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:

$$\sigma_x^2(s) = \varepsilon_x \beta_x(s) + \left(D(s) \frac{\Delta p}{p} \right)^2 \quad \text{and} \quad \sigma_y^2(s) = \varepsilon_y \beta_y(s) \quad \text{(no vertical bend)}$$

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

Typical beam sizes:

e⁻-beam: typically Ø 0.1 to 3 mm, **protons:** typically Ø 1 to 30 mm

A great variety of devices are used:

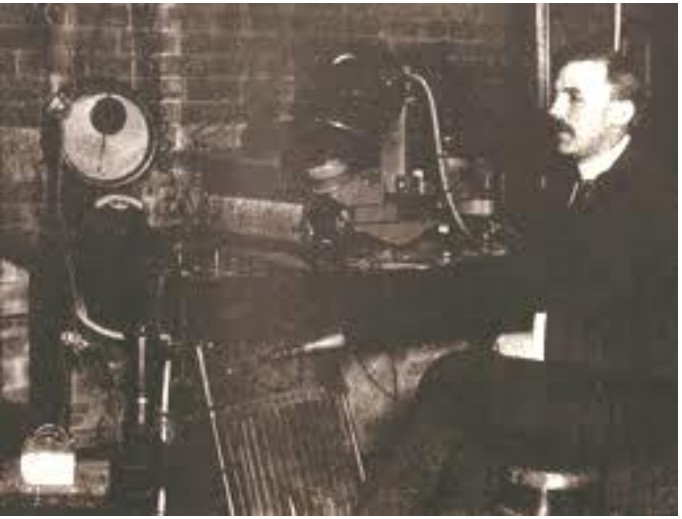
- ***Optical techniques**:* Scintillating screens (all beams),
  synchrotron light monitors (e−), optical transition radiation (e−),
  residual gas fluorescence monitors (protons), ionization profile monitors (protons).
- ***Electronics techniques:*** Secondary electron emission (SEM) grids, wire scanners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

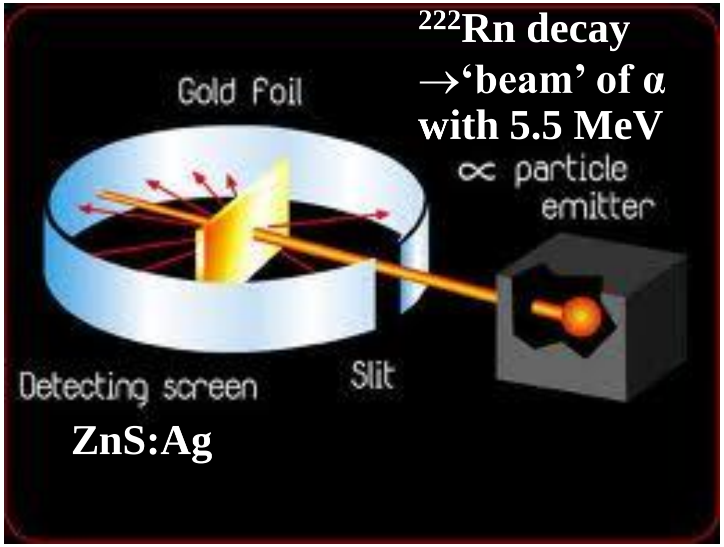
Outline:

- **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**

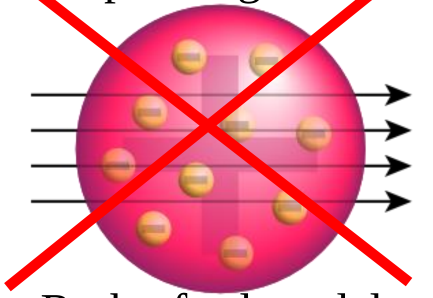
Early Usage of Scintillation Screen by E. Rutherford

Scintillation screens are used from the 'early days' on e.g. by Ernest Rutherford in 1911:

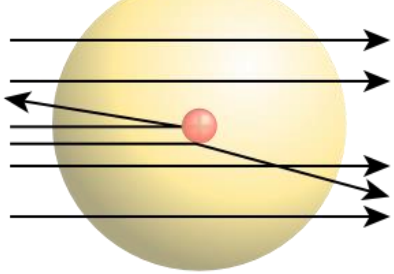




Plum pudding model:



Rutherford model:



Rutherford or 'Geiger-Marsden Experiment':

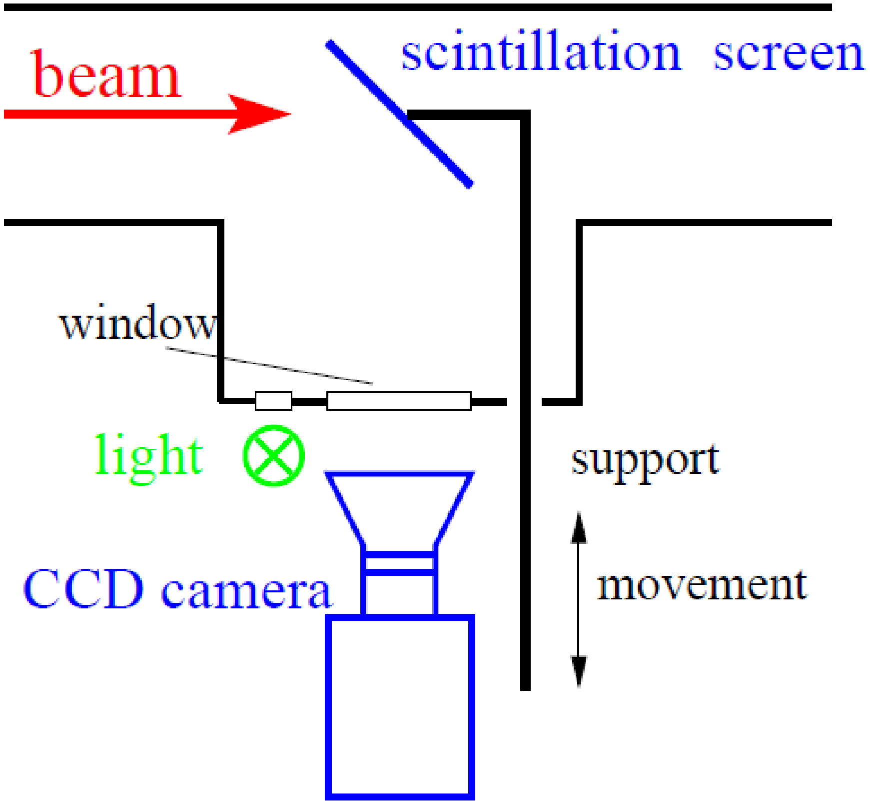
- Nuclei are made of point-like charges

ZnS:Ag

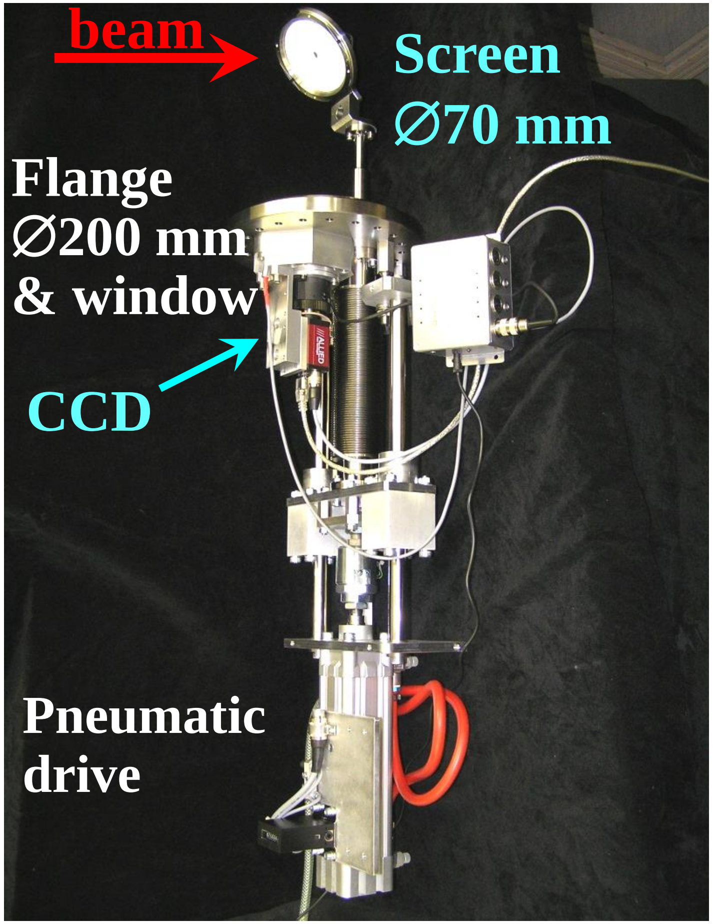
- light emitter excited by the energy release by charged particle → sintillation
- today known as Phosphor P11 and is used in TV tubes etc.

Particle's energy loss in matter produces light

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

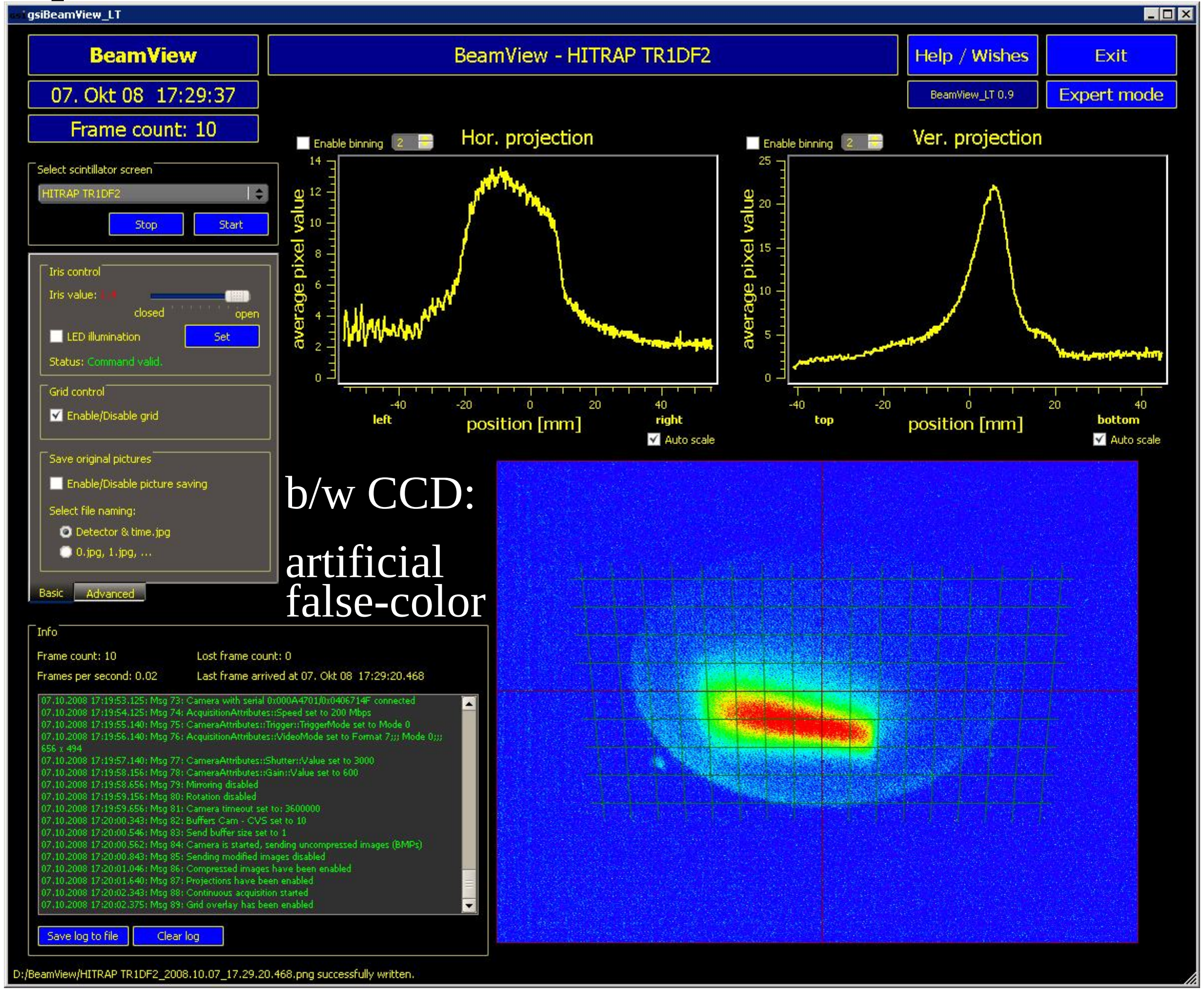


Pneumatic feed-through with Ø70 mm screen :



Example of Screen based Beam Profile Measurement

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



b/w CCD:

artificial false-color

Advantage of screens:

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

Observation with

a CCD or CMOS camera

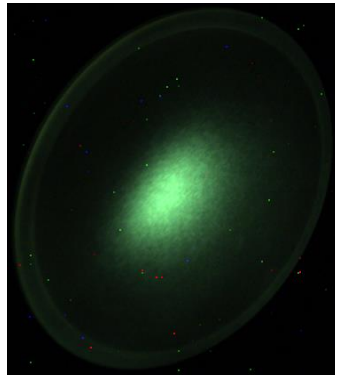
with digital output

or video & frame grabber.

Light output from various Scintillating Screens

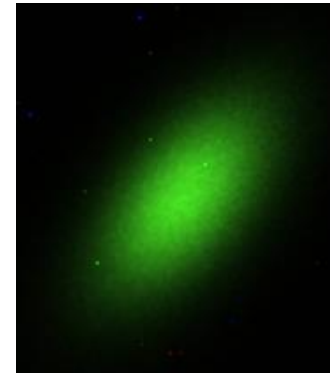
Example: Color CCD camera: Images at different particle intensities determined for U at 300 MeV/u

Al_2O_3

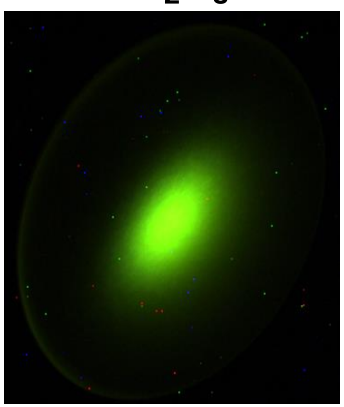


CsI:Tl

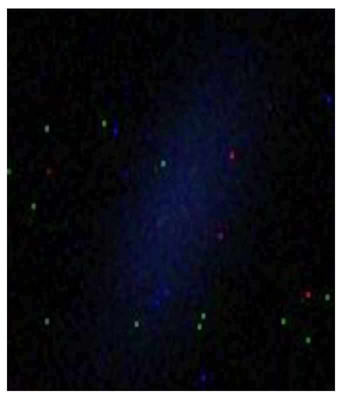
Al_2O_3:Cr



P43

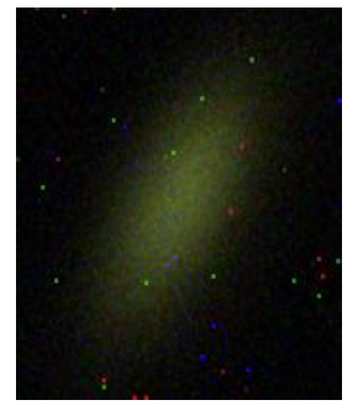


YAG:Ce



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:**

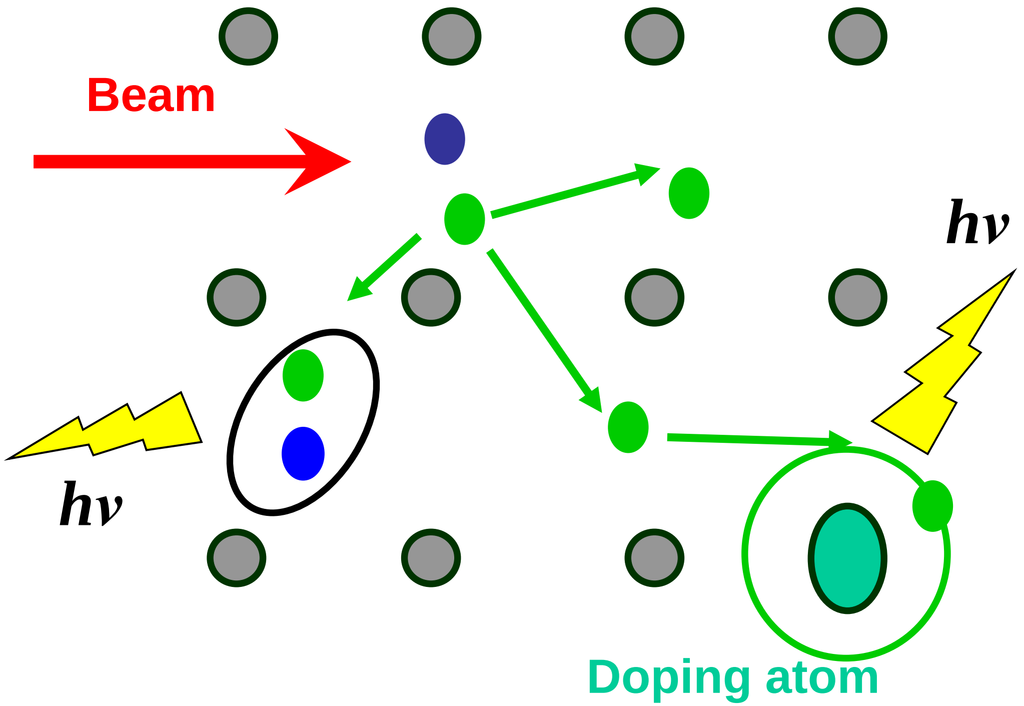
electron – electron scattering

- **thermalization:**

electron – phonon coupling

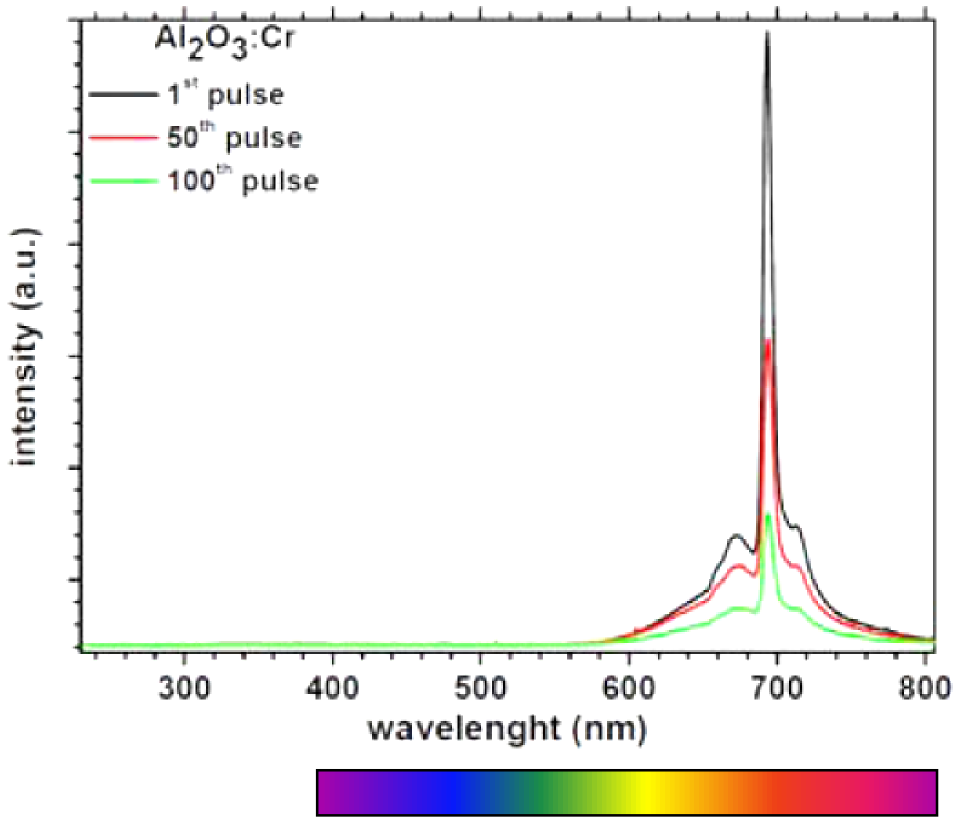
- **capture at doped atom and/or electron - hole pair creation**

- **emission of photons**



Wavelength spectrum of Al_2O_3:Cr (Chromox)

→ Emission is dominated by Chromium dopant

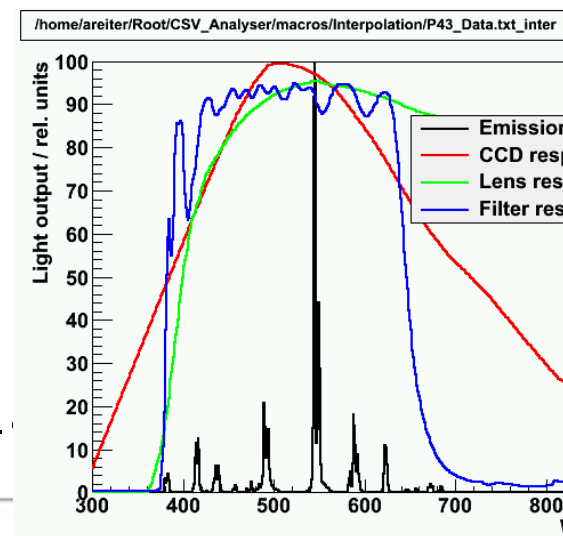


Other materials have different spectra

→ Optimization to sensitivity of detector

→ but others material properties

have to obeyed and weighted



Beam parameters: $^{238}U^{28+}$, 4.8 MeV/u, **$5 \cdot 10^{10}$ ppp** in 500 μs, ~450 μA

[E.

Material Properties for Scintillating Screens

Some materials and their basic properties:

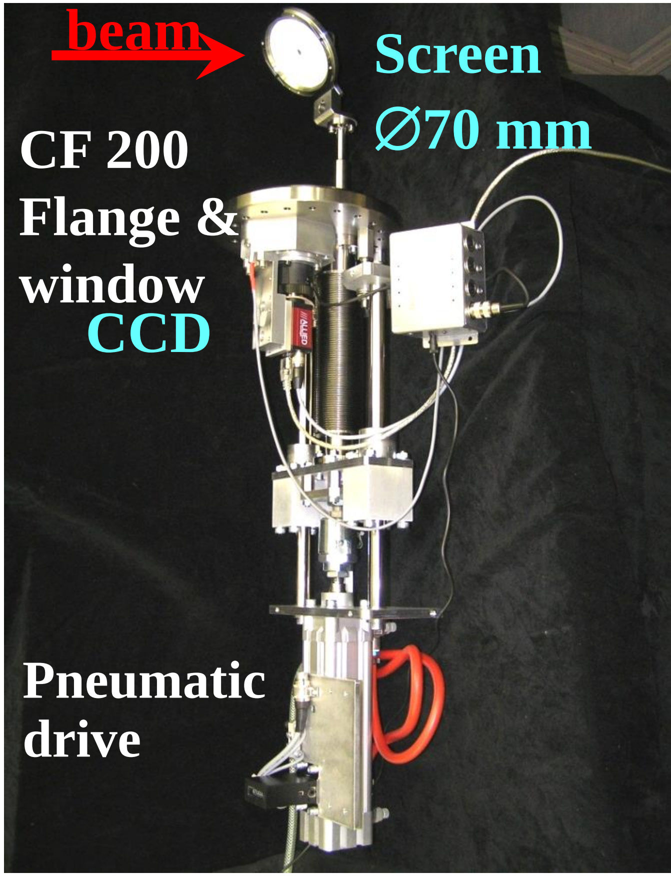
Name	Type	Material	Activ.	Max. λ	Decay
Chromox	Cera-mics	Al_2O_3	Cr	700 nm	≈ 10 ms
Alumina		Al_2O_3	Non	380 nm	≈ 10 ns
YAG:Ce	Crystal	$Y_3Al_5O_{12}$	Ce	550 nm	200 ns
P43	Powder	Gd_2O_3S	Tb	545 nm	1 ms
P46		$Y_3Al_5O_{12}$	Ce	530 nm	300 ns
P47		$Y_3Si_5O_{12}$	Ce&Tb	400 nm	100 ns

Properties of a good scintillator:

