The beam width can be changed by focusing via quadruples.

Transverse matching between ascending accelerators is done by focusing.

→ Profiles have to be controlled at many locations.

Synchrotrons: Lattice functions ***β(s)*** and ***D(s)*** are fixed ⇒ width ***σ*** and emittance ***ε*** are:

$$\sigma_x^2(s) = \varepsilon_x \beta_x(s) + \left(D(s) \frac{\Delta p}{p} \right)^2 \quad \text{and} \quad \sigma_y^2(s) = \varepsilon_y \beta_y(s)$$

LINACs: Lattice functions are 'smoothly' defined due to variable input emittance.

A great variety of devices are used:

- ***Optical techniques:*** Scintillating screens (all beams), synchrotron light monitors (e–), optical transition radiation (e–), residual gas fluorescence monitors (protons), residual gas monitors (protons).
- ***Electronics techniques:*** Secondary electron emission (SEM) grids, wire scanners (all) grids with gas amplification MWPC (protons)

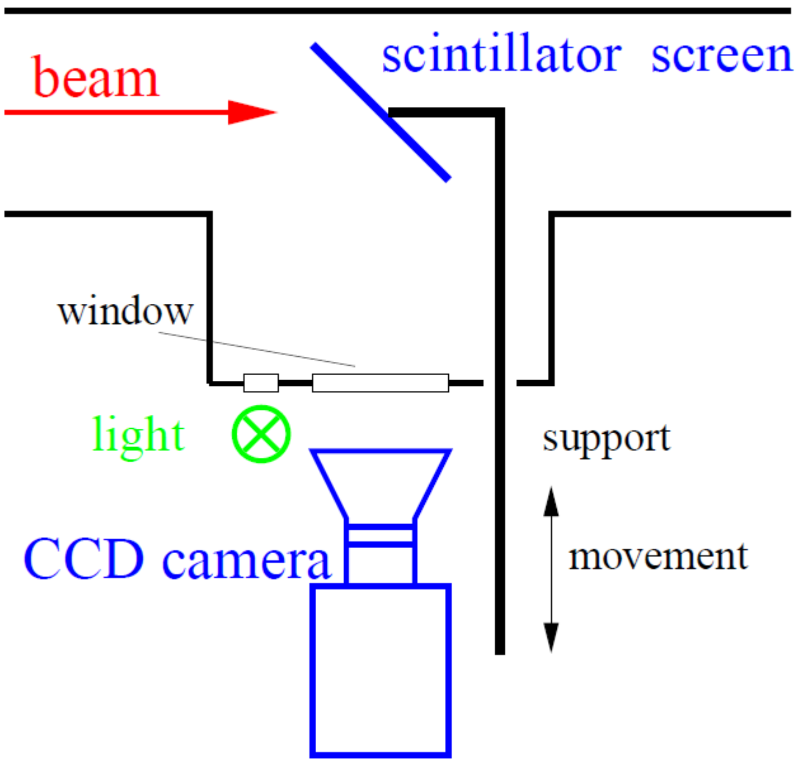
Outline:

- **Scintillation screens:**
  emission of light, universal usage, limited dynamic range
- **SEM-Grid**
- **Wire scanner**
- **Ionization Profile Monitor and Beam Induced Fluorescence Monitor**
- **Optical Transition Radiation**
- **Synchrotron Light Monitors**
- **Summary**

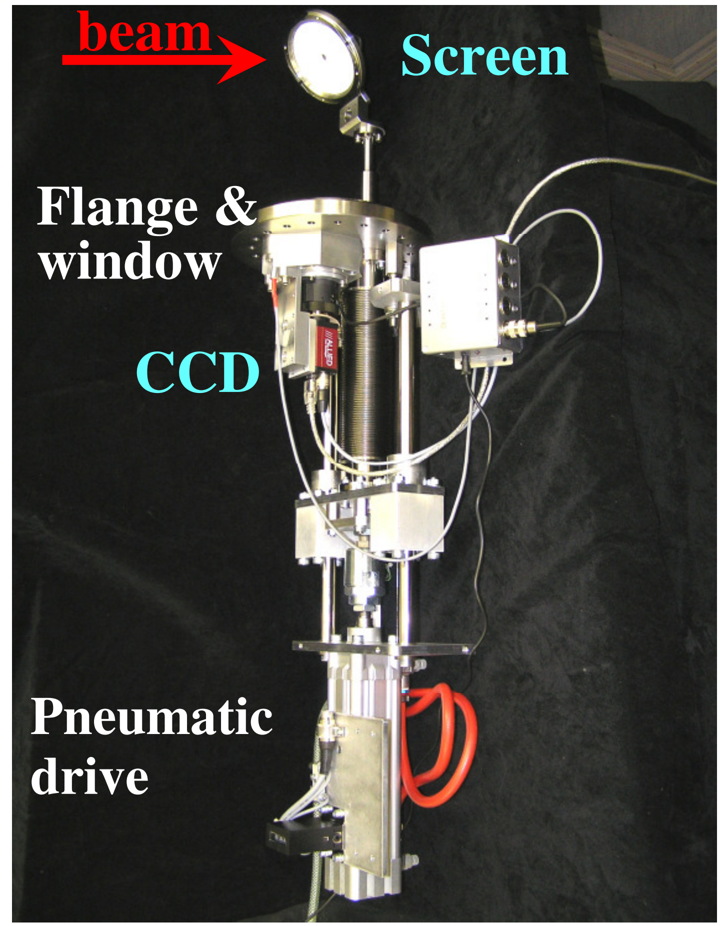
Scintillation Screen

Particle's energy loss in matter produces light

→ the most direct way of profile observation as used from the early days on!



Pneumatic feed-through with Ø70 mm screen :



Example: GSI LINAC, 4 MeV/u, low current, YAG:Ce screen

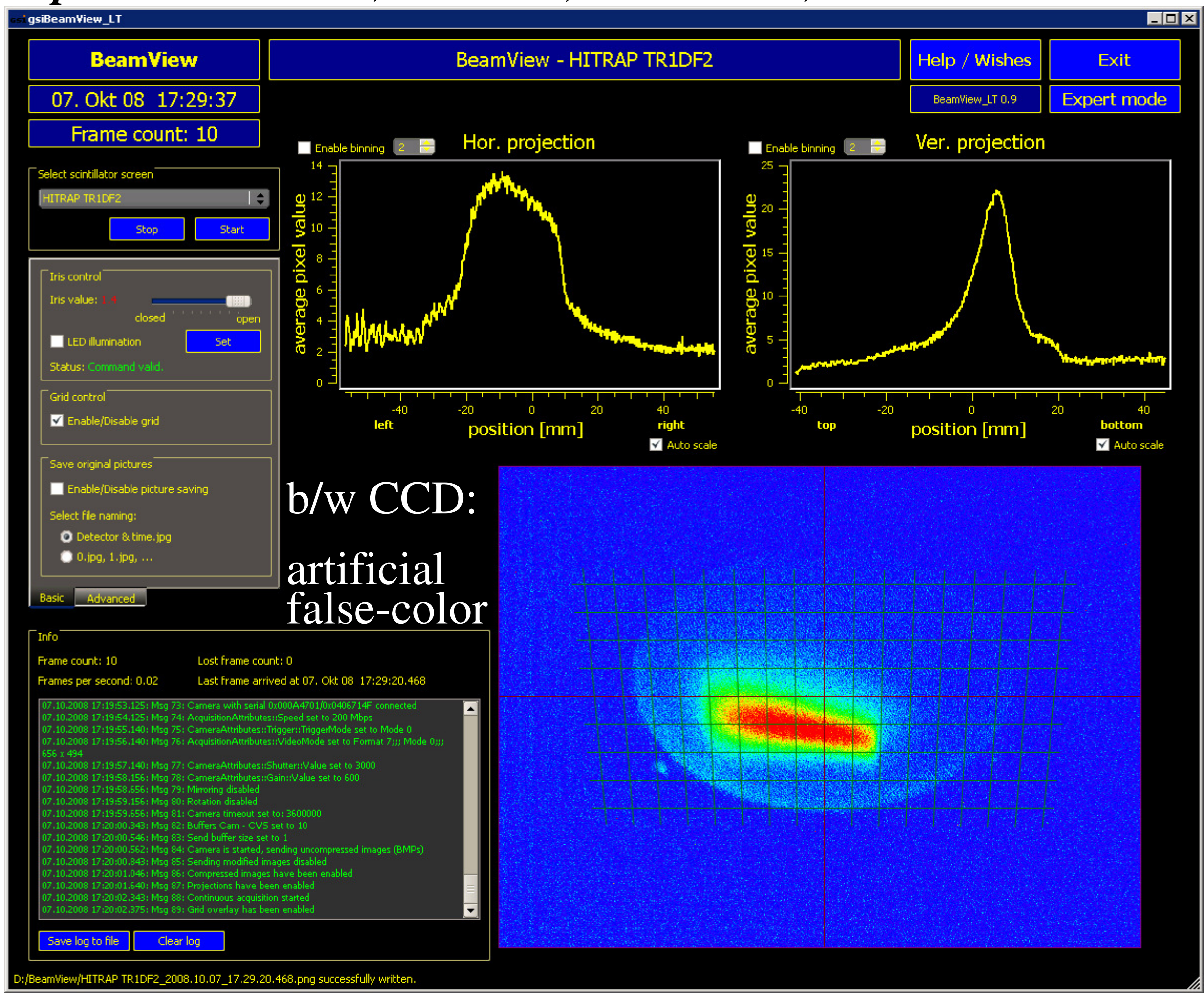
Advantage of screens:

- ➢Direct 2-dim measurement
- ➢High spatial resolution
- ➢Cheap realization

Observation with a CCD camera

with digital output

or video & frame grabber.

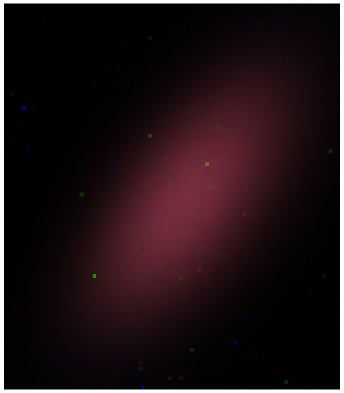


b/w CCD:

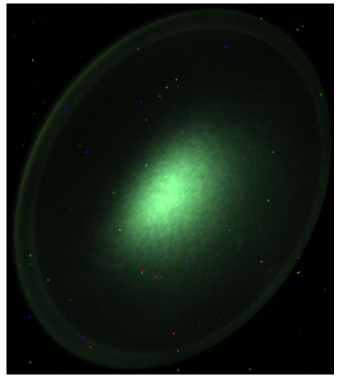
artificial false-color

Light output from various Scintillating Screens

Example: Color CCD camera: Images at different particle intensities determined for U at 300 MeV/u

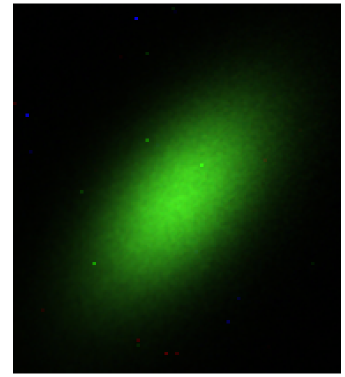


Al_2O_3

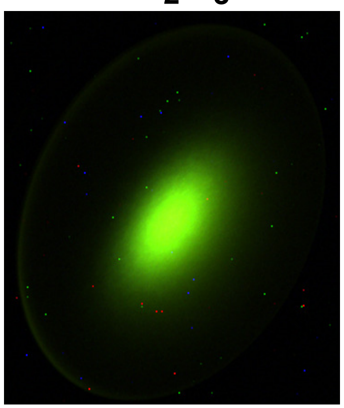


CsI:Tl

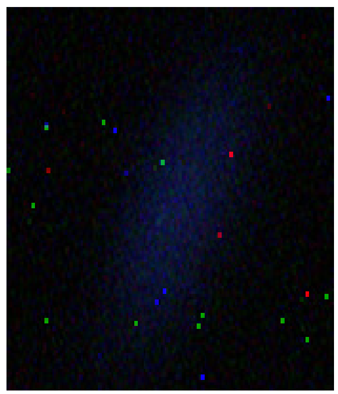
Al_2O_3:Cr



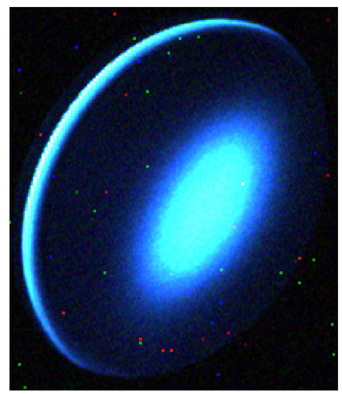
P43



YAG:Ce



Herasil



Quartz:Ce

ZrO_2:Mg

- Very different light yield i.e. photons per ion‘s energy loss
- Different wavelength of emitted light

Interaction steps within the scintillation process

- ➢ beam interaction

→ hot electrons + deep holes

- ➢ multiplication:

electron – electron scattering

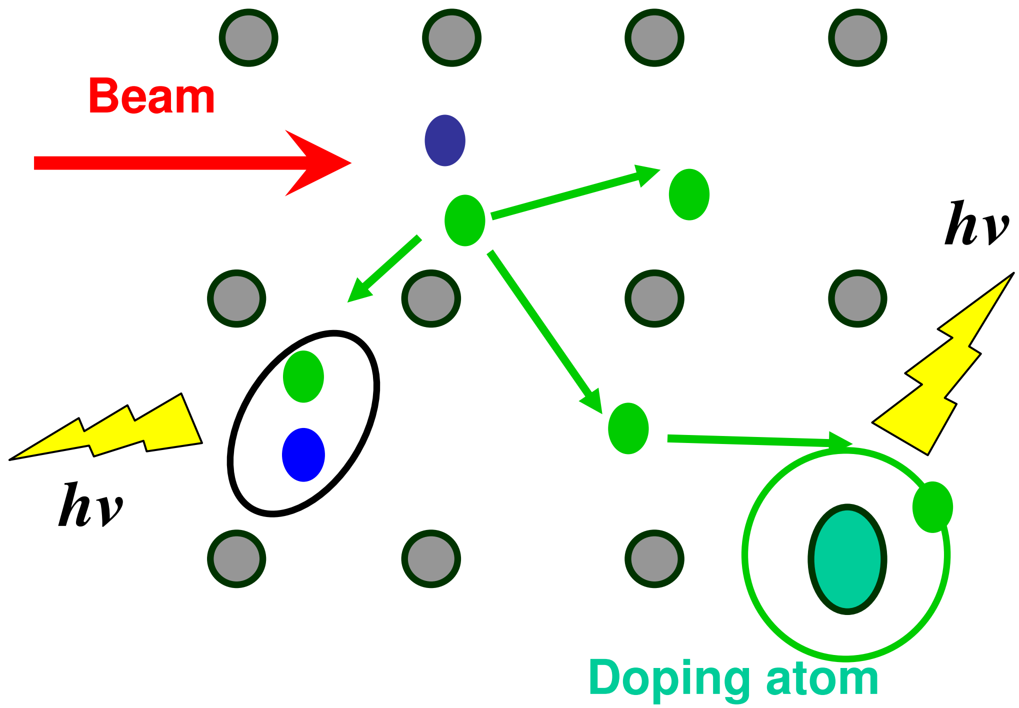
- ➢ thermalization:

electron – phonon coupling

- ➢ capture at doped atom and/or

electron - hole pair creation

- ➢ emission of photons



Material Properties for Scintillating Screens

Some materials and their basic properties:

Abbreviation	Material	Activator	max. emission	decay time
Quartz	SiO_2	none	optical	< 10 ns
	CsI	Tl	550 nm	1 μs
Chromolux	Al_2O_3	Cr	700 nm	100 ms
YAG	$Y_3Al_5O_{12}$	Ce	550 nm	0.2 μs
	Li glass	Ce	400 nm	0.1 μs
P11	ZnS	Ag	450 nm	3 ms
P43	Gd_2O_2S	Tb	545 nm	1 ms
P46	$Y_3Al_5O_{12}$	Ce	530 nm	0.3 μs
P47	$Y_2Si_5O_5$	Ce, Tb	400 nm	100 ns

Properties of a good scintillator:

- Large light output at optical wavelength → standard CCD camera can be used
- Large dynamic range → no deformation due to saturation or self-absorption
- Short decay time → observation of time variations
- Radiation hardness → long lifetime
- Good mechanical properties → typical size up to Ø 10 cm

(Phosphor Pxx grains of Ø ≈ 10 µm on glass or metal).

