Beam Instrumentation & Diagnostics Part 2

CAS Introduction to Accelerator Physics

Santa Susanna, 1st of October 2024

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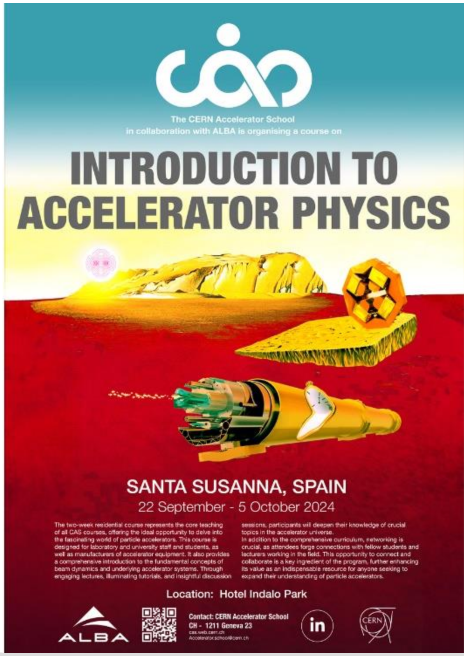
2nd part of this lecture covers:

- **Transverse profile techniques**
- **Emittance determination at transfer lines**
- **Diagnostics for bunch shape determination**



Measurement of Beam Profile

The beam width can be changed by focusing via quadruples.

Transverse matching between ascending accelerators is done by focusing.

→ Profiles have to be controlled at many locations.

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

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

Transfer lines: 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^-, high-energetic p),
  ionization profile monitors (protons)
- ***Electronics techniques:*** Secondary electron emission SEM grids, wire scanners (all beams)

Outline:

- **Scintillation screens:**

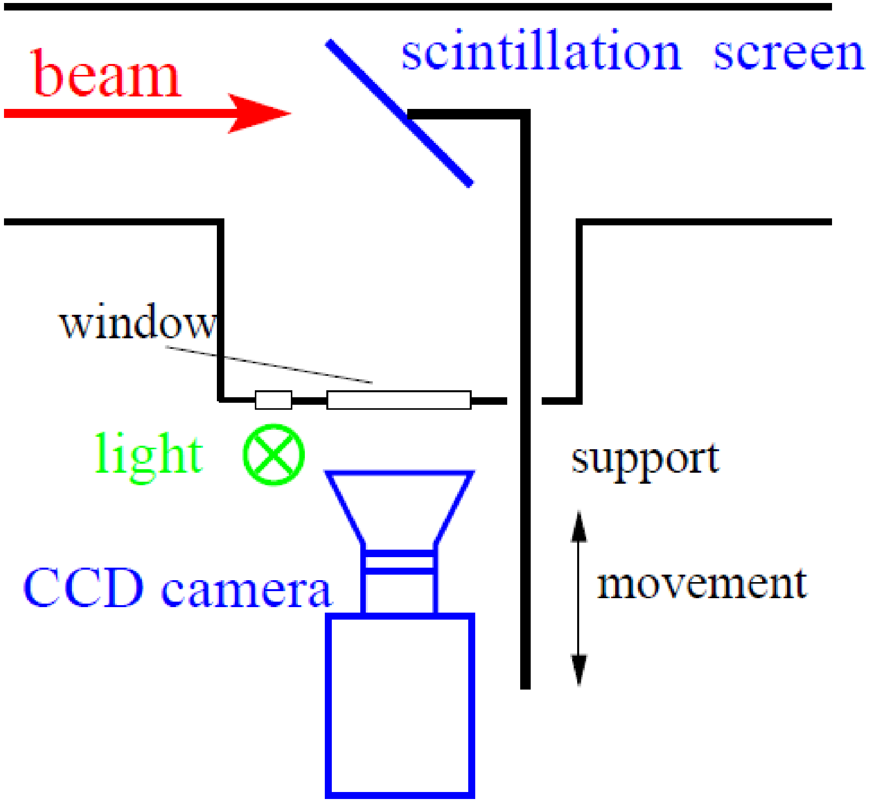
  emission of light, universal usage, limited dynamic range

- **Optical Transition Radiation**
- **SEM-Grid**
- **Wire scanner**
- **Ionization Profile Monitor**
- **Synchrotron Light Monitors**
- **Summary**

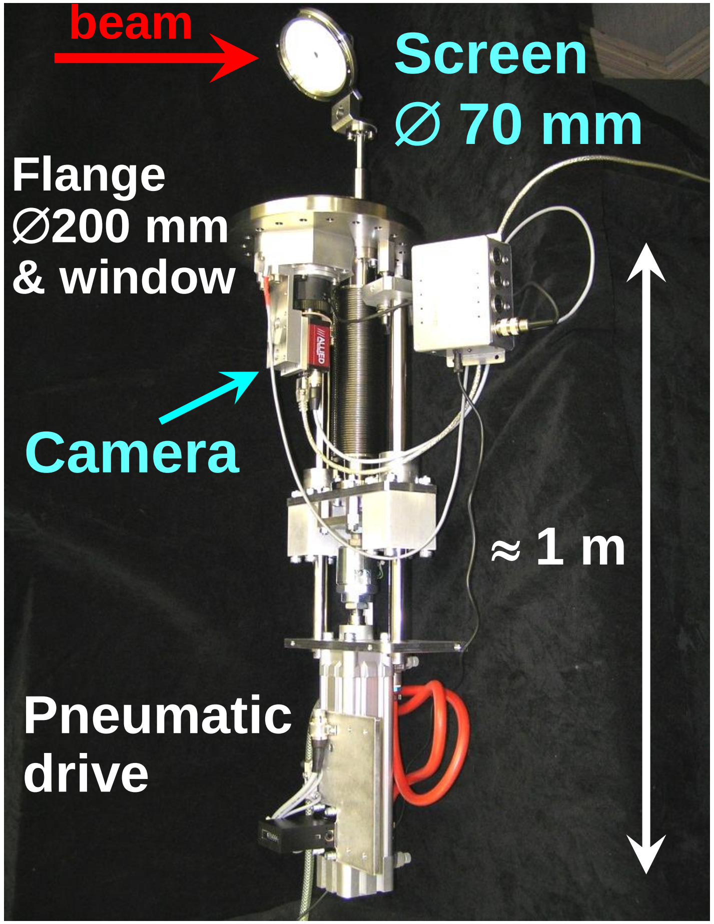
Scintillation Screen

Scintillation: Particle's energy loss in matter causes emission of light

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



Pneumatic drive with Ø70 mm screen:



In beam dynamics and by Volker Ziemann: Profile measurement is called 'Screens'

Example of Screen based Beam Profile Measurement

Advantage of screens:

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

⇒ widely used at transfer lines

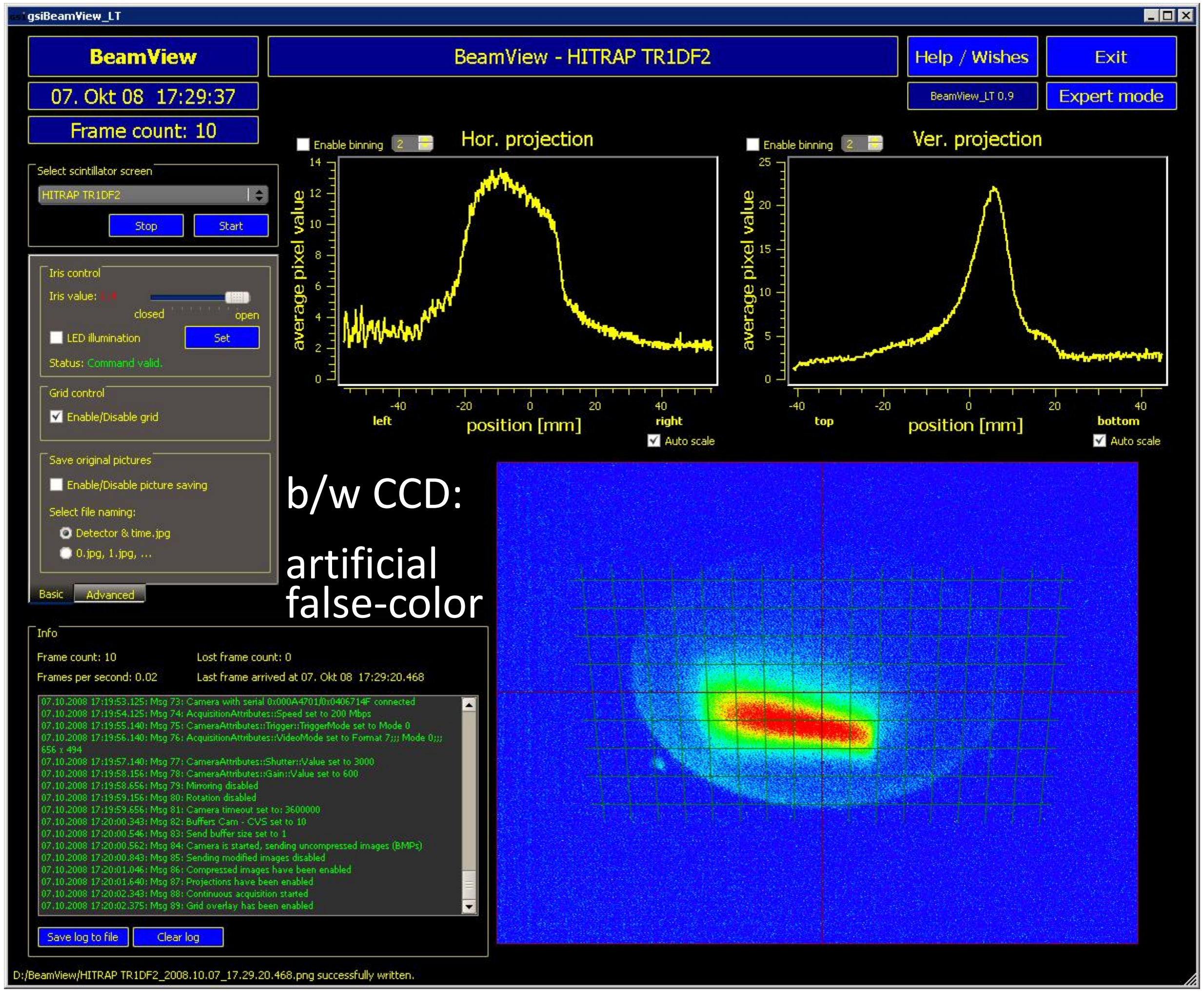
Disadvantage of screens:

- ➢ Intercepting device
- ➢ Some material might be brittle
- ➢ Possible low dynamic range
- ➢Might be destroyed
  by the beam (radiation damage)

Observation with CMOS camera

Scintillation Screen (beam stopped)

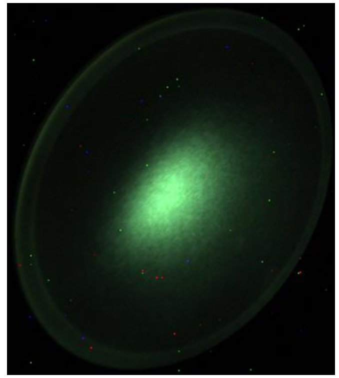
Example: GSI LINAC, 4 MeV/u, low current, YAG:Ce screen



Light output from various Scintillating Screens

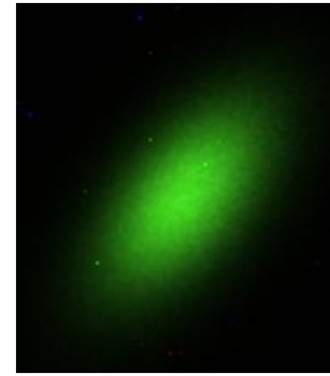
Example: *Color CCD camera: Images at different particle intensities determined for U at 300 MeV/u*

Alumina: Al_2O_3

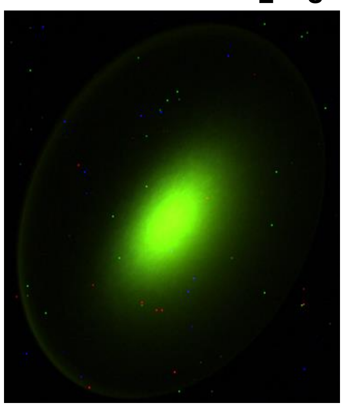


CsI:Tl

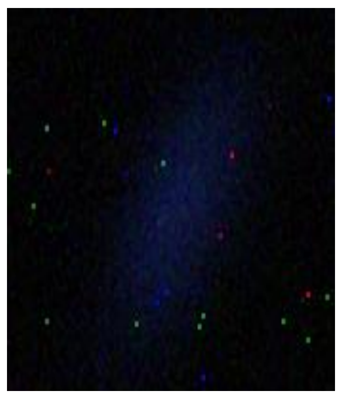
Chromox: Al_2O_3:Cr



P43

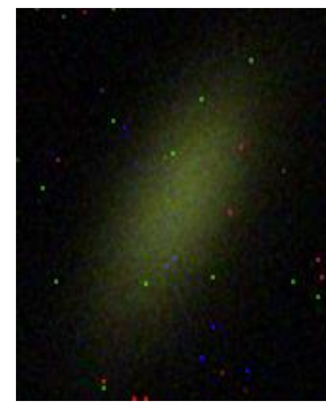


YAG:Ce



Quartz

Quartz:Ce



ZrO_2:Mg

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

Material Properties for Scintillating Screens

Some materials and their basic properties:

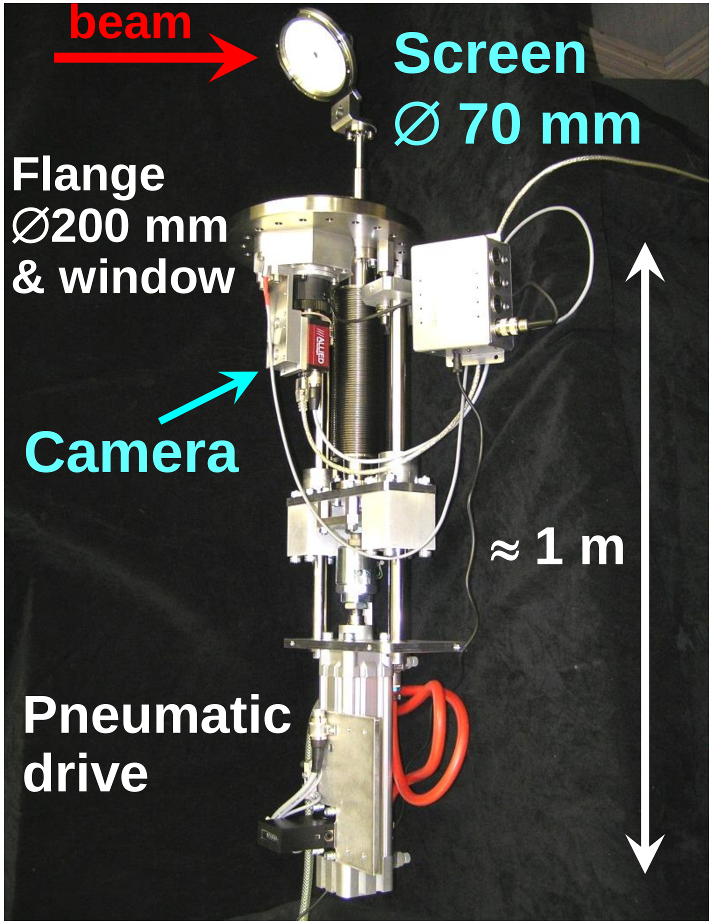
Type	Name	Material	Activ.	Max. λ	Decay
Cera-mics	Chromox	Al_2O_3	Cr	700nm	≈ 10ms
	Alumina	Al_2O_3	Non	380nm	≈ 10ns
Crystal	YAG:Ce	$Y_3Al_5O_{12}$	Ce	550nm	200ns
	LYSO	$Lu_{1.8}Y_{.2}SiO_5$	Ce	420nm	40ns
Powder of gains Ø≈10µm on glass	P43	Gd_2O_3S	Tb	545nm	1ms
	P46	$Y_3Al_5O_{12}$	Ce	530nm	300ns
	P47	Y_2SiO_5	Ce&Tb	400nm	100ns

Properties of a good scintillator:

- Large light output at optical wavelength
  → standard camera can be used
- Large dynamic range → usable for different currents
- 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



Outline:

- Scintillation screens:

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

  light emission due to crossing material boundary, mainly for relativistic beams
- SEM-Grid
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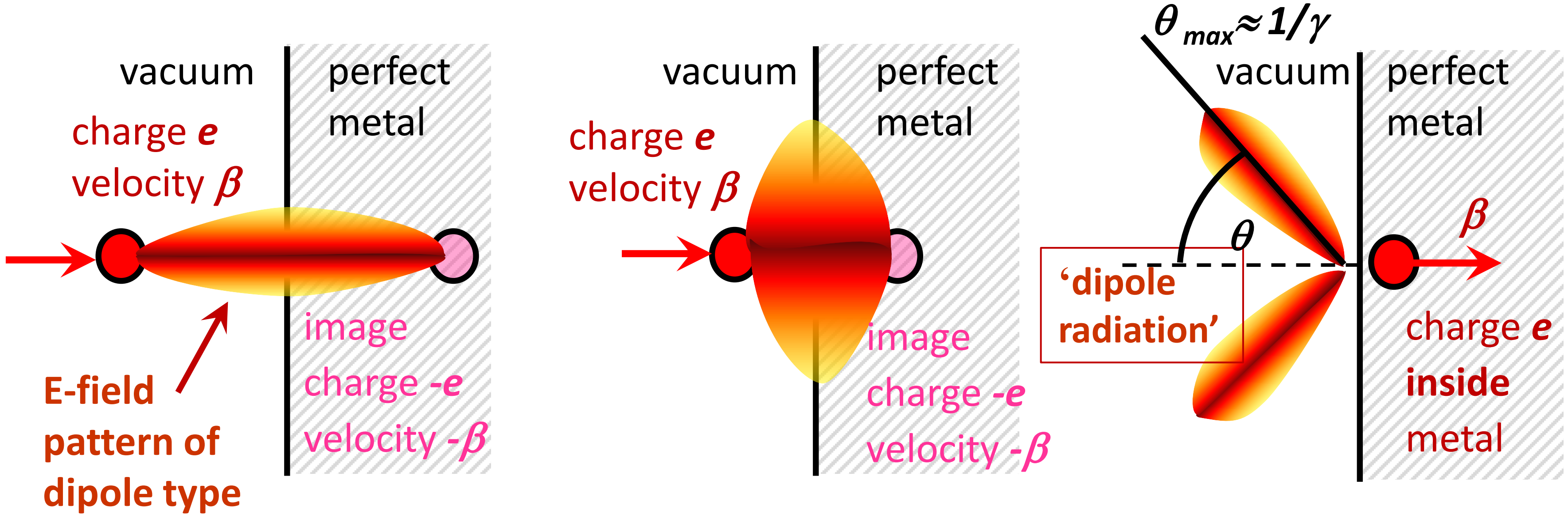
Optical Transition Radiation OTR for a single charge *e*:

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: Depictive Description

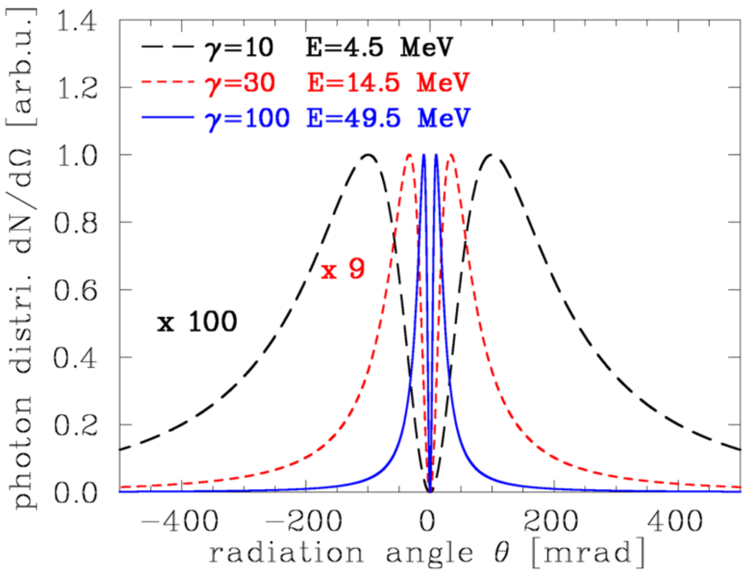
Optical Transition Radiation OTR can be described in classical physics:

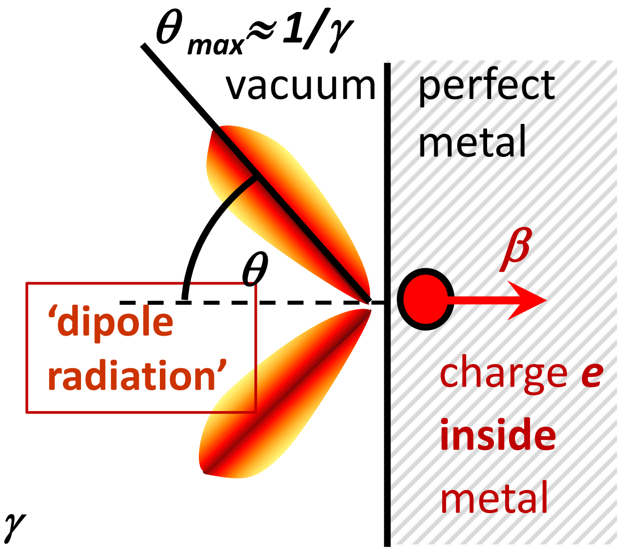
Approximated formula for normal incidence & in-plane polarization:

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

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)

→ Suited for high energy electrons

sudden change charge distribution
rearrangement of sources ⇔ radiation

OTR is emitted by charged particle passage through a material boundary.

