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:

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

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

Typical beam sizes:

e⁻-beam: typically Ø 0.01 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)

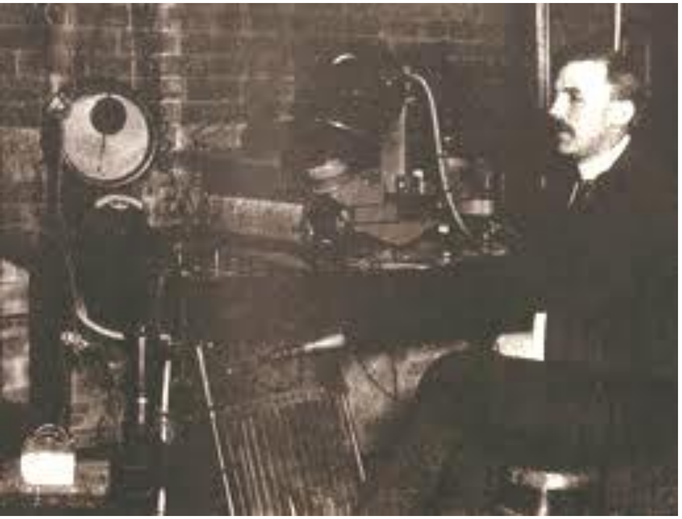
Outline:

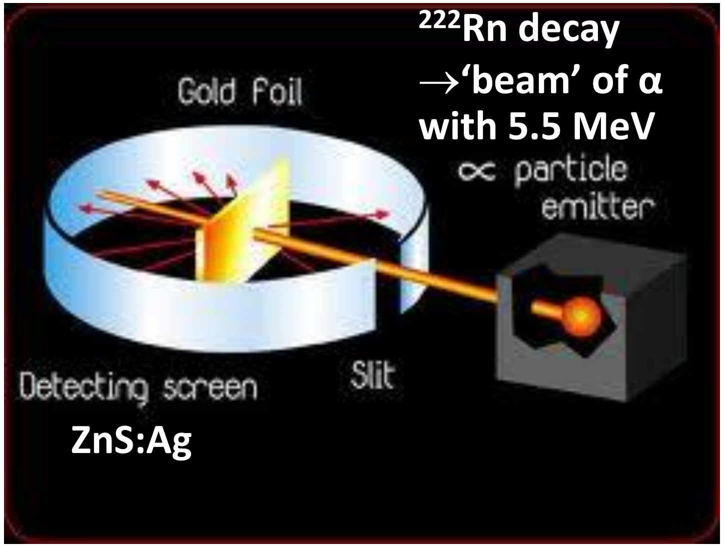
- **Scintillation screens:**

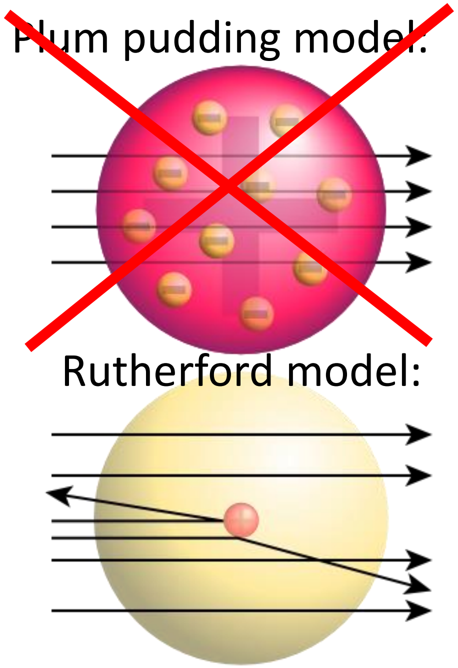
  emission of light, universal usage, limited dynamic range
- **Optical Transition Radiation**
- **SEM-Grid**
- **Wire scanner**
- **Ionization Profile Monitor and Beam Induced Fluorescence Monitor**
- **Synchrotron Light Monitors**
- **Summary**

Early Usage of Scintillation Screen by E. Rutherford

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







Rutherford or 'Geiger-Marsden Experiment':

- Nuclei are made of point-like charges

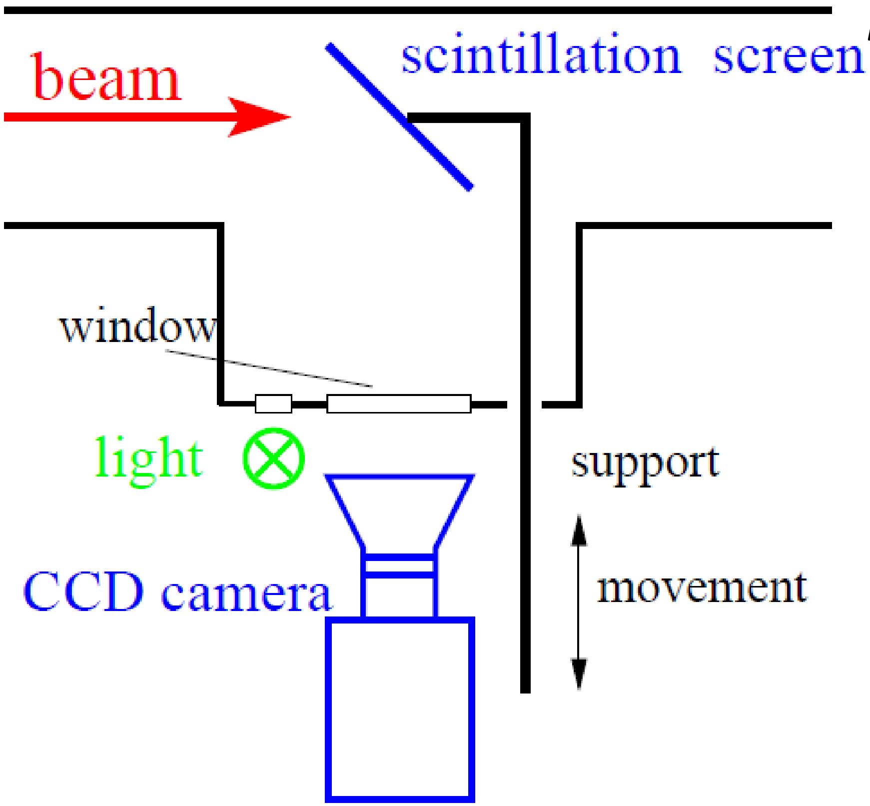
ZnS:Ag

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

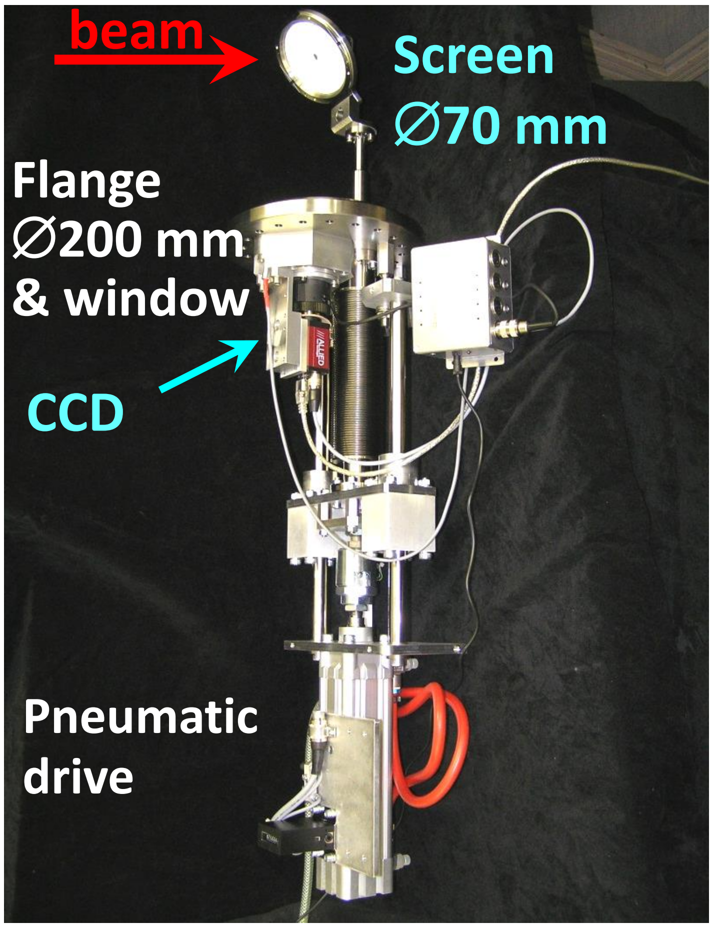
Scintillation Screen

Particle's energy loss in matter produces light

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



Example: Pneumatic drive with Ø70mm screen:



Example of Screen based Beam Profile Measurement

Advantage of screens:

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

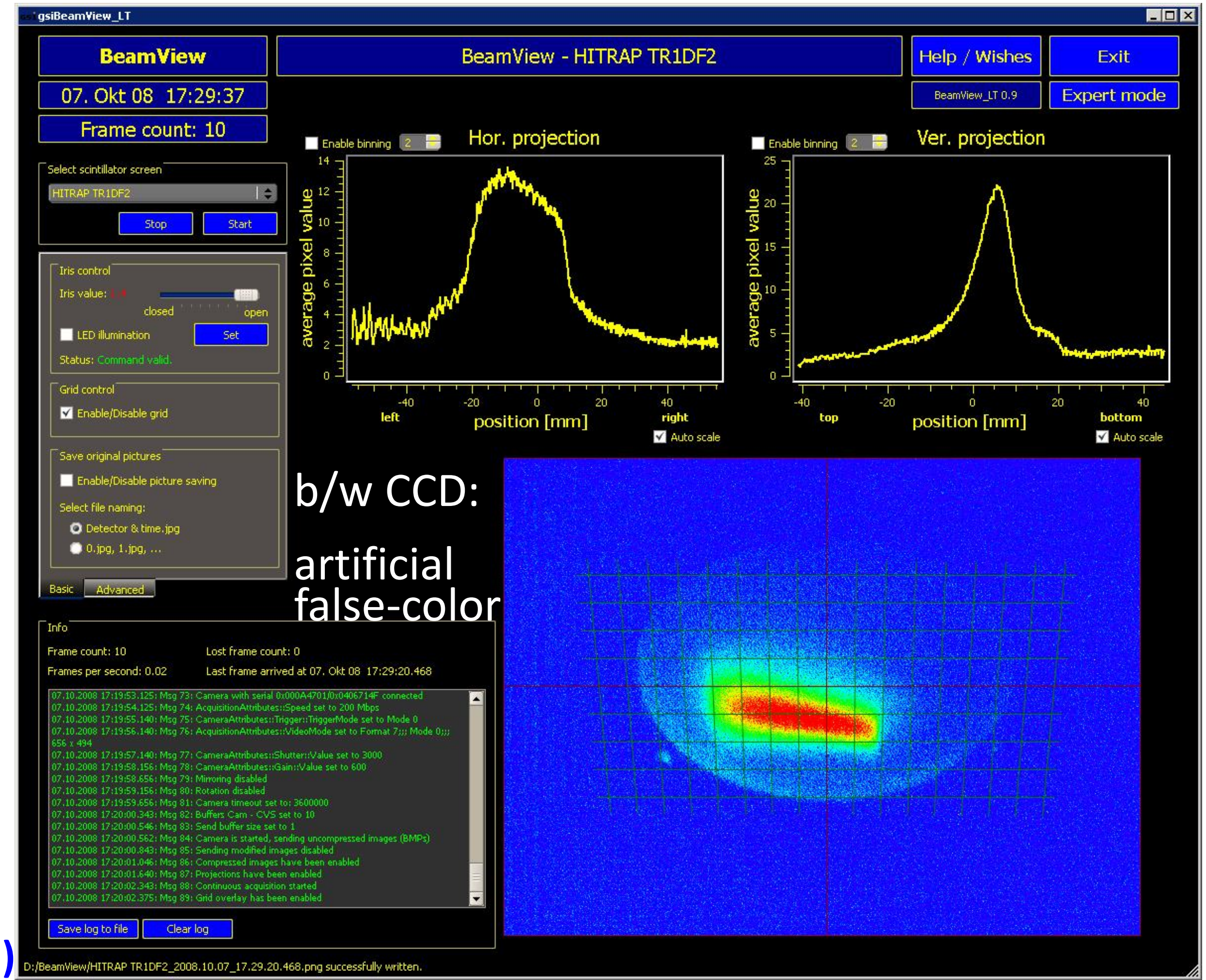
Observation with

a CCD or CMOS camera

with digital output

or video & frame grabber.

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



b/w CCD:

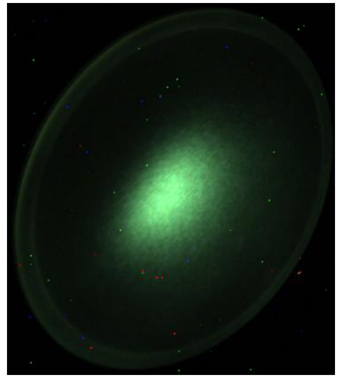
artificial false-color

Scintillation Screen (beam stopped)

Light output from various Scintillating Screens

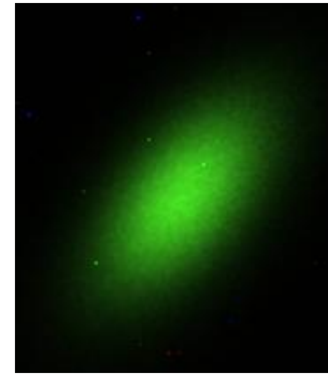
Example: Color CCD camera: Images at different particle intensities determined for U at 300 MeV/u

Al_2O_3

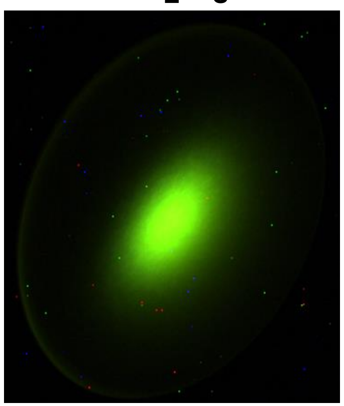


CsI:Tl

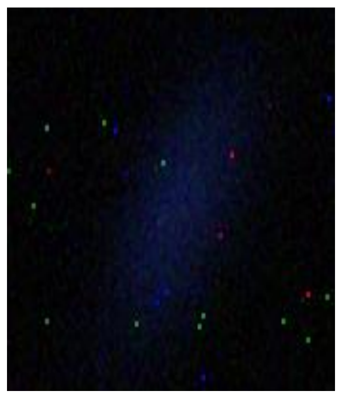
Al_2O_3:Cr



P43

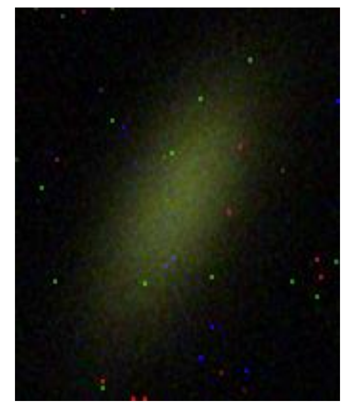


YAG:Ce



Herasil

Quartz:Ce



ZrO_2:Mg

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

Excurse: Physics of Scintillating Mechanism

Interaction steps within the scintillation process

- **beam interaction**

→ **hot electrons + deep holes**

- **multiplication within ≈ 0.01 ps:**

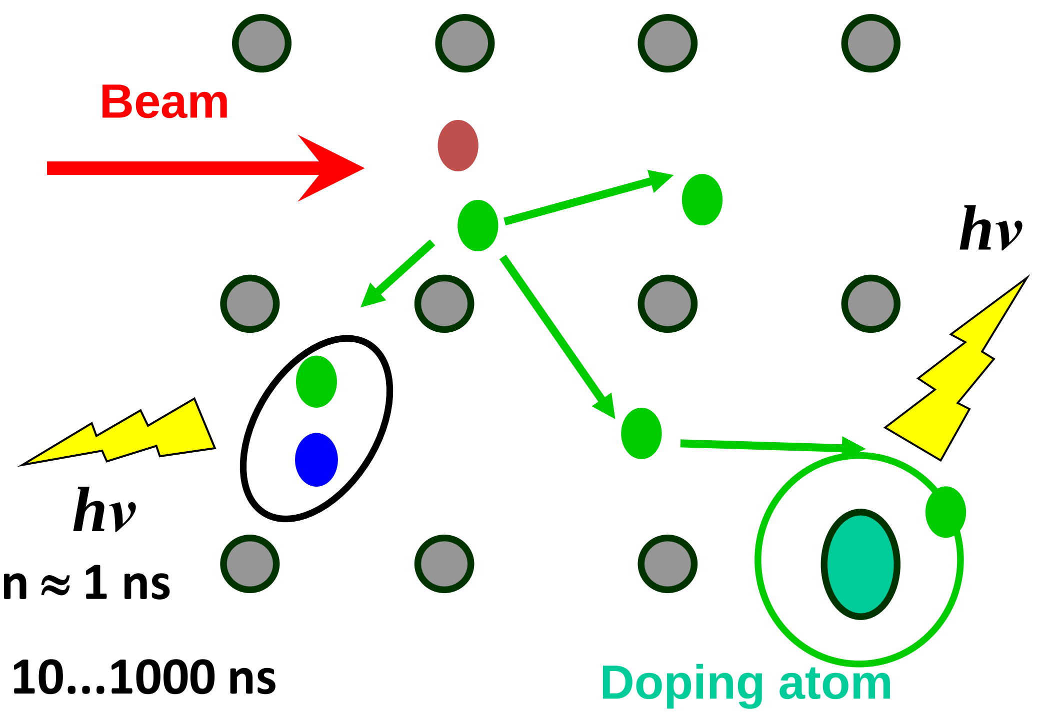
electron – electron scattering

- **thermalization within ≈ 1 ps:**

electron – phonon coupling

- **capture at doped atom and/or**

electron - hole pair creation within ≈ 1 ns



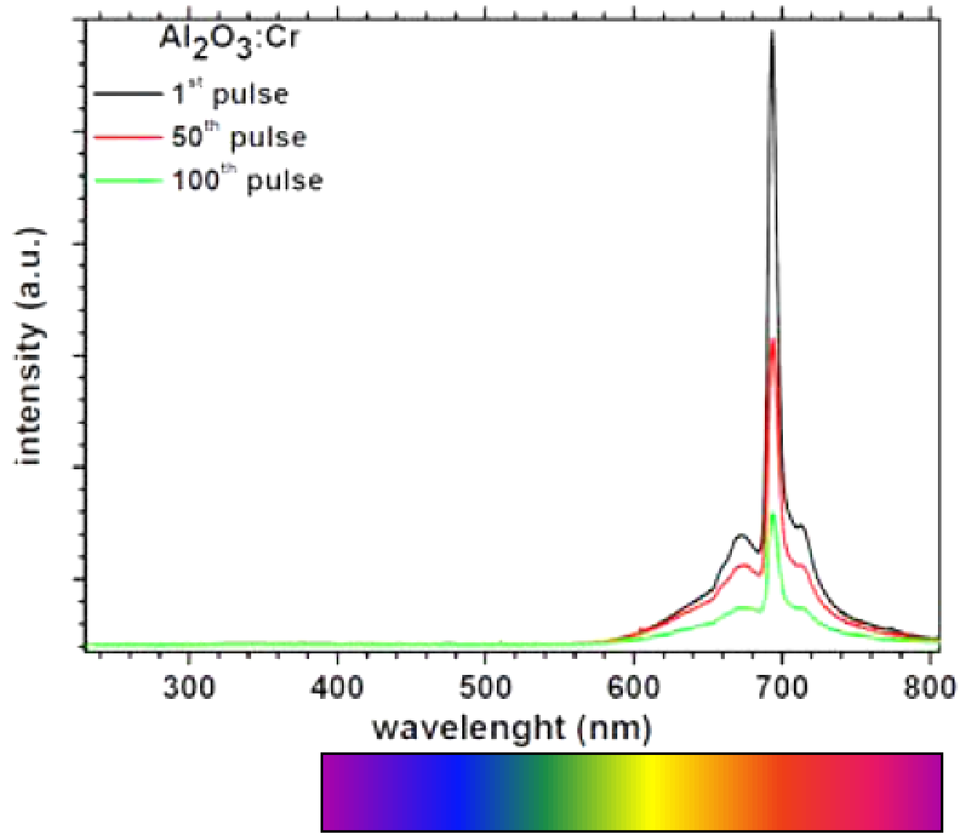
- **emission of photons within ≈ 10...1000 ns**

λ and τ depend strongly on dopant atom or color center nature

Wavelength Spectrum for Scintillation Screens

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 · 10^{10} ppp** in 500 µs, ~450 µA

[E. Gütlich (GSI) et al., BIW 2010]

Material Properties for Scintillating Screens

Some materials and their basic properties:

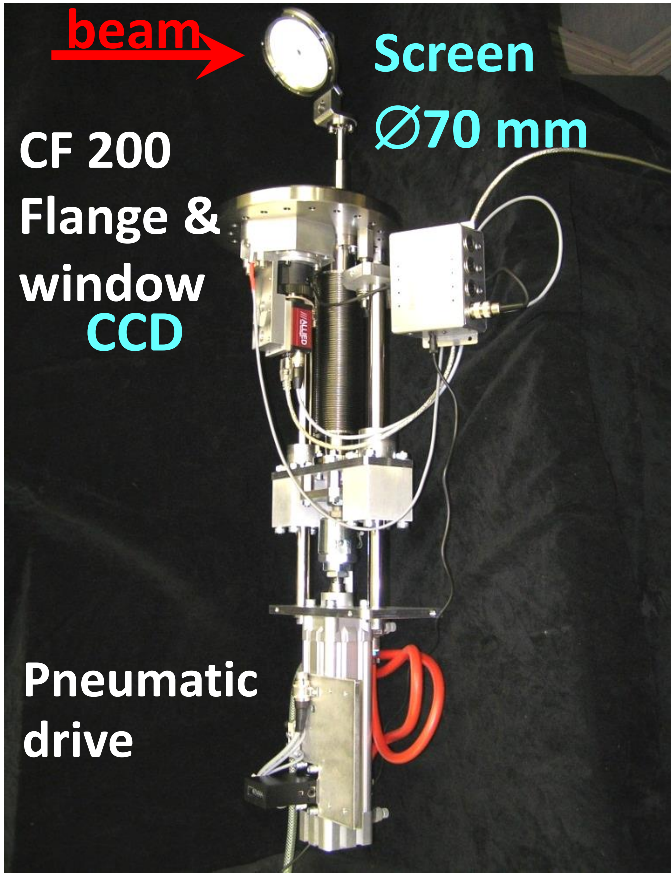
Name	Type	Material	Activ.	Max. λ	Decay
Chromox	Cera-mics	Al_2O_3	Cr	700nm	≈ 10ms
Alumina		Al_2O_3	Non	380nm	≈ 10ns
YAG:Ce	Crystal	$Y_3Al_5O_{12}$	Ce	550nm	200ns
LYSO		$Lu_{1.8}Y_{.2}SiO_5$	Ce	420nm	40ns
P43	Powder of gains Ø≈10µm on glass	Gd_2O_3S	Tb	545nm	1ms
P46		$Y_3Al_5O_{12}$	Ce	530nm	300ns
P47		$Y_3Si_5O_{12}$	Ce&Tb	400nm	100ns

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

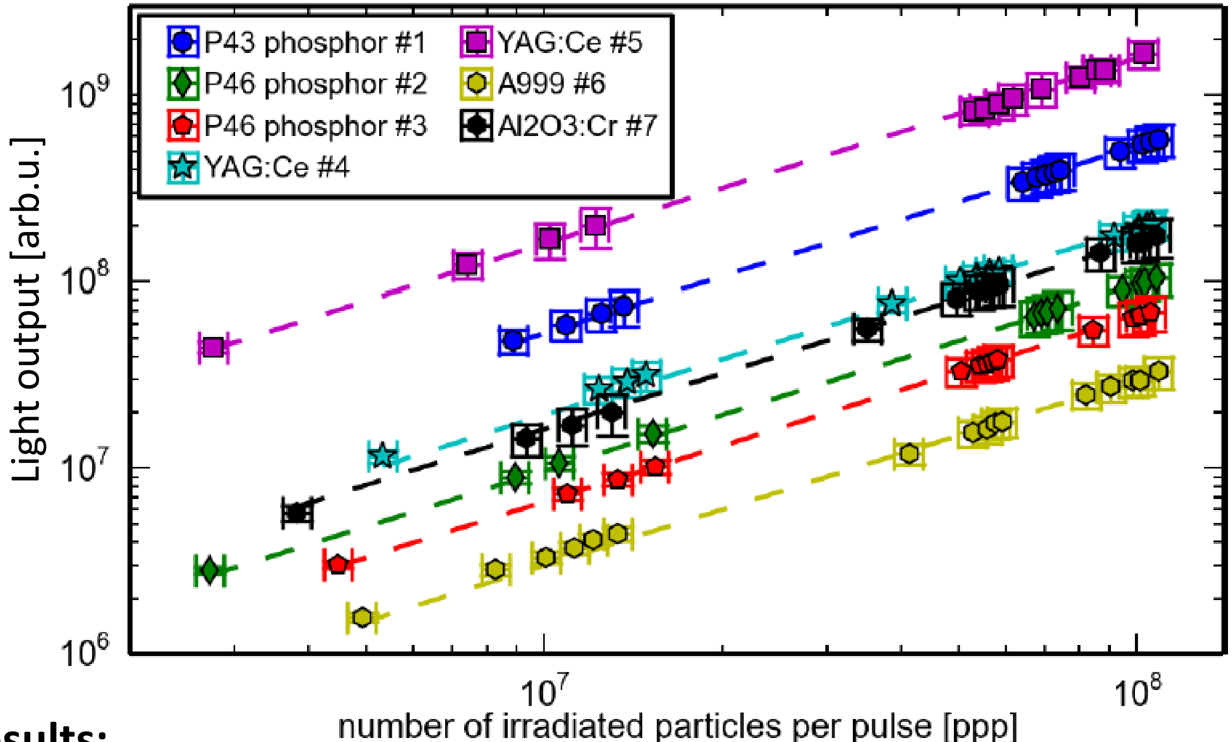
(Phosphor Pxx grains of Ø ≈ 10 µm on glass or metal).

