Particle Beam Diagnostics

Prof. Carsten P. Welsch

Further Reading

- CAS Beam Diagnostics, Dourdan, France (2008)
- DITANET Beam Diagnostics Schools in 2009 and 2011
- DITANET Topical Workshops
  - Transverse Beam Profile Monitoring,
  - Longitudinal beam profile monitoring, CI, UK
  - Beam Loss Monitoring, DESY, Germany

www.liv.ac.uk/ditanet or CERN indico, search for DITANET

Credits

Many thanks to R. Fiorito, T. Lefèvre, E. Bravin,
A. Jeff, H. Braun, R. Jones, P. Forck and S. Jolly.

Overview

- Lecture 1 *(„the basics“)*
  - Transverse beam profile
  - Longitudinal beam profile
  - Beam position
  - Beam energy
- Lecture 2 *(„advanced topics“)*
  - Beam emittance
  - Beam halo
  - Non-invasive beam profile measurements

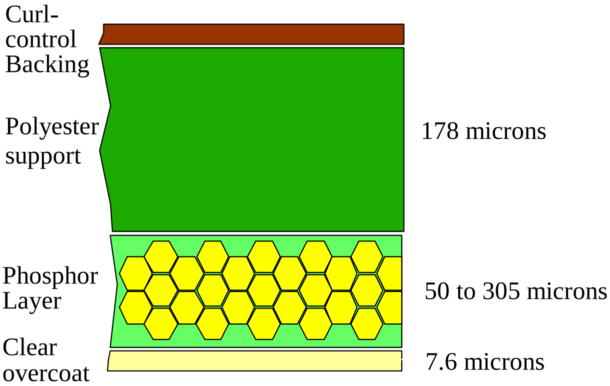
This school covers wide range of charged particle beams in terms if their time structure, profile, energy and other characteristics. Diagnostics suitable for essentially and particle beam will be presented and specific challenges in a *novel accelerators* context highlighted.

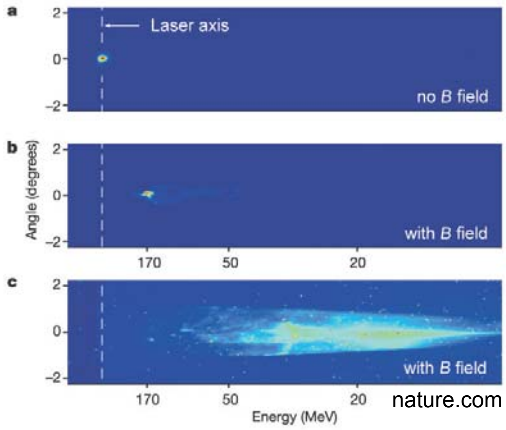
The ideal diagnostics

- Precise information about the beam
  (Sensitivity, time/spatial resolution, accuracy, DR)
- Single shot diagnostics
  - Avoids problems with reproducibility
  - And timing jitter
- Non-interceptive
  - On-line monitoring of the beam
  - No risk of damage by the beam itself
  - Important for high power beams !

Scintillator Screen

- Default scintillator choice is Lanex
  - Manufactured by Kodak.
  - Used in Medical Physics as X-ray phosphor for imaging.
  - Phosphor grains on reflective backing.
  - Properties not particularly well documented/studied
  - Bulk effect – thickness affects signal.

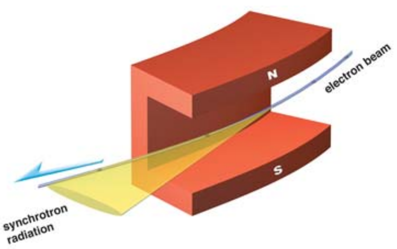




Synchrotron Radiation

See Bernhard's lecture

SR appears when charged particles are accelerated (radially).



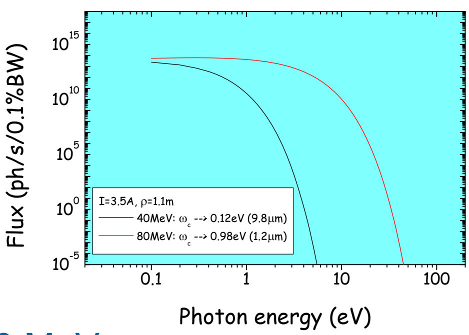
$$\boxed{P_\gamma = \frac{1}{6\pi\varepsilon_0}\frac{q^2 c}{\rho^2}\gamma^4}$$

γ is Lorentz-factor

ρ is the bending radius

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

Beam energy — Beam curvature

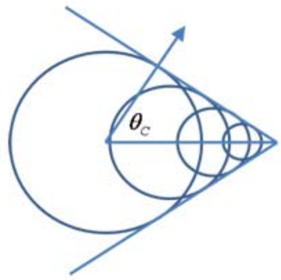


Limitations

- Needs many particles
- For visible light and e⁻ require E > 150 MeV
- Limited to e⁻ and very high energy proton/heavy ions
- Radiation only in bending elements, chicanes, undulators, etc.

Cherenkov Radiation

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



- n is index of refraction (n>1)
- β is relativistic factor v/c
- θ_c is Cherenkov light emission angle

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

- l is the length of the Cherenkov radiator

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

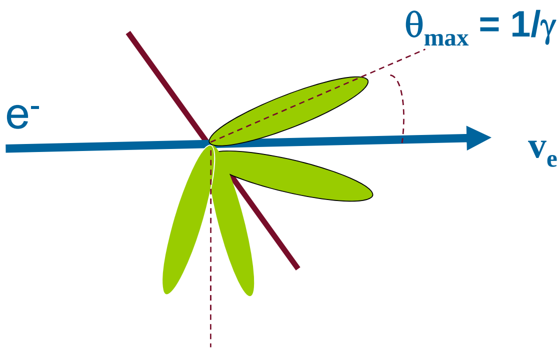
$$\boxed{N_{cherenkov} = 2\pi\alpha l\left(\frac{1}{\lambda_a} - \frac{1}{\lambda_b}\right)\left(1 - \frac{1}{\beta^2 n^2}\right)}$$

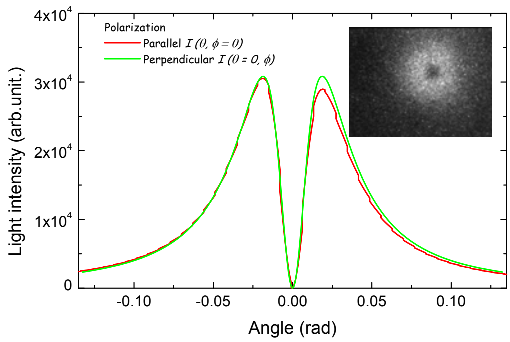
Limitations :
- Using transparent material *(glass n=1.46)*
- Time resolution limited by the length of the radiator

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

Optical Transition Radiation (OTR)

OTR is generated when a charged particle passes through the interface between two materials with different permittivity.





