

Measurement of Beam Profile



The beam width can be changed by focusing via quadrupoles.

Transverse matching between ascending accelerators is done by focusing.

→ Profiles have to be controlled at many locations.

Synchrotrons: Lattice functions $\beta(s)$ and $D(s)$ are fixed \Rightarrow width σ and emittance ϵ are:

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

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:

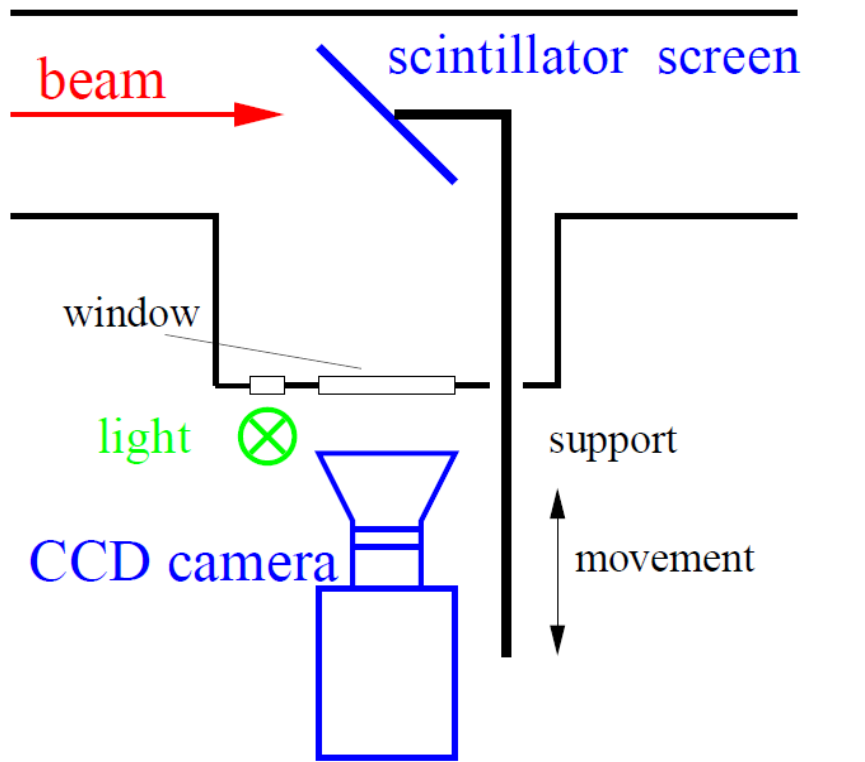
- **Scintillation screens:**
emission of light, universal usage, limited dynamic range
- **SEM-Grid**
- **Wire scanner**
- **Ionization Profile Monitor and Beam Induced Fluorescence Monitor**
- **Optical Transition Radiation**
- **Synchrotron Light Monitors**
- **Summary**

Scintillation Screen

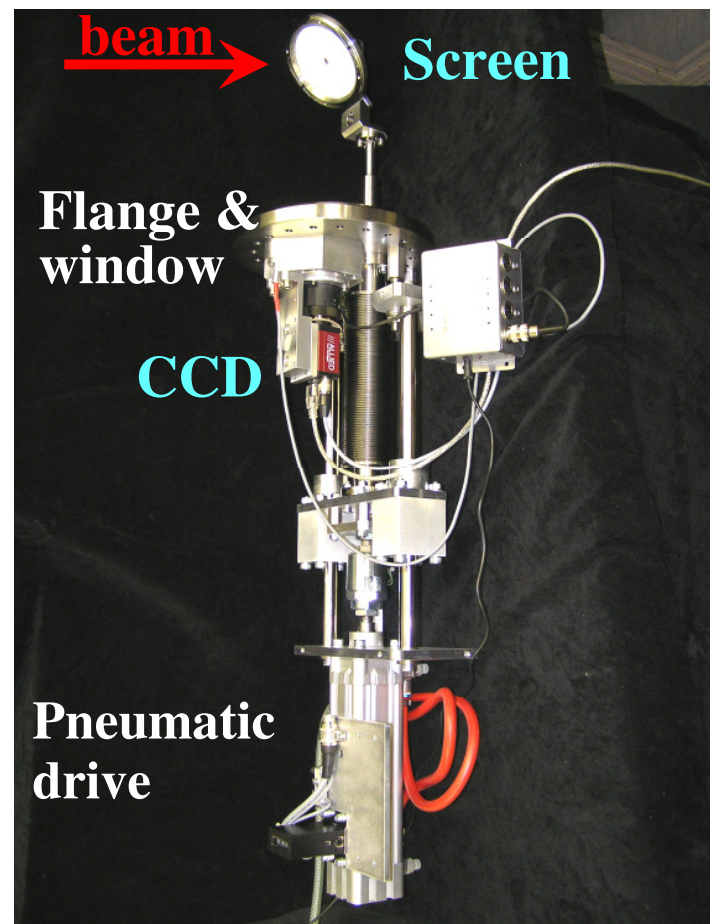


Particle's energy loss in matter produces light

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



*Pneumatic feed-through
with $\varnothing 70$ mm screen :*



Example of Screen based Beam Profile Measurement

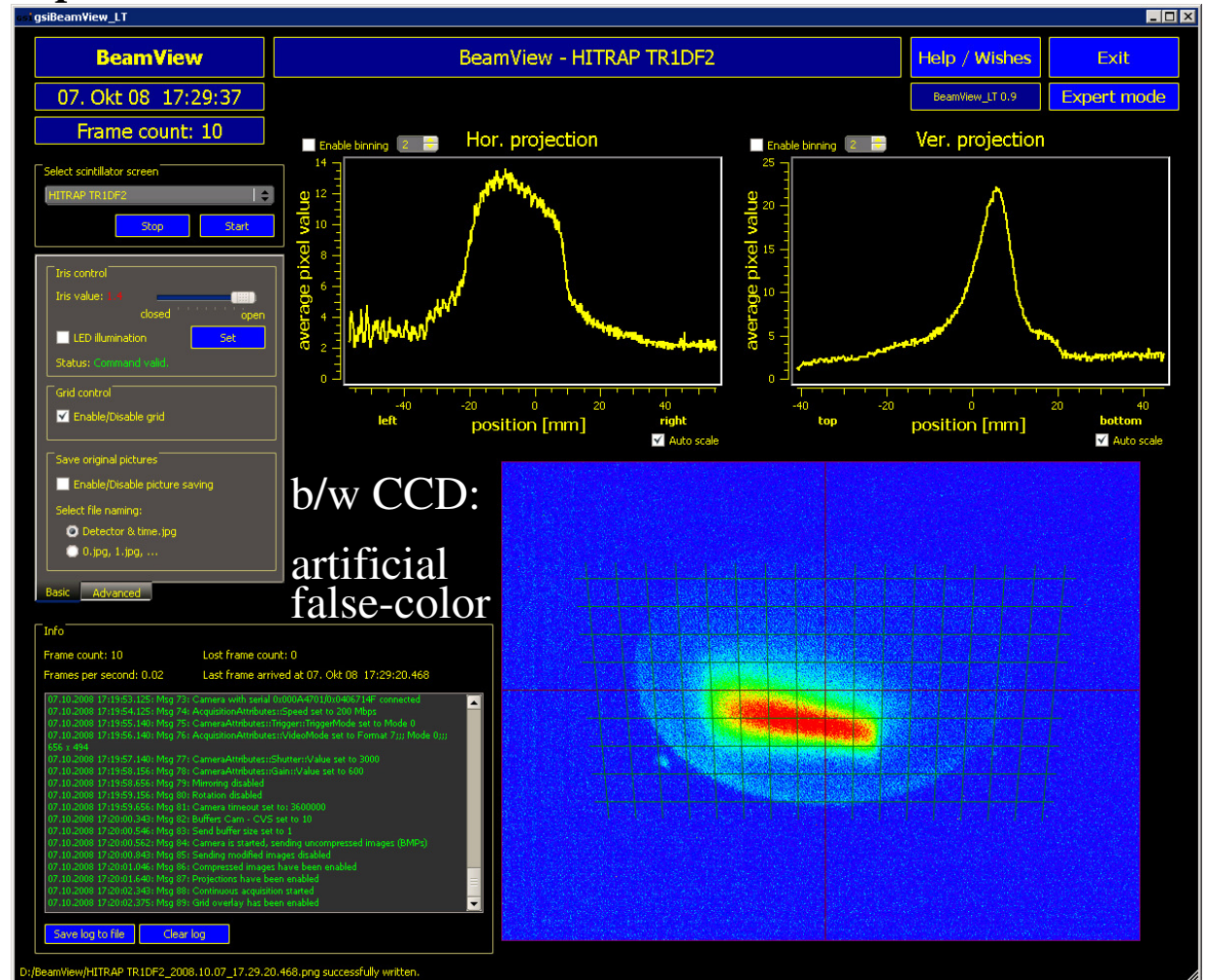


Example: GSI LINAC, 4 MeV/u, low current, YAG:Ce screen

Advantage of screens:

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

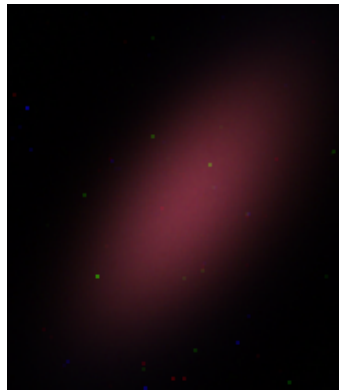
Observation with a CCD camera
with digital output
or video & frame grabber.



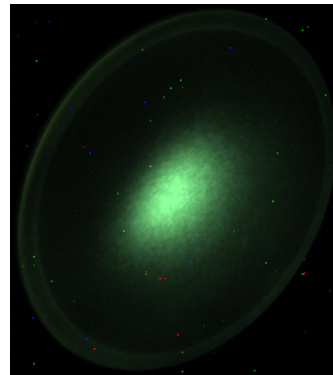
Light output from various Scintillating Screens



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



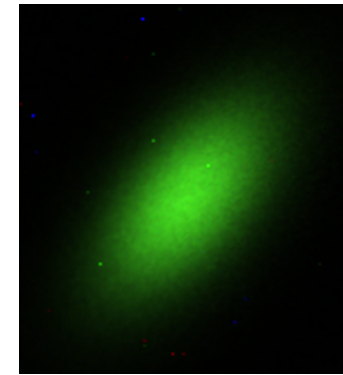
Al₂O₃



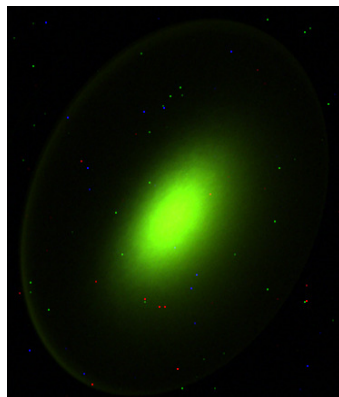
CsI:TI



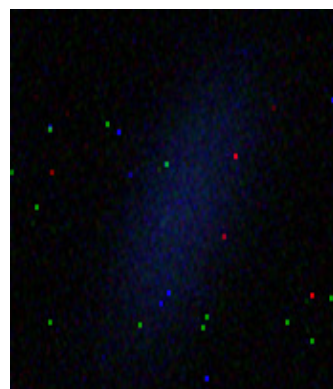
Al₂O₃:Cr



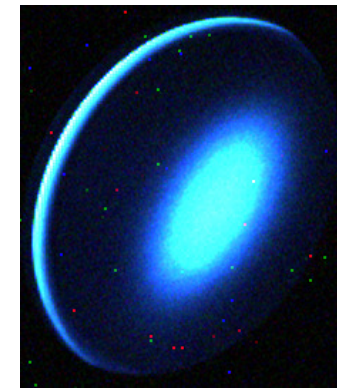
P43



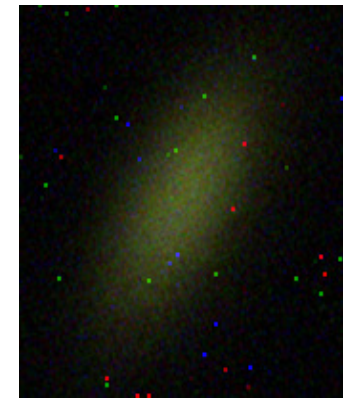
YAG:Ce



Herasil



Quartz:Ce



ZrO₂: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:

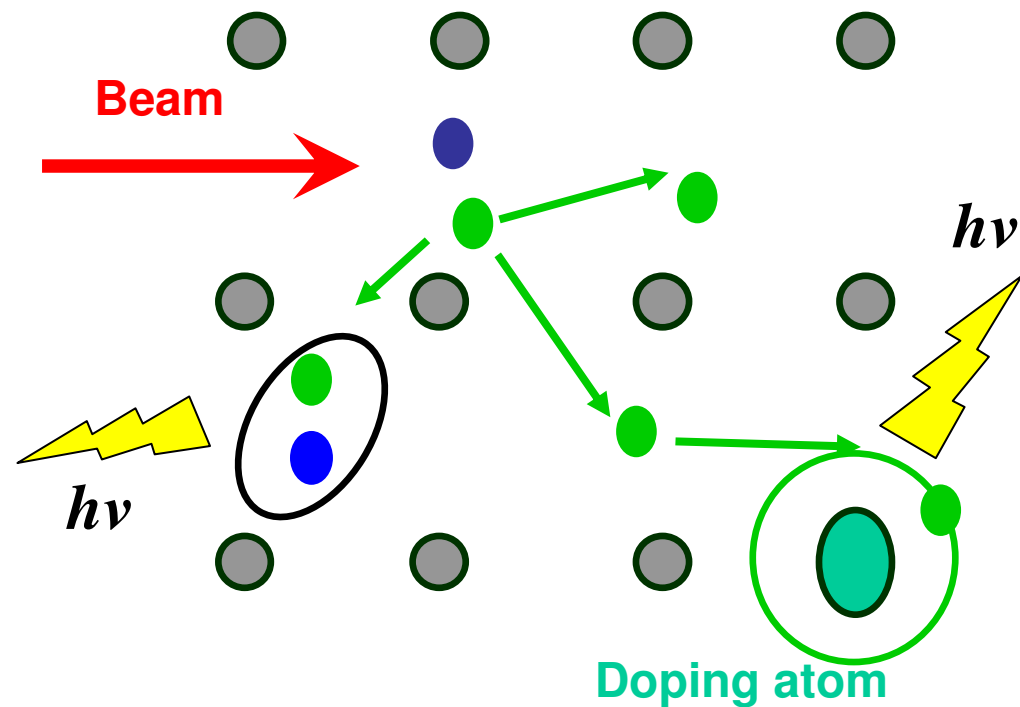
electron – electron scattering

➤ 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 ₂ O ₃	Cr	700 nm	100 ms
YAG	Y ₃ Al ₅ O ₁₂	Ce	550 nm	0.2 μs
	Li glass	Ce	400 nm	0.1 μs
P11	ZnS	Ag	450 nm	3 ms
P43	Gd ₂ O ₂ S	Tb	545 nm	1 ms
P46	Y ₃ Al ₅ O ₁₂	Ce	530 nm	0.3 μs
P47	Y ₂ Si ₅ O 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:

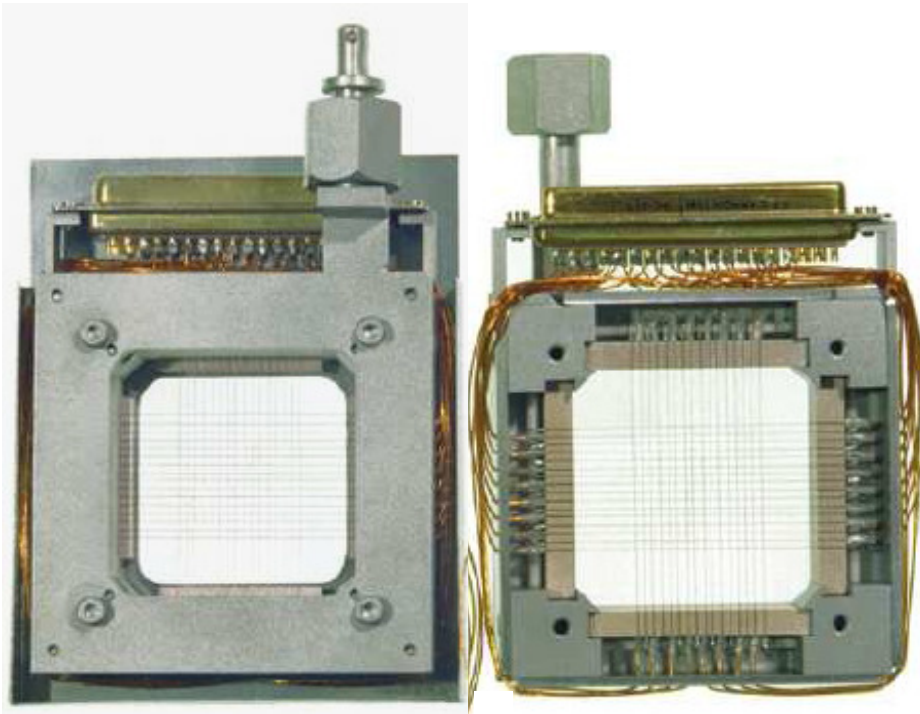
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Secondary Electron Emission Grids = SEM-Grid



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

Example: 15 wire spaced by 1.5 mm:



SEM-Grid feed-through on CF200:

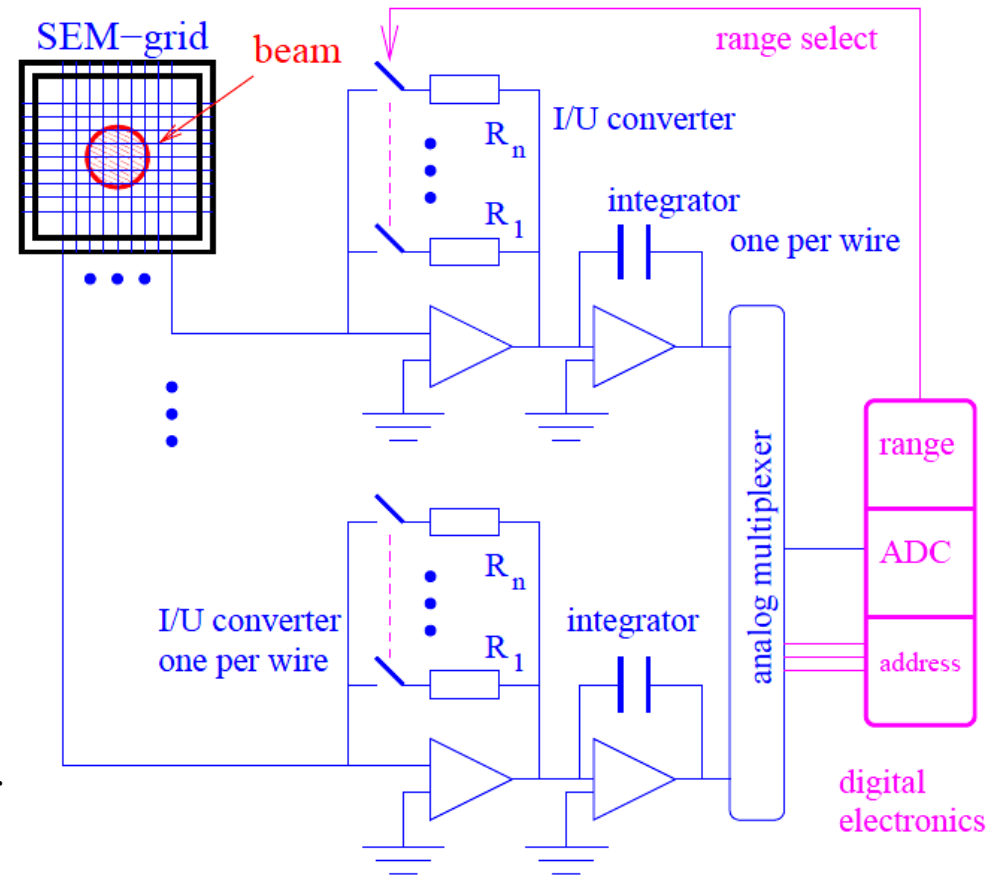
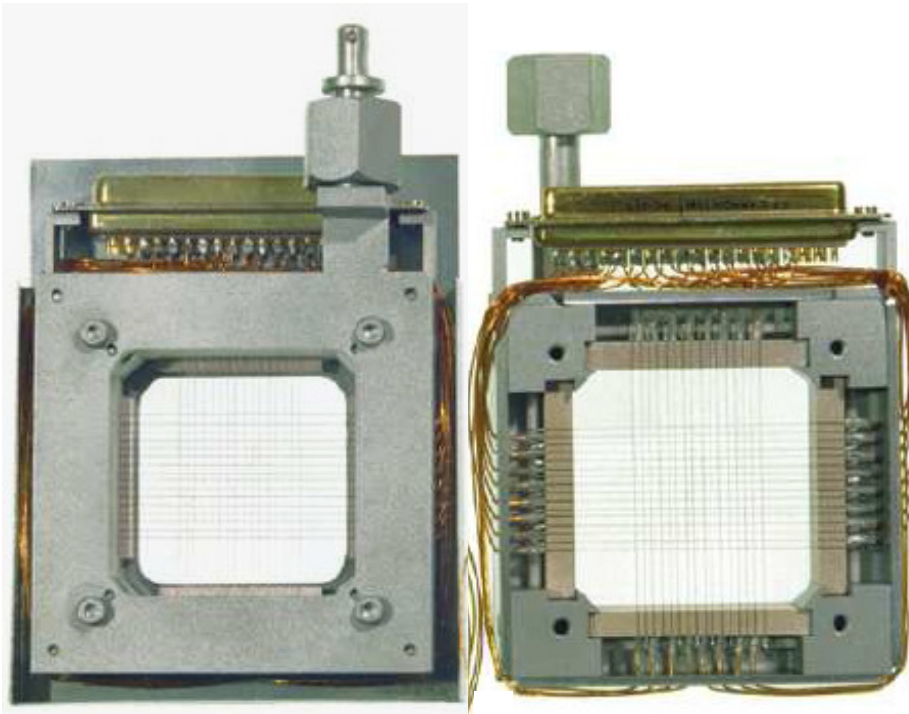


Secondary Electron Emission Grids = SEM-Grid



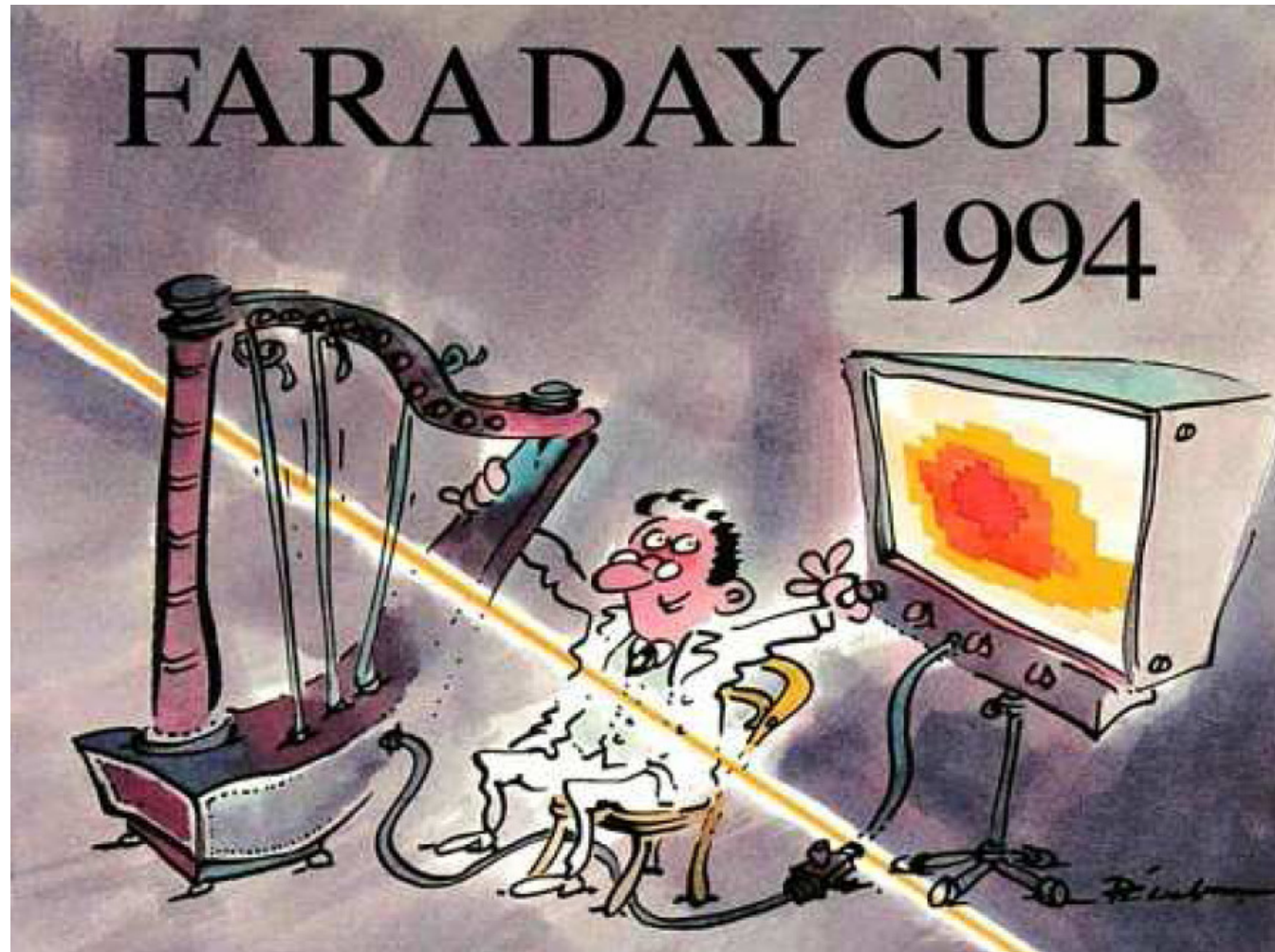
Beam surface interaction: e^- emission \rightarrow measurement of current.

Example: 15 wire spaced by 1.5 mm:



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

The Artist view of a SEM-Grid = Harp



The Faraday Cup is an award granted 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 ₂ O 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: $\simeq 1\text{mm}/0.1\text{mm} = 10 \rightarrow$ only 10 % loss.

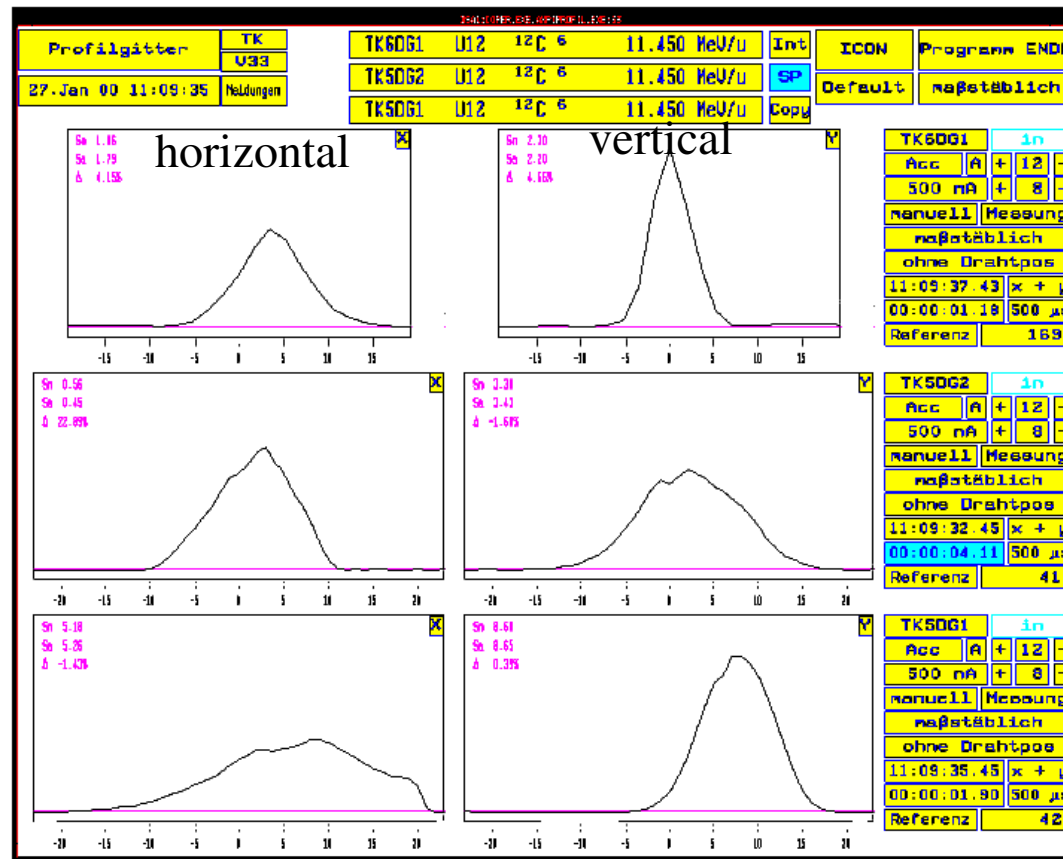
High energy $E_{kin} > 1\text{ GeV}/u$: thin ribbons of larger width are used due to negligible energy loss.