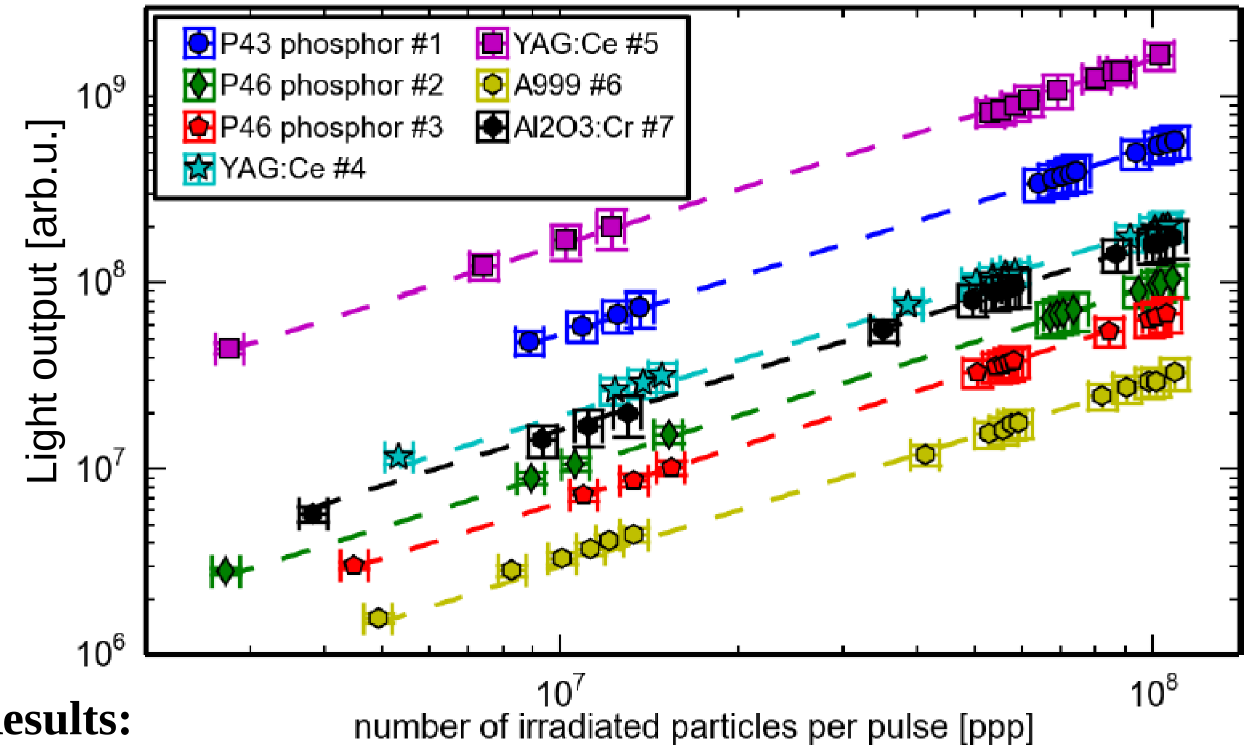
- Large light output at optical wavelength
  → standard CCD camera can be used
- Large dynamic range → usable for different ions
- Short decay time → observation of variations
- Radiation hardness → long lifetime
- Good mechanical properties → typ. size up to Ø 10 cm

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

Standard drive with P43 screen



Example: Beam images for various scintillators irradiated by Uranium at ≈ 300 MeV/u at GSI



From P. Forck et al., IPAC'14,

A. Lieberwirth et al., NIM B 2015

Results:

- Several orders of magnitude different light output
- ⇒ material matched to beam intensity must be chosen
- Well suited: powder phosphor screens P43 and P46
- → cheap, can be sedimeted on large substrates of nearly any shape
- Light output linear with respect to particles per pulse

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
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- Summary

Energy loss of ions in metals close to a surface:

Closed collision with large energy transfer: → fast e^- with E_{kin}>> 100 eV

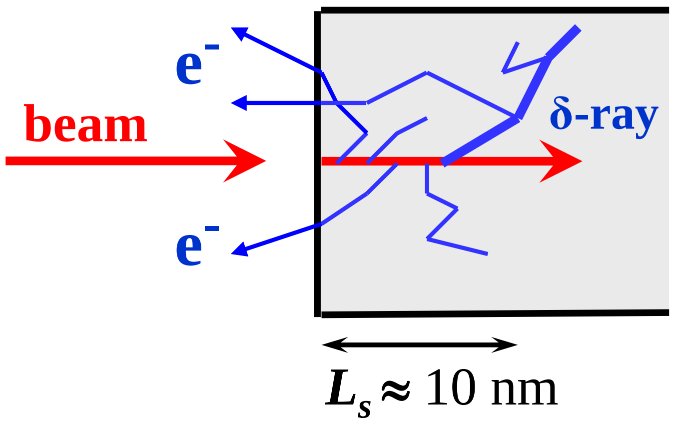
Distant collision with low energy transfer → slow e^- with $E_{kin} \lesssim$ 10 eV

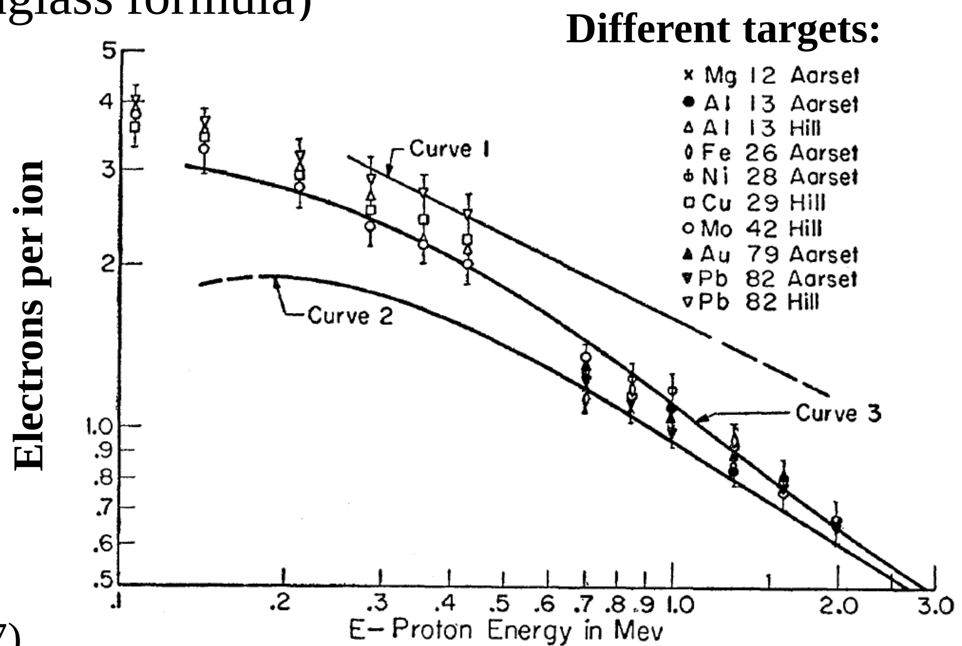
→ 'diffusion' & scattering with other e^-: scattering length $L_s \approx$ 1 - 10 nm

→ at surface ≈ 90 % probability for escape

Secondary **electron yield** and energy distribution comparable for all metals!

$$\Rightarrow \; Y = const. * dE/dx$$ (Sternglass formula)

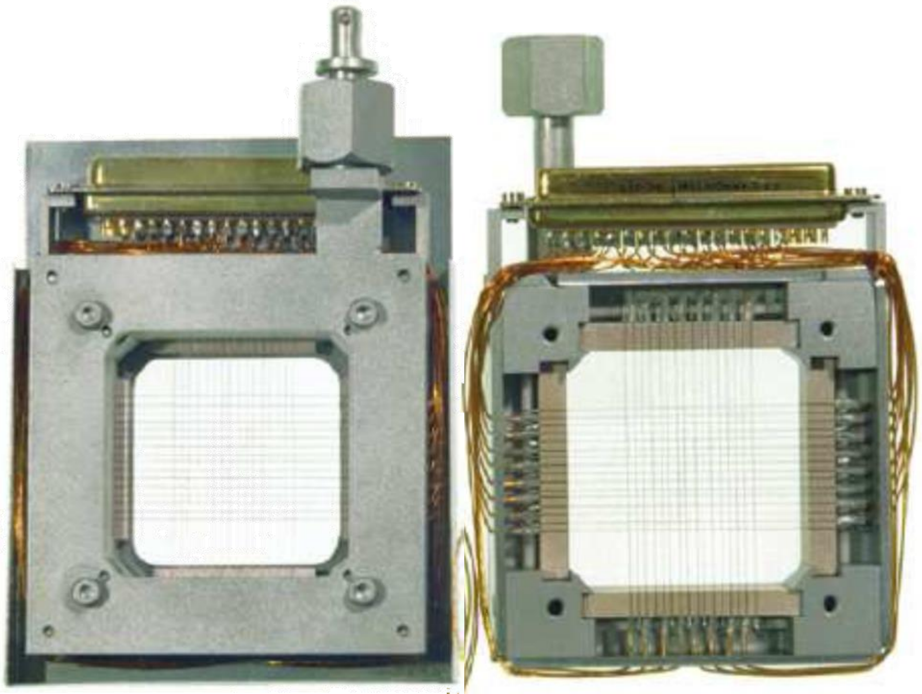




From E.J. Sternglass, Phys. Rev. 108, 1 (1957)

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

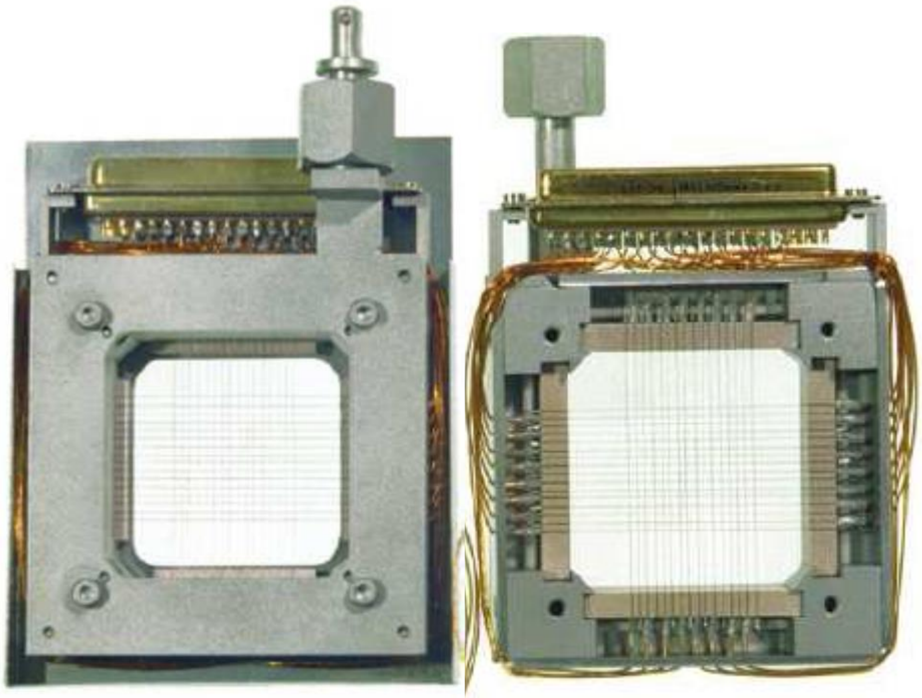
Example: 15 wire spaced by 1.5 mm:

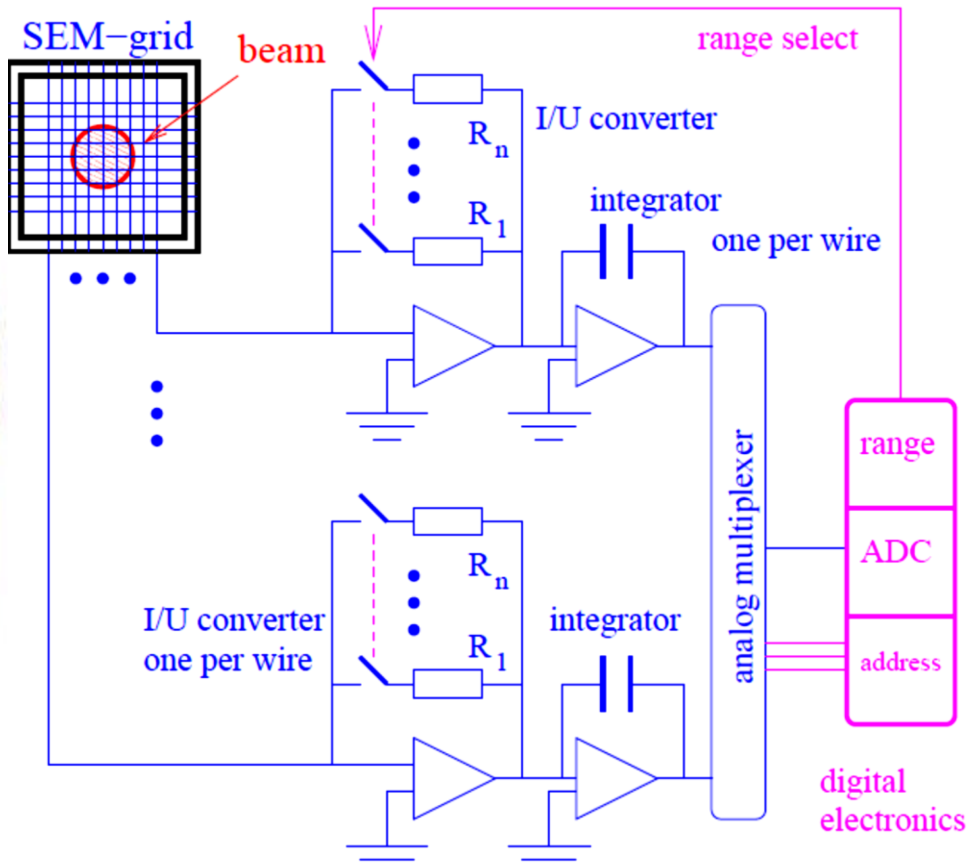


SEM-Grid feed-through on CF200:

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

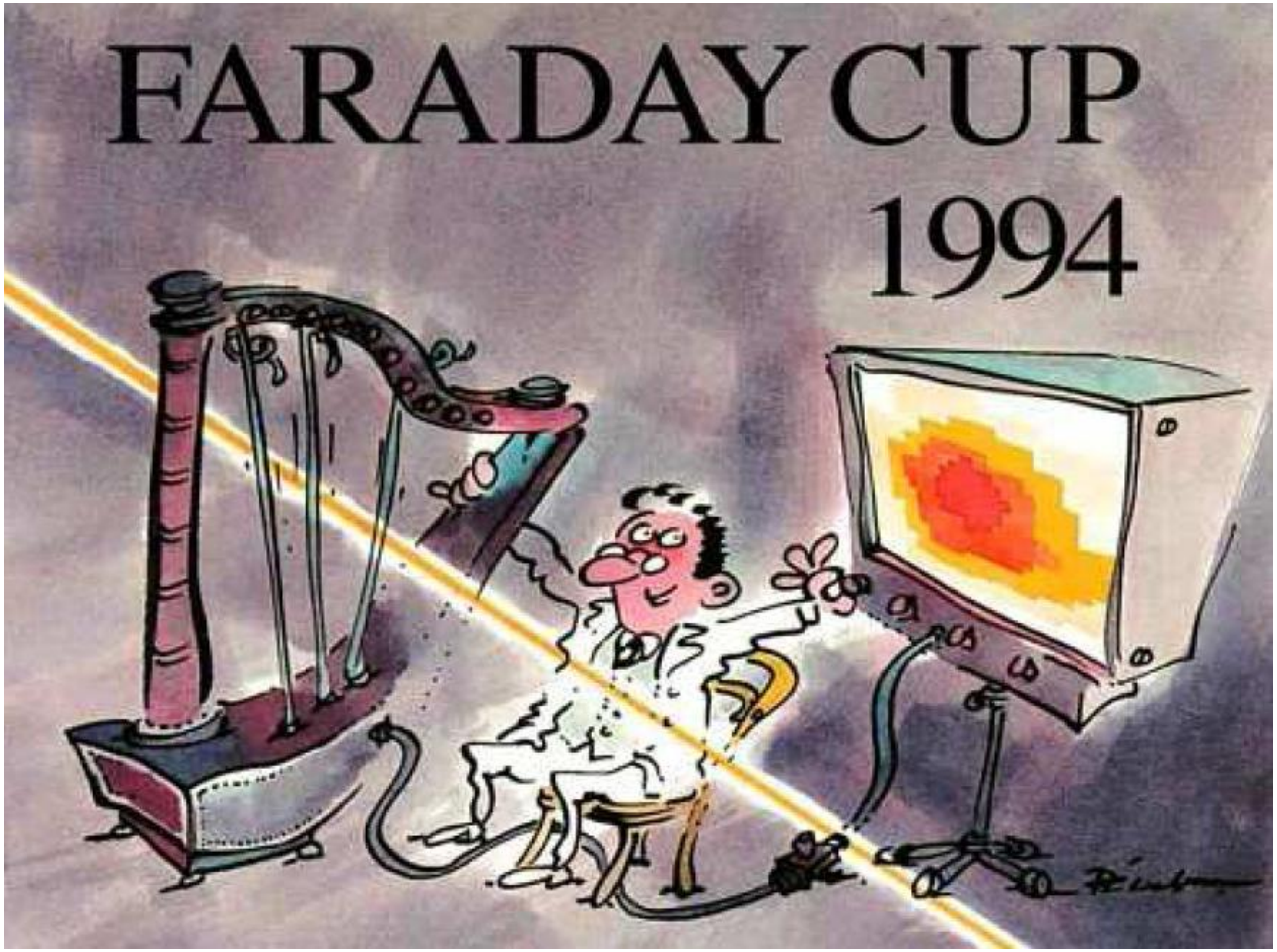
Example: 15 wire spaced by 1.5 mm:





Each wire is equipped with one I/U converter
different ranges settings by 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 .

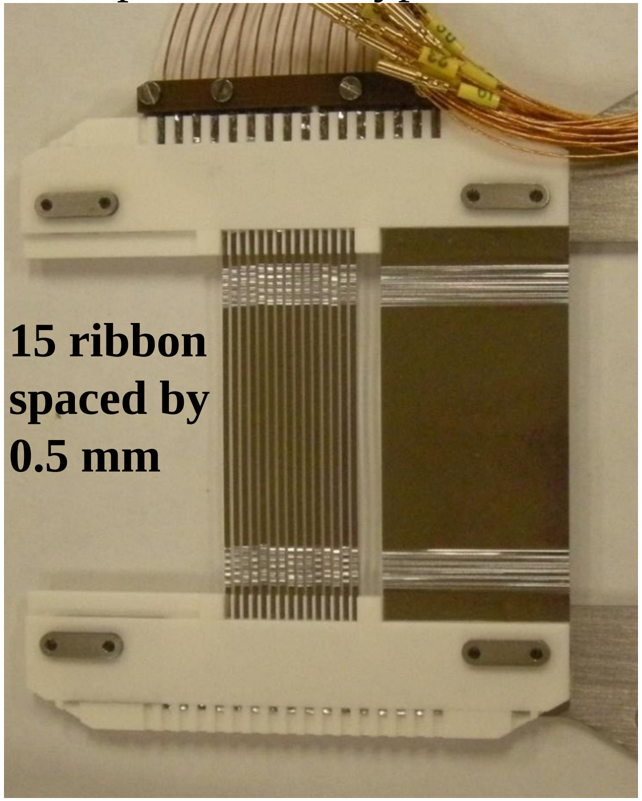
Properties of a SEM-Grid

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

Specifications for SEM-Grids 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

Example: Ribbon type SEM-Grid



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

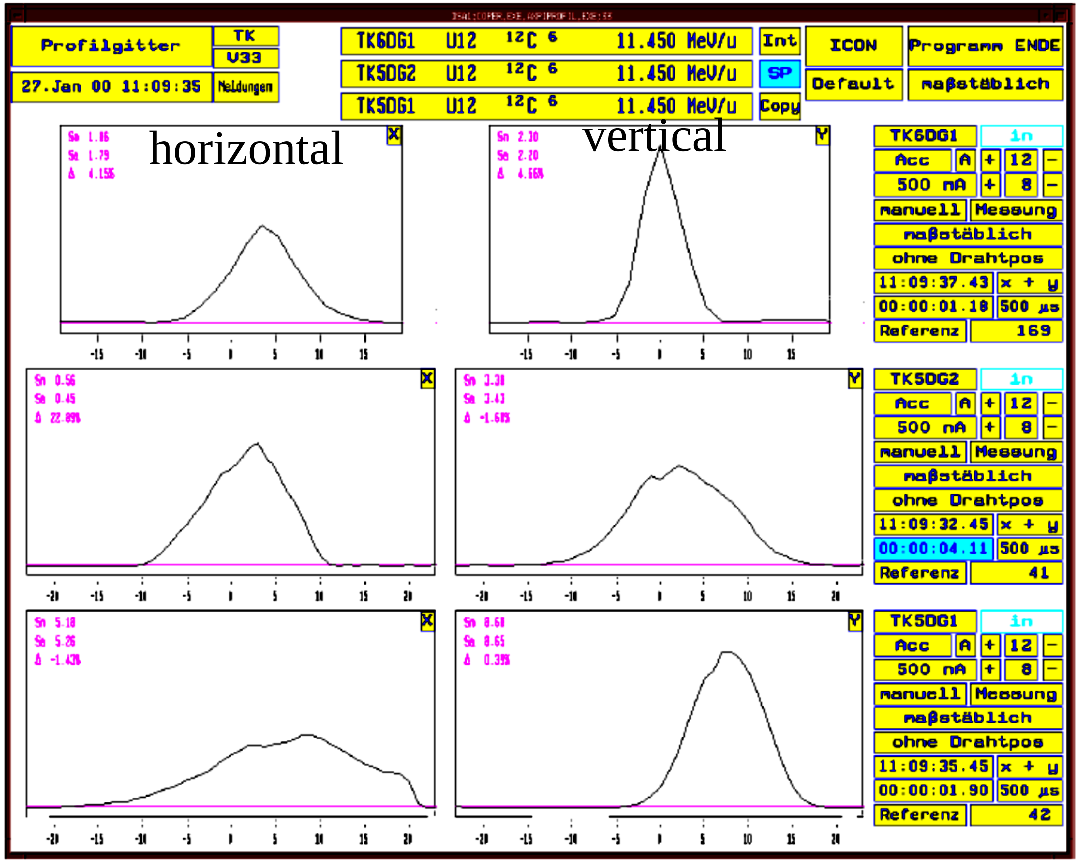
Low energy beam: **Wires** with ratio of spacing/width: ≃ 1mm/0.1mm = 10 → only 10 % loss.

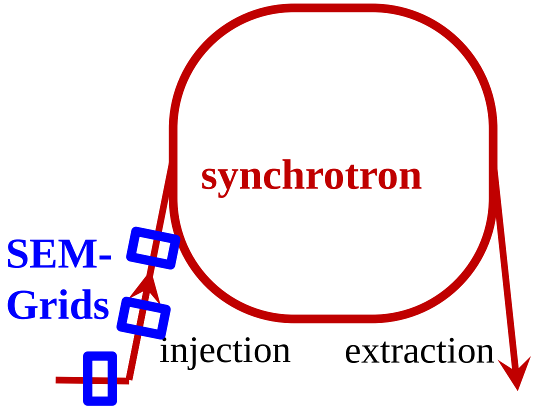
High energy E_{kin} > 1 GeV/u: typ. 25 μm thick **ribbons** & 0.5 mm width → negligible energy loss.

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 locations at GSI-LINAC





Outline:

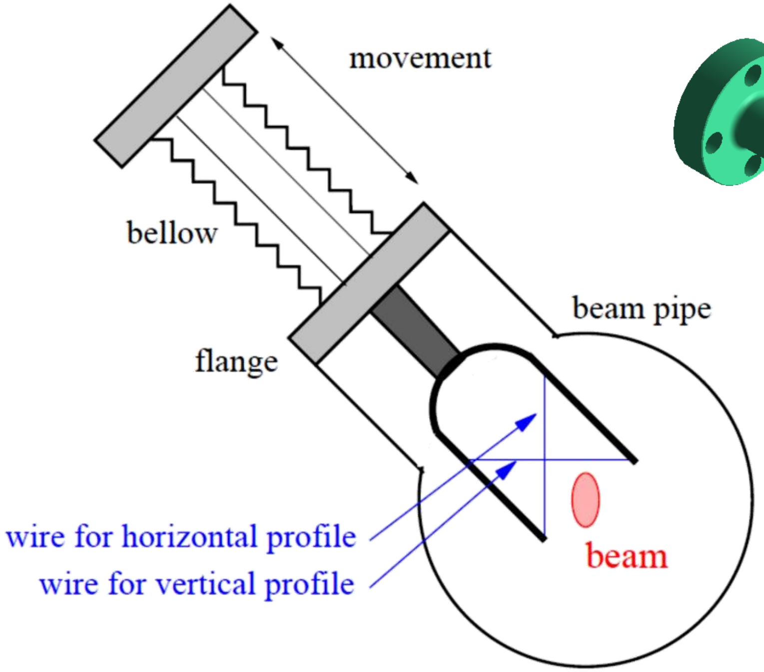
- Scintillation screens:

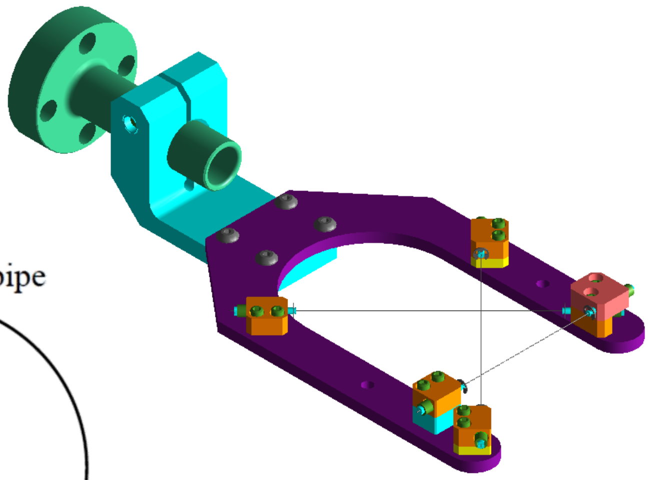
  emission of light, universal usage, limited dynamic range
- SEM-Grid: emission of electrons, workhorse, limited resolution
- **Wire scanner:** emission of electrons, workhorse, scanning method
- Ionization Profile Monitor and Beam Induced Fluorescence Monitor
- Optical Transition Radiation
- Synchrotron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

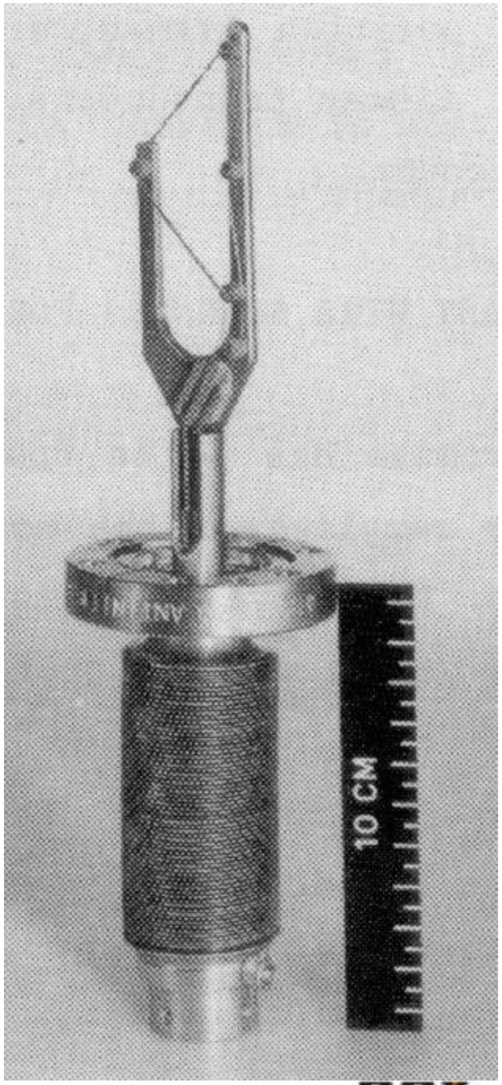
Idea: One wire is scanned through the beam!

