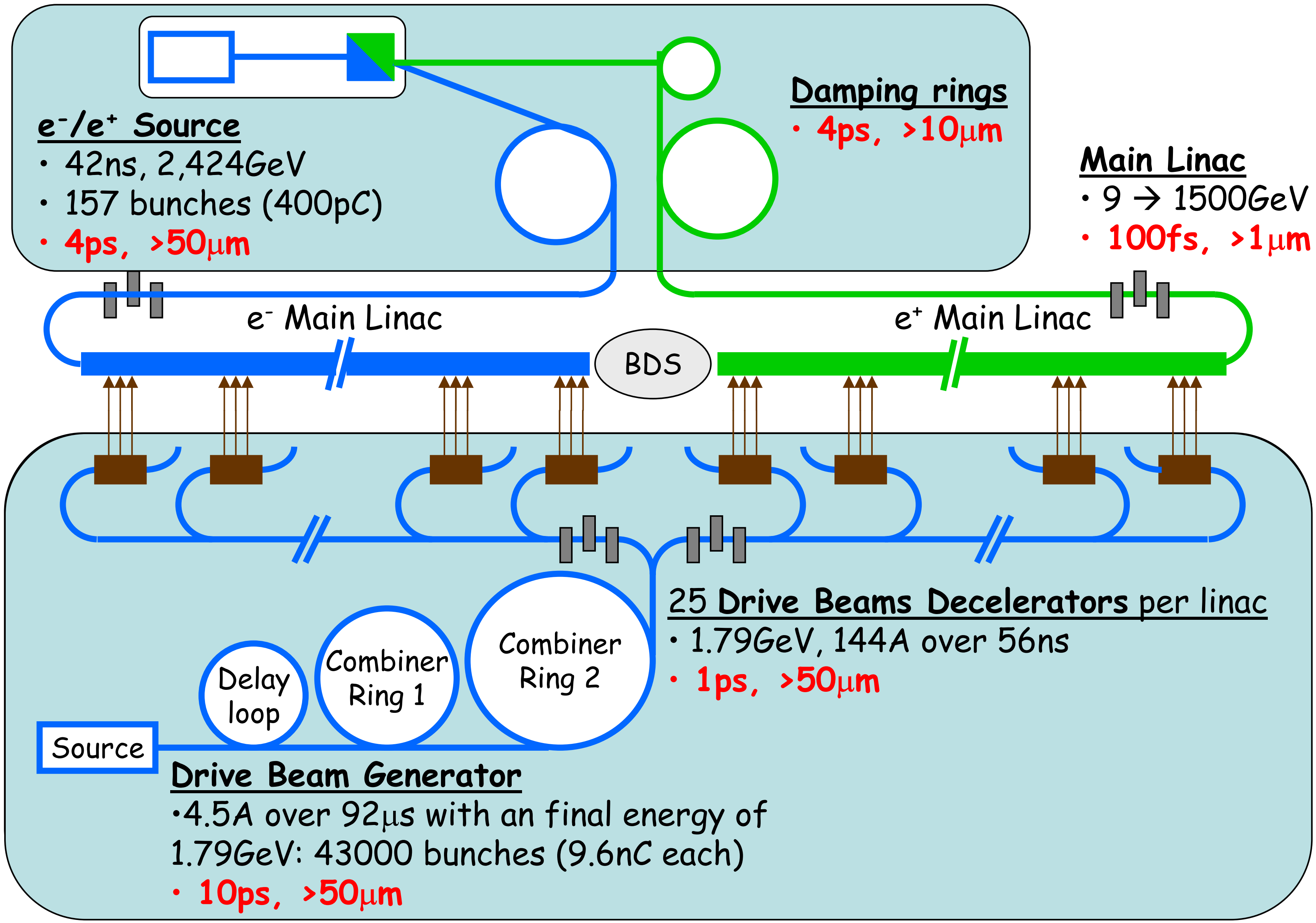
Status of beam profile monitors developments for CLIC

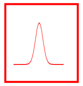
- CLIC complex in terms of beam diagnostic requirements
- Beam diagnostic classification
- Some possible candidates and the status of their development
  'Only experimental results'
- What, Where, How in the CLIC complex
- Conclusion & Perspectives

3TeV Compact LInear Collider



Beam diagnostics classification

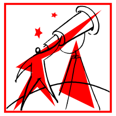
Criteria based on Performances

1- Profile measurements  ← → σ RMS values

- *More precise information on the beam characteristic*

2- Single shot measurements 1 ← → n! Sampling measurements

- *Do not care about the beam reproducibility (100% reproducible ?)*
- *No need for precise timing system (tens of fs in our case)*

3- Non interceptive  ← →  Interceptive

- *Can be used for beam study and beam control for on-line monitoring*
- *No risk of damage by the beam itself*

Bunch length measurement

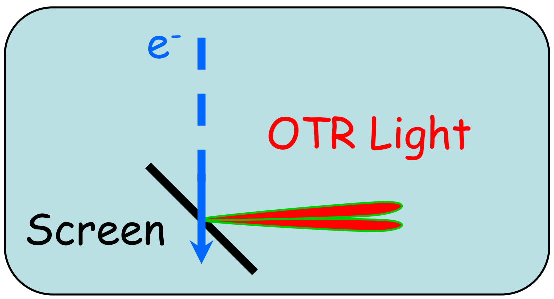
Methods

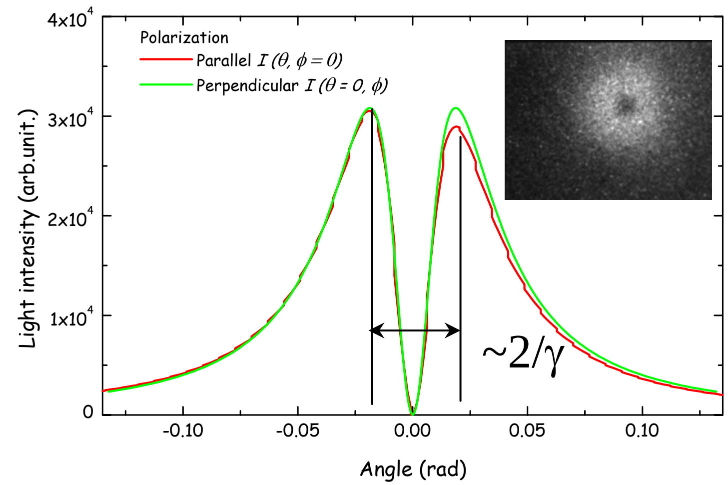
- **Optical radiation**
- Coherent radiation
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- Electro Optic Method
- Laser Wire Scanner

Optical Transition Radiation (OTR)

A huge amount of development for the past 30 years

'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 e⁻

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

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

Radiation wavelength — Beam energy

Limitations :