Photon distribution:

within a solid angle $d\Omega$ and

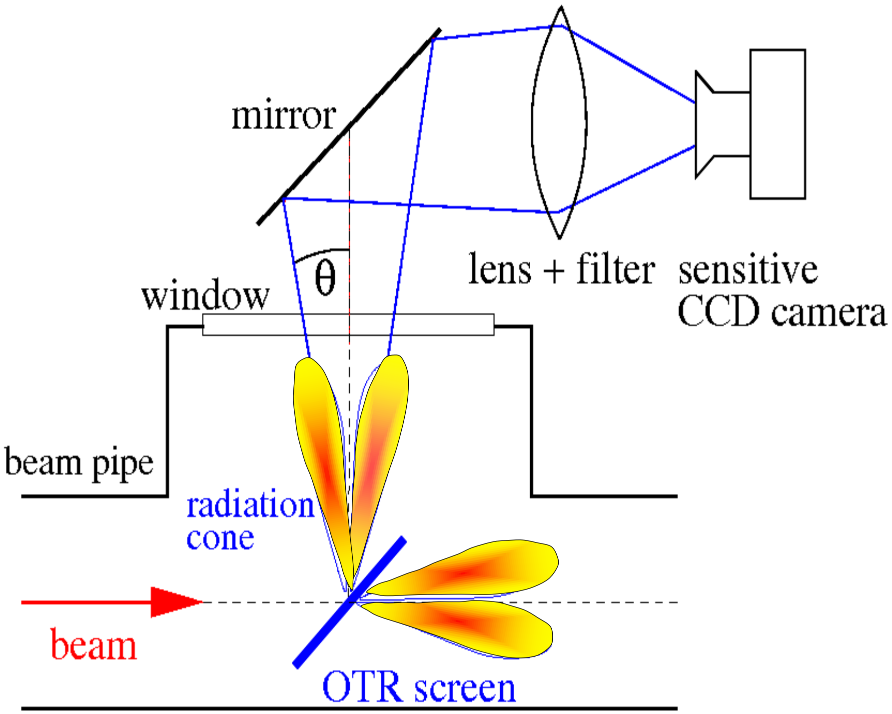
Wavelength interval λ_{begin} to λ_{end}

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

- Detection: Optical 400 nm < λ < 800 nm
- Larger signal for relativistic beam $\gamma \gg 1$
- Low divergence for $\gamma \gg 1 \Rightarrow$ large signal

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

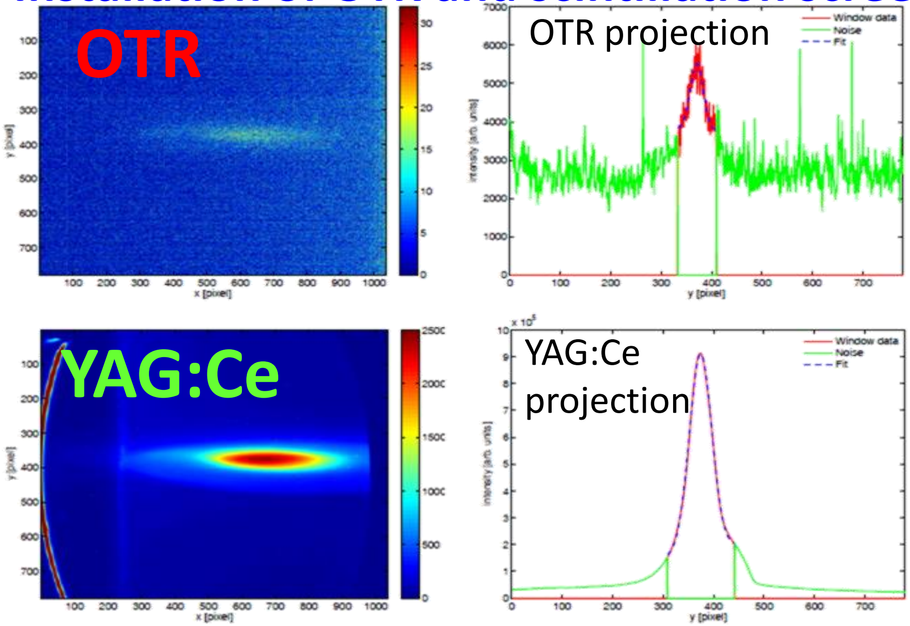
$\Rightarrow$ **p-beam used for $E_{kin} \gtrsim 10$ GeV $\Leftrightarrow \gamma \gtrsim 10$**



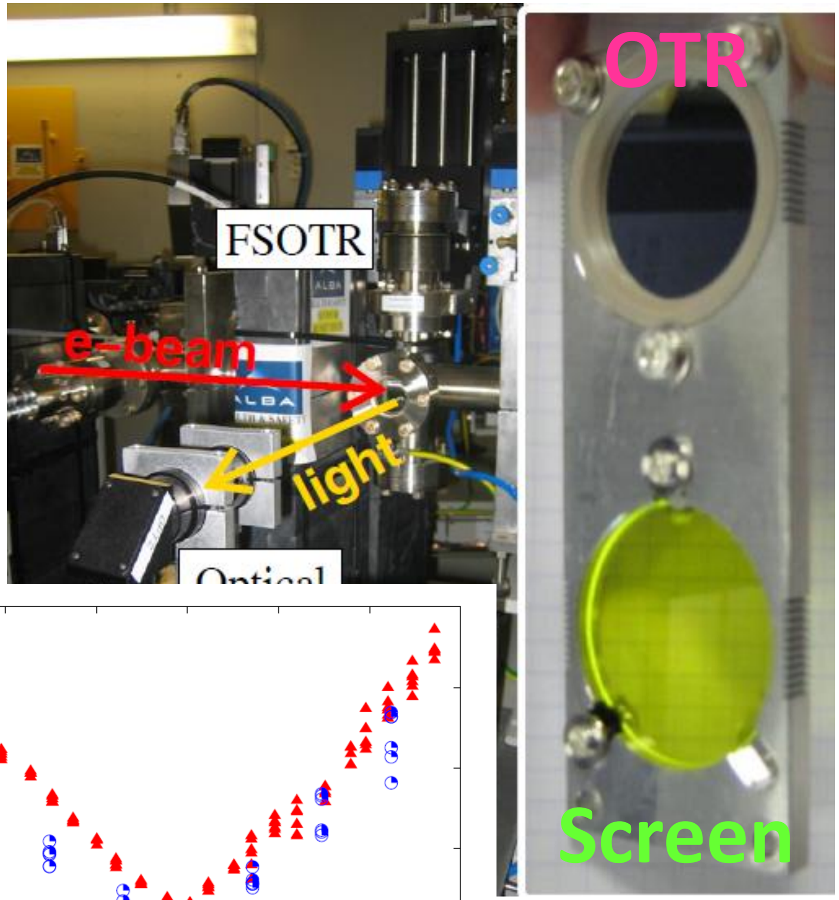
- Insertion of thin Al-foil under 45°
- Observation of low light by CCD.

Optical Transition Radiation compared to Scintillation Screen

Installation of OTR and scintillation screens on same drive:

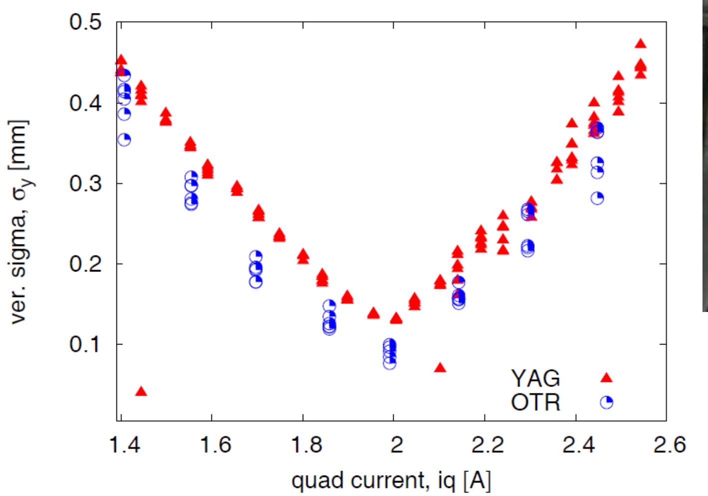


Example: ALBA LINAC 100 MeV



Results:

- Much more light from YAG:Ce for 100 MeV ($\gamma \approx 200$) electrons light output $I_{YAG} \approx 10^5\, I_{OTR}$
- 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

Quantity	OTR screen	Scintillation screen
Physics basis	**Electrodynamic** process → intensity linear to # photons, high radiation hardness	Complex **atomic** process → saturation possible, Possibility: low radiation hardness

Comparison between Scintillation Screens and OTR

Quantity	OTR screen	Scintillation screen
Physics basis	**Electrodynamic** process → intensity linear to # photons, high radiation hardness	Complex **atomic** process → saturation possible, Possibility: low radiation hardness
Target property	**Thin foil** Al or Al on Mylar, down to 0.25 μm thickness → minimizes beam scattering	Thickness ≈ **1 mm** inorganic, fragile material, not always radiation hard
Signal strength	**Low** number of photons → expensive image intensified cam.	Large number of photons → simple camera sufficient
Photon distribution	**Complex** angular distribution → resolution limited	**Isotropic** photon distribution → simple interpretation
Application	**Large γ** needed → e^--beam with E_{kin} > 100 MeV, proton-beam with E_{kin} > 100 GeV	For **all beams**

Remark: OTR is **not** suited for LINAC-FEL due to **coherent** light emission (not covered here) but scintillation screens can be used.

Outline:

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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

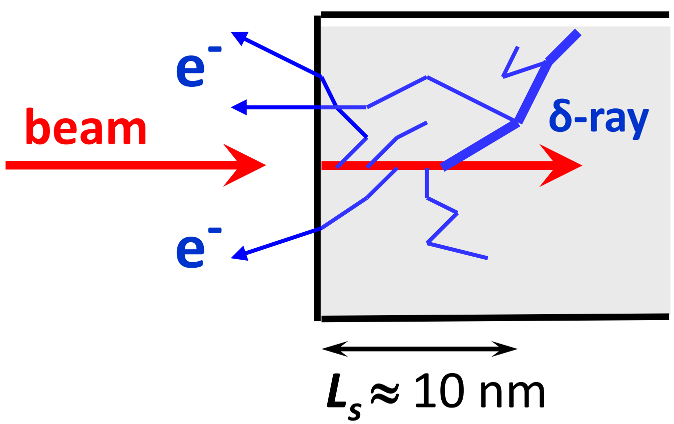
Distant collision with low energy transfer : → slow e^- with $E_{kin} \leq 10$ eV

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

→ at surface ≈ 90 % probability for escape

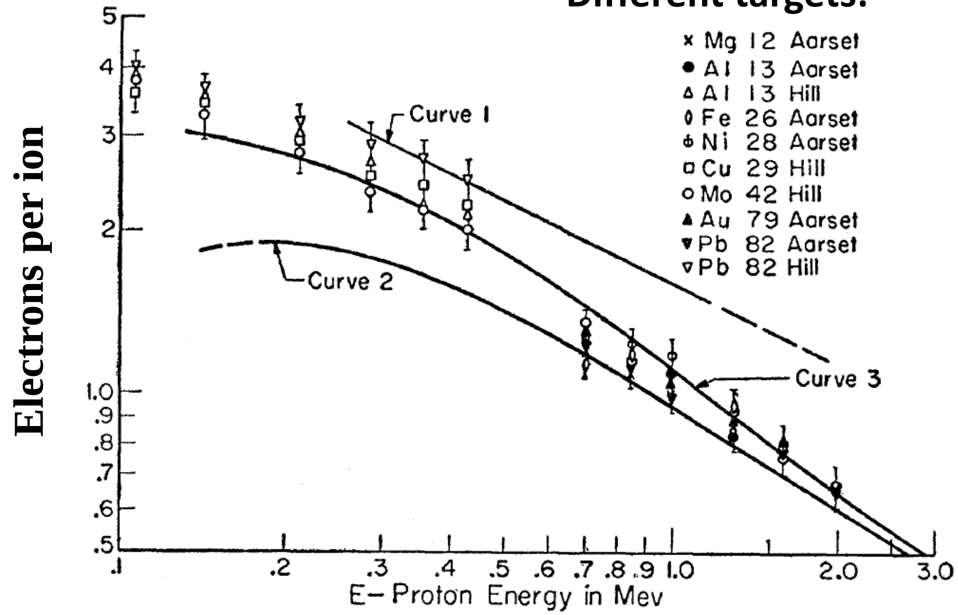
Secondary **electron yield** and energy distribution comparable for all metals!

$$\Rightarrow \quad Y = const. * dE/dx \quad \text{(Sternglass formula)}$$



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

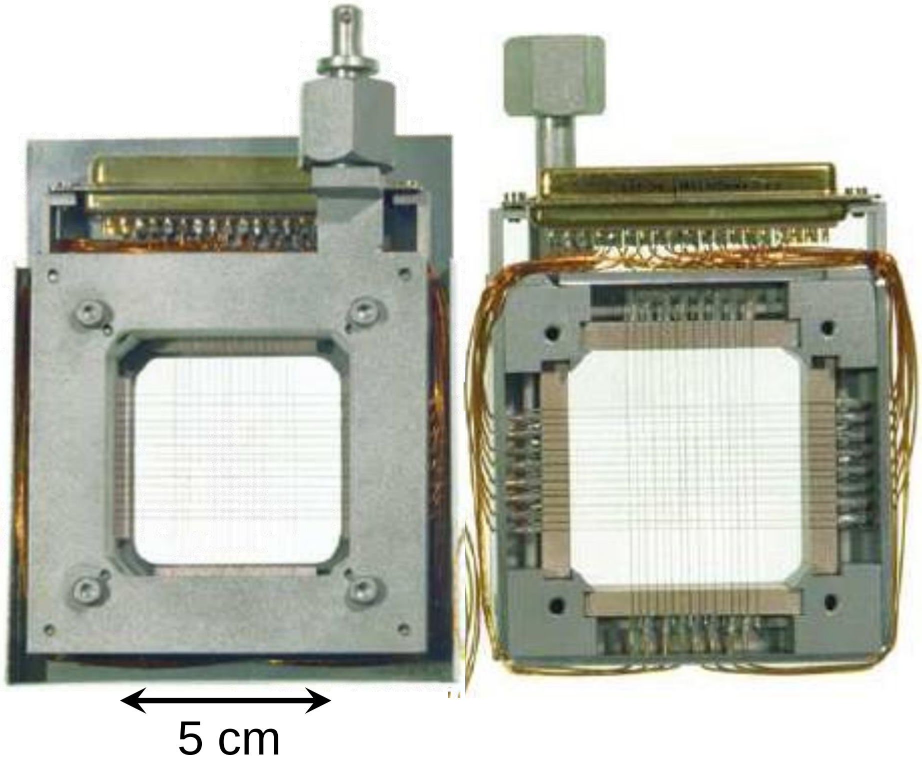
Different targets:



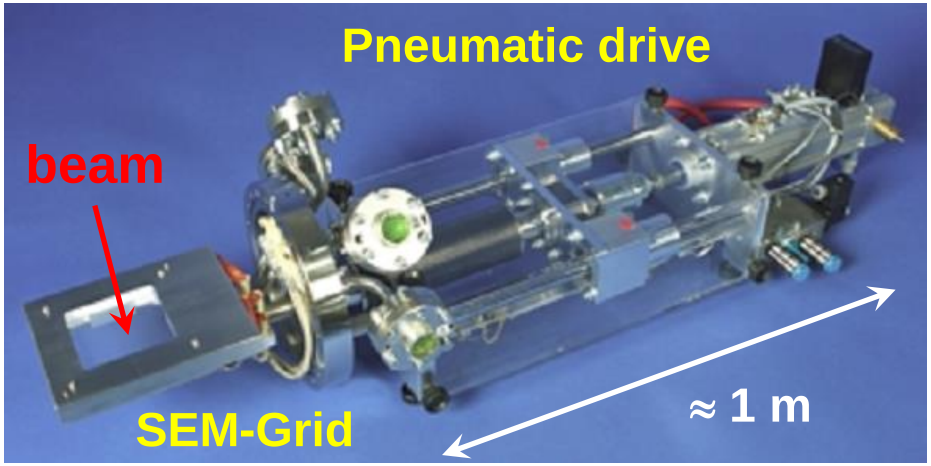
Secondary Electron Emission Grids = SEM-Grid

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

Example: 15 wire spaced by 1.5 mm:



SEM-Grid drive on ∅200 mm flange:



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

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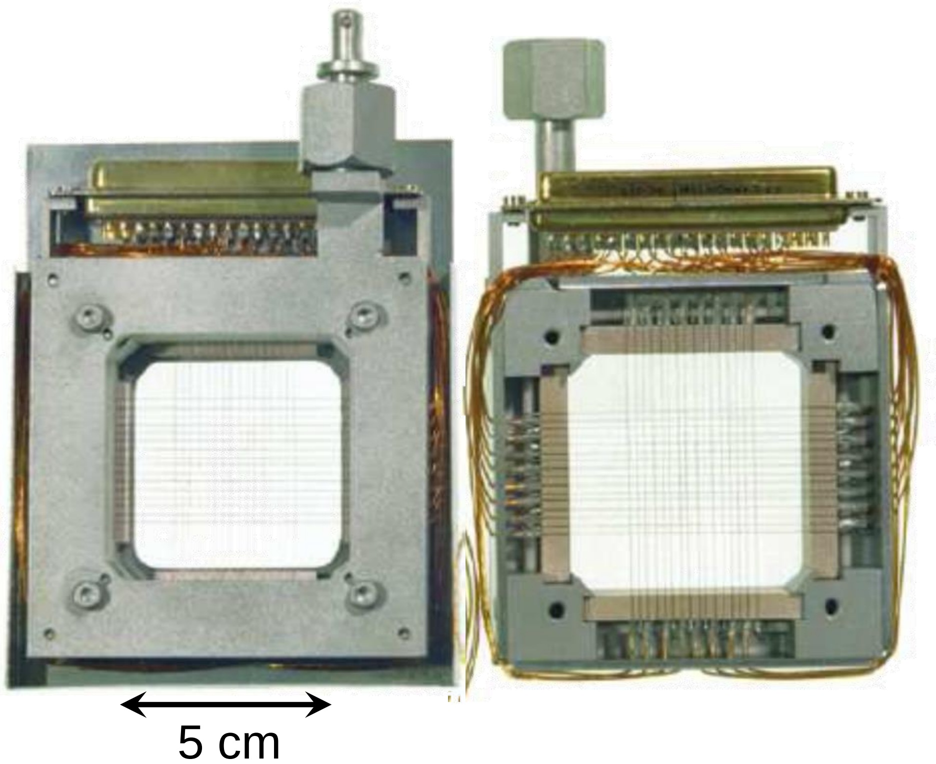
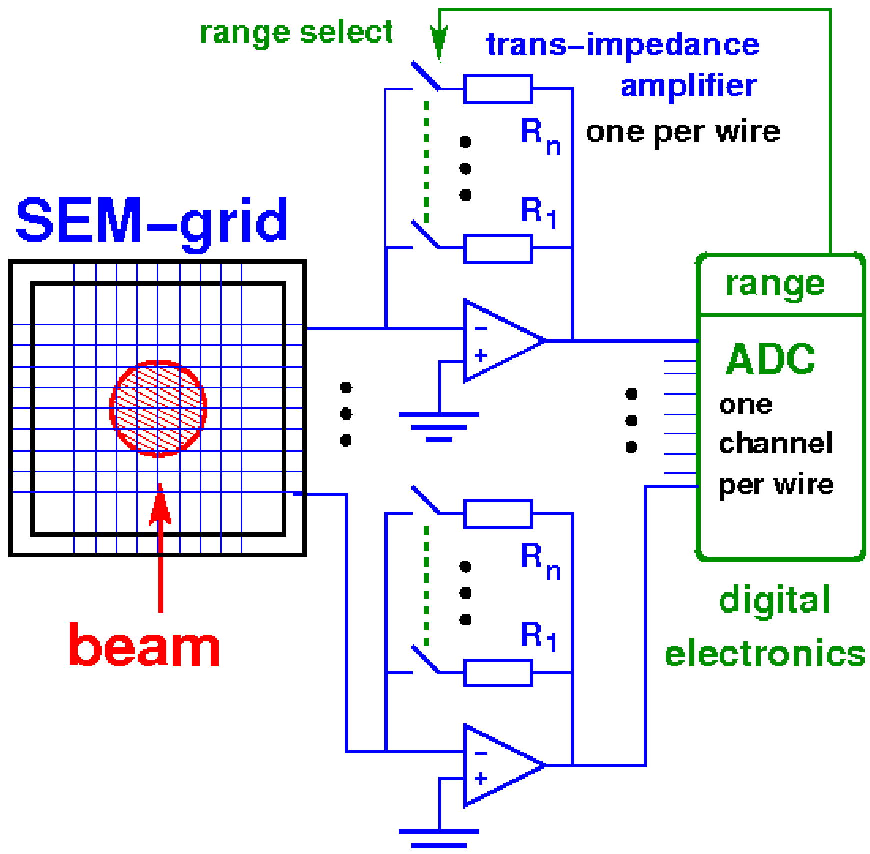




Each wire is equipped with one I/U converter

different ranges settings by R_i

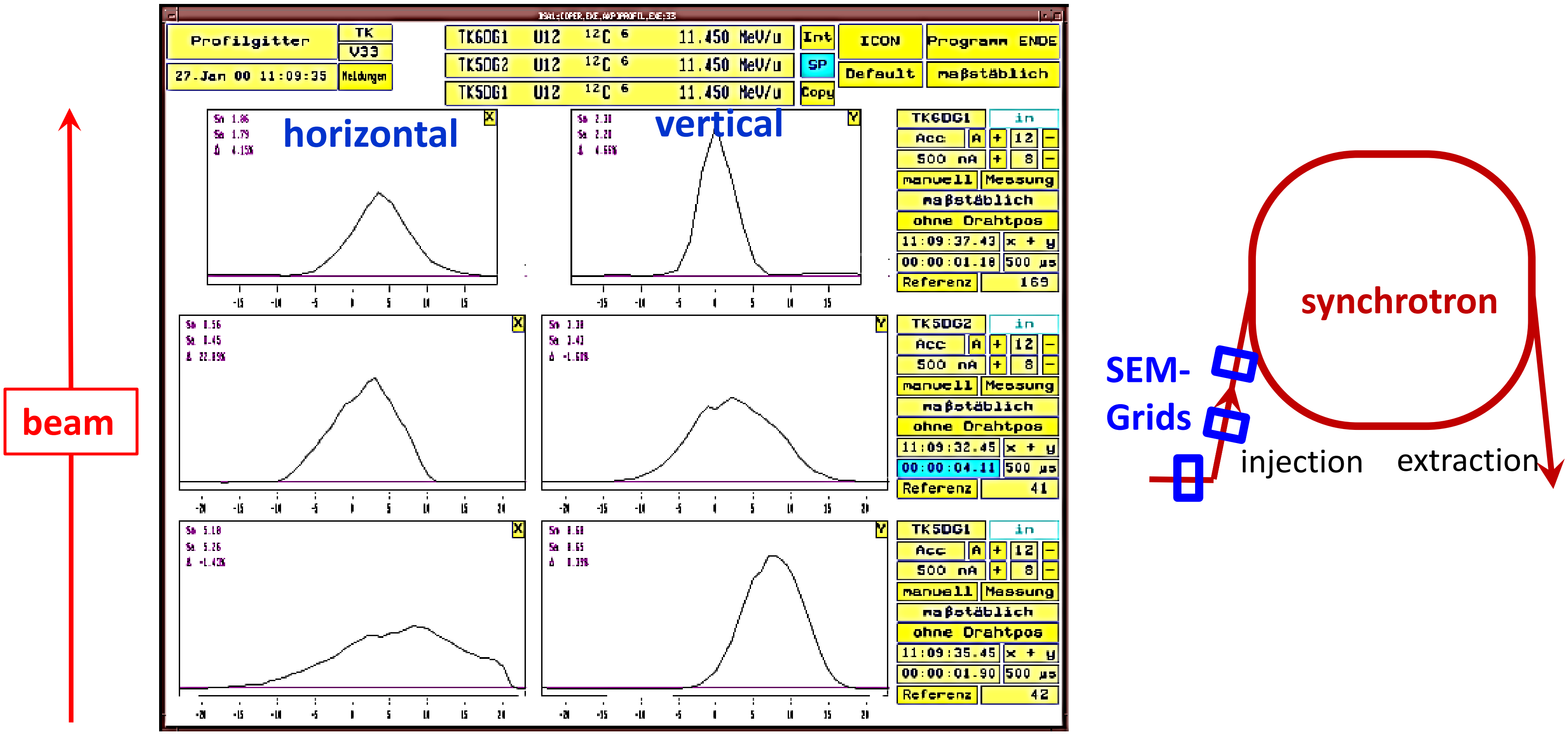
→ very large dynamic range up to 10^6.