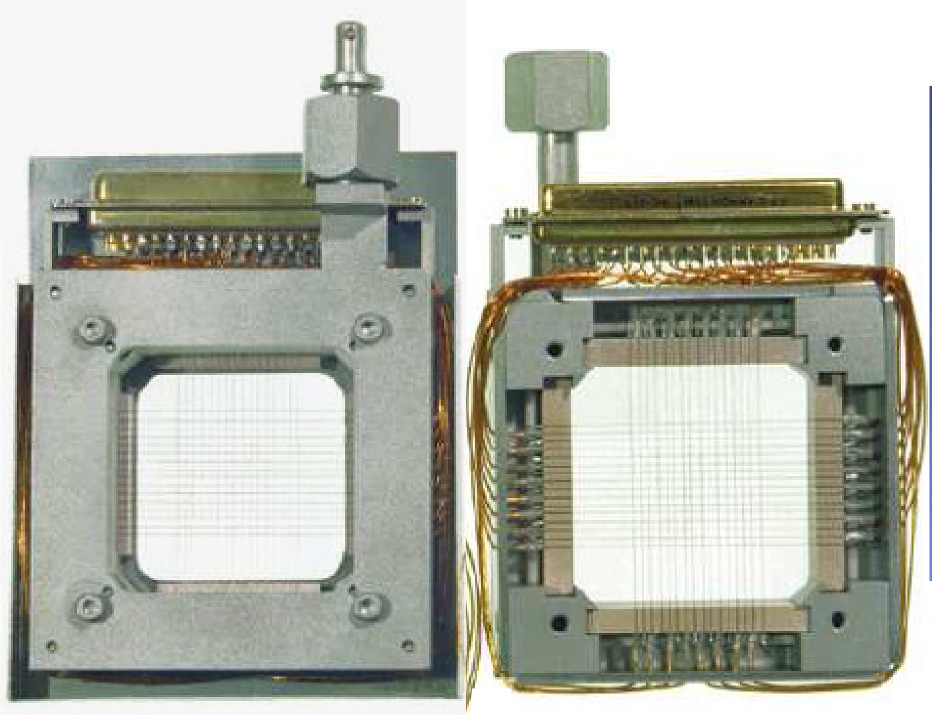
Outline:

- Scintillation screens:

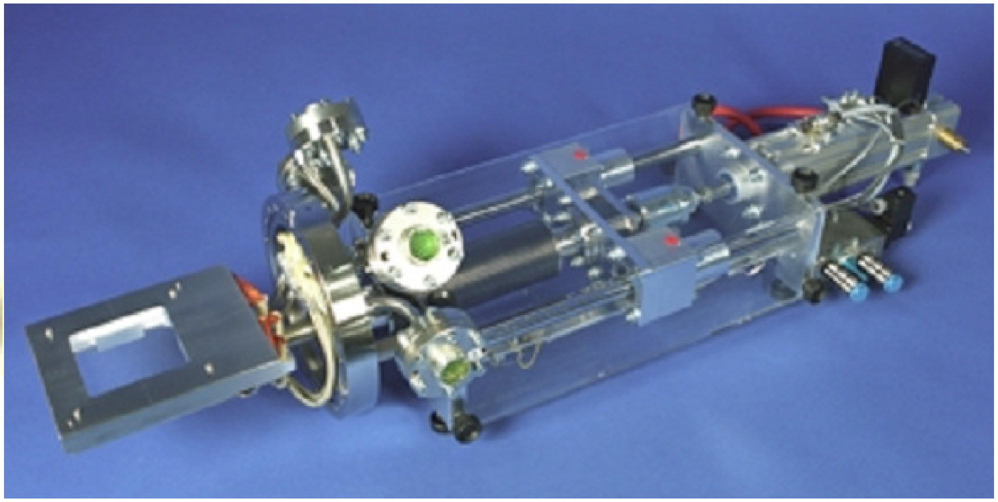
  emission of light, universal usage, limited dynamic range
- **SEM-Grid:** emission of electrons, workhorse, limited resolution
- **Wire scanner**
- **Ionization Profile Monitor and Beam Induced Fluorescence Monitor**
- **Optical Transition Radiation**
- **Synchrotron Light Monitors**
- **Summary**

Beam surface interaction: e$^-$ emission → measurement of current.

Example: 15 wire spaced by 1.5 mm:

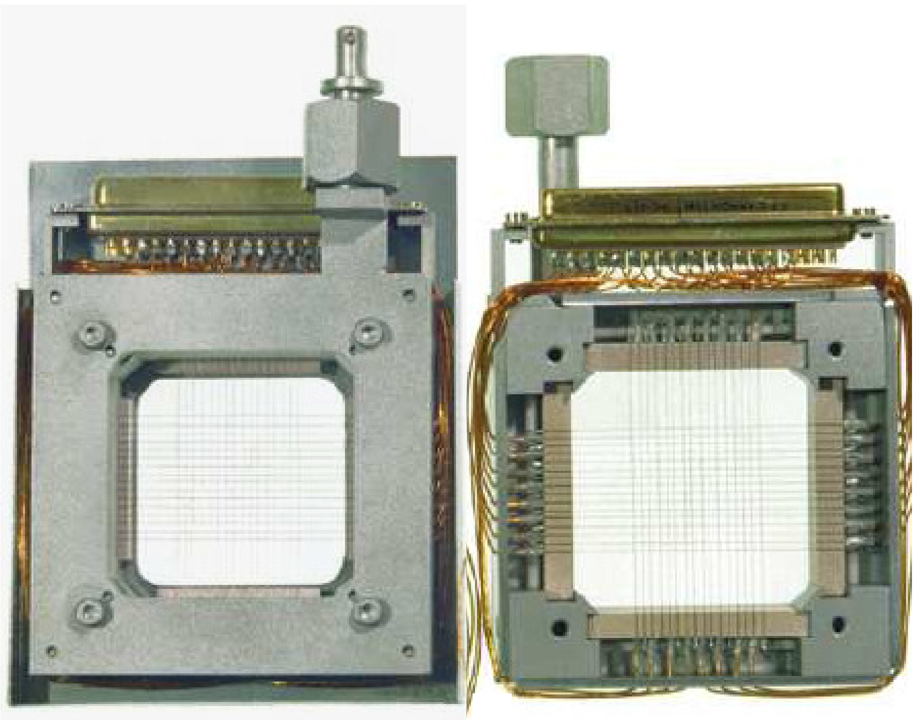


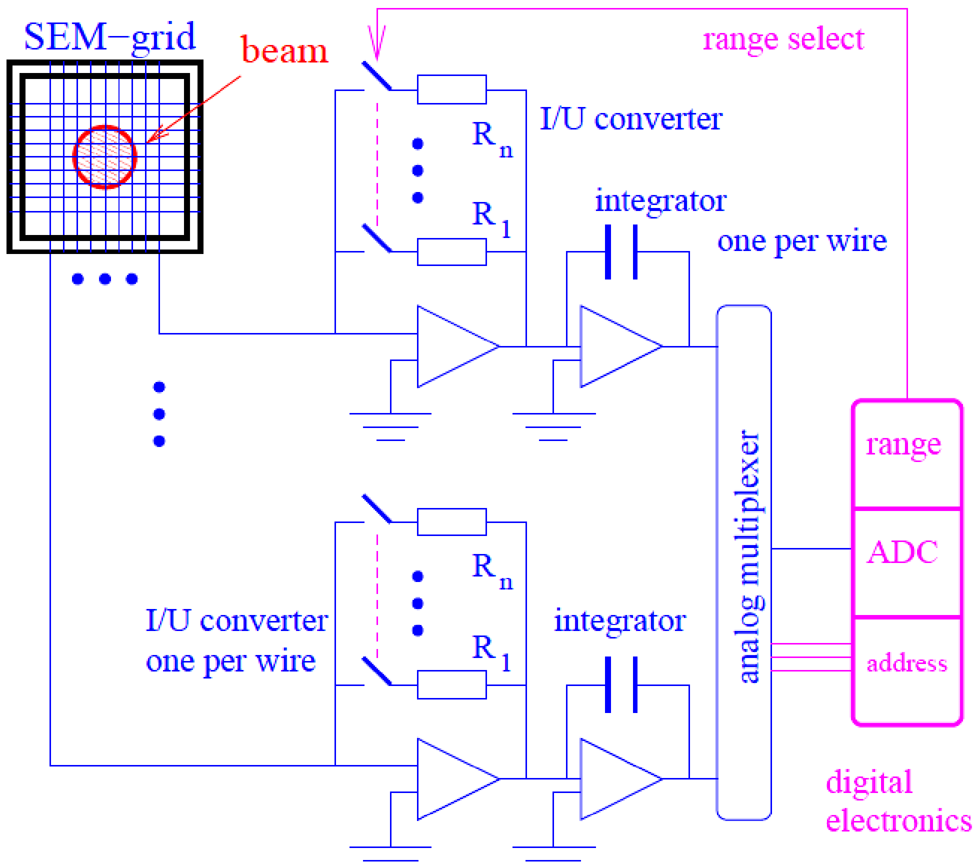
SEM-Grid feed-through on CF200:



Beam surface interaction: e^- emission → measurement of current.

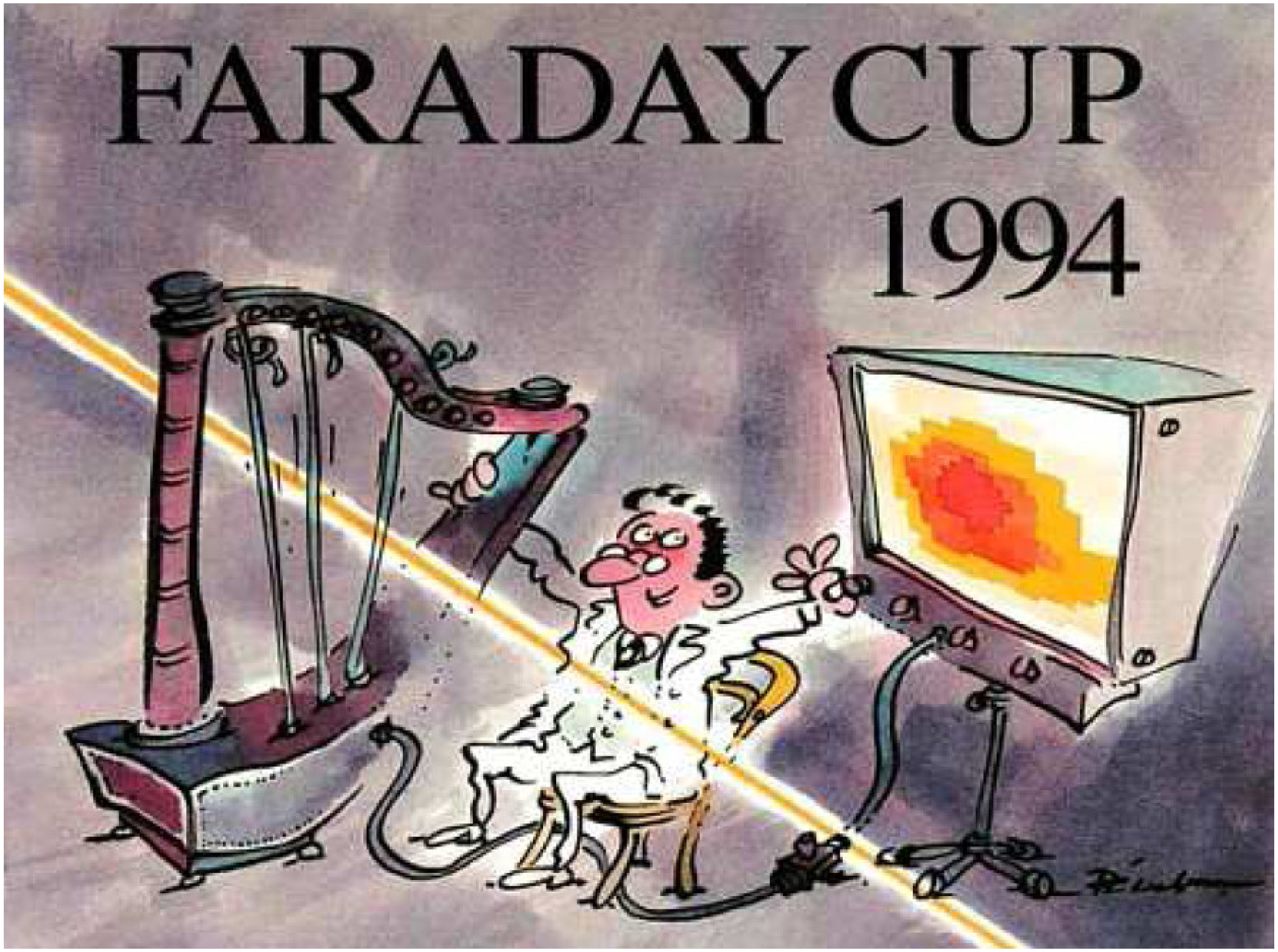
Example: 15 wire spaced by 1.5 mm:





Each wire is equipped with one I/U converter
different ranges settings by $\boldsymbol{R_i}$
→ very large dynamic range up to 10^6.

The Artist view of a SEM-Grid = Harp



The Faraday Cup is an award granded every second year for beam diagnostics inventions .

Properties of a SEM-Grid

Secondary e- emission from wire or ribbons, 10 to 100 per plane.

Typical specifications for a SEM-Grid used at the GSI-LINAC:

Diameter of the wires	0.05 to 0.5 mm
Spacing	0.5 to 2 mm
Length	50 to 100 mm
Material	W or W-Re alloy
Insulation of the frame	glass or Al_2O_3
number of wires	10 to 100
Max. power rating in vacuum	1 W/mm
Min. sensitivity of I/U-conv.	1 nA/V
Dynamic range	$1:10^6$
Number of ranges	10 typ.
Integration time	1 μs to 1 s

Care has to be taken to prevent over-heating by the energy loss!

Low energy beam: Ratio of spacing/width: $\simeq$ 1mm/0.1mm = 10 $\rightarrow$ only 10 % loss.

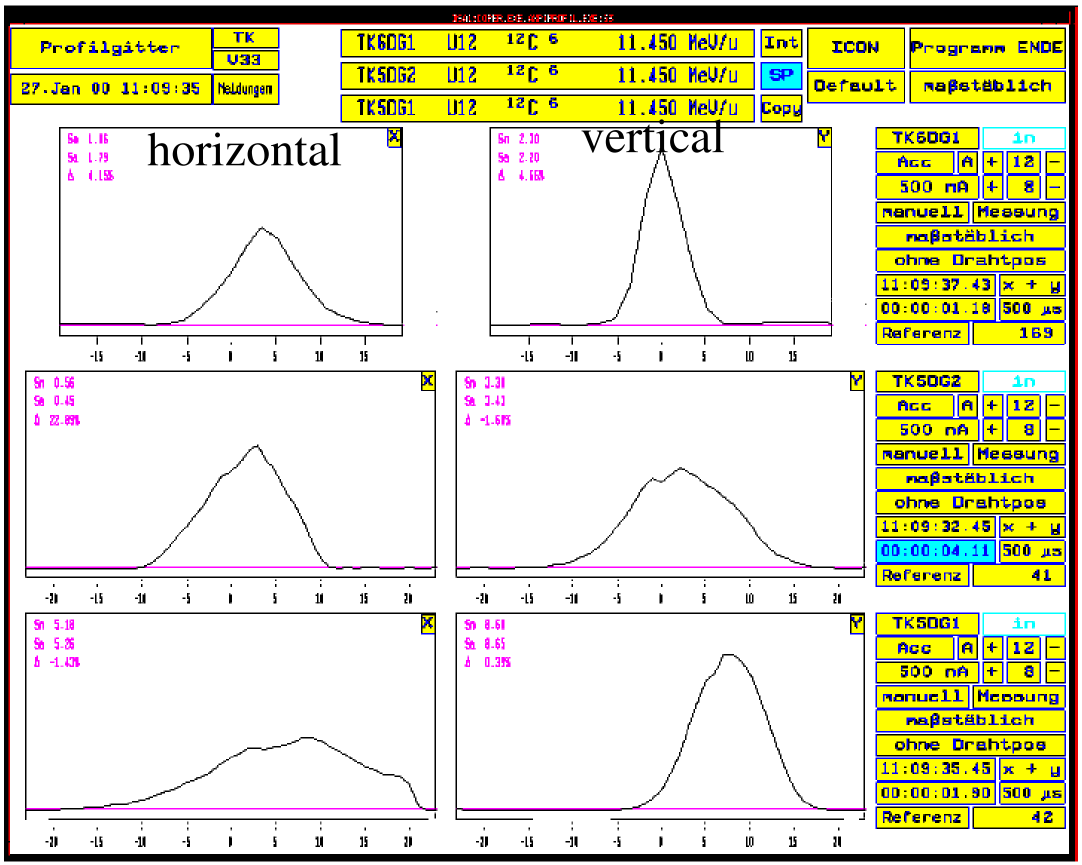
High energy E_{kin} > 1 GeV/u: thin ribbons of larger width are used due to negligible energy loss.