- High charge density beams : DB → **3 10⁹**nC/cm² ; MB→ **9 10⁸** nC/cm²

→ The thermal limit for 'best' screens (C, Be, SiC) is ~ 1 10⁶ nC/cm²
Assuming that the target has enough time to cool down between two consecutive pulses (lowering the machine repetition rate)

Bunch length measurement

Methods

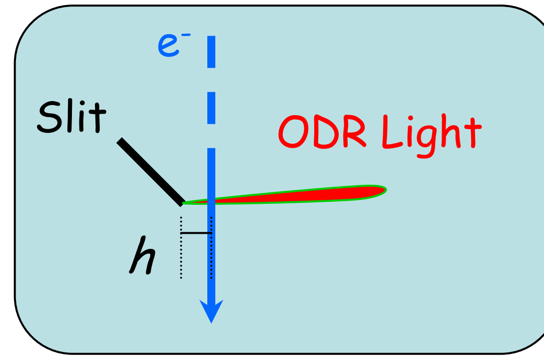
- **Optical radiation**
- Coherent radiation
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- Electro Optic Method
- Laser Wire Scanner

Optical Diffraction Radiation (ODR)

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

Beam energy — Radiation wavelength

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



A lot of activities on ODR, but only one measurement up to now :

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

Limitations :

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

Bunch length measurement

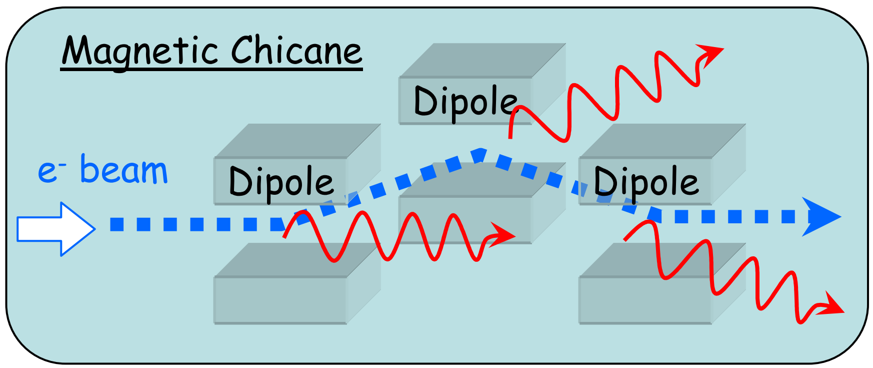
Methods

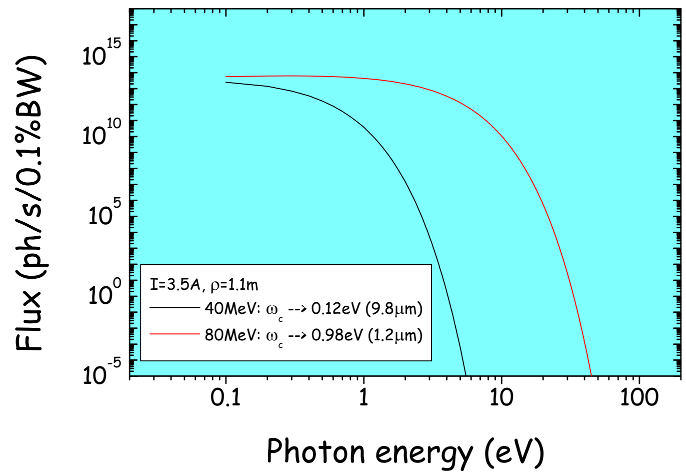
- **Optical radiation**
- Coherent radiation
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- Electro Optic Method
- Laser Wire Scanner

Optical Synchrotron Radiation (OSR)

A huge amount of development for the past 50 years

Only available in the rings or in the magnetic chicane





- Critical frequency :

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

Beam energy (γ) — Beam curvature (ρ)

Limitations :

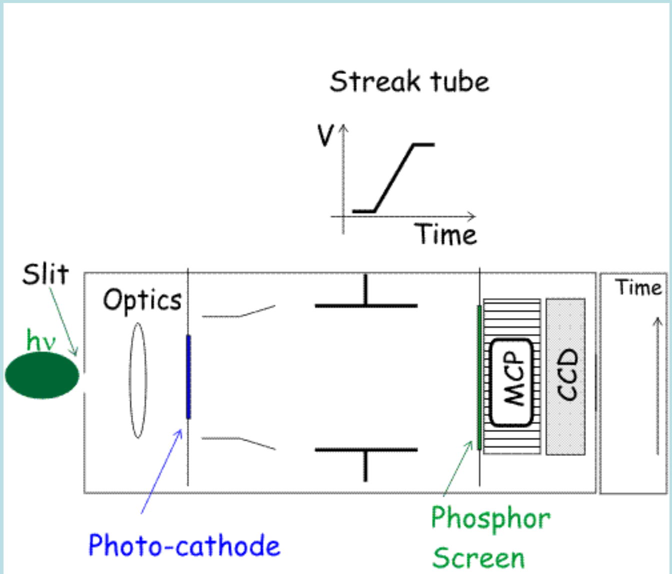
- In our case, not enough photons in the visible for low energy electrons : E > 150 MeV

Methods

- **Optical radiation**
- Coherent radiation
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- Electro Optic Method
- Laser Wire Scanner

1

Streak camera



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

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

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

Limitations : Time resolution of the streak camera :

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

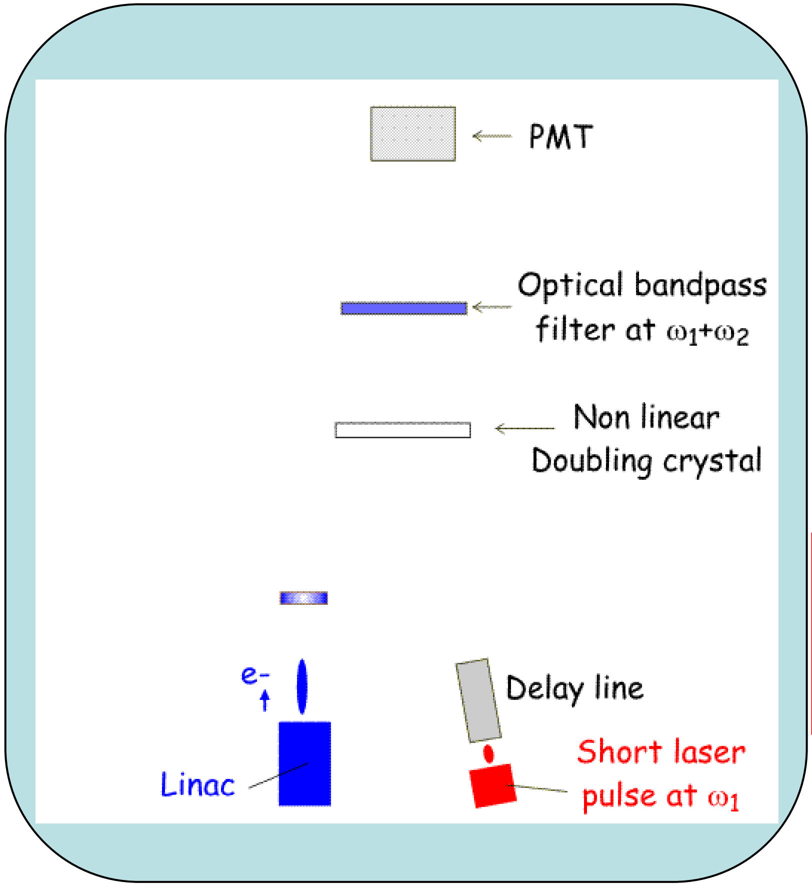
Bunch length measurement

Methods

- **Optical radiation**
- Coherent radiation
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- Electro Optic Method
- Laser Wire Scanner

n!

