Beam Profile Measurements

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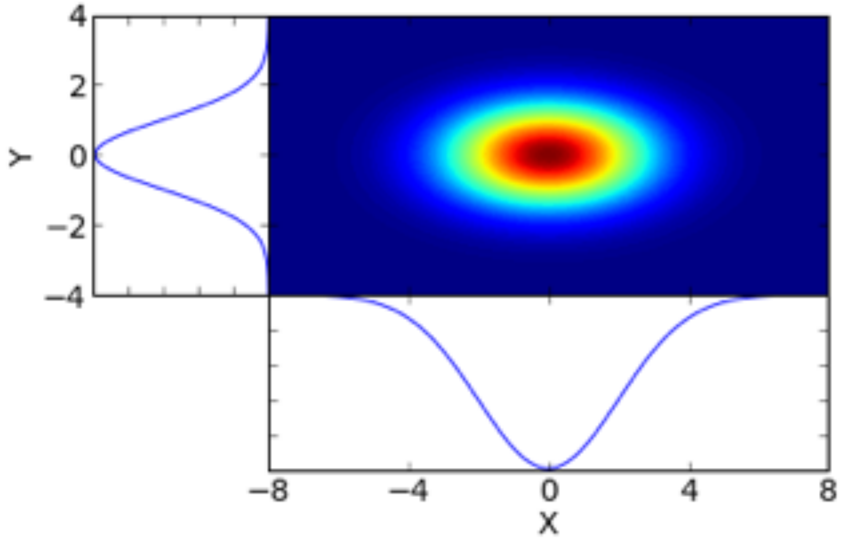
Content

- Definitions
- Transverse space dynamics
- Emittance measurement
- Interaction of particles with matter
- Radiation emission by charged particles
- Sampling of distributions (measurement of profiles)

Beam profiles

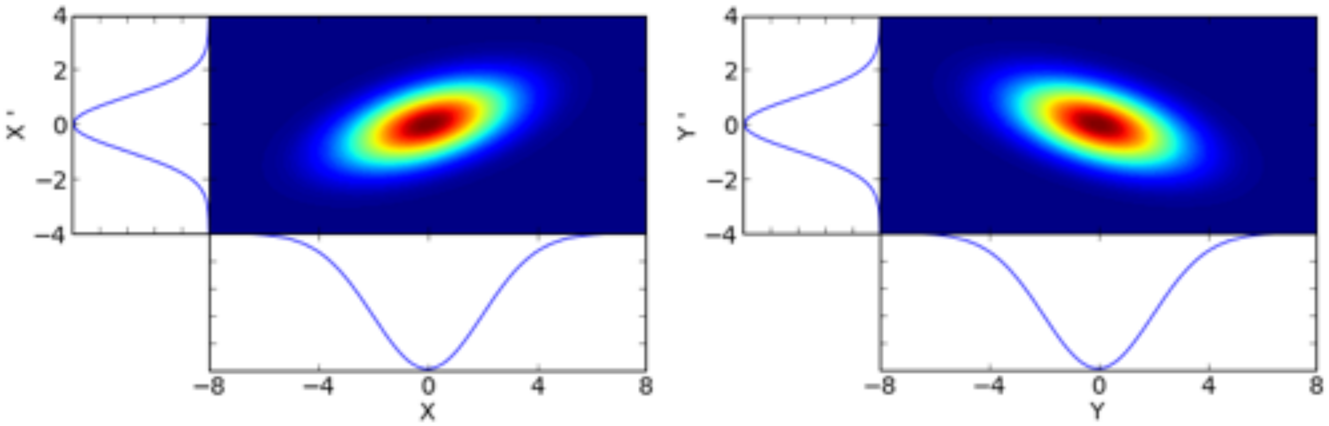
X-Y space (beam image)



Vertical profile

Horizontal profile

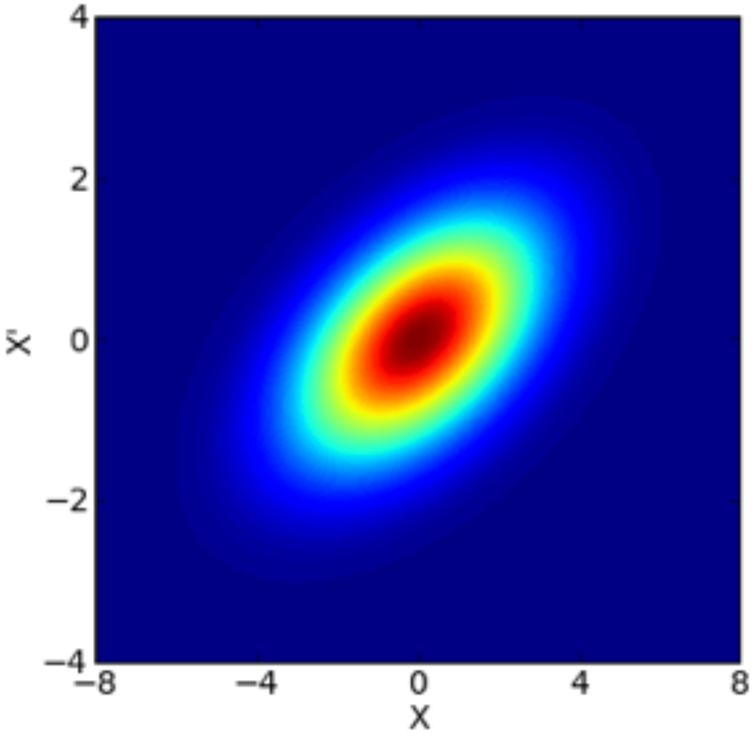
Phase space



Horizontal profile

Vertical profile

Phase space

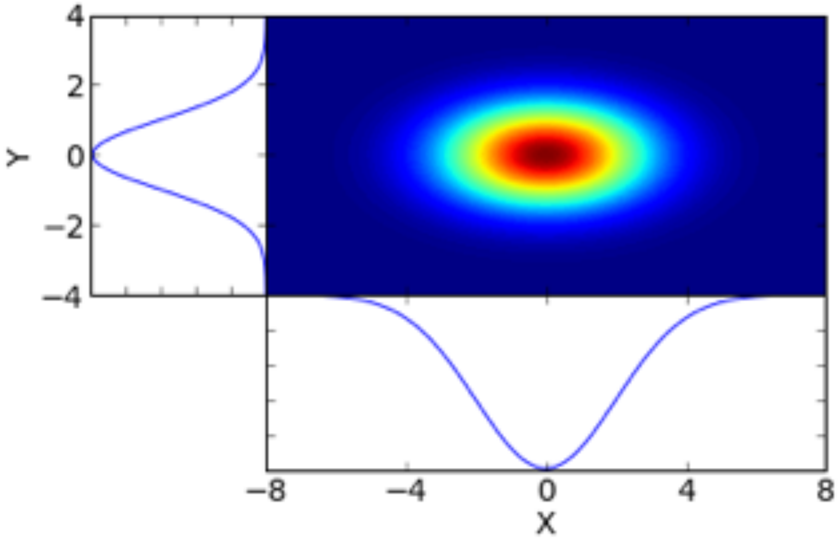


Amplitude distribution

Beam profiles

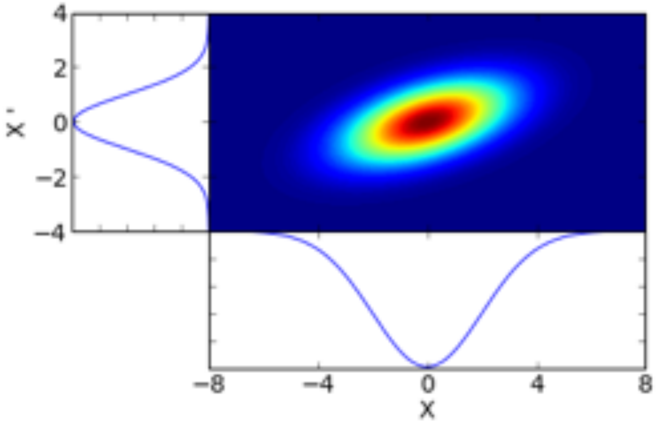
X-Y space (beam image)

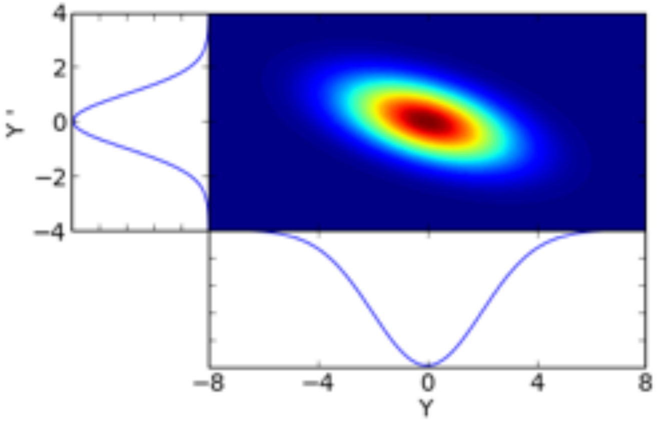
Vertical profile



Horizontal profile

Phase space

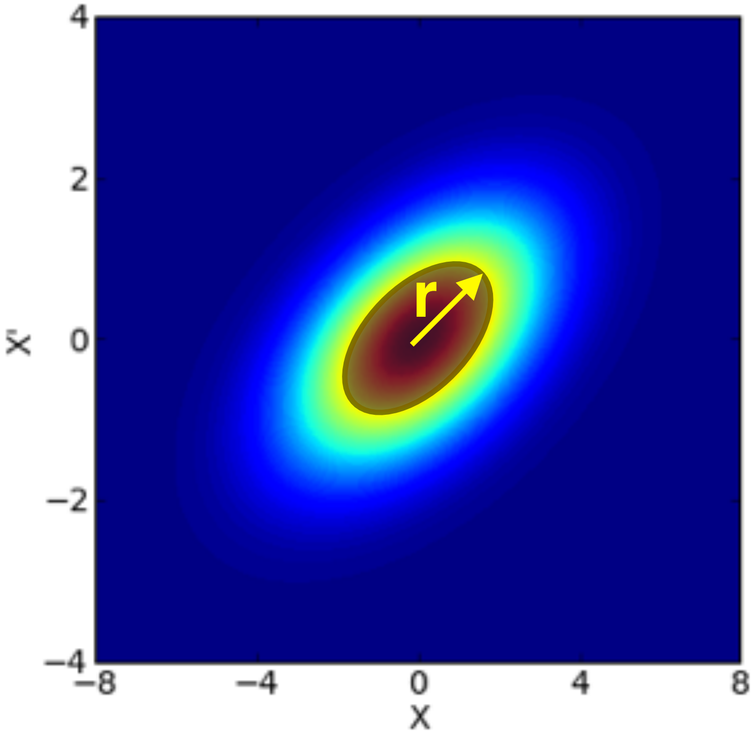




Horizontal profile

Vertical profile

Phase space

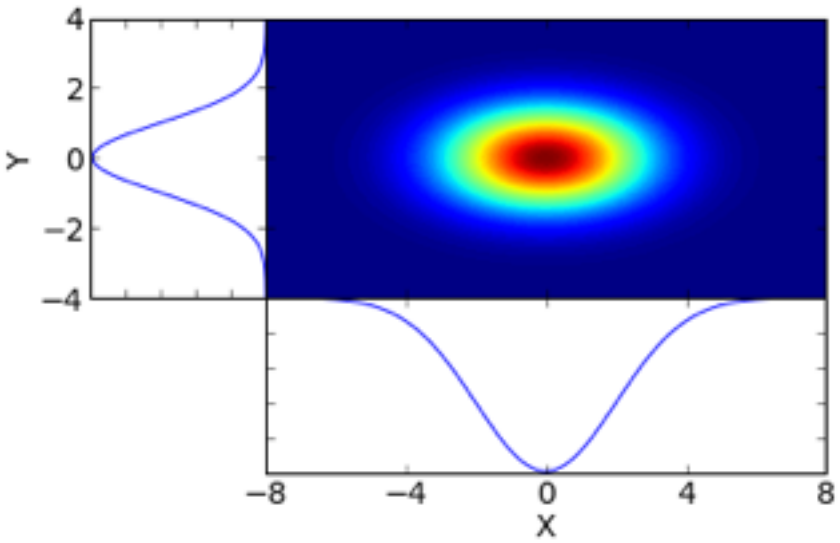


Amplitude distribution

Beam profiles

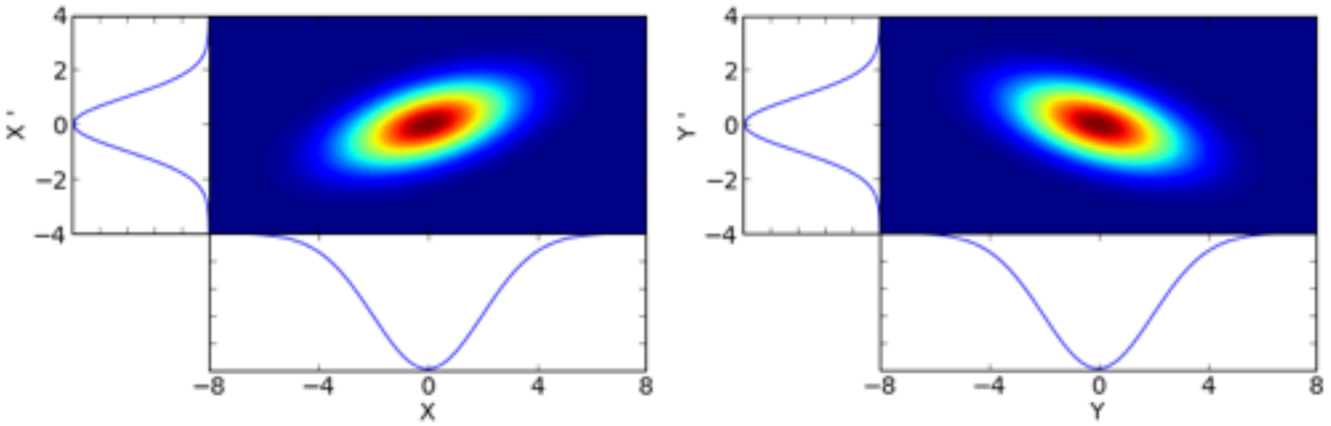
X-Y space (beam image)

Vertical profile



Horizontal profile

Phase space



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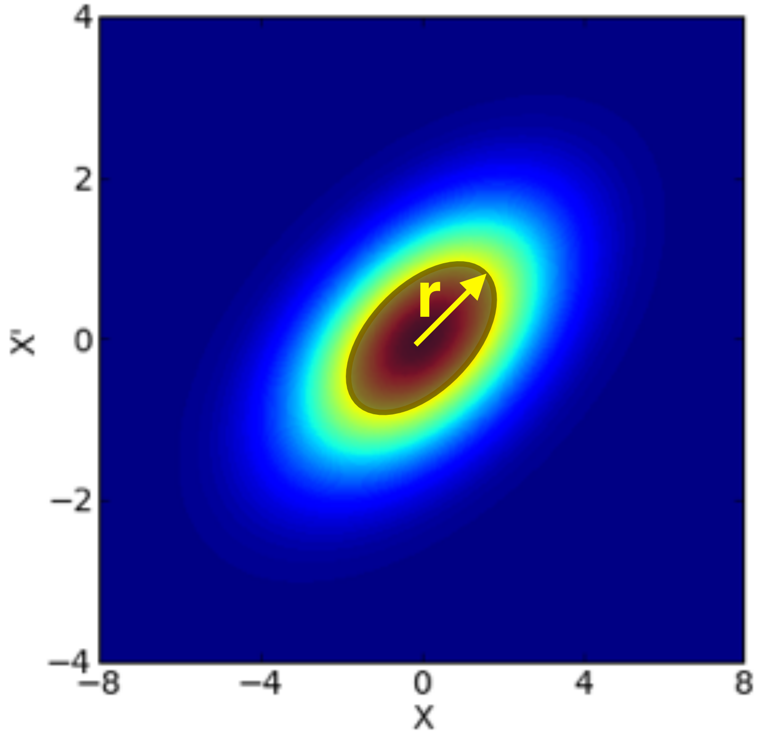
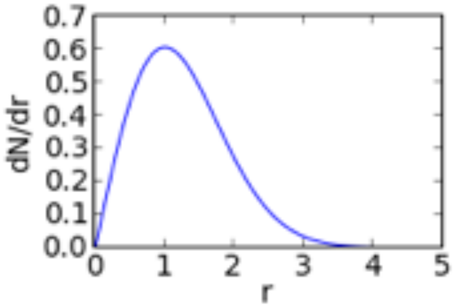
Vertical profile

Phase space





Amplitude distribution

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X-Y space (beam image)

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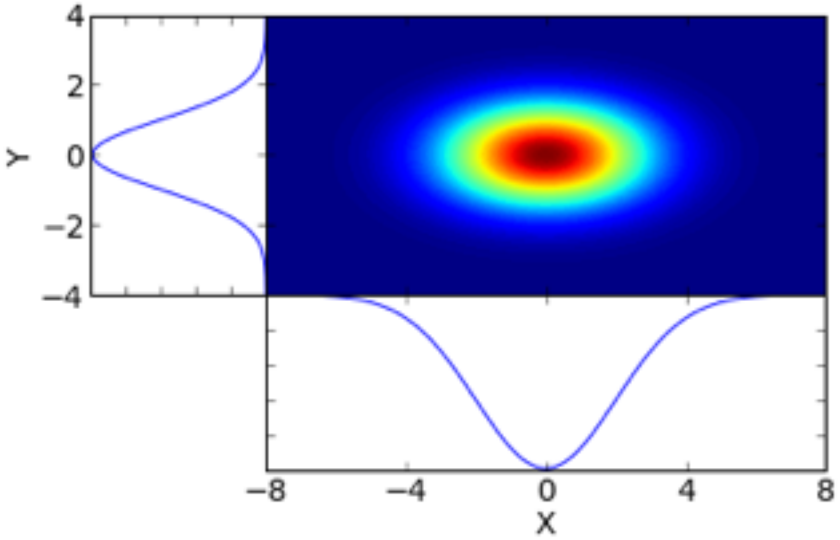