Example of Profile Mesurement with SEM-Grids

Even for low energies, several SEM-Grid can be used due to the ≈80 % transmission

⇒ frequently used instrument beam optimization: setting of quadrupoles, energy….

Example: C^{6+} beam of 11.4 MeV/u at different location at GSI-LINAC



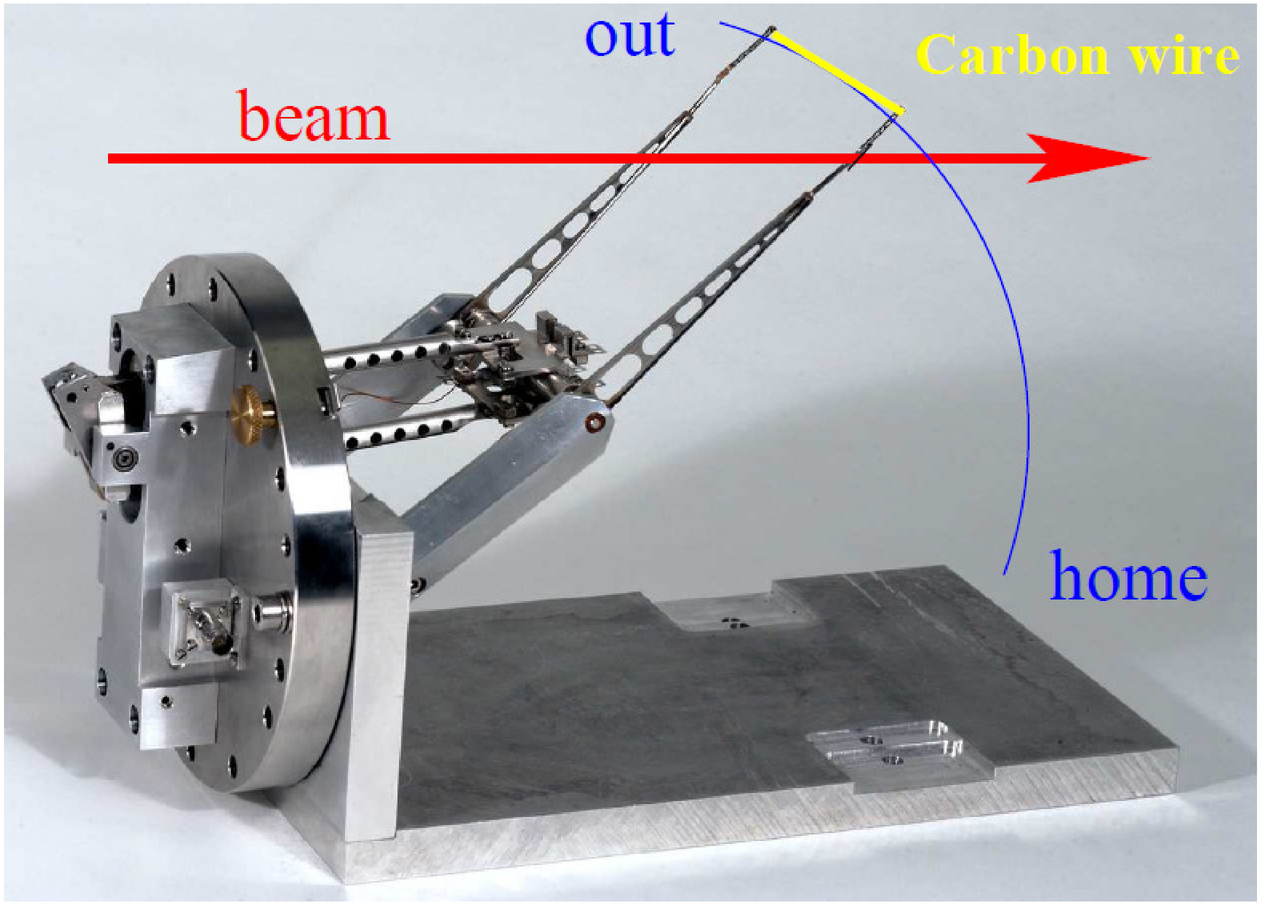
Outline:

- Scintillation screens:

  emission of light, universal usage, limited dynamic range
- SEM-Grid: emission of electrons, workhorse, limited resolution
- **Wire scanner:** emission of electrons, workhorse, scanning method
- **Ionization Profile Monitor and Beam Induced Fluorescence Monitor**
- **Optical Transition Radiation**
- **Synchrotron Light Monitors**
- **Summary**

Instead of several wires, ***one*** wire is scanned though the beam.

Fast pendulum scanner for synchrotrons; sometimes it is called ***'flying wire'***:

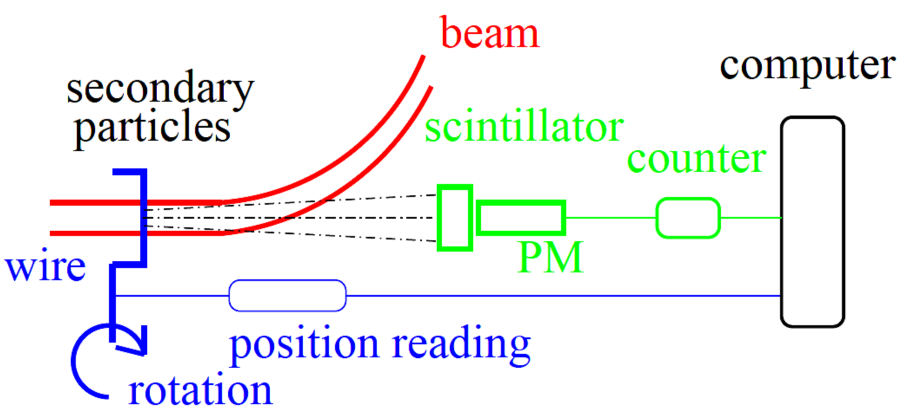


Usage of Wire Scanners

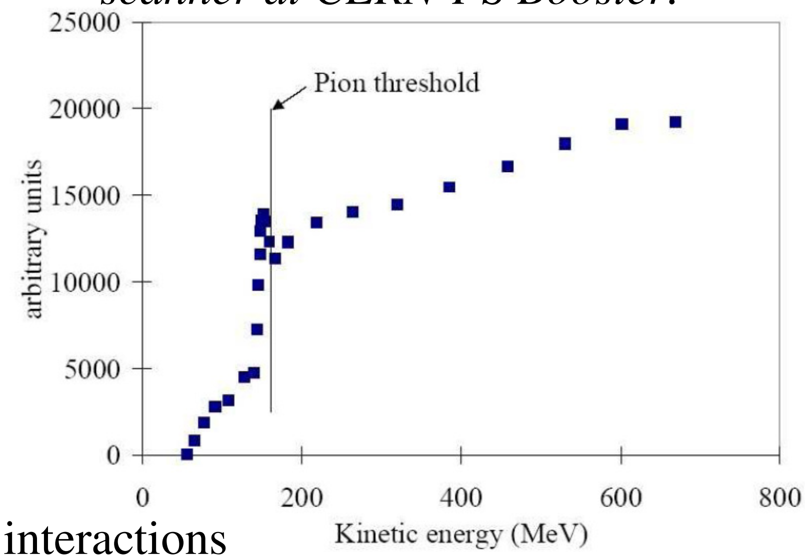
Material: carbon or SiC → low Z-material for low energy loss and high temperature.

Thickness: down to 10 μm → high resolution.

Detection: Either the secondary current (like SEM-grid) or
high energy secondary particles (like beam loss monitor)
flying wire: only sec. particle detection due to induced current by movement.



Proton impact on scanner at CERN-PS Booster:



Secondary particles:

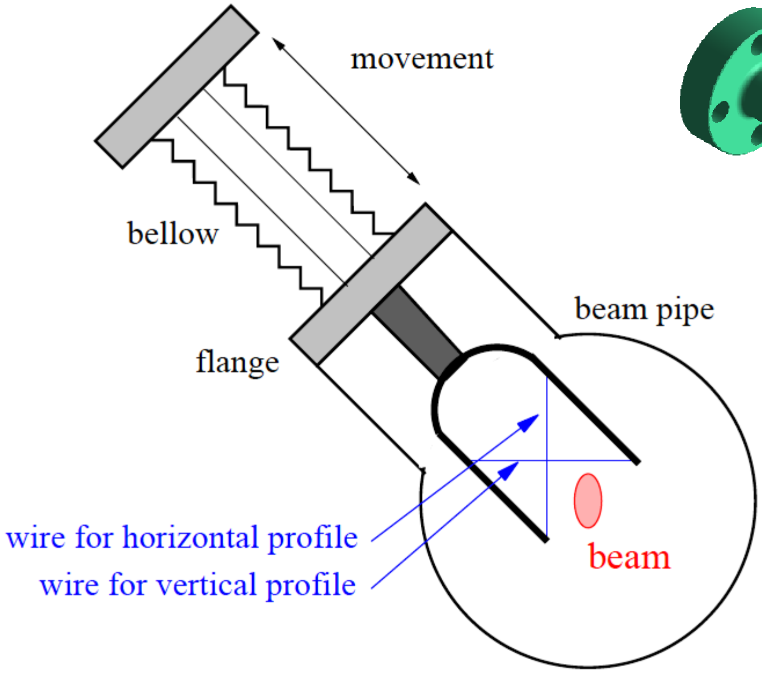
Proton beam → hadrons (π, n, p...) from nuclear interactions

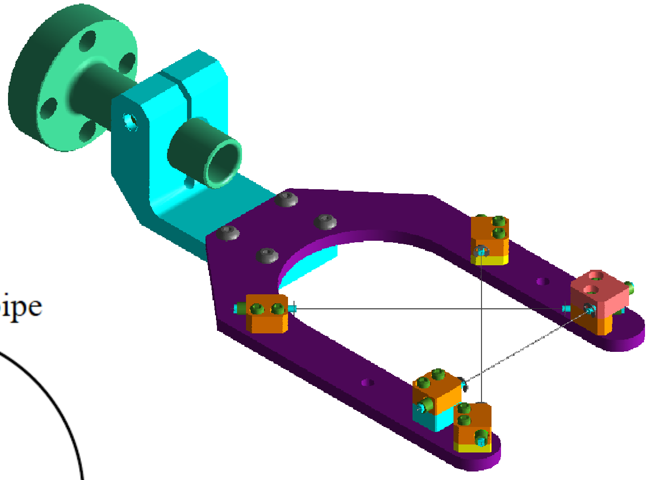
Electron beam → Bremsstrahlung photons.

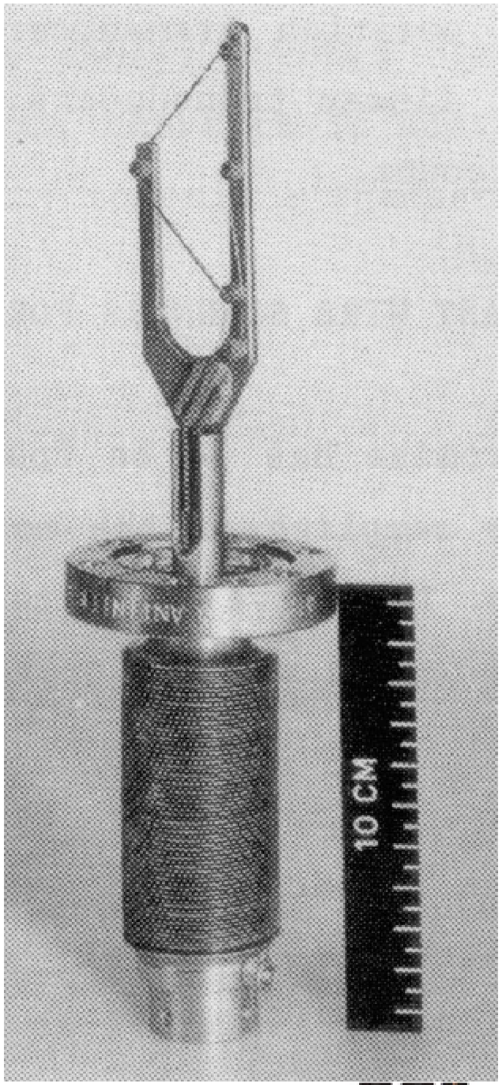
The Artist View of a Wire Scanner

Slow, linear scanner are used for:

- low energy protons due to lack of sec. particles
- high resolution measurements e.g. at e^+-e^- colliders
  by de-convolution $\sigma^2_{beam} = \sigma^2_{meas} - d^2_{wire}$
  $\Rightarrow$ resolution down to μm can be reached
- detection of beam halo.



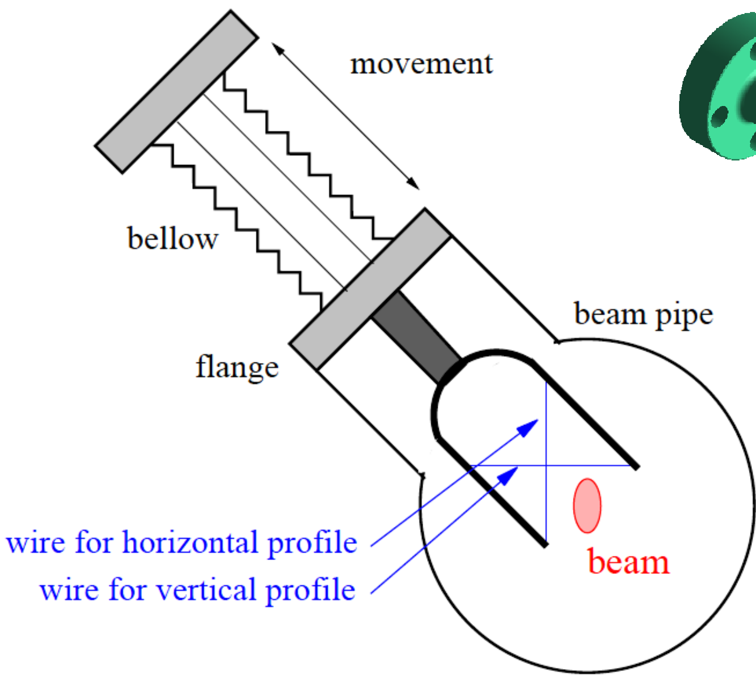


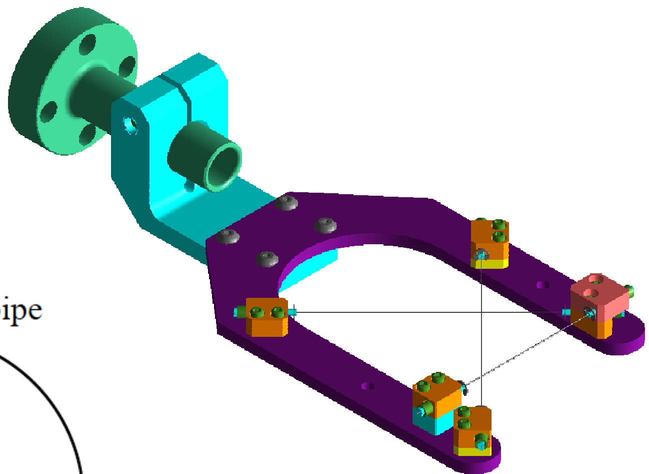


Slow, linear Wire Scanner

Slow, linear scanner are used for:

- low energy protons due to lack of sec. particles
- high resolution measurements e.g. at e^+-e^- colliders
  by de-convolution $\sigma^2_{beam} = \sigma^2_{meas} - d^2_{wire}$
  $\Rightarrow$ resolution down to µm can be reached
- detection of beam halo.





Comparison between SEM-Grid and Wire Scanners

Grid: Measurement at a single moment in time

Scanner: Fast variations can not be monitored

→ for pulsed LINACs precise synchronization is needed

Grid: Not adequate at synchrotrons for stored beam parameters

Scanner: At high energy synchrotrons flying wire scanners are nearly non-destructive

---

Grid: Resolution of a grid is fixed by the wire distance (typically 1 mm)

Scanner: For slow scanners the resolution is about the wire thickness (down to 10 μm)

→ used for e−-beams having small sizes (down to 10 μm)

Grid: Needs one electronics channel per wire

→ expensive electronics and data acquisition

Scanner: Needs a precise movable feed-through → expensive mechanics.

