Longitudinal Beam Profile Measurements

T. Lefevre, CERN

- Longitudinal beam profile in Accelerators
- 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

How to accelerate Particles

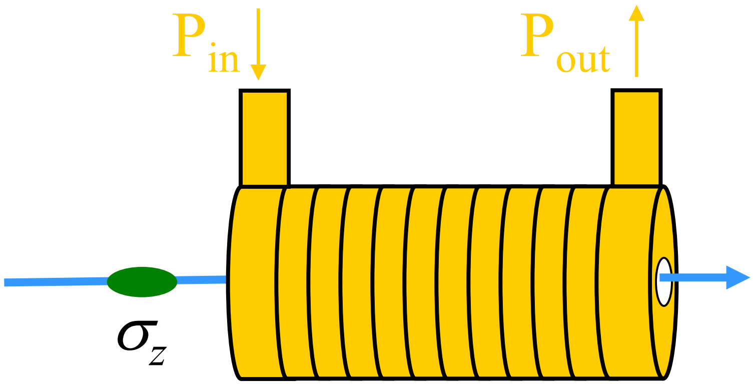
DC Accelerator

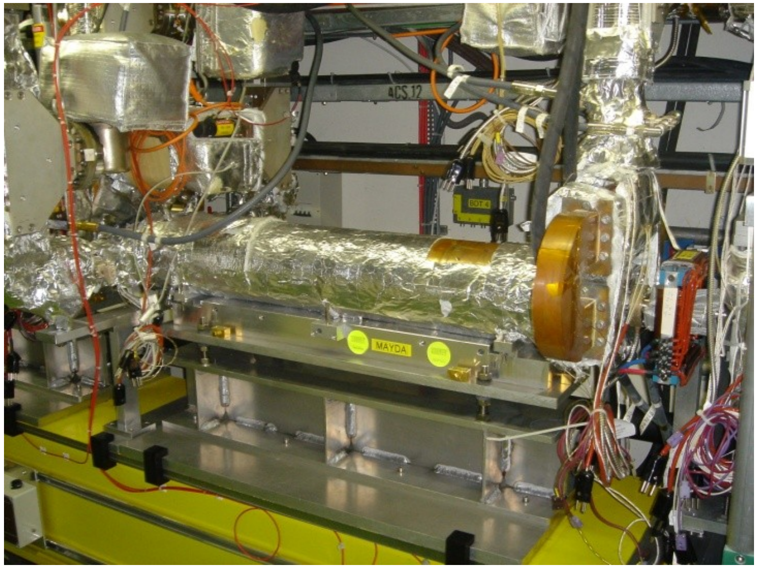
RF Accelerator

synchronize particle
with an
electromagnetic wave!

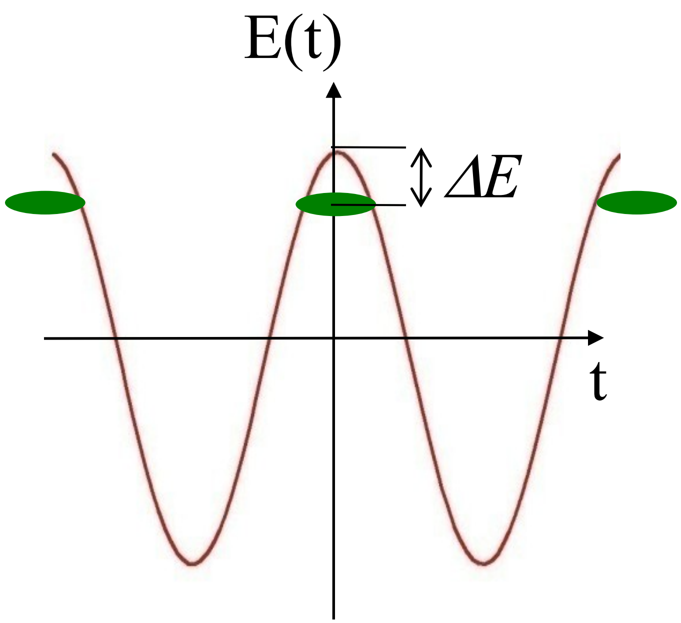
How to accelerate Particles

RF Accelerating structures





RF Accelerating Field

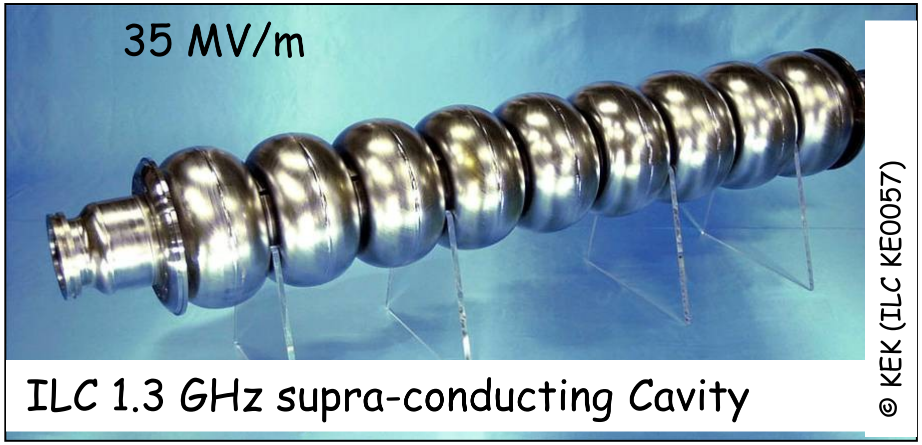


At 3GHz

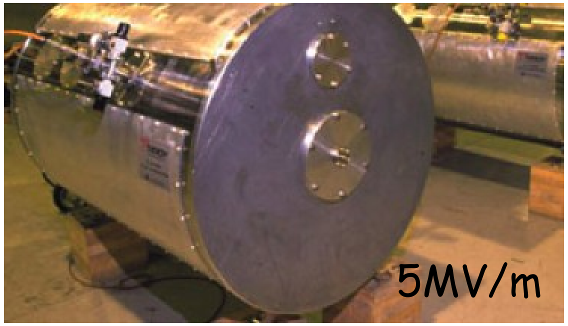
1 period = 333ps : Bunch spacing
Typical bunch length : few deg ~ few ps

Accelerating Cavities

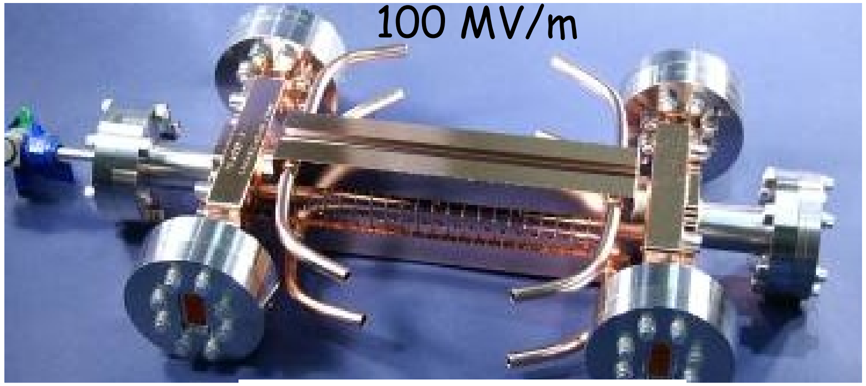
CERN PS 19 MHz Cavity (prototype 1966)



ILC 1.3 GHz supra-conducting Cavity



400MHz LHC Cavity in its cryo-module



CLIC 12 GHz Cavity

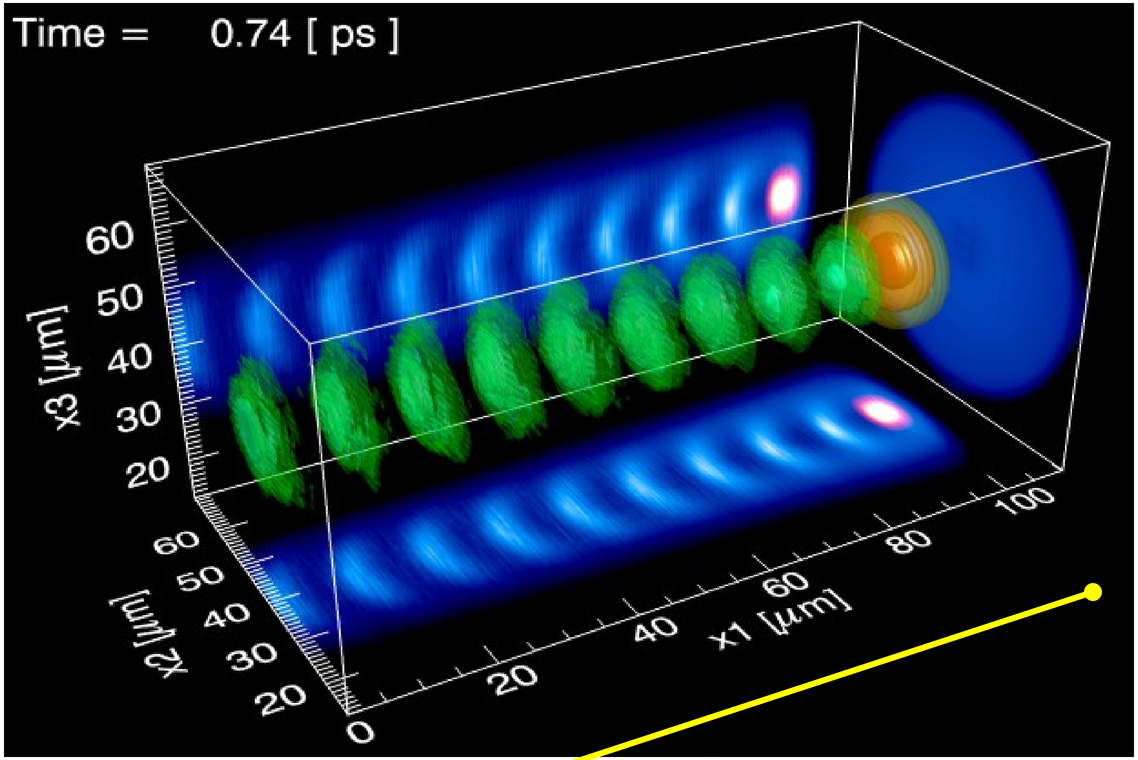
Longitudinal profile in accelerators

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

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

What is the next frontier ?

Courtesy of W. Mori & L. da Silva



100 μm

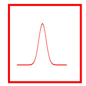
Plasma cavity

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.

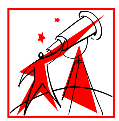
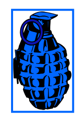
Beam instrumentation

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

Simplicity and Reliability

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

⬇

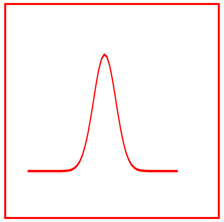
A detector, what for ?

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

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

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

+ 1 +



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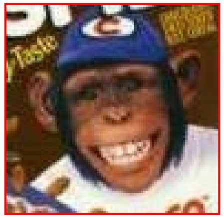


All in red → 'perfect system'

Bunch length measurement techniques

Short bunch length measurements

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

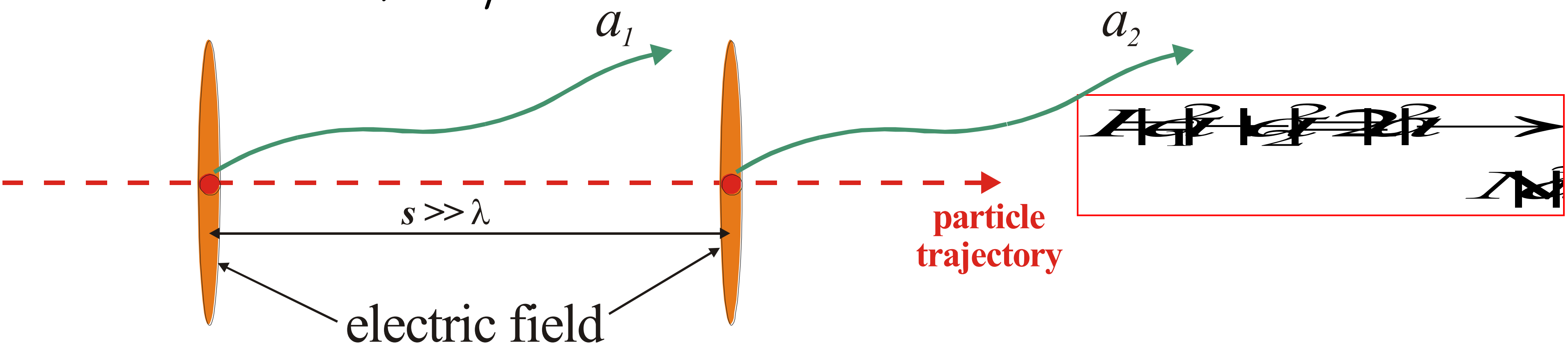
Using short laser pulses and sampling techniques

Radiative techniques

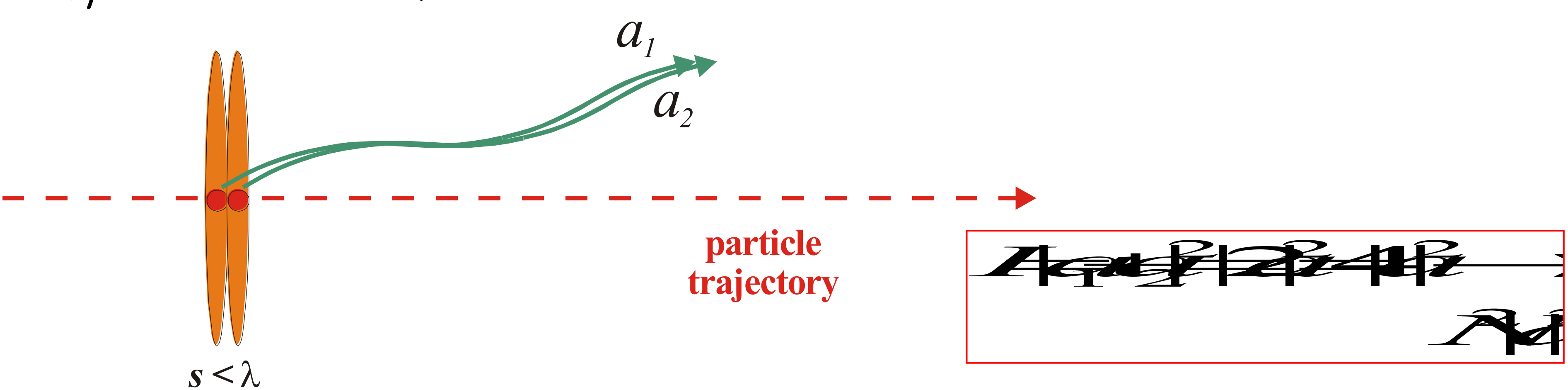
'Convert particles into photons'

Coherent / Incoherent Radiation

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



- *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*



Radiation Spectrum

Incoherent term   Coherent term

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

$S(\omega)$ – radiation spectrum

$S_p(\omega)$ – single particle spectrum

N – number of electrons in a bunch

$F(\omega)$ – longitudinal bunch form factor

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

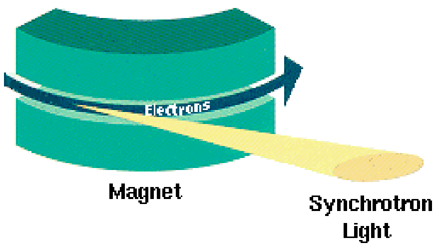
$\rho(s)$ – Longitudinal particle distribution in a bunch

Optical method with Incoherent radiation

'Convert particles into visible photons'

Optical Synchrotron Radiation

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



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

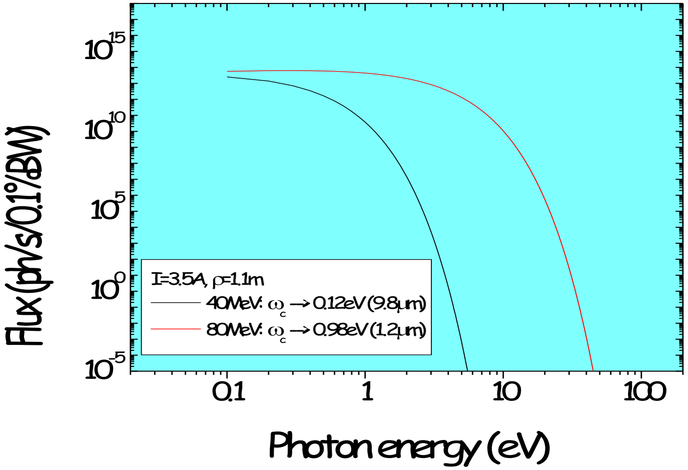
γ charged particle Lorentz-factor

ρ is the bending radius

Critical frequency :

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

Beam energy (γ) — Beam curvature (ρ)



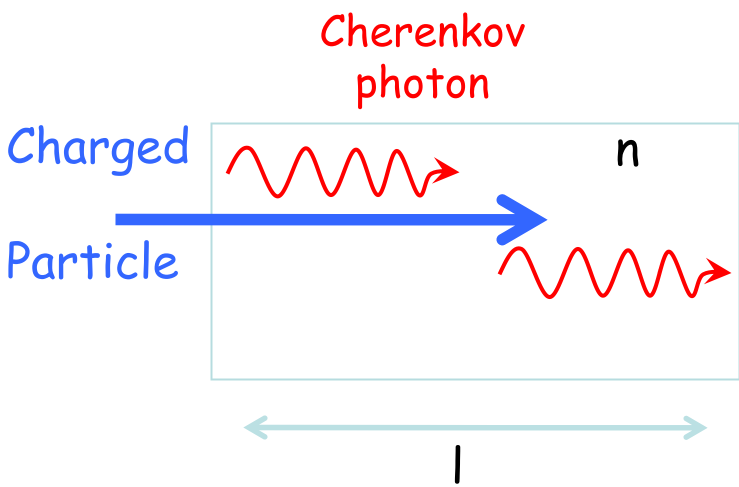
Limitations :

