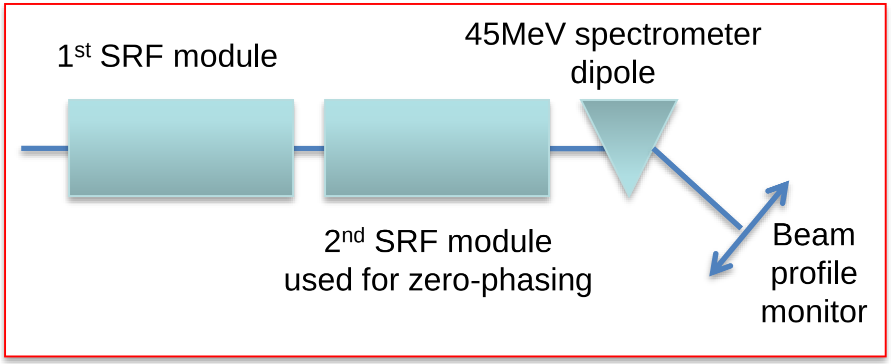
'The electron energy is modulated by the **zero-phasing** RF accelerating field and the bunch distribution is deduced from the **energy dispersion** measured downstream using a spectrometer line'





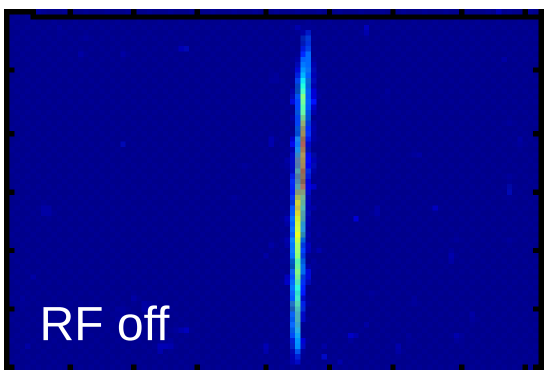
RF Accelerating cavities

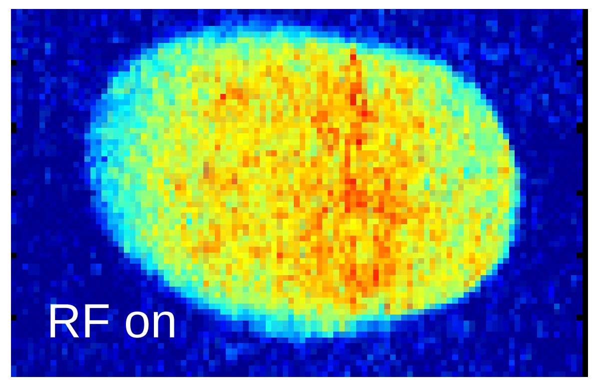
CEBAF injector, Newport News



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

84fs, 45MeV beam but low charge beam



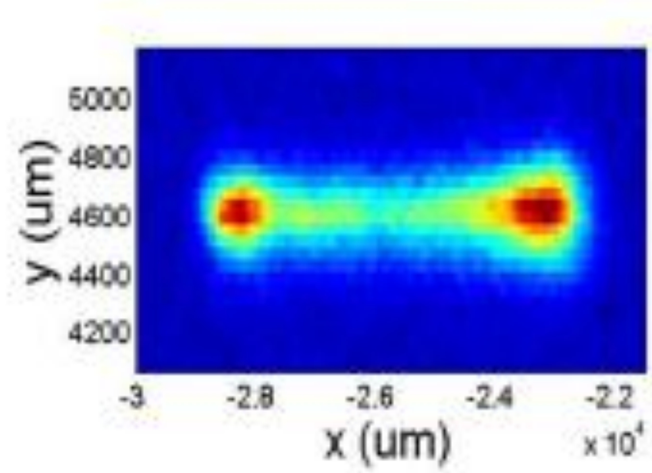


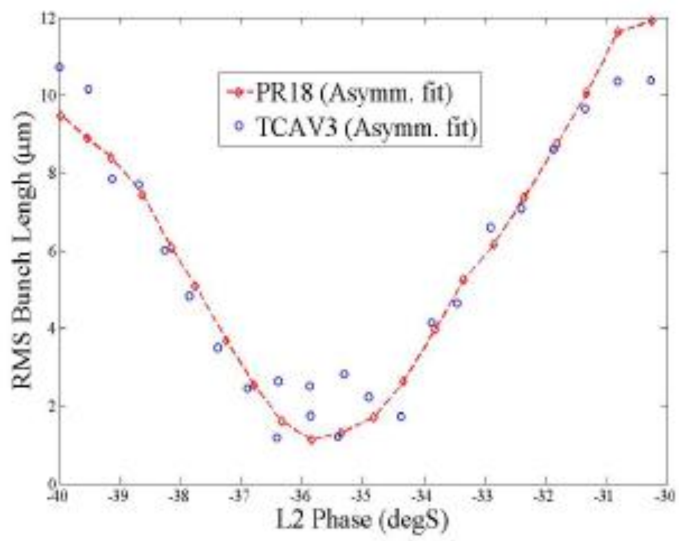
Limitations

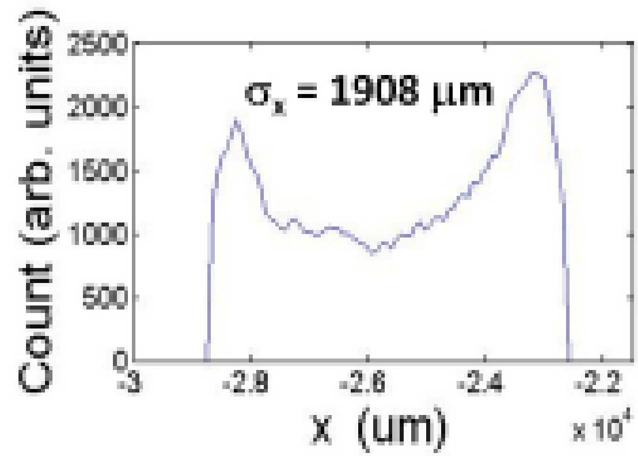
RF non linearities
Beam loading and wakefield for high charge beam

SLAC LCLS: at 4.7 GeV

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







TCAV3

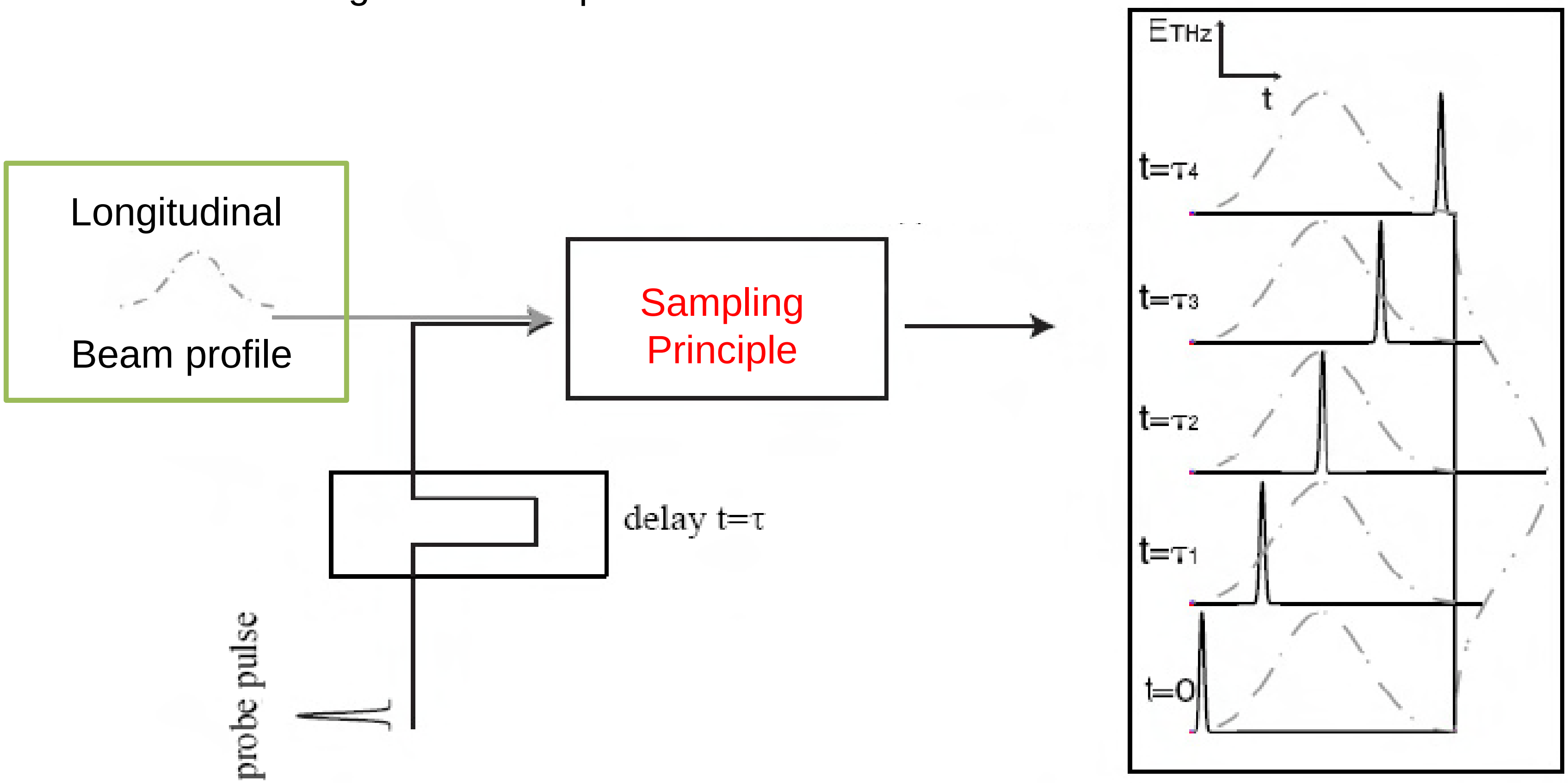
~ 1 fs rms bunch length at 4.7 GeV

Z. Huang et al. PAC 2011, FEL2013

Laser-based diagnostics

Sampling techniques

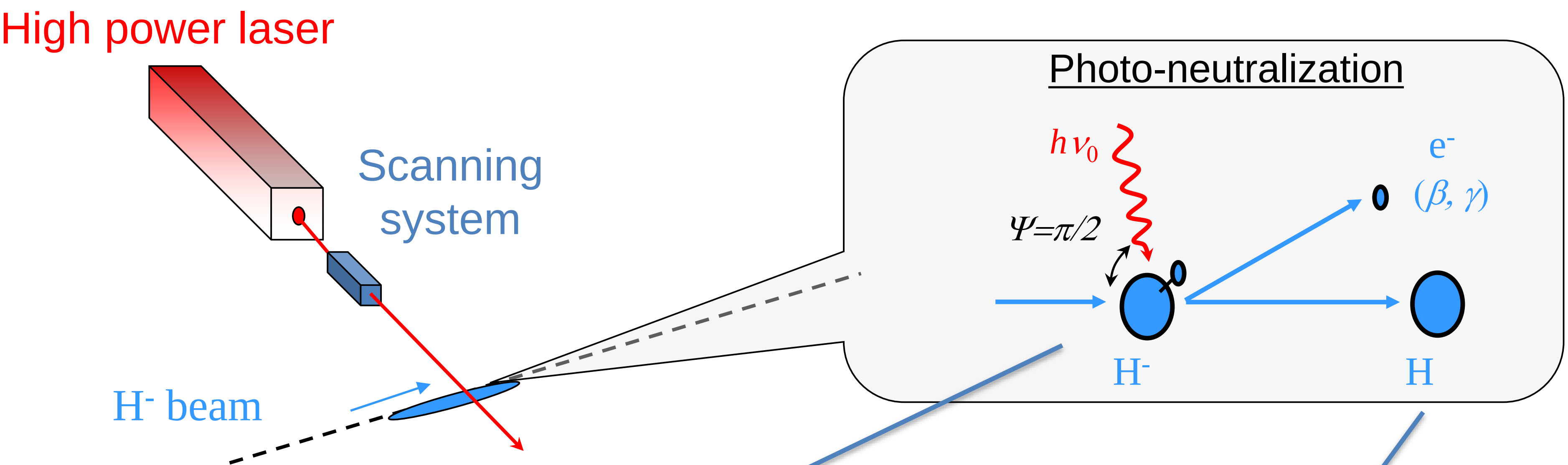
Using a short laser pulse to scan through the beam profile