Outline:

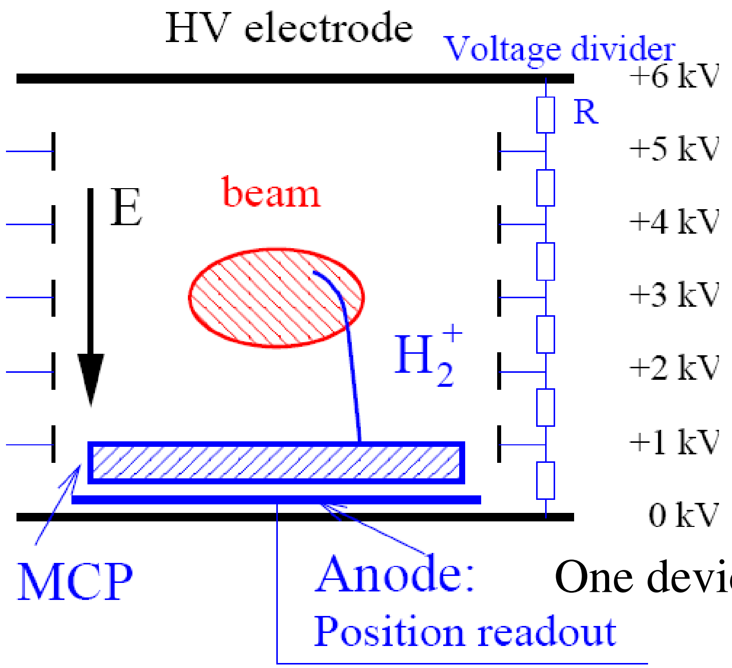
- Scintillation screens:

  emission of light, universal usage, limited dynamic range
- SEM-Grid: emission of electrons, workhorse, limited resolution
- Wire scanner: emission of electrons, workhorse, scanning method
- **Ionization Profile Monitor and Beam Induced Fluorescence Monitor:**

  secondary particle detection from interaction beam-residual gas
- **Optical Transition Radiation**
- **Synchrotron Light Monitors**
- **Summary**

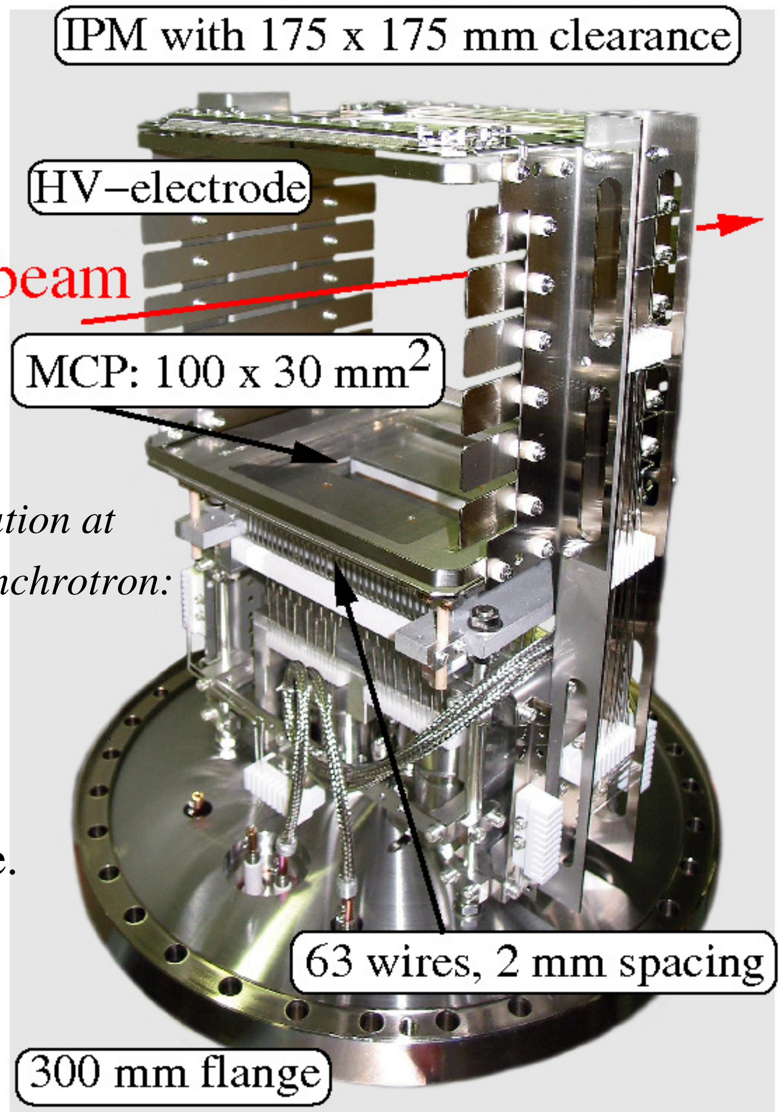
Non-destructive device for proton synchrotron:

- beam ionizes the residual gas by electronic stopping
- gas ions or e⁻ accelerated by E -field ≈1 kV/cm
- spatial resolved single particle detection



One device per plane.

Realization at GSI synchrotron:

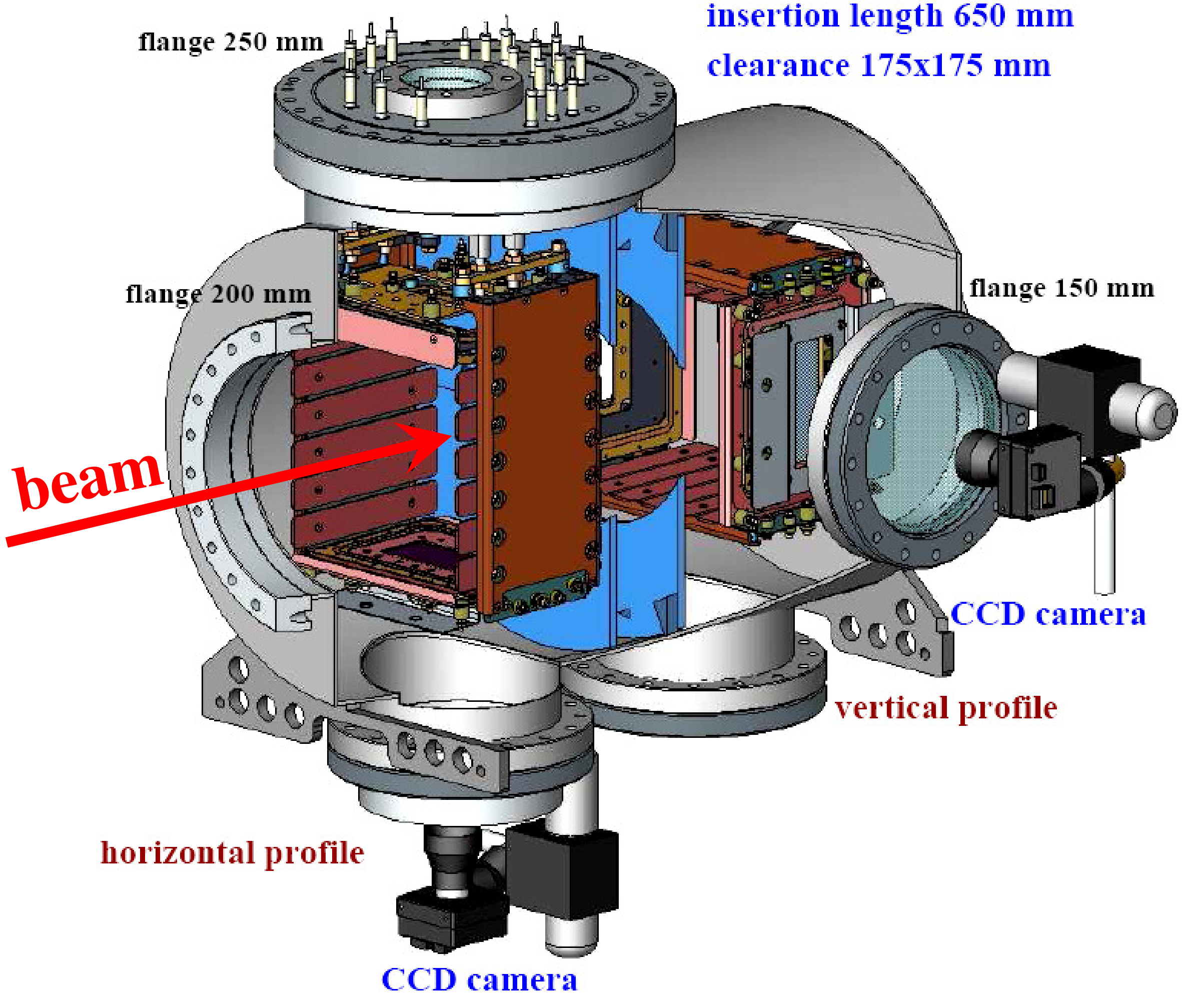


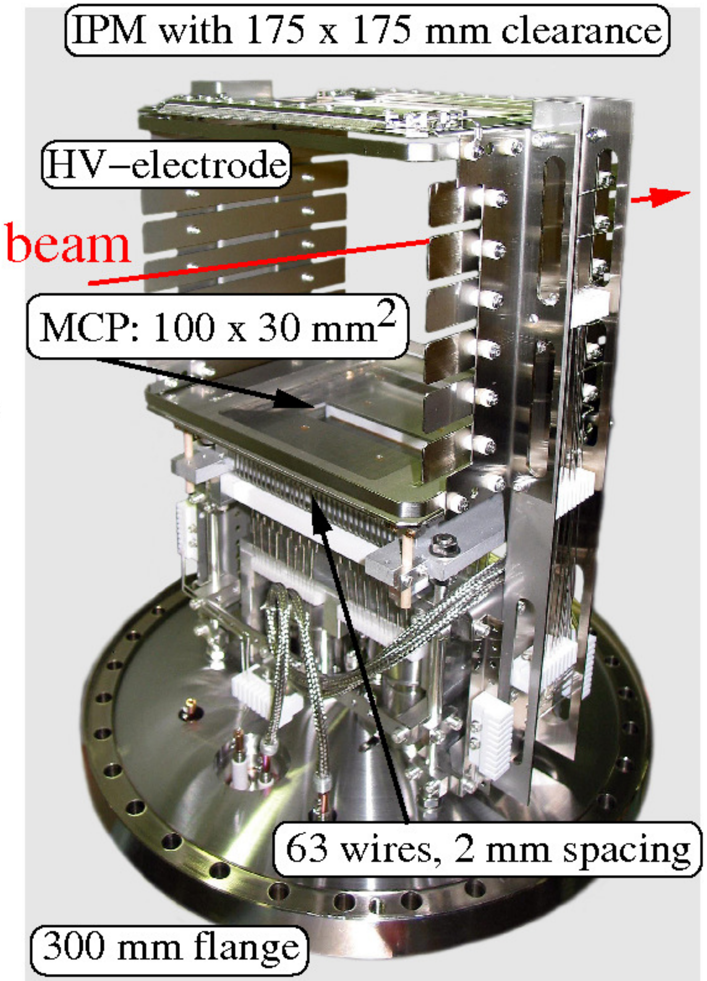
Typical vacuum pressure:

Transfer line: $10^{-8} - 10^{-6}$ mbar (N_2)

Synchrotron: $10^{-11} - 10^{-9}$ mbar (H_2).

The realization for the heavy ion storage ring ESR at GSI:



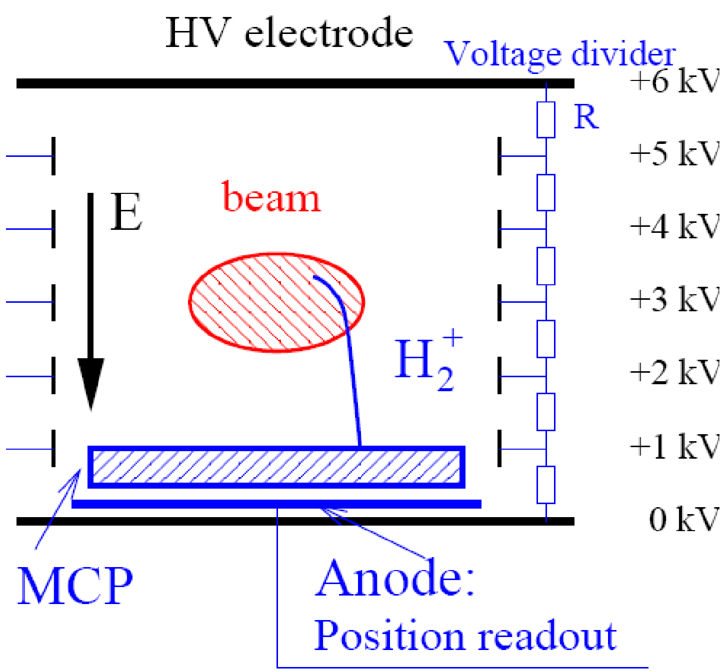


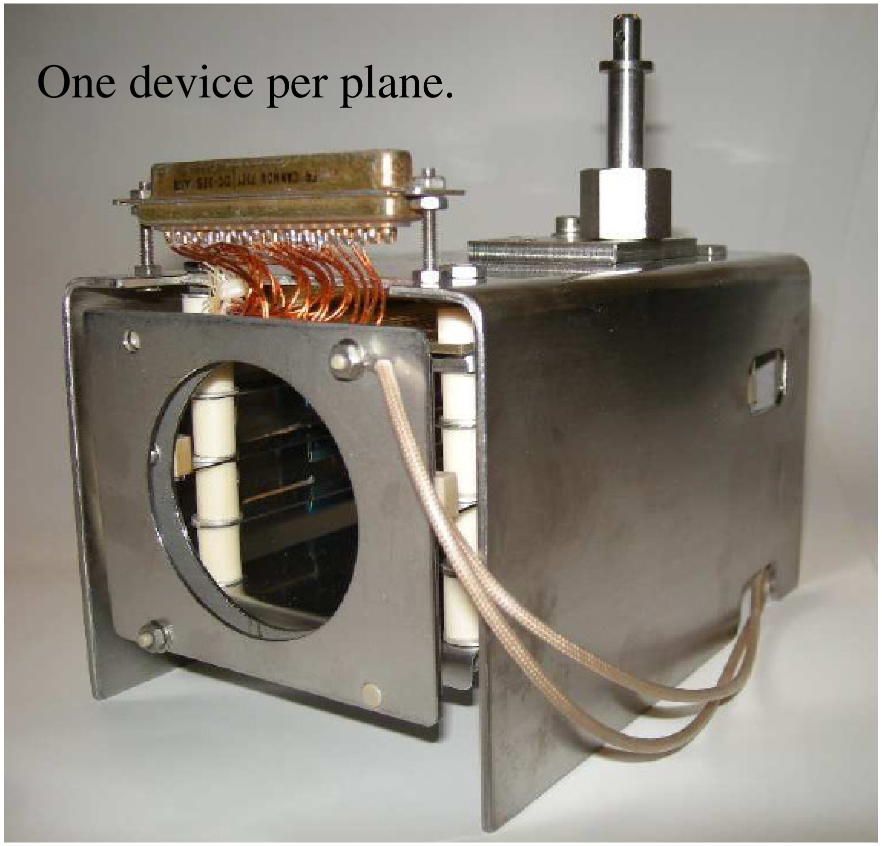
Realization of Ionization Profile Monitor at a LINAC

The realization of an IPM for the use at the GSI LINAC:

Vacuum pressure $p \simeq 10^{-7}$ mbar and high current of $I \simeq 1$ mA $\rightarrow$ no MCP required.

Readout by strips fed to an I/U converter.





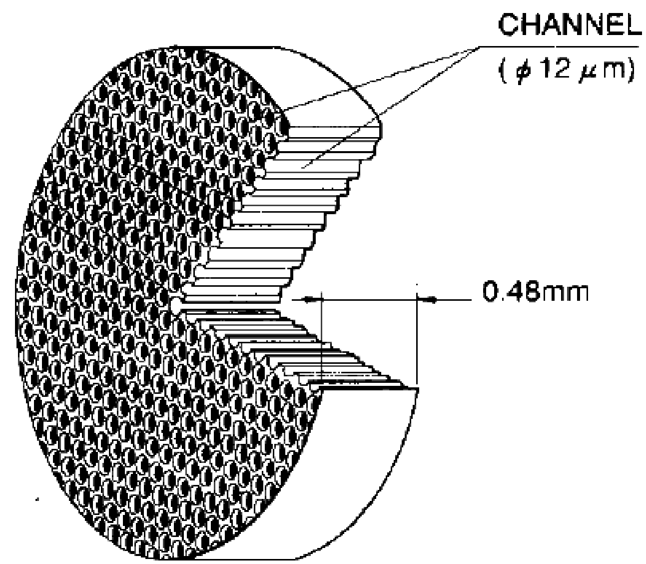
MCP are used as particle detectors with secondary electron amplification.