Standard drive with P43 screen



Example: Light Output from various Screens

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 sedimented 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

- **Optical Transition Radiation:**

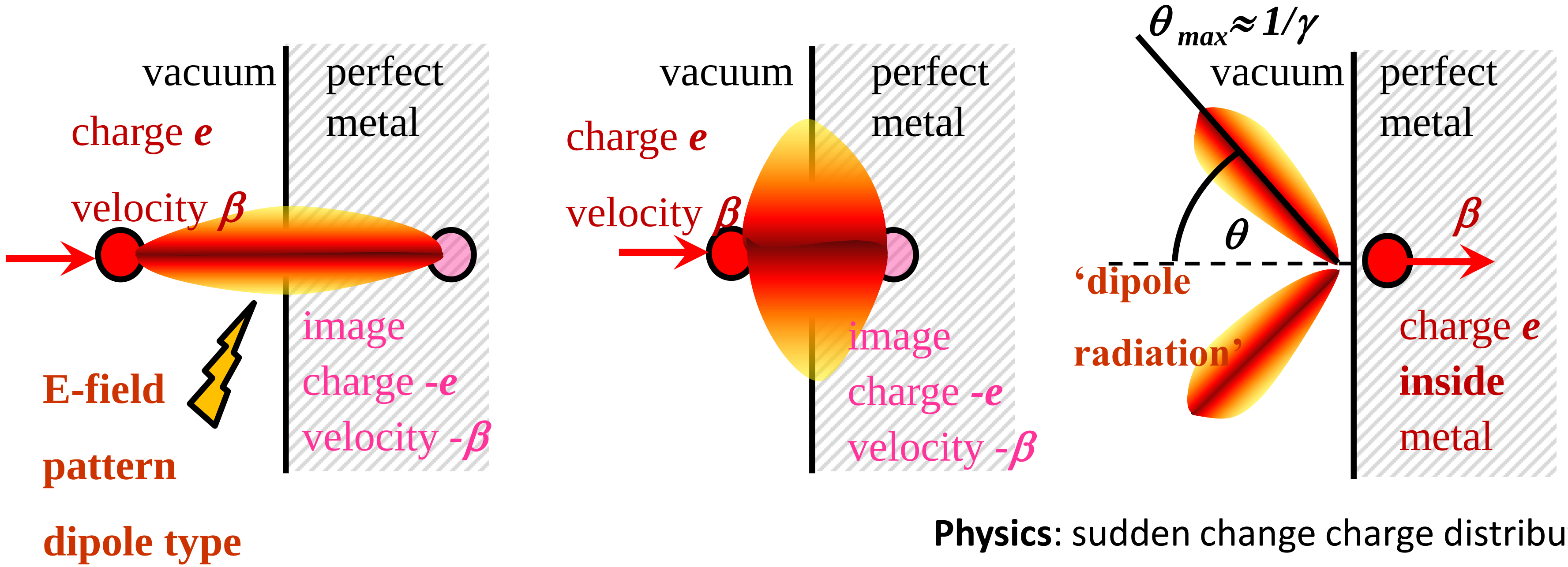
  crossing material boundary, for relativistic beams only

- **SEM-Grid**
- **Wire scanner**
- **Ionization Profile Monitor and Beam Induced Fluorescence Monitor**
- **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



Physics: sudden change charge distribution rearrangement of sources ⇔ radiation

Other physical interpretation: Impedance mismatch at boundary leads to radiation

Excurse: Optical Transition Radiation: Depictive Description

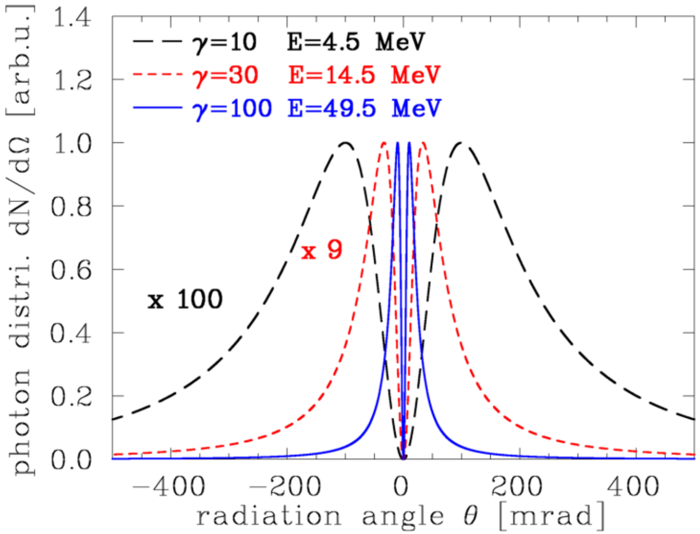
Optical Transition Radiation OTR can be described in classical physics:

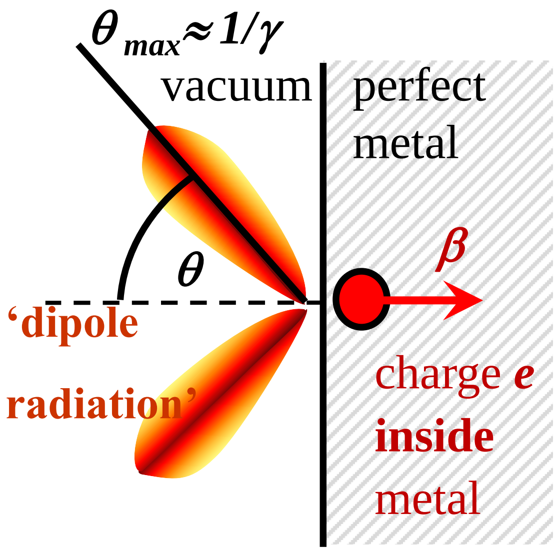
approximated formula
for normal incidence
& in plane polarization:

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

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)

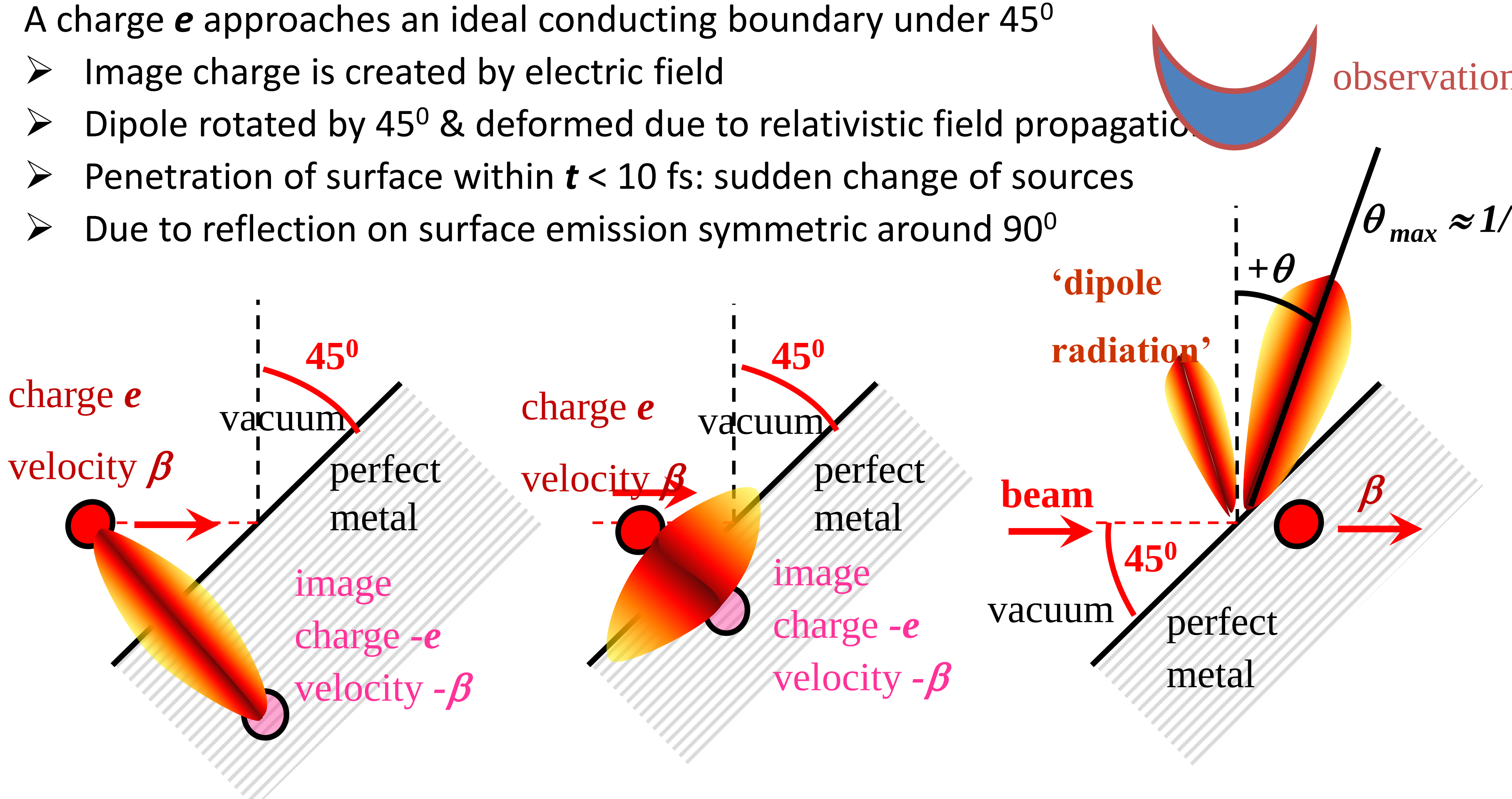
$\rightarrow$ suited for high energy electrons

Physics: sudden change charge distribution
rearrangement of sources $\Leftrightarrow$ radiation

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

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

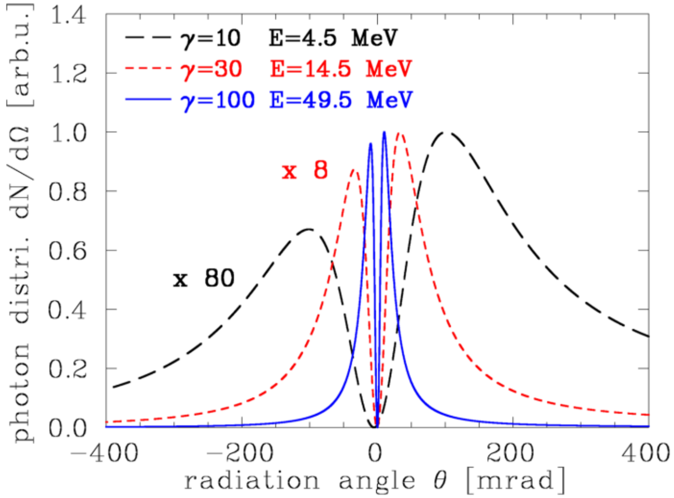
- Image charge is created by electric field
- Dipole rotated by 45^0 & deformed due to relativistic field propagation
- Penetration of surface within ***t*** < 10 fs: sudden change of sources
- Due to reflection on surface emission symmetric around 90^0

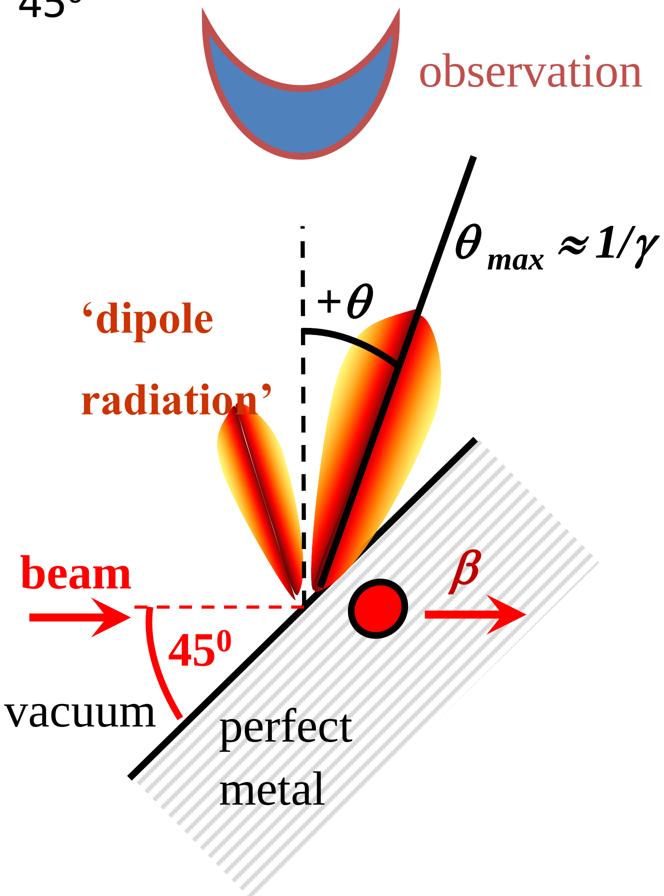


OTR with 45^0 beam incidence and observation at 90^0 :

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

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





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 $\gamma > 100$

Remark: polarization of emitted light:

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

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:

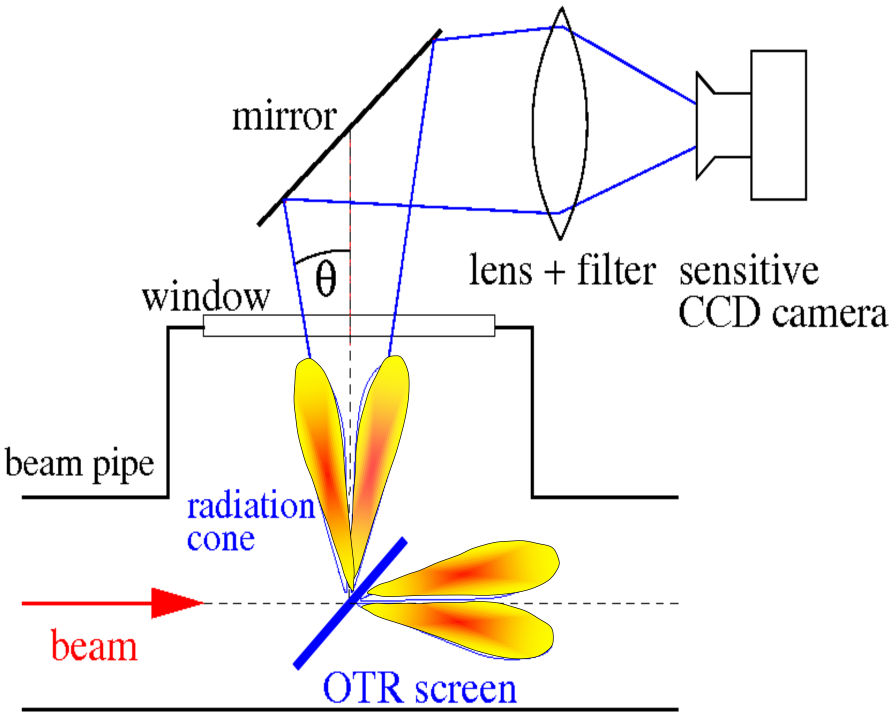
$$\frac{d^2W}{d\Omega d\omega} \approx \frac{2e^2\beta^2}{\pi c} \cdot \frac{\theta^2}{\left(\gamma^{-2}+\theta^2\right)^2}$$

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.

Optical Transition Radiation: Angular Photon Distribution

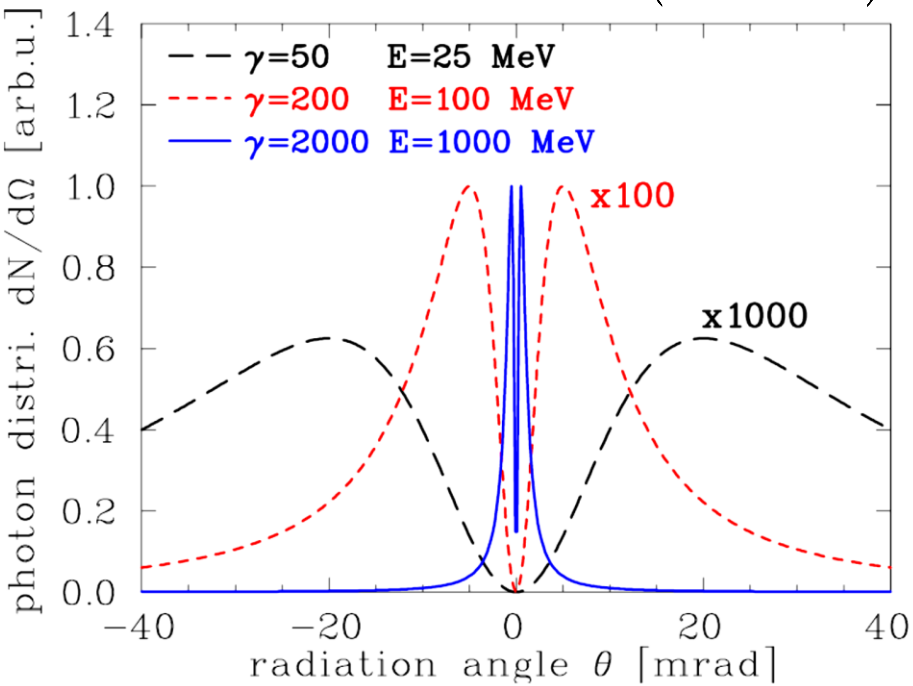
Photon distribution within a solid angle $d\Omega$ and Wavelength interval λ_{begin} to λ_{end}

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

- 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:

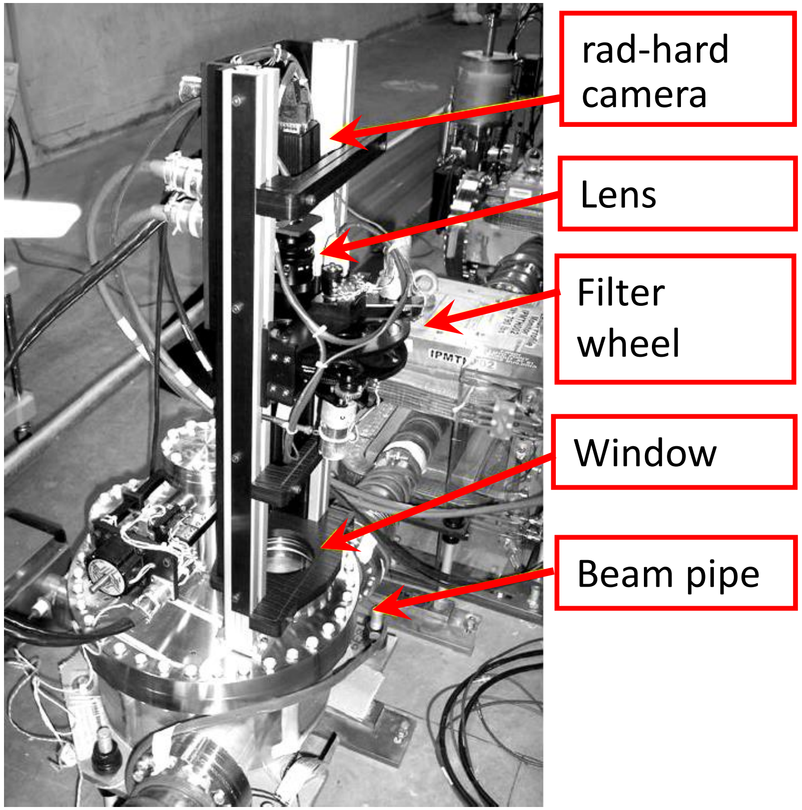
$\rightarrow$ ***Profile*** by focusing to screen

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

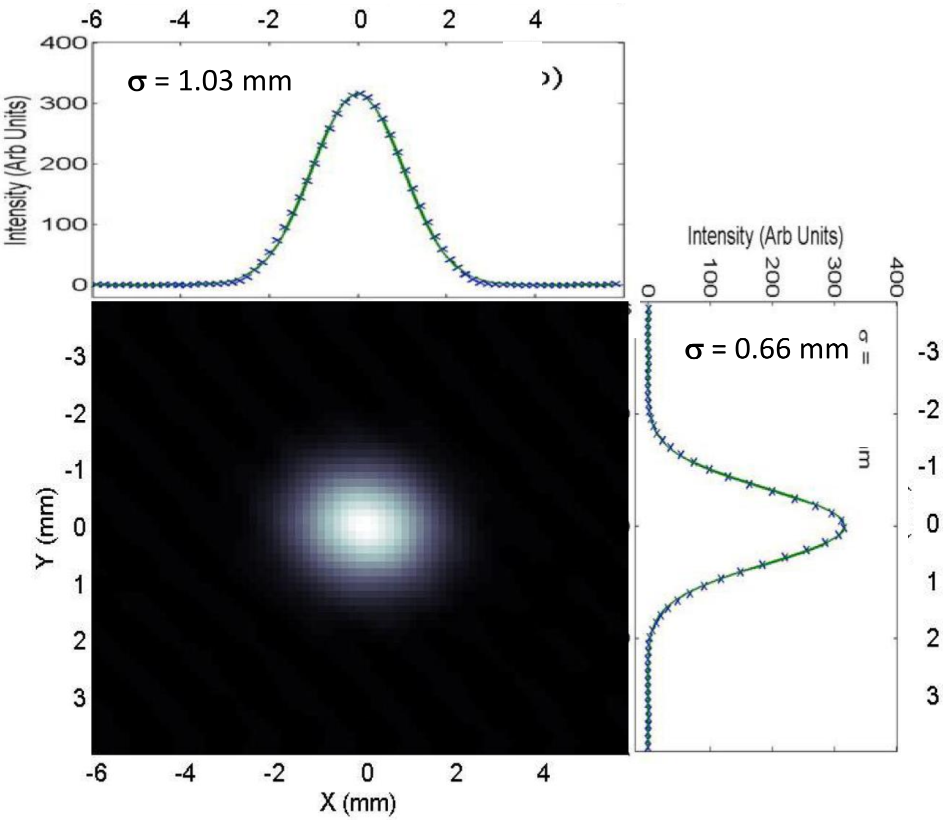
Example of realization at TERATRON:

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

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



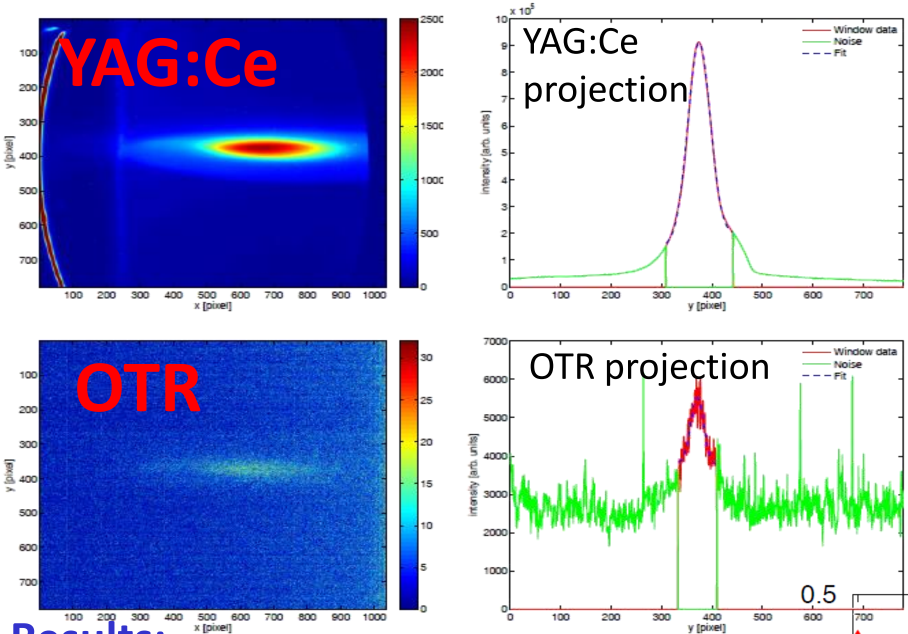
Results at FNAL-TEVATRON synchrotron with 150 GeV proton
Using fast camera: Turn-by-turn measurement



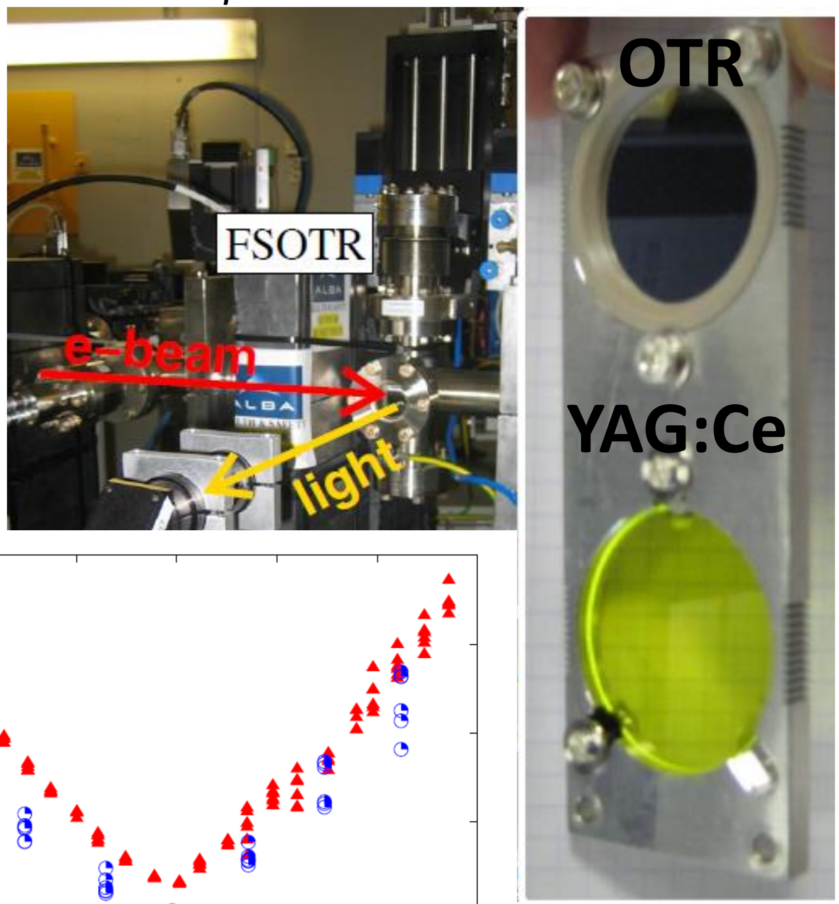
From V.E. Scarpine (FNAL) et al., BIW'06

Optical Transition Radiation compared to Scintillation Screen

Installation of OTR and scintillation screens on same drive:

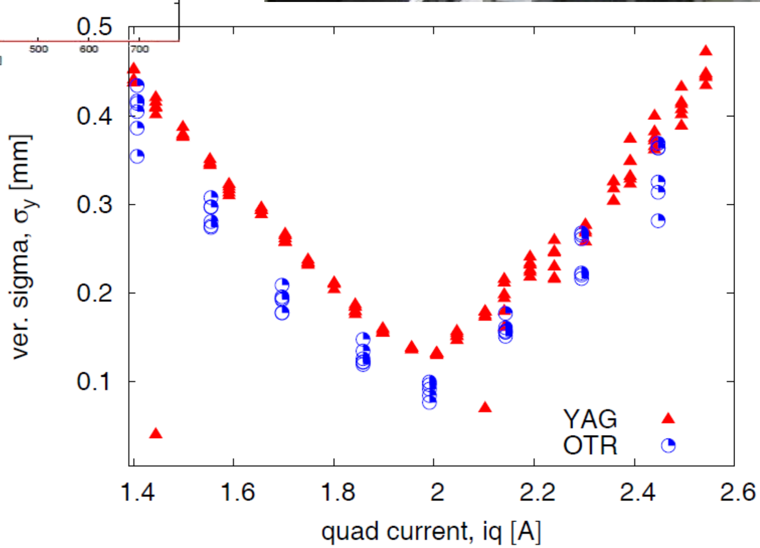


Example: ALBA LINAC 100 MeV



Results:

- Much more light from YAG:Ce for 100 MeV (γ=200) electrons light output $I_{YAG} \approx 10^5\, I_{OTR}$ (ratio depends on Lorentz factor γ)
- Broader image from YAG:Ce due to finite YAG:Ce thickness



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

Scint. Screen: for all beams

Remark:

OTR: Reamrk: beam angular distribution measurable → beam emittance

Scint. Screen: no information concerning the beam angular distribution

Outline:

- Scintillation screens:
  emission of light. universal usage, limited dynamic range
- Optical Transition Radiation:
  crossing material boundary, for relativistic beams only
- **SEM-Grid:** emission of electrons, workhorse, limited resolution
- Wire scanner
- Ionization Profile Monitor and Beam Induced Fluorescence Monitor
- Synchrotron Light Monitors
- Summary