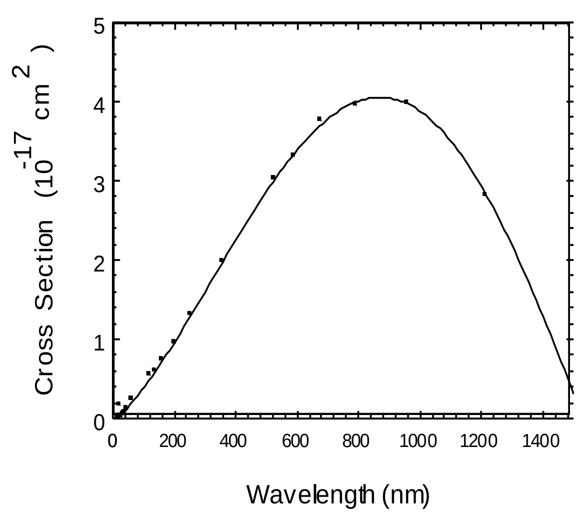
<u>Limitation</u>

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

Laser Wire Scanner



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



Detection system based on

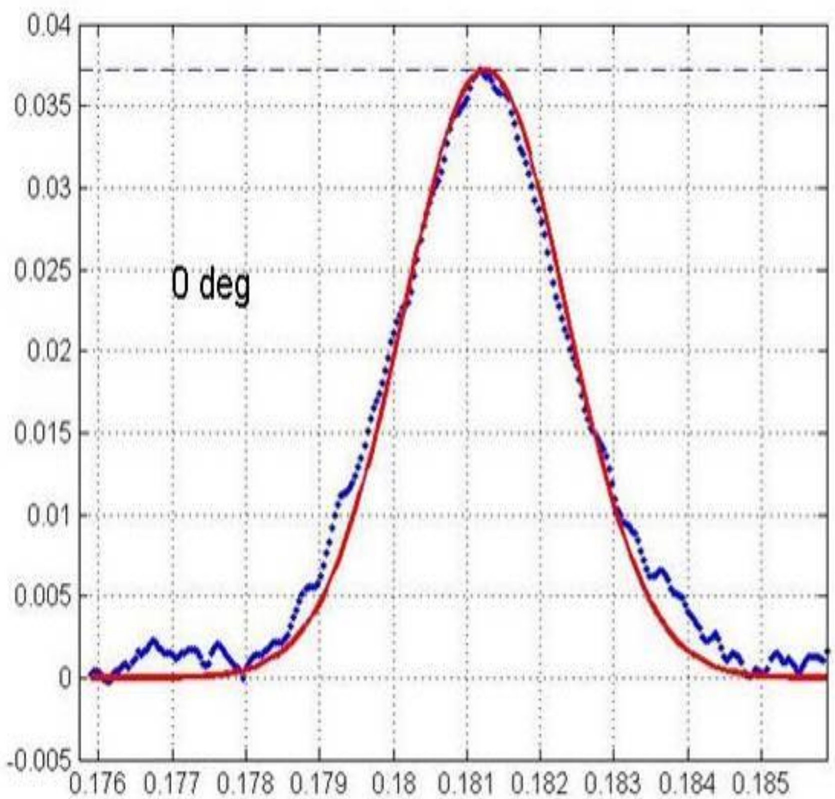
- The measurement of released electrons using a magnet and a collector (faraday cup, MCP,..)

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

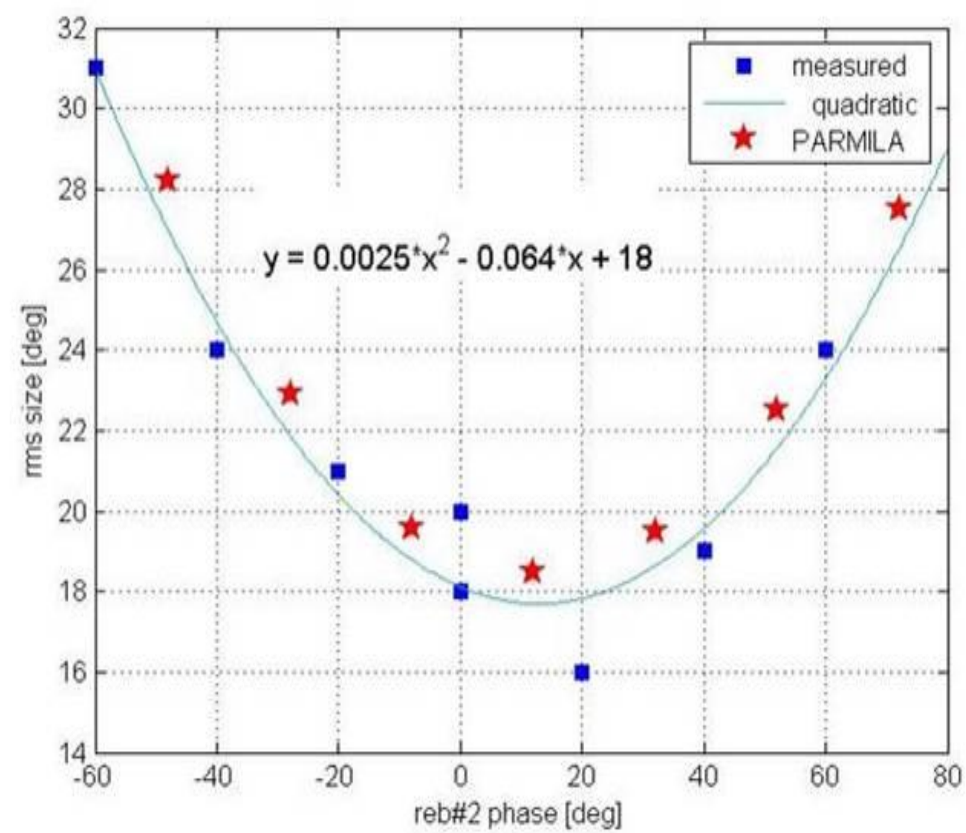
Laser Wire Scanner

Longitudinal Measurements @ SNS

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



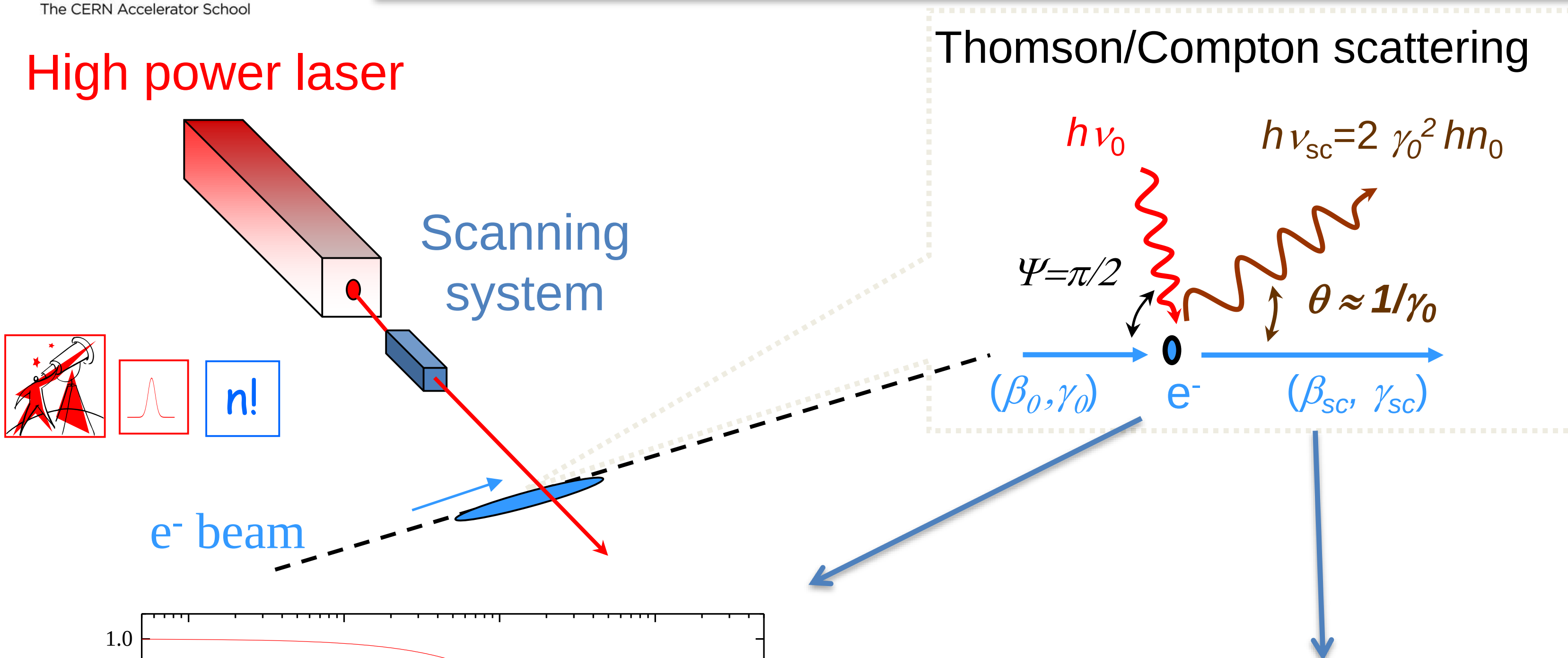
Collected electron signal plotted vs. phase