A MCP is:

- 1 mm glass plate with ≈10 μm holes
- thin Cr-Ni layer on surface
- voltage ≈1 kV/plate across

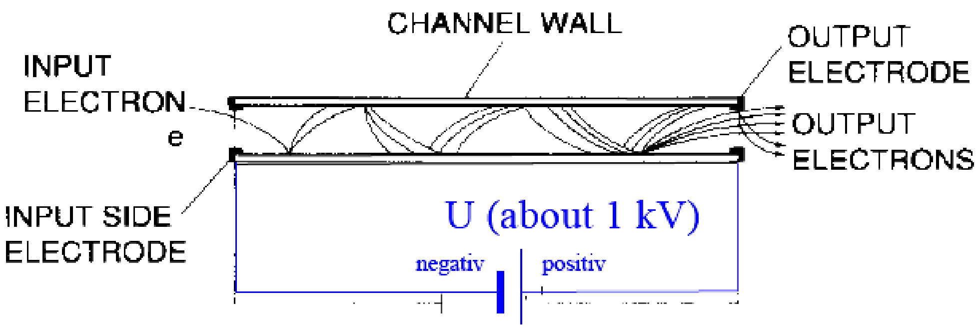
→ e^- amplification of ≈ 10^3 per plate.

→ resolution ≈ 0.1 mm (2 MCPs)



Anode technologies:

- SEM-grid, ≈ 0.5 mm spacing
  → fast electronics readout
- phosphor screen + CCD
  → high resolution, but slow timing
  → fast readout by photo-multipliers
- single particle detection
  → for low beam current.



Application: 'Adiabatic' Damping during Acceleration

The beam emittance $\varepsilon = \int dx dx'$ is defined in the laboratory frame.

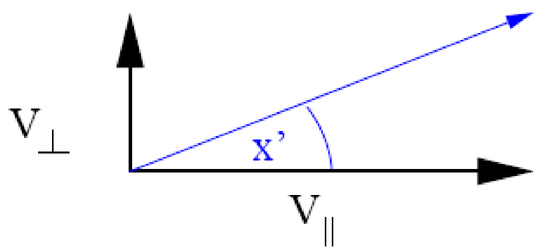
During acceleration:

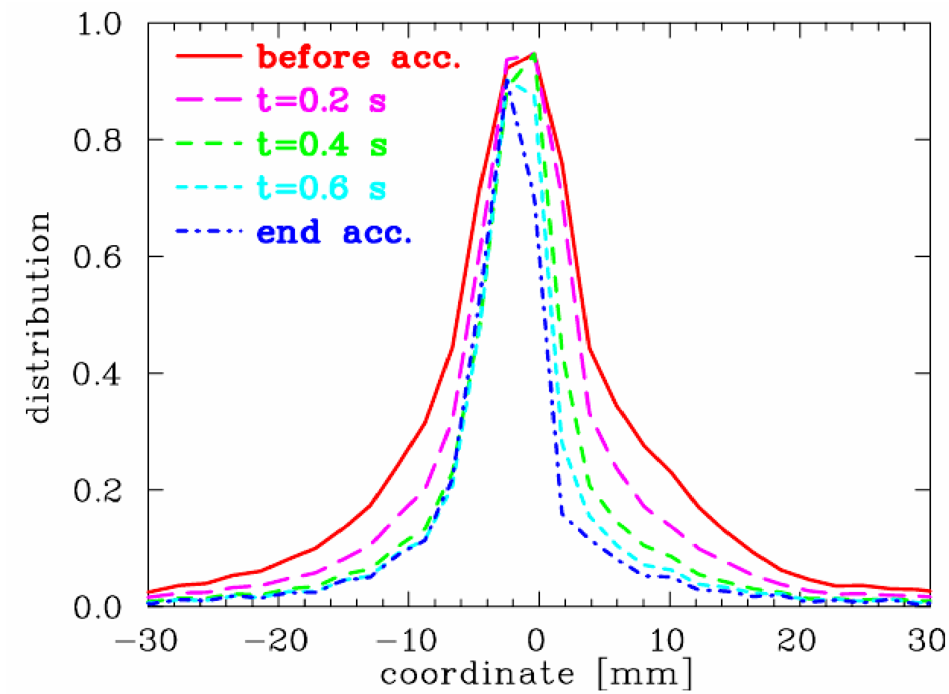
for increasing $\boldsymbol{v}_{||}$ and constant $\boldsymbol{v}_{\square}$:

$\Rightarrow$ $\boldsymbol{x'}$ shrinks

$\Rightarrow$ emittance $\boldsymbol{\varepsilon}$ shrinks

$\Rightarrow$ width $\boldsymbol{x} = \sqrt{\boldsymbol{\beta\varepsilon}}$ shrinks.





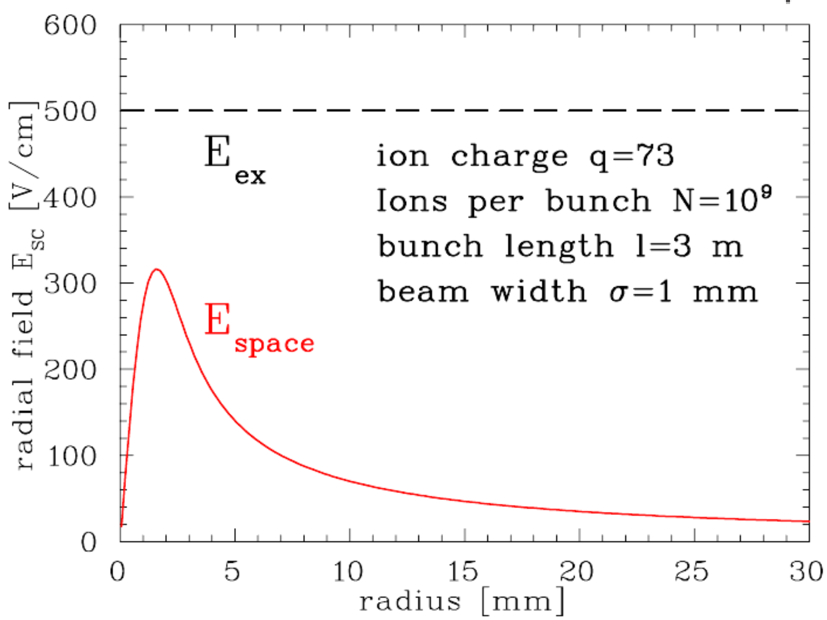
Non-intercepting ionization profile monitor is well suited for long time observations without beam disturbance $\rightarrow$ mainly used at proton synchrotrons.

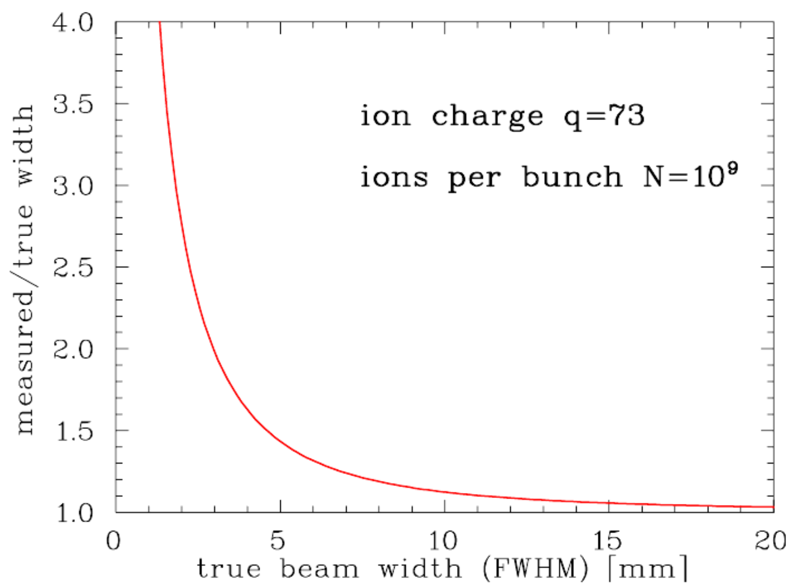
Broadening due to the Beam's Space Charge: Ion Detection

The electrical field of the beam accelerates the residual gas ions
$\Longrightarrow$ broadening of the measured profile $\sigma^2_{beam} = \sigma^2_{meas} - \sigma^2_{corr}$.

Space charge field of round beam: $E_{space}(r) = \frac{1}{2\pi\epsilon_0} \cdot \frac{qeN}{l} \cdot \frac{1}{r}\left(1 - e^{r^2/\sigma^2}\right)$.

Approx. correction: $\sigma^2_{corr} = \frac{e^2 \ln 2}{4\pi\epsilon_0\sqrt{m_p c^2}} \cdot d_{gap} \cdot qN \cdot \sqrt{\frac{1}{eU_{ex}}}$.





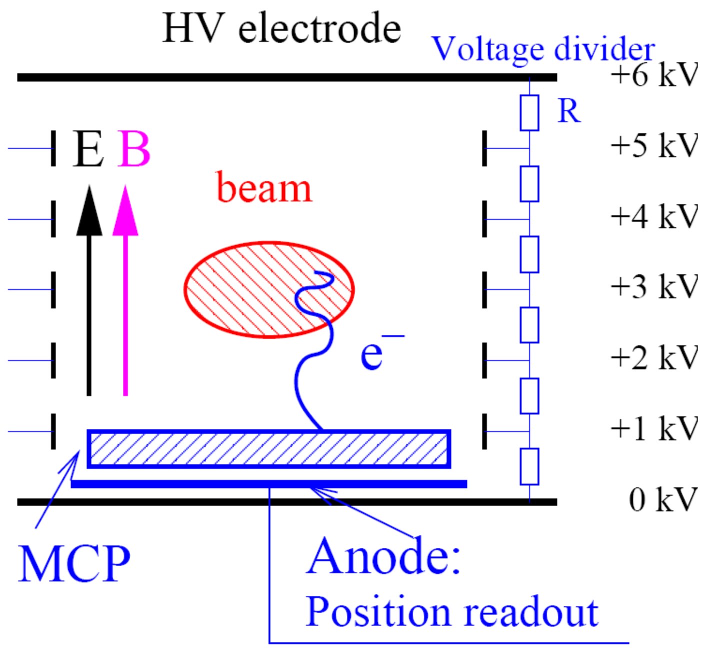
Parameter: U^{73+}, 10^9 particles per 3 m bunch length, cooled beam with 2.5 mm FWHM.

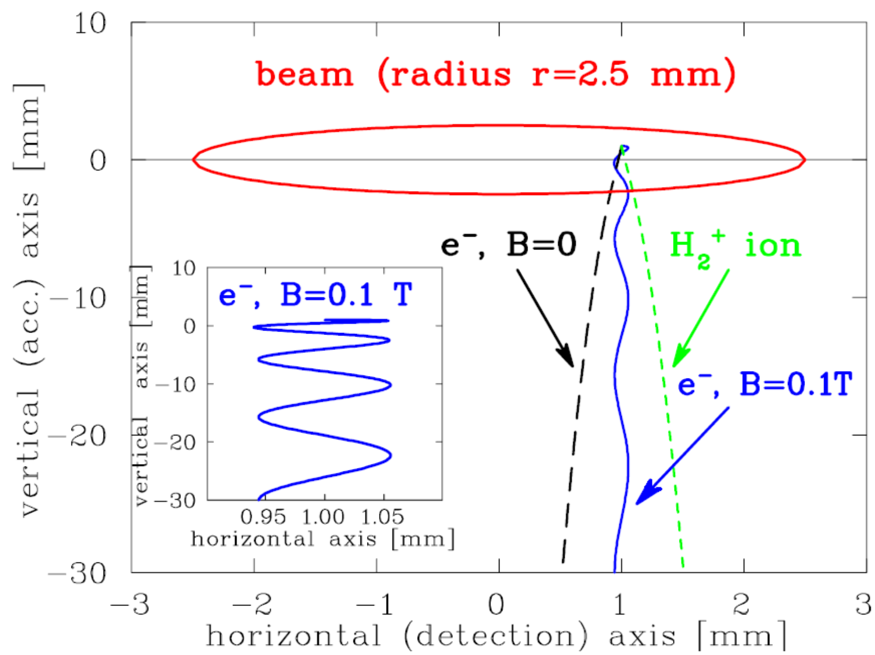
Electron Detection and Guidance by Magnetic Field

Alternative: e⁻ detection in an external magnetic field

→ cyclotron radius $r_c = \sqrt{2m_e E_{kin,\perp}} / eB \Rightarrow r_c < 0.1\,\text{mm}$ for $B = 0.1\,\text{T}$

$E_{kin,}$ given by atomic physics, 0.1 mm is internal resolution of MCP.





Time-of-flight: ≈1 ns → 2 or 3 cycles.

B-field: By dipole magnets with large aperture → IPM is expensive device.

Magnetic field for electron guidance:

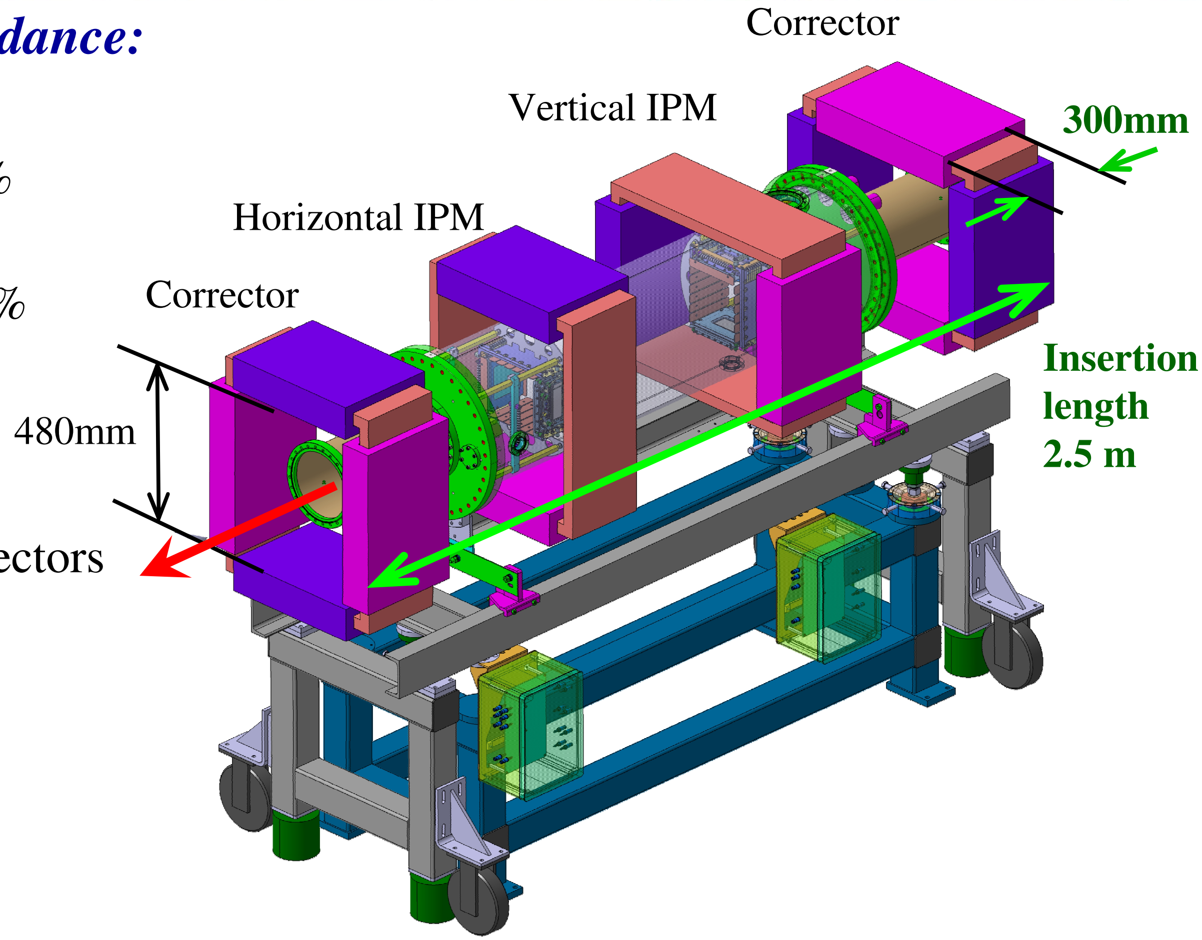
Maximum image distortion:

5% of beam width $\Rightarrow$ $\Delta B/B < 1\,\%$

Challenges:

- High ***B***-field homogeneity of 1%
- Clearance up to 500 mm
- Correctors required to compensate beam steering
- Insertion length 2.5 m incl. correctors

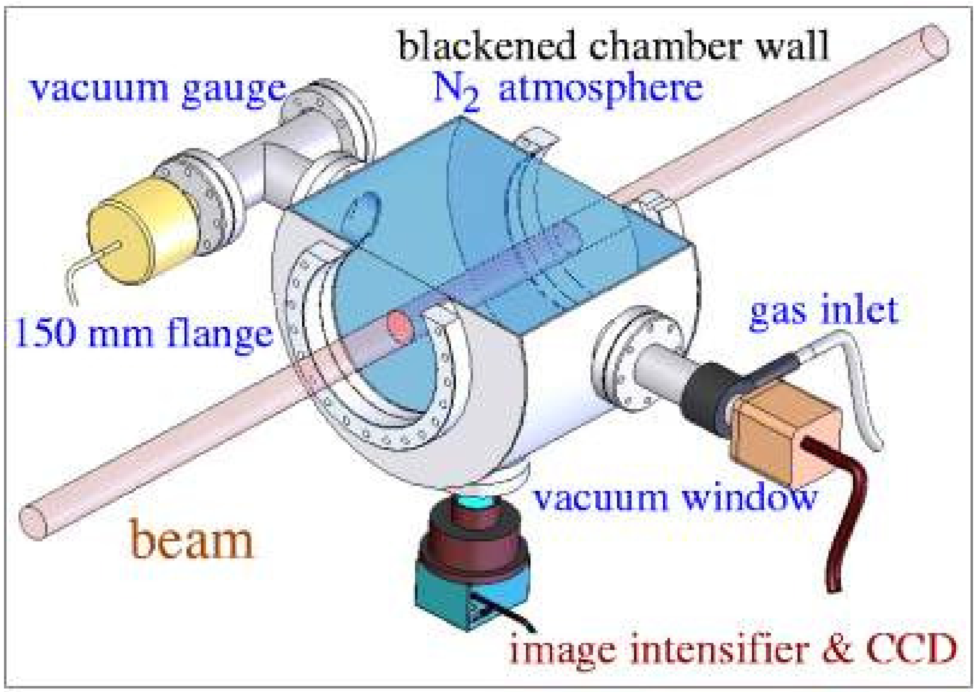
For MCP wire-array readout lower clearance required



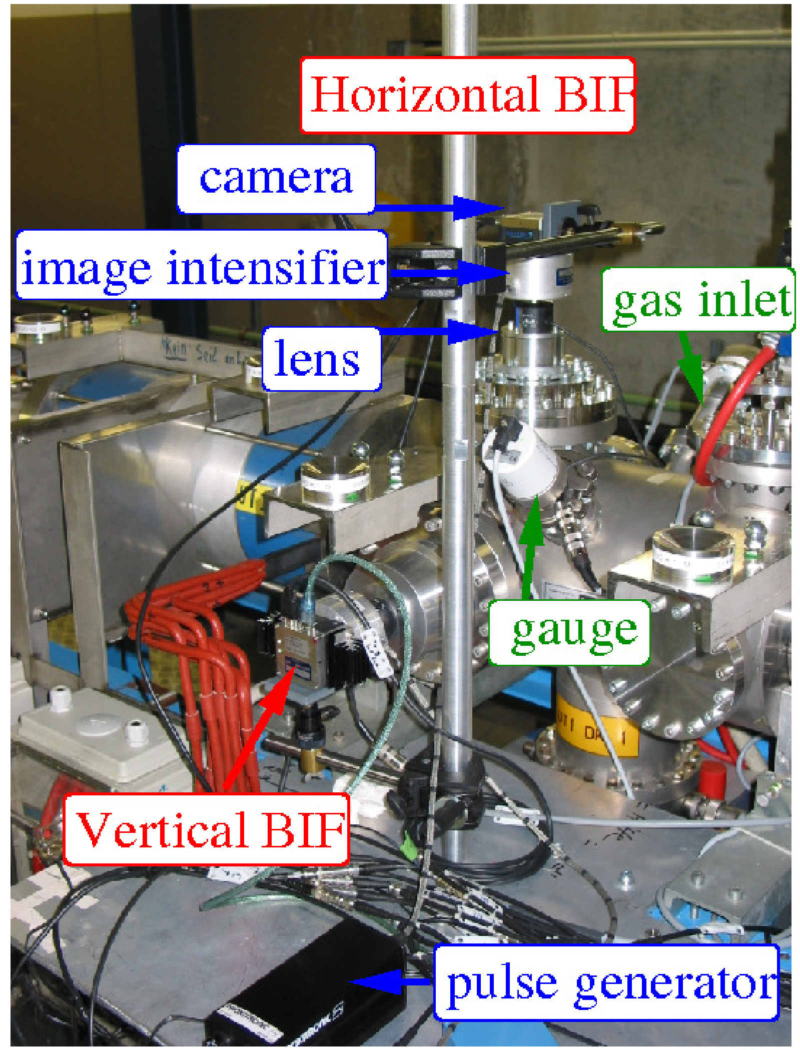
Beam Induced Fluorescence for intense Profiles

Large beam power → Non-intercepting method:
⇒ **Beam Induced Fluorescence** BIF

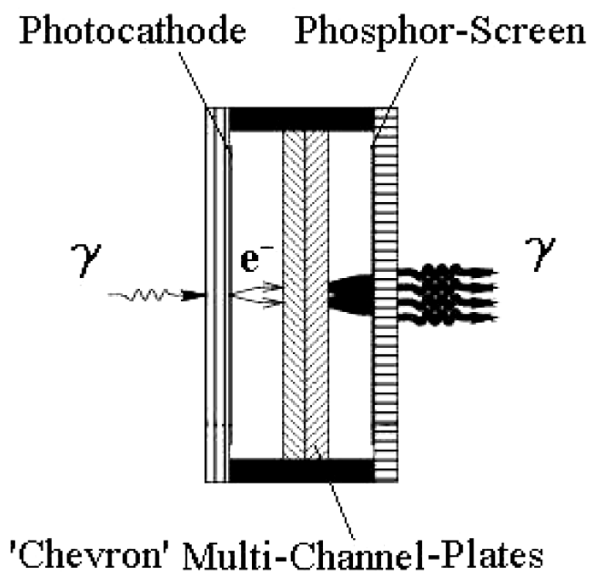
$N_2 + Ion \rightarrow (N_2^+)^* + Ion \rightarrow N_2^+ + \gamma + Ion$
With single photon detection scheme
390 nm< λ< 470 nm
⇒ non-destructive, compact installation.



Installation of hor&vert. BIF Monitor:



Beam Induced Fluorescence Monitor BIF: Image Intensifier



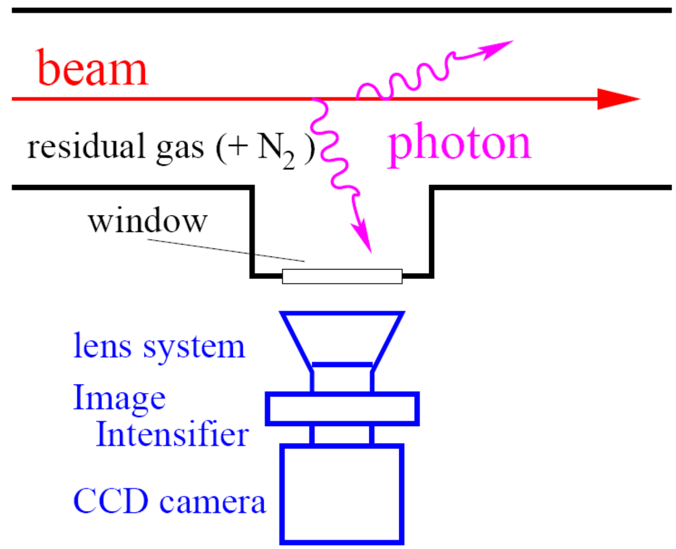


Image intensifier:

- Photo cathode → creation of photo-e⁻
- Accelerated toward MCP for amplification
- Detection of ampl. e⁻ by phosphor screen
- Image recorded by CCD

⇒ Low light amplification
(commercially used for night vision devices)

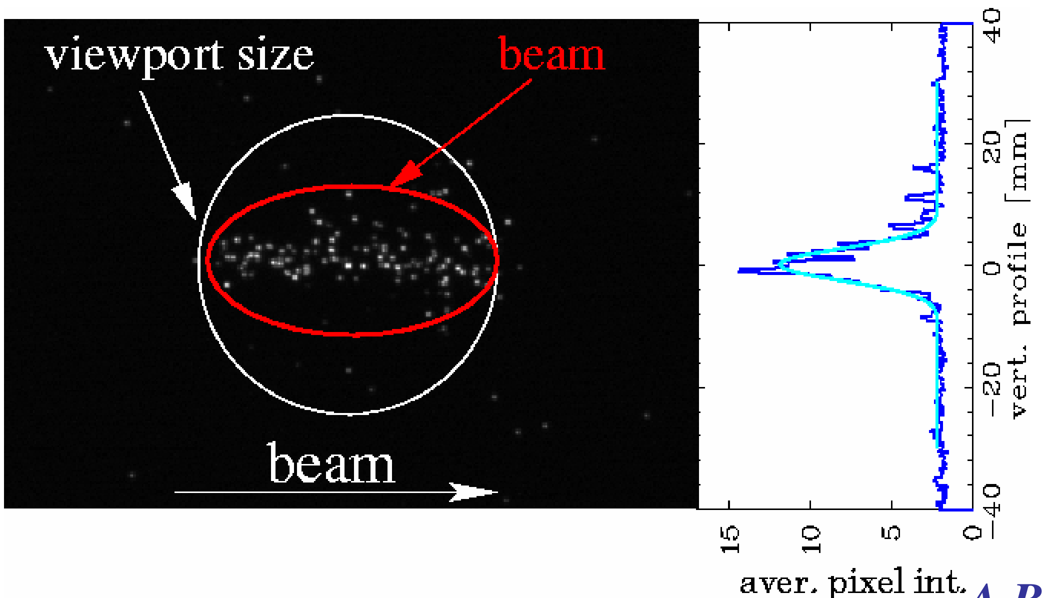
A BIF monitor consists of only:

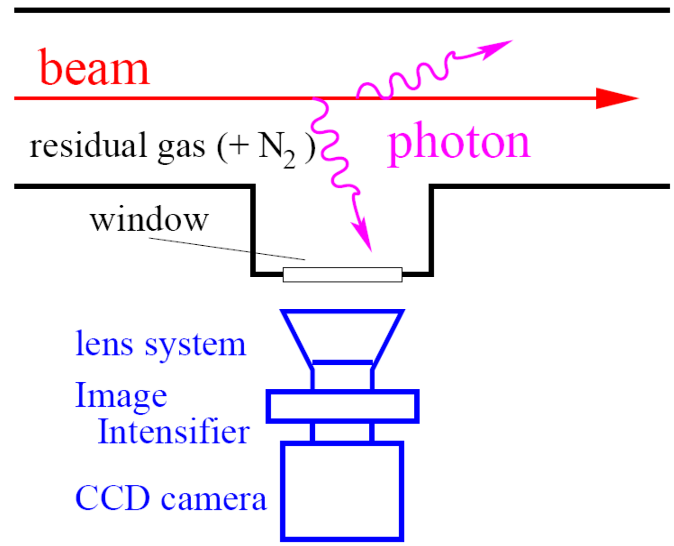
- optics outside beam pipe
- image intensifier + camera
- gas-inlet for pressure increase

⇒ nearly no installation inside vacuum.
only LEDs for calibration

⇒ cheaper than IPM, but lower signal.

'Single photon counting':





Example at GSI-LINAC:

4.7 MeV/u Ar $^{10+}$ beam

I=2.5 mA equals to 10^{11} particle

One single macro pulse of 200 μs

Vacuum pressure: p=10^{-5} mbar (N_2)

A BIF monitor consists of only:

- optics outside beam pipe
- image intensifier + camera
- gas-inlet for pressure increase

⇒ nearly no installation inside vacuum.
only LEDs for calibration

⇒ cheaper than IPM, but lower signal.

Comparison between IPM and BIF

Non-destructive methods preferred:

Beam is not influenced and diagnostics device is not destroyed!

IPM: Beam ionizes the residual gas
→ measurement of all ionization products, $\Omega = 4\pi$-geometry due to E-field

BIF: Beam ionizes and excites the residual gas
→ measurement of photons emitted toward camera, solid angle $\Omega \approx 10^{-3}$

IPM: Higher efficiency than BIF

BIF: Low detection efficiency, only $\approx 10^{-4}$ of IPM
⇒ longer observation time or higher pressure required

IPM: Complex installation inside vacuum

BIF: Nearly no installation inside vacuum

IPM: More expensive, for some beam parameters even guiding magnetic field required

BIF: More sensitive to external parameters like radiation stray light

Outline:

- Scintillation screens:

  emission of light. universal usage, limited dynamic range
- SEM-Grid: emission of electrons, workhorse, limited resolution
- Wire scanner: emission of electrons, workhorse, scanning method
- Ionization Profile Monitor and Beam Induced Fluorescence Monitor:

  secondary particle detection from interaction beam-residual gas
- **Optical Transition Radiation:**

  crossing material boundary, for relativistic beams only
- **Synchrotron Light Monitors**
- **Summary**

Optical transition radiation is emitted by
charged particle passage through a material boundary.

Electrodynamics field configuration changes during the passage:

→ Polarization of the medium

→ emission of energy

Description by ***classical*** electrodynamics & relativity:

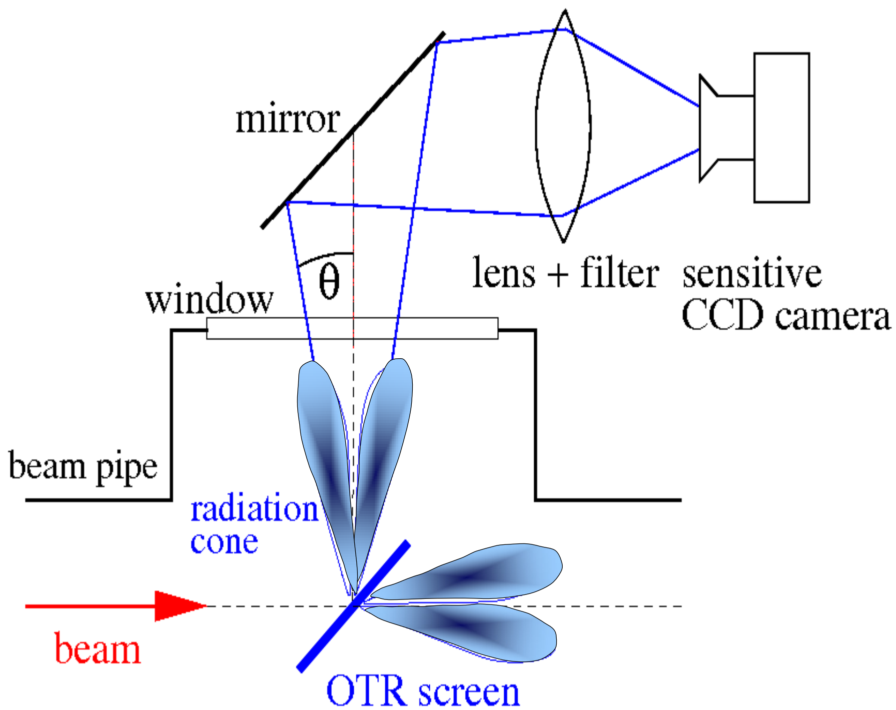
$$\frac{d^2W}{d\Omega d\omega} = \frac{\mu_0 c e^2}{4\pi^3} \cdot \frac{\theta^2}{\left(\gamma^{-2} + \theta^2\right)^2}$$

W: energy emitted in solid angle *Ω*

θ: angle of emission

γ: Lorentz factor

ω: angular frequency intervall $E_{ph}=2\pi h\omega$



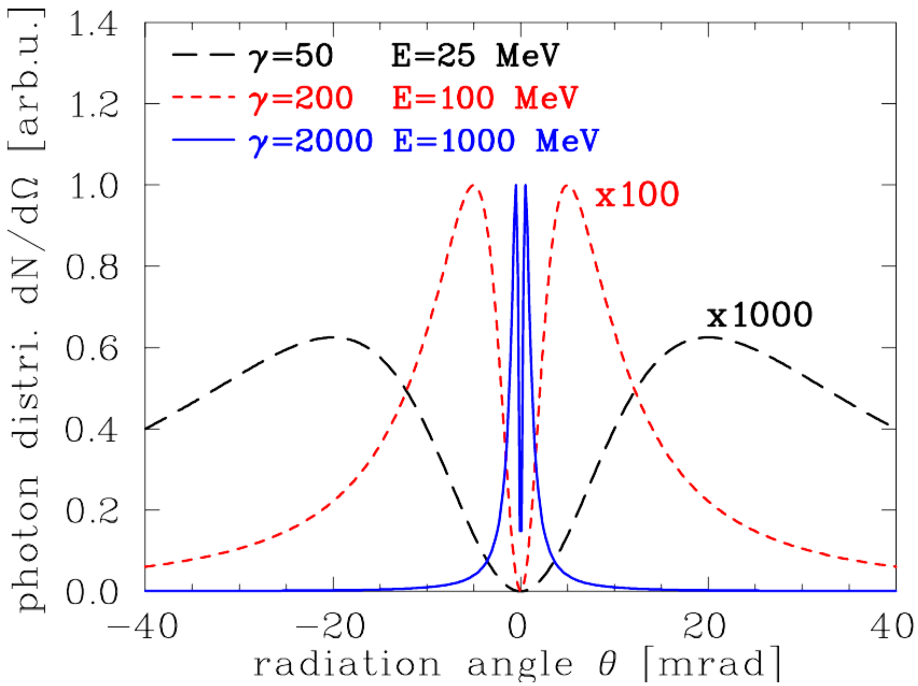
- Insertion of thin Al-foil under 45°
- Observation of low light by CCD.