Excurse: Secondary Electron Emission by Ion Impact

Energy loss of ions in metals close to a surface:

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

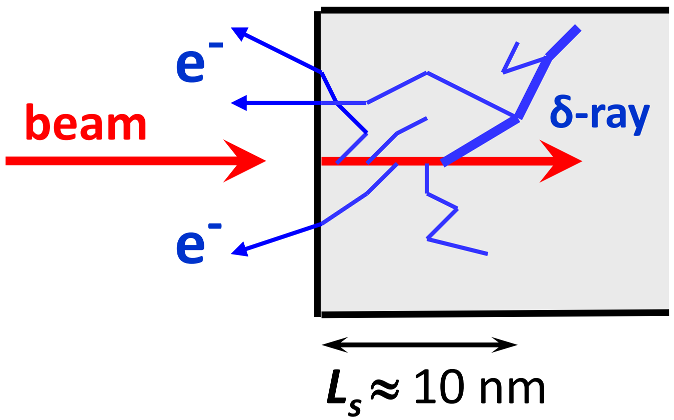
Distant collision with low energy transfer → slow e⁻ with $E_{kin} \lesssim$ 10 eV

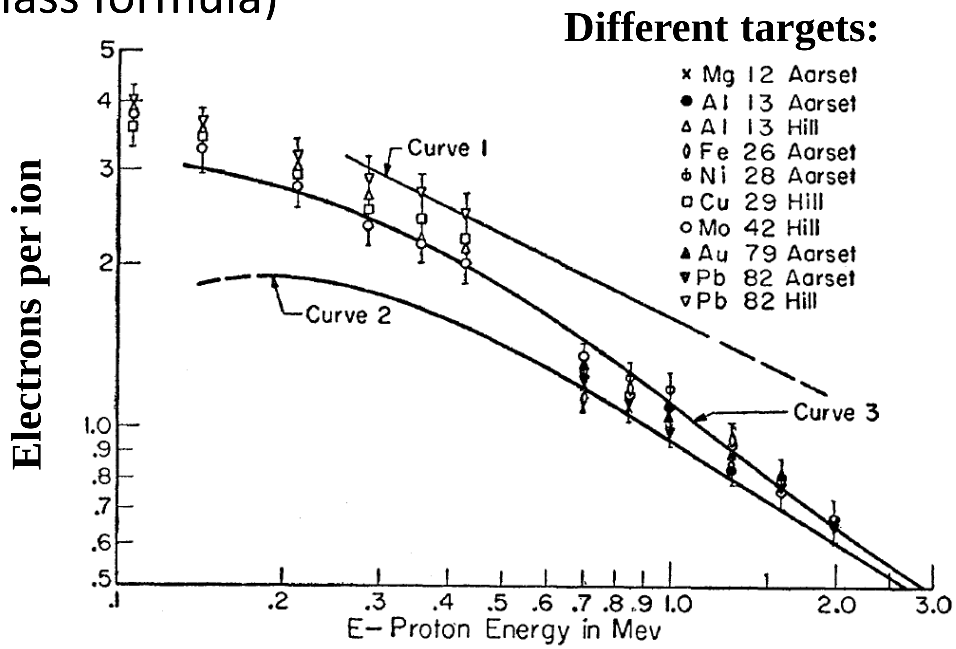
→ 'diffusion' & scattering with other e⁻: scattering length $L_s \approx$ 1 - 10 nm

→ at surface ≈ 90 % probability for escape

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

⇒ ***Y = const. * dE/dx*** (Sternglass formula)

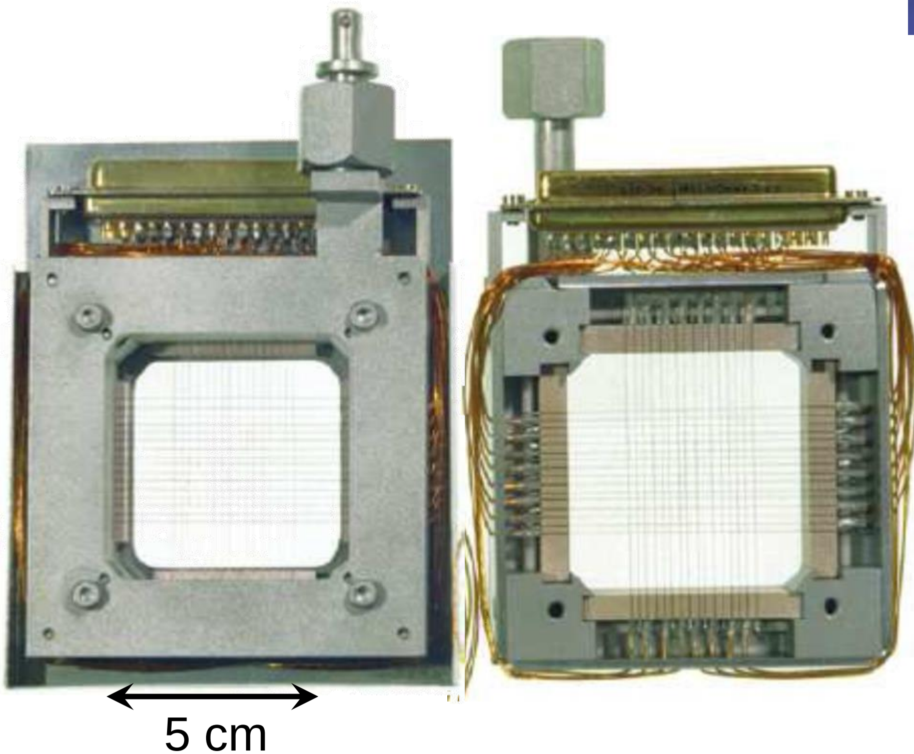




From E.J. Sternglass, Phys. Rev. 108, 1 (1957)

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

Example: 15 wire spaced by 1.5 mm:



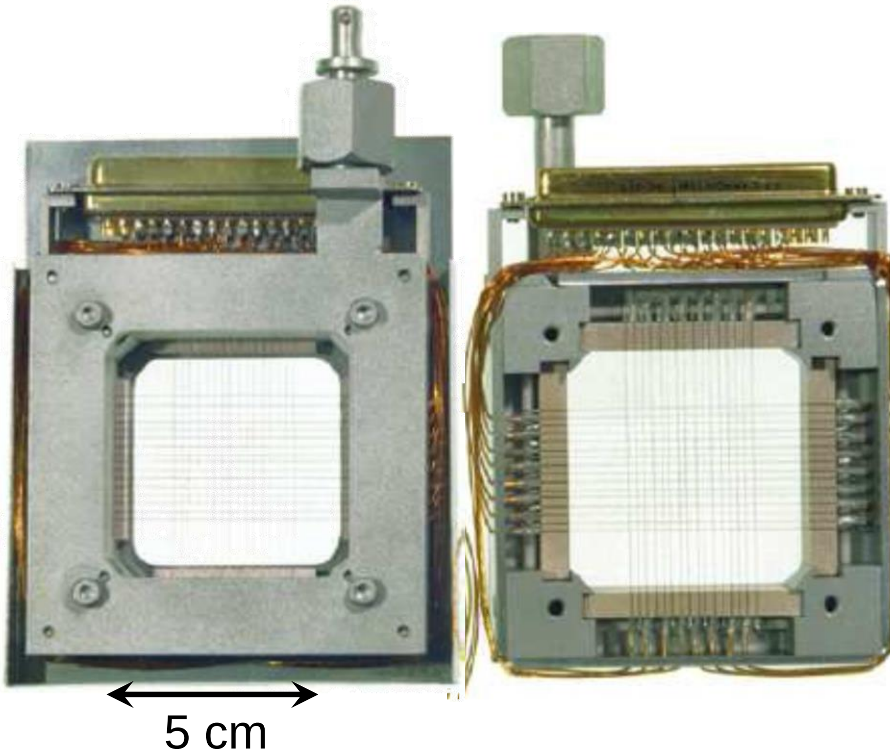
SEM-Grid feed-through on CF200:

Parameter	Typ. value
# wires per plane	10 ...100
Active area	$(5...20\ \text{cm})^2$
Wire ∅	25....100 μm
Spacing	0.3...2 mm
Material	e.g. W or Carbon
Max. beam power	1 W/mm

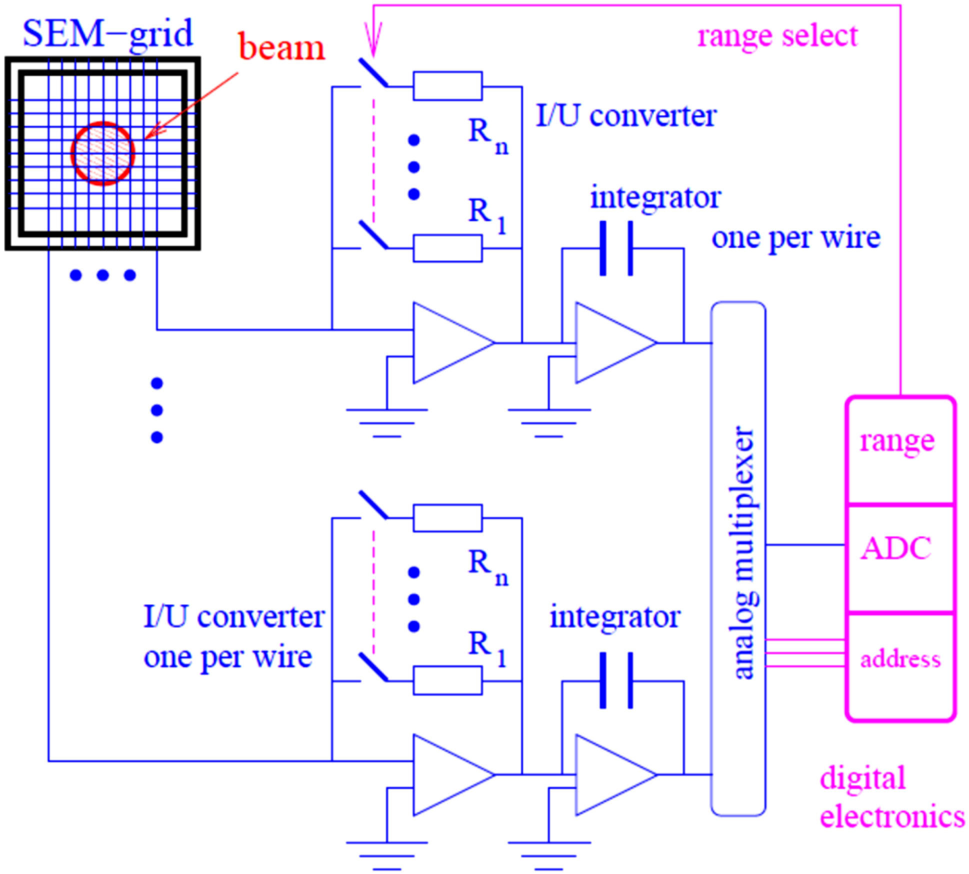
Secondary Electron Emission Grids = SEM-Grid

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

Example: 15 wire spaced by 1.5 mm:



SEM-Grid electroics scheme:

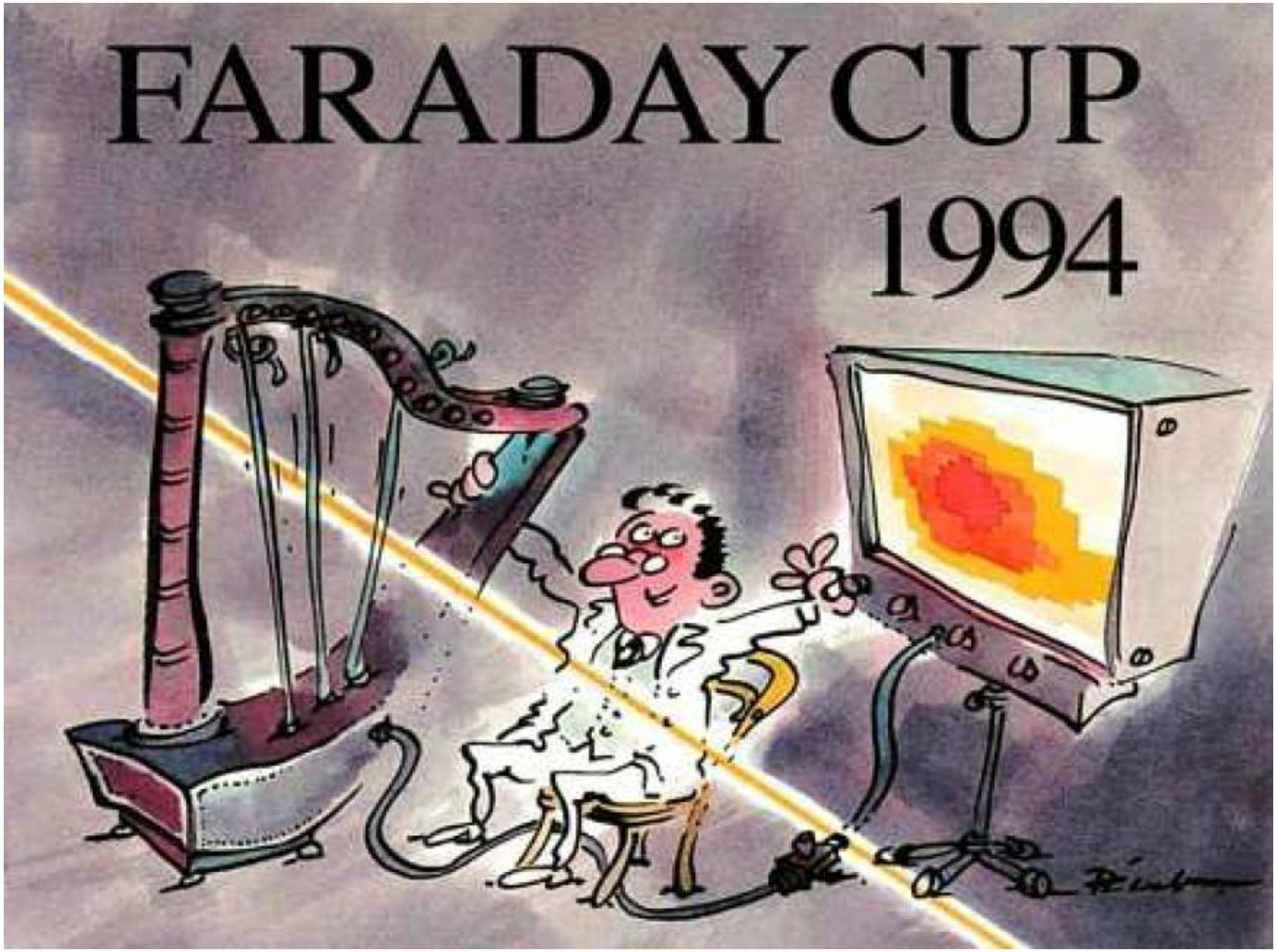


Each wire is equipped with one I/U converter

different ranges settings by R_i

→ very large dynamic range up to 10^6.

The Artist's view of a SEM-Grid = Harp



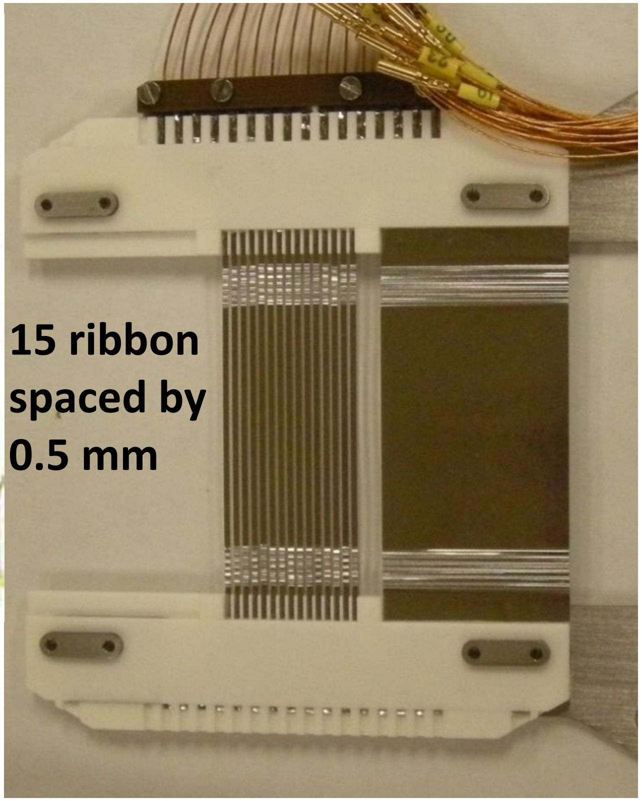
The Faraday Cup is an award granted every second year for beam diagnostics inventions.

Properties of a SEM-Grid

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

Parameter	Typ. value
# wires per plane	10 ...100
Active area	(5...20 cm) ^{2}
Wire ∅	25....100 μm
Spacing	0.3...2 mm
Material	e.g. W or Carbon
Max. beam power	1 W/mm
Sensitivity (I/U conv.)	1 nA/V
Dynamic range	1 : 10^6
Integration time	1ms to 1 s

Example: Ribbon type SEM-Grid



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

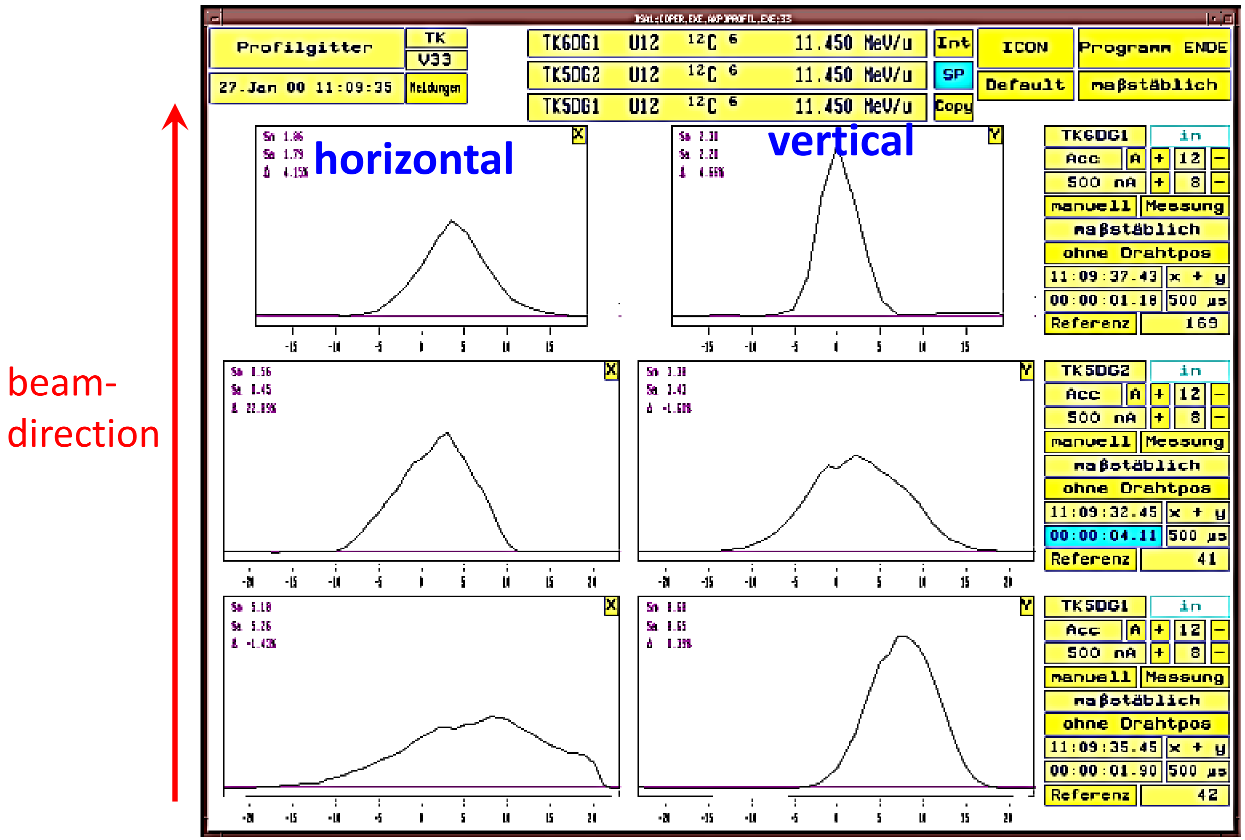
Low energy beam: **Wires** with ratio of spacing/width: ≃ 1mm/0.1mm = 10 → only 10 % loss.

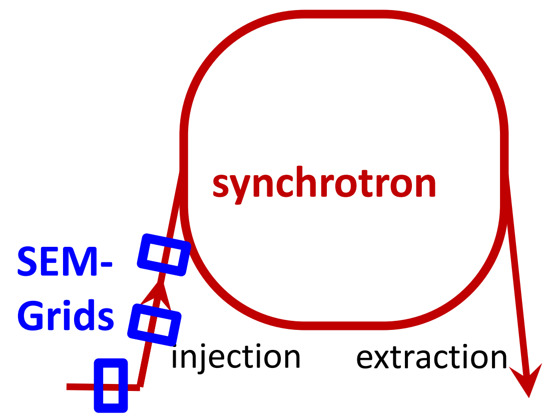
High energy E_{kin} > 1 GeV/u: typ. 25 μm thick **ribbons** & 0.5 mm width → negligible energy loss.

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
- Optical Transition Radiation:

  crossing material boundary, for relativistic beams only
- SEM-Grid: emission of electrons, workhorse, limited resolution
- **Wire scanner:** emission of electrons, workhorse, scanning method
- **Ionization Profile Monitor and Beam Induced Fluorescence Monitor**
- **Synchrotron Light Monitors**
- **Summary**

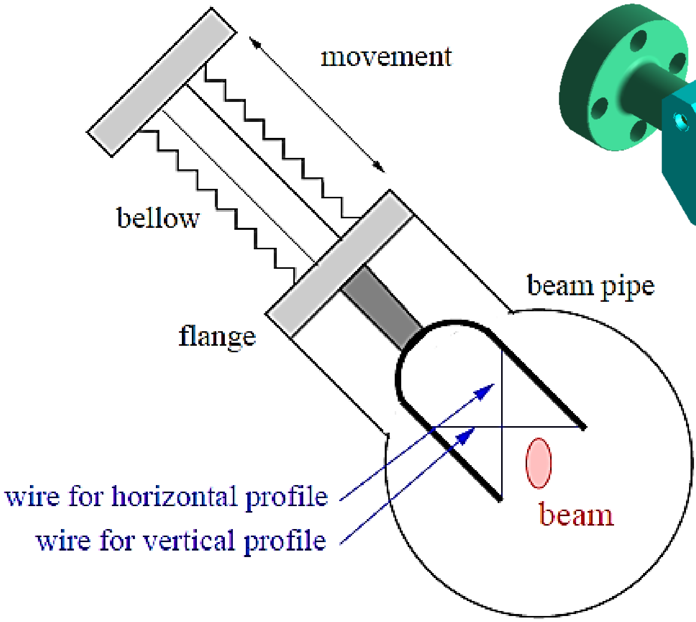
Slow, linear Wire Scanner

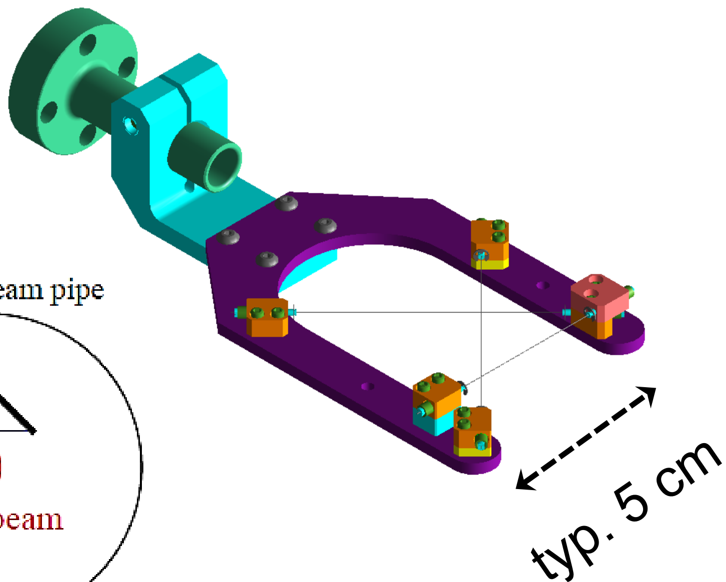
Idea: One wire is scanned through the beam!

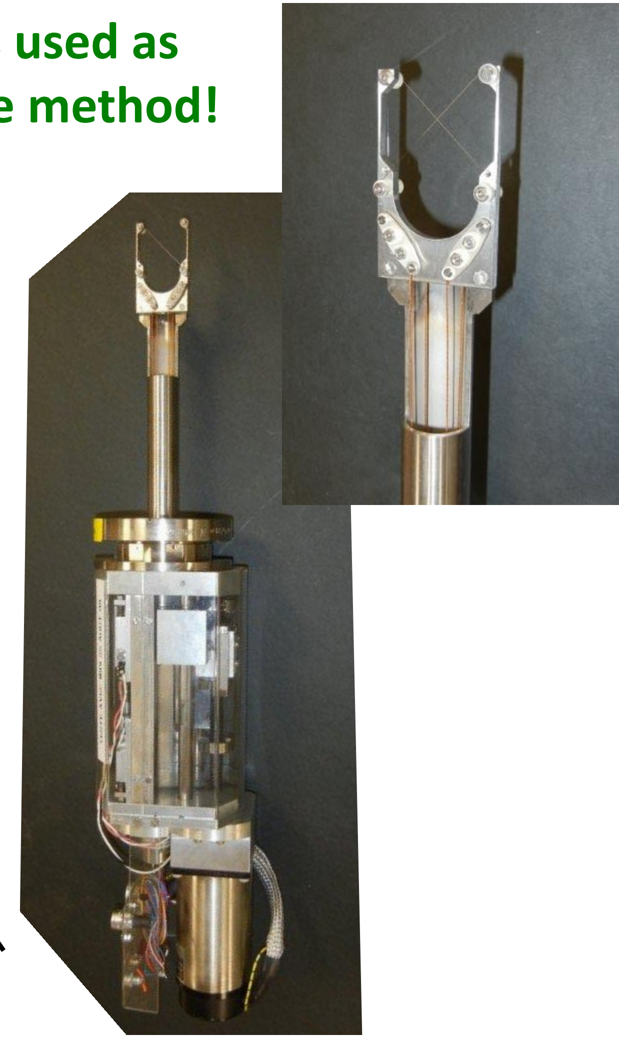
Slow, linear scanner are used for:

Scanners used as reference method!