\# OTR photons/charged particle $\boxed{N_{OTR} = \frac{2\alpha}{\pi}\ln\left(\frac{\lambda_b}{\lambda_a}\right)\left(\ln(2\gamma) - \frac{1}{2}\right)}$ ~ $5\ 10^{-3}$ *in [400-600] nm*

Radiation wavelength   Beam energy

OTR - Properties

- Intensity is linear with bunch charge over wide range
- Obtain information about beam profile, size, but also beam energy and even emittance (more later)
- Source material is critical choice:

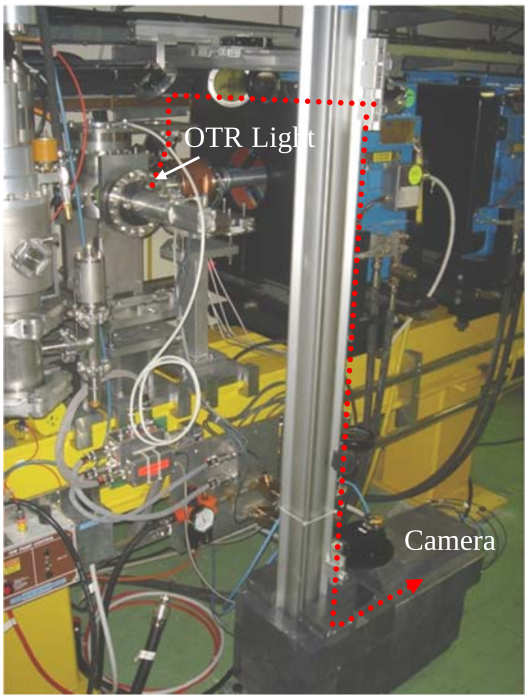
$$\Delta T(r) = \frac{dE}{dx} \frac{N_{tot}}{2\pi\sigma^2 c_p \rho} e^{-\frac{r^2}{2\sigma^2}}$$

Recipe: Use a 'good' material

Low energy: High light yield

High energy: Good thermal conductivity and high thermal limit
e.g. (C, Be, SiC) limit is ~ 10^6 nC/cm^2

A „typical" setup

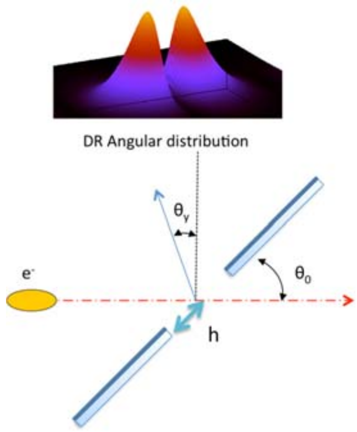


- Material sciences
- Thermodynamics
- Electro-Magnetism
- Optics
- Mechanics
- Electronics
- Nuclear Physics
- …

➡ Diagnostics is exciting !

Optical Diffraction Radiation (ODR)

ODR is generated when a charged particle passes near the edge of a dielectric and the distance to the target h satisfies the condition :



Beam energy

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

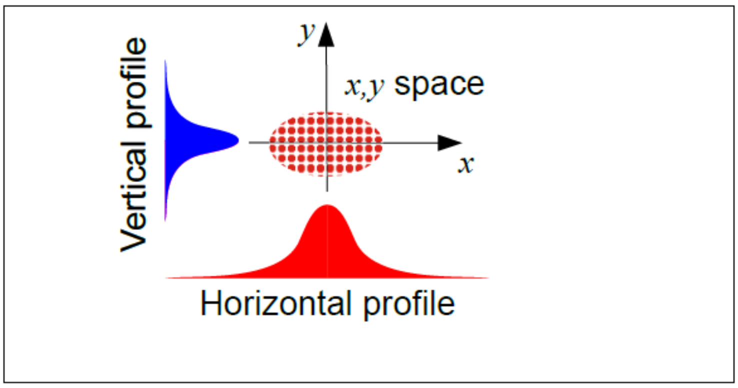
Radiation wavelength

Limitation

Limited # of photons in the visible for low energy particles (E < 1 GeV) and decent impact parameters (100 μm).

What is Beam Profile?

- The beam is made up of many particles which move independently.
- However the distribution generally stays the same.
- The distribution of particles plotted against *x* or *y* is the (horizontal or vertical) profile.



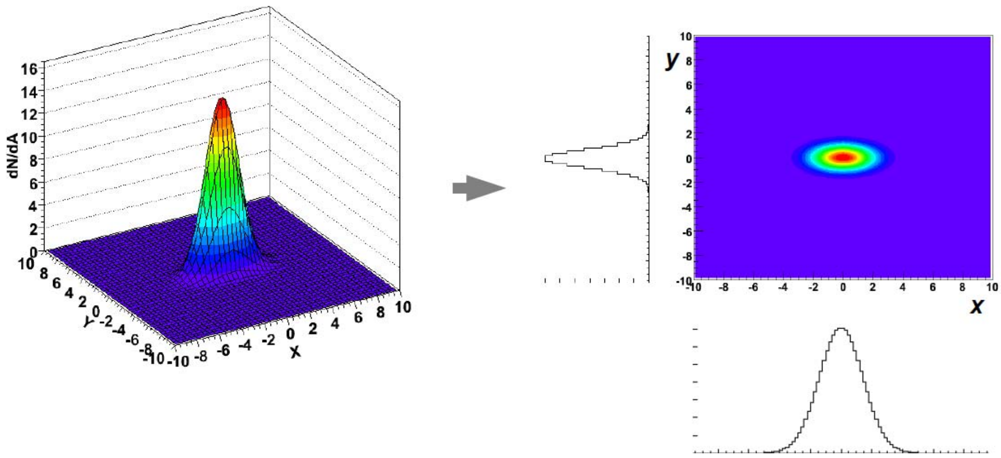
Some instruments measure cross-section, others the profiles.

What is Beam Profile?

- The distribution of particles often follows a Gaussian curve.
- Describe profile by a single number σ
- Beam size is often defined as 4σ.

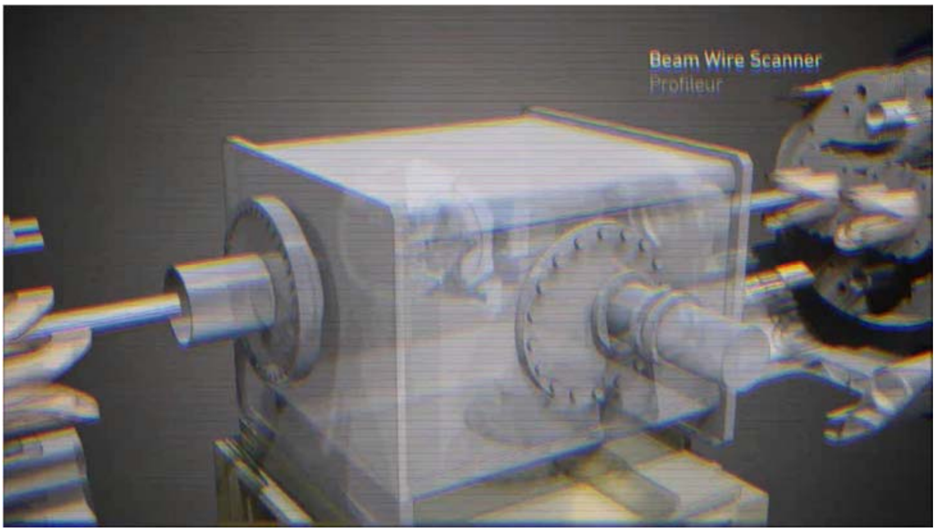
Particles Distribution

Profiles



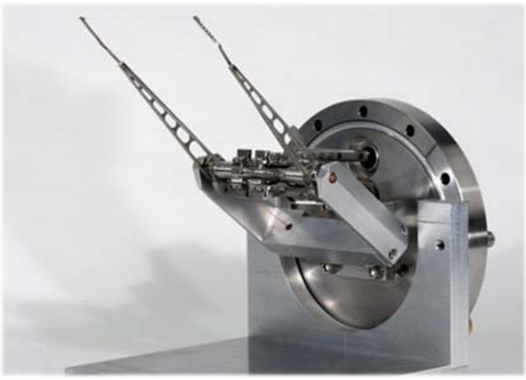
Wire Scanners

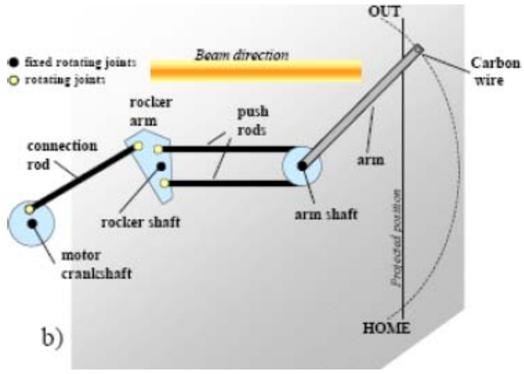
- A very thin wire is passed through the beam
- Correlate number of particles hitting the wire to the position of the wire ➡ Profile.



