“Transverse beam profiles”

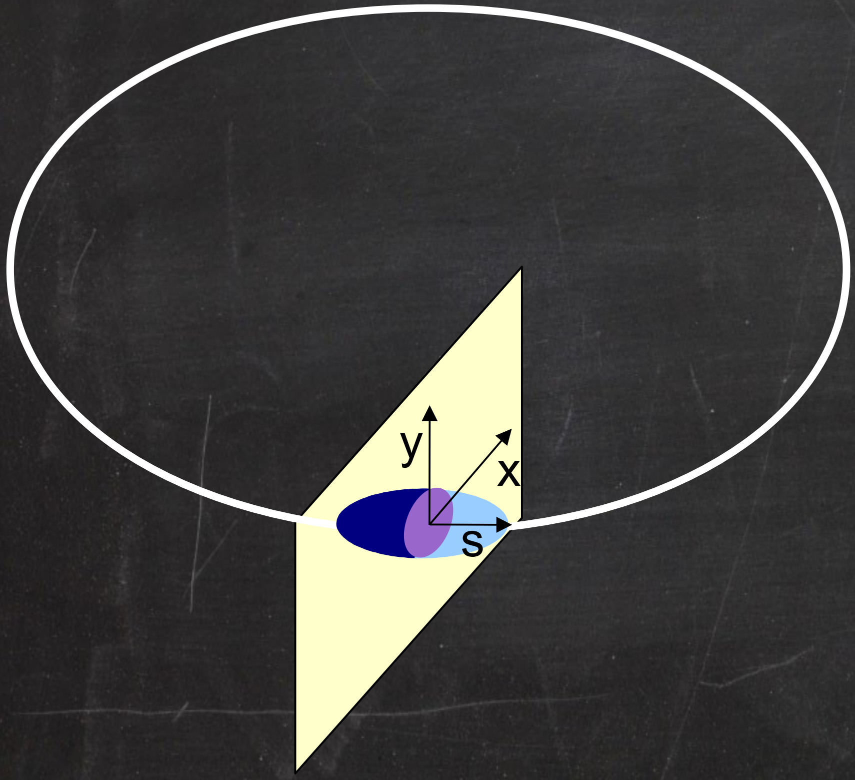
Enrico Bravin - CERN

DITANET school 2011 - Stockholm

Content

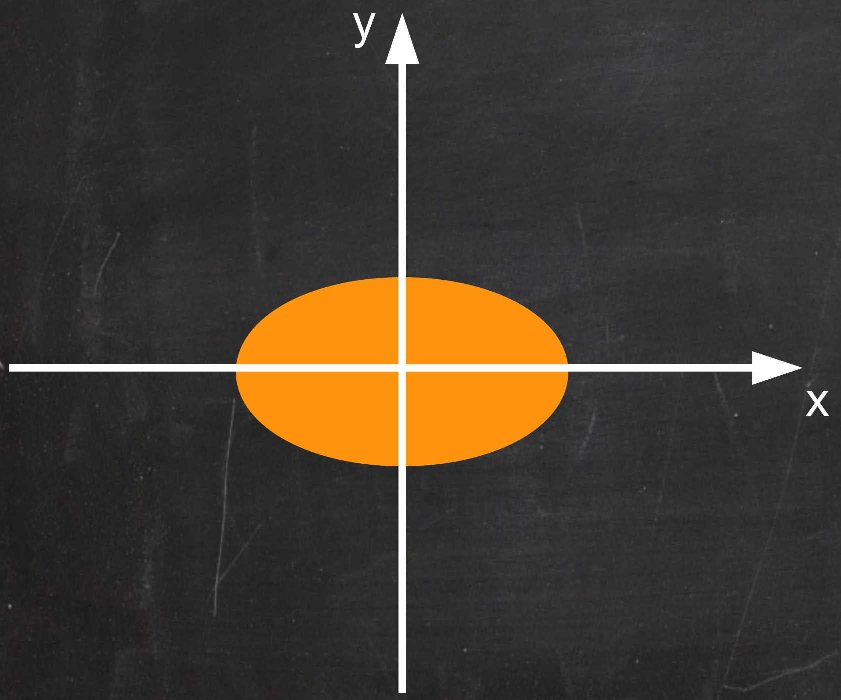
- Coordinate system
- Transverse space
- Transverse phase space
- Phase space dynamics
- Interaction of particles with matter
- Radiation emission by charged particles
- Sampling of distributions in 2D space

Coordinate System



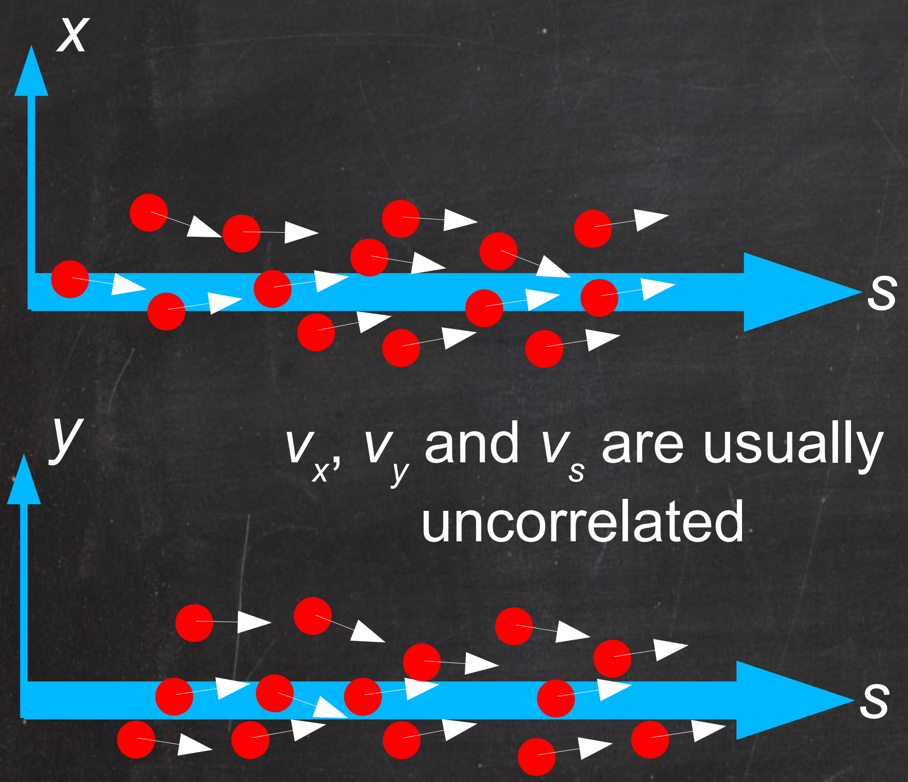
- Longitudinal coordinate
  - defined by the direction of motion of the beam
  - Axis indicated with *s*
- Transverse Plane
  - Plane orthogonal to the close orbit
  - Axes usually indicated with *x* and *y* and referred as *HORIZONTAL* and *VERTICAL*

Transverse *x,y* space

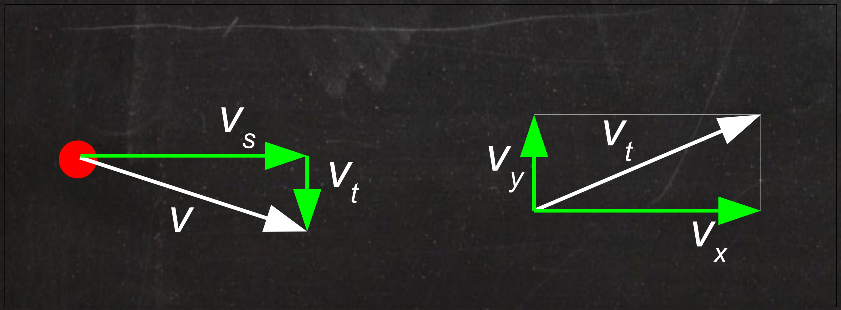


- Define a plane orthogonal to the beam trajectory at a given *s*
- Record the *x,y* coordinates of each particle crossing this plane
- Plot on a 2D chart (*x, y*) each particle

Transverse phase space

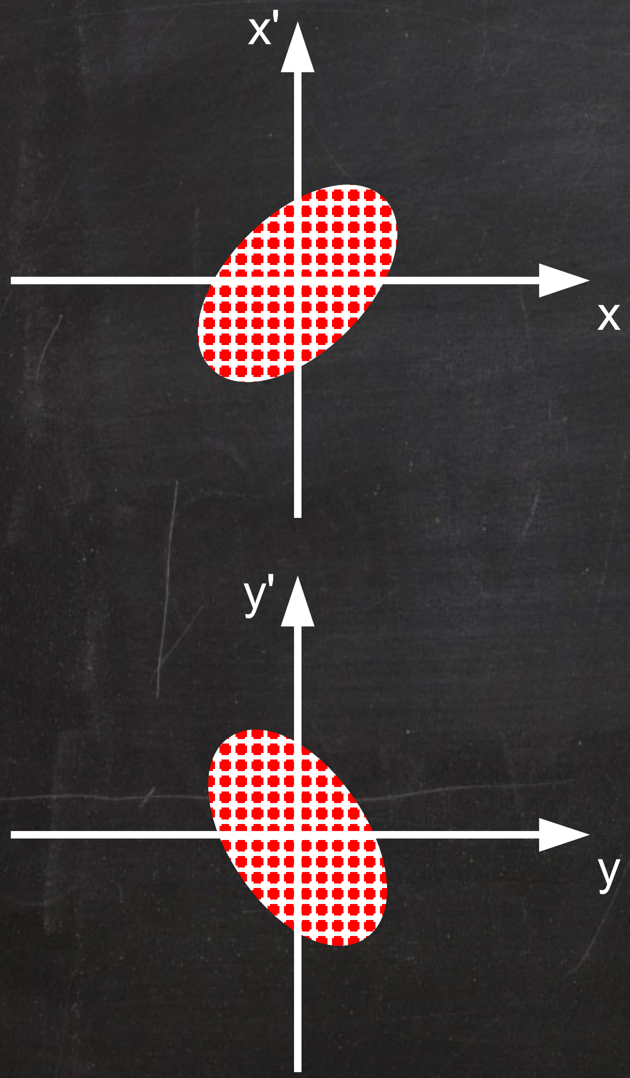


v_x, v_y and v_s are usually uncorrelated



- Beam moves along *s*
- Each particle moves in a different direction
- Velocity has 2 components
  - *Transverse* $v_t = v_x \hat{x} + v_y \hat{y}$
  - *Longitudinal* v_s
- Transverse components also called *x'* and *y'*

Transverse phase space (2)

