BEAM INSTRUMENTATION

Transverse Profile Measurements

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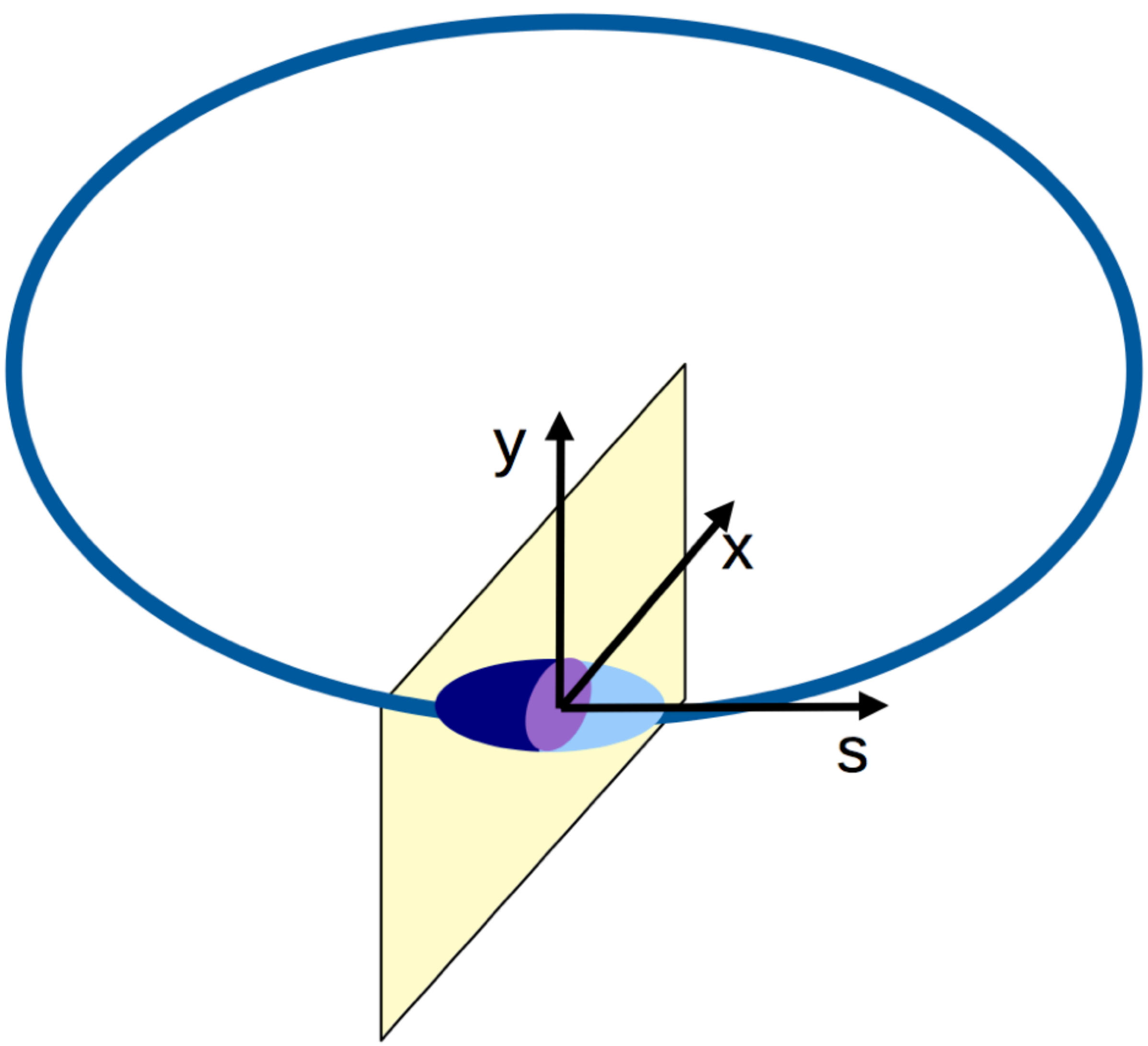
Content

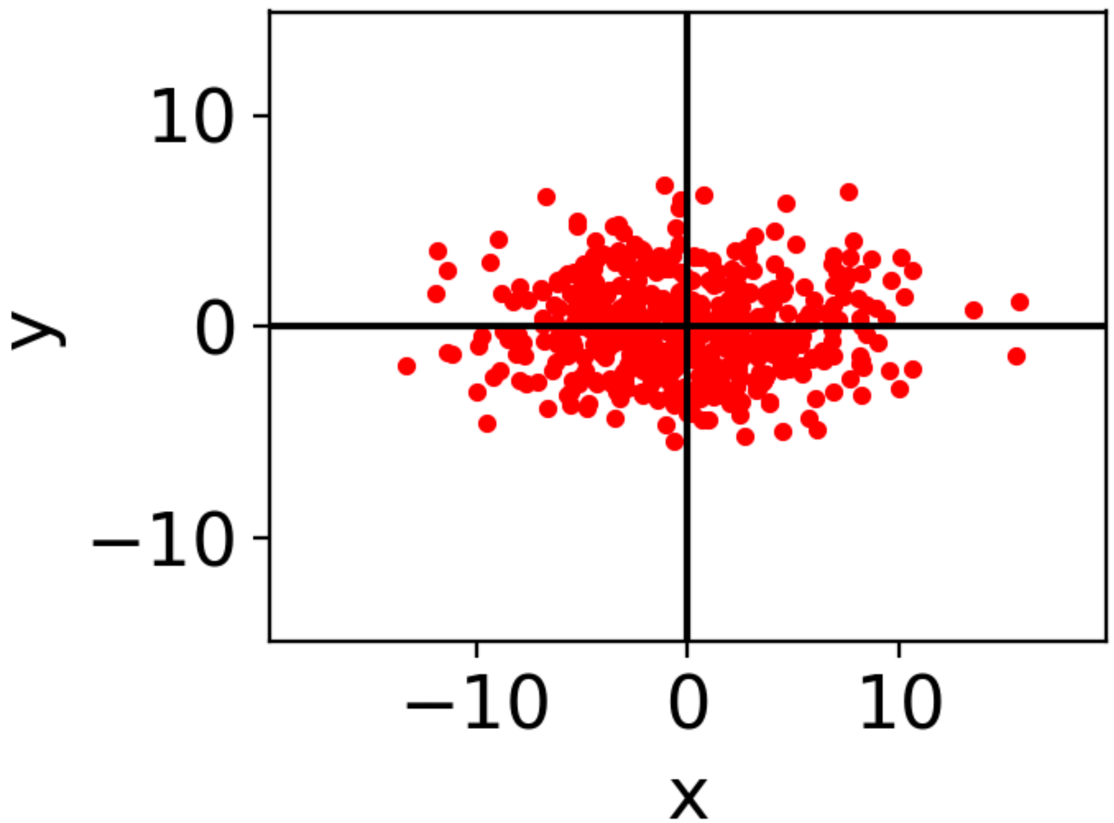
- Coordinate system
- Transverse space
- Transverse phase space
- Interaction of particles with matter
- Radiation emission by charged particles
- Sampling of distributions (measurement of profiles)

Coordinate system



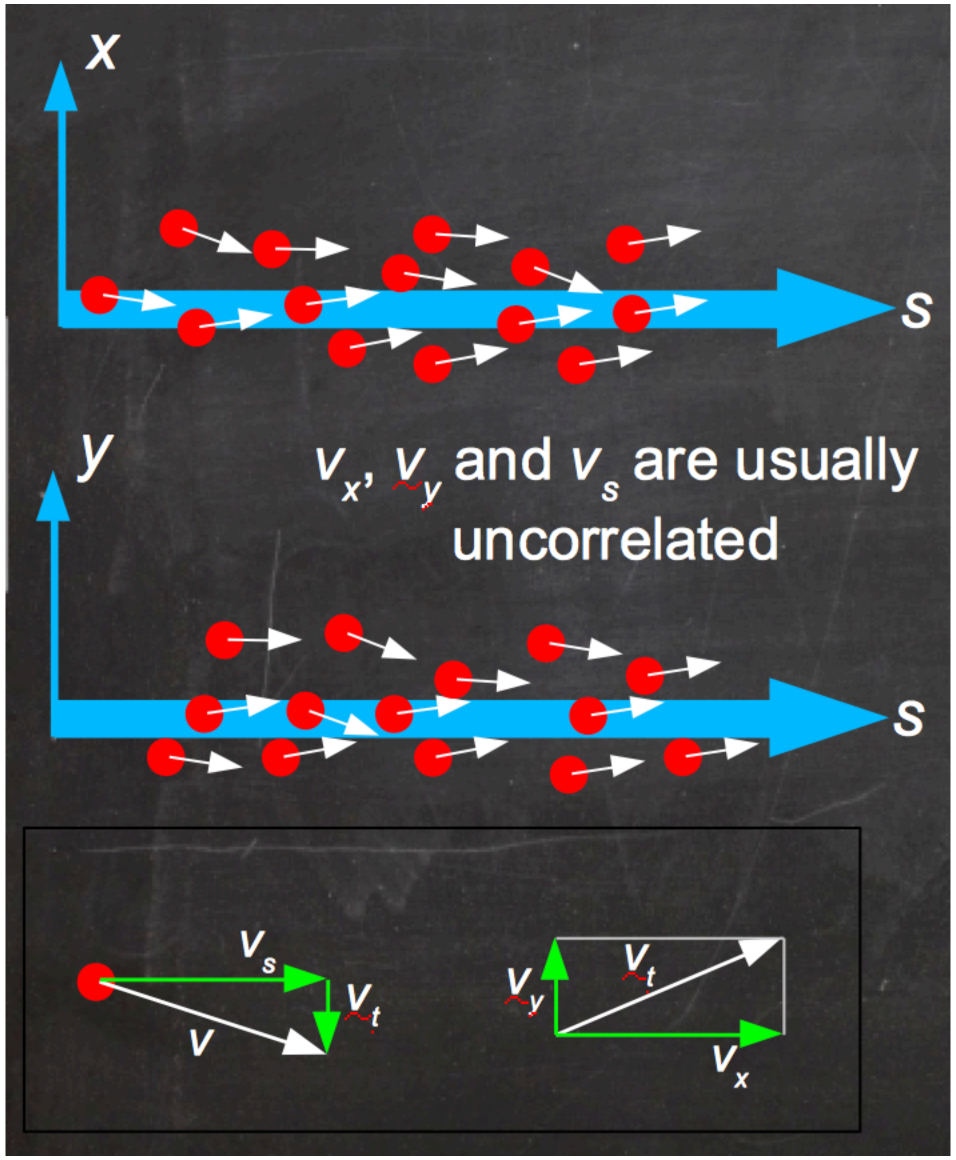
- **Longitudinal coordinate**
  - defined by the direction of motion of the beam
  - Axis indicated with **s**
- **Transverse Plane**
  - Plane orthogonal to the close orbit
  - Axes usually indicated with **x** and **y** and referred as **HORIZONTAL** and **VERTICAL**

Real space distribution



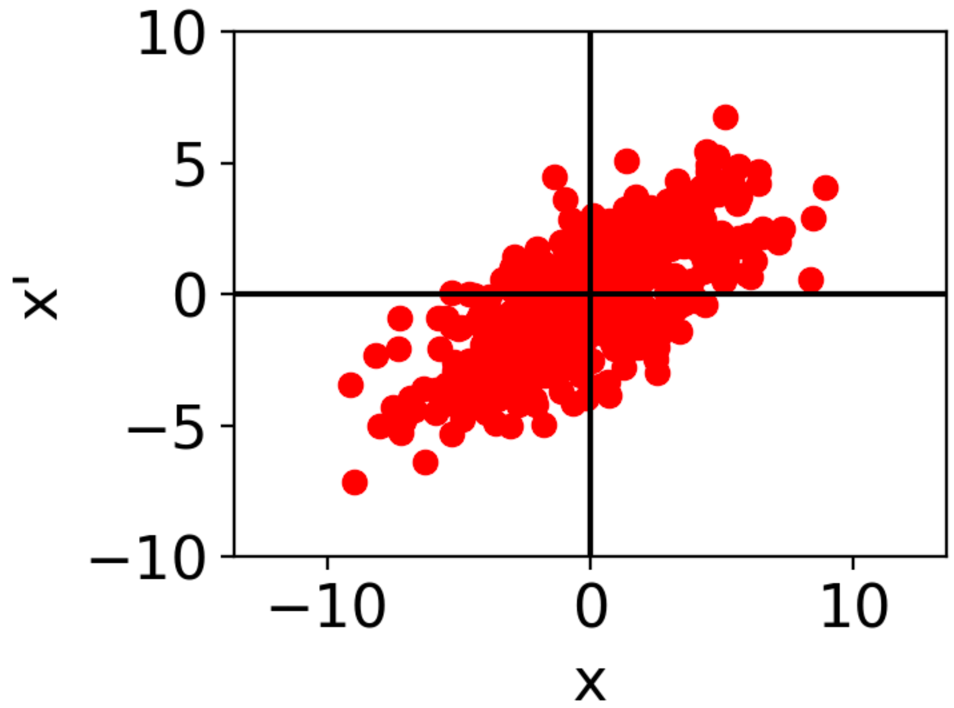
- Define a plane orthogonal to the beam trajectory at a given s
- Record the x, y coordinates of each particle crossing this plane
- Plot on a 2D chart (x, y) each particle

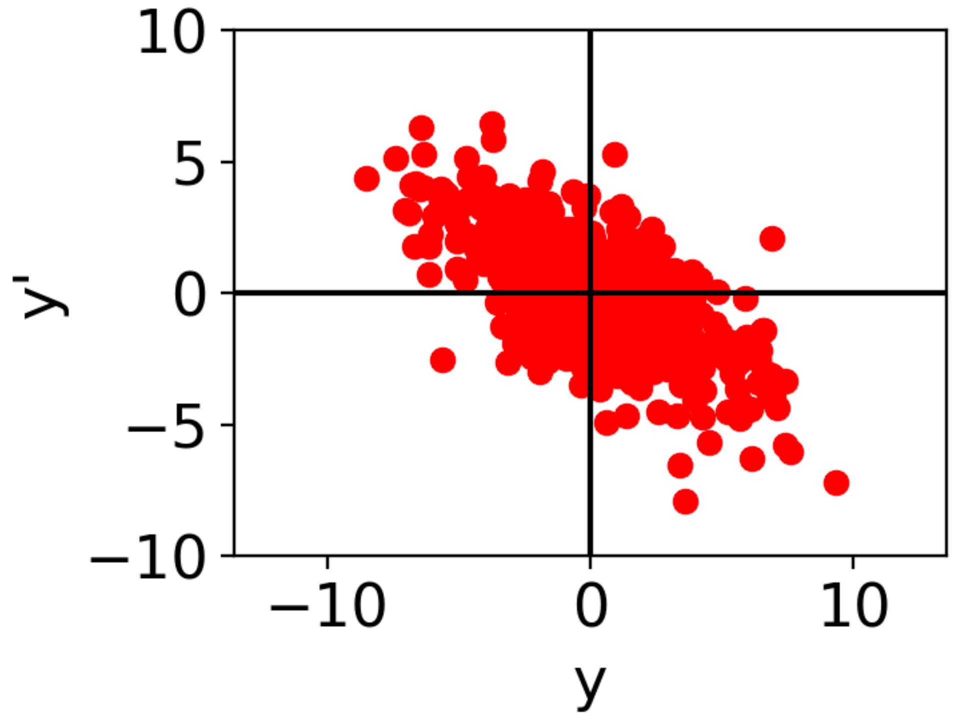
Transverse phase space



- “Beam” moves along s
- Each particle moves in a slightly 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’ (angles)

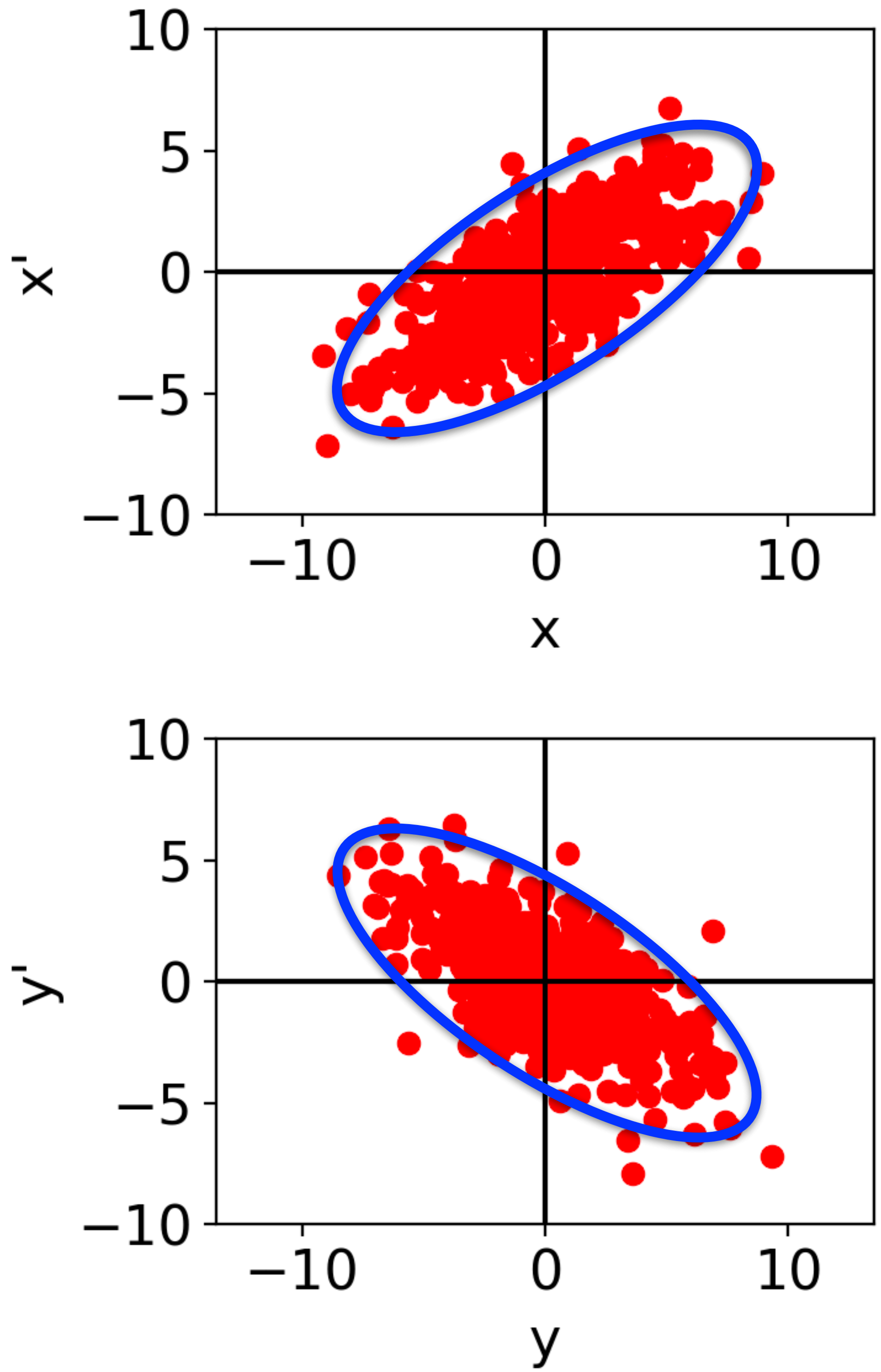
Transverse phase space





- 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" $v_x \rightarrow x'$, $v_y \rightarrow y'$

Transverse phase space



The area of the smallest ellipse that contains "all" the particles is called the transverse emittance

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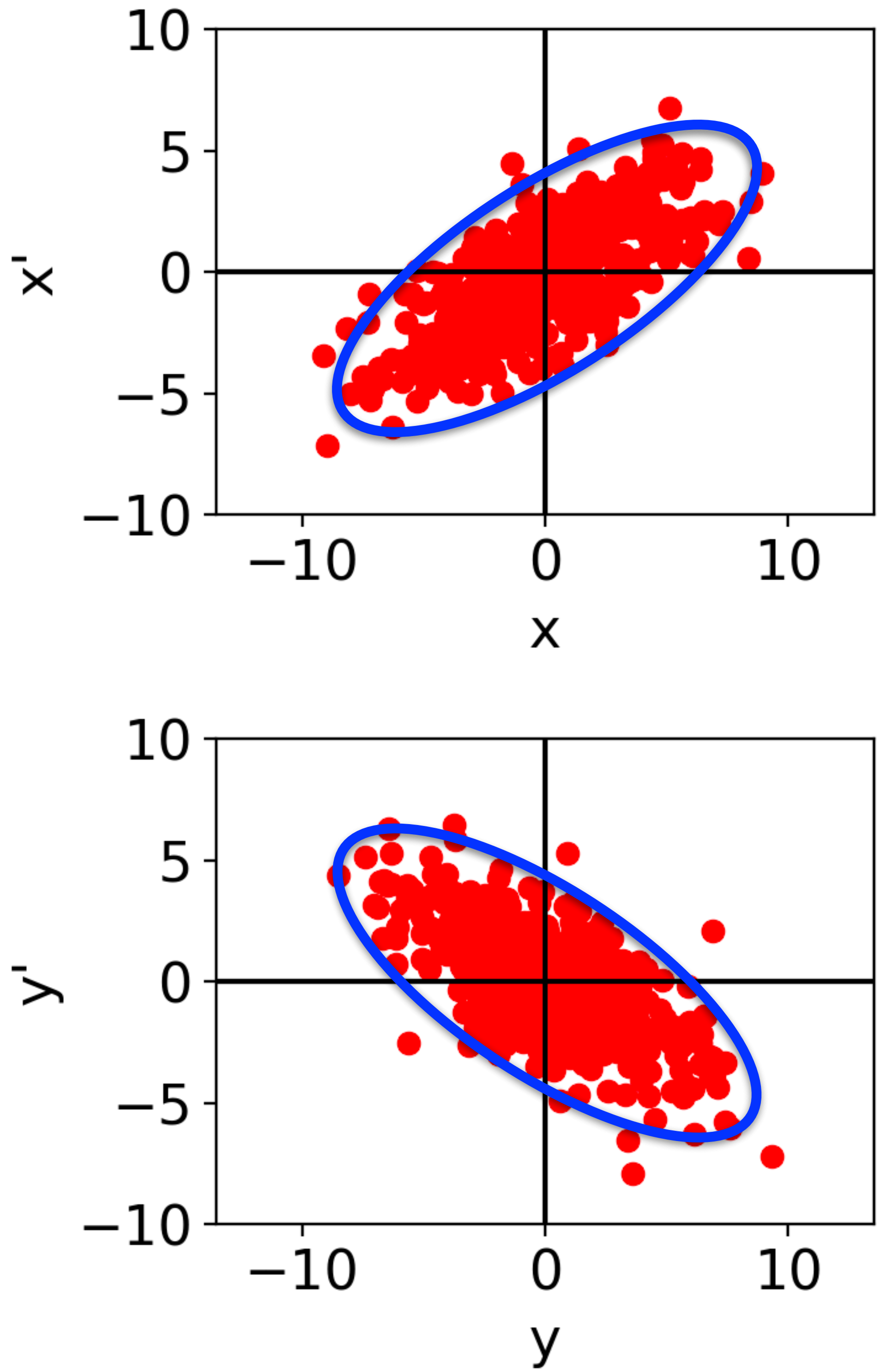
- "Rename" $v_x \rightarrow x'$, $v_y \rightarrow y'$

Transverse phase space



The area of the smallest ellipse that contains “all” the particles is called the

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Area of the ellipse is an invariant

ε_x, ε_y

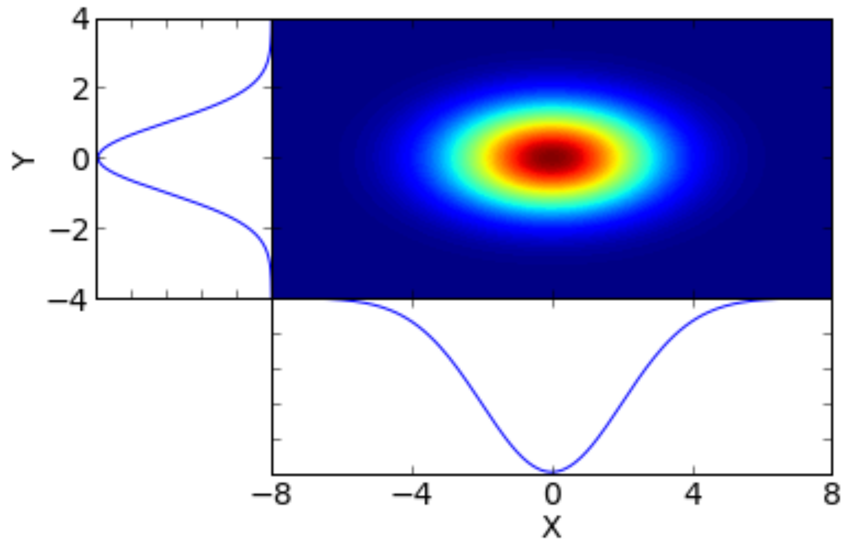
-

- “Rename” $v_x \rightarrow x'$, $v_y \rightarrow y'$

Beam profiles

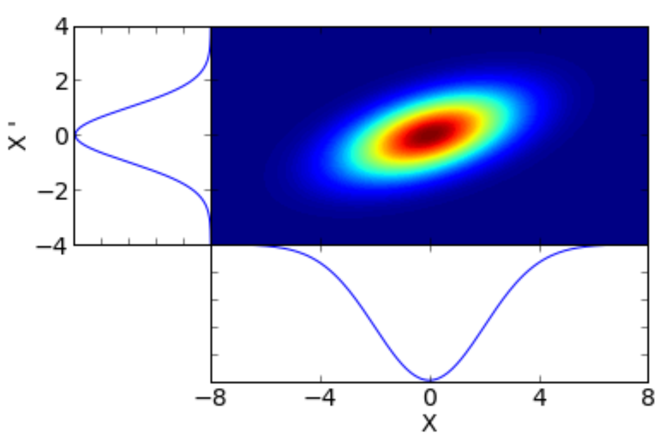
Real space (beam image)

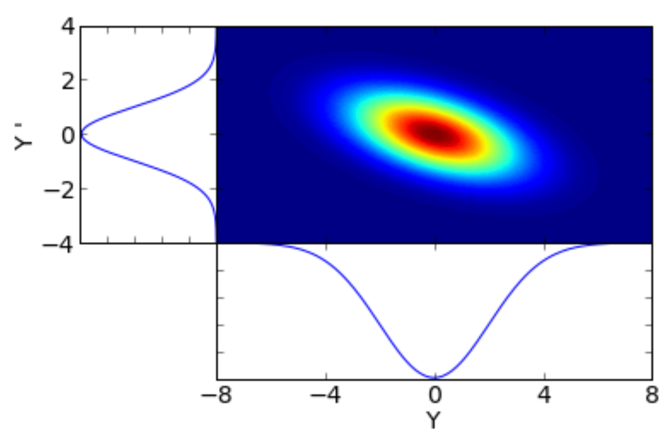
Vertical profile



Horizontal profile

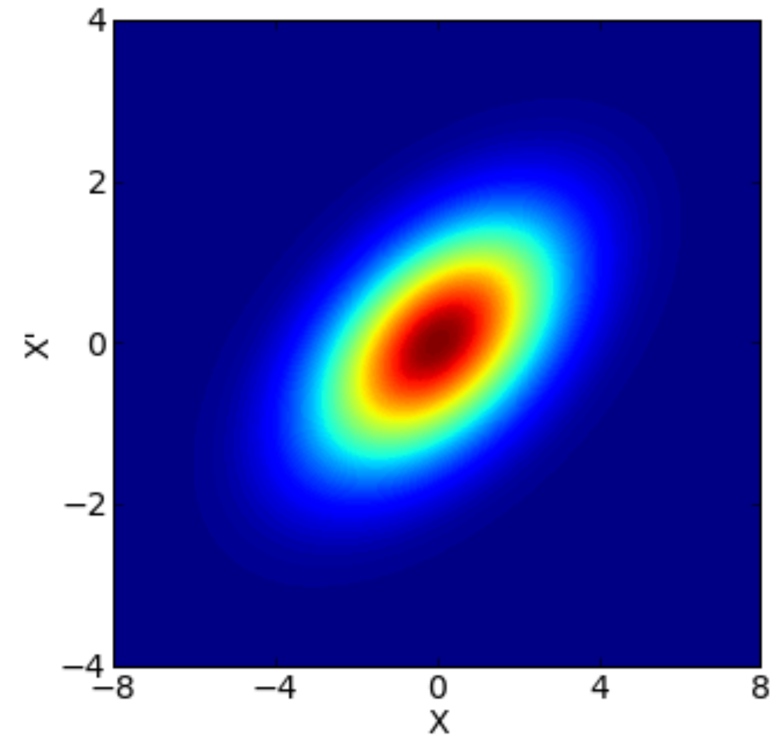
Phase space





Horizontal profile Vertical profile

Phase space

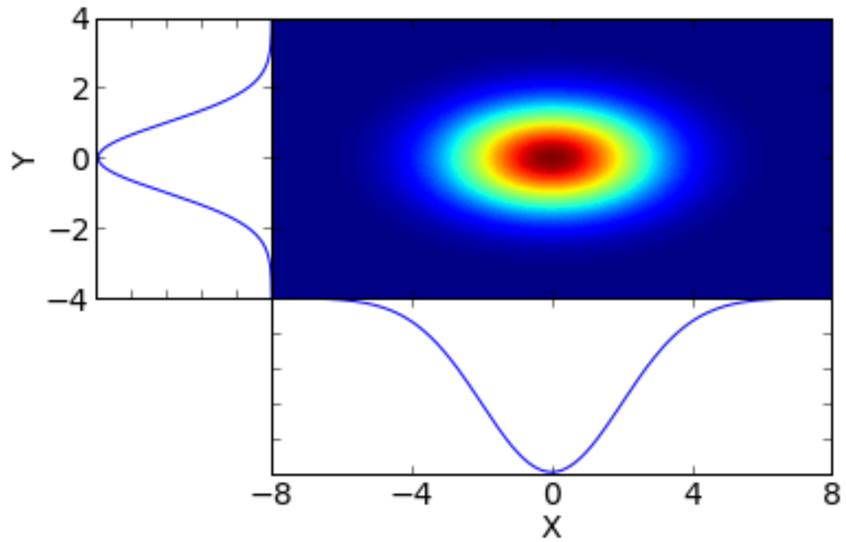


Amplitude distribution

Beam profiles

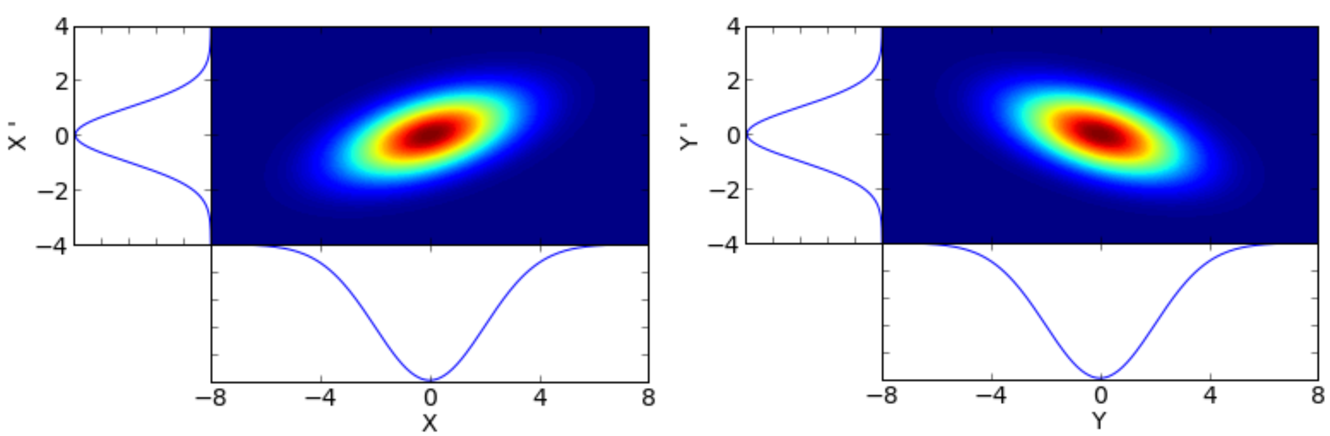
Real space (beam image)