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'

Limitations

- Laser-RF synchronization (500fs)

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

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

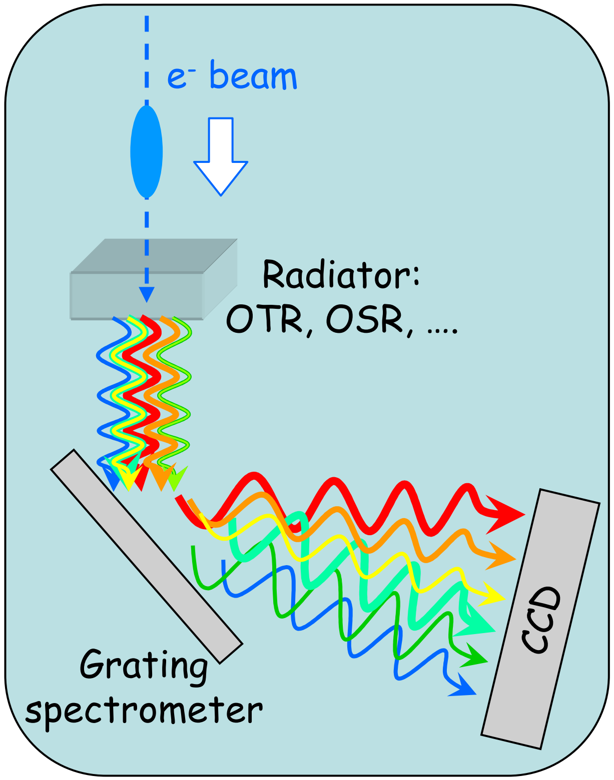
Bunch length measurement

Methods

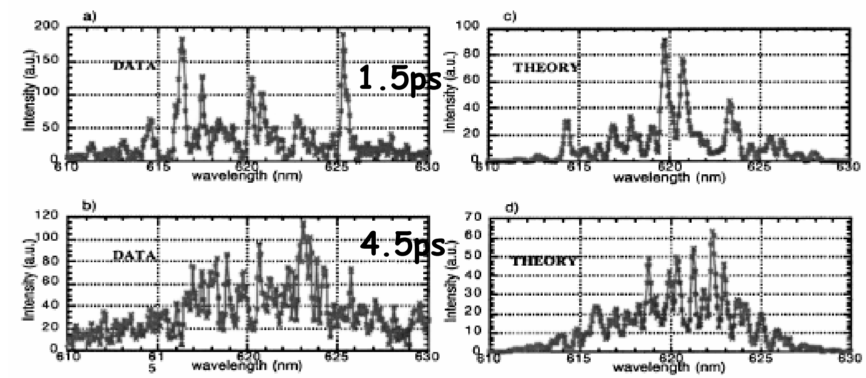
- **Optical radiation**
- Coherent radiation
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- Electro Optic Method
- Laser Wire Scanner

σ 1

Shot noise spectrum analysis



- Based on the measurement the spectrum of incoherent radiation produced by beam
- The spectra are composed of spikes of random amplitude and frequency which have a characteristic width inversely proportional to the bunch length



1.5ps. 200-500pC, 44MeV beam using a spectrometer with a resolution of 0.05nm/pixel

P. Catravas et al, **Physical Review Letters 82 (1999) 5261**

Limitations :

- Works only for a single bunch (or with a gated camera)

Bunch length measurement

Methods

- Optical radiation
- **Coherent radiation**
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- Electro Optic Method
- Laser Wire Scanner

σ

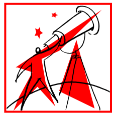
'When the wavelength of the radiation is longer than the bunch length, it is known that the coherent effect occurs inside the bunch.

The longitudinal shapes of the electron bunch can be extracted by analyzing the power spectrum of the radiation'

Coherent Transition Radiation (CTR)

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

- 90fs, 32MeV beam



Coherent Diffraction (CDR)

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**

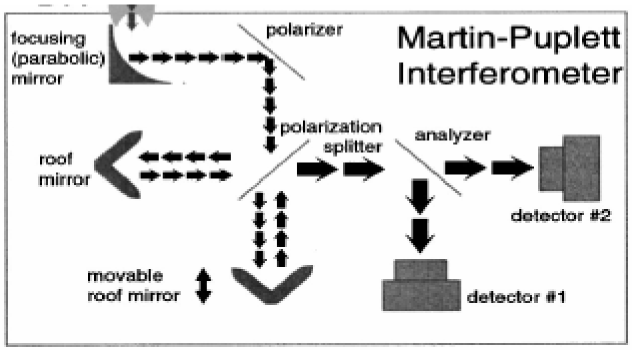
- 700fs, 35MeV beam
- 470fs, 150MeV beam

Bunch length measurement

Methods

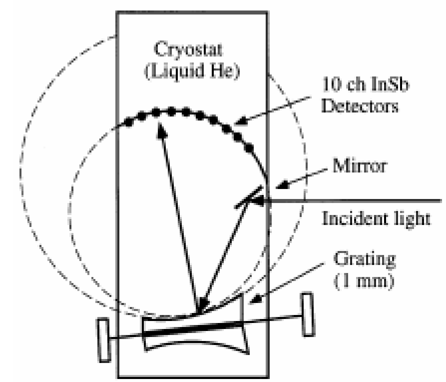
- Optical radiation
- **Coherent radiation**
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- Electro Optic Method
- Laser Wire Scanner

n! *'Michelson or Martin-Pupplet interferometer :*



• The radiation is split in two bunches, one is delayed by a linear stage and the intensity of the recombined bunch is measured by two detectors (one for each polarization)
• The spectrum is obtained from the Fourier transform of the interferometer function'

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



Limitations :
• Narrow dynamic range limited by the small bandwidth sensitivity of the system element (Grating, Beam splitter, …)