Wire Scanners

- A very thin wire is passed through the beam
- When the beam hits the wire there are various effects:
  - Some particles are **lost**
  - X-rays are generated (**bremsstrahlung**)
  - Electrons are kicked out of the wire (**secondary emission**)
- Any of these effects can be measured. All are proportional to the number of particles hitting the wire.





Longitudinal Diagnostics - Overview

Optical Methods

- Produce visible light
- Analyze the light pulse using dedicated instruments

Bunch Frequency Spectrum

Shorter bunches

broader bunch frequency spectrum

RF Manipulation

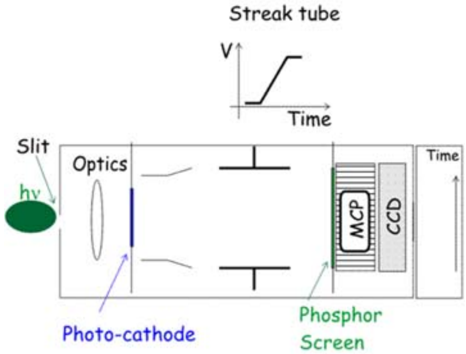
RF techniques to convert time information into spatial information

Laser-based beam diagnostics

Short laser pulses
&
sampling techniques

Streak Camera

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



M. Uesaka et al, Nucl. Instr. Meth. A 406 (1998) 371

200 fs time resolution

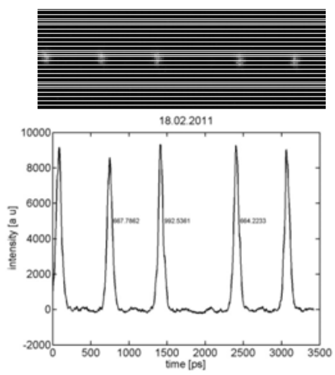
- Using reflective optics
- 12.5 nm bandwidth optical filter (800 nm) and Hamamatsu FESCA 200

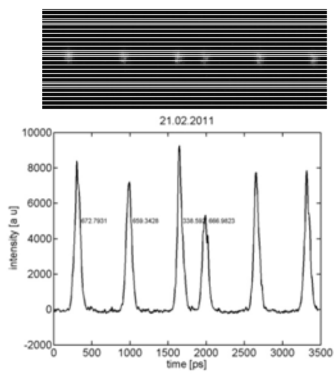
Limitation - Time Resolution

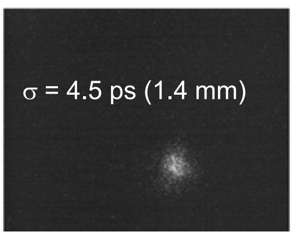
- Initial velocity distribution of photoelectrons
  - Solution: narrow bandwidth optical filter
- Spatial spread of the slit image
  - Solution: small slit width
- Dispersion in the optics

Streak Camera Examples

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

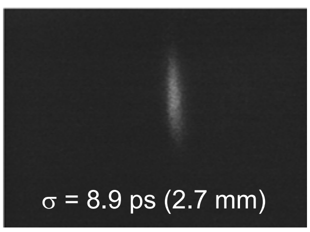






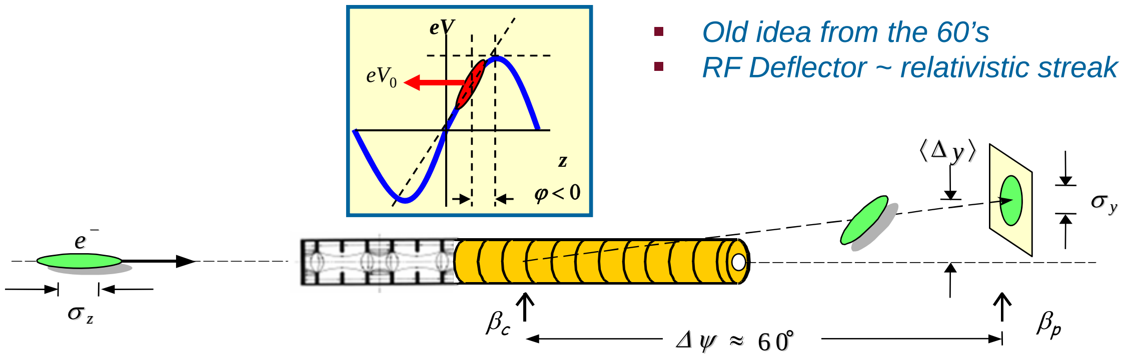
Measure of bunch length using OTR and OSR

Sweep speed of 10 ps/mm



RF Deflecting Cavity

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



Beam profile RF off

Deflecting Voltage

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

Bunch length

Beta function at cavity and profile monitor

RF deflector wavelength

Beam energy

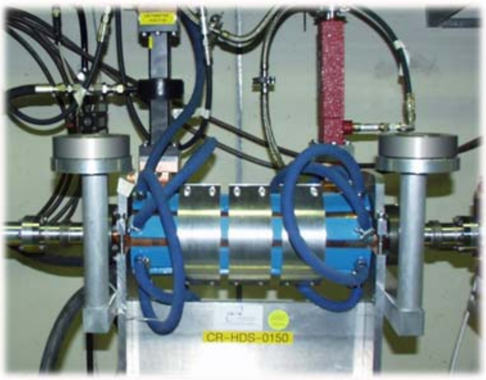
Betatron phase advance (cavity-profile monitor)

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

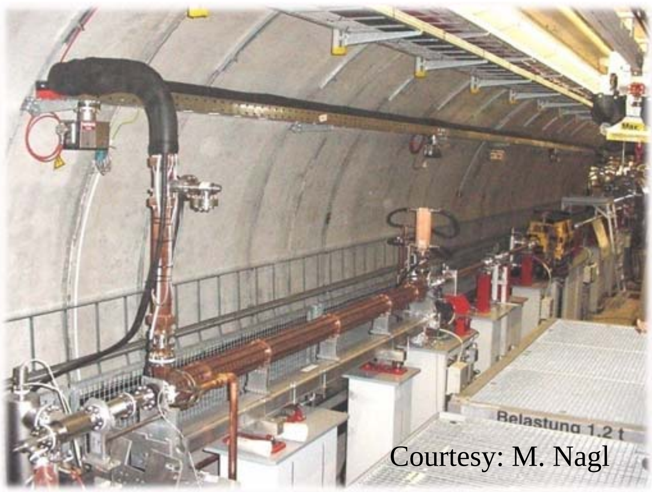
P. Emma et al, LCLS note LCLS-TN-00-12, (2000)

Examples of RF Deflectors

CTF3 @ CERN

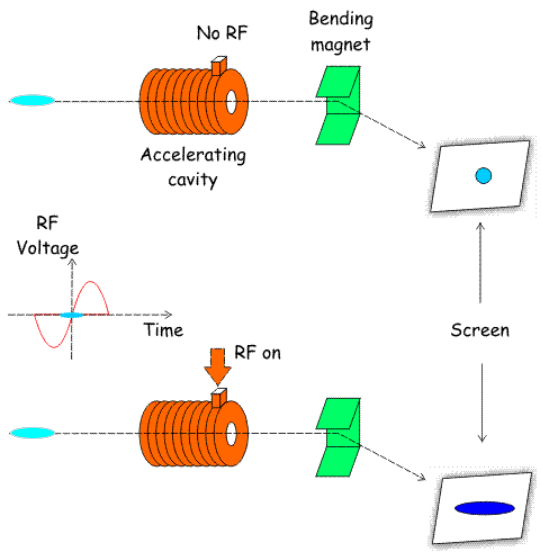


LOLA @ Flash



RF Accelerating Structures

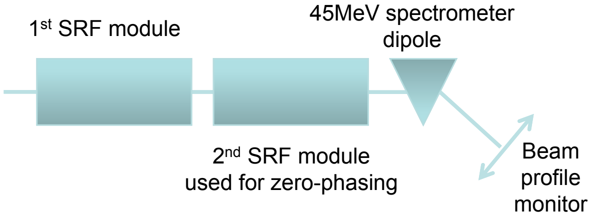
Electron energy is modulated by the zero-phasing RF accelerating field. Bunch distribution is then deduced from the energy dispersion measured downstream.