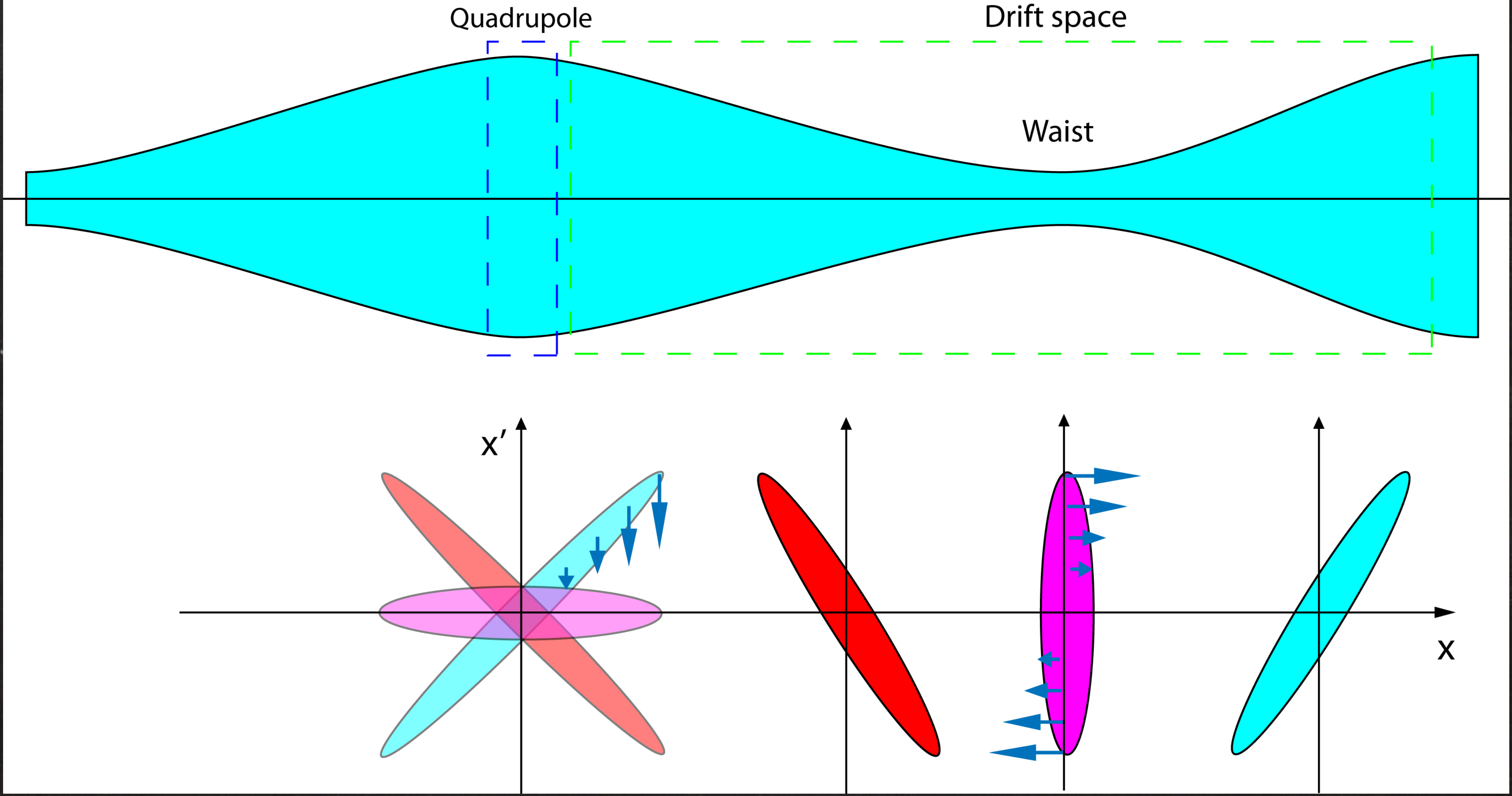


- Take the same plane as before
- Note x, v_x and y, v_y for each particle crossing the plane
- Plot on a 2D chart (x, v_x OR y, v_y) of each particle
- Rename $v_x \rightarrow x'$, $v_y \rightarrow y'$
- Area of the ellipse is an invariant and is called transverse emittance ε_x, ε_y

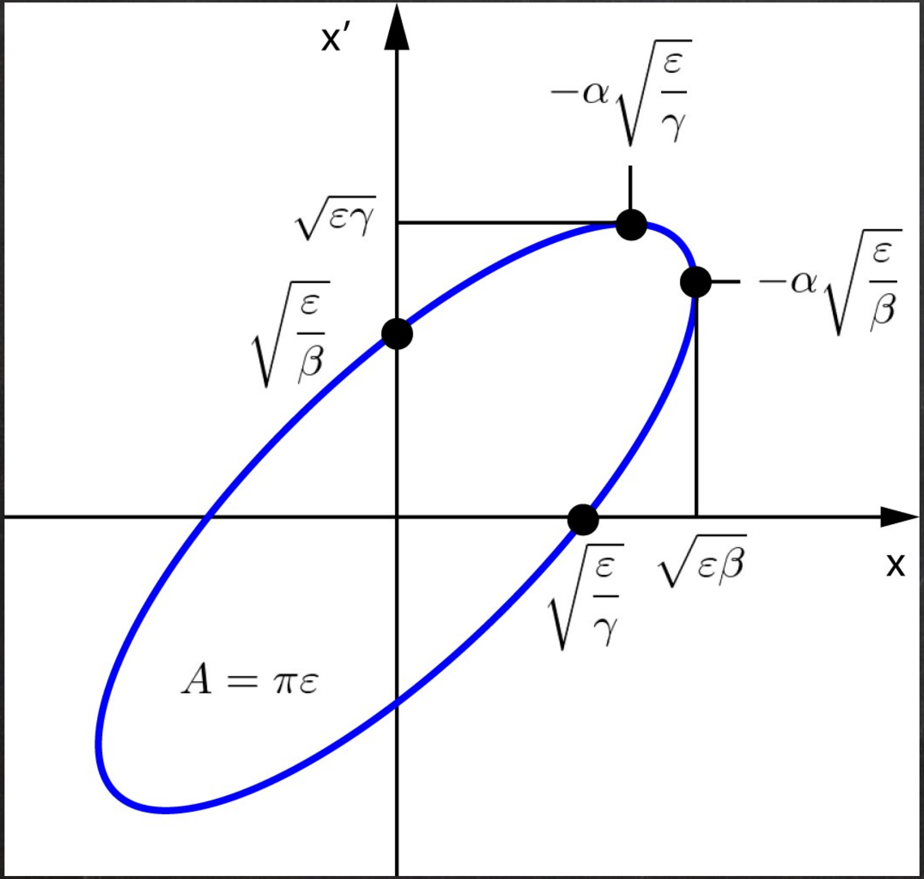
Transverse spaces

- The x,y space and the phase space are different things
- Their projections along x or y are however the same thing
- Phase spaces contain the information needed for beam dynamic calculations
- x,y space is easier to sample
- Perform measurement in x,y and use optics parameters and beam dynamic theories to calculate the phase space

Phase space dynamics



Courant-Snyder parameters



The phase space ellipse can be defined by 4 parameters: ε, β, α and γ, with the relation

$$\gamma = \frac{1+\alpha^2}{\beta}$$

The equation of the ellipse is

$$\varepsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2$$

Particles transport

In a linear system, like a system composed of drift space and quadrupoles, the coordinates of a particle in phase space can be transported using a simple matrix notation

$$\begin{bmatrix} x_1 \\ x_1' \end{bmatrix} = M_1 \begin{bmatrix} x_0 \\ x_0' \end{bmatrix} \qquad \begin{bmatrix} x_2 \\ x_2' \end{bmatrix} = M_2 \begin{bmatrix} x_1 \\ x_1' \end{bmatrix} \qquad \begin{bmatrix} x_3 \\ x_3' \end{bmatrix} = M_3 \begin{bmatrix} x_2 \\ x_2' \end{bmatrix}$$

$$\begin{bmatrix} x_3 \\ x_3' \end{bmatrix} = M_3 M_2 M_1 \begin{bmatrix} x_0 \\ x_0' \end{bmatrix} = M_{0 \Rightarrow 3} \begin{bmatrix} x_0 \\ x_0' \end{bmatrix}$$

$$M_{Drift} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \qquad M_{Quad} = \begin{bmatrix} \cos\left(\sqrt{k}\, L_Q\right) & 1/\sqrt{k}\sin\left(\sqrt{k}\, L_Q\right) \\ -\sqrt{k}\sin\left(\sqrt{k}\, L_Q\right) & \cos\left(\sqrt{k}\, L_Q\right) \end{bmatrix}$$

Twiss parameters transport

If one can transport each point of the phase space one can also transport the ellipse and thus the Courant-Snyder, a.k.a. Twiss, parameters

$$\begin{bmatrix} x_1 \\ x_1' \end{bmatrix} = \begin{bmatrix} c & s \\ c' & s' \end{bmatrix} \begin{bmatrix} x_0 \\ x_0' \end{bmatrix} \quad \Rightarrow \quad \begin{bmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{bmatrix} = \begin{bmatrix} c^2 & 2cs & s^2 \\ -cc' & cs'+c's & -ss' \\ c'^2 & -2c's' & s'^2 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{bmatrix}$$

From the measurement of the beam profiles one obtains $\sigma^2 = \varepsilon\beta$

$$\beta_1 = \begin{bmatrix} c_1^2 & 2c_1 s_1 & s_1^2 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{bmatrix} \qquad \begin{bmatrix} \varepsilon\beta_1 \\ \varepsilon\beta_2 \\ \varepsilon\beta_3 \end{bmatrix} = \varepsilon \begin{bmatrix} c_1^2 & 2c_1 s_1 & s_1^2 \\ c_2^2 & 2c_2 s_2 & s_2^2 \\ c_3^2 & 2c_3 s_3 & s_3^2 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{bmatrix}$$

Twiss parameters measurement

$$\begin{bmatrix} \varepsilon\beta_1 \\ \varepsilon\beta_2 \\ \varepsilon\beta_3 \end{bmatrix} = \varepsilon M \begin{bmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{bmatrix} \quad \Rightarrow \quad M^{-1} \begin{bmatrix} \varepsilon\beta_1 \\ \varepsilon\beta_2 \\ \varepsilon\beta_3 \end{bmatrix} = \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \varepsilon \begin{bmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{bmatrix}$$

$$\begin{cases} a = & \varepsilon\beta_0 \\ b = & \varepsilon\alpha_0 \\ c = & \varepsilon\gamma_0 \\ \gamma_0 = & \dfrac{1+\alpha_0^2}{\beta_0} \end{cases} \quad \Rightarrow \quad \begin{cases} \beta_0 = & \dfrac{a}{\sqrt{ac-b^2}} \\ \alpha_0 = & \dfrac{b}{\sqrt{ac-b^2}} \\ \gamma_0 = & \dfrac{c}{\sqrt{ac-b^2}} \\ \varepsilon = & \sqrt{ac-b^2} \end{cases}$$

Sampling of distributions

- Intercepting methods
  - Scanning wires
  - Wire grids (Harps)
  - Radiative screens
- Non intercepting methods
  - Synchrotron light
  - Rest gas ionization
  - (Inverse Compton scattering / photo dissociation)

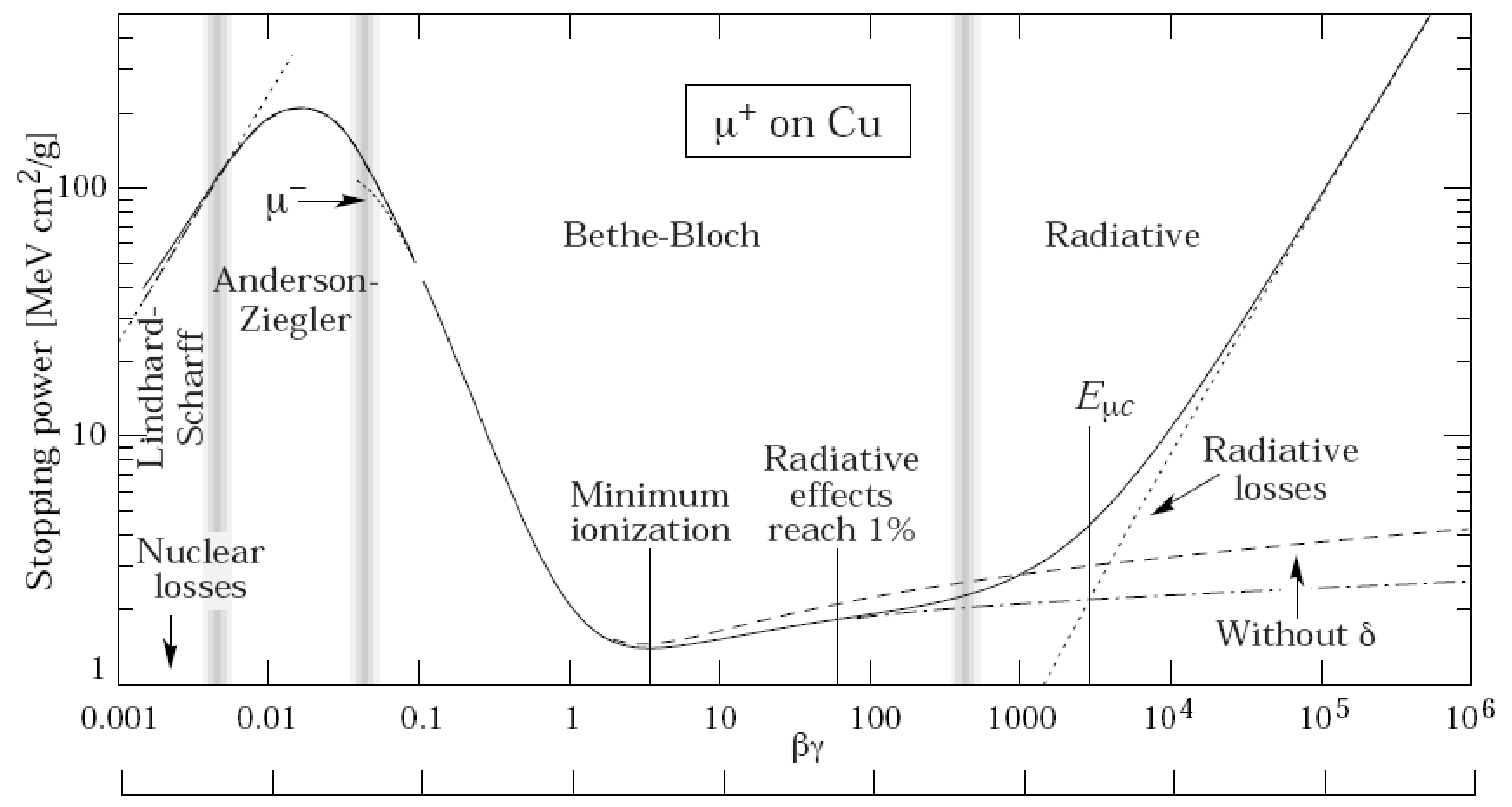
Interaction of particles with matter

- Ionization
  - Creation of electrons/ions pairs
    - Secondary electrons emission (low energy electrons)
  - Emission of photons (decay of excited states)
- Elastic and inelastic scattering
  - Dislocations
  - Production of secondary particles (high energy particles)
- Čerenkov radiation
- Bremsstrahlung
- Optical transition radiation