Example of Profile Measurement with SEM-Grids



Even for low energies, several SEM-Grid can be used due to the $\approx 80\%$ transmission
 \Rightarrow 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:

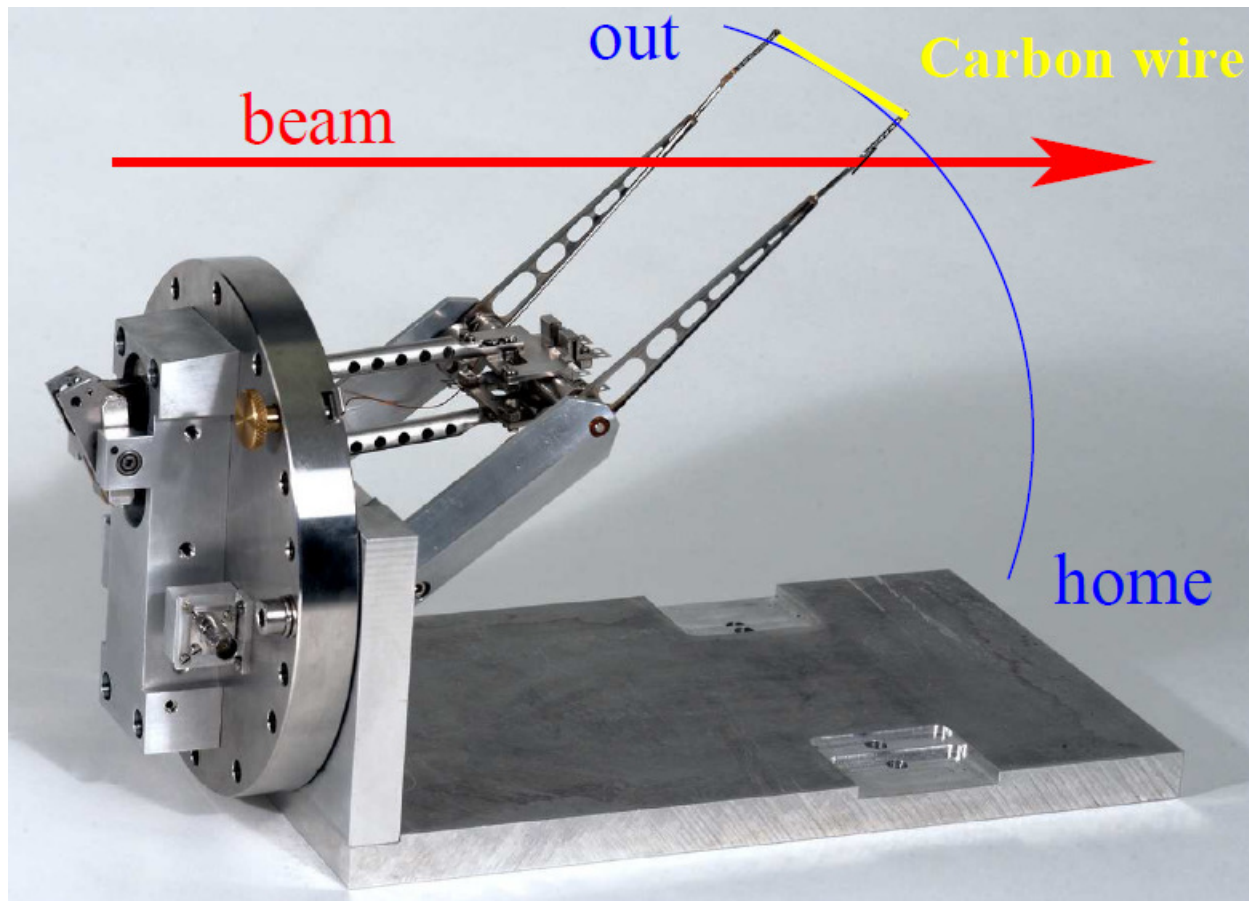
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Wire Scanner



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

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



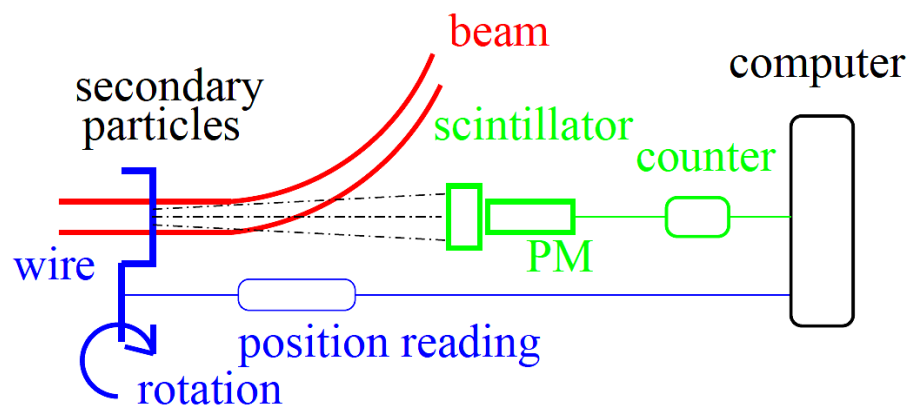
Usage of Wire Scanners



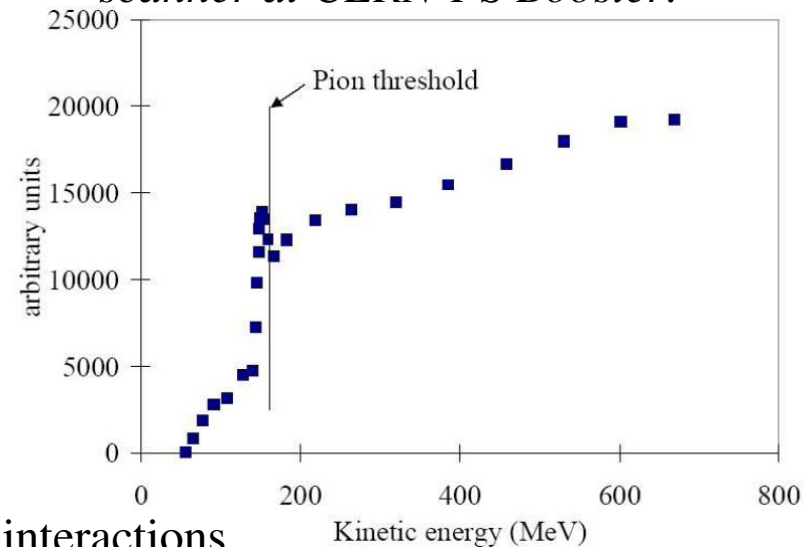
Material: carbon or SiC → low Z-material for low energy loss and high temperature.

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



Purpose: The Faraday Cup Award, donated by Bergov Instrumentation of Saint Genis, France, is intended to recognize and encourage innovative achievements in the field of accelerator beam instrumentation.

Award: The award consists of a \$500 prize and a certificate to be presented at the next US Beam Instrumentation Workshop which will be held at Fermi National Laboratory on May 1- 4, 2006. Winners participating in the BIW will share a \$1,000 travel allowance. The selection of recipients is the responsibility of the BIW Organizing Committee.

Criteria: The Faraday Cup Award shall be presented for outstanding contribution to the development of an innovative beam diagnostics instrument of proven workability. The prize is only awarded for demonstrated device performance and published contribution.

Criteria Interpretation: Beam Diagnostic Instrument: A device to measure the properties of charged elementary particle, atomic or simple molecular beams during or after acceleration, or the properties of neutral particle beams produced in an intermediate state of charged particle acceleration. The device may operate by detecting secondary beams of charged, neutral, massive or mass less particles. But its purpose should be to diagnose the primary charged particle beam. The mass of primary beam particles shall be no greater than the order of 100 atomic mass units.

Delivered performance: The performance of the device should have been evaluated using a charged particle beam, rather than in a "bench top" demonstration. Publication: A description of the device, its operating principle, and its performance should have been published in a journal or in the proceedings of a conference or workshop that is in the public domain. Laboratory design notes, internal technical notes, etc. do not qualify but may be submitted to support other publications. Full and open disclosure is necessary to the extent that a potential user could design a similar device. More than one article may be submitted (together) to satisfy this requirement; for example, an article describing the principle plus another article describing the performance.

Eligibility: Nominations are open to candidates of any nationality for work done at any geographical location. There are no restrictions for candidates; however, in the event of deciding between works of similar quality, preference will be given to candidates in an early stage of their beam instrumentation career. The award may be shared between persons contributing to the same accomplishment. Once accepted by the Award Committee a nomination shall remain eligible for three successive competitions unless withdrawn by a candidate.

Disclosure: The Award Committee may release the names of entrants and a list of publications related to an entry if requested by a third party. Unpublished supporting material will not be disclosed nor will the names of persons supporting a nomination. Discussion regarding individual entries, scoring, etc. is regarded as confidential and will not be disclosed.

Nominations: The nomination package shall include the name of the candidate, relevant publications, a statement outlining his/her personal contribution and that of others, letters from two professional accelerator physicists, engineers or laboratory administrative personnel who are familiar with the device and its development. Two master copies of this package, suitable for copying, must be submitted not later than Oct. 14, 2005 to:

Faraday Cup Proposals - BIW06 Attn: Lisa Lopez
Fermilab MS 308, P. O. Box 500 Batavia, IL 60510, U.S.A.

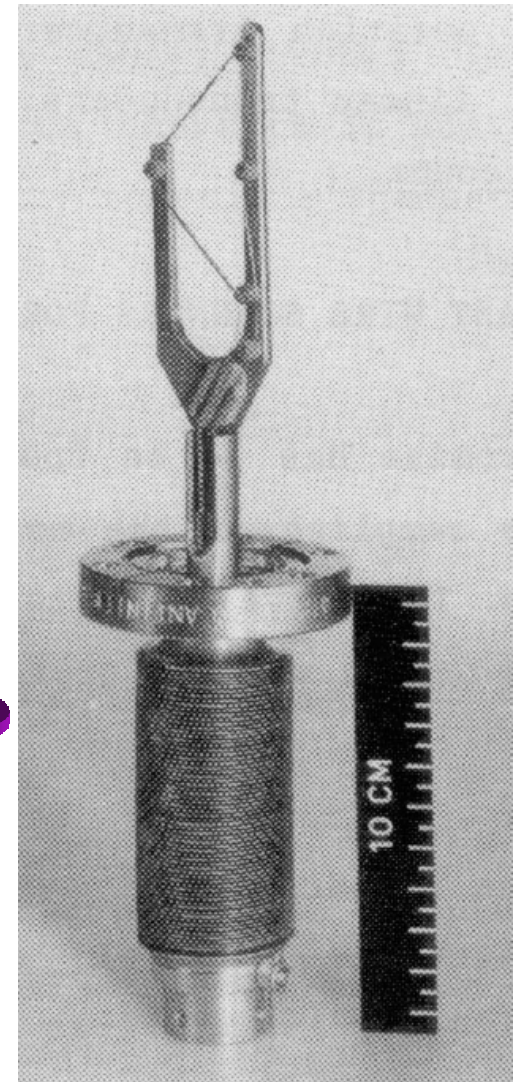
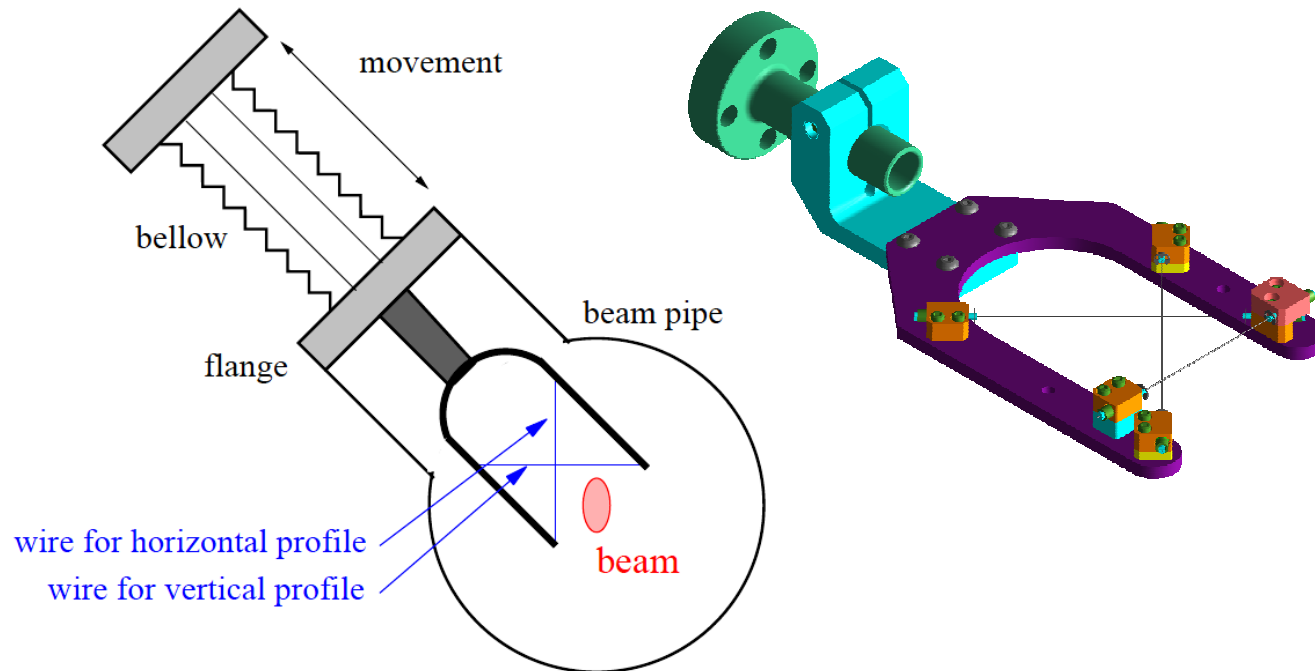


Slow, linear Wire Scanner



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.



