Measurement of Beam Profile

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.

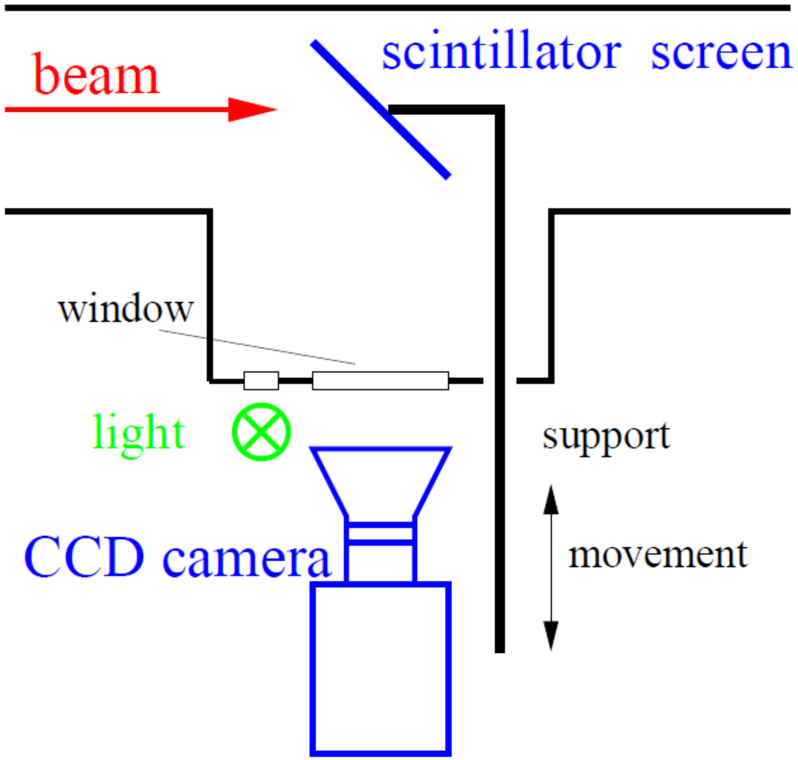
A great variety of devices are used:

- ***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)

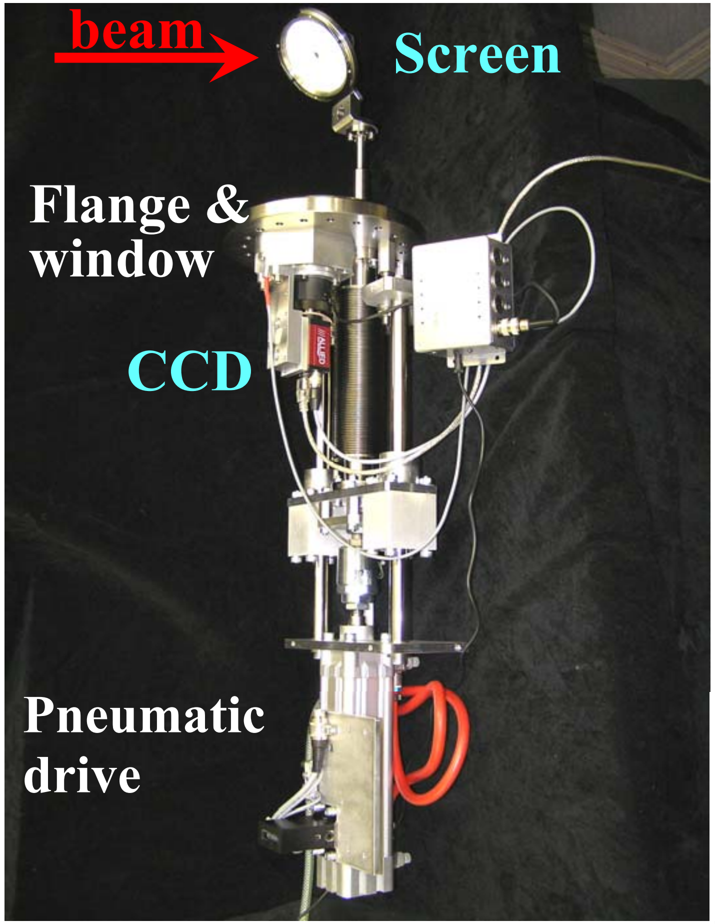
Scintillation Screen

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 of Screen based Beam Profile Measurement

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

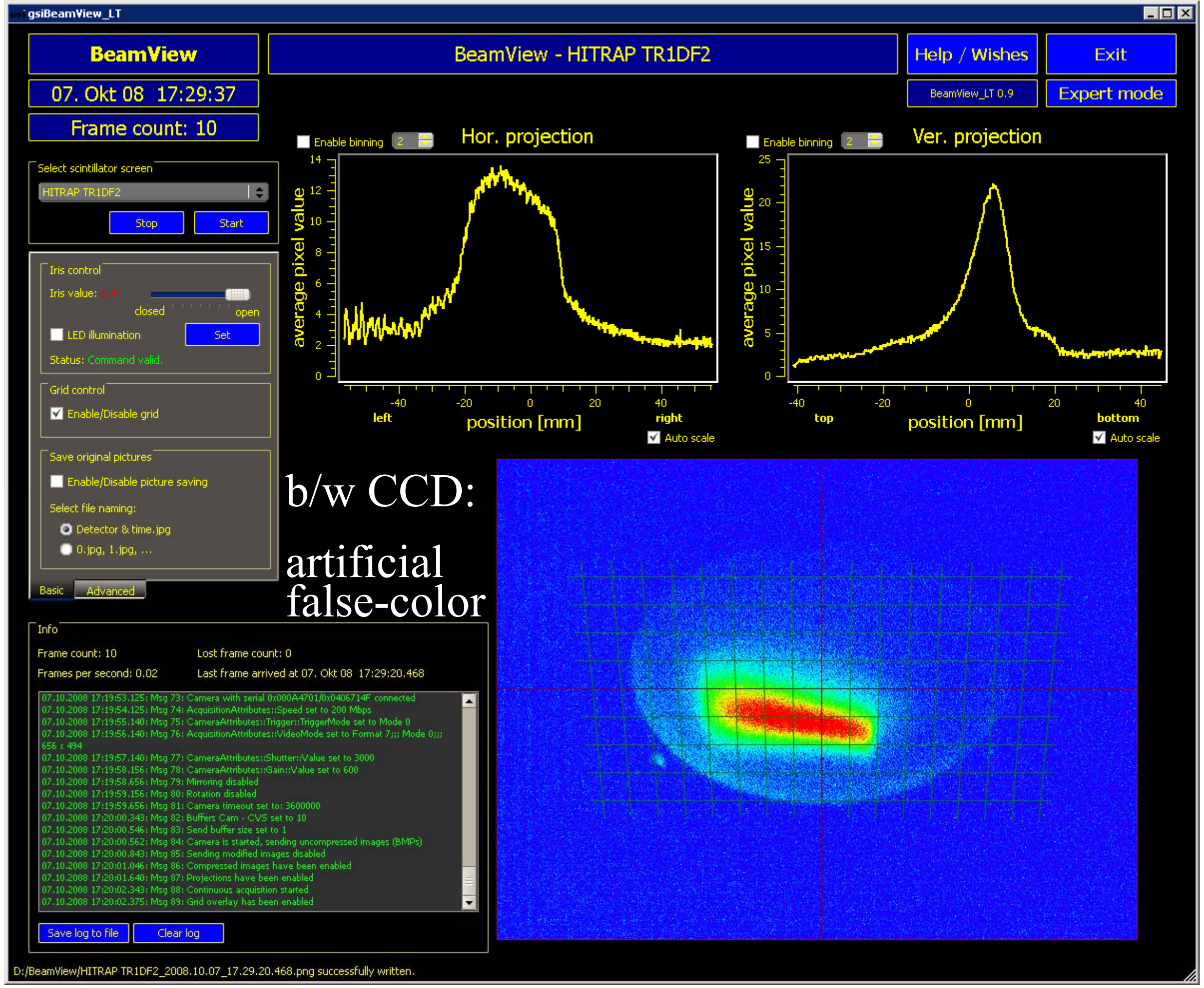
Advantage of screens:

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

Observation with a CCD camera

with digital output

or video & frame grabber.



07. Okt 08 17:29:37

Frame count: 10

Select scintillator screen: HITRAP TR1DF2

Iris control

Iris value: 1.4 (closed … open)

☐ LED illumination

Status: Command valid.

Grid control

☑ Enable/Disable grid

Save original pictures

☐ Enable/Disable picture saving

Select file naming:

● Detector & time.jpg

○ 0.jpg, 1.jpg, …

b/w CCD:

artificial
false-color

Info

Frame count: 10

Lost frame count: 0

Frames per second: 0.02

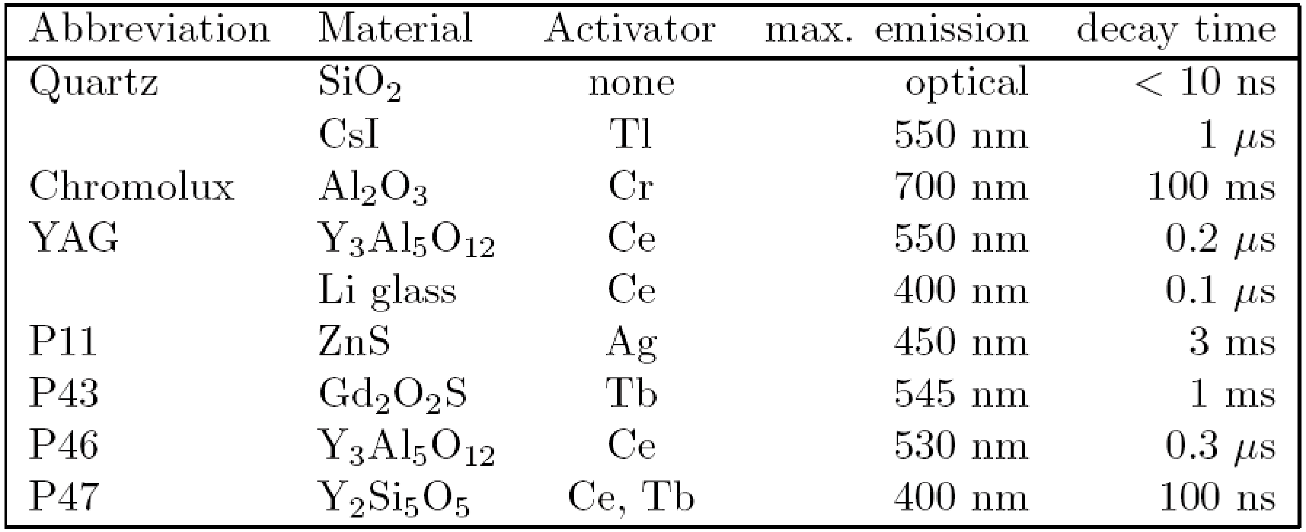
Last frame arrived at 07. Okt 08 17:29:20.468

```
07.10.2008 17:19:53.125: Msg 73: Camera with serial 0x000A4701/0x0406714F connected
07.10.2008 17:19:54.125: Msg 74: AcquisitionAttributes::Speed set to 200 Mbps
07.10.2008 17:19:55.140: Msg 75: CameraAttributes::Trigger::TriggerMode set to Mode 0
07.10.2008 17:19:56.140: Msg 76: AcquisitionAttributes::VideoMode set to Format 7;;; Mode 0;;;
656 x 494
07.10.2008 17:19:57.140: Msg 77: CameraAttributes::Shutter::Value set to 3000
07.10.2008 17:19:58.156: Msg 78: CameraAttributes::Gain::Value set to 600
07.10.2008 17:19:58.656: Msg 79: Mirroring disabled
07.10.2008 17:19:59.156: Msg 80: Rotation disabled
07.10.2008 17:19:59.656: Msg 81: Camera timeout set to: 3600000
07.10.2008 17:20:00.343: Msg 82: Buffers Cam - CVS set to 10
07.10.2008 17:20:00.546: Msg 83: Send buffer size set to 1
07.10.2008 17:20:00.562: Msg 84: Camera is started, sending uncompressed images (BMPs)
07.10.2008 17:20:00.843: Msg 85: Sending modified images disabled
07.10.2008 17:20:01.046: Msg 86: Compressed images have been enabled
07.10.2008 17:20:01.640: Msg 87: Projections have been enabled
07.10.2008 17:20:02.343: Msg 88: Continuous acquisition started
07.10.2008 17:20:02.375: Msg 89: Grid overlay has been enabled
```

D:/BeamView/HITRAP TR1DF2_2008.10.07_17.29.20.468.png successfully written.