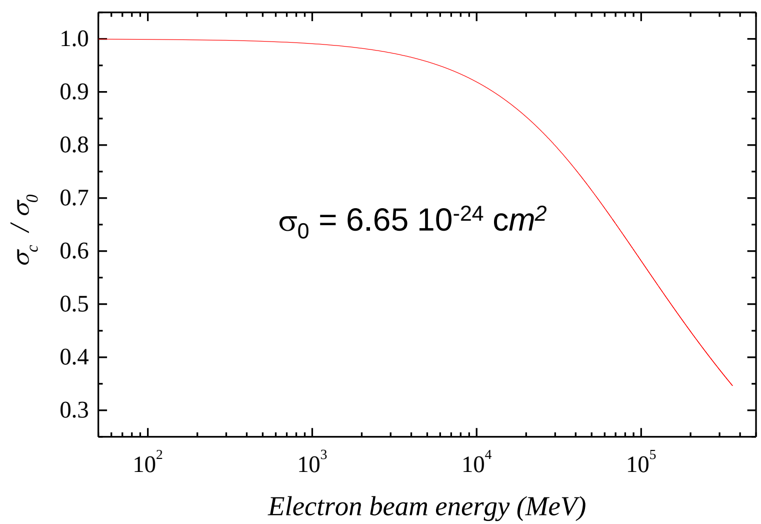


Measured and predicted bunch length vs. cavity phase setting

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

Laser Wire Scanner



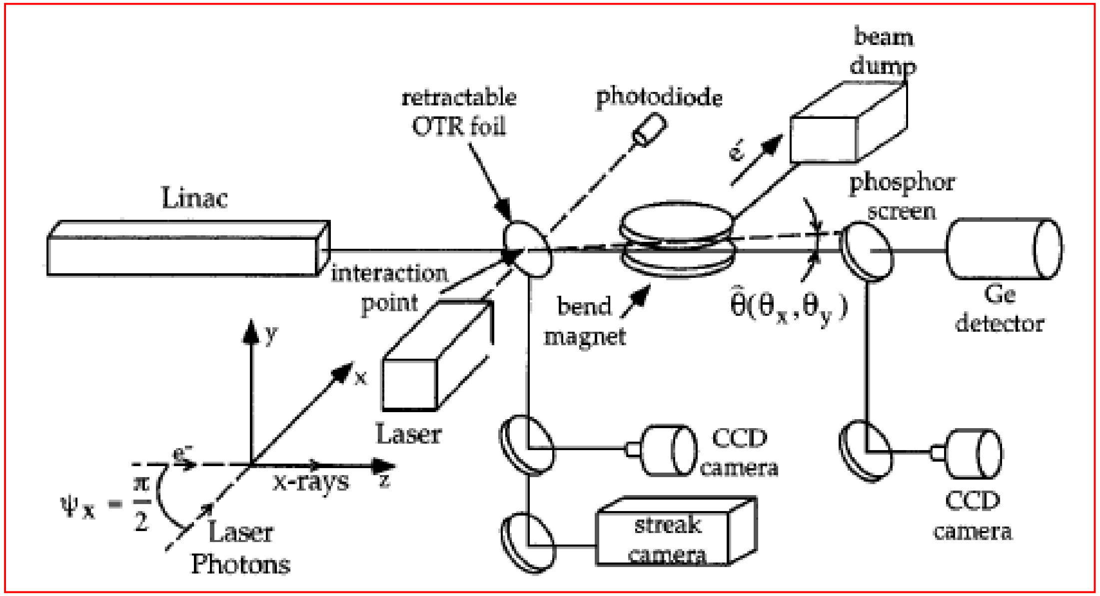


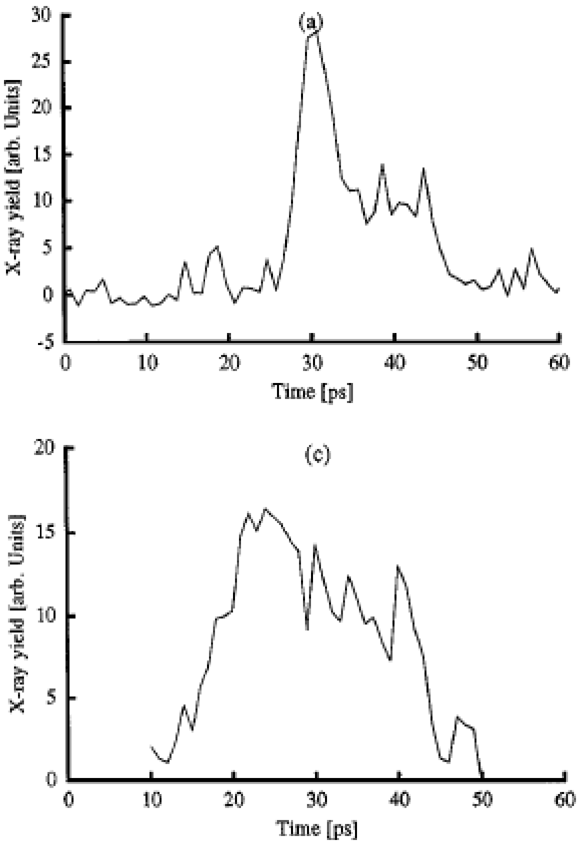
Detection system based on

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

Laser Wire Scanner

ALS @ LBNL





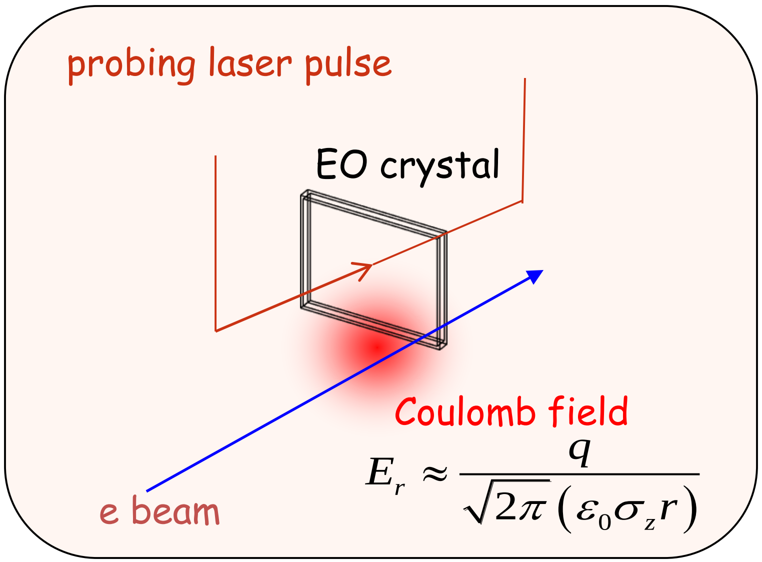
Using a 10TW Ti:Al_2O_3 laser system. Detecting 5.10^4 10-40 keV X-rays using either an X-ray CCD and Ge detector.

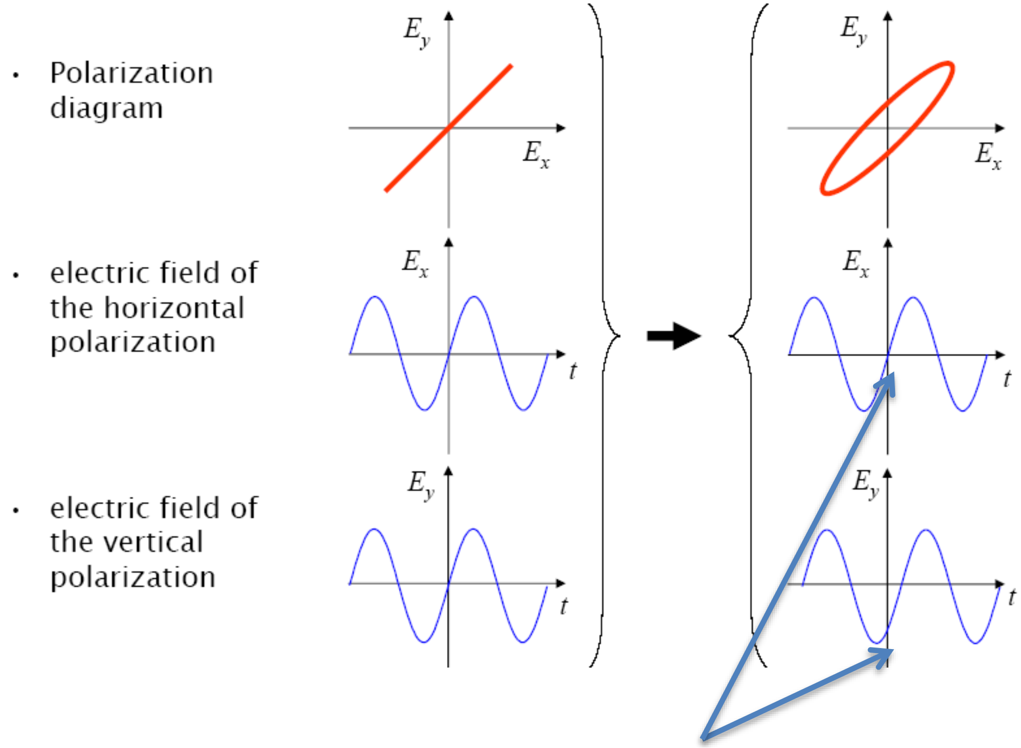
W.P. Leemans et al, PRL 77 (1996) 4182

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

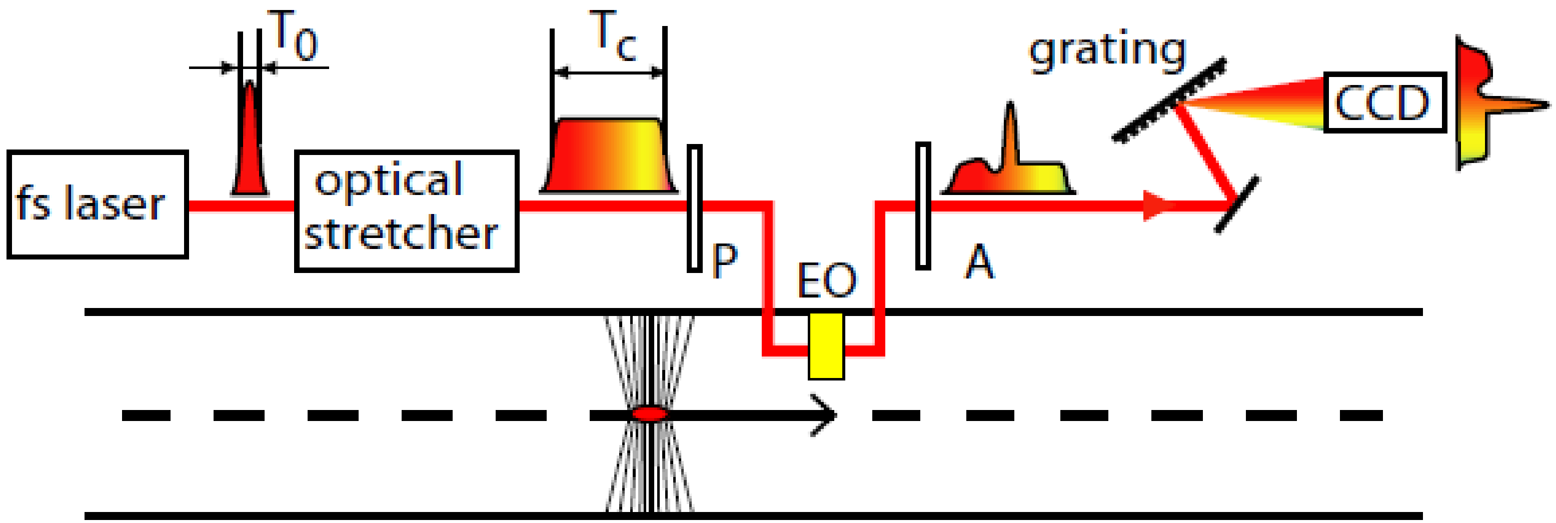




$$\Gamma = \frac{2\pi d}{\lambda_0}(n_x - n_y) = \frac{2\pi d}{\lambda_0} n_0^3 r_{41} E_r$$