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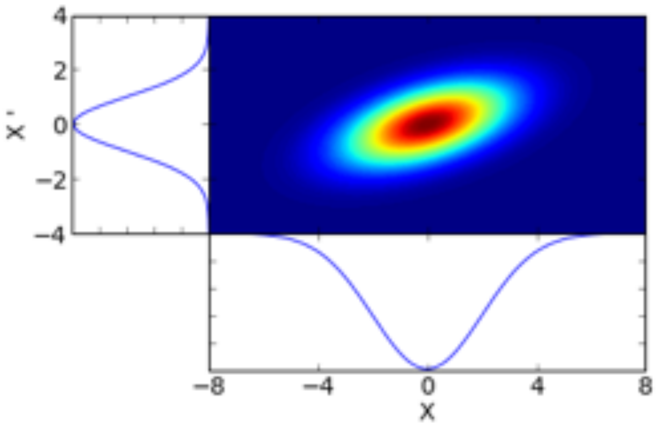
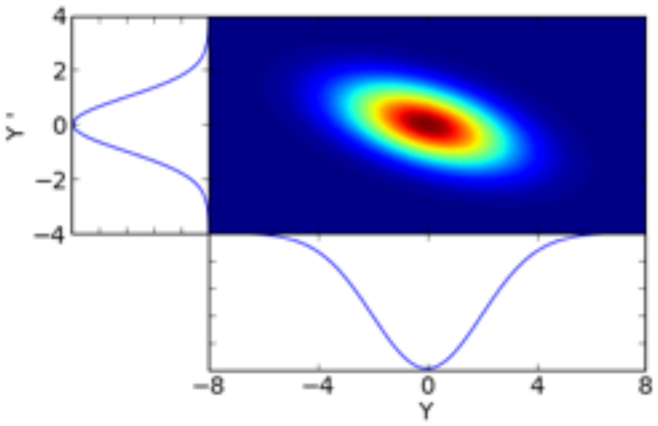
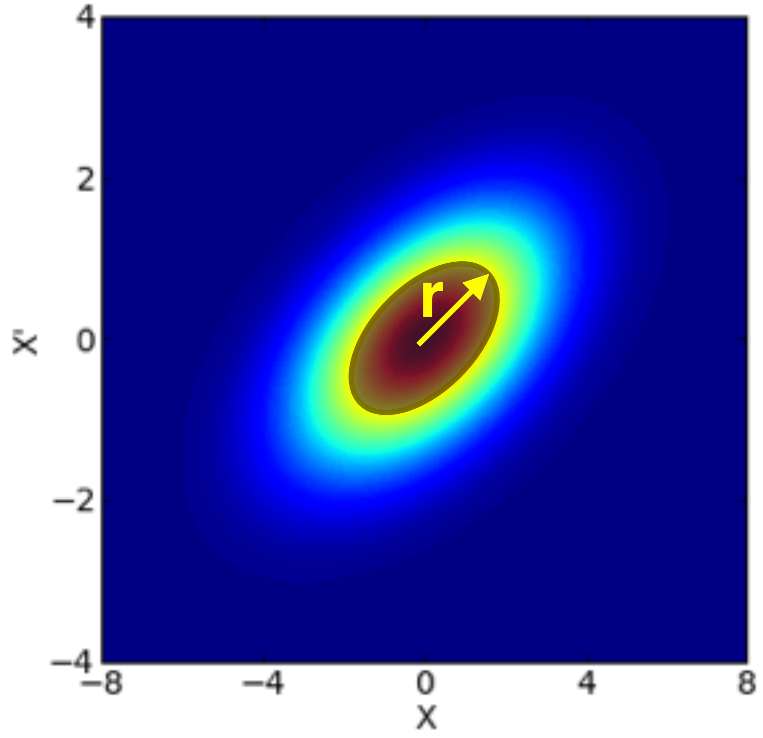


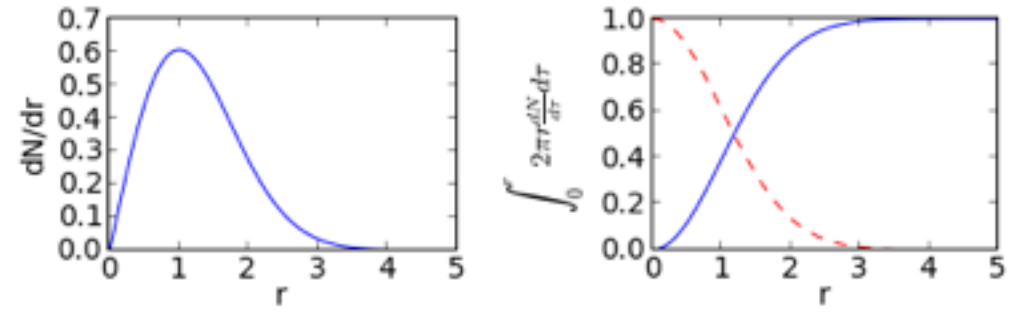
Horizontal profile



Vertical profile

Phase space





Amplitude distribution

Beam profiles

Generic particles distribution

$$i(x,y) \Rightarrow \begin{cases} Prof_H(x) = \int_{-\infty}^{+\infty} i(x,y)dy \\ Prof_V(y) = \int_{-\infty}^{+\infty} i(x,y)dx \end{cases}$$

Gaussian distribution

$$i(x,y) = \frac{N_0}{2\pi\sigma_x\sigma_y} e^{-\left(\frac{x^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2}\right)} \Rightarrow \begin{cases} Prof_H(x) = \frac{N_0}{\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{2\sigma_x^2}} \\ Prof_V(y) = \frac{N_0}{\sqrt{2\pi}\sigma_y} e^{-\frac{y^2}{2\sigma_y^2}} \end{cases}$$

Amplitude distribution

Particles distribution in phase space:

$$i(x, x') = \frac{N_0}{2\pi\sigma_x\sigma_{x'}} e^{-\left(\frac{x^2}{2\sigma_1^2} + \frac{x'^2}{2\sigma_2^2} + \frac{2xx'}{\sigma_3^2}\right)}$$

In normalised space:

$$\begin{cases} \sigma = \bar{\sigma_1} = \bar{\sigma_2} \\ r = X^2 + X'^2 \end{cases}$$

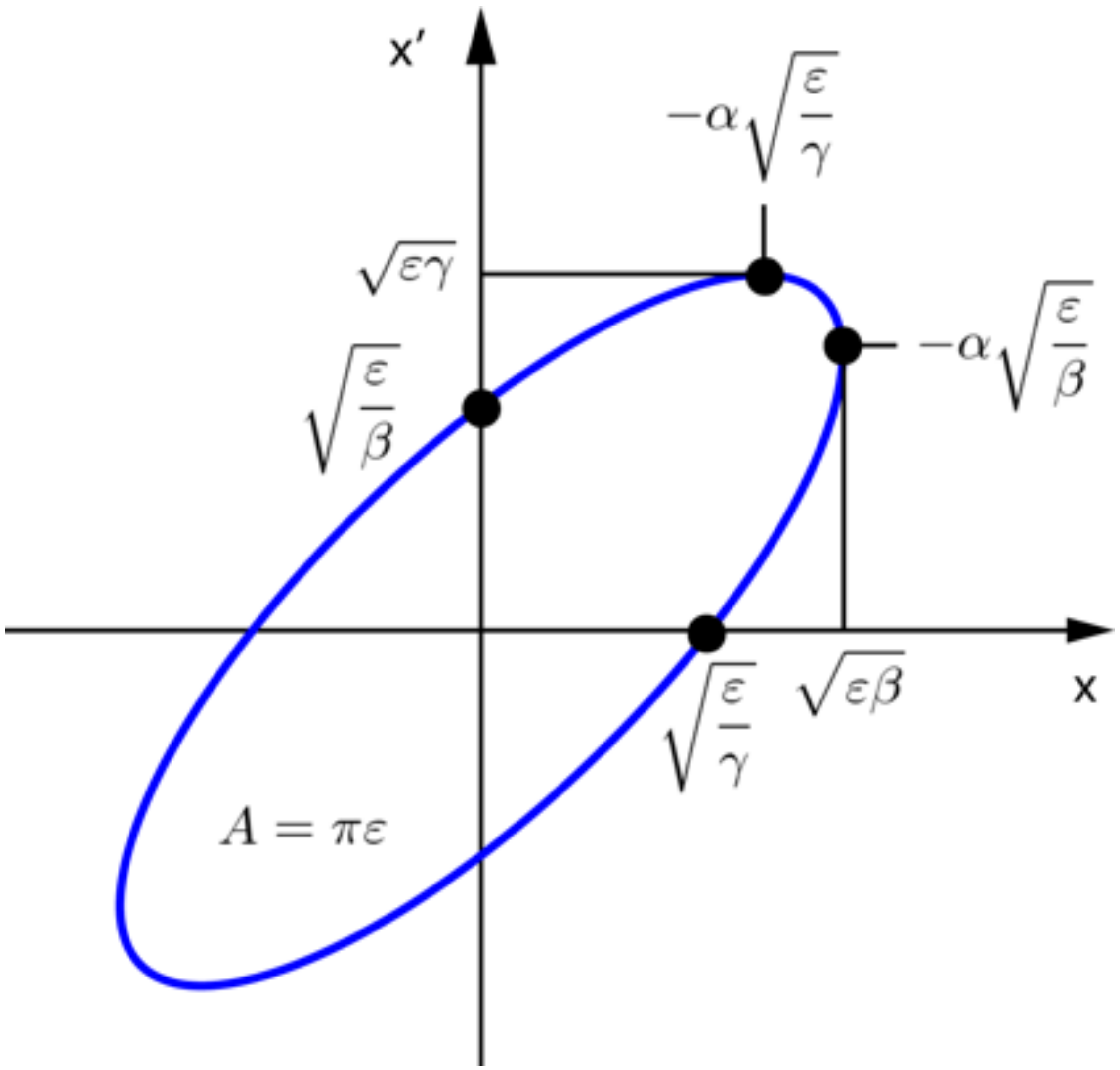
Radial density:

$$\frac{dN}{dr}(r) = \frac{N_0}{\sigma^2} r \cdot e^{-\frac{r^2}{2\sigma^2}}$$

Amplitude distribution

$$I(r) = \int_0^r \frac{N_0}{\sigma^2} \tau \cdot e^{-\frac{\tau^2}{2\sigma^2}} d\tau = N_0 \left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)$$

Courant-Snyder parameters



The phase space ellipse can be defined by 4 parameters:

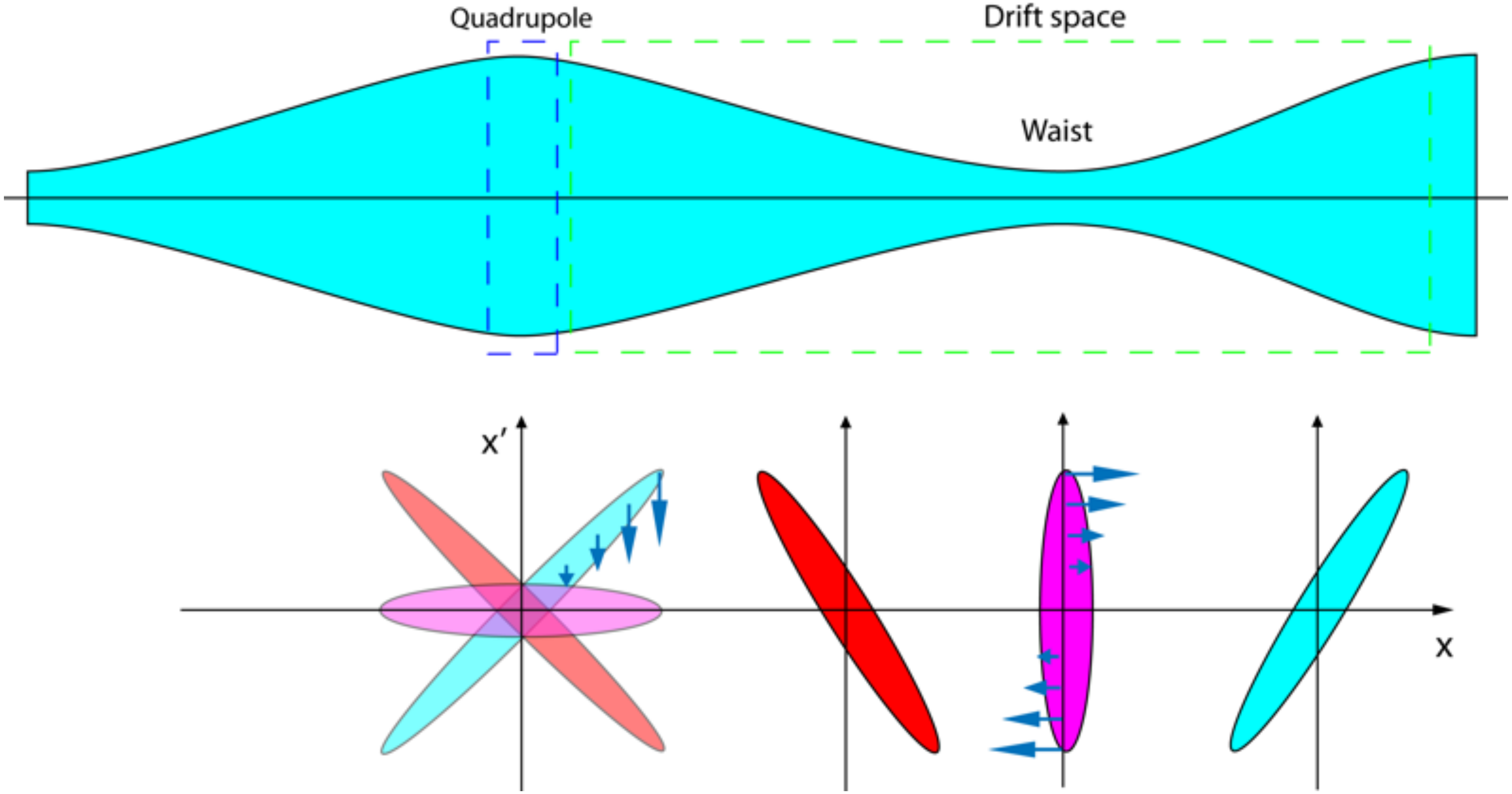
$$(\varepsilon, \beta, \alpha, \gamma)$$

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

And the equation of the ellipse is:

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

Phase space dynamics



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

$$\begin{bmatrix} x_1 \\ x'_1 \end{bmatrix} = M_1 \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix} \qquad \begin{bmatrix} x_2 \\ x'_2 \end{bmatrix} = M_2 \begin{bmatrix} x_1 \\ x'_1 \end{bmatrix} \qquad \begin{bmatrix} x_3 \\ x'_3 \end{bmatrix} = M_3 \begin{bmatrix} x_2 \\ x'_2 \end{bmatrix}$$

$$\begin{bmatrix} x_3 \\ x'_3 \end{bmatrix} = M_3 M_2 M_1 \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix} = M_{0 \Rightarrow 3} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix}$$

$$M_{\text{Drift}} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \qquad M_{\text{Quad}} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} = \begin{bmatrix} \cos(\sqrt{k} L_Q) & \frac{1}{\sqrt{k}} \sin(\sqrt{k} L_Q) \\ -\sqrt{k} \sin(\sqrt{k} L_Q) & \cos(\sqrt{k} L_Q) \end{bmatrix}$$

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

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

3 profiles emittance

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

$$\boxed{\sqrt{\varepsilon\beta} = \text{Beam Size}}$$

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

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

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)

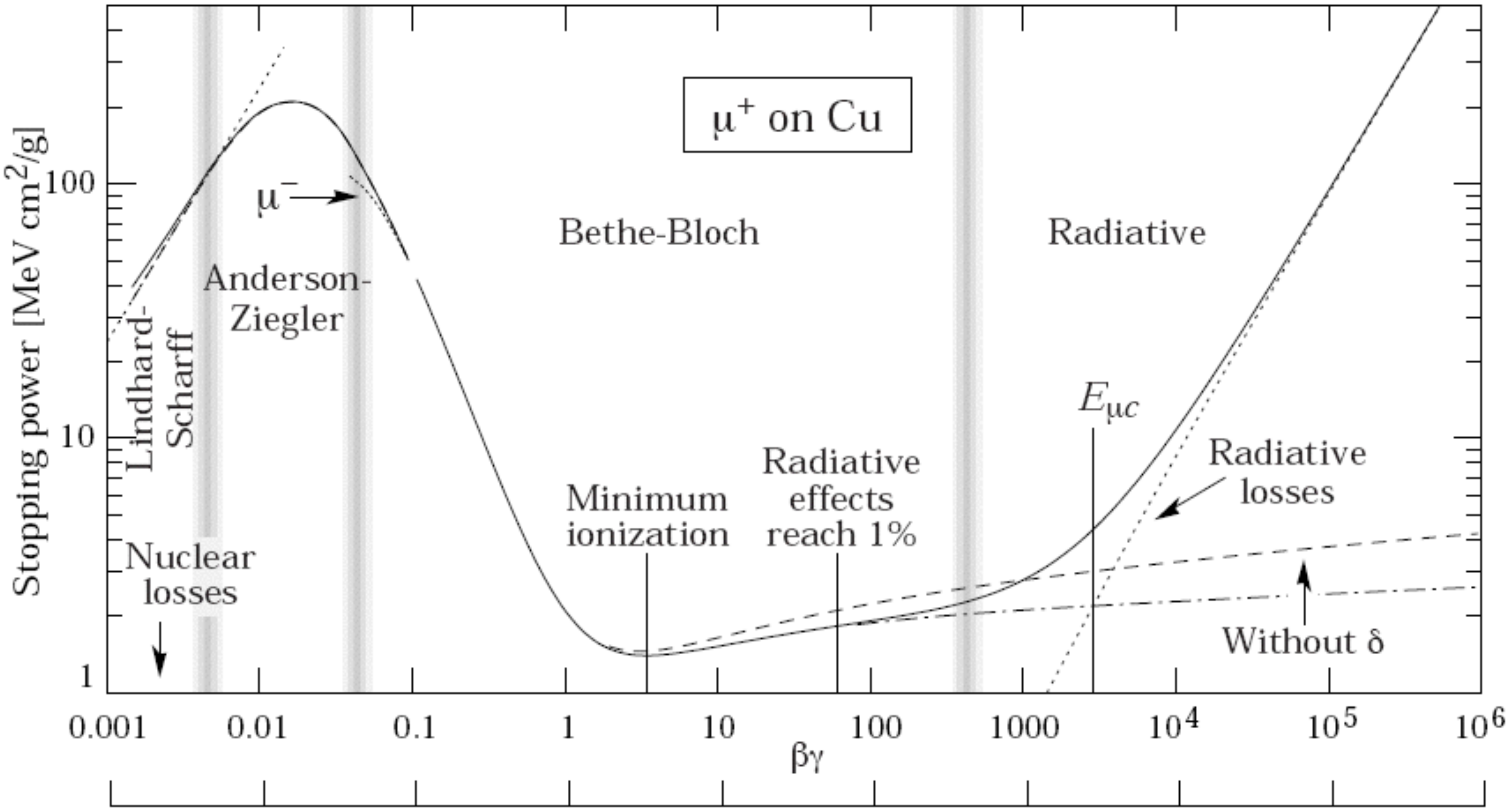
Interaction of particles with matter

- **Ionisation**
  - 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)
- **Radiation**
  - Cherenkov radiation
  - Bremsstrahlung
  - Optical transition radiation