- Use a lot on electrons (for visible light: E > 150 MeV)
- Limited to very high energy proton or heavy ion beams

Cherenkov radiation

'Equivalent to the supersonic boom but for photons'

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



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

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

- l the length of the cherenkov radiator

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

$$N = 2\pi\alpha l\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)\left(1-\frac{1}{\beta^2 n^2}\right)$$

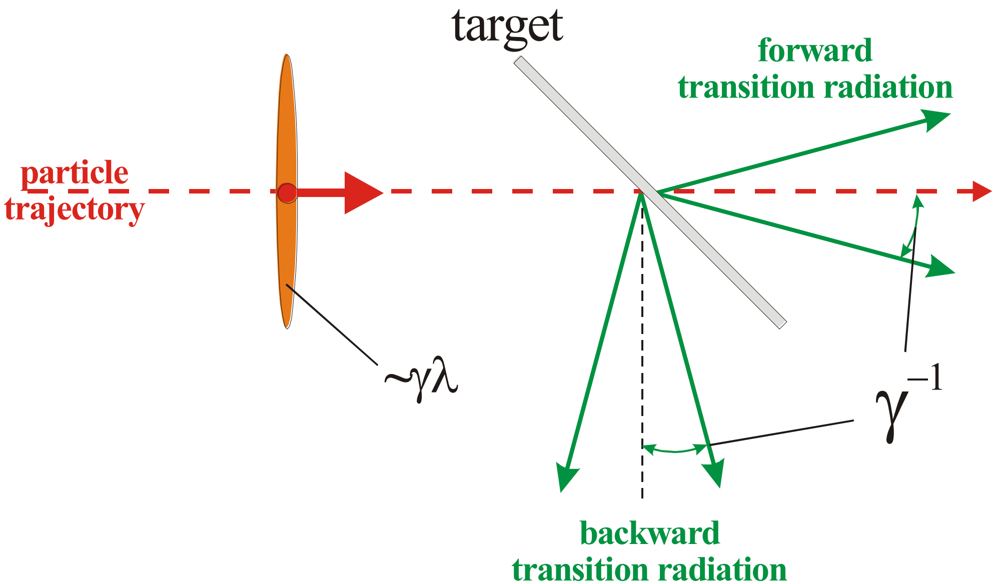
Limitations :

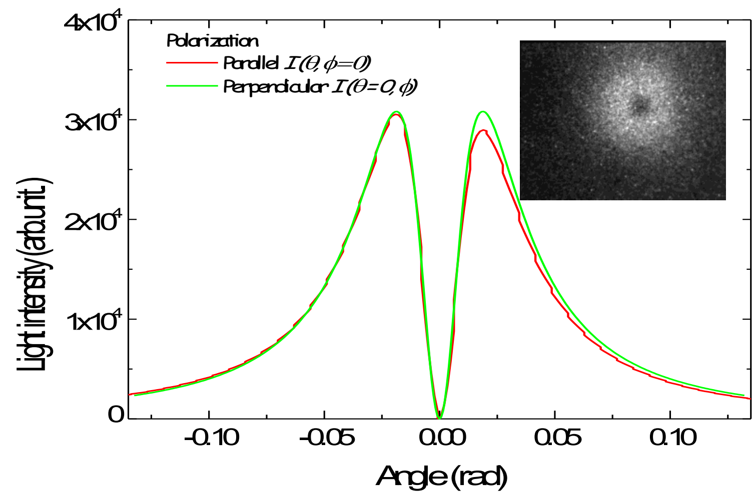
- Using transparent material (Glass n=1.46)
- Time resolution limited by the length of the radiator

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

Optical Transition Radiation

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





Number of OTR photons per charge particle

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

Radiation wavelength

Beam energy

Using good reflecting material

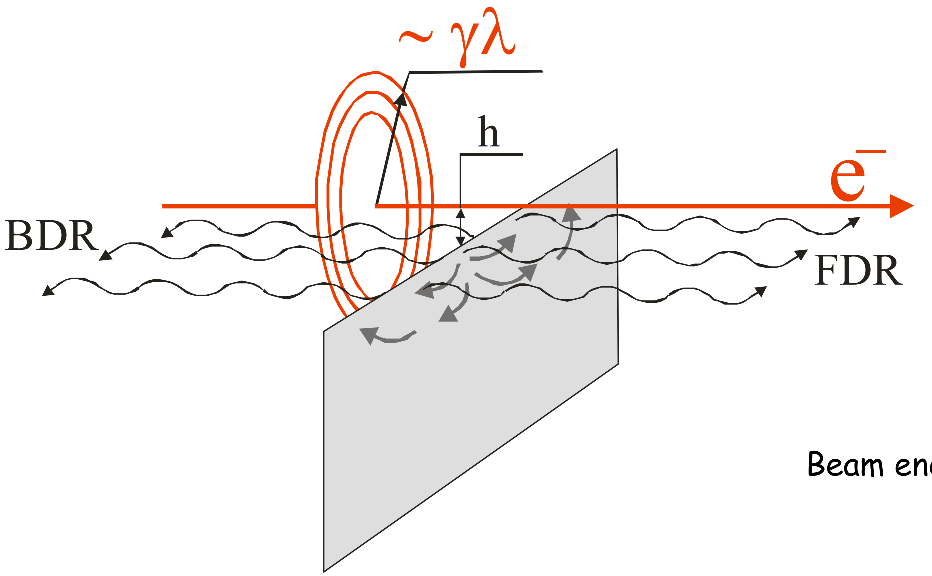
The thermal limit for 'best' screens (C, Be, SiC) is ~ 1 10^6 nC/cm²

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

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

Optical Diffraction Radiation

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



Beam energy

Radiation wavelength

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

<u>**Limitations :**</u>

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

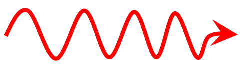
T. Muto et al, ***Physical Review Letters 90 (2003) 104801***

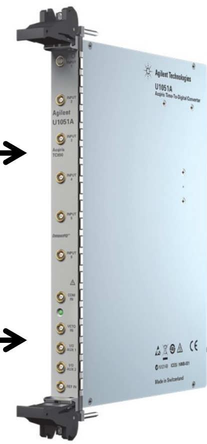
Time Correlated Single Photon Counting

n!

Geiger-mode Avalanche photodiode converts photon to electrical pulse

Visible photon





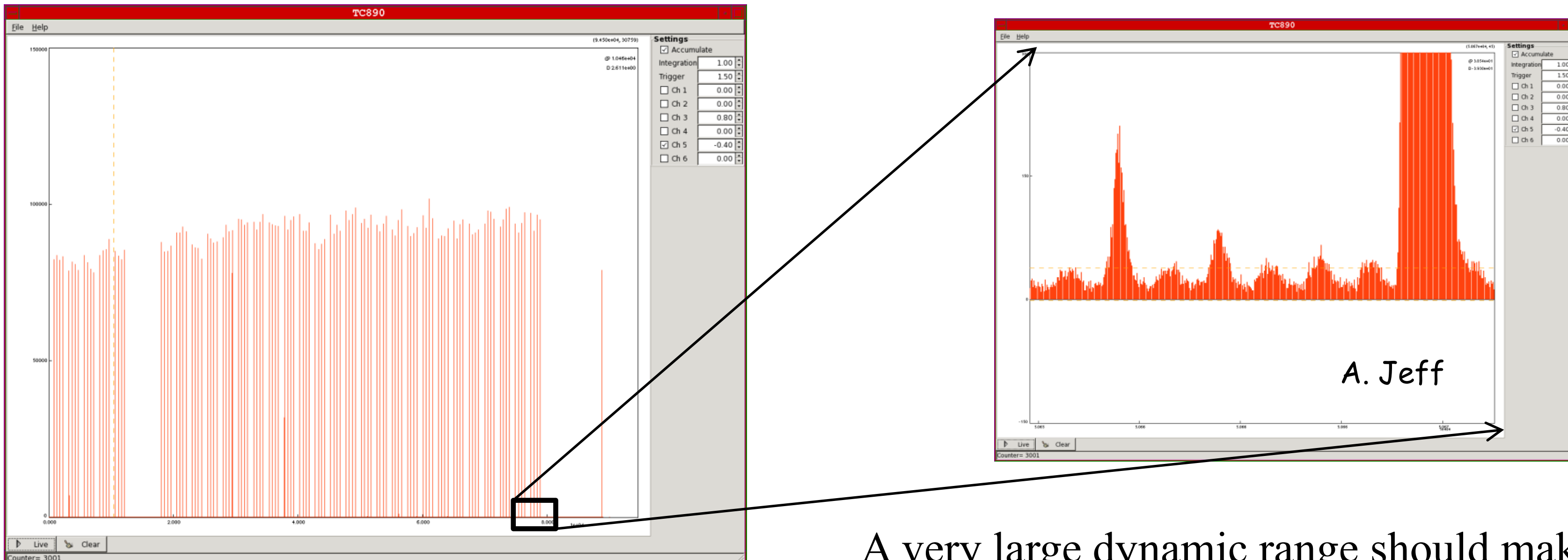
Time to Digital converter records pulse arrival time

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 afterpulsing
- State of the art TDC typically limited to 10ps sampling

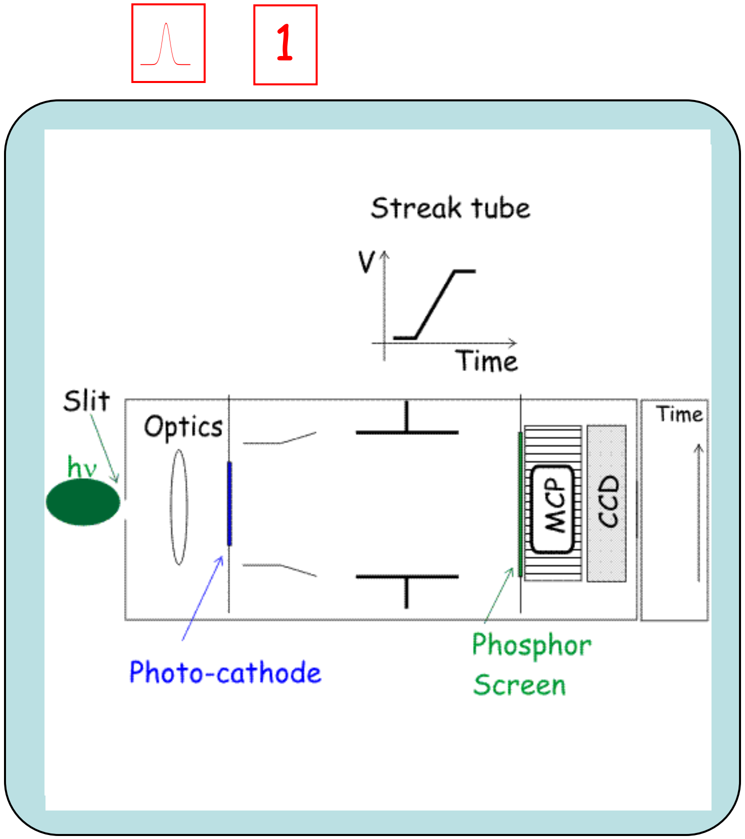
D.V. O'Connor, D. Phillips, Time-correlated Single Photon Counting, Academic Press, London, 1984
C.A. Thomas et al., Nucl. Instr. and Meth. A566 (2006) p.762

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



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

Streak Camera



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

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

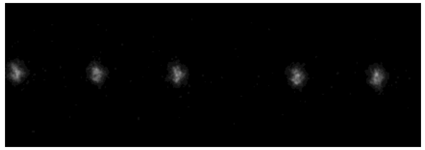
200fs time resolution obtained using reflective optics and 12.5nm bandwidth optical filter (800nm) and the Hamamatsu FESCA 200

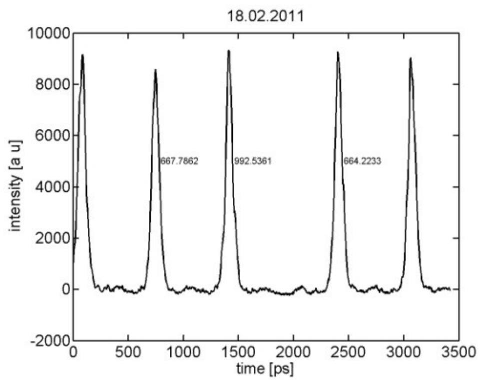
<u>Limitations : Time resolution of the streak camera :</u>

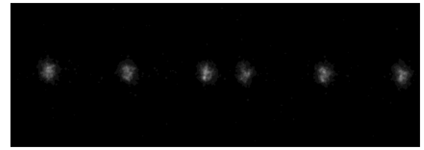
(i) Initial velocity distribution of photoelectrons : *narrow bandwidth optical filter*
(ii) Spatial spread of the slit image: *small slit width*
(iii) Dispersion in the optics

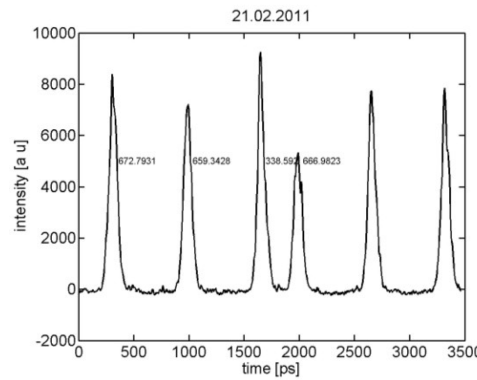
Streak camera examples

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

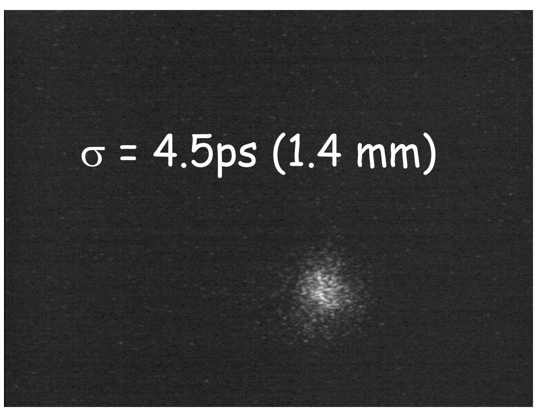




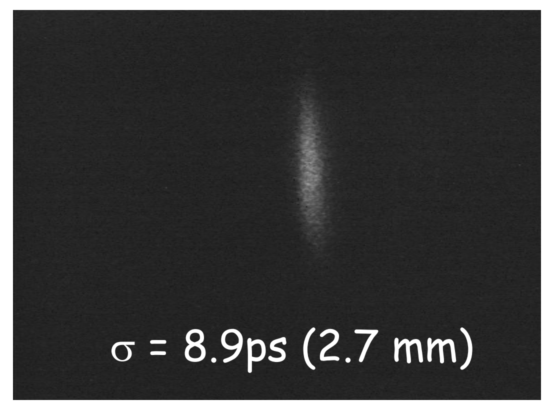




Measure of bunch length using OTR and OSR



Sweep speed of 10ps/mm



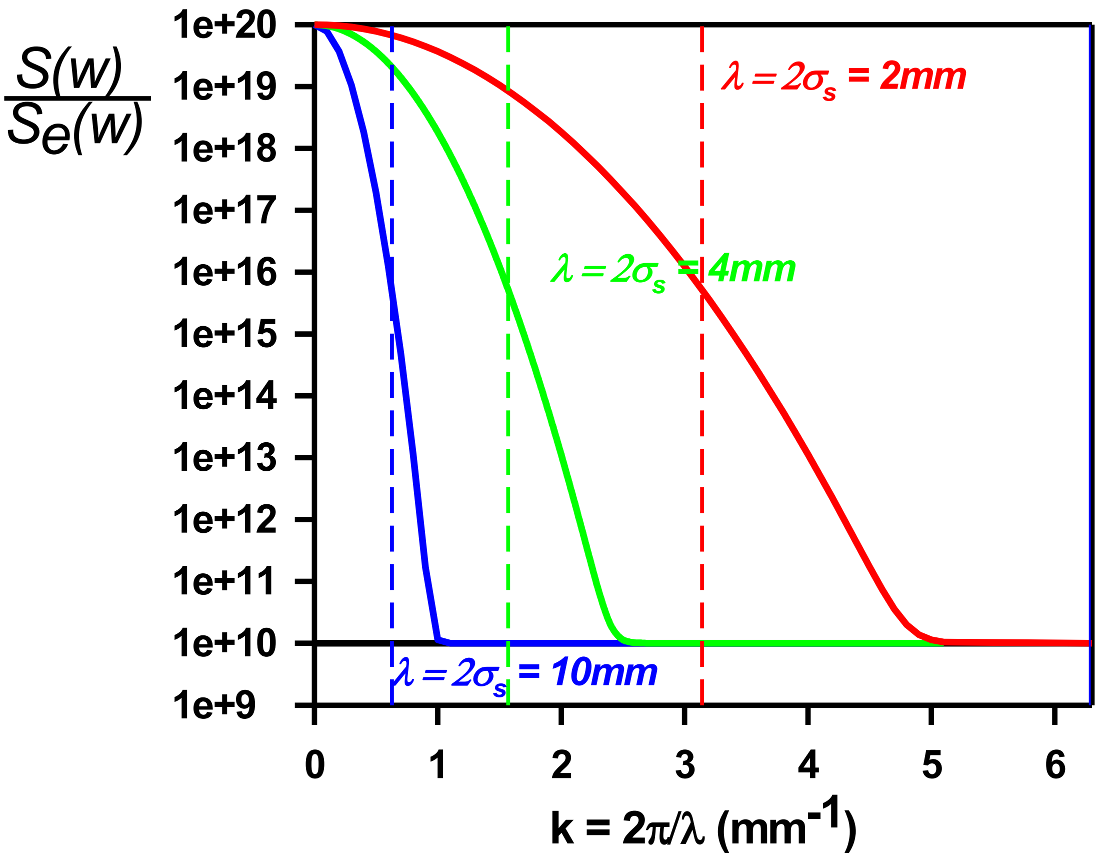
Bunch Length measurement with Coherent Radiation