Example of Profile Measurement 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



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- Wire scanner:

  emission of electrons, workhorse, scanning method

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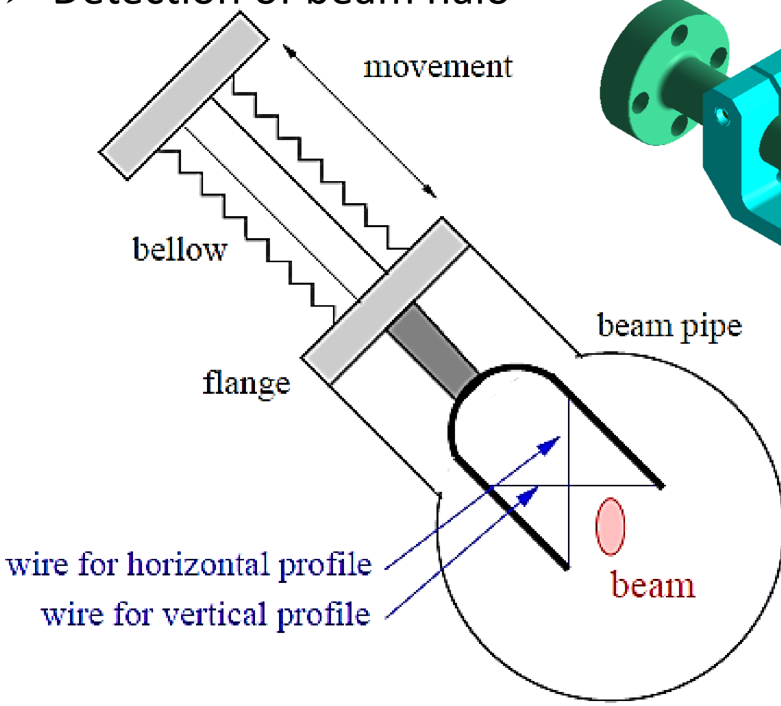
Slow, linear Wire Scanner

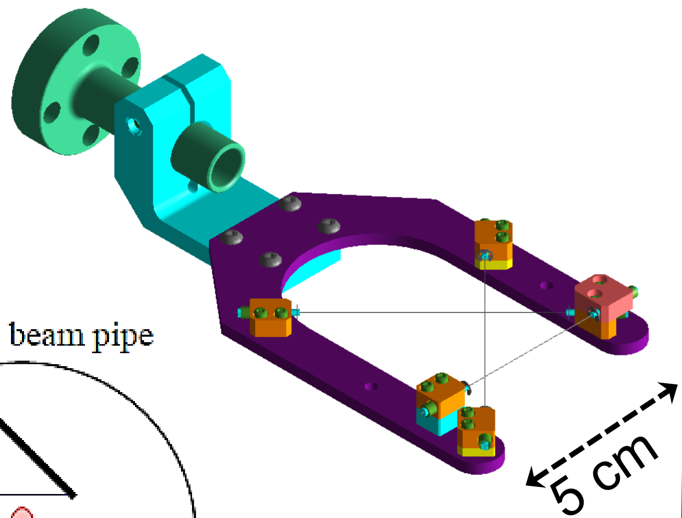
Idea: One wire is scanned through the beam!

Wire diameter 100 µm < ***d**$_{wire}$* < 10 µm

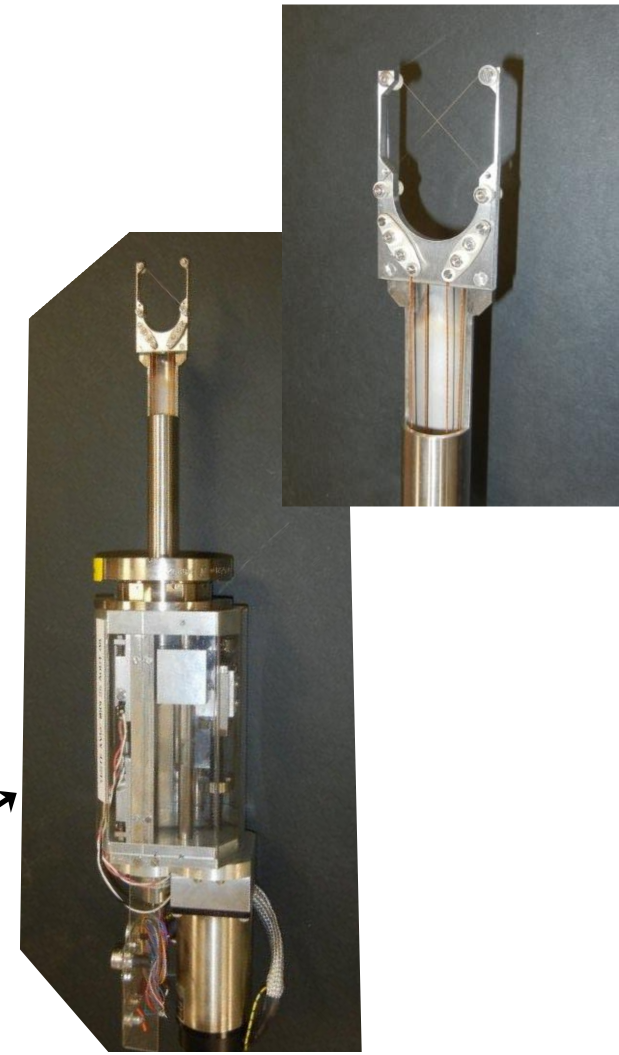
Slow, linear scanner are used for:

- Low energy protons
- High resolution measurements for e⁻ beam
  by de-convolution $\sigma_{beam}^2 = \sigma_{meas}^2 + r_{wire}^2$
  $\Rightarrow$ resolution down to 1 µm range can be reached
- Detection of beam halo



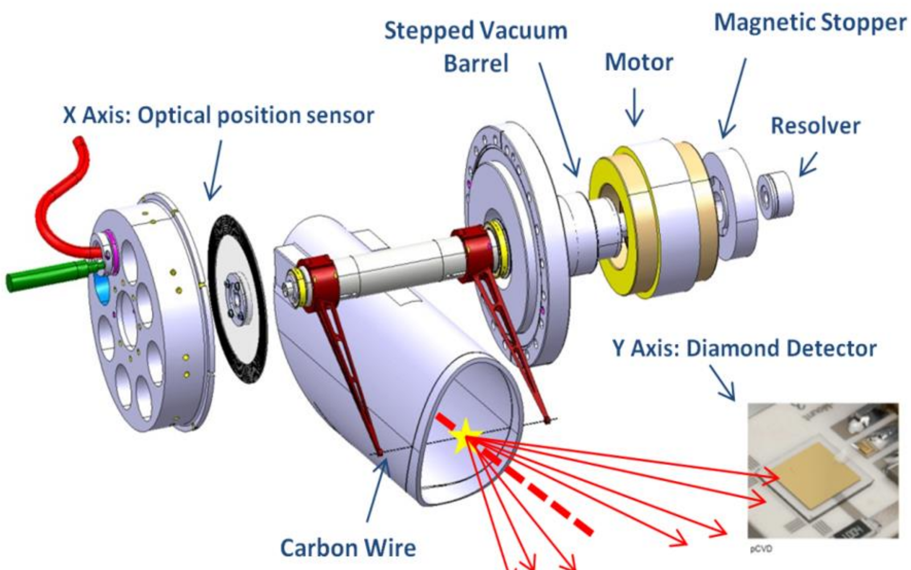


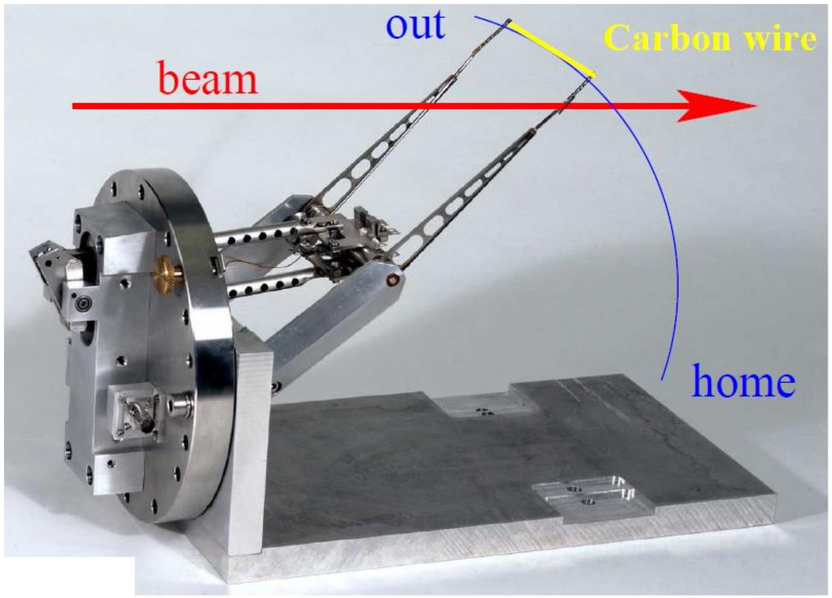
Example: Wires scanner at CERB LINAC4

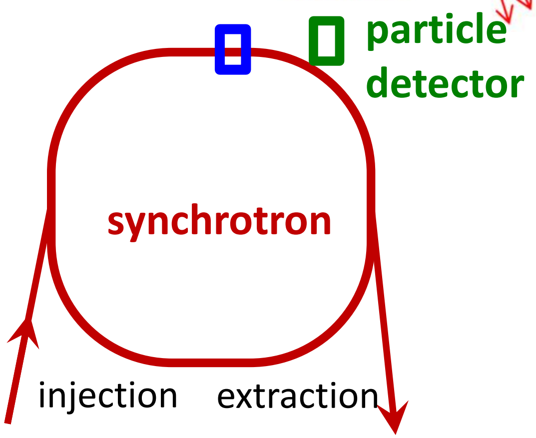


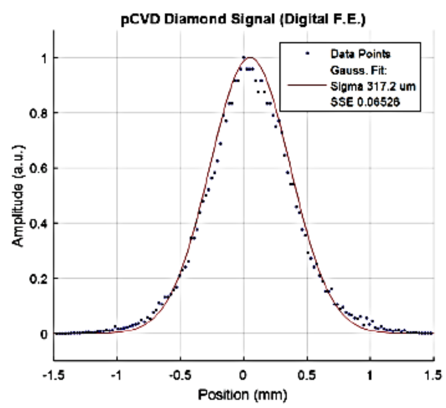
In a synchrotron ***one*** wire is scanned though the beam as fast as possible.

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









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.

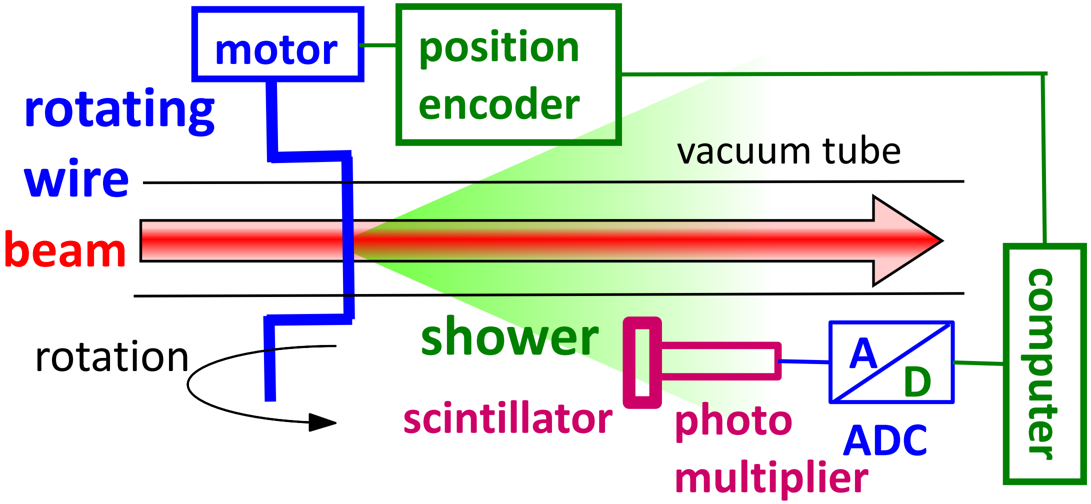
Thickness: Down to 10 μm → high resolution.

Detection: High energy **secondary particles** with a detector like a beam loss monitor

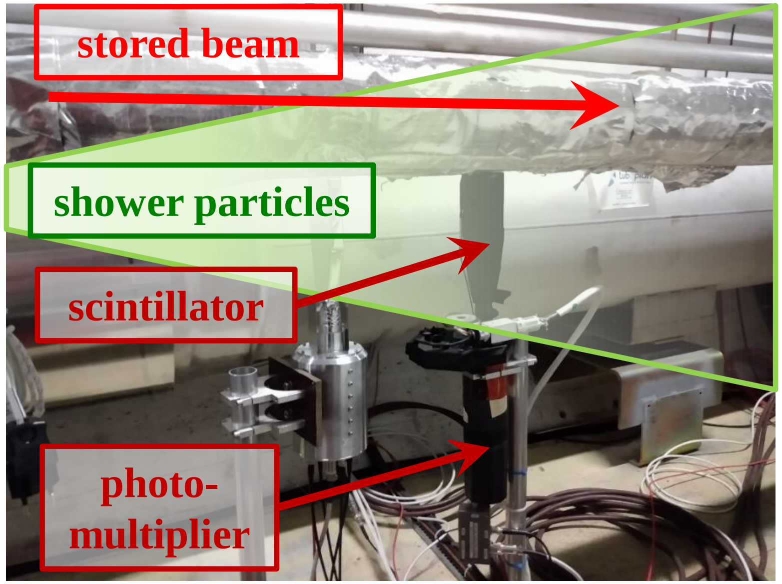
Secondary particles:

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

Electron beam → Bremsstrahlung photons



Detector in LHC:



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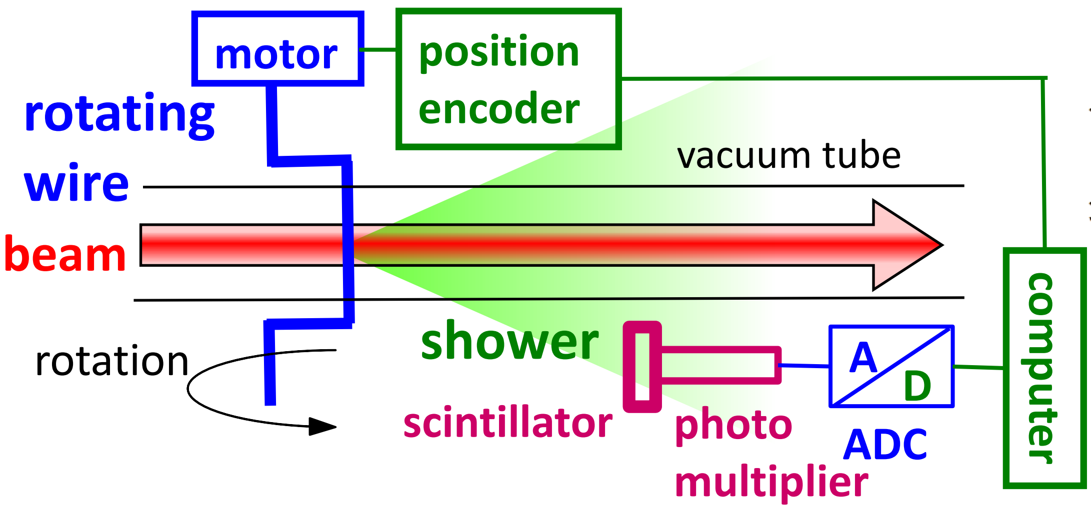
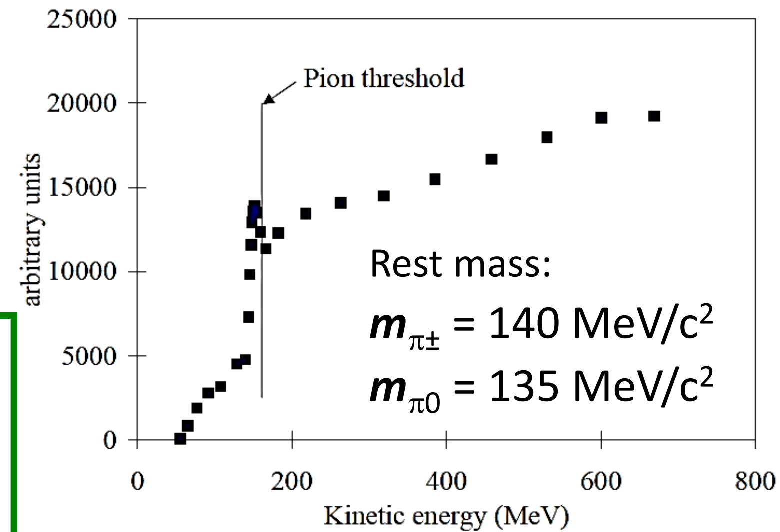


Proton impact on scanner at CERN-PS Booster:



U. Raich et al., DIPAC 2005

Kinematics of flying wire:

Velocity during passage typi. 10 m/s = 36 km/h & typical beam size ∅ 10 mm

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

Challenges: Wire stability for fast movement with high acceleration

Comparison between SEM-Grid and slow linear Wire Scanners

Quantity	Grid	Linear scanner
Time resolution	Measurement at a **single moment** in time	**Scanning method** → fast variations can't be monitored

Comparison between SEM-Grid and slow linear Wire Scanners

Quantity	Grid	Linear scanner
Time resolution	Measurement at a **single moment** in time	**Scanning method** → fast variations can't be monitored
Spatial resolution	Fixed by the wire **distance** (typically 1 mm)	Fixed by the wire **thickness** (typically 0.1 mm)
Electronics	**Multi-channel**, one for each wire → expensive	**Single channel** → cheap
Mechanics	**Pneumatics** for in ↔ out → cheap	**Stepping motor** required → expensive
Application	Required for **pulsed** beams	Required for **small** beams
	However, related to tradition at laboratory	

Flying wire scanner:

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

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

Measurement of Beam Profile

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  emission of electrons, workhorse, scanning method

- Ionization Profile Monitor:

  secondary particle detection from interaction beam-residual gas

- Synchrotron Light Monitors
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Interaction between Residual Gas and the Beams

Physics: Energy loss of ions in gas ***dE/dx***

⇒ Profile determination from residual gas

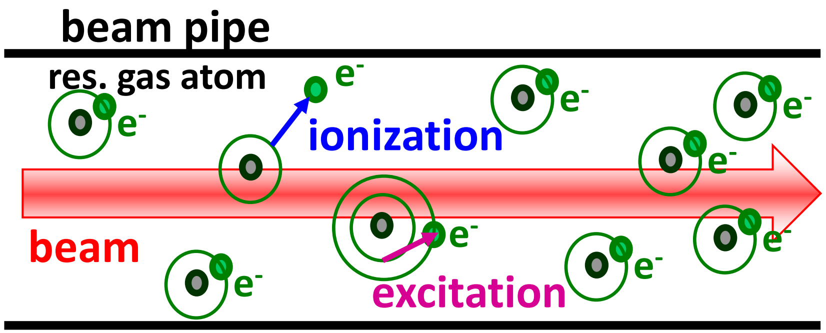
- **Ionization:**

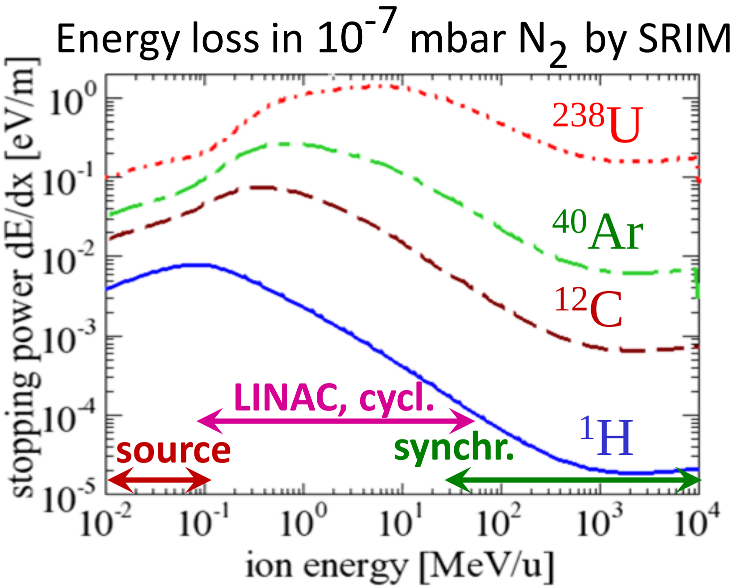
  in average roughly ≈ 100 eV/ionization

- **Excitation** followed by photon emission:

in average roughly ≈ 300 eV/event e.g. N_2

However, depends strongly on gas molecule





Typical vacuum pressure & ideal gas law $pV = nk_BT$

Transfer line:

N_2 pressure $p \approx 10^{-8} \ldots 10^{-6}$ mbar

⇔ density $\rho_{gas} \approx 3\cdot10^{8} \ldots 3\cdot10^{10} \text{cm}^{-3}$

Synchrotron:

H_2 pressure $p \approx 10^{-11} \ldots 10^{-9}$ mbar

⇔ density $\rho_{gas} \approx 3\cdot10^{5} \ldots 3\cdot10^{7}\ \text{cm}^{-3}$

Beam density for comparison:

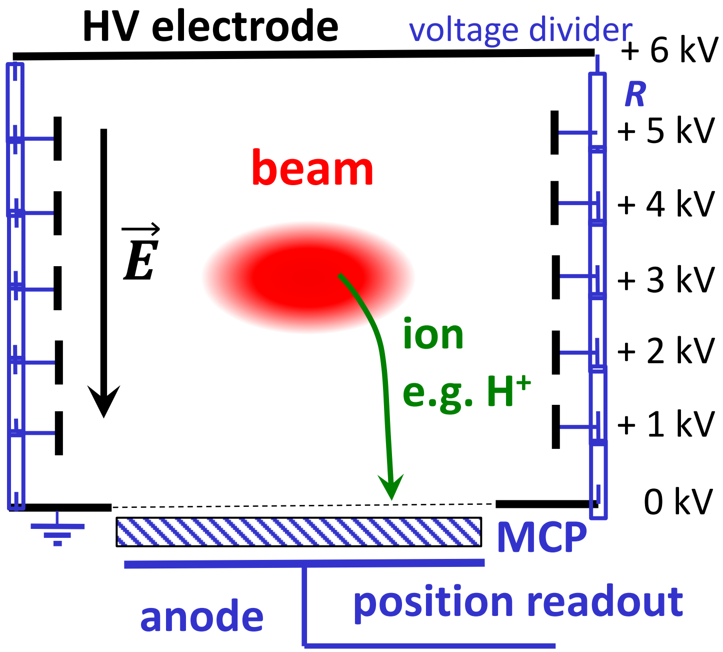
Proton accelerator at 1 GeV, 100 mA, trans. width σ = 300 μm, coasting beam

⇒ density $\rho_{beam} \approx 10^{8}\ \text{cm}^{-3}$ → beam density might be lower the vacuum density!