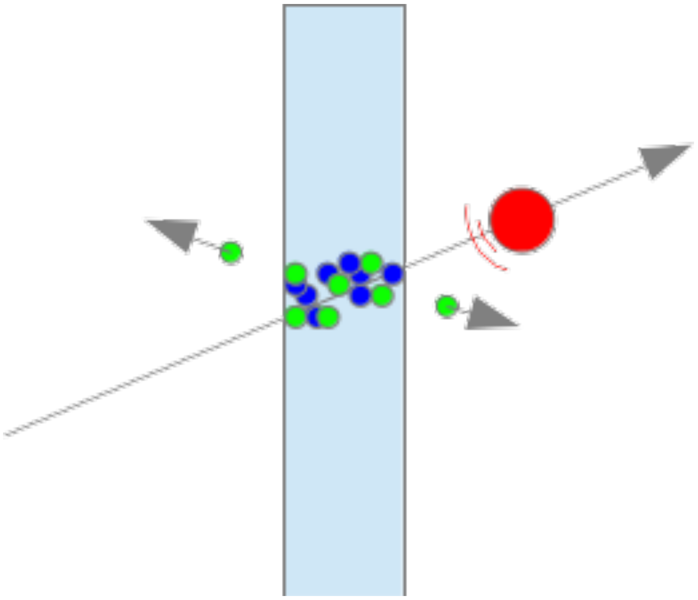
Energy deposition

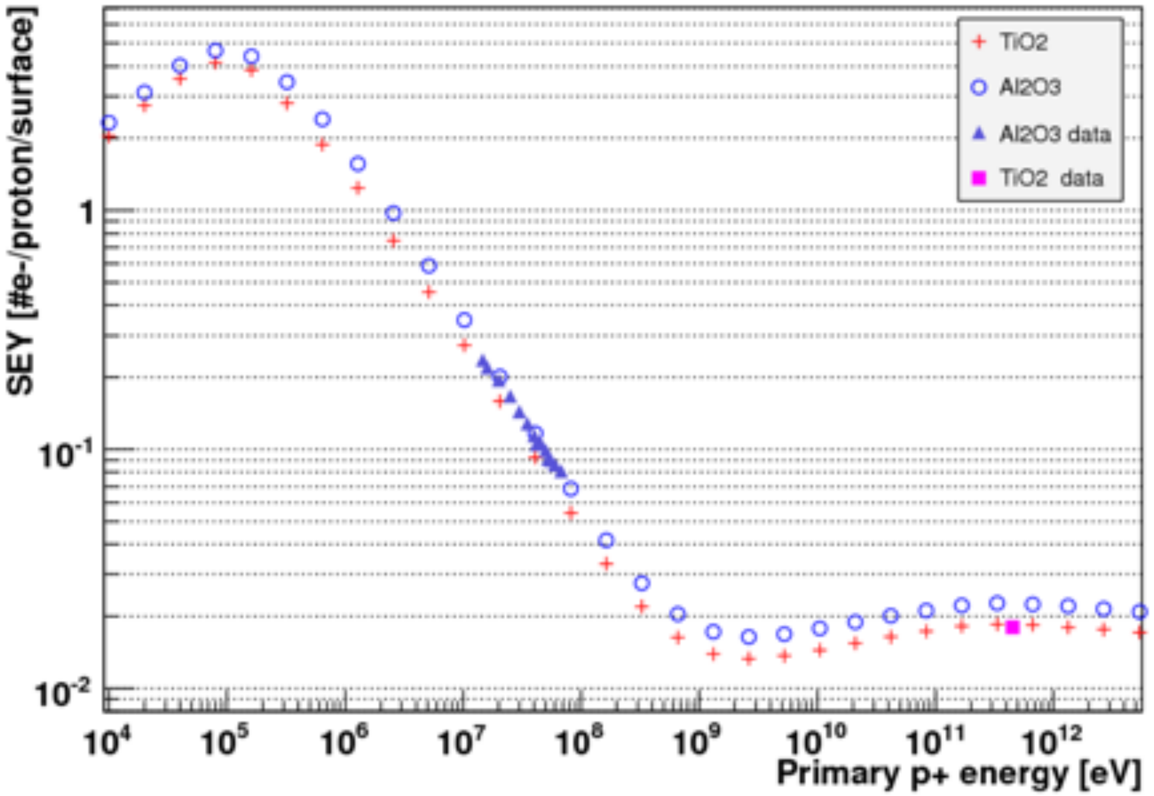
- Energy deposition is probably the most important aspect for all intercepting devices
    - Signals are often proportional to the deposited energy
    - Energy deposition can cause damage to the instrument
- The Bethe-Bloch formula describes energy losses for many of our cases
- The energy lost by the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

Energy deposition - dE/dx



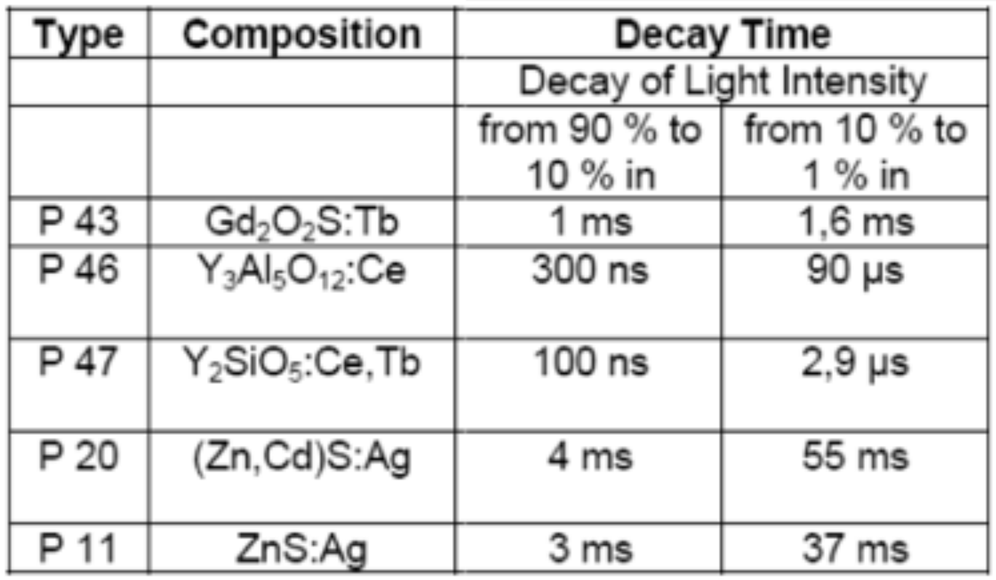
Secondary emission - SEM



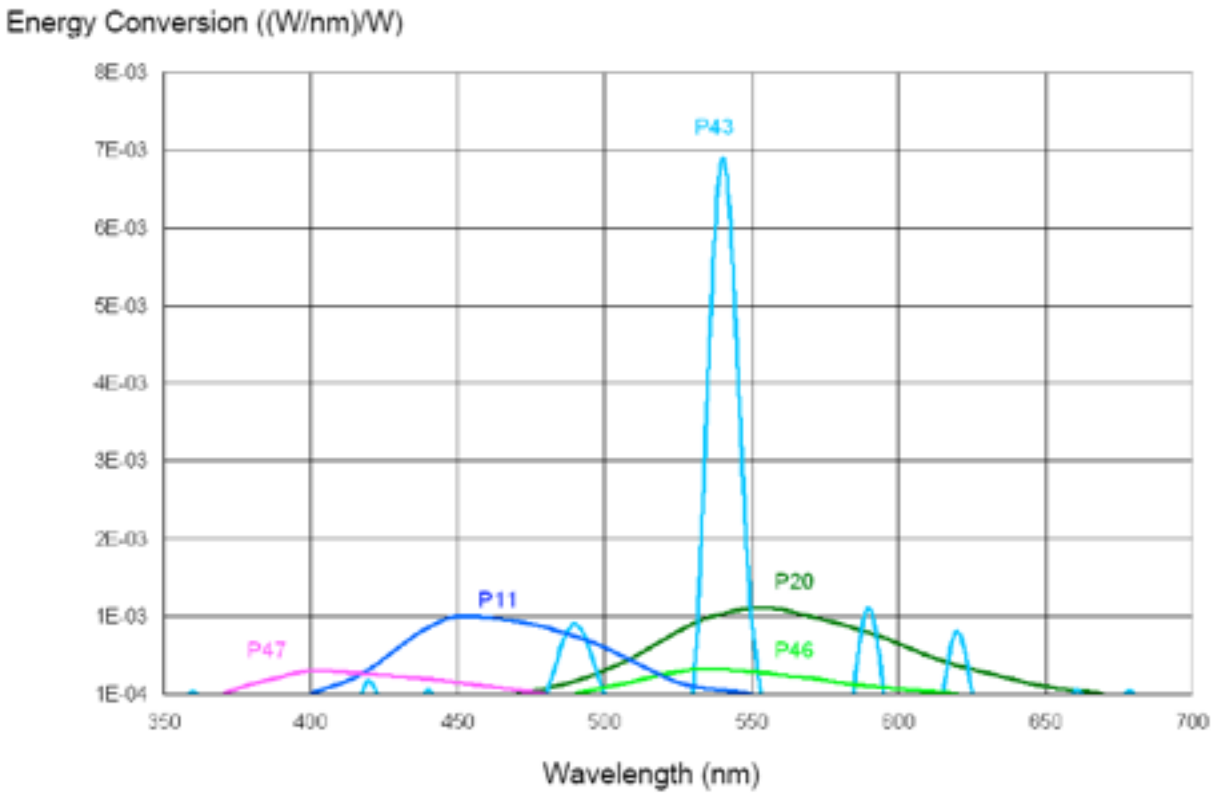


- Linked to ionisation
- Surface electrons receive sufficient energy to travel to the surface and leave
- Emission yield depends on particles energy, material, surface state, EM fields, etc.

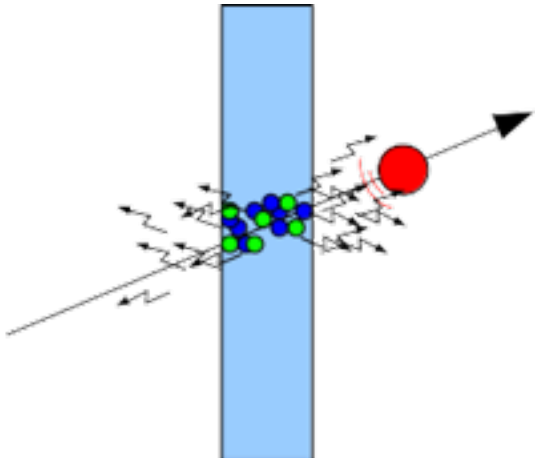
Scintillation



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



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



1MeV 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

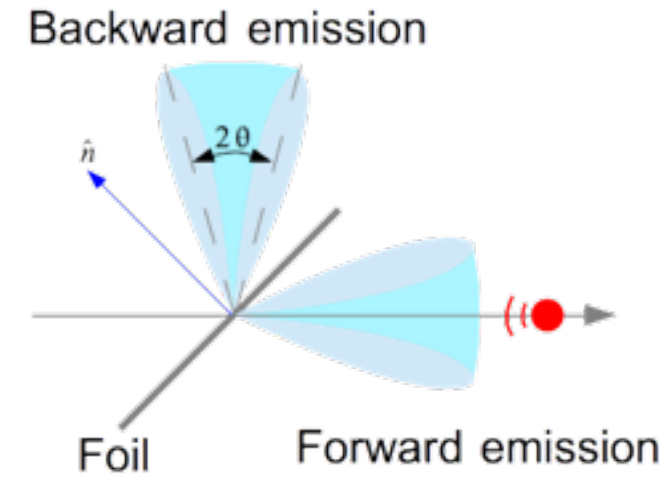
- Normally used only for very low intensity beams

- Ceramics, glasses and crystals are a more popular choice in high energy accelerators

- CHROMOX (Al_2O_3:CrO_2, Aluminium Oxide) is a very common choice because it is a very robust ceramic

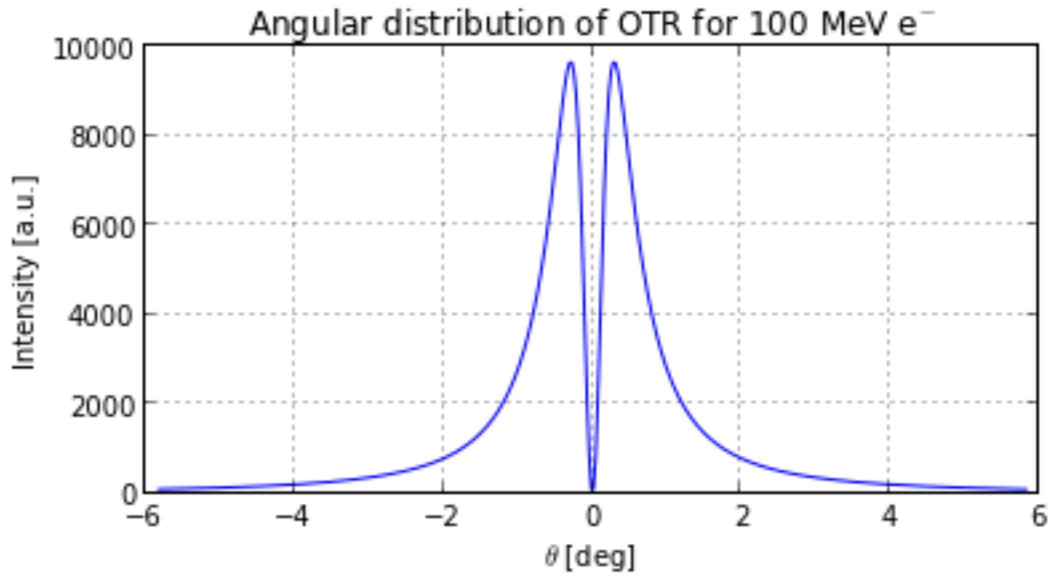
- YAG ($Y_3Al_5O_{12}$) is also a very frequent choice (fast)

Optical Transition Radiation (OTR)



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

$$W \propto \begin{cases} \beta^2 & if \quad \beta \ll 1 \\ \ln(2\gamma) & if \quad \gamma \gg 1 \end{cases}$$



Peaks at

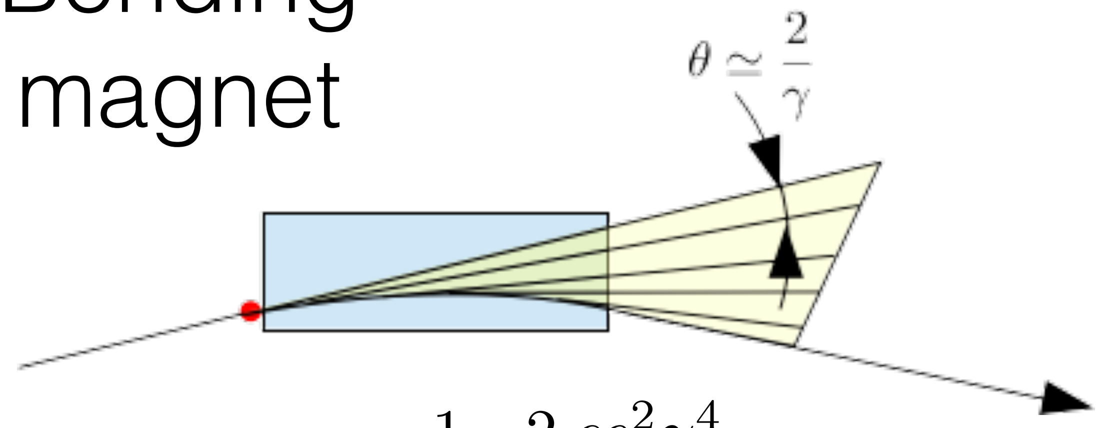
$$\theta = \frac{1}{\gamma}$$

For λ ∈ [400, 600] nm
100 keV electrons ~ 0.001 ph./el.
50 MeV electrons ~ 0.3 ph./el.

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

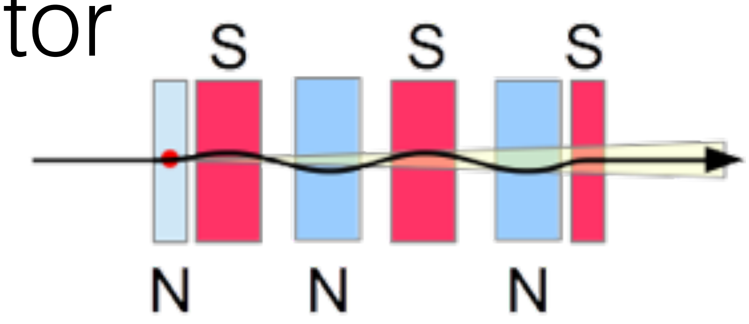
Synchrotron radiation

Bending magnet



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

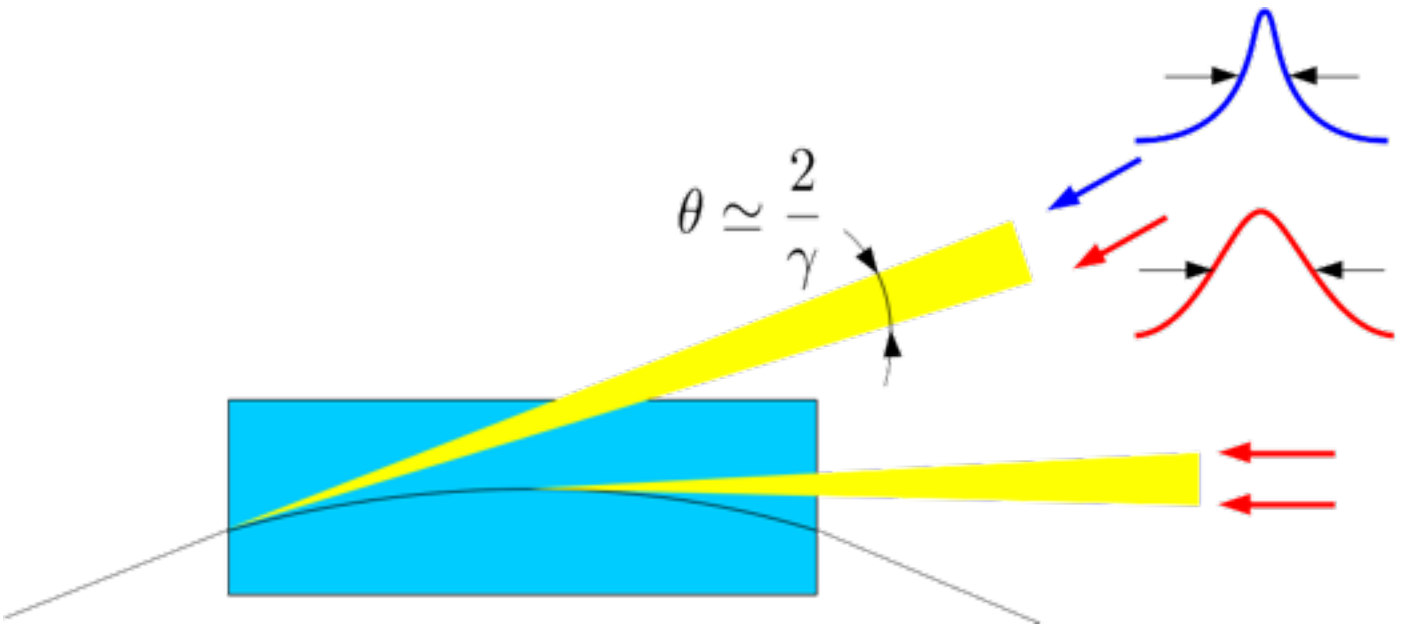
Undulator



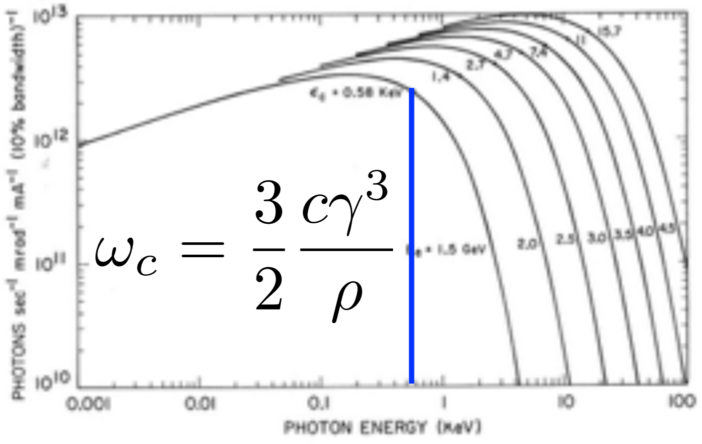
$$\lambda = \frac{\lambda_u}{2\gamma^2} \qquad W \propto B_0^2\gamma^2$$

- 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

Edge radiation

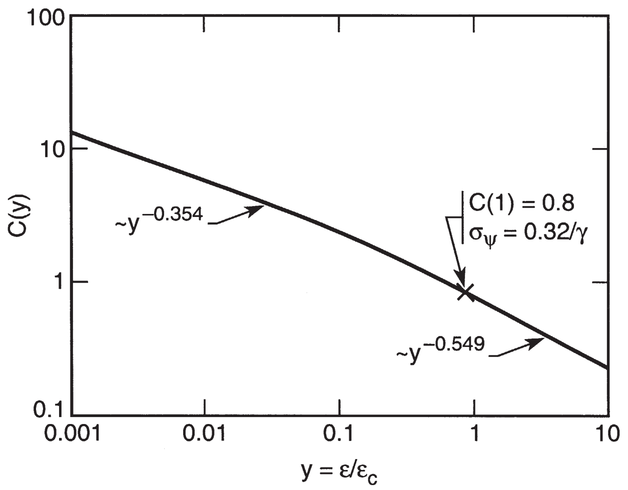


$$\theta \simeq \frac{2}{\gamma}$$



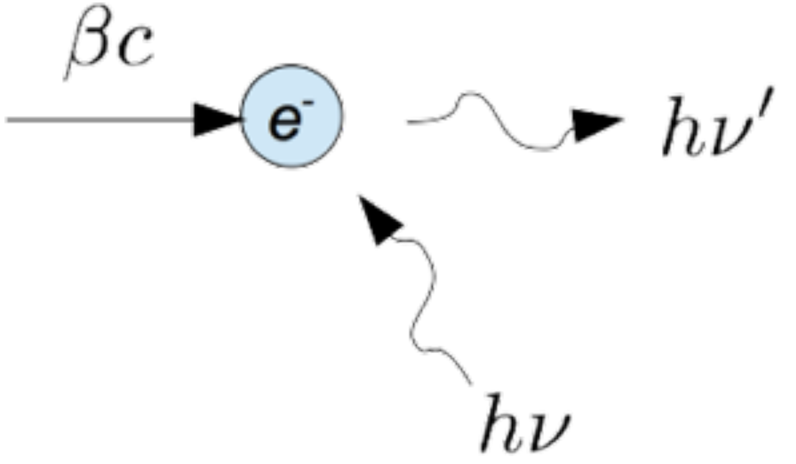
$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}$$

$$\sigma_\theta = \frac{2}{\gamma\sqrt{2\pi}}C(y)$$



Red observers sees longer pulses and narrower spectrum.
Blue observer sees shorter pulses and as a consequence broader spectrum (edge radiation).