'The shorter in time, The broader in frequency'

Bunch Form Factor for Gaussian distribution

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

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



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

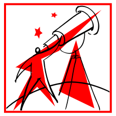
Measuring Radiation Spectrum

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

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

Coherent Transition Radiation (CTR)

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



Coherent Diffraction (CDR) or Coherent Synchrotron (CSR)

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

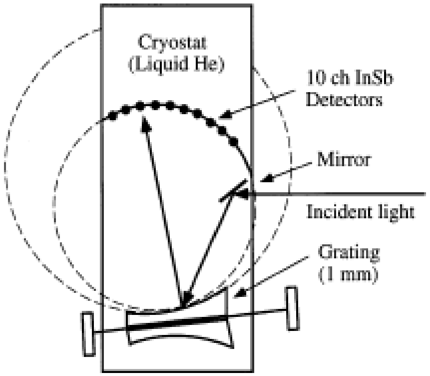
T. Watanabe et al, **NIM A 437 (1999) 1-11 & NIM A 480 (2002) 315-327**

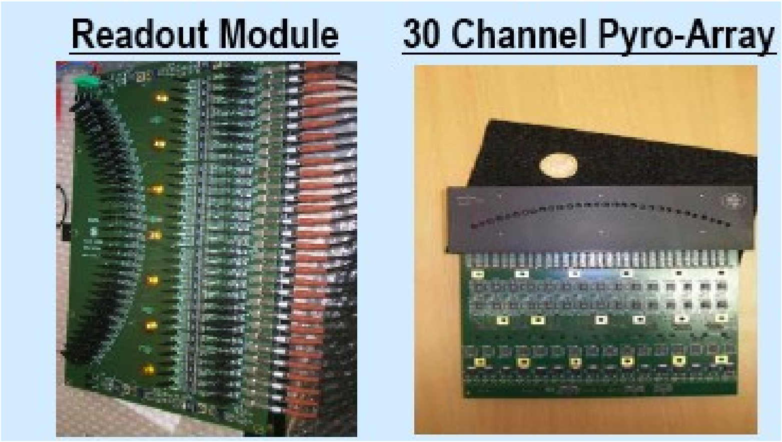
Bunch Frequency Spectrum by Coherent Radiation

1

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

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





B. Schmidt, DESY

Bunch Frequency Spectrum by Coherent Radiation

Frequency Domain

Spectral Intensity
$A(\omega)$

Extrapolation
(high and low frequencies)

Correction
(transfer function of detection system)

→

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

↓

Inverse Fourier Transform for
symmetric bunch distribution

Long. Bunch profile
$S(z)$

Time Domain

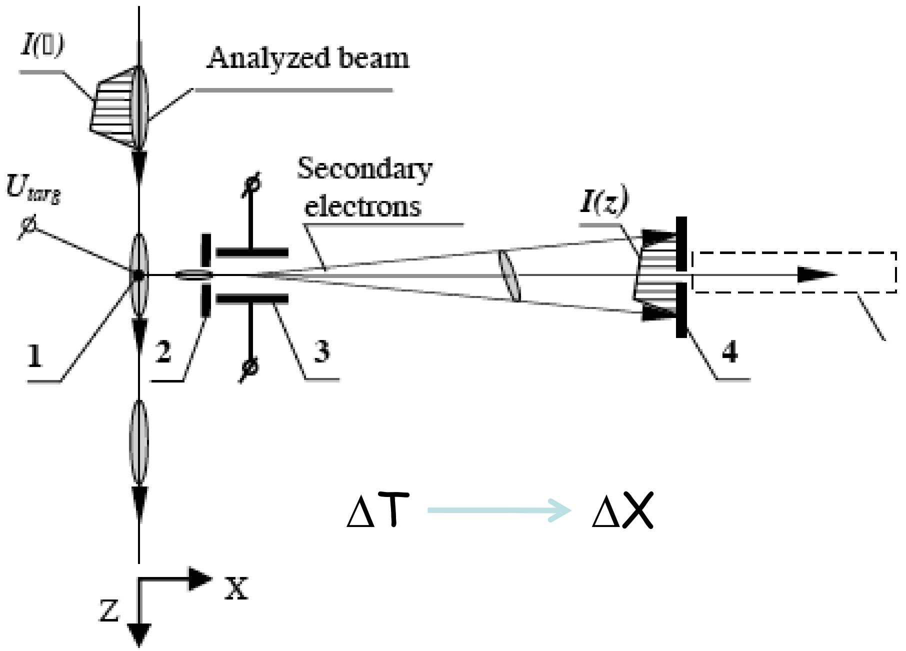
Kramers-Kronig relation
for non symmetric bunches

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

RF techniques

'Transforming time information into spatial information'

Bunch Shape Monitor - Feschenko monitor

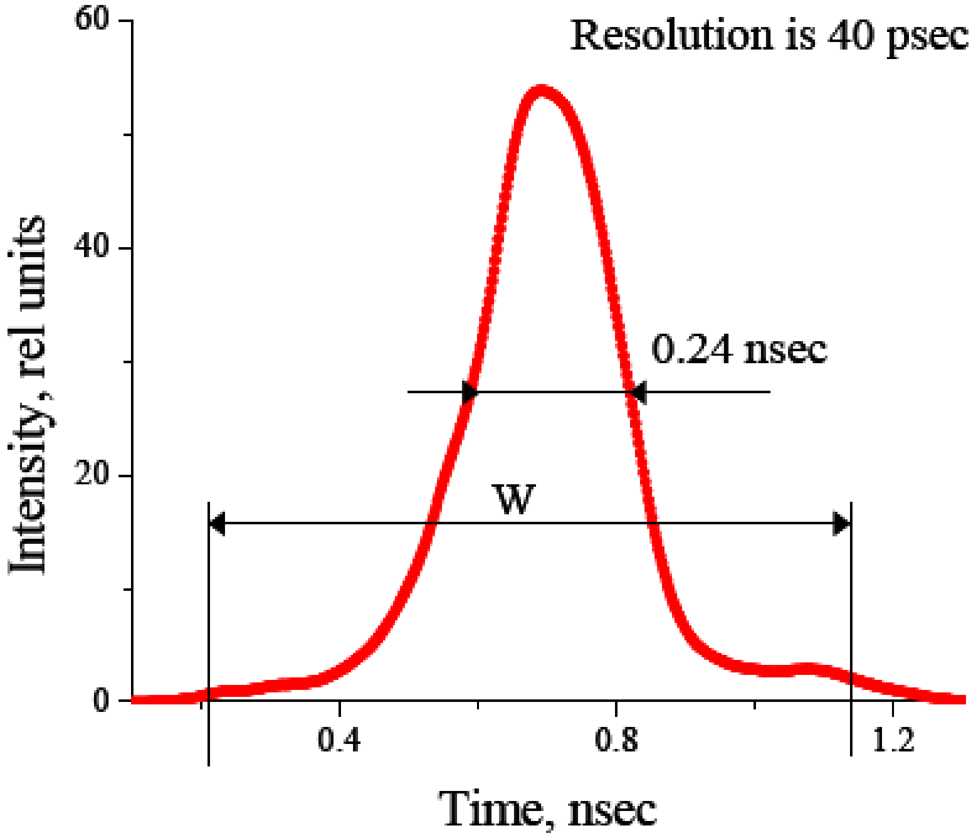


1 - Target (wire, screen, laser for H^-) : Source of secondary electrons
2 - Input collimator
3 - RF deflector (100MHz, 10kV) combined with electrostatic lens
4 - Electron Beam detector (electron multiplier, ..)

1

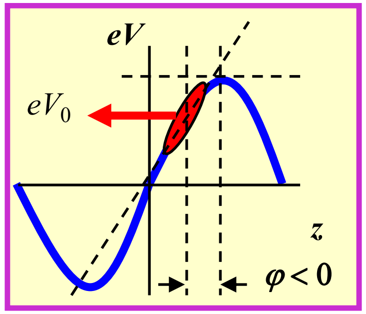
Bunch Shape monitor - Feschenko monitor

Longitudinal Bunch profile @ SNS

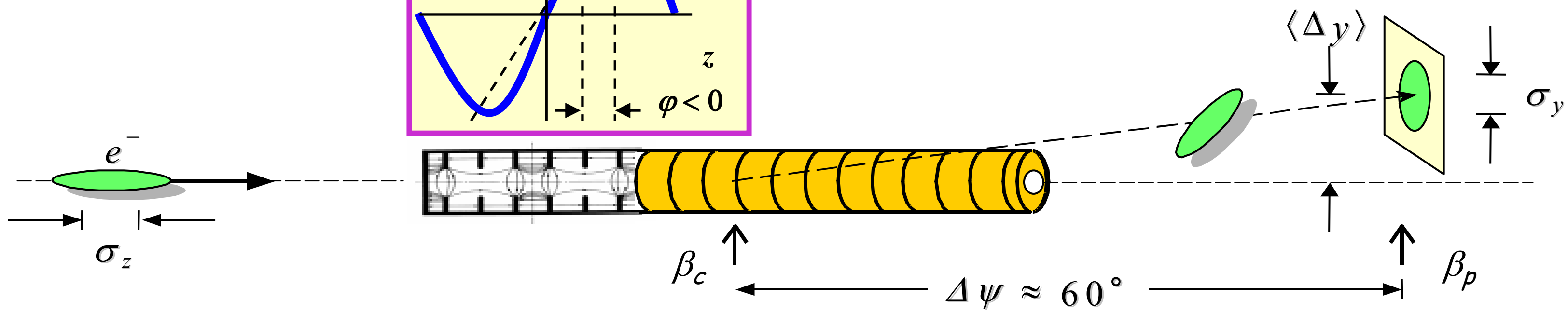


A. Feschenko *et al*, Proceedings of LINAC 2004, Lübeck, p408

RF Deflecting Cavity



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



Beam profile RF on

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

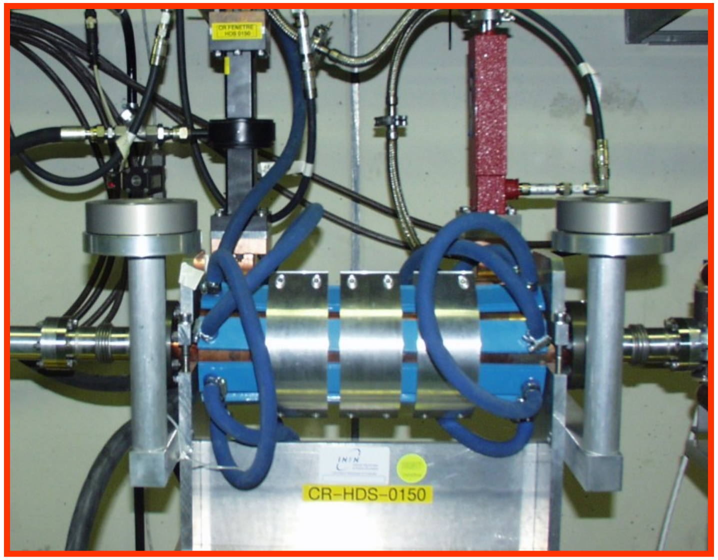
- Beam profile RF off: σ_{y_0}
- Bunch length: σ_z
- Deflecting Voltage: eV_0
- Beta function at cavity and profile monitor: $\beta_c \beta_p$
- RF deflector wavelength: λ
- Beam energy: E_0
- Betatron phase advance (cavity-profile monitor): $\Delta\Psi$

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

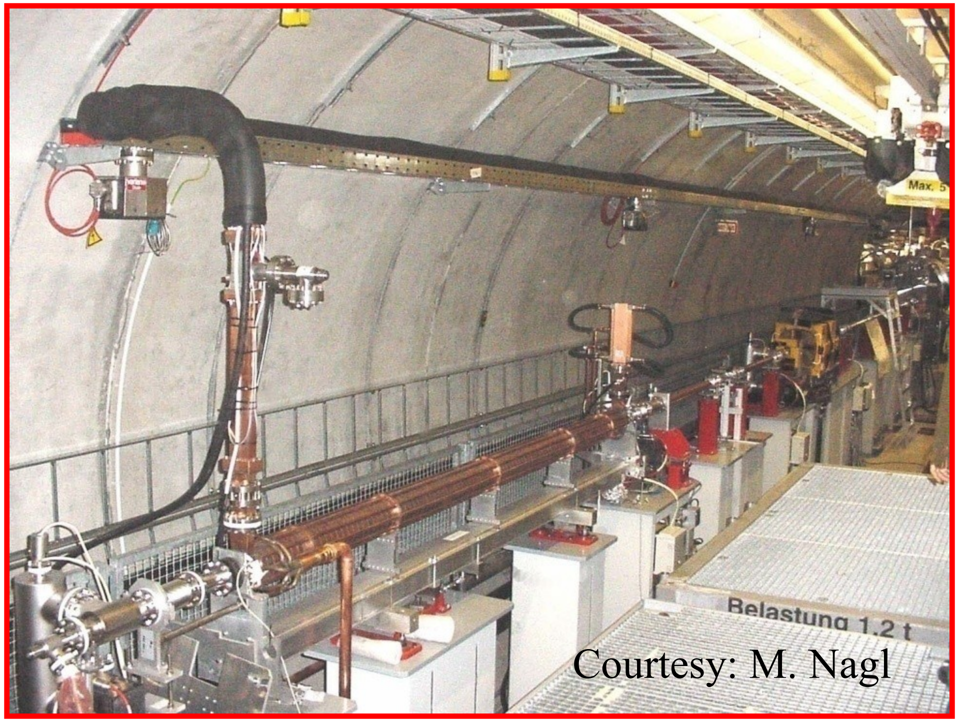
P. Emma et al, LCLS note LCLS-TN-00-12, (2000)

RF Deflecting Cavity

CTF3

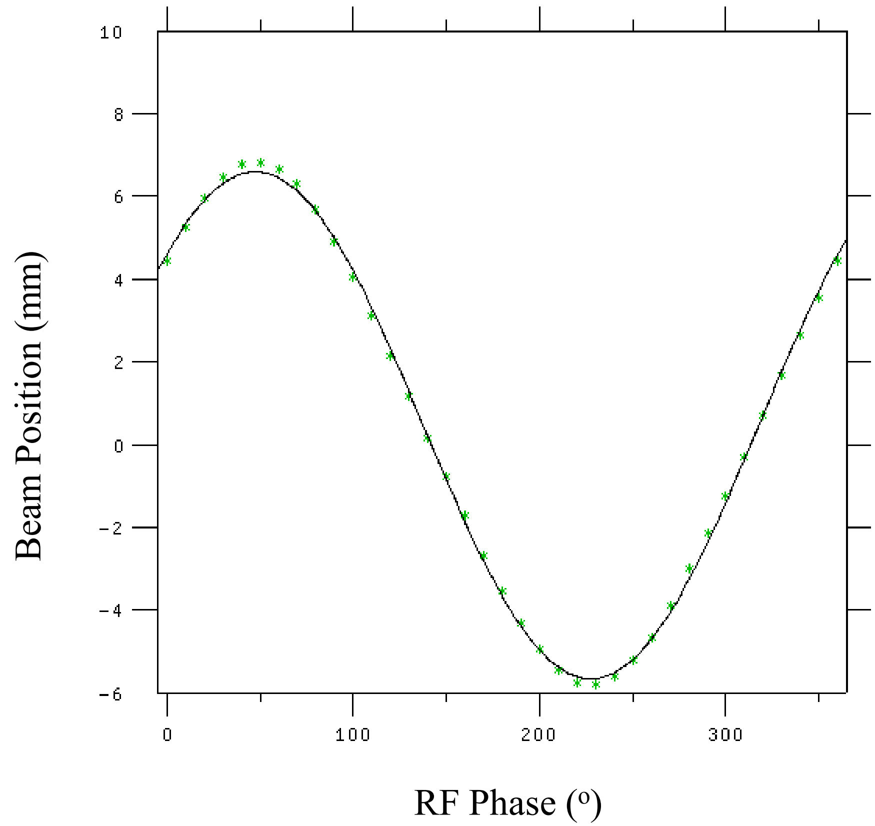


LOLA @ Flash



Calibration of RF Deflector

ΔX(mm) → Δφ(°) ΔT(ps)



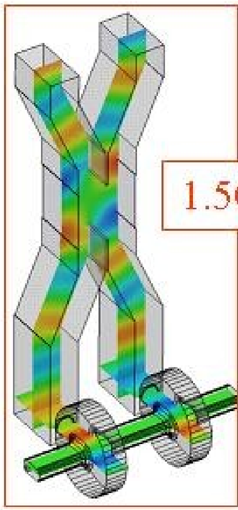
Monitor the Beam Position on (or close to) the Profile monitor to calibrate the deflection angle