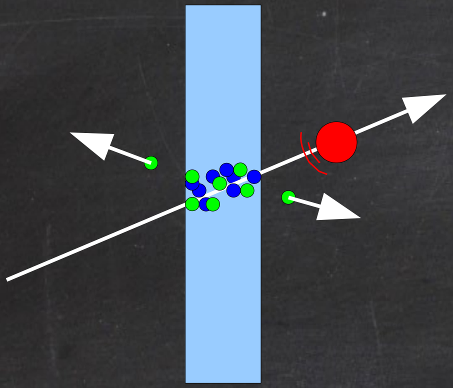
Energy deposition

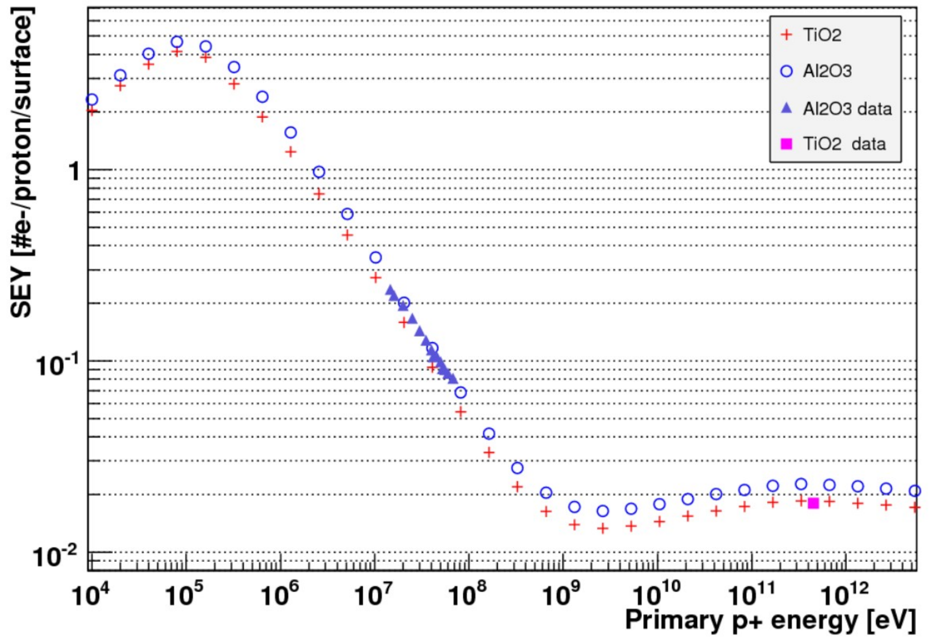
- Energy deposition is probably the most important aspect for all intercepting devices
  - Signals are often proportional to the deposited energy
  - Energy deposition can cause damage to the instrument
- The Bethe-Bloch formula describes energy losses in most cases
- The energy lost by the particles is not necessarily deposited in the sensor

Energy deposition - dE/dx



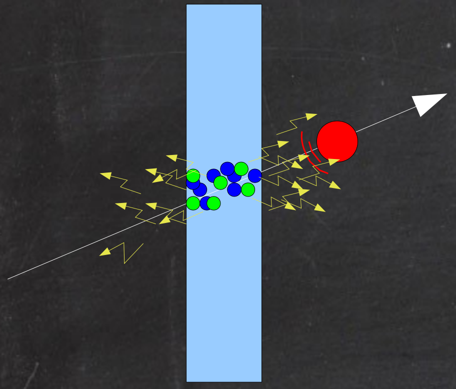
Secondary emission - SEM



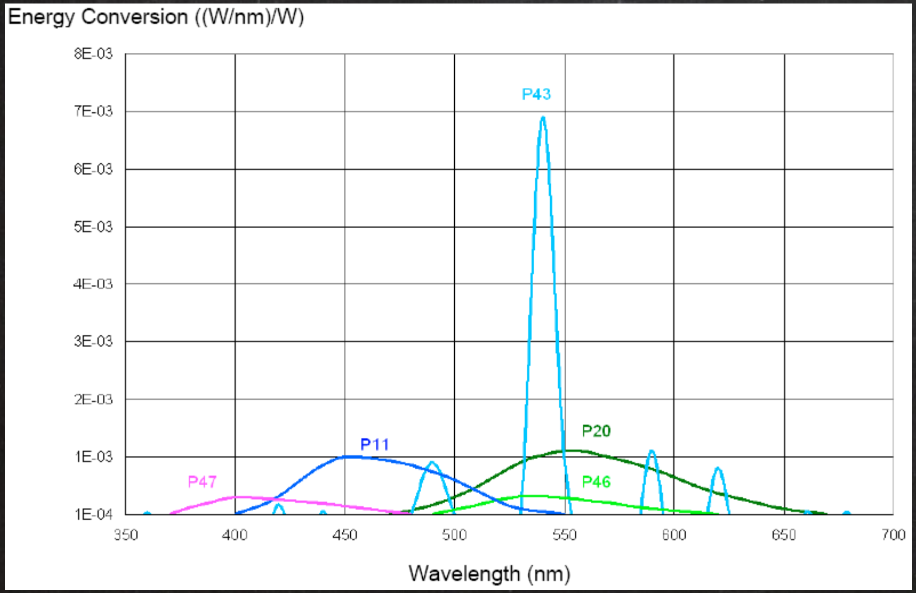


- Linked to ionization
- Surface electrons receive sufficient energy to travel to the surface and leave
- Emission yield depends on particles energy, material, surface state etc.

Scintillation



- Linked to ionization
- Photons are emitted by the de-excitation of atomic states populated by the passage of the particle
- Emission time *ns* to *hours*



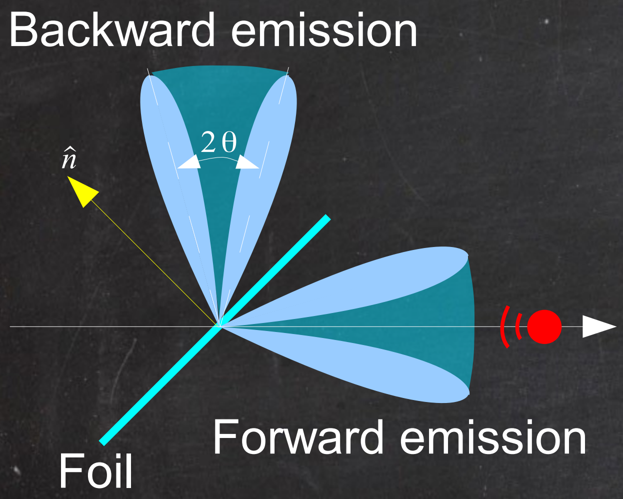
Type	Composition	Decay Time	
		Decay of Light Intensity	
		from 90 % to 10 % in	from 10 % to 1 % in
P 43	Gd_2O_2S:Tb	1 ms	1,6 ms
P 46	$Y_3Al_5O_{12}$:Ce	300 ns	90 µs
P 47	Y_2SiO_5:Ce,Tb	100 ns	2,9 µs
P 20	(Zn,Cd)S:Ag	4 ms	55 ms
P 11	ZnS:Ag	3 ms	37 ms

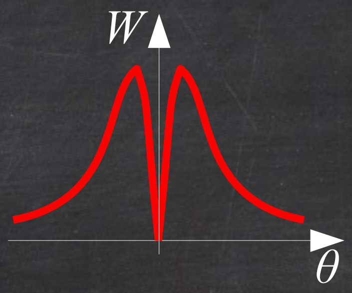
1*MeV* e^- on *5µm* P43 yields ~ *60 ph.*

Scintillation (2)

- Phosphors have very high light yields, but can only be used as thin coating on a rigid support and get damaged very quickly
- Normally used only for very low intensity beams
- Ceramics, glasses and crystals are a more popular choice in high energy accelerators
- Al_2O_3 (Alumina, Aluminium Oxide) is a very common choice (usually doped with Cr) because it is a very robust ceramic (Cromox)

Optical Transition Radiation (OTR)





- Radiation is emitted when a charged particle crosses the boundary of different dielectric properties
- Radiation has defined angular distribution
- Radiation is radially polarized
- Thickness of radiator not important

$$\frac{d^2 W}{d\Omega\, d\omega} \approx \frac{N q^2}{\pi^2 c}\left(\frac{\theta}{\gamma^{-2}+\theta^2}\right)^2$$

Maximum at $\theta = \frac{1}{\gamma}$

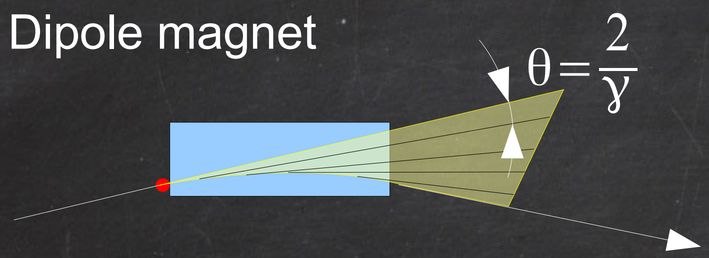
$$W \propto \left\{\begin{matrix} \beta^2 & \beta \ll 1 \\ \ln(2\gamma) & \gamma \gg 1 \end{matrix}\right\}$$

For *50* MeV electrons ~ *0.3* $ph./el.$

For *100* keV electrons ~ *0.001* $ph./el.$

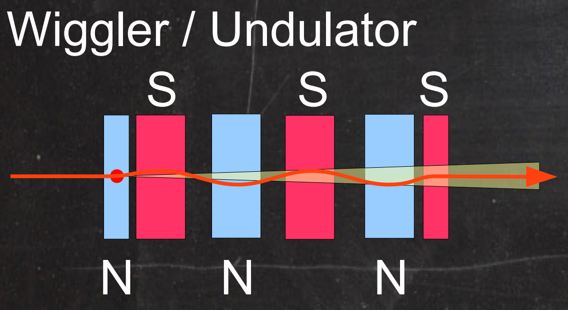
($\lambda \in$ [400, 600] nm)

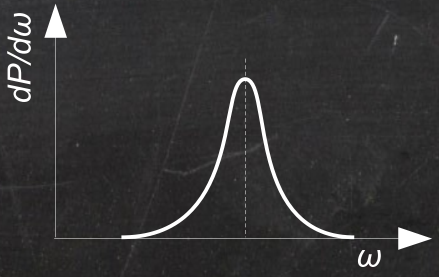
Synchrotron radiation



$$\theta = \frac{2}{\gamma}$$

$$P = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{c e^2 \gamma^4}{\rho^2}$$