Slow, linear scanner are used for:

- low energy protons
- 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.





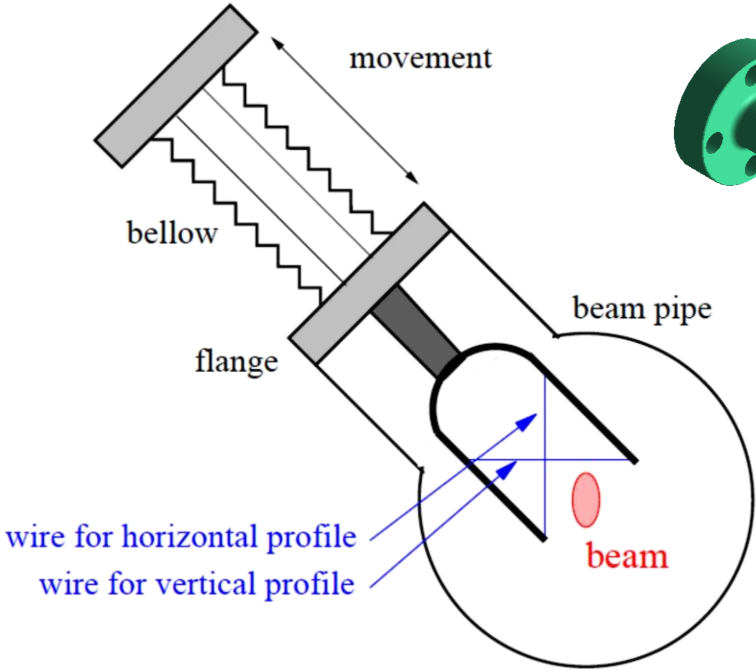


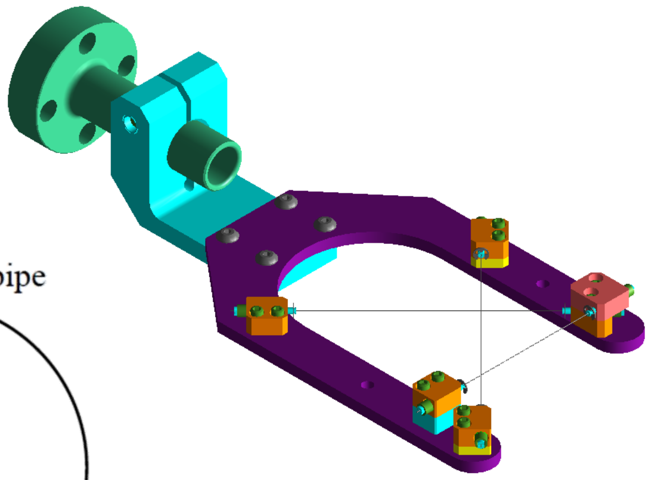
Slow, linear Wire Scanner

Idea: One wire is scanned through the beam!

Slow, linear scanner are used for:

- low energy protons
- 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.

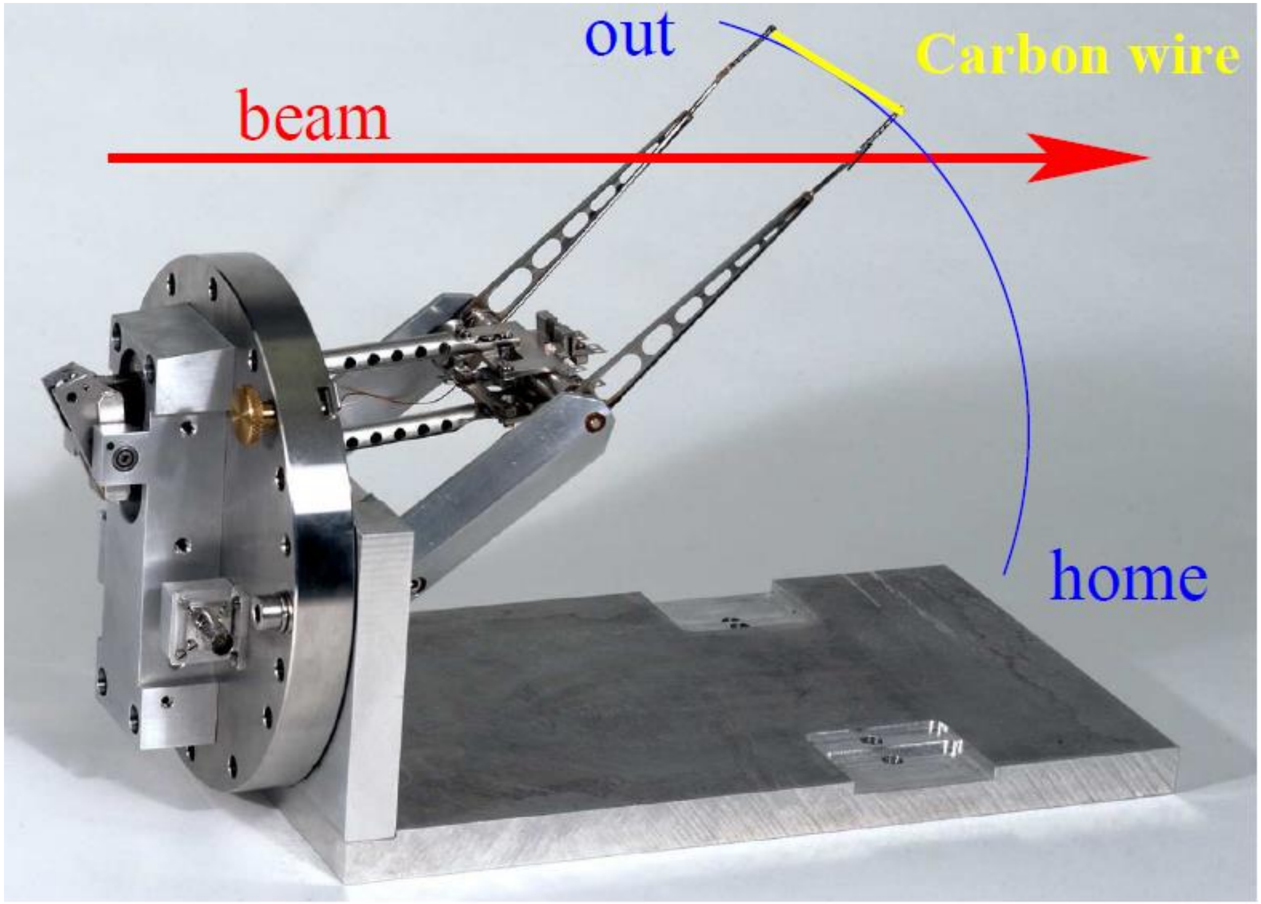




The Artist view of a Beam Scraper or Scanner

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

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



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

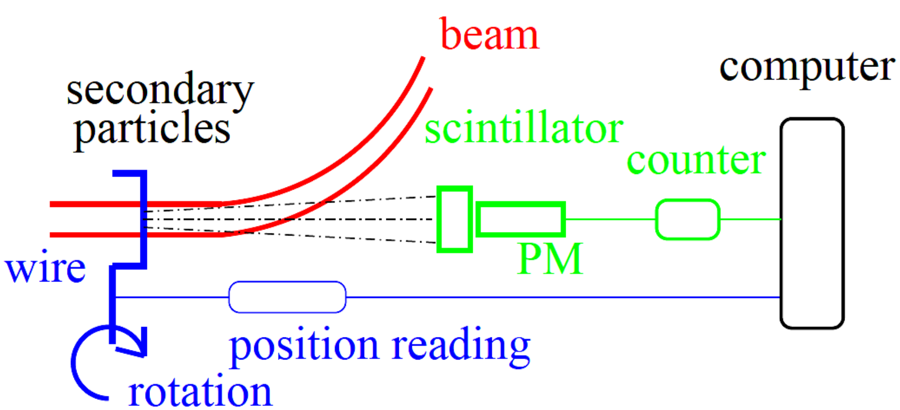
Thickness: down to 10 µm → high resolution.

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.

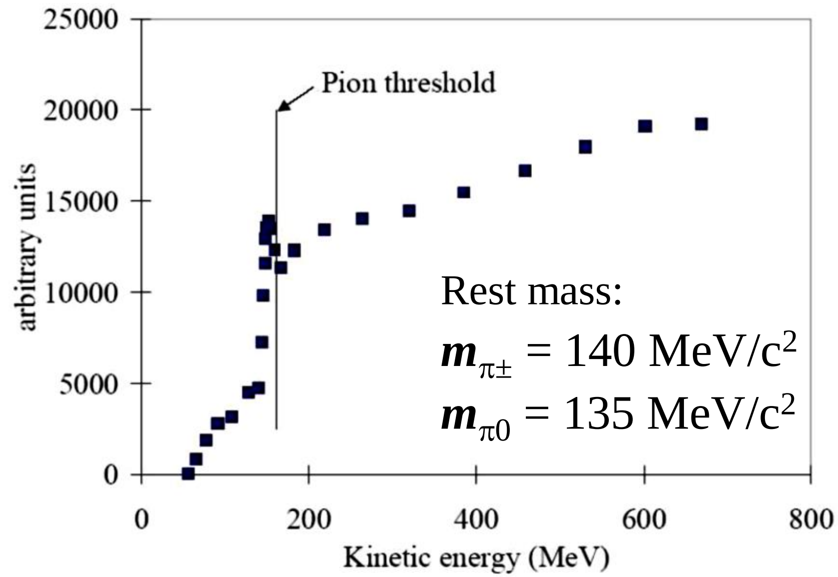
Secondary particles:

Proton beam → hadrons shower (π, n, p...)

Electron beam → Bremsstrahlung photons.



Proton impact on scanner at CERN-PS Booster:

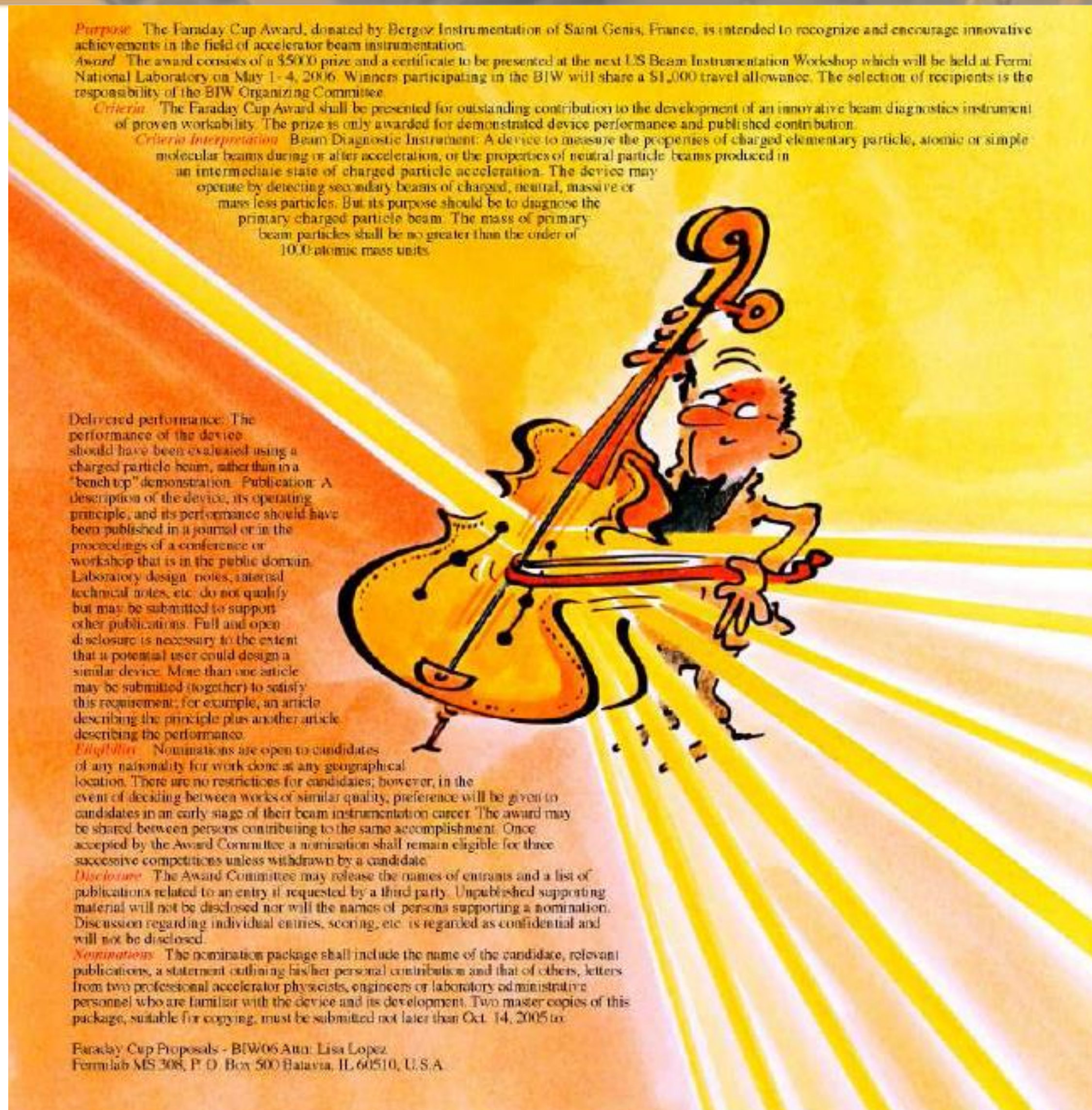


Kinematics of flying wire:

Velocity during passage typically 10 m/s = 36 km/h and typical beam size ∅ 10 mm

⇒ time for traversing the beam $t \approx 1$ ms

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 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.

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:

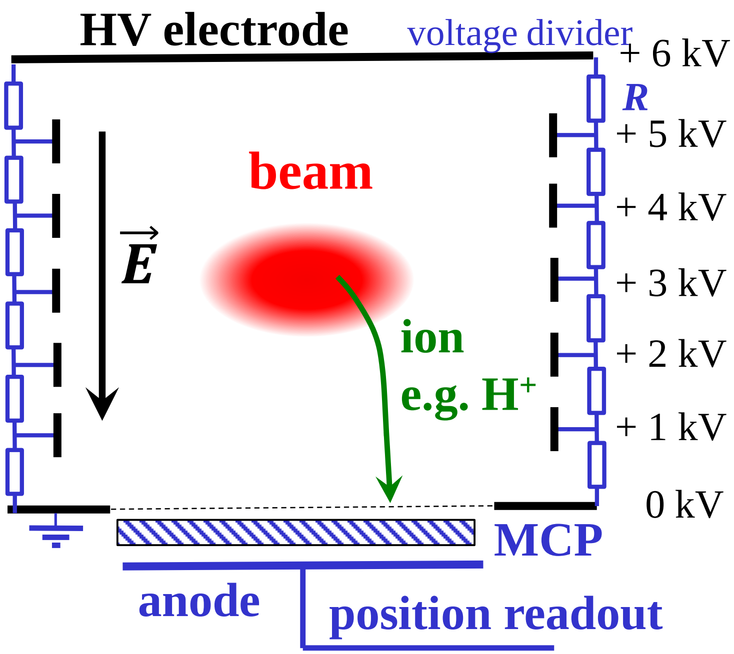
- Scintillation screens:

  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



Typical vacuum pressure:

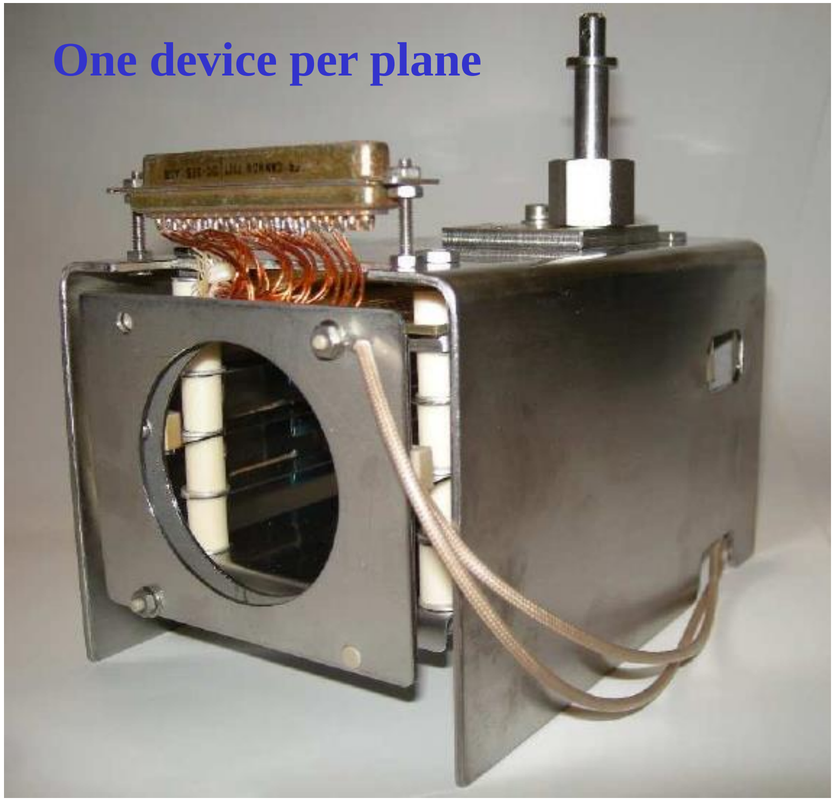
Transfer line: N_2 $10^{-8}...10^{-6}$ mbar ≅ $3\cdot10^{8}...3\cdot10^{10}cm^{-3}$

Synchrotron: H_2 $10^{-11}...10^{-9}$ mbar ≅ $3\cdot10^{5}...3\cdot10^{7}cm^{-3}$

IPM for the use at the GSI LINAC:

Vacuum p ≃ 10^{-7} mbar, I ≃ 1 mA

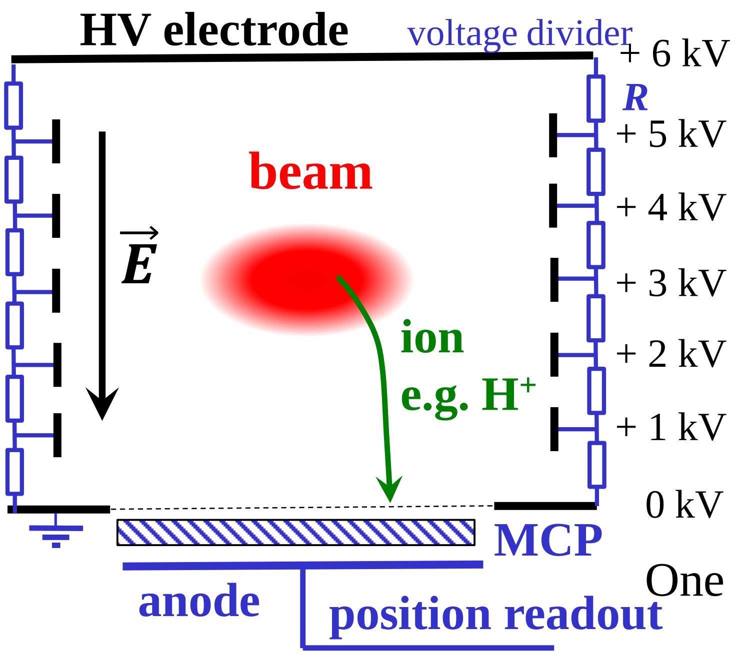
Readout by strips fed to an I/U converter.



Ionization Profile Monitor at GSI Synchrotron

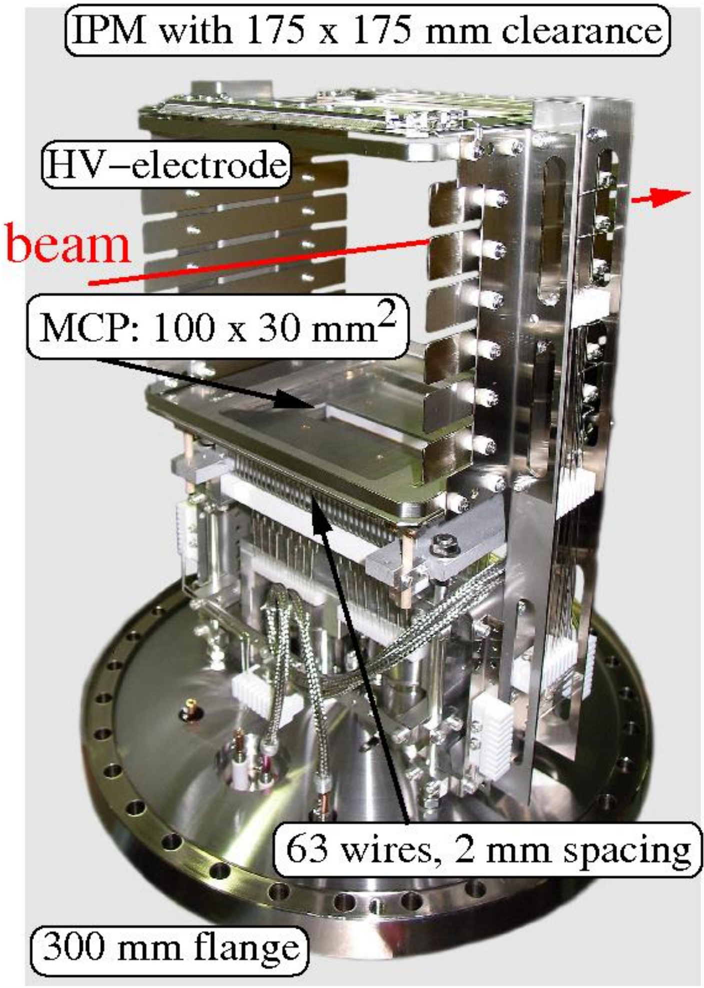
Non-destructive device for proton synchrotron:

- 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:

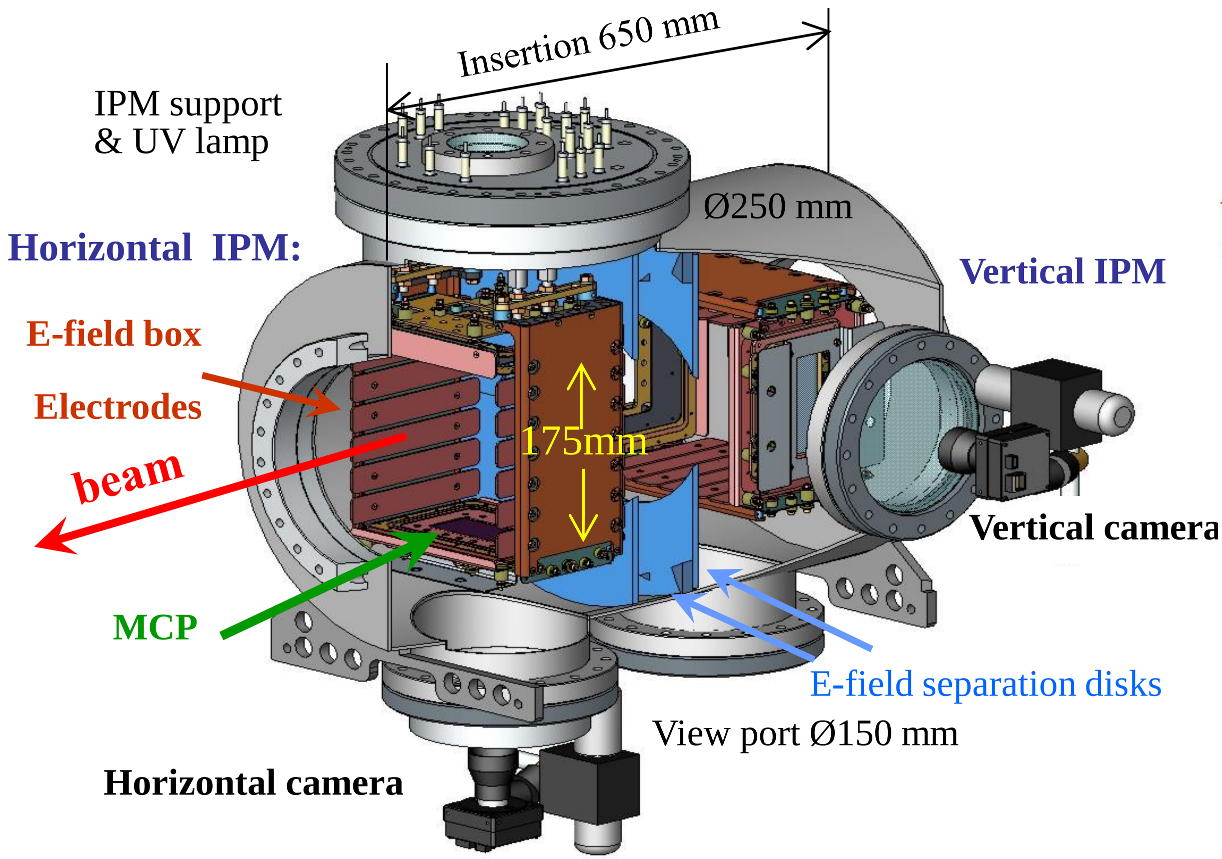


Typical vacuum pressure:

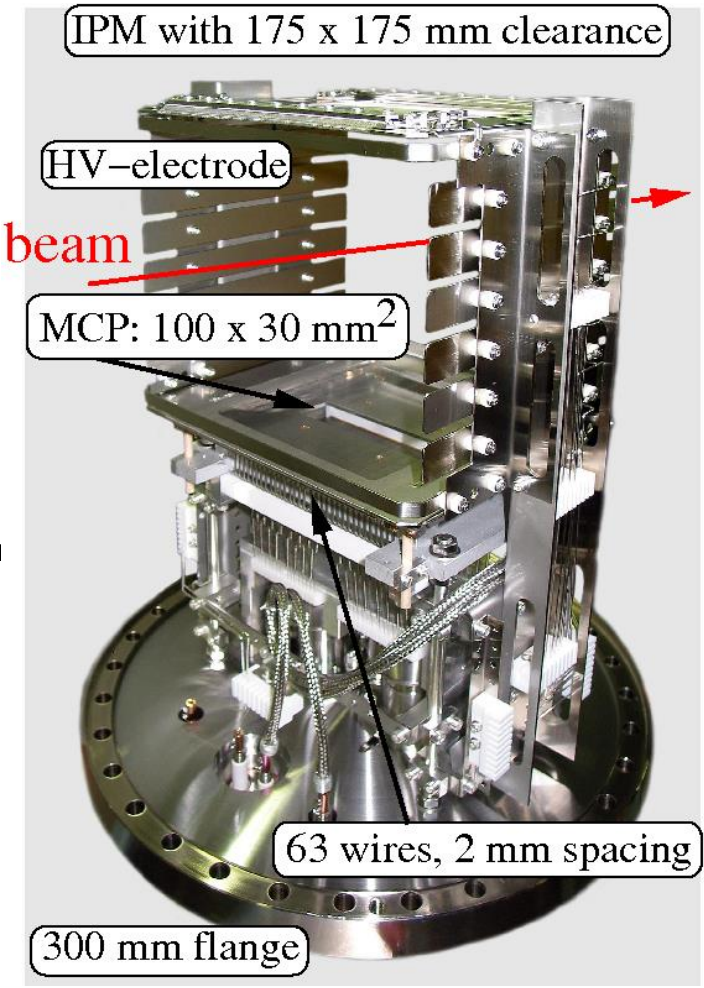
Transfer line: N_2 $10^{-8}...10^{-6}$ mbar $\cong 3\cdot10^{8}...3\cdot10^{10}$ cm^{-3}

Synchrotron: H_2 $10^{-11}...10^{-9}$ mbar $\cong 3\cdot10^{5}...3\cdot10^{7}$ cm^{-3}

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

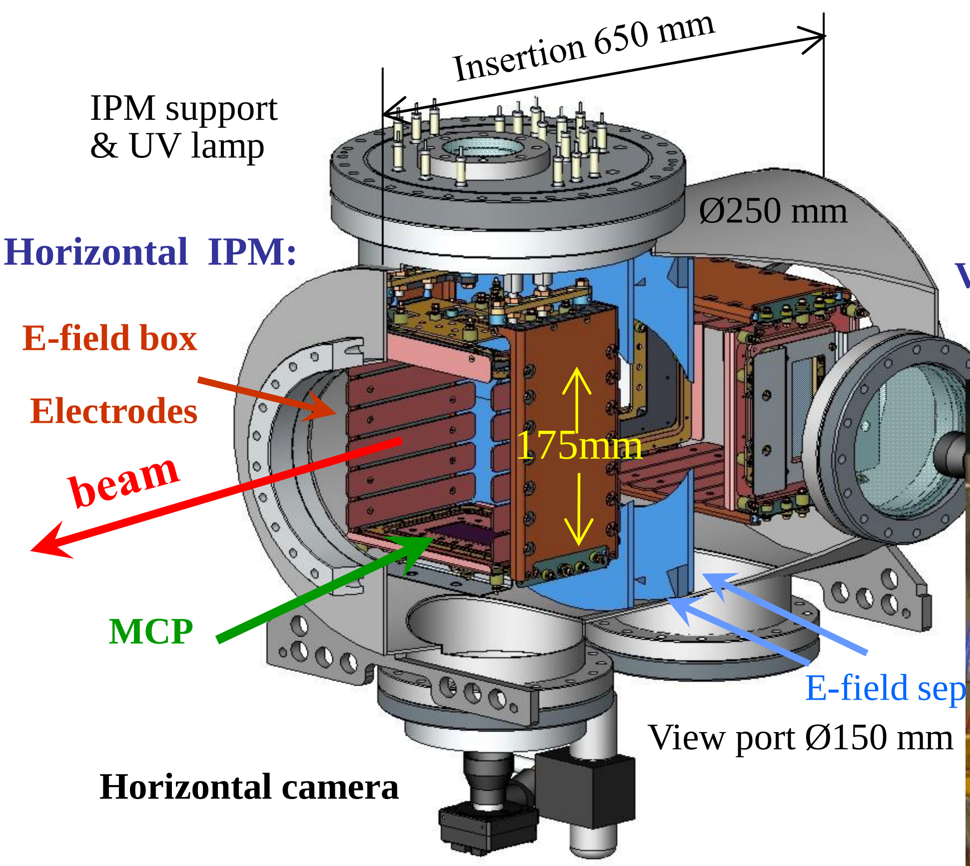


Realization at GSI synchrotron:



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

Realization at GSI synchrotron:



MCP are used as particle detectors with secondary electron amplification.

A MCP is:

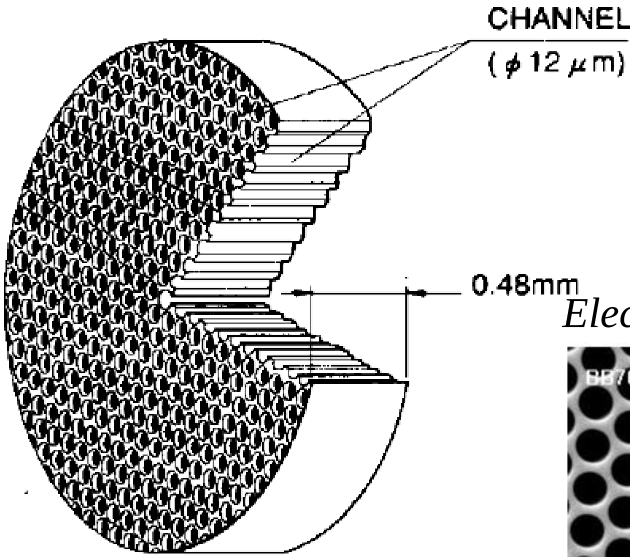
- 1 mm glass plate with ≈10 μm holes
- thin Cr-Ni layer on surface
- voltage ≈1 kV/plate across

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

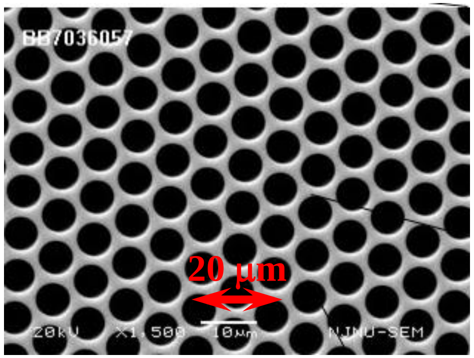
→ resolution ≈ 0.1 mm (2 MCPs)

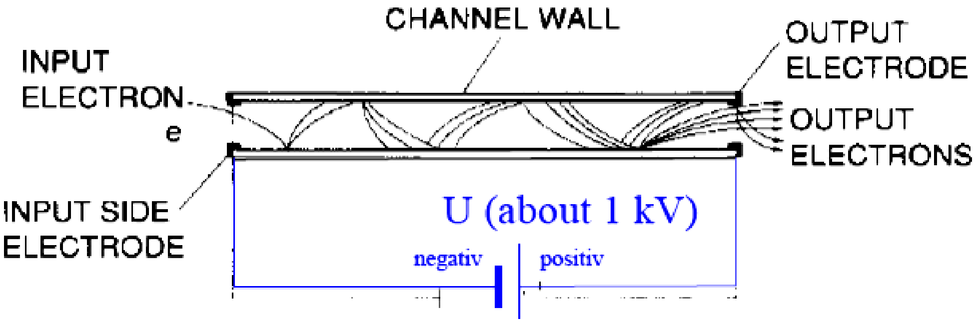
Anode technologies:

- 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.



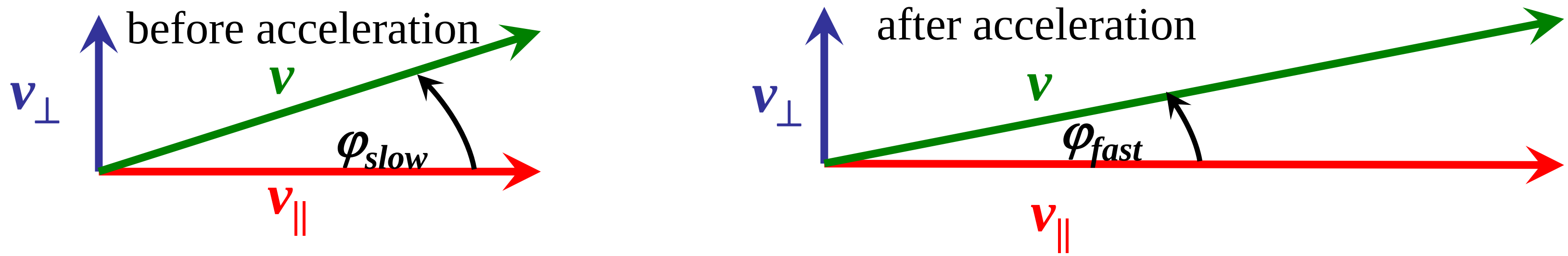
Electron microscope image:





Application: 'Adiabatic' Damping during Acceleration

The emittance $\varepsilon = \int dx dx'$ is defined via the position deviation and angle in **lab-frame**



After acceleration the longitudinal velocity is increased $\Rightarrow$ angle φ is smaller

The angle is expressed in momenta: $x' = p_\perp / p_\parallel$

the emittance is for $<xx'> = 0$: $\varepsilon = x \cdot x' = x \cdot p_\perp / p_\parallel = const.$

$\Rightarrow$ under ideal conditions the emittance can be normalized to the momentum $p_\parallel = \gamma \cdot m \cdot \beta c$

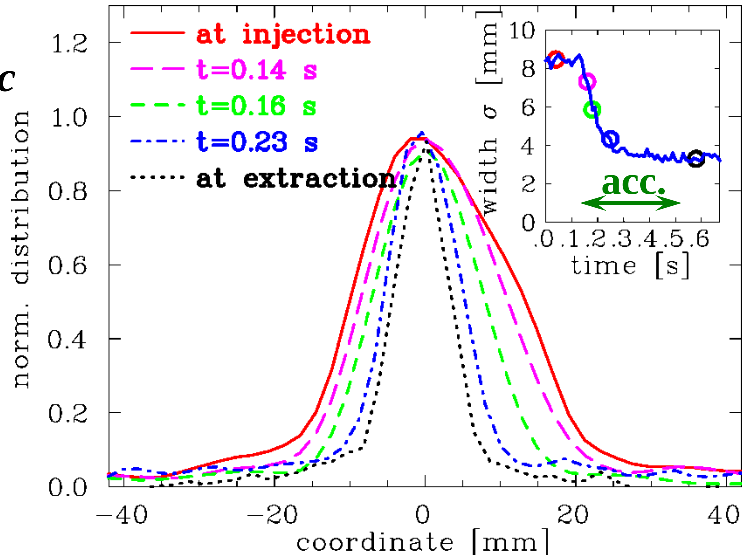
$\Rightarrow$ normalized emittance $\varepsilon_{norm} = \beta \gamma \cdot \varepsilon$ is preserved

with the Lorentz factor $\gamma = (1-\beta^2)^{-1/2}$ and velocity $\beta = v/c$

Example: Acceleration in GSI-synchrotron for C^{6+} from 6.7 $\rightarrow$ 600 MeV/u (β = 12 $\rightarrow$ 79%) observed by IPM

theoretical width: $\langle x \rangle_f = \sqrt{\frac{\beta_i \cdot \gamma_i}{\beta_f \cdot \gamma_f}} \cdot \langle x \rangle_i = 0.33 \cdot \langle x \rangle_i$

measured width: $\langle x \rangle_f \approx 0.37 \cdot \langle x \rangle_i$



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

Influence of the residual gas ion trajectory by :

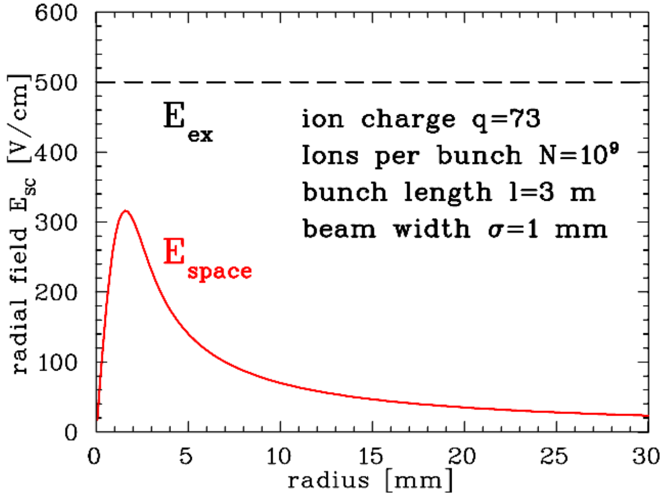
- External electric field $\boldsymbol{E_{ex}}$
- Electric field of the beam's space charge $\boldsymbol{E_{space}}$

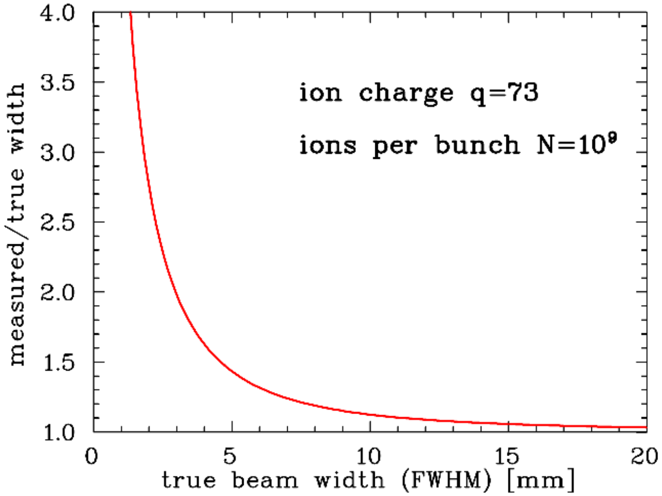
e.g. Gaussian density distribution for round beam: $E_{space}(r) = \frac{1}{2\pi\varepsilon_0} \cdot \frac{qeN}{l} \cdot \frac{1}{r} \cdot \left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right]$

Estimation of correction: $\sigma_{corr}^2 \approx \frac{e^2 \ln 2}{4\pi\varepsilon_0 \sqrt{m_p c^2}} \cdot \frac{qN}{l} \cdot d_{gap} \cdot \sqrt{\frac{1}{eU_{ex}}} \propto N \cdot d_{gap} \cdot \sqrt{\frac{1}{U_{ex}}}$

With the measured beam width is given by convolution: $\sigma_{meas}^2 = \sigma_{true}^2 + \sigma_{corr}^2$

Example: U^{73+}, 10^9 particles per 3 m bunch length, cooled beam with $\boldsymbol{\sigma_{true}}$ = 1 mm FWHM.

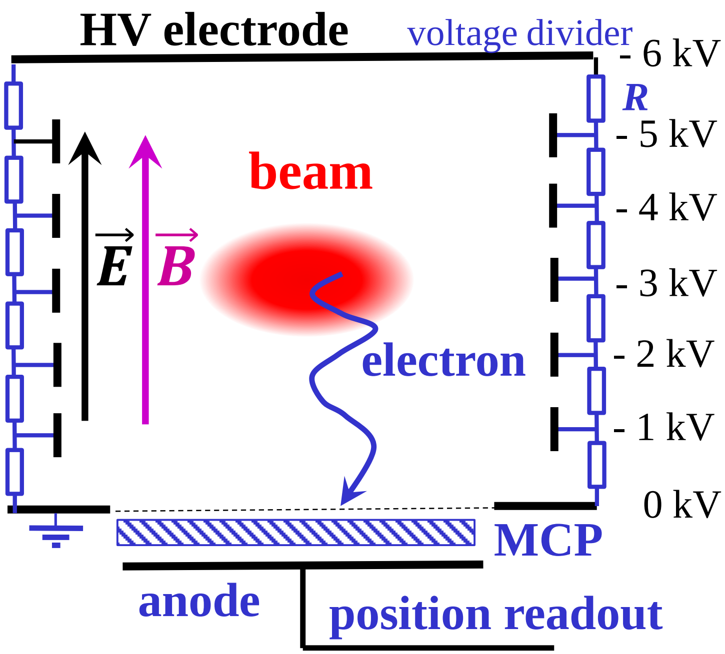


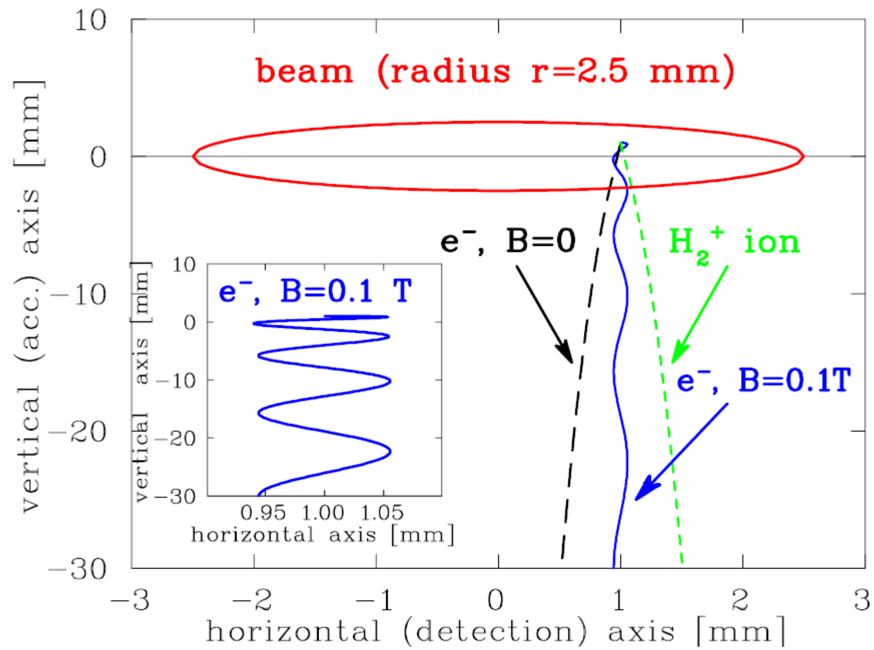


Alternative: e^- detection in an external magnetic field

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

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





Time-of-flight: ≈1 ns $\rightarrow$ 2 or 3 cycles.

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

Magnetic field for electron guidance:

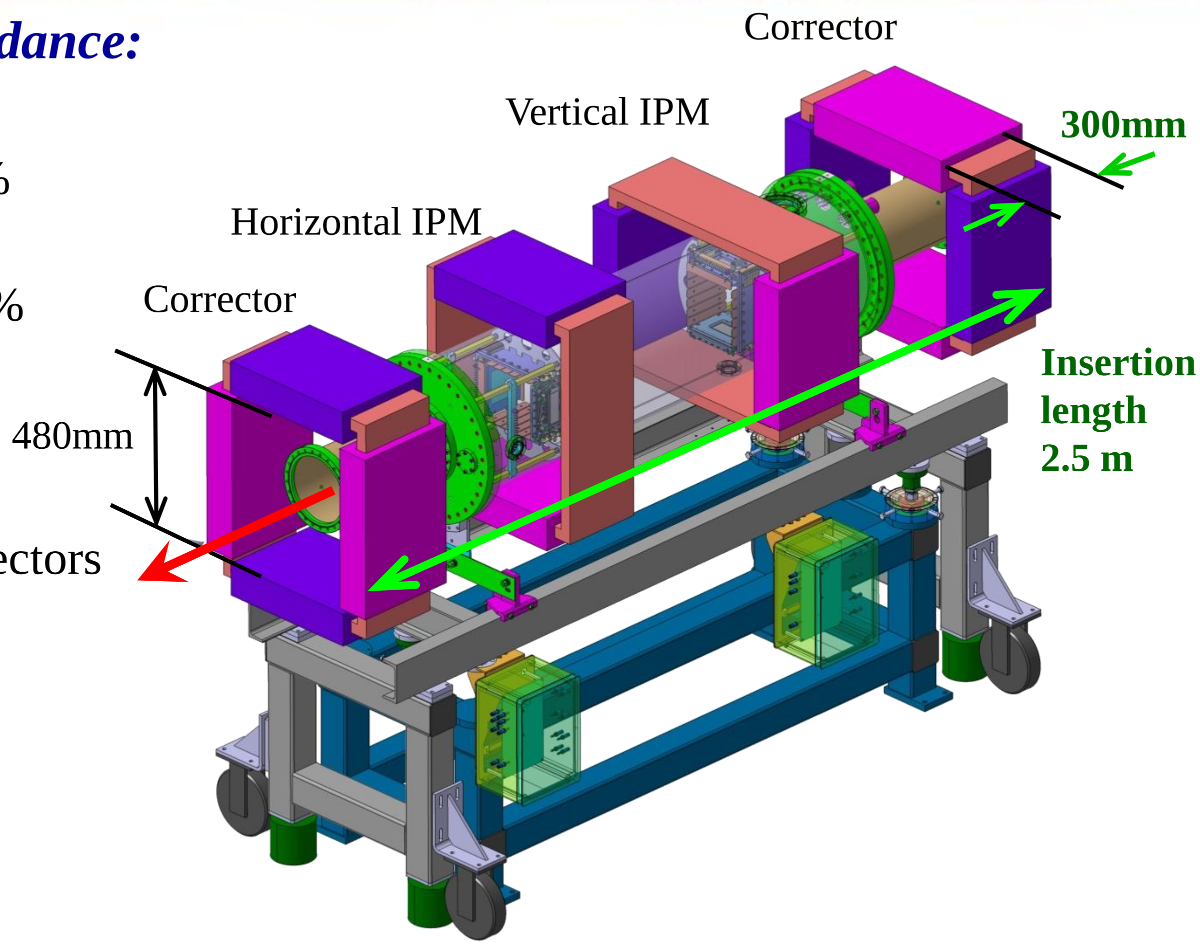
Maximum image distortion:

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

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



Magnetic field for electron guidance:

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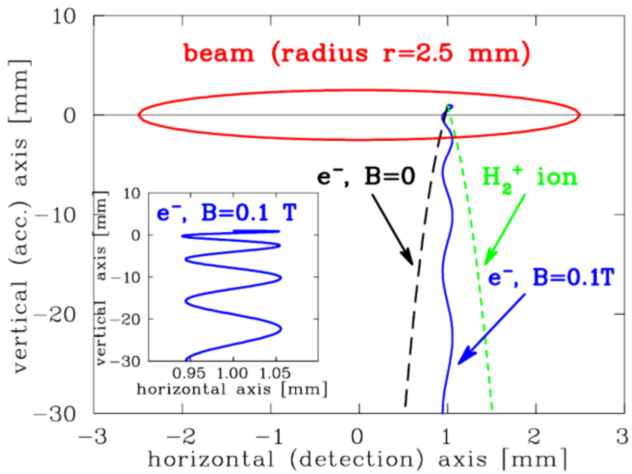
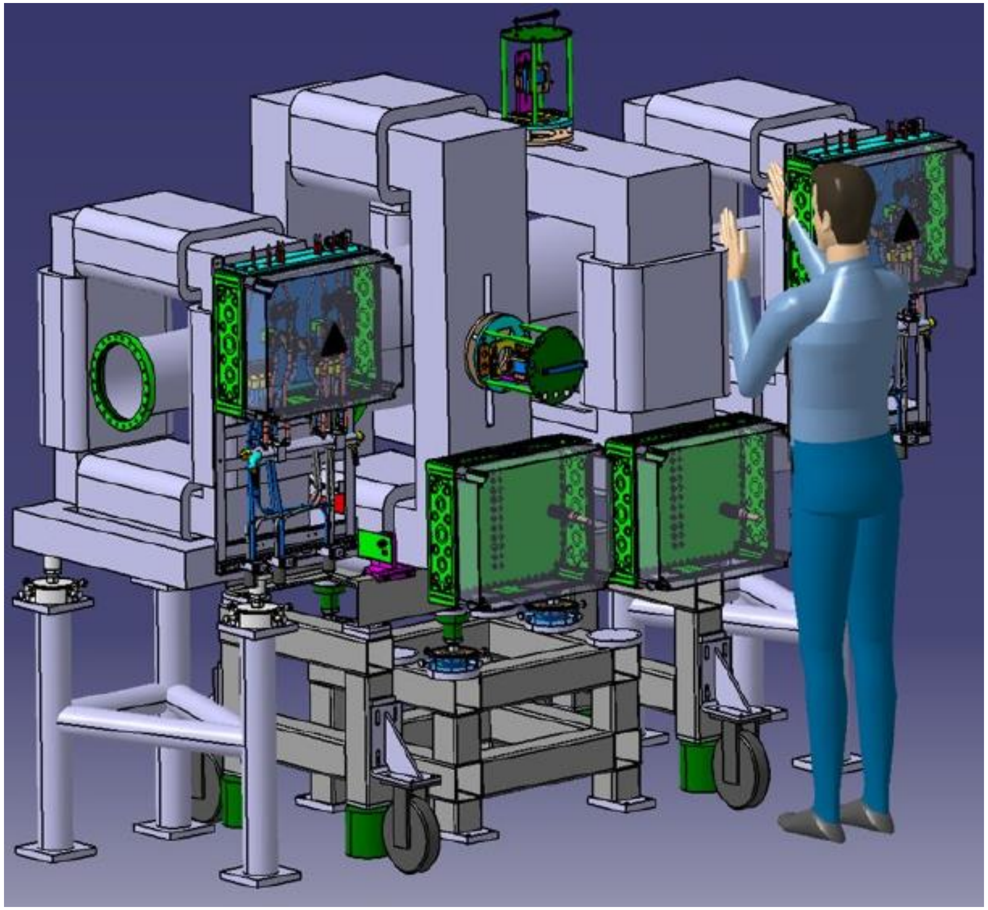