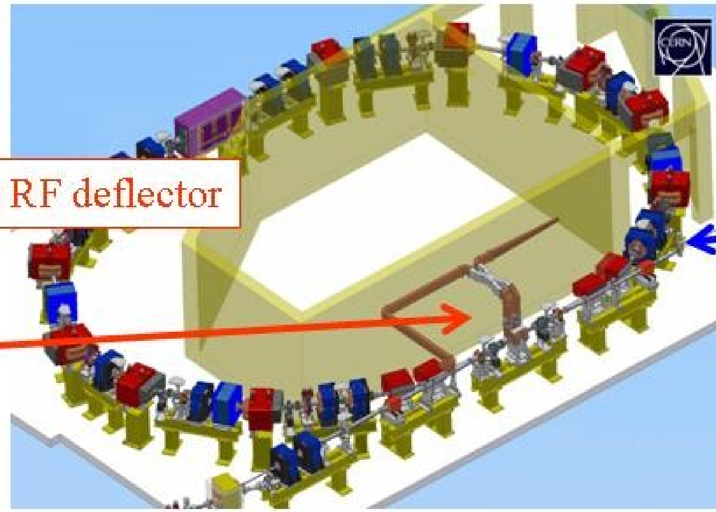
RF deflector phase

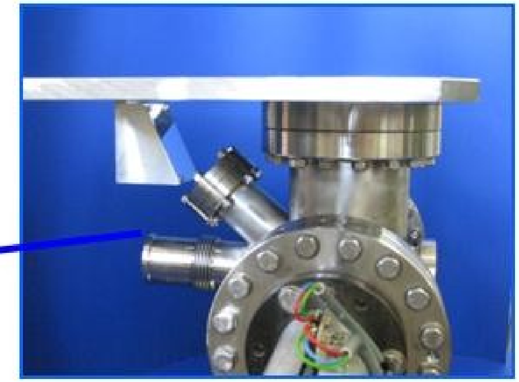
Beam offset on the screen

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

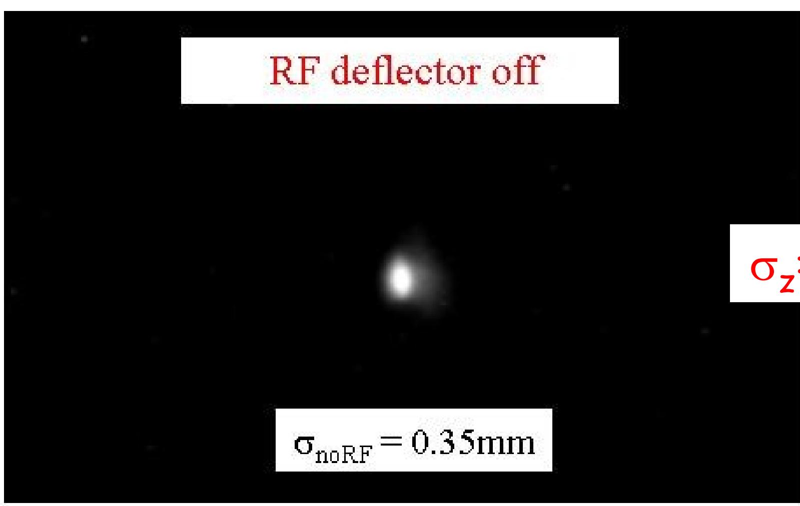
RF by Deflecting Cavity



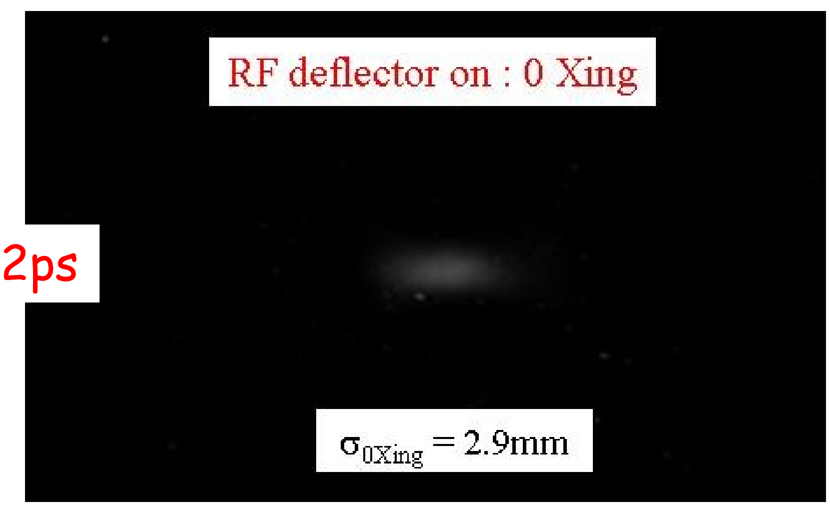




OTR screen

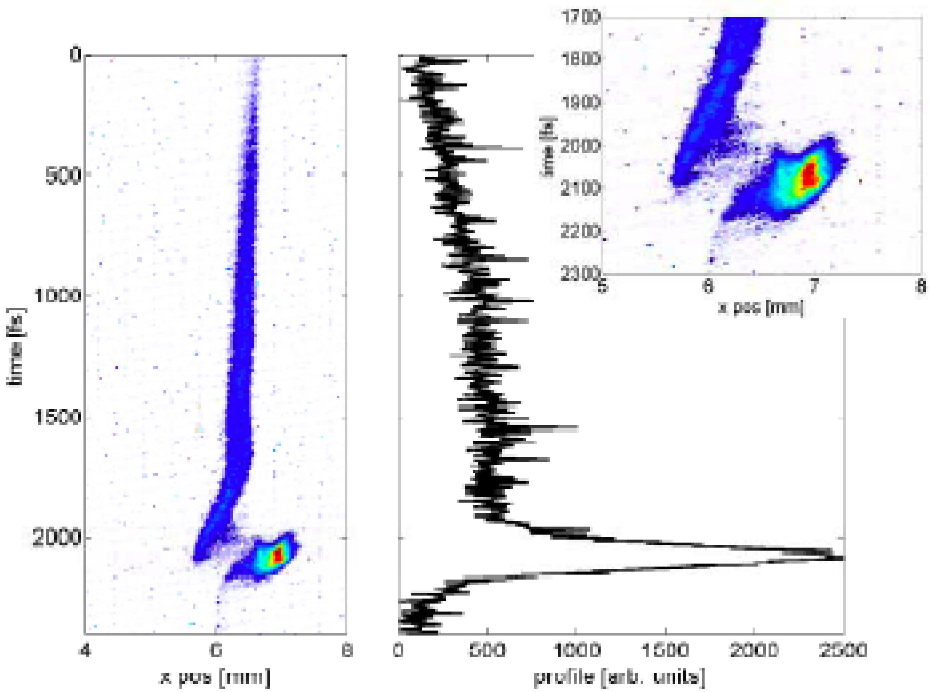


σ_z=2ps

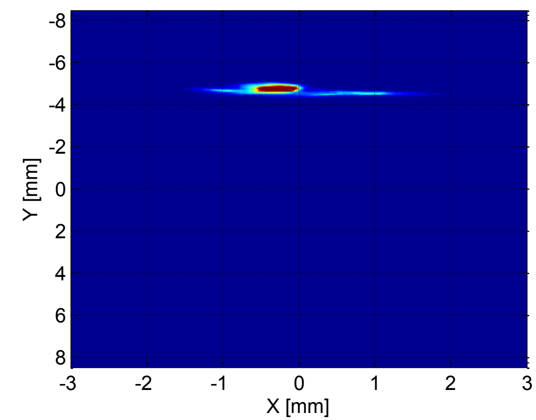


RF by Deflecting Cavity

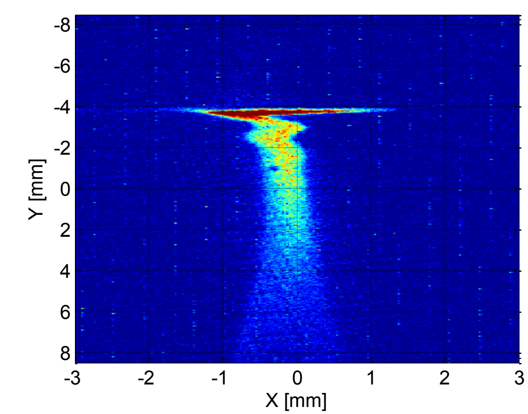
Bunch length measurement @ Flash



LOLA off:



LOLA on:

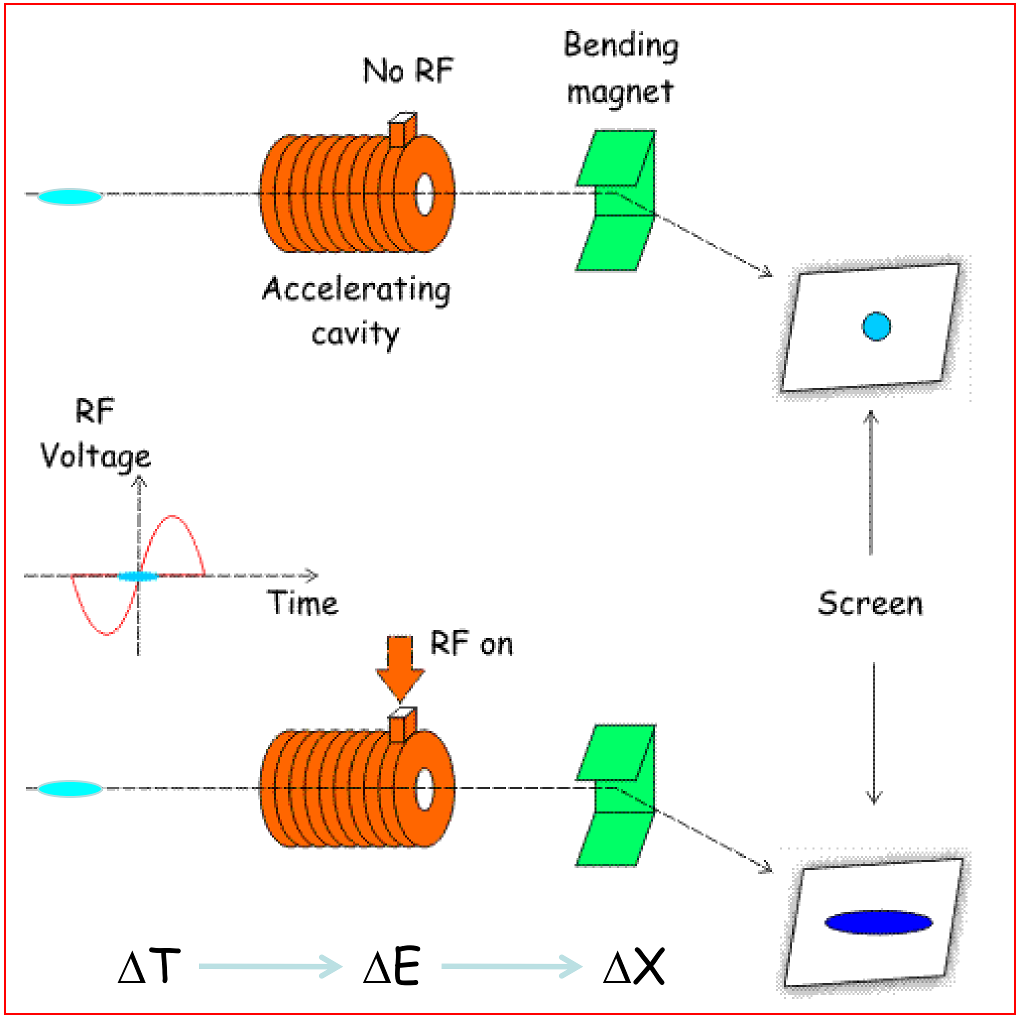


→ Resolution of 4fs/pixels

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

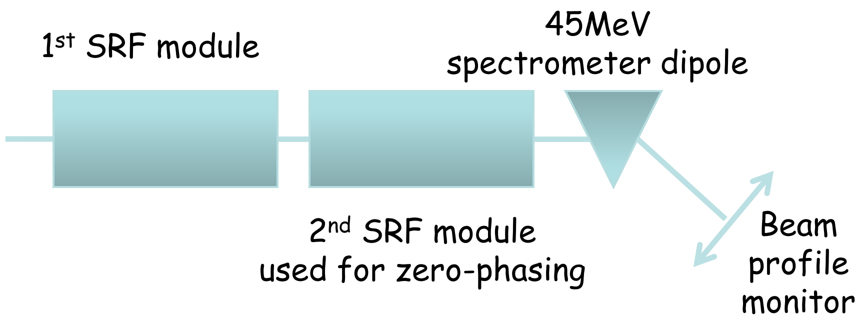
RF accelerating structures

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



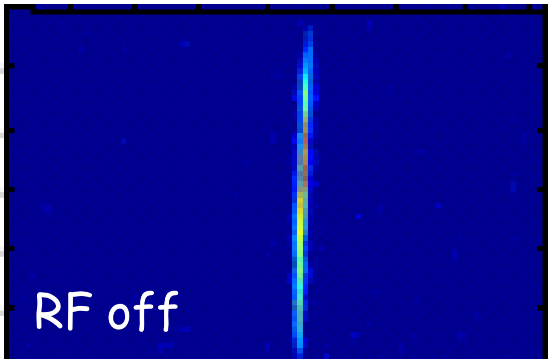
RF accelerating structures

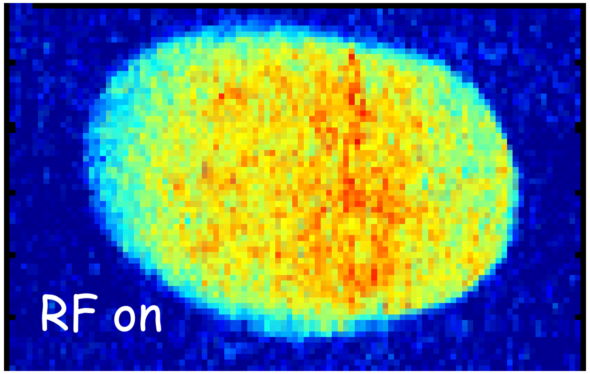
CEBAF injector, Newport News



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

84fs, 45MeV beam but low charge beam





Limitations

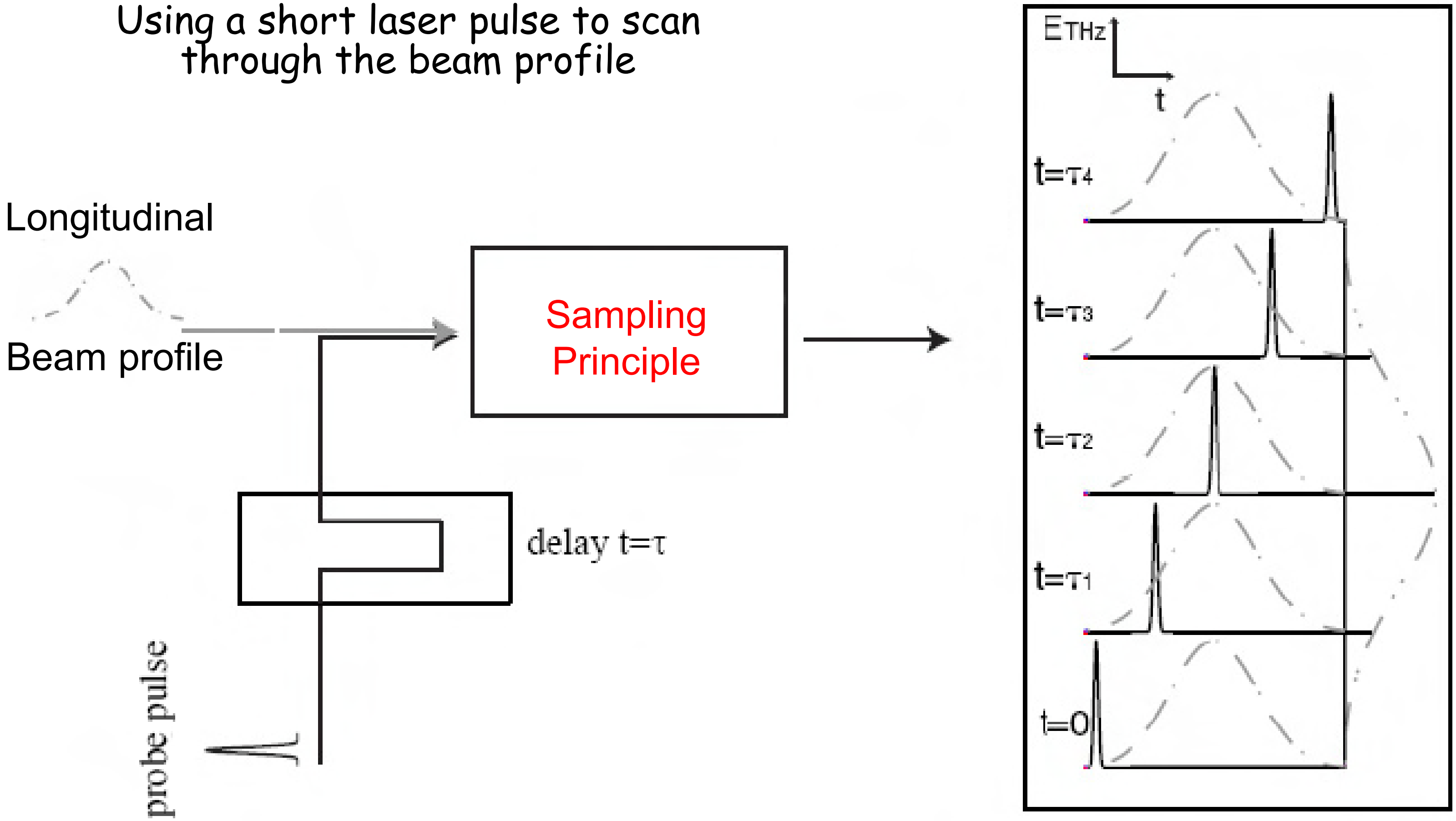
RF non linearities

Beam loading and wakefield for high charge beam

Laser based techniques

Sampling Techniques

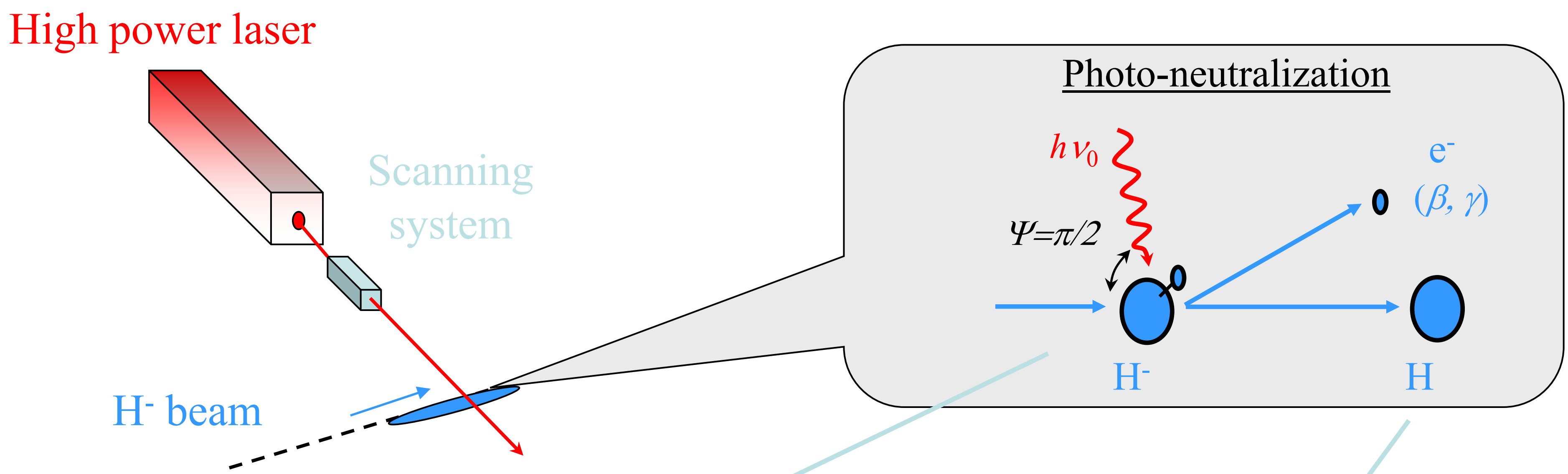
Using a short laser pulse to scan through the beam profile