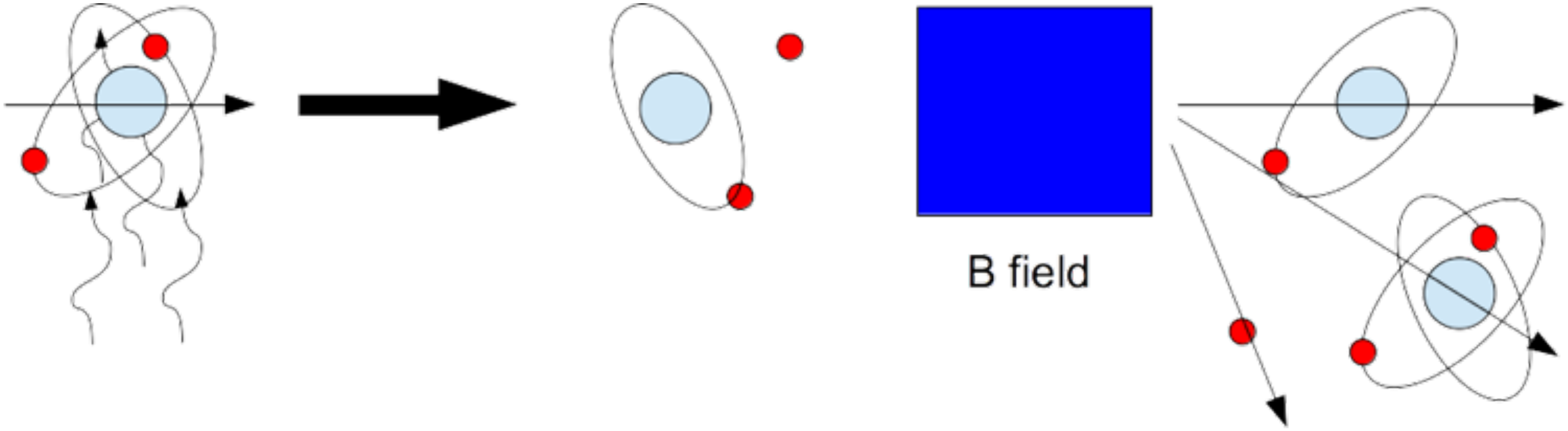
Inverse Compton scattering



$$\nu'_{\max} = \gamma^2 \nu$$

- 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 particle
- Cross section is small, but usable for e^- and e^+, it is very small for hadrons (protons)

Photo dissociation
(H^- beams)



Photons from a laser are used to separate one electron from the H^- ion. This can be facilitated by external electric or magnetic fields

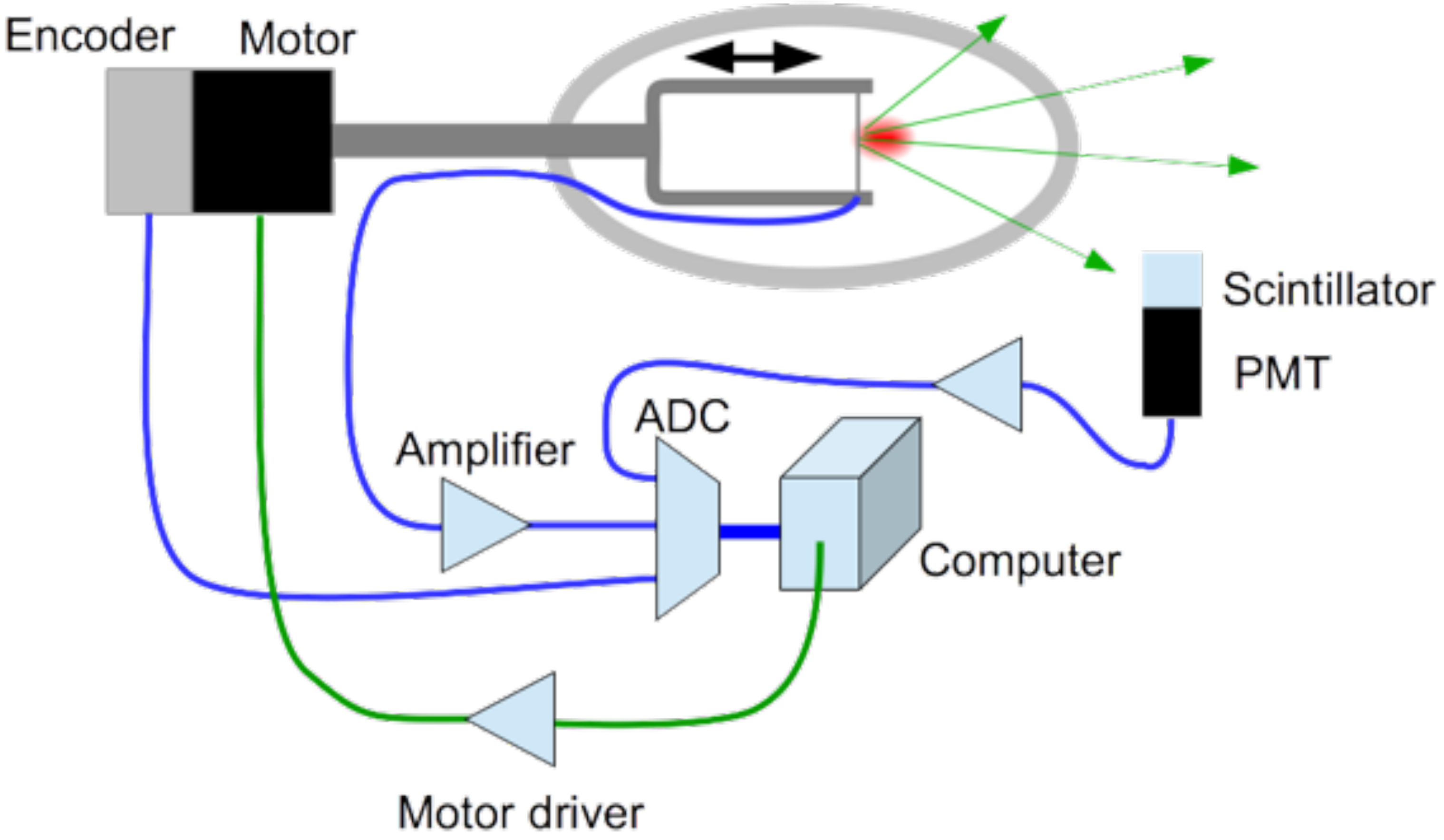
Some of the ions will lose the extra electron and become neutral H^0

The different species can be separated by a bending magnet

Sampling distributions

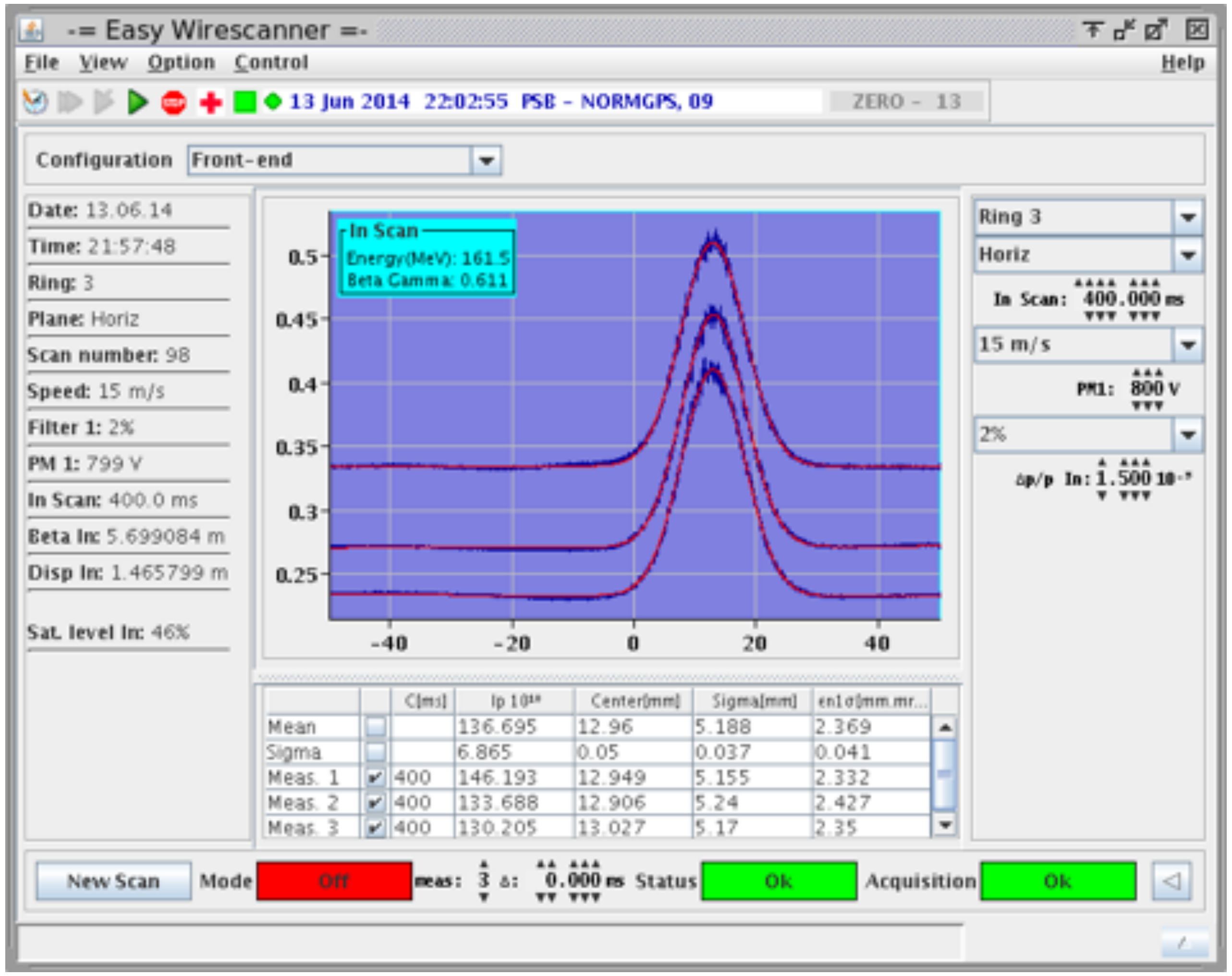
- **One dimension sampling**
  - Wire scanners
  - Wire grids
  - Rest gas ionisation monitors
  - Laser Wire Scanner
- **Two dimension sampling**
  - Screens and radiators
  - Synchrotron radiation

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



13 Jun 2014 22:02:55 PSB - NORMGPS, 09

ZERO - 13

Configuration: Front-end

Date: 13.06.14

Time: 21:57:48

Ring: 3

Plane: Horiz

Scan number: 98

Speed: 15 m/s

Filter 1: 2%

PM 1: 799 V

In Scan: 400.0 ms

Beta In: 5.699084 m

Disp In: 1.465799 m

Sat. level In: 46%

Energy(MeV): 161.5

Beta Gamma: 0.611

Ring 3

Horiz

In Scan: 400.000 ms

15 m/s

PM1: 800 V

2%

Δp/p In: 1.500 10^{-3}

		C[ms]	Ip 10^{10}	Center[mm]	Sigma[mm]	en1σ[mm.mr...
Mean	☐		136.695	12.96	5.188	2.369
Sigma	☐		6.865	0.05	0.037	0.041
Meas. 1	☑	400	146.193	12.949	5.155	2.332
Meas. 2	☑	400	133.688	12.906	5.24	2.427
Meas. 3	☑	400	130.205	13.027	5.17	2.35

Mode: Off

meas: 3 Δ: 0.000 ms

Status: Ok

Acquisition: Ok

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

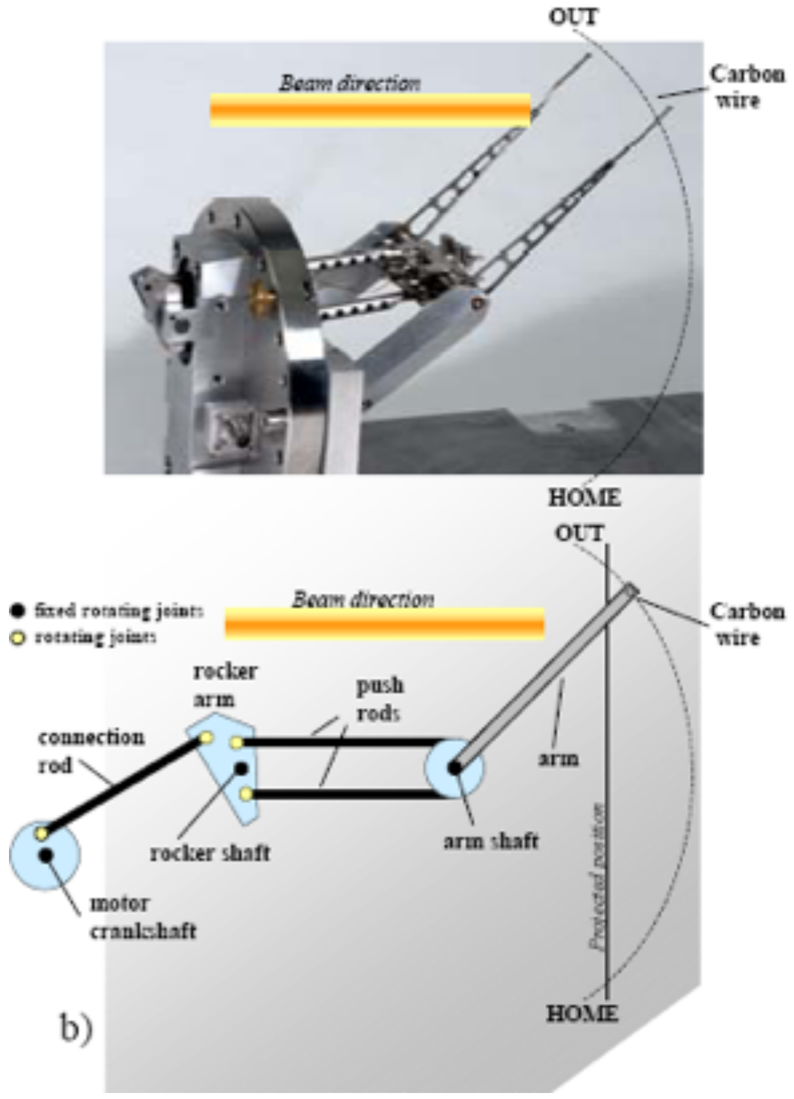
Wire scanner

- **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

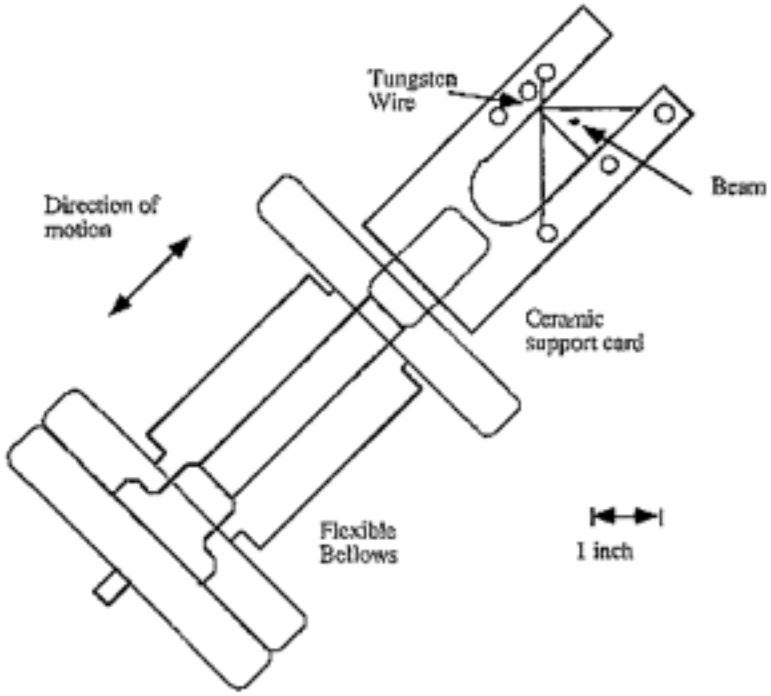
Wire scanner

- **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

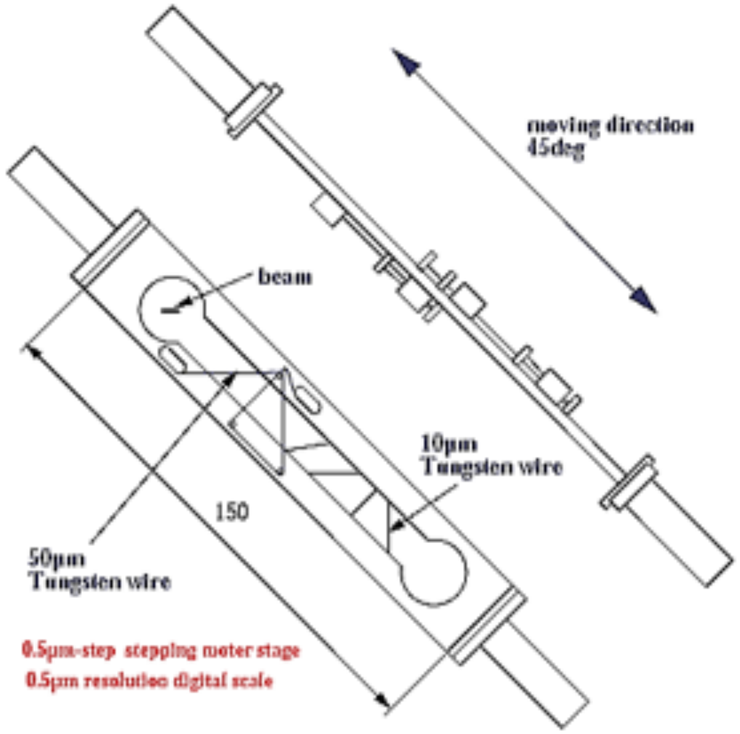
Wire scanner



CERN “flying wires”