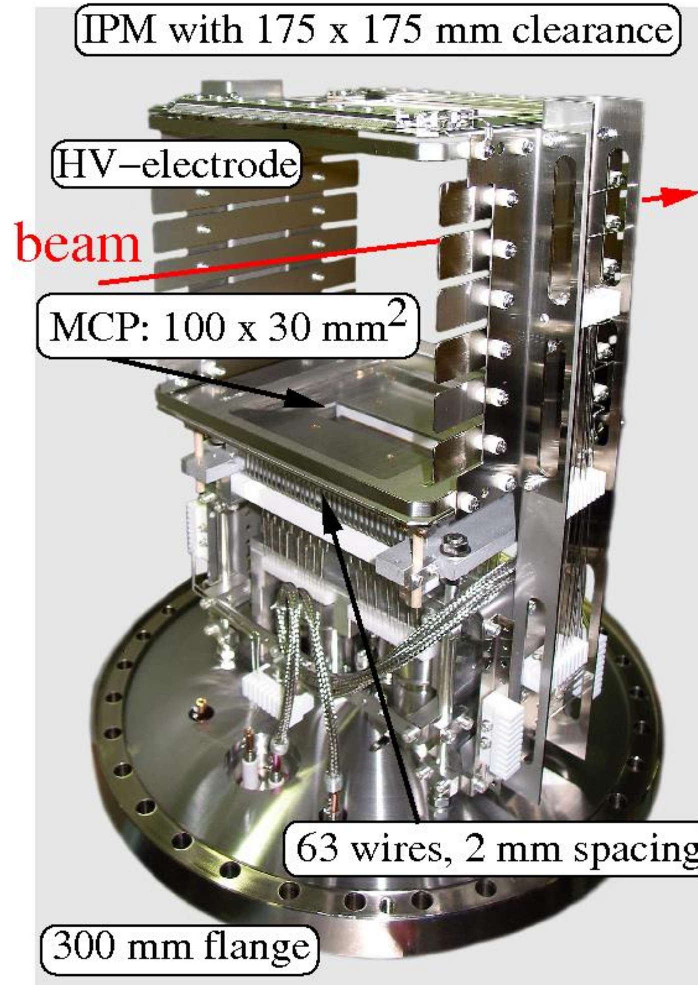
Ionization Profile Monitor at GSI Synchrotron

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

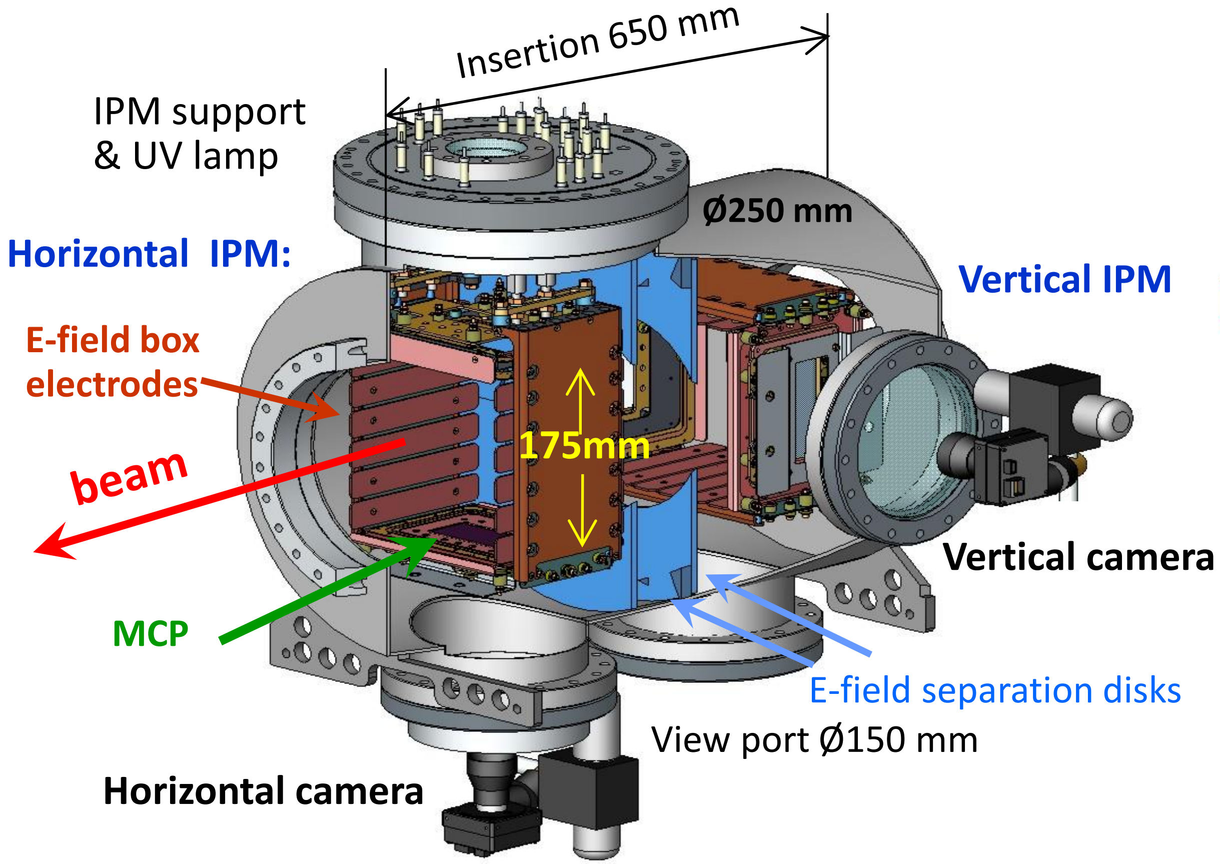


Realization at GSI synchrotron:
One monitor per plane

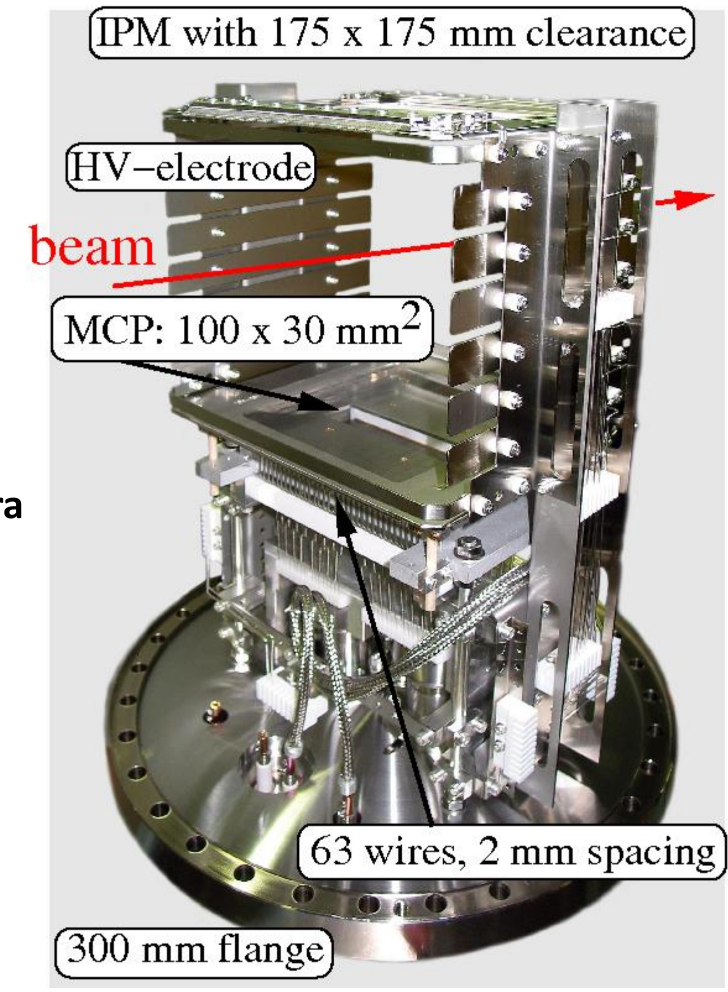


Ionization Profile Monitor Realization

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



Realization at GSI synchrotron:
One monitor per plane



Ionization Profile Monitor Realization

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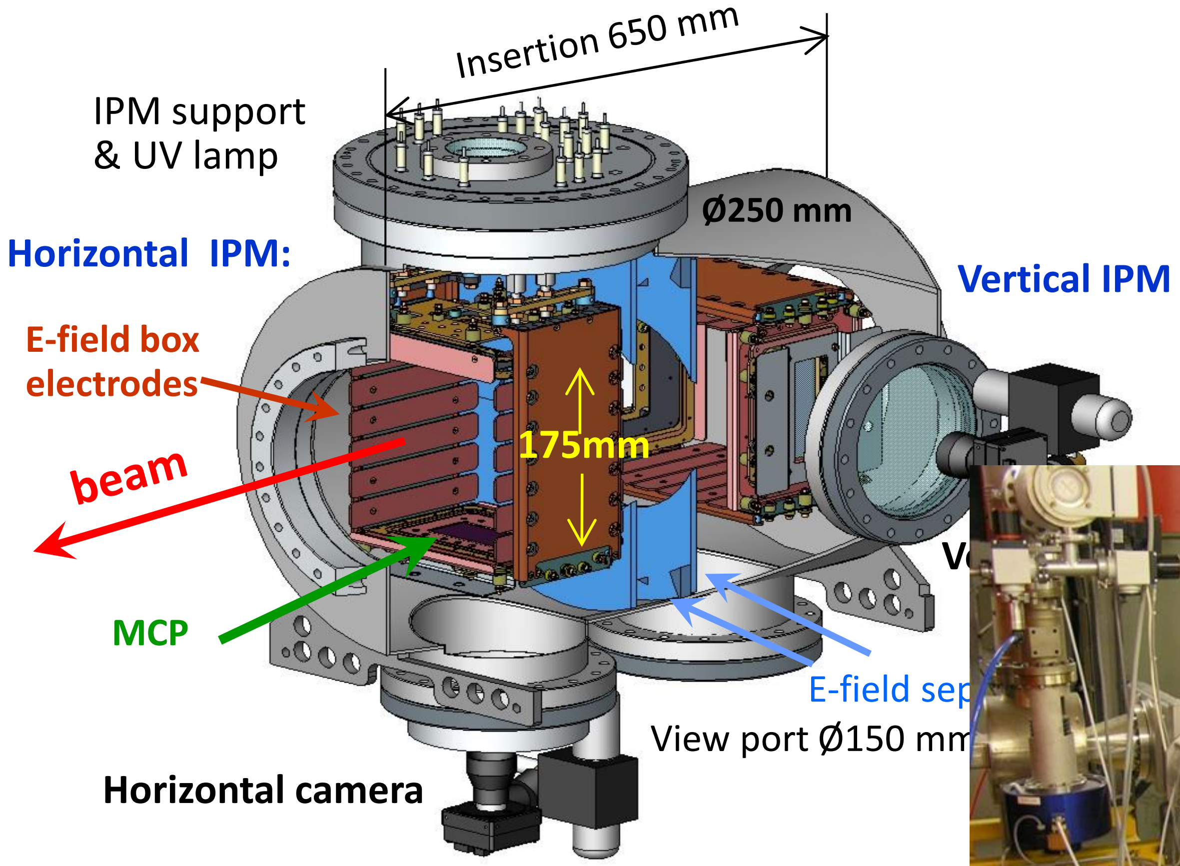


Realization at COSY synchrotron for one plane:

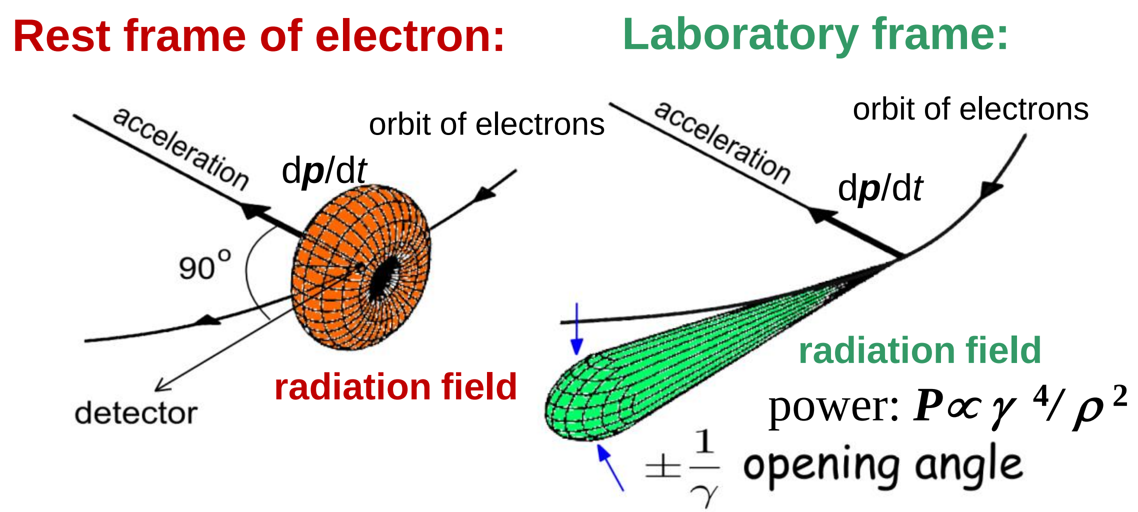
Outline:

- Scintillation screens:
  emission of light, universal usage, limited dynamic range
- Optical Transition Radiation:
  light emission due to crossing material boundary, mainly for relativistic beams
- SEM-Grid:
  emission of electrons, workhorse, limited resolution
- Wire scanner:
  emission of electrons, workhorse, scanning method
- Ionization Profile 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**

An electron bent (i.e. accelerated) by a dipole magnet emit synchrotron light
see lecture 'Electron Beam Dynamics' by Lenny Rivkin

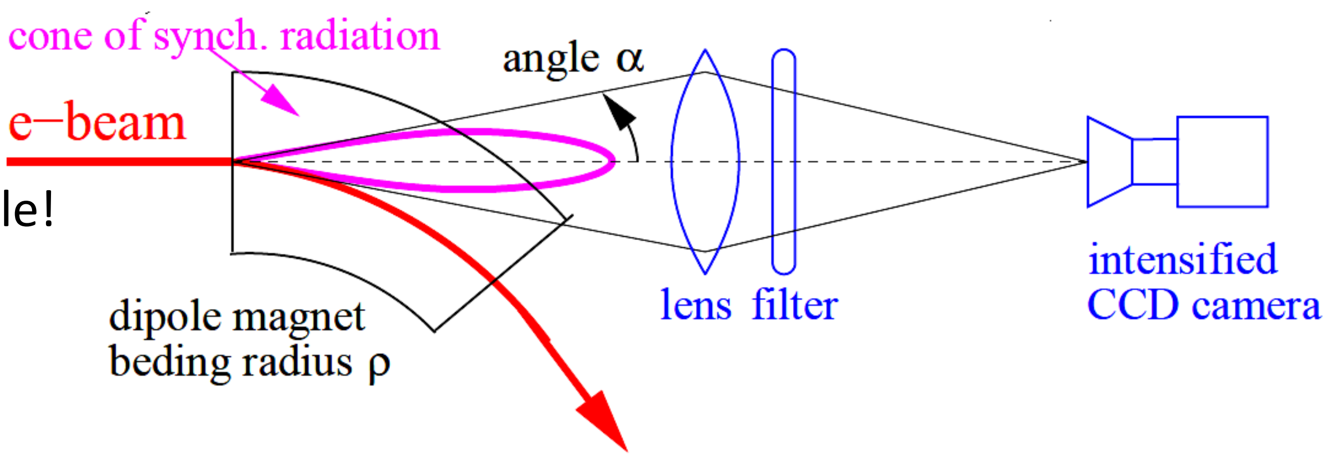
This light is emitted into a cone of opening $2/\gamma$ in lab-frame.
$\Rightarrow$Well suited for rel. e^-

For protons:
Only for energies E_{kin} > 100 GeV



The light is focused to a intensified CCD.

Advantage:
Signal anyhow available!



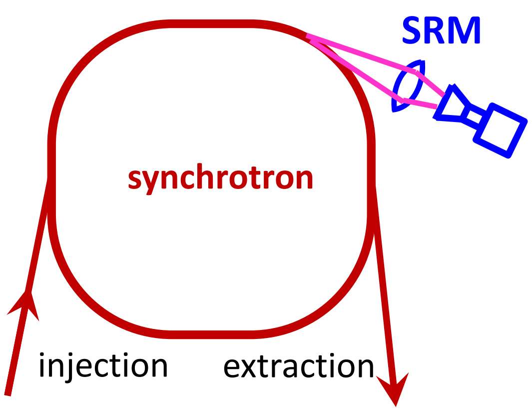
Realization of a Synchrotron Radiation Monitor

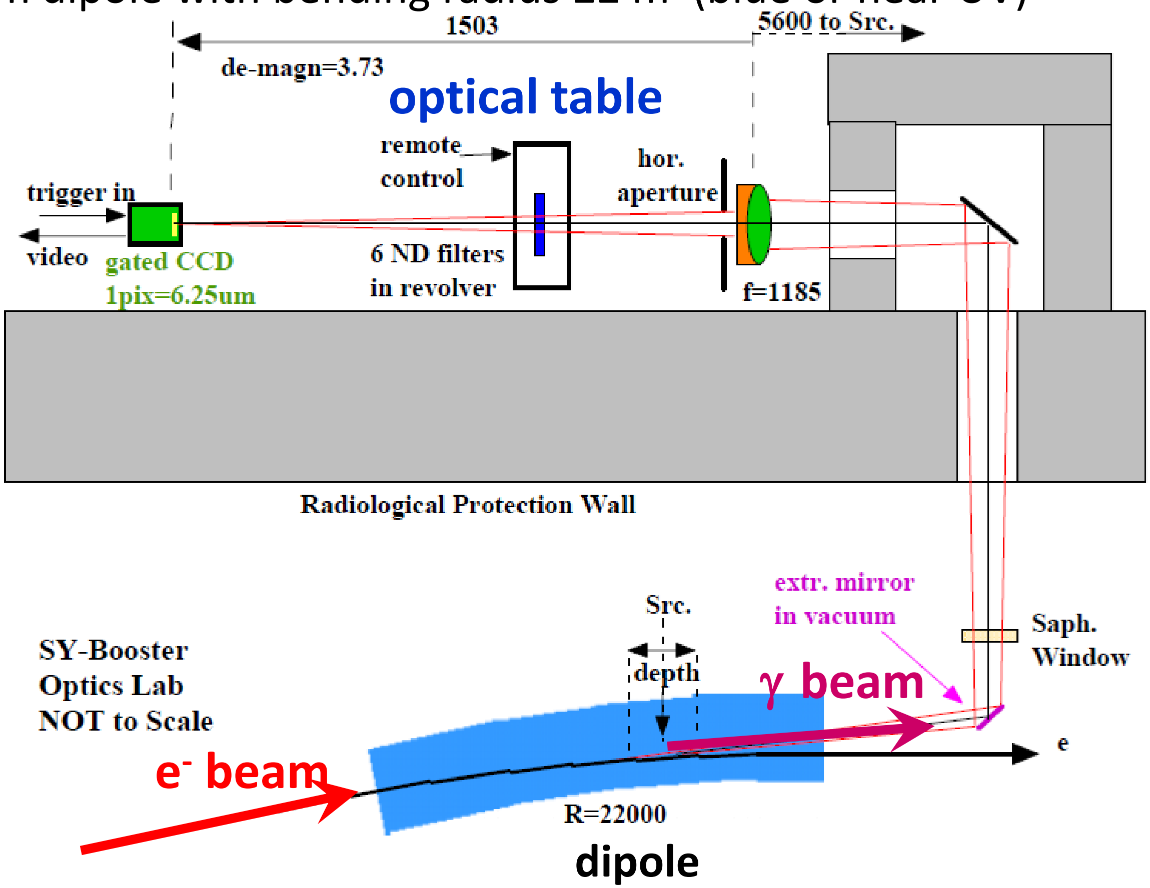
Extracting out of the beam's plane by a (cooled) mirror

→ Focus to a slit + wavelength filter for optical wavelength

→ Image intensified CCD camera

Example: ESRF monitor from dipole with bending radius 22 m (blue or near UV)

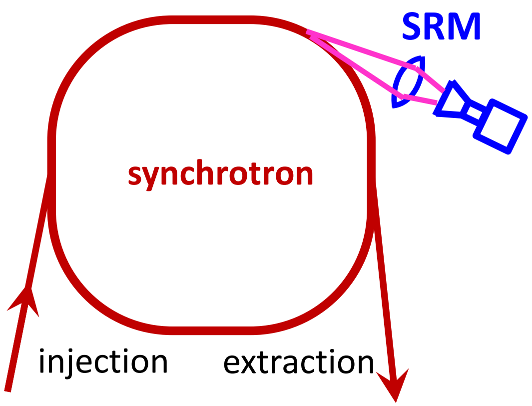


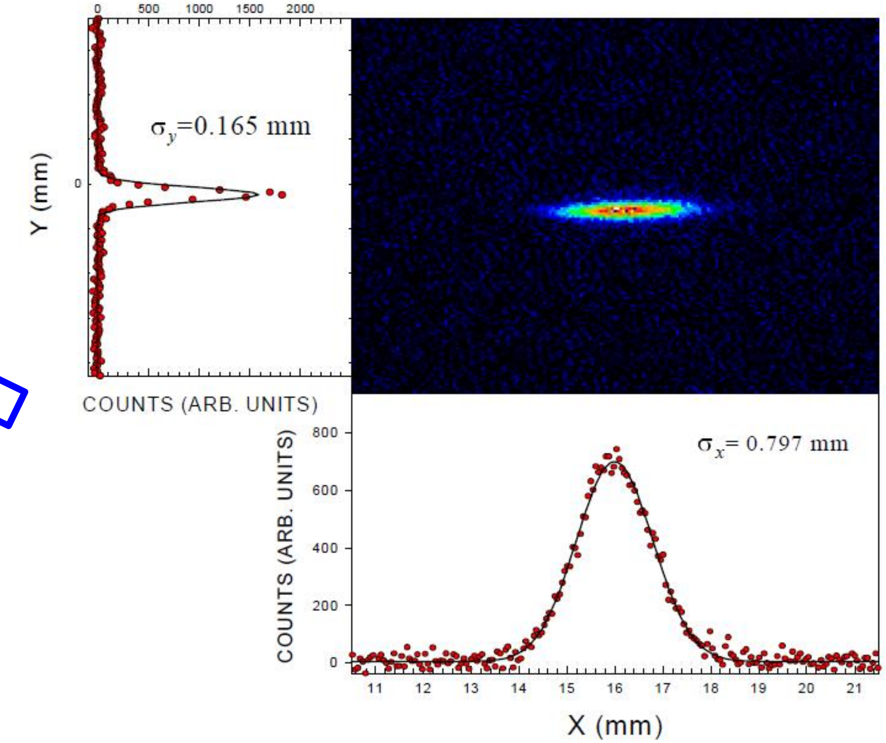


Courtesy K. Scheidt et al., DIPAC 2005

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, good optics for visible light

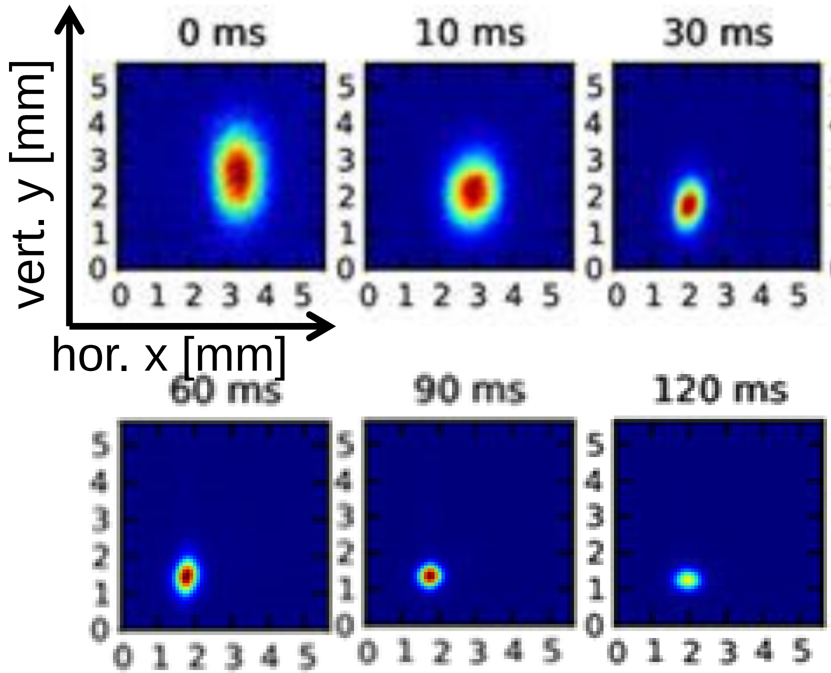
Realization: Optics outside of vacuum pipe

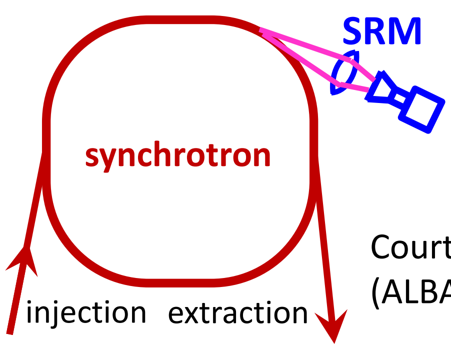
Disadvantage: Resolution limited by the diffraction due to finite apertures in the optics.