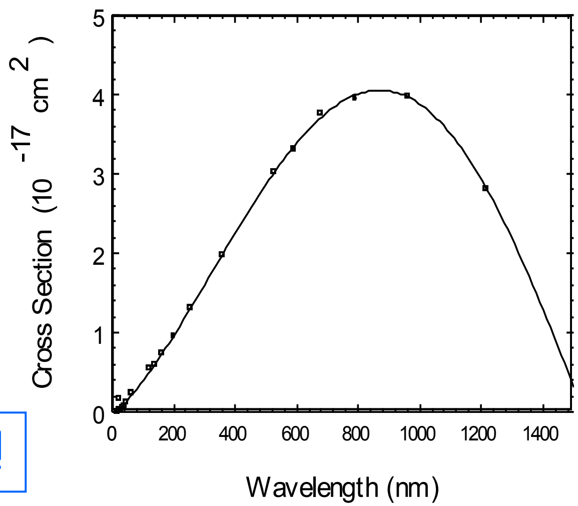
Limitation

Laser-beam synchronization jitter (50fs)

Laser Wire Scanner : Photo-neutralization

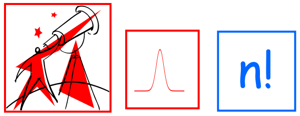


- First ionization potential for H^- ions is 0.75eV
- Photo-neutralization cross section : $\sigma \sim 4.10^{-17}$ cm^2



Detection system based on

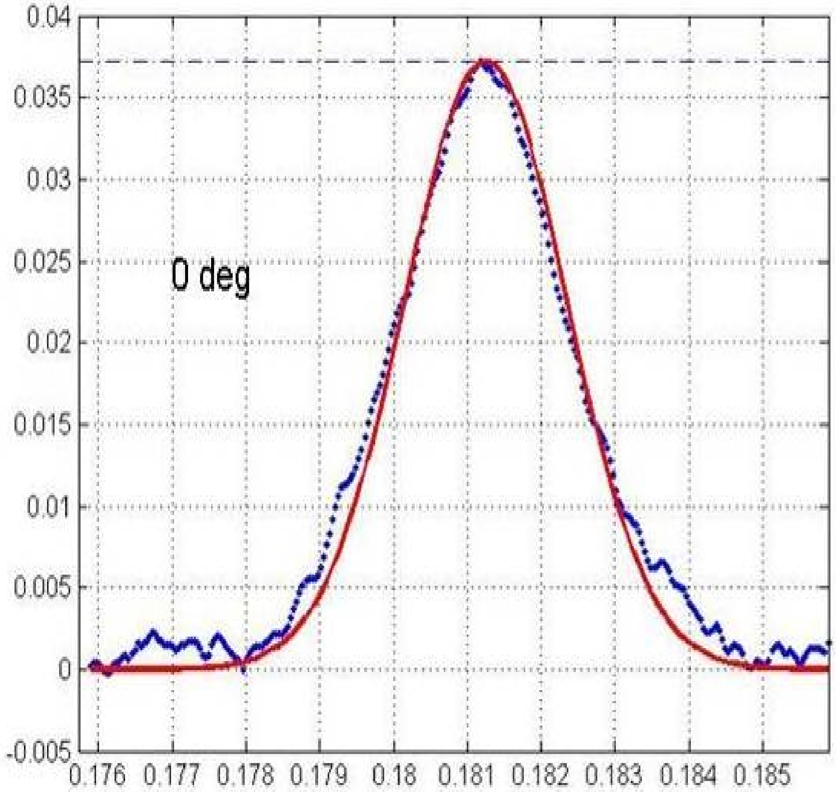
- The measurement of released electrons using a magnet and a collector (faraday cup, MCP,..)
- *Measured the conversion of H^- into H with a current monitor*



Laser Wire Scanner : Photo-neutralization

Mode Locked Laser Longitudinal Measurements @ SNS

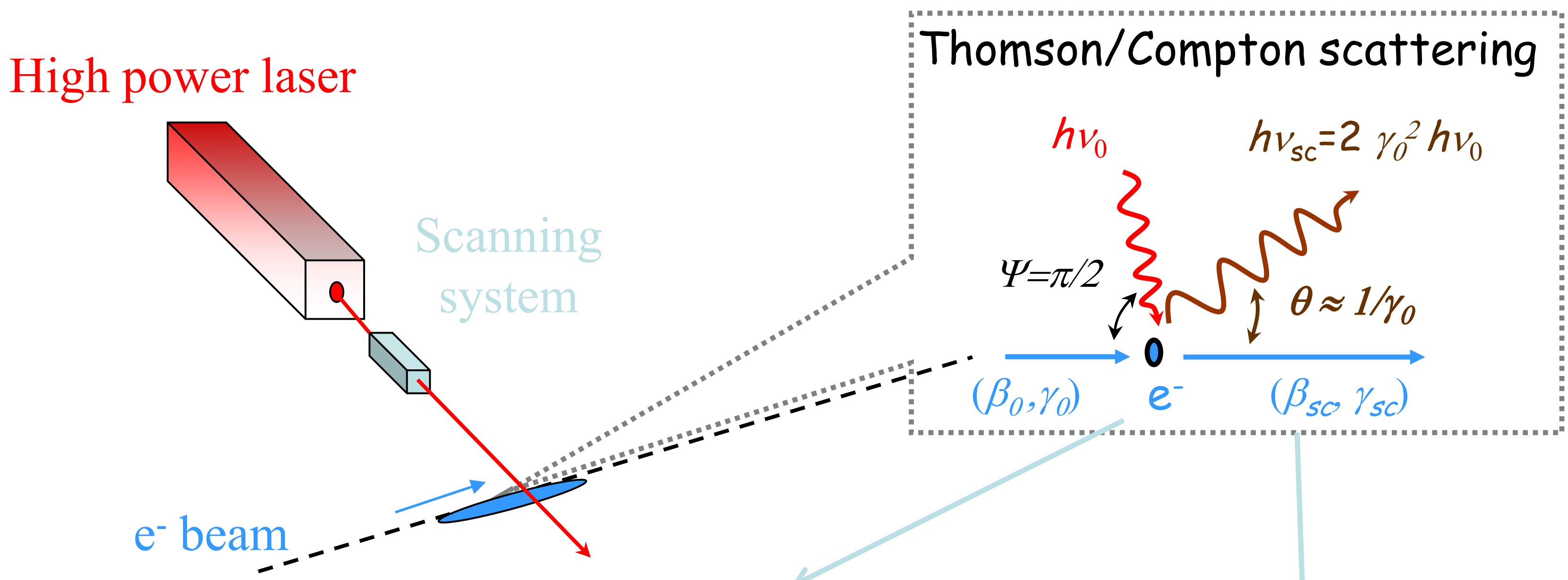
2.5 MeV H^-, 402.5 MHz bunching freq, Ti-Sapphire laser phase-locked @ 1/5th bunching frequency

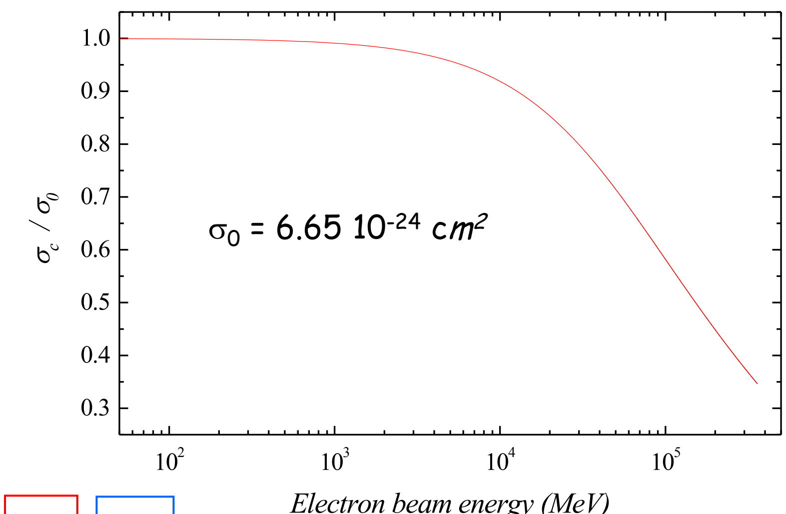


Collected electron signal plotted vs. phase

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

Laser Wire Scanner - Compton scattering





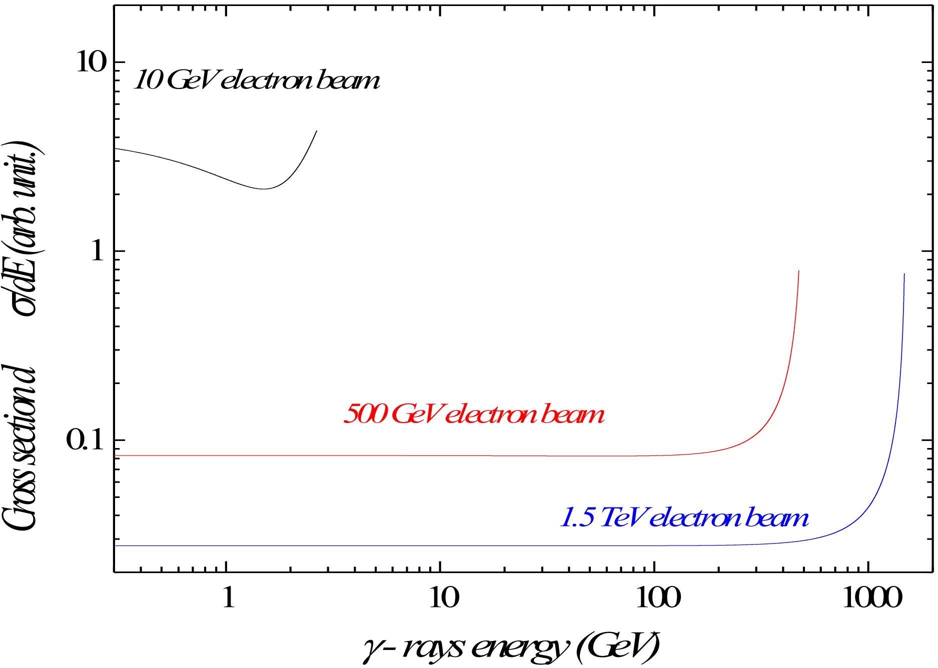
Detection system based on

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

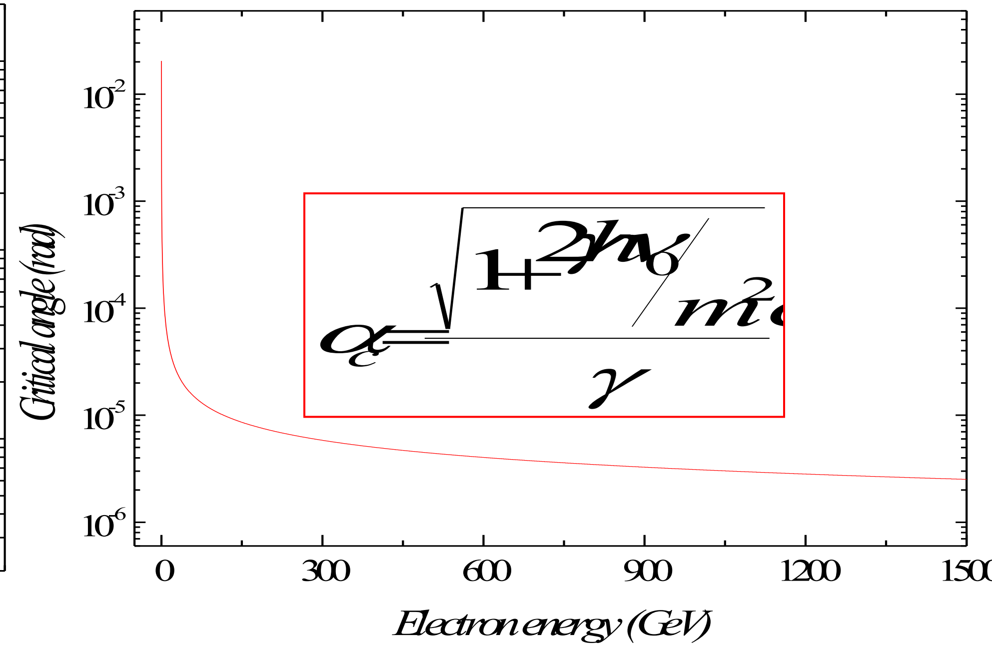
Laser Wire Scanner – Compton scattering

Energy spectrum of scattered photons

Using a 266nm wavelength laser



Emission angle of the scattered photons



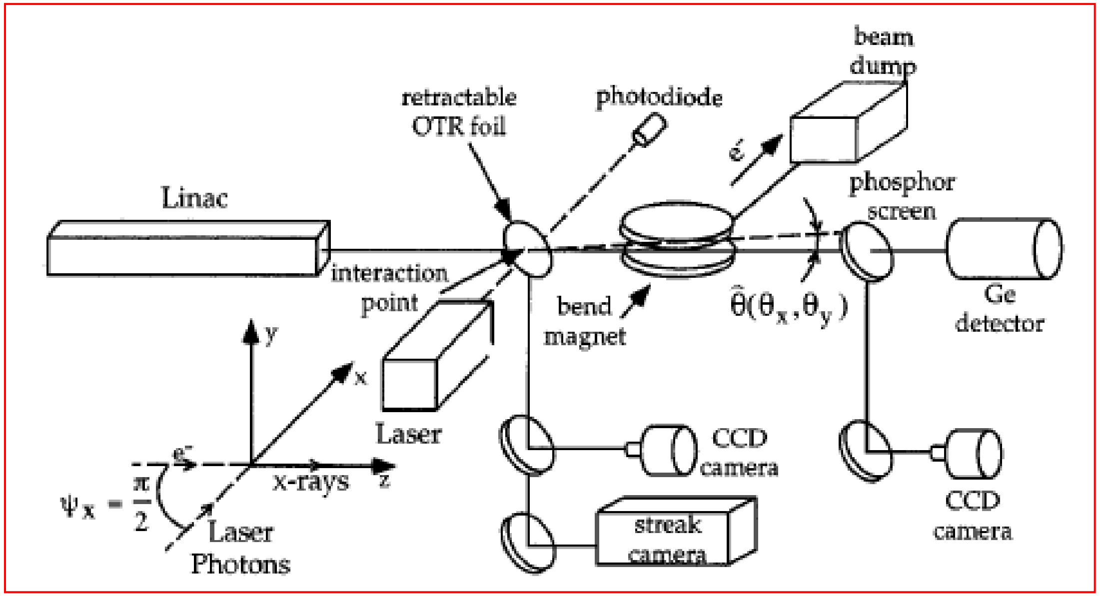
At very high energy

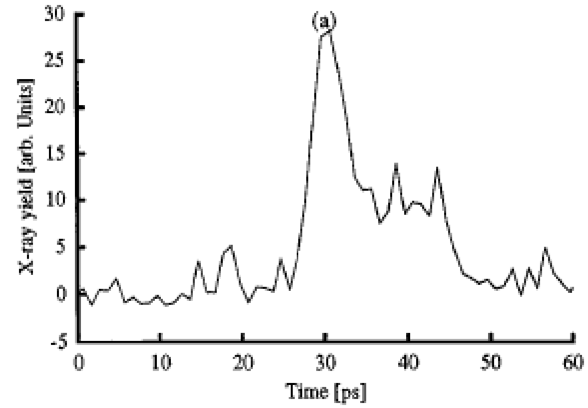
- The photons steal most of the electron energy *(electron recoil becomes extremely important)*
- The photons are emitted within a very small angle (a few μrad) in the forward direction

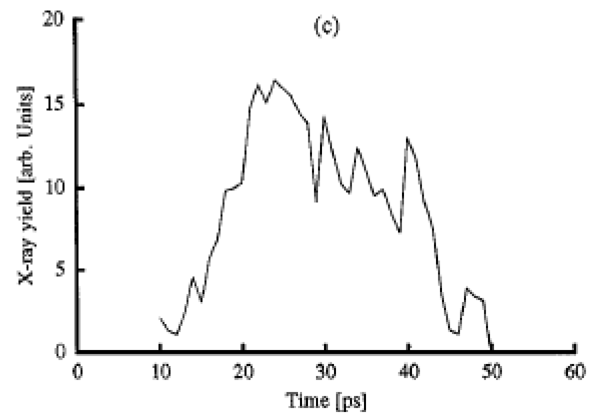
•Measurement of degraded electrons only feasible at high energies