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:

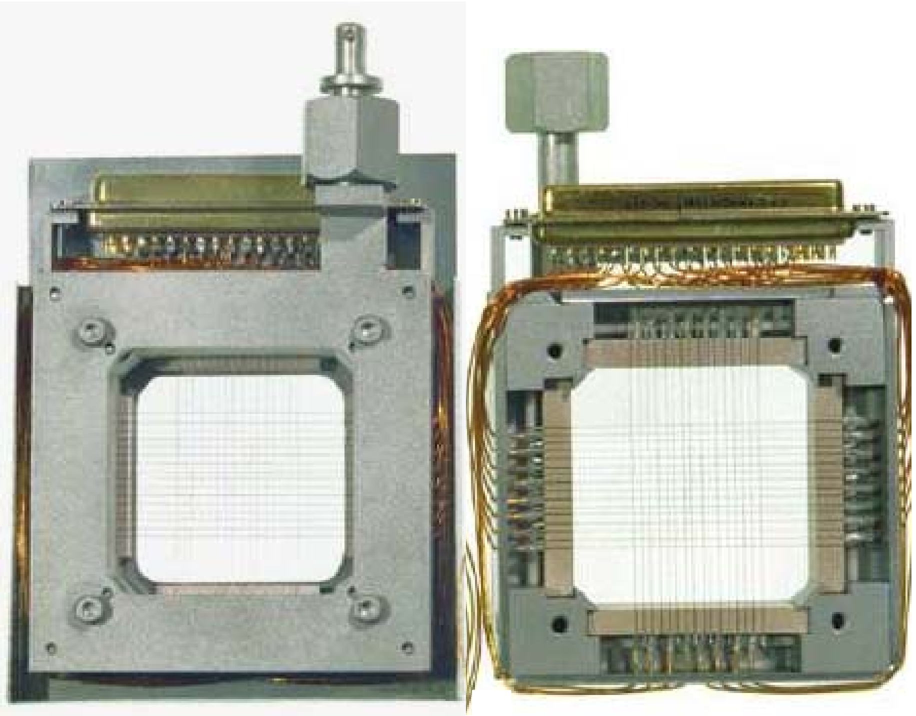
- Large light output at optical wavelength → standard CCD camera can be used
- Large dynamic range → no deformation due to saturation or self-absorption
- Short decay time → observation of time variations
- Radiation hardness → long lifetime
- Good mechanical properties → typical size up to Ø 10 cm

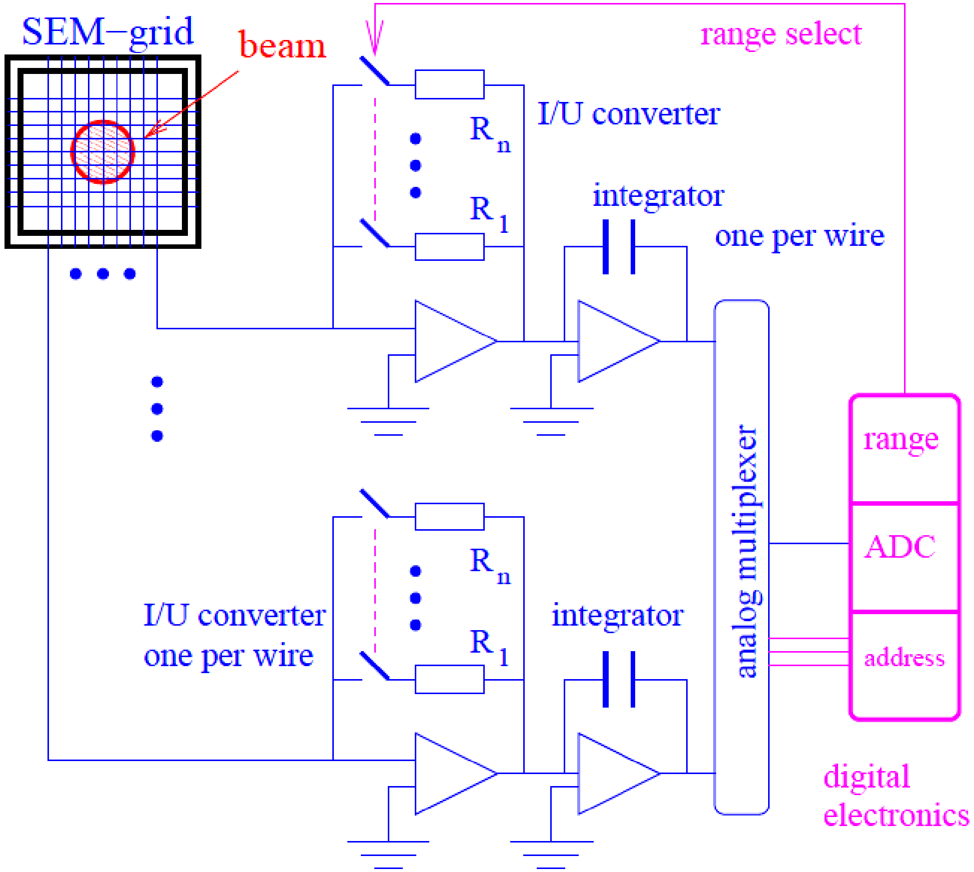
(Phosphor Pxx grains of Ø ~ 10 μm on glass or metal).

Secondary Electron Emission Grids = SEM-Grid

Beam surface interaction: e⁻ emission → measurement of current.

Example: 15 wire spaced by 1.5 mm:



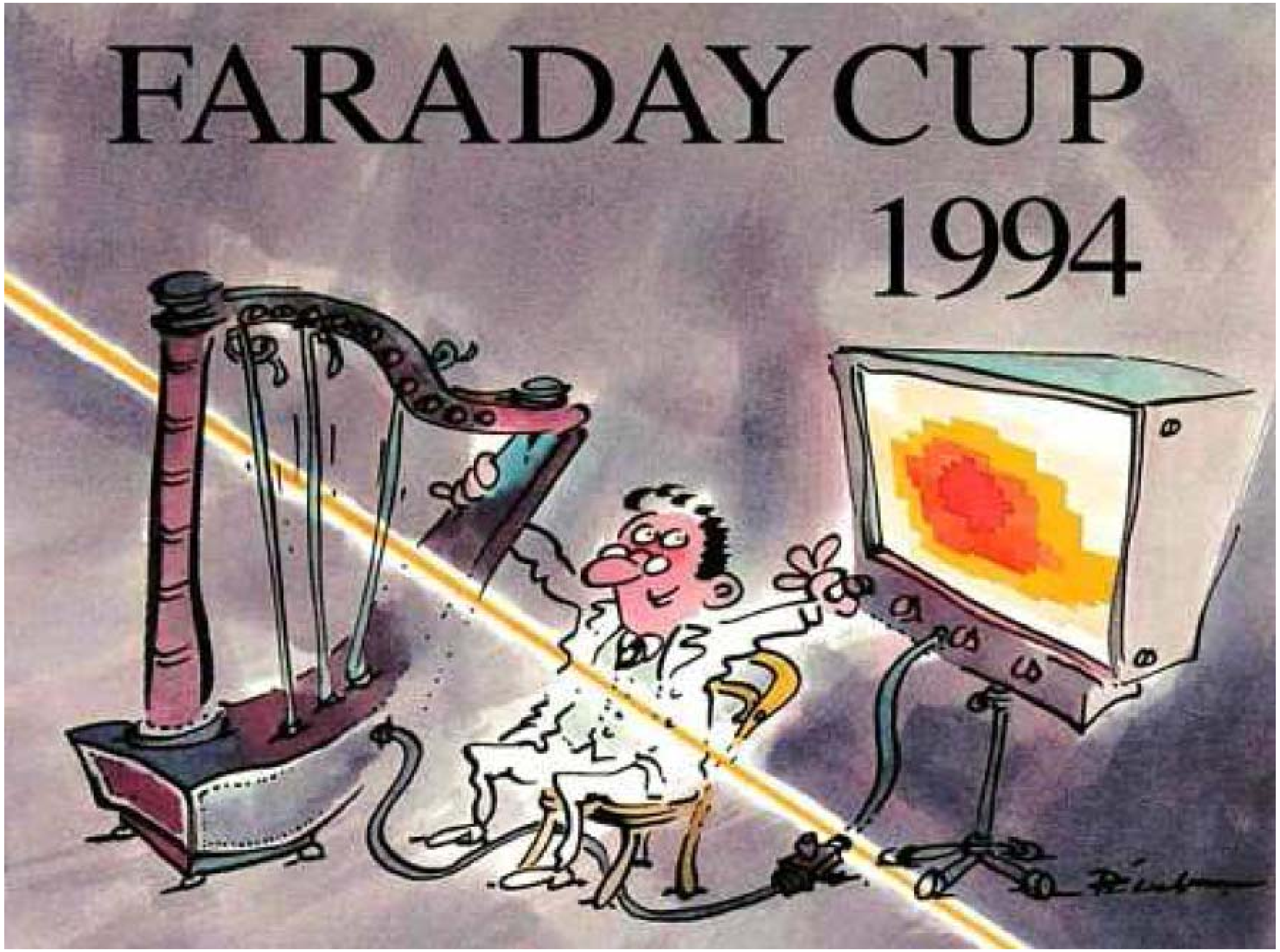


Each wire is equipped with one I/U converter

different ranges settings by 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 ⇒ only 10 % loss.

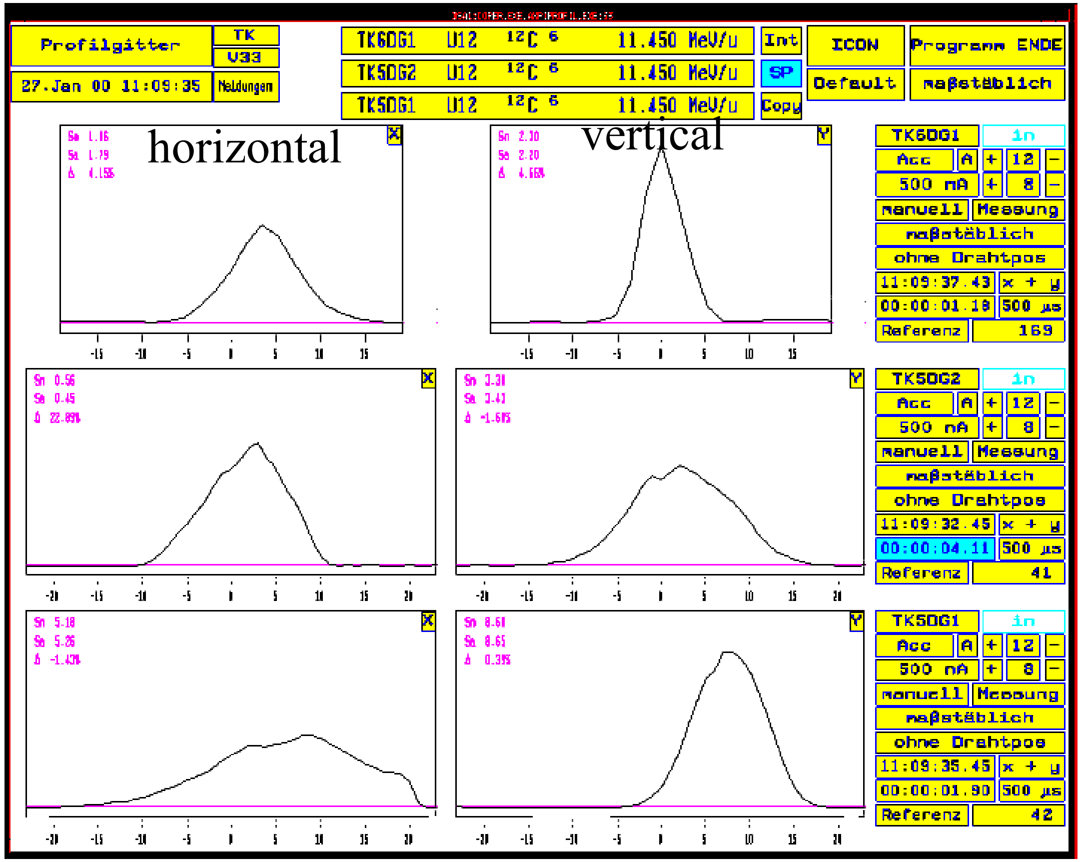
High energy $E_{kin} > 1$ GeV/u: thin ribbons of larger width are used due to negligible energy loss.