Relative phase shift between polarizations increases with the beam electric field

Spectral decoding

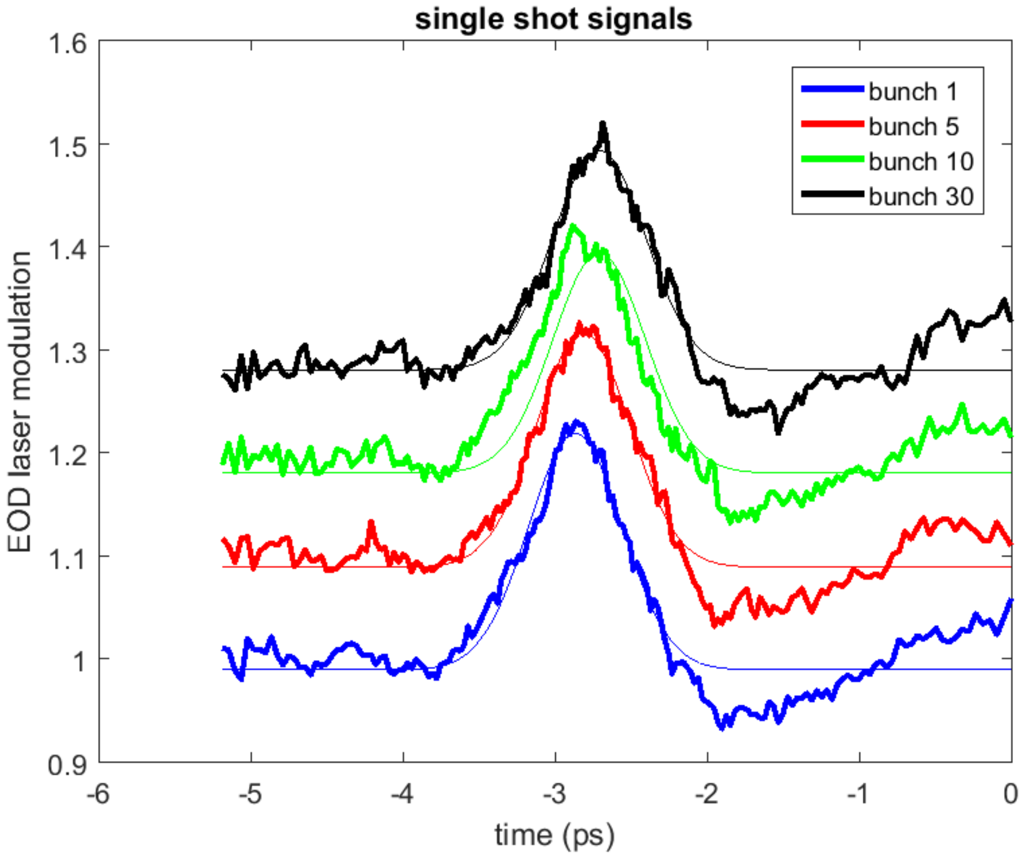


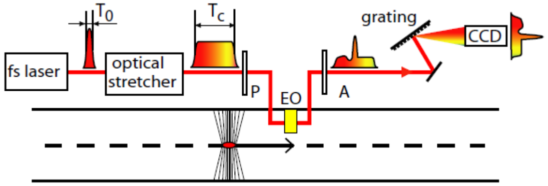
- Artifacts due to frequency mixing
- Minimum resolution in the order $T_{\rm lim} \approx 2.6\sqrt{T_0 T_c}$