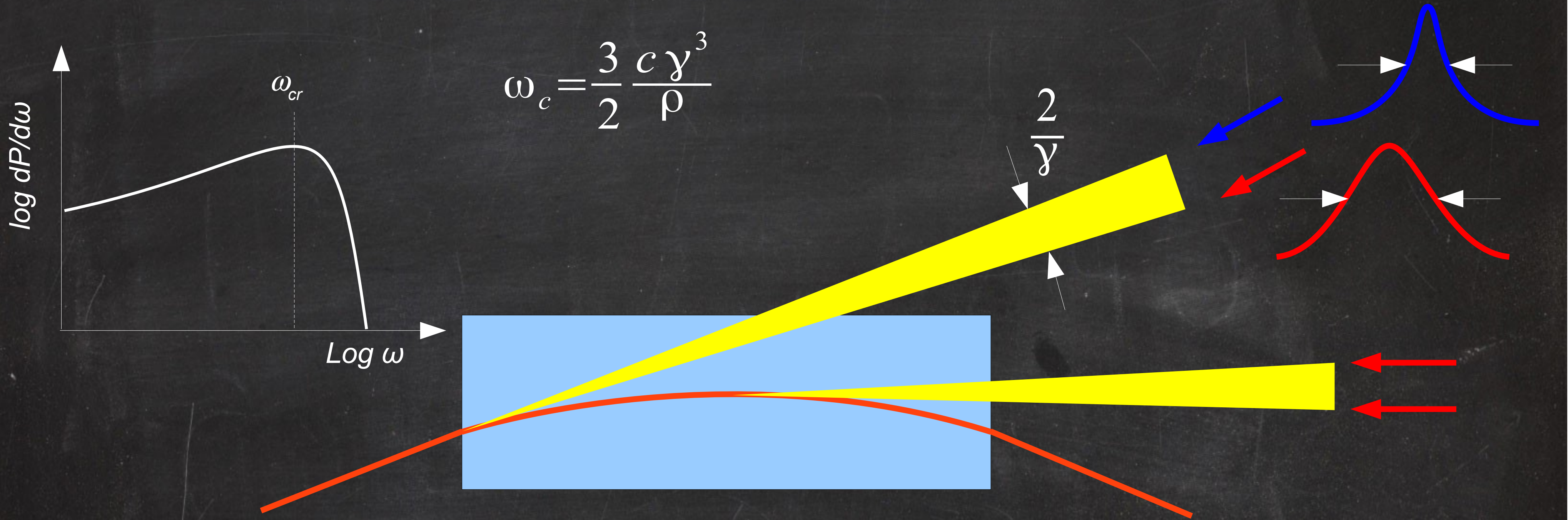


$$\lambda \propto \frac{\lambda_u}{2\gamma^2}$$

$$W \propto B_0^2 \gamma^2$$

- Charged particles emit electromagnetic radiation when accelerated
  - Bremsstrahlung: reduction of velocity
  - Synchrotron radiation: change of direction
- Synch. rad. from dipole magnet emits in a fan
- Radiation from undulator has different properties

Synchrotron radiation (2)

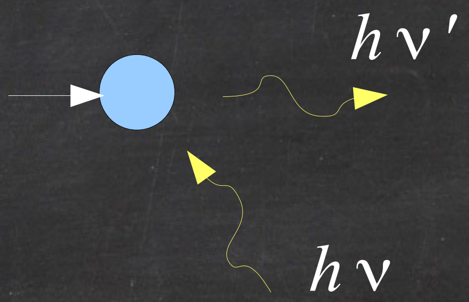


$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}$$

The red observers will see a pulse which duration is equal to the time it takes to the particle to be deviated by an angle 2/γ and an emission spectrum as the one depicted above.

The blue observer being at the edge of the emission cone will see a shorter pulse. As a consequence the spectrum of the emission will be broadened and extend to higher frequencies (shorter wavelengths)

(Inverse) Compton scattering



$$\nu' = \gamma^2 \nu$$

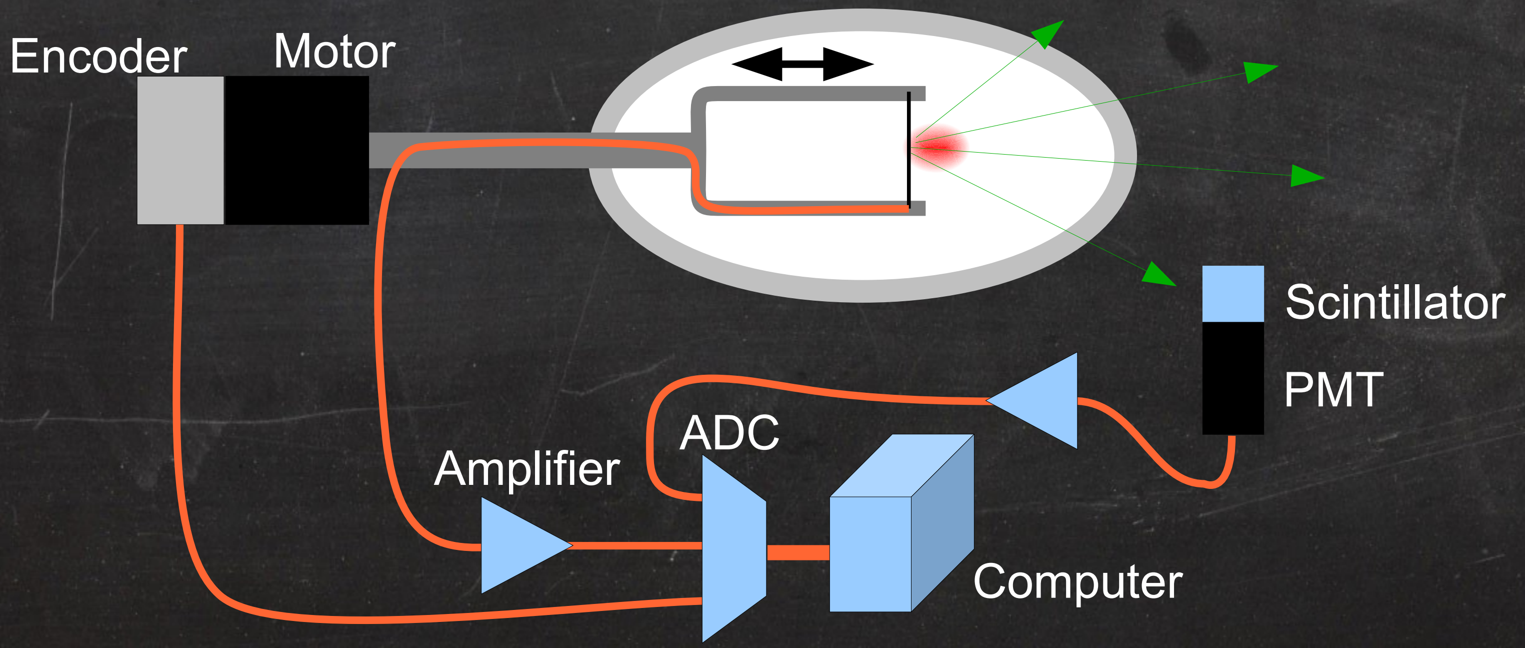
- A low energy photon (few eV) interacts with a high energy charged lepton (e-, e+)
- The photon gets boosted and gains energy to the expense of the particles
- Cross section is small, but usable for leptons, it is however too small for hadrons (protons)

Sampling particle distributions

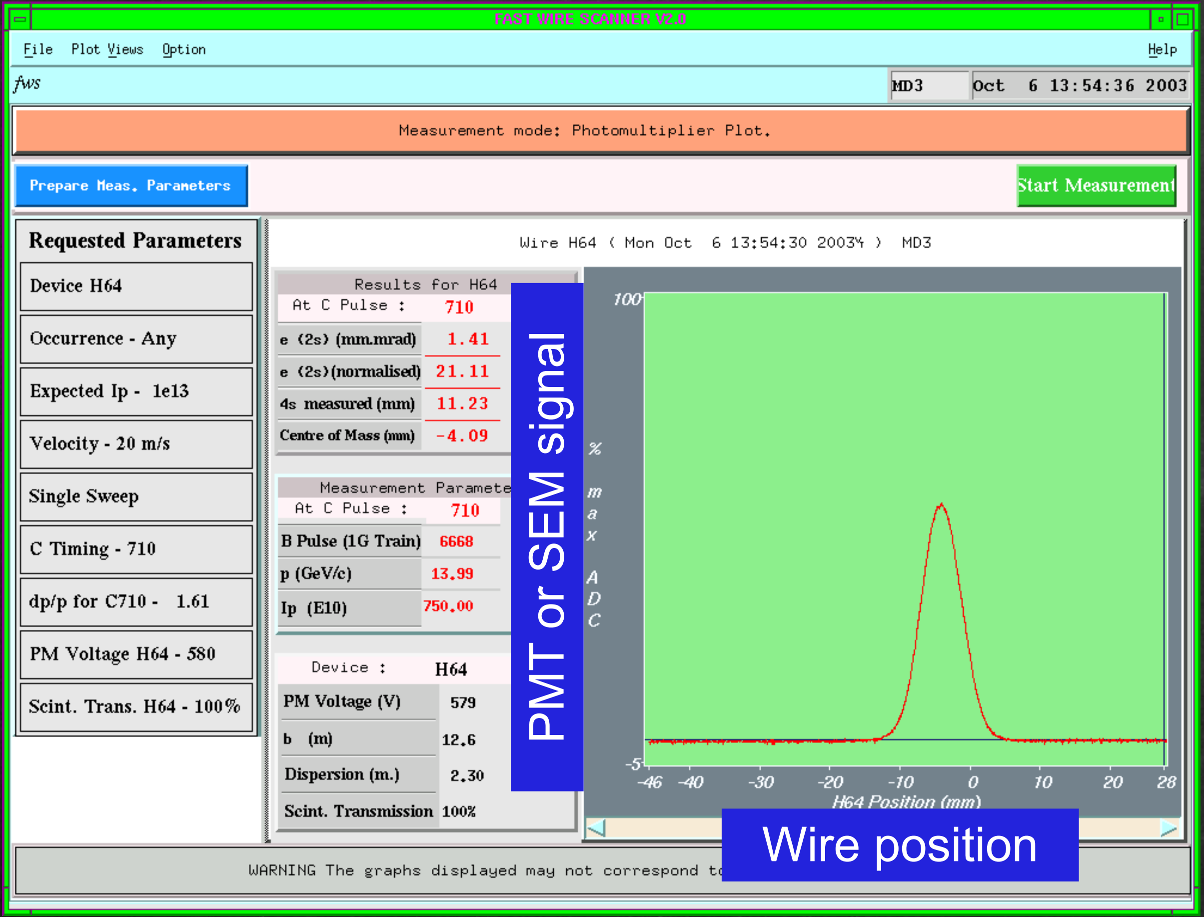
- One dimension sampling
  - Wire scanners
  - Wire grids
  - Rest gas ionization monitors
  - Laser Wire Scanner
- Two dimension sampling
  - Screens and radiators
  - Synchrotron radiation

Wire scanner

- Scans a thin wire or a needle across the beam
- Detects secondary emission current or high energy secondary particles (scintillator + PMT)



Wire scanner (2)



MD3 Oct 6 13:54:36 2003

Measurement mode: Photomultiplier Plot.

Requested Parameters

- Device H64
- Occurrence - Any
- Expected Ip - 1e13
- Velocity - 20 m/s
- Single Sweep
- C Timing - 710
- dp/p for C710 - 1.61
- PM Voltage H64 - 580
- Scint. Trans. H64 - 100%

Wire H64 (Mon Oct 6 13:54:30 2003) MD3

Results for H64	
At C Pulse :	710
e (2s) (mm.mrad)	1.41
e (2s)(normalised)	21.11
4s measured (mm)	11.23
Centre of Mass (mm)	-4.09

Measurement Paramete	
At C Pulse :	710
B Pulse (1G Train)	6668
p (GeV/c)	13.99
Ip (E10)	750.00

Device :	H64
PM Voltage (V)	579
b (m)	12.6
Dispersion (m.)	2.30
Scint. Transmission	100%

WARNING The graphs displayed may not correspond to

PMT or SEM signal

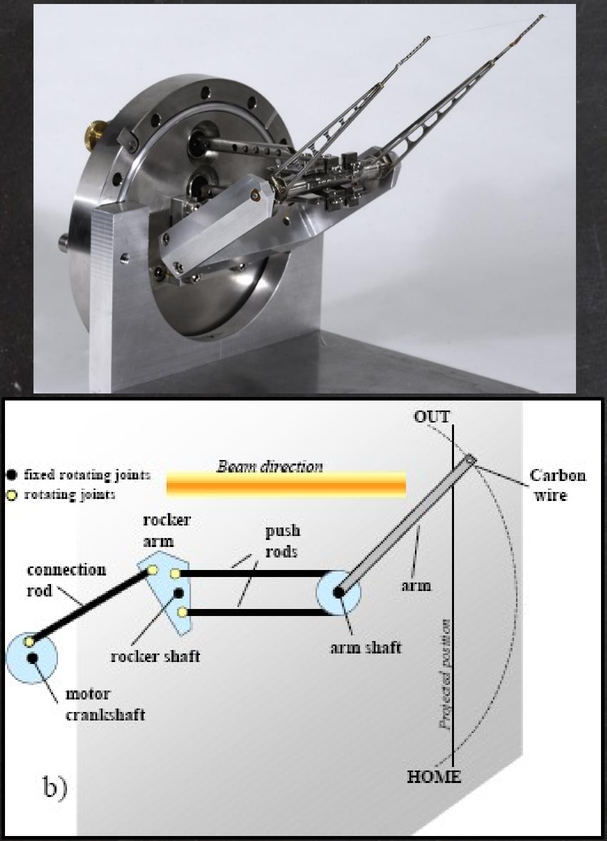
Wire position

- The position of the wire is read by resolver or an encoder and sampled simultaneously with the signal
- On complex, fast mechanism the error on the position can be the largest contribution, need calibration