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



horizontal

vertical

Profilgitter TK V33

27.Jan 00 11:09:35

TK6DG1 U12 ^{12}C 6 11.450 MeV/u

TK5DG2 U12 ^{12}C 6 11.450 MeV/u

TK5DG1 U12 ^{12}C 6 11.450 MeV/u

TK6DG1 in · Acc A + 12 − · 500 nA + 8 − · manuell Messung · maßstäblich · ohne Drahtpos · 11:09:37.43 x + y · 00:00:01.18 500 µs · Referenz 169

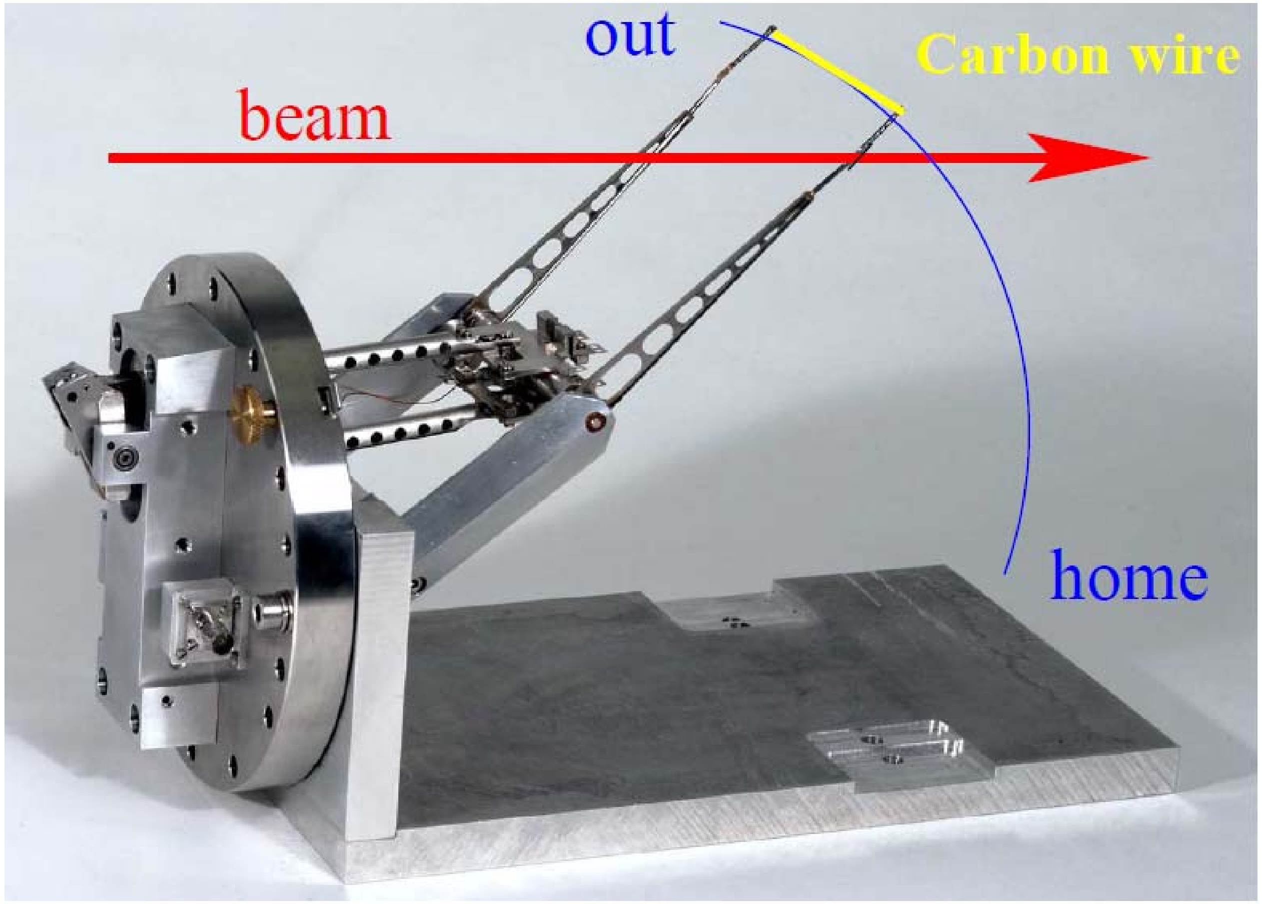
TK5DG2 in · Acc A + 12 − · 500 nA + 8 − · manuell Messung · maßstäblich · ohne Drahtpos · 11:09:32.45 x + y · 00:00:04.11 500 µs · Referenz 41

TK5DG1 in · Acc A + 12 − · 500 nA + 8 − · manuell Messung · maßstäblich · ohne Drahtpos · 11:09:35.45 x + y · 00:00:01.90 500 µs · Referenz 42

Wire Scanner

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

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

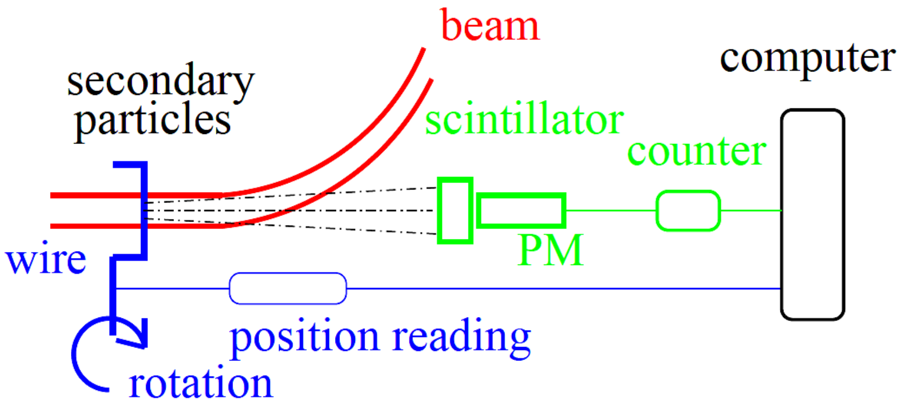


Usage of Wire Scanners

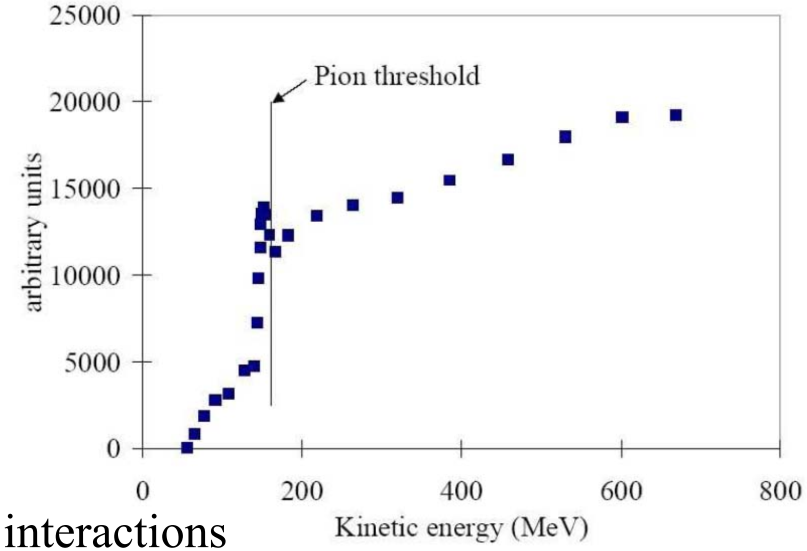
Material: carbon or SiC → low Z-material for low energy loss and high temperature.

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.



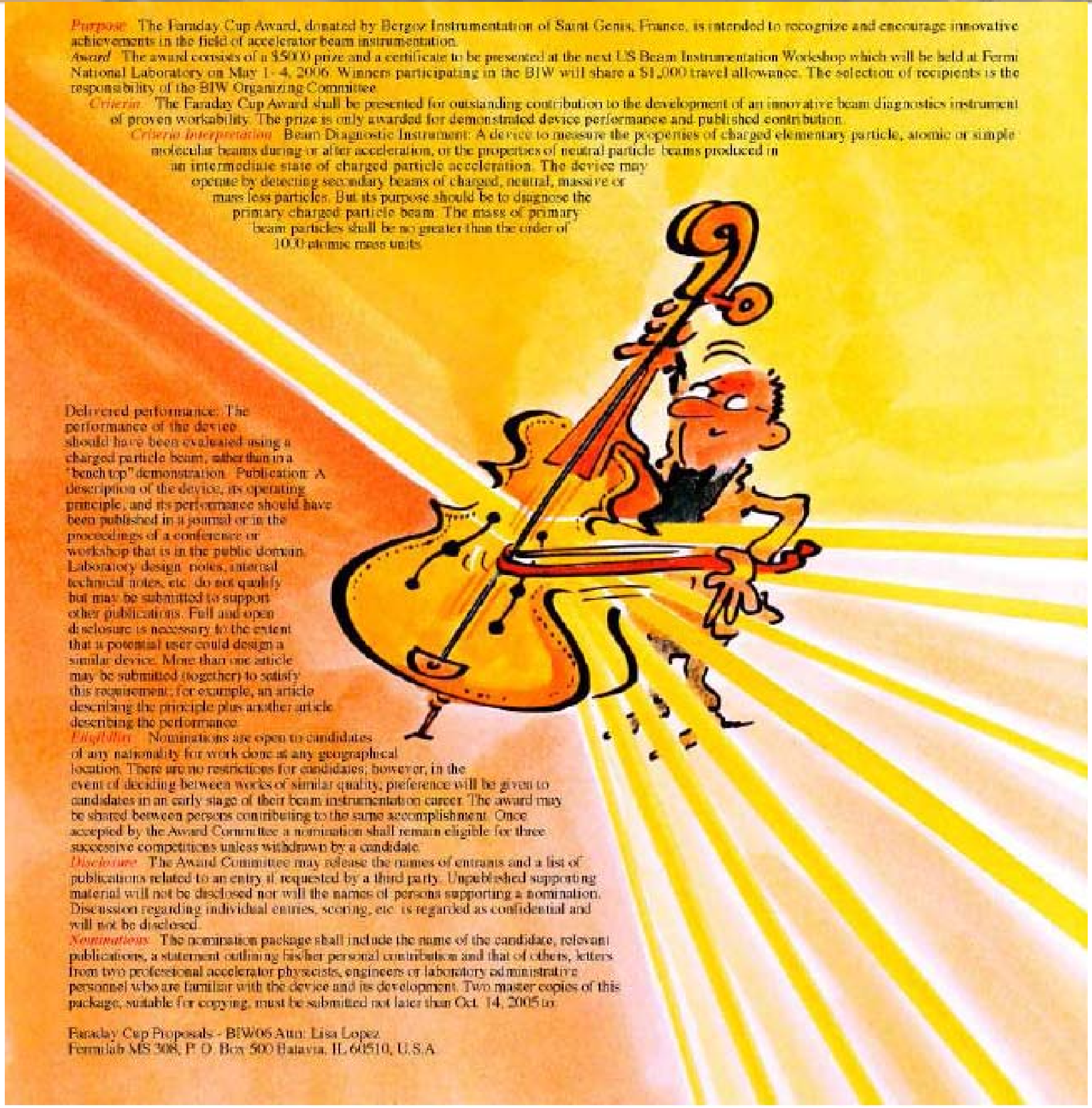
Proton impact on scanner at CERN-PS Booster:



Secondary particles:

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

The Artist View of a Wire Scanner



Purpose The Faraday Cup Award, donated by Bergoz 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 $5000 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 1000 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:

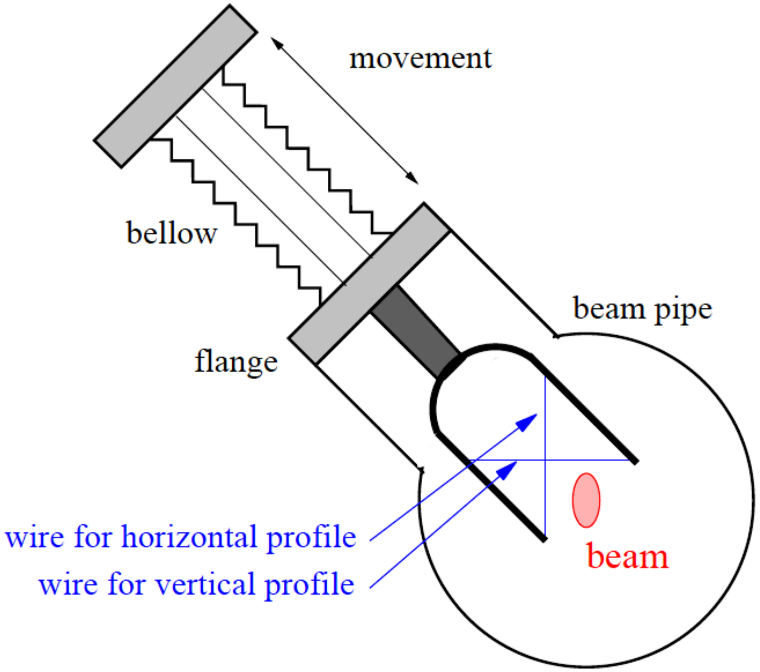
Faraday Cup Proposals - BIW06 Attn: Lisa Lopez
Fermilab MS 308, P. O. Box 500 Batavia, IL 60510, U.S.A.