$\Delta t \longrightarrow \Delta E \longrightarrow \Delta x$

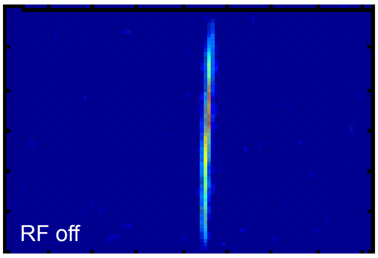
RF Accelerating Structures

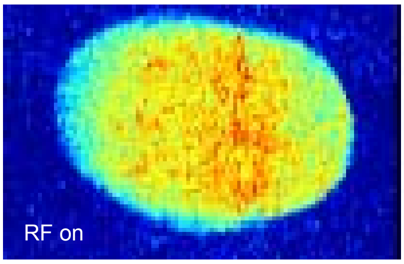
CEBAF injector, Newport News



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

84 fs, 45 MeV beam but low charge beam

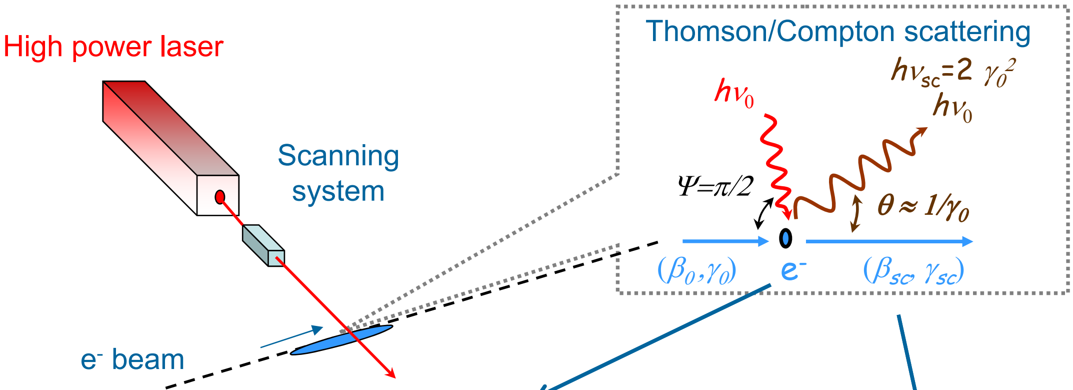


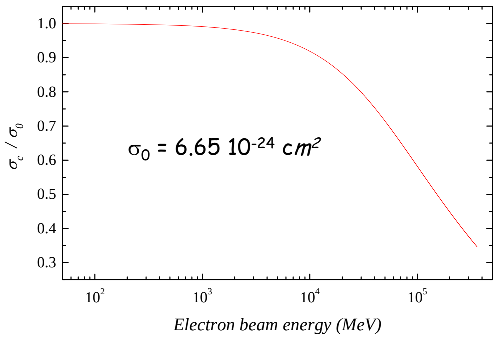


Limitations

- RF non-linearities
- Beam loading and wakefields for high charge beam

Laser Wire Scanner – Compton scattering





Detection system based on

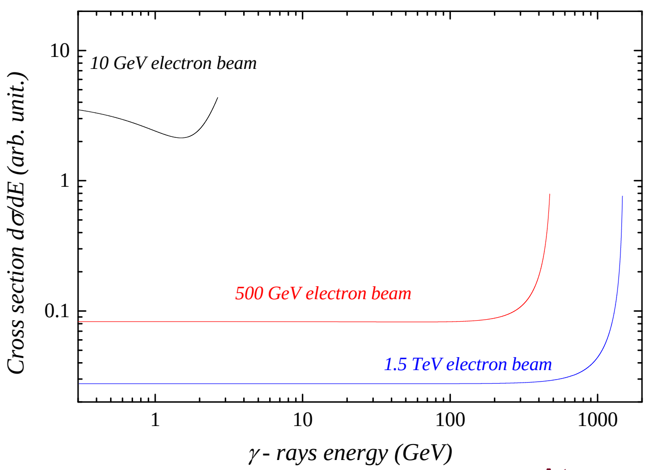
- The measurement of the scattered photons
- The measurement of degraded electrons

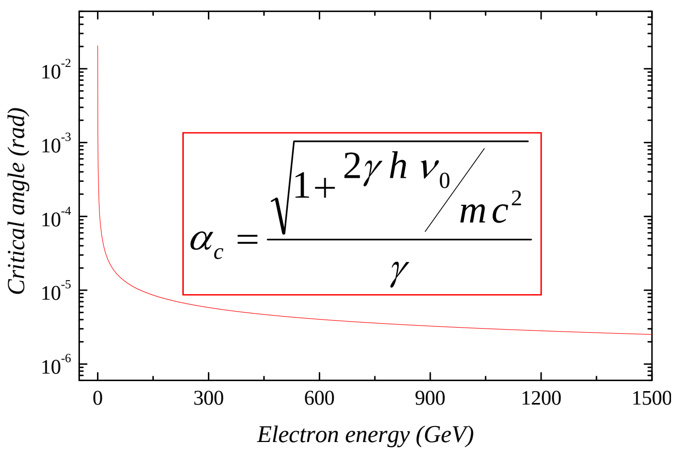
Laser Wire Scanner – Compton scattering

Energy spectrum of scattered photons

Using a 266nm wavelength laser

Emission angle of the scattered photons



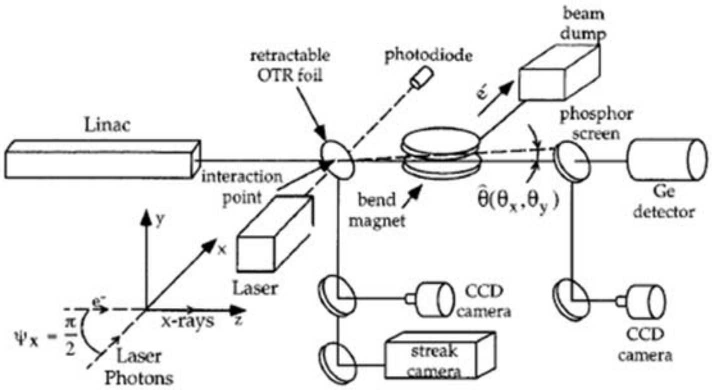


At very high energy

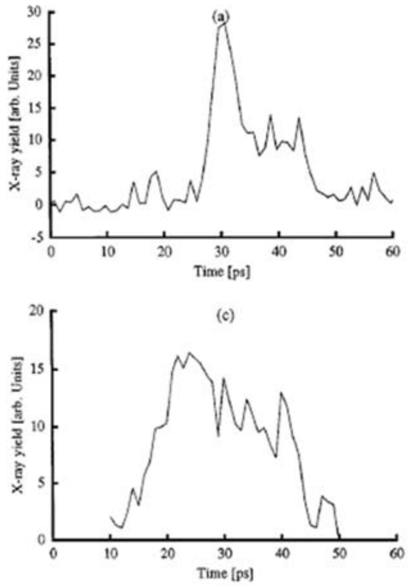
- The photons steal most of the electron energy *(electron recoil becomes extremely important)*
- The photons are emitted within a very small angle (a few mrad) in the forward direction
- Measurement of degraded electrons only feasible at high energies

Laser Wire Scanner – Compton scattering

ALS @ LBNL



Using a 10TW Ti:Al_2O_3 laser system. Detecting $5 \cdot 10^4$ 10-40 keV X-rays using either an X-ray CCD and Ge detector