‘Adiabatic Damping’ for an Electron Beam

Example: Booster at the light source ALBA acceleration from 0.1 → 3 GeV within 130 ms

Profiles from synchrotron radiation monitor:





Courtesy U. Iriso & M. Pont (ALBA) et al. IPAC 2011

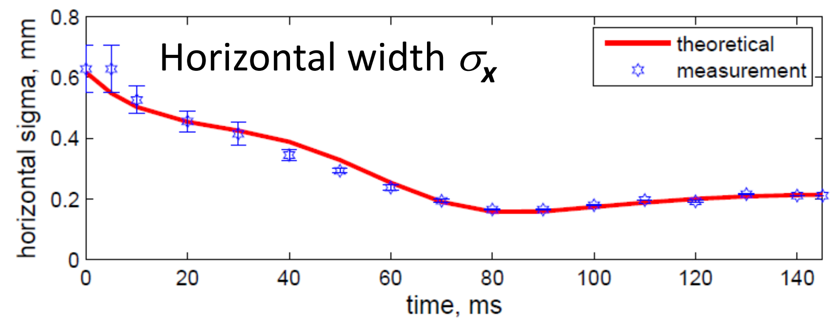
The beam emittance in influenced by:

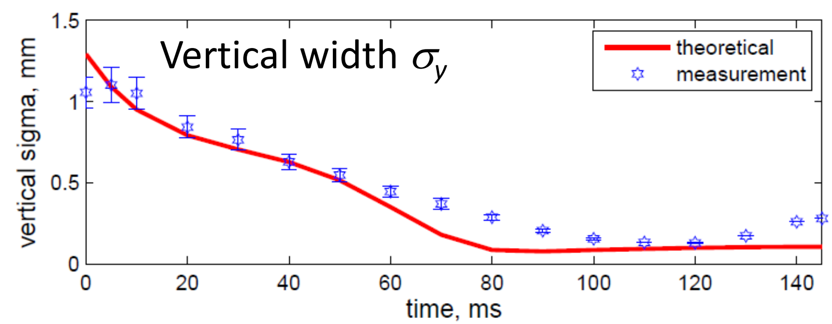
- Adiabatic damping
- Longitudinal momentum contribution

  via dispersion $D(s) \Rightarrow \Delta x_D(s) = D(s) \cdot \frac{\Delta p}{p}$

$\Rightarrow$ total width $\sigma_{tot}(s) = \sqrt{\varepsilon\beta(s) + \left(D(s) \cdot \frac{\Delta p}{p}\right)^2}$

- Quantum fluctuation due to light emission





Diffraction Limit for a Synchrotron Light Monitor

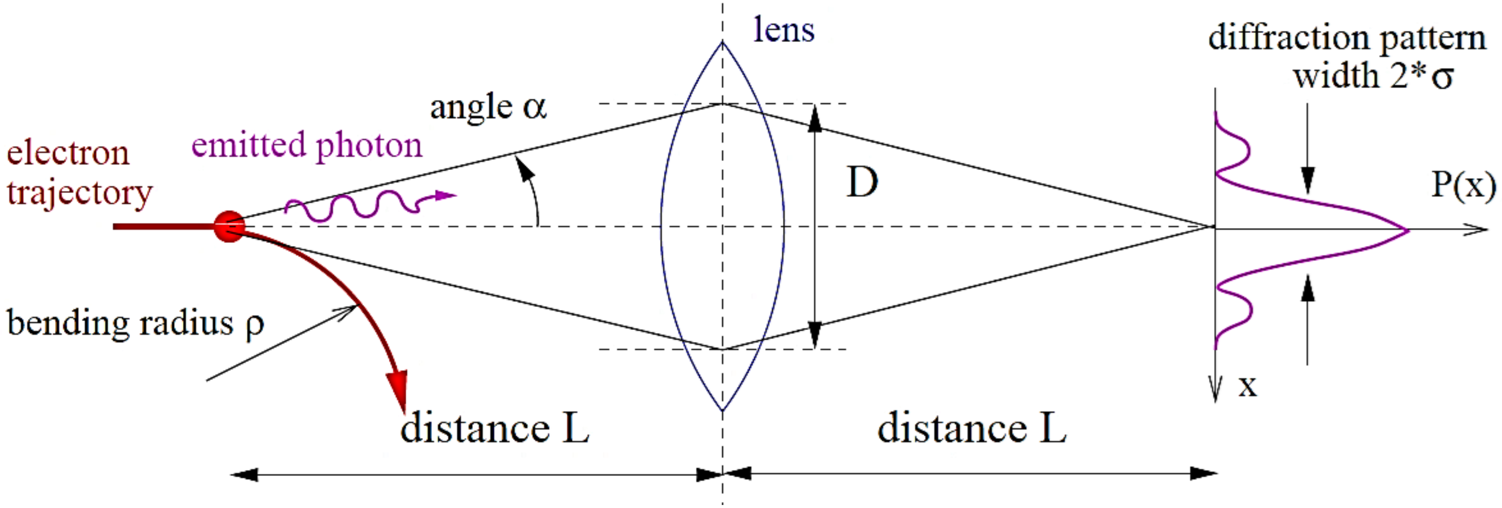
Use of optical wavelength and camera: λ above critical λ_{crit} (spectrum fall-off).

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

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

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

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



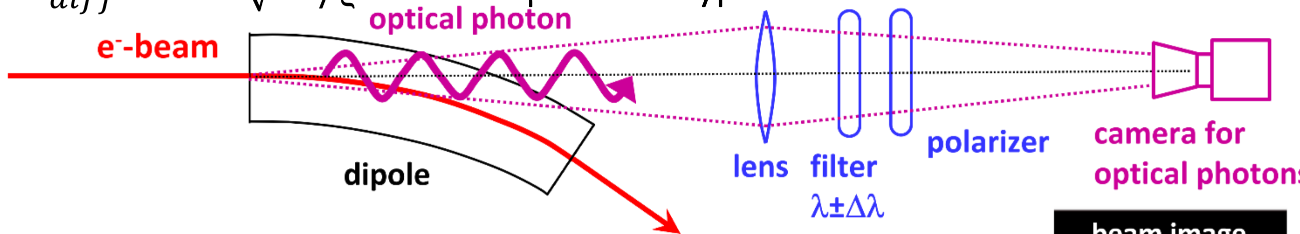
A good resolution for:

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

Synchrotron Light Monitor overcoming Diffraction Limit

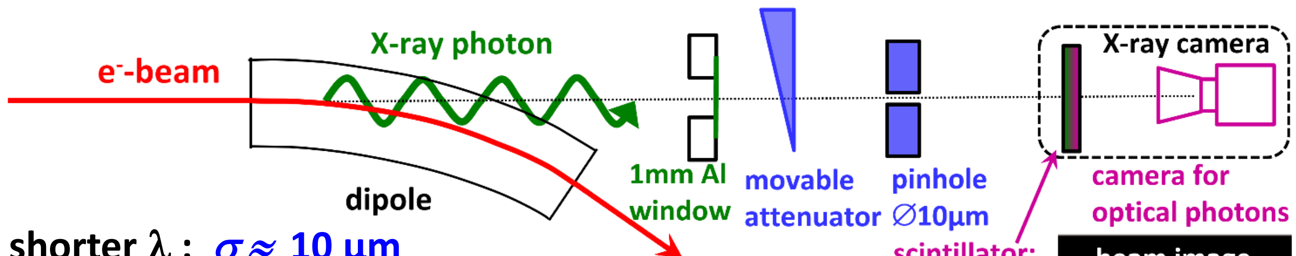
Problem: The diffraction limit is $\sigma_{diff} \approx 0.6\sqrt[3]{\lambda^2/\varrho} \approx 100\ \mu\text{m}$ for a typical case

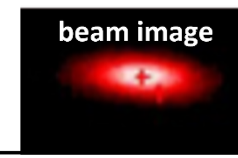
Optical imaging:
Spatial resolution
roughly ≈ 100 μm



Direct optical observation: $\sigma \approx 100\ \mu\text{m}$
→ **relative simple installation, but** resolution insufficient for modern light sources

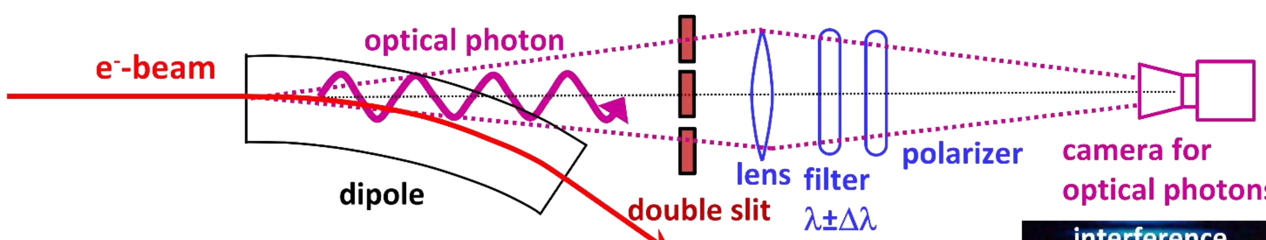
X-ray imaging:
Spatial resolution
roughly ≈ 10 μm

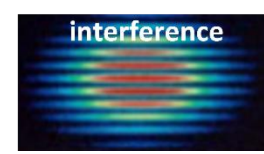




Direct X-ray observation with shorter λ : $\sigma \approx 10\ \mu\text{m}$
→ **medium complex but expensive installation,**
installed at most synchr. light sources referred to as **pinhole camera**

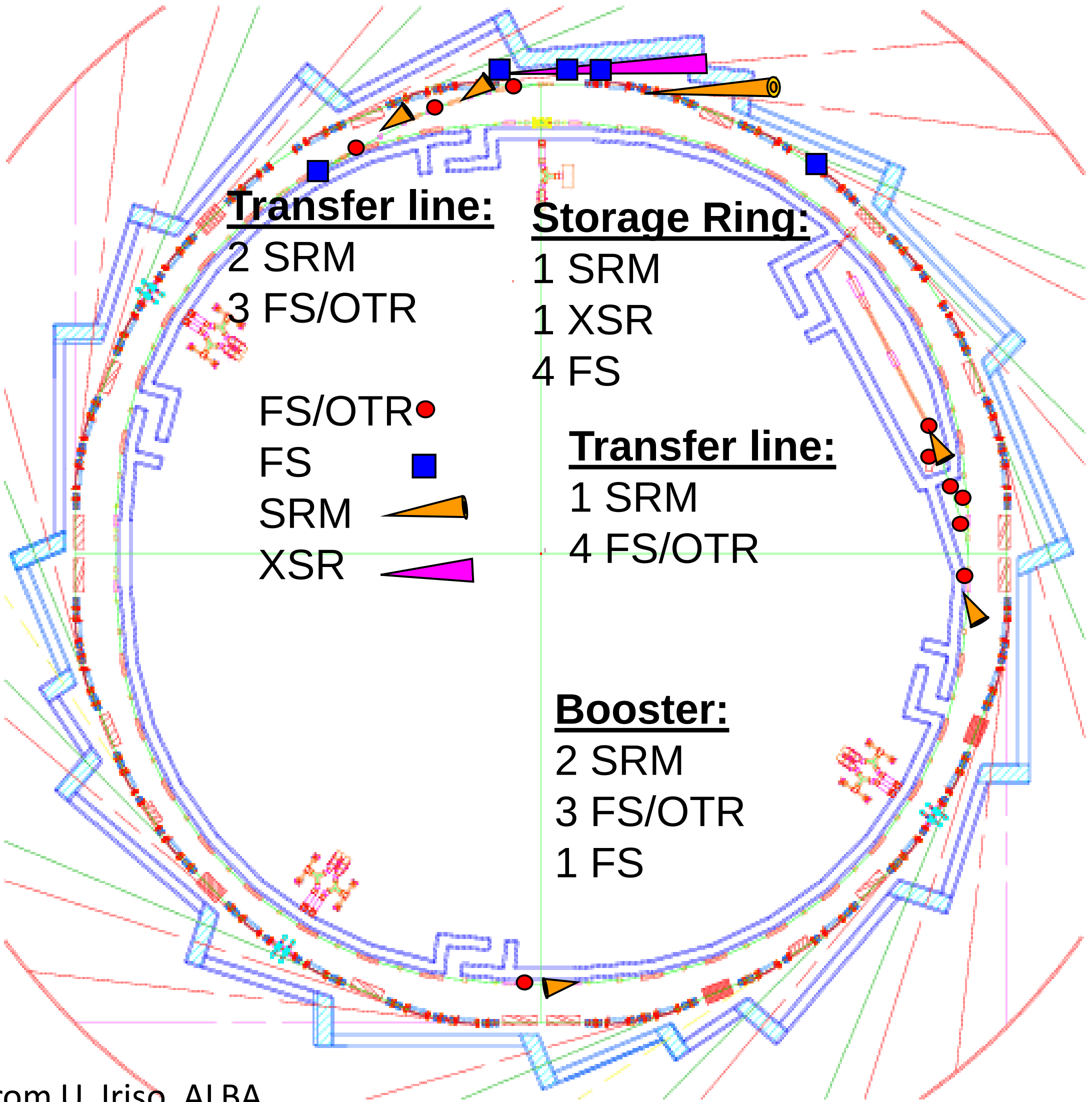
Optical interference:
Spatial resolution
roughly ≈ 1 μm





Interference optical observation: $\sigma \approx 1\ \mu\text{m}$
→ **complex installation,** seldom installed; basis: blurring of interference pattern

Appendix: The Synchrotron Light Facility ALBA: Profile Measurement



From U. Iriso, ALBA

Transverse profile:

- Many location in transport line
- Single location in ring
- Different devices used

Abbreviation:

FS: Fluorescence Screen

OTR: Optical Trans. Rad. Screen

FS & OTR are destructive

SRM: Synchr. Radiation Monitor

XSR: X-ray pin hole camera

both **non**-destructive

Summary for Beam Profile Measurement

Different techniques are suited for different beam parameters:

e⁻-beam: typically Ø 0.01 to 3 mm, **protons:** typically Ø 1 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 setup, all beams
- Ionization profile monitor: non-destructive, expensive, limited resolution, 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.

Outline of the 2nd Lecture on Beam Diagnostics

Outline of this lecture:

- Transverse profile techniques
- Emittance determination at transfer lines
- Diagnostics for bunch shape determination

Measurement of transverse Emittance

The emittance characterizes the whole beam quality, assuming linear behavior as described by second order differential equation.

It is defined within the phase space as: $\varepsilon_x = \frac{1}{\pi} \int_A dx dx'$

The measurement is based on determination of:

Either profile width $\boldsymbol{\sigma_x}$ and angular width $\boldsymbol{\sigma_x'}$ at one location
Or profile width $\boldsymbol{\sigma_x}$ at different locations and linear transformations.

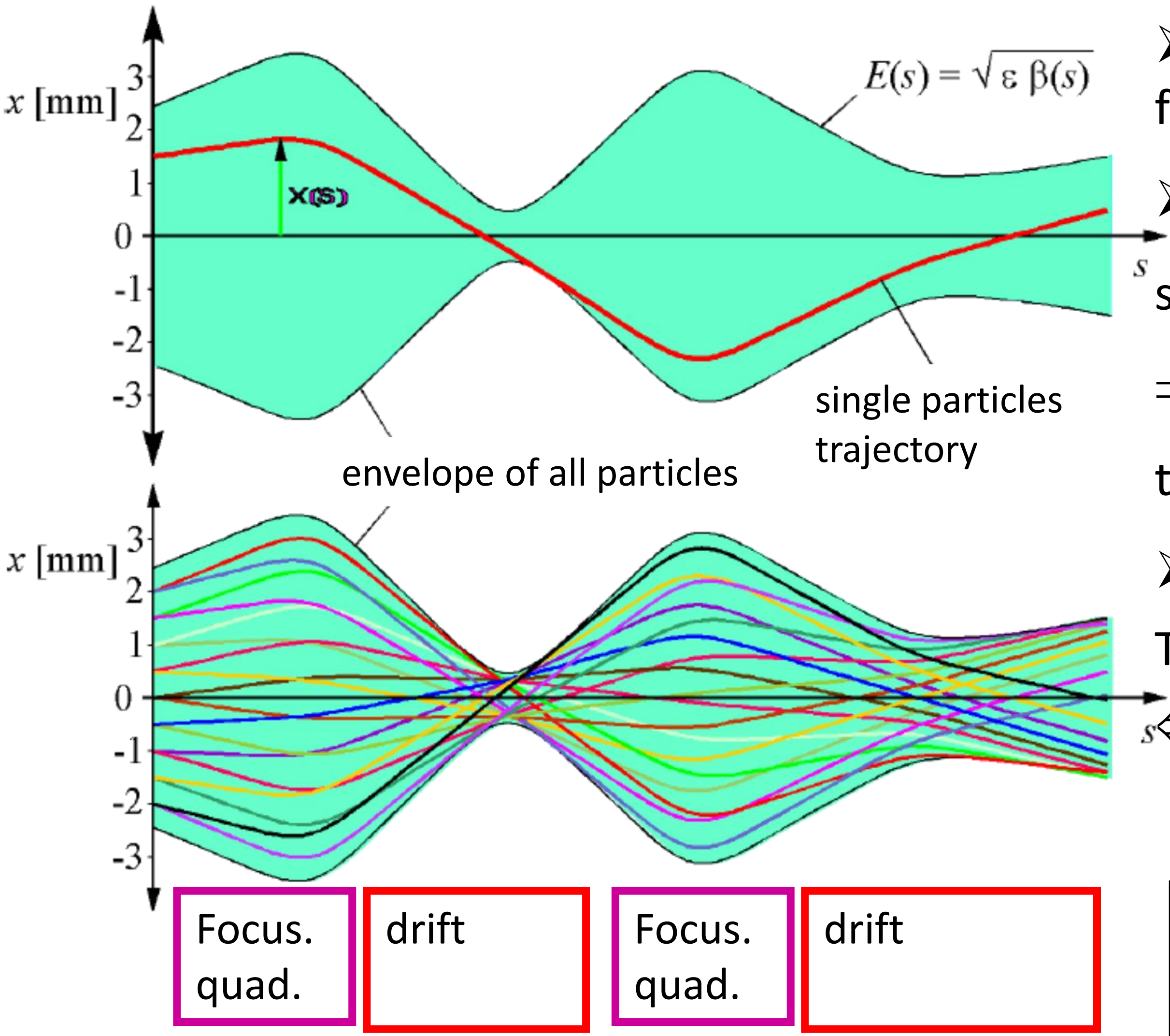
Different devices are used at transfer lines:

- Lower energies E_{kin} < 100 MeV/u: slit-grid device, pepper-pot (suited in case of non-linear forces).
- All beams: Quadrupole variation method using linear transformations (**not** well suited in the presence of non-linear forces)

Synchrotron: lattice functions results in stability criterion

$\Rightarrow$ beam width delivers emittance: $\varepsilon_x = \frac{1}{\beta_x(s)}\left[\sigma_x^2 - \left(D(s)\frac{\Delta p}{p}\right)\right]$ and $\varepsilon_y = \frac{\sigma_y^2}{\beta_y(s)}$

Trajectory and Characterization of many Particles



Courtesy K.Wille

- Single particle trajectories are forming a beam
- They have a distribution of start positions and angles

⇒ Characteristic quantity is the **beam envelope**

- **Goal:**

Transformation of envelope ⇔ behavior of whole ensemble

see lecture
'Transverse linear Beam Dynamics'
by Wolfgang Hillert

Definition of Coordinates and basic Equations

The basic vector is 6 dimensional:

$$\vec{x} = \begin{pmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{pmatrix} = \begin{pmatrix} \text{hori. spatial deviation} \\ \text{horizontal divergence} \\ \text{vert. spatial deviation} \\ \text{vertical divergence} \\ \text{long. deviation} \\ \text{momentum deviation} \end{pmatrix} = \begin{pmatrix} [\text{mm}] \\ [\text{mrad}] \\ [\text{mm}] \\ [\text{mrad}] \\ [\text{mm}] \\ [10^{-3}] \end{pmatrix}$$

The transformation of a single particle from a location s_0 to s_1 is given by the Transfer Matrix R: $\vec{x}(s_1) = \mathrm{R}(s) \cdot \vec{x}(s_0)$

The transformation of a the envelope from a location s_0 to s_1 is given by the Beam Matrix σ : $\sigma(s_1) = \mathrm{R}(s) \cdot \sigma(s_0) \cdot \mathrm{R}^{\mathrm{T}}(s)$

6-dim Beam Matrix with *decoupled* hor., vert. and long. plane:

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} & 0 & 0 & 0 & 0 \\ \sigma_{12} & \sigma_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_{33} & \sigma_{34} & 0 & 0 \\ 0 & 0 & \sigma_{34} & \sigma_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_{55} & \sigma_{56} \\ 0 & 0 & 0 & 0 & \sigma_{56} & \sigma_{66} \end{pmatrix}$$

horizontal
vertical
longitudinal
hor.-long. coupling
→ 9 values

Beam width for the three coordinates:

$x_{rms} = \sqrt{\sigma_{11}}$

$y_{rms} = \sqrt{\sigma_{33}}$

$l_{rms} = \sqrt{\sigma_{55}}$

Horizontal beam matrix:

$\sigma_{11} = \langle x^2 \rangle$

$\sigma_{12} = \langle x\, x' \rangle$

$\sigma_{22} = \langle x'^2 \rangle$

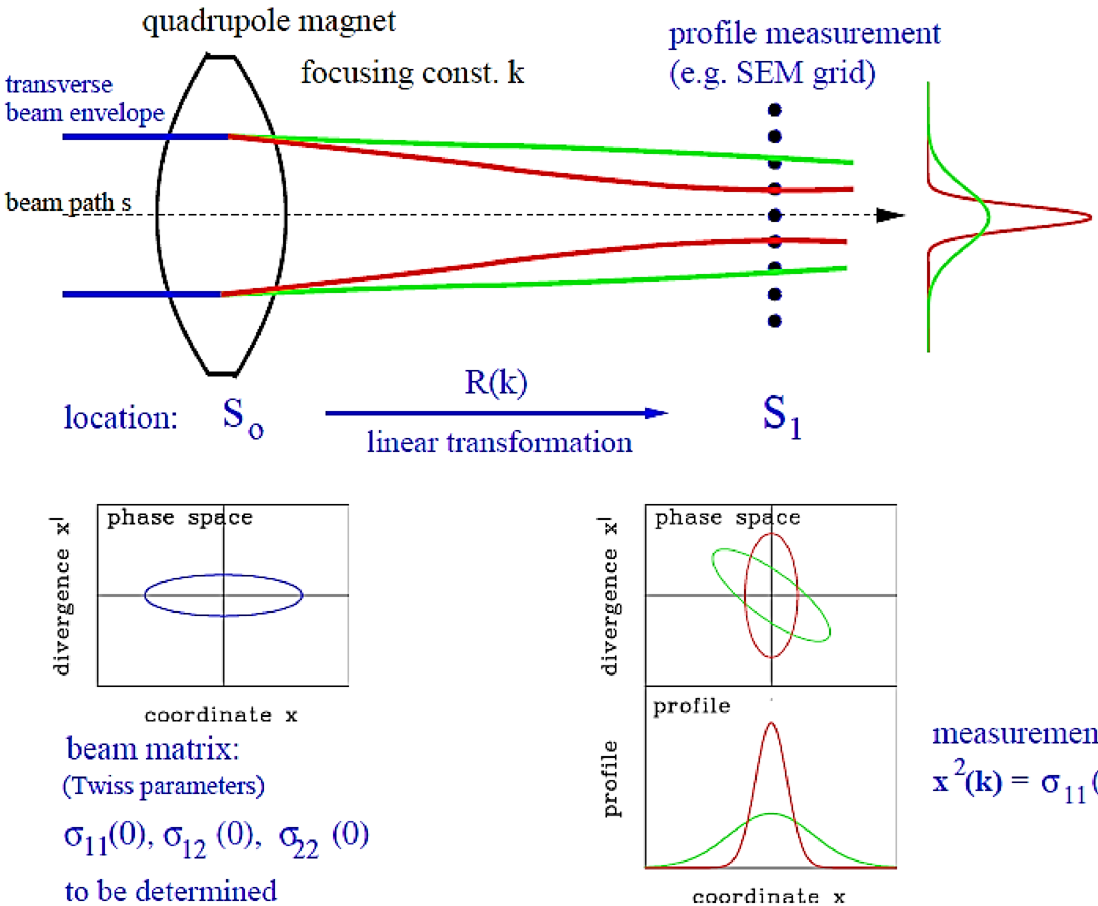
Outline:

- Definition and some properties of transverse emittance
- Quadrupole strength variation and position measurement

  emittance from several profile measurement and beam optical calculation
- Slit-Grid device: scanning method

Emittance Measurement by Quadrupole Variation

From a profile determination, the emittance can be calculated via linear transformation, if a well known and constant distribution (e.g. Gaussian) is assumed.



beam matrix:
(Twiss parameters)
$\sigma_{11}(0)$, $\sigma_{12}(0)$, $\sigma_{22}(0)$
to be determined

measurement:
$x^2(k) = \sigma_{11}(1,k)$

- Measurement of beam width

$$x^2_{max} = \sigma_{11}(s_1, k)$$

matrix **R(*k*)** describes the focusing.