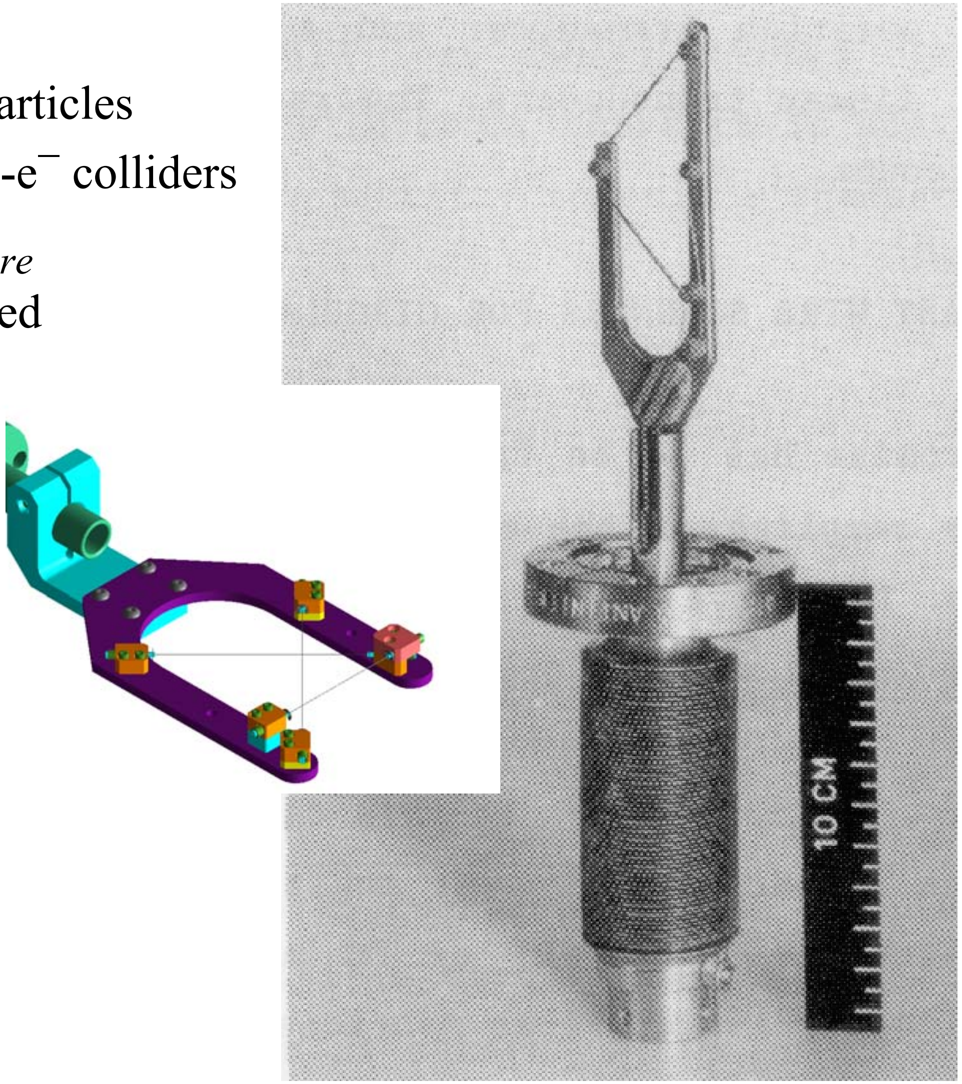
Slow, linear Wire Scanner

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.





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

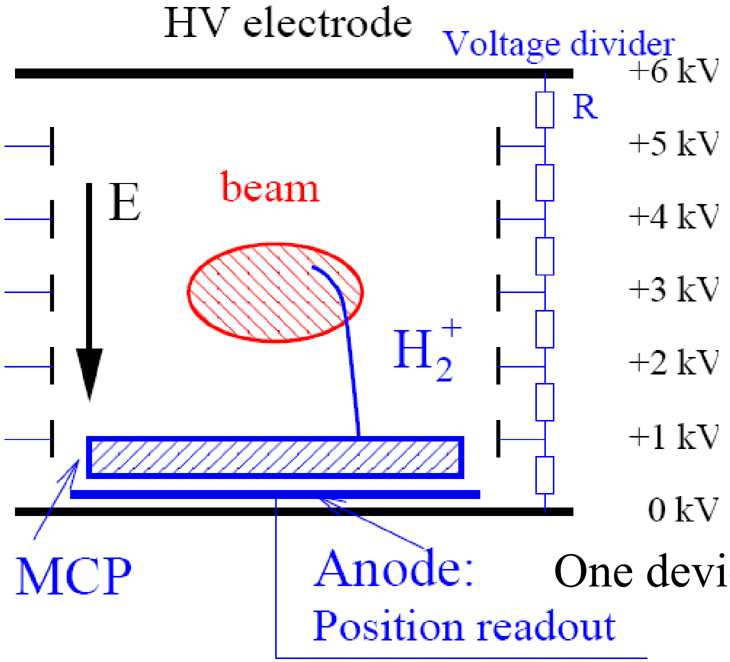
→ expensive electronics and data acquistion

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

Ionization Profile Monitor

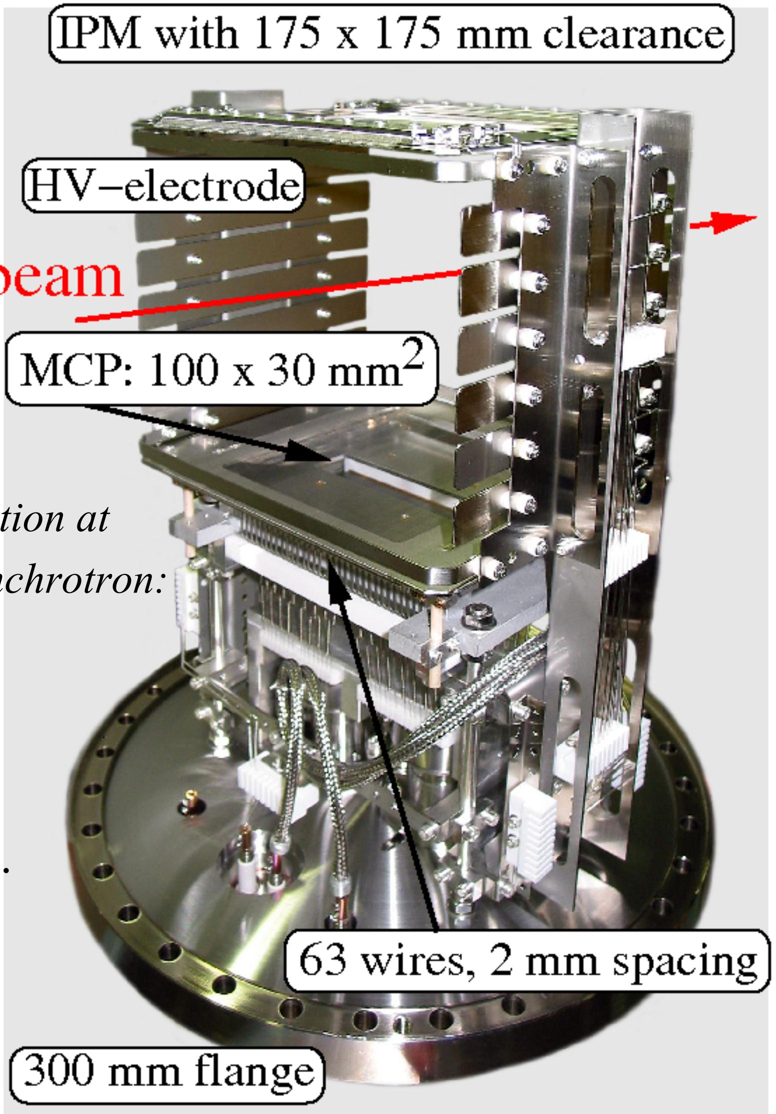
Non-destructive device for proton synchrotron:

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



One device per plane.

Realization at GSI synchrotron:



Typical vacuum pressure:

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

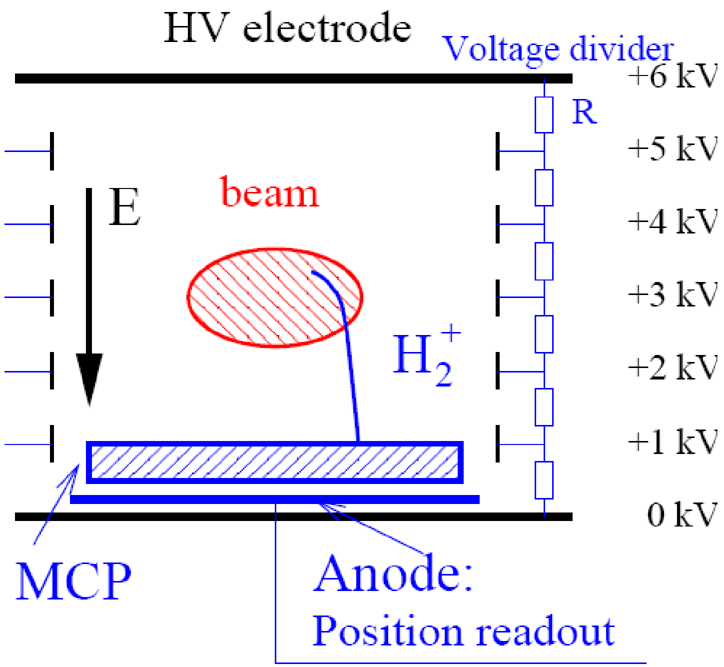
Synchrotron: $10^{-11} - 10^{-9}$ mbar (H_2).

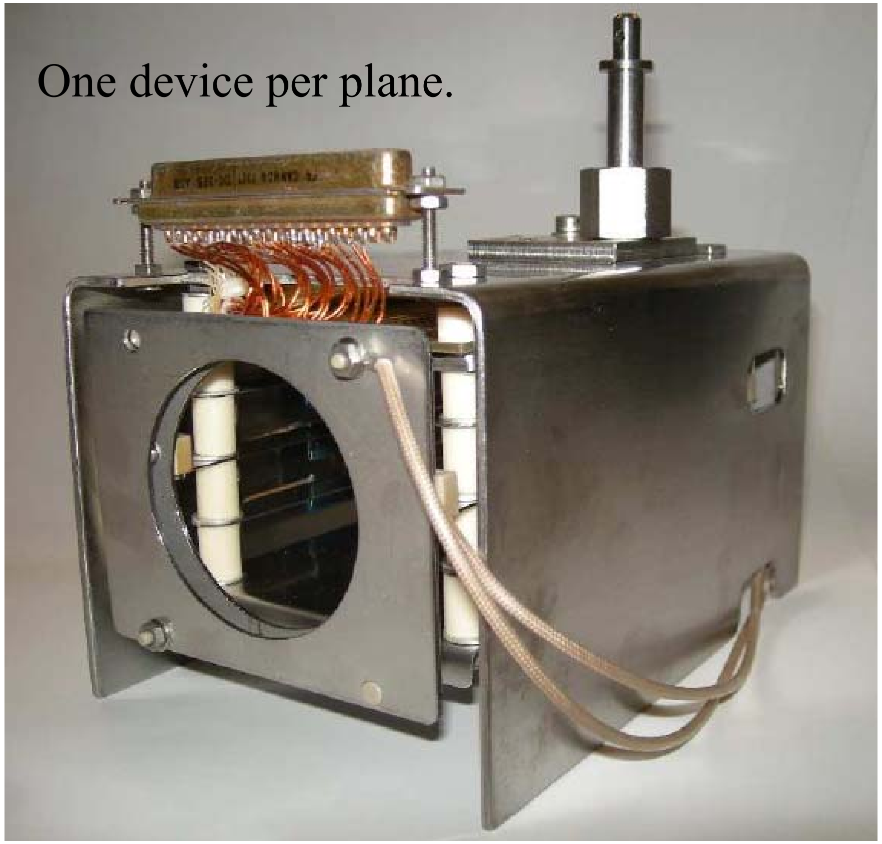
Realization of Ionization Profile Monitor at a LINAC

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 ⇒ no MCP required.

Readout by strips fed to an I/U converter.





One device per plane.

Multi Channel Plate MCP

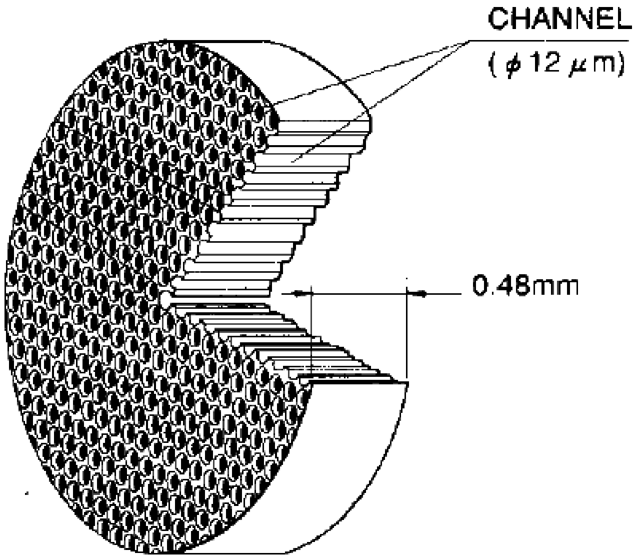
MCP are used as particle detectors with secondary electron amplification.

A MCP is:

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

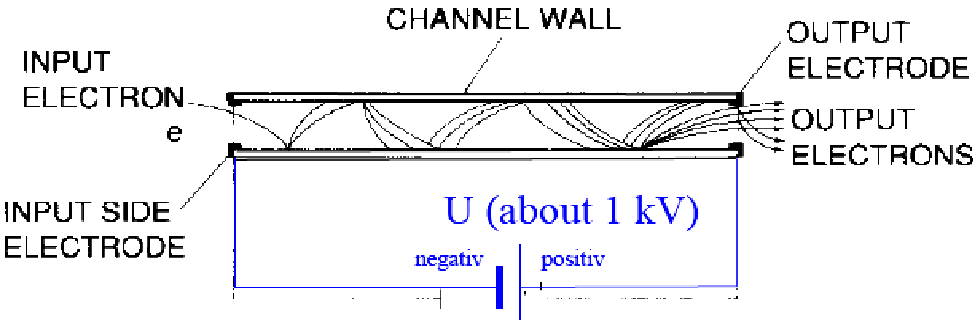
⇒ e^- amplification of ≈ 10^3 per plate.

→ 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 $\varepsilon = \int \rho(x,x')dxdx'$ is defined in the laboratory frame.