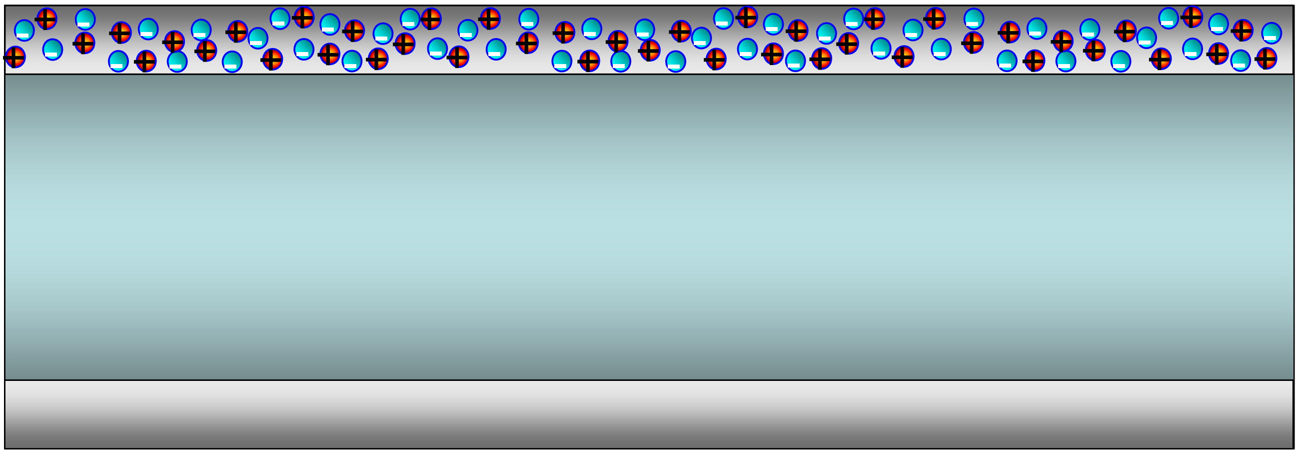
W.P. Leemans *et al*, PRL 77 (1996) 4182

Limitations

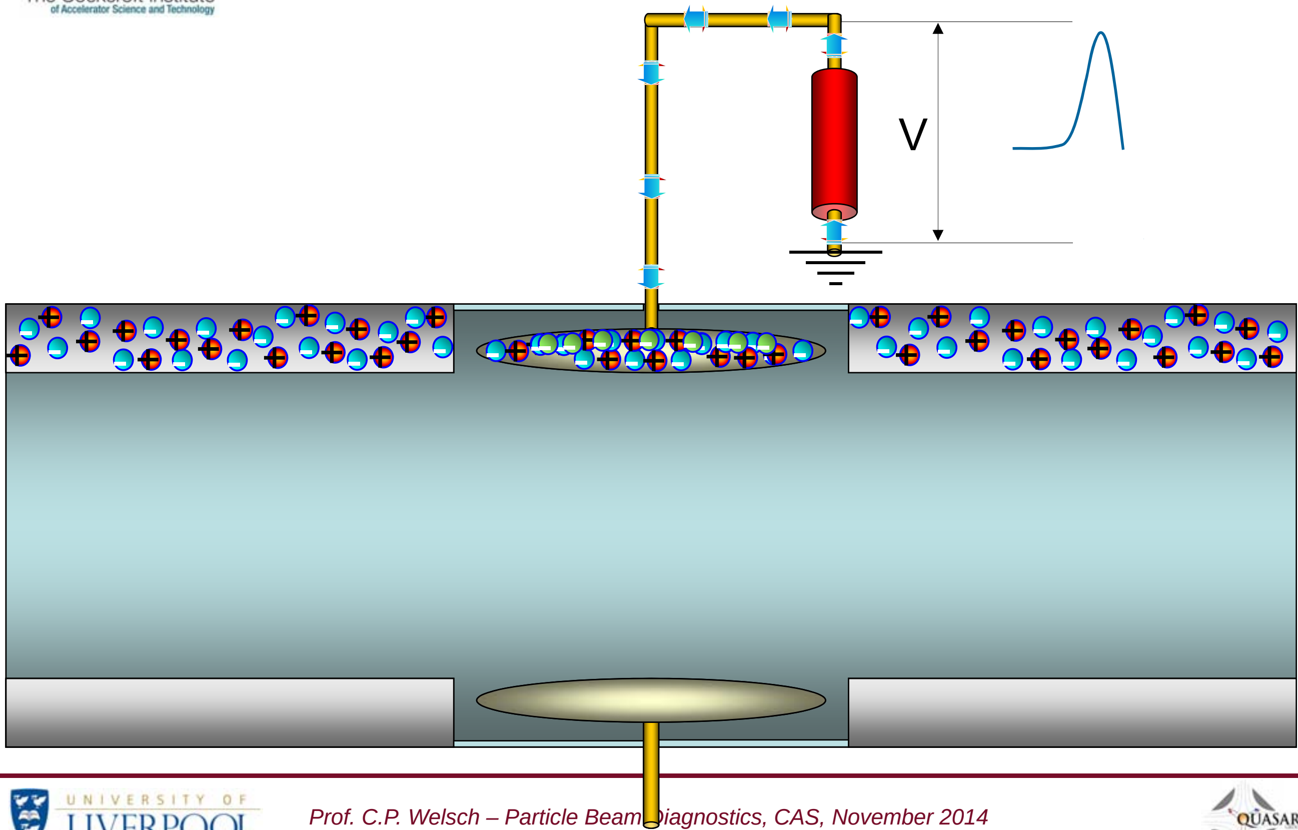
- Not all techniques non-invasive
- Interested in fs beam pulses – most techniques struggle
- EO Diagnostics ? Not (yet) possible with required time resolution
- Use CTR/DR for diagnostics...more later.

Beam Position

- Idea: Benefit from charge induced by the beam



Beam Position



Beam Position

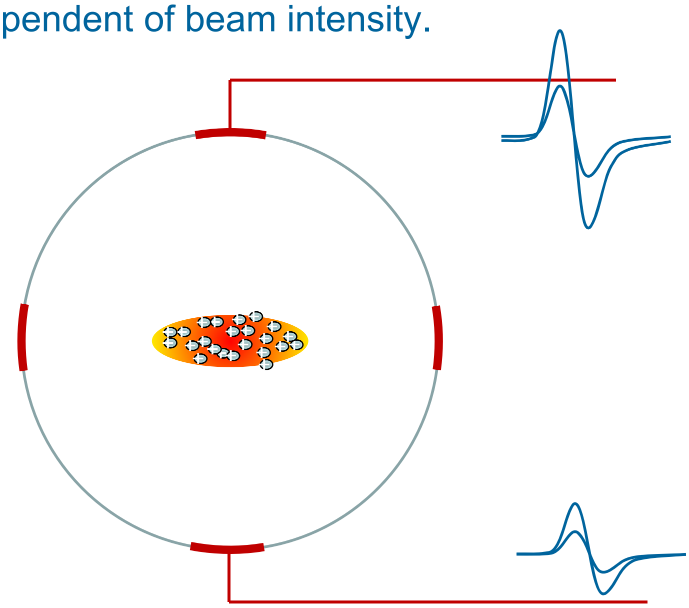
- Signal strength depends on distance between beam and electrode
- Use **sum** and the **difference** of opposite pick-ups, to get a position measurement that is independent of beam intensity.

$$y = \frac{1}{S_y(f)} \cdot \frac{U_{up} - U_{down}}{U_{up} + U_{down}} + \delta_y(f)$$

$$\equiv \frac{1}{S_y} \cdot \frac{\Delta U_y}{\Sigma U_y} + \delta_y$$

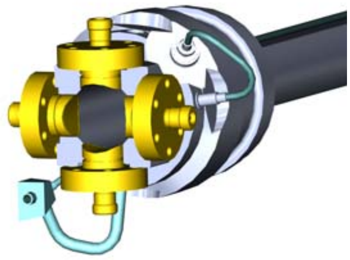
$$x = \frac{1}{S_x(f)} \cdot \frac{U_{right} - U_{left}}{U_{right} + U_{left}} + \delta_x(f)$$