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

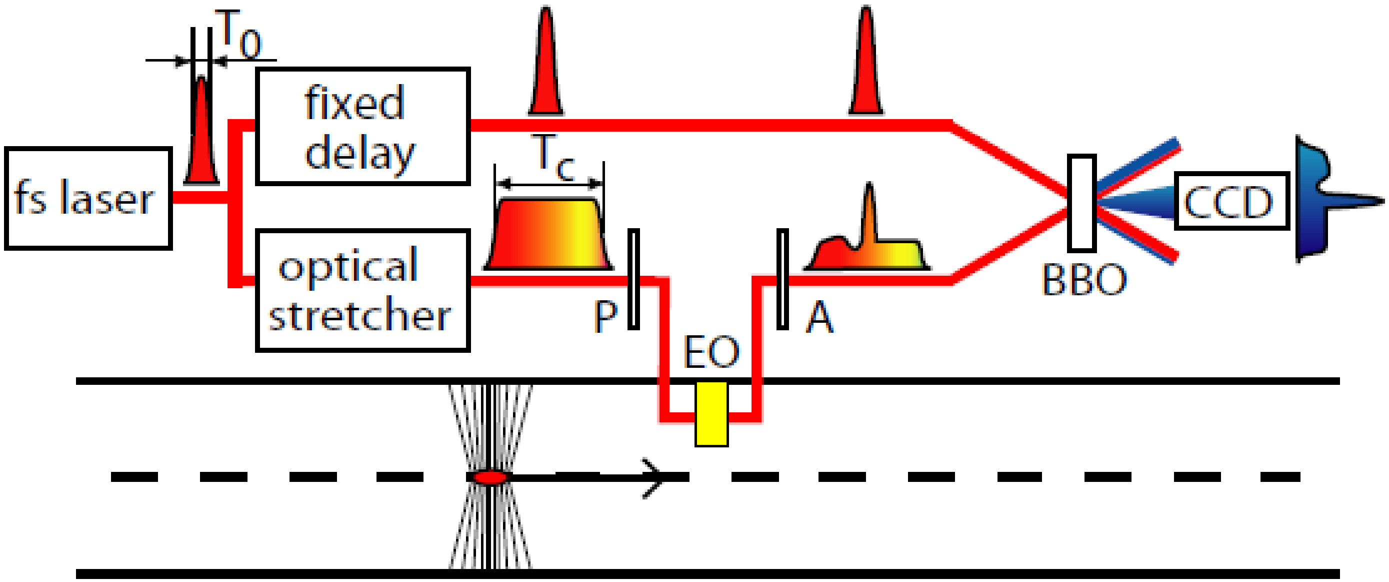
Spectral decoding

Single shot measurements at the XFEL bunch compressor 1





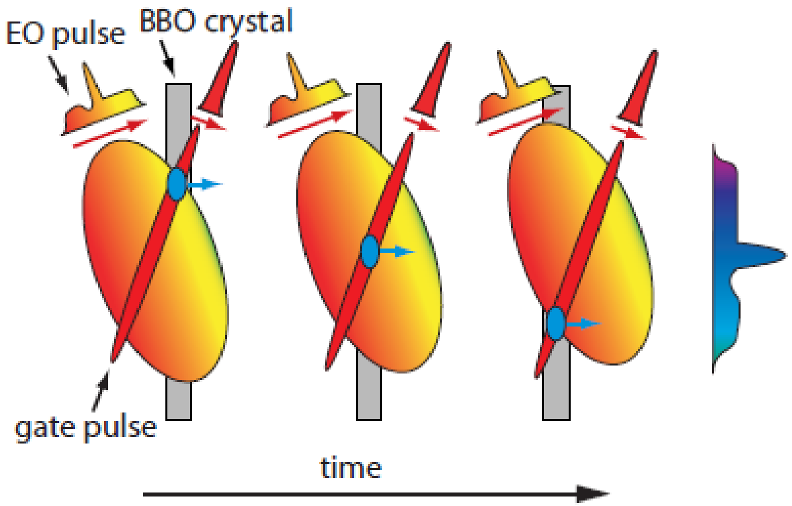
Temporal decoding



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

Berden et.al, PRL 93 (2004) 114802

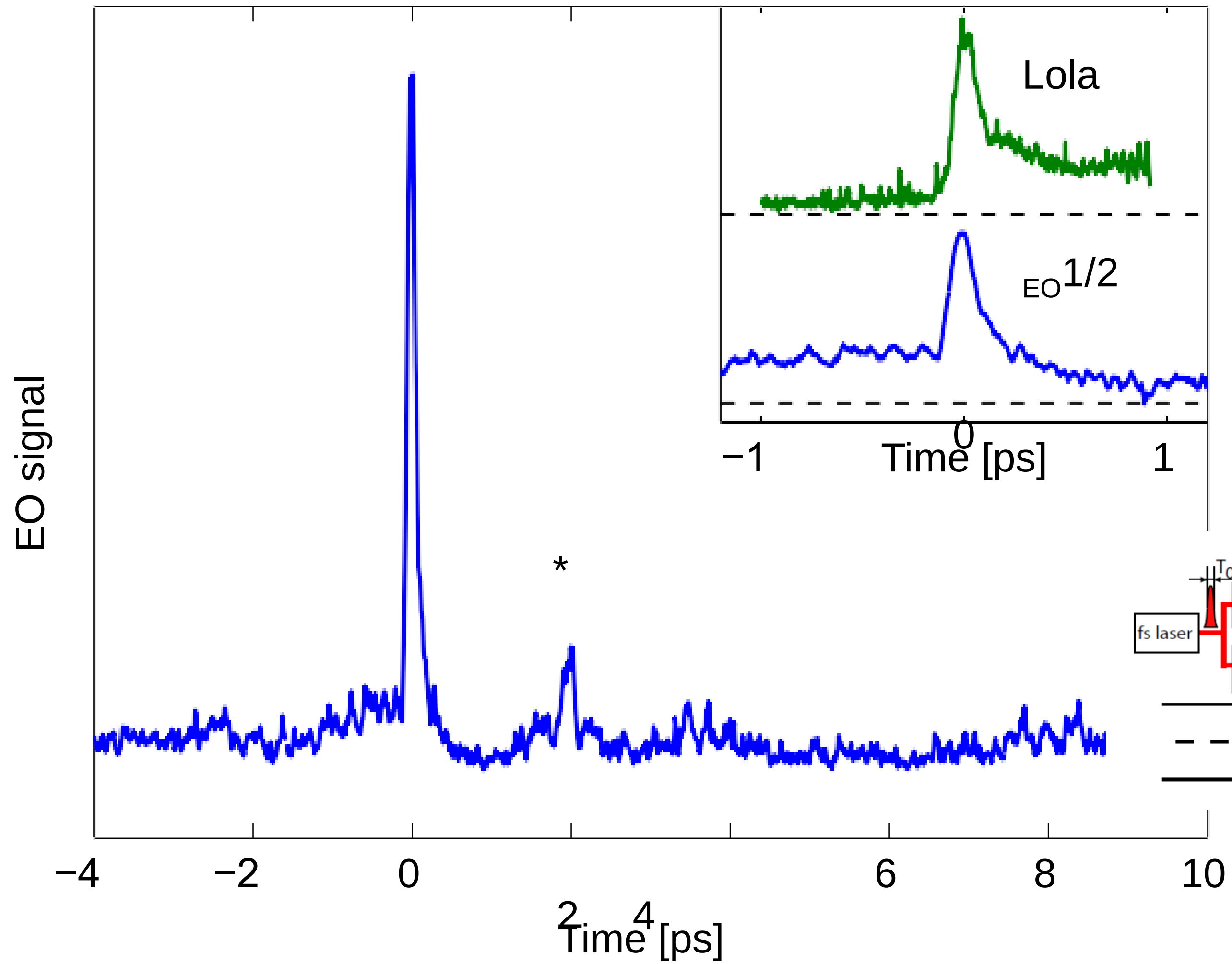
Temporal decoding

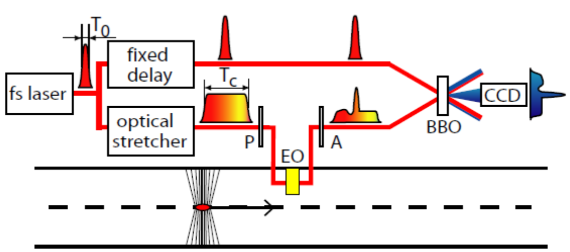


- The short gate pulse overlaps with different temporal slices of the EO pulse at different spatial positions of the BBO crystal. Thus the temporal modulation of the EO pulse is transferred to spatial distribution of the SHG light.

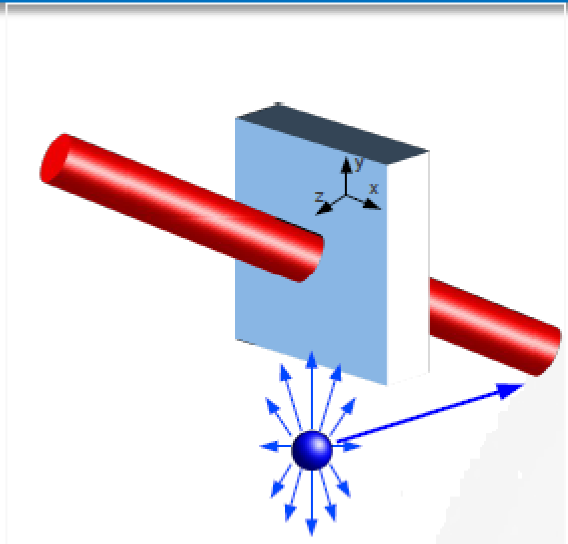
Temporal decoding.

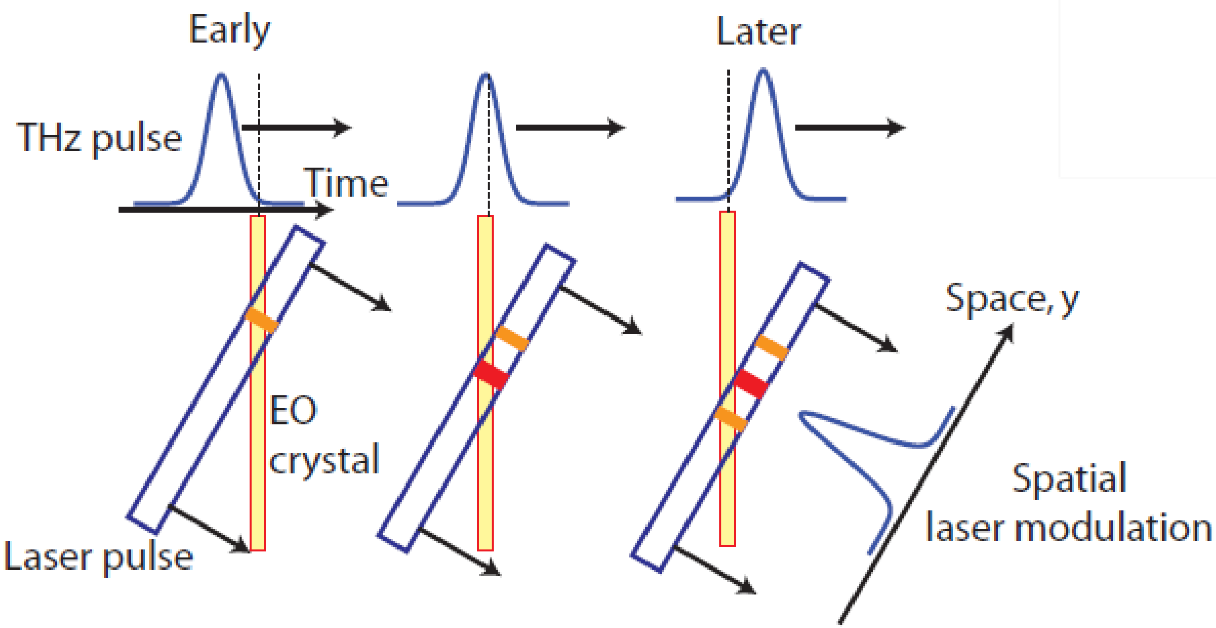
Measurement performed at FLASH/DESY





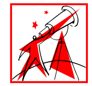
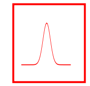
Spatial decoding





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
- An exciting field as well !

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. “

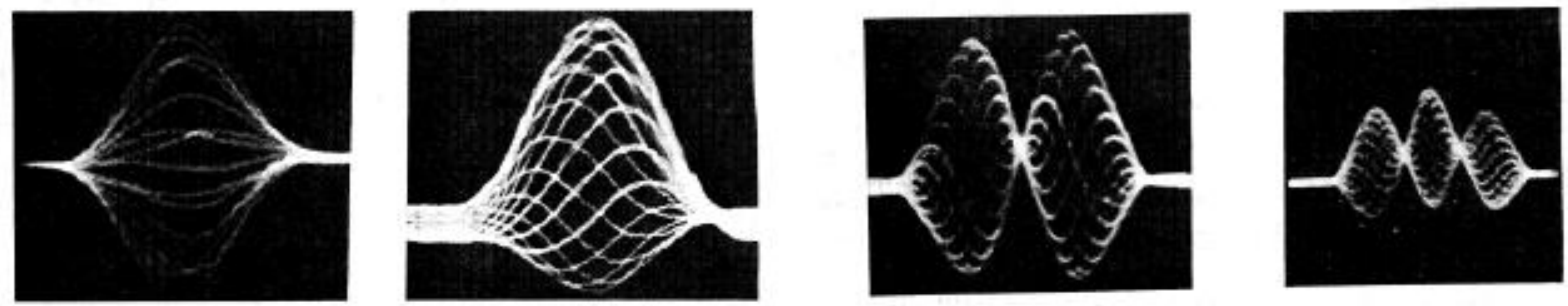
Albert Einstein

The CERN Accelerator School

Transverse Diagnostics
for measuring instabilities

Instability triggering

From Booster in 70’s



a) mode $m = 0$, $\chi = 0$ b) $m = 0$, $\chi = 2.3$ radians b) $m = 1$, $\chi = 6.9$ radians d) $m = 2$, $\chi = 6.9$ radians

Very long pulses – 100ns

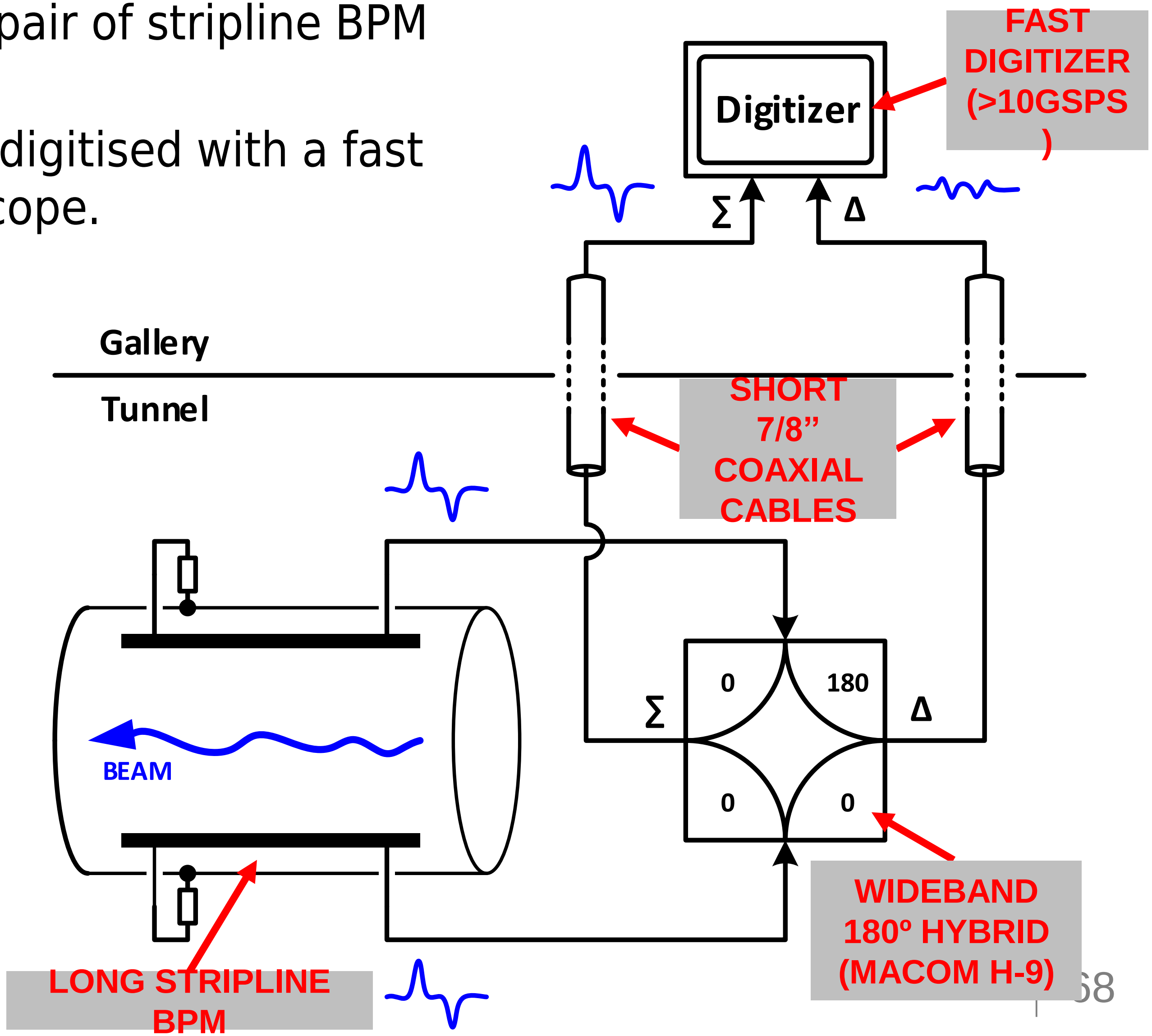
Transverse instability monitoring

A wideband 180º hybrid calculates the sum and difference of a pair of stripline BPM electrodes.