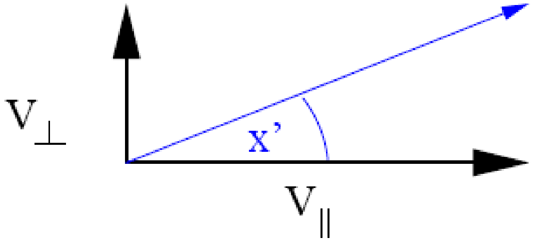
During acceleration:

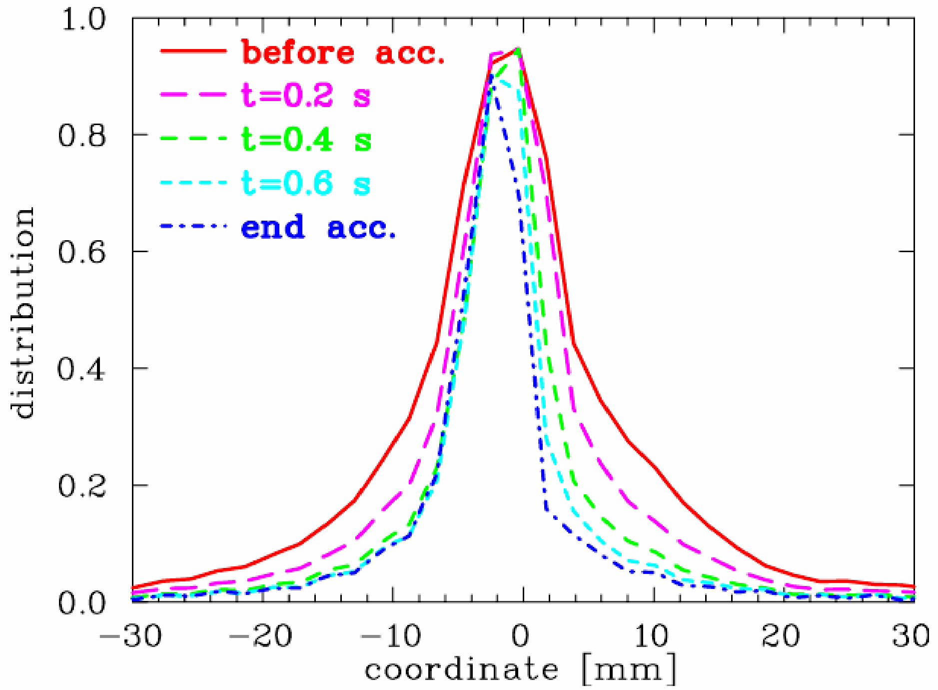
for increasing $\boldsymbol{v}_{\|}$ and constant $\boldsymbol{v}_{\perp}$:

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

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

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





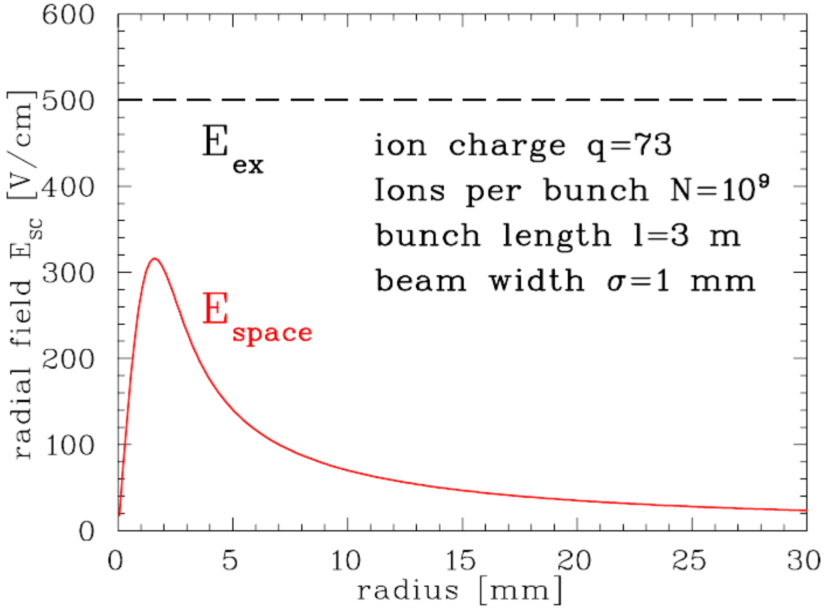
Non-intercepting ionization profile monitor is well suited for long time observations without beam disturbance → mainly used at proton synchrotrons.

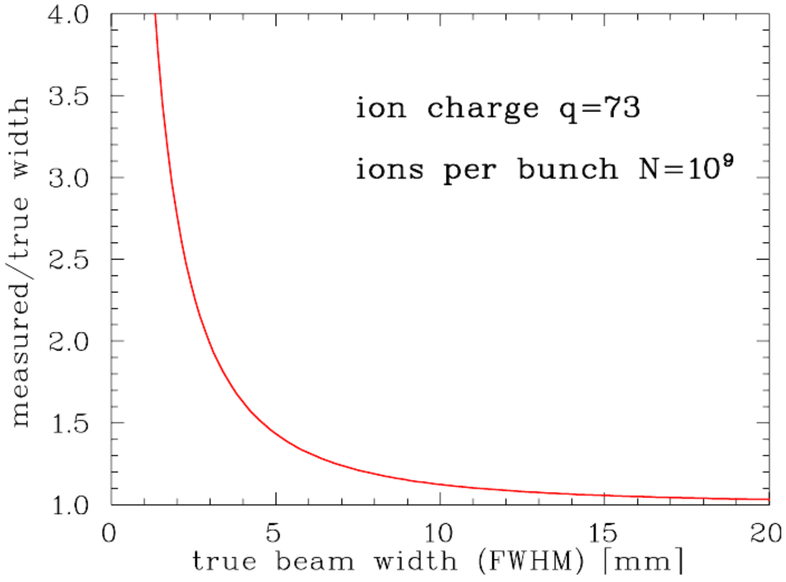
Broadening due to the Beam's Space Charge: Ion Detection

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





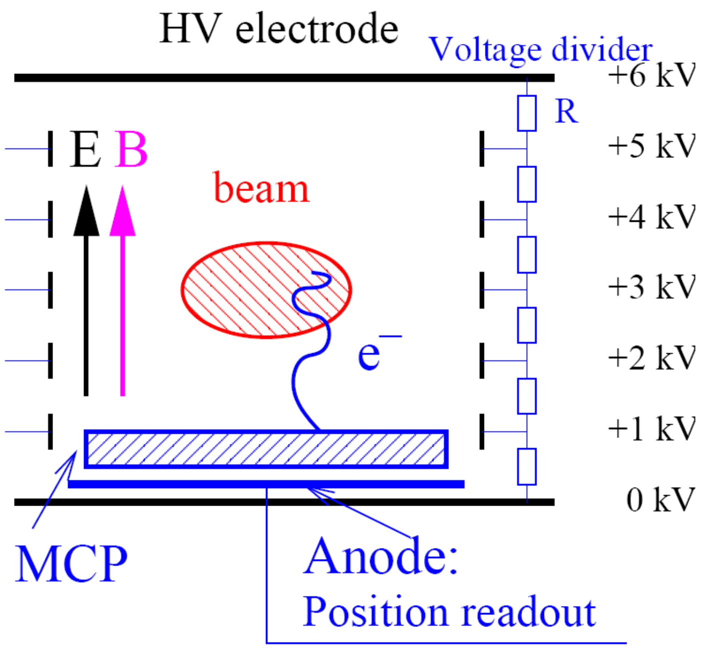
Parameter: U^{73+}, 10^9 particles per 3 m bunch length, cooled beam with 2.5 mm FWHM.

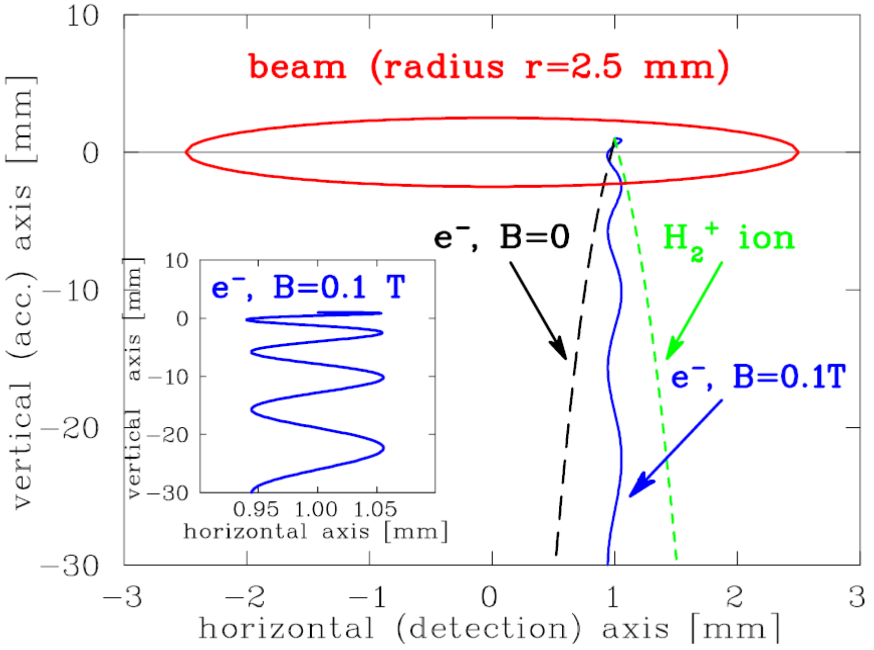
Electron Detection and Guidance by Magnetic Field

Alternative: e^- detection in an external magnetic field

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

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



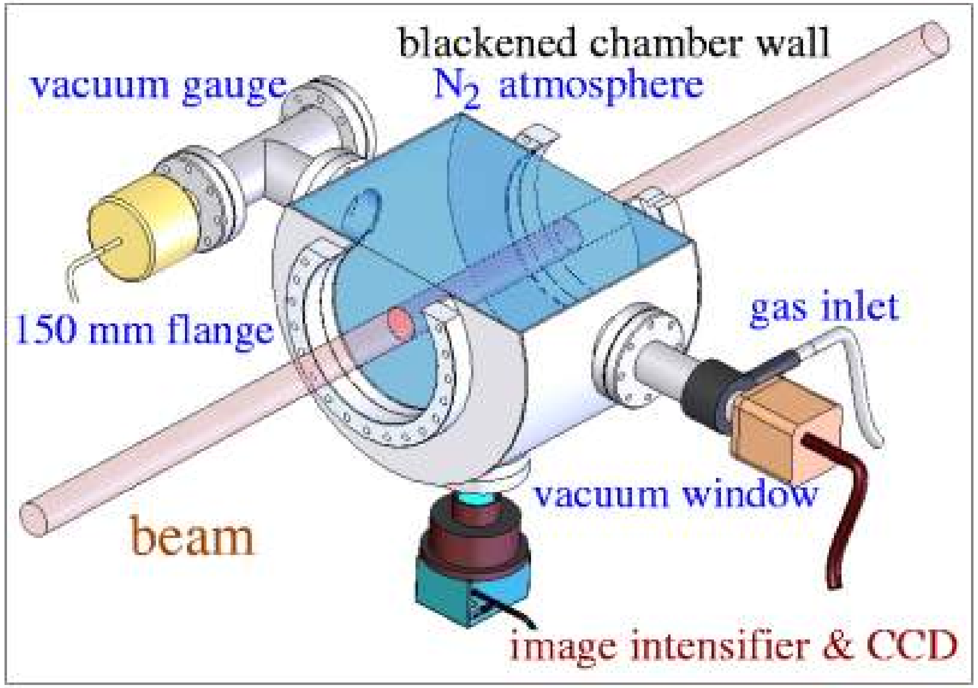


Time-of-flight: ≈1 ns ⇒ 2 or 3 cycles.

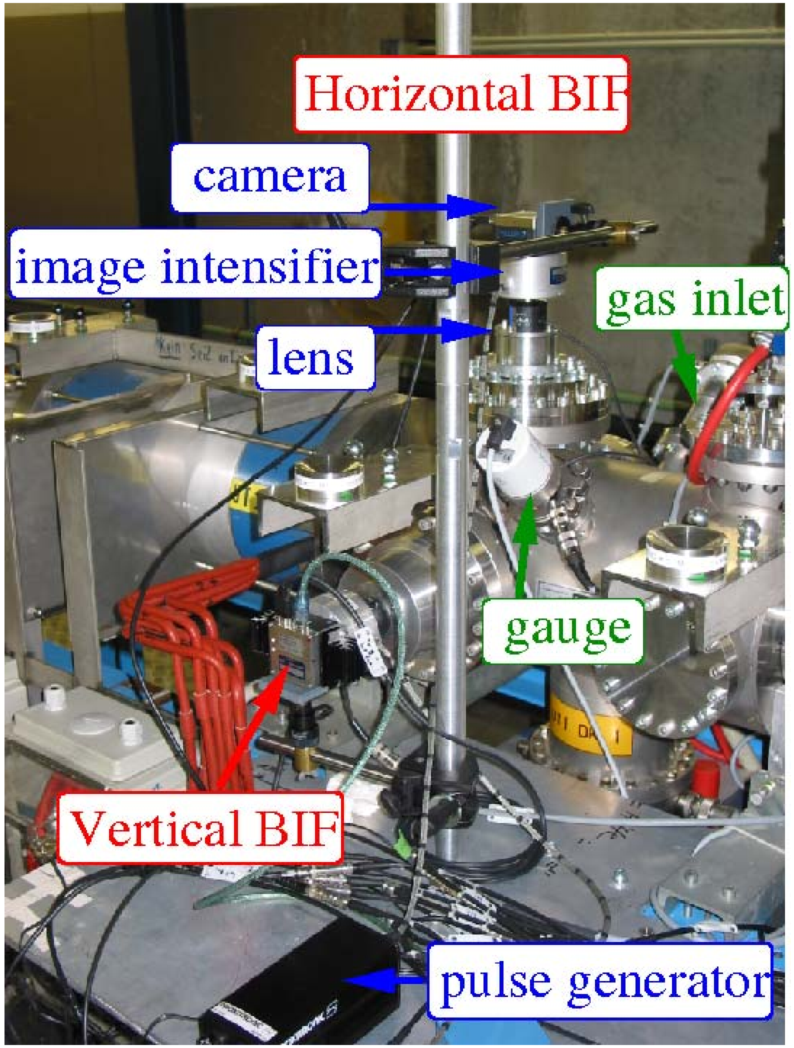
B-field: By dipole magnets with large aperture → IPM is expensive device.