• Need cross calibrations

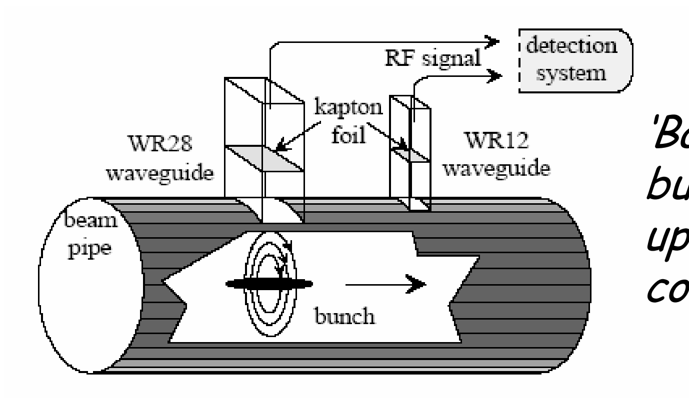
• Resolution depends on the number of detectors (**polychromator**)

Bunch length measurement

Methods

- Optical radiation
- Coherent radiation
- **RF Pick-Up**
- RF Deflector
- RF accelerating phase scan
- Electro Optic Method
- Laser Wire Scanner

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 :
- Reproducibility of the beam charge and position
- Size of the waveguides for very high frequency (>100GHz) makes the detection of very short bunches not well adapted

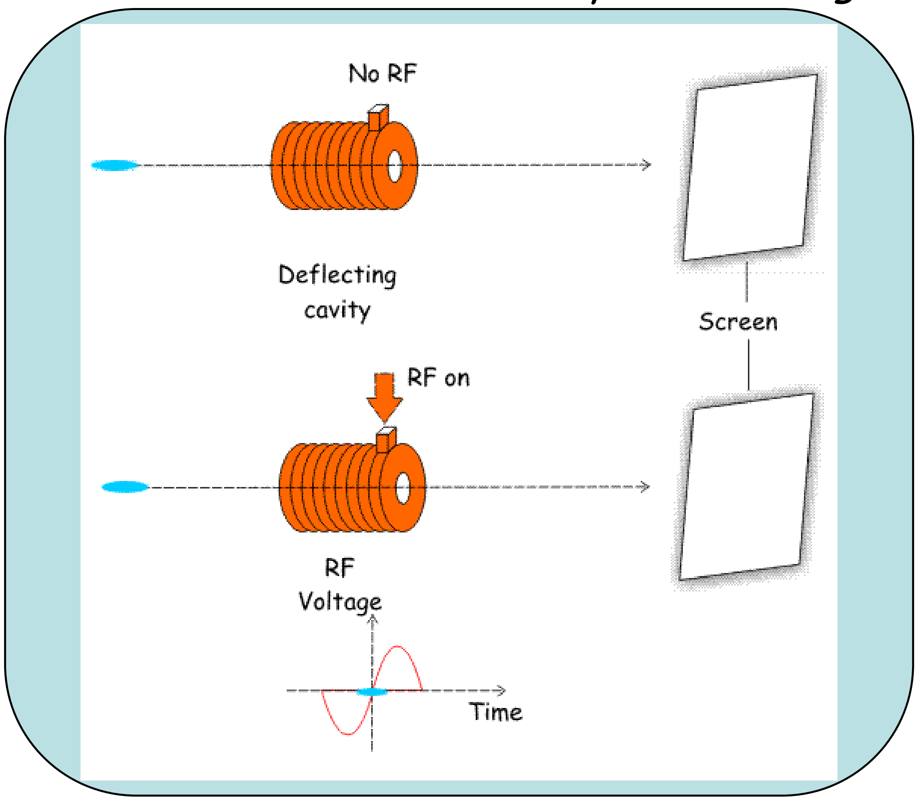
Bunch length measurement

Methods

- Optical radiation
- Coherent radiation
- RF Pick-Up
- **RF Deflector**
- RF accelerating phase scan
- Electro Optic Method
- Laser Wire Scanner

1

'The RF Deflector can be seen as a relativistic streak tube. The time varying deflecting field of the cavity transforms the time information into a spatial information
The bunch length is then deduced measuring the beam size at a downstream position using a screen or (LWS)



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

- 300μm, 28GeV beam using a S-band RF deflector

- Can extract even more information than the bunch length
- ex: coupled to a bending magnet for energy dispersion along the bunch

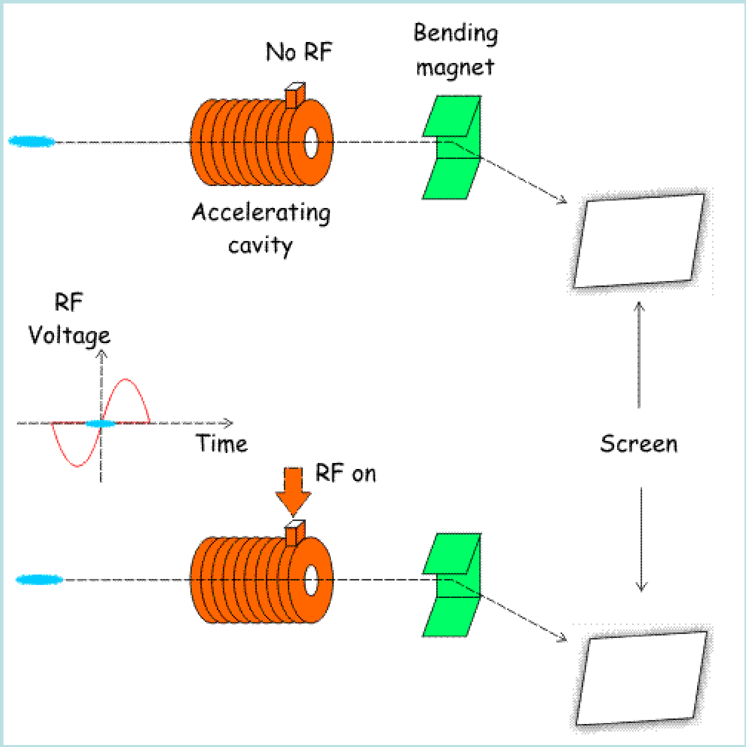
Bunch length measurement

Methods

- Optical radiation
- Coherent radiation
- RF Pick-Up
- RF Deflector
- **RF accelerating phase scan**
- Electro Optic Method
- Laser Wire Scanner

1

'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'



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

- 84fs, 45MeV beam but low charge beam

Limitations :