Optical Transition Radiation: Angular Photon Distribution

Photon distribution $\frac{dN_{photon}}{d\Omega} = N_{beam} \cdot \frac{\mu_0 c e^2}{4\hbar\pi^3} \cdot \log\left(\frac{\lambda_{begin}}{\lambda_{end}}\right) \cdot \frac{\theta^2}{\left(\gamma^{-2}+\theta^2\right)^2}$

within a solid angle $d\Omega$ and

Wavelength interval λ_{begin} to λ_{end}



- Detection: Optical 400 nm < λ < 800 nm
  using image intensified CCD
- Larger signal for relativistic beam $\gamma \gg 1$
- Angular focusing for $\gamma \gg 1$

⇒ **well suited for e⁻ beams**

⇒ **p-beam only for E_{kin}>10 GeV (γ>10)**

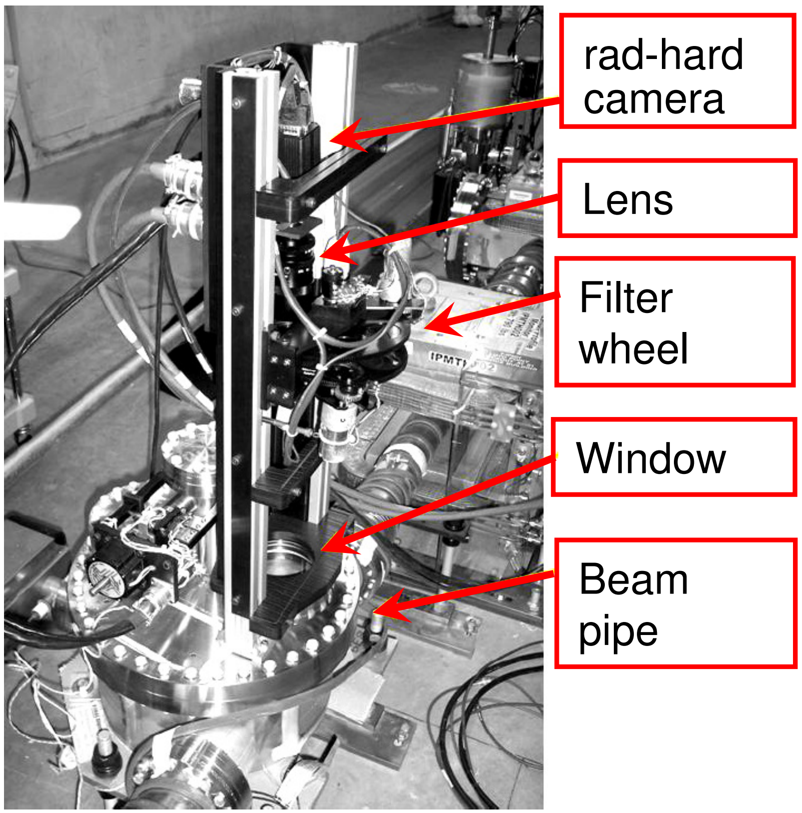
→ ***Profile*** by focusing to screen

→ ***Beam angular distribution*** by focusing on infinity
due to emission dependence on beam angular distribution.

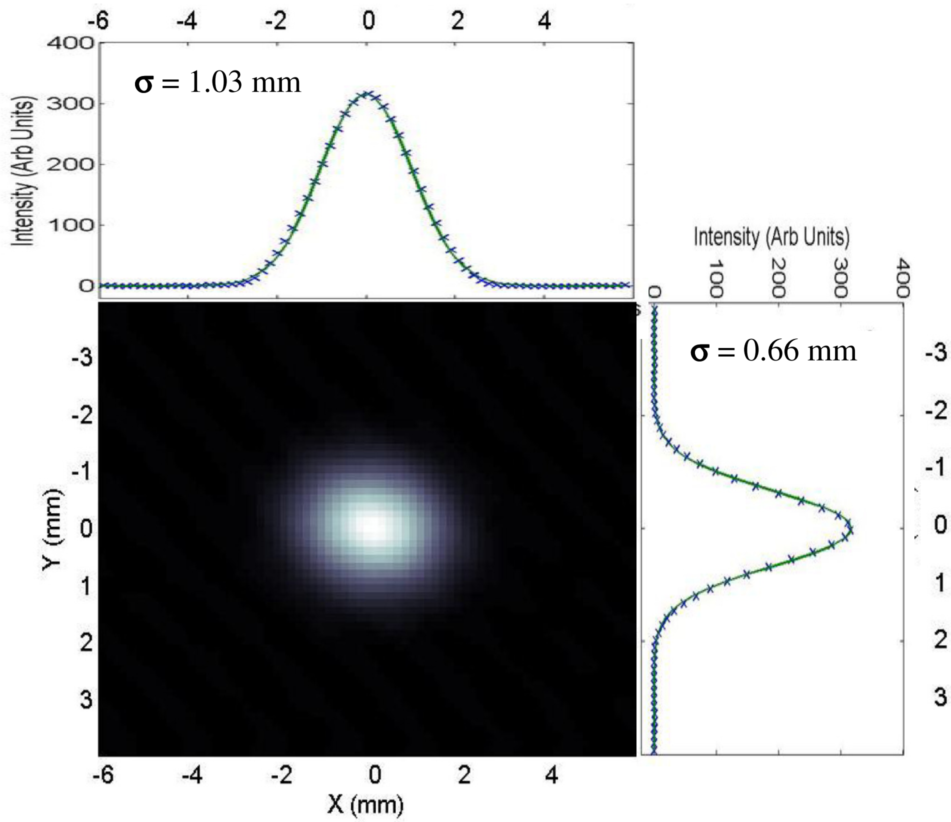
Example of realization at TERATRON:

- Insertion of foil
  e.g. 5 μm Kapton coated with 0.1μm Al

Advantage: thin foil ⇒ low heating & straggling
2-dim image visible



Results at FNAL-TEVATRON synchrotron with 150 GeV proton
Using fast camera: Turn-by-turn measurement



V.E. Scarpine (FNAL) et al., BIW'06

Comparison between Scintillation Screens and OTR

OTR: electrodynamic process → beam intensity linear to # photons

Scint. Screen: complex atomic process → saturation possible

OTR: thin foil Al or Al on Mylar, down to 0.25 μm thickness

→ minimization of beam scattering (Al is low Z-material)

Scint. Screen: thickness ≈ 1 mm inorganic, fragile material, not radiation hard

---

OTR: low number of photons → expensive image intensified CCD

Scint. Screen: large number of photons → simple CCD sufficient

---

OTR: complex angular photon distribution → resolution limited

Scint. Screen: isotropic photon distribution → simple interpretation

---

OTR: beam angular distribution measurable→ beam emittance

Scint. Screen: no information concerning the beam angular distribution

---

OTR: large γ needed → e^--beam with E_{kin} > 100 MeV, proton-beam with E_{kin} > 100 GeV

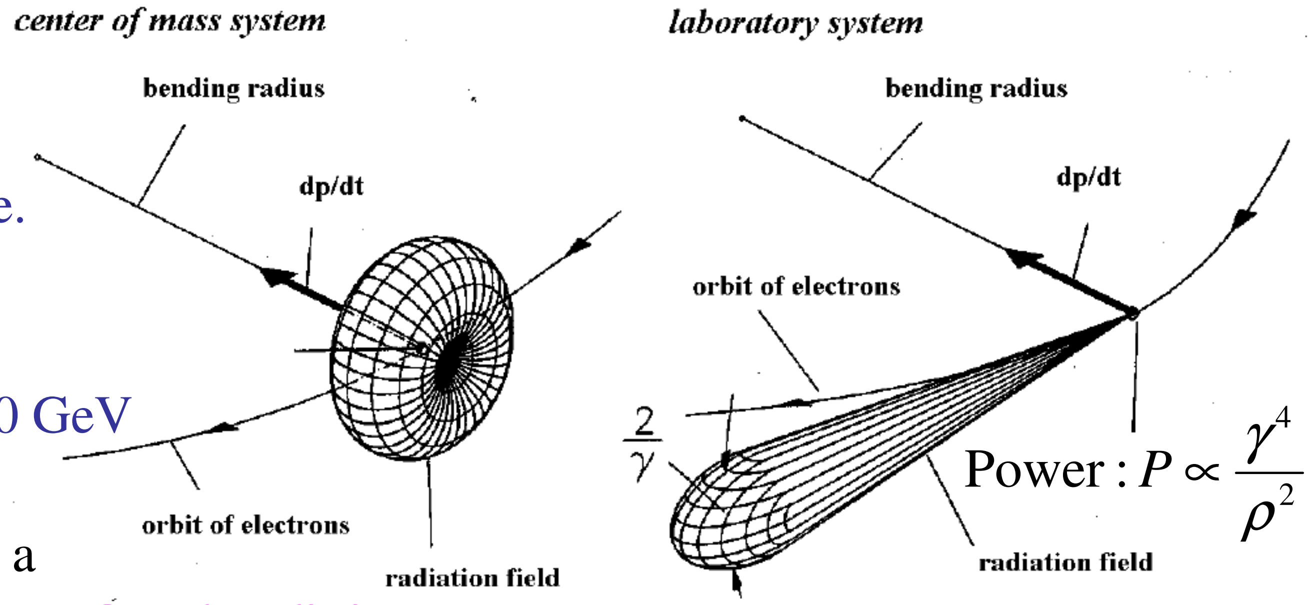
Scint. Screen: for all beams

Outline:

- Scintillation screens:
  emission of light, universal usage, limited dynamic range
- SEM-Grid: emission of electrons, workhorse, limited resolution
- Wire scanner: emission of electrons, workhorse, scanning method
- Ionization Profile Monitor and Beam Induced Fluorescence Monitor:
  secondary particle detection from interaction beam-residual gas
- Optical Transition Radiation:
  crossing optical boundary, for relativistic beams only
- **Synchrotron Light Monitors**
  photon detection of emitted synchrotron light
- **Summary**

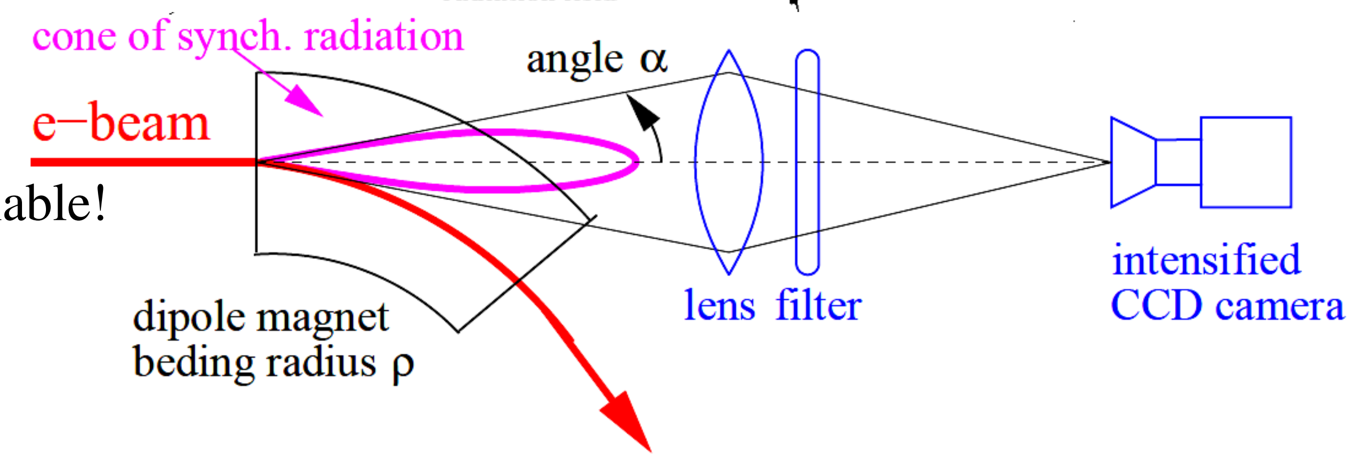
An electron bent (i.e. accelerated) by a dipole magnet emit synchrotron light.

This light is emitted into a cone of opening 2/γ in lab-frame.
⇒Well suited for rel. e⁻
For protons:
Only for energies E>100 GeV



The light is focused to a intensified CCD.

Advantage:
Signal anyhow available!



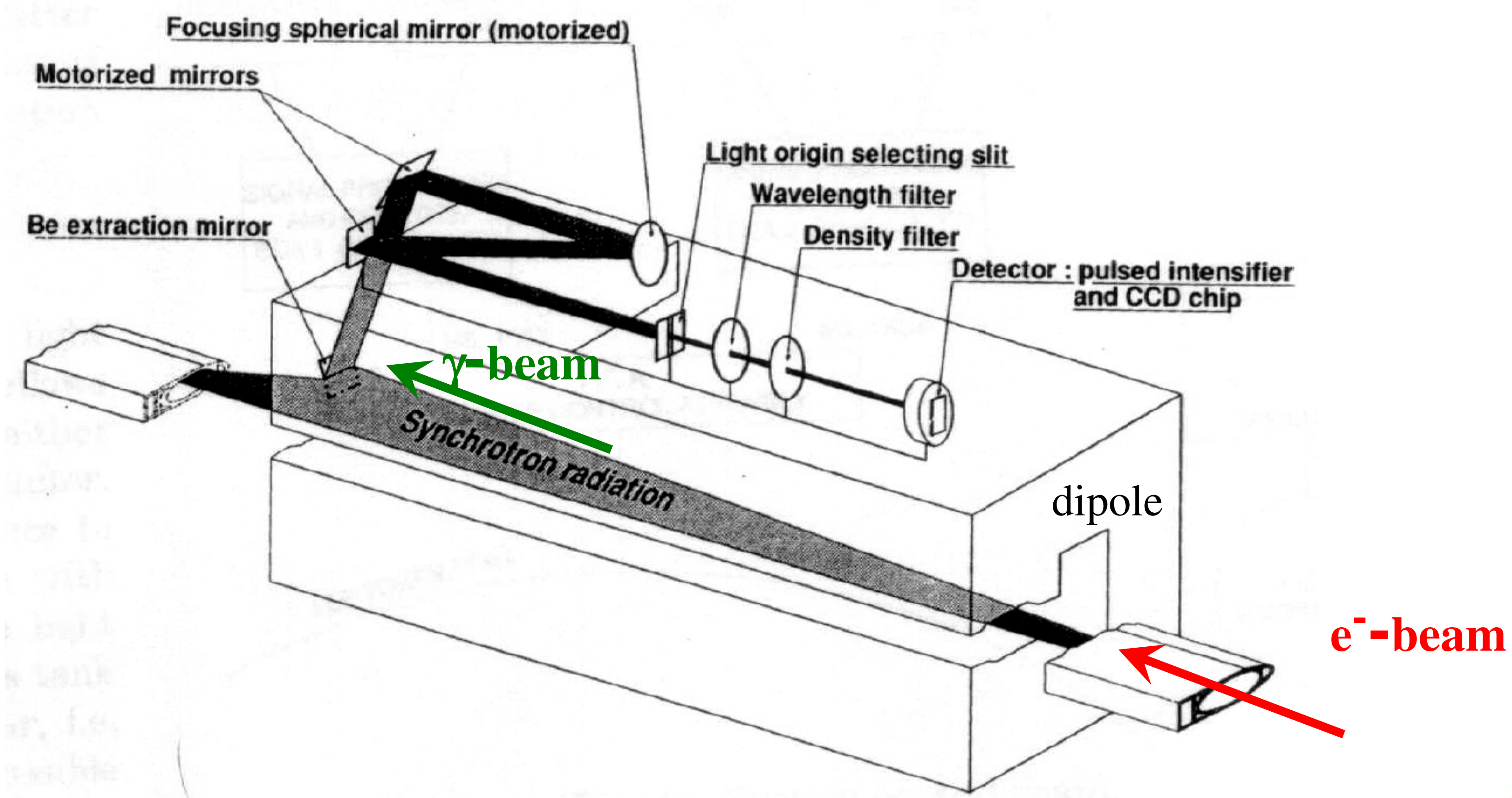
Realization of a Synchrotron Light Monitor