Beam **I**nduced **F**luorescence for intense Profiles

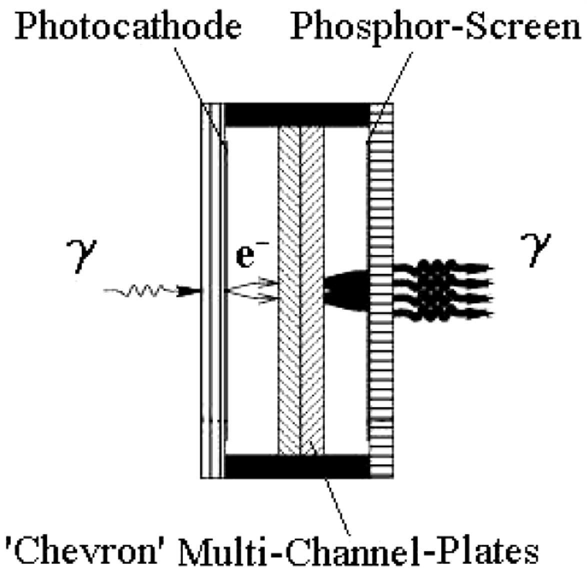
Large beam power → Non-intercepting method:
⇒ **B**eam **I**nduced **F**luorescence BIF
$N_2 + \text{Ion} \rightarrow (N_2^+)^* + \text{Ion} \rightarrow N_2^+ + \gamma + \text{Ion}$
With single photon detection scheme
$390\ \text{nm} < \lambda < 470\ \text{nm}$
⇒ non-destructive, compact installation.



Installation of hor&vert. BIF Monitor:



Beam Induced Fluorescence Monitor BIF: Image Intensifier



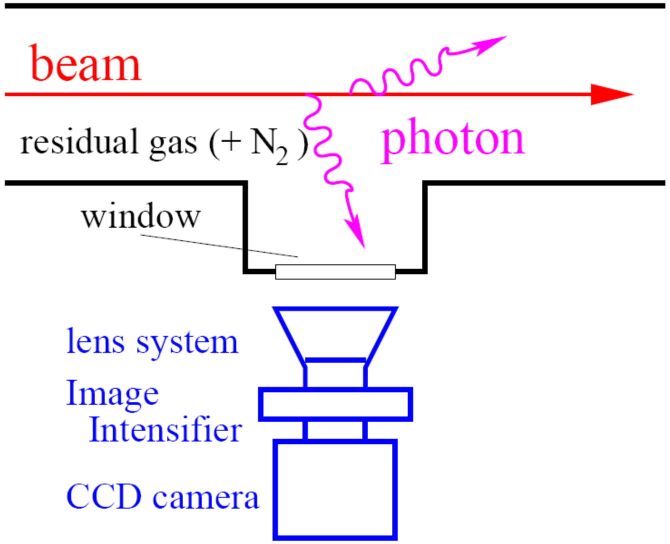


Image intensifier:

- ➢Photo cathode → creation of photo-e⁻
- ➢accelerated to MCP for amplification
- ➢Detection of ampl. e⁻ by phosphor screen
- ➢Image recored by CCD

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

A BIF monitor consists of only:

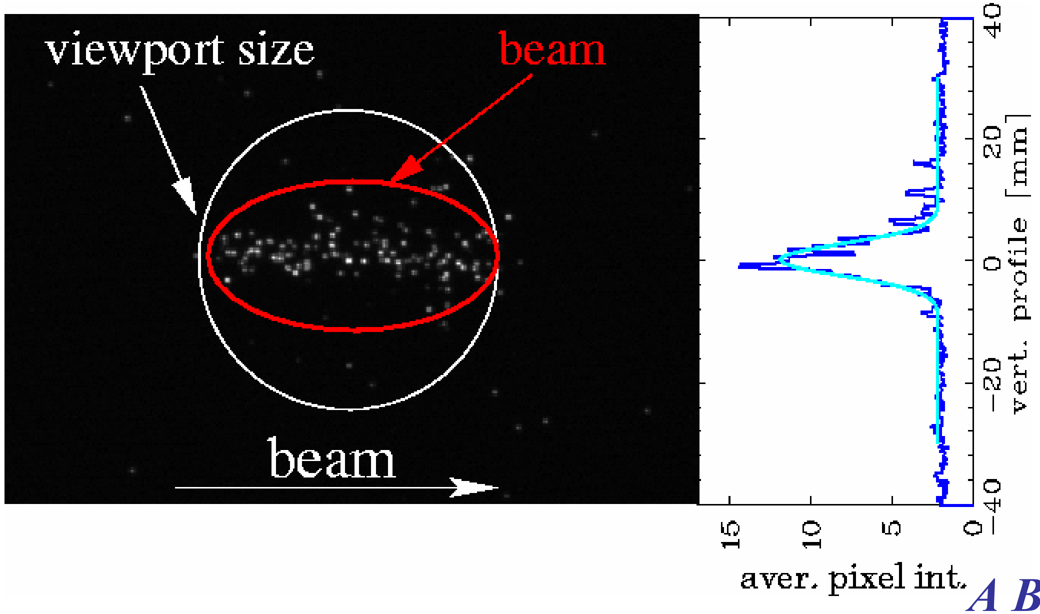
- ➢ optics outside beam pipe
- ➢ image intensifier + camera
- ➢ gas-inlet for pressure increase

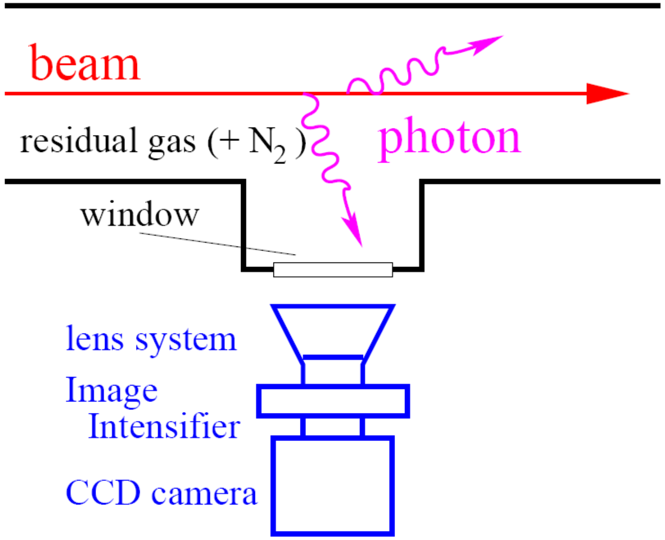
⇒ nearly no installation inside vacuum.
only LEDs for calibration

⇒ cheaper than IPM, but lower signal.

Beam Induced Fluorescence Monitor BIF: Image Intensifier

‘Single photon counting’:





Example at GSI-LINAC:

4.7 MeV/u 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.

Optical Transition Radiation OTR

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

Electrodynamic field configuration changes during the passage:

⇒ Polarization of the medium

⇒ emission of energy

Description by

classical electrodynamics & relativity:

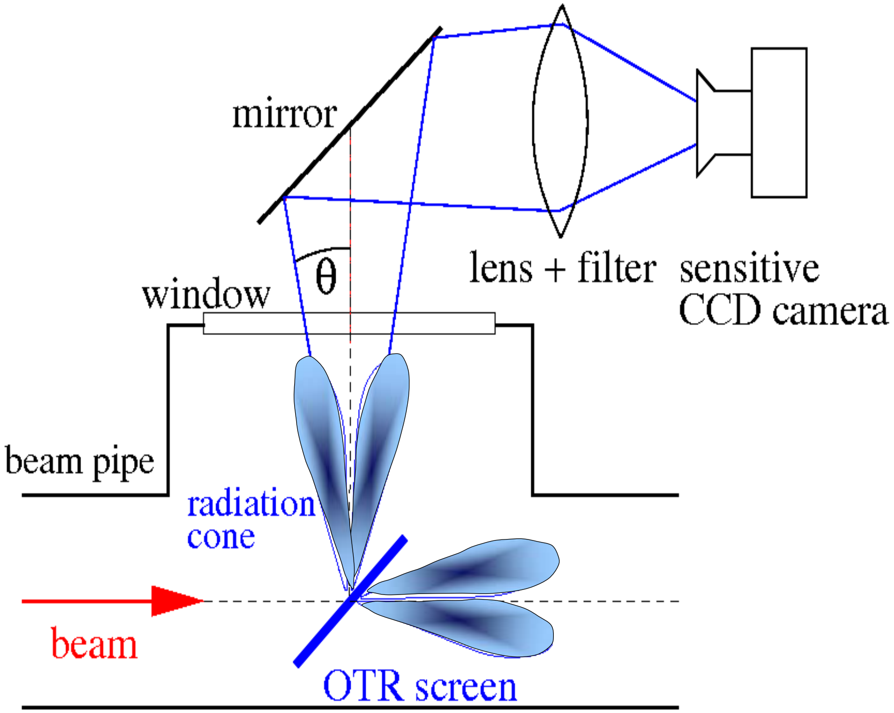
$$\frac{d^2W}{d\Omega d\omega} = \frac{\mu_0 ce^2}{4\pi^3} \cdot \frac{\theta^2}{\left(\gamma^{-2} + \theta^2\right)^2}$$

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.

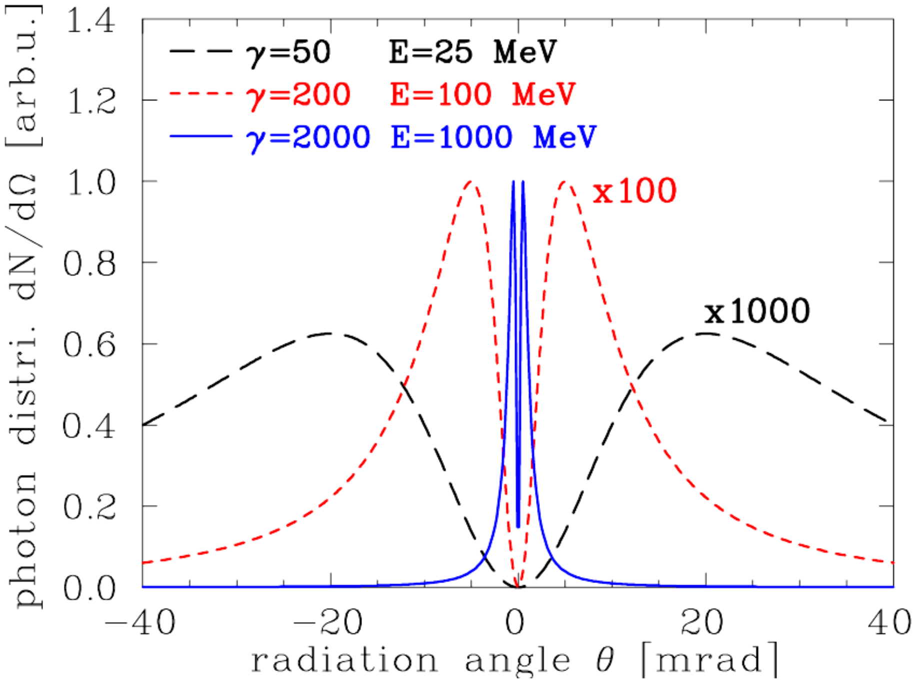
Optical Transition Radiation: Angular Photon Distribution

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*Ω** and

Wavelength interval λ_{begin} to λ_{end}



- ➢ Detection: Optical 400 nm < λ < 800 nm

  using image intensified CCD

- ➢ Larger signal for relativistic beam $\gamma >> 1$
- ➢ Angular focusing for $\gamma >> 1$

⇒ **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.