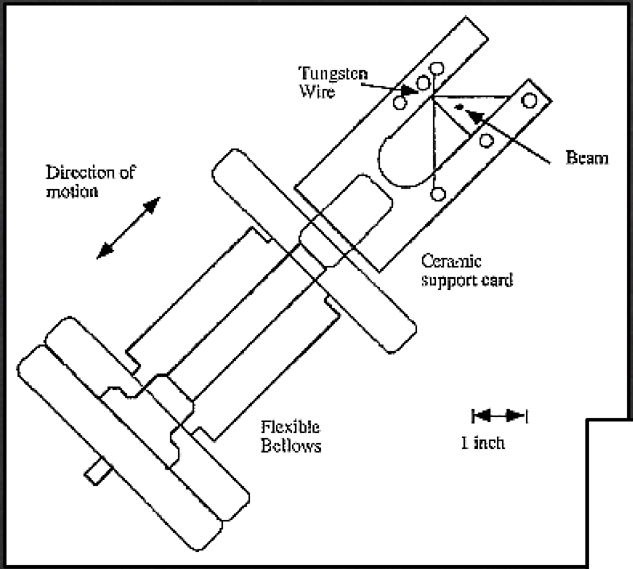
Wire scanner (3)

- Secondary emission
  - Good for low energy beams (no high energy secondary)
  - Small signal
  - If the wire becomes too hot it can start to emit thermionic electrons spoiling the measurement
- High energy secondary
  - No problem with wire heating (well...)
  - Strong signal
  - Detection may be non homogeneous leading to distorted profiles

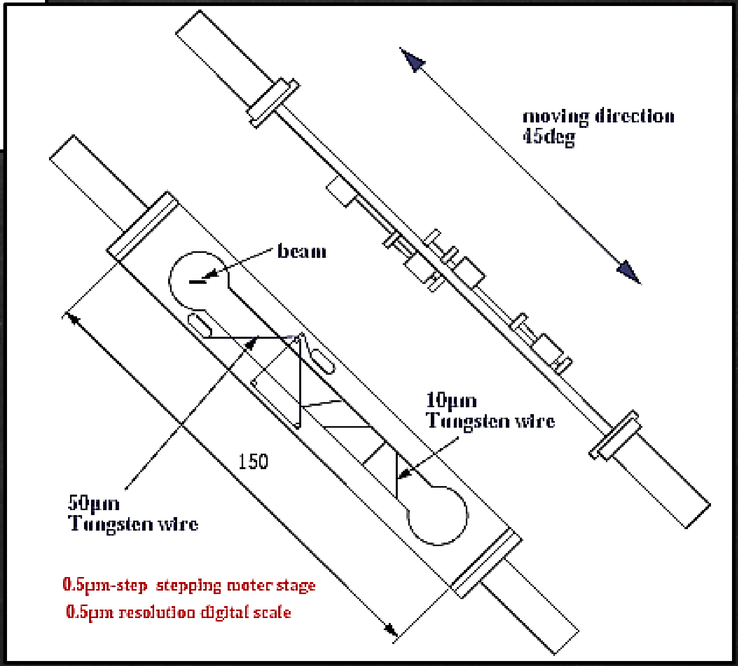
Wire scanner (4)



CERN "flying wires"



SLAC SLC high resolution 3 axis scanners



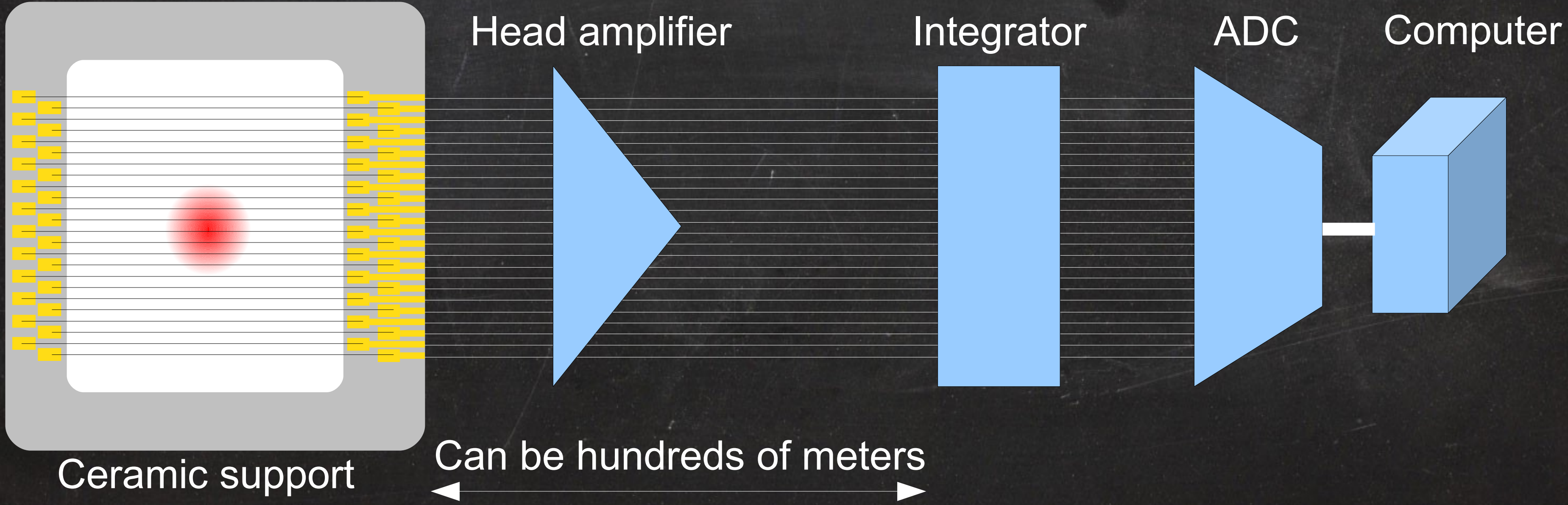
KEK ATF high resolution 3 axis scanners

Wire scanner (5)

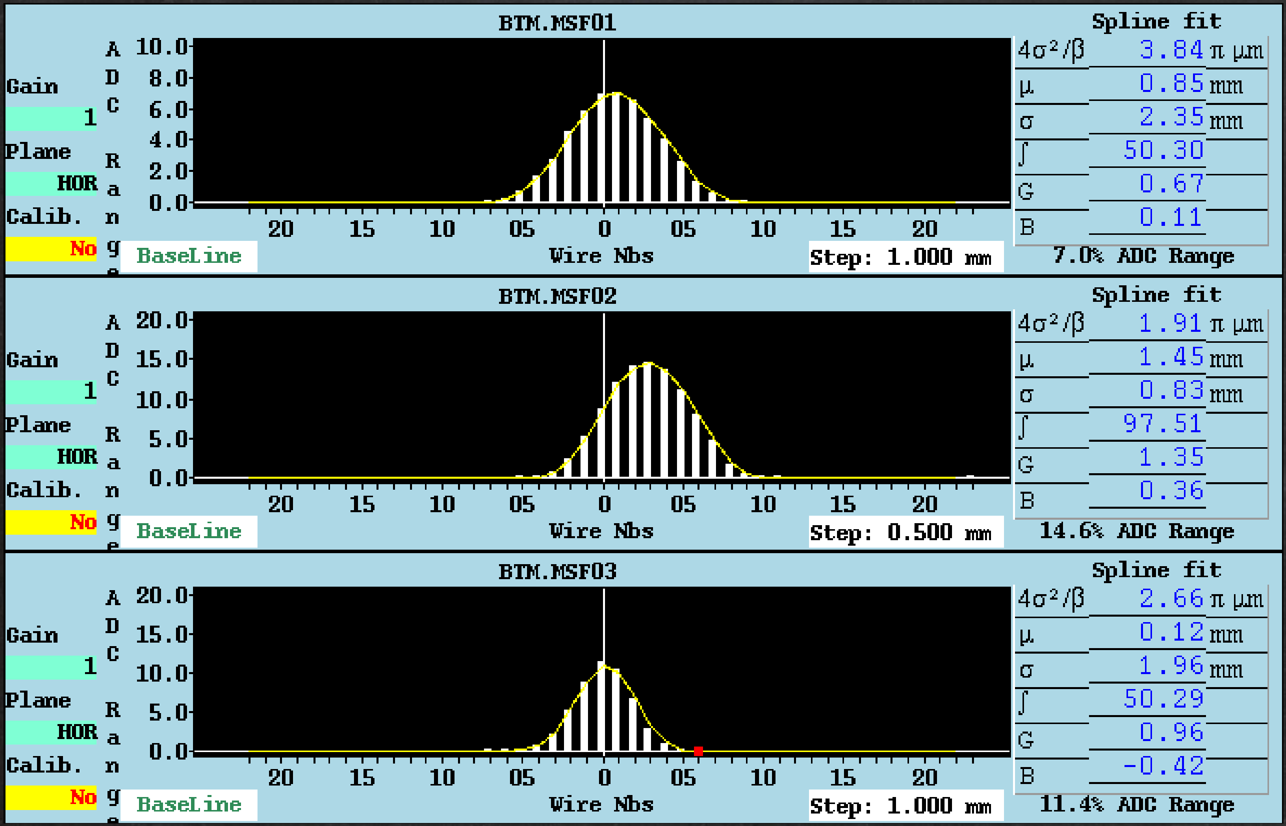
- Fast scanners
  - Present limit is around 20 m/s
  - Usually rotational mechanism
  - Acquire profile snapshots during acceleration without need of plateaus
  - Reduce wire heating (short scan time)
- Slow scanners
  - High wire position accuracy
  - Possibly thinner wires (low accelerations)
  - More reliable mechanisms
  - Long(er) measurement time
  - Tighter intensity limits

SEM Grids (Harps)

- The SEM current from each wire or strip is acquired independently
- Complex (=expensive) cabling/electronics
- Wire spacing down to a few hundreds microns



SEM Grids (2)



BTM.MSF01

Gain 1
Plane HOR
Calib. No
BaseLine
Step: 1.000 mm

Spline fit		
$4\sigma^2/\beta$	3.84	π μm
μ	0.85	mm
σ	2.35	mm
∫	50.30	
G	0.67	
B	0.11	

7.0% ADC Range

BTM.MSF02

Gain 1
Plane HOR
Calib. No
BaseLine
Step: 0.500 mm

Spline fit		
$4\sigma^2/\beta$	1.91	π μm
μ	1.45	mm
σ	0.83	mm
∫	97.51	
G	1.35	
B	0.36	