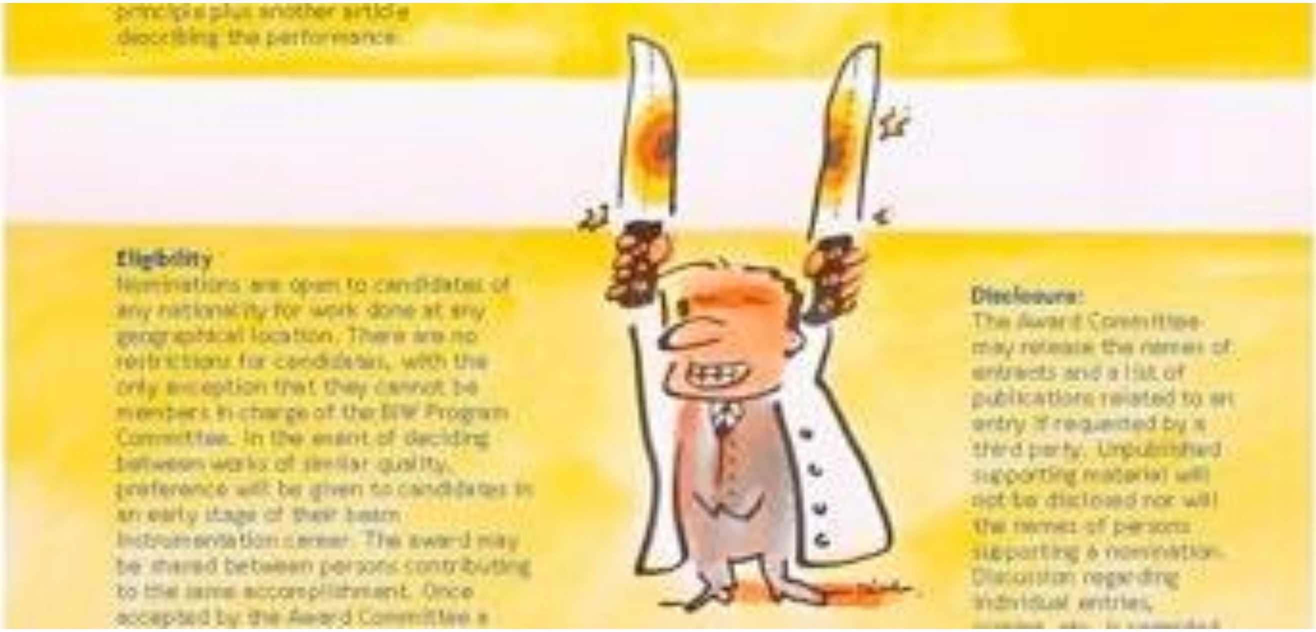
- low energy protons
- high resolution measurements e.g. at e^+-e^- colliders
  by de-convolution $\sigma^2_{beam} = \sigma^2_{meas} - d^2_{wire}$
  $\Rightarrow$ resolution down to µm can be reached
- detection of beam halo.







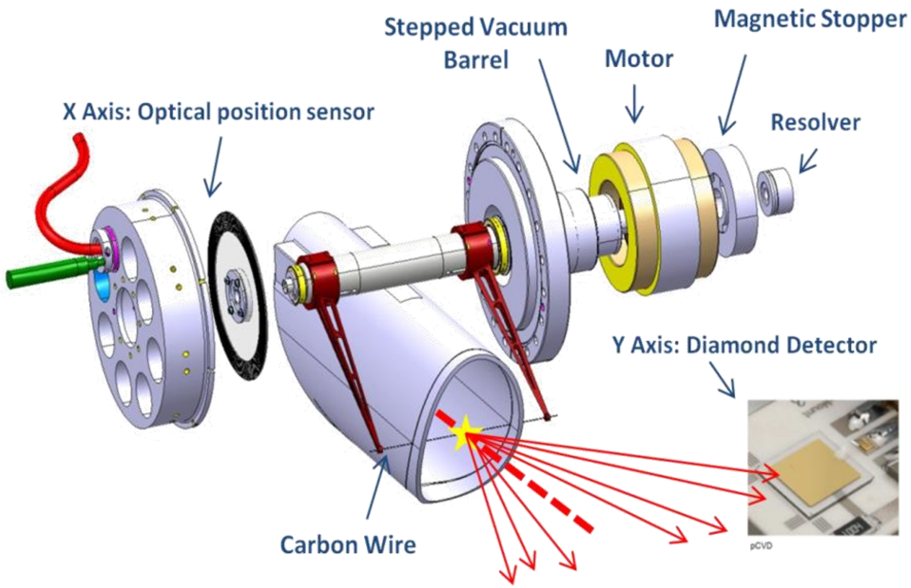
The Artist's view of a Beam Scraper or Scanner

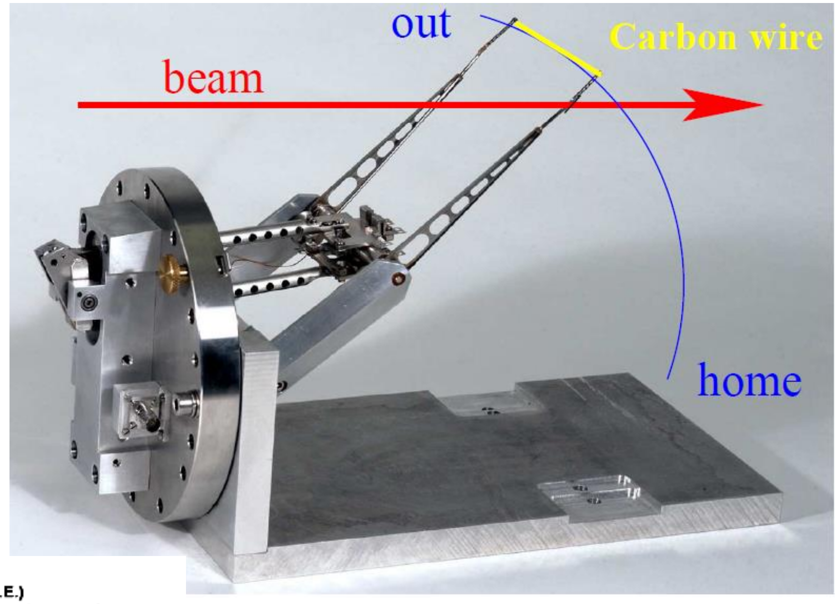


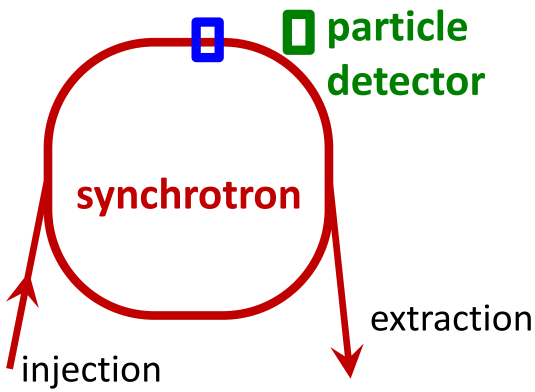
Fast, Flying Wire Scanner

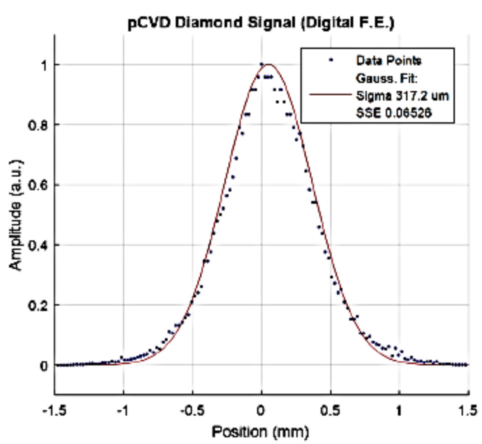
In a synchrotron ***one*** wire is scanned though the beam as fast as possible.

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









Scanners used as reference method!

From https://twiki.cern.ch/twiki/bin/viewauth/BWSUpgrade/

Usage of Flying Wire Scanners

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

Thickness: down to 10 µm → high resolution.

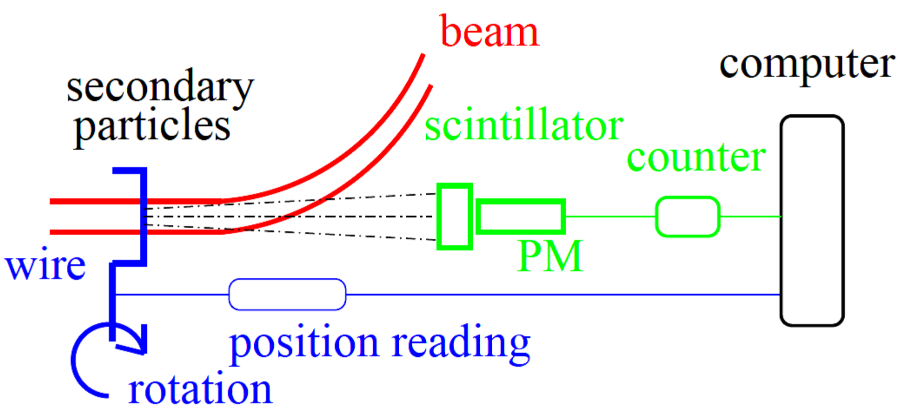
Detection: High energy **secondary particles** (like beam loss monitor)

flying wire: only sec. particle detection due to induced current by movement.

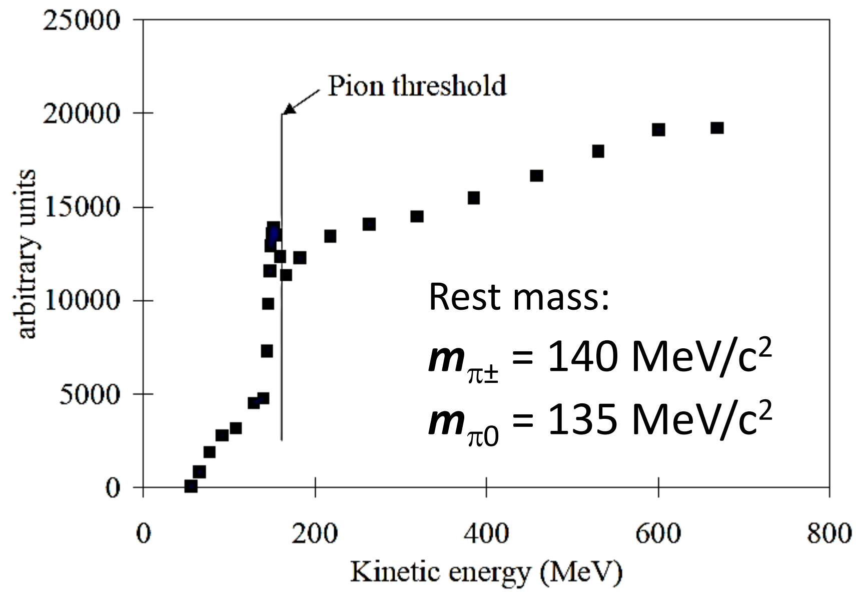
Secondary particles:

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

Electron beam → Bremsstrahlung photons.



Example: Proton impact on scanner at CERN-PS Booster



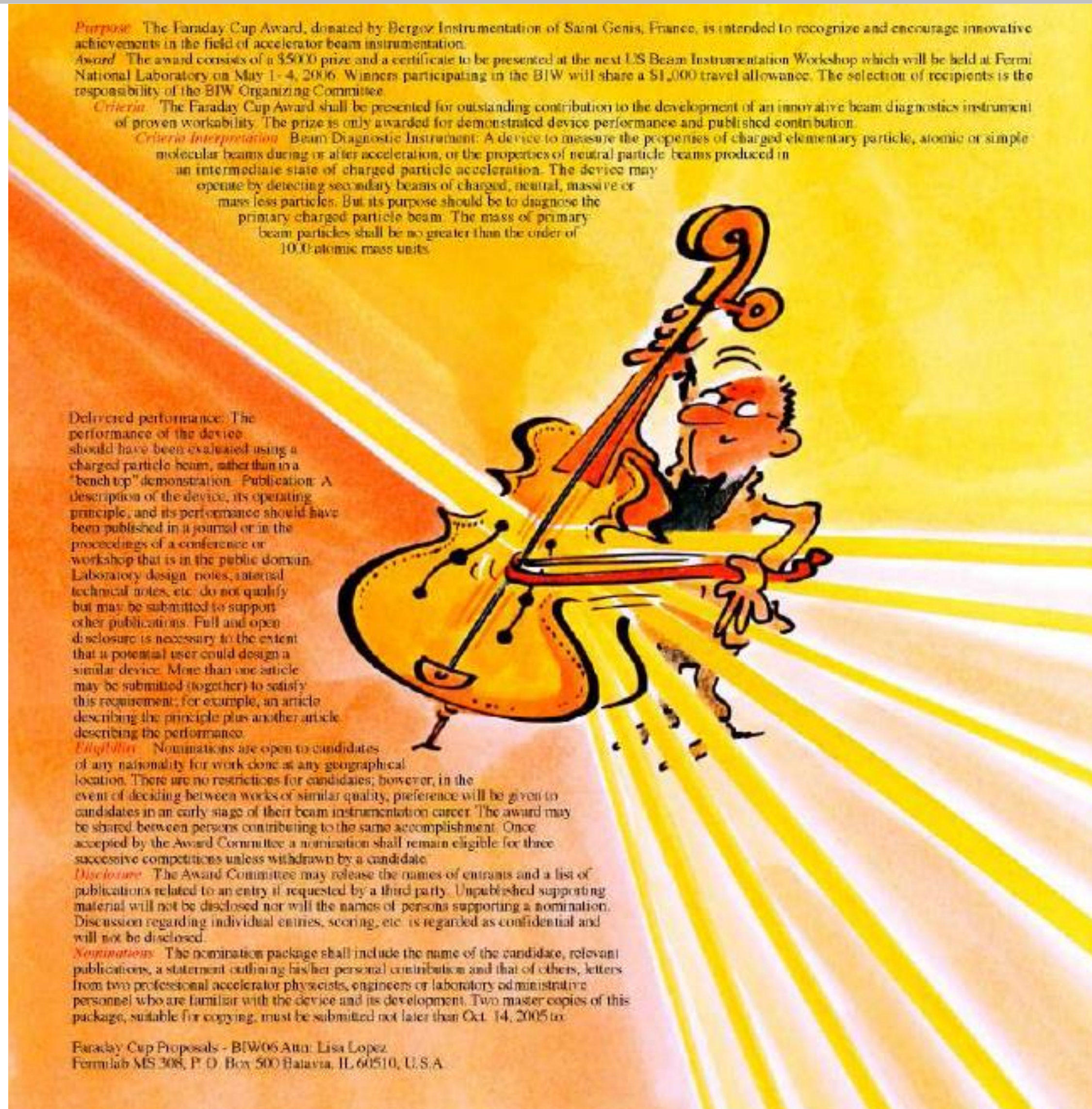
U. Raich et al., DIPAC 2005

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

Challenges: Wire stability for fast movement with high acceleration

The Artist's View of a Wire Scanner



Comparison between SEM-Grid and slow linear Wire Scanners

Grid: Measurement at a single moment in time

Scanner: Fast variations can not be monitored

$\rightarrow$ for pulsed LINACs precise synchronization is needed

---

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)

$\rightarrow$ used for e−-beams having small sizes (down to 10 µm)

Grid: Needs one electronics channel per wire

$\rightarrow$ expensive electronics and data acquisition

Scanner: Needs a precise movable feed-through $\rightarrow$ expensive mechanics.

Grid: **Not** adequate at synchrotrons for stored beam parameters

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

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 0.01 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)

Material Properties for Scintillating Screens

Some materials and their basic properties:

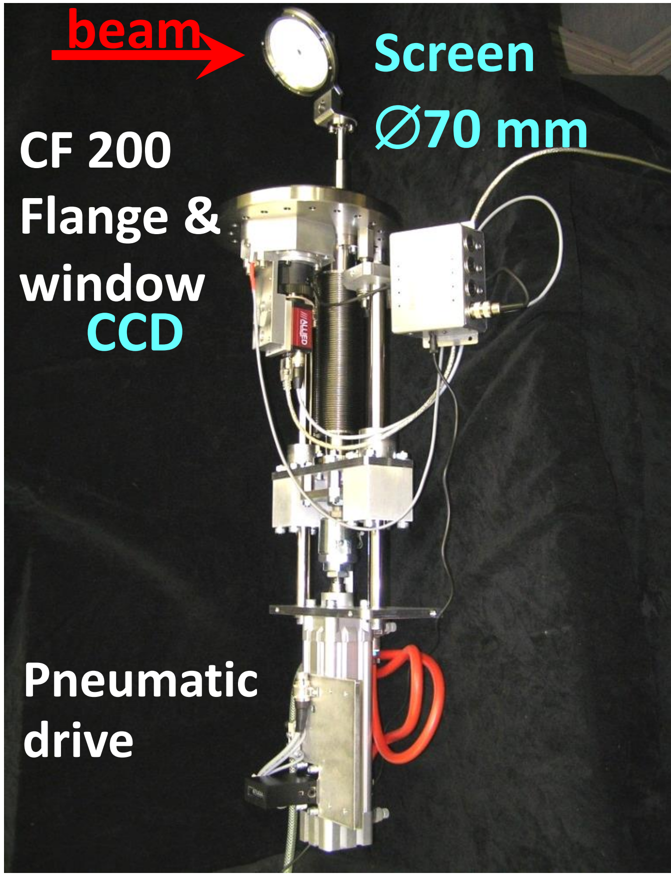
Name	Type	Material	Activ.	Max. λ	Decay
Chromox	Cera-mics	Al_2O_3	Cr	700nm	≈ 10ms
Alumina		Al_2O_3	Non	380nm	≈ 10ns
YAG:Ce	Crystal	$Y_3Al_5O_{12}$	Ce	550nm	200ns
LYSO		$Lu_{1.8}Y_{.2}SiO_5$	Ce	420nm	40ns
P43	Powder of gains Ø≈10μm on glass	Gd_2O_3S	Tb	545nm	1ms
P46		$Y_3Al_5O_{12}$	Ce	530nm	300ns
P47		$Y_3Si_5O_{12}$	Ce&Tb	400nm	100ns

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



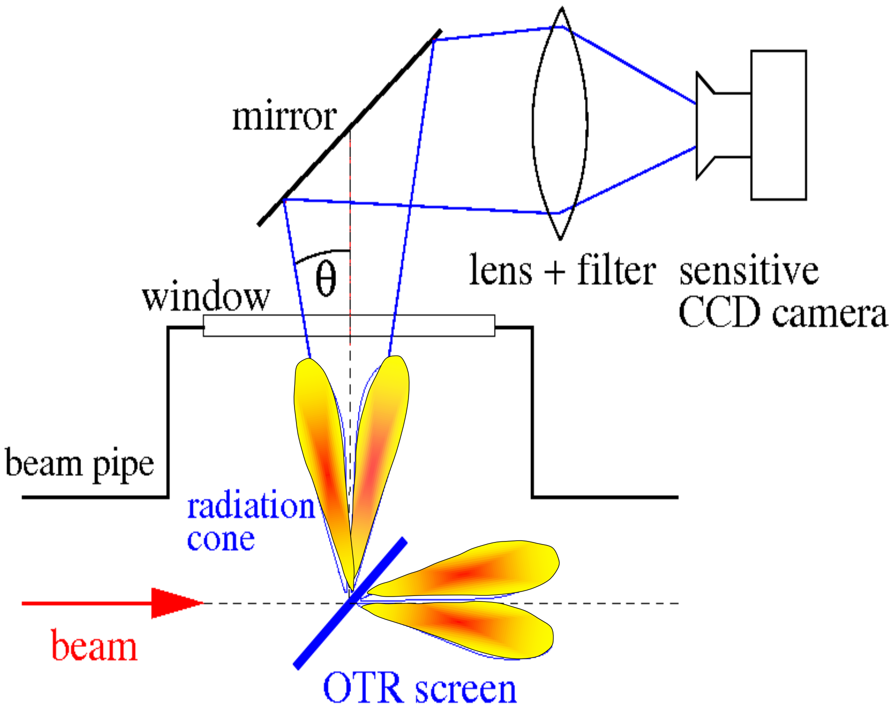
Optical Transition Radiation OTR

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:

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

W: energy emitted in solid angle Ω
θ: angle of emission
γ: Lorentz factor
ω: angular frequency intervall $E_{ph}=2\pi h\omega$

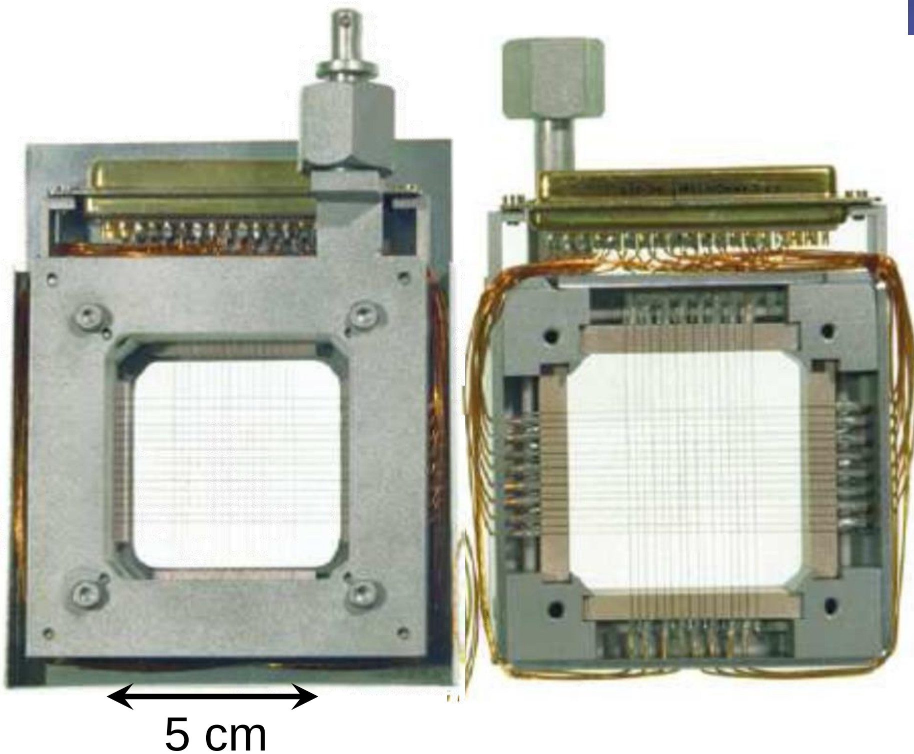


- Insertion of thin Al-foil under 45°
- Observation of low light by CCD.

Secondary Electron Emission Grids = SEM-Grid

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

Example: 15 wire spaced by 1.5 mm:



SEM-Grid feed-through on CF200:

Parameter	Typ. value
# wires per plane	10 ...100
Active area	$(5...20\text{ cm})^2$
Wire ∅	25....100 μm
Spacing	0.3...2 mm
Material	e.g. W or Carbon
Max. beam power	1 W/mm

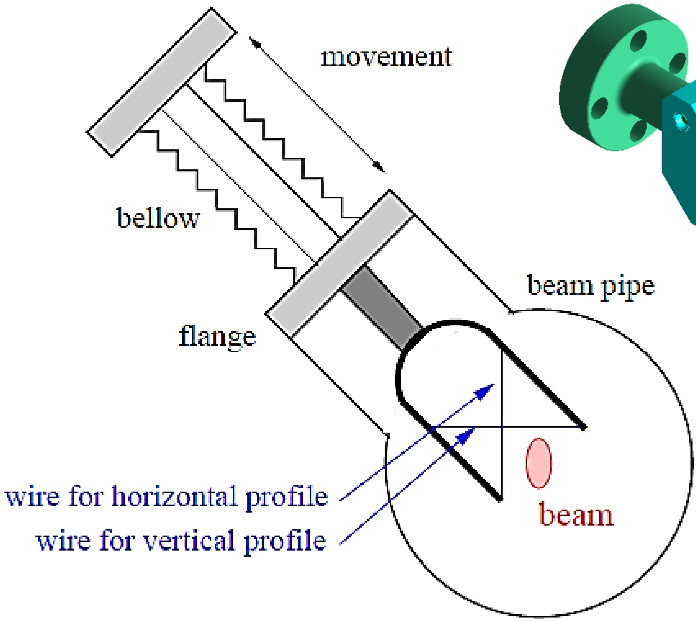
Slow, linear Wire Scanner

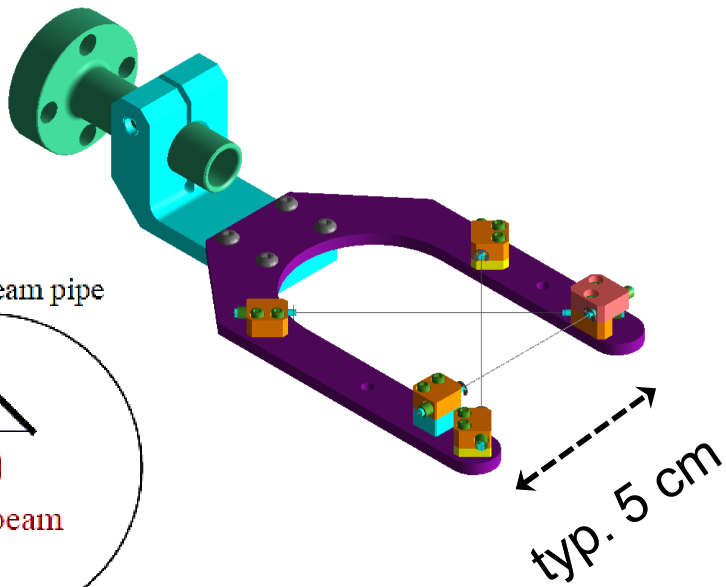
Idea: One wire is scanned through the beam!

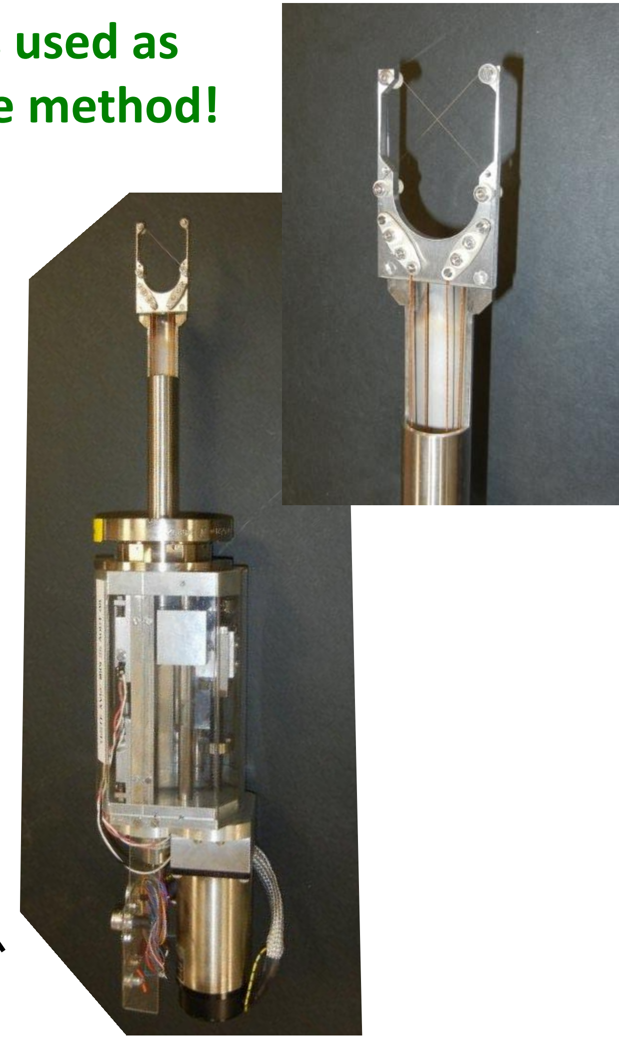
Slow, linear scanner are used for:

- 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.

Scanners used as reference method!