- For high charge beam → Beam loading, Wakefields, …

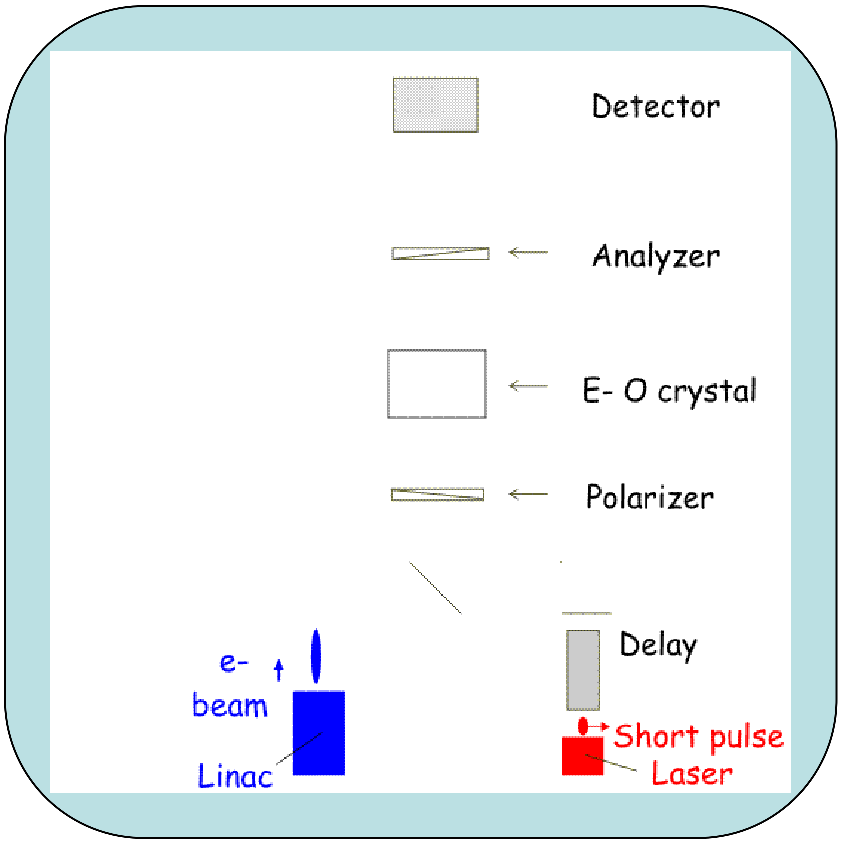
Bunch length measurement

Methods

- Optical radiation
- Coherent radiation
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- **Electro Optic Method**
- Laser Wire Scanner

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

n! *Bunch length is reconstructed by measuring the intensity of the polarization change as a function of laser timing*



A. M. MacLeod et al, **Physical Review Letters 85 (2000) 3404**

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

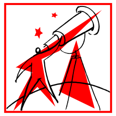
<u>Limitations :</u>

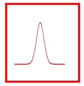
- Presence of phonon (5.3THz for ZnTe) can distort the measurement for bunch length < 200fs
- Radiation hardness (no problem observed up to now)
- Jitter of the laser-RF synchronization

Bunch length measurement

Methods

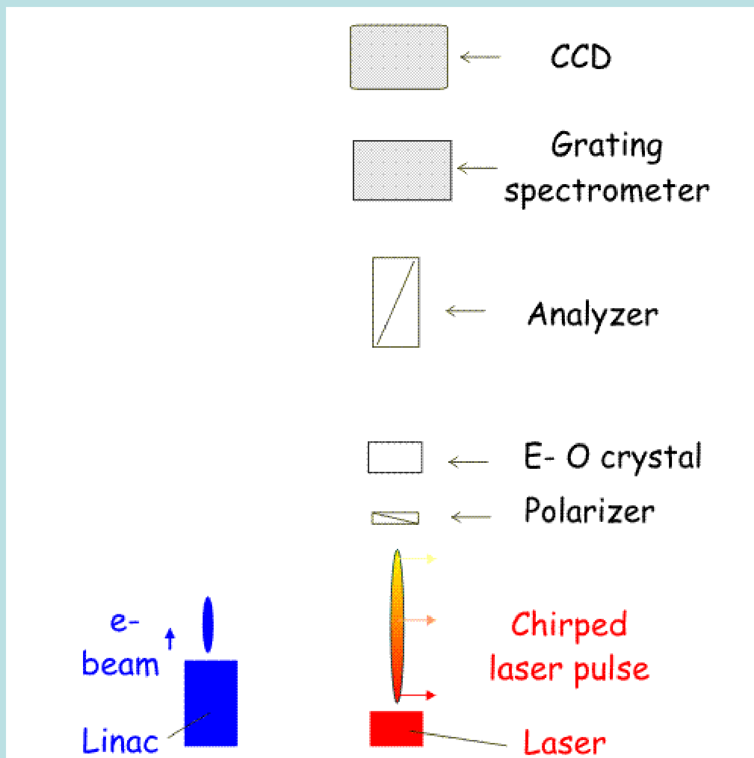
- Optical radiation
- Coherent radiation
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- **Electro Optic Method**
- Laser Wire Scanner





1

- *Using a longer laser, the change in polarization will affect the laser during a time equivalent to the bunch length*
- *Since the laser is chirped, the time info's are converted into position using a grating spectrometer and measured by a CCD*



A. M. MacLeod et al, **Physical Review Letters 88 (2002) 124801 & Proceeding of the DIPAC conference, 2003.**

Measurements of 1.72ps bunches using a 20ps chirped laser pulse

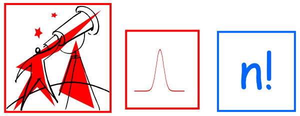
<u>Limitations :</u>

- Temporal resolution depends on the chirp and the bandwidth of the laser (370fs), the resolution of the spectrometer (300fs).
- 70fs temporal resolution seems feasible