Vertical profile



Horizontal profile

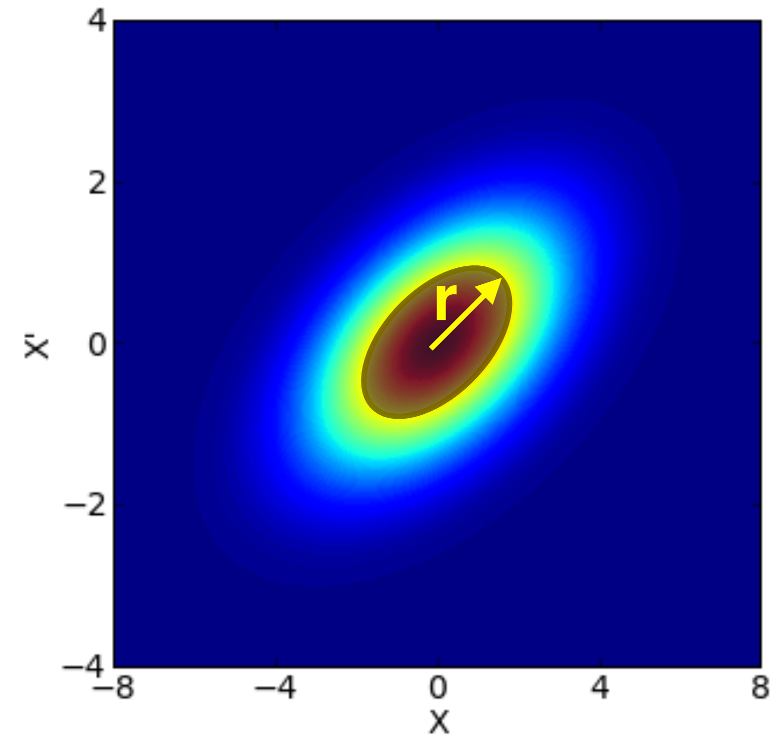
Phase space



Horizontal profile

Vertical profile

Phase space



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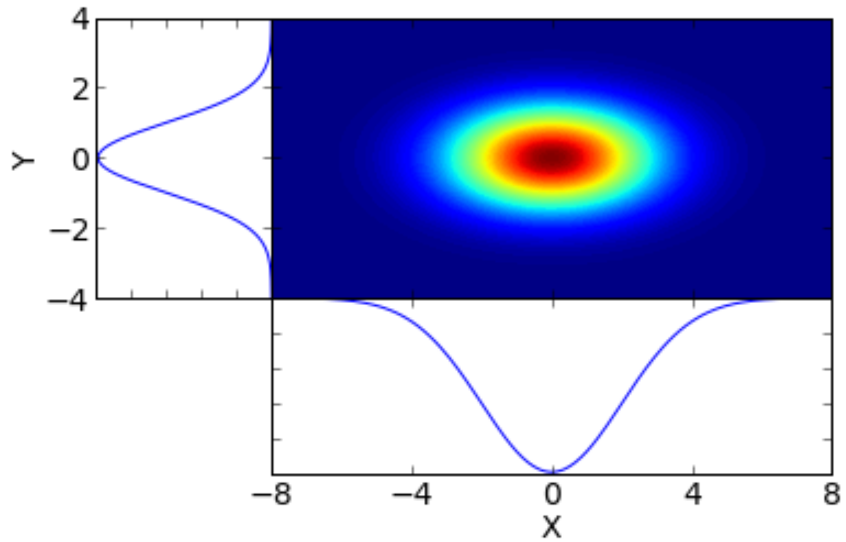

Horizontal profile

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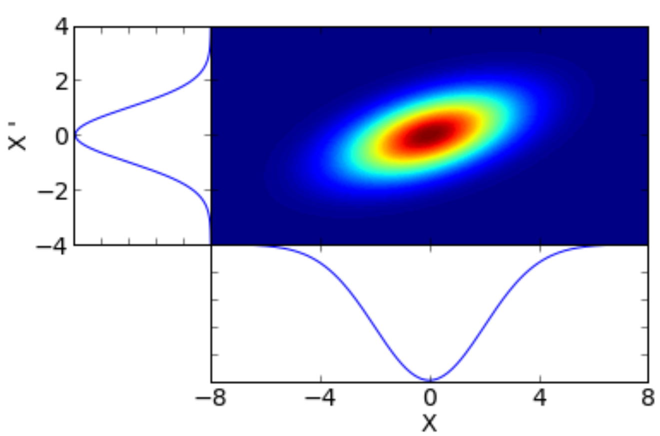

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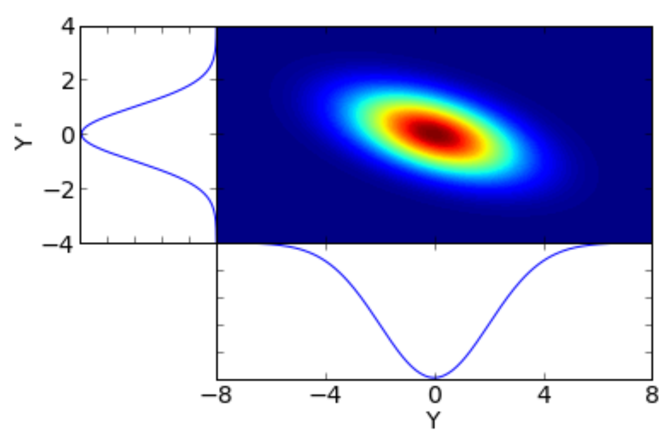

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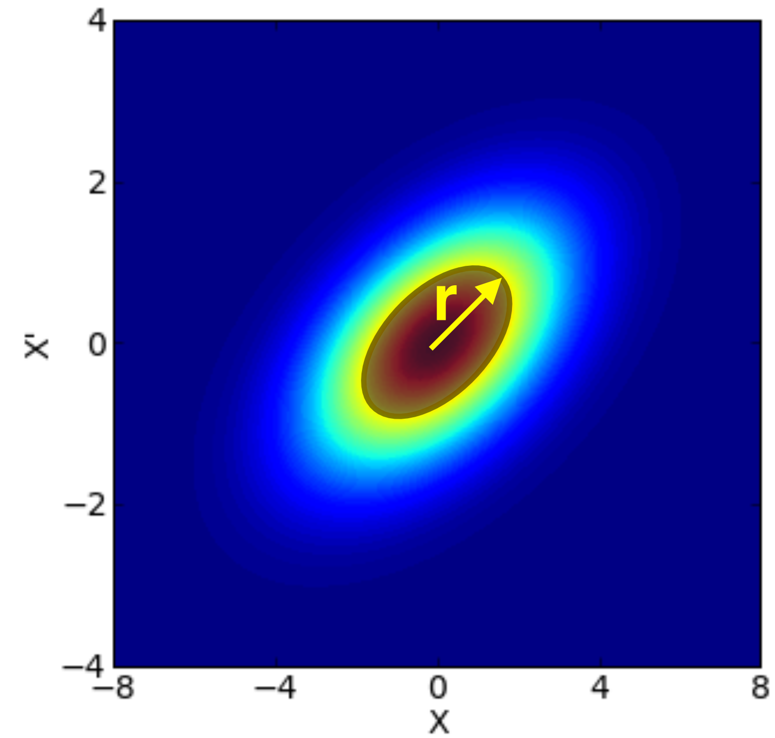
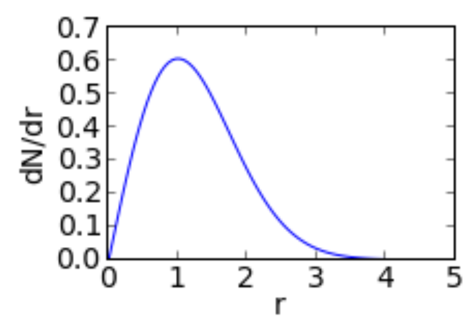


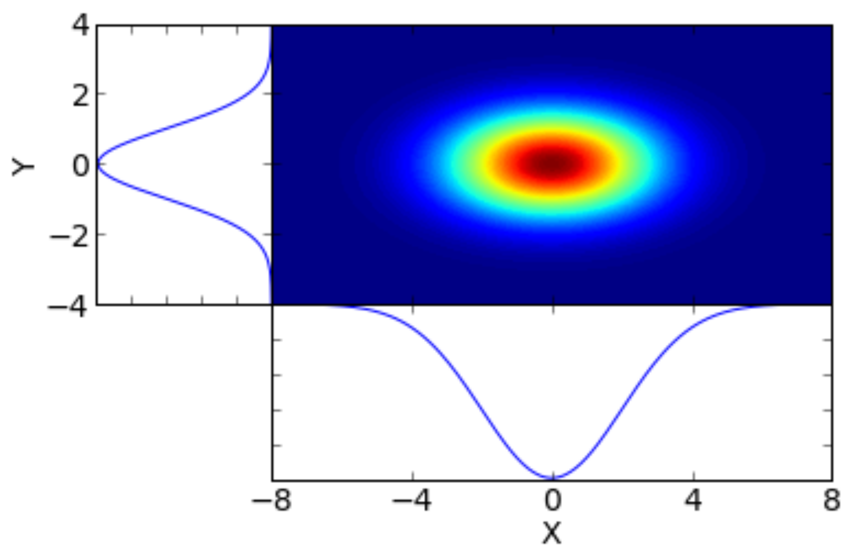


Amplitude distribution

Beam profiles

Real space (beam image)

Vertical profile



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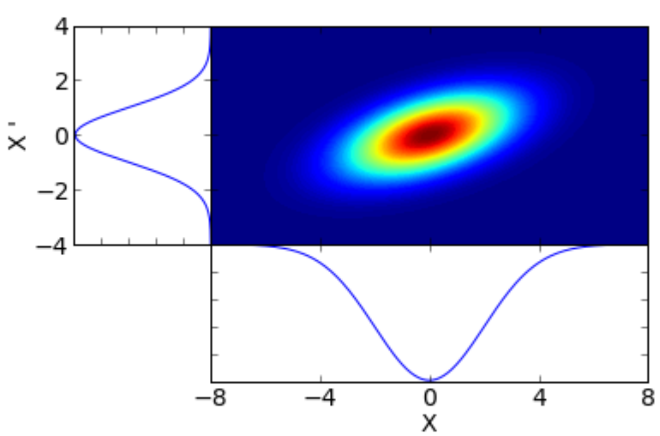

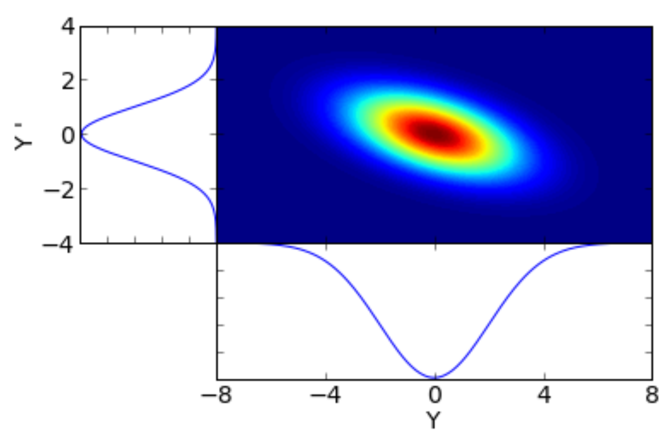

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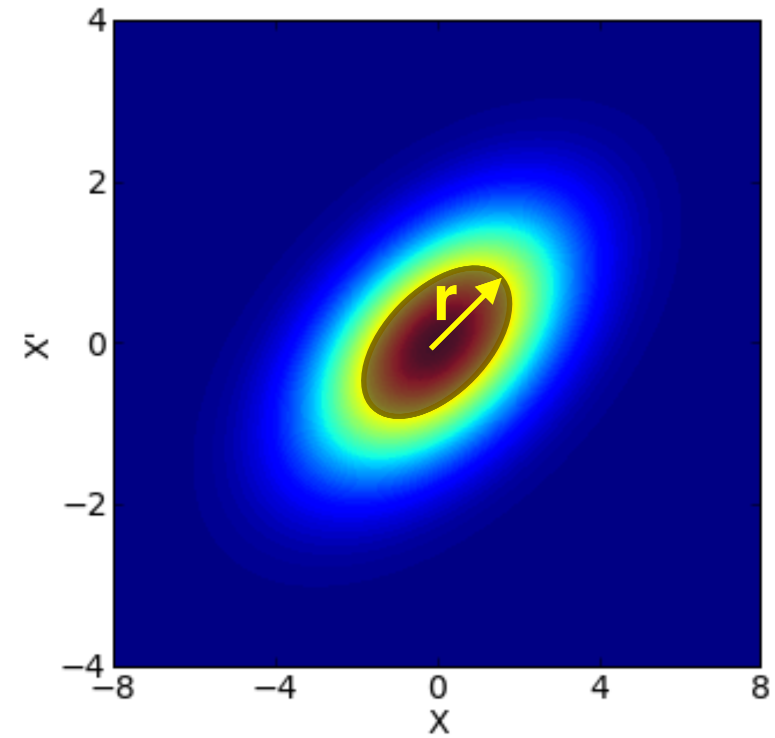
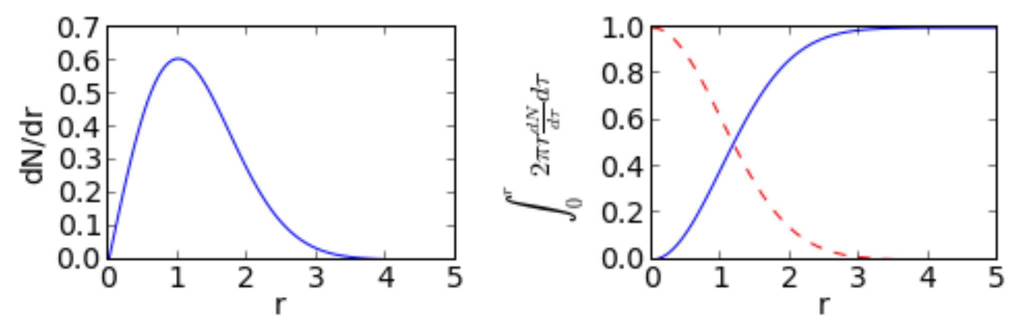




Amplitude distribution

Beam profiles

Generic particles distribution

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

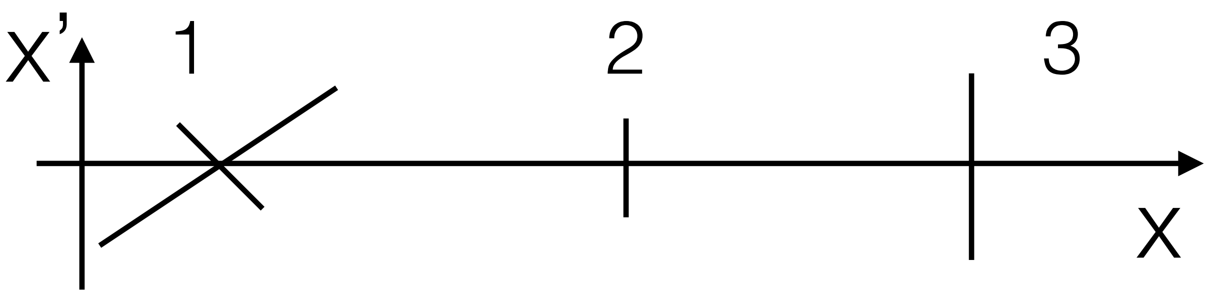
Gaussian distribution

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

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: (Rotate and rescale)

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

Radial density:

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

Amplitude distribution

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

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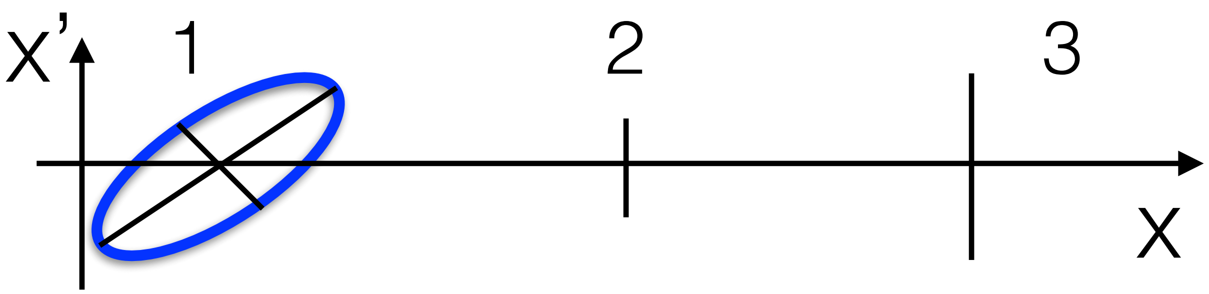

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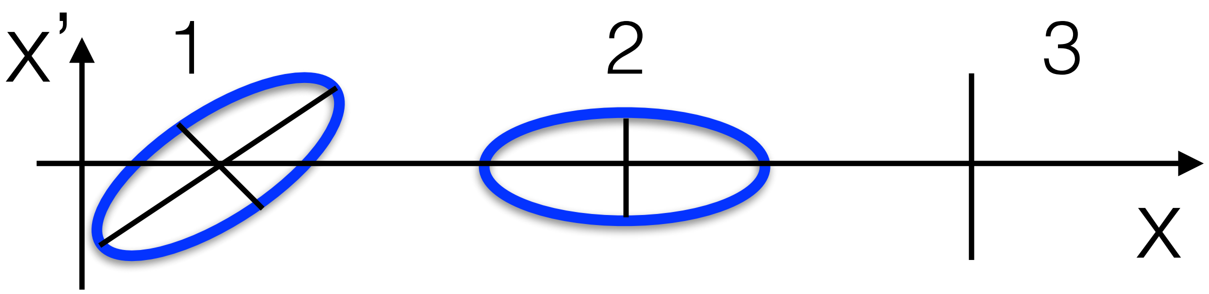

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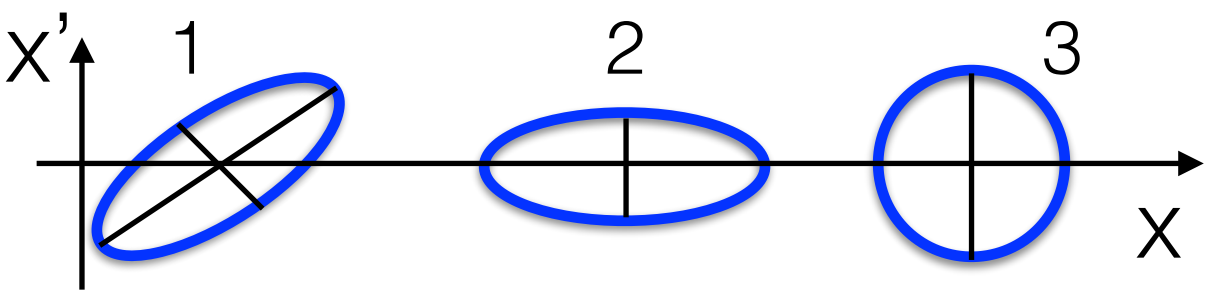

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Transverse spaces

- The REAL (x,y) space and the PHASE (x, x’) space are different things

- Their projections along x or y are however the same thing

- Phase space contains 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

Sampling of distributions

- **Intercepting methods**
  - Scanning wires
  - Wire grids (Harps)
  - Radiative screens

- **Non intercepting methods**
  - Synchrotron light
  - Rest gas ionisation
  - (Inverse Compton scattering / photo dissociation)

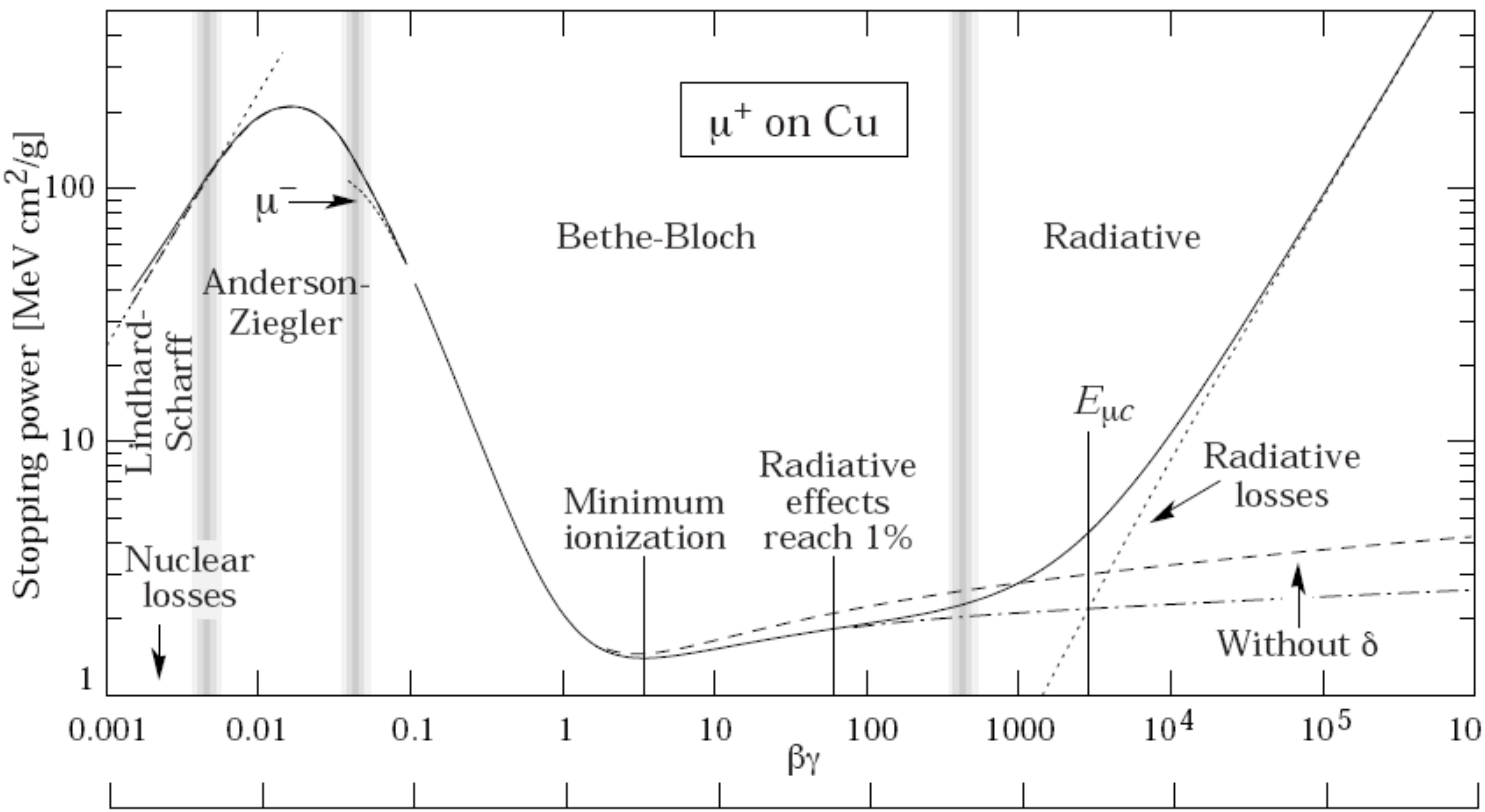
Interaction of particles with matter

- **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

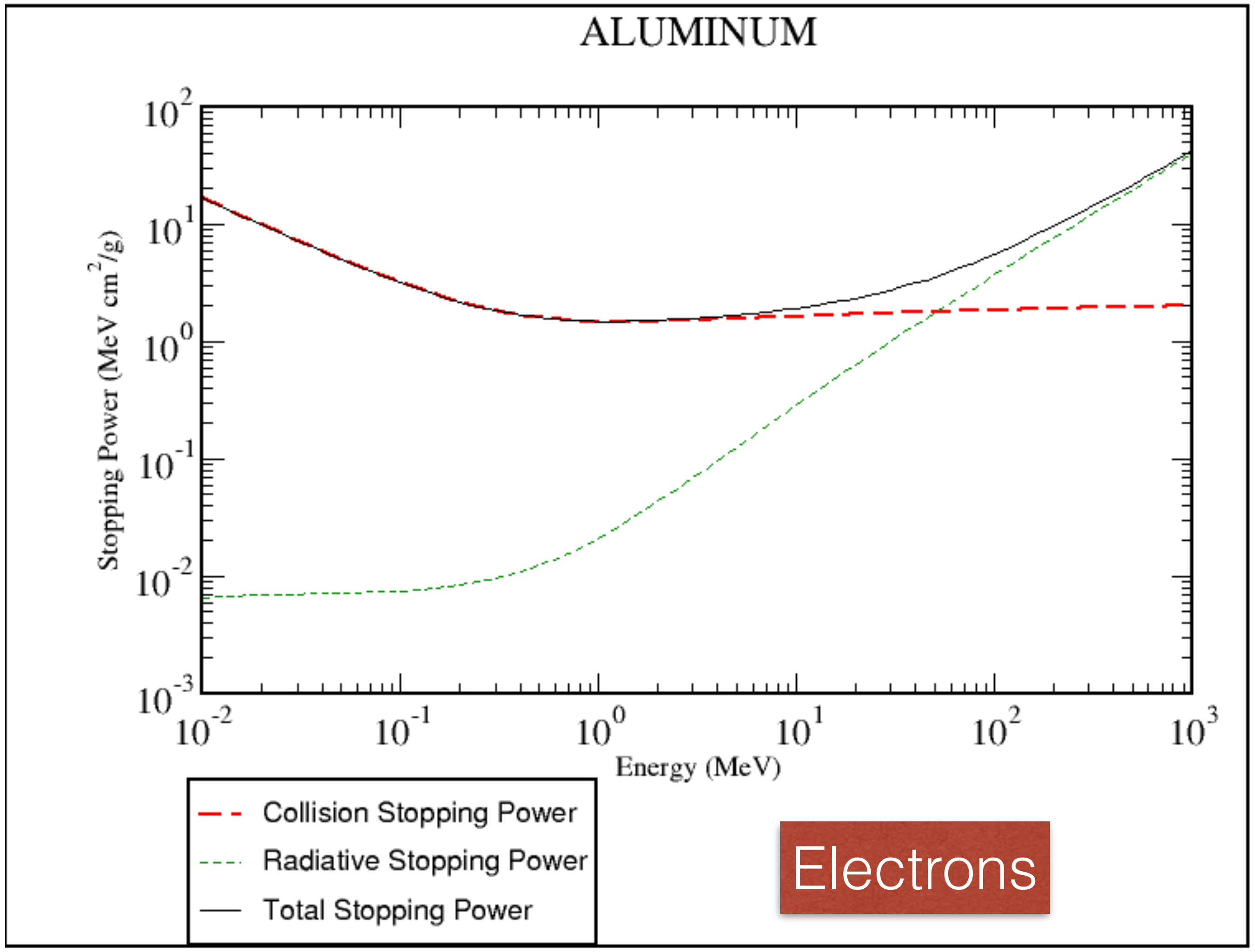
Energy deposition

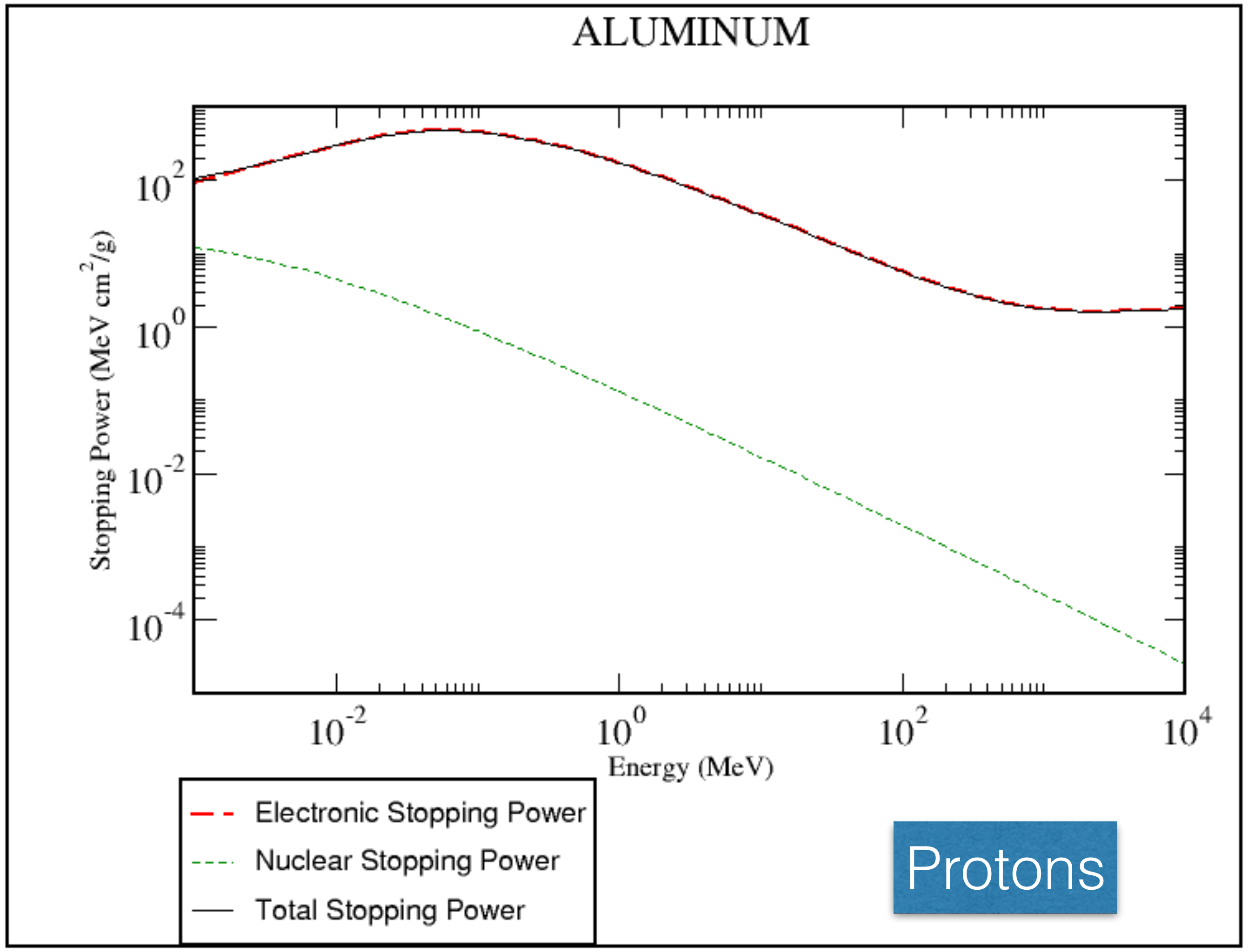
- Energy deposition is probably the most important aspect for all intercepting devices
  - Signals are often proportional to the deposited energy
  - Energy deposition can cause damage to the instrument
- The Bethe-Bloch formula describes energy losses for many of our cases
- The energy lost by the particles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