Outline:

- Scintillation screens:

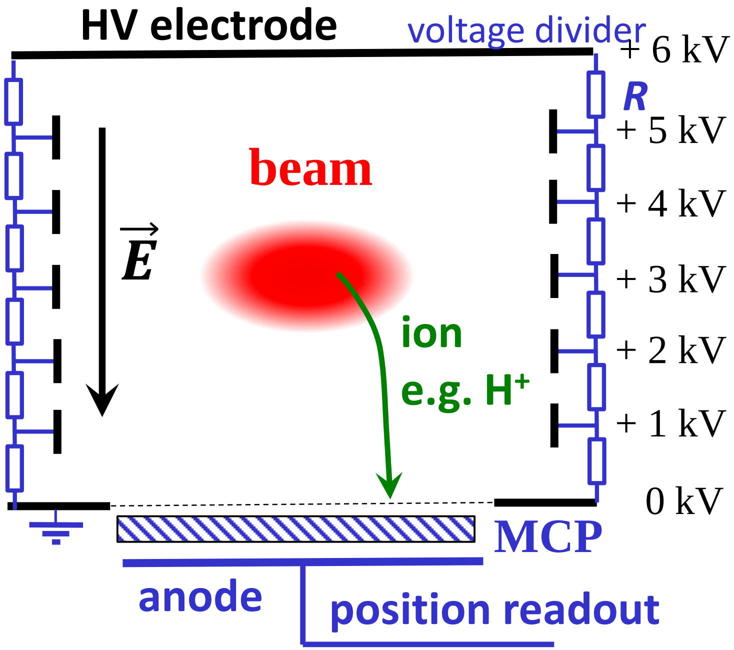
  emission of light. universal usage, limited dynamic range
- Optical Transition Radiation:

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

Non-destructive device for proton synchrotron:

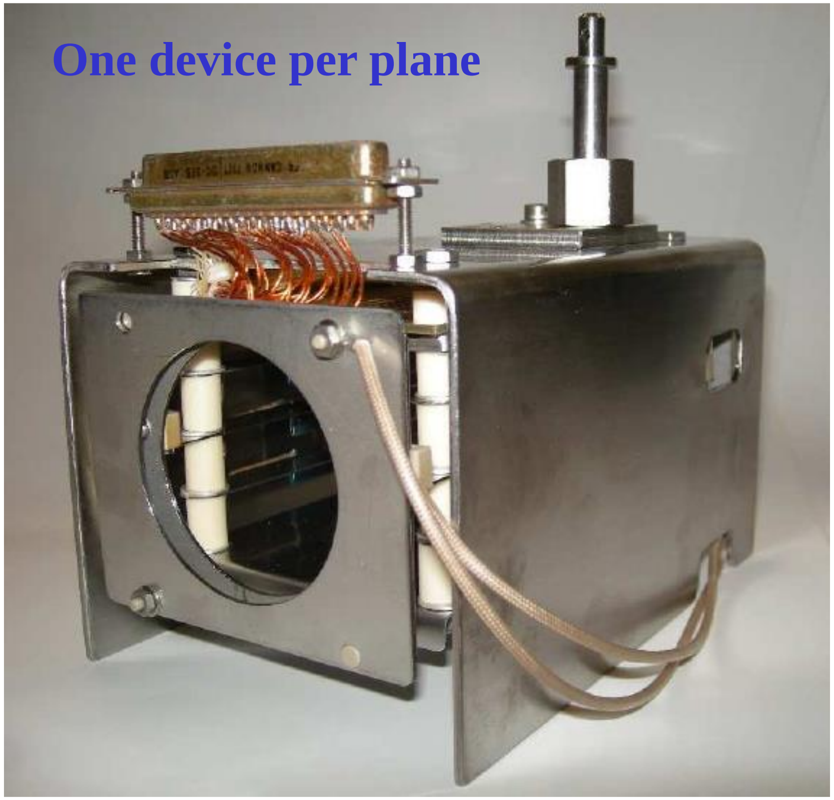
- beam ionizes the residual gas by electronic stopping
- gas ions or e⁻ accelerated by E -field ≈1 kV/cm
- spatial resolved single particle detection



IPM for the use at the GSI LINAC:

Vacuum p $\simeq 10^{-7}$ mbar, I $\simeq$ 1 mA

Readout by strips fed to an I/U converter.



Typical vacuum pressure:

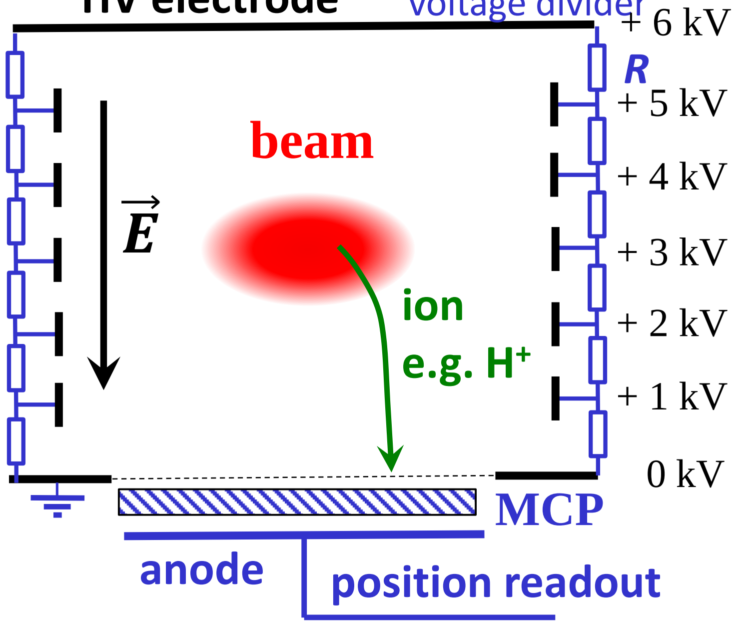
Transfer line: N_2 10^{-8}... 10^{-6} mbar ≅ $3\cdot10^{8}$...$3\cdot10^{10}$cm^{-3}

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

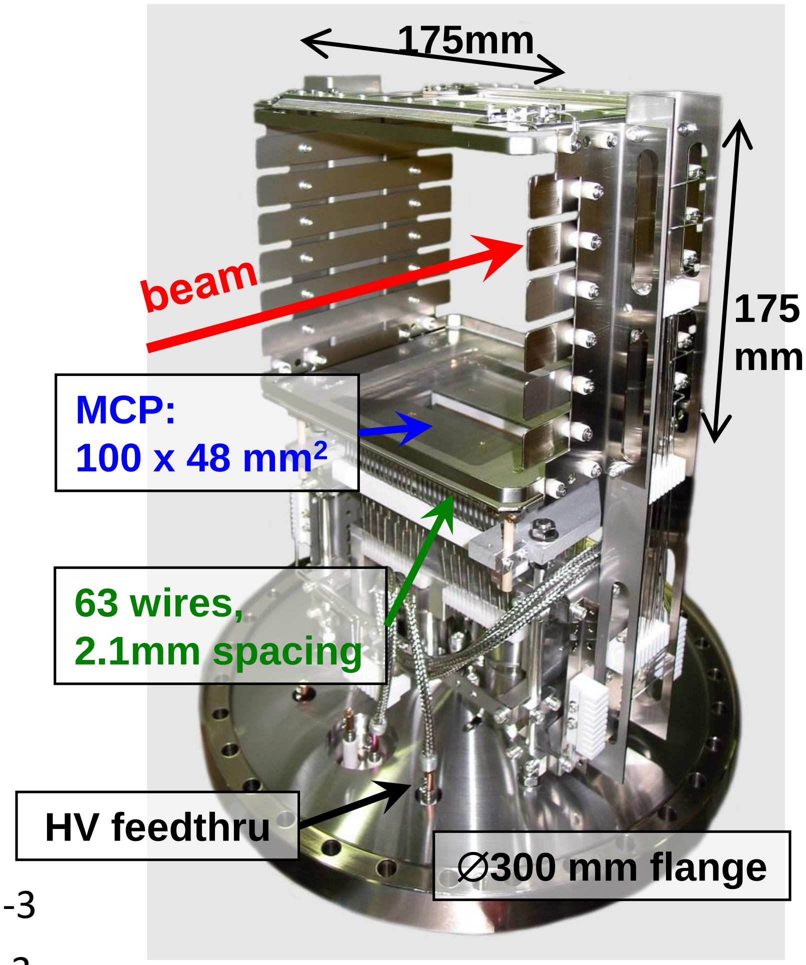
Ionization Profile Monitor at GSI Synchrotron

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



Realization at GSI synchrotron:
One device per plane



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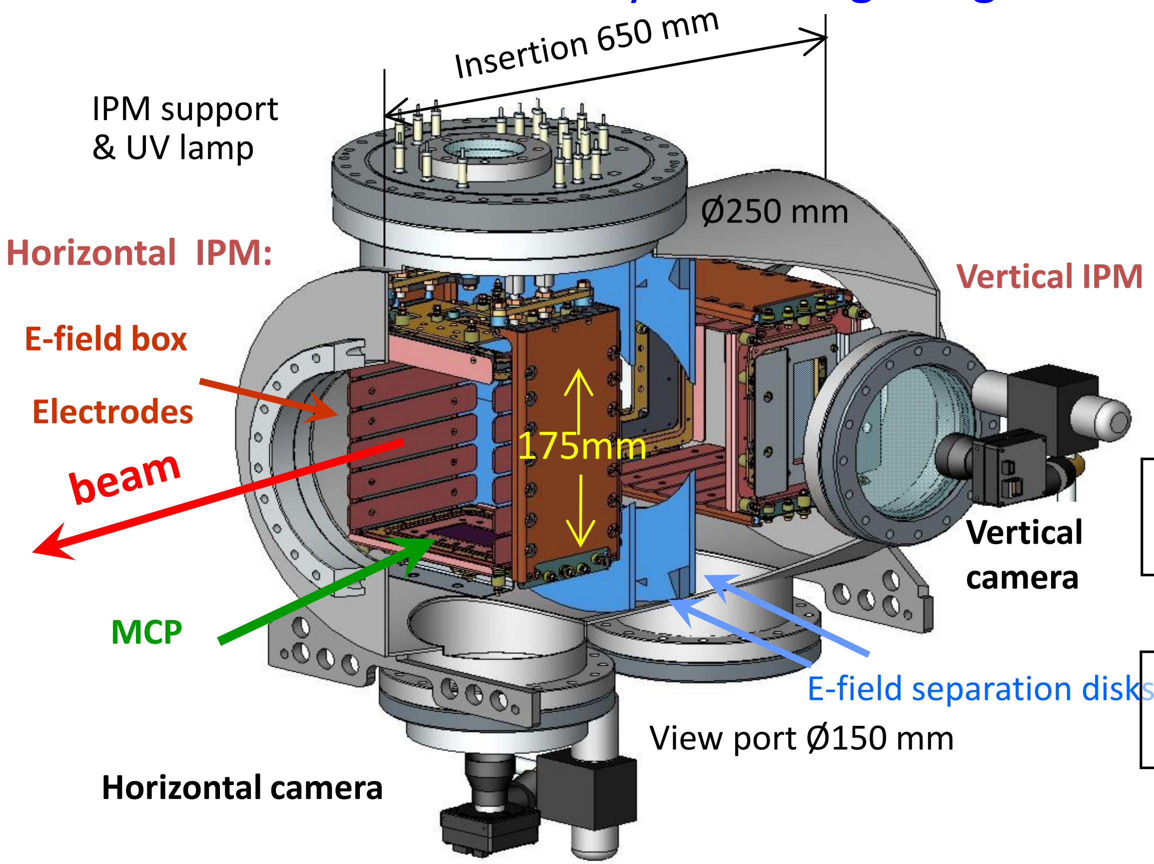
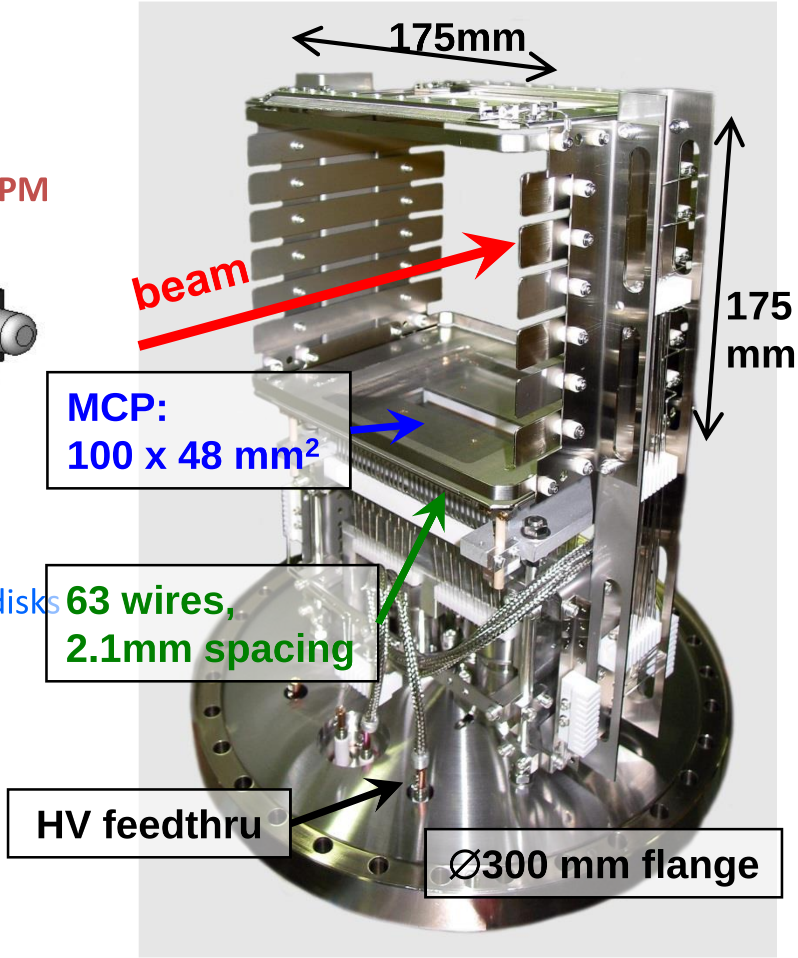
Ionization Profile Monitor Realization

The realization for the heavy ion storage ring at GSI:



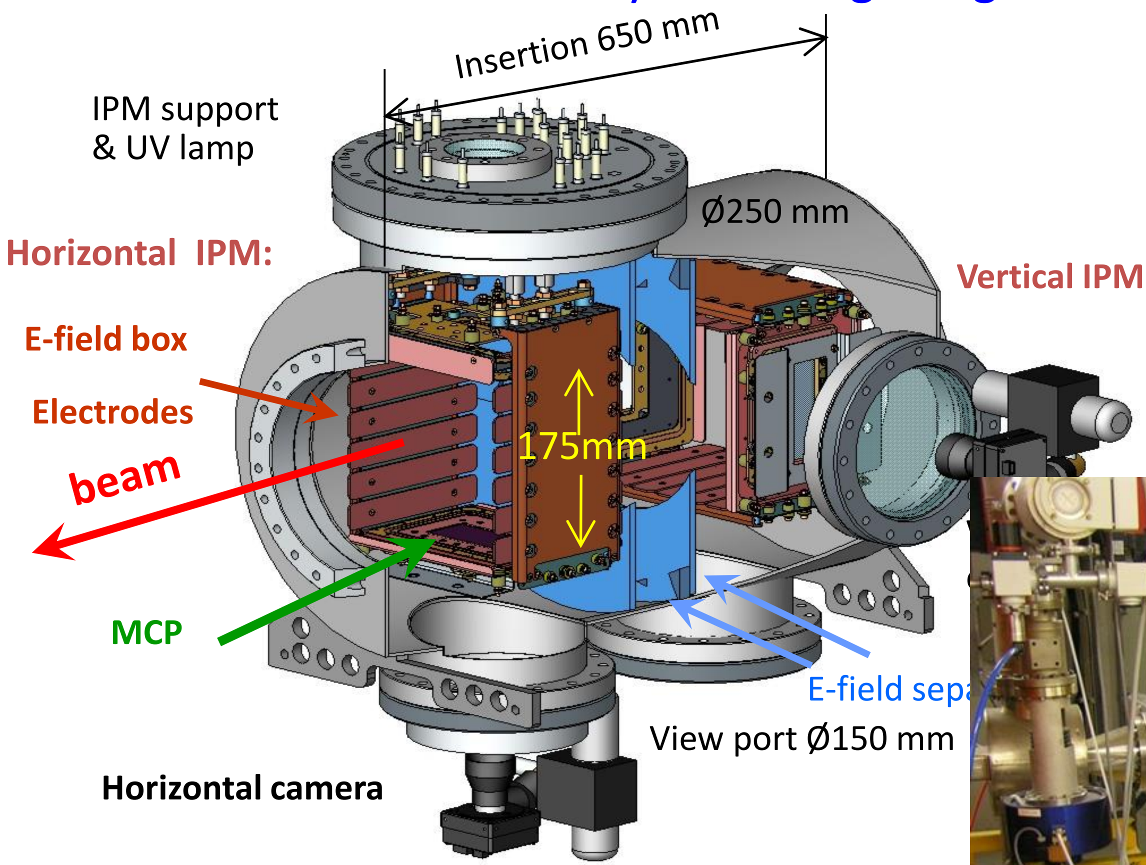
Realization at GSI synchrotron:
One device per plane



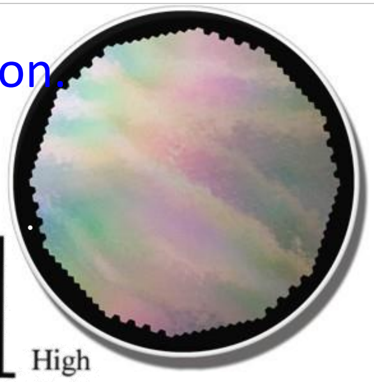
Ionization Profile Monitor Realization

The realization for the heavy ion storage ring at GSI:

Realization at GSI synchrotron:
One device per plane



MCP are used as particle detectors with secondary electron amplification.

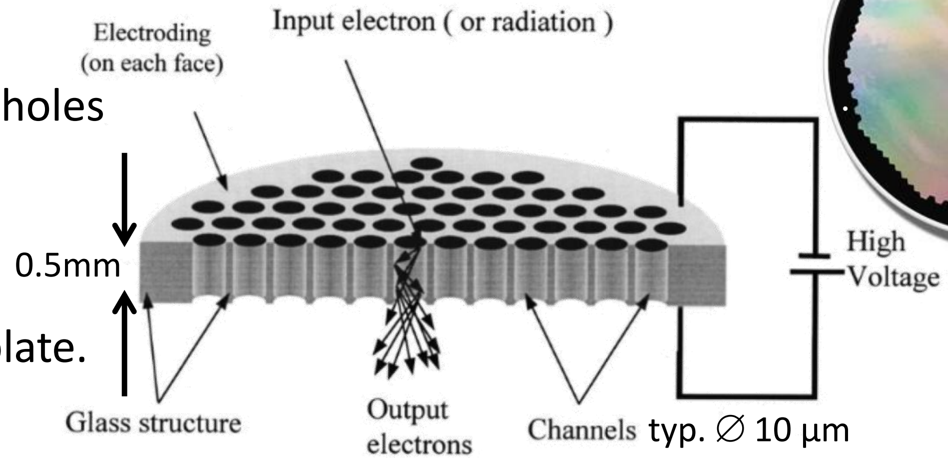


A MCP is:

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

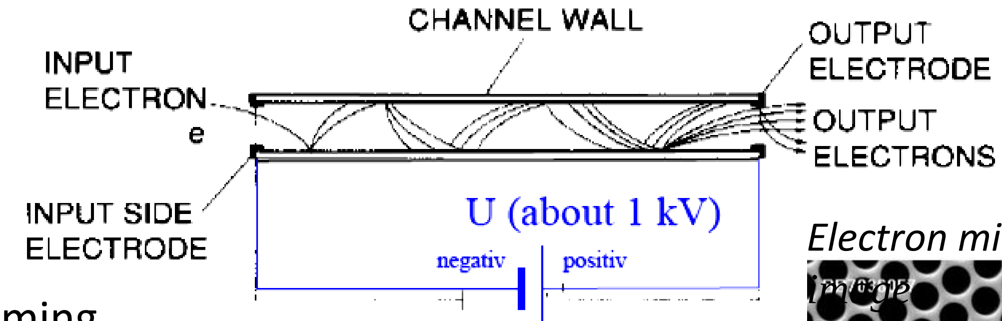
→ e⁻ amplification of ≈ 10^3 per plate.

→ resolution ≈ 0.1 mm (2 MCPs)

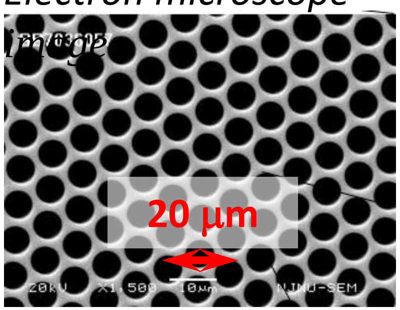


Anode technologies:

- 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.

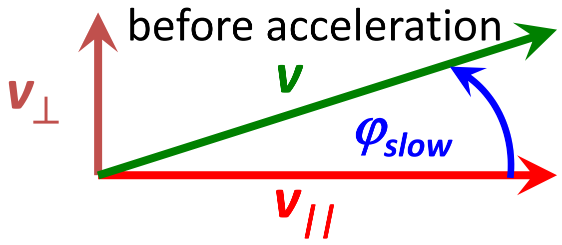


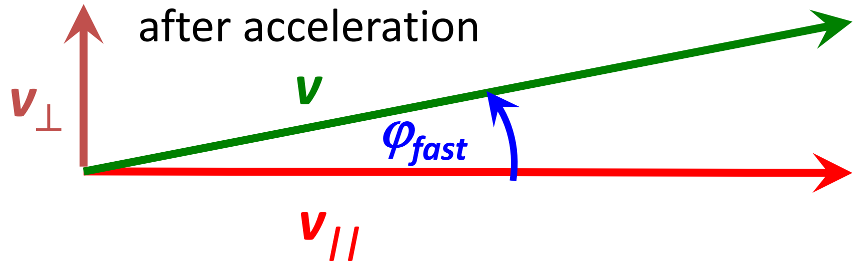
Electron microscope image



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: $x' = p_\perp / p_{//}$

the emittance is for $\langle xx' \rangle = 0$: $\varepsilon = x \cdot x' = x \cdot p_\perp / p_{//} = const.$

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

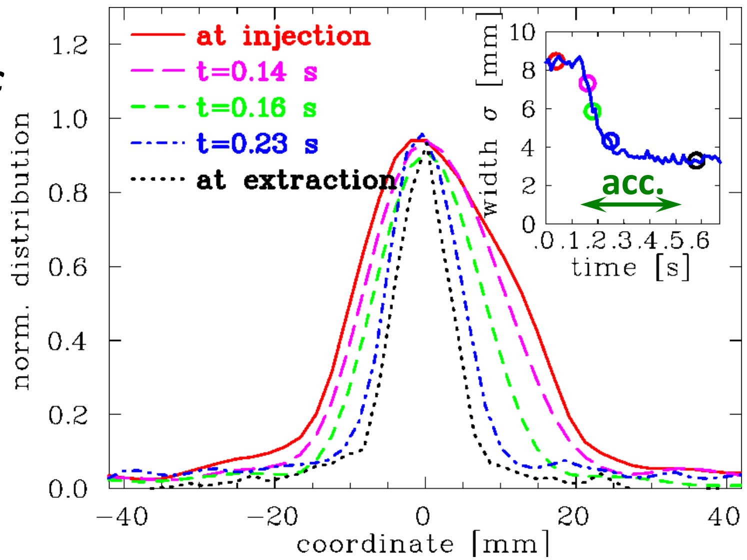
$\Rightarrow$ normalized emittance $\varepsilon_{norm} = \beta \gamma \cdot \varepsilon$ is preserved
with the Lorentz factor $\gamma = (1-\beta^2)^{-1/2}$ and velocity $\beta = v/c$

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

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

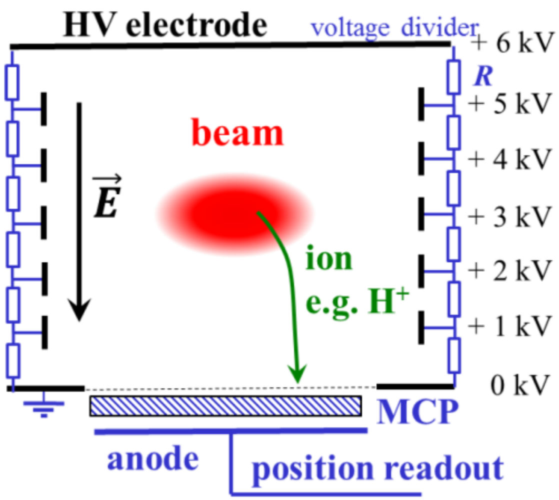
measured width: $\langle x \rangle_f \approx 0.37 \cdot \langle x \rangle_i$

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

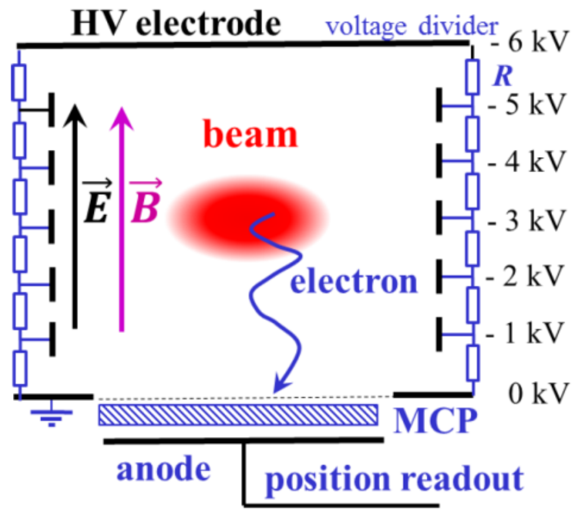


Electron Detection and Guidance by Magnetic Field

Ion detection mode:

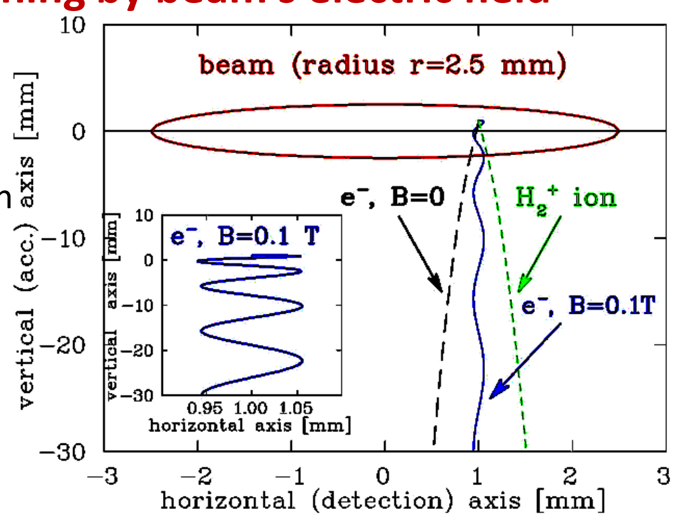


Electron detection mode:



⇒ broadening by beam's electric field

$7 \cdot 10^{10}$ charges per 10 m bunch



e^- detection in an external magnetic field

→ cyclotron radius $r_C = \frac{mv_\perp}{eB}$

for $E_{kin,\perp} = 10$ eV & B = 0.1 T ⇒ $r_c \approx 100$ µm

E_{kin} from atomic physics, ≈100 µm resolution of MCP

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

B-field: Dipole with large aperture

→ IPM is expensive & large device!