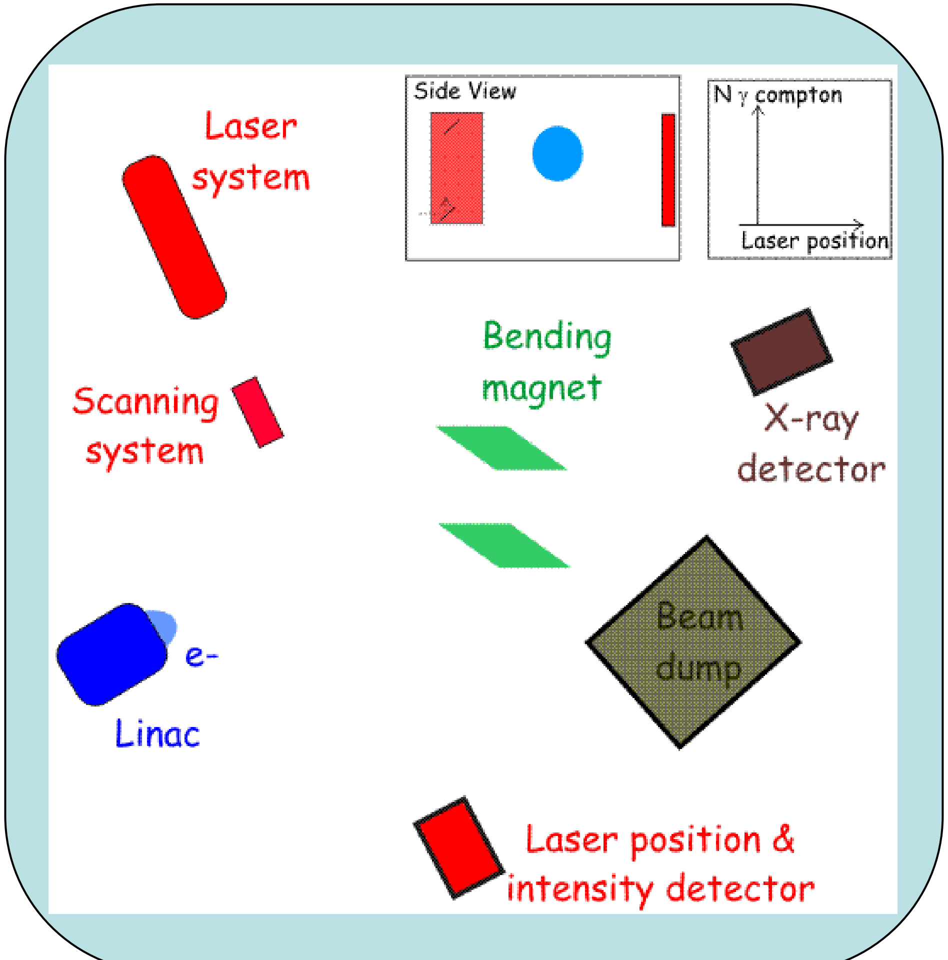
Bunch length measurement

Methods

- Optical radiation
- Coherent radiation
- RF Pick-Up
- RF Deflector
- RF accelerating phase scan
- Electro Optic Method
- **Laser Wire Scanner**



- *Scattered photons are produced by 90 Compton scattering sending a high power ultra-short laser onto the beam*
- *By counting the number of Compton photons as a function of the laser timing, the bunch length is measured*



W.P Leemans et al, **Physical Review Letters 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.

Limitations :

- Impact of beam losses very important for electrons energy < few GeV
- Jitter of the laser-RF synchronization

Bunch length measurement

↓

Beam size measurement

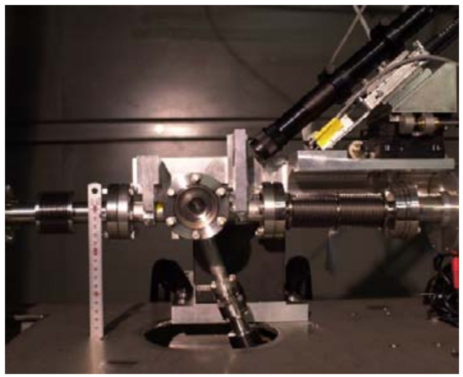
Methods

- **Optical radiation**
- X-ray radiation
- Laser Wire Scanner
- Quadrupolar Pick-up

1 Optical Transition Radiation

A huge amount of development for the past 30 years

• Small beam size observation



S. Anderson et al, **KEK-ATF-2001-08**

5μm beam size measured using a high magnification telescope using a backward OTR screen tilted at 10°
→ Avoid field depth limitations

Limitations :

• Spatial resolution not limited diffraction but by the optical aperture of the detection system:

$$\delta \approx 1.44 \lambda / \theta$$ with $\theta (>> \gamma^{-1})$ the optical aperture

X. Artru et al, **NIM AB 145 (1998) 160-168**

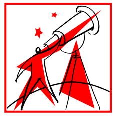
C. Castellano and V.A. Verzilov, **Physical Review STAB 1, (1998) 062801**

• Thermal limitations for high charge densities

Beam size measurement

Methods

- **Optical radiation**
- X-ray radiation
- Laser Wire Scanner
- Quadrupolar Pick-up

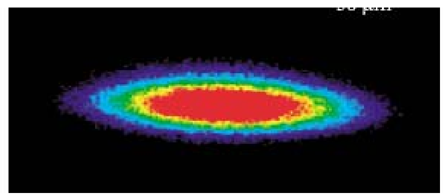


Optical Synchrotron Radiation (OSR)

A huge amount of development for the past 30 years

1

- Beam Imaging:



Limitation :

- Diffraction limits the measurements $\delta \approx \gamma\lambda$
- for us : beam size < 100μm (damping ring)

Beam size measurement

Methods

- **Optical radiation**
- X-ray radiation
- Laser Wire Scanner
- Quadrupolar Pick-up

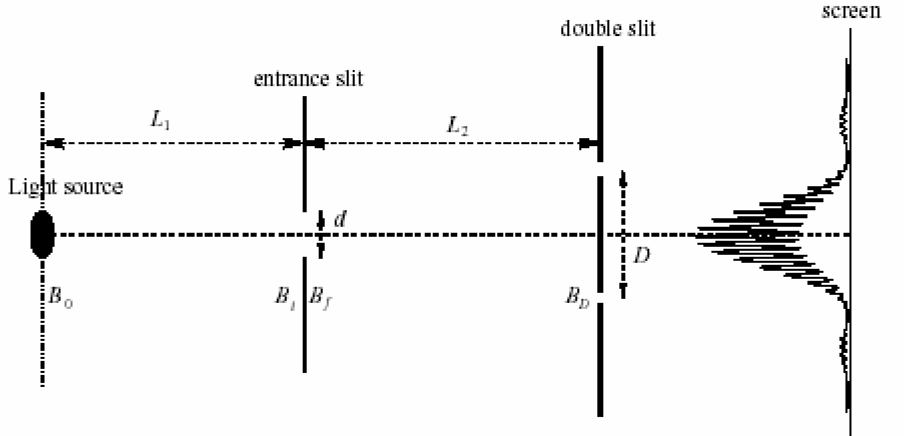
Optical Synchrotron Radiation (OSR)

σ n!

- Interferometry Method : 'Van Citterut-Zernike theorem'

- *Beam size is given by the Fourier transform of the complex degree of spatial coherence, which can be obtained using double slit interferometer, measuring to the fringes visibility of the interference pattern.*

- *The interferometer function is obtained by measuring the fringe visibility as a function of the slit width*



J. Urakawa et al, **Proceeding of the PAC conference 1999, 256 & 2143**

Measurement of 15-40μm beam size at KEK-ATF (1.19GeV)

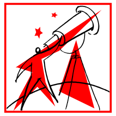
Limitations : Y. Takayama et al, **Proceeding of the PAC conference 1999, 2155**

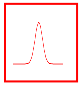
- Required conditions to apply the beam size reconstruction theorem
  → Limited at beam size > 10μm

Beam size measurement

Methods

- Optical radiation
- **X-ray radiation**
- Laser Wire Scanner
- Quadrupolar Pick-up