Energy deposition - dE/dx



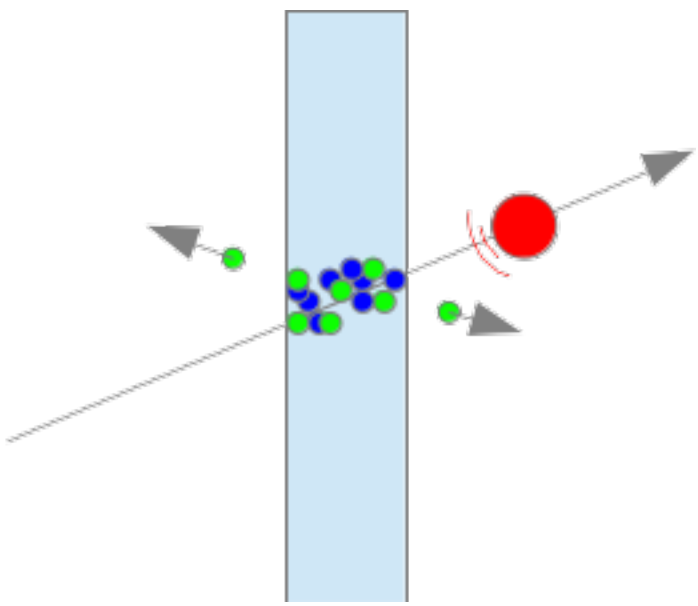
Energy loss

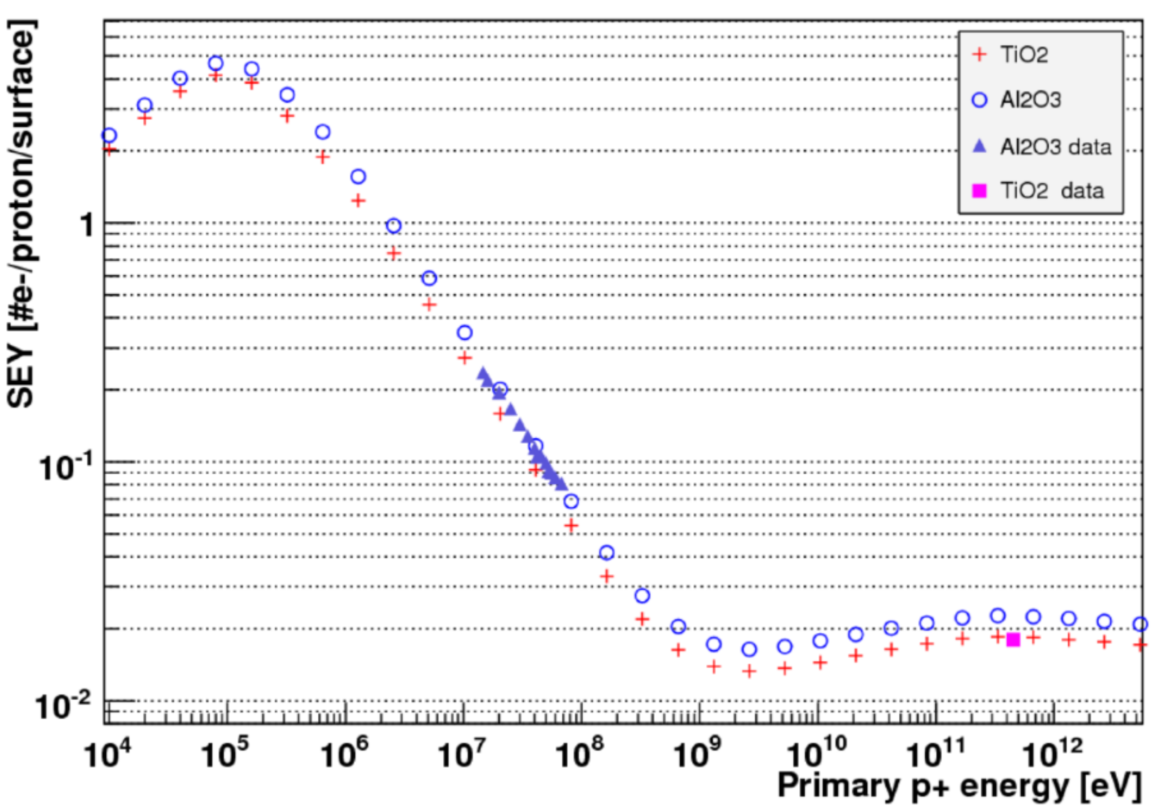




https://physics.nist.gov

Secondary emission - SEM

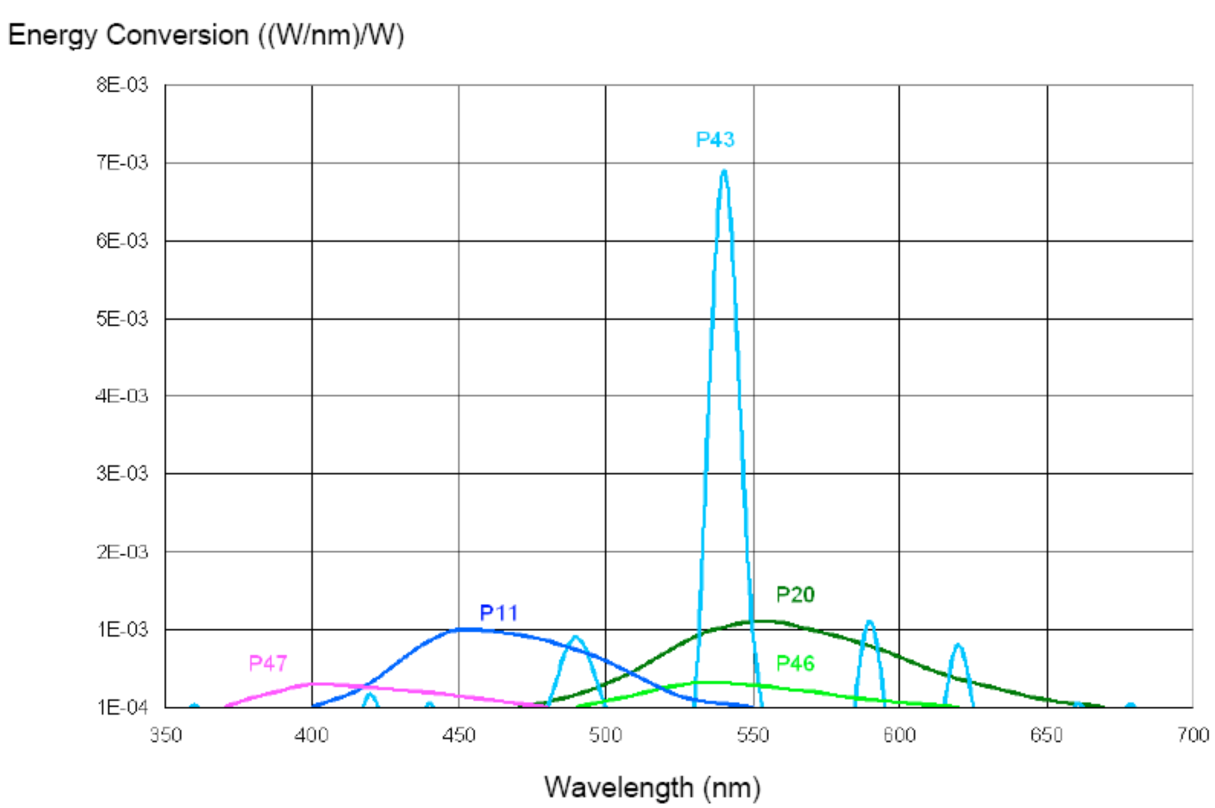




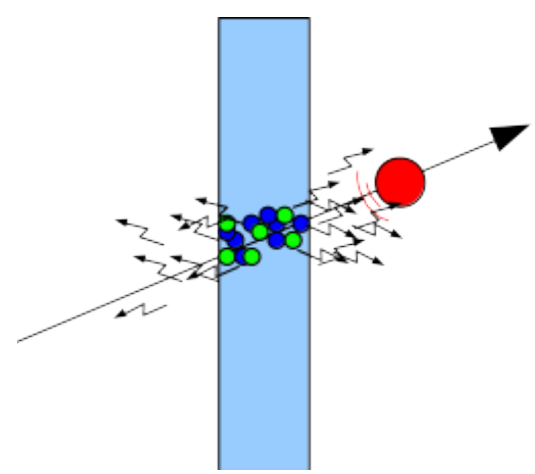
- Linked to ionisation
- Surface electrons receive sufficient energy to travel to the surface and leave
- Emission yield depends on particles energy, material, surface state, EM fields, etc.

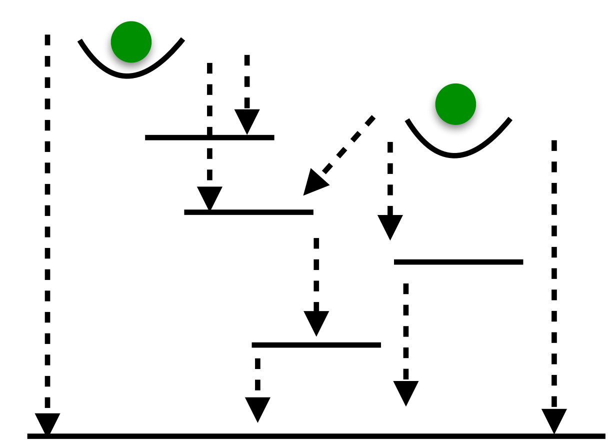
Scintillation

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)

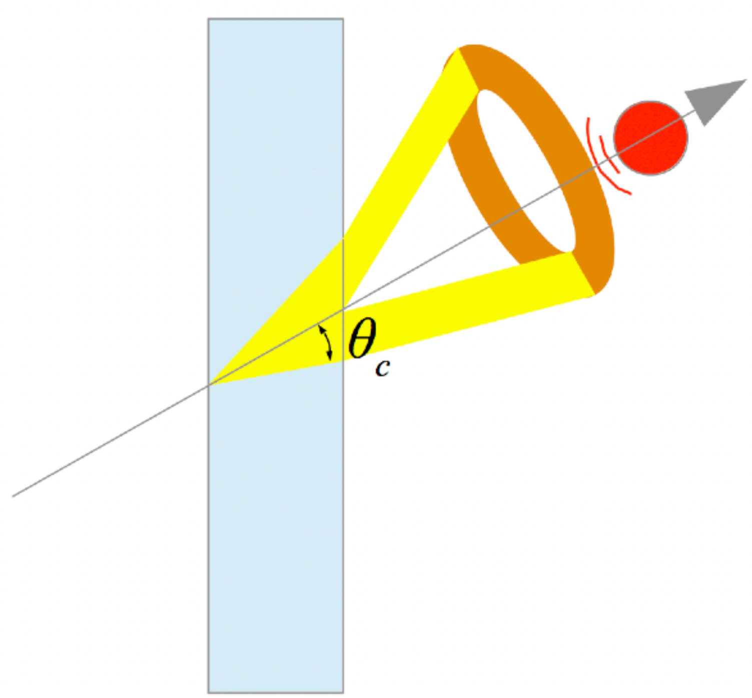
Čerenkov radiation

Index of refraction $n = n(\omega)$

Velocity of particle $v = \beta c$

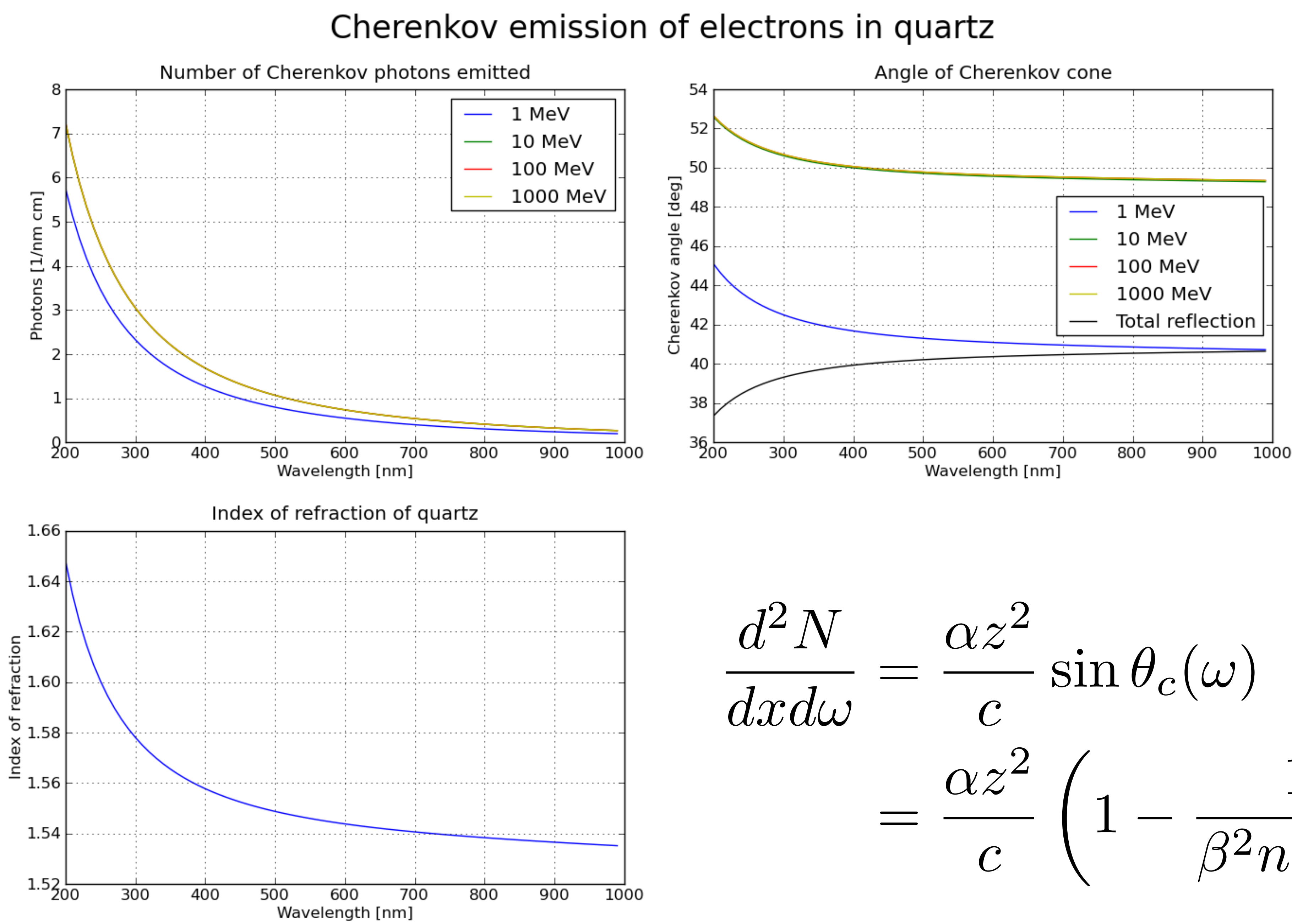
Čerenkov angle $\cos\theta_c = \dfrac{1}{n(\omega)\beta}$

Velocity Threshold $\beta_t = \dfrac{1}{n(\omega)}$



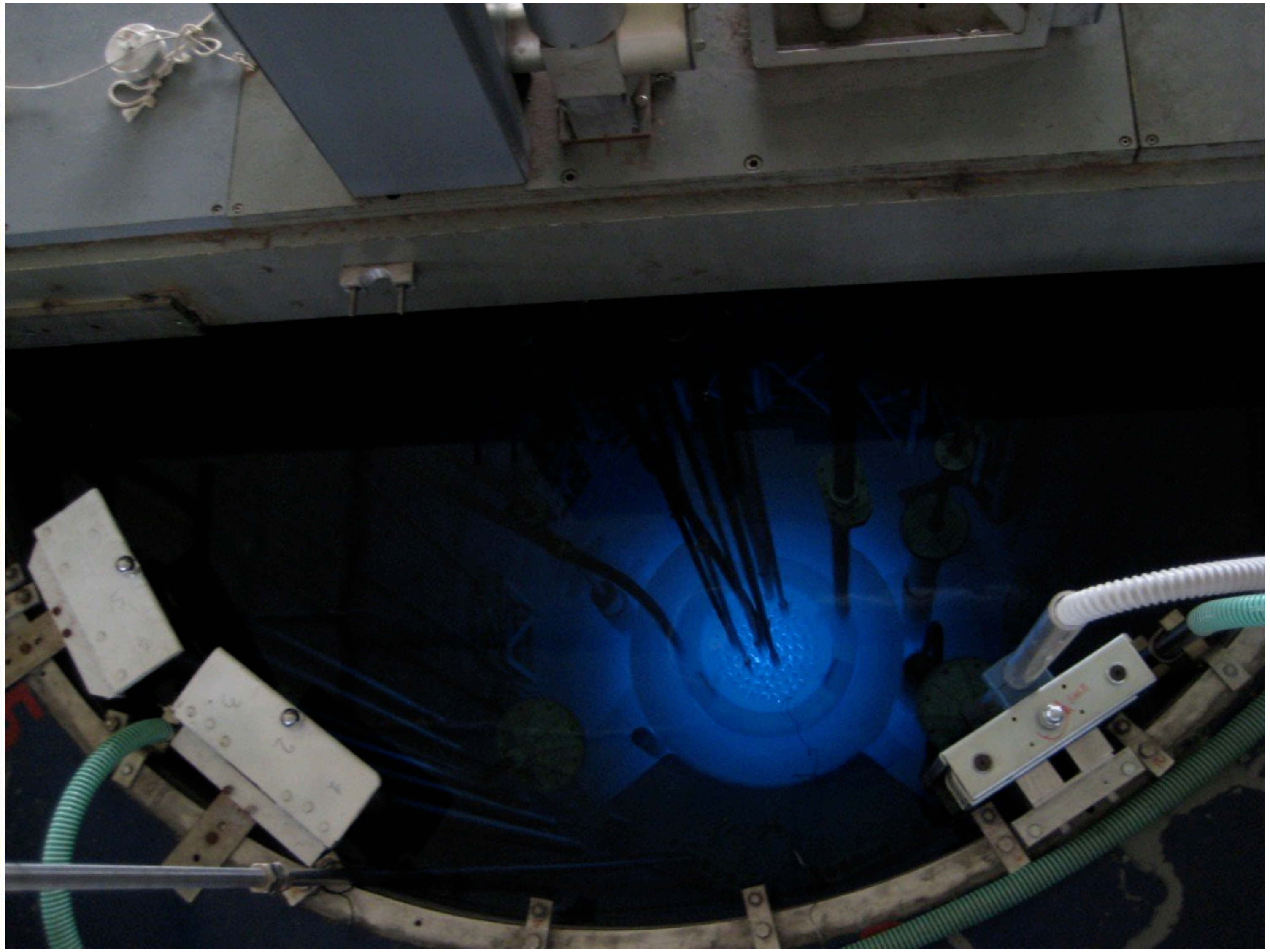
- Linked to the polarisation of the atoms in the material
- Threshold effect: particle travels faster than phase velocity of light in material
- Radiation has defined angular distribution
- Not very good resolution in imaging
- Can be a source of background for optical detectors in air

Čerenkov radiation

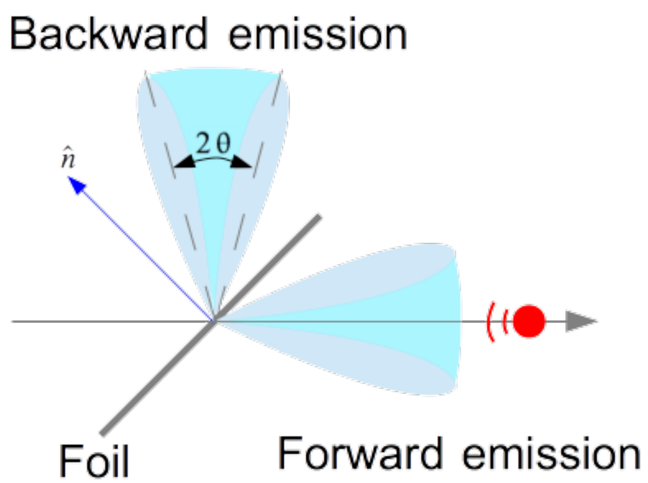


$$\frac{d^2N}{dx\,d\omega} = \frac{\alpha z^2}{c}\sin\theta_c(\omega)$$
$$= \frac{\alpha z^2}{c}\left(1 - \frac{1}{\beta^2 n^2(\omega)}\right)$$

Čerenkov radiation

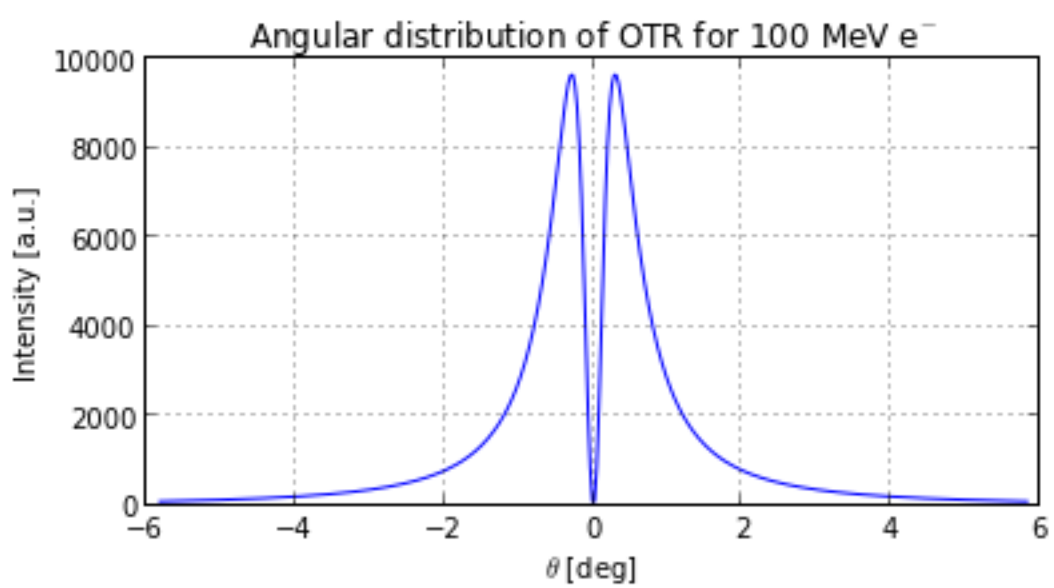


Optical Transition Radiation (OTR)



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

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



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

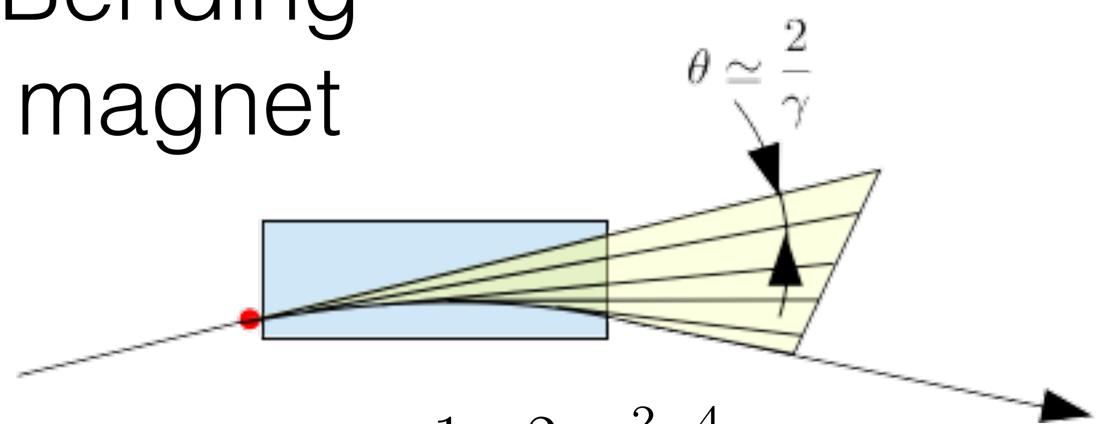
Peaks at

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

- 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

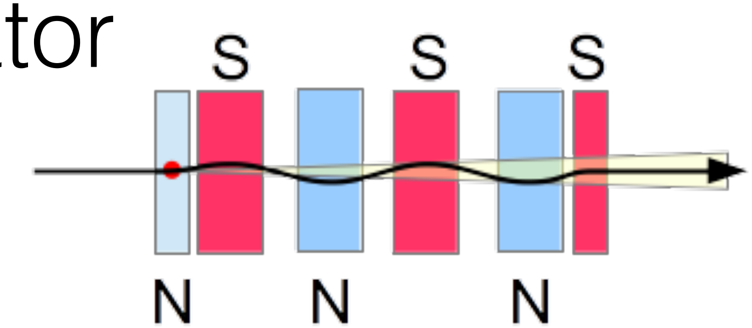
Synchrotron radiation

Bending magnet



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

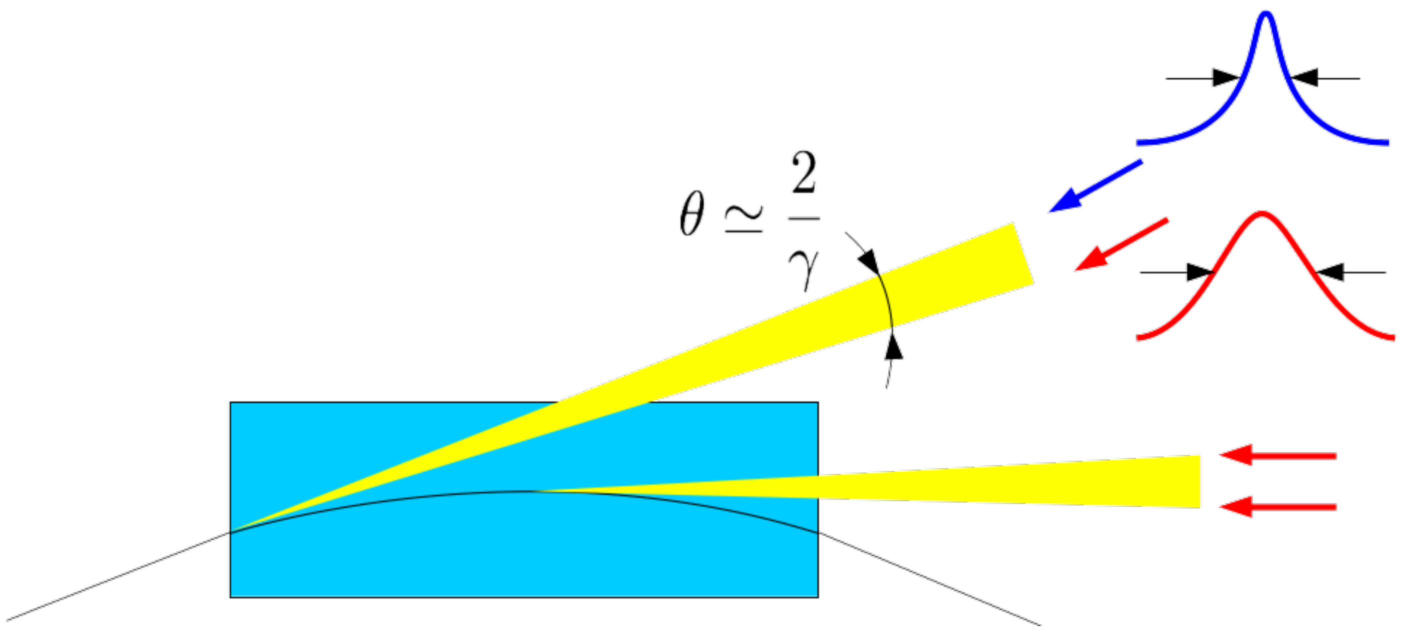
Undulator

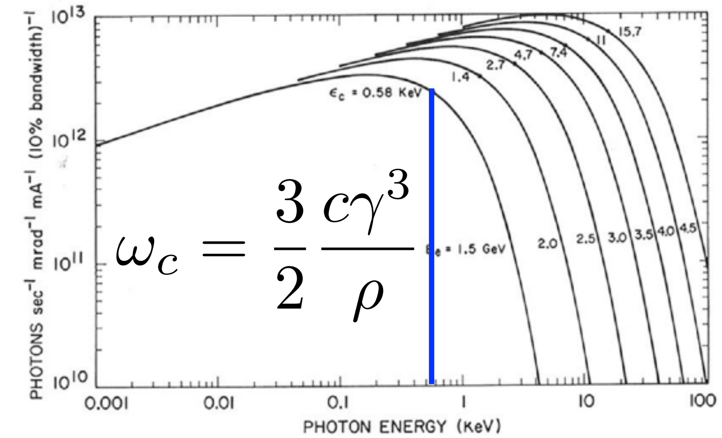


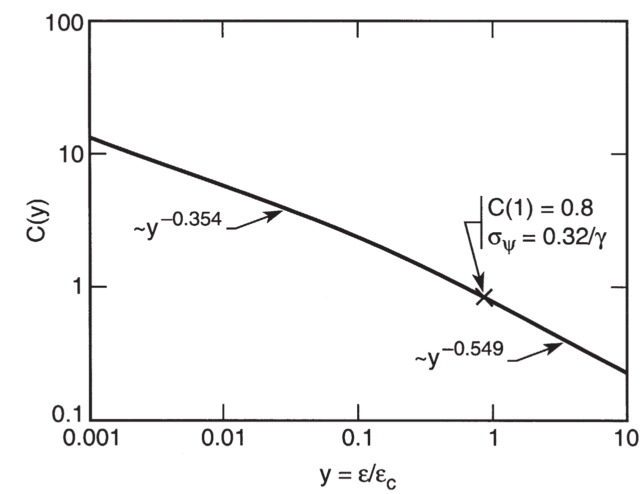
$$\lambda = \frac{\lambda_u}{2\gamma^2} \qquad W \propto B_0^2\gamma^2$$

- 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





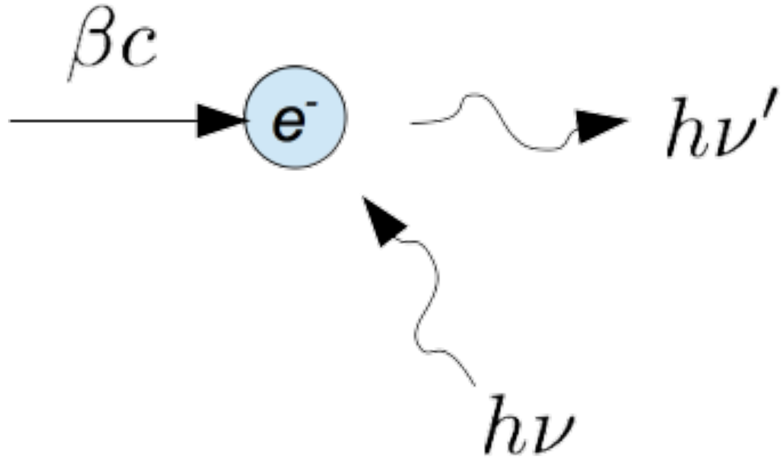


$$\sigma_\theta = \frac{2}{\gamma\sqrt{2\pi}} C(y)$$

Red observer sees longer pulses and thus narrower spectrum.