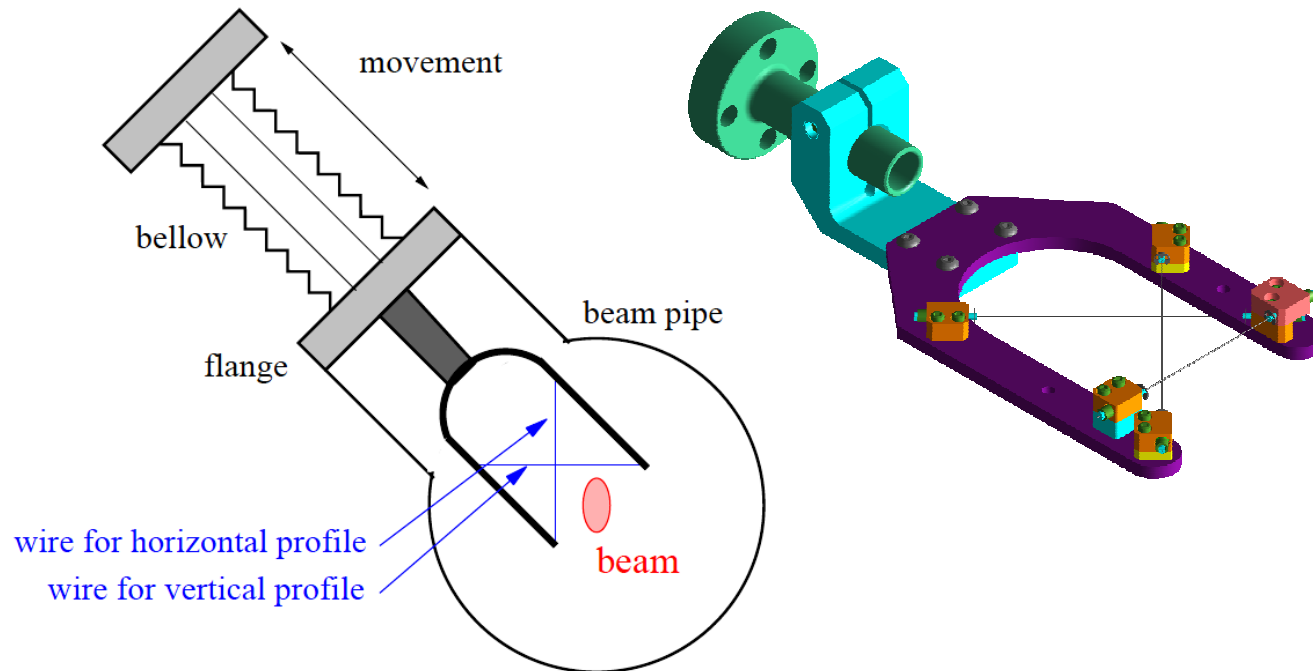
GSI

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GSI

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:

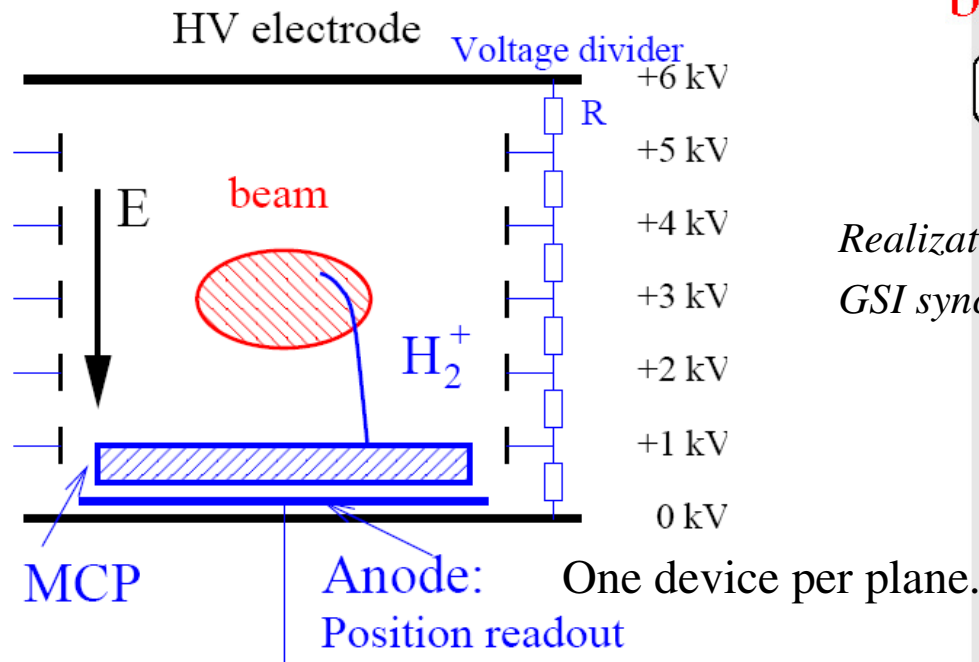
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- **Ionization Profile Monitor and Beam Induced Fluorescence Monitor:**
secondary particle detection from interaction beam-residual gas
- **Optical Transition Radiation**
- **Synchrotron Light Monitors**
- **Summary**

Ionization Profile Monitor



Non-destructive device for proton synchrotron:

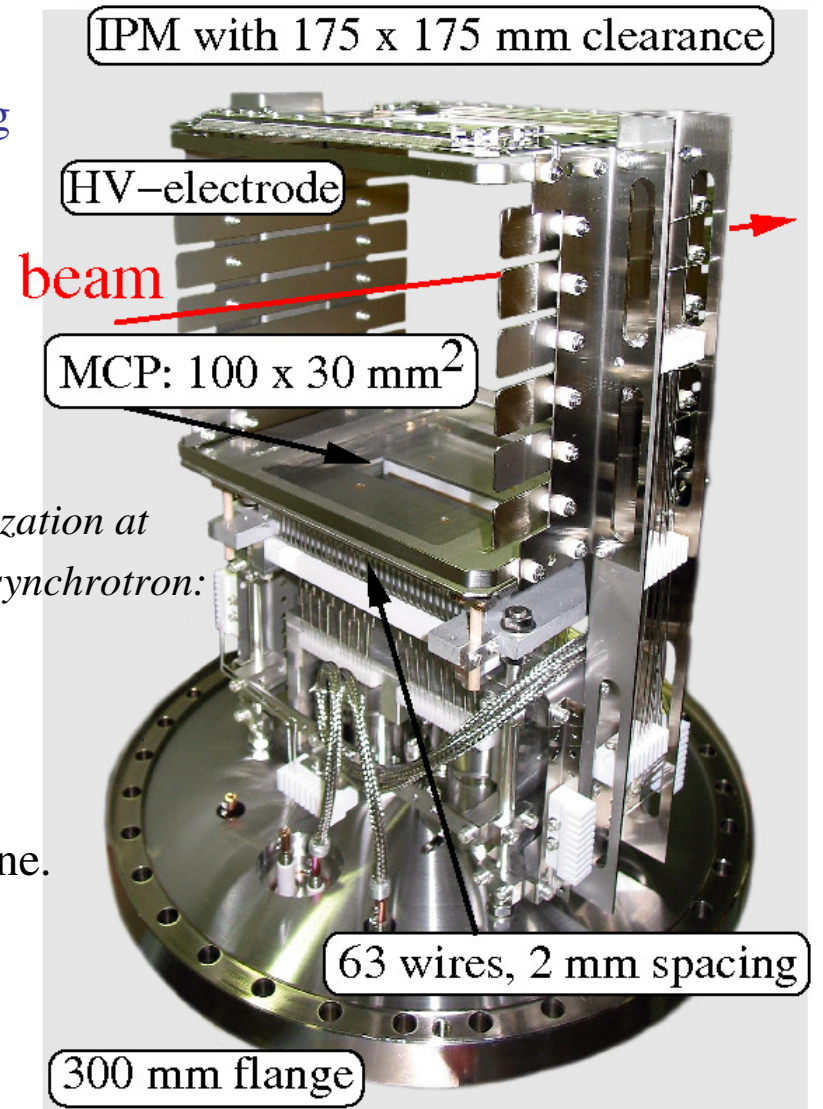
- beam ionizes the residual gas by electronic stopping
- gas ions or e^- accelerated by E -field ≈ 1 kV/cm
- spatial resolved single particle detection



Typical vacuum pressure:

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

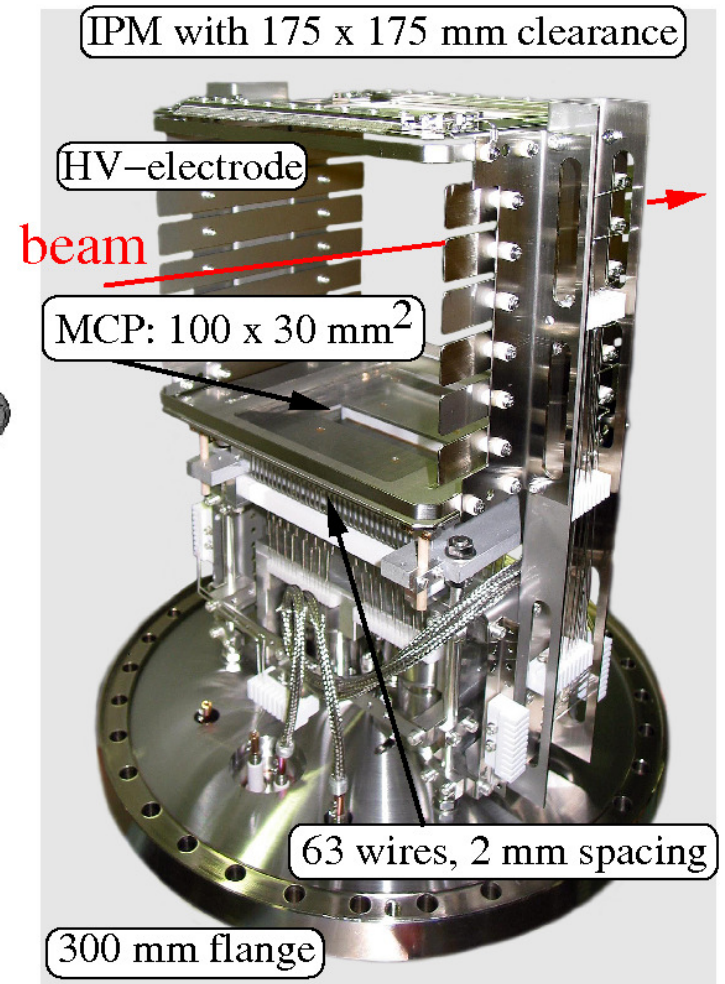
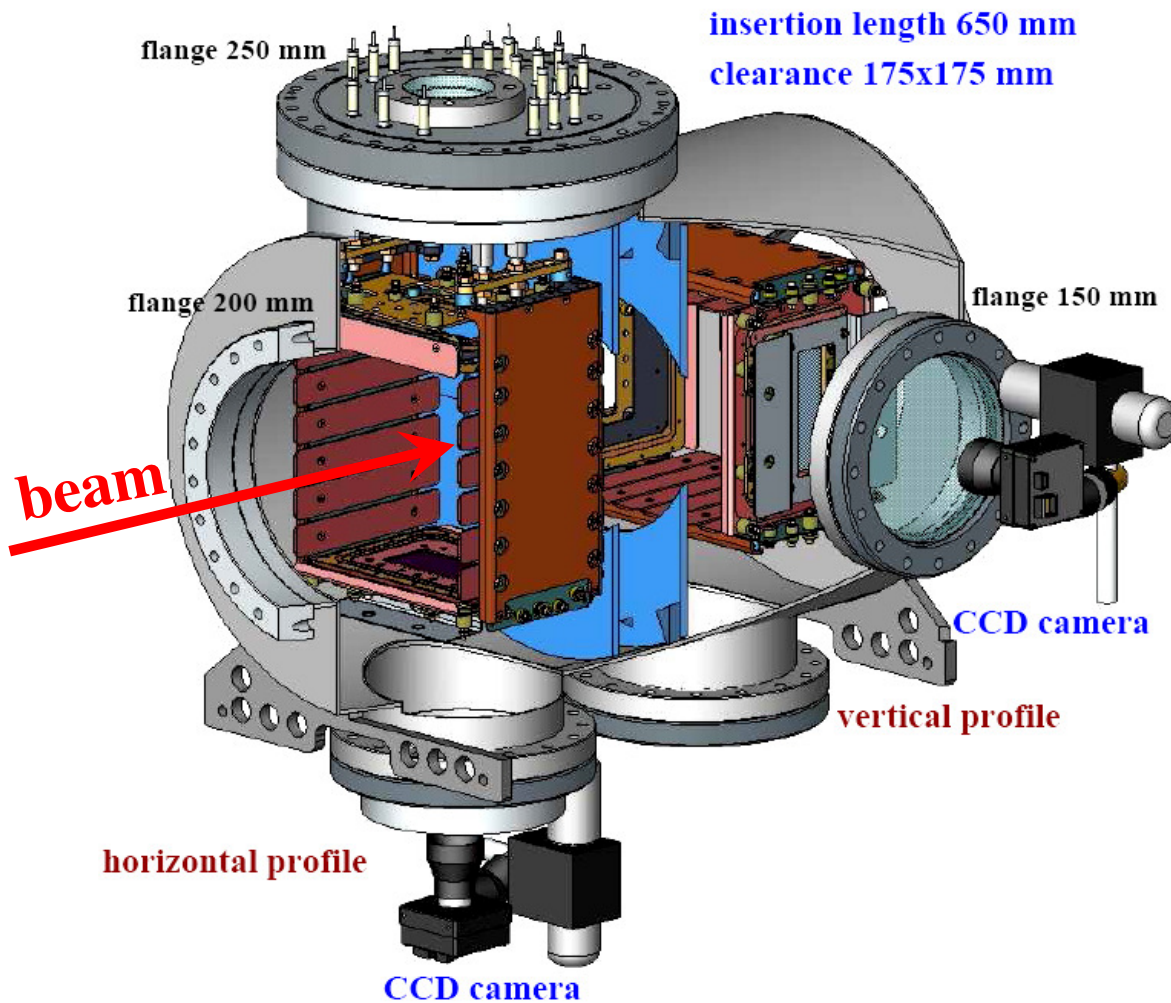
Synchrotron: $10^{-11} - 10^{-9}$ mbar (H_2).