Laser Wire Scanner – Compton scattering

ALS @ LBNL





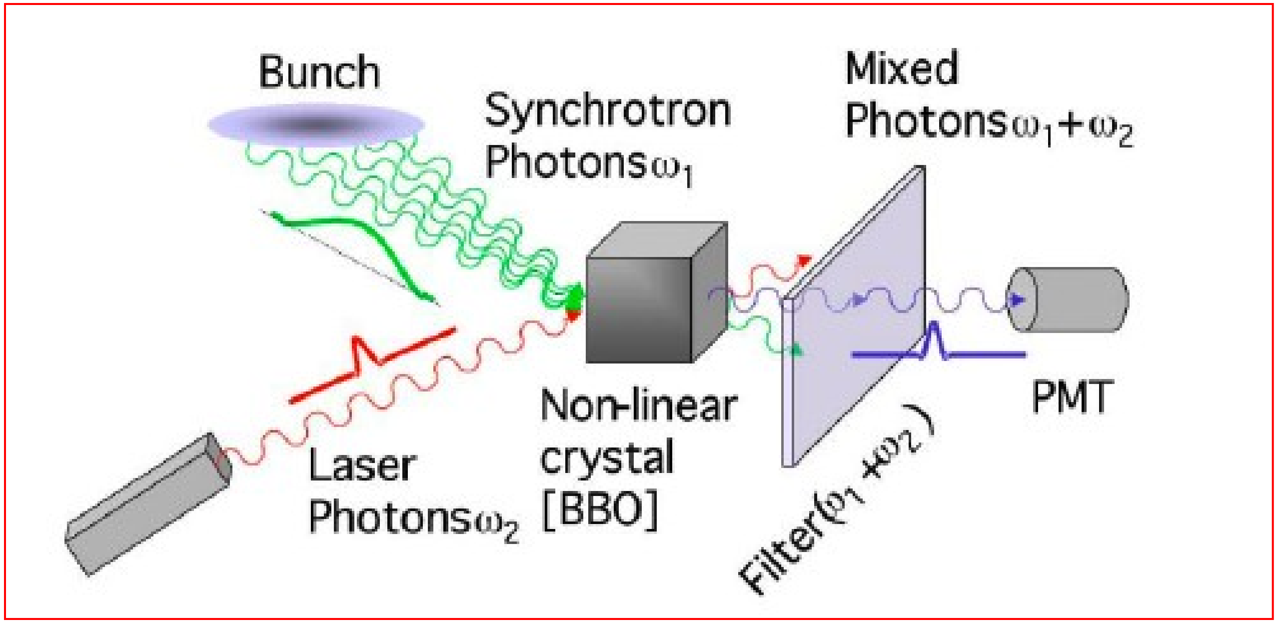


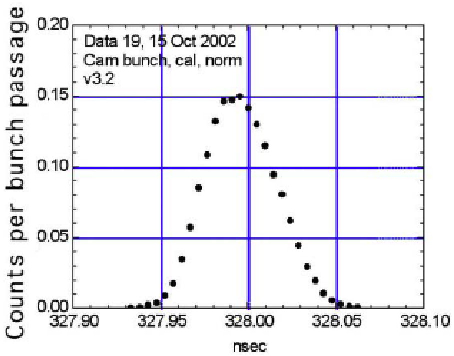
Using a 10TW Ti:Al_2O_3 laser system. Detecting 5.10^4 10-40 keV X-rays using either an X-ray CCD and Ge detector

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'





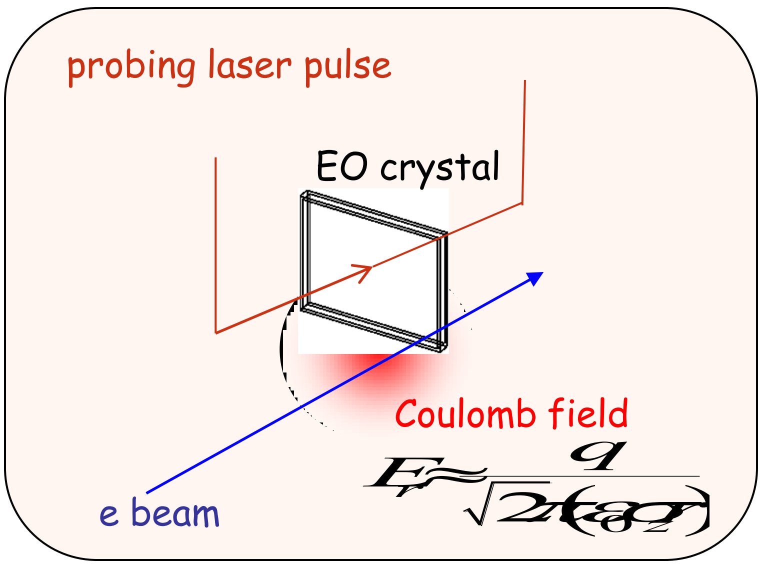
M. Zolotorev *et al*, **Proceeding of the PAC 2003, pp.2530**

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

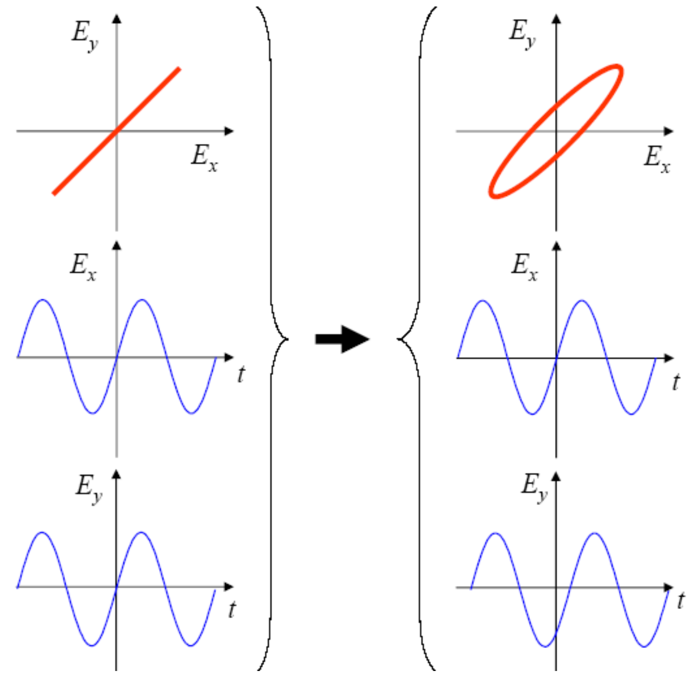
Electro Optic Sampling

'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



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

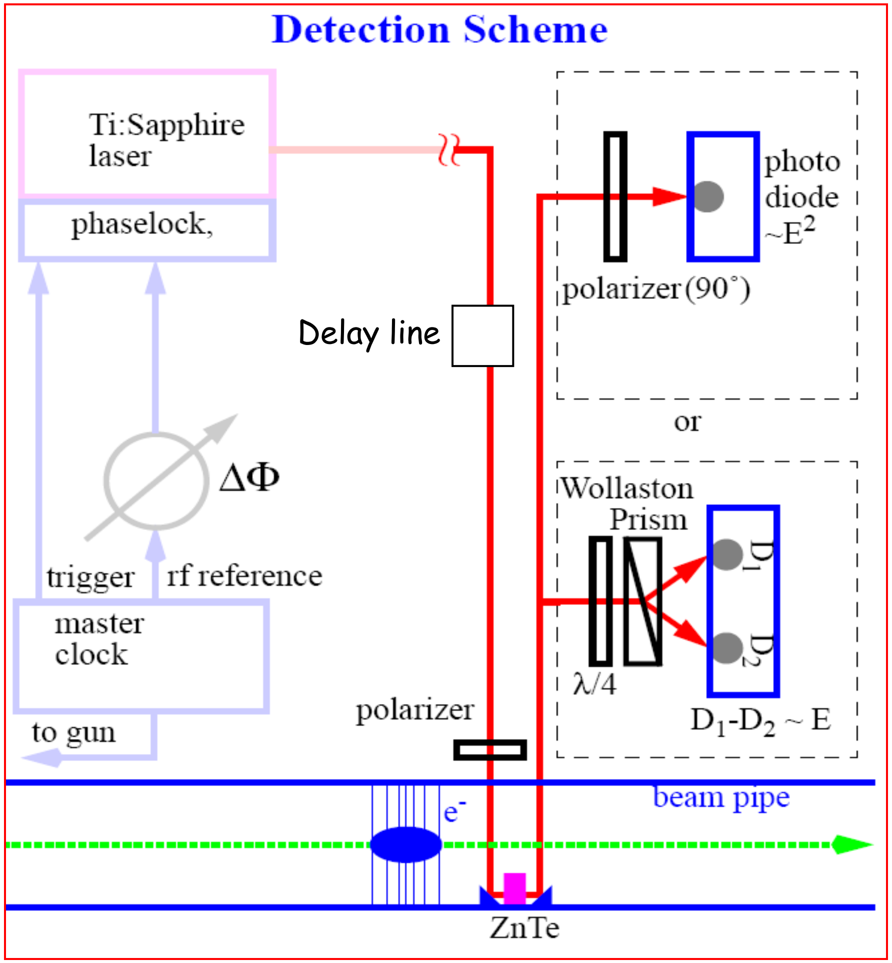


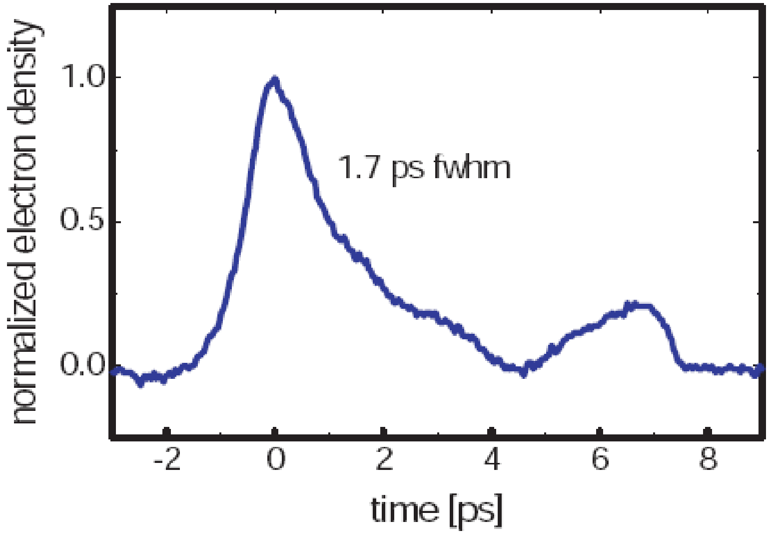
$$\Gamma = \frac{2\pi d}{\lambda_0}\left(n_x - n_y\right) = \frac{2\pi d}{\lambda_0} n_0^3 r_{41} E_r$$

Relative phase shift between polarizations increases with the beam electric field

Electro Optic Sampling

EOS @ FELIX

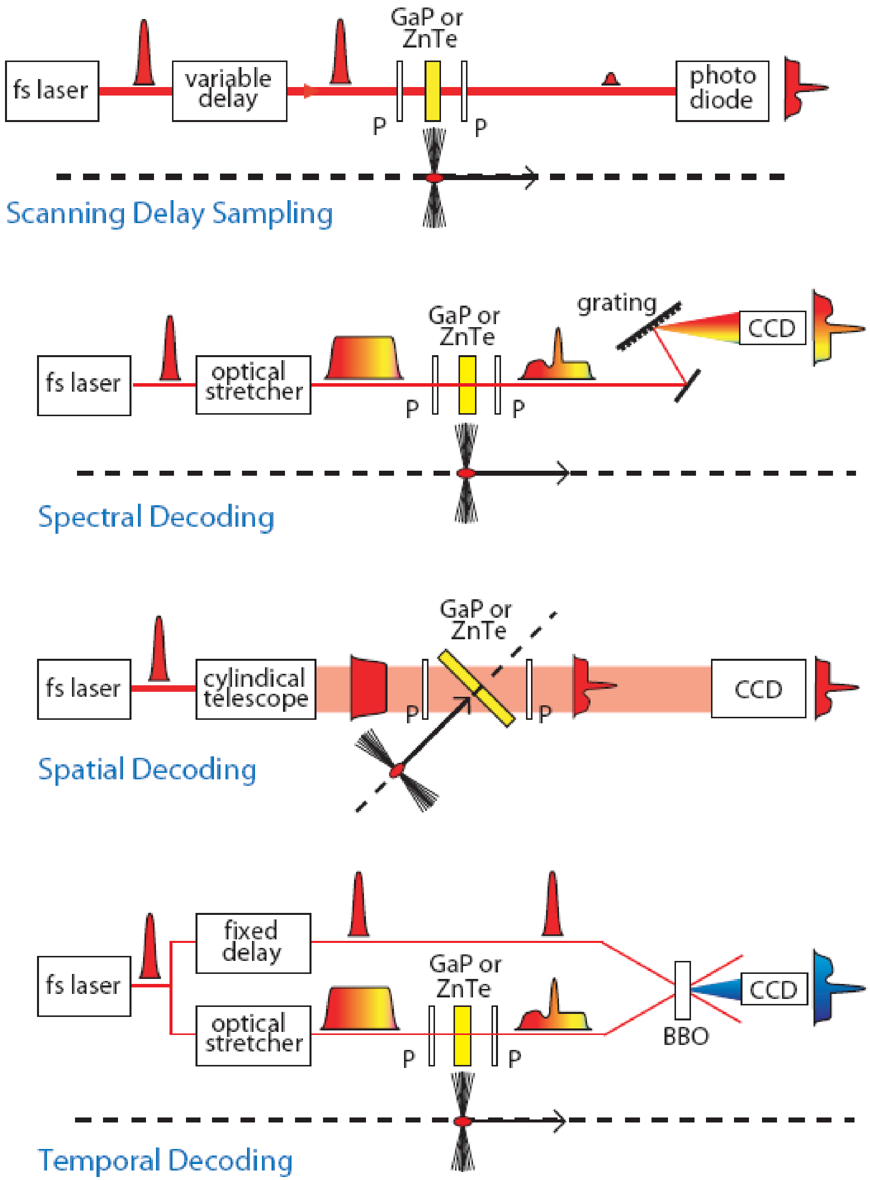




Using 12fs Ti:Al2O3 laser at 800nm and ZnTe crystal 0.5mm thick and a beam of 46MeV, 200pC, 2ps.

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

Electro Optic based bunch length monitors



1

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

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

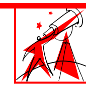
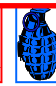
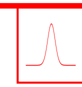
Jamison *et. al*, Opt. Lett. 28 (2003) 1710

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

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

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

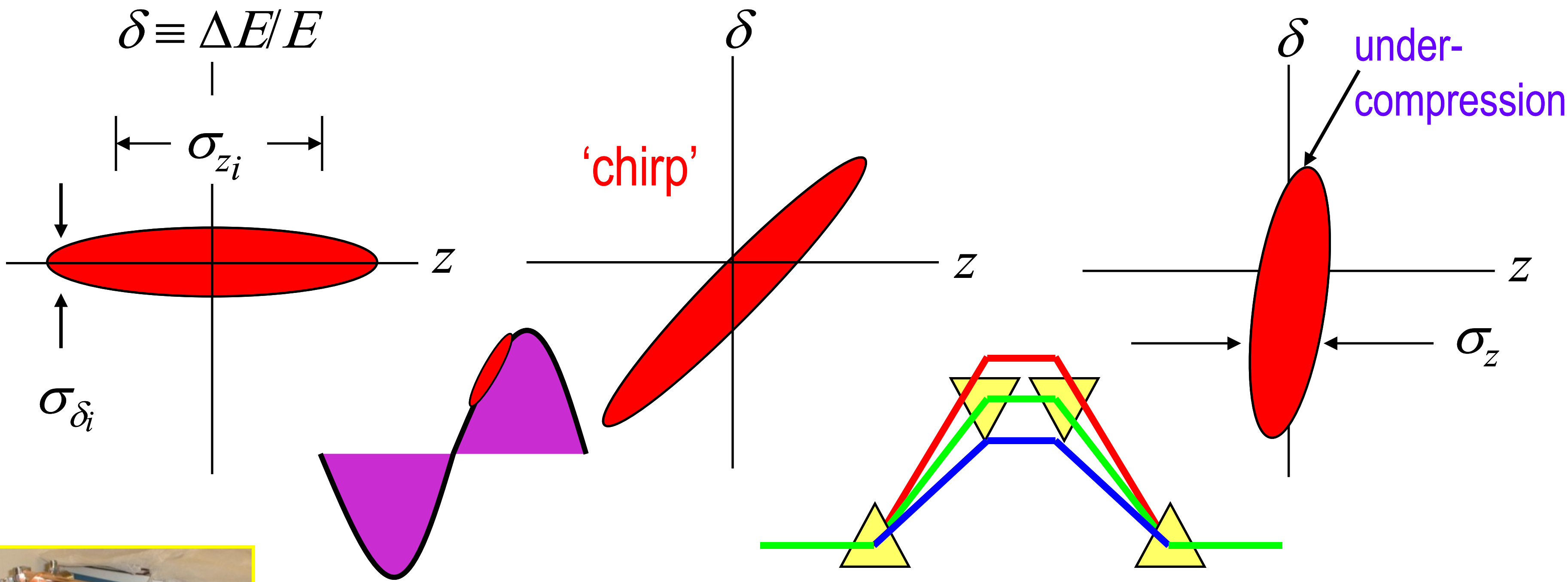
Summary

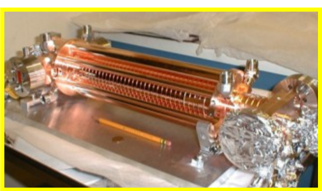
	 	 σ	1 n!	Limitations
• **Optical radiation**				
• Cherenkov / OTR radiation	X (blue)			
• ODR / OSR Radiation	X (red)			
• TCSPC		X (red)		10ps
• Streak camera		X (red)		200fs
• **Coherent radiation : Bunch spectrum**				
• Interferometry		X (blue)	X (blue)	
• Polychromator		X (blue)	X (red)	
• **RF techniques**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