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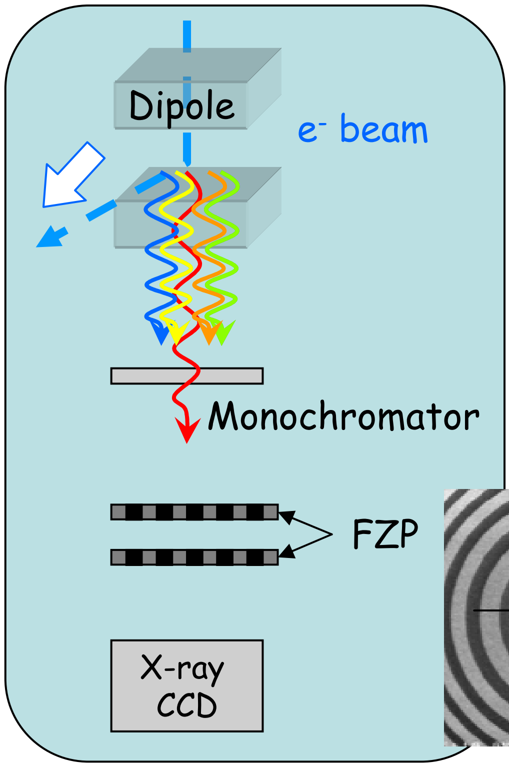
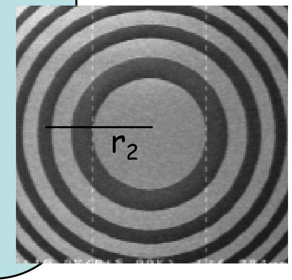
X-ray Synchrotron Radiation (XSR)



- *The beam if deflected also produces X-ray radiations, not affected anymore by diffraction limitations. They are then focused using Fresnel Zone Plates onto an X-ray CCD camera.*

- *In order to minimize aberrations in the FZP's, a monochromator is first used to select the desired X-ray energy*

- Si crystal oriented at the corresponding braagg angle



- FZP Focal length (radius) depends on photon energy : $r_n = (n\lambda f)^{1/2}$

- FZP are 0.8μm thick Tantalum absorbers spaced by 6μm on a 0.2μm Silicon Nitride (SiN) membranes

K. Iida et al, **NIM A 506 (2003) 41-49**.

Beam size smaller than 10μm with a resolution better than 2μm using 3.235keV X-ray and two Fresnel zone plates

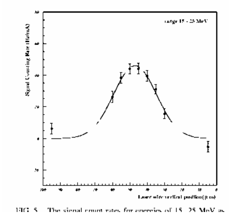
Beam size measurement

Methods

- Optical radiation
- X-ray radiation
- **Laser Wire Scanner**
- Quadrupolar Pick-up

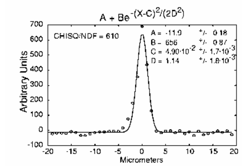
• Scattered photons are produced by 90 Compton scattering sending a high power ultra-short laser onto the beam
• By measuring the number of Compton photons as a function of the laser position, the beam size is reconstructed

H. Sakai et al, **Physical Review ST AB 4 (2001) 022801 & ST AB 6 (2003) 092802**



10μm beam spot size at the KEK damping ring (1.28GeV) using a Fabry-perot CW optical cavity

R. Alley et al, **NIM A 379 (1996) 363** & P. Tenenbaum et al, **SLAC-PUB-8057, 1999**



• Test done a SLAC on a 30GeV, few microns size electrons beam using 350nm Nd:YAG laser and reflective optics in order to achieve a sub micron laser spot size.
• Both measuring the Compton photons and/or electrons

Limitations :
• Not efficient for the measurement of mm beam size
• Cannot focused a laser better than a wavelength spot size
• Need precise μm spatial alignment and stabilization (To avoid vibrations and to check laser spot size stability)
• Need to study beam loss to estimate the S/N ratio

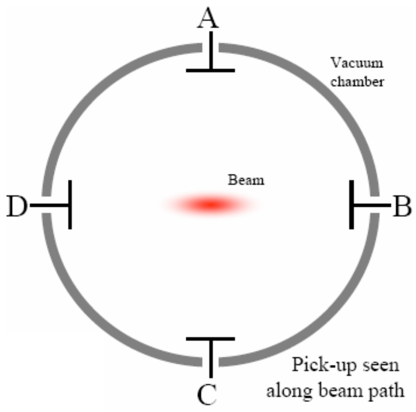
Beam size measurement

Methods

- Optical radiation
- X-ray radiation
- Laser Wire Scanner
- **Quadrupolar Pick-up**

σ 1

'Quadrupole moment is a measure of the beam ellipticity'



- Suppresses the dominating intensity signal (zero order) by coupling to the radial magnetic field component.
- Position contribution (first order) can not be avoided, but can be measured and subtracted.

S.J. Russell, **Review of Scientific Instruments, 70 (1999) 1362** & **Proceeding of the 1999 PAC conference, 477, 1999**

A. Jansson, **Physical Review STAB** & **NIM A (2002)**

→ Time evolution of the beam emittance

Limitations :

- Probably not well adapted to the measurement of small beam size

Beam diagnostics classification

Level of Difficulty and Reliability

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

A detector, what for ?

- Online Beam stability → non intercepting and reliable

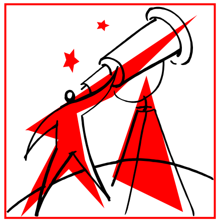
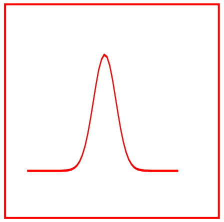
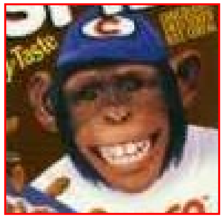
Only have access to a partial information (RMS values,..)

- Beam characterization and beam physics study → full information

Complexity and time consuming

Beam diagnostics classification

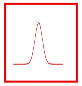
Can we do non intercepting, single shot, beam profile measurement in an easy way ?

 + 1 +  + 

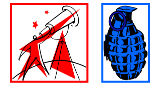
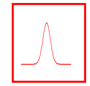
= ?