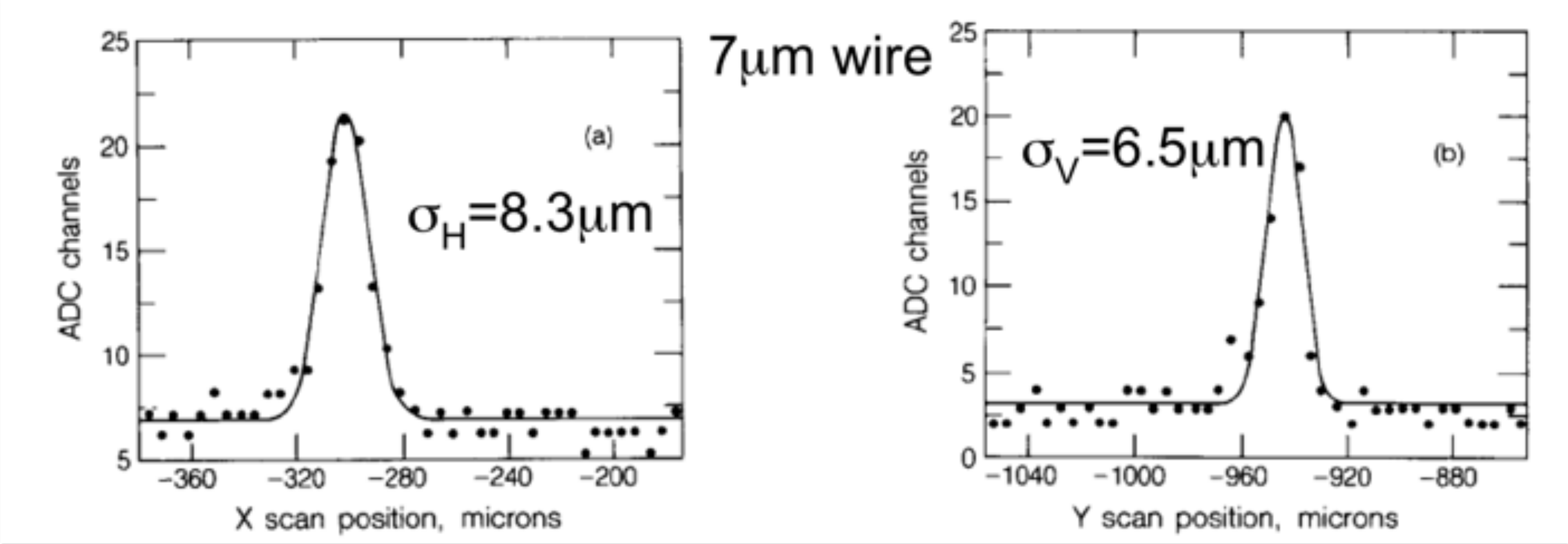


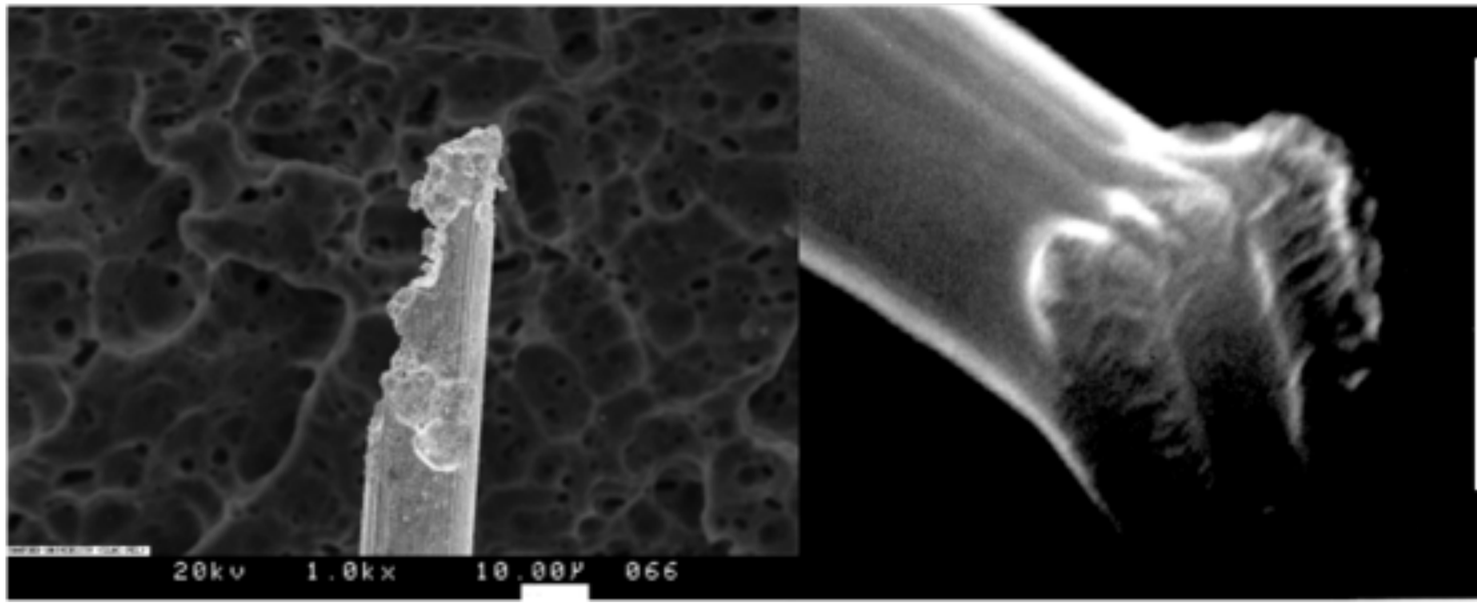
SLAC SLC high resolution 3 axis scanners

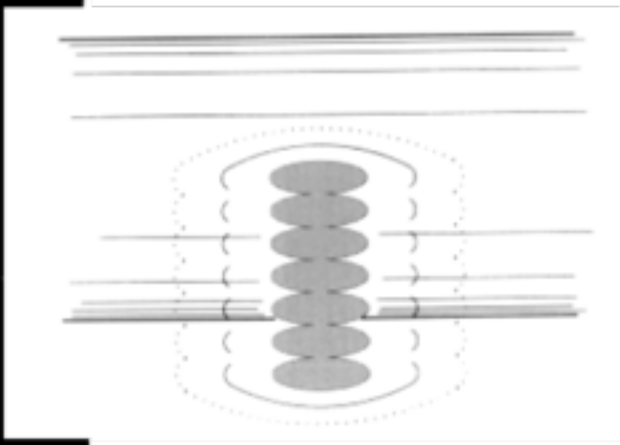


KEK ATF high resolution 3 axis scanners

Wire Scanner (SLC)

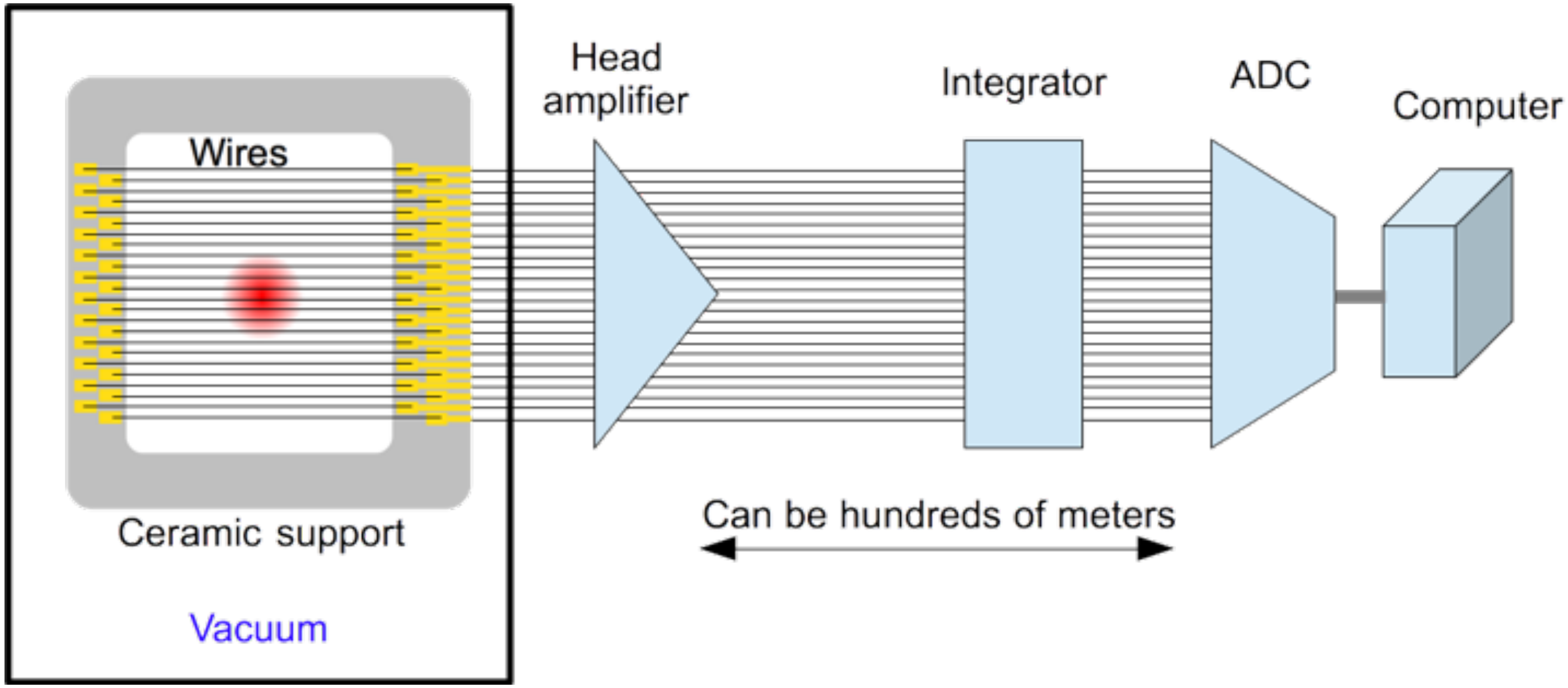




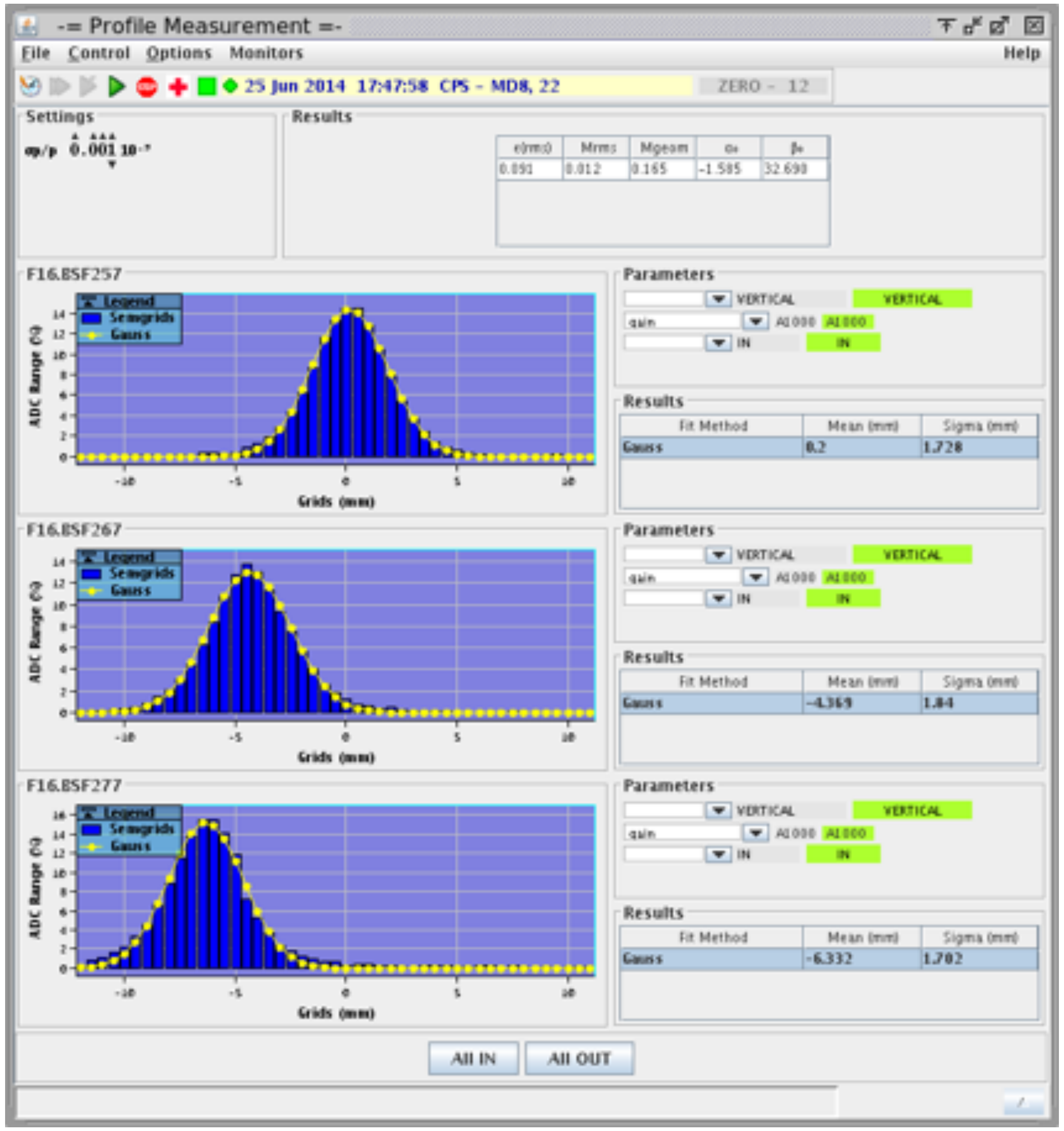


SEM Grid (Wire Harp)

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



SEM Grid



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dp/p 0.001 10⁻³

ε(rms)	Mrms	Mgeom	α	β
0.091	0.012	0.165	-1.585	32.690

F16.BSF257

VERTICAL — VERTICAL
gain — A1000 — A1000
IN — IN

Fit Method	Mean (mm)	Sigma (mm)
Gauss	0.2	1.728

F16.BSF267

VERTICAL — VERTICAL
gain — A1000 — A1000
IN — IN

Fit Method	Mean (mm)	Sigma (mm)
Gauss	-4.369	1.84

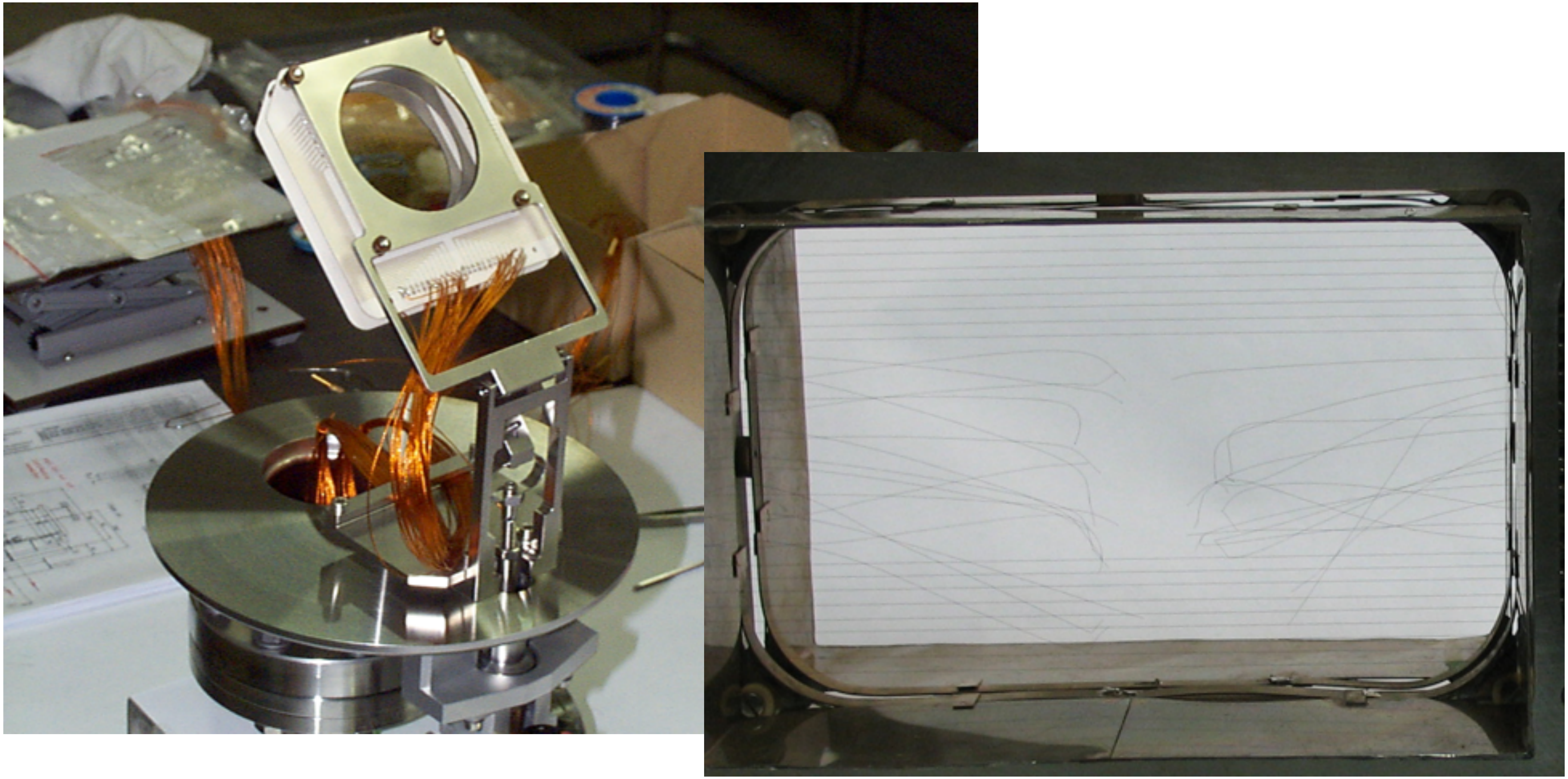
F16.BSF277

VERTICAL — VERTICAL
gain — A1000 — A1000
IN — IN

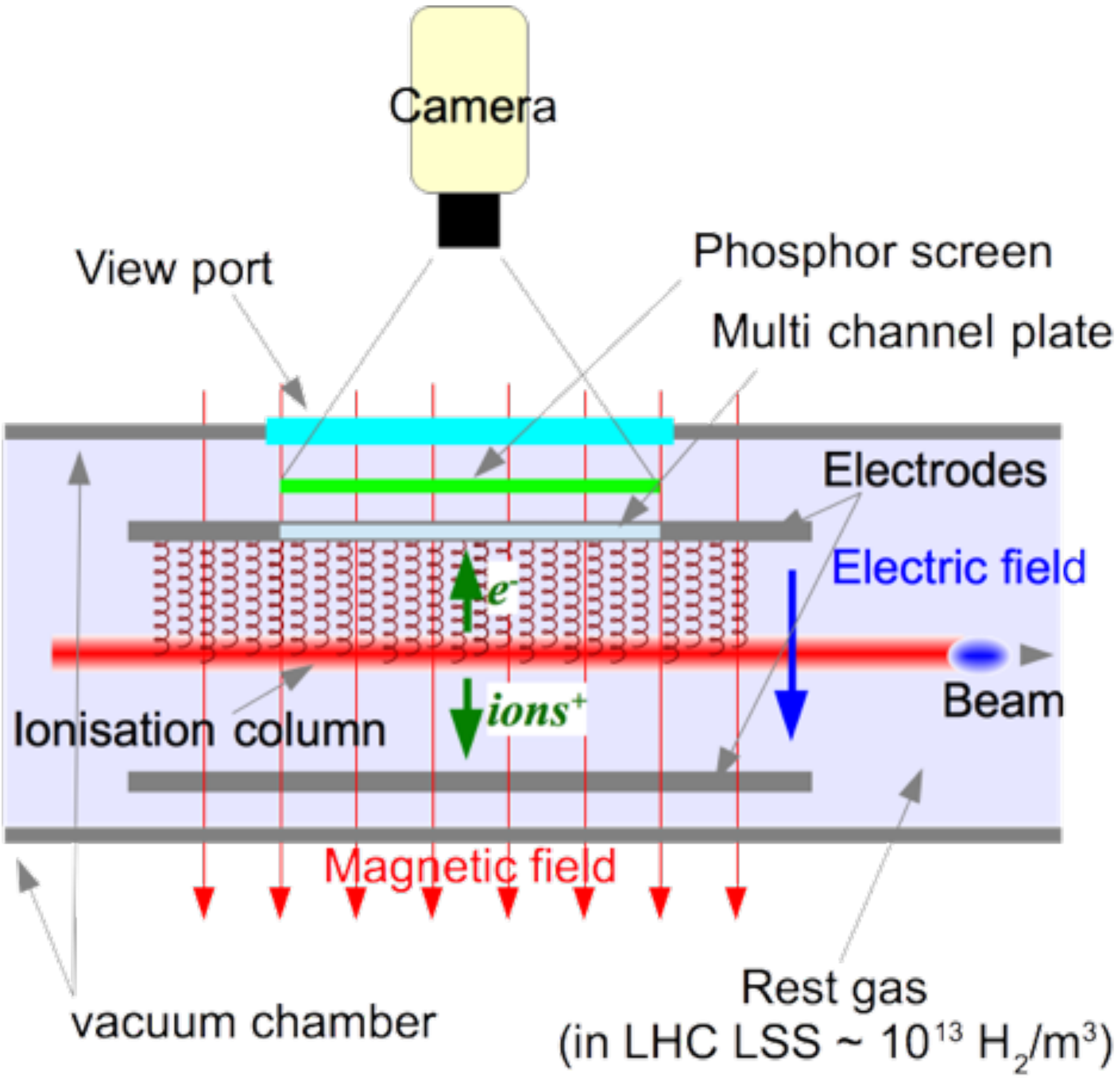
Fit Method	Mean (mm)	Sigma (mm)
Gauss	-6.332	1.702