Ionization Profile Monitor Realization



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



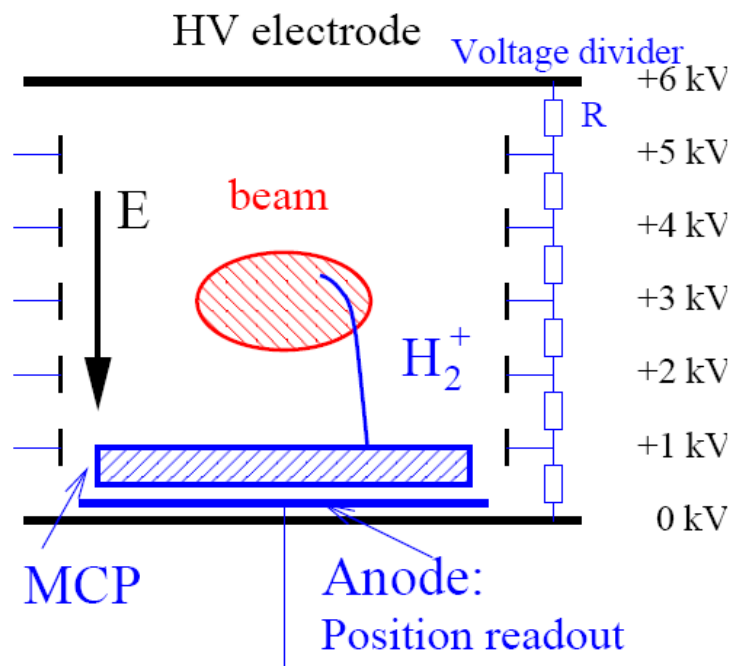
Realization of Ionization Profile Monitor at a LINAC



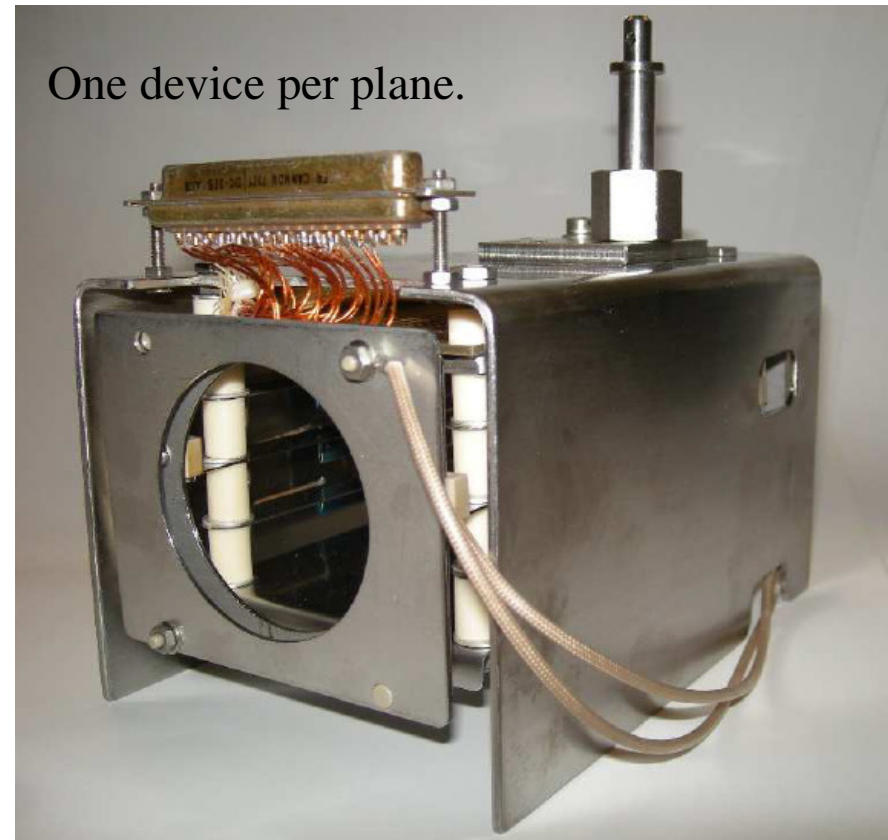
The realization of an IPM for the use at the GSI LINAC:

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

Readout by strips fed to an I/U converter.



One device per plane.



Multi Channel Plate MCP



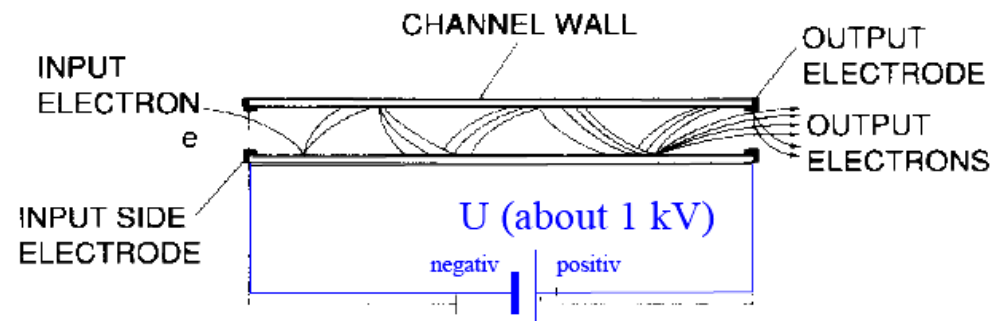
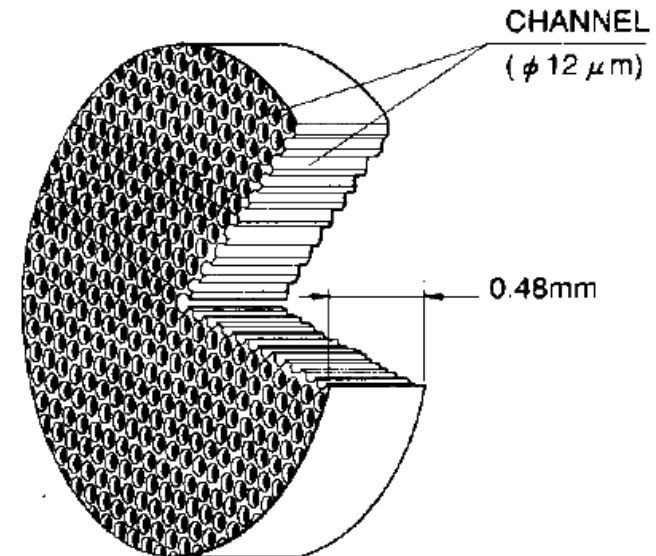
MCP are used as particle detectors with secondary electron amplification.

A MCP is:

- 1 mm glass plate with $\approx 10 \mu\text{m}$ holes
- thin Cr-Ni layer on surface
- voltage $\approx 1 \text{ kV/plate}$ across
 - e^- amplification of $\approx 10^3$ per plate.
 - resolution $\approx 0.1 \text{ mm}$ (2 MCPs)

Anode technologies:

- SEM-grid, $\approx 0.5 \text{ mm}$ 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.

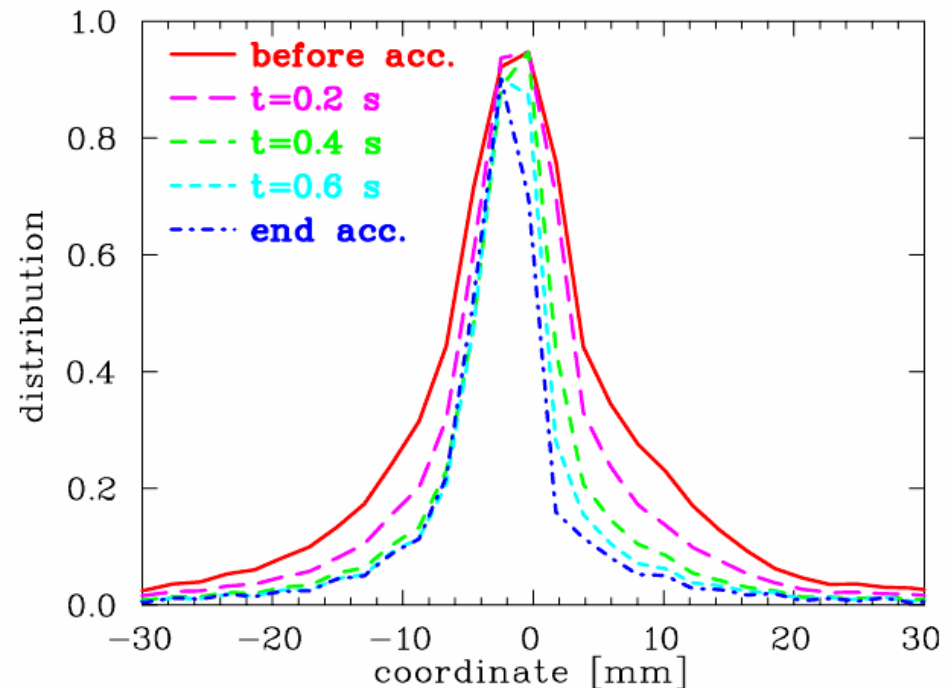
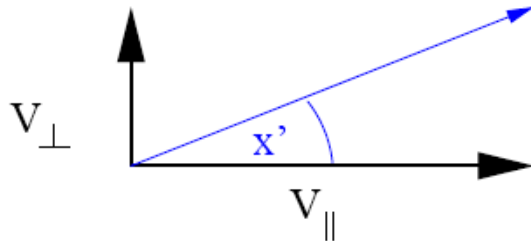
During acceleration:

for increasing v_{\parallel} and constant v_{\perp} :

$\Rightarrow x'$ shrinks

\Rightarrow emittance ε shrinks

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



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

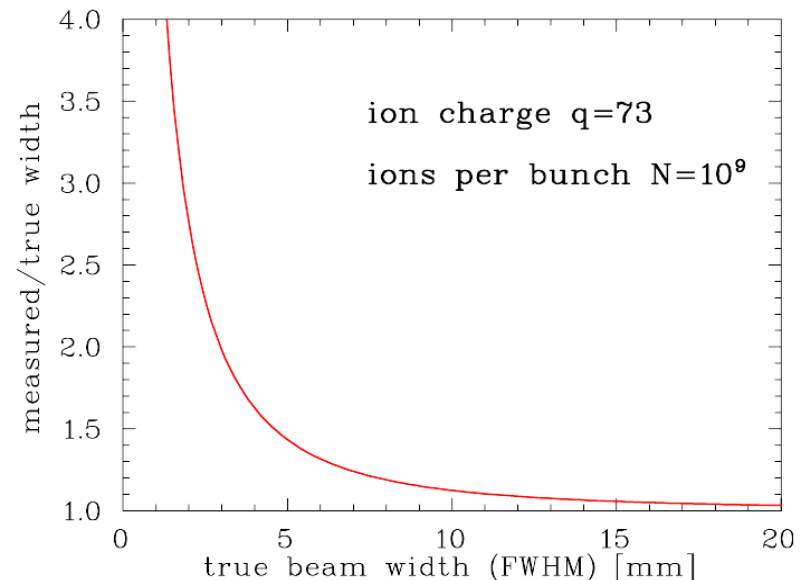
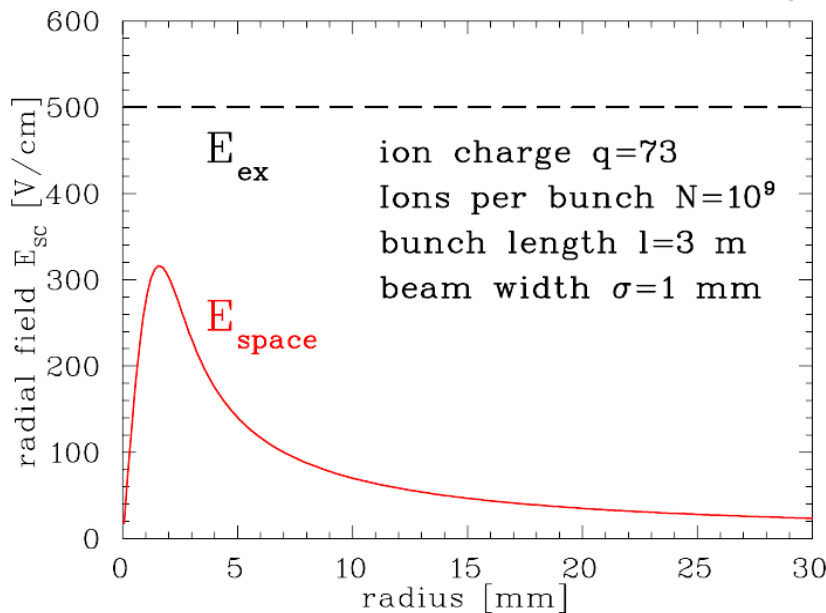
Broadening due to the Beam's Space Charge: Ion Detection



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

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



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

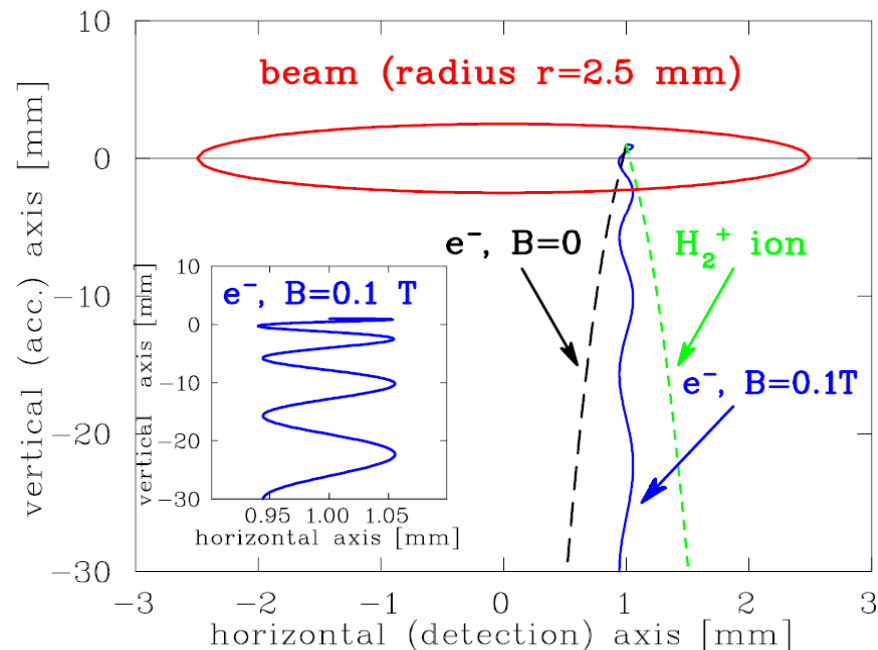
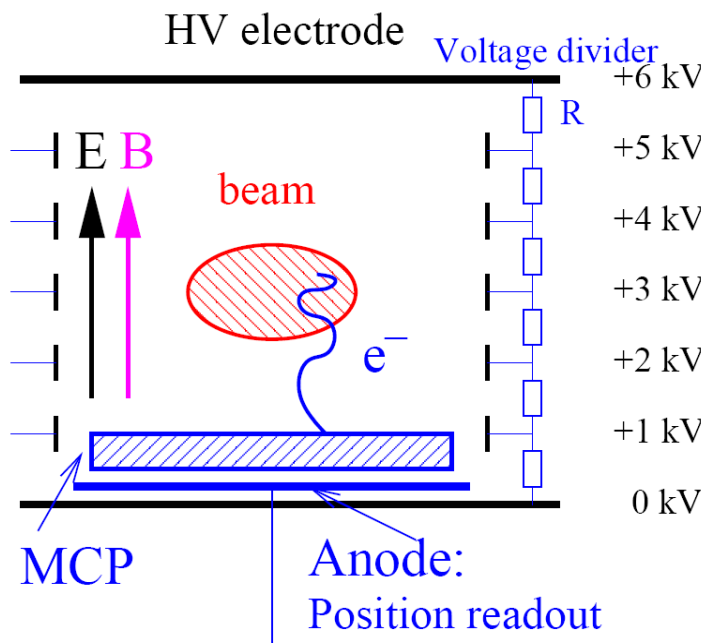
Electron Detection and Guidance by Magnetic Field



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: $\approx 1 \text{ ns} \rightarrow 2$ or 3 cycles.