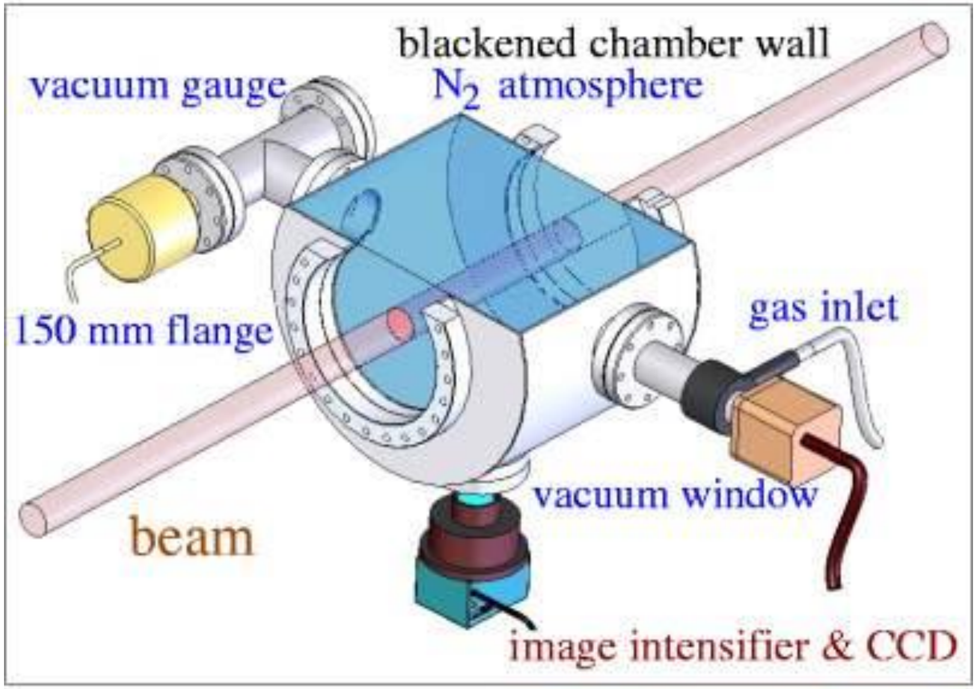


Remark: For MCP wire-array readout lower clearance required

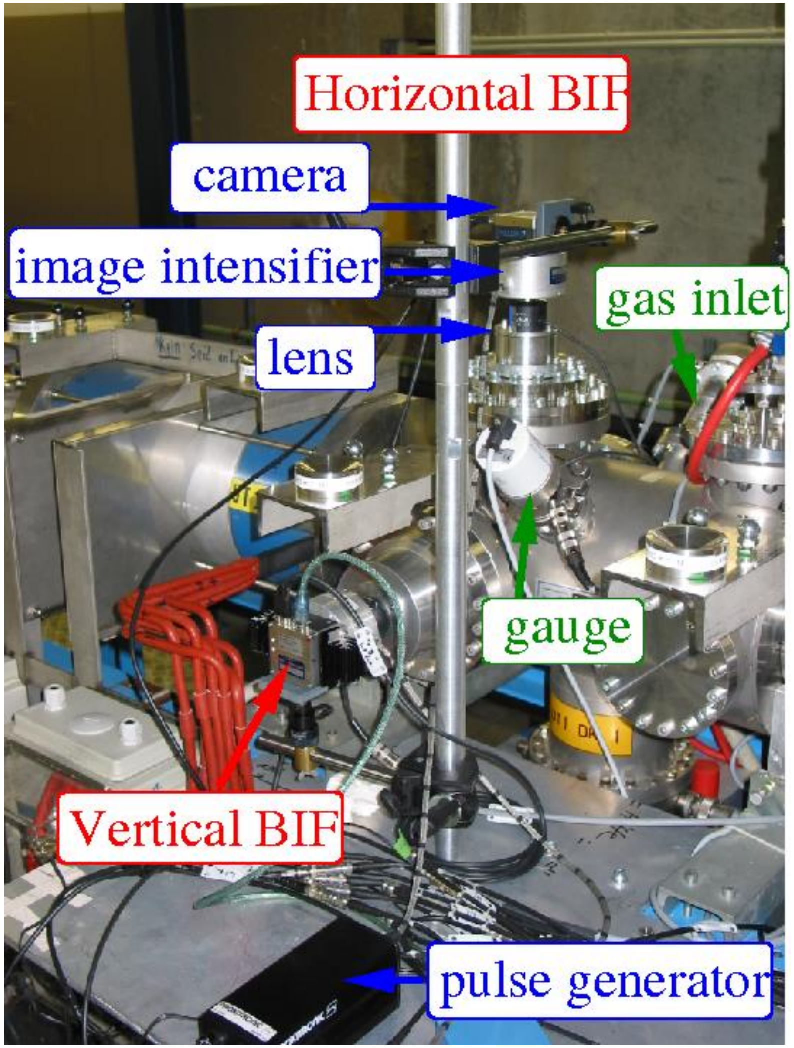
Beam Induced Fluorescence for intense Profiles

Large beam power → Non-intercepting method:
⇒ **B**eam **I**nduced **F**luorescence BIF

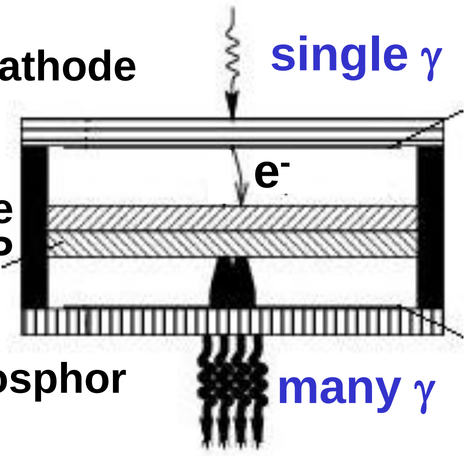
N_2 + Ion → $(N_2^{+})^*$+ Ion → N_2^{+} + γ + Ion
With single photon detection scheme
390 nm< λ< 470 nm
⇒ non-destructive, compact installation.



Installation of hor&vert. BIF Monitor:



Scheme of Image intensifier:



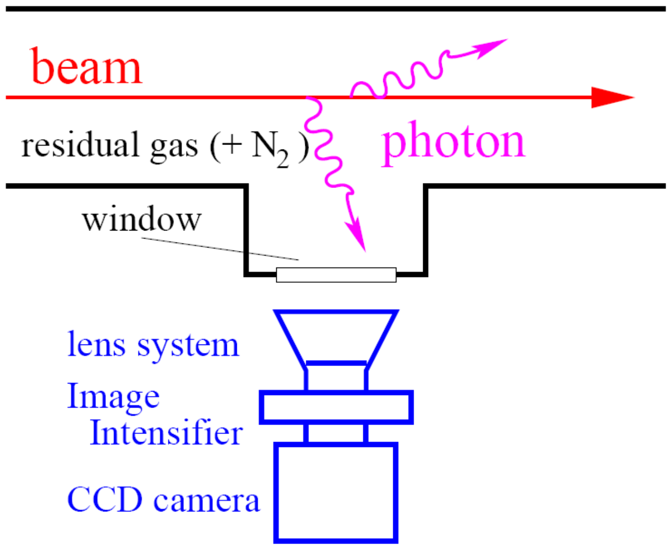


Image intensifier:

- ➢ 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)

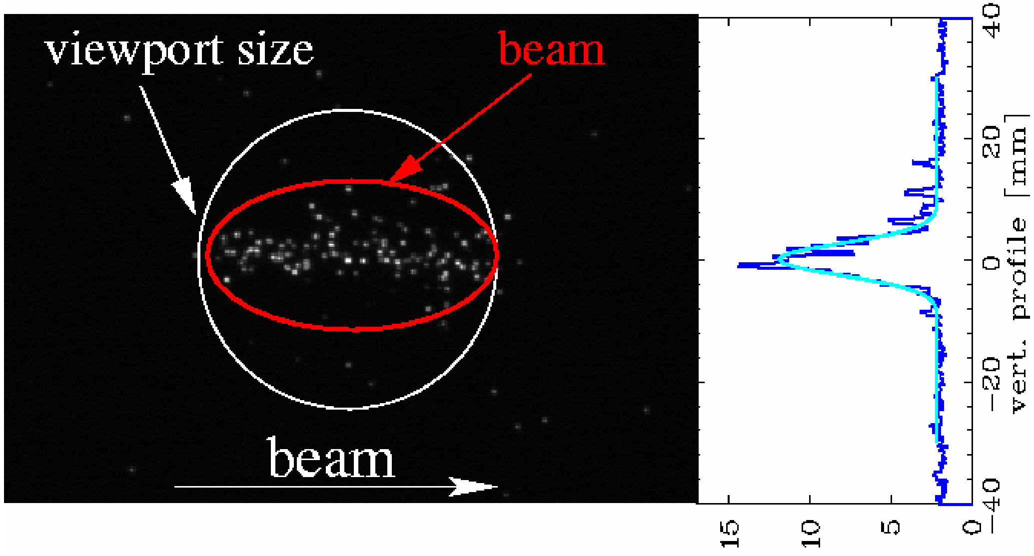
A BIF monitor consists of only:

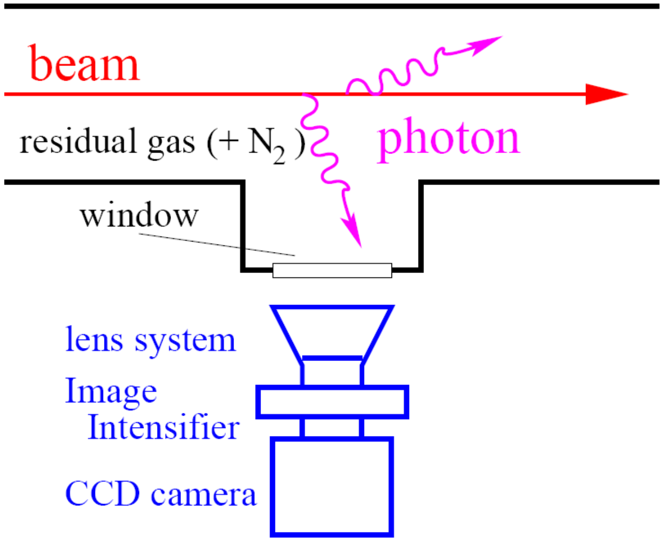
- ➢ optics outside beam pipe
- ➢ image intensifier + camera
- ➢ gas-inlet for pressure increase

⇒ 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 $\Omega \approx 10^{-4}$

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

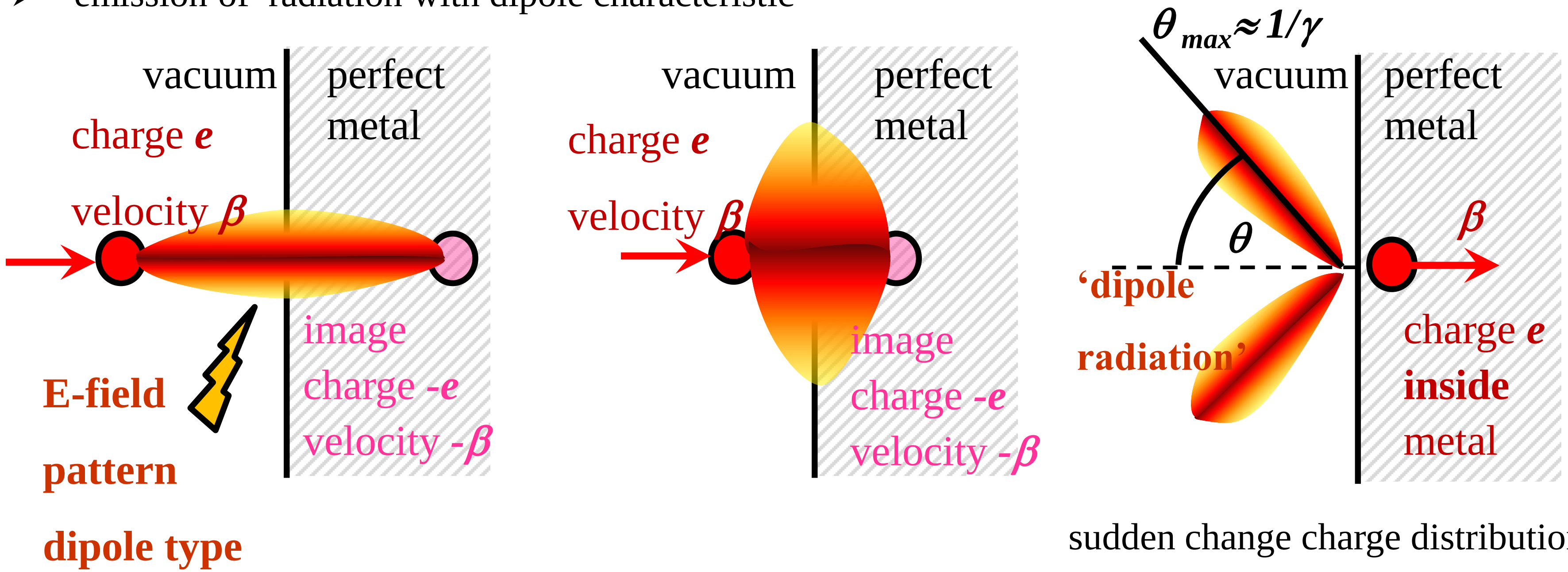
Outline:

- 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 for a single charge *e*:

Assuming a charge ***e*** approaches an ideal conducting boundary e.g. metal foil

- image charge is created by electric field
- dipole type field pattern
- field distribution depends on velocity β and Lorentz factor γ due to relativistic trans. field increase
- penetration of charge through surface within t < 10 fs: sudden change of source distribution
- emission of radiation with dipole characteristic



sudden change charge distribution
rearrangement of sources ⇔ radiation

Other physical interpretation: Impedance mismatch at boundary leads to radiation

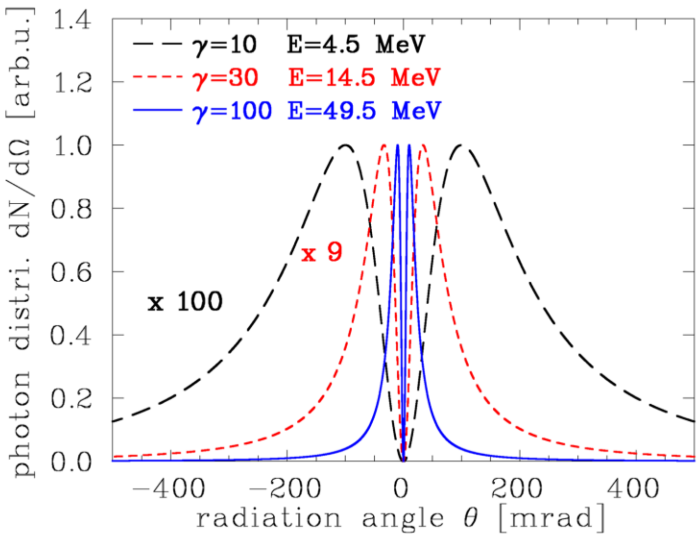
Optical Transition Radiation OTR can be described in classical physics:

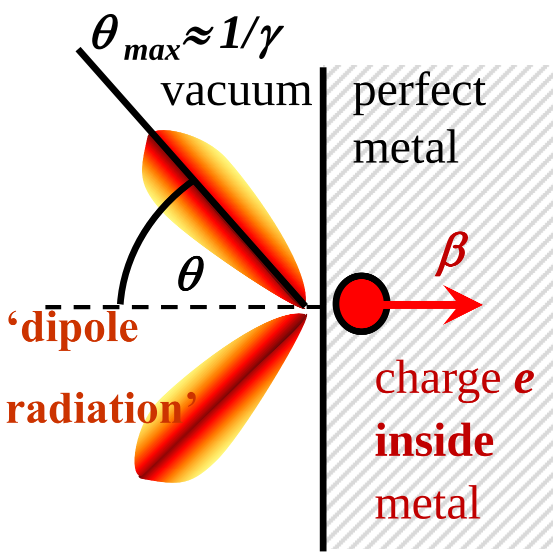
approximated formula for normal incidence & in plane polarization:

$$\frac{d^2W}{d\theta\, d\omega} \approx \frac{2e^2\beta^2}{\pi c} \cdot \frac{\sin^2\theta \cdot \cos^2\theta}{\left(1-\beta^2\cos^2\theta\right)^2}$$

W: radiated energy

ω: frequency of wave





Angular distribution of radiation in optical spectrum:

- lope emission pattern depends on velocity or Lorentz factor γ
- peak at angle $\theta \approx 1/\gamma$
- emitted energy i.e. amount of photons scales with $W \propto \beta^2$
- broad wave length spectrum (i.e. no dependence on ω)

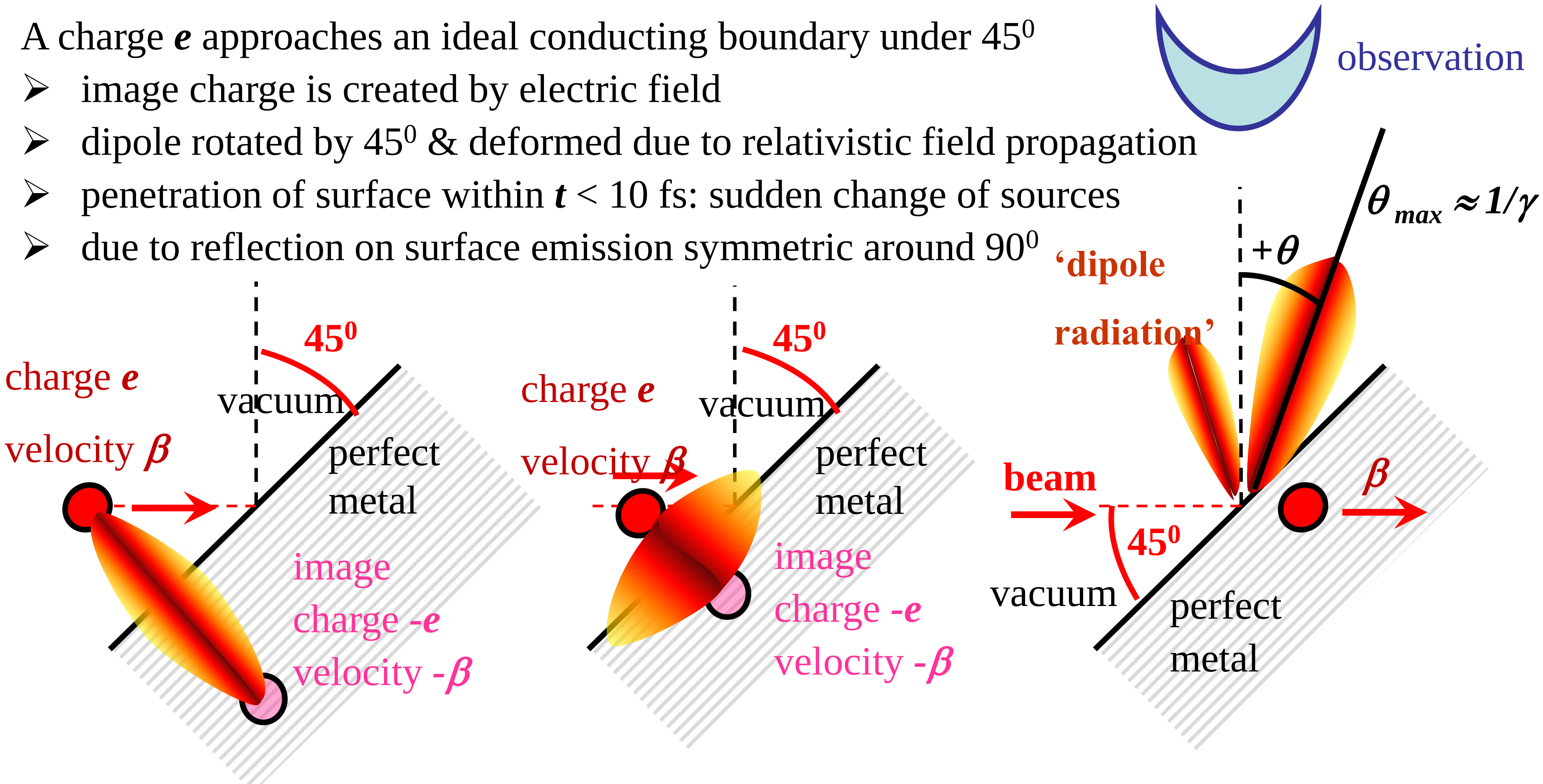
→ suited for high energy electrons

sudden change charge distribution
rearrangement of sources ⇔ radiation

OTR with 45^0 beam incidence and observation at 90^0 :

A charge ***e*** approaches an ideal conducting boundary under 45^0

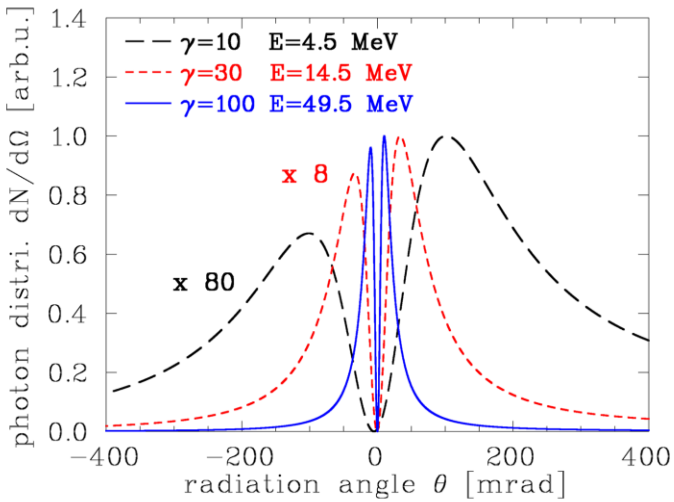
- image charge is created by electric field
- dipole rotated by 45^0 & deformed due to relativistic field propagation
- penetration of surface within ***t*** < 10 fs: sudden change of sources
- due to reflection on surface emission symmetric around 90^0

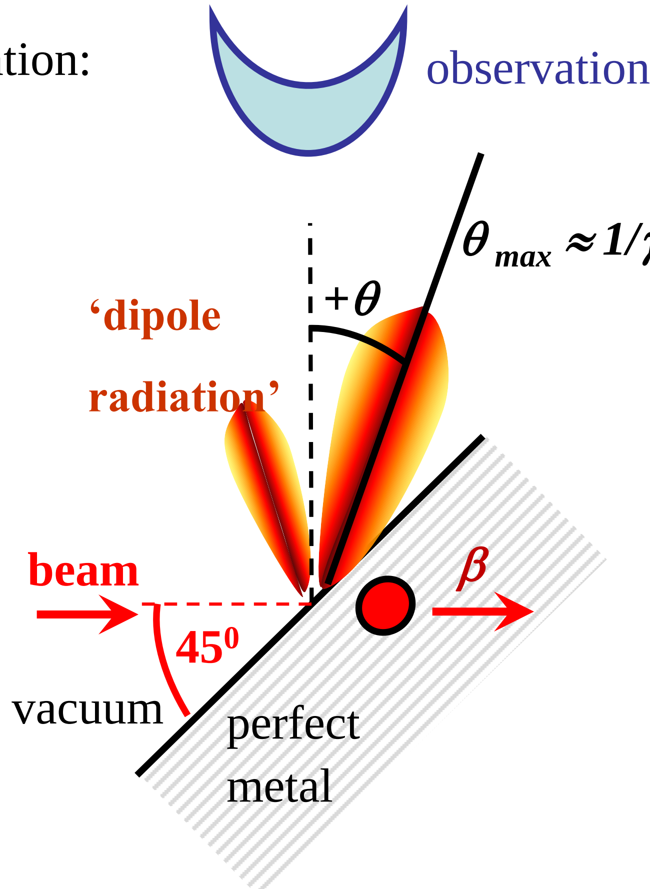


OTR with 45⁰ beam incidence and observation at 90⁰ :

approximated formula for 45⁰ incidence& in plane polarization:

$$\frac{d^2W}{d\theta\, d\omega} \approx \frac{2e^2\beta^2}{\pi c} \cdot \left(\frac{\sin\theta}{1-\beta\cos\theta} + \frac{\cos\theta}{1-\beta\sin\theta} \right)^2$$





Angular distribution of radiation in optical spectrum:

- emission pattern depends on velocity
- peak at angle $\theta \approx 1/\gamma$
- emitted energy scales with $W \propto \beta^2$
- symmetric with respect to θ for γ > 100

Remark: polarization of emitted light:

- in scattering plane → parallel E-vector
- perpendicular plane → rectangular E-vector

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:

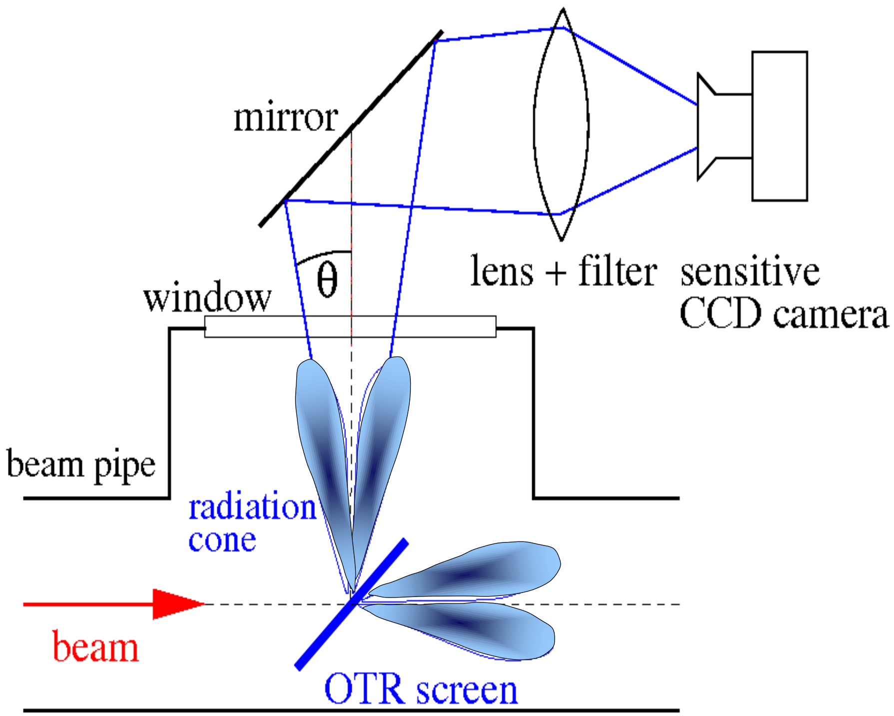
$$\frac{d^2W}{d\Omega d\omega} \approx \frac{2e^2\beta^2}{\pi\, c} \cdot \frac{\theta^2}{\left(\gamma^{-2}+\theta^2\right)^2}$$

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.