OTR-Monitor: Technical Realization and Results

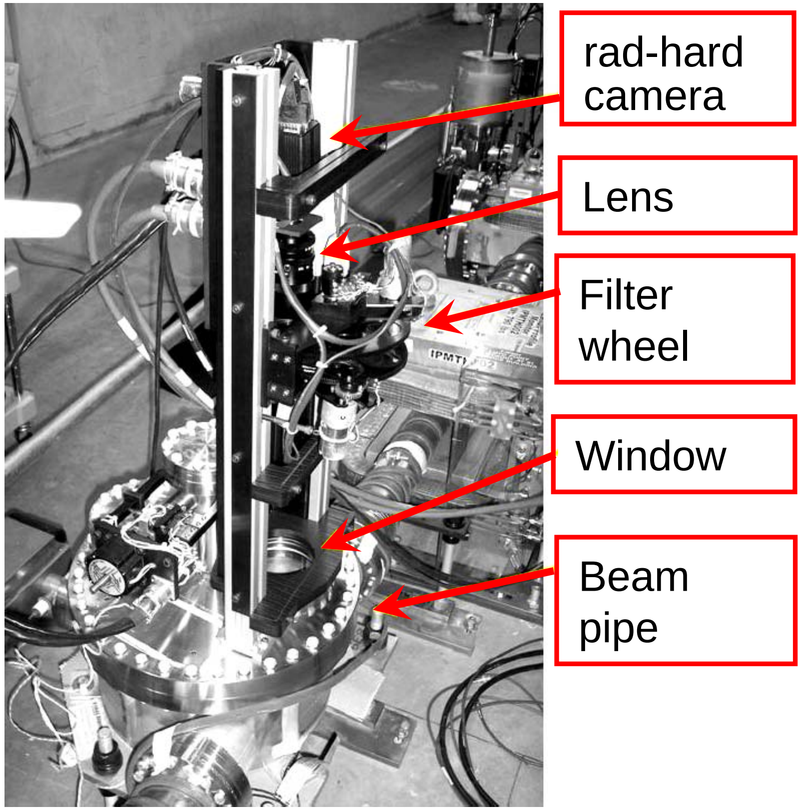
Example of realization at TERATRON:

➢Insertion of foil

e.g. 5 µm Kapton coated with 0.1µm Al

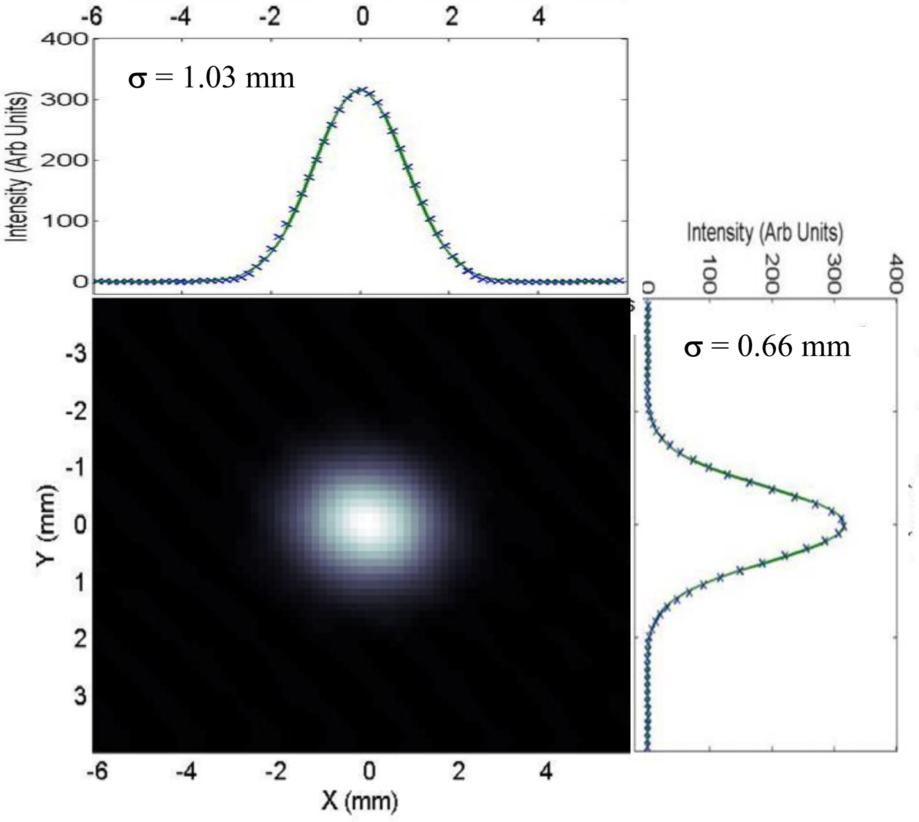
Advantage: thin foil ⇒ low heating & straggling

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

---

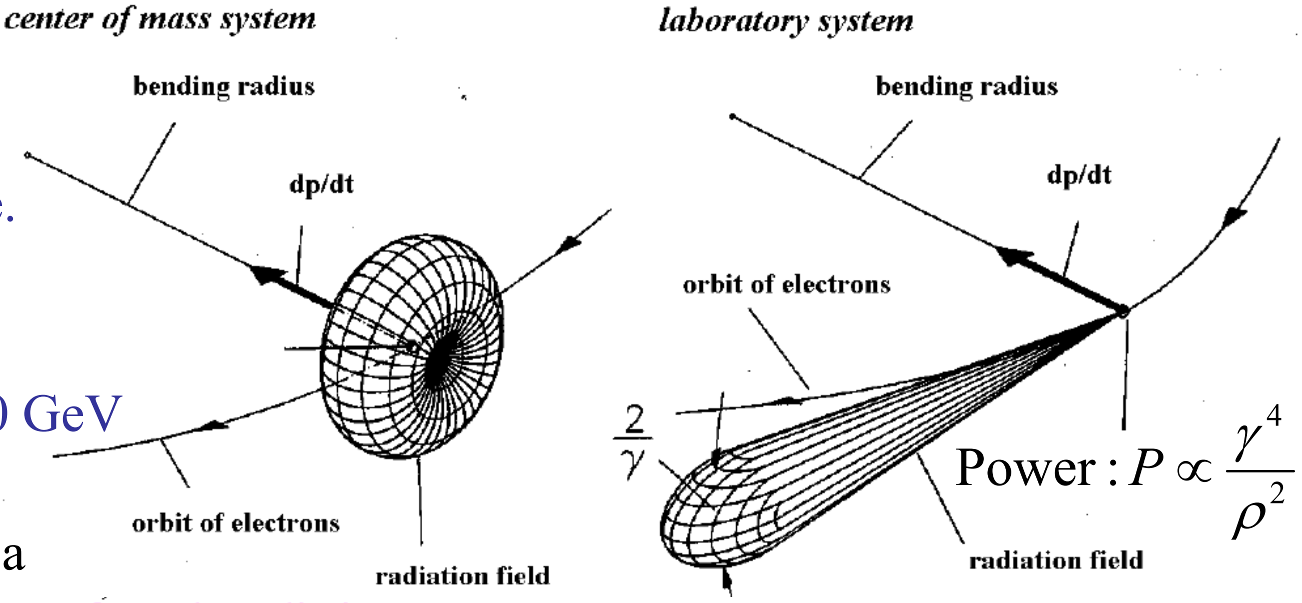
OTR: large γ needed → e^--beam with $E_{kin} > 100$ MeV, proton-beam with $E_{kin} > 100$ GeV

Scint. Screen: for all beams

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/γ in lab-frame.
⇒Well suited for rel. e^-
For protons:
Only for energies E>100 GeV

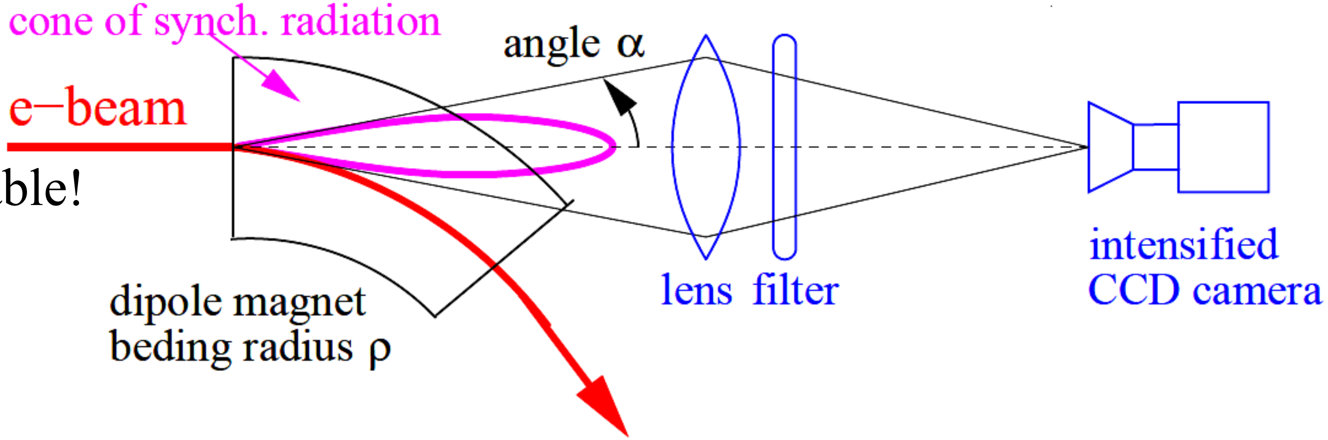


$$\text{Power}: P \propto \frac{\gamma^4}{\rho^2}$$

The light is focused to a intensified CCD.

Advantage:

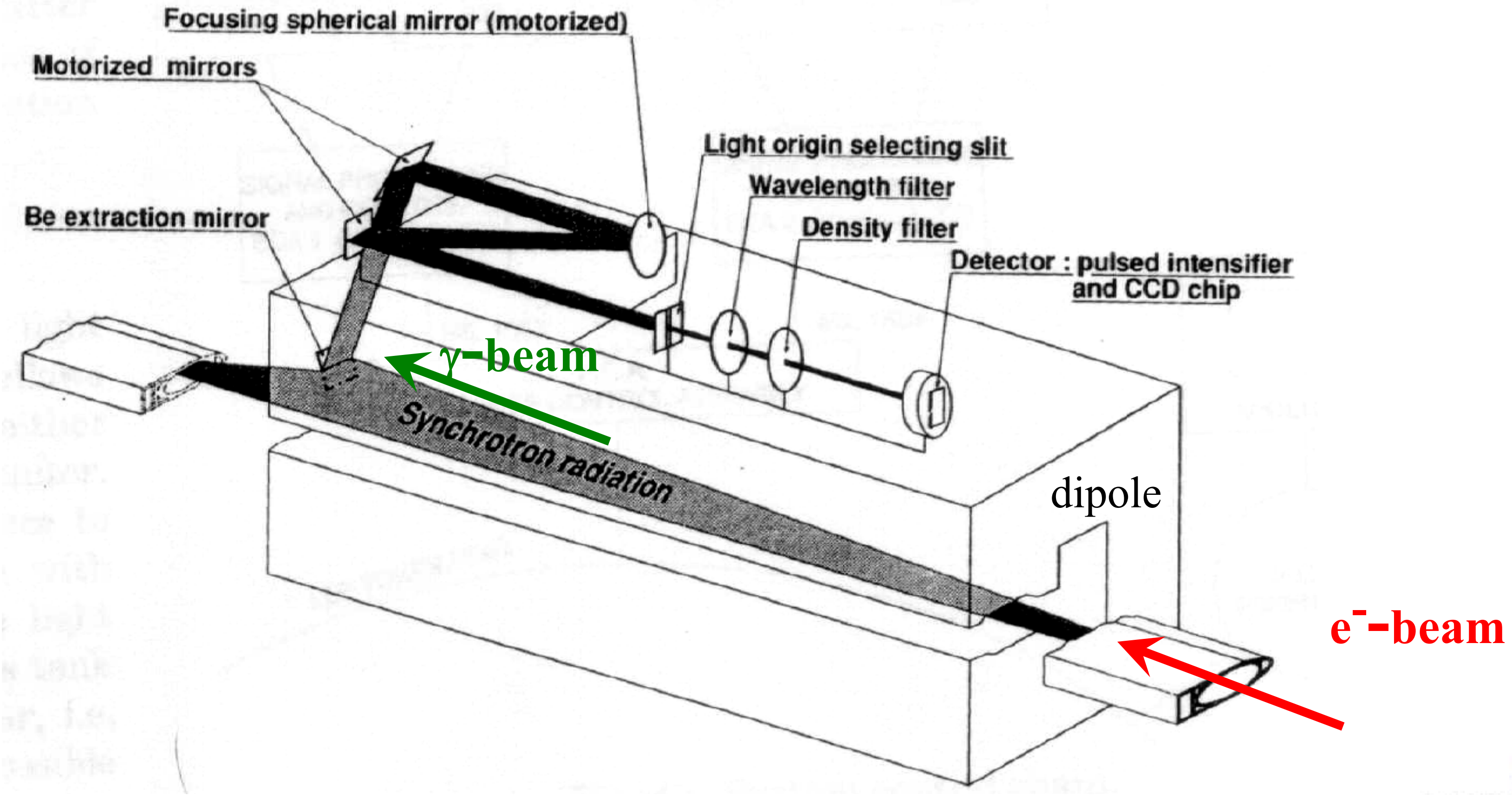
Signal anyhow available!