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

IPM: Magnet Design



Magnetic field for electron guidance:

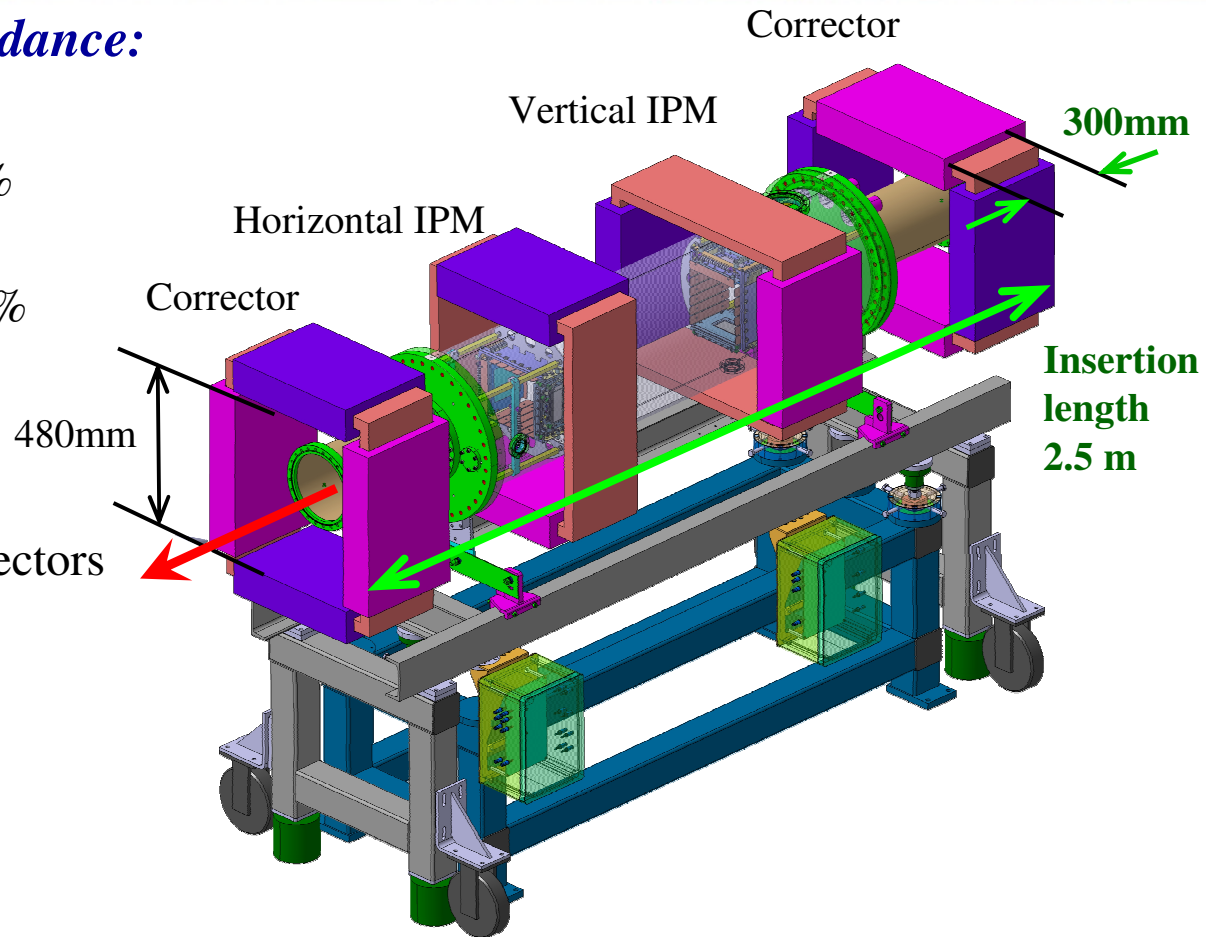
Maximum image distortion:

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:

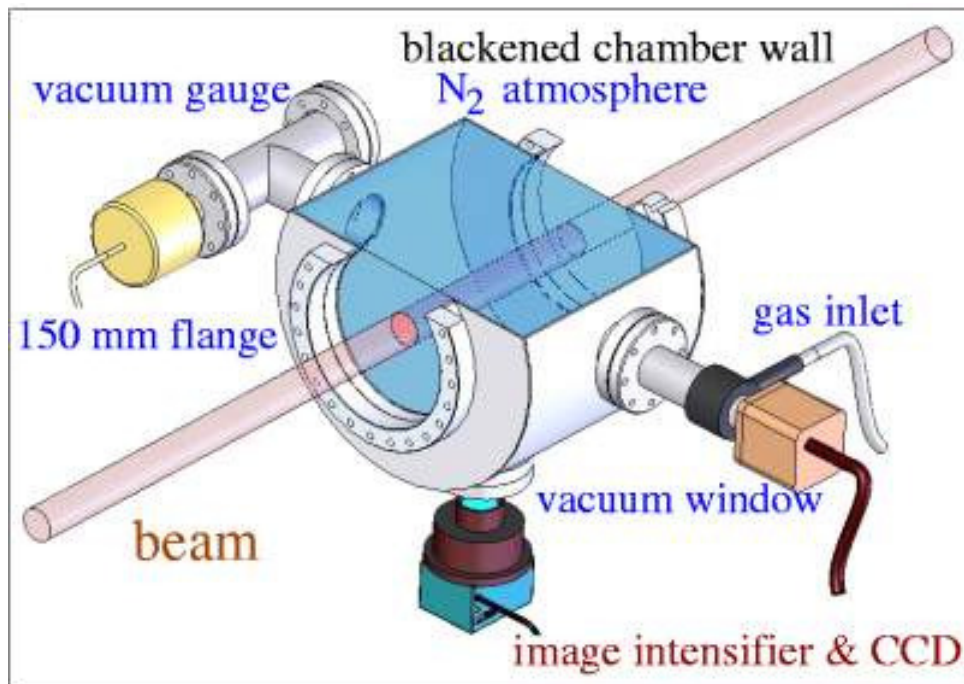
⇒ **B**eam **I**nduced **F**luorescence BIF



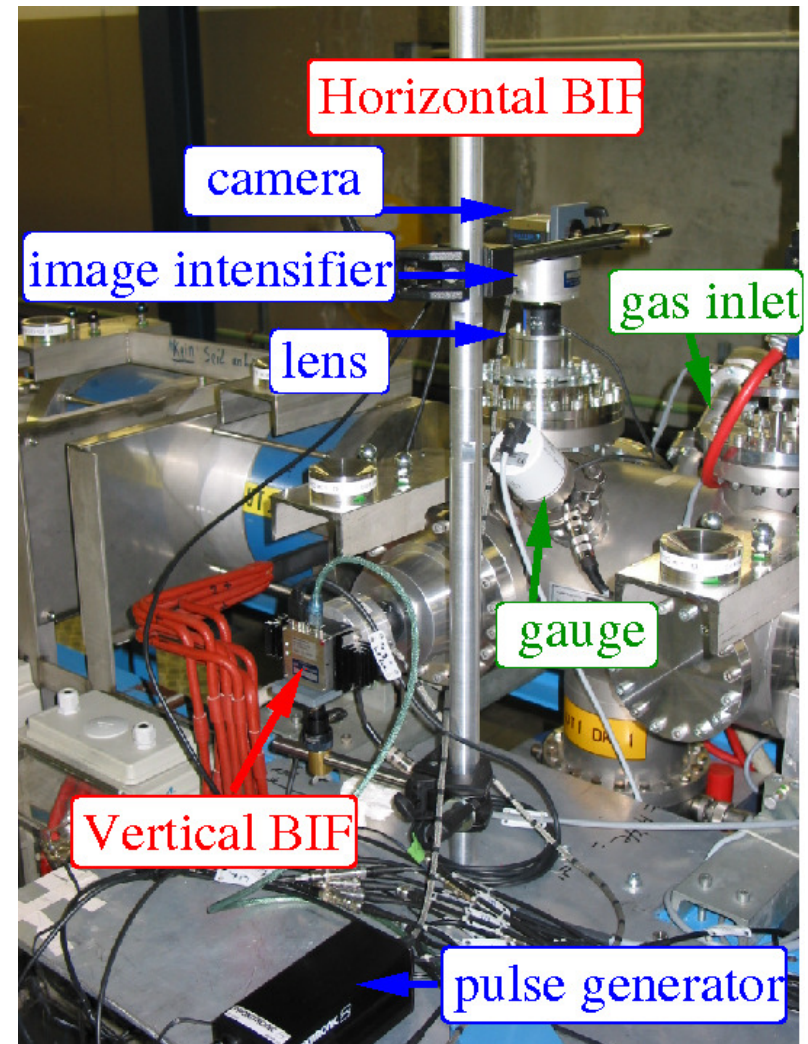
With single photon detection scheme

$390 \text{ nm} < \lambda < 470 \text{ nm}$

⇒ non-destructive, compact installation.



Installation of hor&vert. BIF Monitor:



Beam Induced Fluorescence Monitor BIF: Image Intensifier

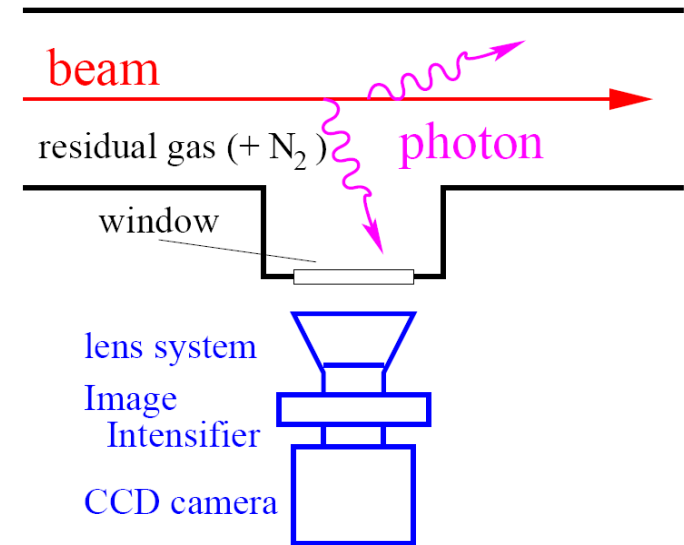
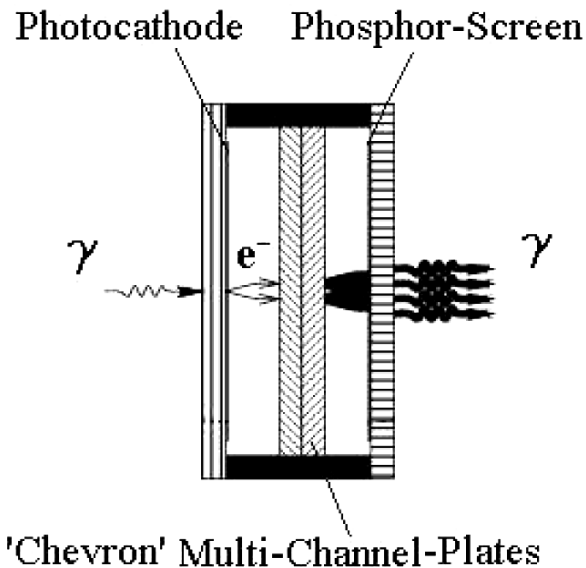


Image intensifier:

- 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)

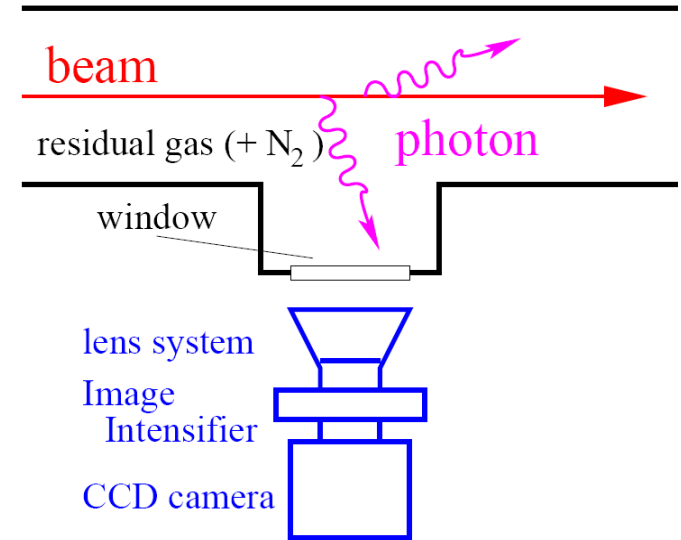
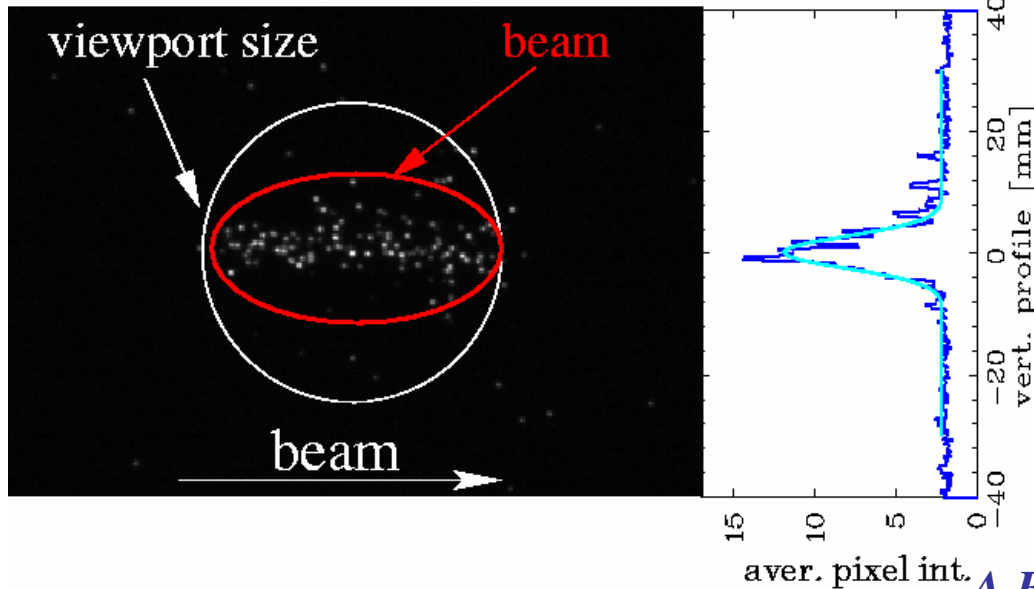
A BIF monitor consists of only:

- 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.