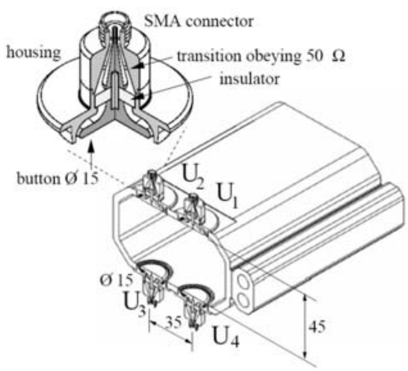
S(f,x) is position sensitivity,



Button BPMs

Button BPM
Bunch length comparable to BPM
∅1 to 5 cm per button
Orthogonal or planar orientation
100 MHz to 5 GHz
50 Ω
0.3… 1 GHz (C=2…10pF)
Non-linear, x-y coupling
Good, care: signal matching
electron, proton Linacs, f_{rf} > 100 MHz



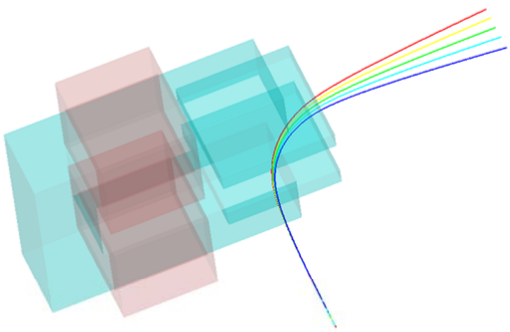


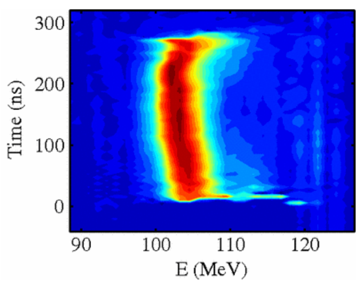
S. Varnasseri, Sesame button

Button BPMs

- Currently not required for PWA as no long beam transport done;
- Real multi-stage acceleration would require similar (established) monitors;
- DLAs: Future designs will need to include ‚whole‘ accelerator on a chip, including:
  – Quadrupole and higher order fields
  – Instrumentations, such as BPMs and ICTs

Beam Energy Measurement

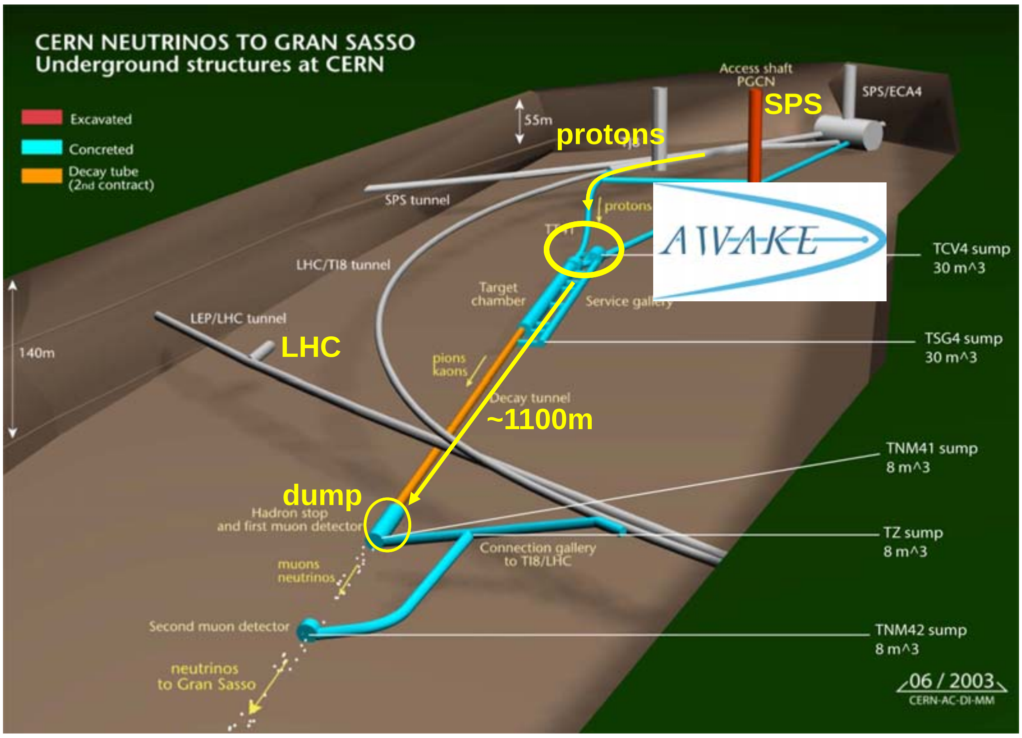




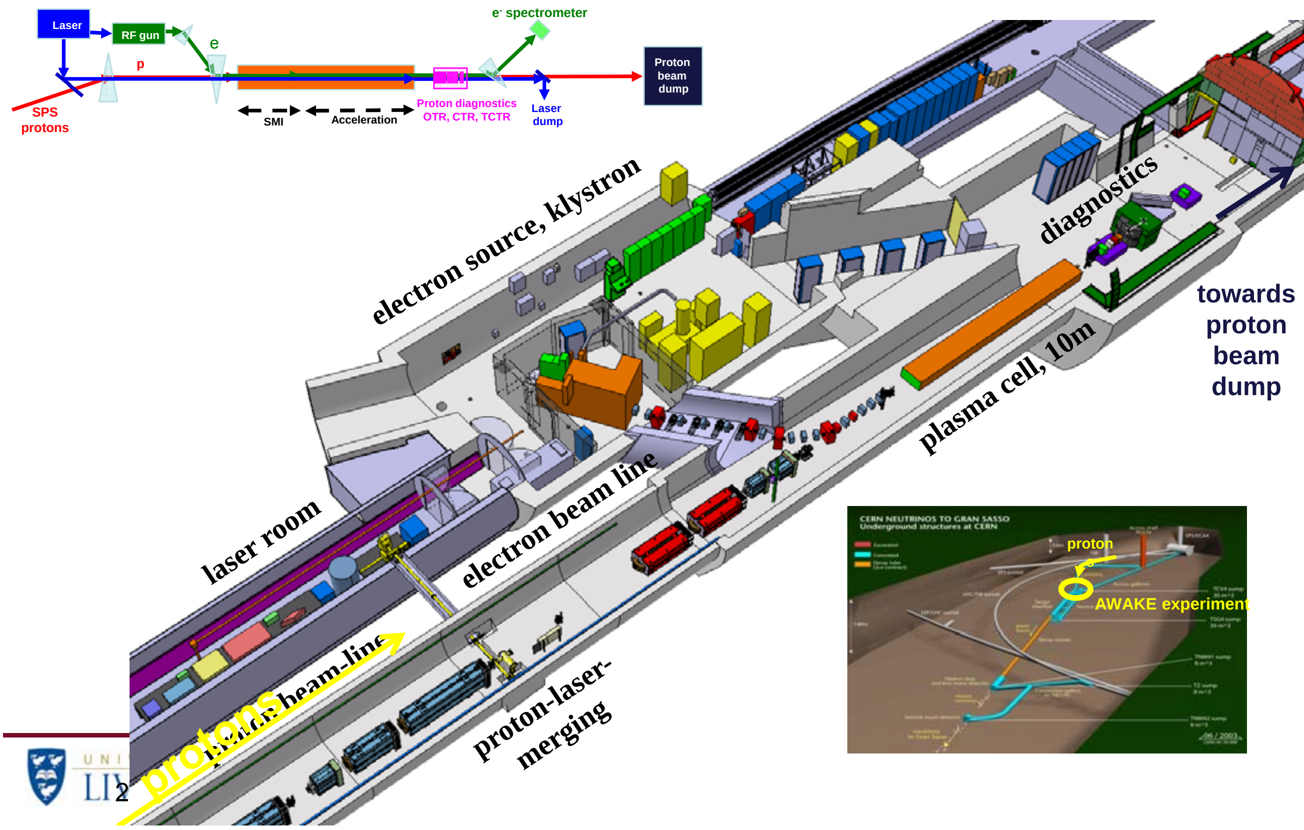
M. Olvegaard, et al., PRST-AB 16, 022802 (2013).