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

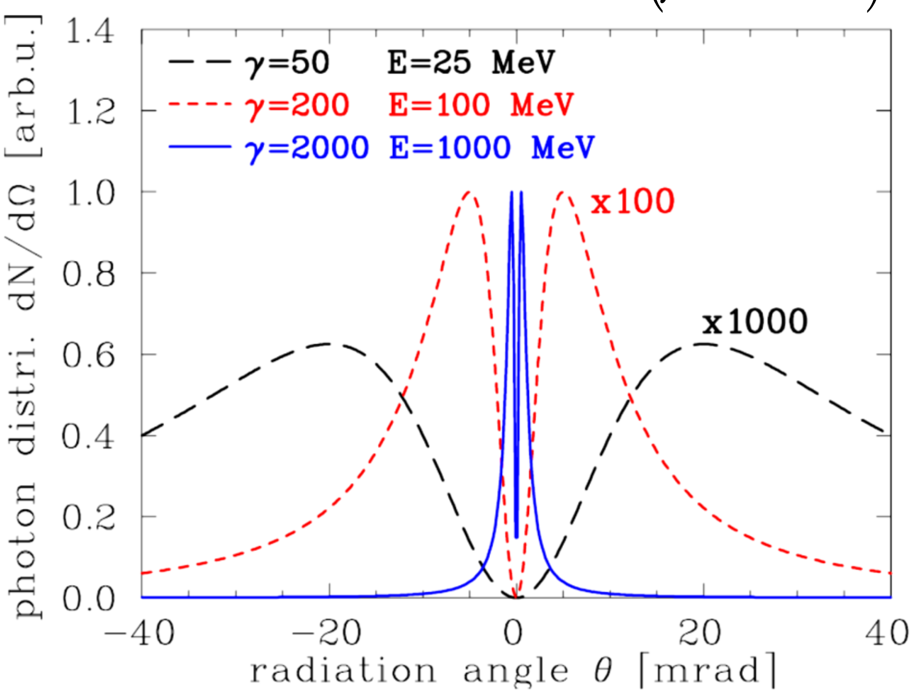
$$\frac{dN_{photon}}{d\Omega} = N_{beam} \cdot \frac{2e^2\beta^2}{\pi c} \cdot \log\left(\frac{\lambda_{begin}}{\lambda_{end}}\right) \cdot \frac{\theta^2}{\left(\gamma^{-2} + \theta^2\right)^2}$$

- Detection: Optical 400 nm < λ < 800 nm

  using image intensified CCD
- Larger signal for relativistic beam γ >> 1
- Angular focusing for γ >> 1

$\Rightarrow$ **well suited for e⁻ beams**

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



Remark:

$\rightarrow$ ***Profile*** by focusing to screen

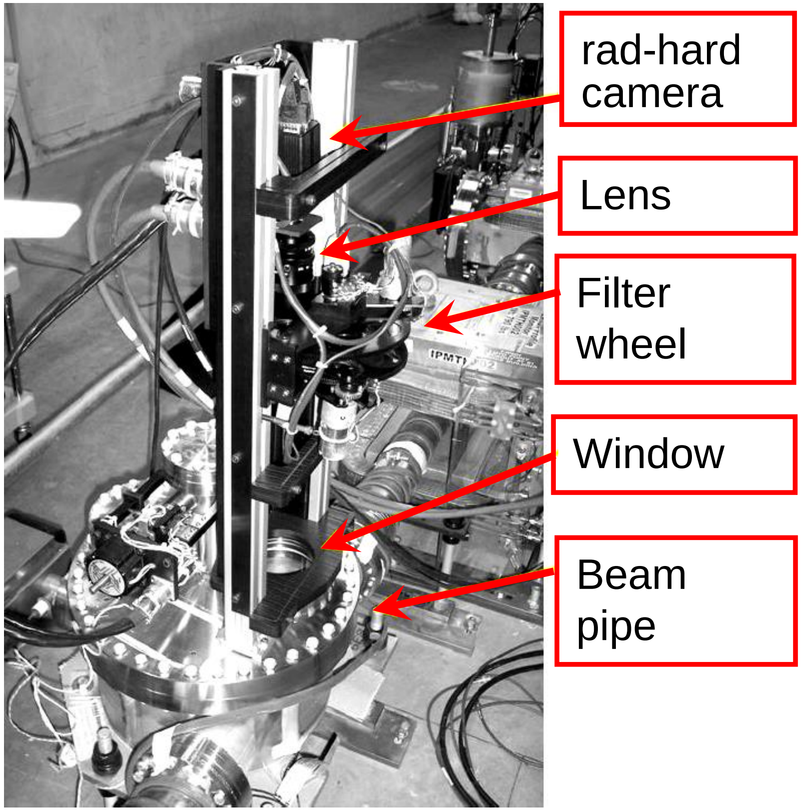
$\rightarrow$ ***Beam angular distribution*** by focusing on infinity due to emission dependence on beam angular distribution.

OTR-Monitor: Technical Realization and Results

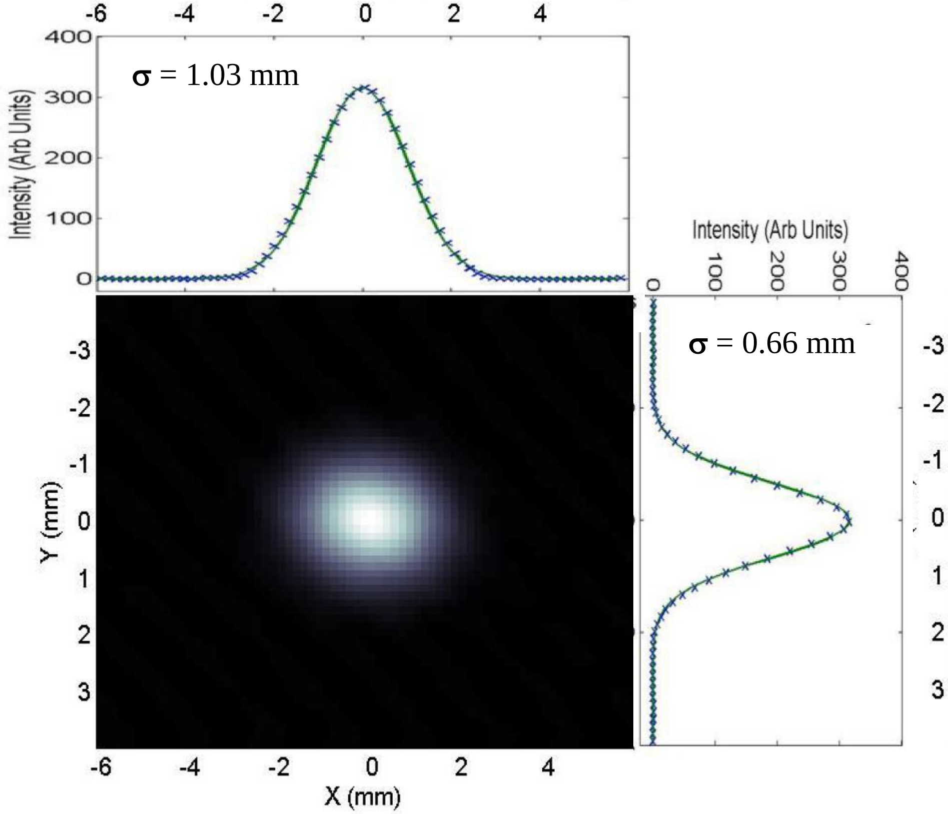
Example of realization at TERATRON:

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

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

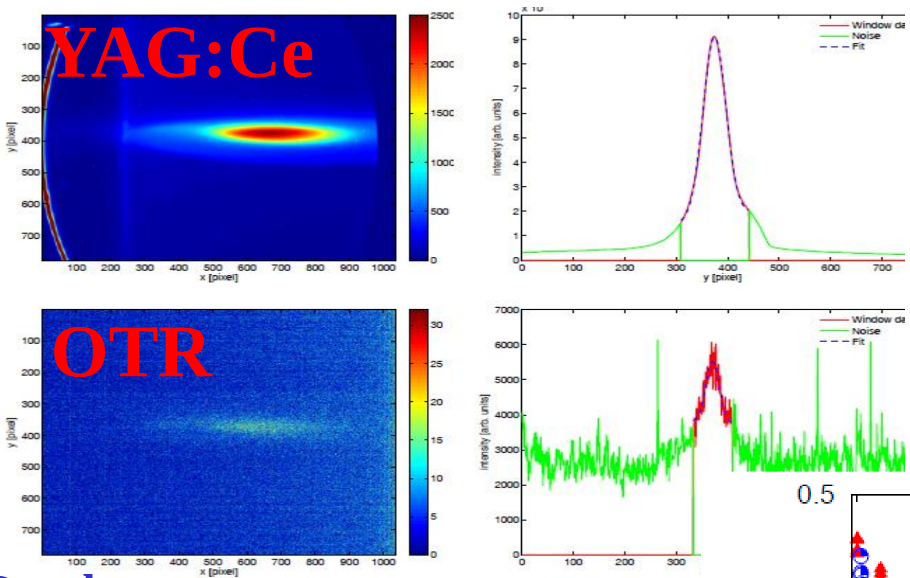


Results at FNAL-TEVATRON synchrotron with 150 GeV proton
Using fast camera: Turn-by-turn measurement

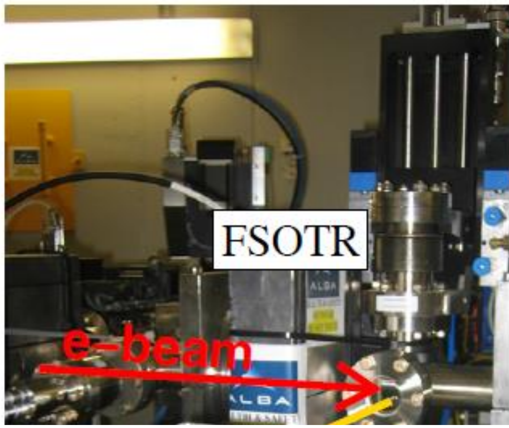


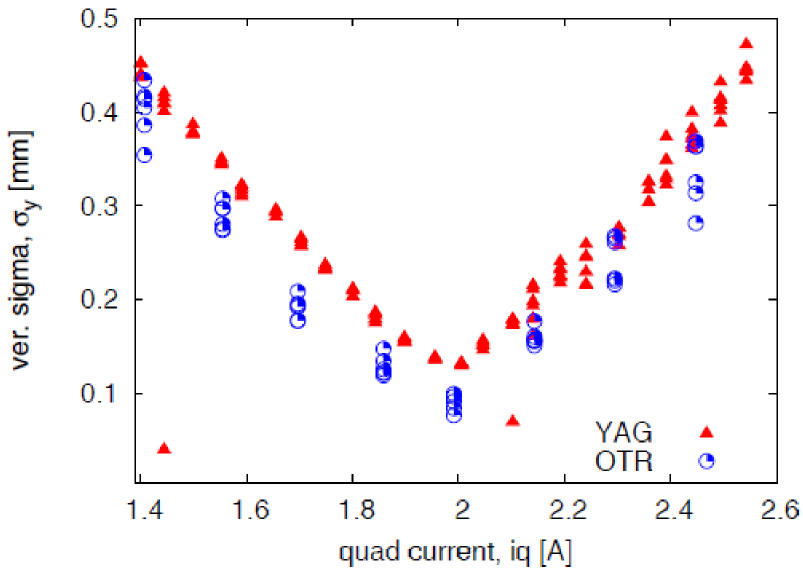
From V.E. Scarpine (FNAL) et al., BIW'06

Installation of OTR and scintillation screens on same drive :



Example: ALBA LINAC 100 MeV





Results:

- Much more light from YAG:Ce for 100 MeV (γ=200) electrons light output $I_{YAG} \approx 10^5 I_{OTR}$
- Broader image from YAG:Ce due to finite shoulders or CCD saturation(?)

Courtesy of U. Iriso et al., DIPAC'09

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 in optical and x-ray range
- Summary

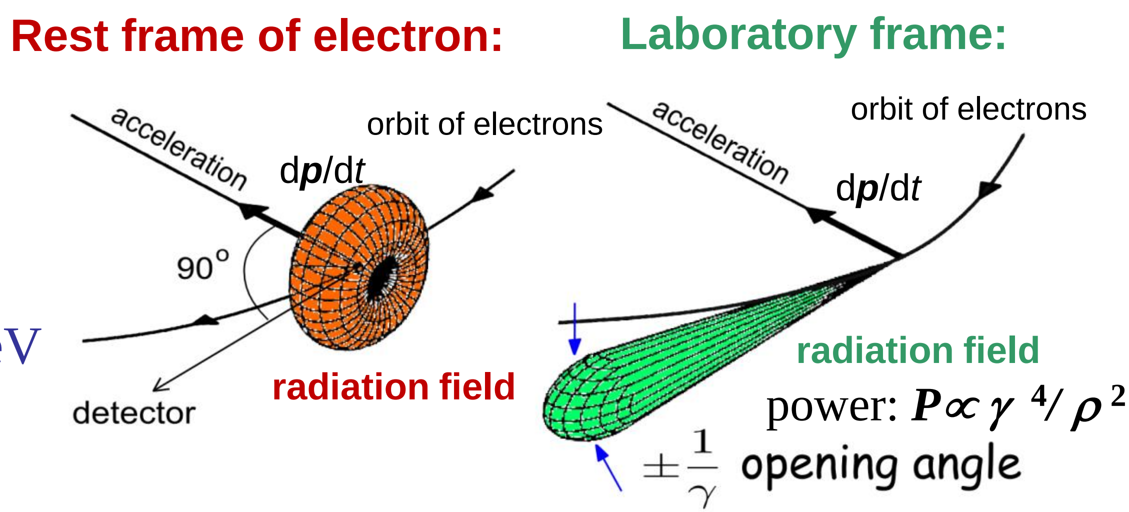
An electron bent (i.e. accelerated) by a dipole magnet emit synchrotron light.

This light is emitted into a cone of opening $2/\gamma$ in lab-frame.

$\Rightarrow$ Well suited for rel. e^-

For protons:

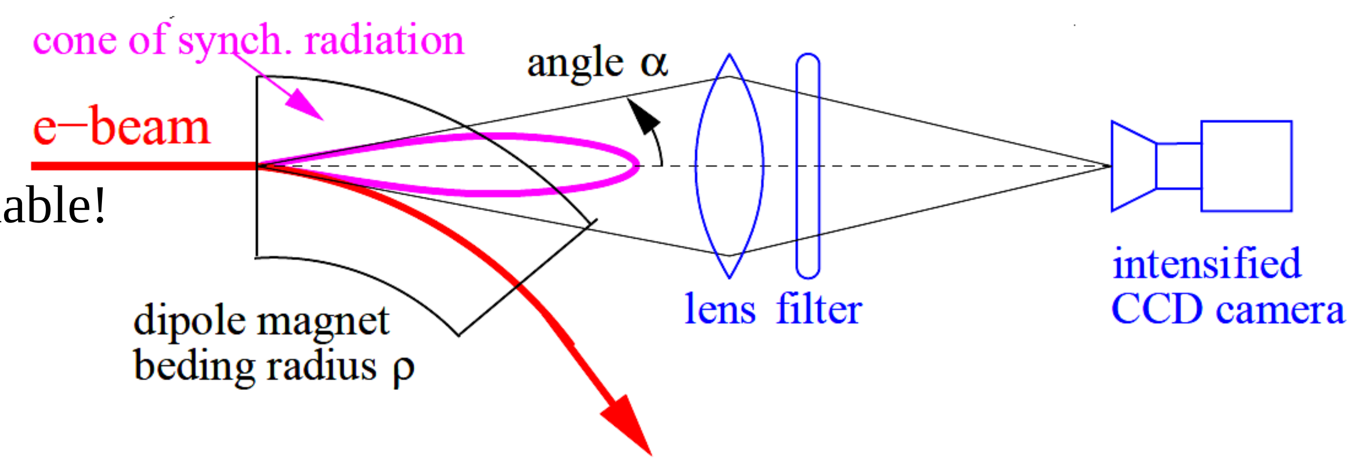
Only for energies $E_{kin} > 100$ GeV



The light is focused to a intensified CCD.

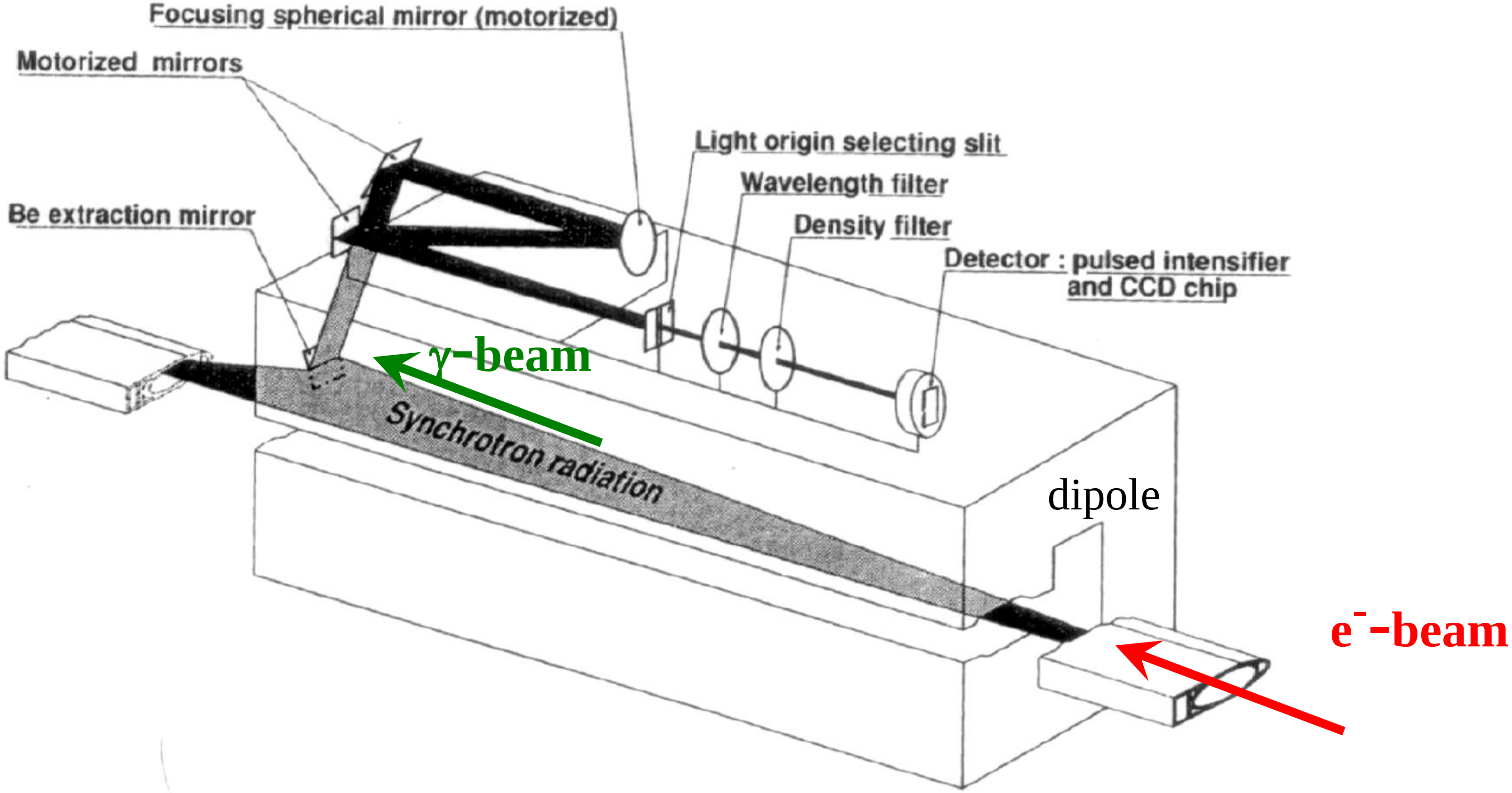
Advantage:

Signal anyhow available!