Bunch length manipulation

- Magnetic Compression
- Ballistic Compression

Short bunches by Magnetic Compression





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

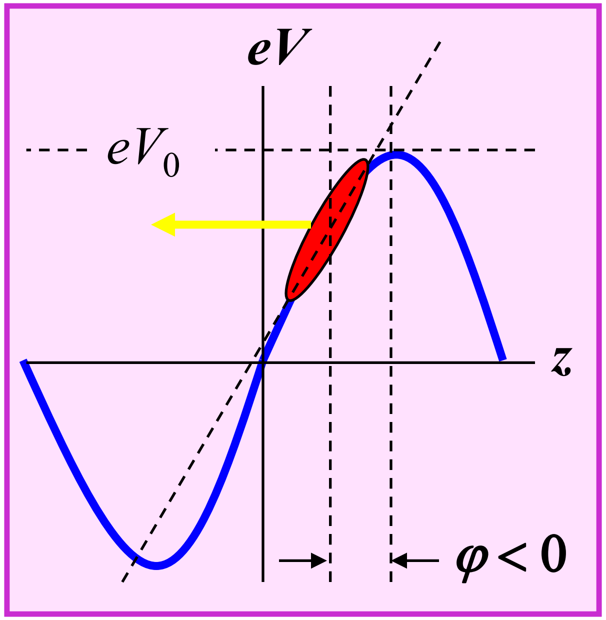
$$\Delta z = R_{56}\delta$$

RF Accelerating Voltage

Path-Length Energy-Dependent Beamline

ΔT → ΔE → ΔX → ΔT

Short bunches by Magnetic Compression



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

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

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

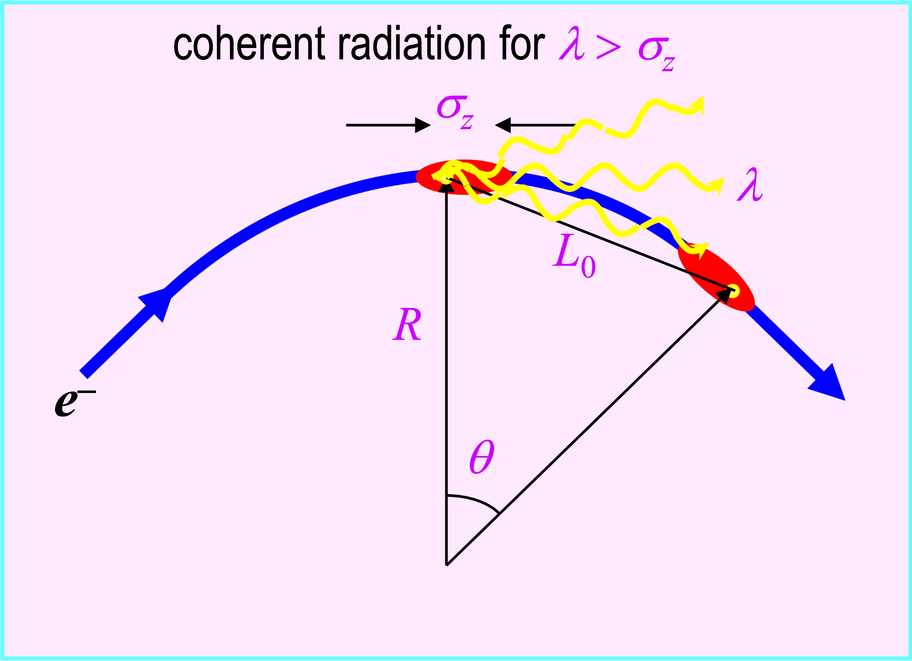
$$k(\varphi) \equiv \frac{\partial \delta}{\partial z} = -\frac{2\pi}{\lambda}\left(1 - \frac{E_0}{E}\right)\frac{\sin(\varphi + \Delta\varphi)}{\cos(\varphi)}$$ 'chirp'

final bunch length and energy spread…

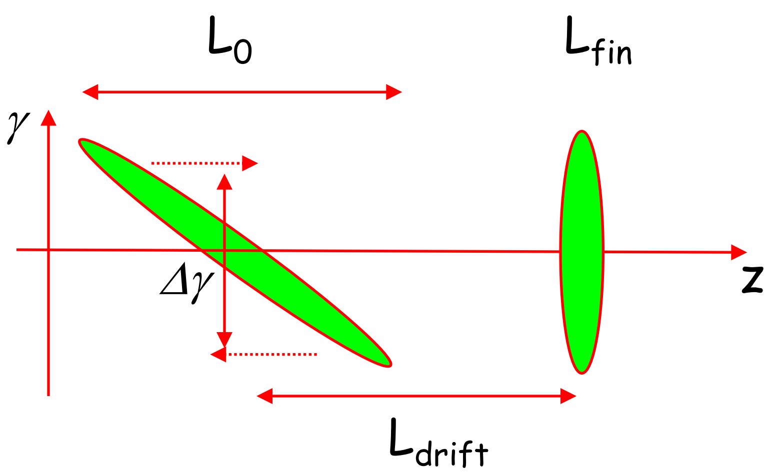
$$\sigma_z = \sqrt{(1 + kR_{56})^2 \sigma_{z0}^2 + R_{56}^2 \sigma_{\delta 0}^2 E_0^2 / E^2} \quad , \quad \sigma_\delta = \sqrt{k^2 \sigma_{z0}^2 + \sigma_{\delta 0}^2 E_0^2 / E^2}$$

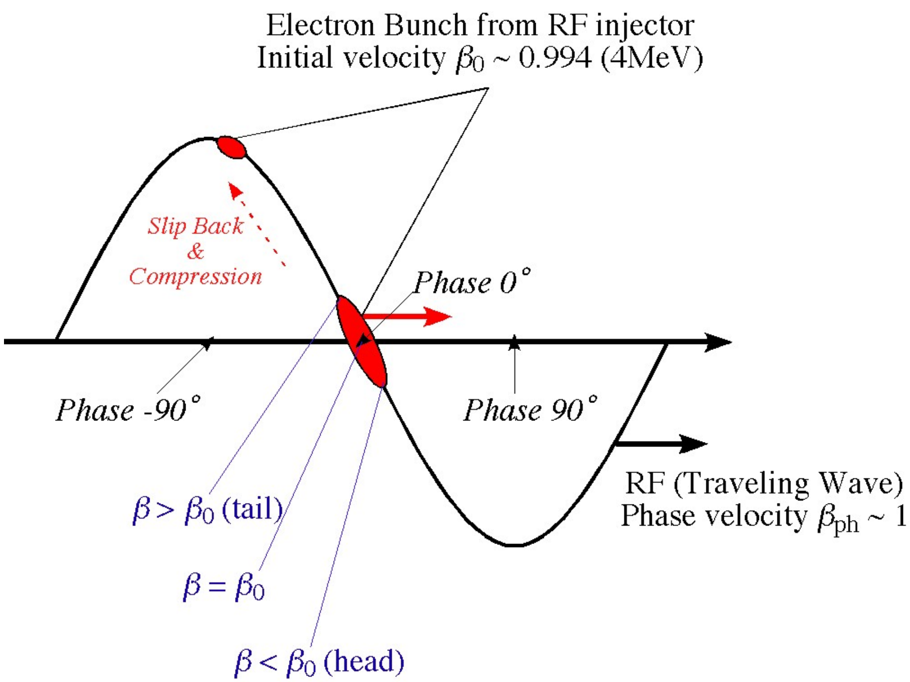
Coherent Synchrotron Radiation in Magnetic Chicane

- Powerful radiation generates energy spread in bends
- Causes bend-plane emittance growth (short bunch worse)



Short bunches by Ballistic/Velocity Compression





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

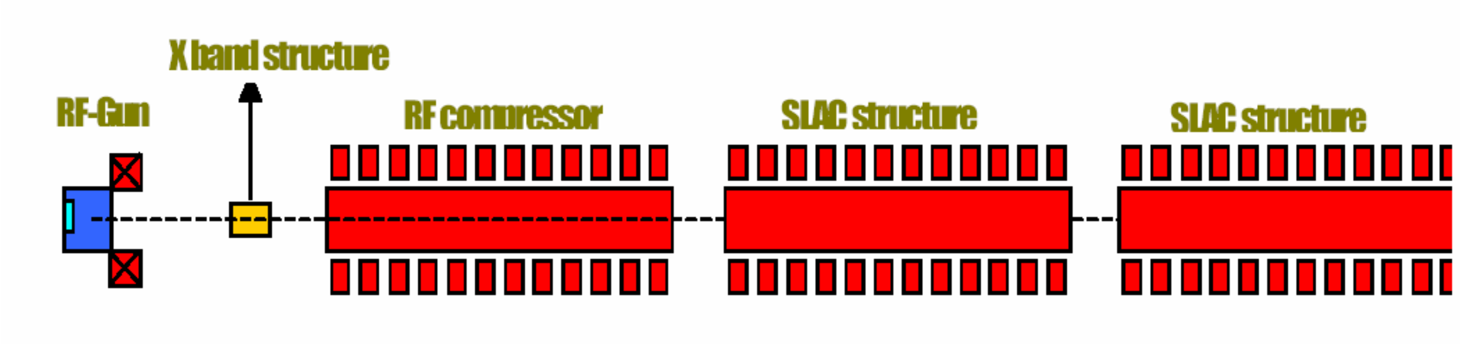
$\Delta\gamma$

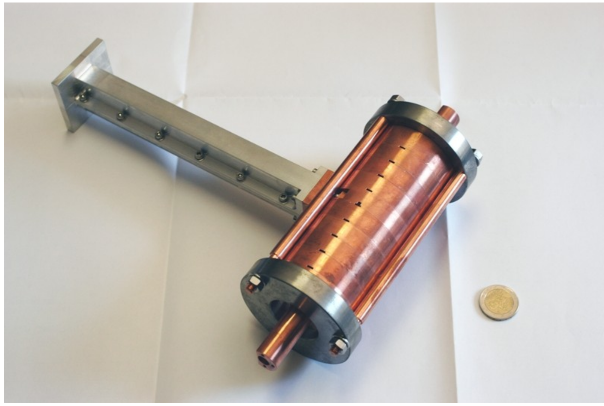
Provide a correlated velocity spread enough to produce, in a drift of length L_{drift} a *path difference* equal to ΔL

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

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

Short bunches by Ballistic Compression





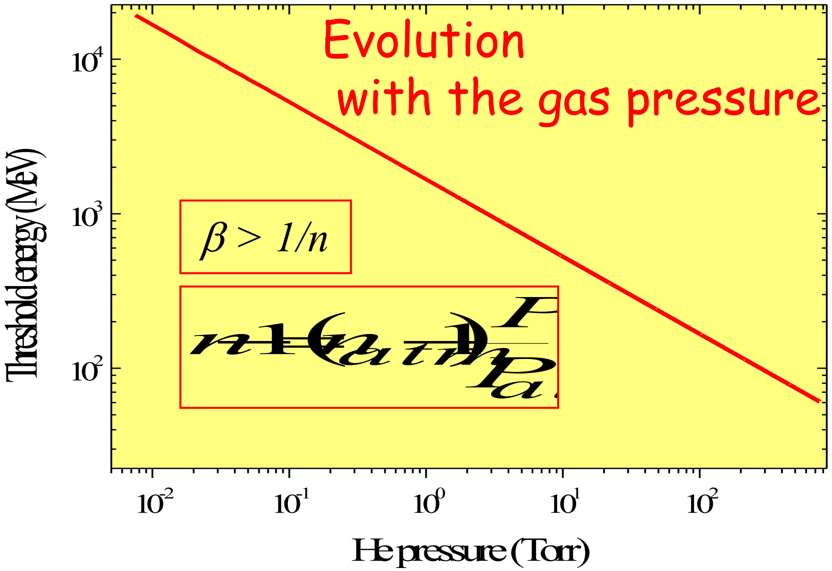
- Works well for non ultra-relativistic beam energies
- no Coherent Synchrotron Radiation effect and bend-plane emittance growth
- Longitudinal emittance growth due to RF non linearities

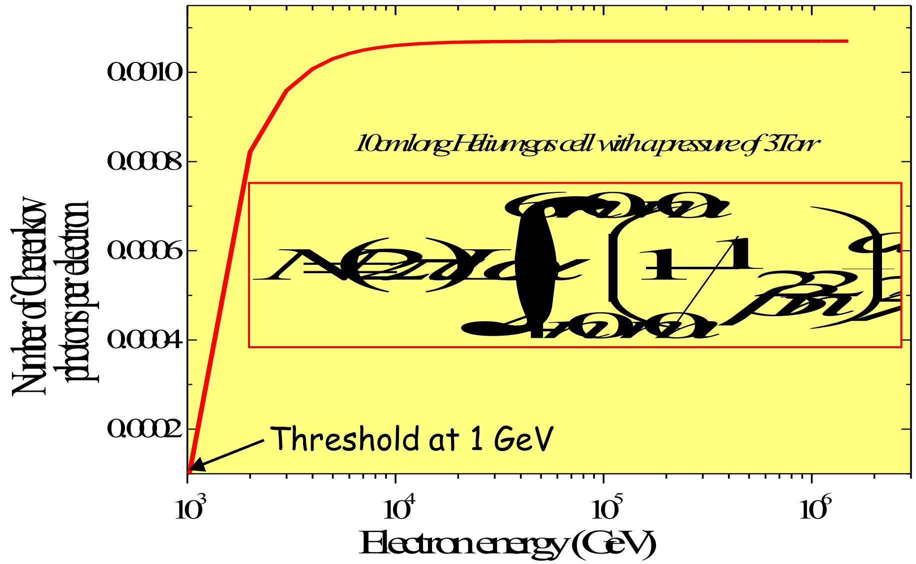
Reserved Slides

Cherenkov in gases

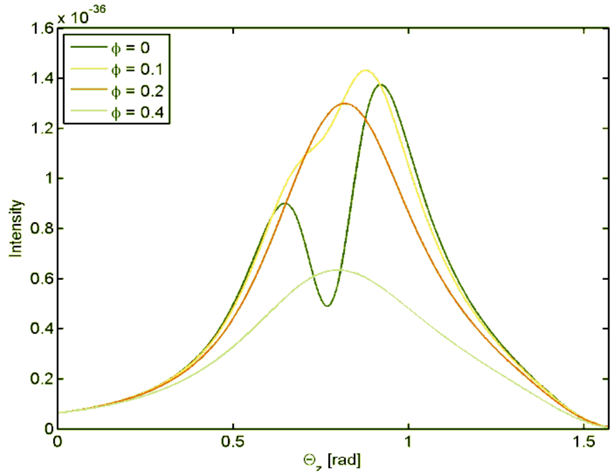
Threshold Cherenkov detector : $\beta > 1/n$

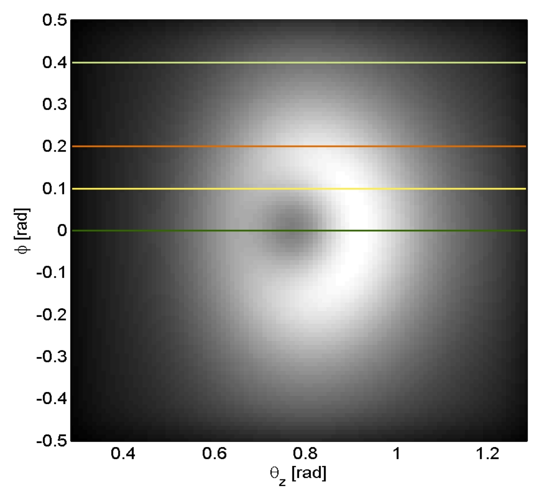
Cherenkov radiator (1atm)	Silica aerogel	Pentane C_5H_{12}	Ethane C_2H_6	Argon Ar	Neon Ne	Helium He
Index of refraction (n-1)	$8.4\ 10^{-3}$	$1.7\ 10^{-3}$	$7.1\ 10^{-4}$	$2.8\ 10^{-4}$	$6.7\ 10^{-5}$	$3.5\ 10^{-5}$
Cherenkov threshold (MeV)	3.5	8.2	13.1	20.9	43.5	60.4





Optical Transition Radiation

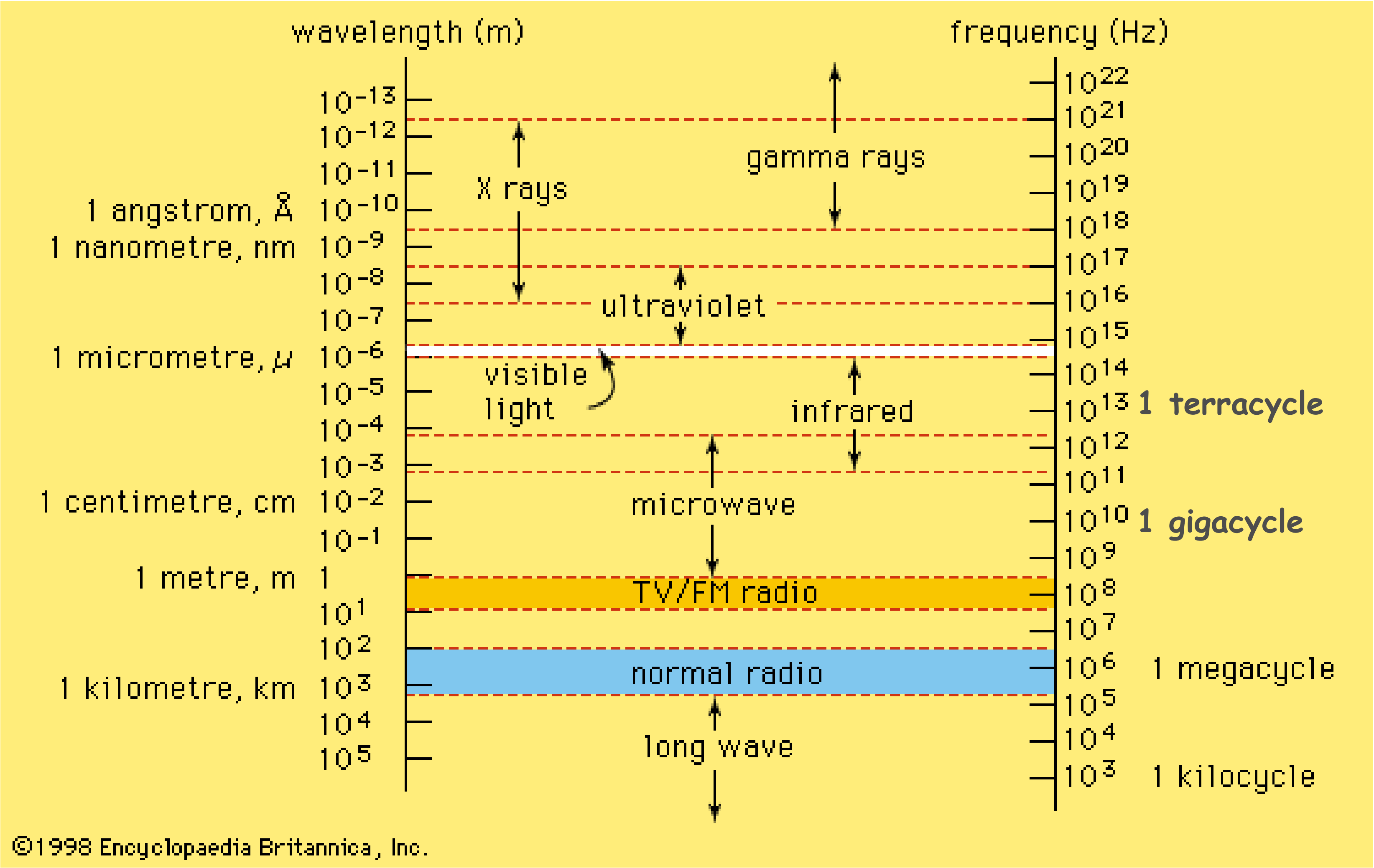




The angular intensity distribution is given by:

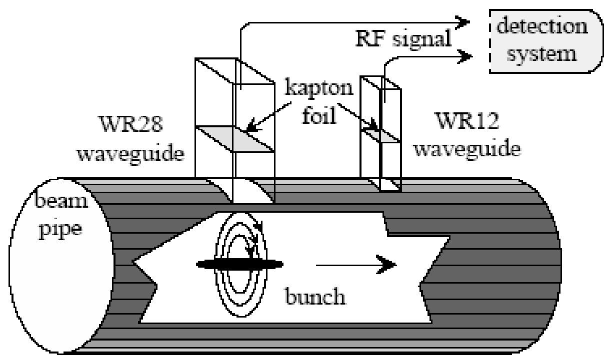
The actual angular intensity distribution becomes:

Bunch Frequency Spectrum



Bunch frequency spectrum by RF Pick-up

σ



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

1

- Simple diode detectors and fixed frequency filters

n!