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

SEM Gid

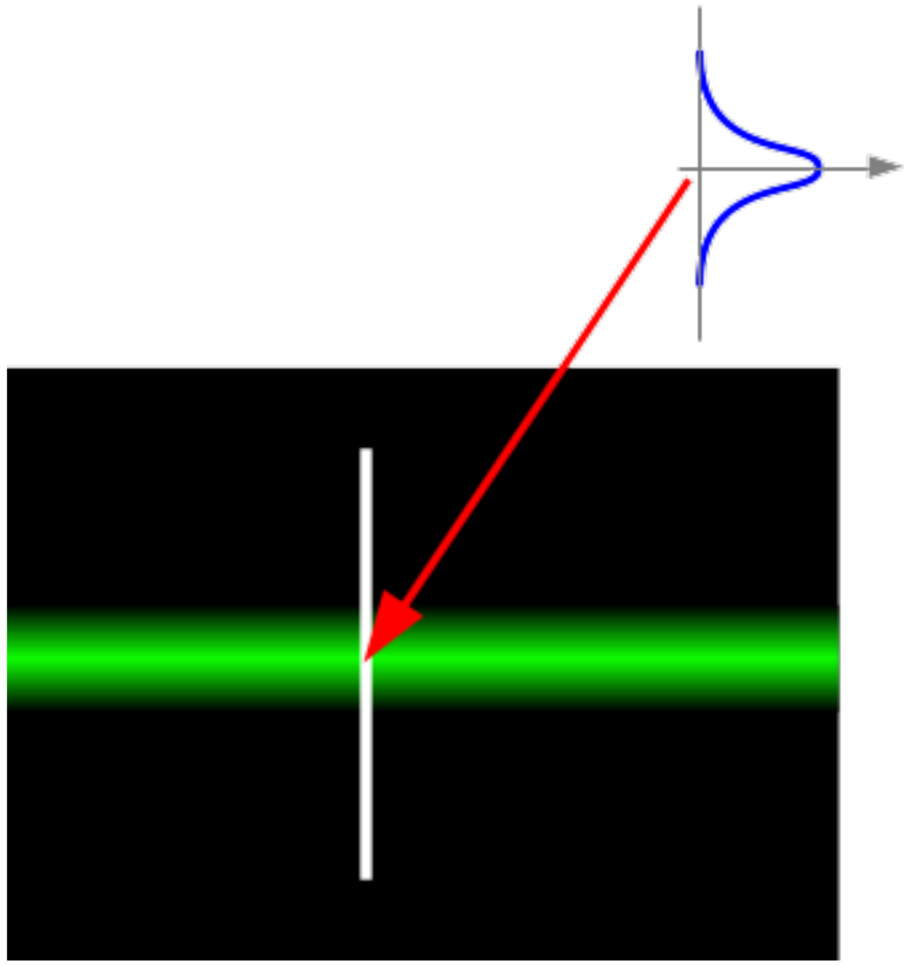


Ionisation profile monitor



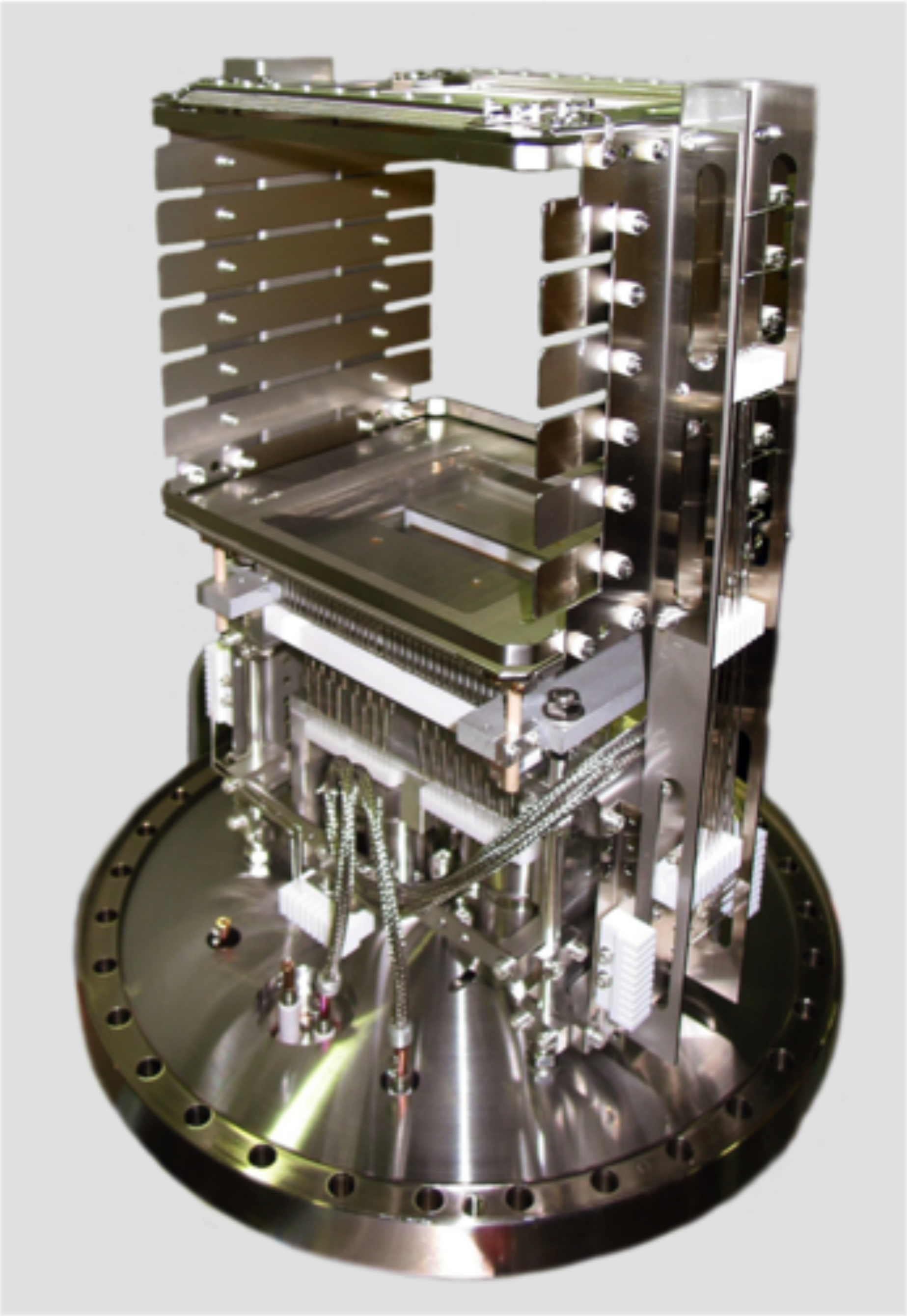
- Beam creates ionisation column in rest gas
- Electric field drifts electrons Ions) toward detector
- Magnetic field guides the electron (ions)
- MCP+phosphor+CCD detects electrons (ions)
- If E is reversed ions can be detected instead of electrons (less need for B field)

Ionisation profile monitor

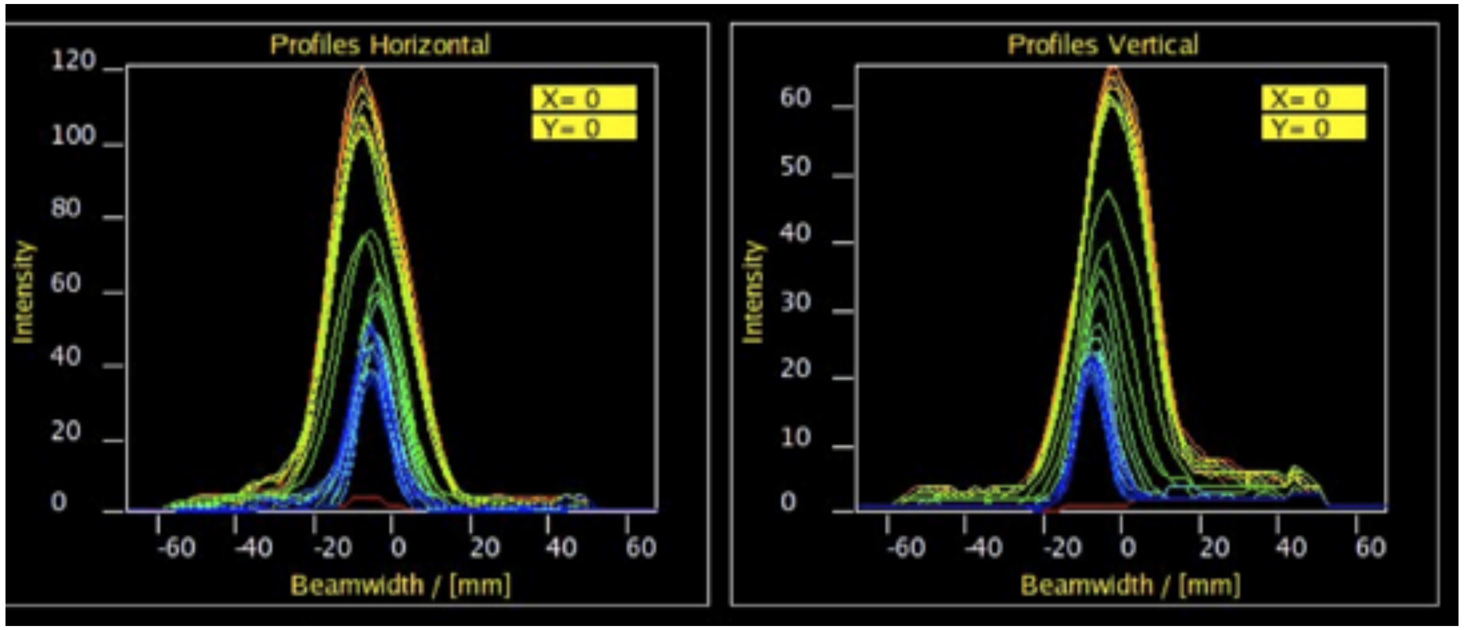


- Image shows a stripe
- Intensity profile of stripe proportional to beam profile
- Detector measures only one plane
- Transverse drift of electrons introduces broadening (need intense B field) and creates “tails”

IPM (GSI)

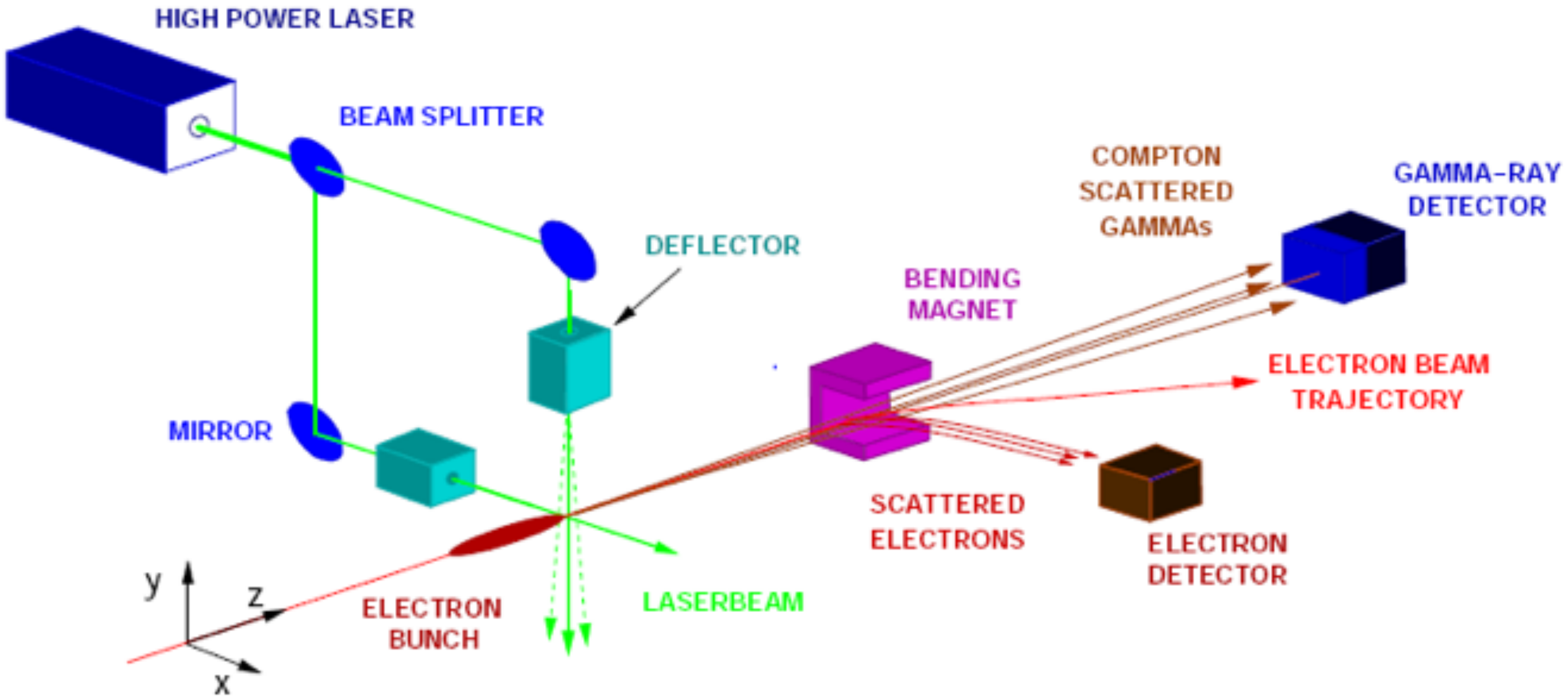


- IPMs allow the continuous monitoring of the transverse plane
- Needs a “minimum” of rest gas

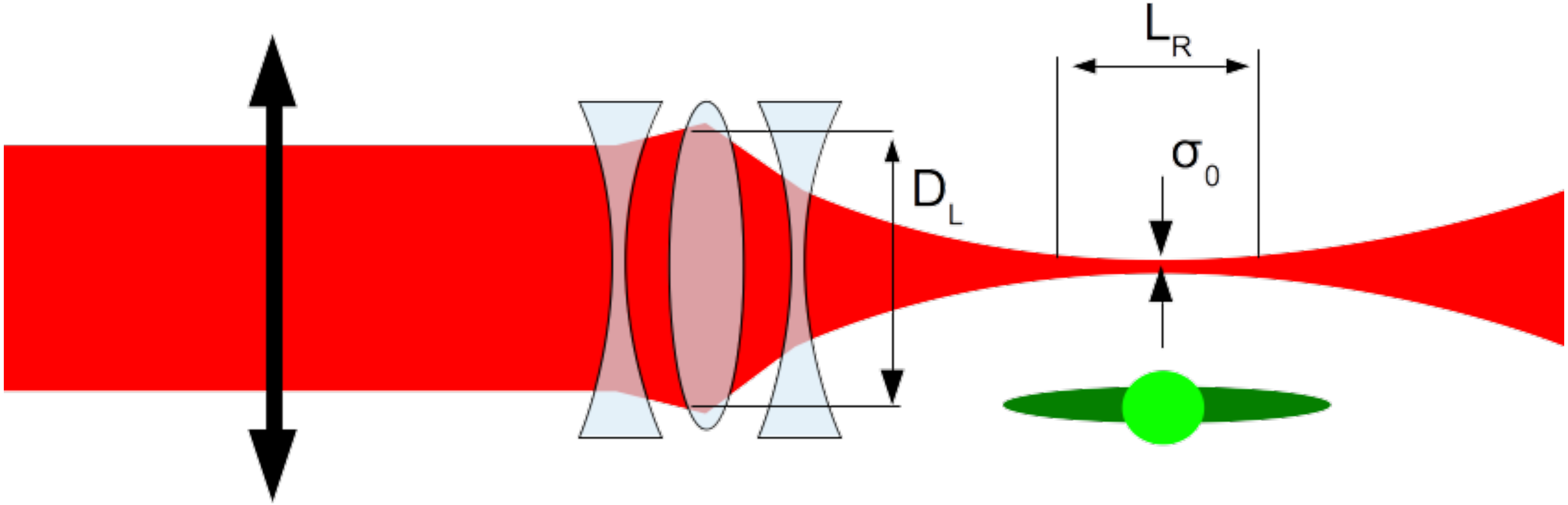


Laser Wire Scanner

- 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



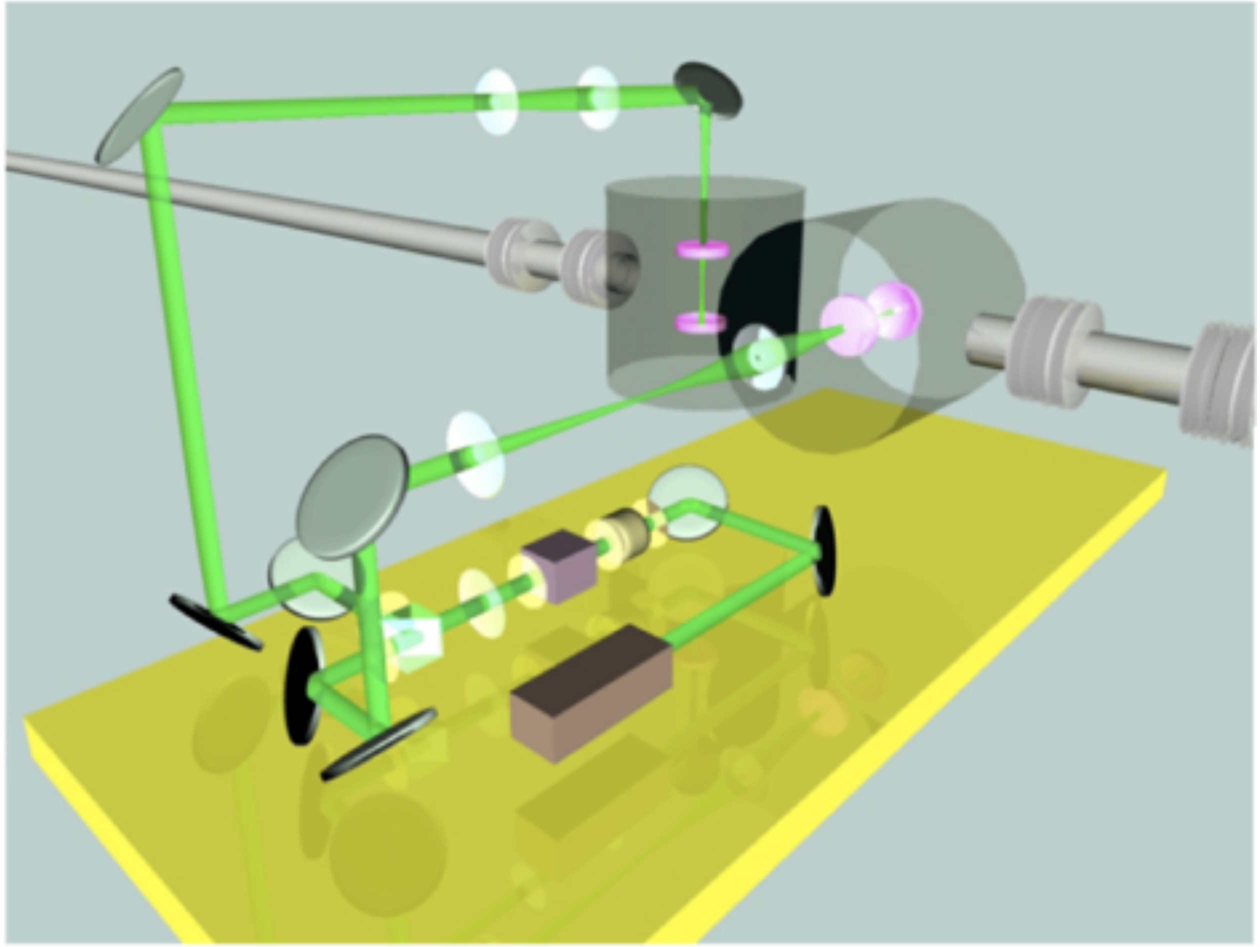
Laser Wire Scanner



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

$$\sigma_0 = \frac{\lambda f}{D_L} = \lambda\, f/\# \qquad\qquad L_R = \frac{2\pi\sigma_0}{\lambda}$$