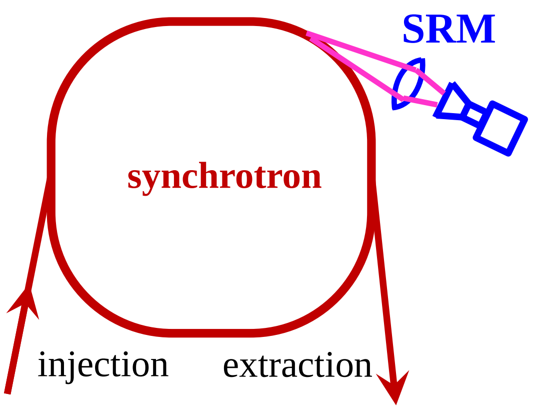


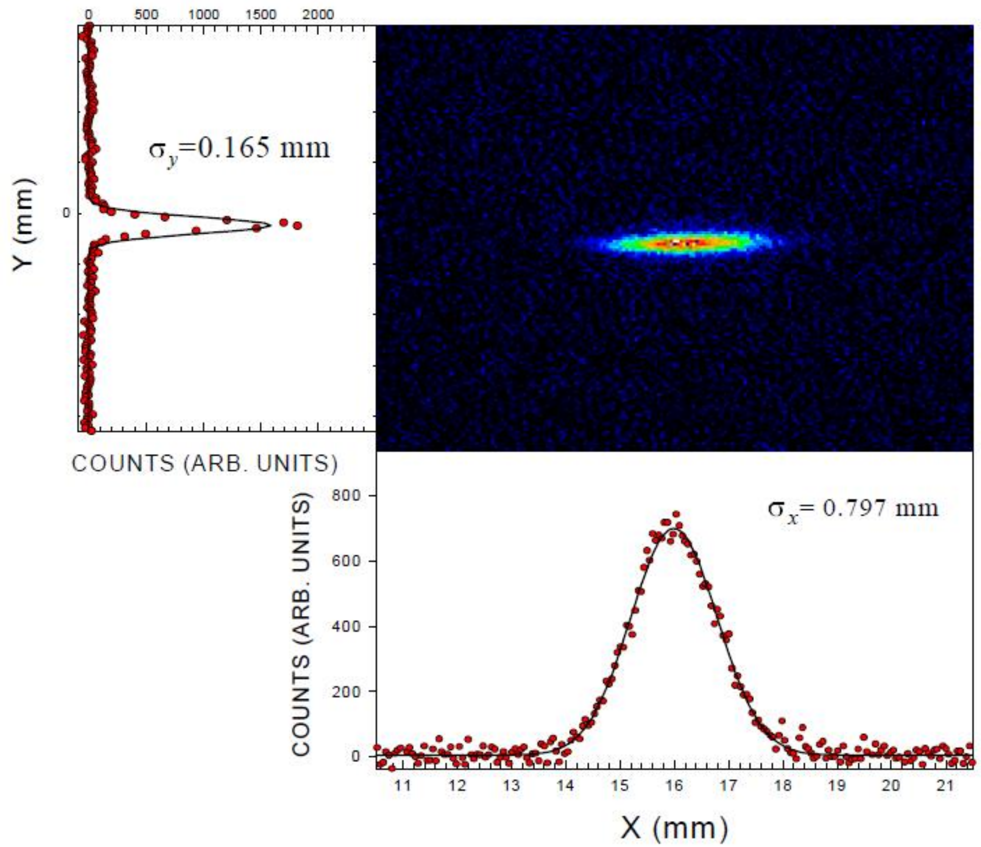
Extracting out of the beam's plane by a (cooled) mirror
→ Focus to a slit + wavelength filter for optical wavelength
→ Image intensified CCD camera

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



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



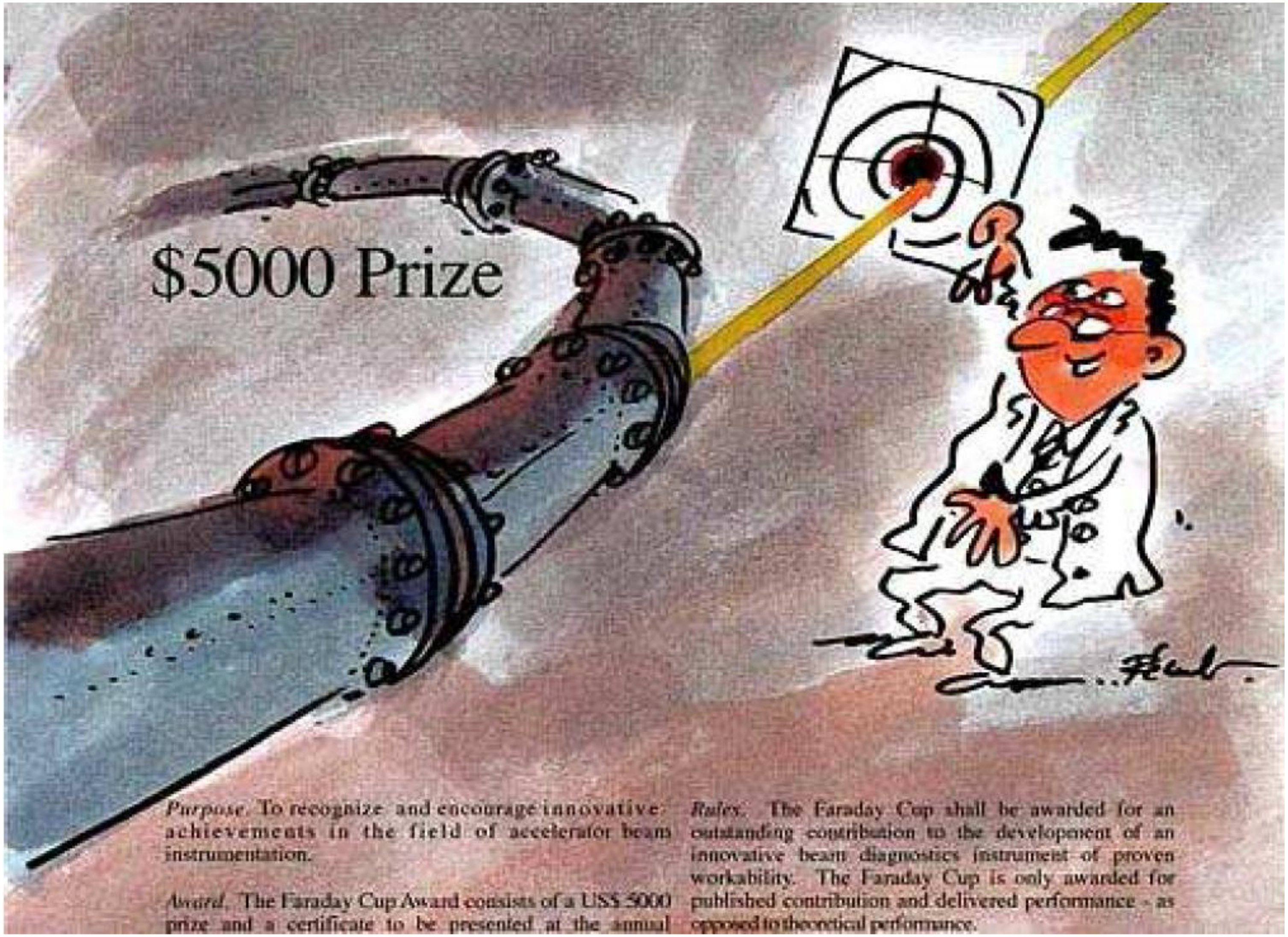


Advantage: Direct measurement of 2-dim distribution, only mirror installed in the vacuum pipe

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

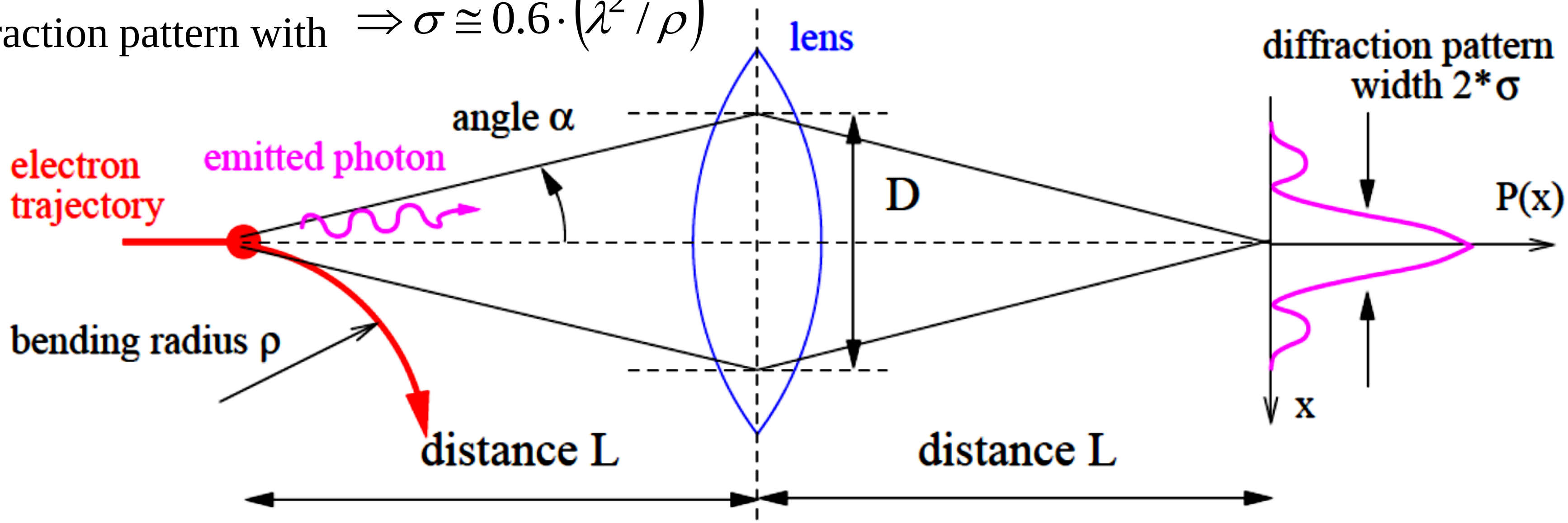
Use of optical wavelength and CCD: λ above critical λ_{crit} (spectrum fall-off).

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

Resolution Limits for Synchrotron Radiation Monitor

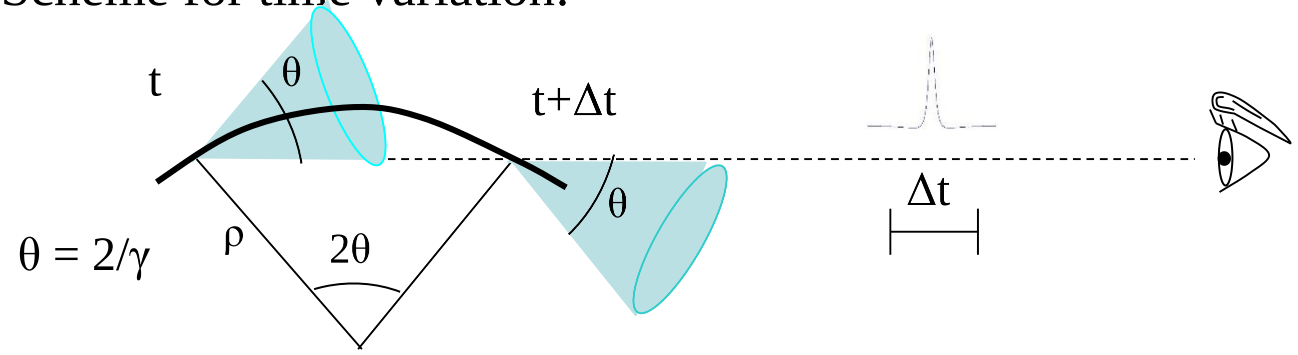
The resolution is limited by:

- Fraunhofer diffraction due to finite emission cone and finite size of optics
- Depth of field
- Spectral width of observed light → usage of interference filters
- Time variation of light due to finite observation angle → usage of aperture
- Light intensity and related noise → usage of sensitive CCD camera

⇒ typical value for resolution $\boldsymbol{\sigma \approx 100\ \mu m}$

→ which is comparable to the electron beam size of **modern** 3rd generation light source

Scheme for time variation:



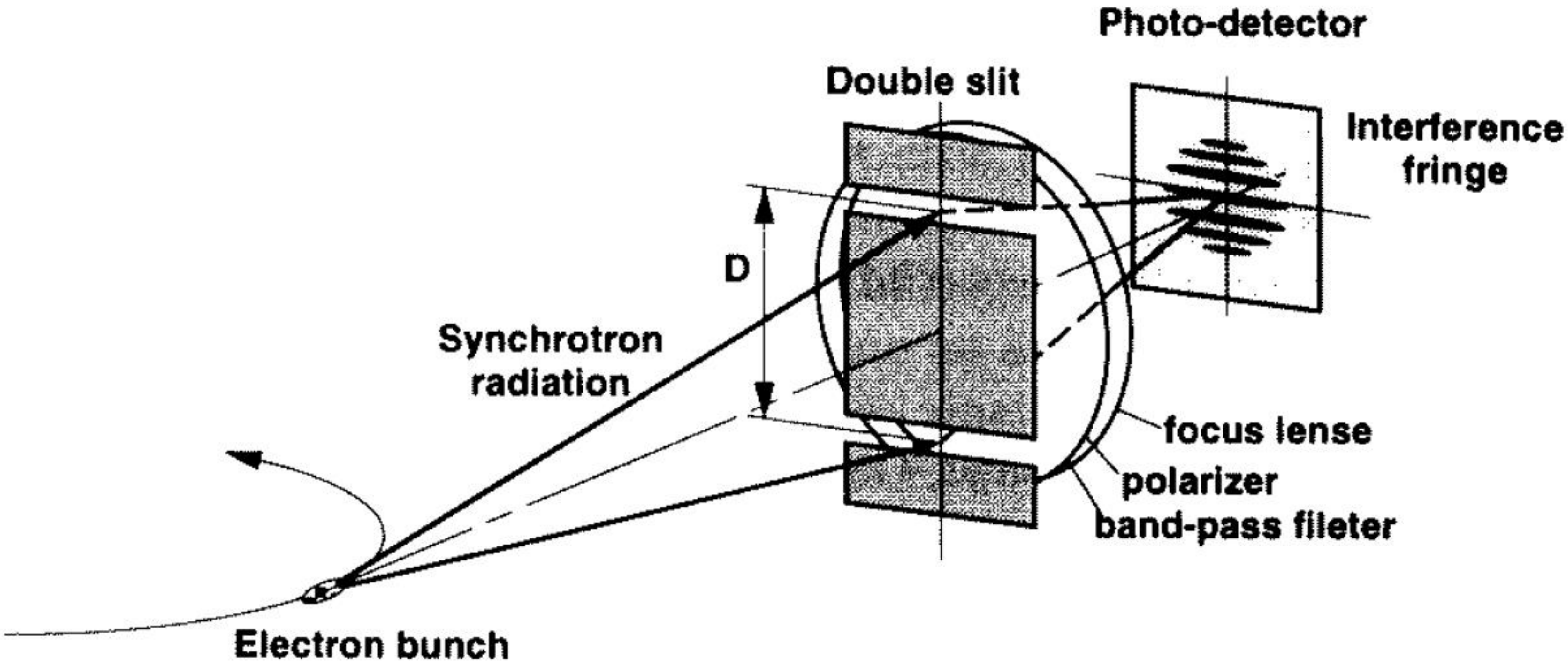
$$\Delta t = \frac{4\rho}{3\gamma^3 c}$$

Courtesy of G. Kube DESY

The diffraction limit is $\Rightarrow \sigma \cong 0.6 \cdot \left(\lambda^2 / \rho\right)^{1/3} \approx 100$ µm for typical case

Possible improvements:

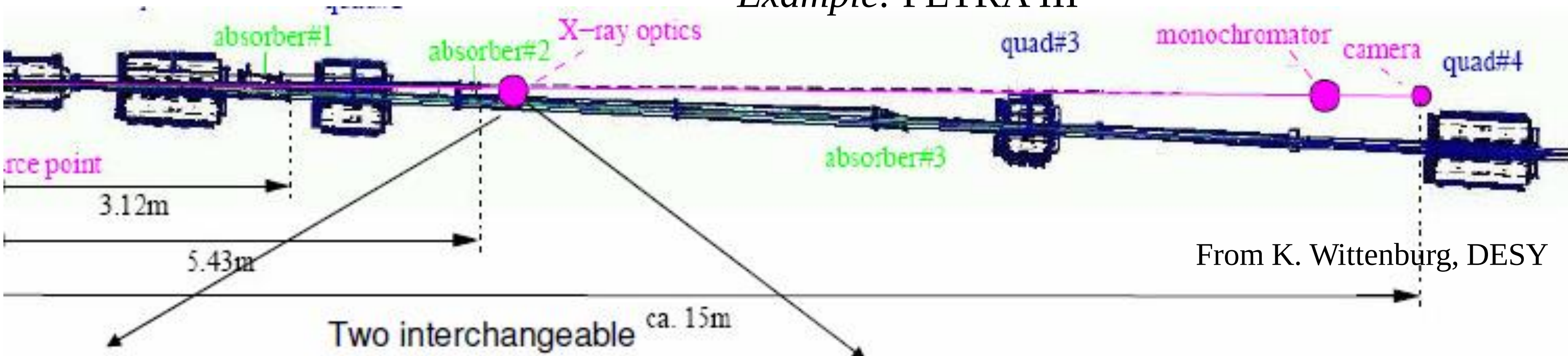
- ***Shorter wavelength:*** Using x-rays and an aperture of Ø 1mm
  → 'x-ray pin hole camera', achievable resolution $\sigma \approx 10$ µm
- ***Interference technique:*** At optical wavelength using a double slit
  → interference fringes leading to a resolution $\sigma \approx 1$ µm.



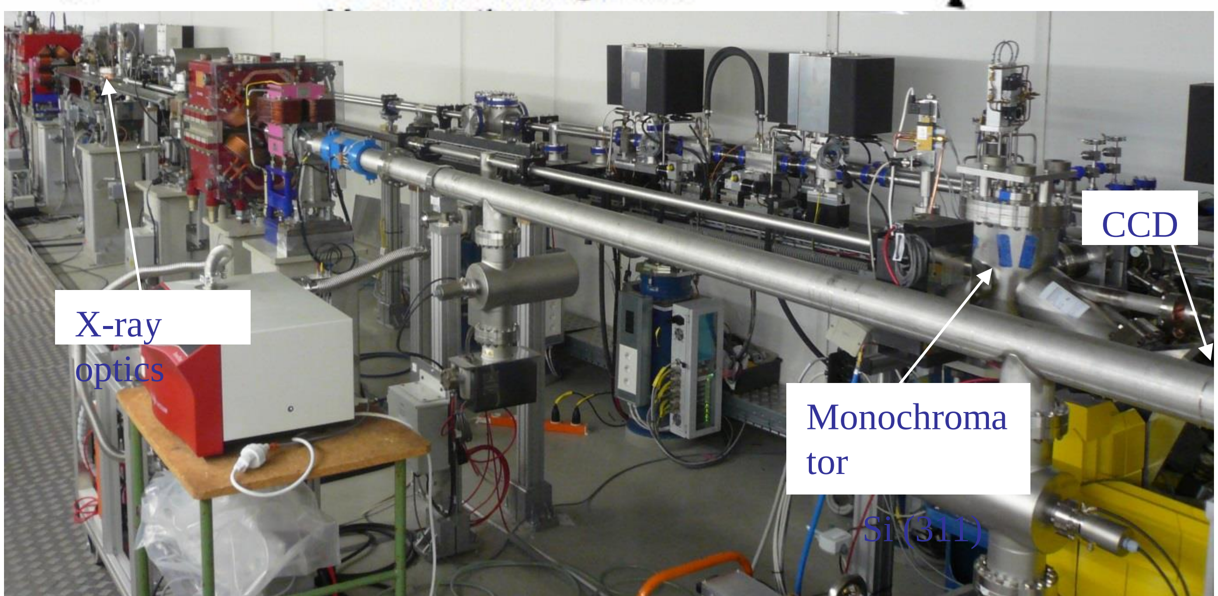
x-ray Pin-Hole Camera: Installation

The diffraction limit is $\Rightarrow \sigma \cong 0.6 \cdot \left(\lambda^2 / \rho\right)^{1/3}$ $\Rightarrow$ s***horter wavelength by x-rays***.

Example: PETRA III

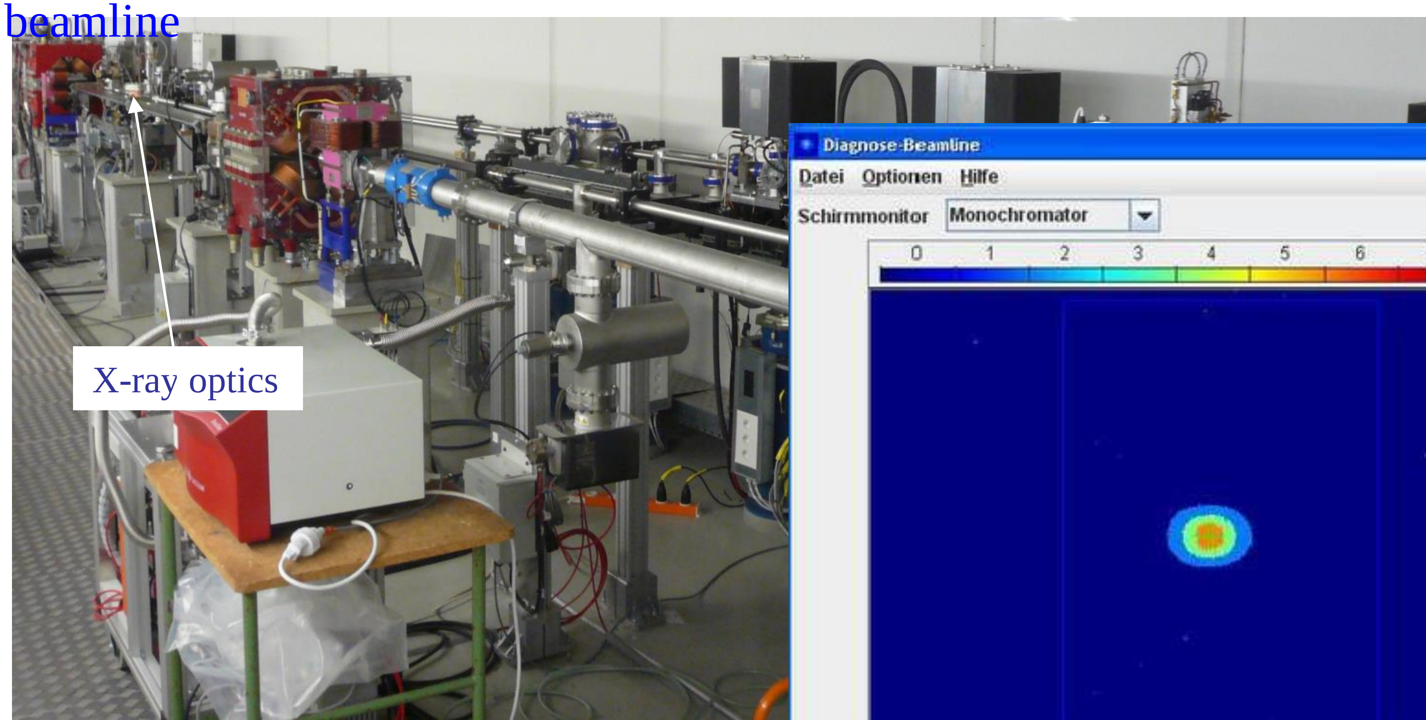


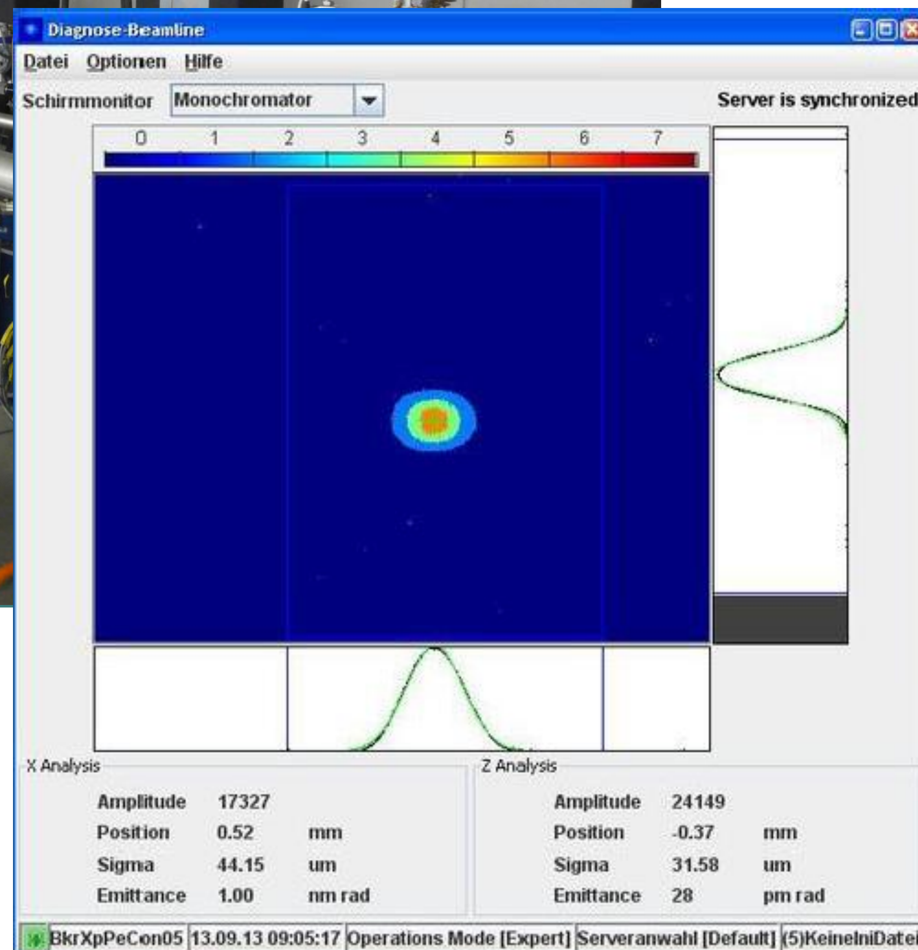
From K. Wittenburg, DESY



Emittance Diagnostics

- imaging with Compound Refractive Lens (CRL) optics: X-ray beamline



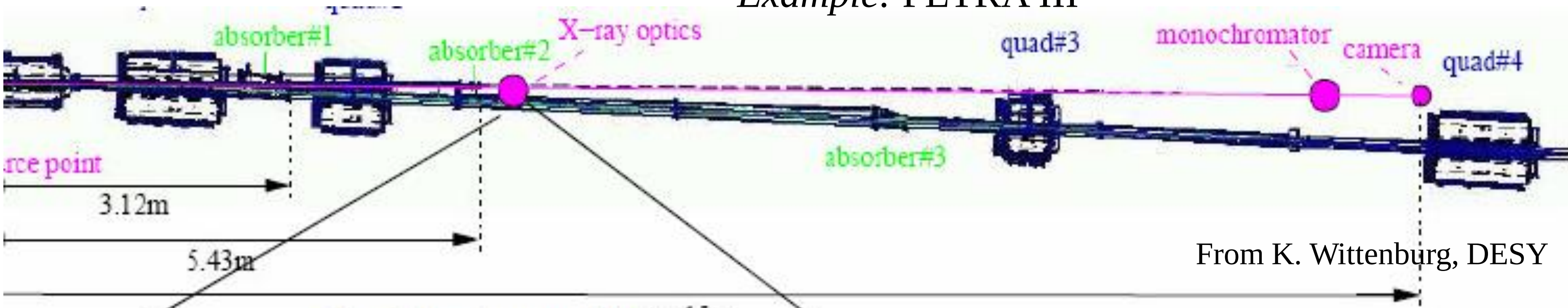


- design photon energy
  - → $\hbar\omega$ = 20 keV
- vertical resolution broadening
  - → design emittance: ε_v = 10 pm.rad

x-ray Pin-Hole Camera: Installation

The diffraction limit is $\Rightarrow \sigma \cong 0.6 \cdot \left(\lambda^2 / \rho\right)^{1/3}$ $\Rightarrow$ s***horter wavelength by x-rays***.