- Pass the beam through a strong bending magnet;
- Particles with **higher** energy are bent **less** and vice versa;
- A segmented detector is often used to measure the ‘spread’ beam;
- Destructive measurement.

CNGS Facility at CERN



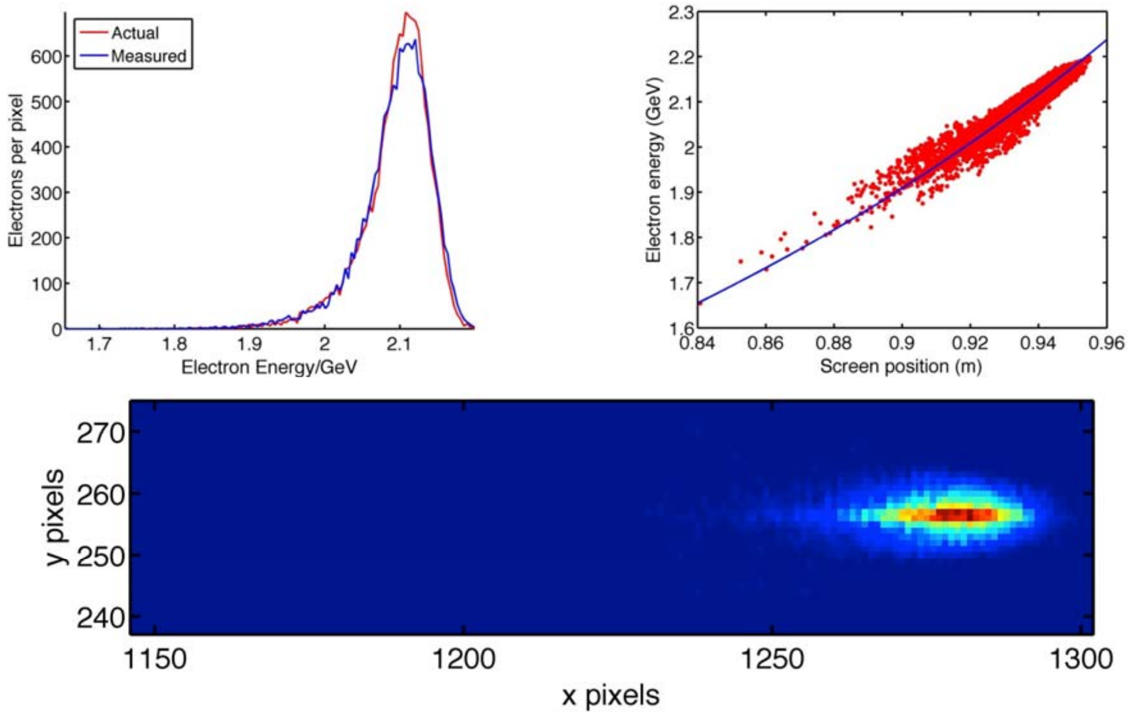
AWAKE Experimental Layout



How to measure the energy ?

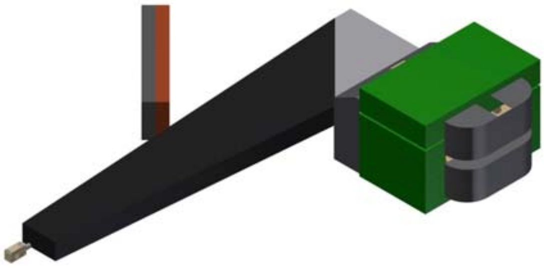
- Wakefield accelerated electrons ejected collinear with proton beam: Separate the 2 and measure energy of electron beam only.
- Resolve energy spread as well as energy in energy range 0 - 5 GeV.
- Current (conceptual) layout:
  - Dipole mounted ~2 m downstream of plasma exit;
  - Scintillator screen 1 m downstream of dipole intercepts electron beam only.
  - Dispersion gives energy-dependent position spread on screen.
  - Scintillator imaged by intensified CCD camera viewing upstream face of scintillator screen.

2 GeV Beam, 1.86 T Field

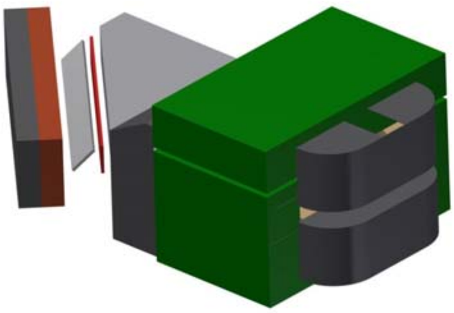


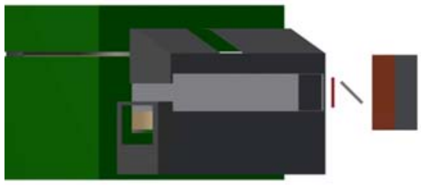
Experimental Issues

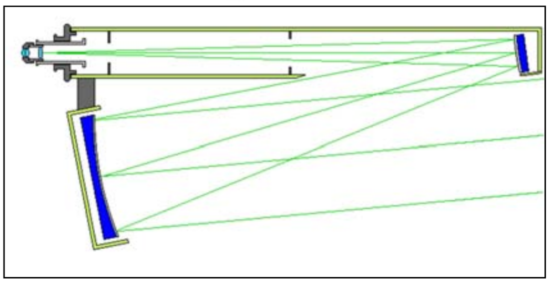
- CERN MBPS dipole selected:
  - It's free;
  - It's at CERN;
  - Field uniformity only good in 300 mm wide central region
  - Magnet quality may not be good enough ?
- Enough space for spectrometer downstream of plasma cell ?
  - Camera needs to be well-shielded from backgrounds;
  - Far away better for backgrounds, close better for photon collection;
  - Needs light tight path !
  - Optical path under floor or large chamber ?

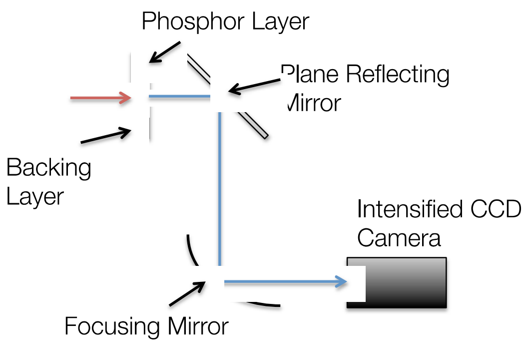


Off-Axis Camera & Focusing Mirror

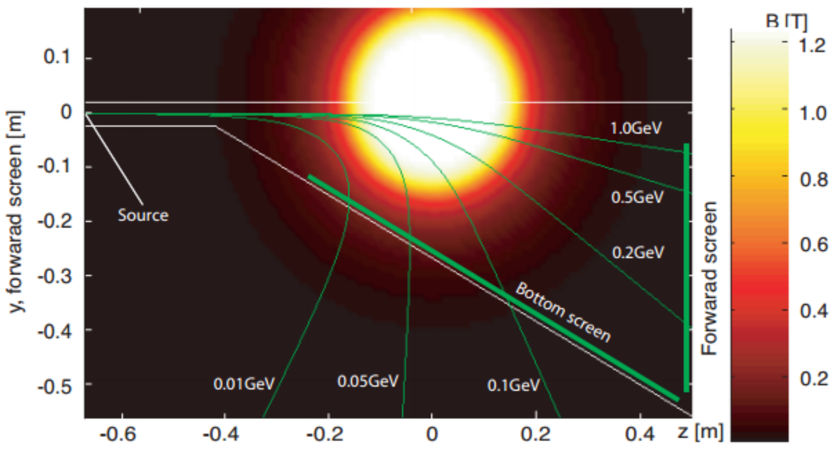








Understanding your system



K. Nakamura, et al., Rev. Sci. Instr. **79**, 053301 (2008)

Example: HZDR

- 200 nm – 12 μm
- Input splitted by GaAs and ZnSe in:
  - UV-VIS
  - Near-IR
  - Middle-IR