Signals are directly digitised with a fast (>10GSPS) oscilloscope.

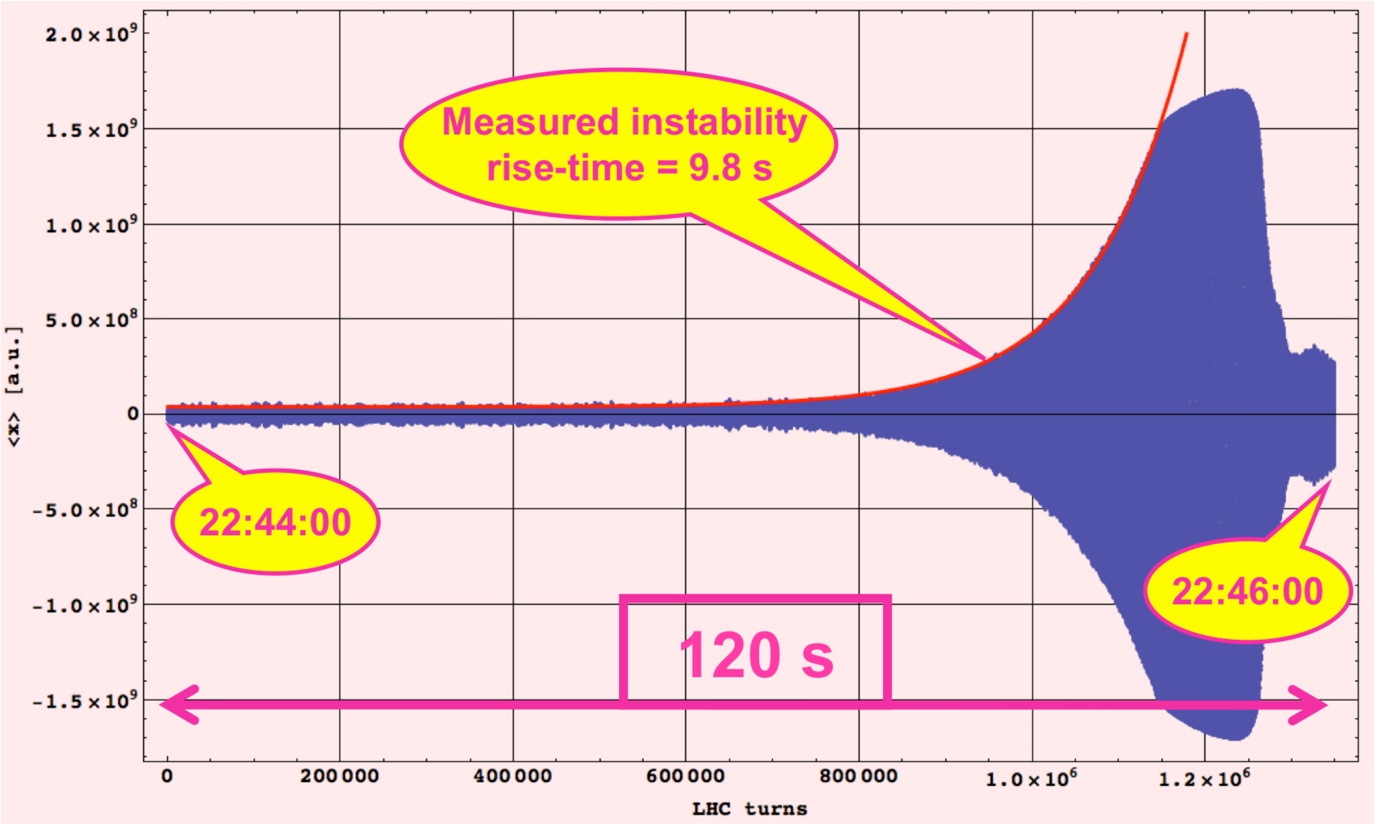
Originally planned for chromaticity measurement (H-T phase shift), but excitation amplitude too large for regular operation.

Now primarily used for measuring intra-bunch instabilities.



Transverse instability monitoring

Looking at the beginning of an instability on Large Hadron Collider



The rise time is defined as the time taken for the amplitude of the envelope to increase by: $e^1 \approx 2.7$.

Transverse instability monitoring

The LHC BBQ system is most sensitive instrument available for detecting transverse oscillations. Instability detection can be performed by looking at the growth in BBQ amplitude spectrum. Initial developments of algorithm by J. Ellis. Since 2015 the algorithm has been running online in the LHC (FPGA implementation).

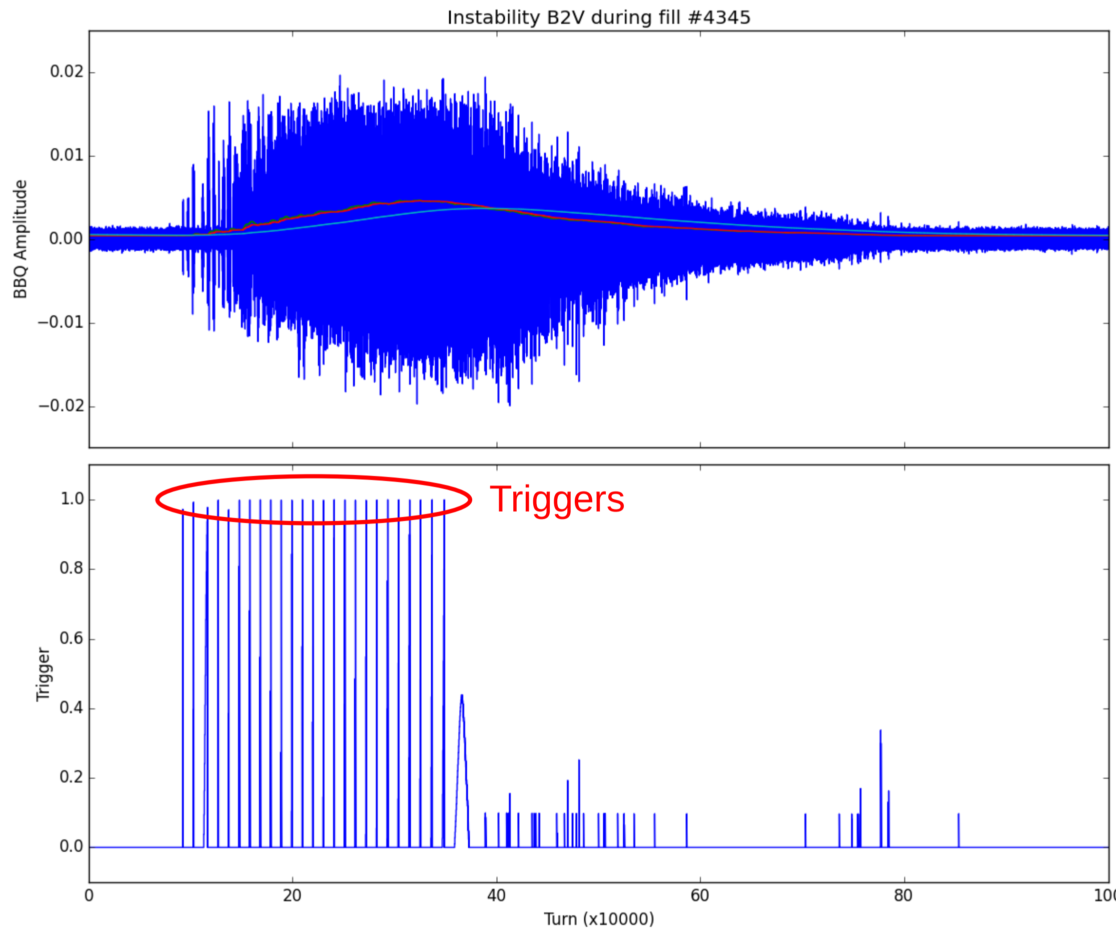
Three moving average filters of different lengths are applied to r.m.s. input signal.

If the condition:

$$\sigma_{short} > \sigma_{medium} > \sigma_{long}$$

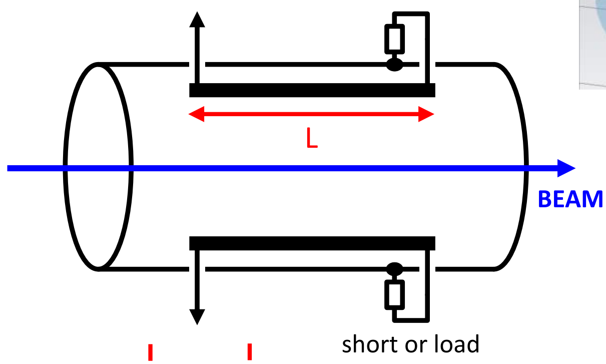
is exceeded for a certain number of turns the trigger is fired.