- With the drift matrix the transfer is

$$\mathbf{R}(k_i) = \mathbf{R}_{drift} \cdot \mathbf{R}_{focus}(k_i)$$

- Transformation of the beam matrix

$$\sigma(s_1,k_i) = \mathbf{R}(k_i) \cdot \sigma(s_0) \cdot \mathbf{R}^T(k_i)$$

Task: Calculation of matrix $\sigma(s_0)$ at entrance s_0, i.e. three elements

see lecture 'Linear Imperfections' by Volker Ziemann

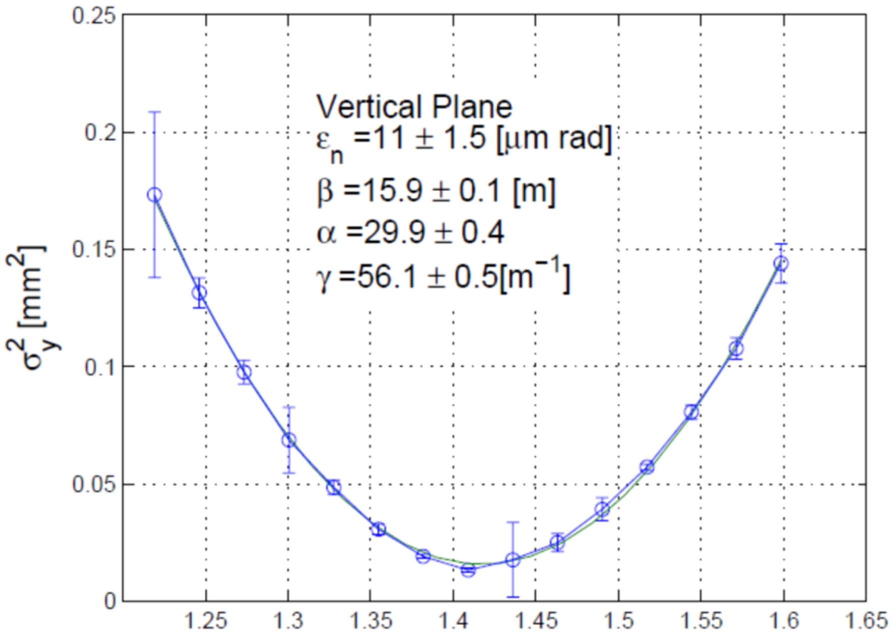
Measurement of transverse Emittance

Using the 'thin lens approximation' i.e. the quadrupole has a focal length of ***f***:

$$\mathrm{R}_{focus}(K) = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \equiv \begin{pmatrix} 1 & 0 \\ K & 1 \end{pmatrix} \Rightarrow \mathrm{R}(L,K) = \mathrm{R}_{drift}(L) \cdot \mathrm{R}_{focus}(K) = \begin{pmatrix} 1+LK & L \\ K & 1 \end{pmatrix}$$

Measurement of matrix-element $\sigma_{11}(s_1, K)$ from matrices $\sigma(s_1,K_i) = \mathbf{R}(K_i) \cdot \sigma(s_0) \cdot \mathbf{R}^T(K_i)$

Example: Square of the beam width at ELETTRA 100 MeV e$^-$ Linac, YAG:Ce:



Focusing strength K [m^{-1}]

G. Penco (ELETTRA) et al., EPAC'08

For completeness: The relevant formulas

$$\begin{aligned}\sigma_{11}(1,K) = {} & L^2\sigma_{11}(0)\cdot K^2 \\ & + 2\cdot(\ L\sigma_{11}(0) + L^2\sigma_{12}(0)\ )\cdot K \\ & + L^2\sigma_{22}(0) + \sigma_{11}(0) \\ \equiv {} & a\cdot K^2 - 2ab\cdot K + ab^2 + c \\ = {} & a\cdot(K-b)^2 + c\end{aligned}$$

A fit delivers the beam matrix elements $\sigma_{ij}(s_0)$

Assumptions:

- 'Regular' phase space distribution
- Well aligned beam, no steering
- No emittance blow-up due to space charge

Improved methods:

Based on e.g. tomographic reconstruction

Outline:

- Definition and some properties of transverse emittance
- Quadrupole strength variation and position measurement
  emittance from several profile measurement and beam optical calculation
- **Slit-Grid device: scanning method**
  scanning slit $\rightarrow$ beam position & grid $\rightarrow$ angular distribution

The Emittance for Gaussian and non-Gaussian Beams

The beam distribution can be non-Gaussian, e.g. at:

- Beams behind ion source
- Space charged dominated beams at LINAC & synchrotron
- Cooled beams in storage rings

Generally: Emittance by 2nd statistical moments of 2-dim distribution:

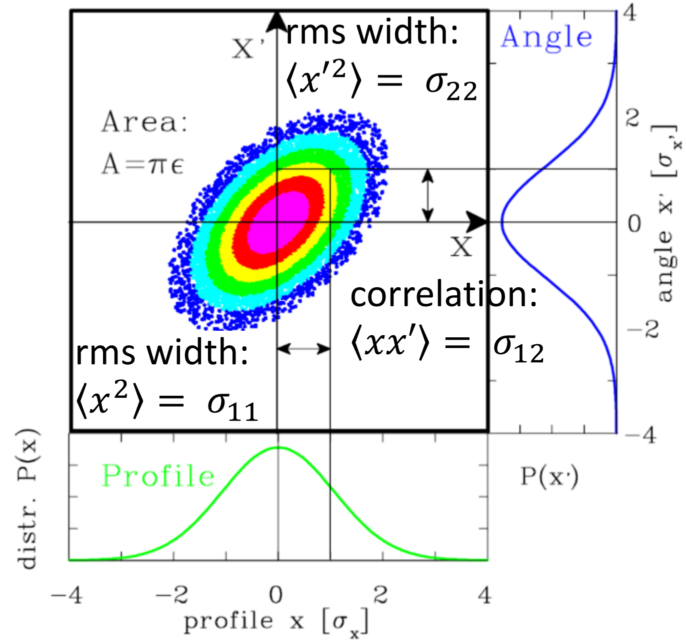
Beam matrix: $\boldsymbol{\sigma} = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{pmatrix}$

Emittance: $\varepsilon_{rms} = \sqrt{\det \boldsymbol{\sigma}}$

$$\varepsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

Variances (for $\langle x^2 \rangle \langle x'^2 \rangle$)

Covariance i.e. correlation (for $\langle xx' \rangle^2$)



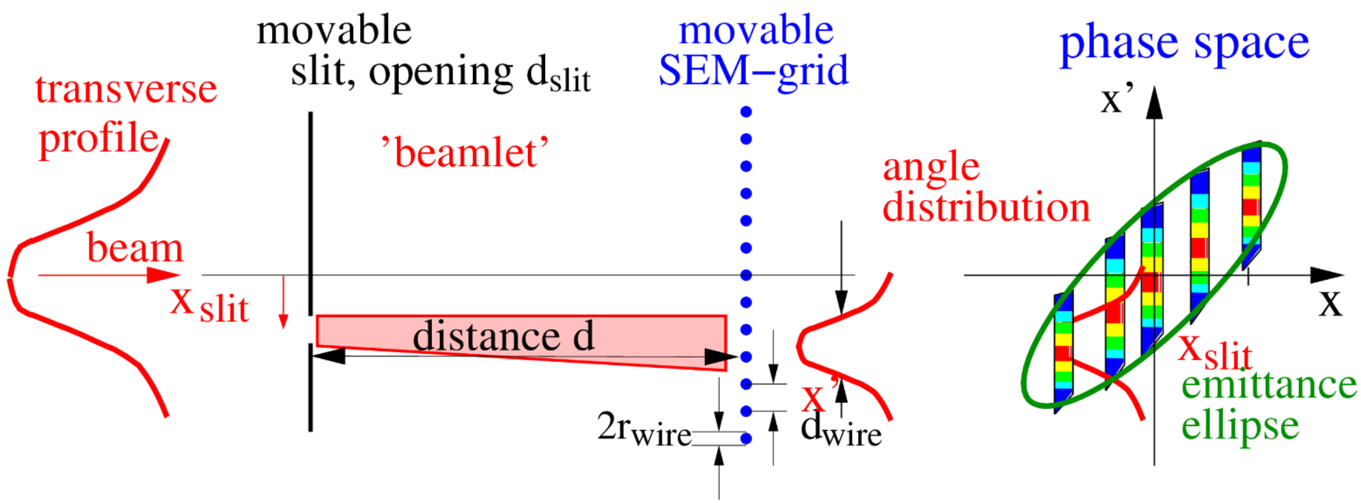
It describes the value for 1 standard derivation.

The Slit-Grid Measurement Device

Slit-Grid: Direct determination of position and angle distribution.

Used for protons with E_{kin} < 100 MeV/u ⇒ range R < 1 cm.

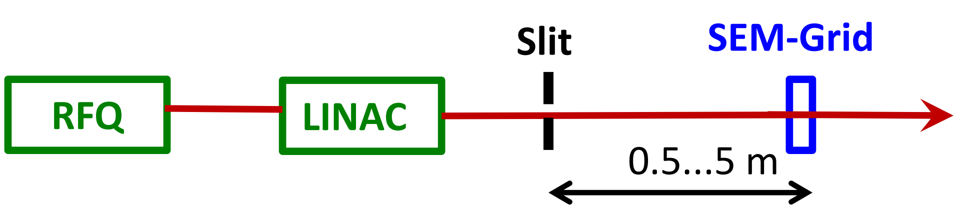
Hardware **Analysis**



Slit: position ***P(x)*** with typical width: 0.1 to 0.5 mm

Distance: typ. 0.5 to 5 m (depending on beam energy 0.1 ... 100 MeV)

SEM-Grid: angle distribution ***P(x')***



Display of Measurement Results

The distribution is depicted as a function of position [mm] & angle [mrad]

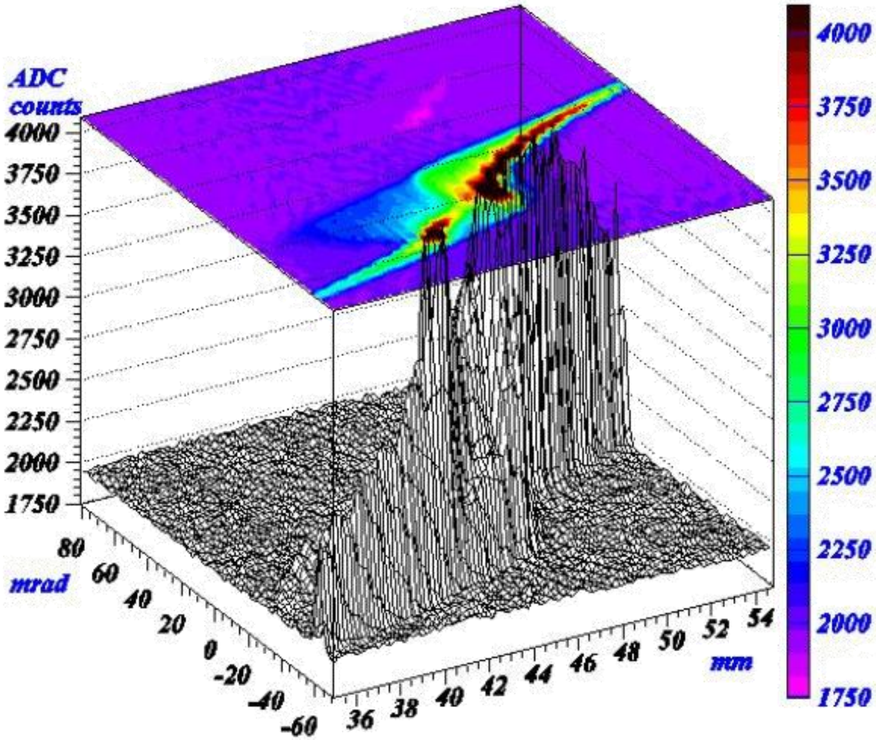
The distribution can be visualized by

- Mountain plot
- Contour plot

Calc. of 2nd moments $\langle x^2 \rangle$, $\langle x'^2 \rangle$ & $\langle xx' \rangle$

Emittance value ε_{rms} from

$$\varepsilon_{rms} = \sqrt{\langle x^2 \rangle \cdot \langle x'^2 \rangle - \langle xx' \rangle^2}$$



Beam: Ar^{4+}, 60 keV, 15 µA

at Spiral2 Phoenix ECR source.

P. Ausset, DIPAC 2009

Problems:

- Finite **binning** results in limited resolution
- **Background** → large influence on $\langle x^2 \rangle$, $\langle x'^2 \rangle$ & $\langle xx' \rangle$
- **Or fit of distribution with an ellipse**

⇒ **Effective emittance only**

Remark: Behind a ion source the beam might be non-Gaussian due to plasma density and aberration at quadrupoles

See lecture 'Sources' by dan Faircloth

Summary for transverse Emittance Measurement

Emittance is the important quantity for comparison to theory.

It includes absolute value (value of $\boldsymbol{\varepsilon}$) & orientation in phase space ($\boldsymbol{\sigma_{ij}}$ or $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$)

three independent values $\varepsilon_{rms} = \sqrt{\sigma_{11} \cdot \sigma_{22} - \sigma_{12}} \equiv \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$

assuming **no** coupling between horizontal, vertical and longitudinal planes

Transfer line, all beams → profile measurement + linear transformation:

- ***Quadrupole variation:*** one location, different setting of a quadrupole

  Assumptions:
  - well aligned beam, no steering
  - no emittance blow-up due to space charge

Transfer line, low energy beams → direct measurement of x- and x'-distribution:

- ***Slit-grid:*** movable slit → ***x***-profile, grid → ***x'***-profile
- Requirement: Beam is stopped in ≈ 1cm ⇔ protons $E_{kin} \lesssim 100$ MeV

Remark: Non-linear transformation possible via tomographic reconstruction

Important remark: For a synchrotron with a *stable beam storage*,

width measurement is sufficient using $x_{rms} = \sqrt{\varepsilon_{rms} \cdot \beta}$

Outline of the 2nd Lecture on Beam Diagnostics

Outline of this lecture:

- Transverse profile techniques
- Emittance determination at transfer lines
- Diagnostics for bunch shape determination and longitudinal parameters

Measurement of longitudinal parameter:

Bunch length measurement at

- **Synchrotron light sources: Streak camera**
- **Linear light sources: Electro-optical modulator**
- **Summary**

Longitudinal ↔ transverse correspondences:

- position relative to rf ↔ transverse center-of-mass
- bunch structure in time ↔ transverse profile
- momentum or energy spread ↔ transverse divergence
- longitudinal emittance ↔ transverse emittance.

The Bunch Position measured by a Pick-Up

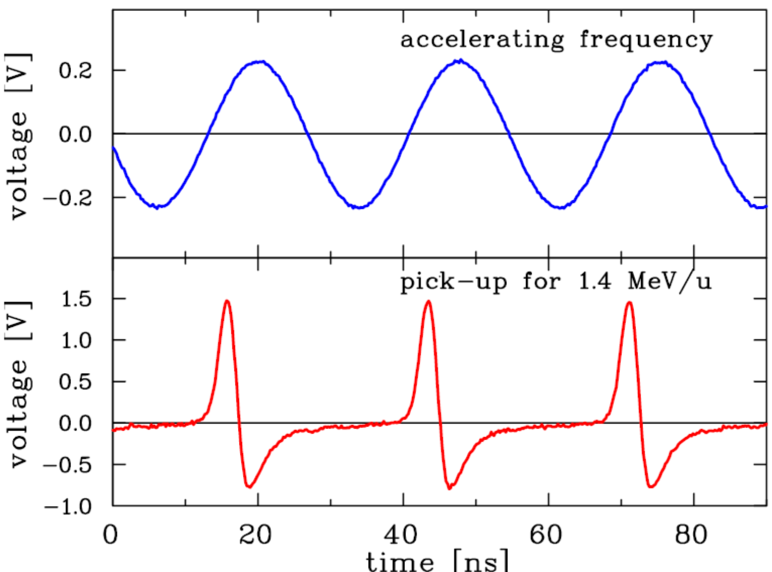
The ***bunch position*** is given relative to the accelerating rf.

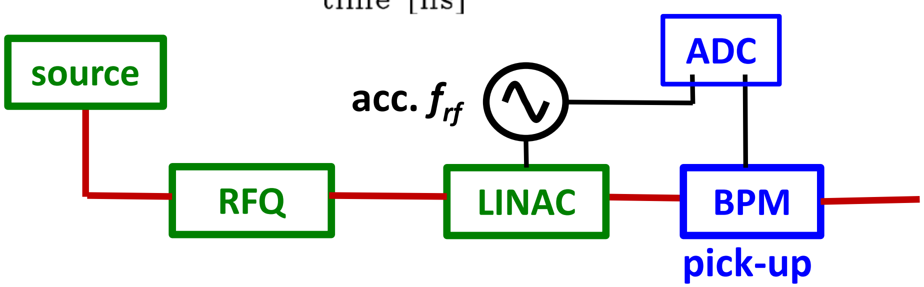
e.g. $\boldsymbol{\varphi_{ref}}$=-30° inside a rf cavity

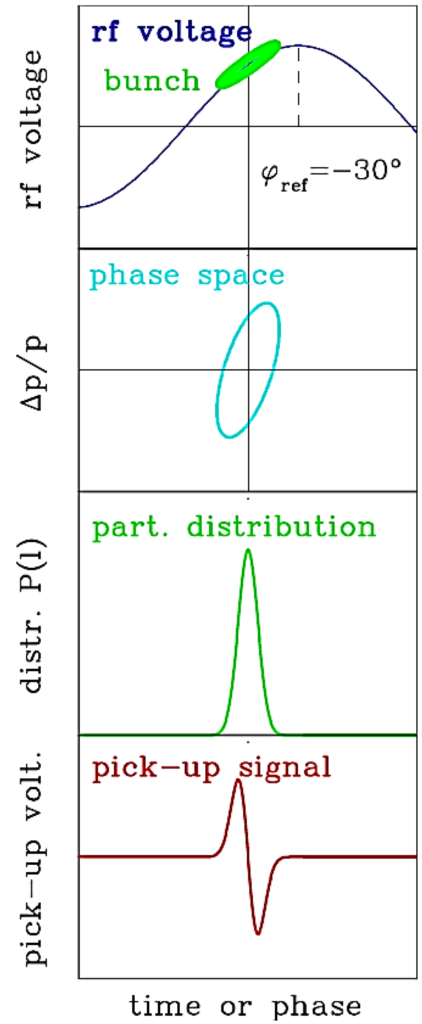
must be well aligned for optimal acceleration

Transverse correspondence: Beam position

Example: Pick-up signal for $\boldsymbol{f_{rf}}$=36 MHz rf at GSI-LINAC:





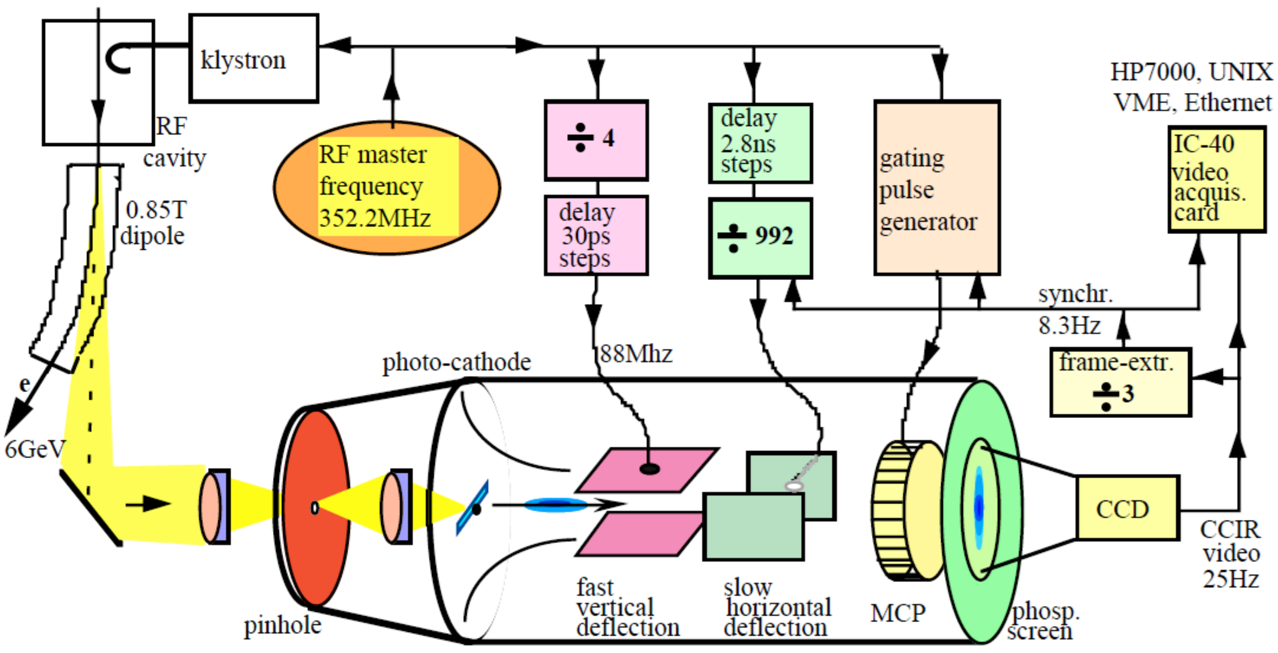


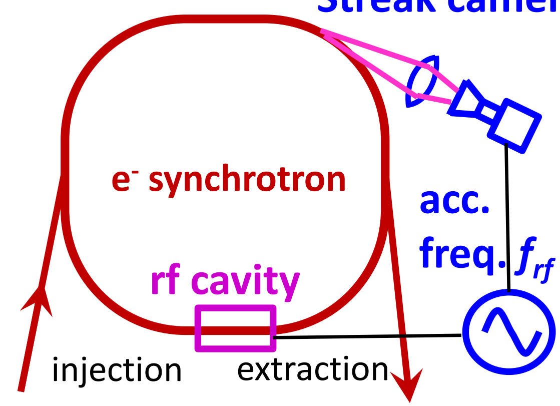
Bunch Length Measurement for relativistic Electrons

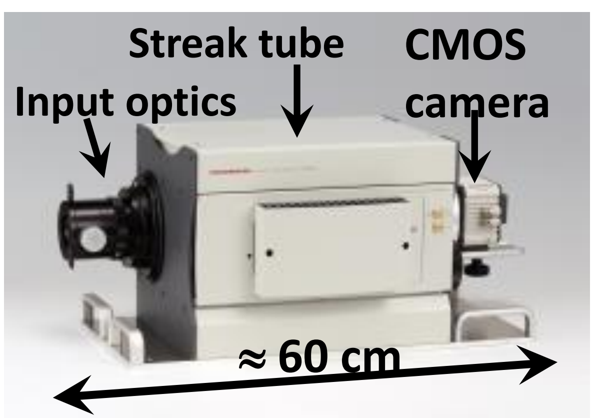
Electron bunches are too short (σ_t < 100 ps) to be covered by the bandwidth of pick-ups (f < 3 GHz ⇔ t_{rise} > 100 ps) for structure determination.