14.6% ADC Range

BTM.MSF03

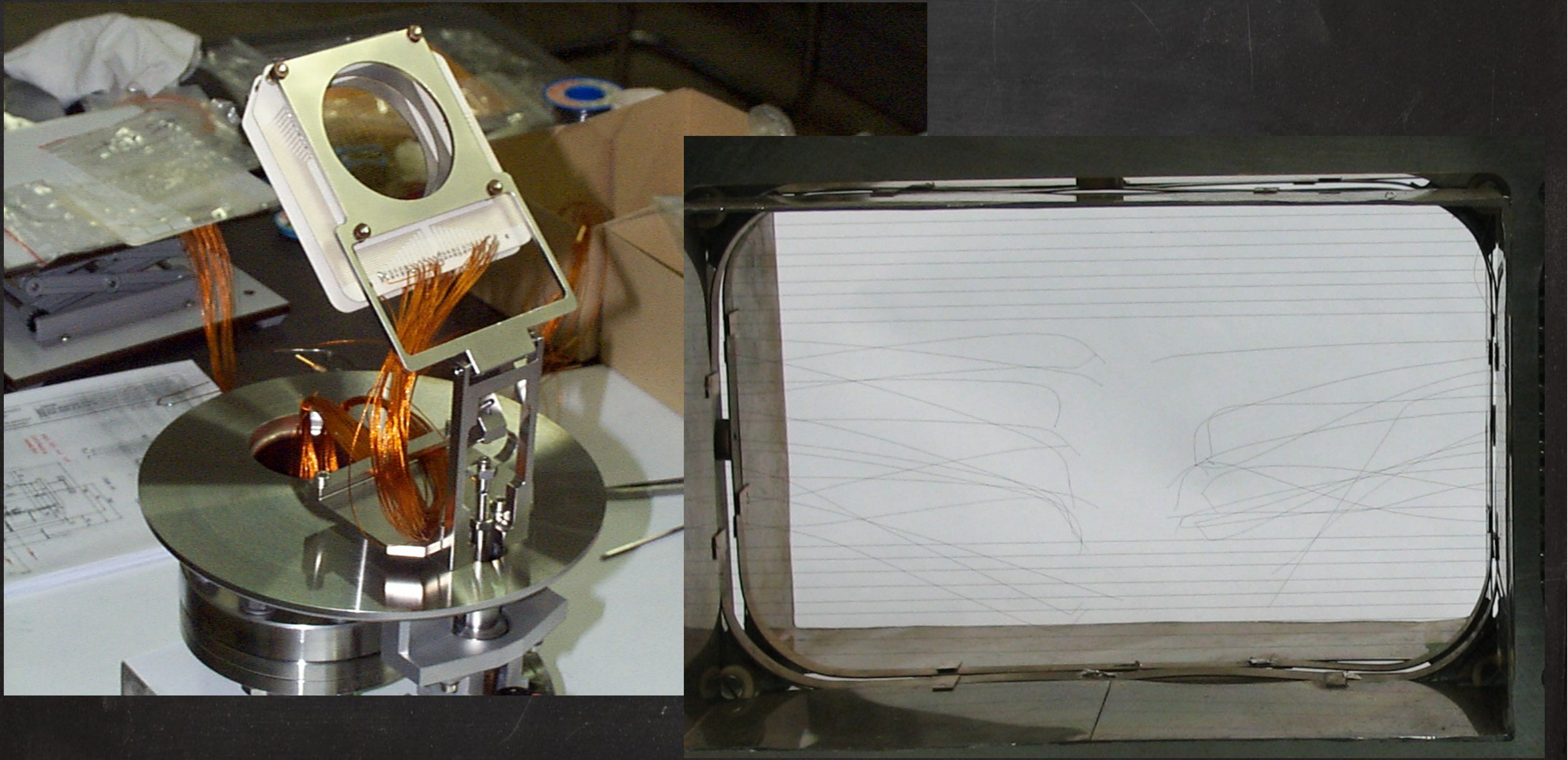
Gain 1
Plane HOR
Calib. No
BaseLine
Step: 1.000 mm

Spline fit		
$4\sigma^2/\beta$	2.66	π μm
μ	0.12	mm
σ	1.96	mm
∫	50.29	
G	0.96	
B	-0.42	

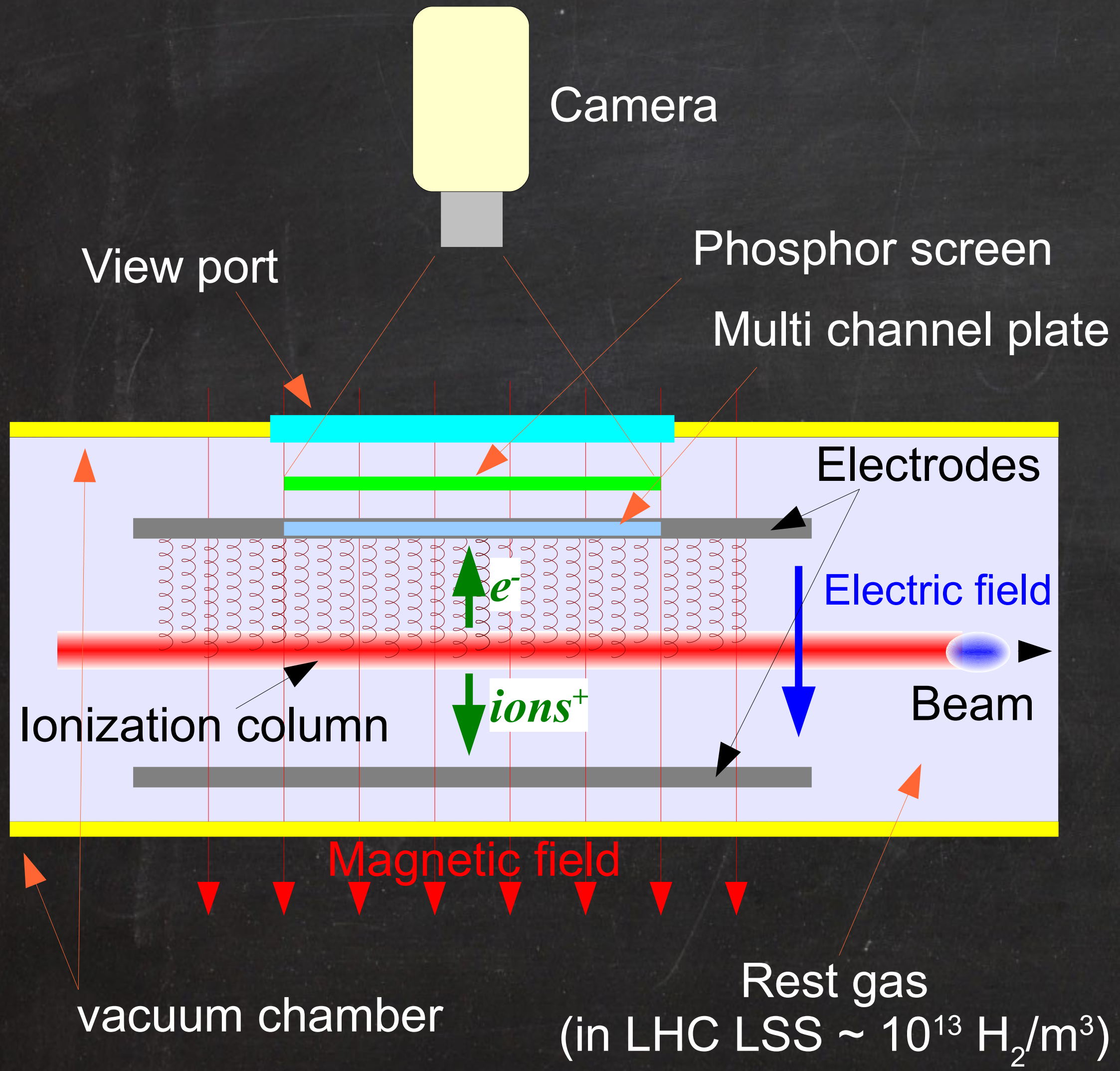
11.4% ADC Range

- Advantage of Grids is single shot measurement
- Time resolved measurement is possible (up to ~100 MHz)
- Damage to a single wire can make device unusable

SEM Grids (3)

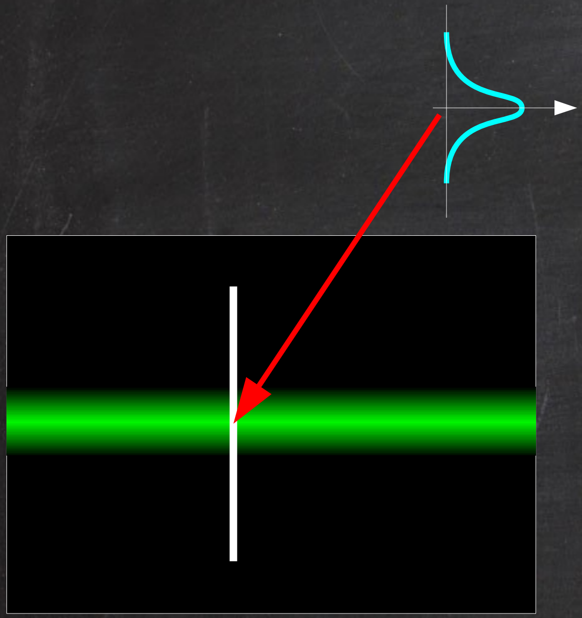


Ionization profile monitor



- Beam creates ionization column in rest gas
- Electric field drifts electrons toward detector
- Magnetic field guides the electron
- MCP+phosphor+CCD detects electrons
- If E is reversed ions can be detected instead of electrons (less need for B field)

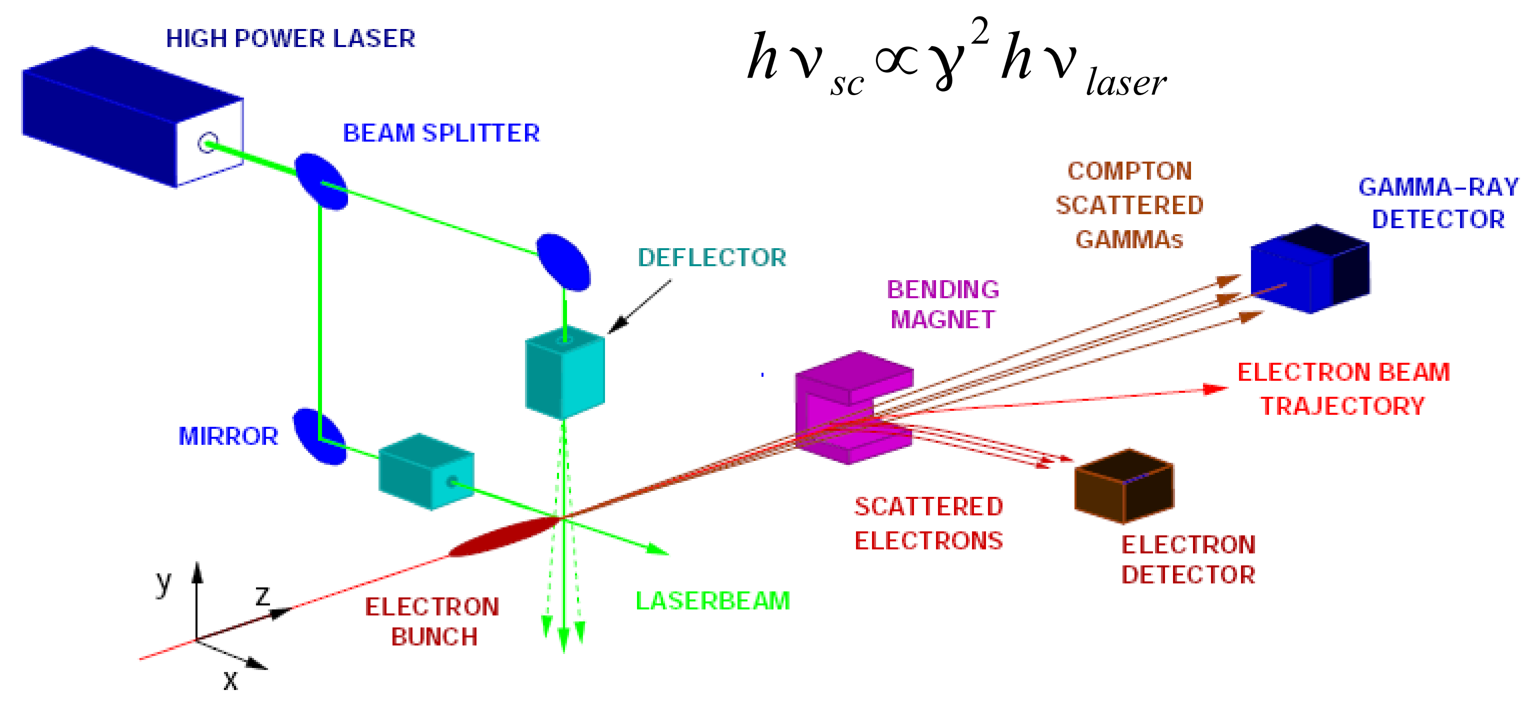
Ionization profile monitor (2)



- Image shows a stripe
- Intensity profile of stripe proportional to beam profile
- Detector measures only one plane
- Transverse drift of electrons introduces broadening (need intense B field) and creates "tails"