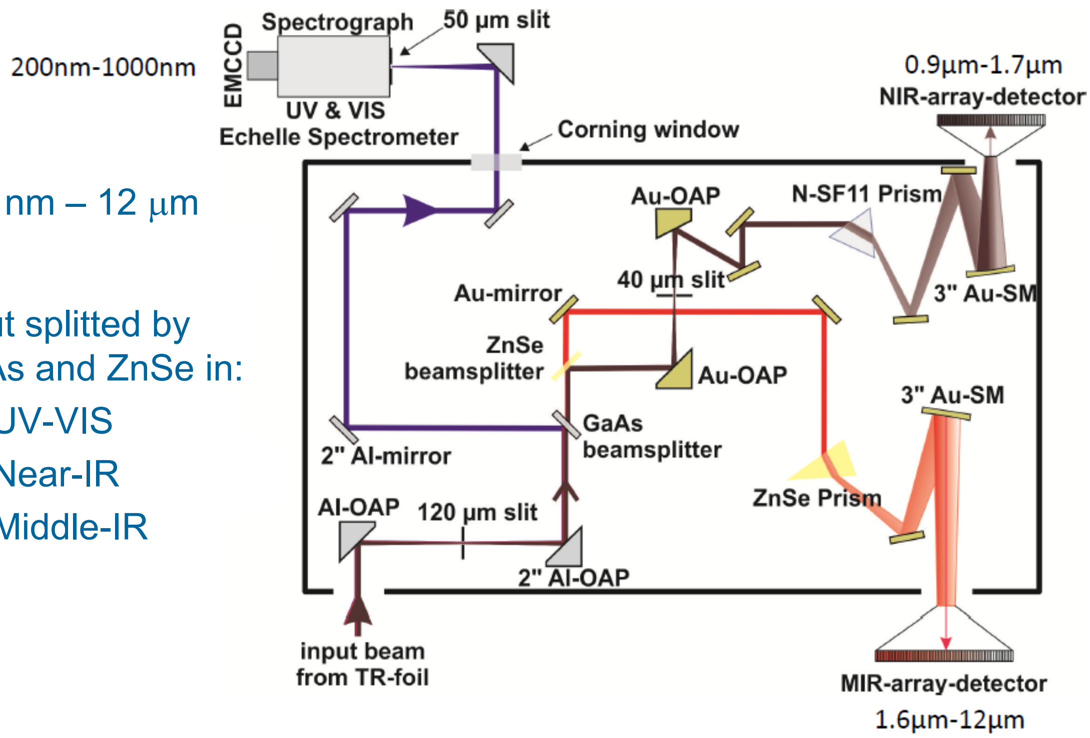


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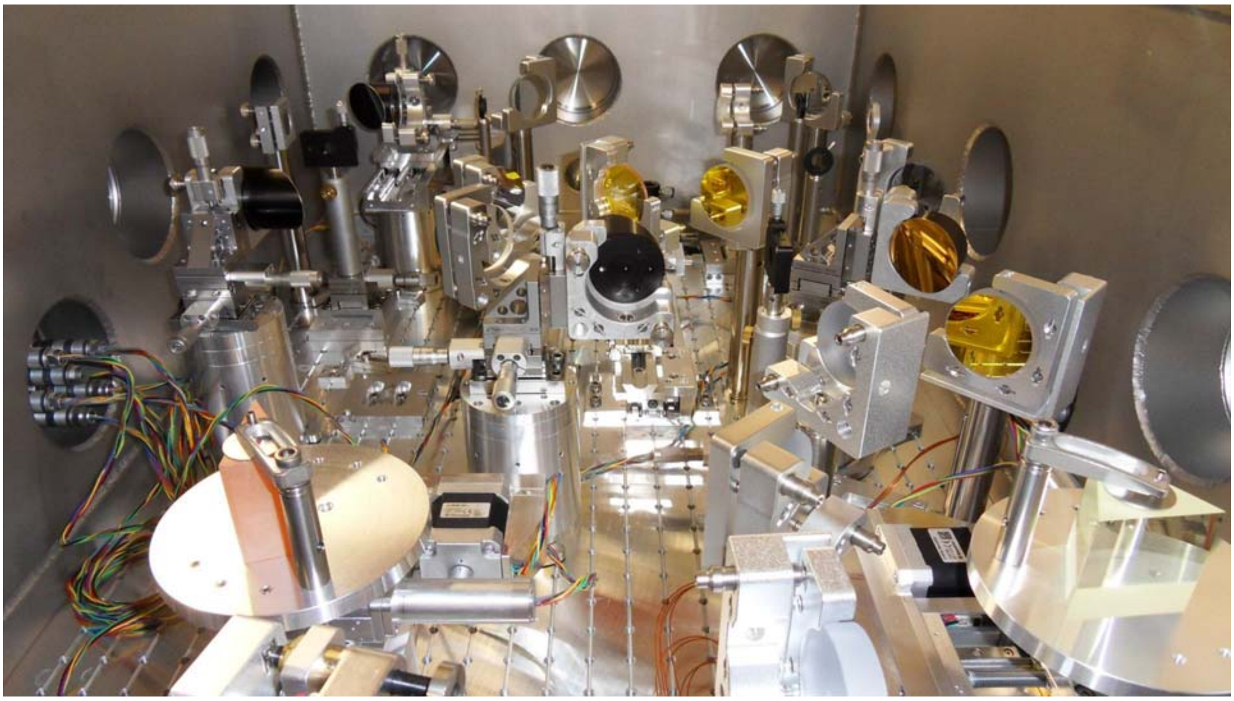
Photo of setup



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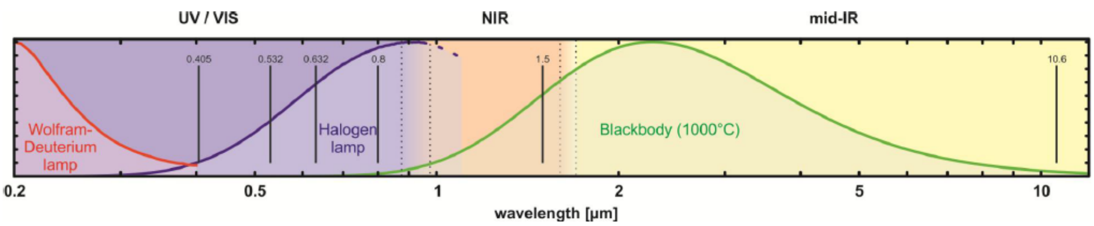
Callibration

- Absolute, polarization-dependent callibration is a challenge !
  - **Wavelength calibration**
    UV-VIS : Mercury-Argon lamp
    NIR : Argon lamp
    MIR : absorption lines of Teflon foils (HDPE, Mylar, PP, TPX)
  - **Relative response calibration**
    UV-VIS : Halogen and Deuterium lamps, blackbody radiator
    NIR & MIR : blackbody radiator
  - **Absolute photometric calibration**
    UV-VIS : 532 nm diode laser
    NIR : 1.5 μm fibre laser
    MIR : 10.6 μm CO2-laser



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Summary

- Wide range of powerful diagnostics available for electron beams at all energies and various characteristics;
- Specific application always requires optimization process;
- Specific challenges arise in novel accelerators:

  Large(r) divergence, pulsed nature of beam, required time resolution, etc.