IPM: Magnet Design

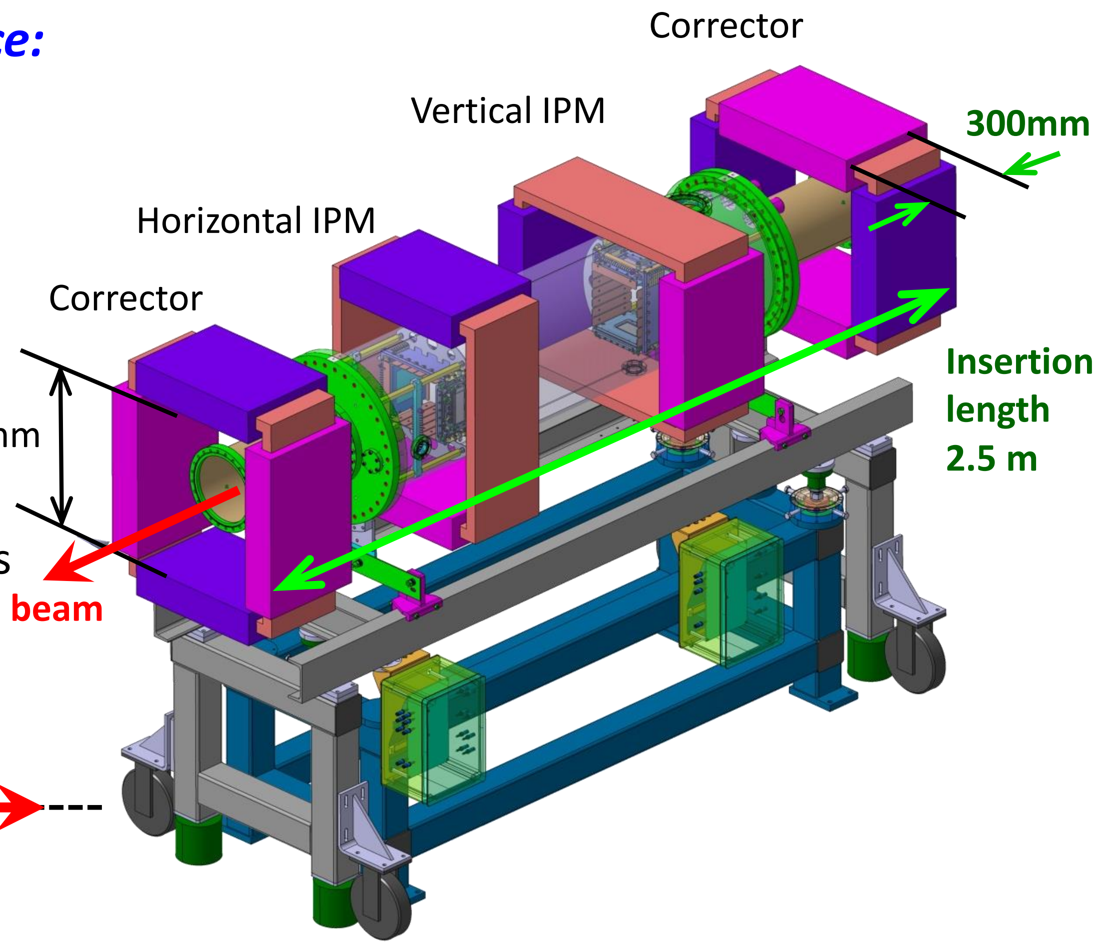
Magnetic field for electron guidance:

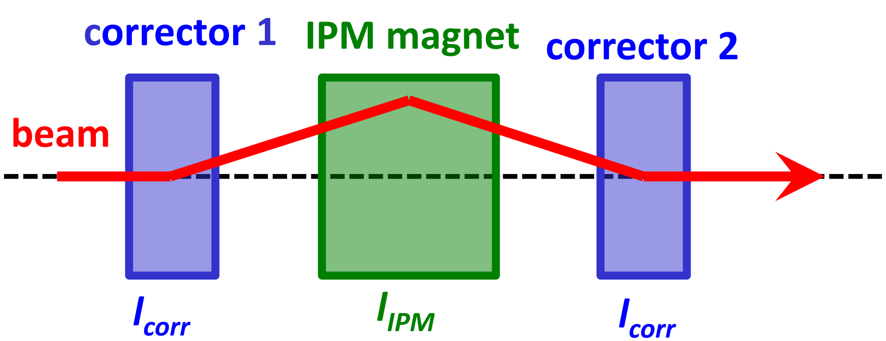
Maximum image distortion:

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





$$B_{cor} \cdot l_{corr} = -\tfrac{1}{2}\, B_{IPM} \cdot l_{IPM}$$

Remark: For MCP wire-array readoutlower clearance required

IPM: Magnet Design

Magnetic field for electron guidance:

Maximum image distortion:

5% of beam width ⇒ $\Delta B/B <$ 1 %

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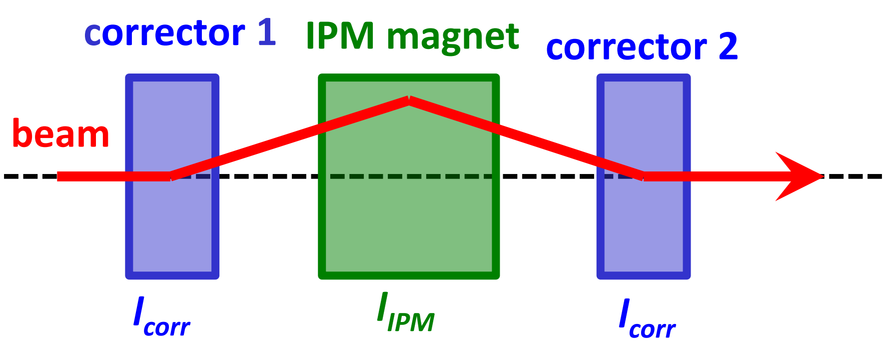
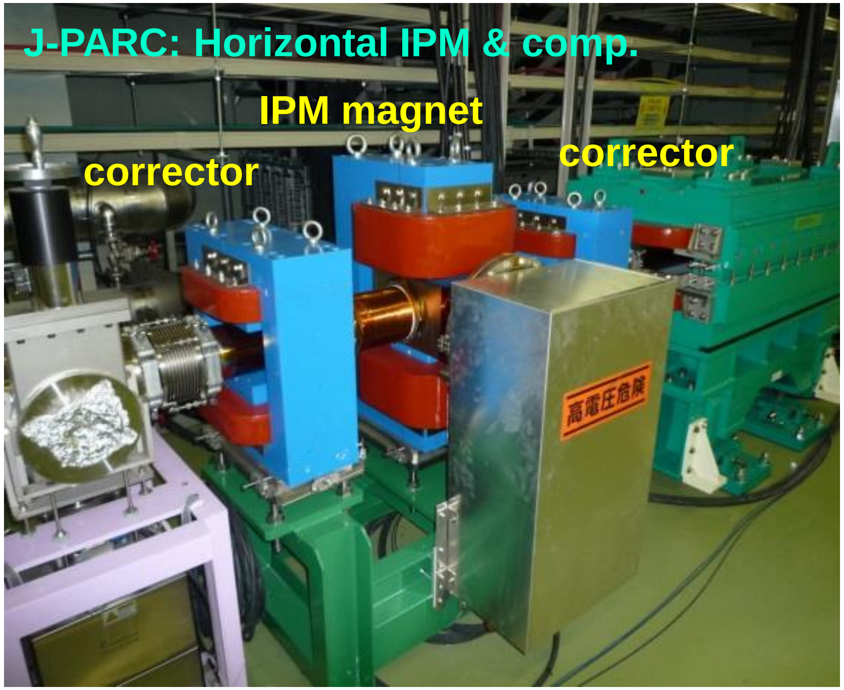


$$B_{cor} \cdot l_{corr} = - ½\, B_{IPM} \cdot l_{IPM}$$



Magnet: B = 250 mT, Gap 220 mm

IPM: Profile 32 strips, 2.5 mm width

Remark for electron beams:

Resolution of 50 µm is insufficient,

but sometimes used for photon beams

Remark: For MCP wire-array readout lower clearance required

Beam Induced Fluorescence for intense Profiles

Large beam power → Non-intercepting method:

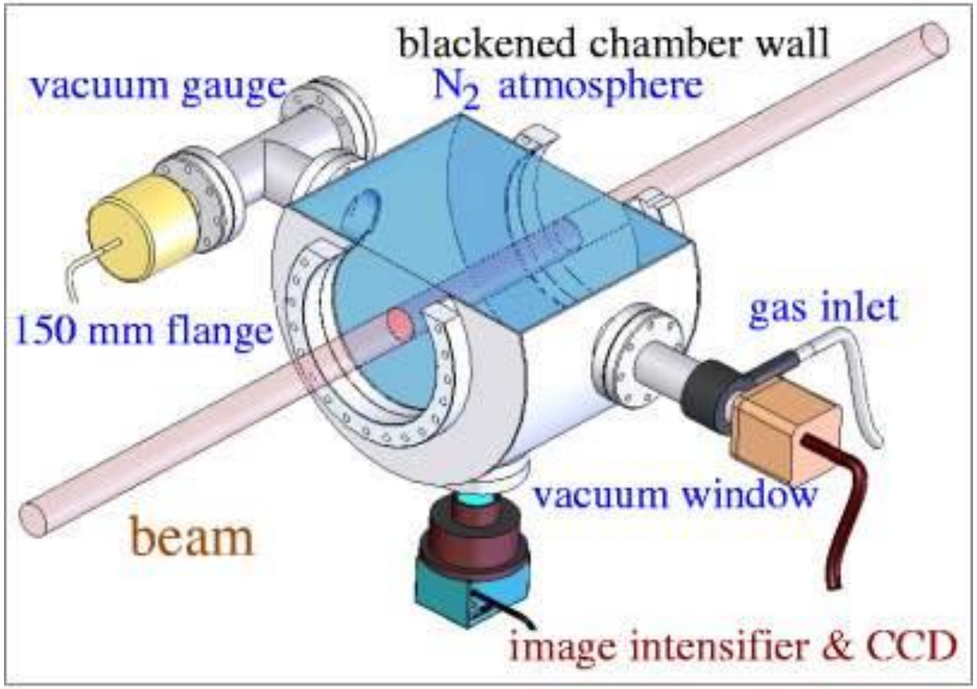
⇒ **B**eam **I**nduced **F**luorescence BIF

$N_2 + Ion \rightarrow (N_2^{+})^{*} + Ion \rightarrow N_2^{+} + \gamma + Ion$

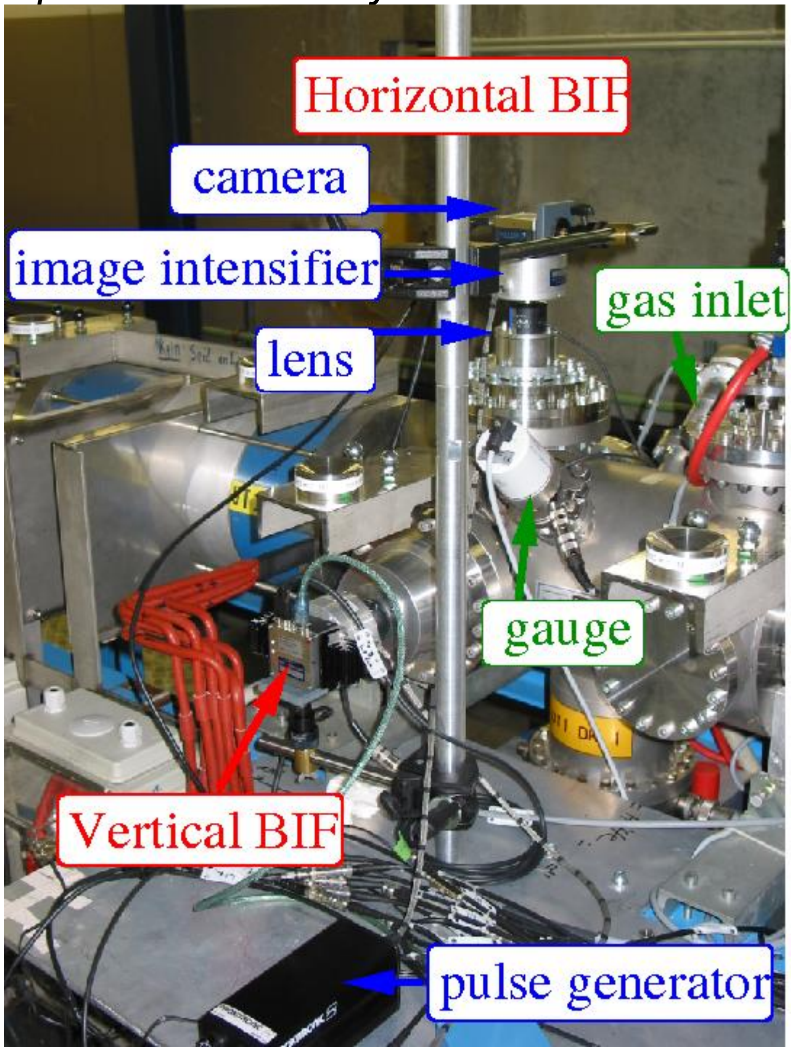
With single photon detection scheme

390 nm< λ< 470 nm

⇒ non-destructive, compact installation.

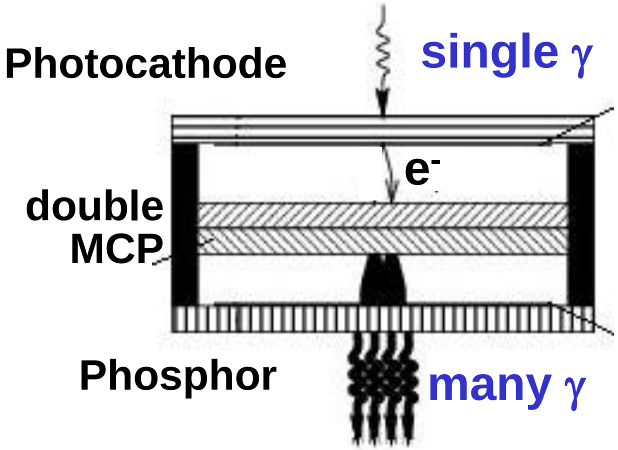


Example: Installation of hor&vert. BIF Monitor:



Beam Induced Fluorescence Monitor BIF: Image Intensifier

Scheme of Image intensifier:



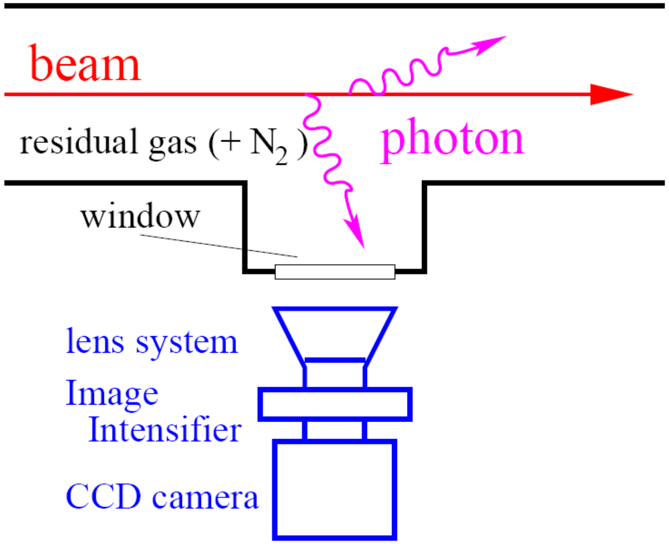


Image intensifier:

- 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:

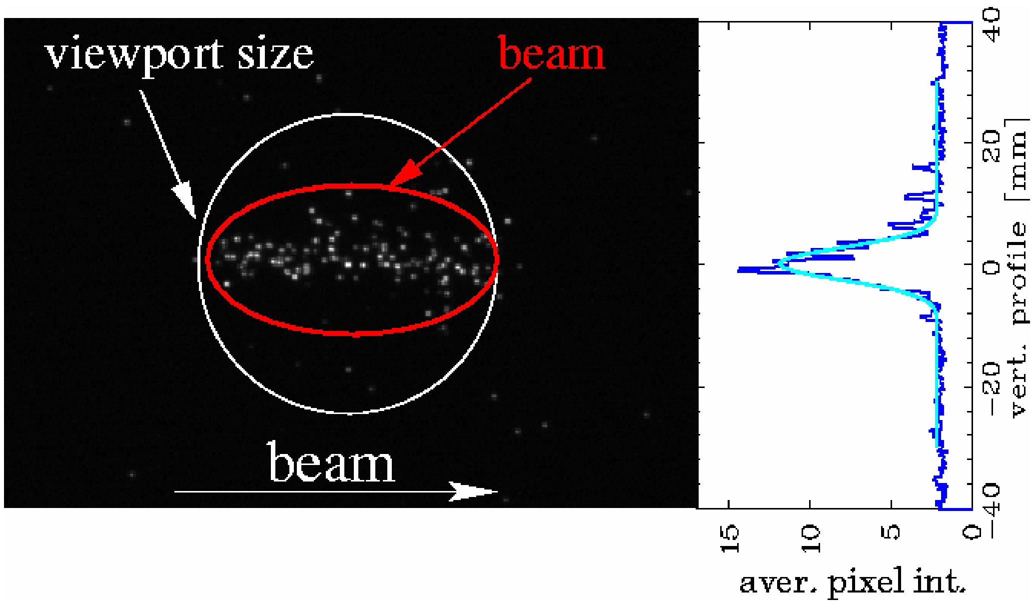
- optics outside beam pipe
- image intensifier + camera
- gas-inlet for pressure increase

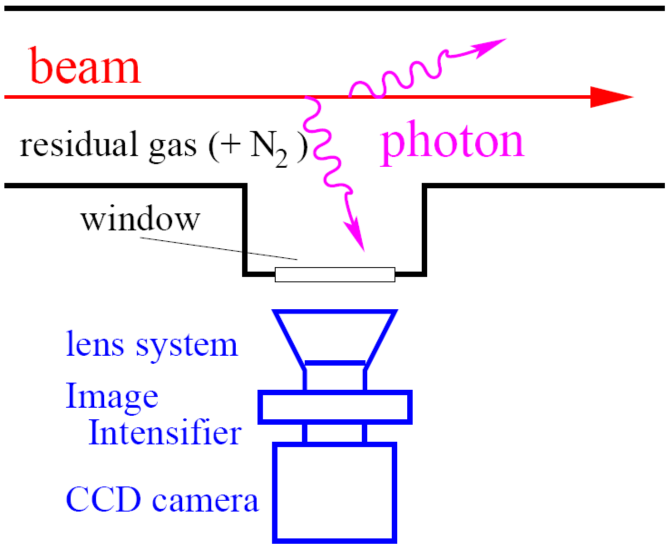
⇒ nearly no installation inside vacuum.
only LEDs for calibration

⇒ cheaper than IPM, but lower signal.

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.

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

$\rightarrow$ measurement of all ionization products, $\boldsymbol{\Omega = 4\pi}$-geometry due to E-field

BIF: Beam ionizes and excites the residual gas

$\rightarrow$ measurement of photons emitted toward camera, solid angle $\boldsymbol{\Omega \approx 10^{-4}}$

IPM: Higher efficiency than BIF

BIF: Low detection efficiency, only $\approx 10^{-4}$ of IPM

$\Rightarrow$ 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
- Optical Transition Radiation:

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

  photon detection of emitted synchrotron light in optical and x-ray range
- **Summary**

Synchrotron Light Monitor

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

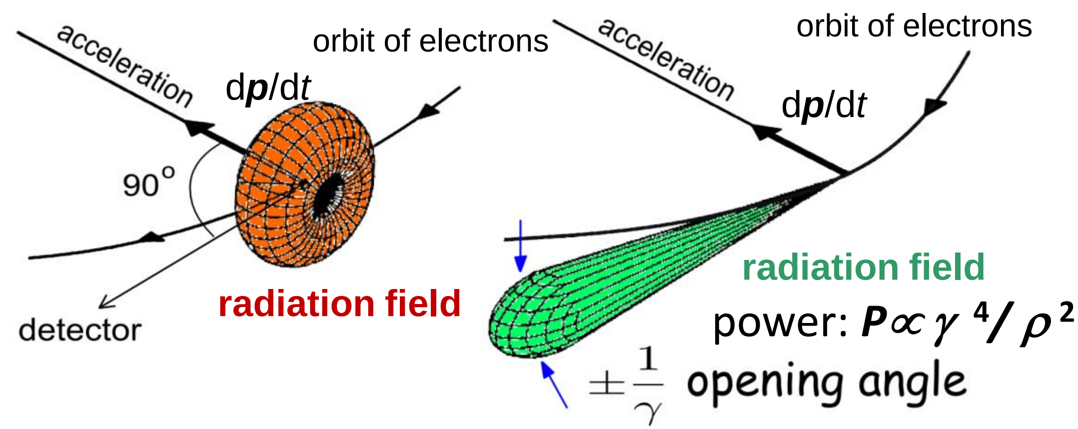
This light is emitted
into a cone of
opening $2/\gamma$ in lab-frame.

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

For protons:

Only for energies E_{kin} > 100 GeV

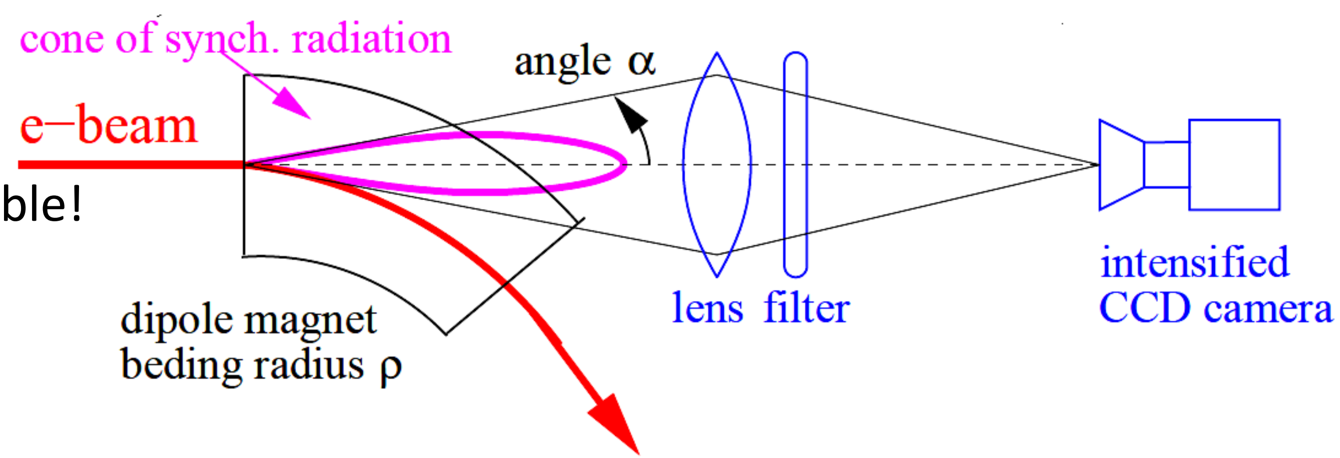
Rest frame of electron: **Laboratory frame:**



The light is focused to a intensified CCD.

Advantage:

Signal anyhow available!