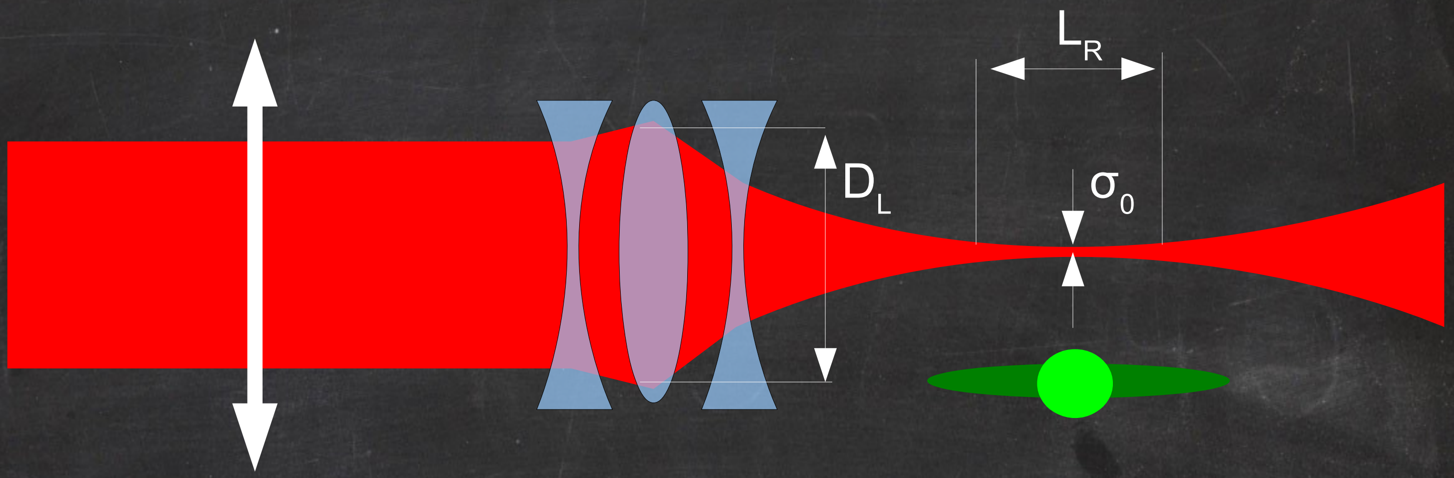
Laser Wire Scanner

- Collide a high power, focused, pulsed laser with an electron beam
- X-ray or γ-ray are produced by Inverse Compton Scattering
- Detect the x-ray / γ-ray or the degraded electrons downstream
- Can also be used on H^- beams exploiting the photo neutralization detecting either the neutral H atoms or the freed electrons



$$h\nu_{sc} \propto \gamma^2 h\nu_{laser}$$

Laser Wire Scanner (2)



There is a physical limit on the smallest laser spot size and on the distance over which it can remain focused

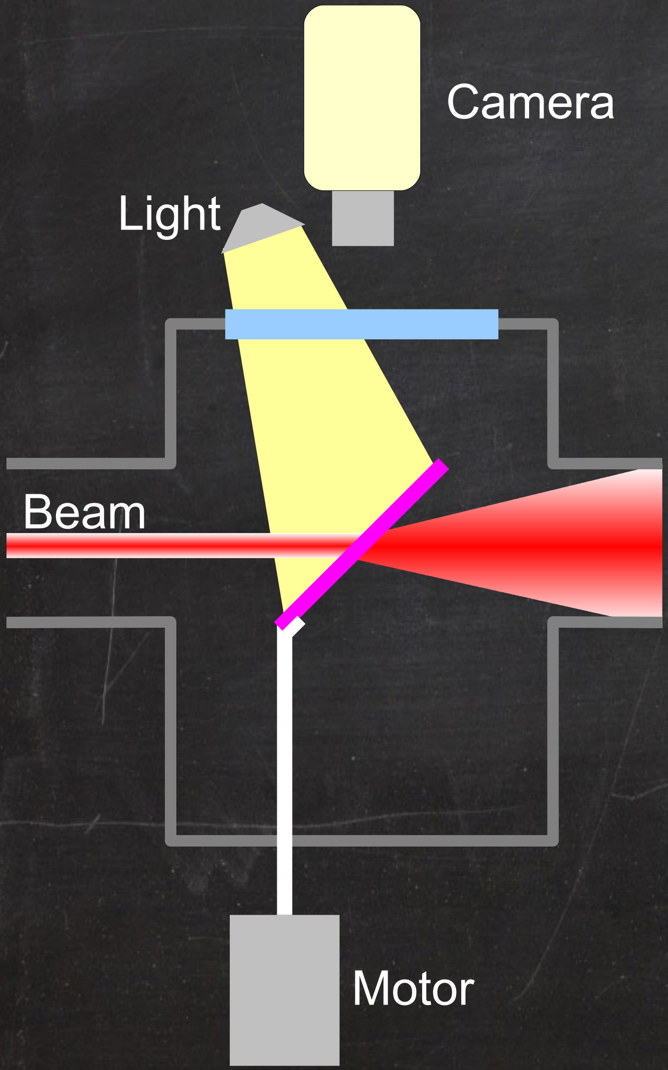
$$\sigma_0 = \frac{\lambda f}{D_L} = \lambda f/\#$$

$$L_R = \frac{2\pi \sigma_0^2}{\lambda}$$

Laser Wire Scanner (4)

- High resolution LWS require
  - High power, high quality lasers (mJ, ps, M^2~1)
  - Complex focusing systems
  - Precise scanning systems (as an alternative the beam can be moved around)
- The resolution of the laser wire scanners is limited by the minimum waist size (of the order of the wavelength)
- A strongly focused laser beam will have a short waist length (Rayleigh length) and is not adapted for small beams with large aspect ratios
- Other limiting factors are laser stability, vibrations, x-ray detection (if low energy x-rays)

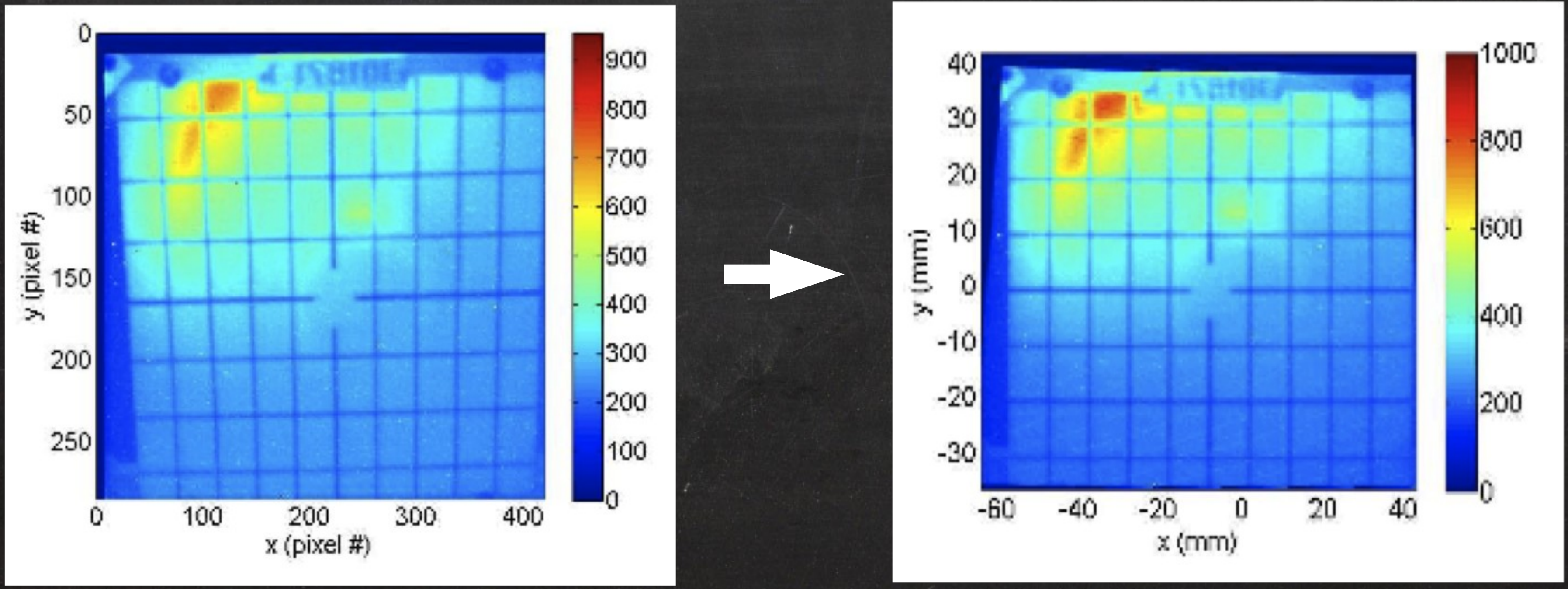
Scintillating screens



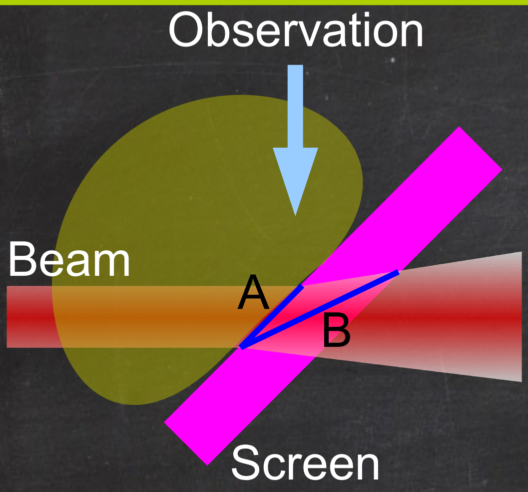
- Particles passing trough the screen excite atoms and molecules
- The screen emits photons that can be observed with a TV camera (CCD)
- Multiple scattering inside screen increases beam divergence
- Typical screens are Al_2O_3 1mm thick. Robust and good for beam observation, but not for precise profile measurements.

Scintillating screens (2)

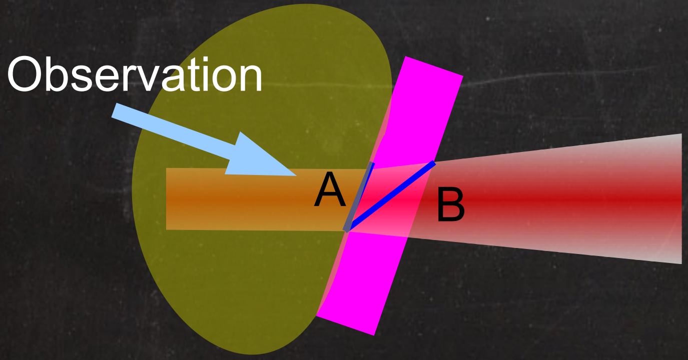
- Optical setup may introduce deformations (ex 45° screens)
- Need to perform off line corrections and calibrations



Scintillating screens (2)

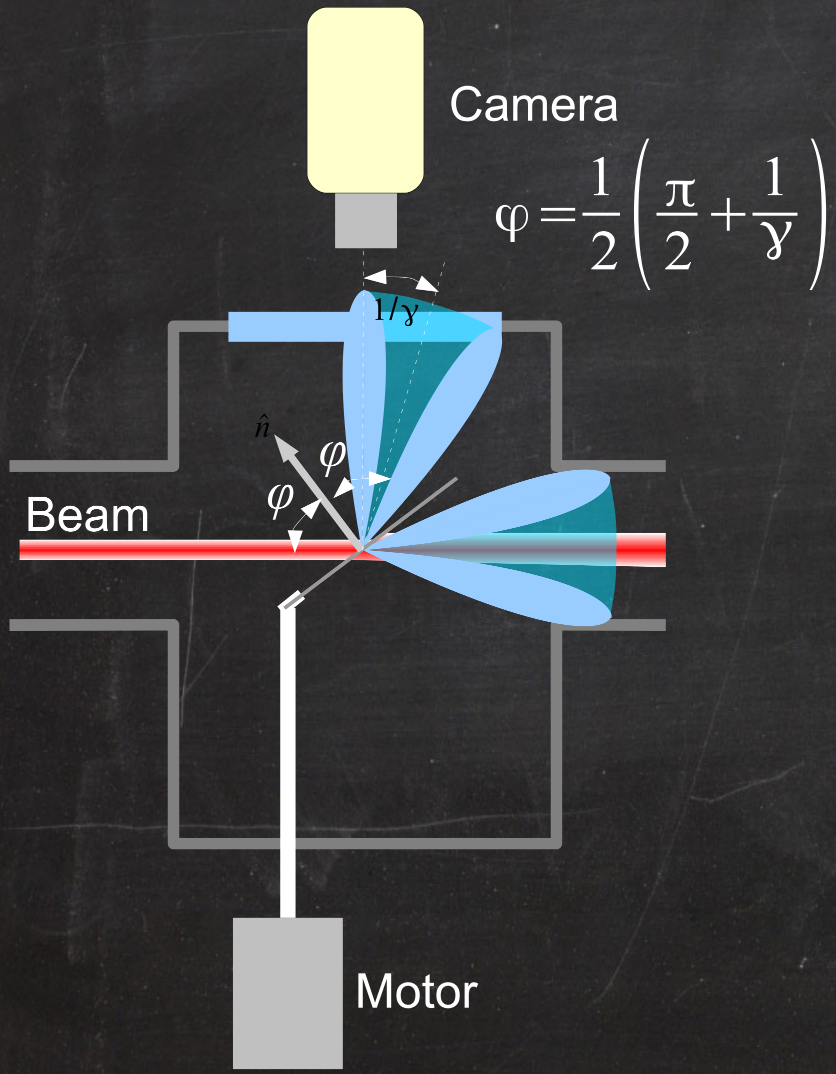


A is what we would like to observe
B is what we really obtain



- Photons created inside the screen can escape
- The image observed is distorted
- Thickness of the screen should be small (compared to beam size)
- Observation at 90° is easy to use, but very bad for quality, also for field depth and aberrations