→ Time resolved observation of synchr. light with a streak camera: Resolution ≈ 1 ps.

Scheme of a streak camera







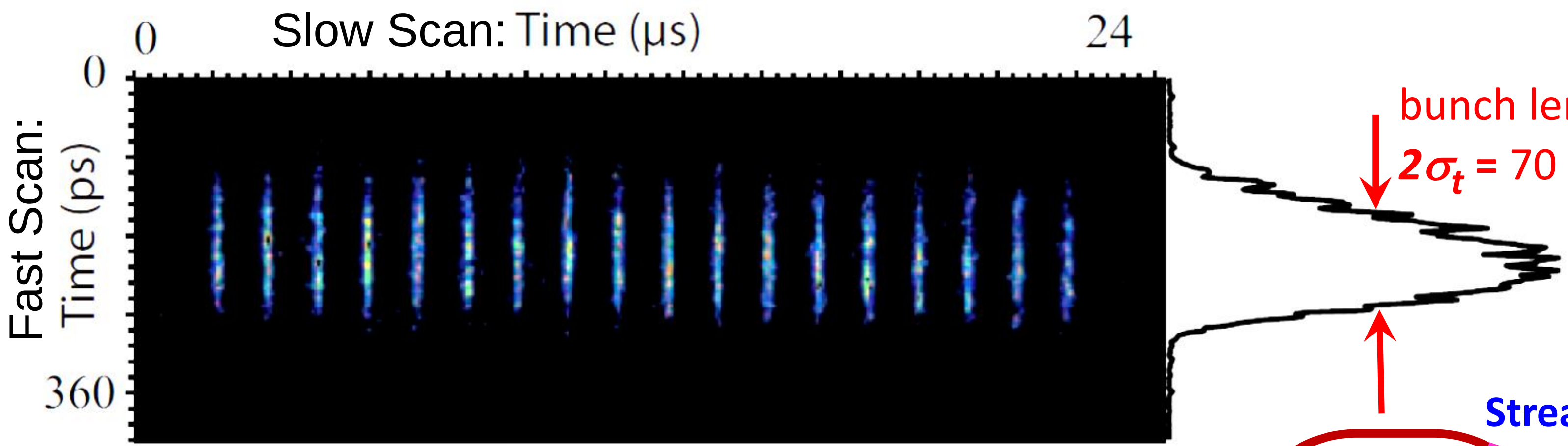
Results of Bunch Length Measurement by a Streak Camera

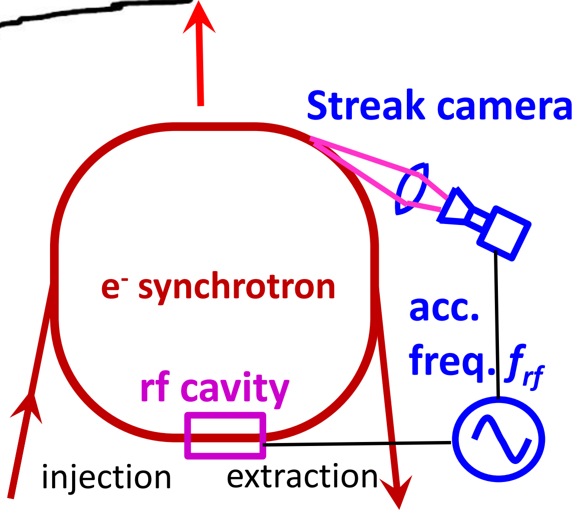
The streak camera delivers a fast scan in vertical direction (here 360 ps full scale)

and a slower scan in horizontal direction (24 μs).

Example: Bunch length at the synchrotron light source SOLEIL for U_{rf} = 2 MV

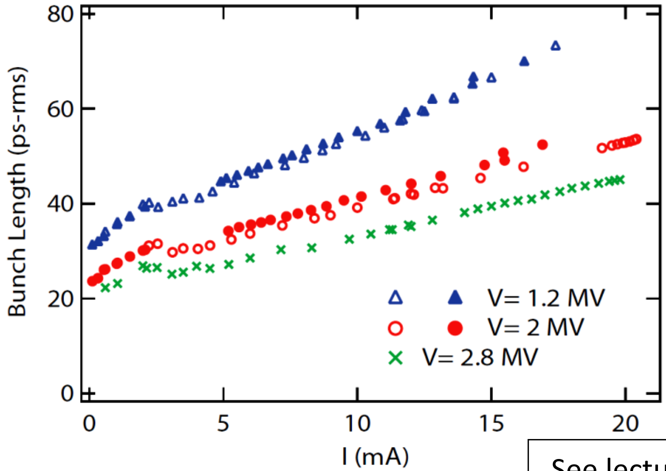
for slow direction 24 μs and scaling for fast scan 360 ps: measure σ_t = 35 ps.





Short bunches are desired by the users

Example: Bunch length σ_t as a function of stored current (i.e. space charge de-focusing) at SOLEIL



Courtesy of M. Labat et al., DIPAC'07

See lecture 'Electron Beam Dynamics' by Lenny Rivkin

Measurement of longitudinal parameter:

Bunch length measurement at

- Synchrotron light sources: Streak camera
- **Linear light sources: Electro-optical modulators**
- **Summary**

Bunch Length Measurement by electro-optical Method

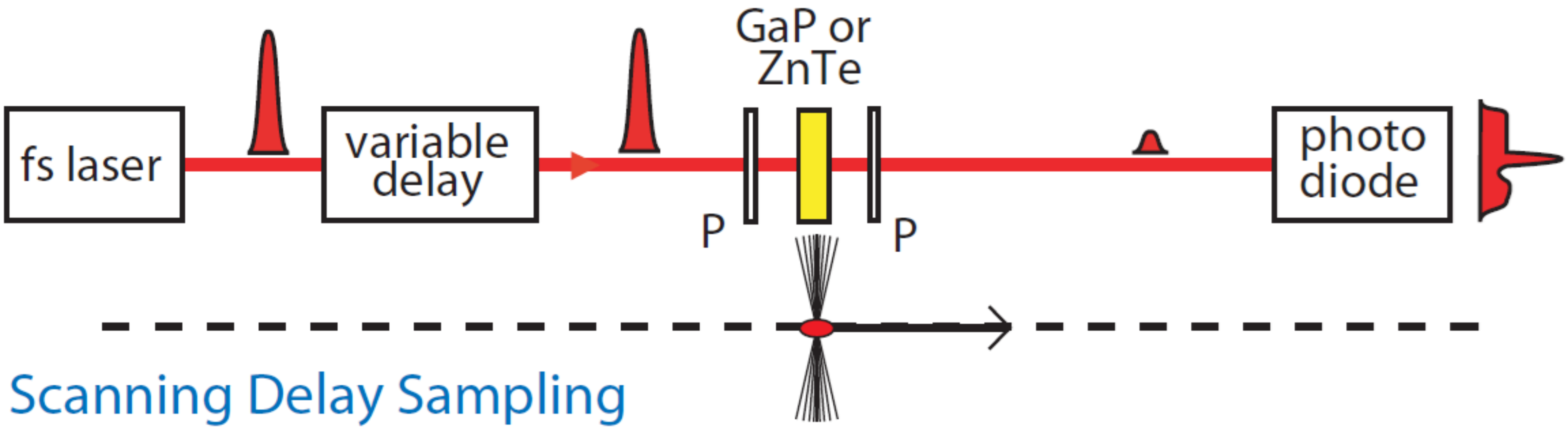
For Free Electron Lasers → bunch length below 1 ps is achieved

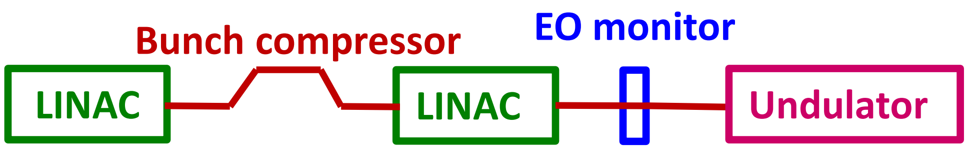
- Below the resolution of streak camera
- Short laser pulses with ***t*** **≈ 10 fs** and electro-optical modulator

Electro optical modulator: Birefringent, rotation angle depends on external electric field

Relativistic electron bunch: transverse ele. field $E_{\perp,lab} = \gamma E_{\perp,rest}$ carries the time information

Scanning of delay between bunch and laser → time profile after several pulses.





Courtesy S.P.Jamison et al., EPAC 2006

See lecture 'Synchrotron light circular machines & FELs' by Eduard Prat

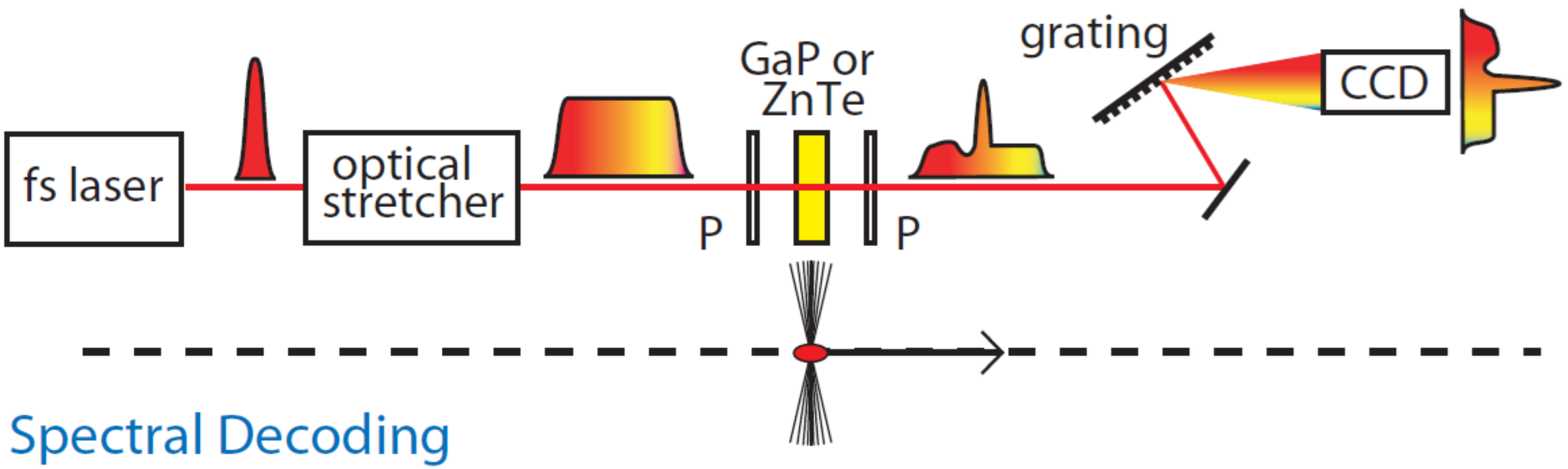
Bunch Length Measurement by electro-optical Method

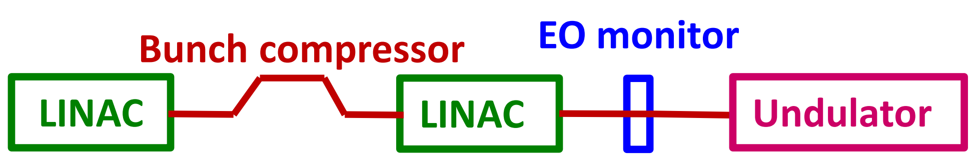
For Free Electron Lasers → bunch length below 1 ps is achieved

Short laser pulse ⇔ broad frequency spectrum (property of Fourier Transformation)

Optical stretcher: Separation of colors by different path length

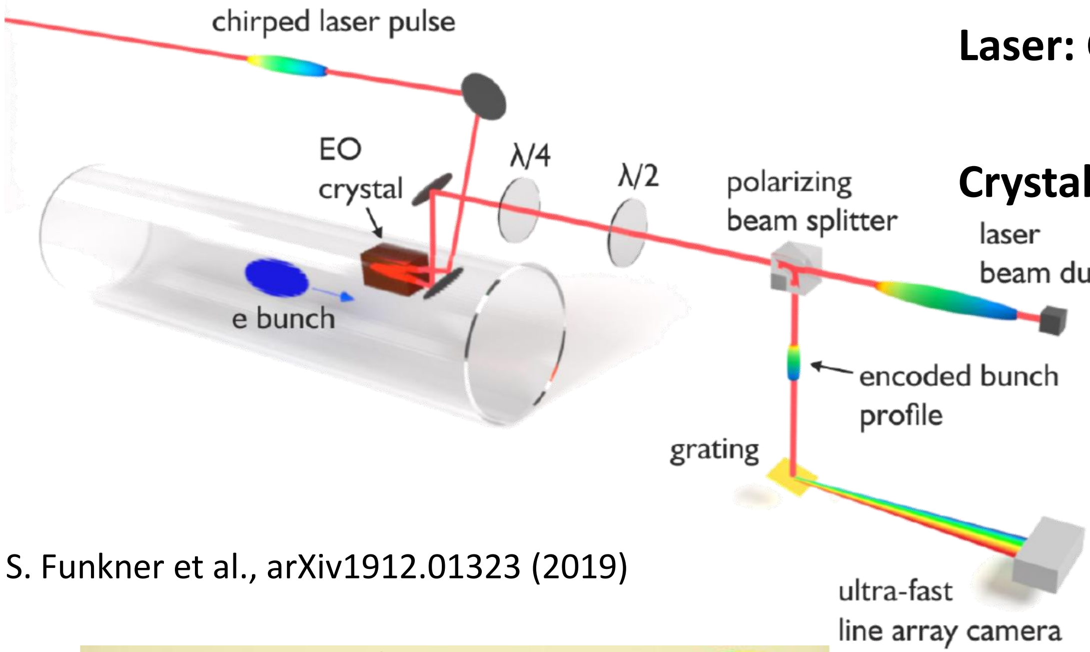
⇒ different colors at different time ⇒ **single-shot observation**





Courtesy S.P.Jamison et al., EPAC 2006

Hardware of a spectral-decoded EOSD Scanning Setup

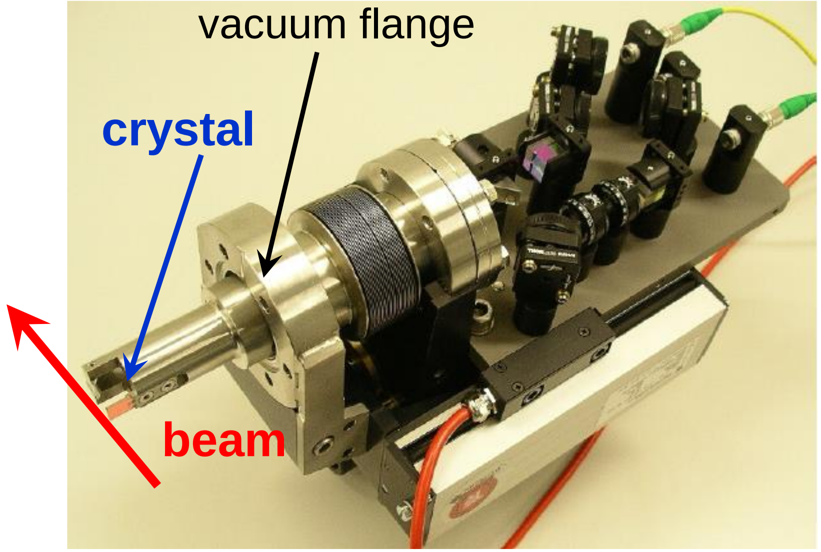


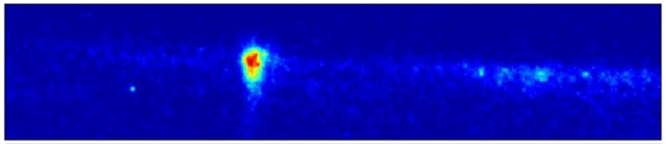
S. Funkner et al., arXiv1912.01323 (2019)

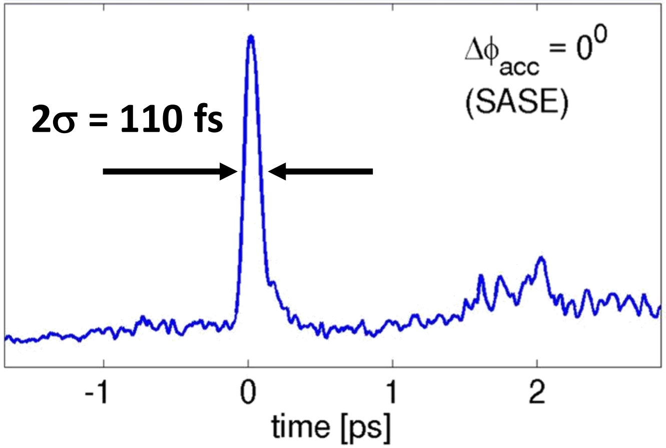
Laser: Commercial Ti:Sa or Yb-fibre,
10 fs duration, near IR,

Crystal: GaP or ZnTe, 100 µm thickness

Example: Bunch length at FLASH
100 fs bunch duration = 30 µm length!







B. Steffen et al, DIPAC 2009

B. Steffen et al., Phys. Rev. AB 12, 032802 (2009)

Summary of longitudinal Measurements

Devices for bunch length at light sources:

Streak cameras:

- Time resolved monitoring of synchrotron radiation

  → for relativistic e^--beams, 10 ps < t_{bunch} < 1 ns

  Time resolution limit of streak camera ≈ 1 ps

Laser-based electro-optical modulation:

- Electro-optical modulation of short laser pulse

  → very high time resolution down to some fs time resolution

  Technical complex installation

Conclusion for Beam Diagnostics Course

Diagnostics is the 'sensory organ' for the beam.

It required for operation and development of accelerators

Several categories of demands leads to different installations:

- Quick, non-destructive measurements leading to a single number or simple plots
- Complex instrumentation used for hard malfunction and accelerator development
- Automated measurement and control of beam parameters i.e. feedback

The goal and a clear interpretation of the results is a important design criterion.

General comments:

- Quite different technologies are used, based on various physics processes
- Accelerator development goes parallel to diagnostics development

($\Rightarrow$ it makes fun as many skills are required).

Thank you for your attention!

General Reading on Beam Instrumentation

- H. Schmickler (Ed.) *Beam Instrumentation*, Proc. CERN Accelerator School, Tuusula 2018.
- D. Brandt (Ed.), *Beam Diagnostics for Accelerators*, Proc. CERN Accelerator School, Dourdan, CERN-2009-005, 2009.
- Proceedings of several CERN Acc. Schools (introduction & advanced level, special topics).
- V. Smaluk, *Particle Beam Diagnostics for Accelerators: Instruments and Methods*, VDM Verlag Dr. Müller, Saarbrücken 2009.
- P. Strehl, *Beam Instrumentation and Diagnostics*, Springer-Verlag, Berlin 2006.
- M.G. Minty and F. Zimmermann, *Measurement and Control of Charged Particle Beams*, Springer-Verlag, Berlin 2003.
- S-I. Kurokawa, S.Y. Lee, E. Perevedentev, S. Turner (Eds.), *Proceeding of the School on Beam Measurement*, Proceedings Montreux, World Scientific Singapore (1999).
- P. Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS School, JUAS Indico web-site.
- Contributions to conferences, in particular to **I**nternational **B**eam **I**nstrumentation **C**onference **IBIC**.

Backup slides

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

Influence of the residual gas ion trajectory by :

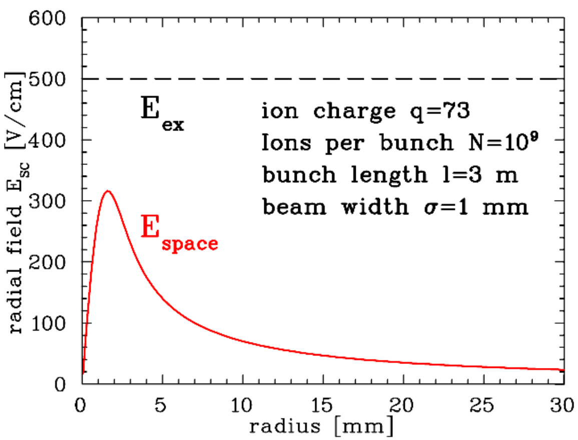
- External electric field $\boldsymbol{E_{ex}}$
- Electric field of the beam's space charge $\boldsymbol{E_{space}}$

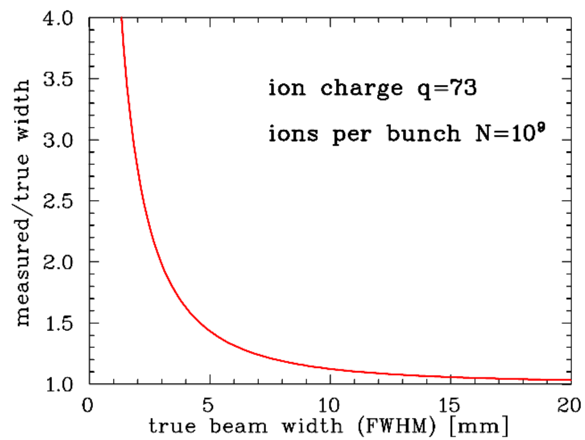
e.g. Gaussian density distribution for round beam: $E_{space}(r) = \frac{1}{2\pi\varepsilon_0} \cdot \frac{qeN}{l} \cdot \frac{1}{r} \cdot \left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right]$

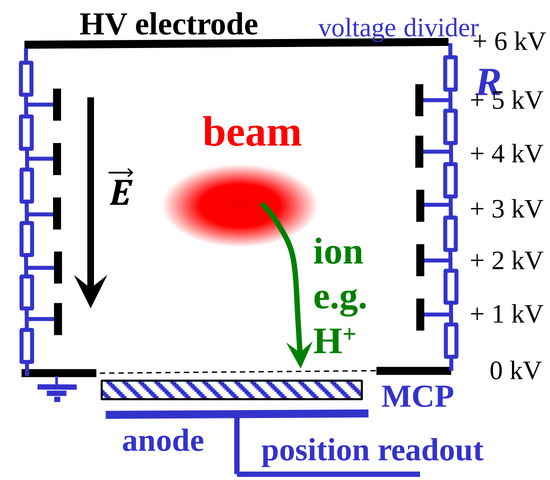
Estimation of correction: $\sigma_{corr}^2 \approx \frac{e^2 \ln 2}{4\pi\varepsilon_0 \sqrt{m_p c^2}} \cdot \frac{qN}{l} \cdot d_{gap} \cdot \sqrt{\frac{1}{eU_{ex}}} \propto N \cdot d_{gap} \cdot \sqrt{\frac{1}{U_{ex}}}$

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.