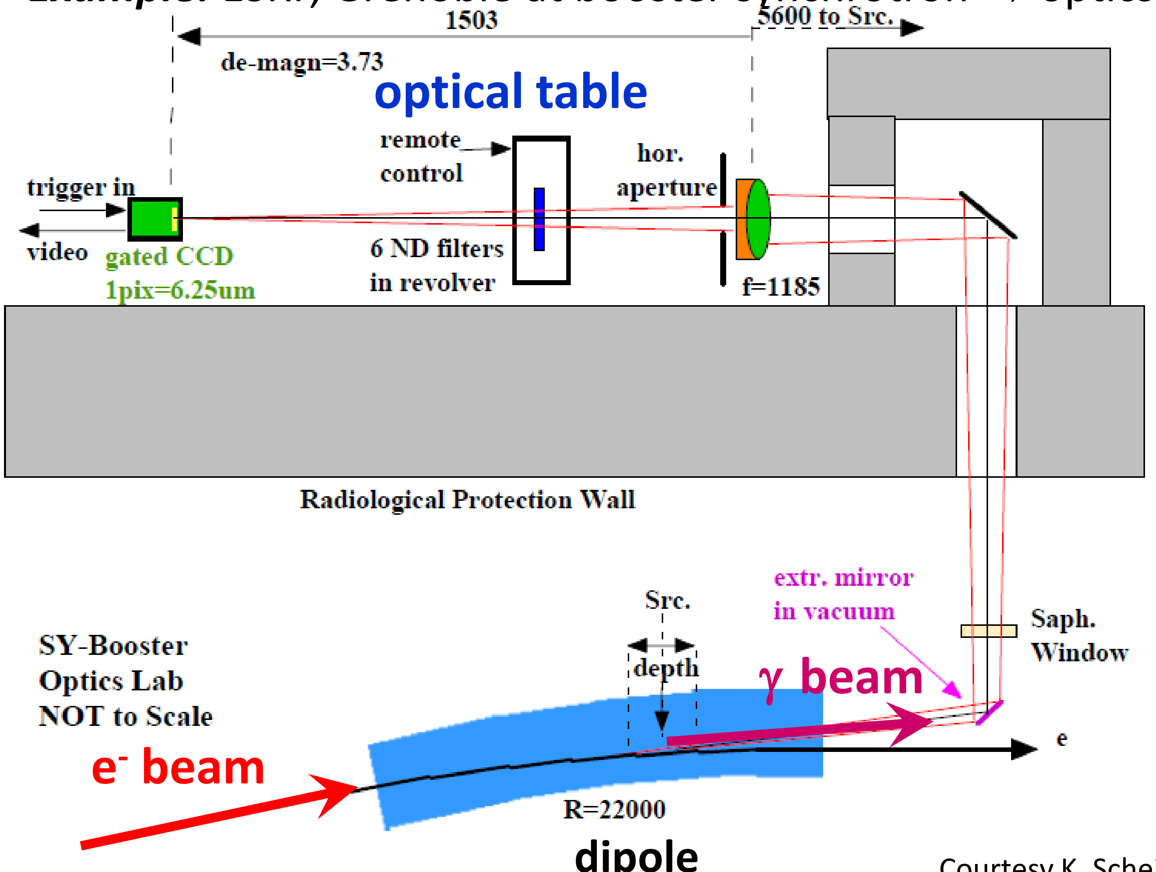
Realization of a Synchrotron Light Monitor

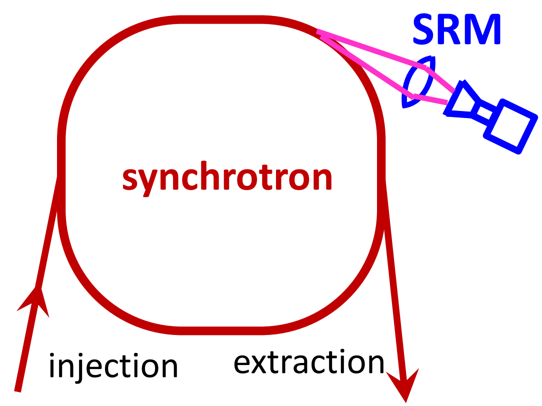
Extracting out of the beam's plane by a mirror (sometimes cooled)

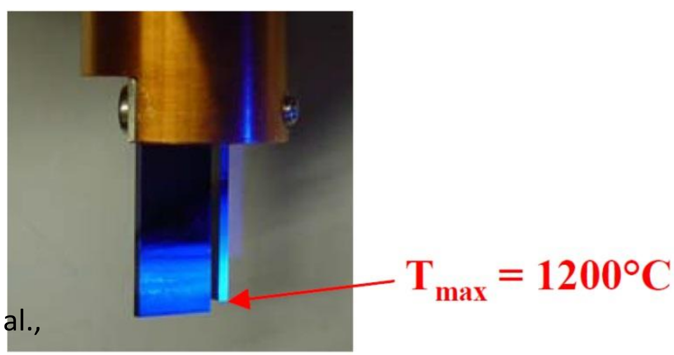
→ Focus to a slit + wavelength filter for optical wavelength

→ (Image intensified) CCD camera

Example: ESRF, Grenoble at booster synchrotron → optics outside for better maintenance



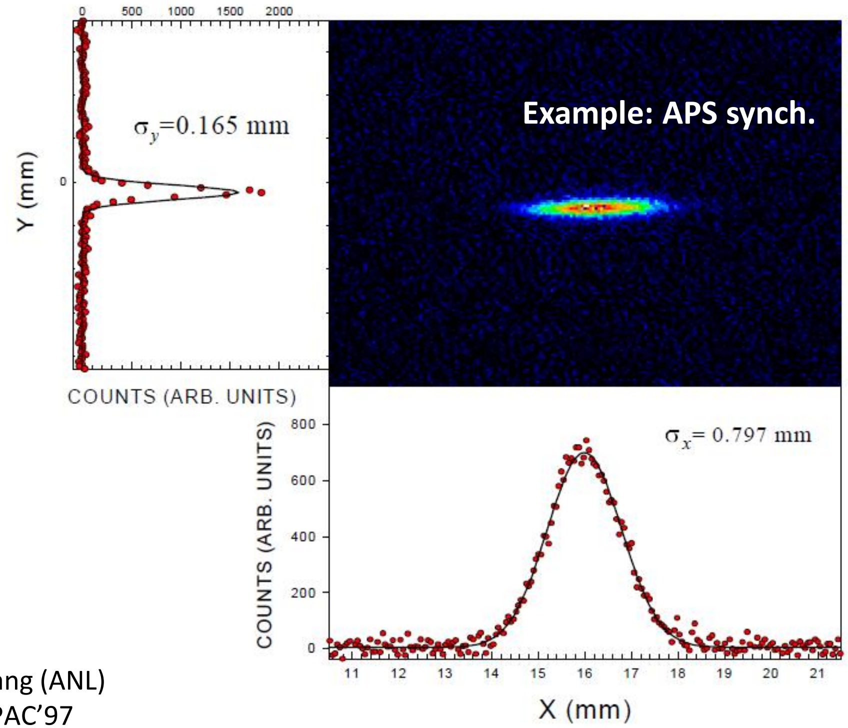




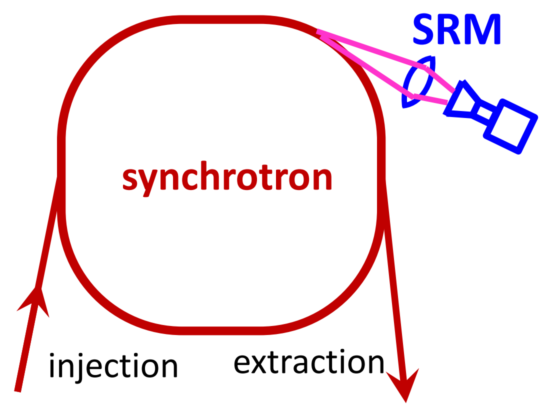
Courtesy K. Scheidt et al.,
DIPAC 2005

Result from a Synchrotron Light Monitor

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



B.X. Yang (ANL)
et al. PAC'97

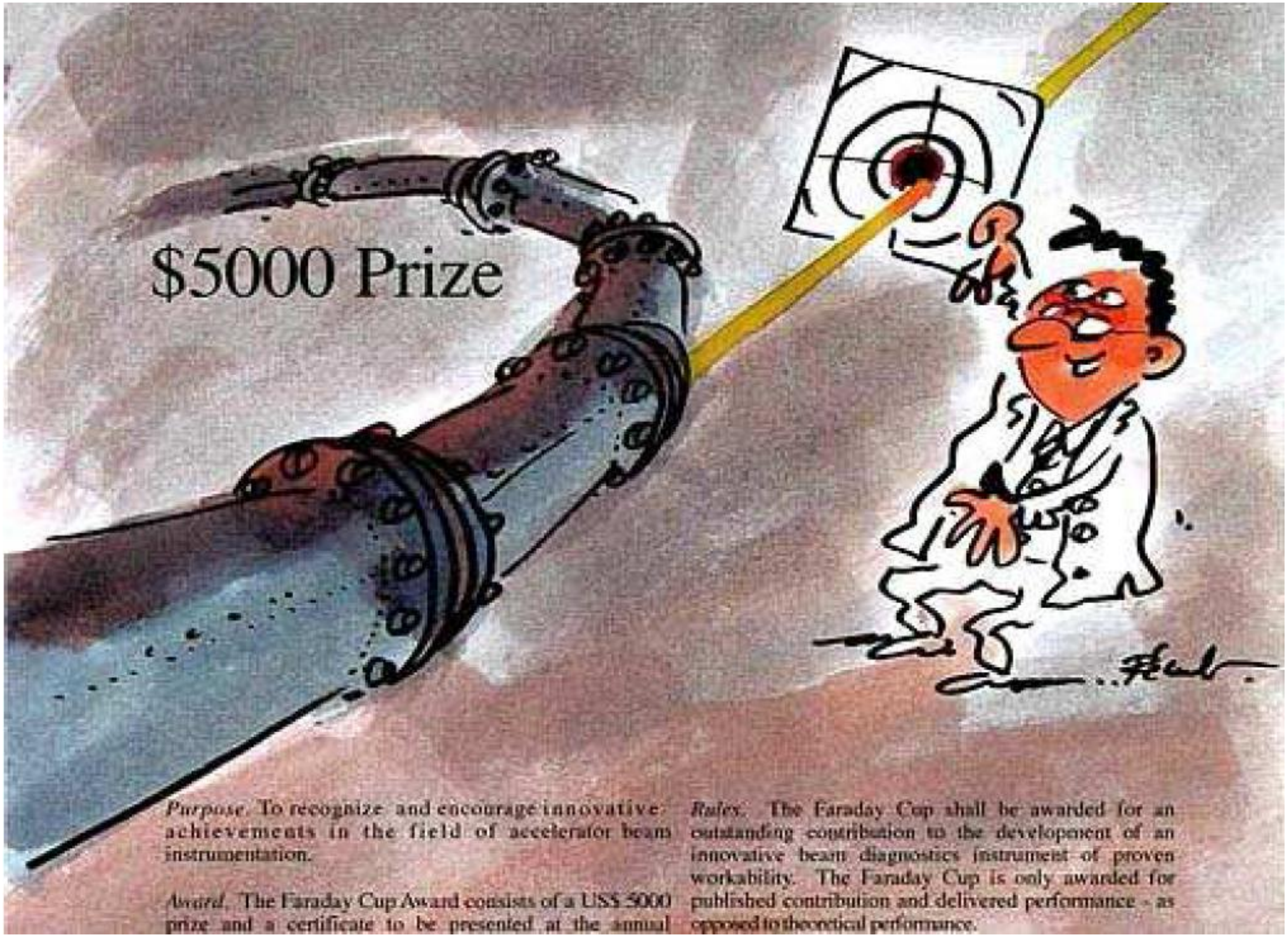


Advantage: Direct measurement of 2-dim distribution, only mirror installed in the vacuum pipe

Realization: Optics outside of vacuum pipe

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

The Artist's View of a Synchrotron Light Monitor



Diffraction Limit for a Synchrotron Light Monitor

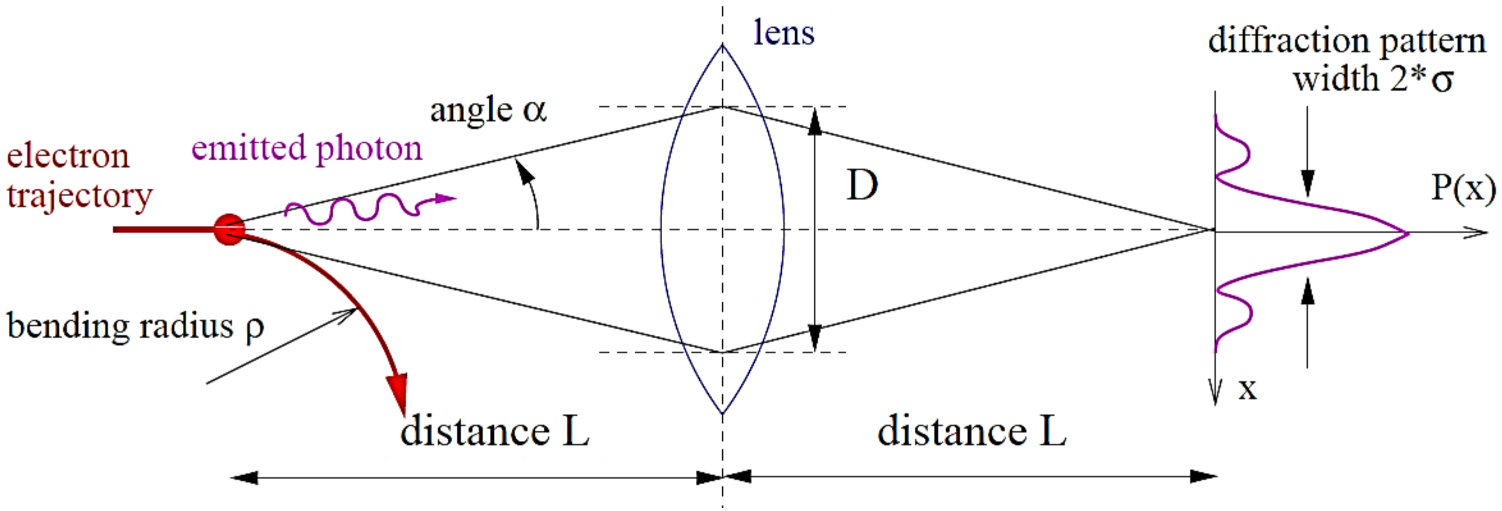
Use of optical wavelength and CCD: λ above critical λ_{crit} (spectrum fall-off).

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



A good resolution for:

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

Resolution Limits for Synchrotron Radiation Monitor

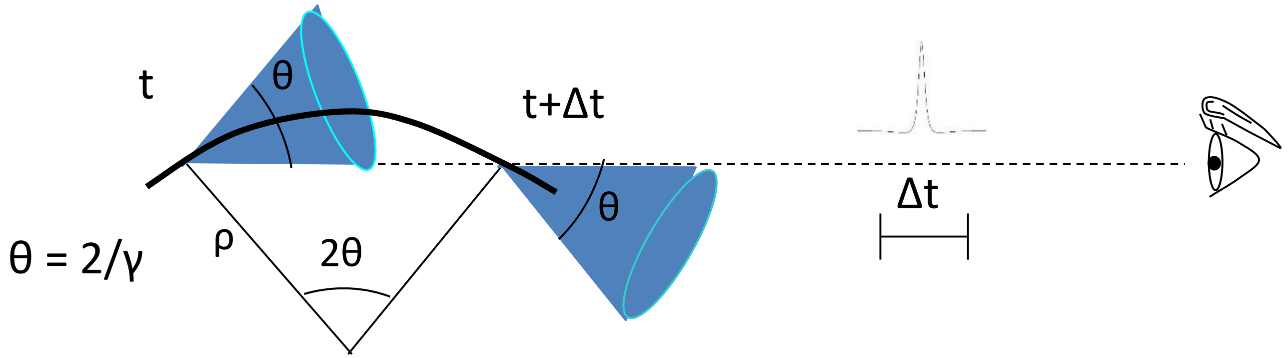
The resolution is limited by:

- 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 ***σ ≈ 100* µm**

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

Scheme for time variation:



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

Courtesy of G. Kube DESY

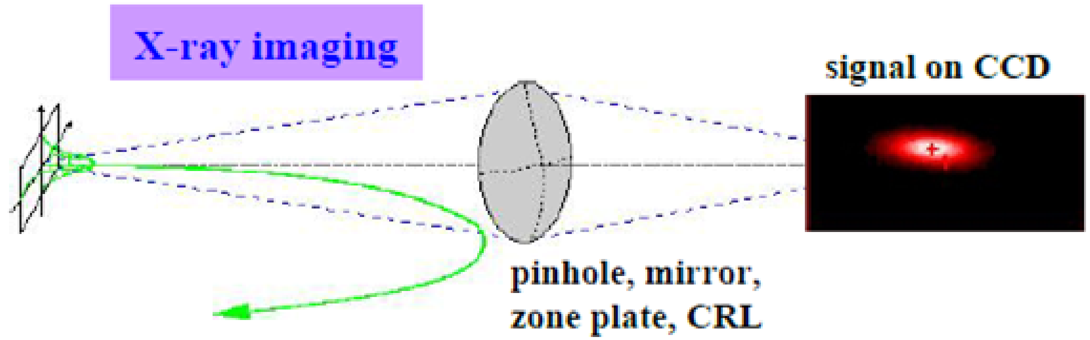
Synchrotron Light Monitor overcoming Diffraction Limit

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

Possible improvements:

- ***Shorter wavelength:***

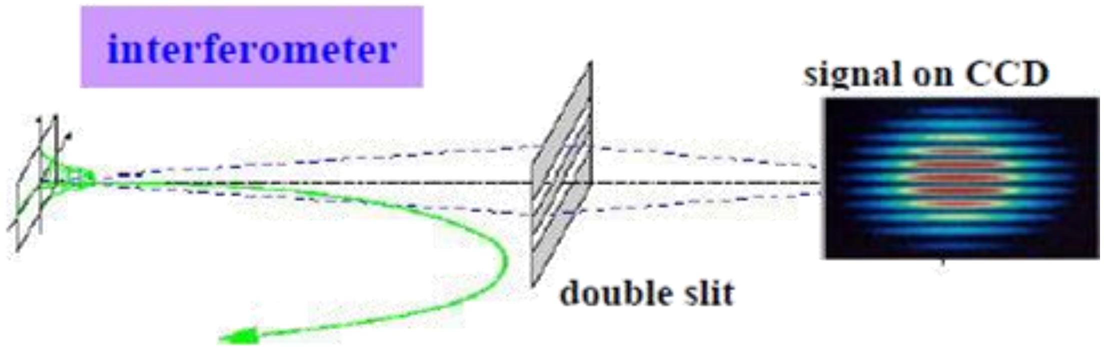
  Using x-rays &aperture of Ø 1mm
  → 'x-ray pin hole camera'
  ⇒ achievable resolution $\boldsymbol{\sigma} \approx 10\ \mu\text{m}$



- ***Interference technique:***

  At optical wavelength

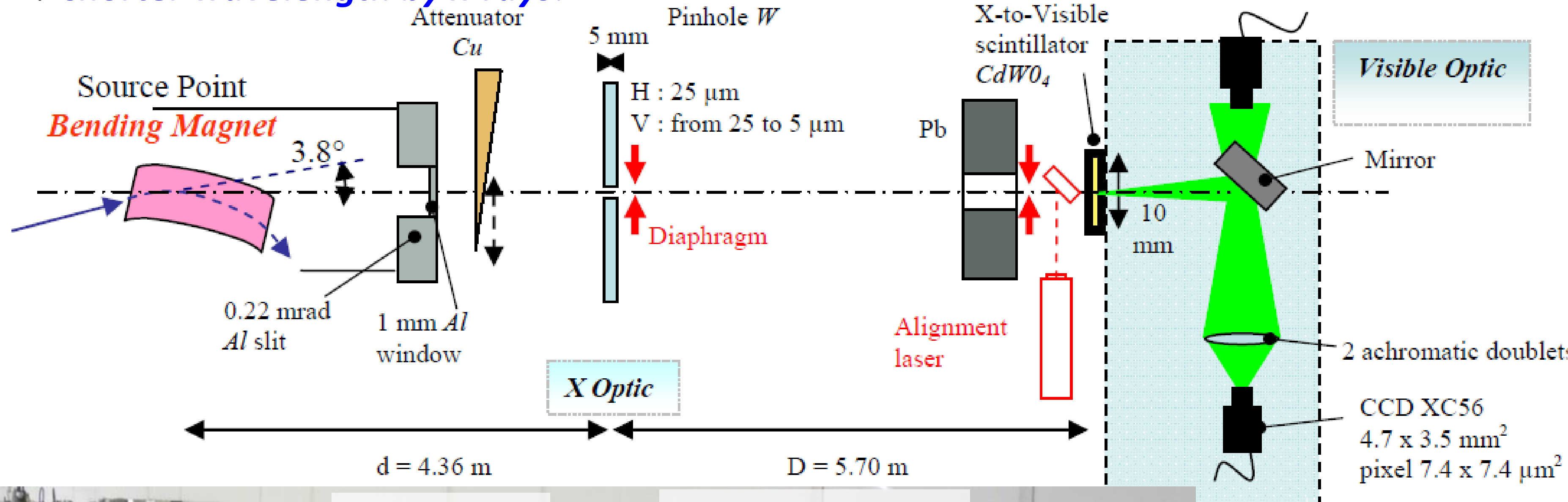
  using a double slit
  → interference fringes
  ⇒ achievable resolution $\boldsymbol{\sigma} \approx 1\ \mu\text{m}$

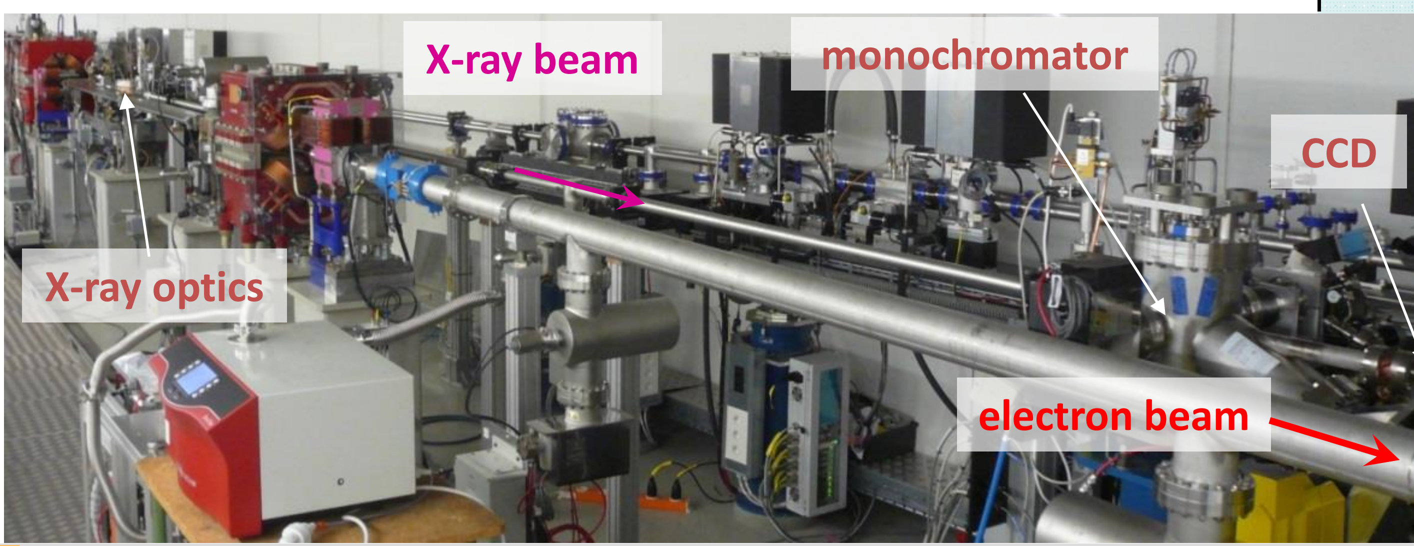


X-ray Pin-Hole Camera: Installation

The diffraction limit is Fraunhofer Diff. with resolution $\sigma_{diff} \approx 0.6 \sqrt[3]{\lambda^2 / \varrho}$

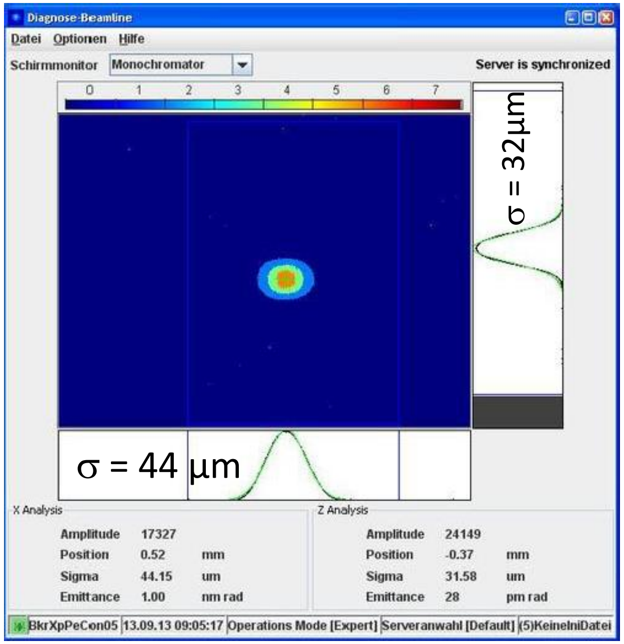
$\Rightarrow$ ***shorter wavelength by x-rays.***





X-ray pin-hole Camera: X-ray Detector

From K. Wittenburg, DESY



Typical result using X-ray pinhole camera:

⇒ resolution sufficient for modern, 'ultra-low emittance' light sources

Goal of 'ultra-low emttiance' storage rings:

Photons are emitted from beam of σ_{beam} < 10 µm

⇒ high brightness of photon beam

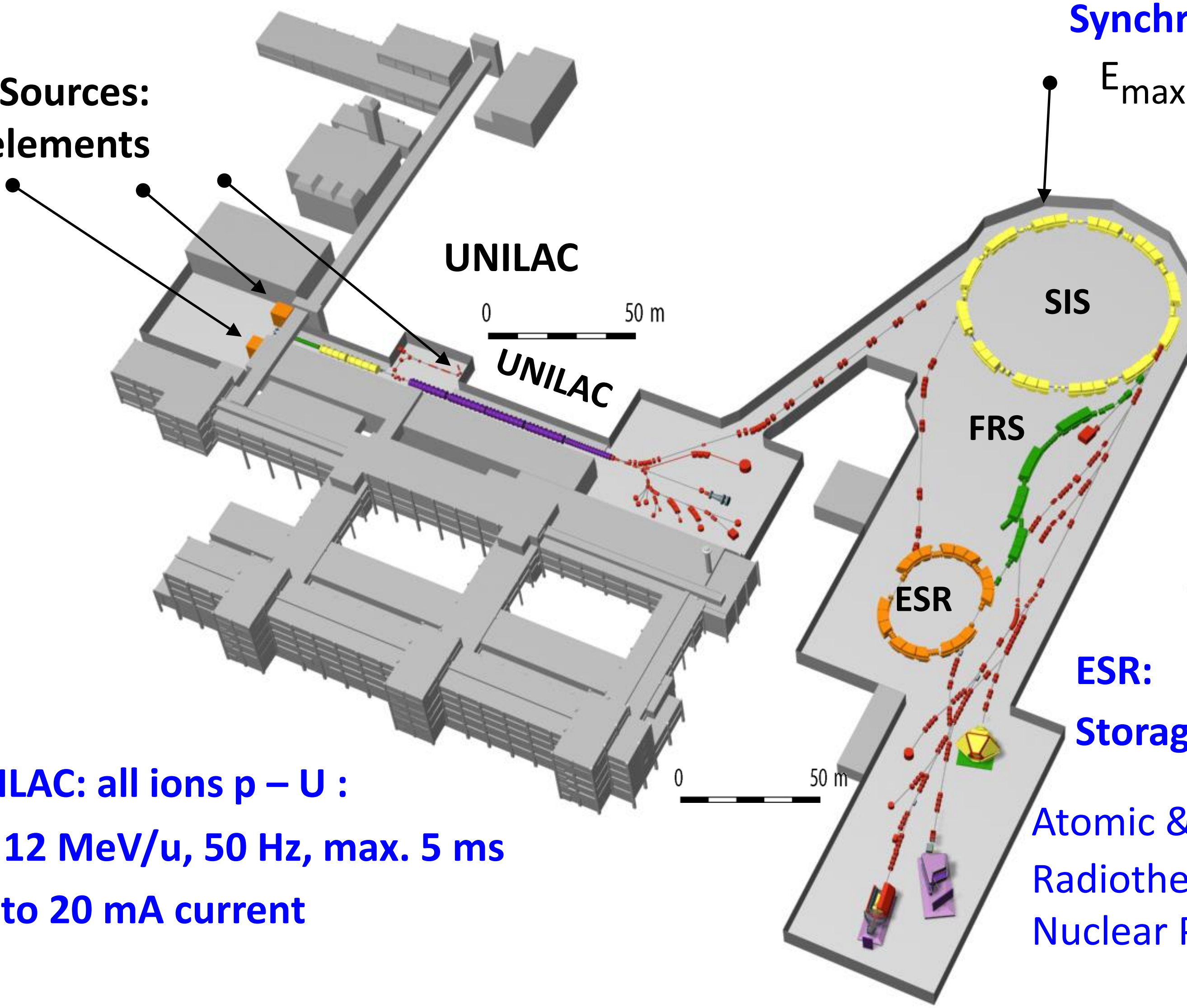
⇒ better focusing and poiting stability

Typical resolution for three methods:

- direct optical observation: $\sigma \approx$ **100 µm**
  → **relative simple installation, but** resolution insufficient for modern synchr. light sources
- interference optical observation $\sigma \approx$ **1 µm**
  → **complex installation,** seldom installed
- direct X-ray observation : $\sigma \approx$ **10 µm** (installed at most Synchr..light sources)
  → **medium complex but expensive installation,** installed at most synchr. light sources

Appendix: The Accelerator Facility at GSI

Ion Sources: all elements



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

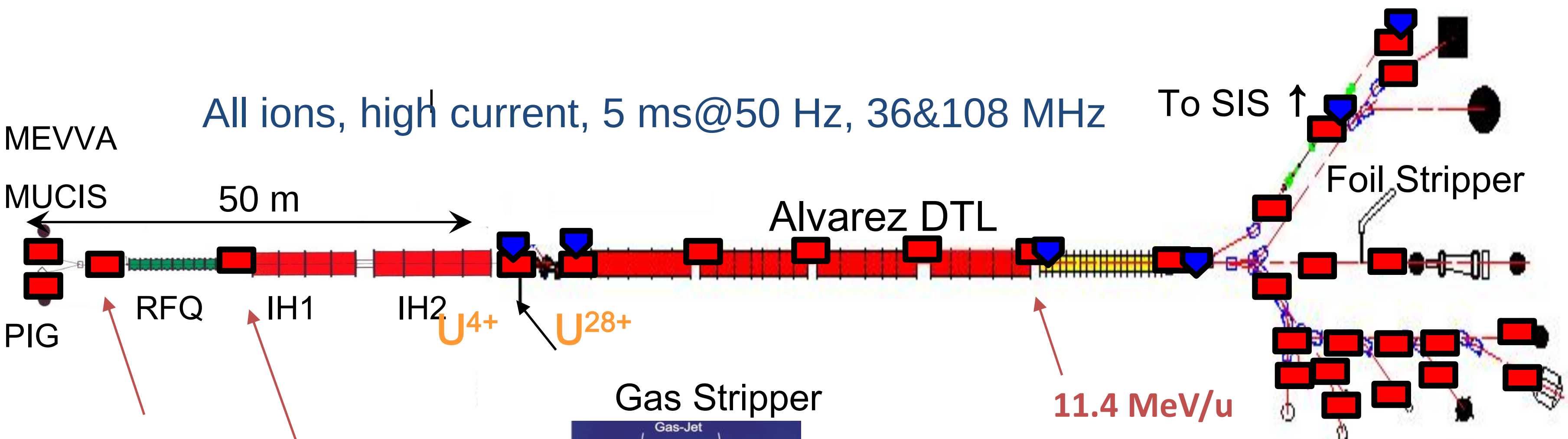
UNILAC: all ions p – U :