Beam Induced Fluorescence Monitor BIF: Image Intensifier



‘Single photon counting’:



Example at GSI-LINAC:

4.7 MeV/u Ar¹⁰⁺ beam

I=2.5 mA equals to 10¹¹ particle

One single macro pulse of 200 μs

Vacuum pressure: p=10⁻⁵ mbar (N₂)

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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 OTR

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:

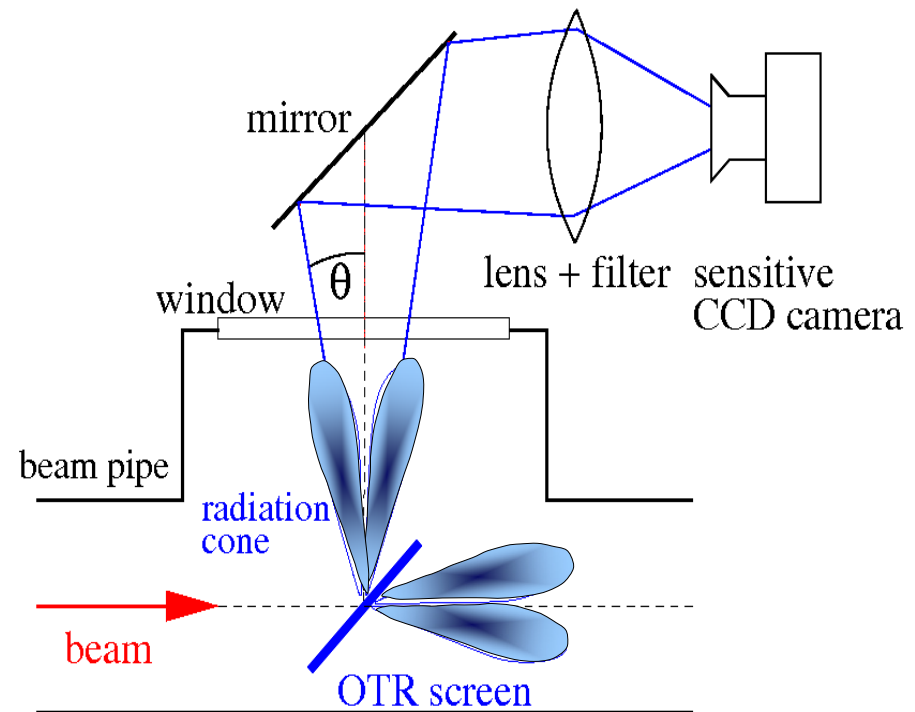
$$\frac{d^2W}{d\Omega d\omega} = \frac{\mu_0 c e^2}{4\pi^3} \cdot \frac{\theta^2}{(\gamma^{-2} + \theta^2)^2}$$

W : energy emitted in solid angle Ω

θ : angle of emission

γ : Lorentz factor

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



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

Optical Transition Radiation: Angular Photon Distribution

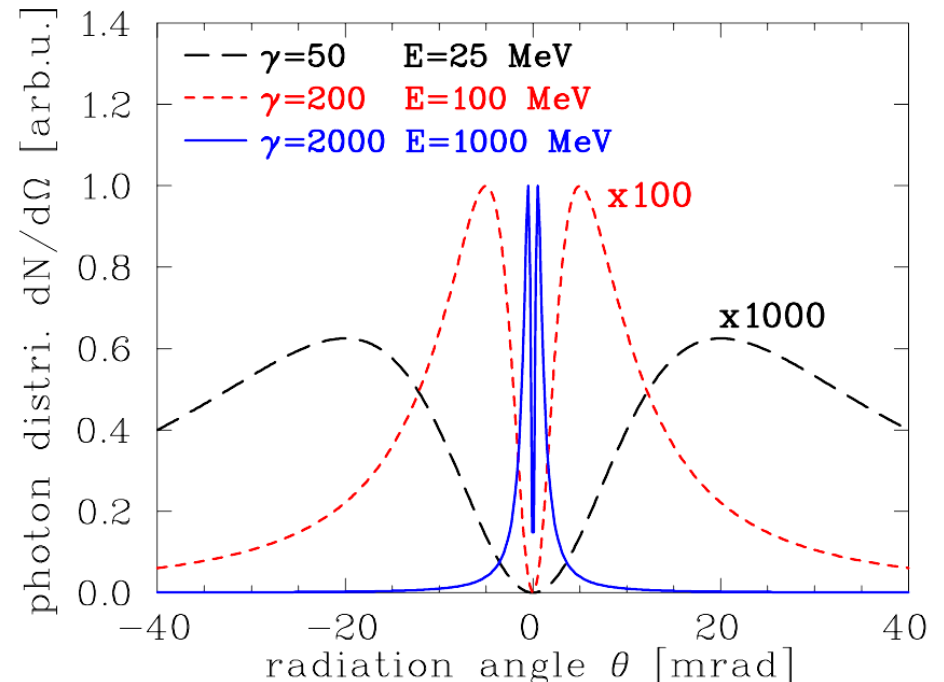


Photon distribution within a solid angle $d\Omega$ and Wavelength interval λ_{begin} to λ_{end}

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

Wavelength interval λ_{begin} to λ_{end}

- Detection: Optical $400 \text{ nm} < \lambda < 800 \text{ nm}$
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 $E_{kin} > 10 \text{ GeV}$ ($\gamma > 10$)



→ *Profile* by focusing to screen

→ *Beam angular distribution* by focusing on infinity

due to emission dependence on beam angular distribution.

OTR-Monitor: Technical Realization and Results

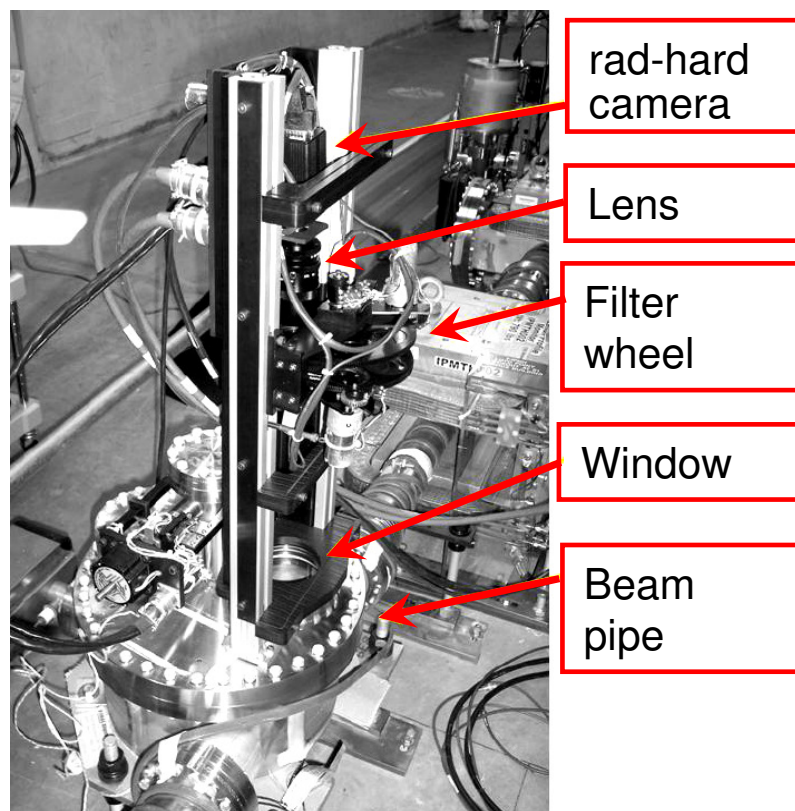


Example of realization at TERATRON:

➤ Insertion of foil

e.g. 5 μm Kapton coated with 0.1 μm Al

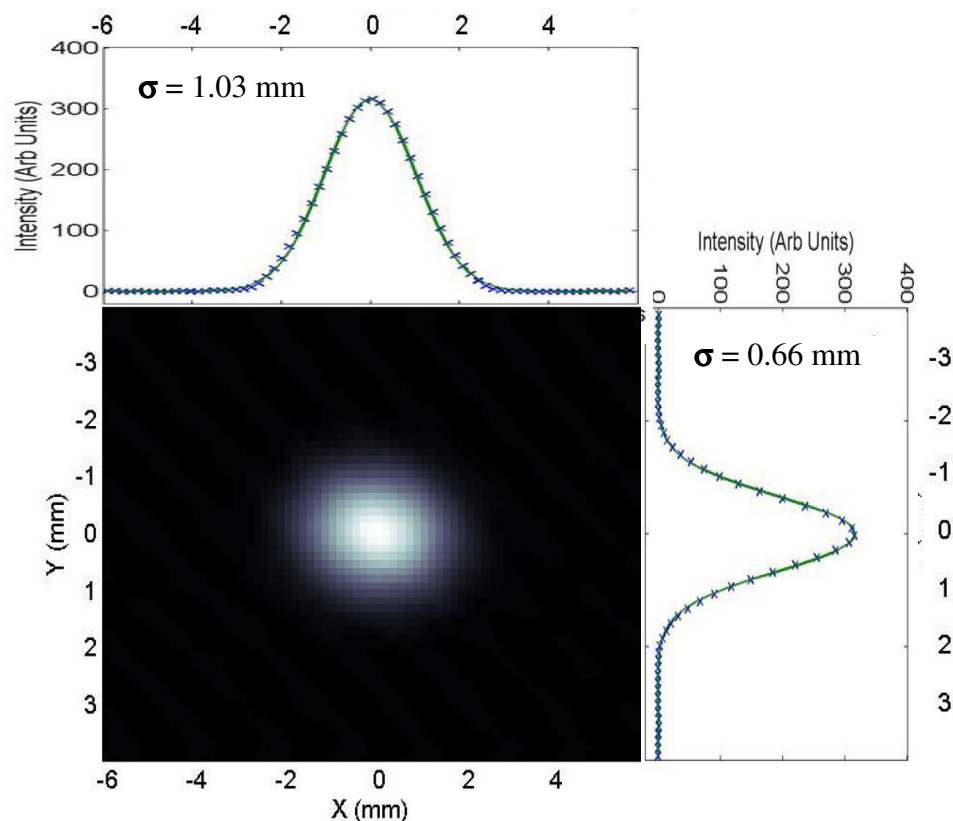
Advantage: thin foil \Rightarrow low heating & straggling
2-dim image visible



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



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photon detection of emitted synchrotron light
- **Summary**

Synchrotron Light Monitor



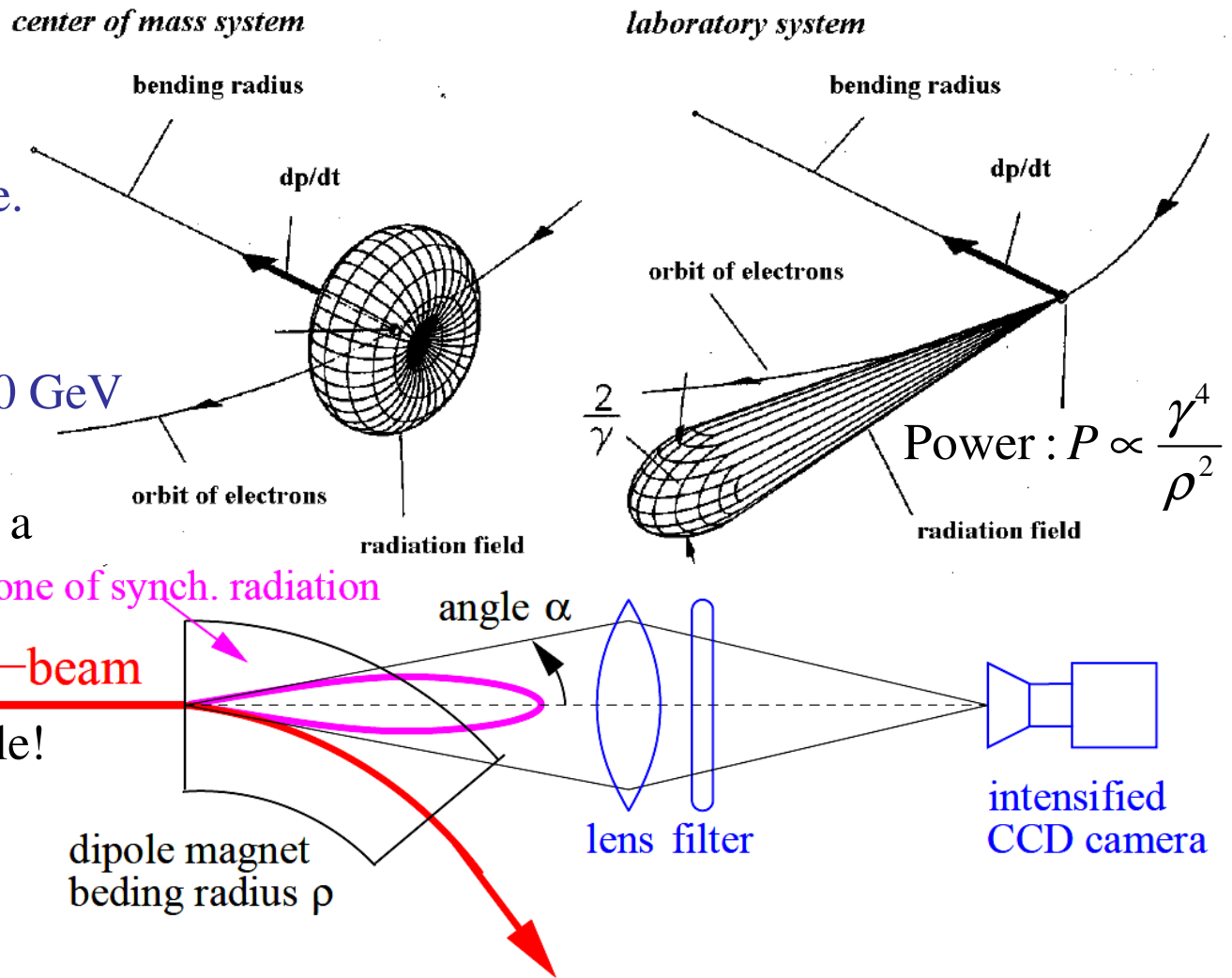
An electron bent (i.e. accelerated) by a dipole magnet emit synchrotron light.