Example: PETRA III

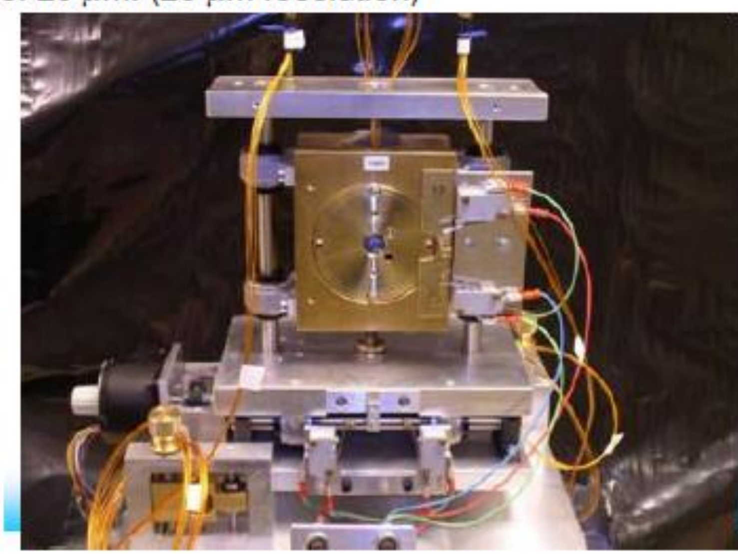


From K. Wittenburg, DESY

Two interchangeable X-ray optics:

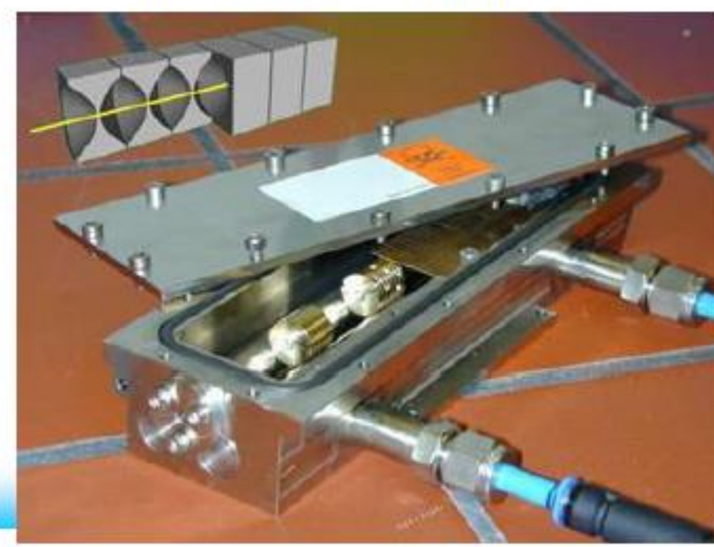
Pinhole

0.5 mm thick tungsten blade with a circular hole of 20 μm. (20 μm resolution)



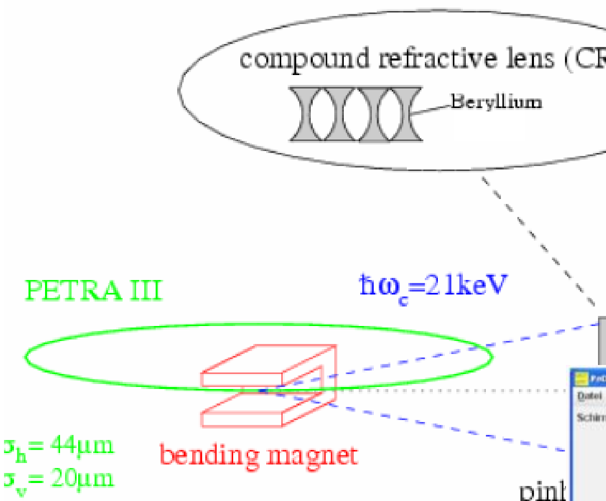
Compound reflective lens (RWTH Aachen)

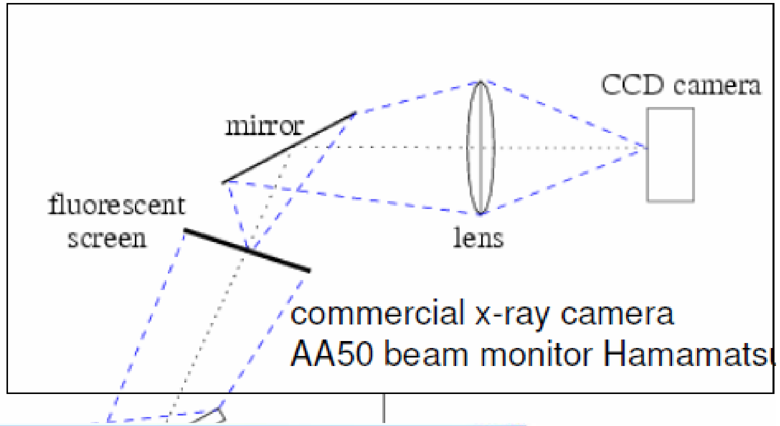
N=31, ≈ 2 μm res. < 1 μm aligned



x-ray pin-hole Camera: x-ray Detector

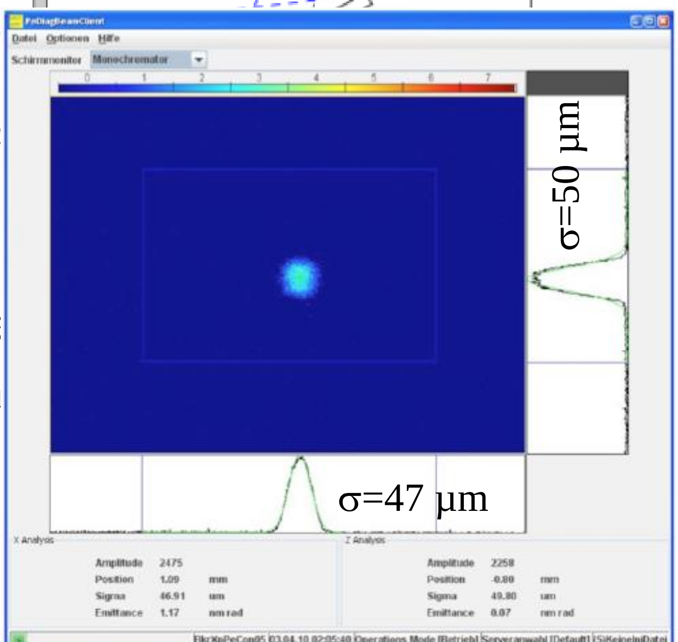
x-ray optics → scintillator detector (shifting x-ray to optical light) → CCD camera



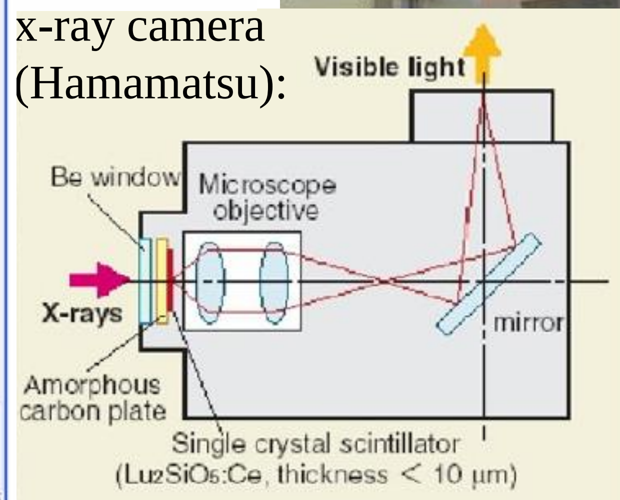


Example: PETRA III

- Pinhole with ∅ 20 μm or novel focusing device
- monochromator (silicon
- scintillator to convert x-ray to optical photons
- CCD sensor



Commercial x-ray camera (Hamamatsu):



From K. Wittenburg, DESY

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:

- Optical synchrotron radiation monitor: non-destructive, for e^--beams, complex, limited res.
- X-ray synchrotron radiation monitor: non-destructive, for e^--beams, very complex
- OTR screen: nearly non-destructive, large relativistic γ needed, e^--beams mainly

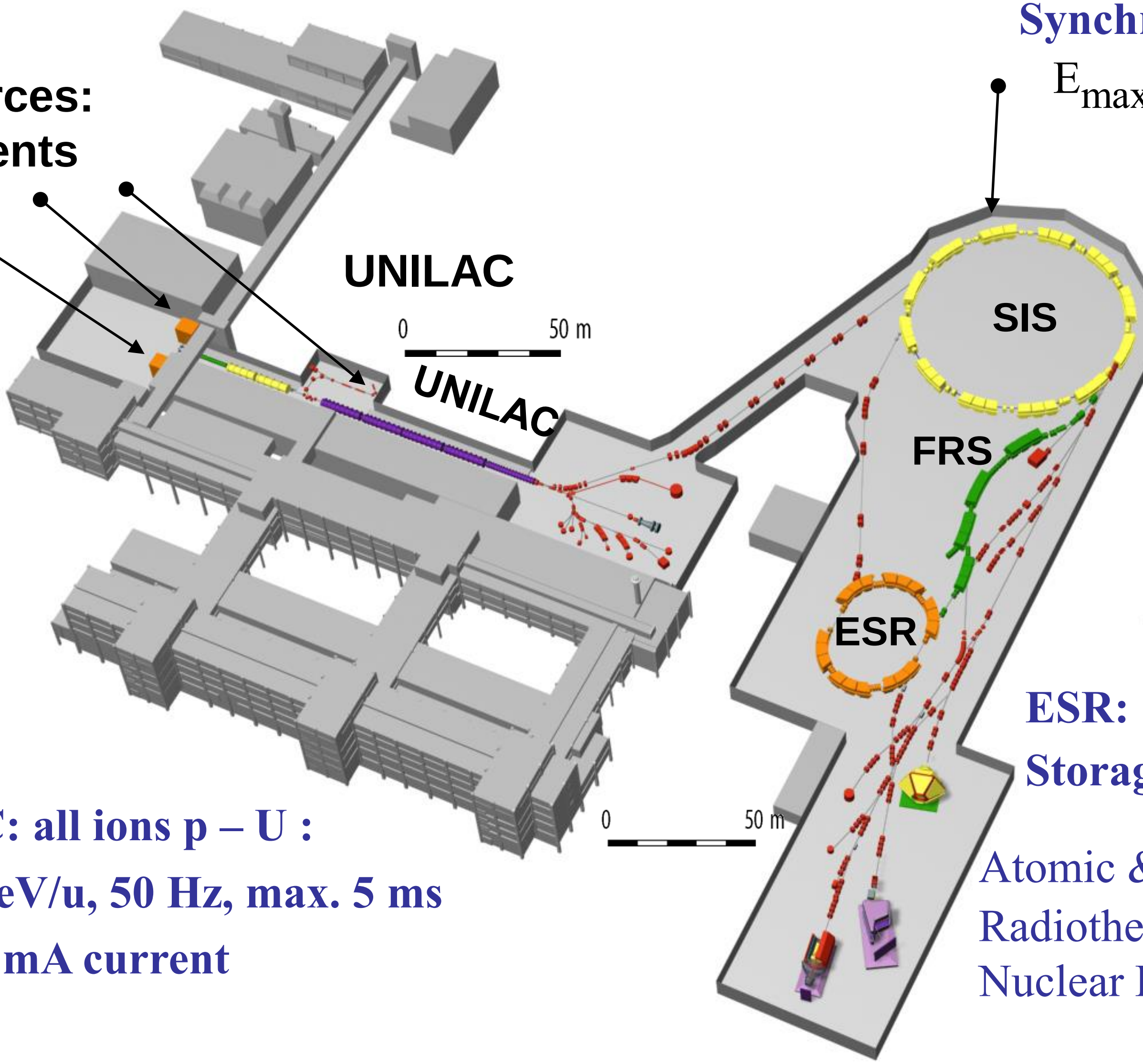
Detection of secondary photons, electrons or ions:

- 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.

Appendix: The Accelerator Facility at GSI



Synchrotron, Bρ=18 Tm

E_{max} p: 4.7 GeV
U: 1 GeV/u

Achieved e.g.:

Ar^{18+}: $1\cdot10^{11}$

U^{28+}: $3\cdot10^{10}$

U^{73+}: $1\cdot10^{10}$

ESR:

Storage Ring, Bρ=10 Tm

Atomic & Plasma Physics
Radiotherapy
Nuclear Physics

UNILAC: all ions p – U :

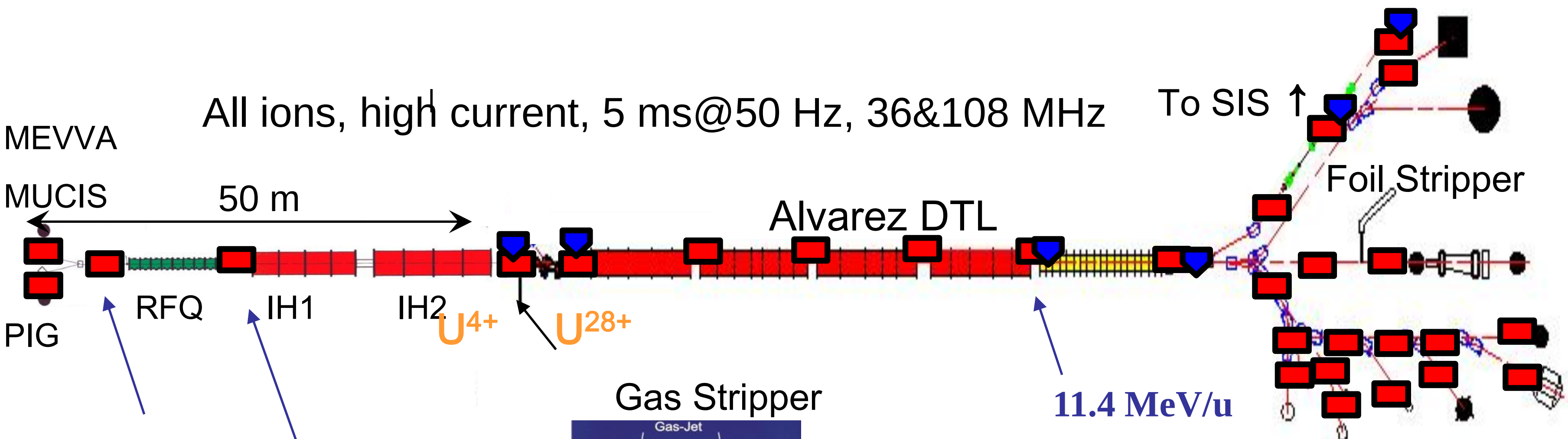
3 – 12 MeV/u, 50 Hz, max. 5 ms

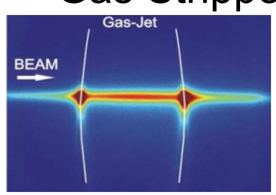
Up to 20 mA current

Appendix: GSI Heavy Ion LINAC: Profile Measurement

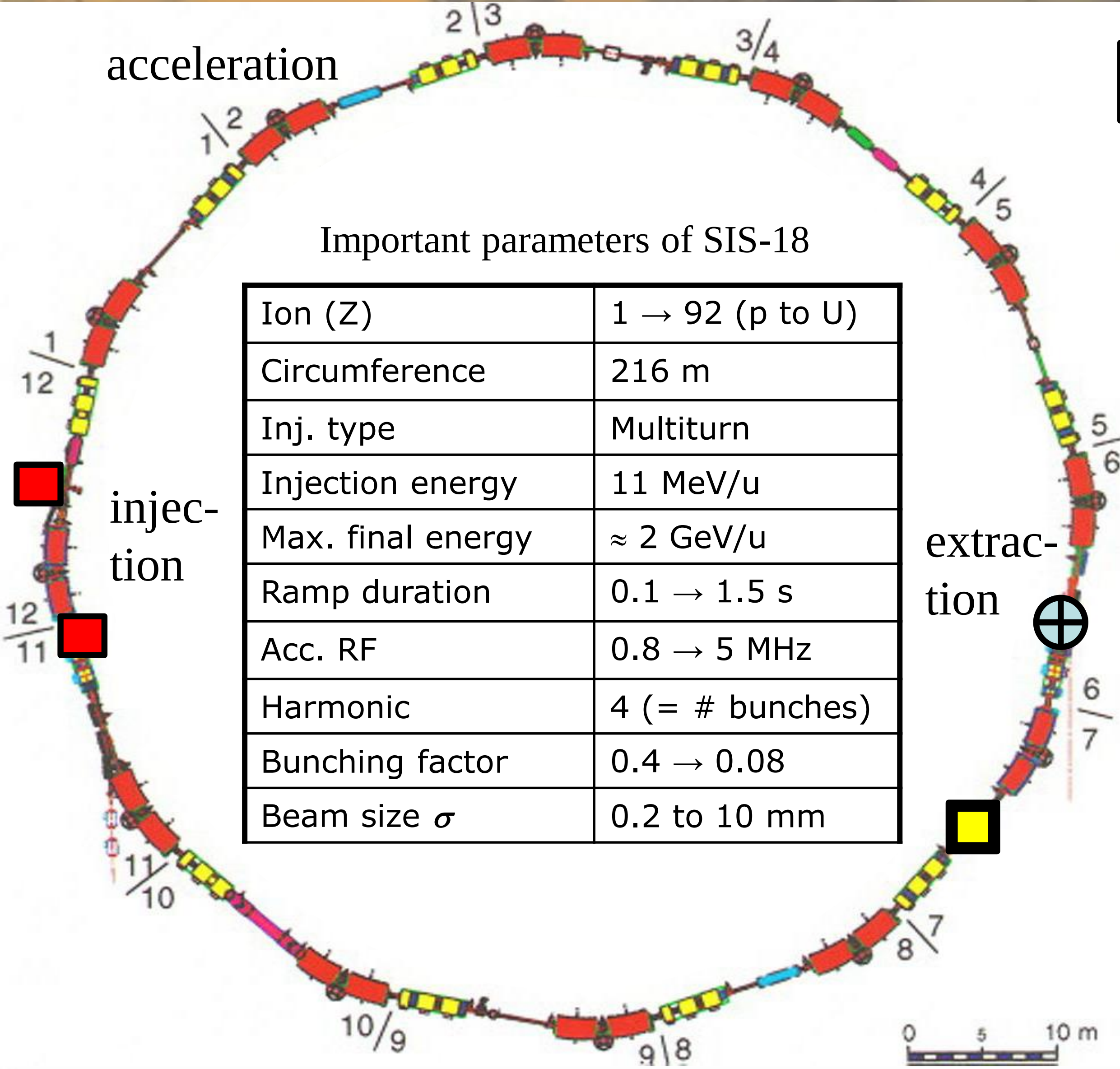
SEM-Grid: Intersecting, high dynamic range, total 81 device

Beam Induced Fluorescence: Non-destructive, for high current operation total 6 device





Constructed in the 70th, Upgrade 1999, further upgrades in preparation



Important parameters of SIS-18

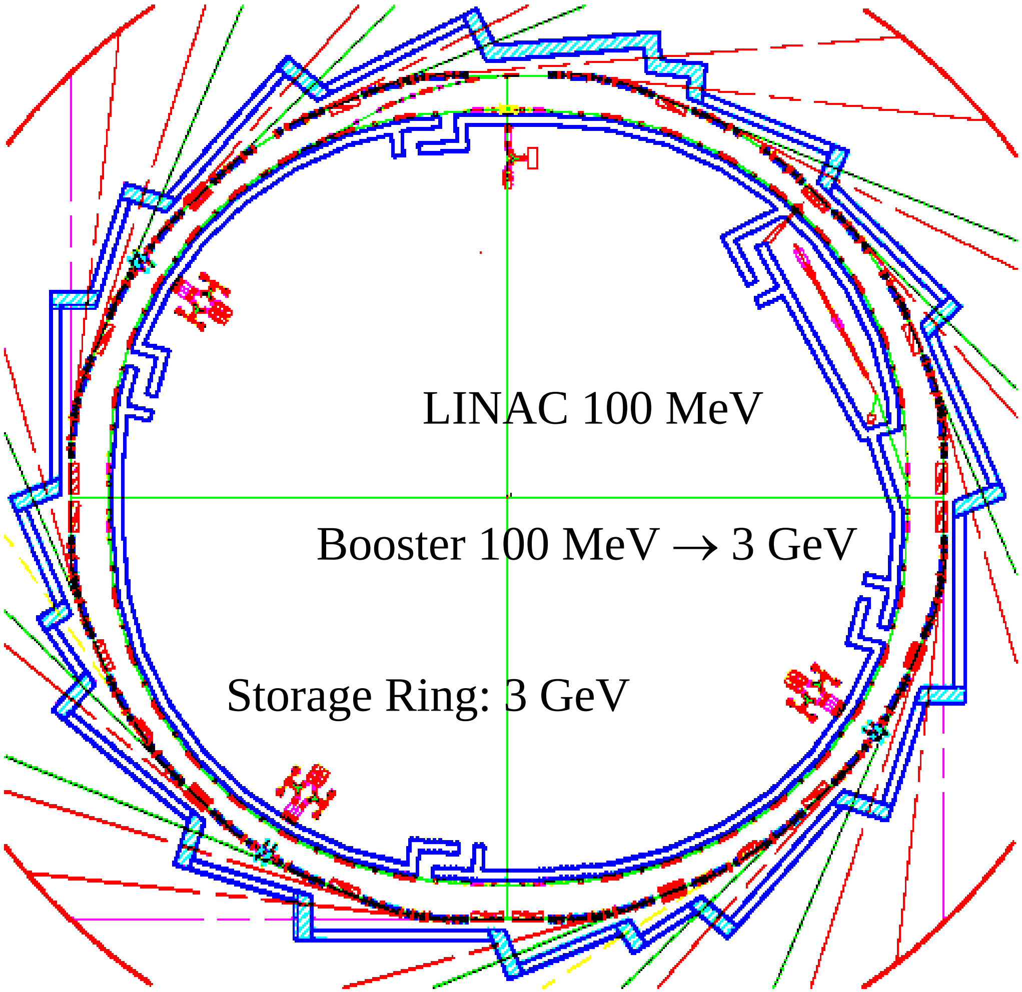
Ion (Z)	1 → 92 (p to U)
Circumference	216 m
Inj. type	Multiturn
Injection energy	11 MeV/u
Max. final energy	≈ 2 GeV/u
Ramp duration	0.1 → 1.5 s
Acc. RF	0.8 → 5 MHz
Harmonic	4 (= # bunches)
Bunching factor	0.4 → 0.08
Beam size σ	0.2 to 10 mm

SEM-Grid: injection
first turn
destructive

Screen: extraction
0.01... 500 MHz

IPM:
profile for stored beam
10 ms time resolution
non-destructive

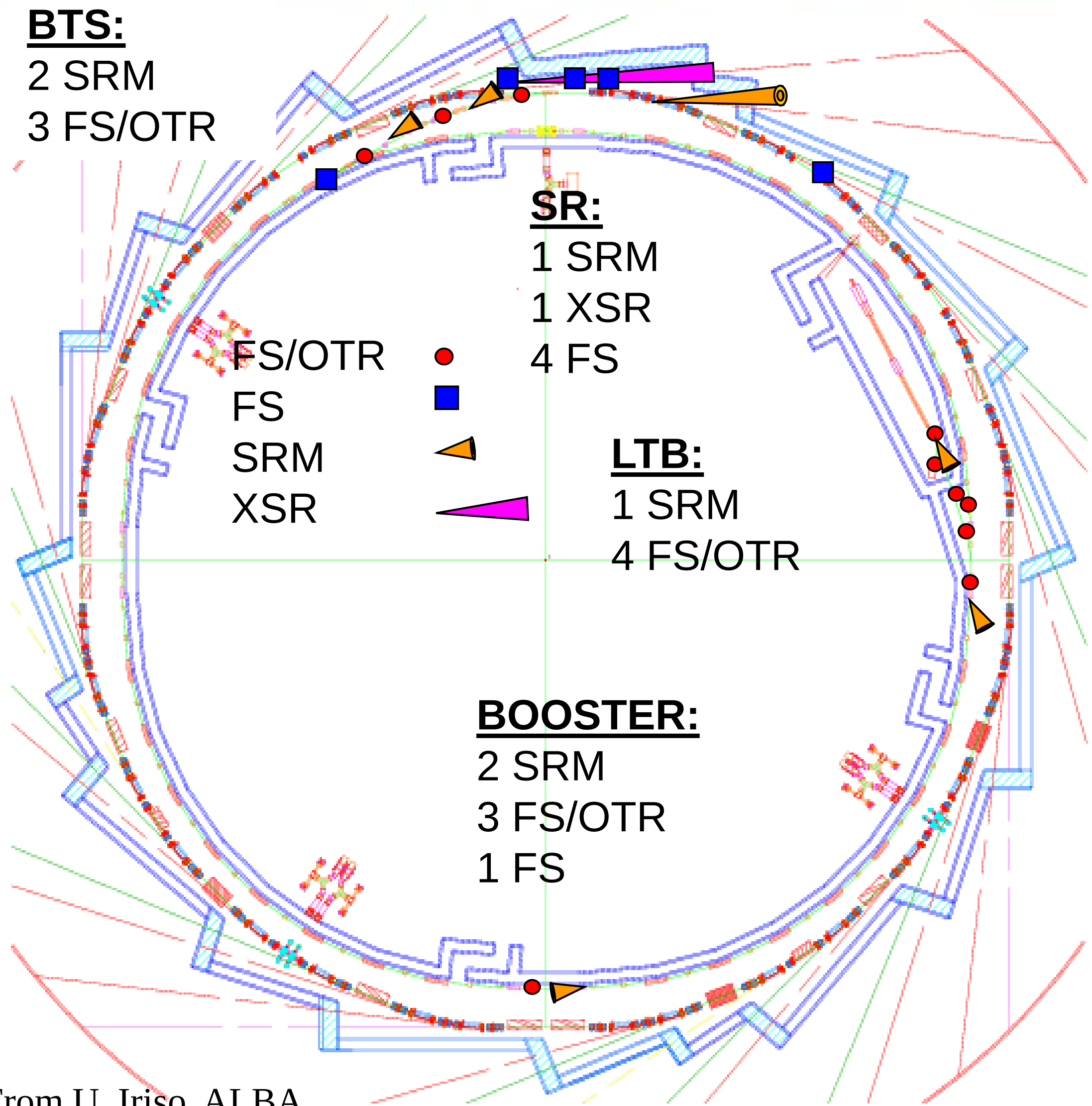
3rd generation Spanish national synchrotron light facility in Barcelona



From U. Iriso, ALBA

Layout:

Beam lines: up to 30
Electron energy: 3 GeV
Top-up injection
Storage ring length: 268 m
Max. beam current: 0.4 A
Commissioning in 2011



From U. Iriso, ALBA

Transverse profile:

Many location in transport line

Single location in ring

Quite different devices used

Abbreviation:

FS: Fluorescence Screen

OTR: Optical Trans. Radi. Screen

both destructive

SRM: Synchr. Radiation Monitor

XSR: X-ray pin hole camera

both **non-**destructive