All in red → 'perfect system'

Performances of Bunch Length detectors

	 	 σ	1 n!	Limitations
• Optical radiation				
• Streak camera --------------------		xxxxxxx	xxxxxxx	> 200fs
• Non linear mixing -----------------		xxxxxxx	xxxxxxx	Laser to RF jitter : 500fs
• Shot noise frequency spectrum --		xxxxxxx	xxxxxxx	Single bunch detector
• Coherent radiation				
• Interferometry -------------------		xxxxxxx	xxxxxxx	
• Polychromator --------------------		xxxxxxx	xxxxxxx	
• RF Pick-Up --------------------------------	xxxxxxx	xxxxxxx	xxxxxxx	> 500fs
• **RF Deflector** ----------------------------	xxxxxxx	xxxxxxx	xxxxxxx	
• RF accelerating phase scan --------------	xxxxxxx	xxxxxxx	xxxxxxx	High charge beam
• **Electro Optic Method**				
• Short laser pulse ------------------	xxxxxxx	xxxxxxx	xxxxxxx	Laser to RF jitter : 500fs
• **Chirped pulse** --------------------	xxxxxxx	xxxxxxx	xxxxxxx	> 70fs
• Laser Wire Scanner ---------------------	xxxxxxx	xxxxxxx	xxxxxxx	Laser to RF jitter : 500fs

Performances of Beam size detectors

		 σ	1 n!	Limitations
• Optical radiation				
• **OTR** -------------------------	xxxxxxx	xxxxxxx	xxxxxxx	For high current density & high beam energy
• OSR imaging ---------------	xxxxxxx	xxxxxxx	xxxxxxx	< 100μm beam size
• OSR interferometer ------	xxxxxxx	xxxxxxx	xxxxxxx	< 10μm beam size
• **X-ray radiation** -------------------	xxxxxxx	xxxxxxx	xxxxxxx	Only for Ring or magnetic chicane
• **Laser Wire Scanner** --------------	xxxxxxx	xxxxxxx	xxxxxxx	For low current density & low beam energy
• Quadrupolar pick-up --------------	xxxxxxx	xxxxxxx	xxxxxxx	For small beam size

My opinion *up to now*

Bunch length measurement

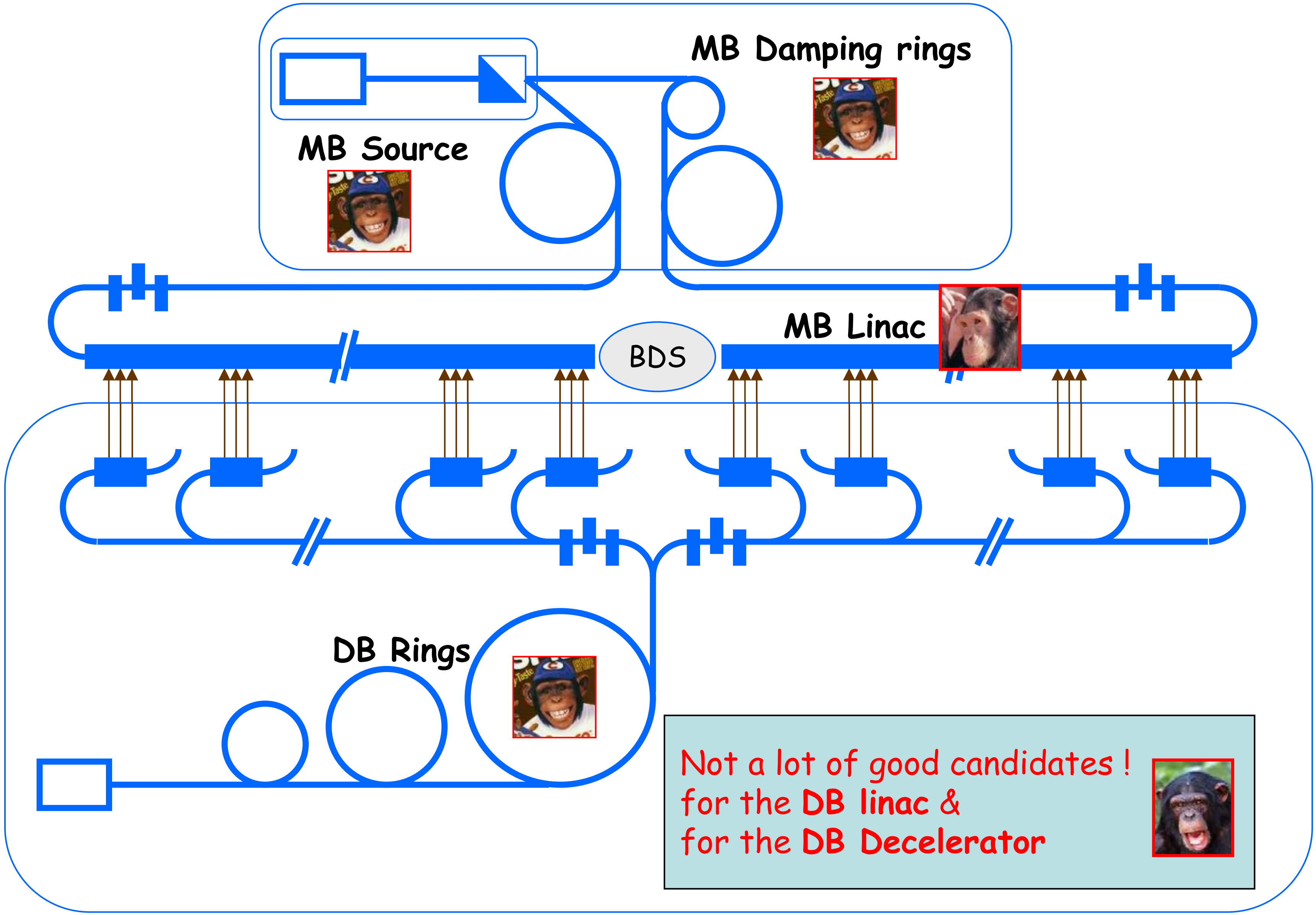
- High resolution for precise beam study
  - **RF Deflector**
  - **Electro Optic Method (chirped laser pulse)**
- Reliability and simplicity for beam operation (non-interceptive method)
  - **RF pick-up**

Beam size measurement

'Less solutions than for bunch length'

- High resolution for precise beam study
  - **OTR (low charge density)**
  - **Laser wire scanner (high energy linac and ring)**
  - **X-ray imaging (ring)**

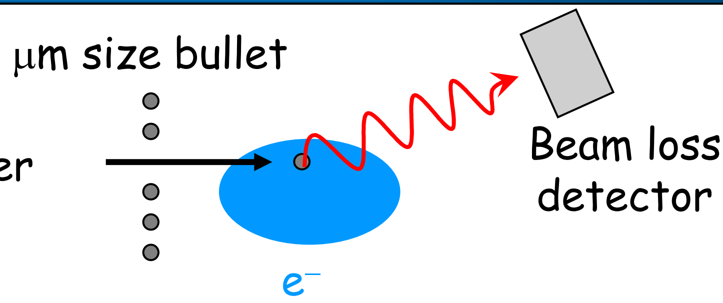
Potential use on CLIC



Perspectives

- Drive beam size monitors ?

- Degradable detector
  - 'Kalachnikov' : bullet scanner



- Neutral beam scanner

C. Dimopoulou, PS/BD note 99-12

- Plasma target as forward OTR radiator

already observed at LBNL not published yet

- To avoid diffraction limitations in the Main beam linac

- XTR & XDR :
  - Backward radiation is reflected by the material up to frequency ~ plasma frequency ω_p
  - Forward radiation is emitted at frequencies up to $\gamma\omega_p$

K.A. Ispirian, NIM A 522 (2004) 5-8

M.A. Piestrup, et al., Phys. Rev. A 45 (1992) 1183.