Realization of a Synchrotron Light Monitor

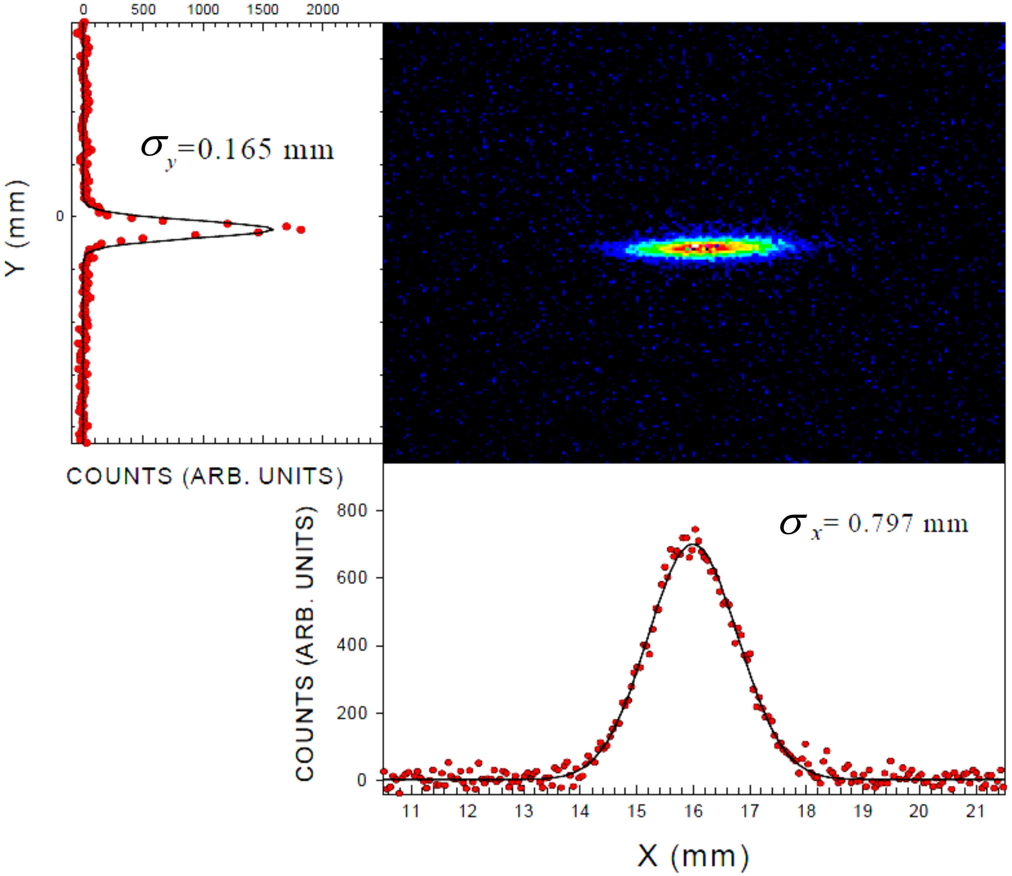
Extracting out of the beam's plane by a (cooled) mirror
→ Focus to a slit + wavelength filter for optical wavelength
→ Image intensified CCD camera

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:

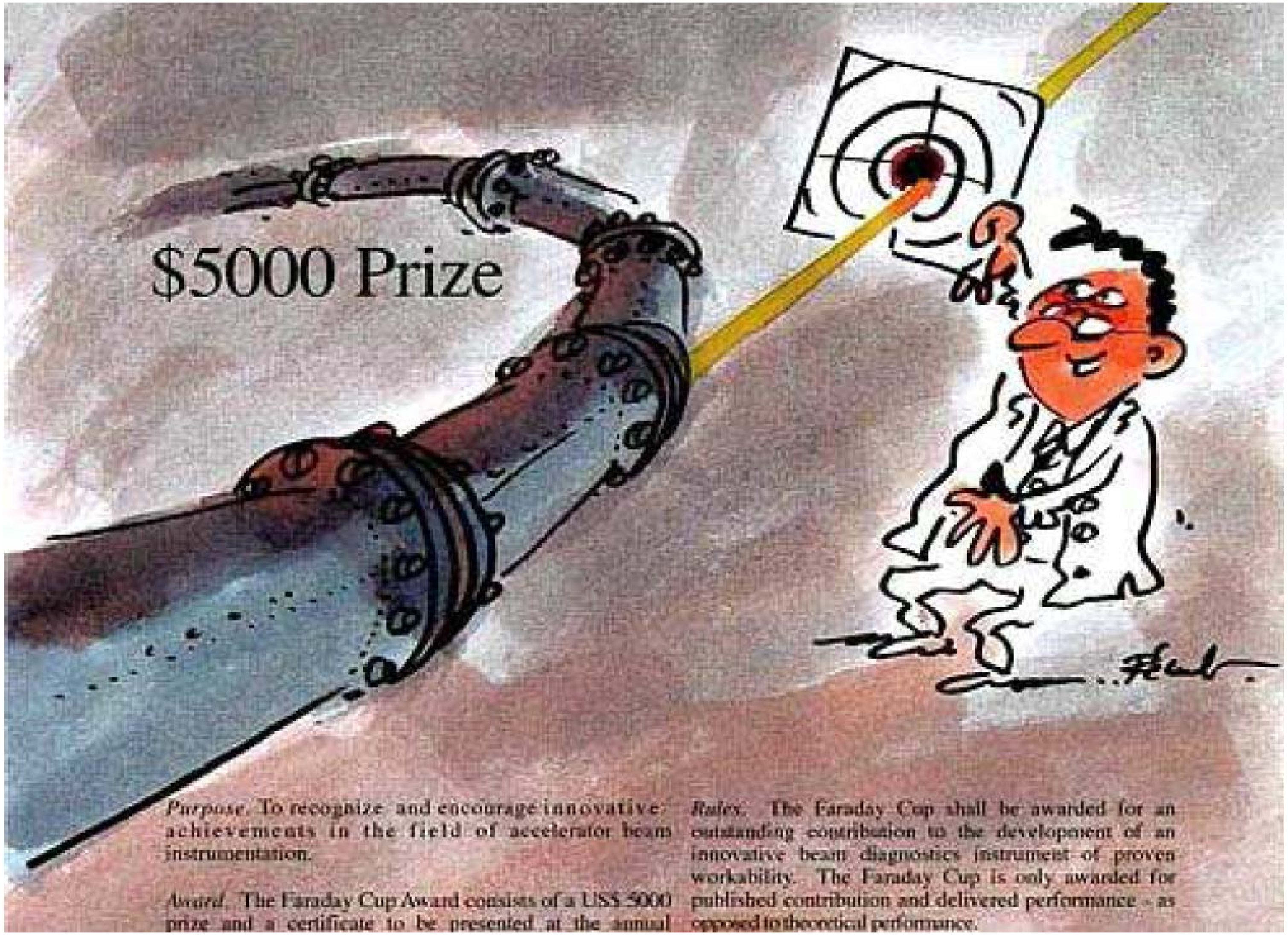


Advantage: Direct measurement of 2-dim distribution, only mirror installed in the vacuum pipe

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



Purpose. To recognize and encourage innovative achievements in the field of accelerator beam instrumentation.

Award. The Faraday Cup Award consists of a US$ 5000 prize and a certificate to be presented at the annual

Rules. The Faraday Cup shall be awarded for an outstanding contribution to the development of an innovative beam diagnostics instrument of proven workability. The Faraday Cup is only awarded for published contribution and delivered performance - as opposed to theoretical performance.

Diffraction Limit for a Synchrotron Light Monitor

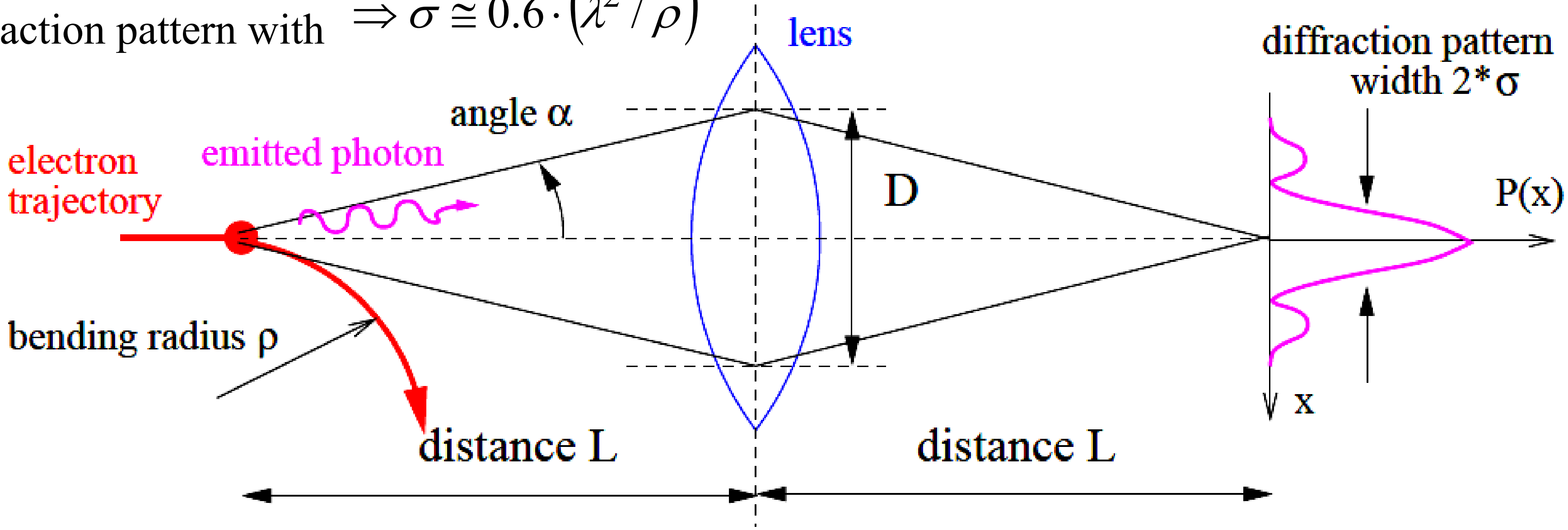
Use of optical wavelength and CCD: λ above critical λ_{crit} (spectrum fall-off).

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:

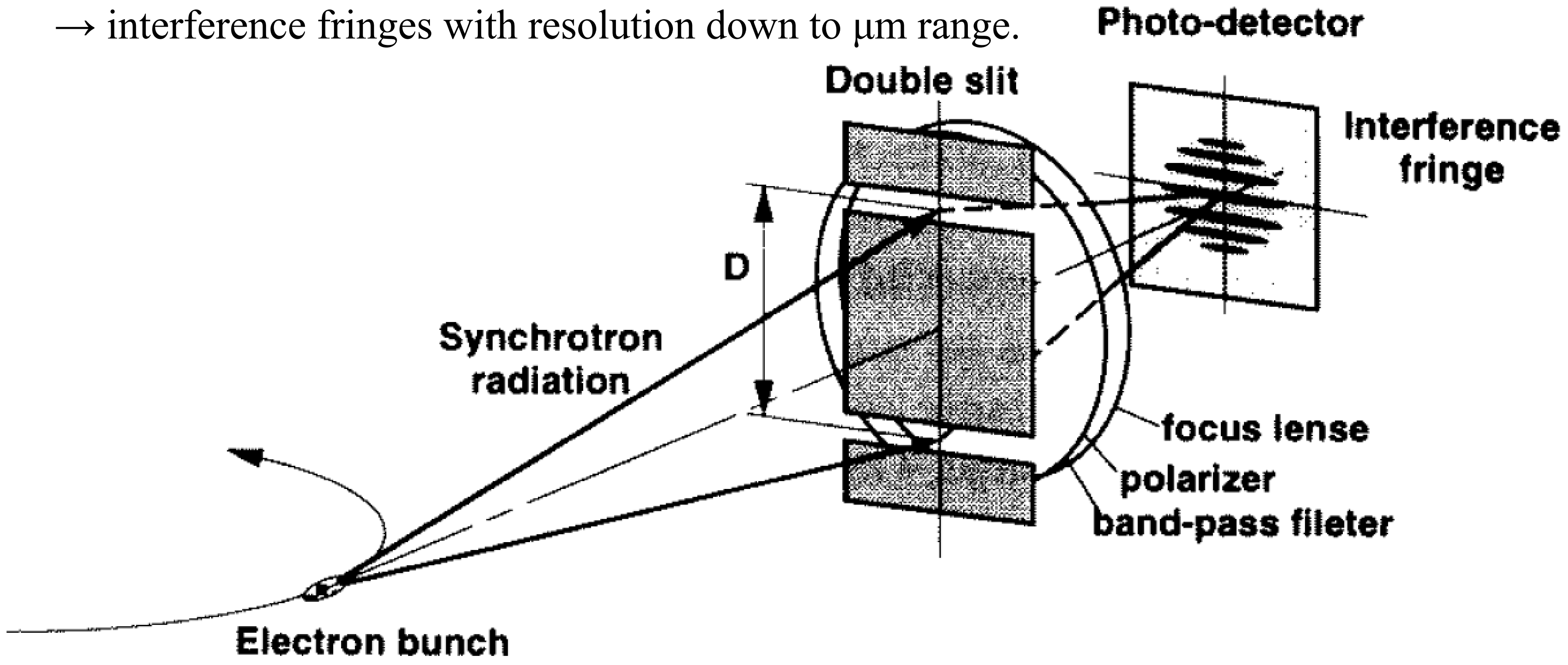
- large dipole bending radius ρ, **but** fixed by the accelerator
- short wavelength, **but** good optics only for $\lambda > 300$ nm

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.



Summery 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
- Residual gas 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.