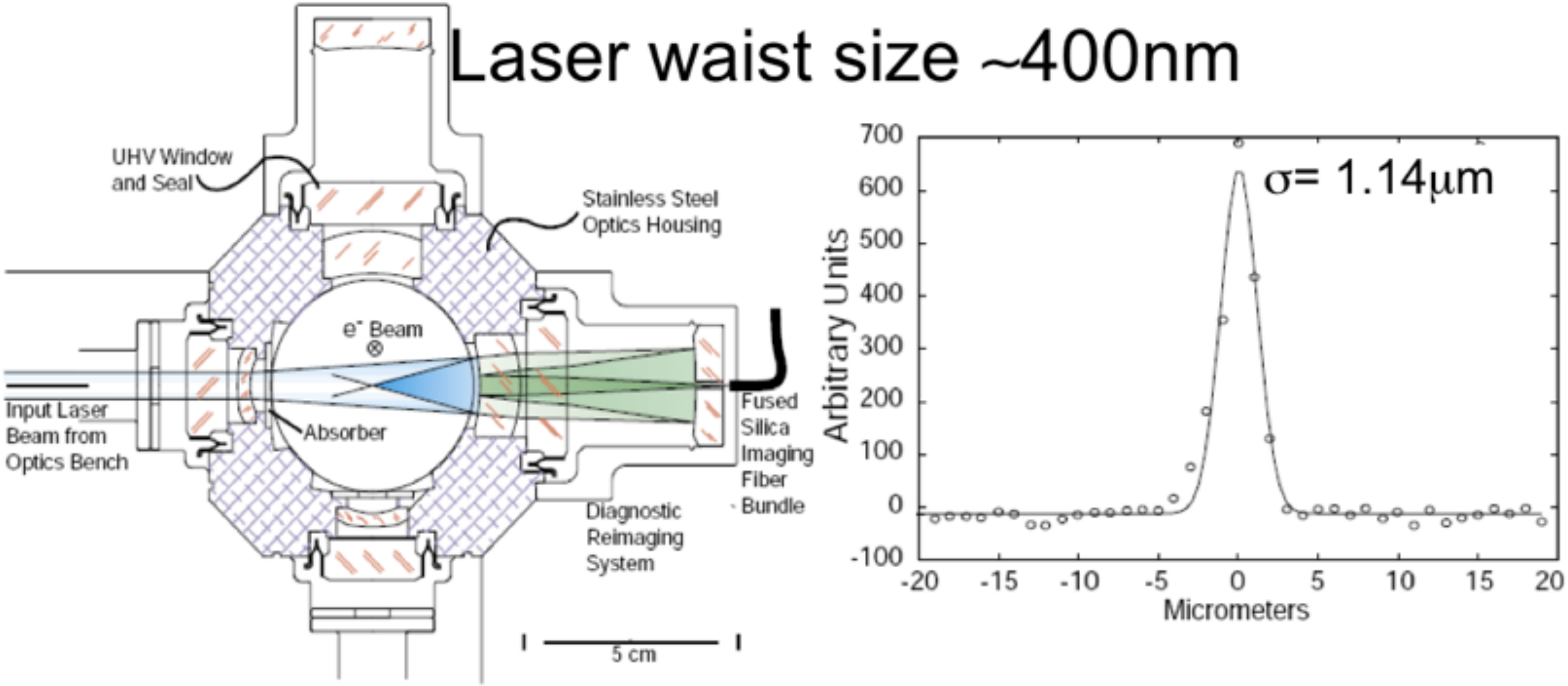
Laser Wire Scanner



- On the ATF ring original solution
- Instead of using a powerful laser an optical cavity surrounds the electrons beam
- The whole table is scanned

Laser Wire Scanner

LWS used at SLC to measure the beam size at the IP

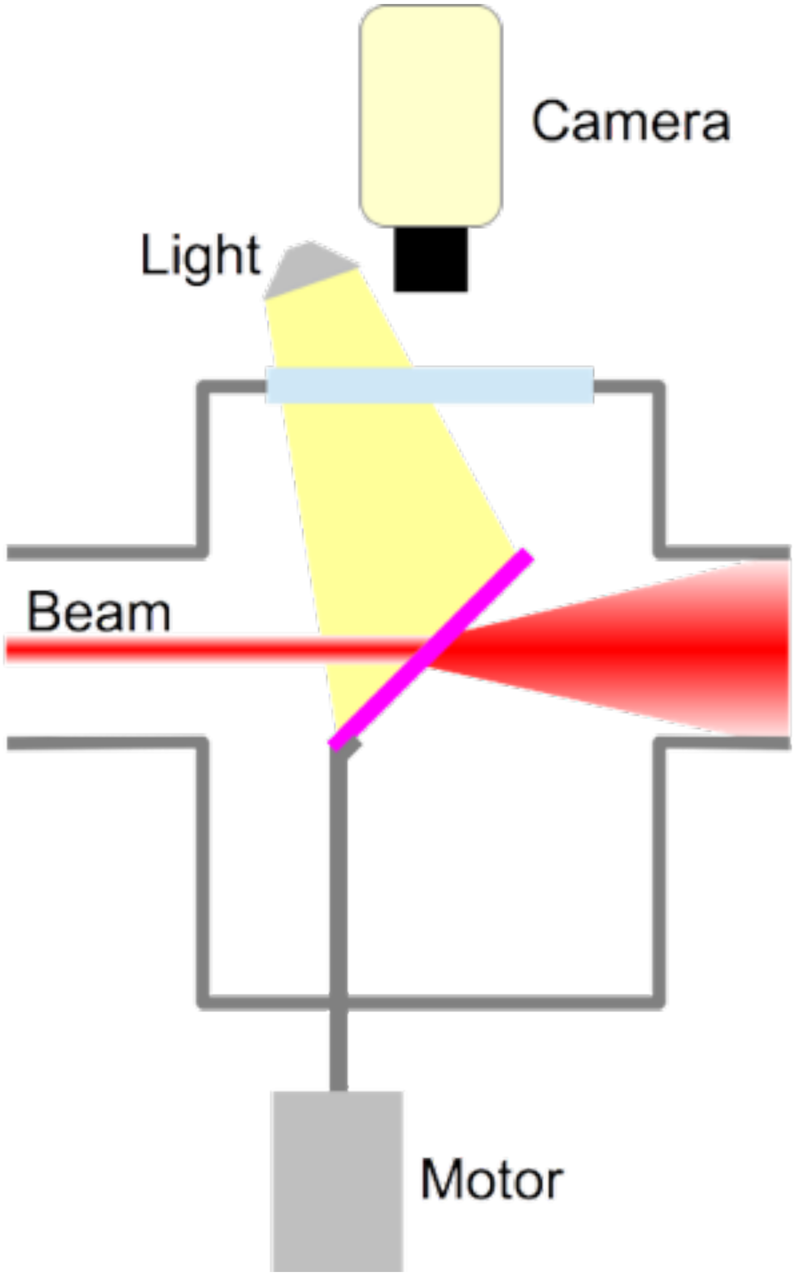


Laser waist size ~400nm

Laser Wire Scanner

- 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)

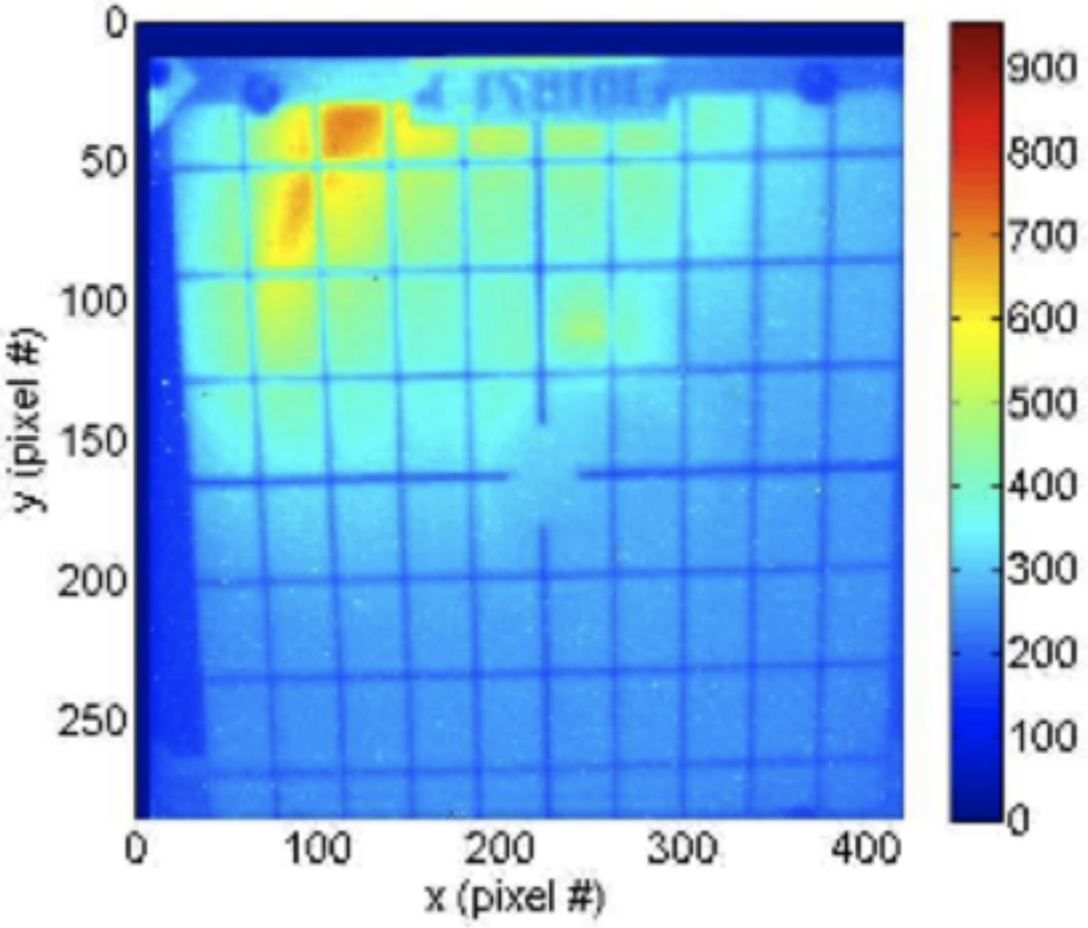
Scintillating screen

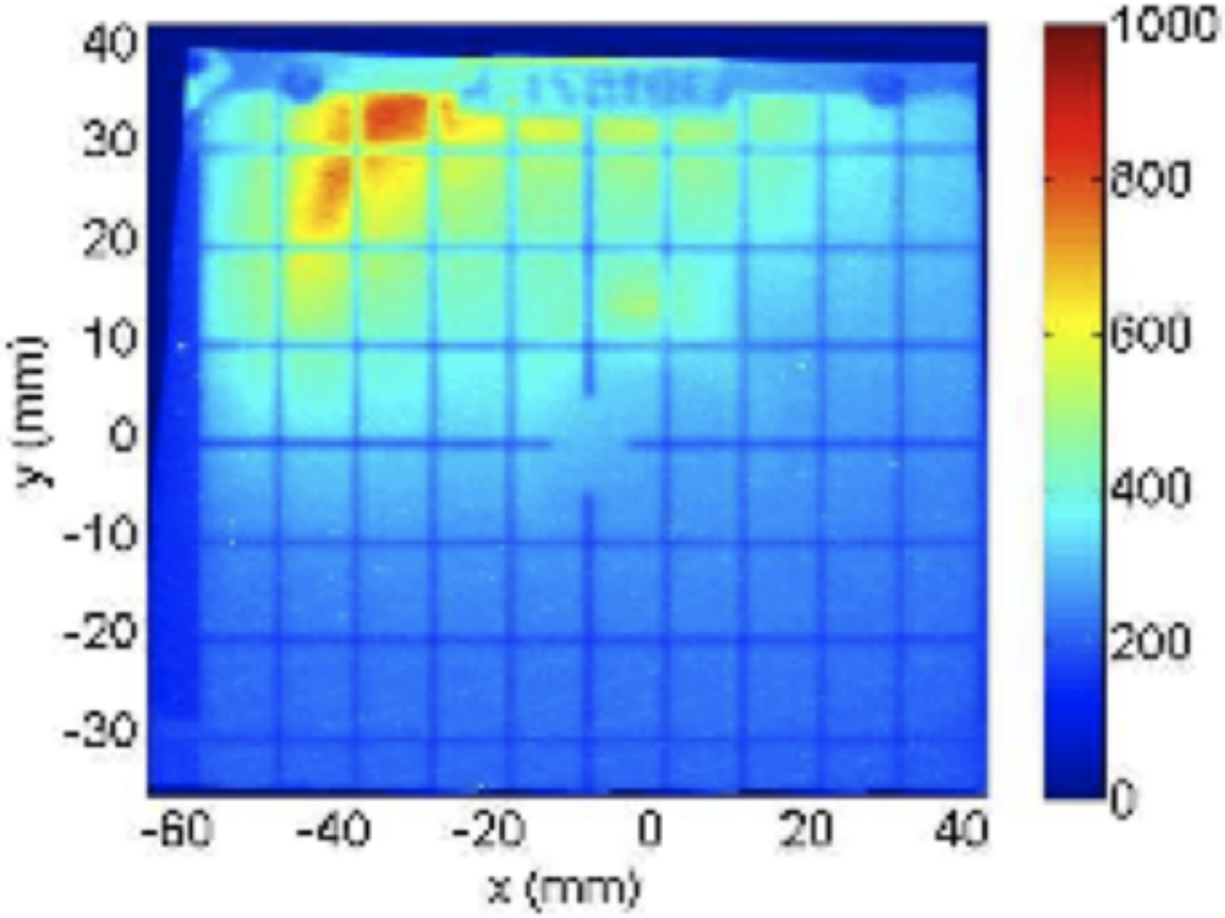


- Particles passing trough the screen excite atoms and molecules
- The screen emits photons that can be observed with a TV camera (CCD, VIDICON etc.)
- Multiple scattering inside screen increases beam divergence
- Typical screens are Al_2O_3:CrO_2 1mm thick. Robust and good for beam observation, but not for precise profile measurements.

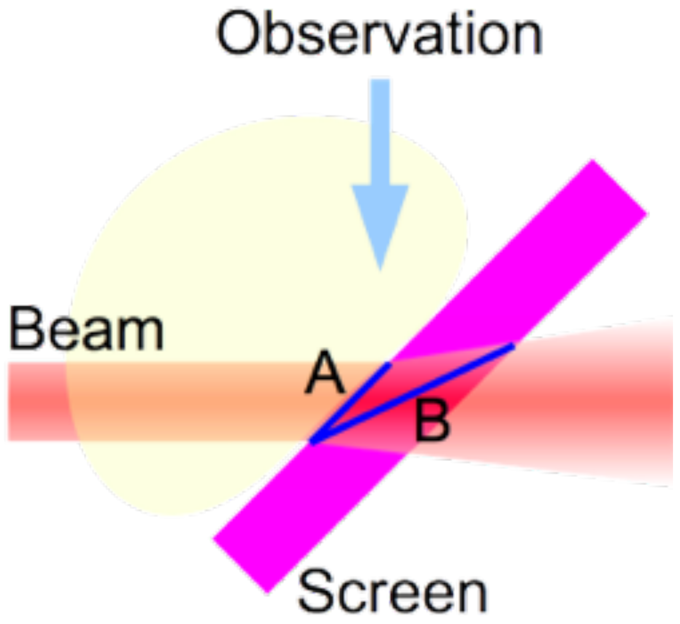
Scintillating screen

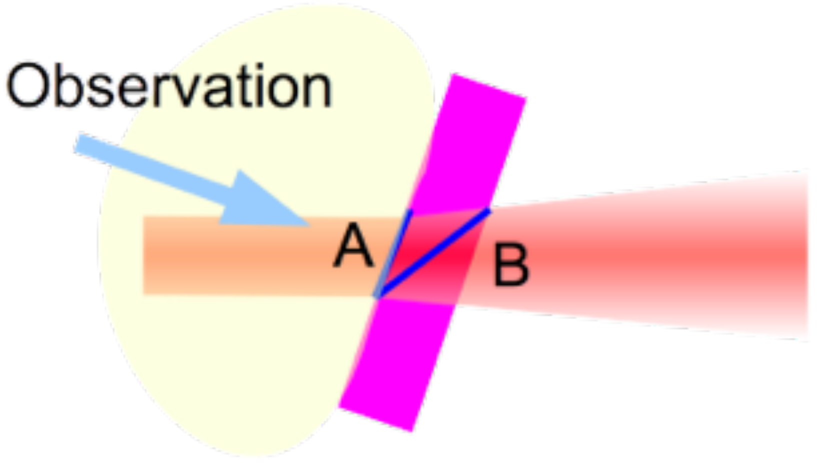
Optical setup may introduce deformations (tilted screen)
Need to perform off line corrections and calibrations