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

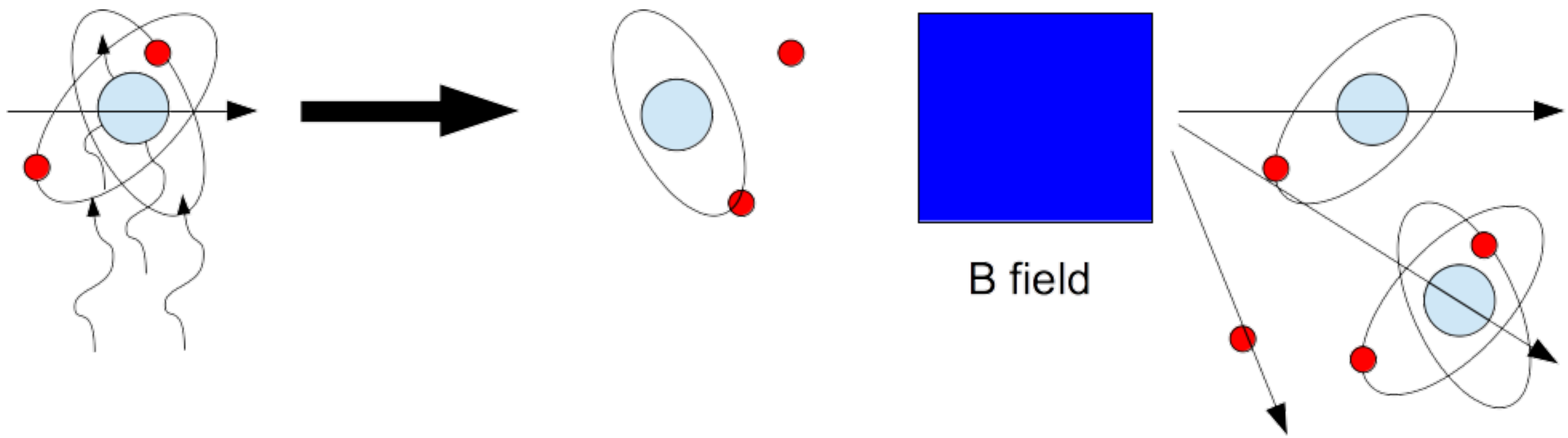
Inverse Compton scattering



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

- 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 m_p/m_e~1/2000)

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

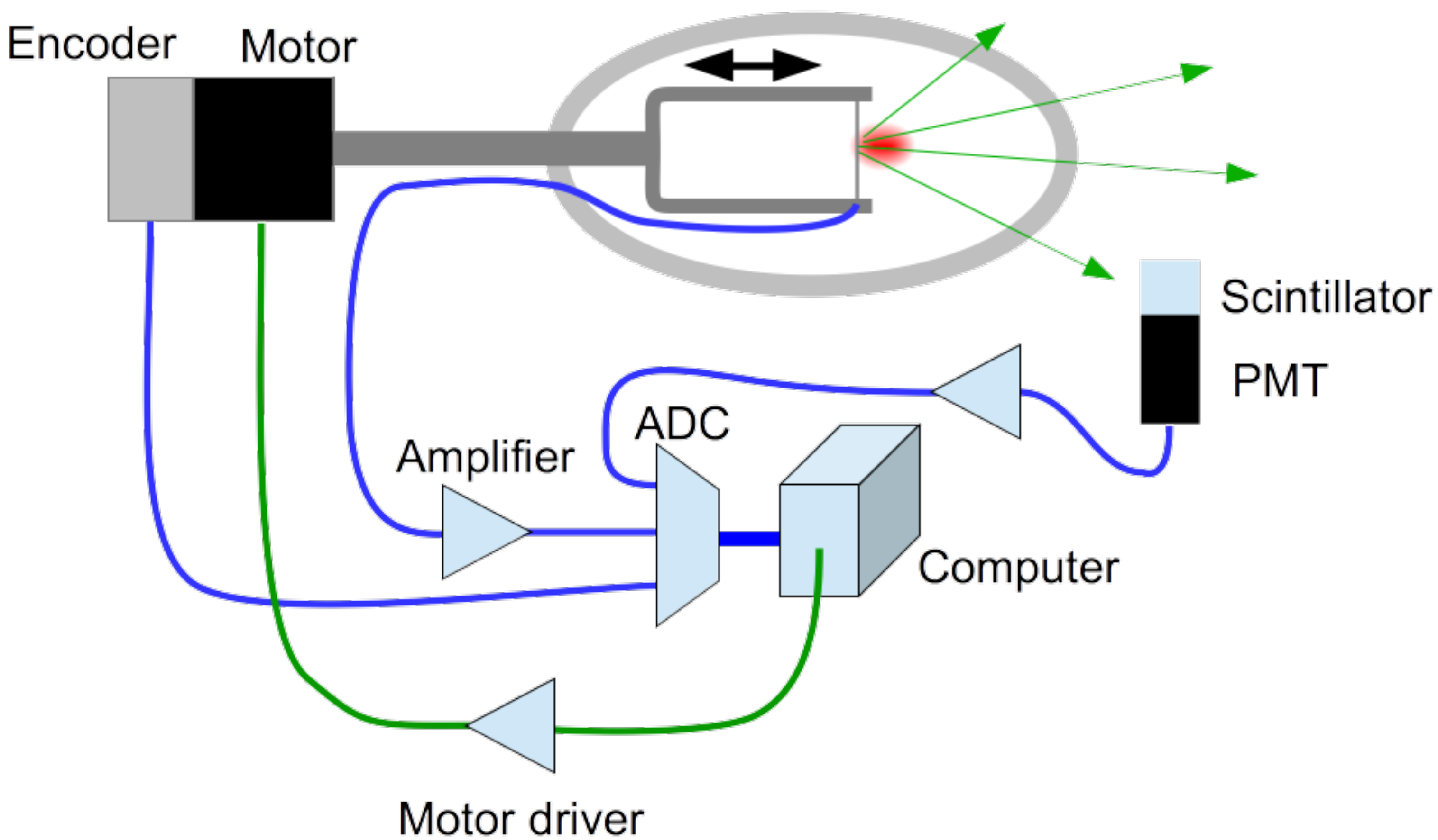
Some of the ions will lose the extra electron and become neutral H^0

The different species can be separated by a bending magnet

Sampling distributions

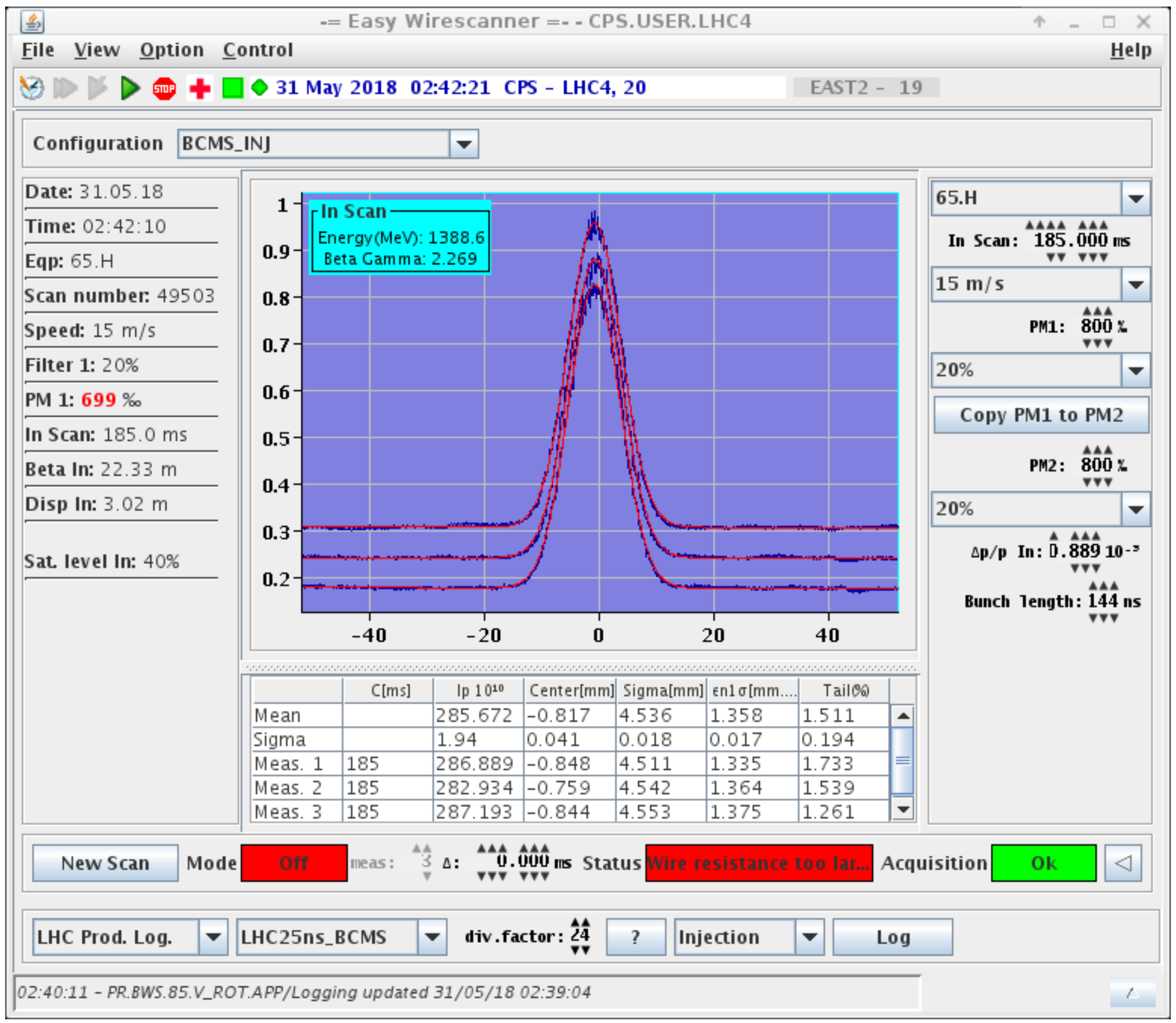
- **One dimension sampling**
  - Wire scanners
  - Wire grids
  - Rest gas ionisation monitors
  - Laser Wire Scanner
- **Two dimension sampling**
  - Screens and radiators
  - Synchrotron radiation

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



- 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

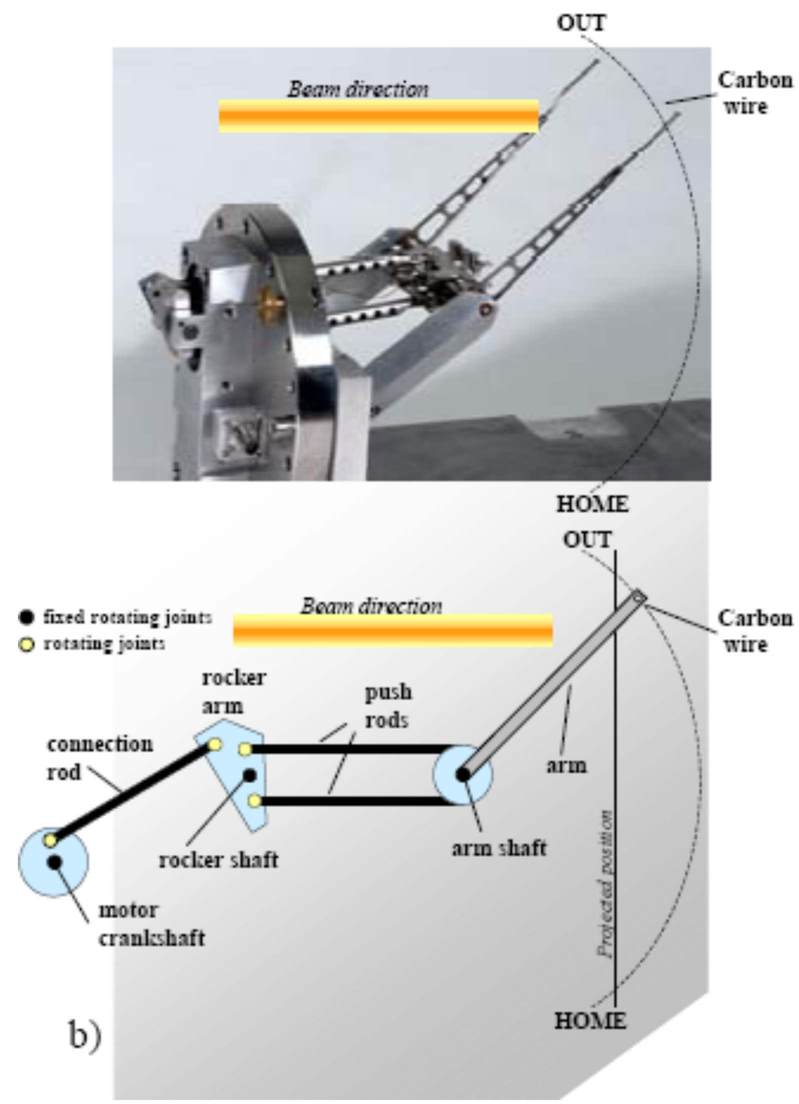
Wire scanner

- **Secondary emission**
  - Good for low energy beams (no high energy secondary)
  - Small signal
  - If the wire becomes too hot it can start emitting 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

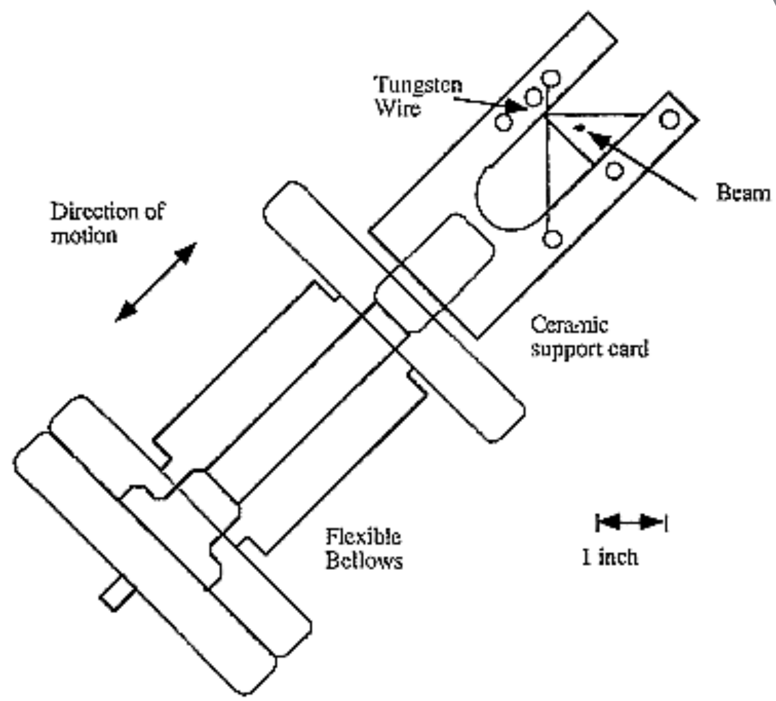
Wire scanner

- **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

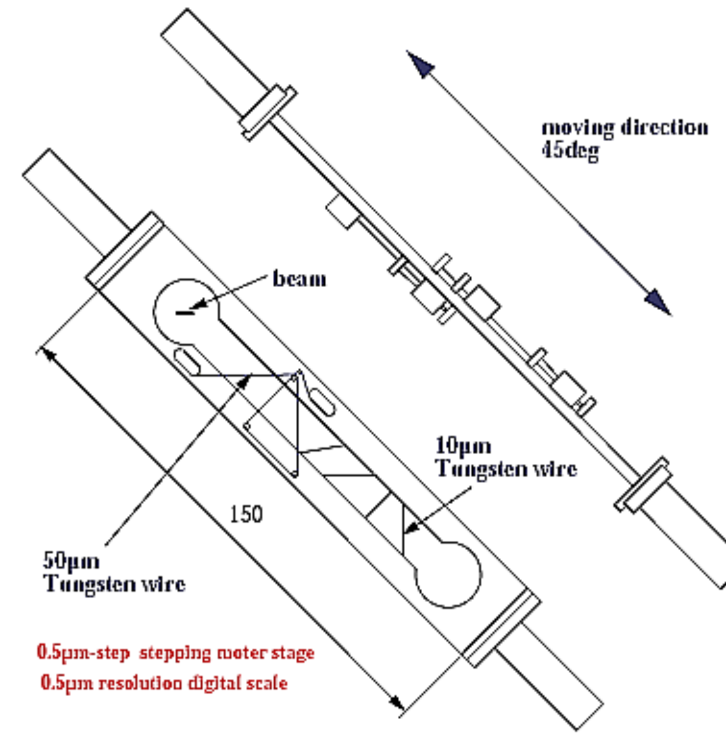
Wire scanner



CERN "flying wires"

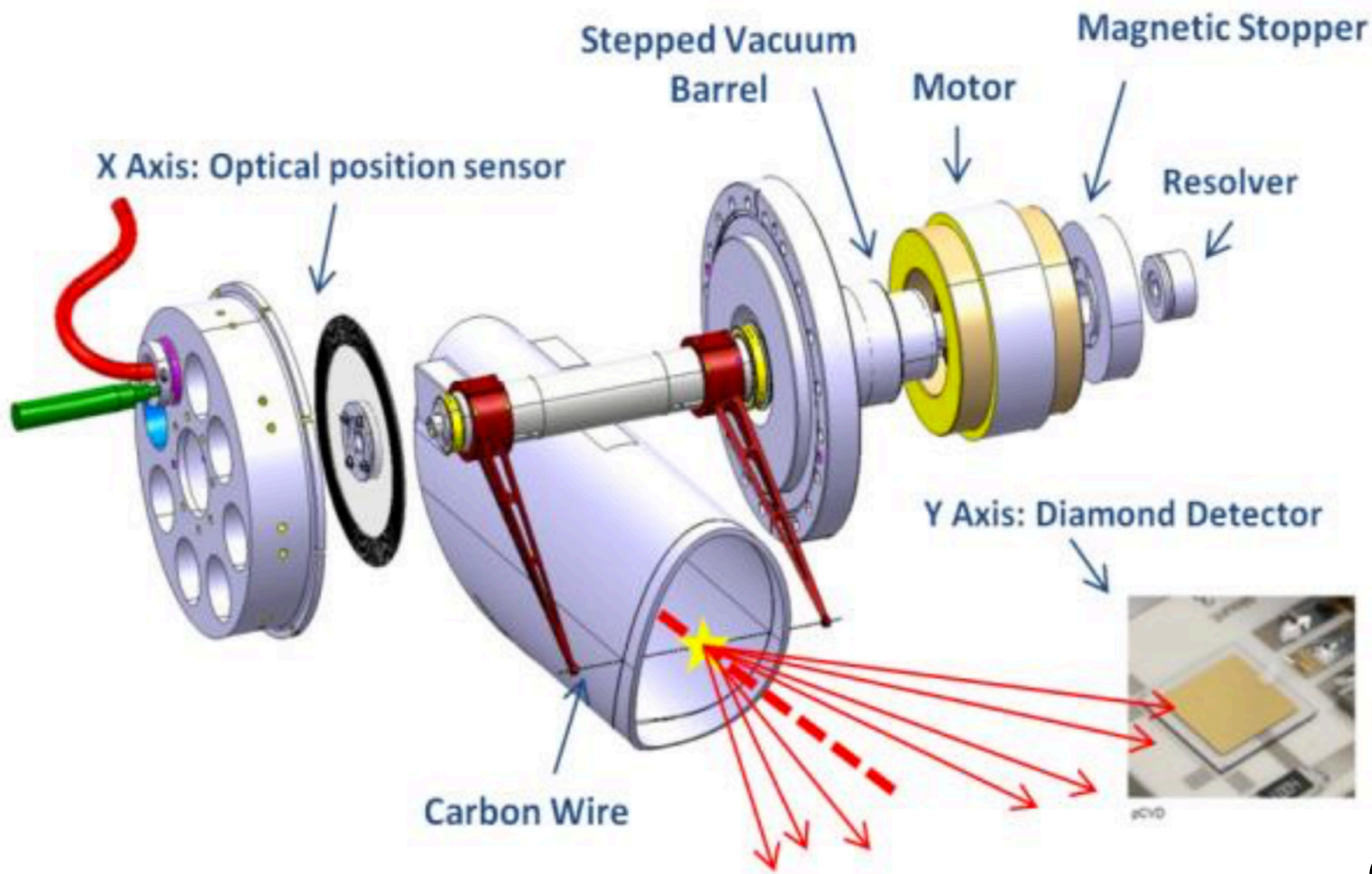


SLAC SLC high resolution 3 axis scanners



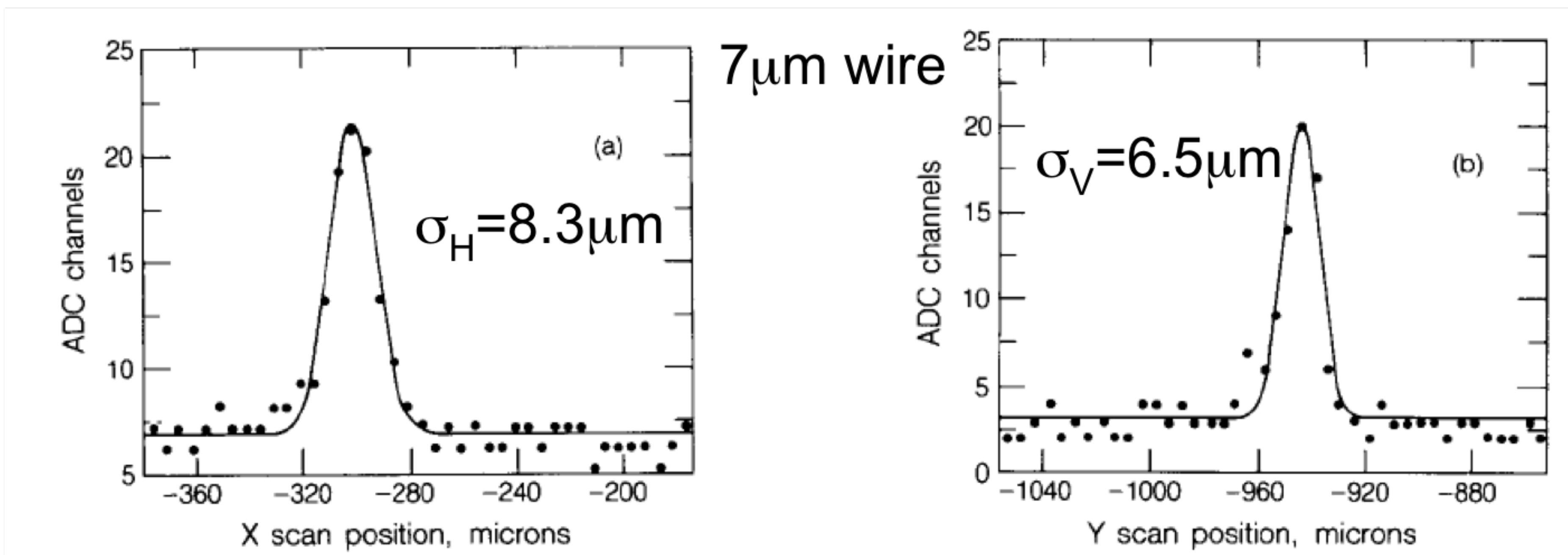
KEK ATF high resolution 3 axis scanners

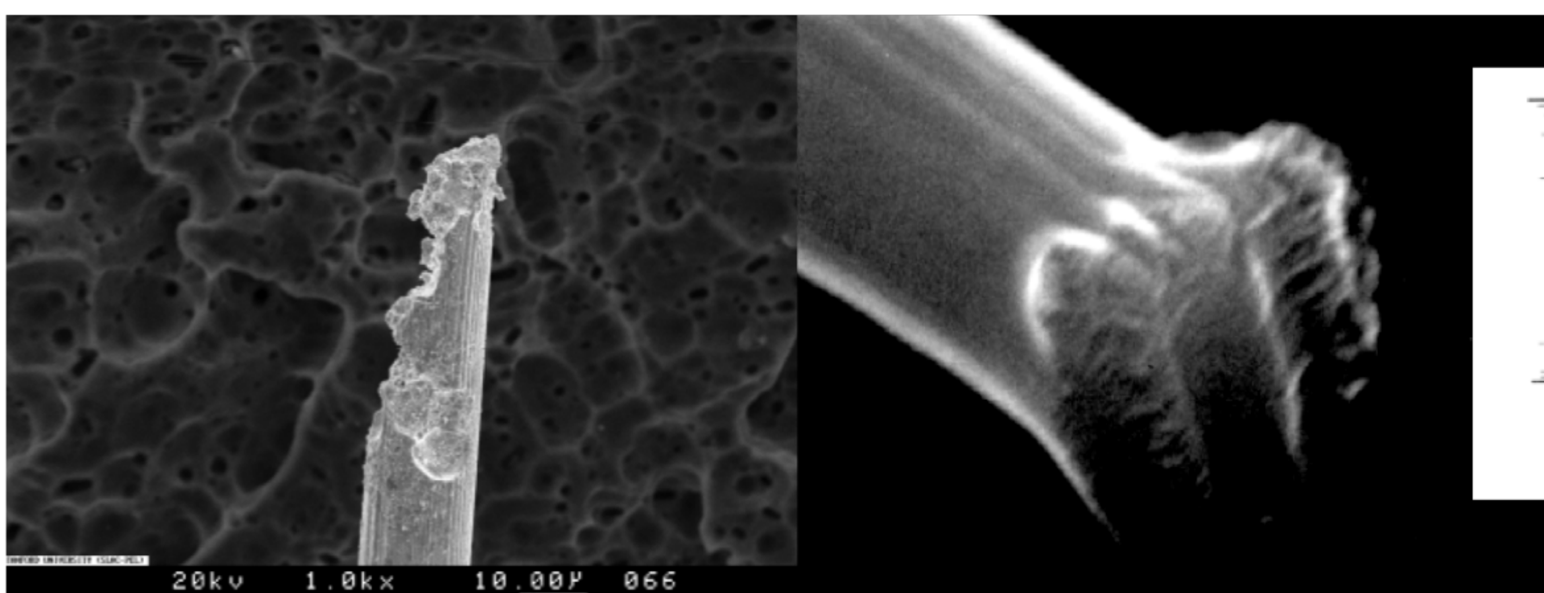
Fast rotational WS

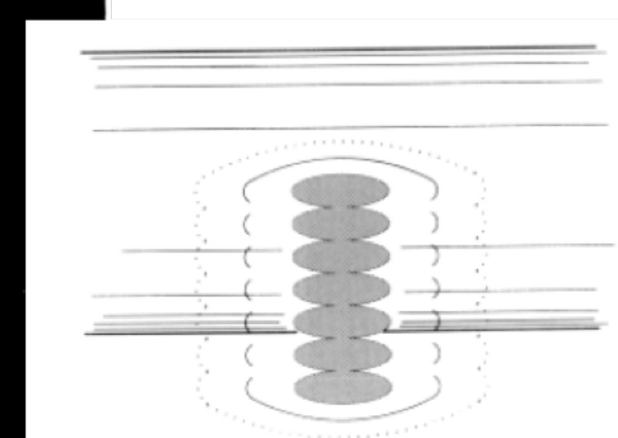


CERN

Wire Scanner (SLC)







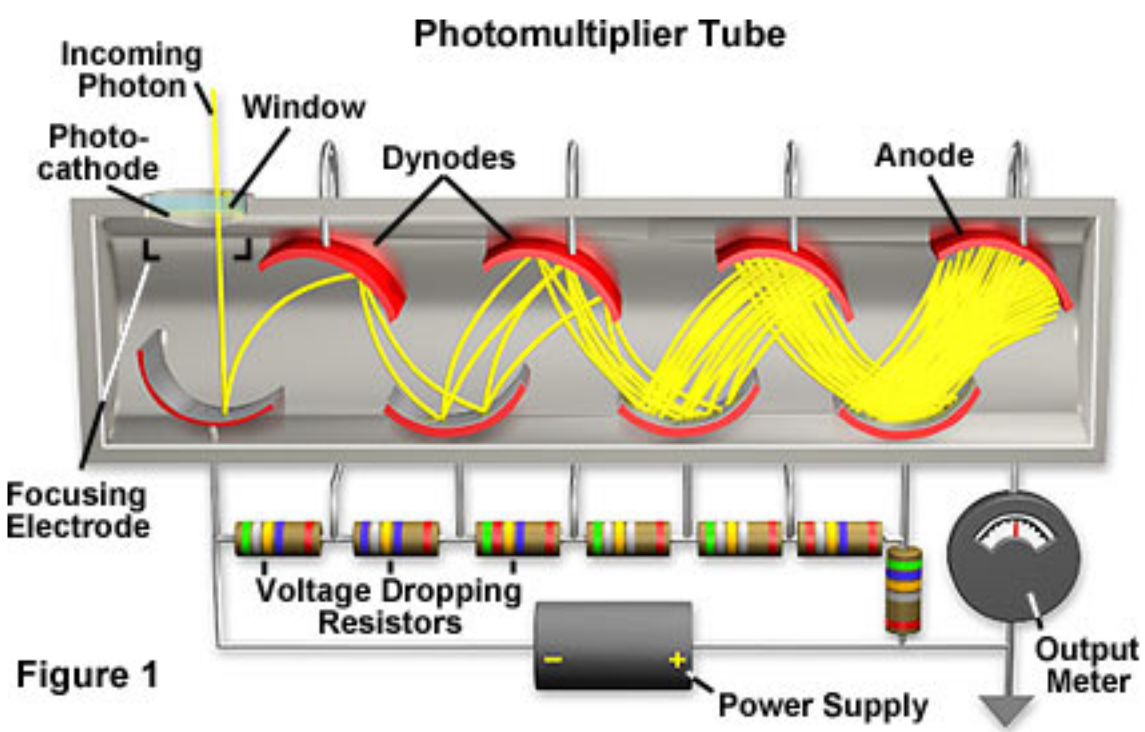
Wire scanner remarks

- Wire and mechanics may vibrate
  - Wire position does not correspond to reading
- Wire may glow and emit electrons (SEM)
- Scintillator may saturate (unlikely)
- PMT may saturate (usual! Space charge, voltage drop, etc.)