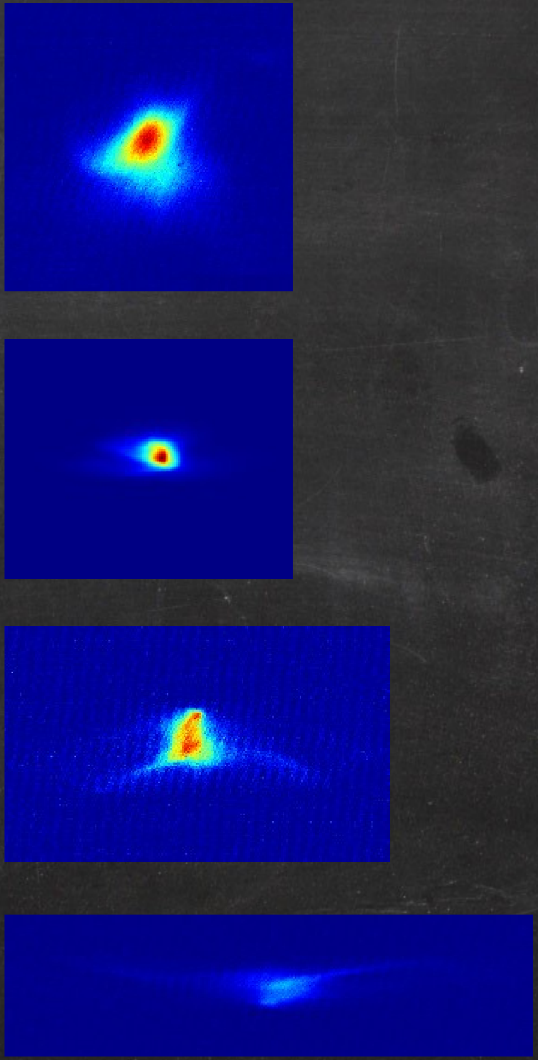
OTR radiators

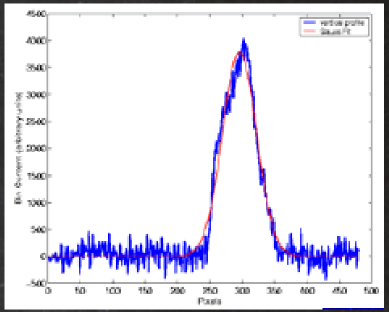


$$\varphi = \frac{1}{2}\left(\frac{\pi}{2} + \frac{1}{\gamma}\right)$$

- Use backward emission
- Reflecting properties of radiator are important (metal foil or metal coating)
- Use thin foil (few µm) or "wafers", typically Al coated Si ~300 µm
- Angle of radiator depends on beam momentum
- For dense beams use carbon foils or SiC wafers

OTR example (DESY)





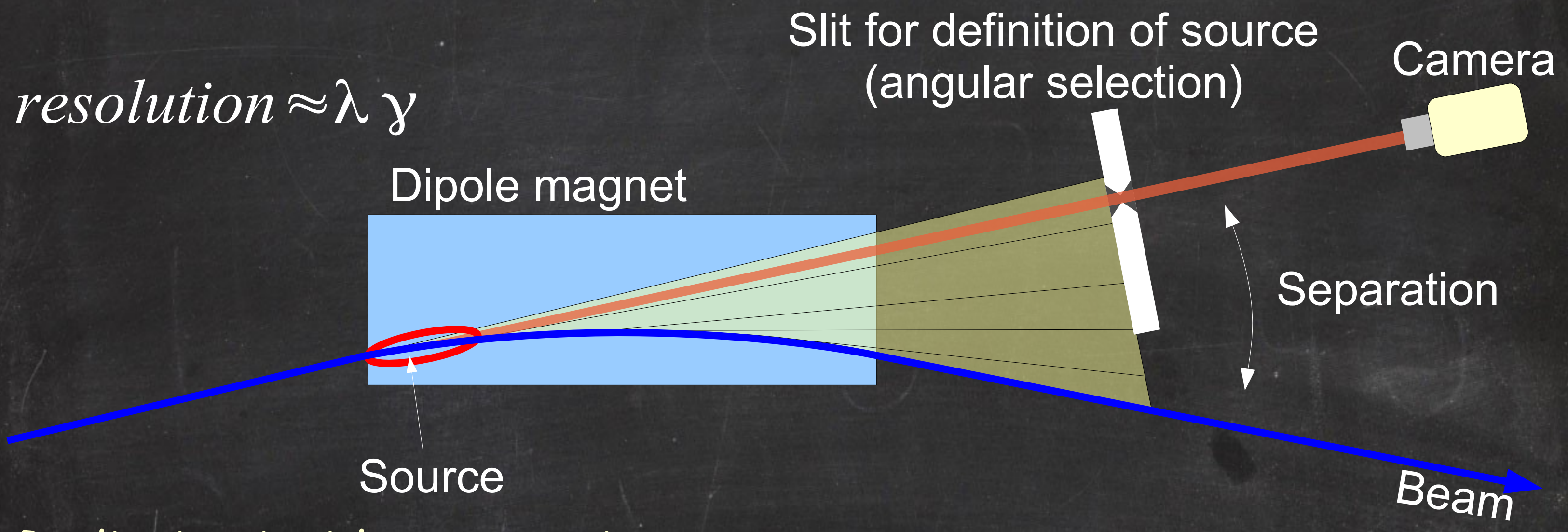
Often beams are far from Gaussian especially in linacs

Camera must be protected from radiation requiring a complex optical lines

Filters are needed to avoid saturating the camera

Synchrotron radiation

$$resolution \approx \lambda\,\gamma$$



- Radiation inside magnet is constant
- Radiation at the entrance and exit edge has higher frequency components (shorter pulse) “edge radiation”
- Magnet also useful for separating photons from particles
- Source normally near entrance or even entrance edge
- Resolution limited by diffraction

Light sensors

- 1D sensors (Can be fast up to hundreds of MHz)
  - Photo diode array
  - Linear CCD
  - Segmented photomultiplier
- 2D sensors (usually slow ~50Hz, possible up to 100 kHz)
  - image CCD
  - image CMOS
  - (Segmented photomultiplier)

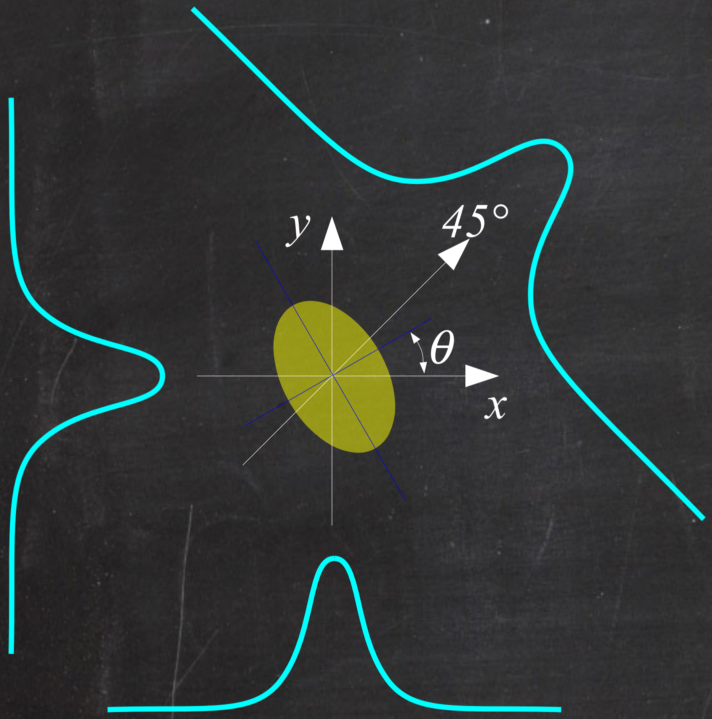
Light sensors (2)

- 1D arrays (photo diodes or photo multipliers)
  - Parallel readout of each channel allows high speed, but limits resolution
- 1D CCD
  - serial readout, good resolution, but reduced speed
- 2D CCD or CMOS
  - serial readout, very good resolution, but reduced speed.
  - Special sensors with local memory and partial parallel readout allow higher acquisition speed.

Light sensors (3)

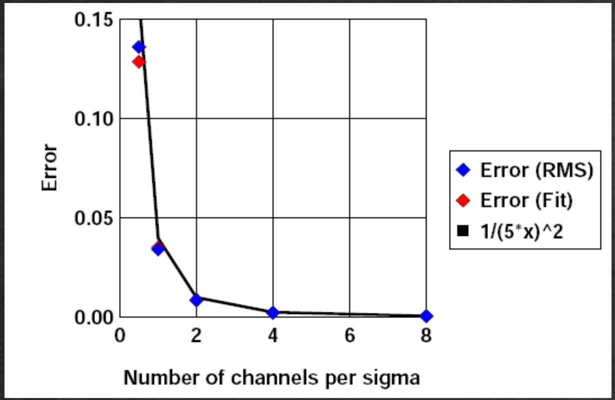
- Photomultipliers are radiation resistant (glass and metal)
- CCD and CMOS are silicon based and thus not very tolerant to radiation
- Tube cameras (ex. VIDICON) are radiation hard, but have worse resolution and sensitivity
- Special fast cameras contain loads of memory and electronics and are very sensitive to radiation (and expensive)
- Sensitivity of image sensors can be increased using image intensifiers, but usually at the expense of resolution

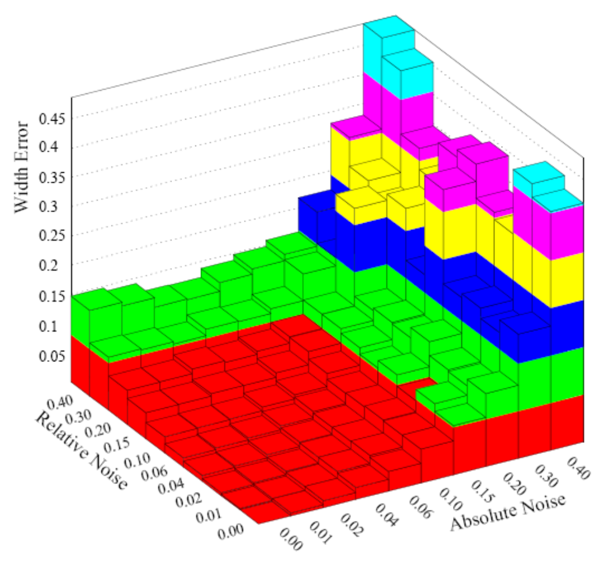
1D vs. 2D



- The 2D image contains the whole spatial information
- With only 2 1D profiles (X and Y) it is impossible to see coupling (rotated ellipse in x,y) or other effects
- Need at least the profile along a third direction (45°)
- Assuming bi-Gaussian beam with tilt: σ_I, σ_{II}, θ.
- 3 D.O.F. need 3 samples

Measurement accuracy





- Accuracy of measurement depends on
  - Detector size
    - Min ±3σ
  - Number of points
    - Min 2 points per σ
  - Accuracy of each point
    - Both position and signal
  - Noise level
- Use fit wherever possible

Thank you very much for your attention

Questions?