- Use of RF mixers with a sweeping oscillator

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

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

700fs bunch length on a 40MeV beam

Limitations :
- Sensitive to beam position and beam charge
- Limited to some 300-500fs bunch length (>170GHz)

Bunch frequency spectrum by RF Pick-up

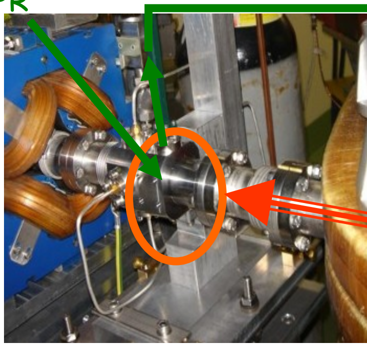
Filters, Horns and mixers

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

Acqiris DC282 Compact PCI Digitizer

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

BPR



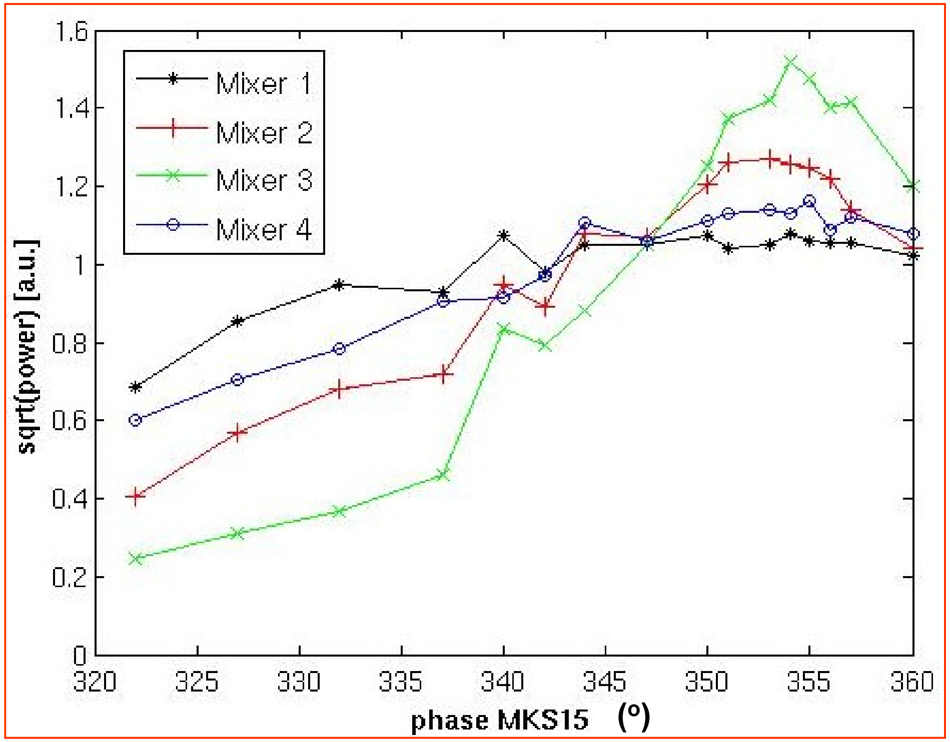
WR-28 Waveguide ~20m long

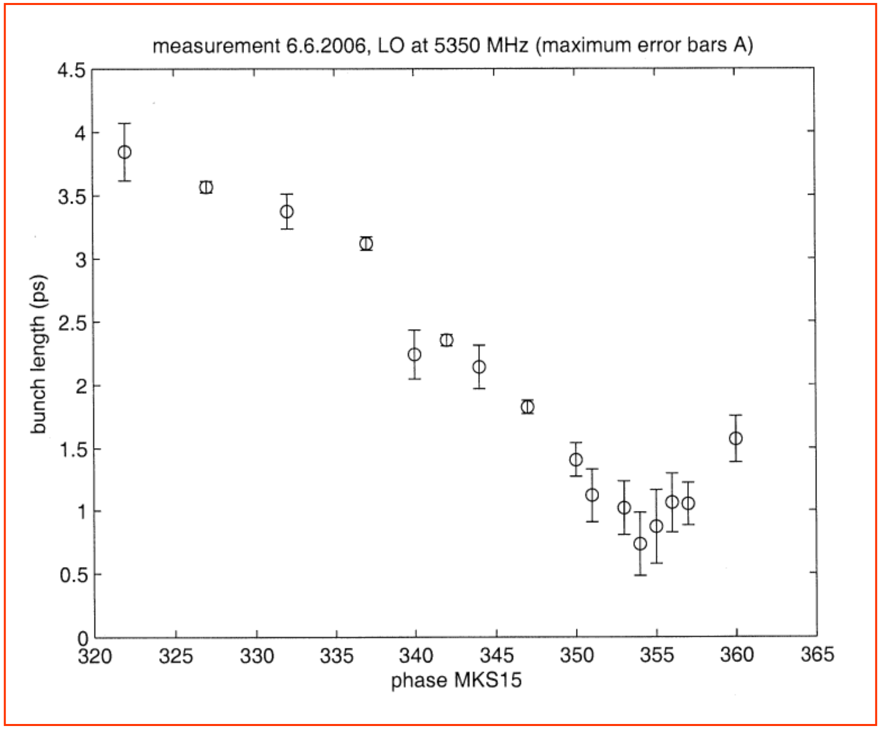
Beam

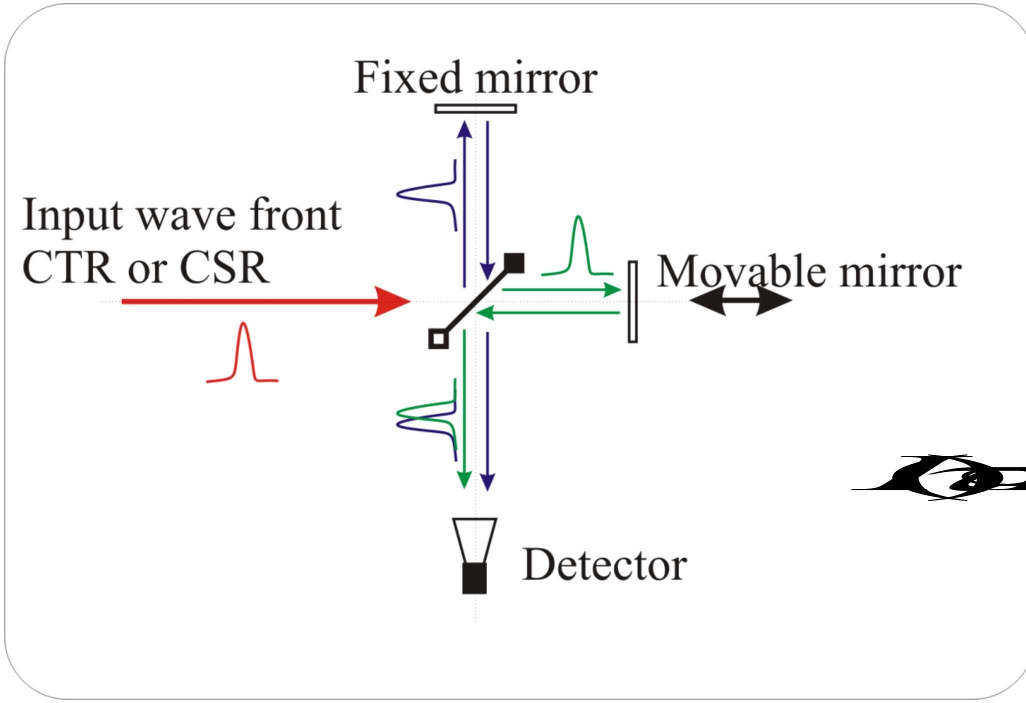
Data acquisition controlled by a Labview program, with built in Matlab FFT analysis routine

Bunch Frequency Spectrum by RF Pick-up

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







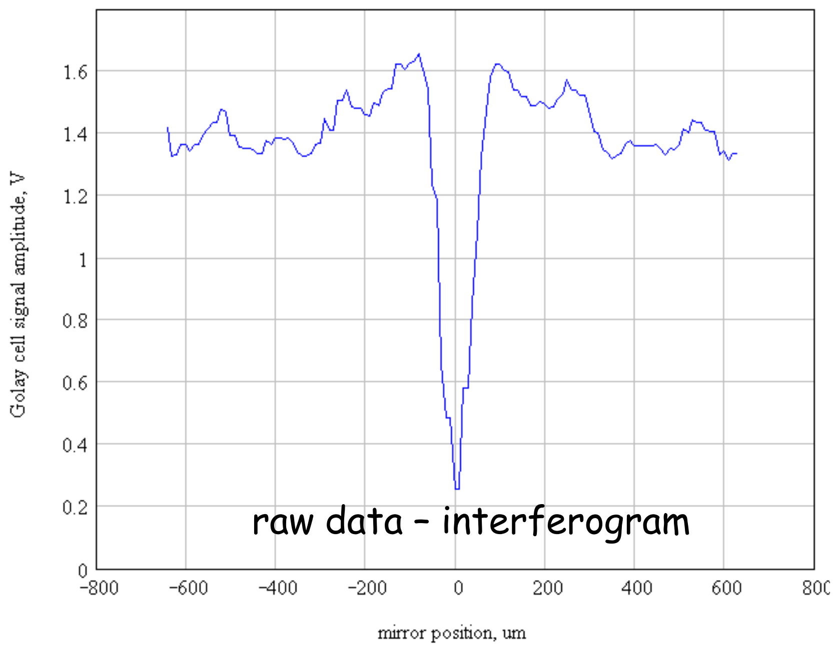
detectors measure intensity $I \propto E^2$

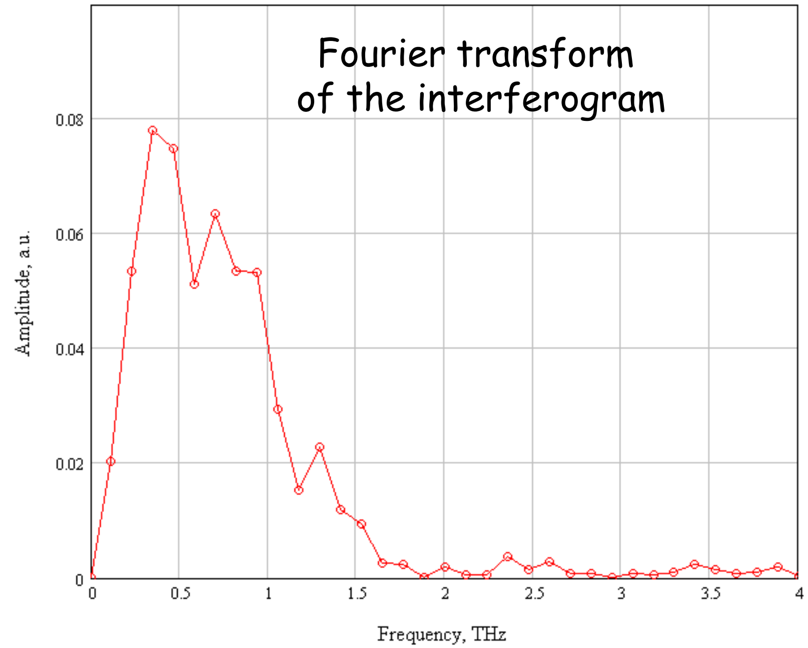
$$I(\tau) \propto \int_{-\infty}^{+\infty} E(t)\,E(t-\tau)\,dt$$

the autocorrelation function is measured with the help of an interferometer

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

Bunch Frequency Spectrum by Coherent Radiation





- the Gaussian shape of the bunch is assumed

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

- its power spectrum is also Gaussian

$$\rho(\omega) = e^{-(\omega\sigma_t)^2}$$

- The fit function is used

[illegible]

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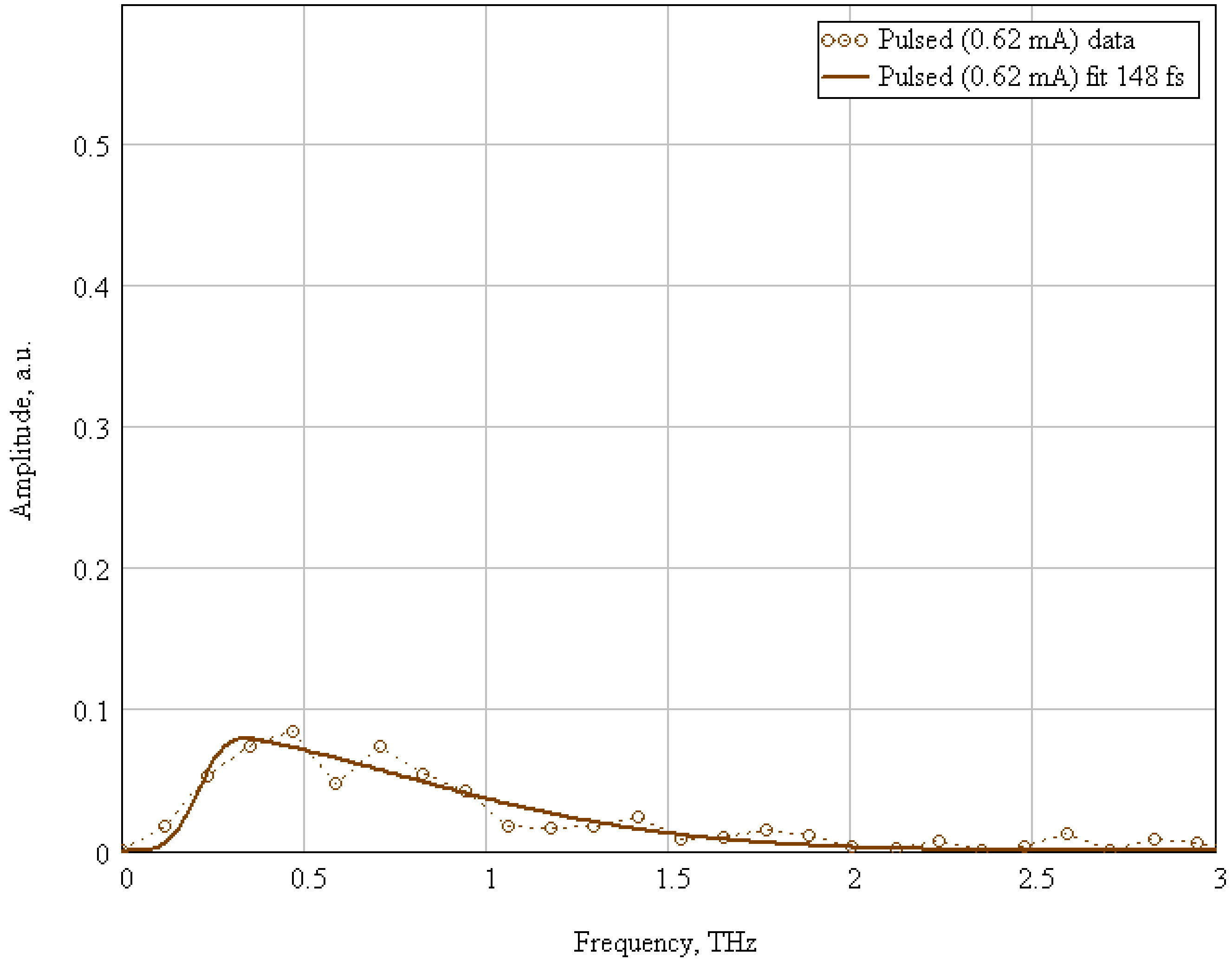

RF by Deflecting Cavity

Calibration curves @ Flash

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

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

- For arbitrary power:

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