WS detectors remarks

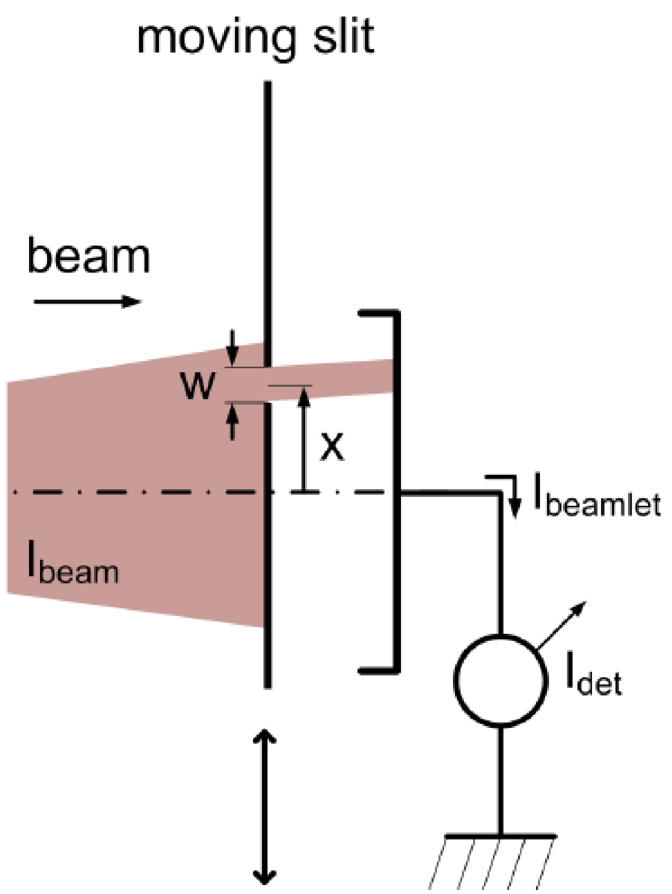
- Usually scintillator + PMT near beam pipe downstream of WS (cheap, large and sensitive detector)
- Shower detection may be non homogenous
  - Correlation btwn particle direction and position
  - Different interaction with vacuum chamber of magnetic elements
- Shape and geometry of the detector require simulations (FLUKA, GEANT etc.) including photon tracking.

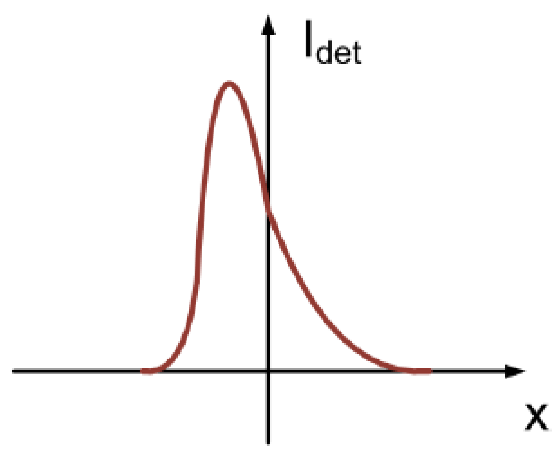
Photomultipliers

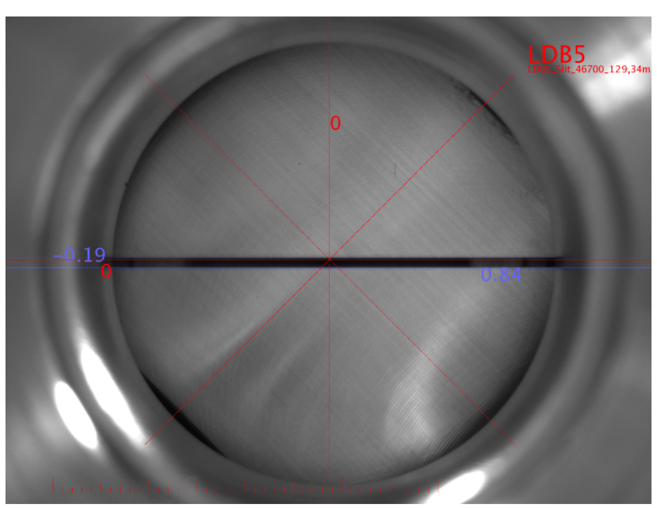


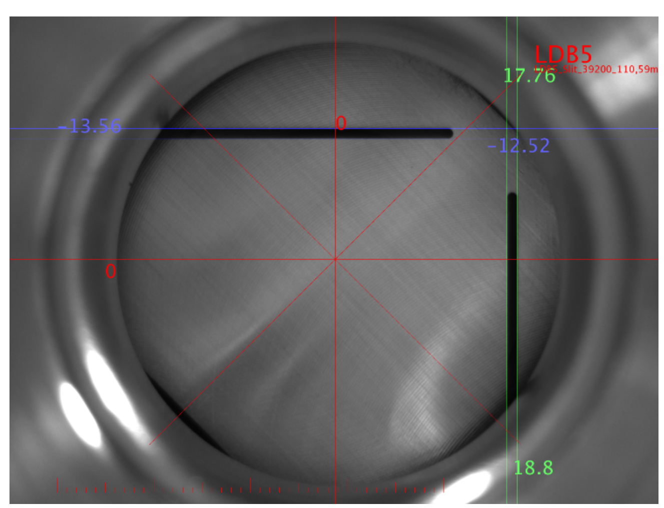
- Cascade current influences voltage divider network
- Gain depends strongly on dynodes potential
- Active bases allow larger output currents

Slit scanner



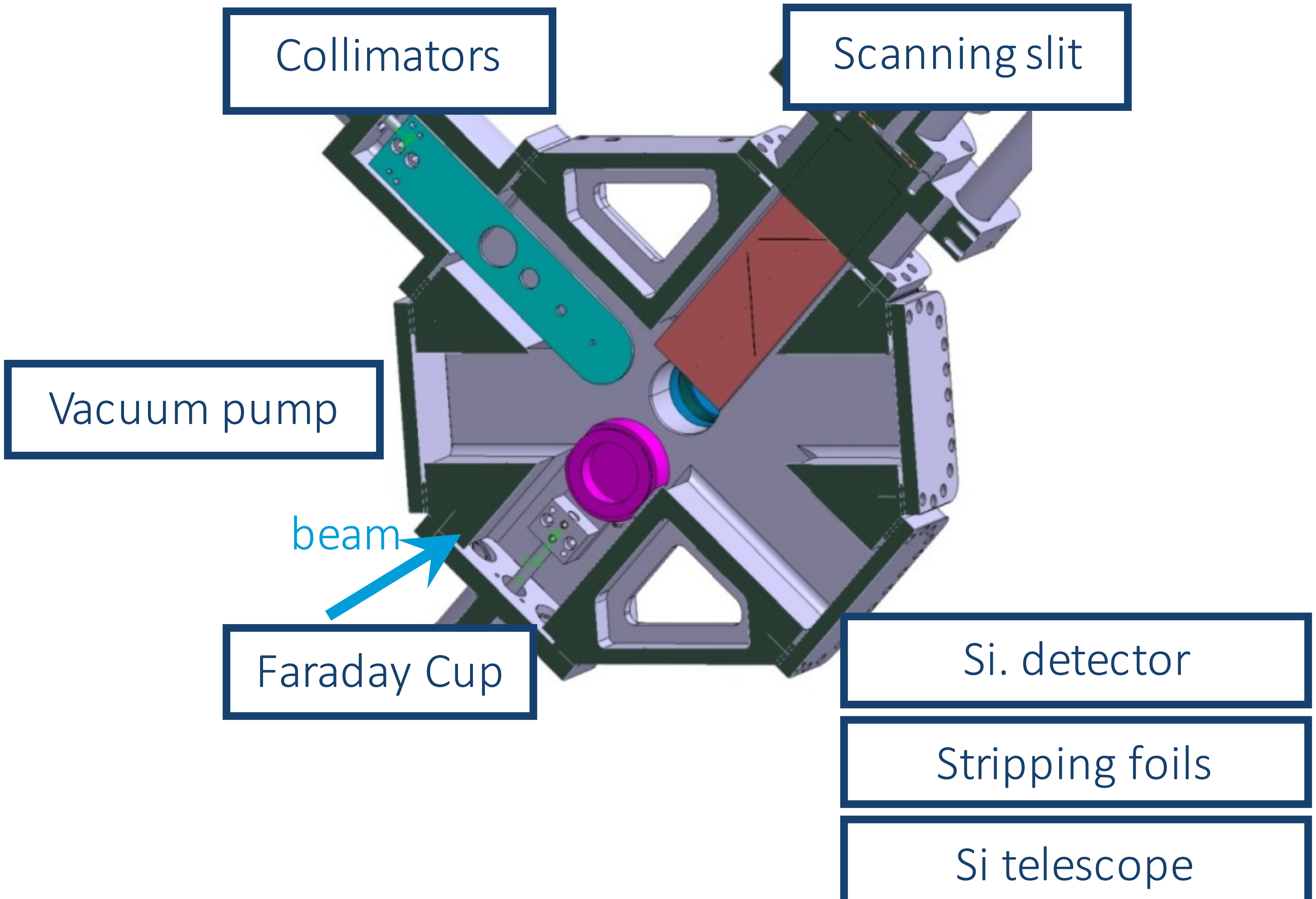






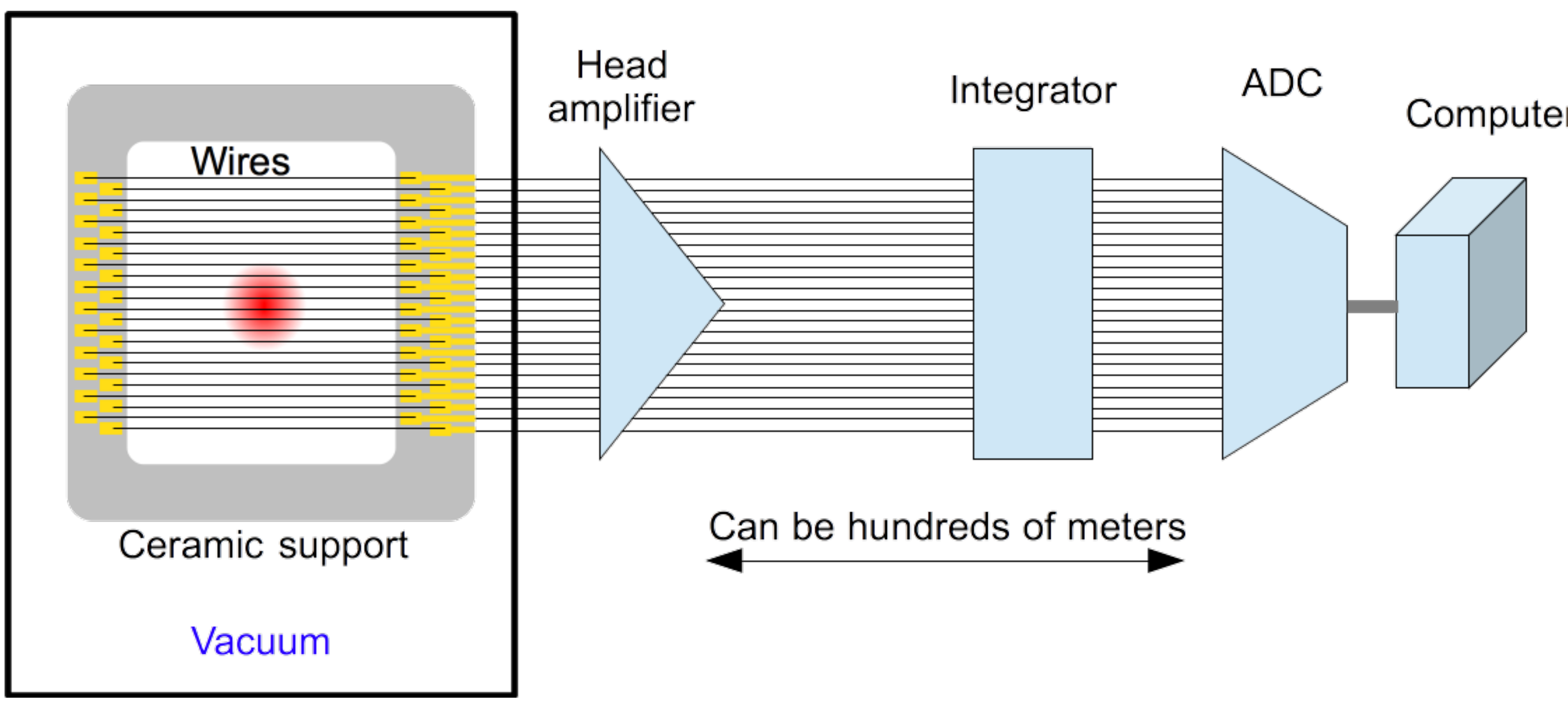
- Pass a thin slit across the beam and detect the beam current passing trough the slit
- Similar to wire scanner
- Useful for low energy and low intensity (I>> I_{SEM})
- Detector typically is a Faraday cup, but could also be a scintillator, silicon or diamond detector.

Example of compact diagnostic box for RIB

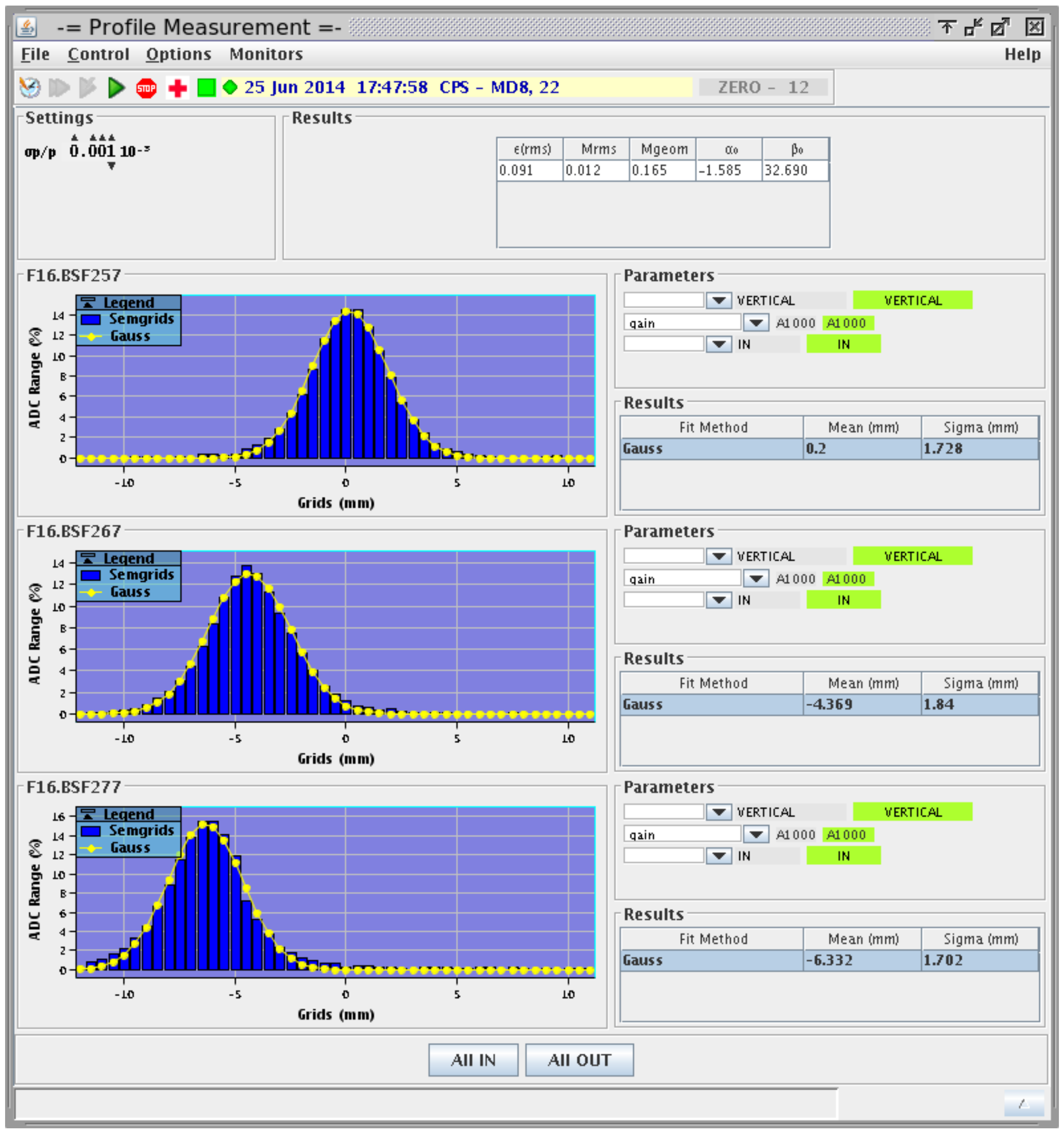


SEM Grid (Wire Harp)

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

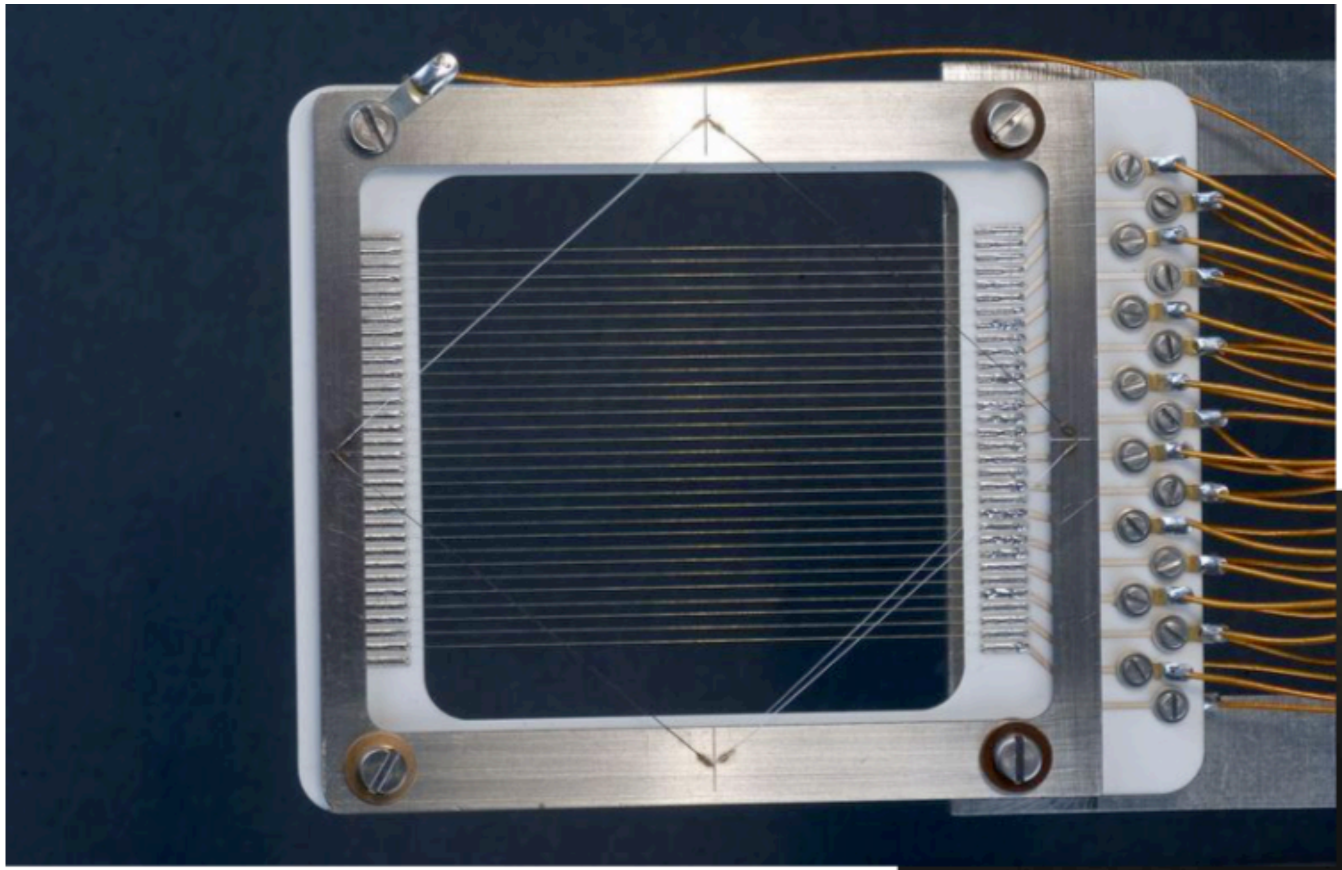


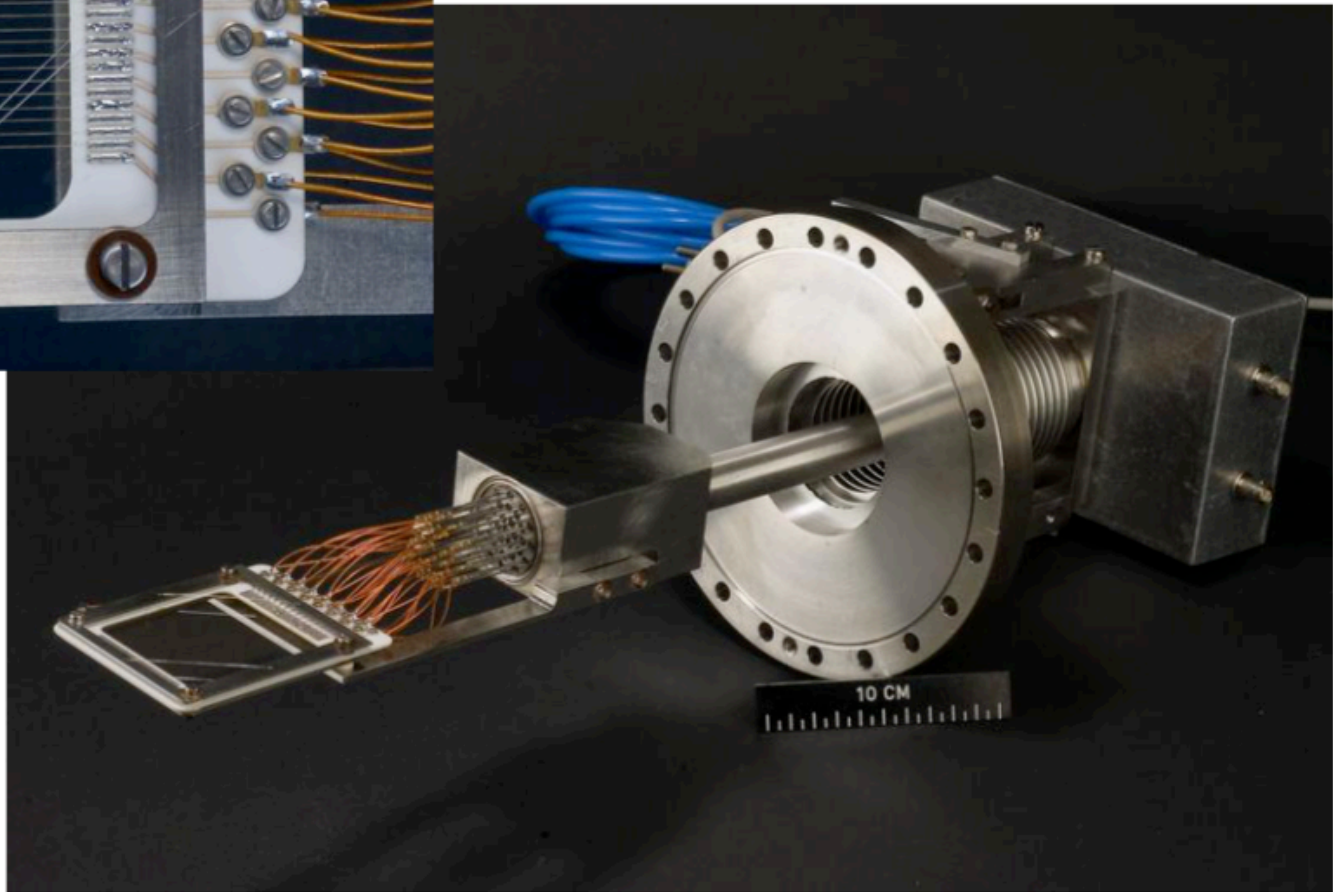
SEM Grid



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

SEM Gid





SEM Gid (no more)

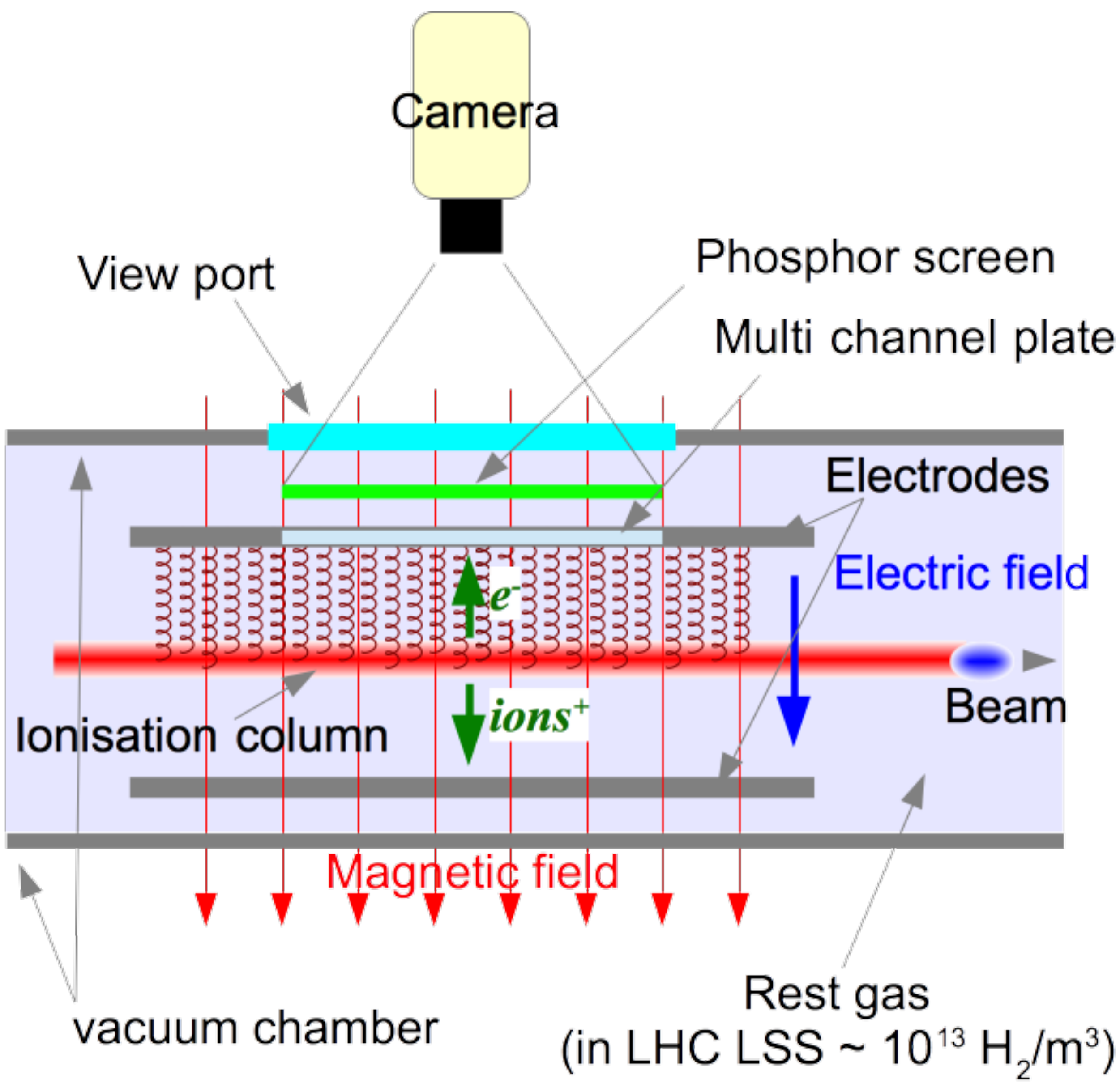
SEM Grid

- The development of radiation resistant ASICS is very interesting fro the SEM grids, in particular if it is vacuum compatible
  - Reduce the complexity (and cost) of the signal acquisition
  - Increases the read out speed possibilities
  - Reduces the read out noise
- Main source of cost remains the manual labor to mount the wires