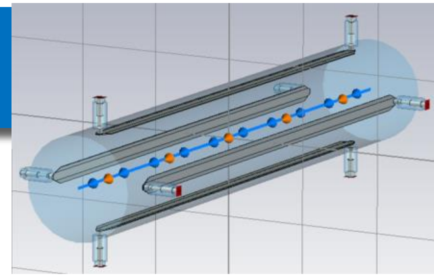
Works reasonably but still being tuned in order to be robust against injection transients, abort gap cleaning excitation, …

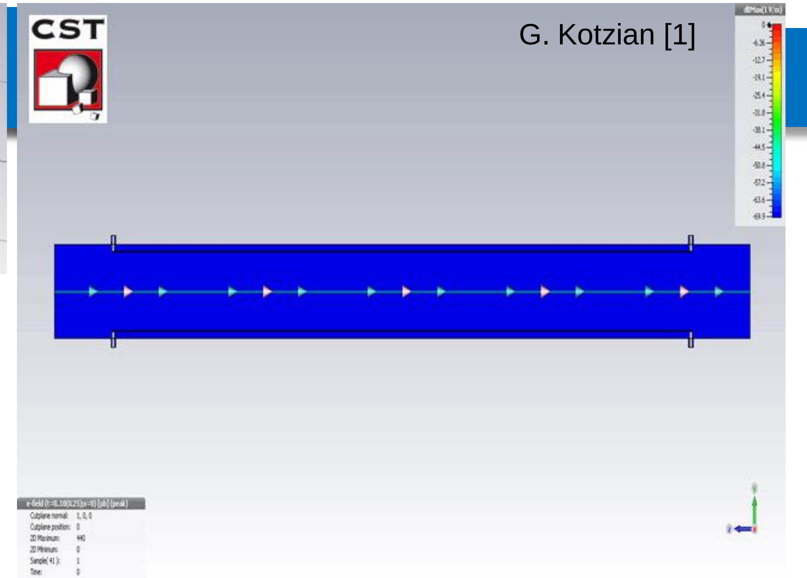


Stripline BPM

The CERN Accelerator School

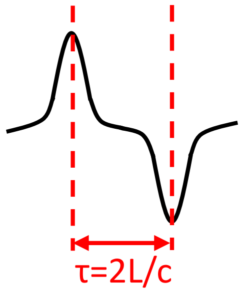






LHC BPLX
L=40cm, τ=2.6ns

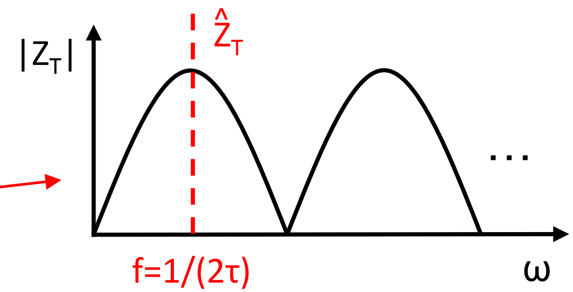
SPS BPCL
L=60cm, τ=4.0ns



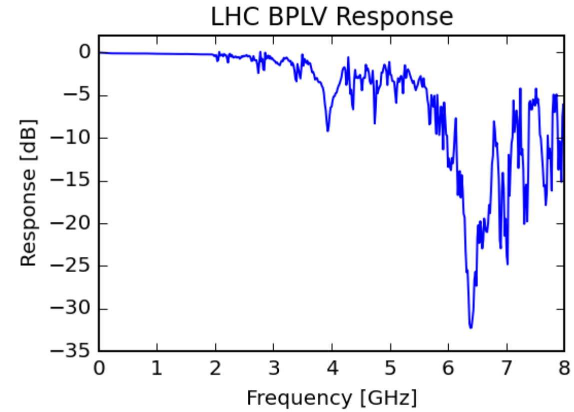
$$V_{PU}(t) = Z_T I_b(t) * [\delta(t) - \delta(t-\tau)]$$

BUNCH PROFILE (for $Z_T I_b(t)$)

NOTCHES IN FREQ. RESPONSE (for $[\delta(t) - \delta(t-\tau)]$)

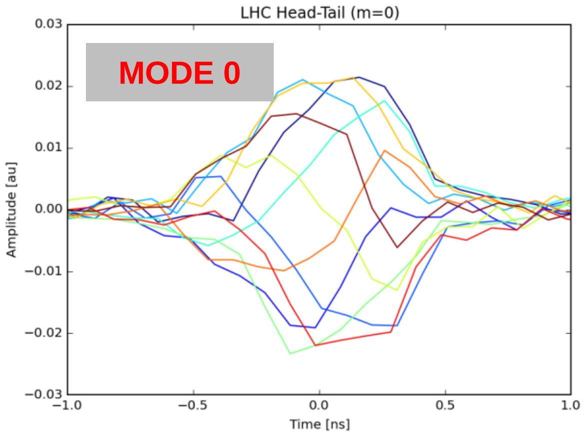


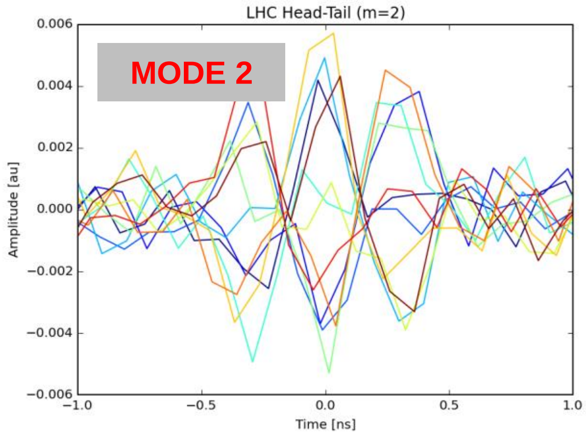
Notches can be removed gating on the initial pulse in the time domain and discarding second pulse. Frequency response is then limited by the BPM structure, feed-throughs, etc.
NB: This requires long BPM and adequate bunch spacing to avoid mixing of the two pulses from the same or subsequent bunches.

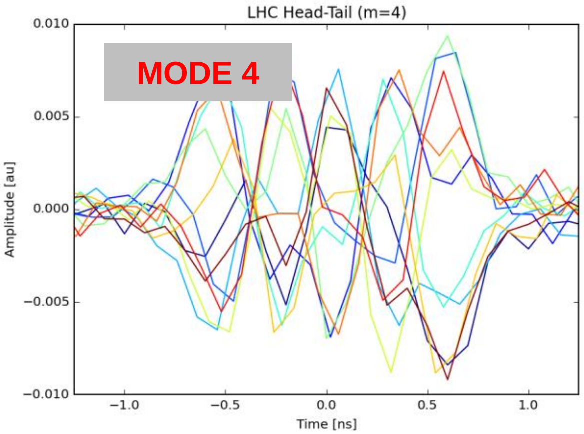


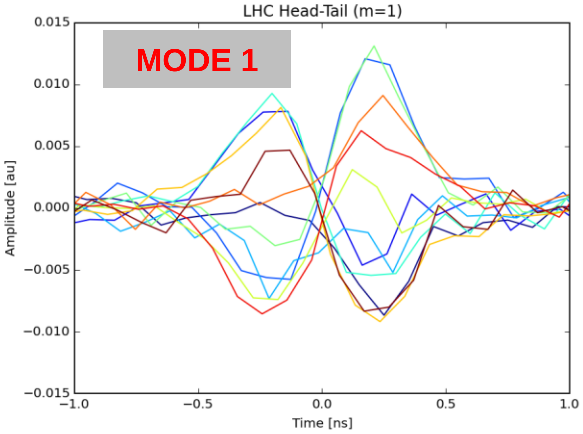
Instability triggering

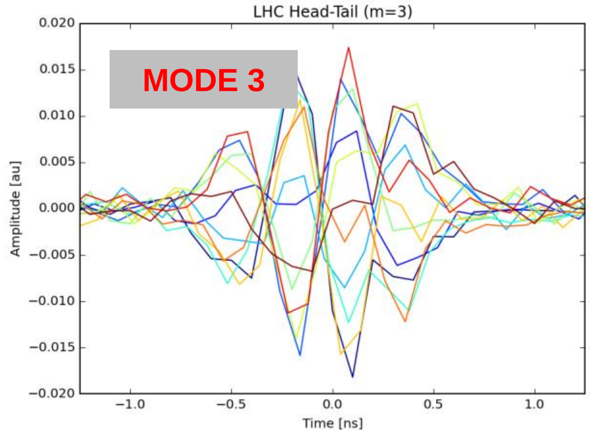
From LHC in 2018







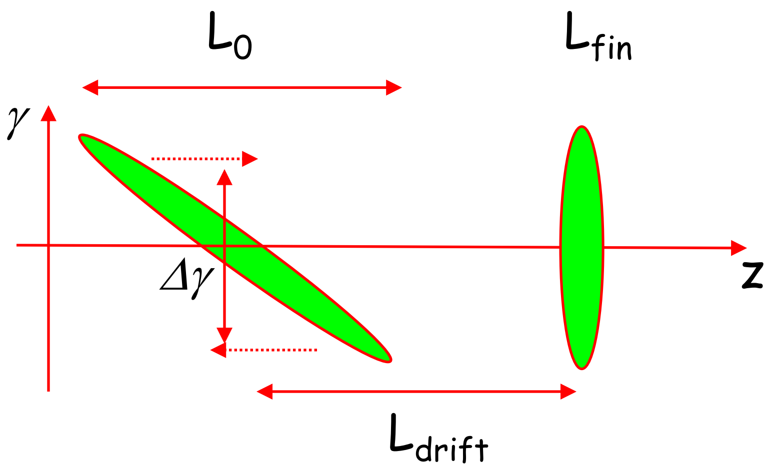




Bunch length manipulation

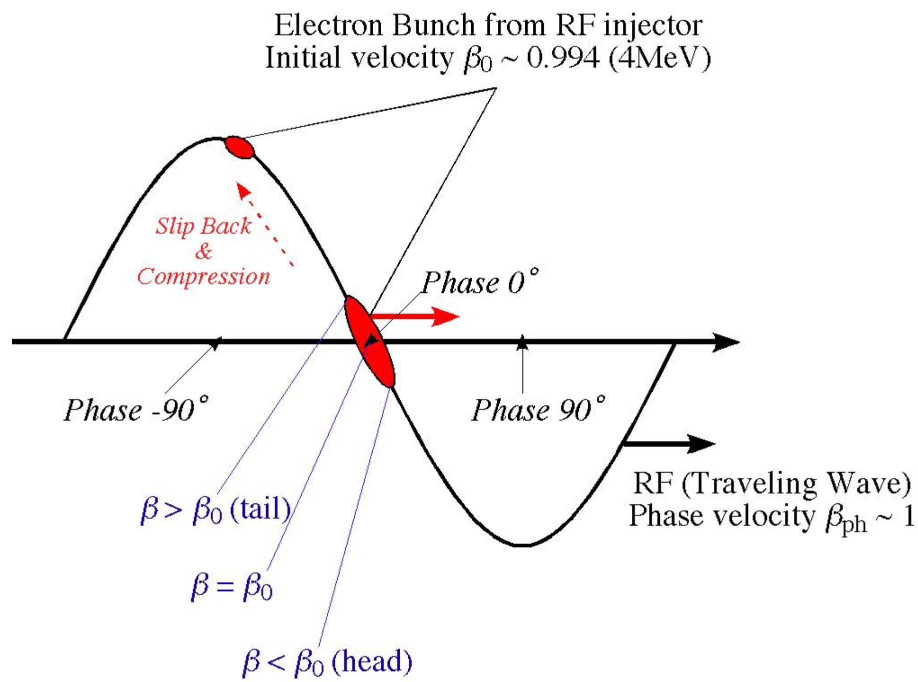
- Ballistic Compression
- Magnetic Compression