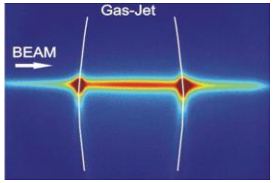
3 – 12 MeV/u, 50 Hz, max. 5 ms

Up to 20 mA current

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

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





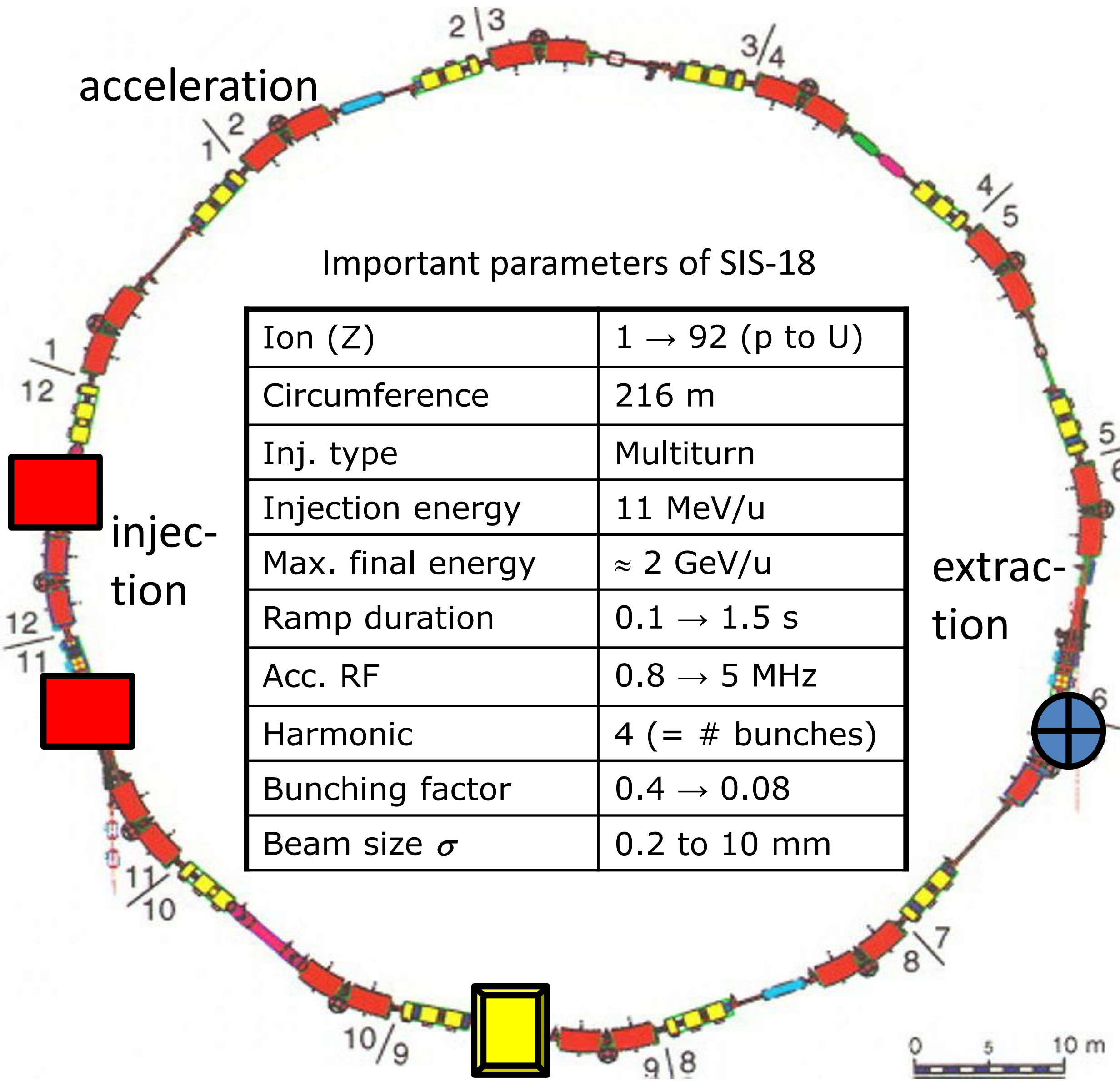
2.2 keV/u
β = 0.0022

120 keV/u
β = 0.016

1.4 MeV/u ⇔β = 0.054

11.4 MeV/u
β = 0.16

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



Important parameters of SIS-18

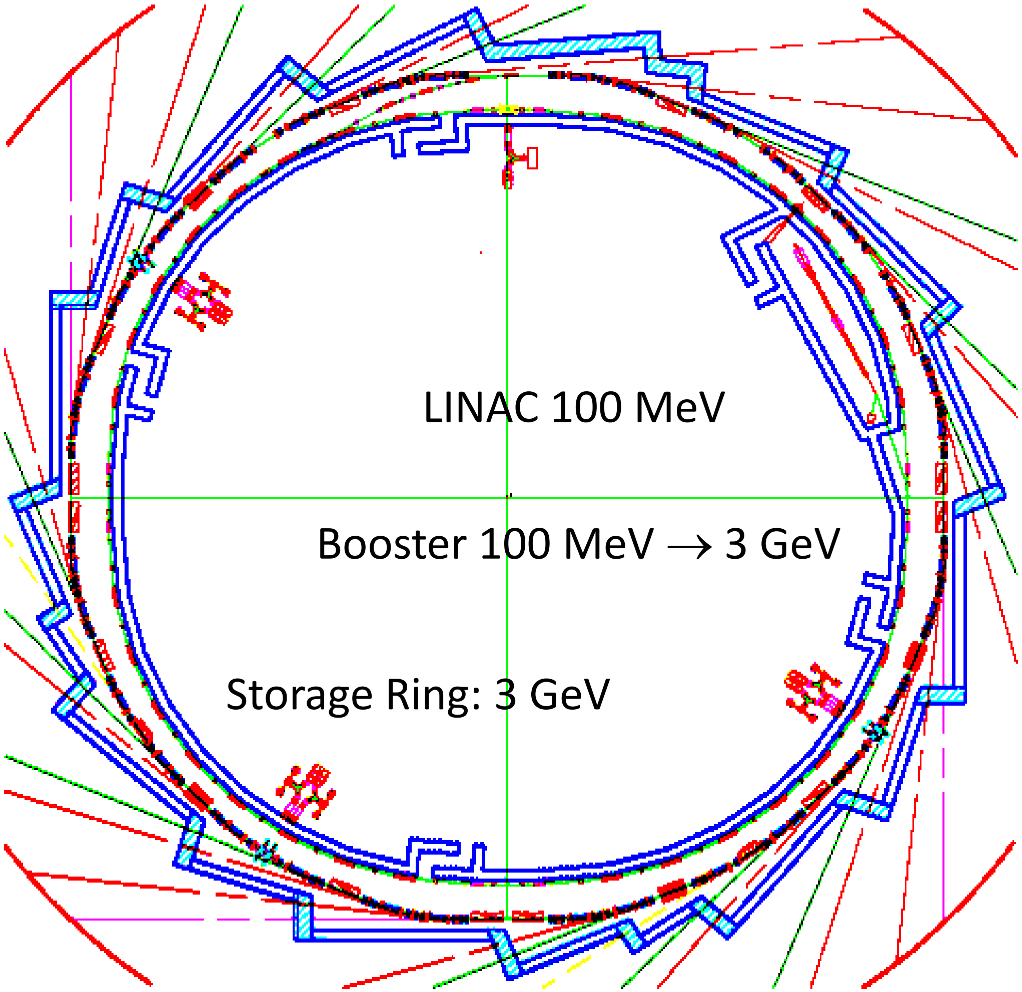
Ion (Z)	1 → 92 (p to U)
Circumference	216 m
Inj. type	Multiturn
Injection energy	11 MeV/u
Max. final energy	≈ 2 GeV/u
Ramp duration	0.1 → 1.5 s
Acc. RF	0.8 → 5 MHz
Harmonic	4 (= # bunches)
Bunching factor	0.4 → 0.08
Beam size σ	0.2 to 10 mm

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

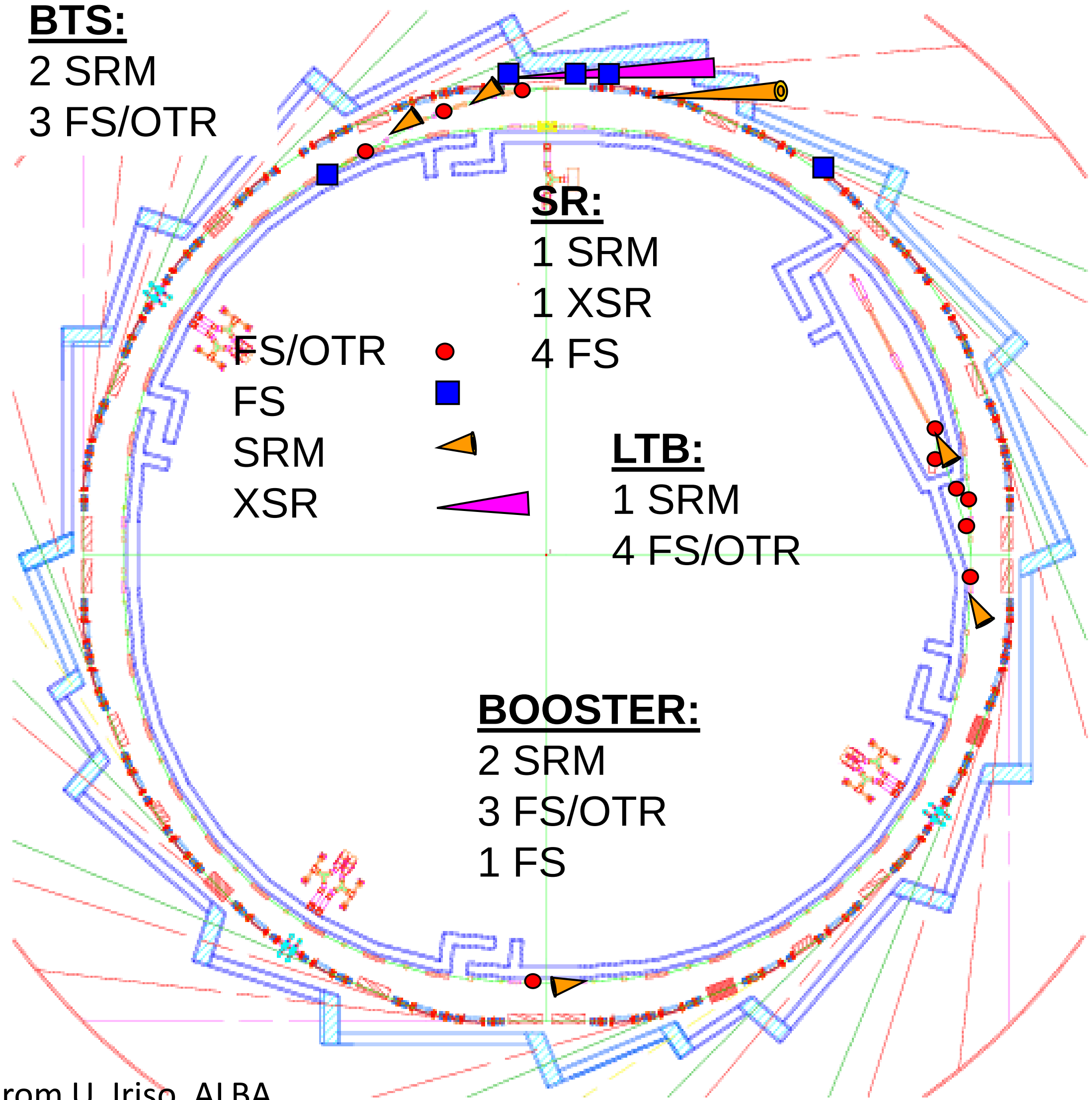
Top-up injection

Storage ring length: 268 m

Max. beam current: 0.4 A

Commissioning in 2011

Appendix: The Synchrotron Light Facility ALBA: Profile Measurement



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

Summary for Beam Profile

Different techniques are suited for different beam parameters:

e⁻-beam: typically Ø 0.01 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:

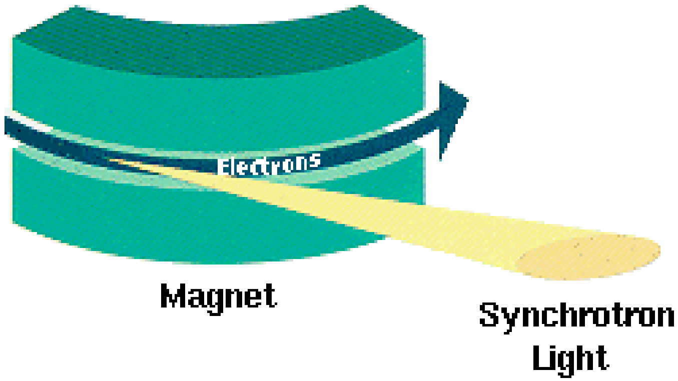
- Scintillation screen: destructive, large signal, simple, all beams
- Ionization profile monitor: non-destructive, expensive, limited resolution, for protons
- Residual fluorescence monitor: non-destructive, limited signal strength, for protons

Wire based electronic methods:

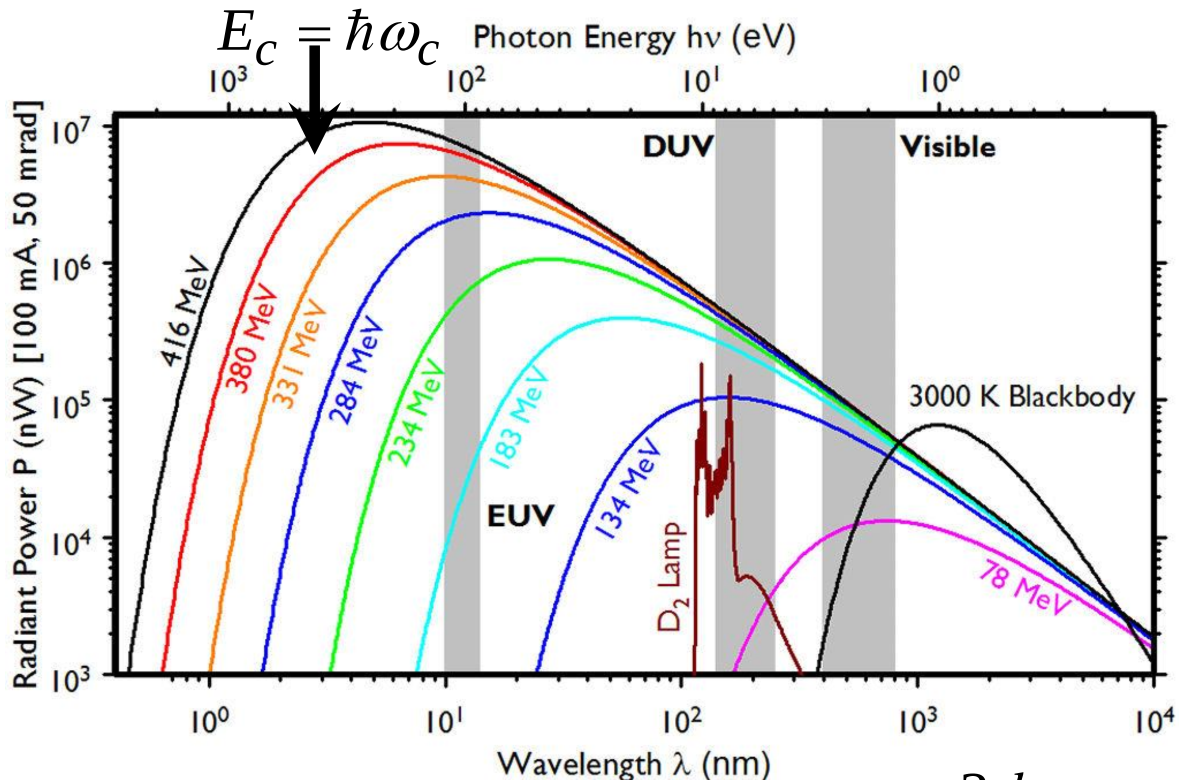
- SEM-grid: partly destructive, large signal and dynamic range, limited resolution
- Wire scanner: partly destructive, large signal and dynamics, high resolution, slow scan.

Backup slides

Emission from **bending magnet** with $\boldsymbol{B} \approx 1$ T for electrons



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

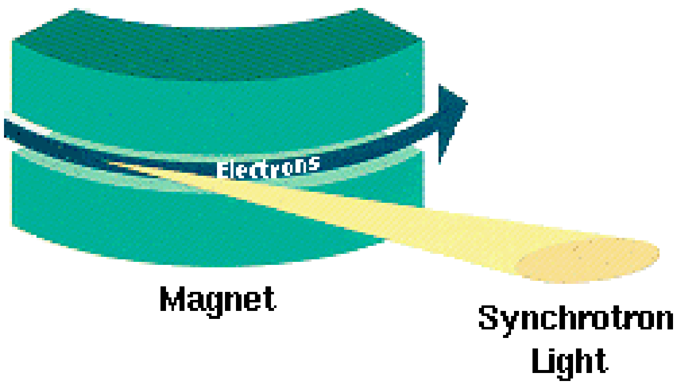


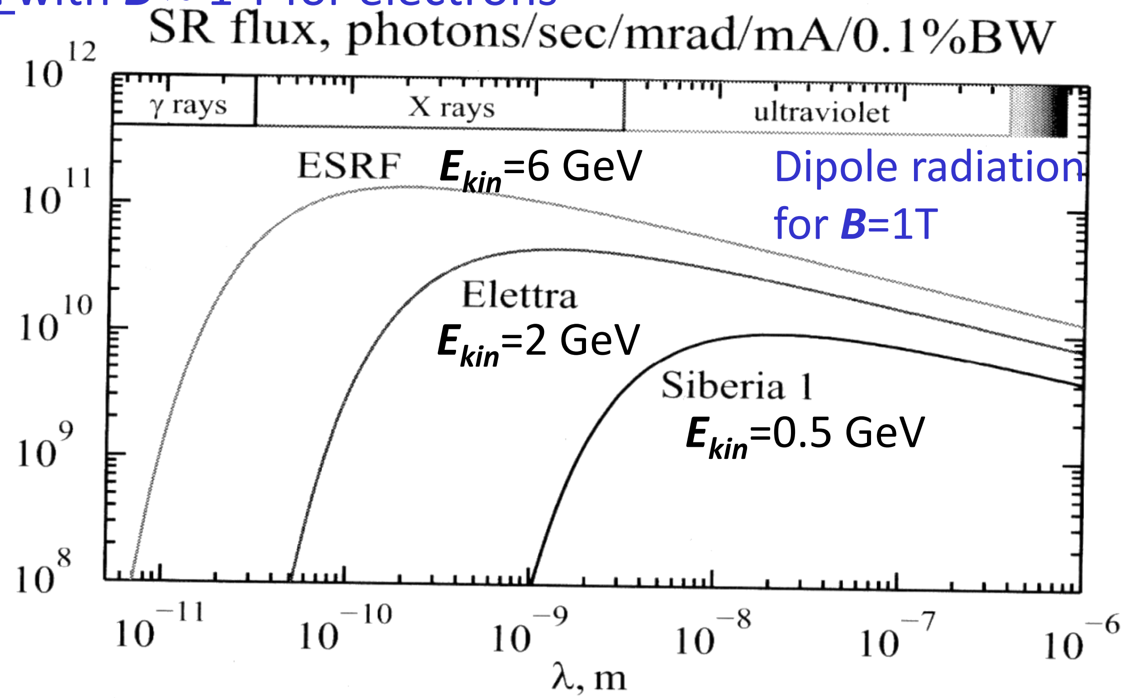
Definition: **critical photon energy** dividing spectrum in two halves $E_c = \hbar\omega_c = \frac{3}{2}\frac{\hbar c}{\rho}\gamma^3$

Scaling: $\frac{dW}{d\omega} \approx \frac{e^2}{4\pi\varepsilon_0 c}\left(\frac{\omega\rho}{c}\right)^{1/3}$ for $\omega << \omega_c$ **and** $\frac{dW}{d\omega} \approx \sqrt{\frac{3\pi}{2}\frac{e^2}{4\pi\varepsilon_0 c}}\,\gamma\left(\frac{\omega}{\omega_c}\right)^{1/2} e^{-\omega/\omega_c}$ for $\omega >> \omega_c$

Excurse: Spectrum for Synchrotron Radiation

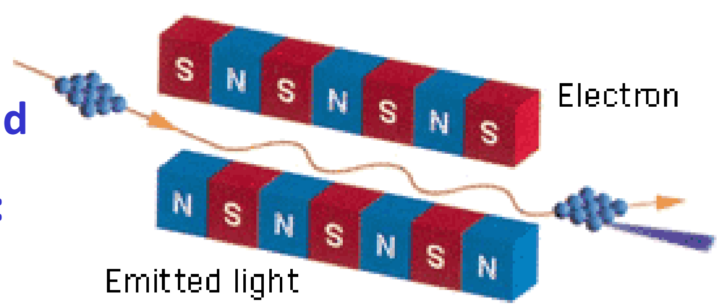
Emission from **bending magnet** with $B \approx 1$ T for electrons

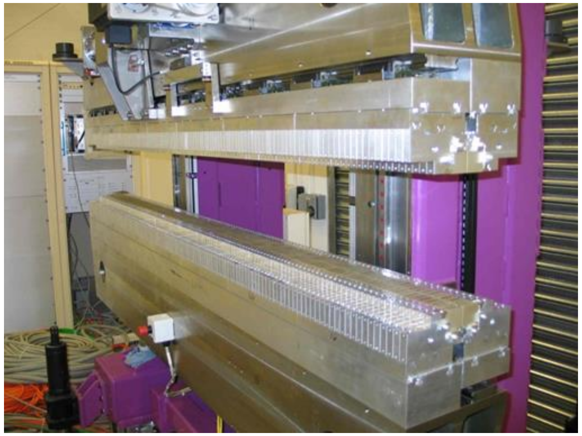




$$\text{Power}: P \propto \frac{\gamma^4}{\rho^2}$$

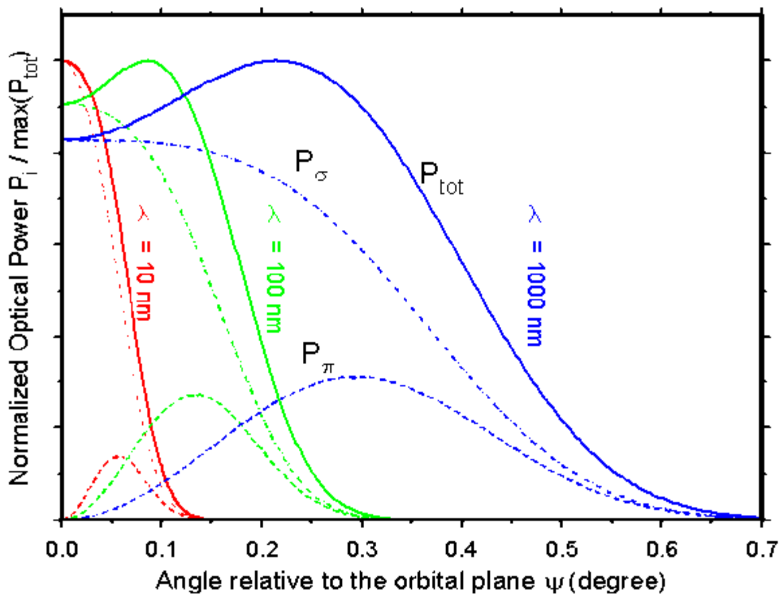
Wiggler and Undulator:



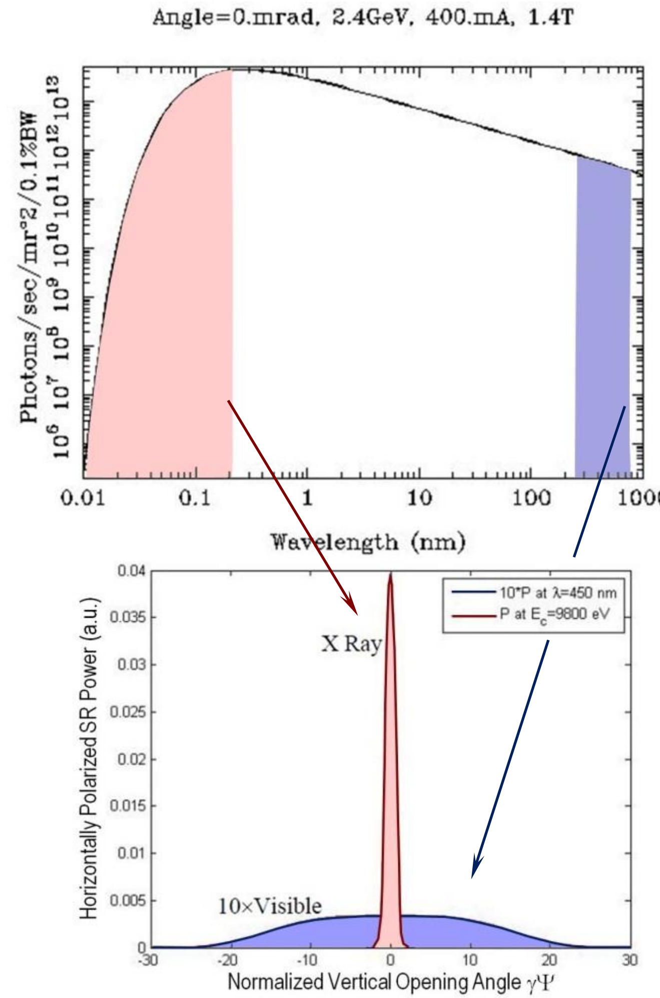


Excurse: Properties of Synchrotron Radiation from Dipole

- SR is "freely available" at light sources and always non-invasive
- SR covers visible to hard x-rays
- SR is classical process ⇒ properties & transport computable
- SR is strongly collimated in the vertical plane
  - → but usable opening angle depends on wavelength
- SR main power (heat load) at small opening angle
  - → (hard) x-ray optical elements require water cooling
- SR is emitted with p and s polarization



Courtesy of V. Schlott PSI



* **hard x-ray (@ l_c) opening angle: DY ~ 1/g**

opening angle in visible: $\Delta\Psi \approx \frac{1}{\gamma}\left(\frac{\omega_c}{\omega}\right)^{\frac{1}{3}}$

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.