SEM Grid read-out

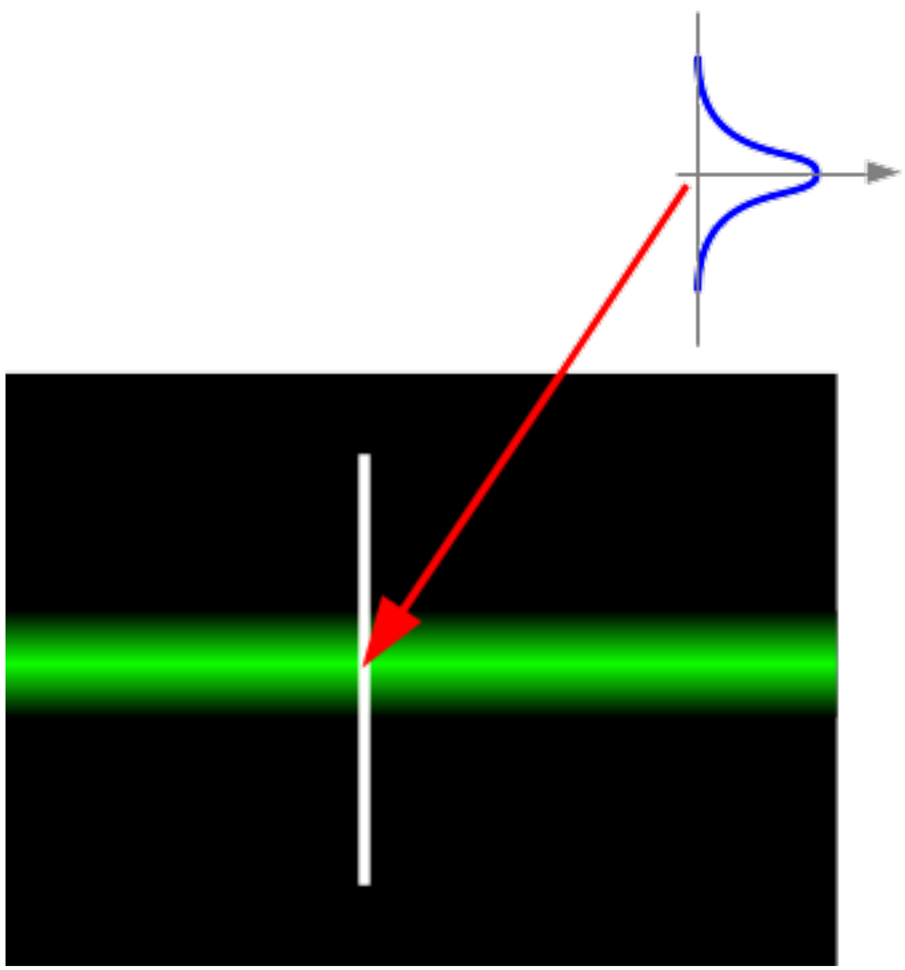
- Two possible solutions for the front end electronics
  - Linear amplifiers
    - Time resolved readout
    - Simple
    - No dead times
  - Integrators
    - Time resolution is lost
    - Requires timing signals
    - Dead time while resetting the integrator
    - Better signal to noise

Ionisation profile monitor



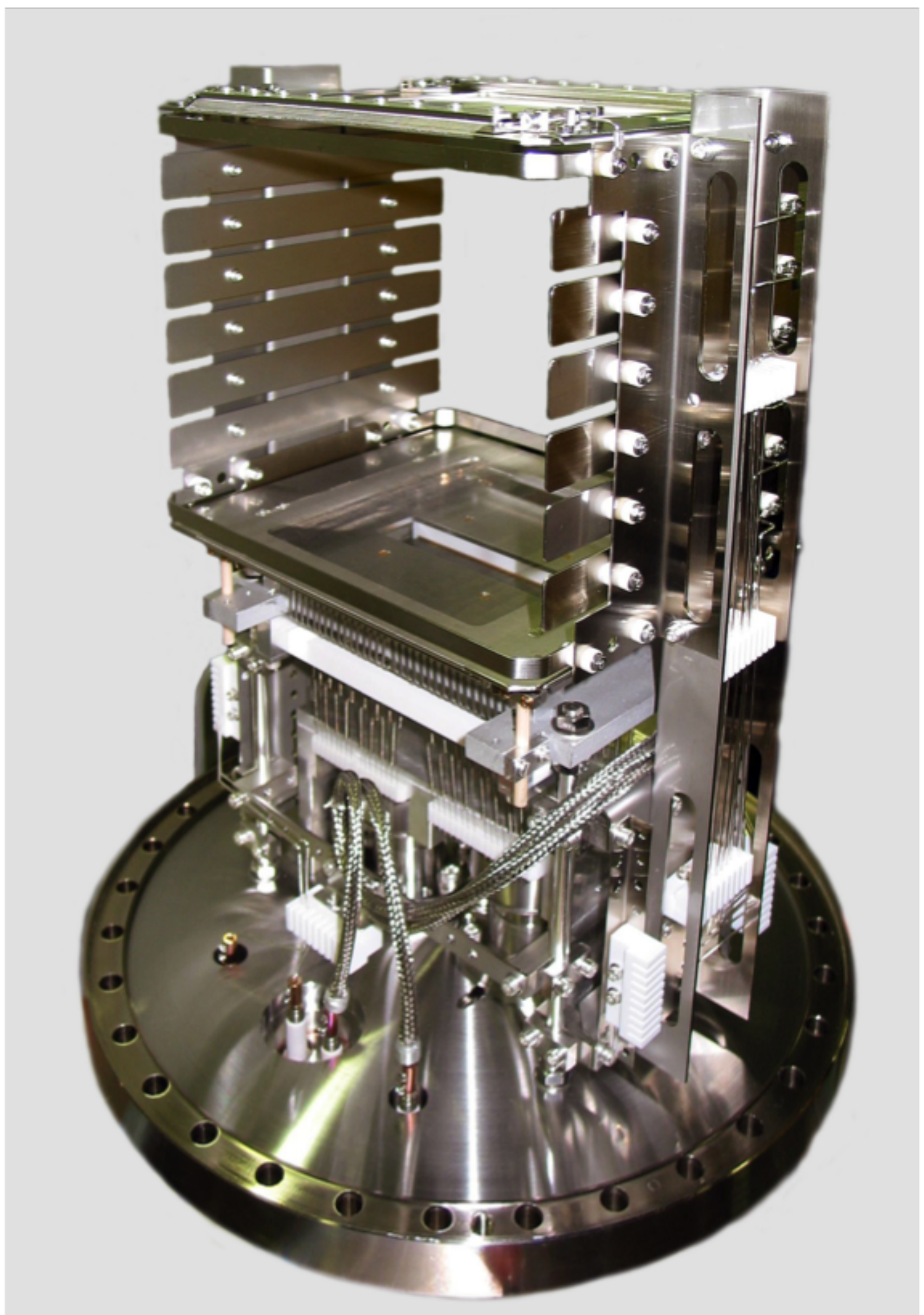
- Beam creates ionisation column in rest gas
- Electric field drifts electrons Ions) toward detector
- Magnetic field guides the electron (ions)
- MCP+phosphor+CCD detects electrons (ions)
- If E is reversed ions can be detected instead of electrons (less need for B field)

Ionisation profile monitor

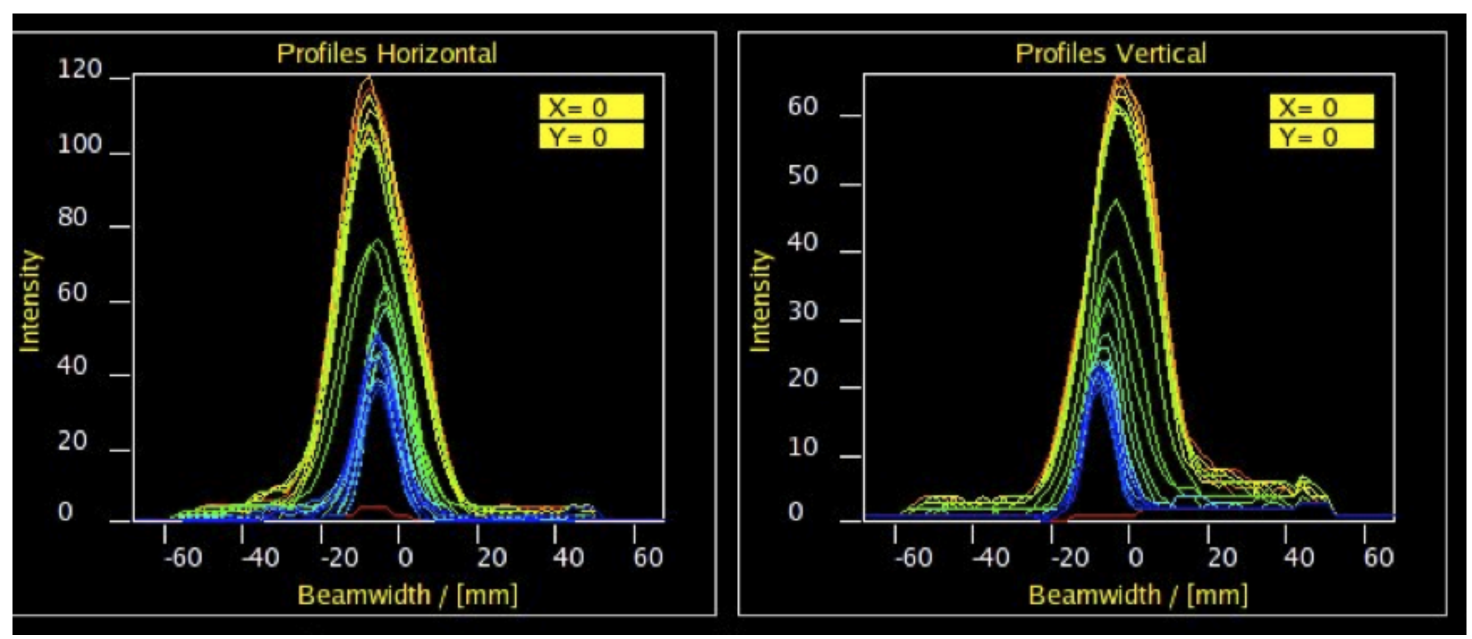


- Image shows a stripe
- Intensity profile of stripe proportional to beam profile
- Detector measures only one plane
- Transverse drift of electrons introduces broadening (need intense B field) and creates “tails”

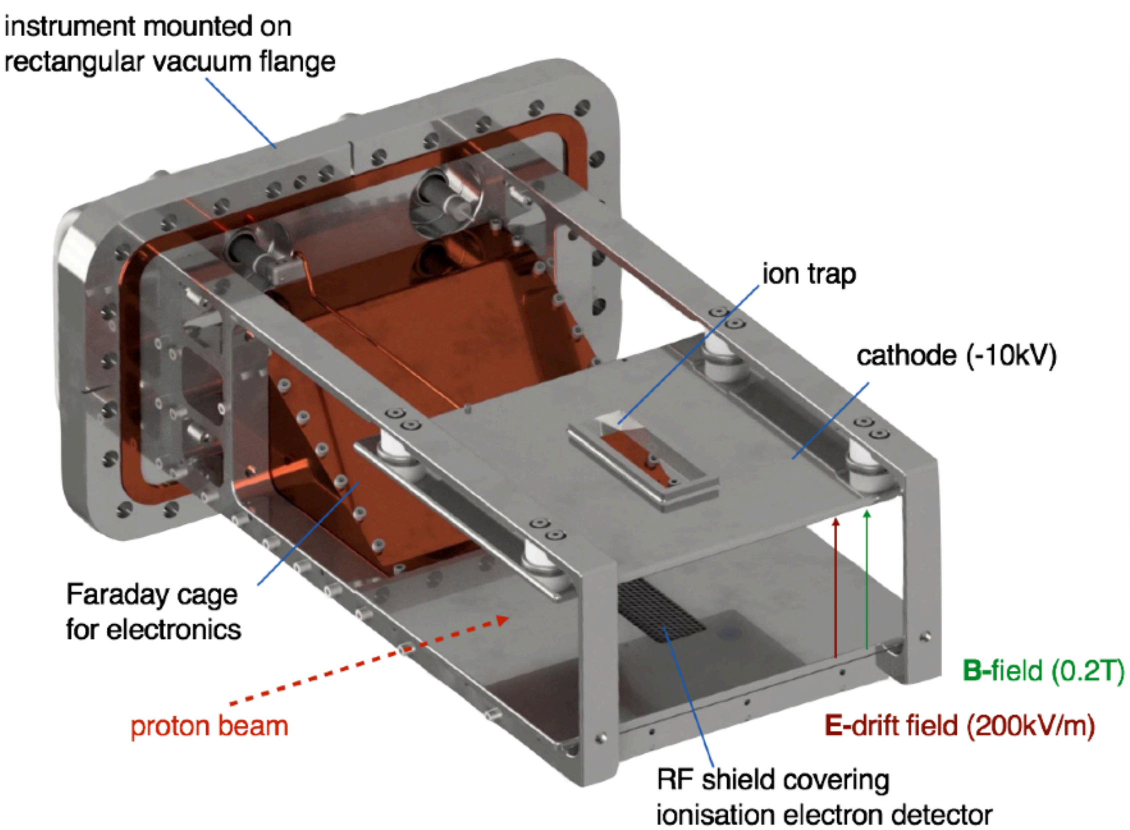
IPM (GSI)

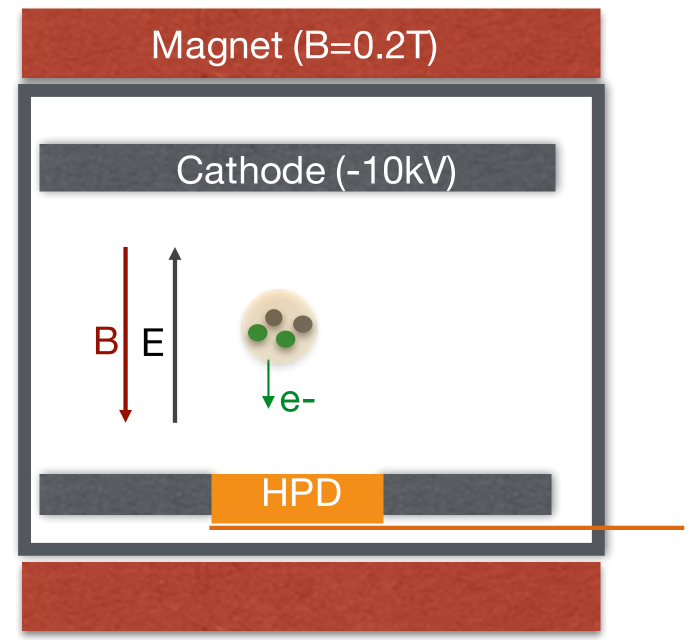


- IPMs allow the continuous monitoring of the transverse plane
- Needs a “minimum” of rest gas

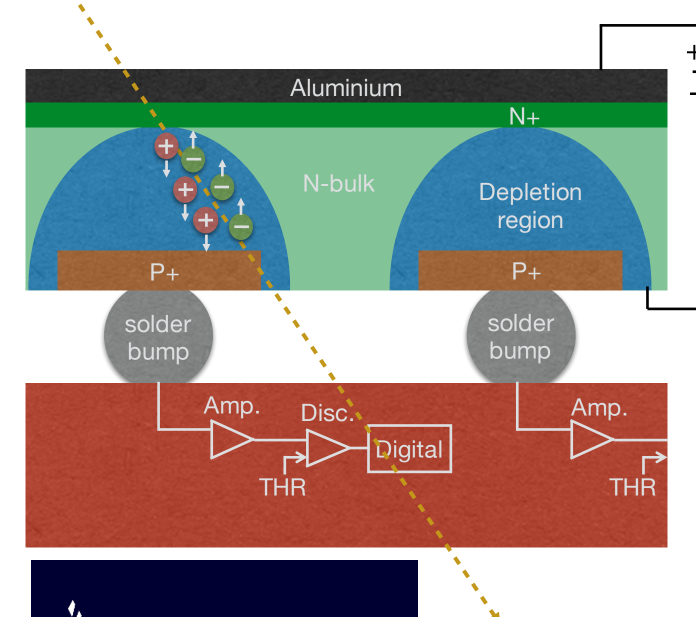


IPM (CERN PS)