This light is emitted into a cone of opening $2/\gamma$ in lab-frame.
 \Rightarrow Well suited for rel. e^-

For protons:
 Only for energies $E > 100 \text{ GeV}$

The light is focused to a intensified CCD.

Advantage:
 Signal anyhow available!



Realization of a Synchrotron Light Monitor

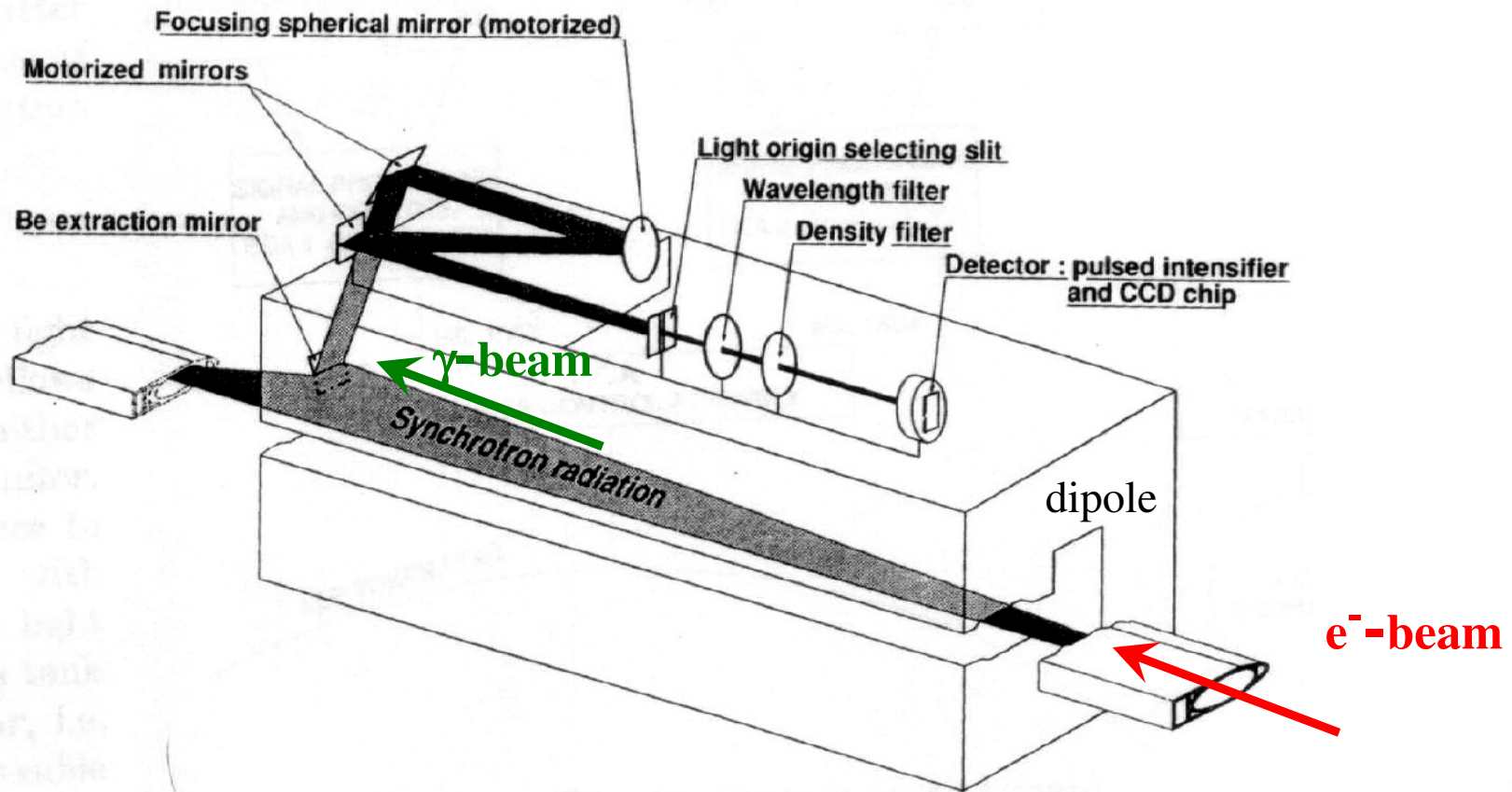


Extracting out of the beam's plane by a (cooled) mirror

→ Focus to a slit + wavelength filter for optical wavelength

→ Image intensified CCD camera

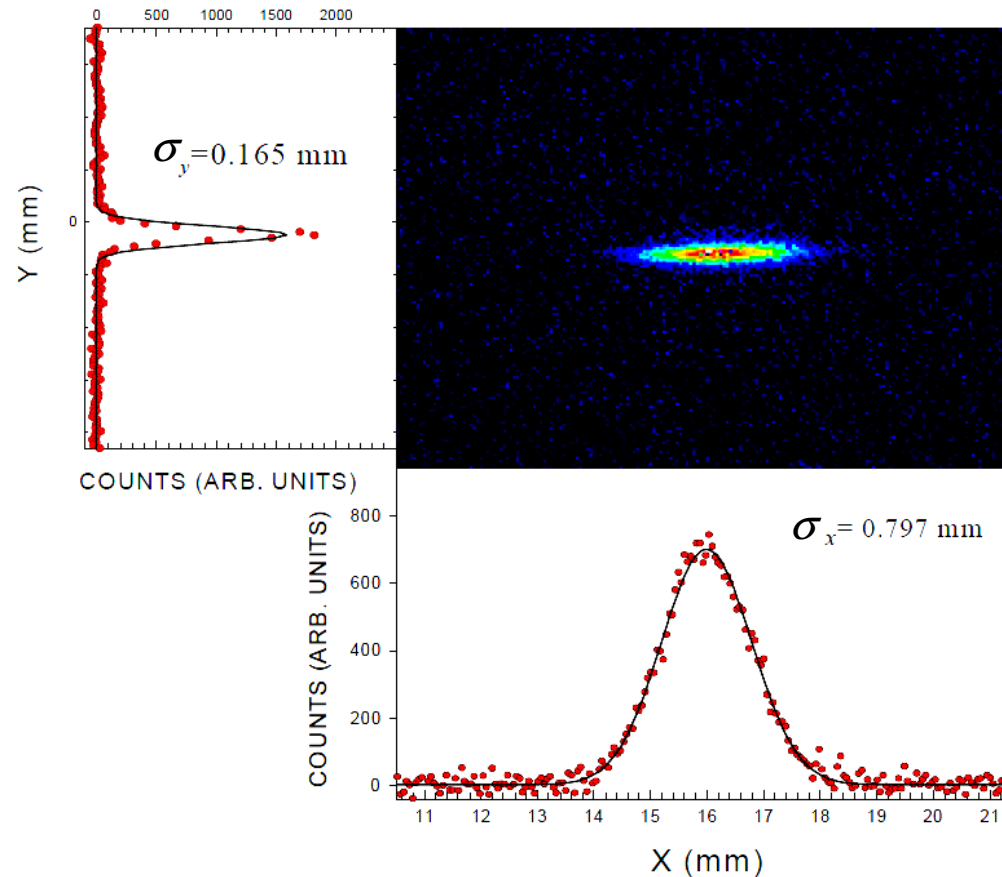
Example: CERN LEP-monitor with bending radius 3.1 km (blue or near UV)



Result from a Synchrotron Light Monitor



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



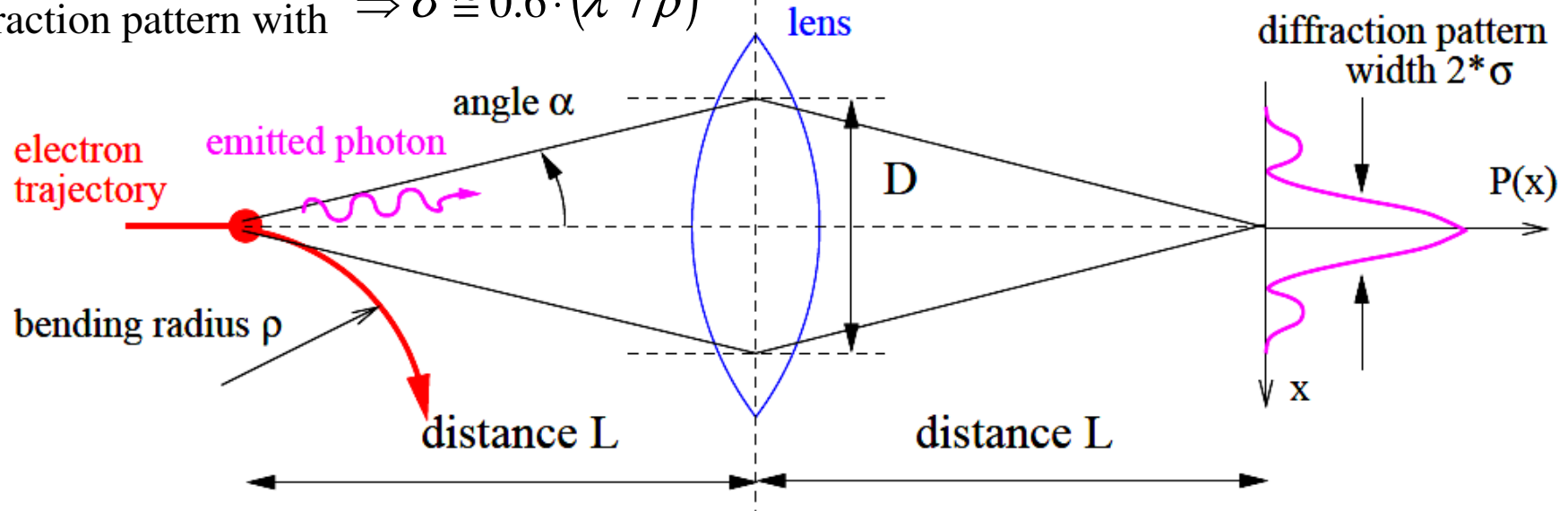
Use of optical wavelength and CCD: λ above critical λ_{crit} (spectrum fall-off).

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): $\sigma = \frac{\lambda}{2D/L}$

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

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



A good resolution for:

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

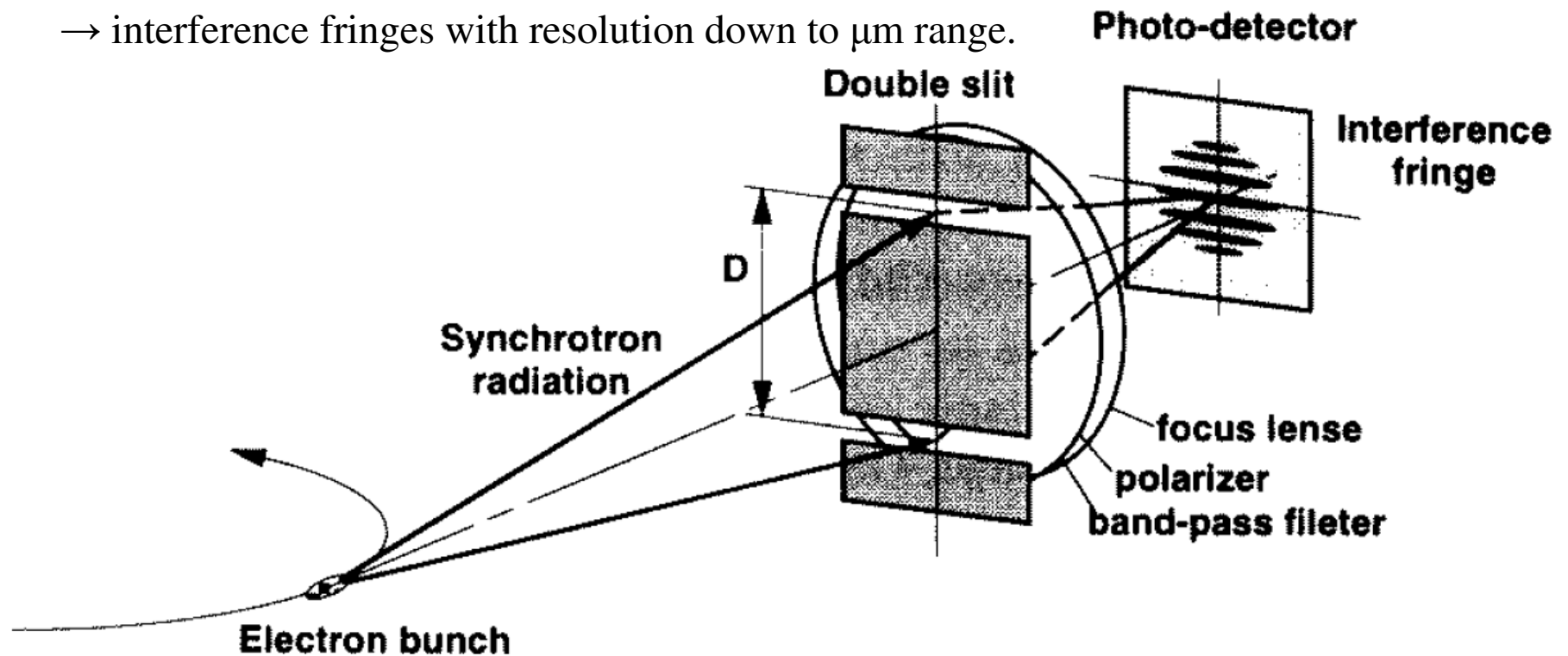
Synchrotron Light Monitor overcoming Diffraction Limit



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

Possible improvements:

- **Shorter wavelength:** Using x-rays and an aperture of \varnothing 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 electrodynamic 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.