Extracting out of the beam's plane by a (cooled) mirror

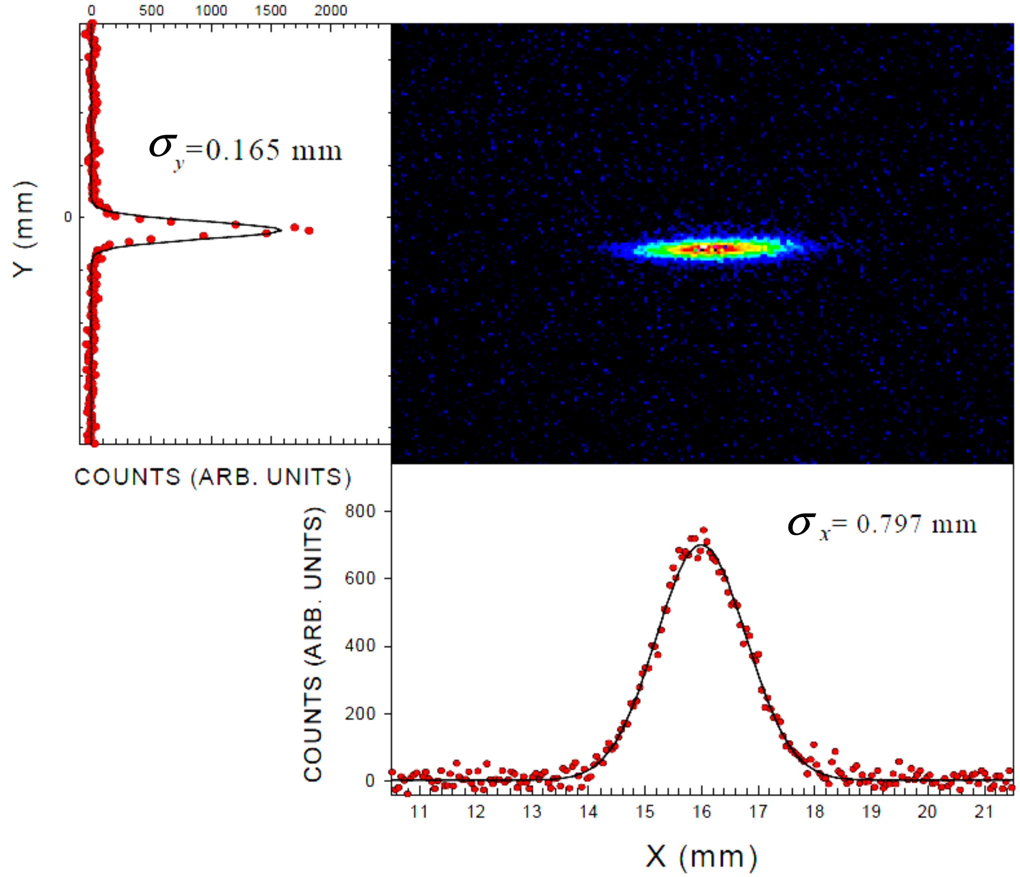
→ Focus to a slit + wavelength filter for optical wavelength

→ Image intensified CCD camera

Example: CERN LEP-monitor with bending radius 3.1 km (blue or near UV)



Example: Synchrotron radiation facility APS accumulator ring and blue wavelength:

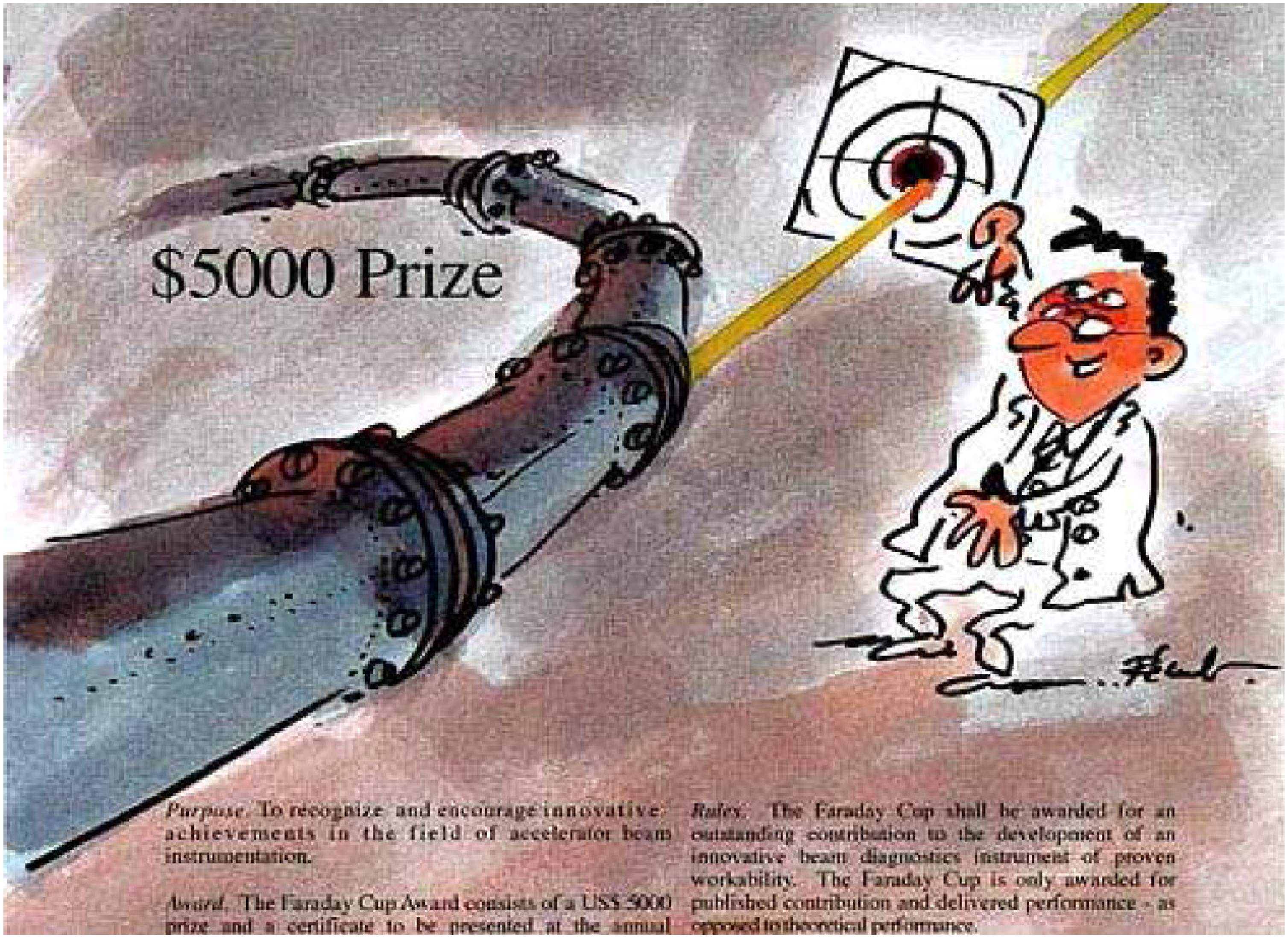


Advantage: Direct measurement of 2-dim distribution, only mirror installed in the vacuum pipe

Realization: Optics outside of vacuum pipe

Disadvantage: Resolution limited by the diffraction due to finite apertures in the optics.

The Artist View of a Synchrotron Light Monitor



Diffraction Limit for a Synchrotron Light Monitor

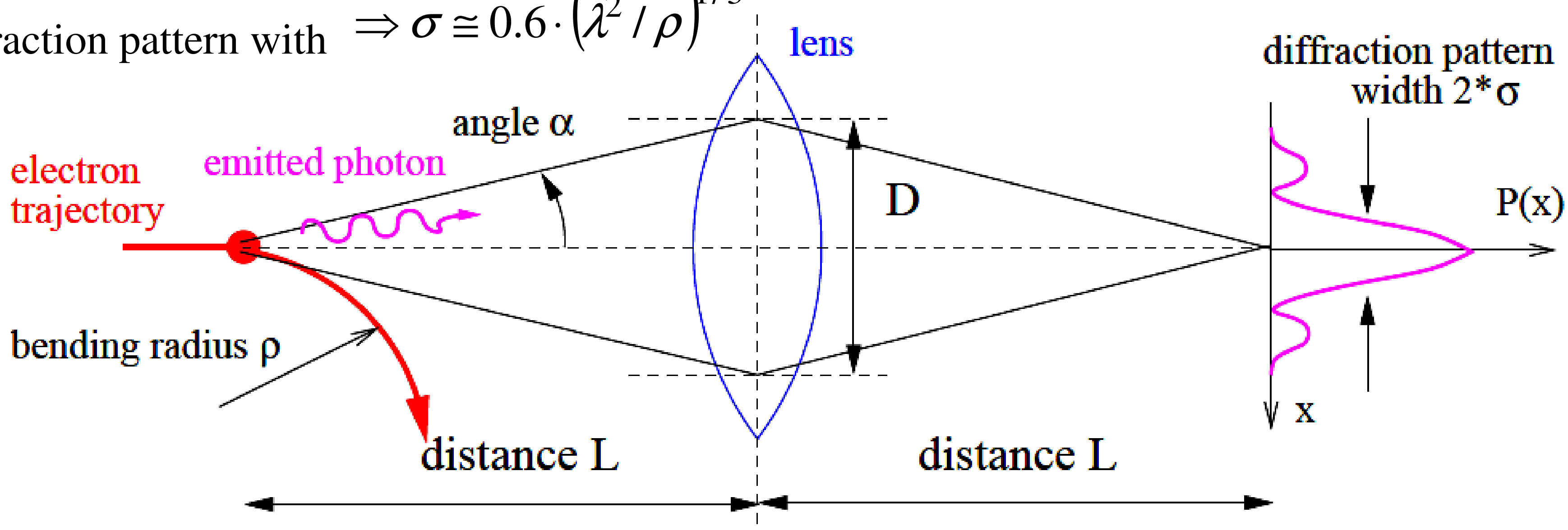
Use of optical wavelength and CCD: λ above critical λ_{crit} (spectrum fall-off).

Example 1:1 image: Cone of emission for horizontally polarized light: $\alpha = 0.41\ (\lambda/\rho)^{1/3}$

General Fraunhofer diffraction limit (given by emission cone): $\sigma = \dfrac{\lambda}{2D/L}$

Opening angle of optics: $D = 2\alpha \cdot L$

Diffraction pattern with $\Rightarrow \sigma \cong 0.6 \cdot \left(\lambda^2 / \rho\right)^{1/3}$



A good resolution for:

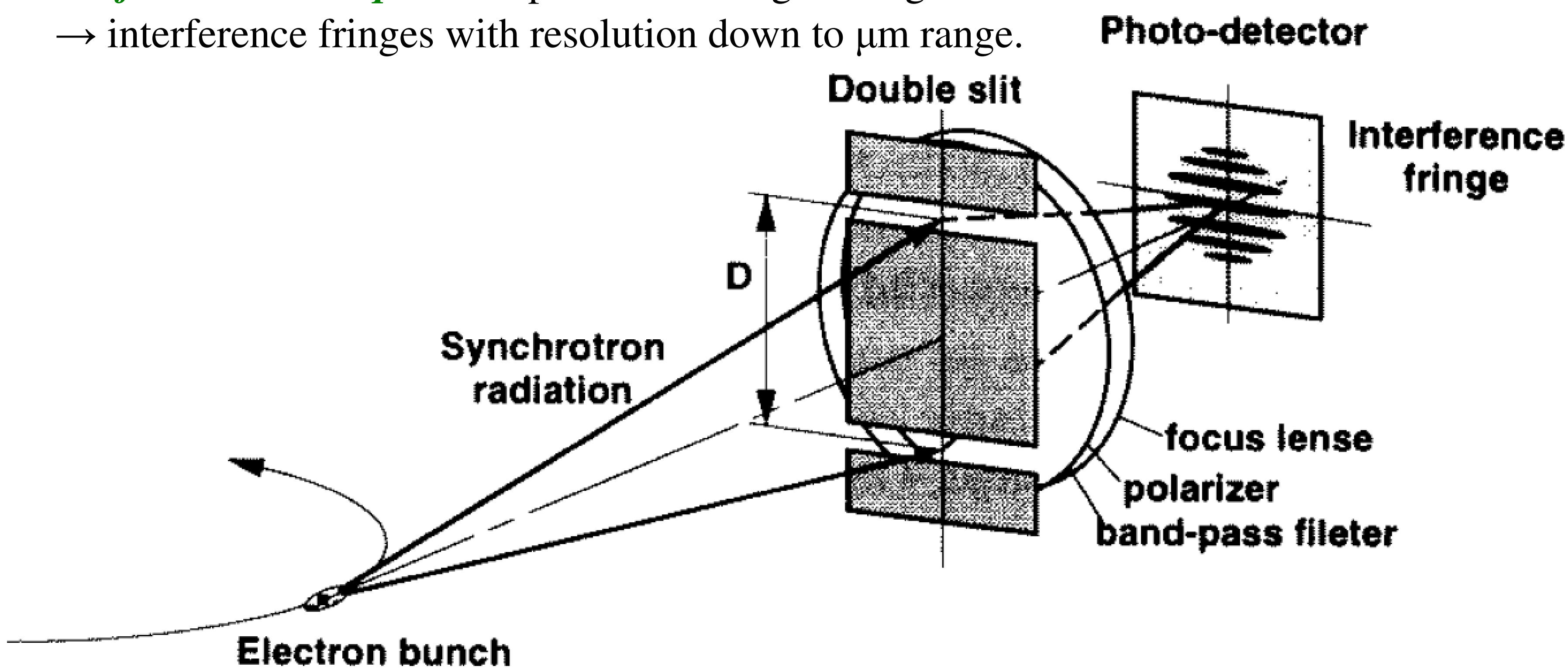
- large dipole bending radius ρ, **but** fixed by the accelerator
- short wavelength, **but** good optics only for $\lambda > 300$ nm

Synchrotron Light Monitor overcoming Diffraction Limit

The diffraction limit is $\Rightarrow \sigma \cong 0.6 \cdot \left(\lambda^2 / \rho\right)^{1/3}$

Possible improvements:

- ***Shorter wavelength:*** Using x-rays and an aperture of Ø 1mm
  → 'x-ray pin hole camera'.
- ***Interference technique:*** At optical wavelength using a double slit
  → interference fringes with resolution down to μm range.



Summary for Beam Profile

Different techniques are suited for different beam parameters:

e⁻-beam: typically Ø 0.3 to 3 mm, **protons:** typically Ø 3 to 30 mm

Intercepting ↔ non-intercepting methods

Direct observation of electrodynamics processes:

- Synchrotron radiation monitor: non-destructive, only for e⁻-beams, complex
- OTR screen: nearly non-destructive, large relativistic γ needed, e⁻-beams mainly

Detection of secondary photons, electrons or ions:

- Scintillation screen: destructive, large signal, simple, all beams
- Ionization profile monitor: non-destructive, expensive, limited resolution, for protons
- Residual fluorescence monitor: non-destructive, limited signal strength, for protons

Wire based electronic methods:

- SEM-grid: partly destructive, large signal and dynamic range, limited resolution
- Wire scanner: partly destructive, large signal and dynamics, high resolution, slow scan.
- MWPC-grid: internal amplification, for low current proton-beam.