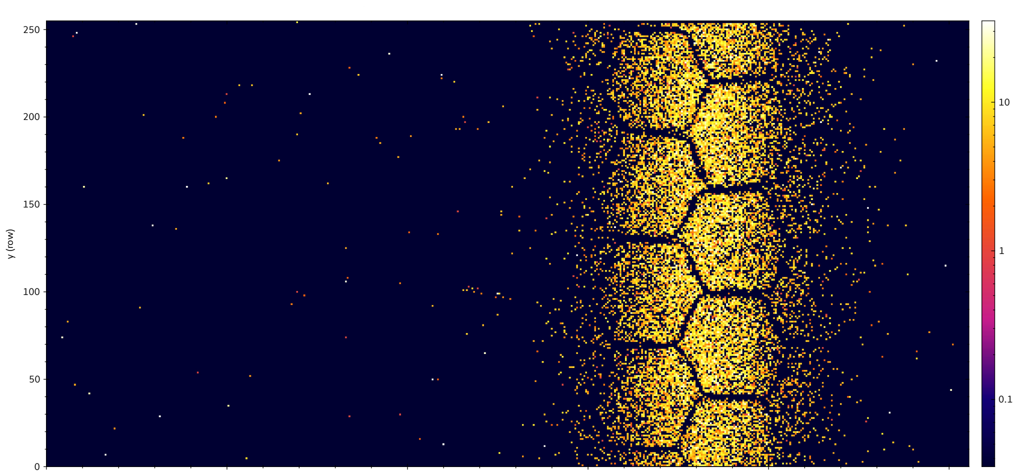


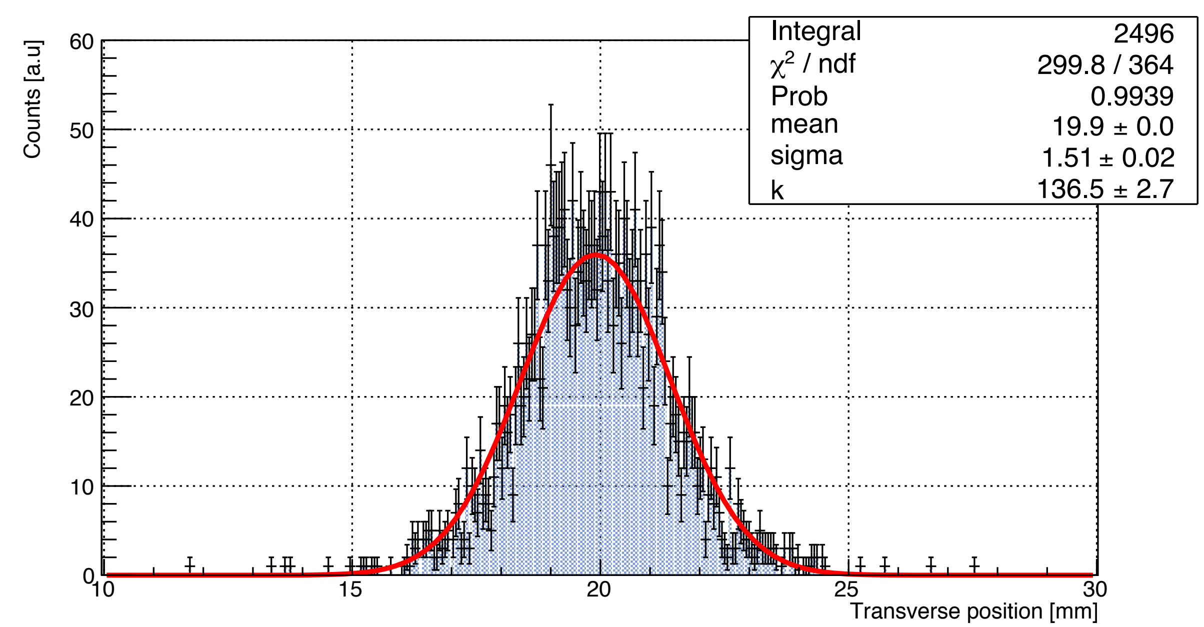


Timepix chip



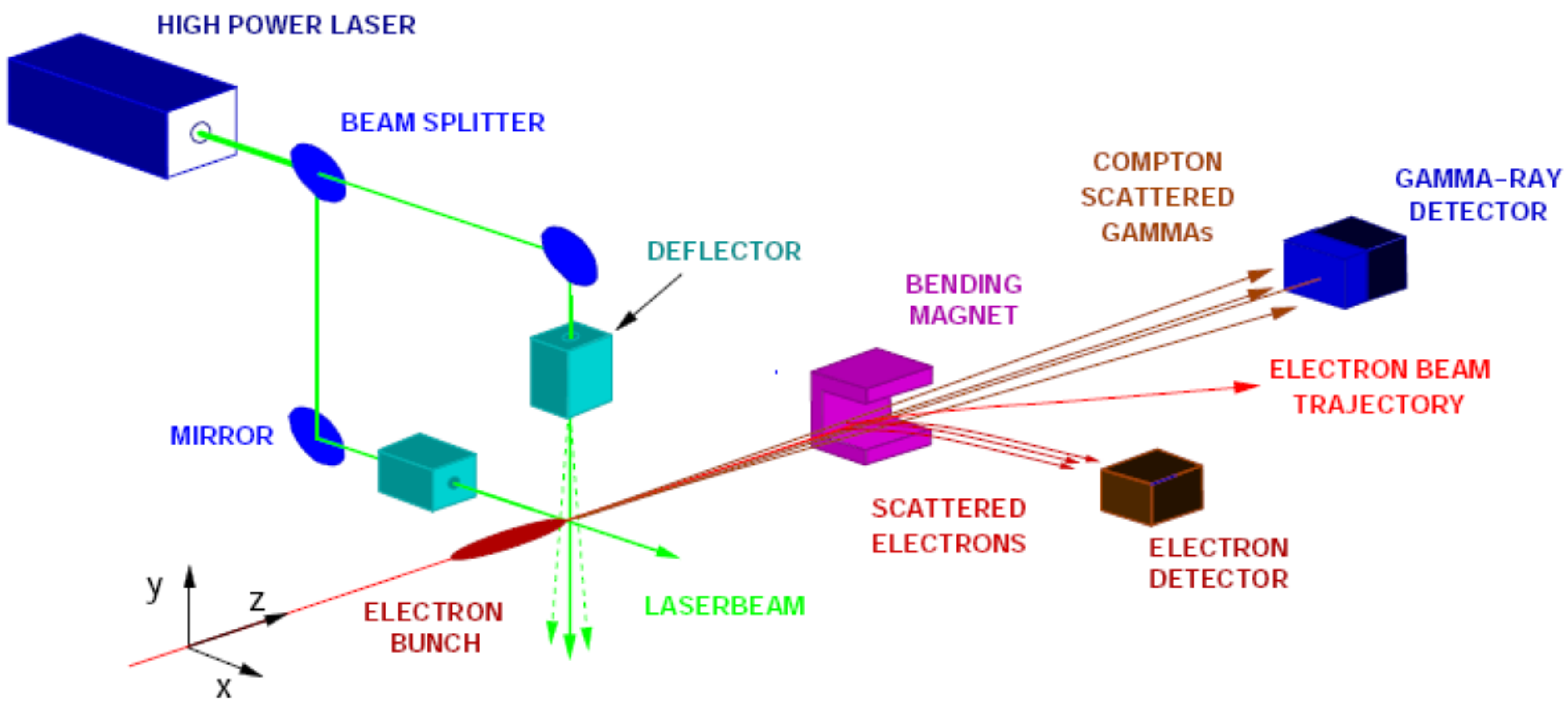
medipix collaboration



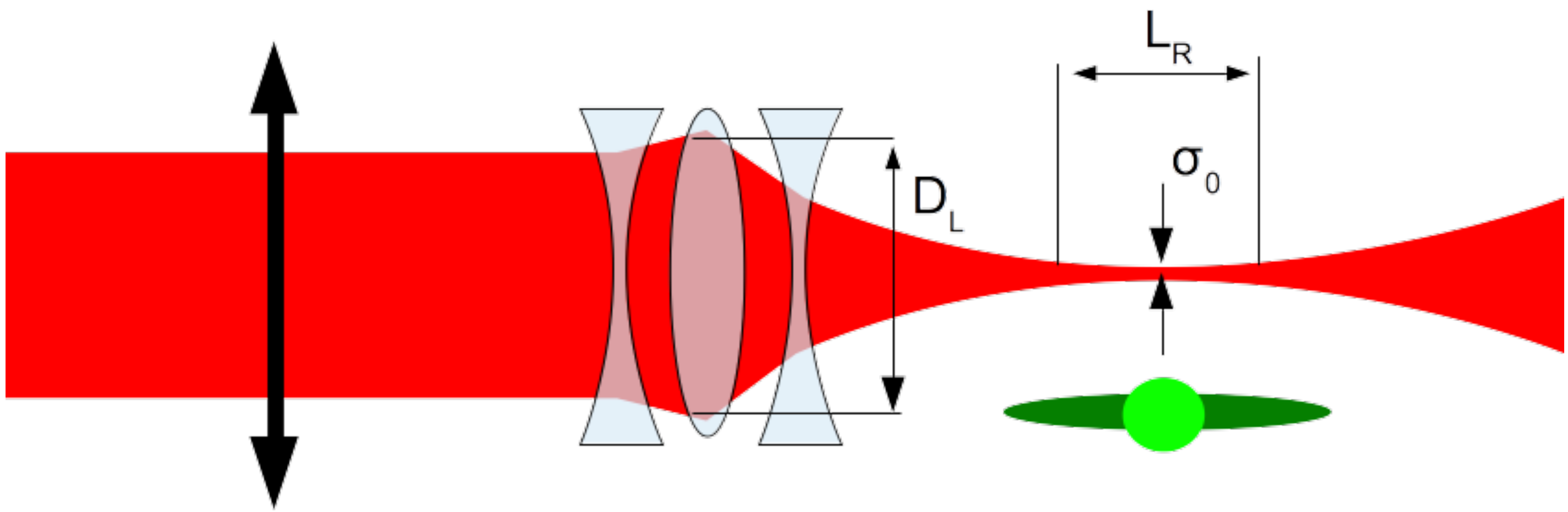


Laser Wire Scanner

- 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



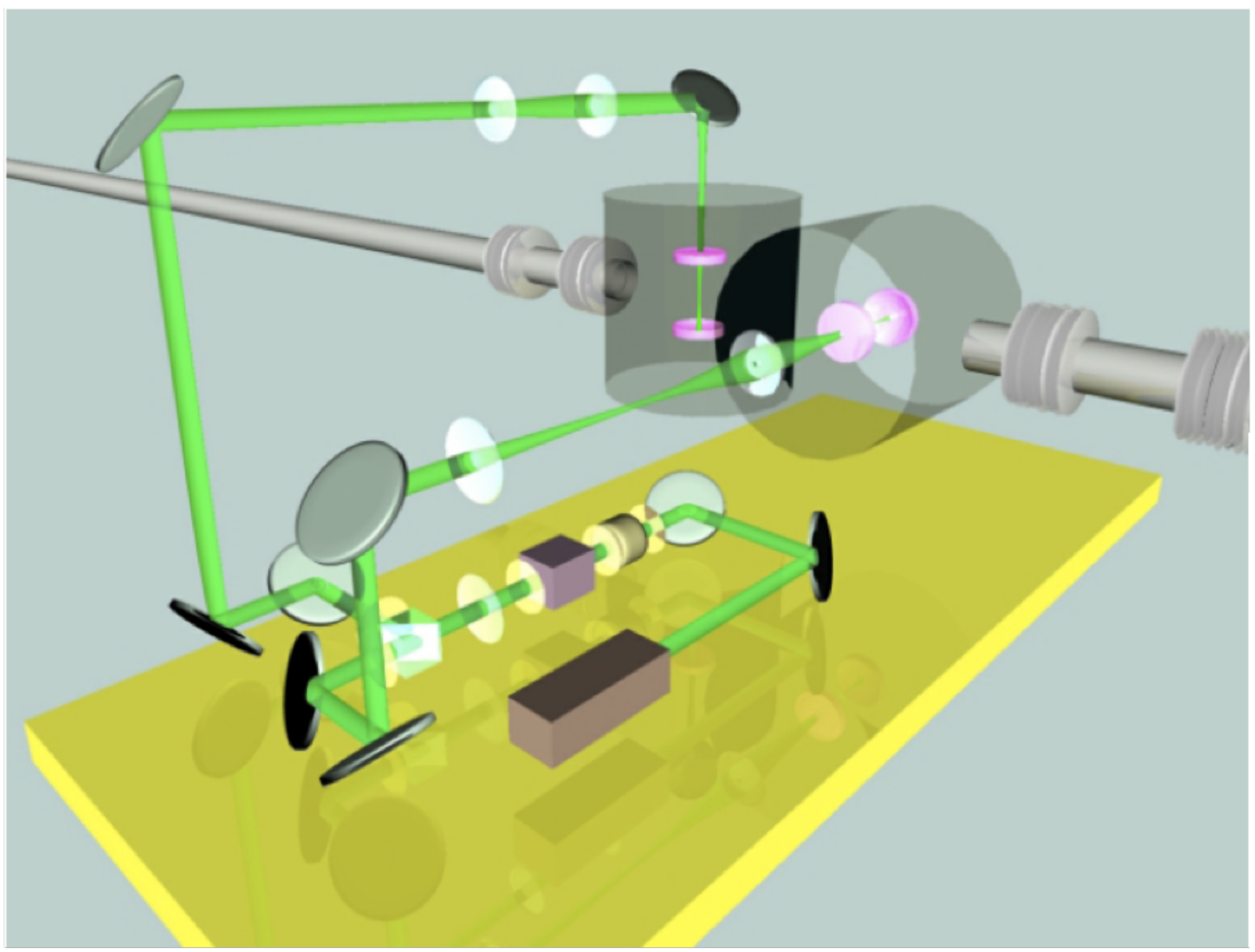
Laser Wire Scanner



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

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

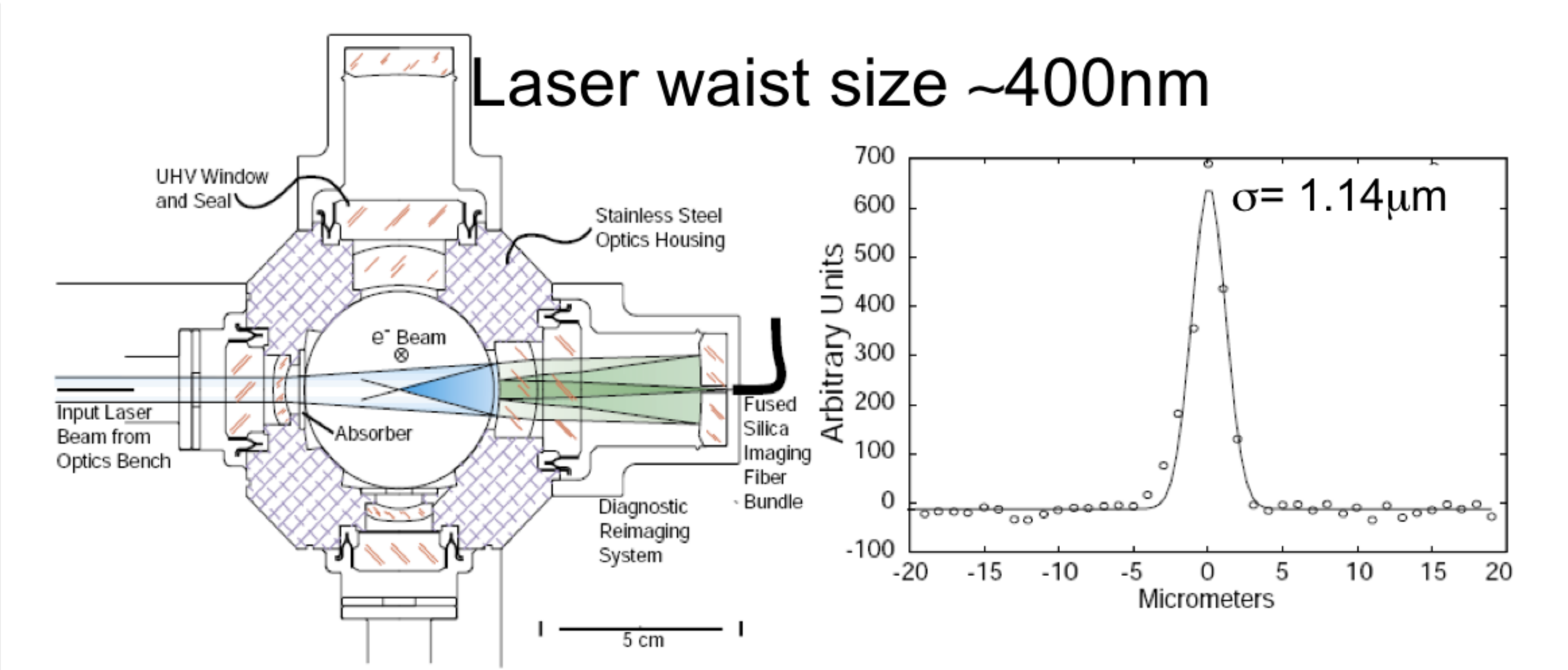
Laser Wire Scanner



- 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

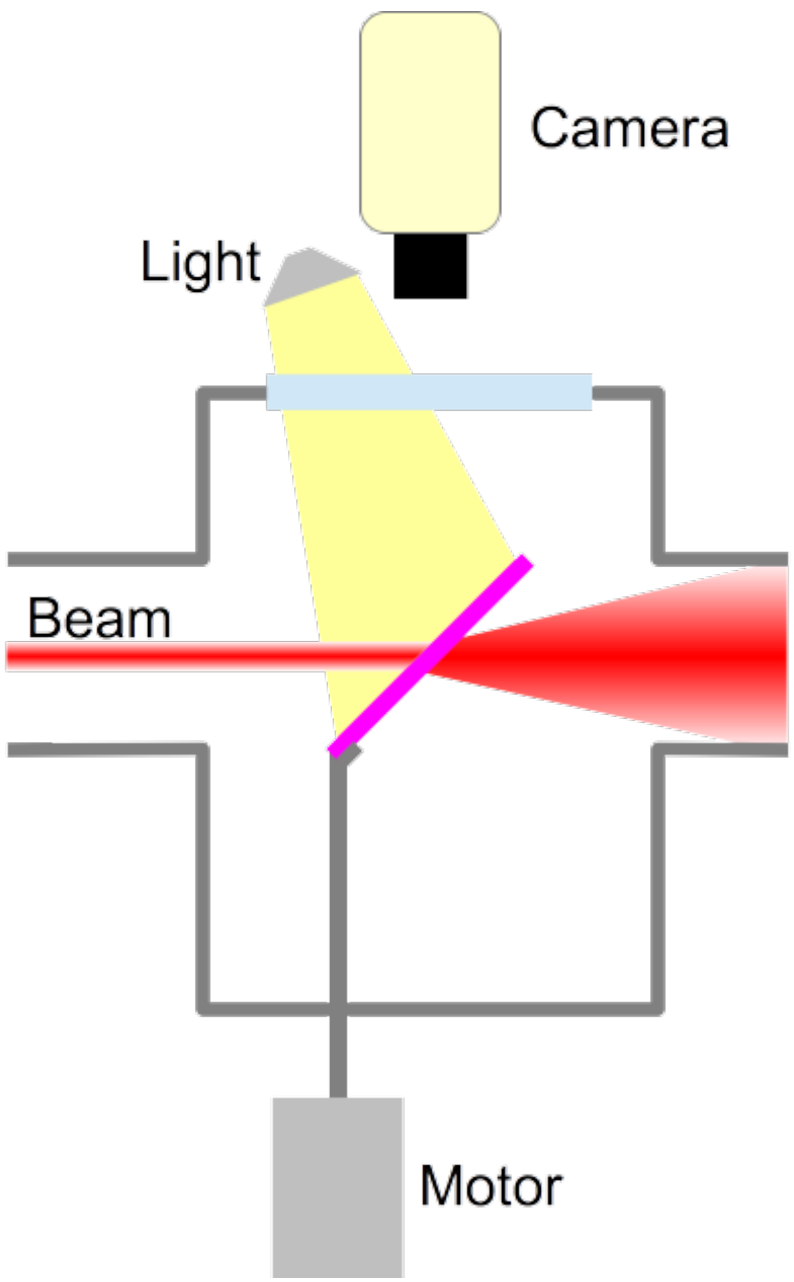
LWS used at SLC to measure the beam size at the IP



Laser 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)

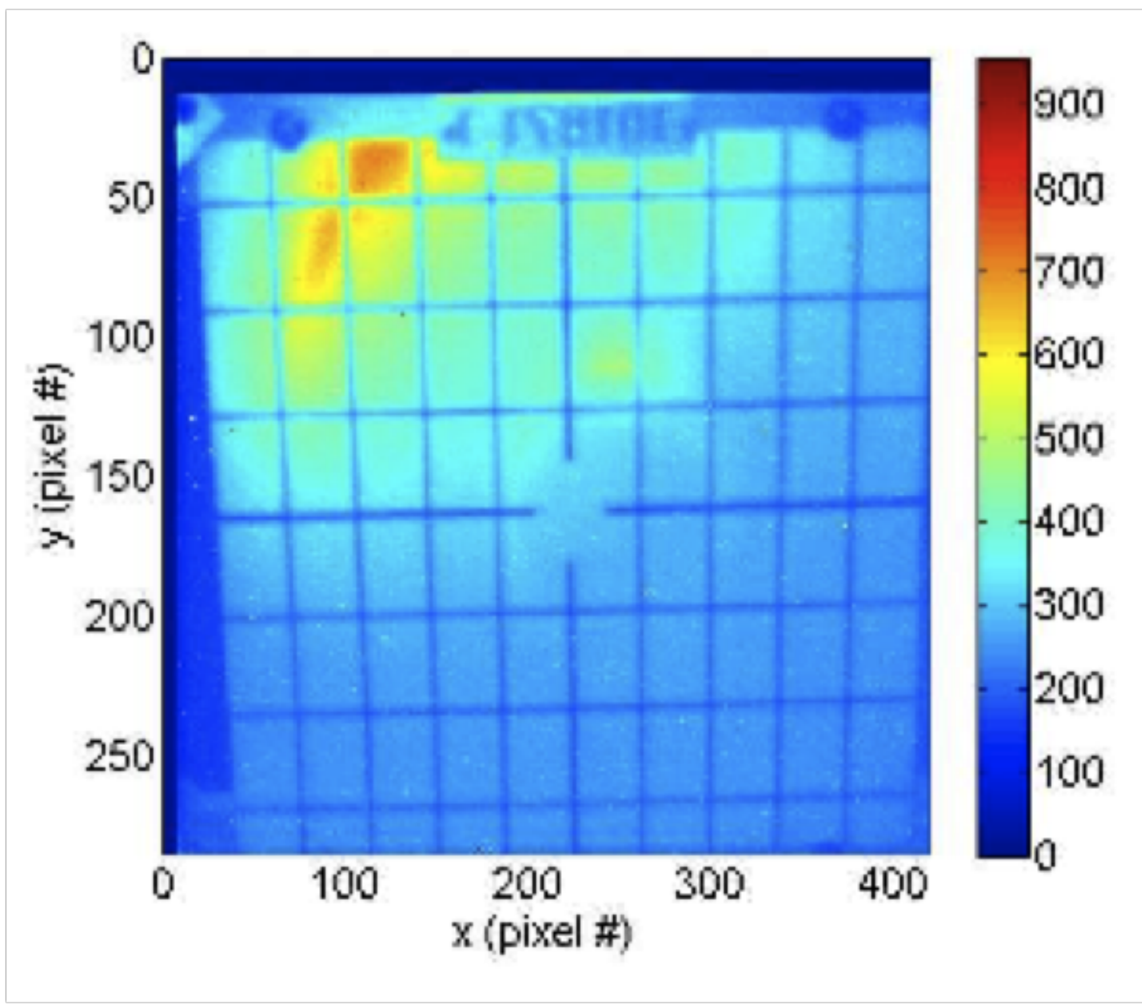
Scintillating screen

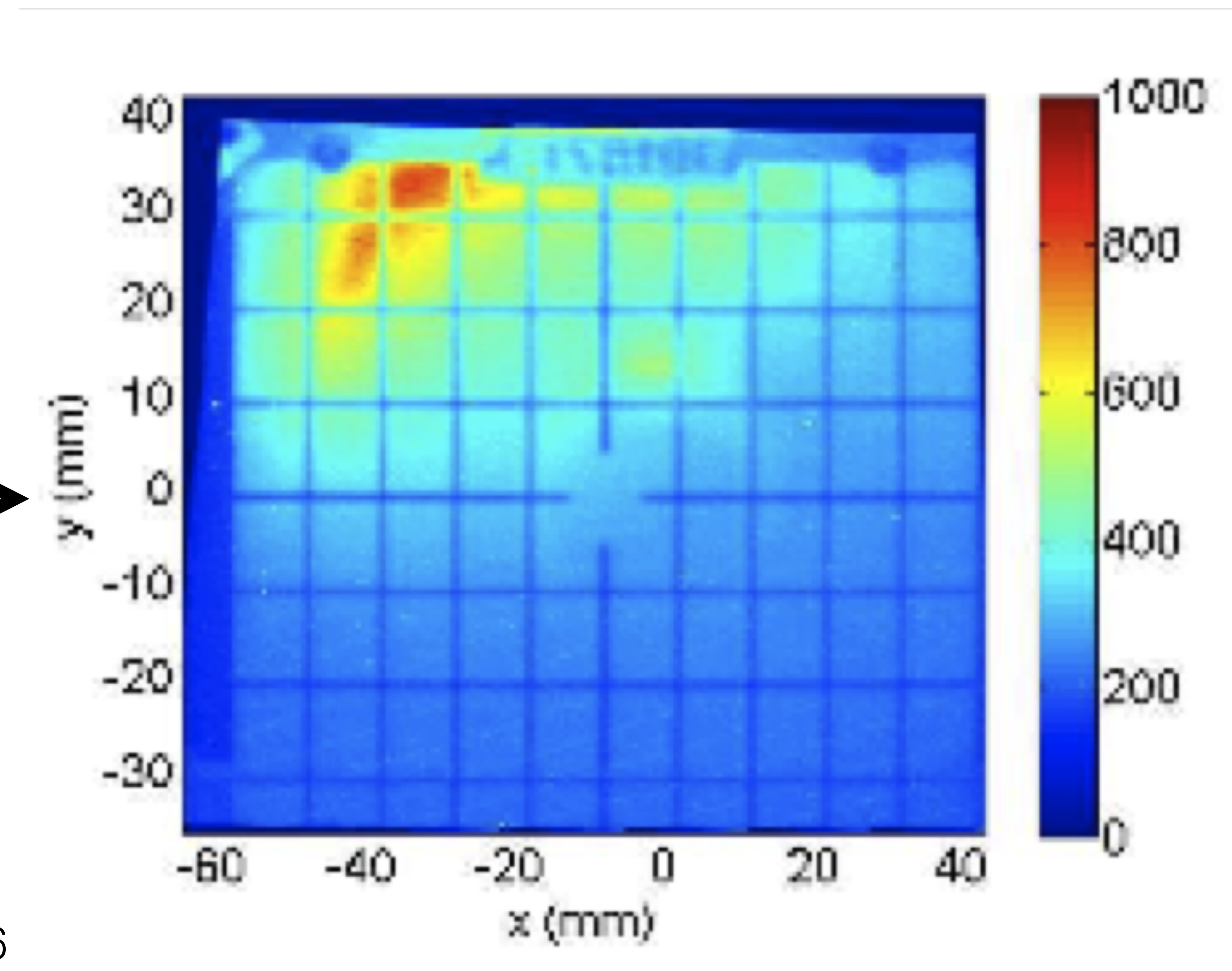


- Particles passing trough the screen excite atoms and molecules
- The screen emits photons that can be observed with a TV camera (CCD, VIDICON etc.)
- Multiple scattering inside screen increases beam divergence
- Typical screens are Al_2O_3:CrO_2 1mm thick. Robust and good for beam observation, but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

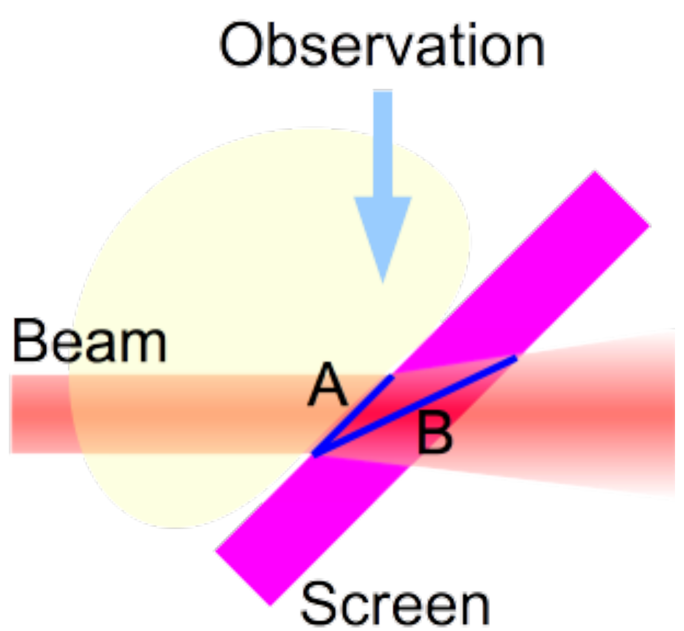
Scintillating screen

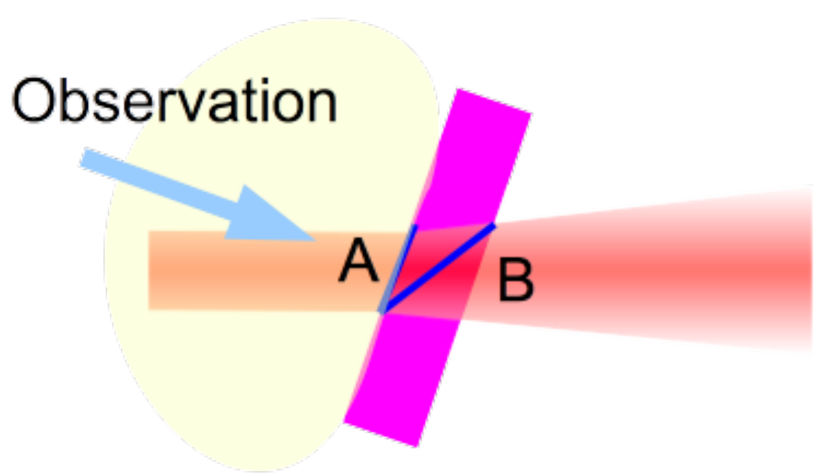
Optical setup may introduce deformations (tilted screen)
Need to perform off line corrections and calibrations





Scintillating screen

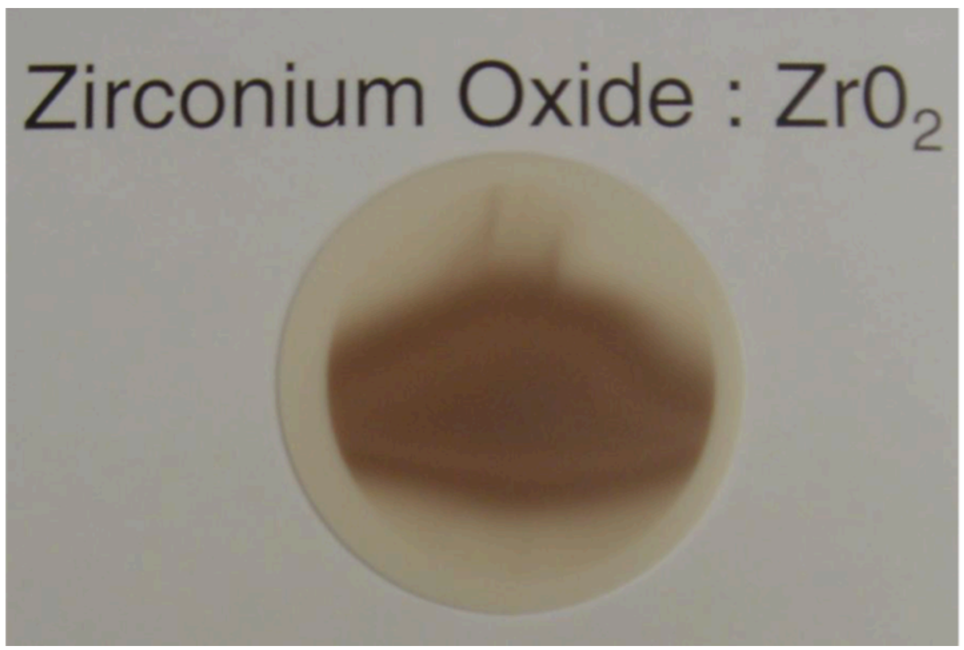




A is what we would like to observe
B is what we really obtain

- 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

Beam induced damage



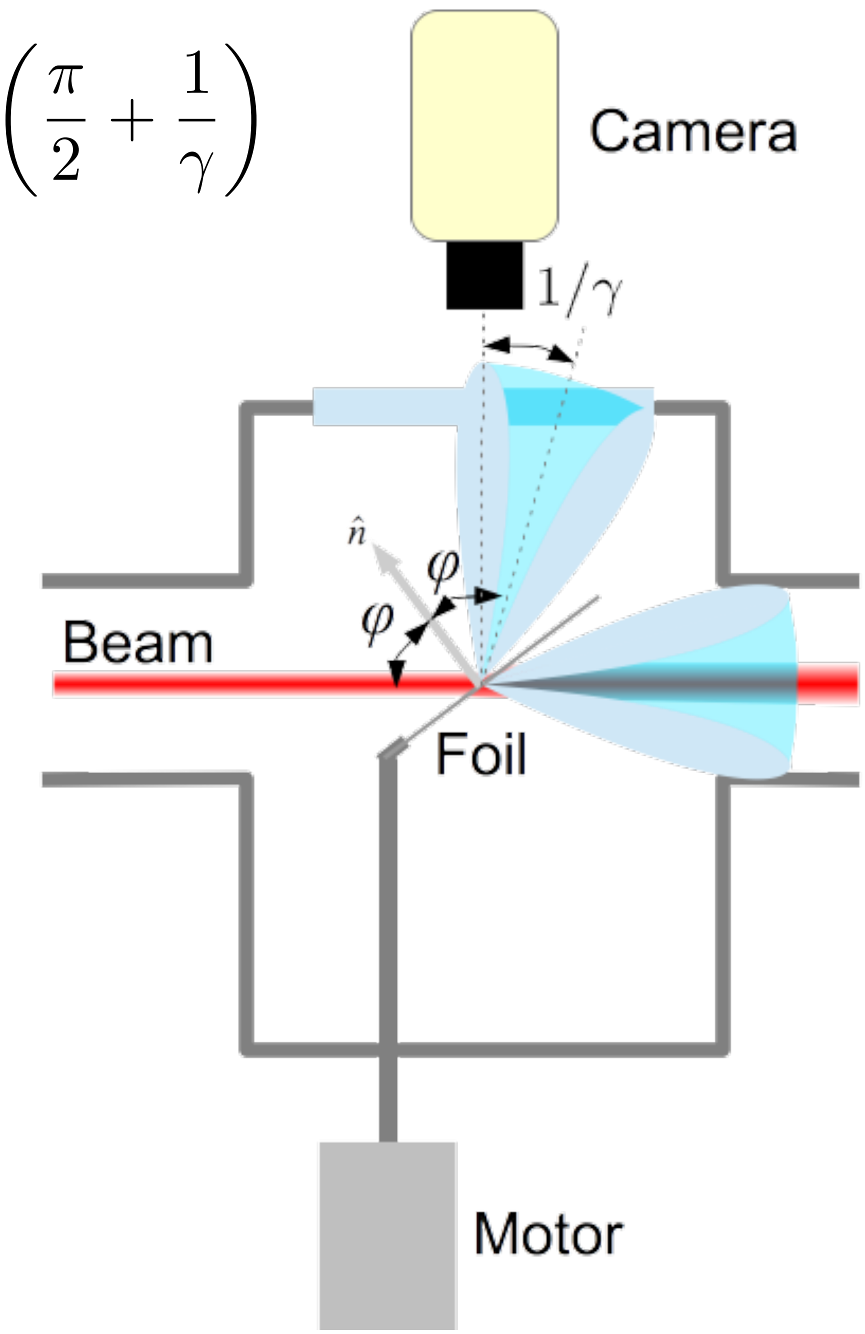
$$\Delta T(x,y) = \frac{\frac{dE}{dx}\rho \cdot i(x,y)}{\rho c_v} = \frac{\frac{dE}{dx} \cdot i(x,y)}{c_v}$$

- Screens can be damaged by the beam
- High temperature can induce chemical changes in the material
- Dislocations can create “quenching” paths
- High temperature can melt/ sublimate the surface
- High temperature can induce mechanical stresses (cracks)

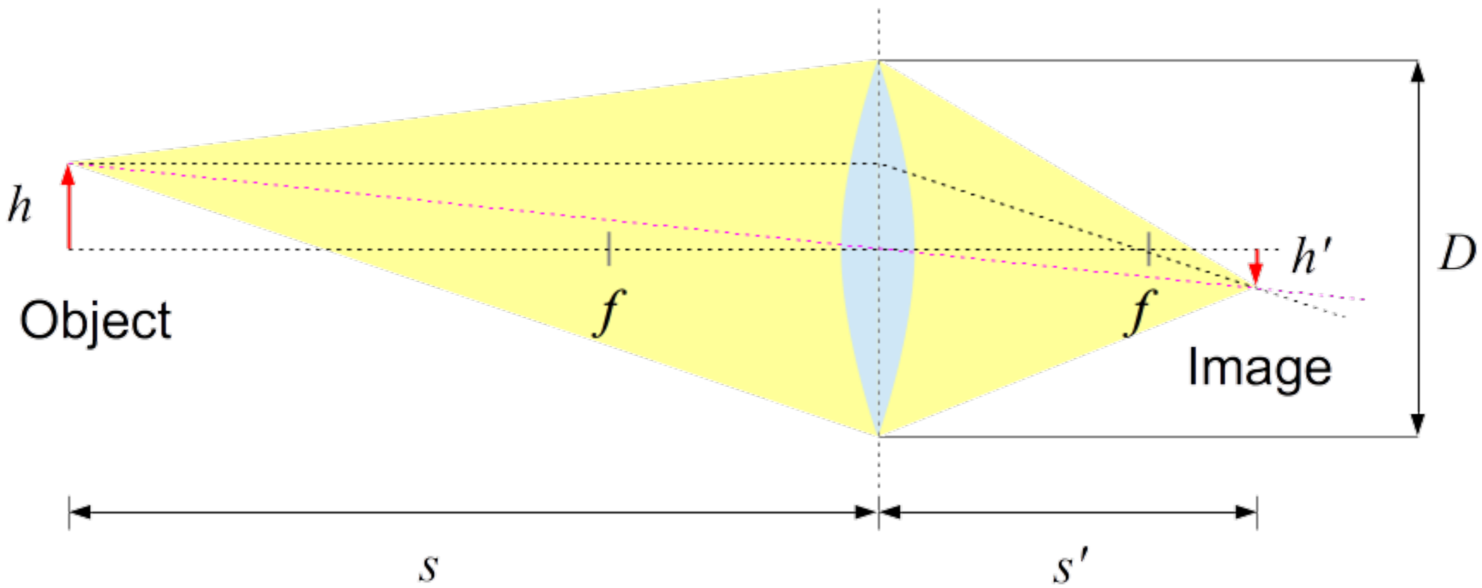
OTR radiators

- 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

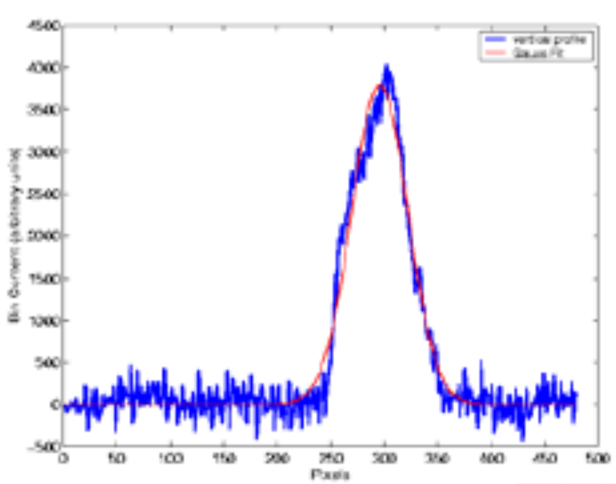
A “good” CCTV 50 mm lens has f/# ~ 1.4

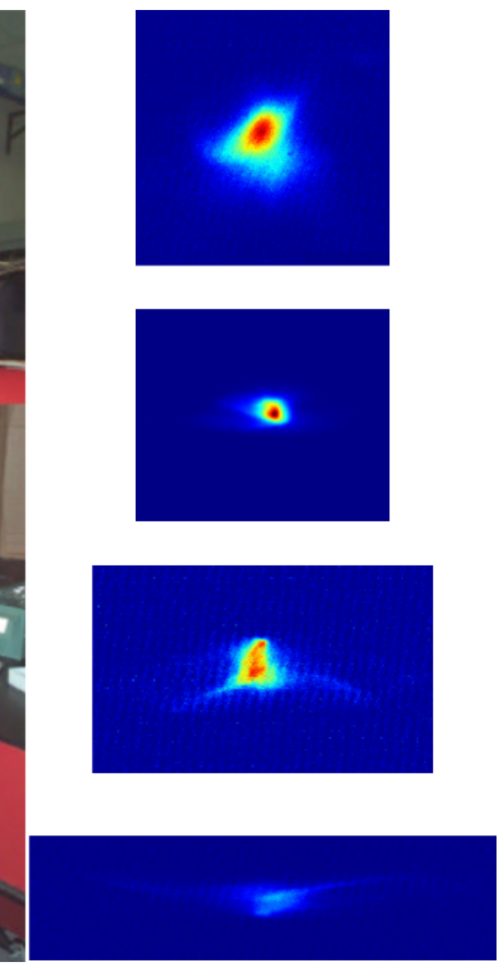
$$D = \frac{f}{f/\#} = \frac{50}{1.4} = 36$$

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

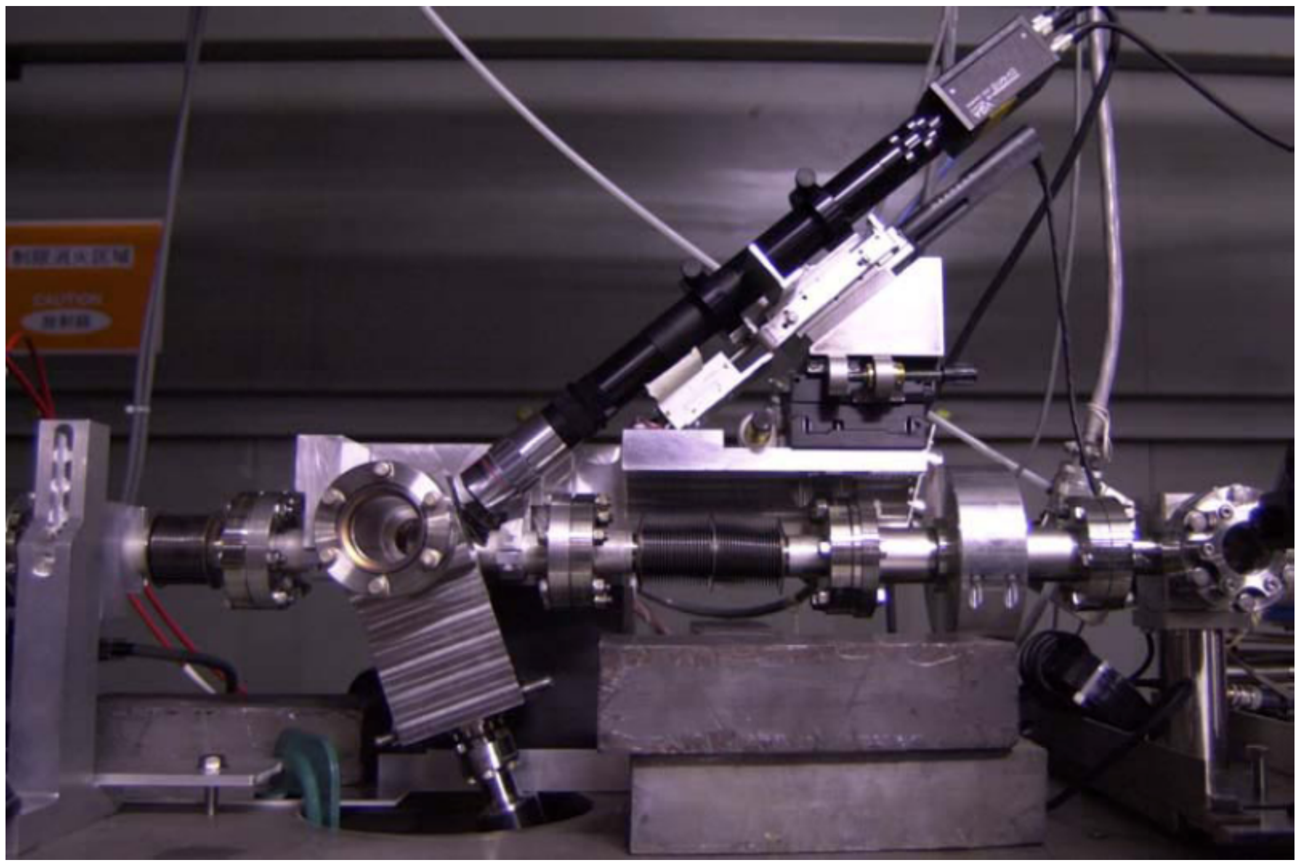
OTR example (DESY)