Scintillating screen





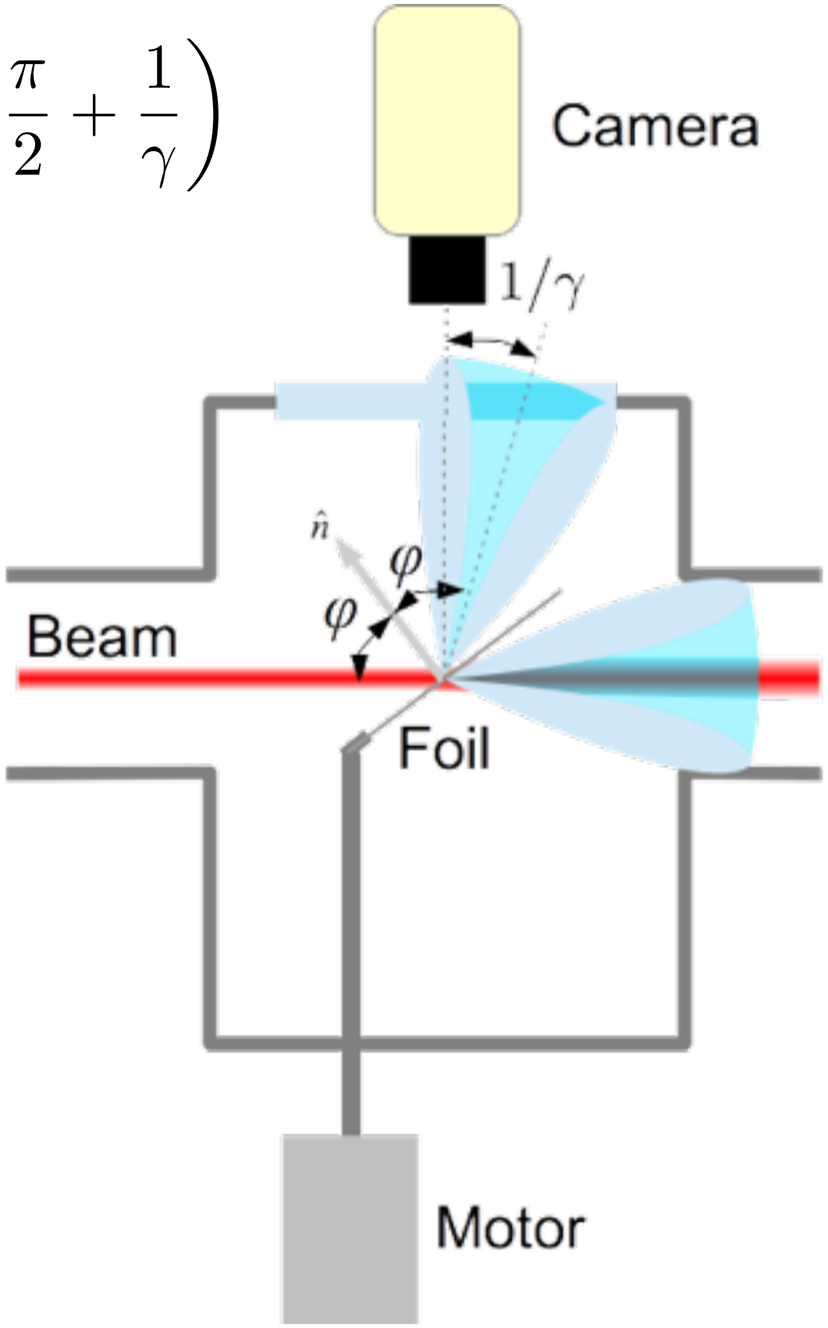
A is what we would like to observe
B is what we really obtain

- 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

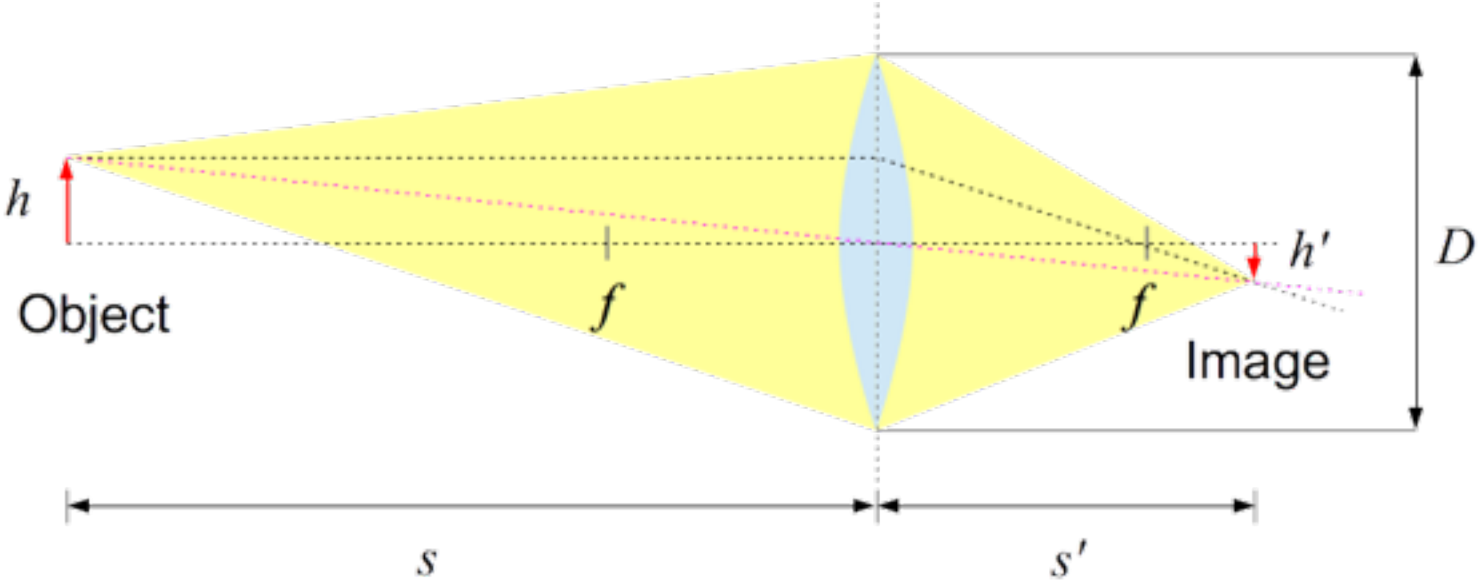
OTR radiators

- 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. N passages possible.
- Angle of radiator depends on beam momentum
- For dense beams use carbon foils or SiC wafers

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



Optics primer



$$m = \frac{h'}{h} = \frac{s'}{s} \qquad f = \frac{sm}{m+1}$$

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'} \qquad s' = \frac{sf}{s-f}$$

If 1/γ < D/(2 s) the whole lobe can be collected and the observation angle is equal to the specular reflection.
If 1/γ > D/(2 s) only part of the lobe can be collected and the specular reflection differs from the observation angle

Typical case:
s= 300 mm, m=0.2 ⇒ f= 50 mm, s'= 60 mm

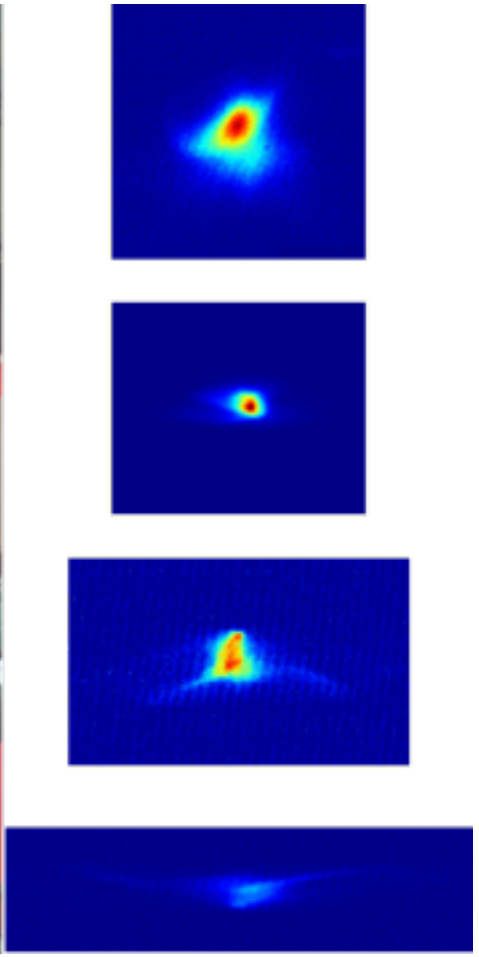
A “good” CCTV 50 mm lens has f/# ~ 1.4

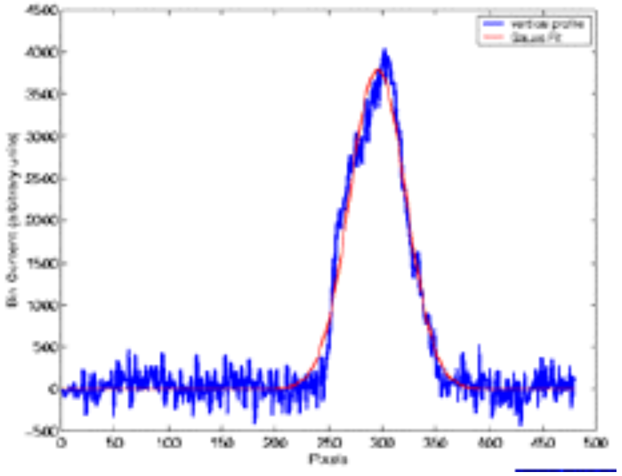
$$D = \frac{f}{f/\#} = \frac{50}{1.4} = 36$$

$$\gamma_{\min} = \frac{1}{\frac{D}{2s}} = \frac{2 \cdot 300}{36} = 17$$

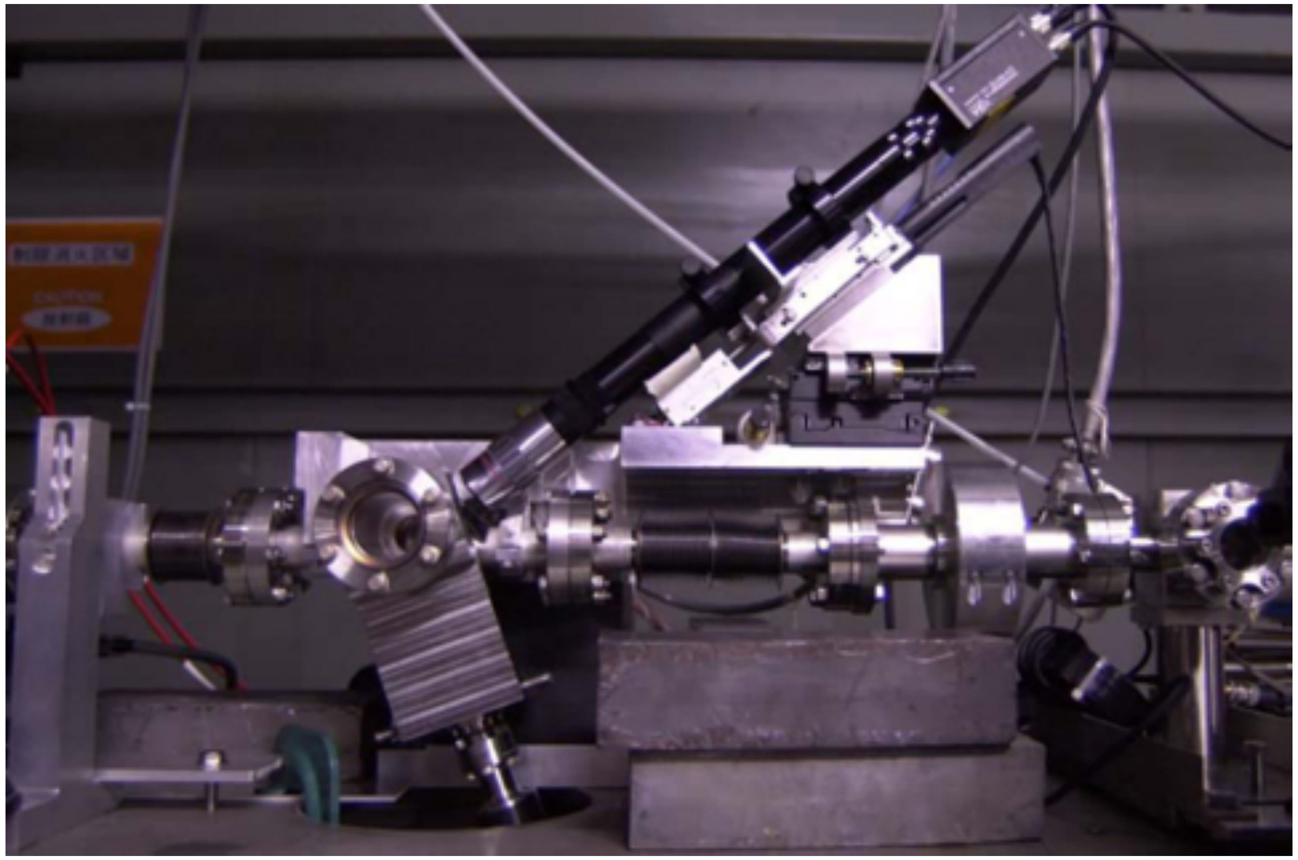
OTR example (DESY)

- Often beams are far from Gaussian especially in linacs
- Camera must be protected from radiation requiring complex optical lines
- Filters are needed to avoid saturating the camera

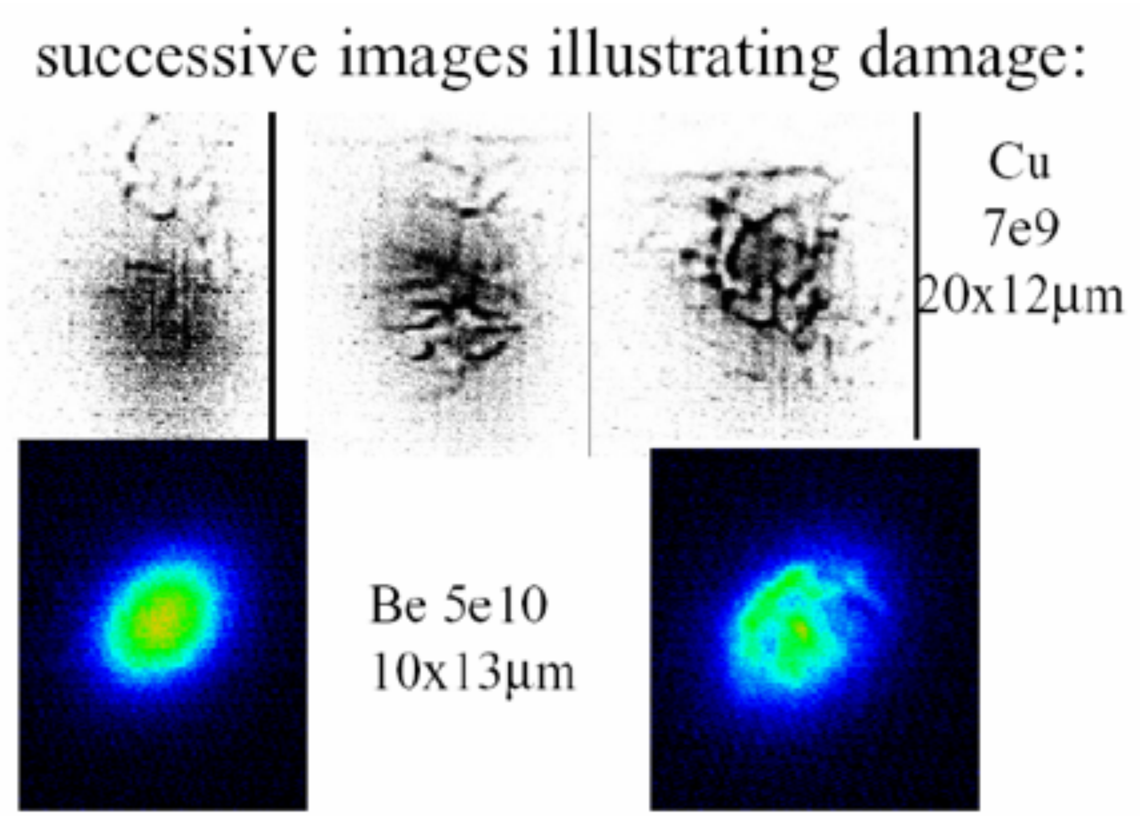




OTR example (KEK)



- Small beams can be very dense and damage the radiator.
- Choosing the right material is essential.

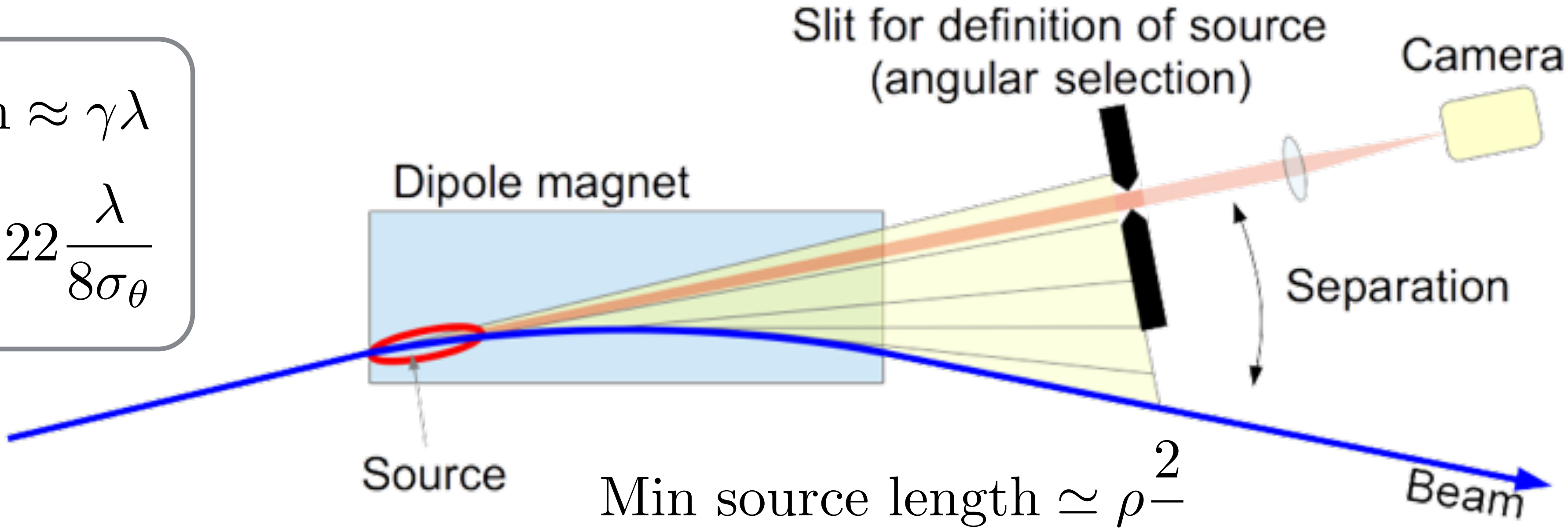


$$\Delta T(x,y) = \frac{\frac{dE}{dx}\rho \cdot i(x,y)}{\rho c_v} = \frac{\frac{dE}{dx} \cdot i(x,y)}{c_v}$$

Synchrotron radiation

$$\text{Resolution} \approx \gamma\lambda$$

$$\sigma_{\text{Diffr.}} \simeq 1.22\frac{\lambda}{8\sigma_\theta}$$



$$\text{Min source length} \simeq \rho\frac{2}{\gamma}$$

- 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 often limited by diffraction

Example:
E= 2 GeV, λ= 400 nm, ρ= 10 m
E_{cr}=1.7 keV
resolution is around 25 μm
(240 μm using 1/γ)

Light sensors

- **1D** sensors
  - Photo diode array (up to 50kHz)
  - Linear CCD (same as above)
  - Segmented photomultiplier (Can be fast up to hundreds of MHz)
- **2D** sensors (usually slow 50-100 Hz)
  - image CCD (naturally global shutter)
  - image CMOS (naturally rolling shutter! g.s. can be implemented)
    - CMOS sensors can have very high frame rates hundreds of kHz
  - (Segmented photomultiplier) (Can be fast up to hundreds of MHz)

Light sensors

- Photomultipliers are radiation resistant (glass and metal)
- CCD and CMOS are silicon based and thus not very tolerant to radiation (max few M Rad)
- Tube cameras (ex. VIDICON) are radiation hard, but have worse resolution and sensitivity (obsolete!)
- 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

Cameras

- **Analog**
  - Simple to use (only need 12V and a monitor)
  - Well defined signal format (interchangeable)
- **Digital**
  - Often bound to drivers/lib from builder
  - Better S/N
  - No need for a frame grabber (for normal camera)
  - Less expensive to transport signal over long distances

That’s all folks!

Thank you for your attention