Short bunches by Ballistic/Velocity Compression



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

$\Delta\gamma$

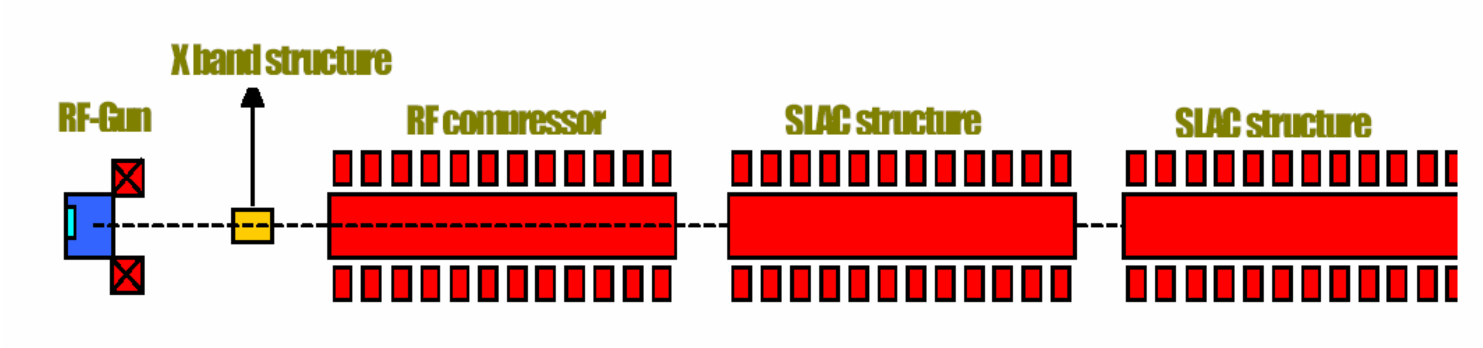


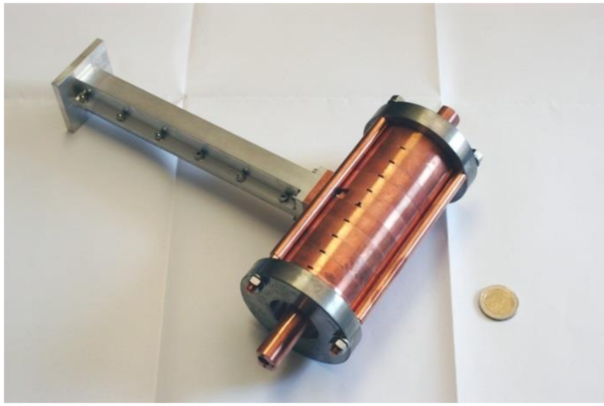
Provide a correlated velocity spread enough to produce, in a drift of length L_{drift} a *path difference* equal to ΔL

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

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

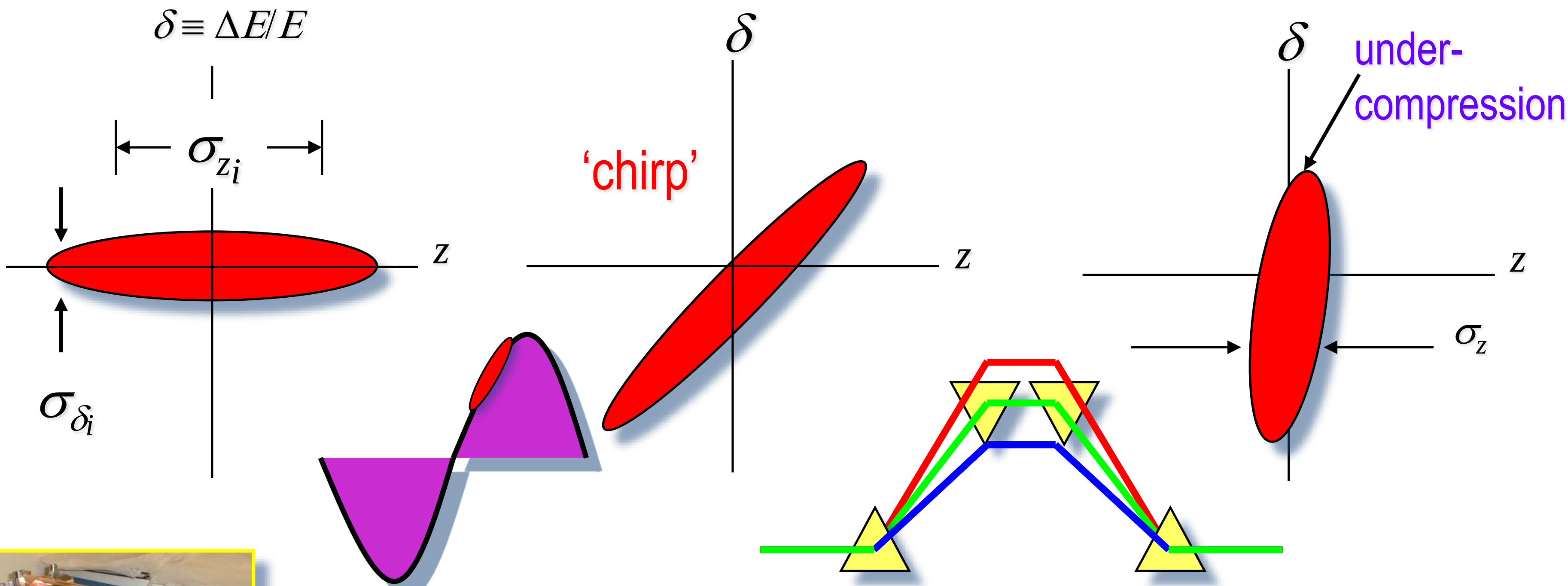
Short bunches by Ballistic Compression





- 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



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

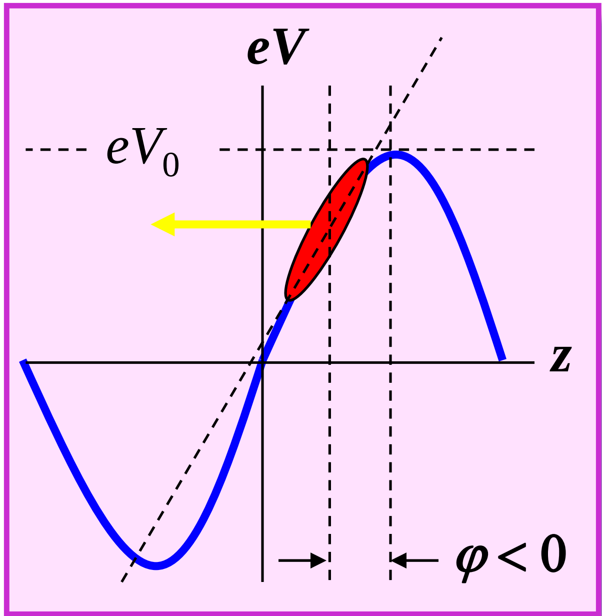
$$\Delta z = R_{56}\delta$$

RF Accelerating Voltage

Path-Length Energy-Dependent Beamline

ΔT → ΔE → ΔX → ΔT

Short bunches by Magnetic Compression



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

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

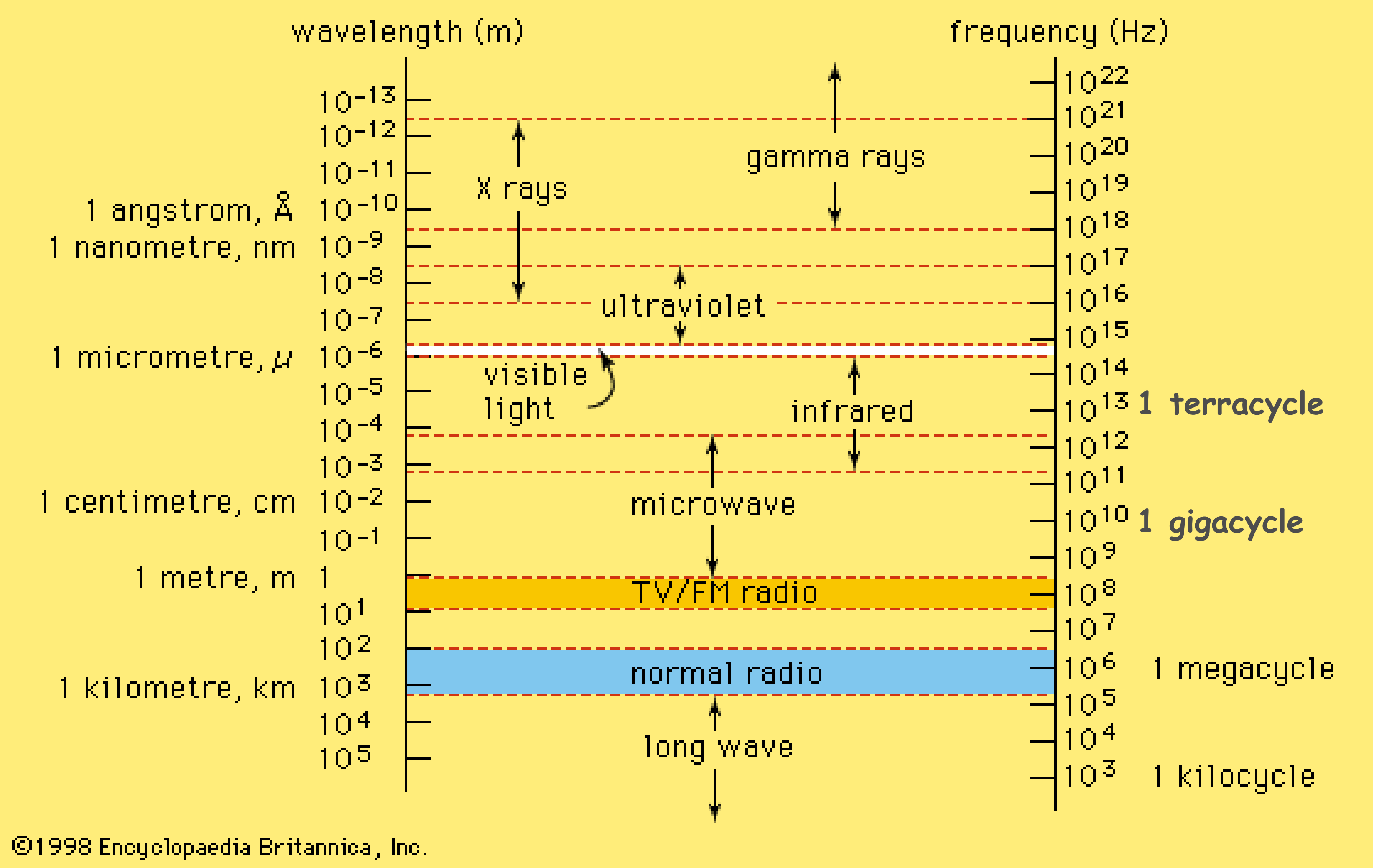
$$\delta_0 \frac{E_0}{E} + \left(1 - \frac{E_0}{E}\right)\left[\frac{\cos(\varphi + \Delta\varphi) - (2\pi z/\lambda)\sin(\varphi + \Delta\varphi)}{\cos(\varphi)} - 1\right]$$

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



Coherent Synchrotron Radiation in Magnetic Chicane

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