- 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

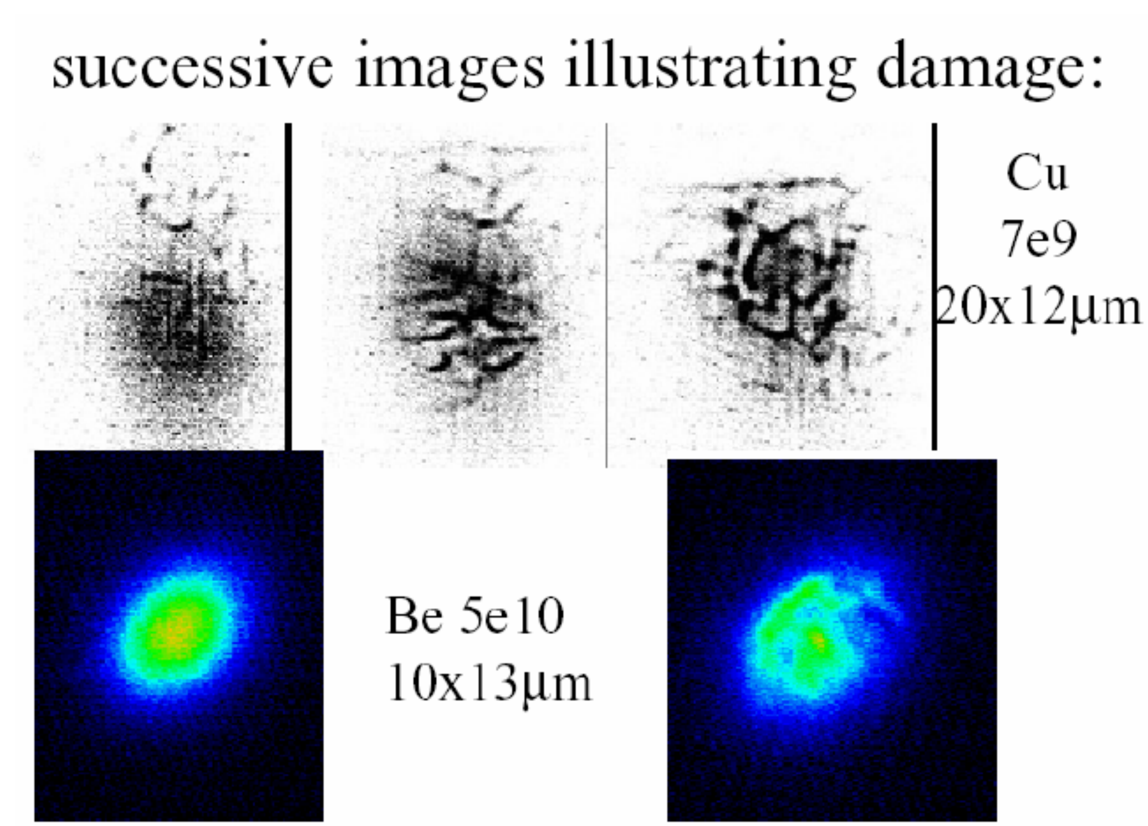




OTR example (KEK)



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



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

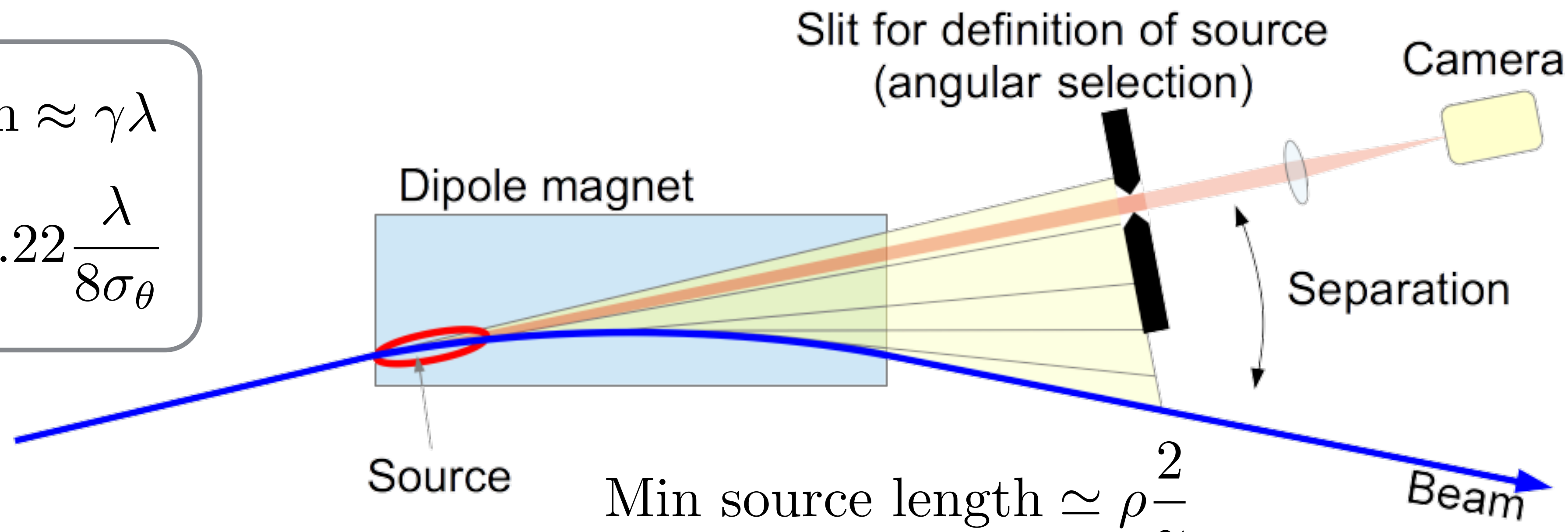
Another OTR example

- Multiturn injection mismatch monitor in the SPS
- Aluminised MYLAR foil
- Did not dump the beam in time…

Synchrotron radiation

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

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

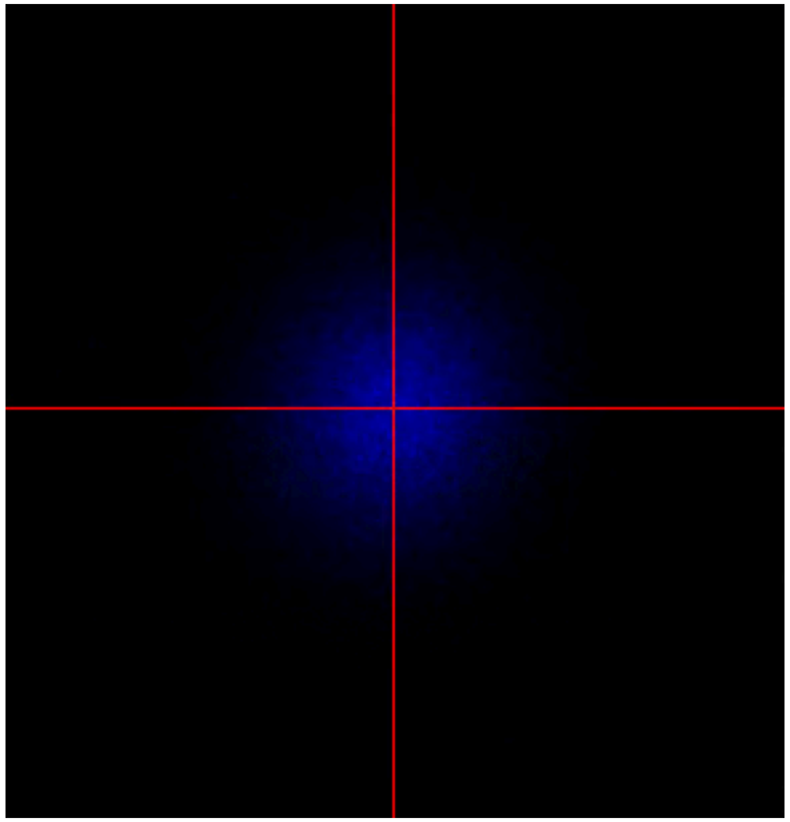


$$\text{Min source length} \simeq \rho \frac{2}{\gamma}$$

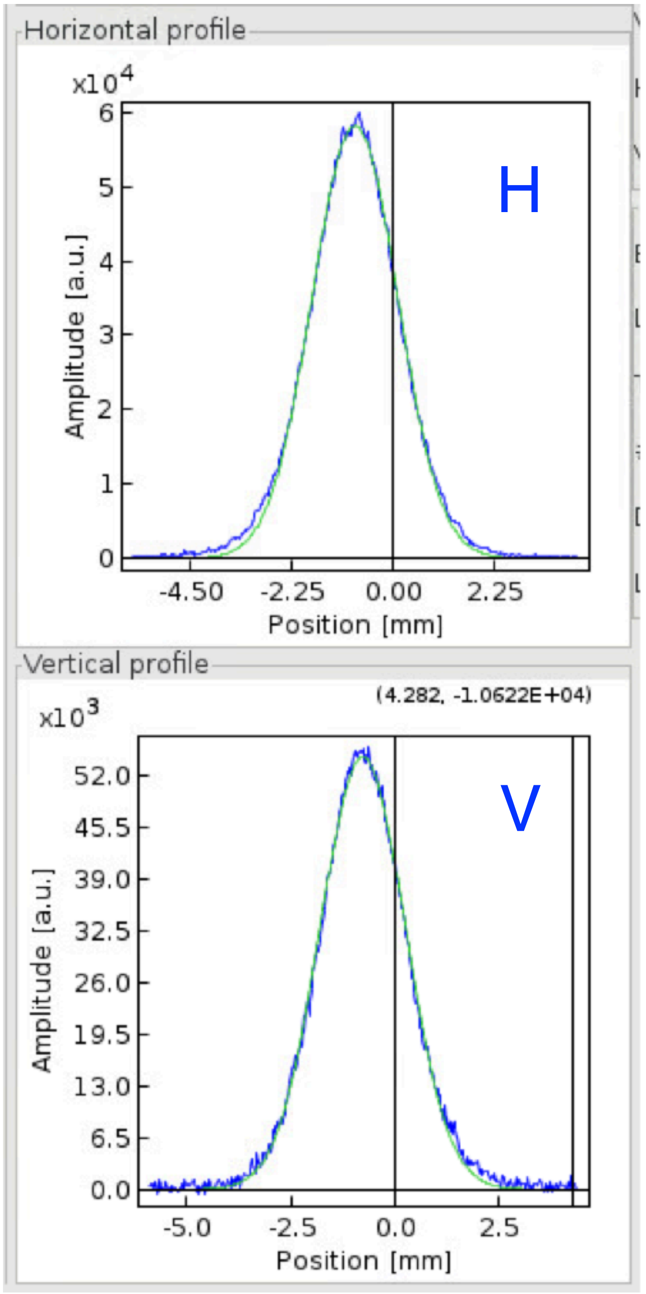
- Radiation inside magnet is constant
- Radiation at the entrance and exit edge has higher frequency components (shorter pulse) “edge radiation”
- Magnet also useful for separating photons from particles
- Source normally near entrance or even entrance edge
- Resolution often limited by diffraction

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)

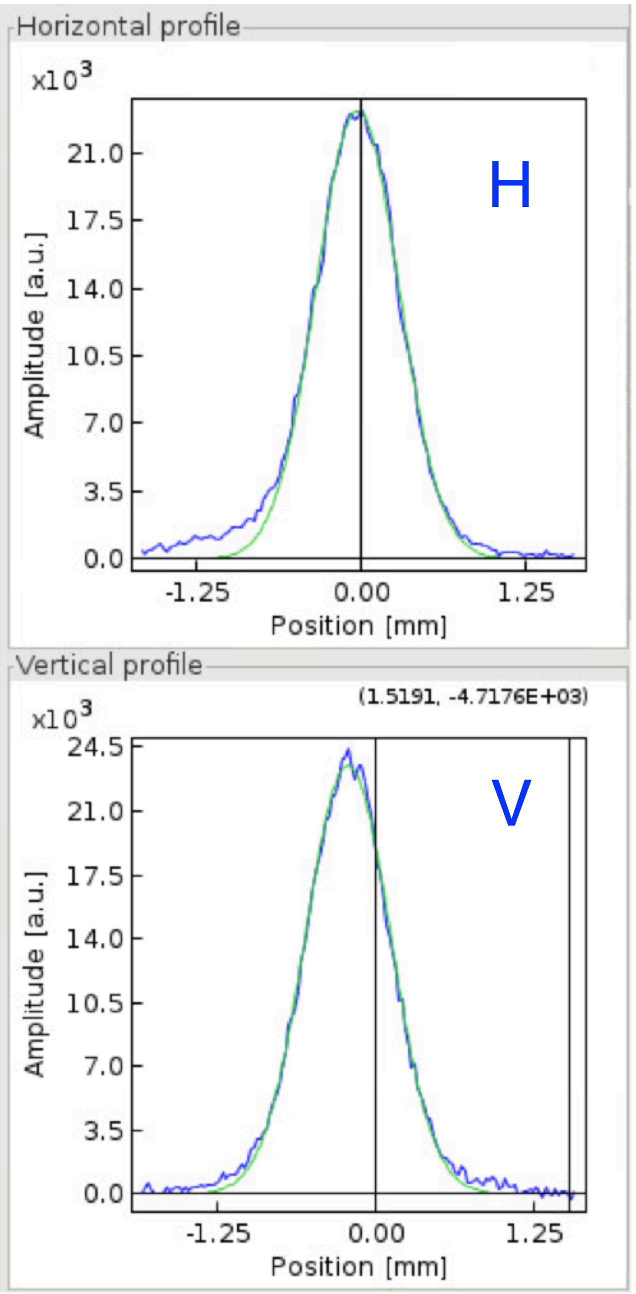
Synchrotron Monitor @LHC



Undulator
450 GeV



Dipole
6.5 TeV



SR Extraction Mirrors

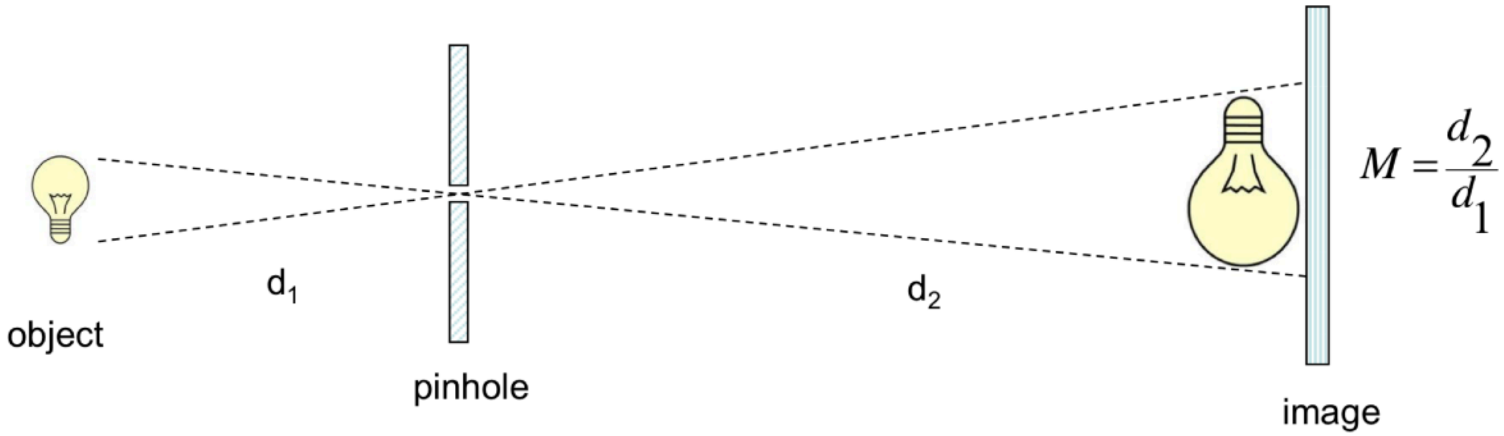
Multilayer coated
silicon

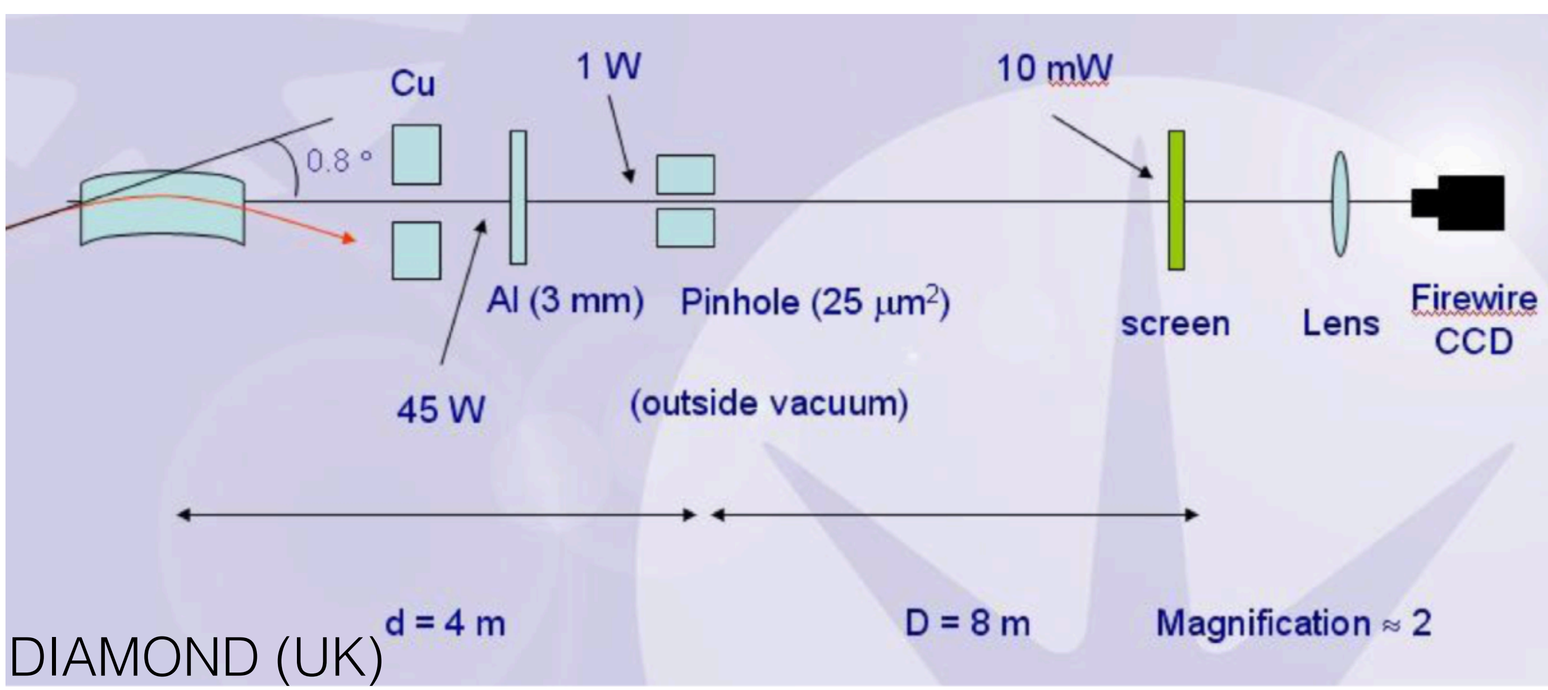
Al coated
fused silica

Multilayer coated
fused silica

- At LHC beam induced heating is a problem (impedance)
- In electron machines X-ray heating is often a problem

Pin Hole camera for x-ray





DIAMOND (UK)

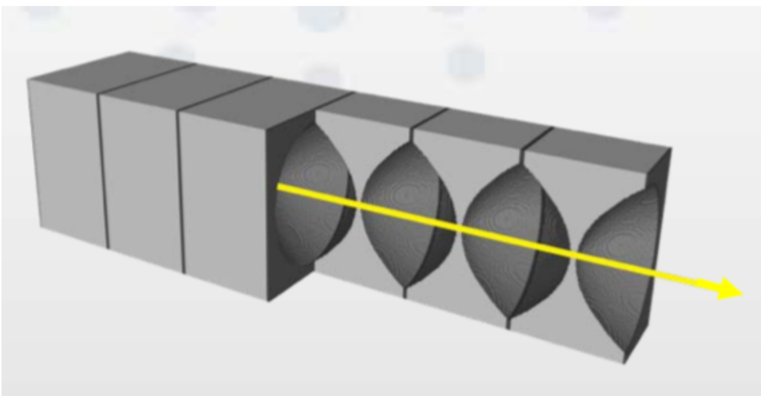
- X-ray optics is difficult to make
- Go back to the origin of photography: the "Camera oscura"

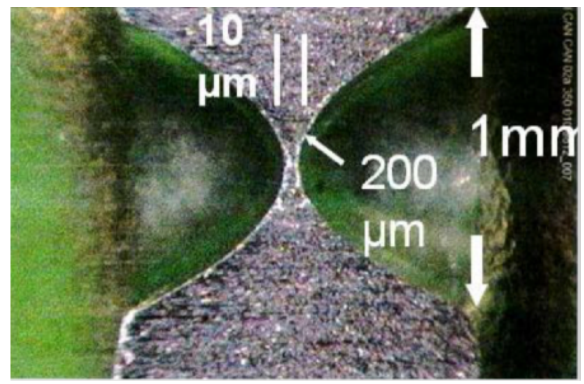
$$(\sigma_{image})^2 = \left(\frac{\sigma_{source}}{demag}\right)^2 + (\sigma_{blur})^2 + (\sigma_{diffraction})^2$$

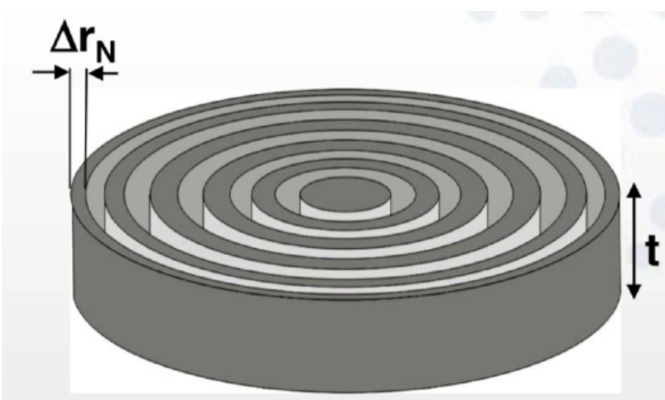
$$\sigma_{blur} = \frac{w}{\sqrt{2\pi}} \frac{(L_1 + L_2)}{L_1}$$

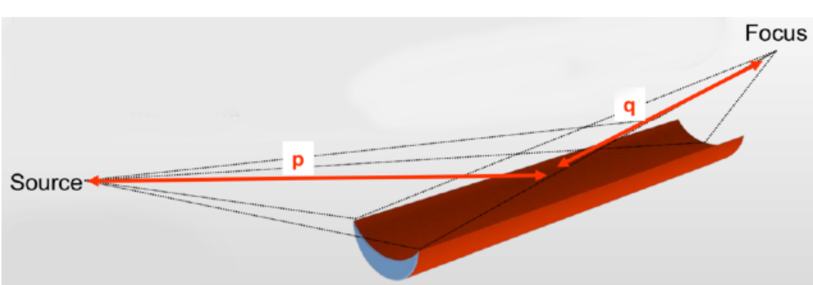
$$\sigma_{diffraction} = \frac{\sqrt{12}}{4\pi} \frac{\lambda L_2}{w}$$

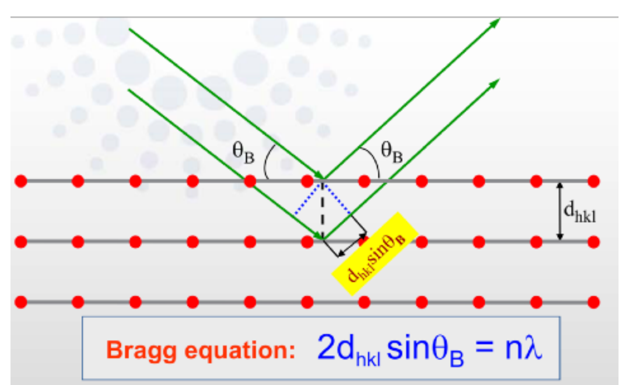
X-ray optics





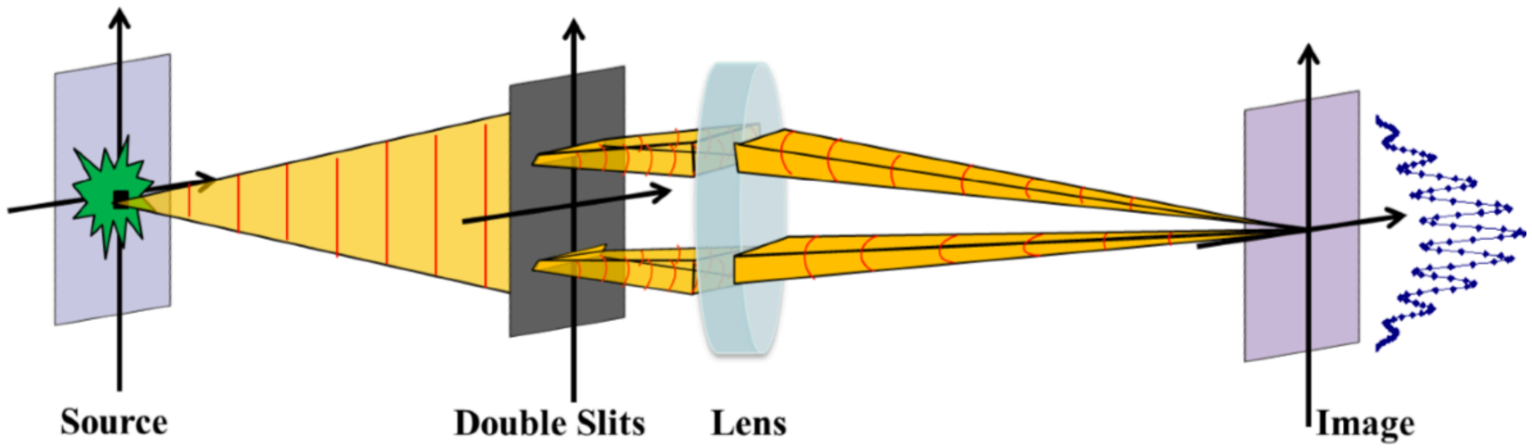


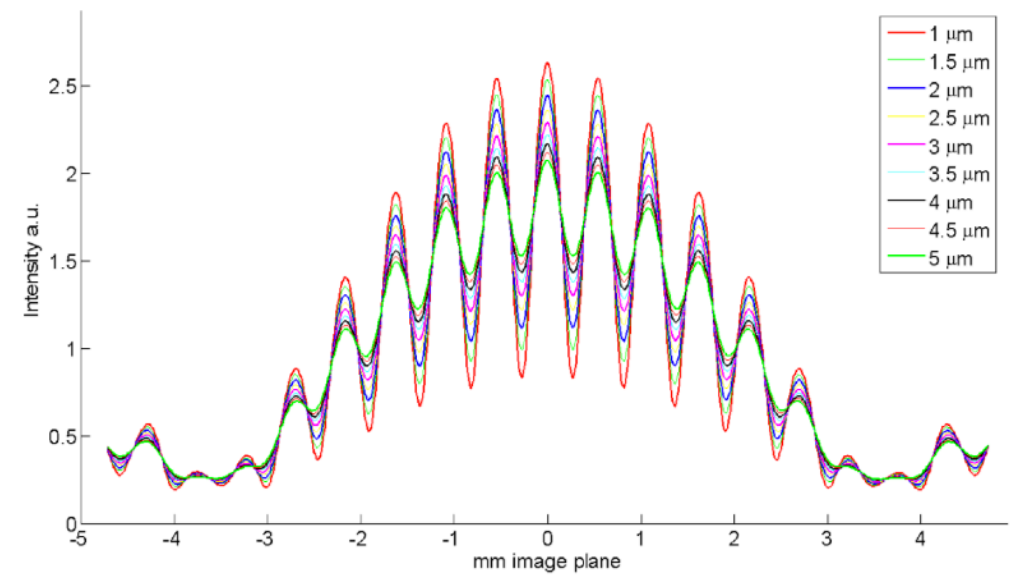




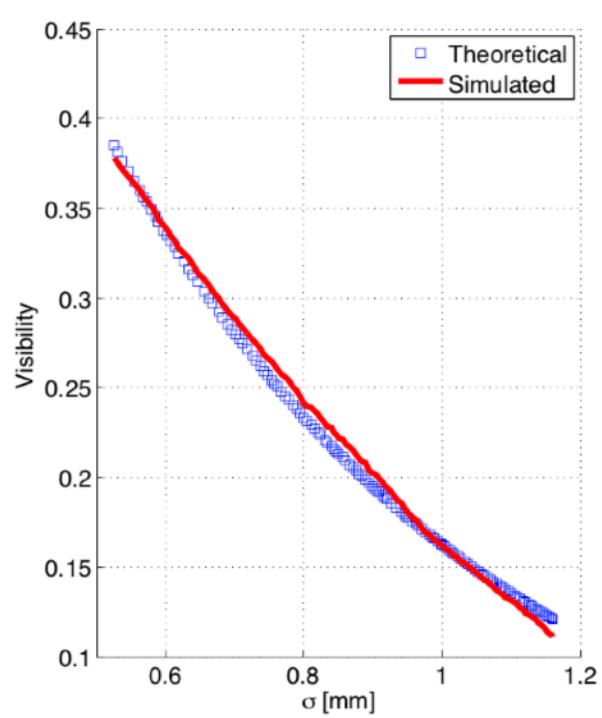
- X-ray imaging achieved in the last 20 year
- Three possibilities:
  - Zone plates
  - X-ray lenses
  - Curved mirrors (grazing)

Double slit interferometer





$$I(x) = I_0\left[sinc\left(\frac{2\pi a}{\lambda_0 R}x\right)\right]^2 \cdot \left\{1 + |\Gamma|\, cos\left(\frac{2\pi D}{\lambda_0 R}x + \phi\right)\right\}$$



- Visibility of fringes depends on the spatial coherence of the source, i.e. on the source size

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 (becoming obsolete)**
  - 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 (much better for last generation C-MOS)
  - 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