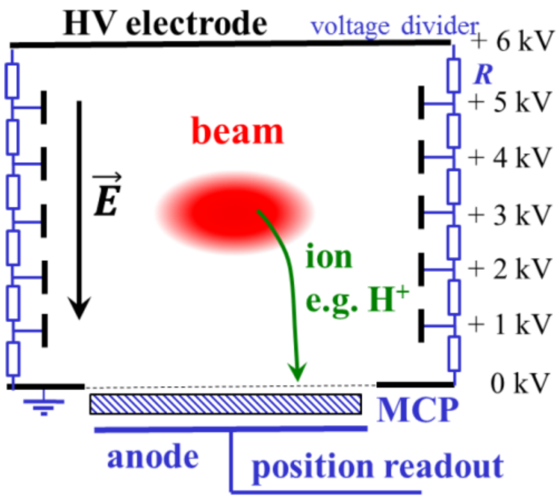




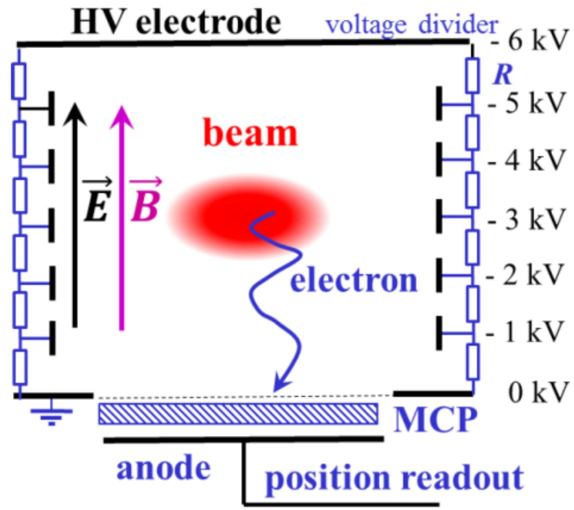


Electron Detection and Guidance by Magnetic Field

Ion detection mode:

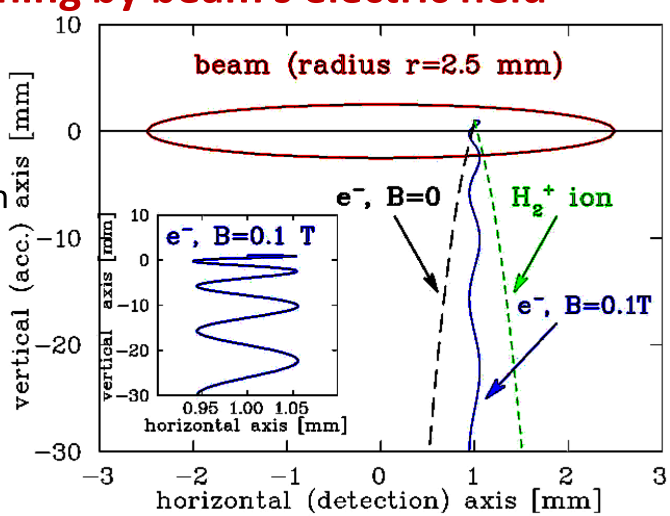


Electron detection mode:



⇒ **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

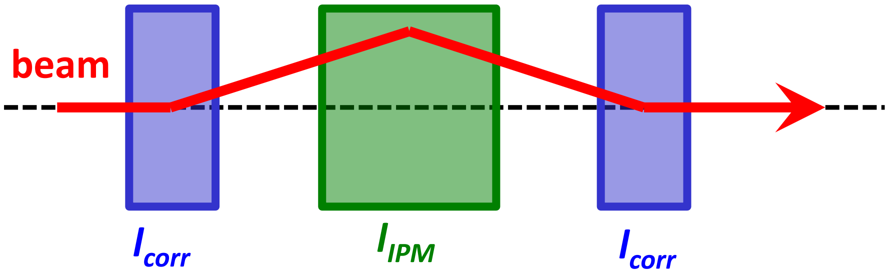
Magnetic field for electron guidance:

Maximum image distortion:

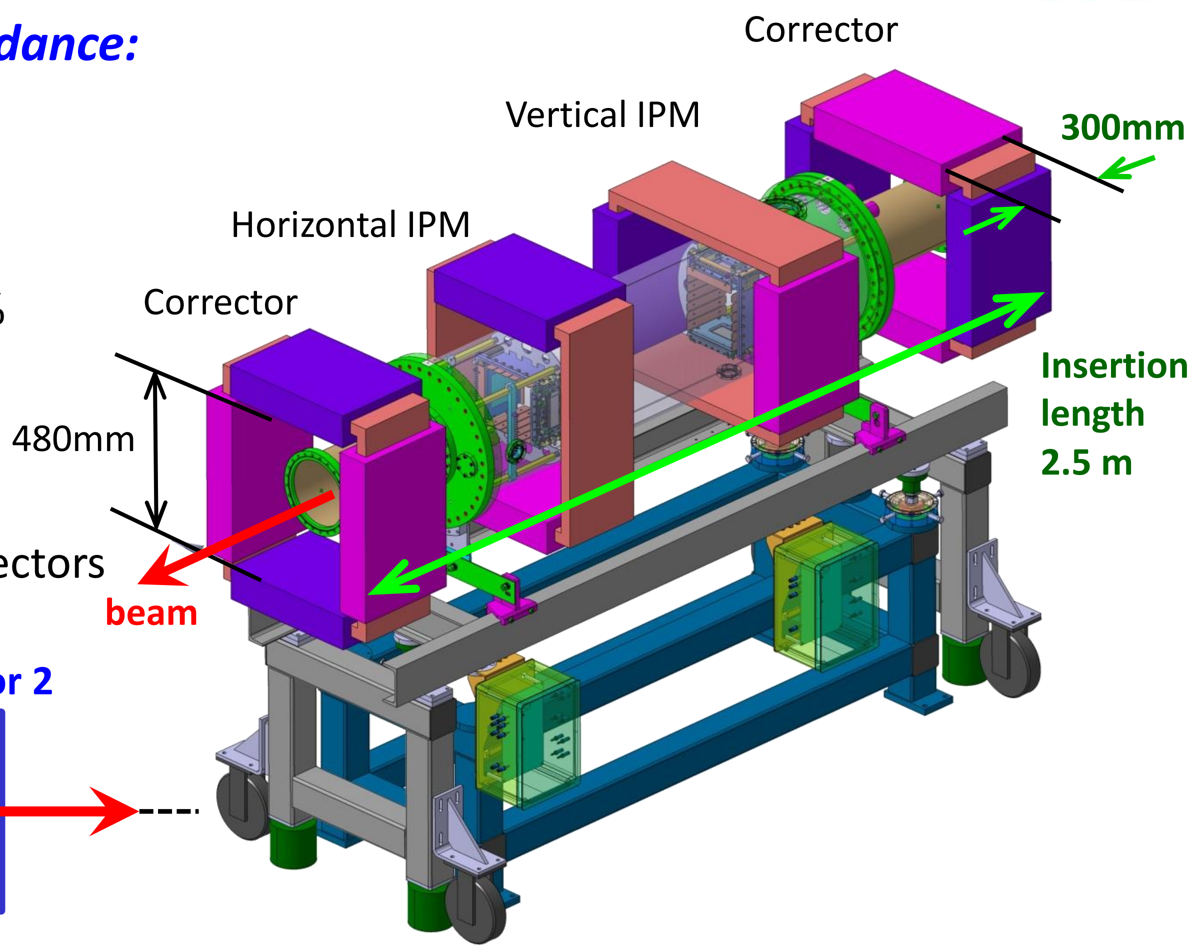
5% of beam width ⇒ $\Delta B/B < 1\,\%$

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 %

Challenges:

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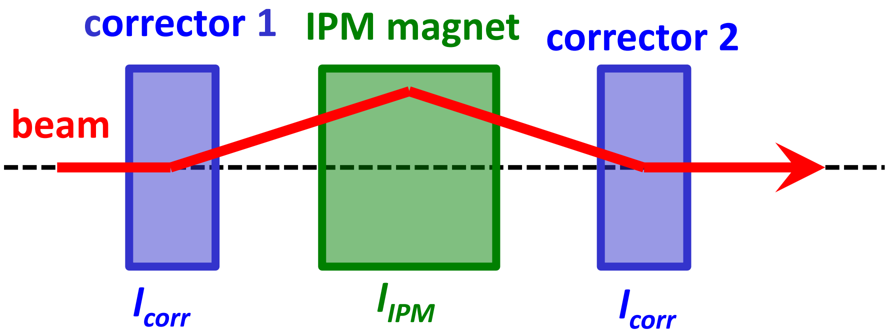
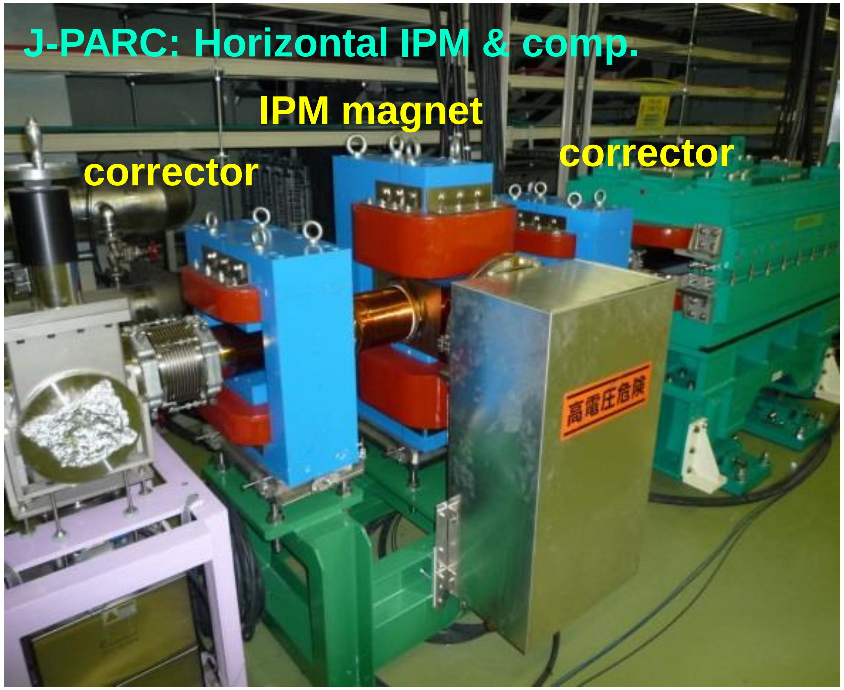


$$B_{cor} \cdot l_{corr} = -\tfrac{1}{2} B_{IPM} \cdot l_{IPM}$$



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

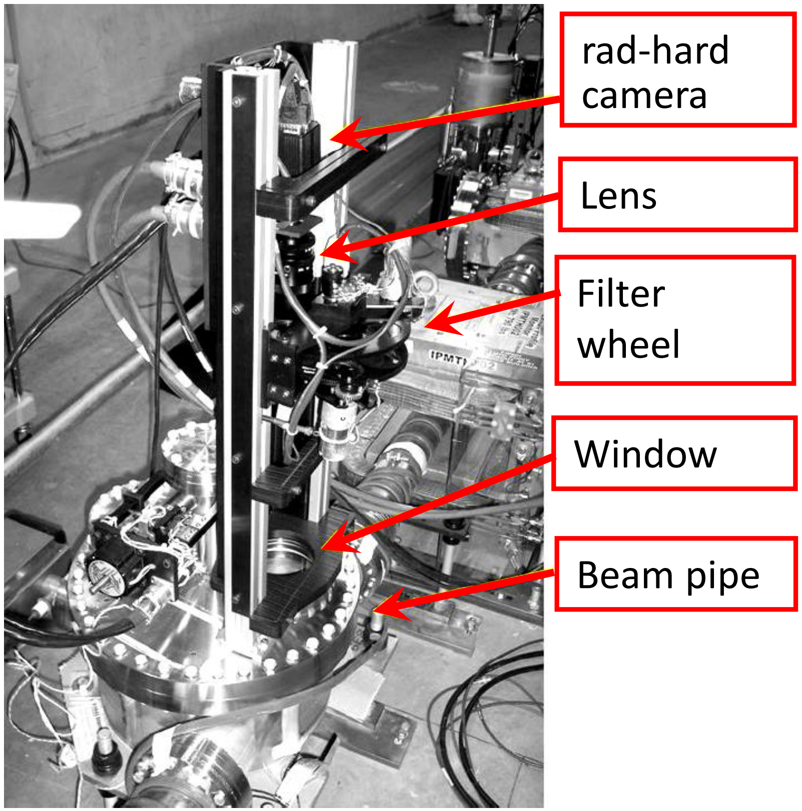
Remark: For MCP wire-array readout lower clearance required

OTR-Monitor: Technical Realization and Results

Example of realization at TERATRON:

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

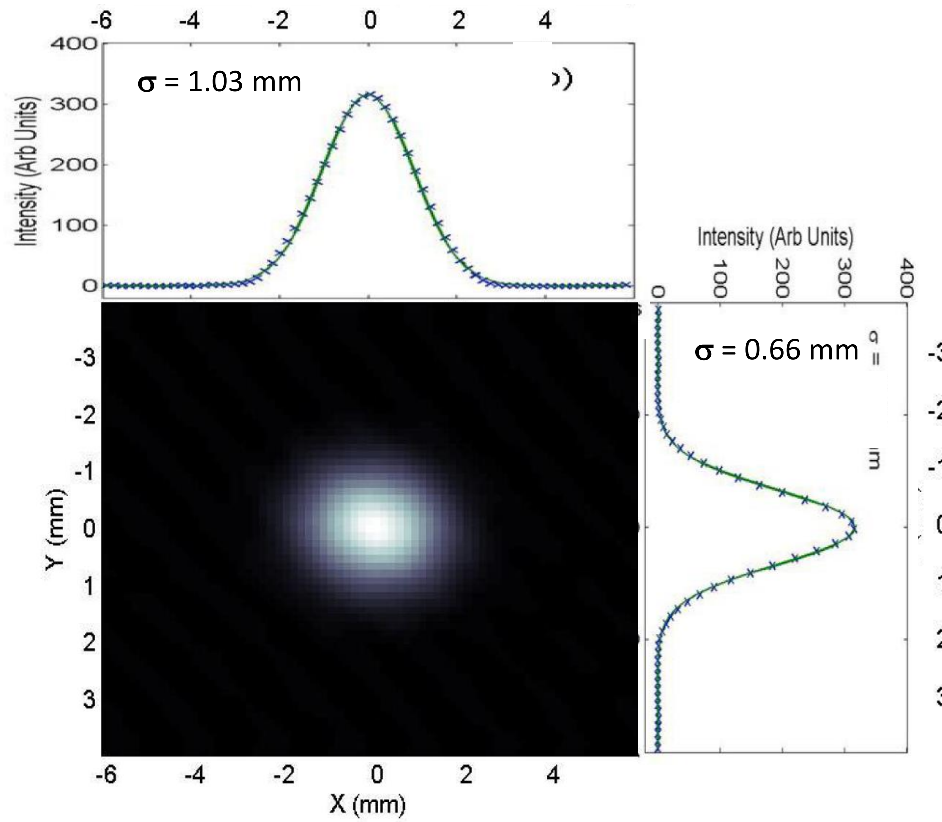
Advantage: thin foil ⇒ low heating & straggling
2-dim image visible



Results at FNAL-TEVATRON synchrotron

with 150 GeV proton

Using fast camera: Turn-by-turn measurement



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

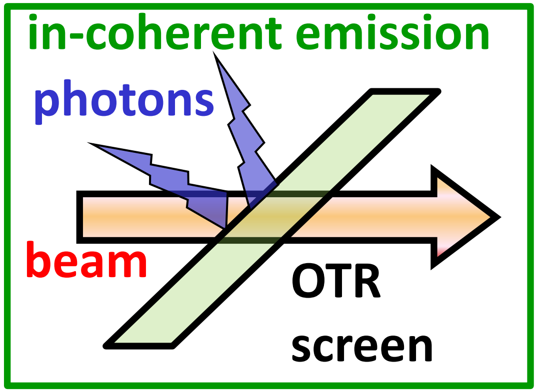
Coherent Optical Transition Radiation

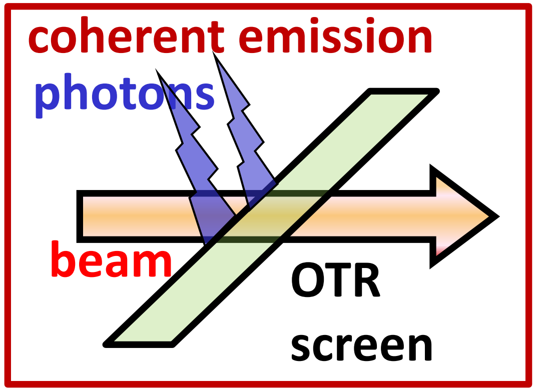
Observation of coherent OTR for **compressed** bunches at LINAC based light sources

Reason: Coherent emission **if** bunch length ≈ wavelength (t_{bunch}=2 fs ⇔ l_{bunch} =600 nm)

or bunch fluctuations ≈ wavelength

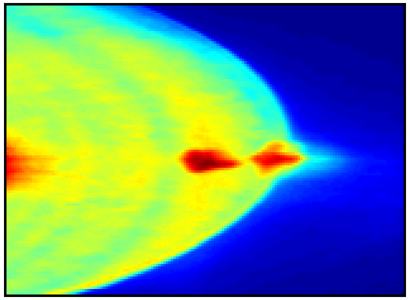
Parameter reach
for most LINAC-based FELs!

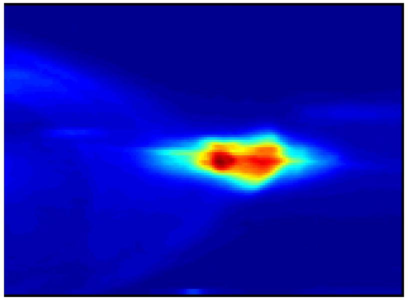




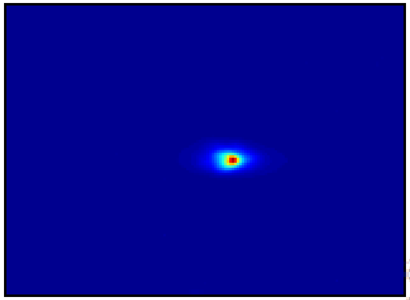
Beam parameter: FLASH, 700 MeV, 0.5 nC, with bunch compression

OTR screen *scint. screen*


(a) OTR screen


(c) LuAG screen


(b) OTR screen, +100ns delay


(d) LuAG screen, +100ns delay

prompt emission for OTR and scint. screen
→ **coherent and in-coherent OTR**

100 ns delayed emission
→ no OTR as expected (classical process)
→ emission by scint. screen due to lifetime
⇔ correct profile image!

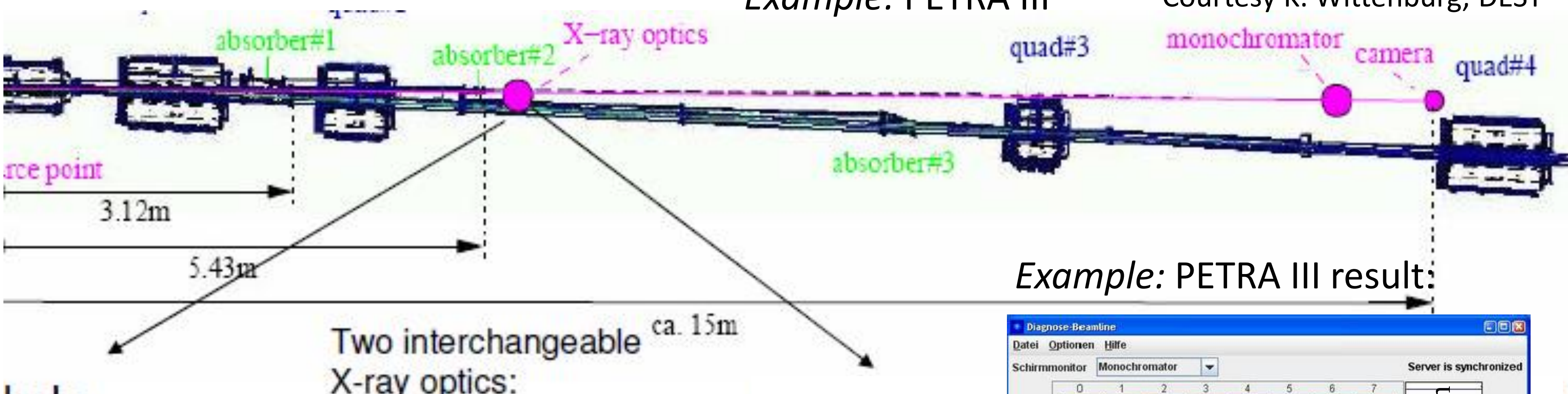
Contrary of M. Yan et al., DIPAC'11 & S. Wesch, DIPAC'11

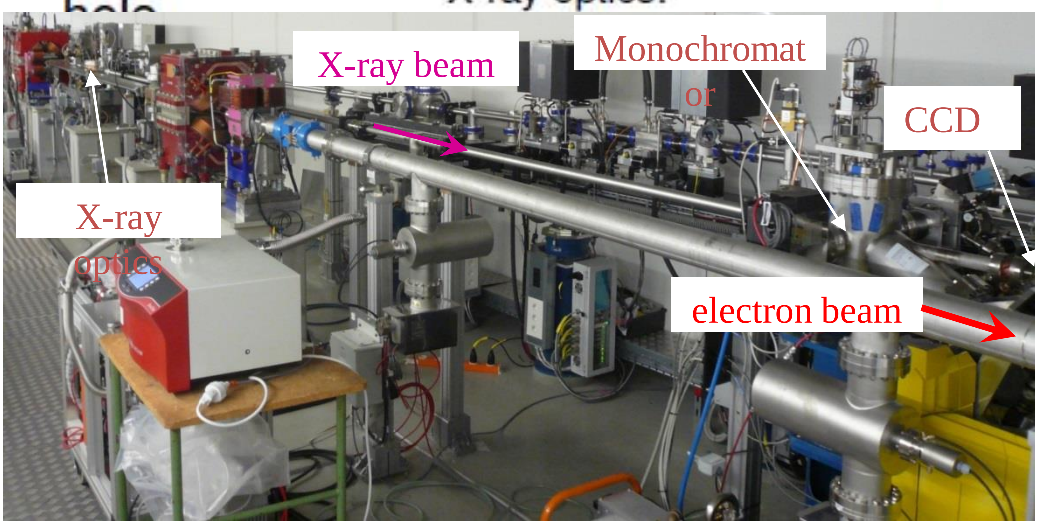
X-ray Pin-Hole Camera

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

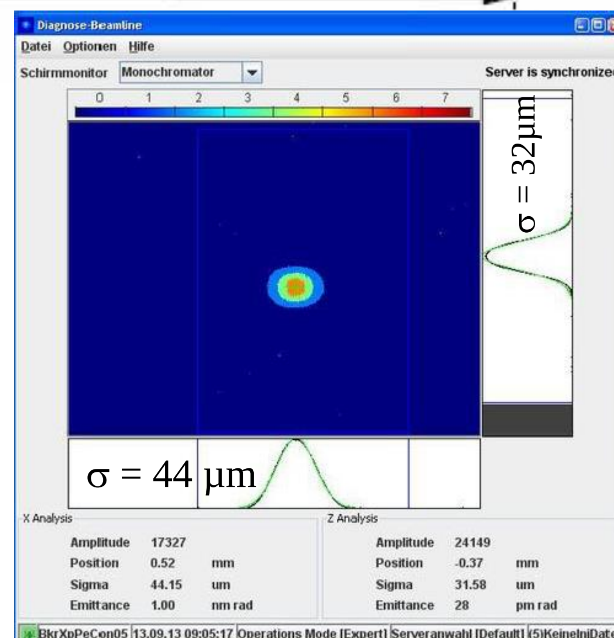
Example: PETRA III

Courtesy K. Wittenburg, DESY





Example: PETRA III result:



Double Slit Interference for Radiation Monitors

The **blurring of interference pattern** due to finite size of the sources

⇒spatial coherence parameter γ delivers ***rms*** beam size

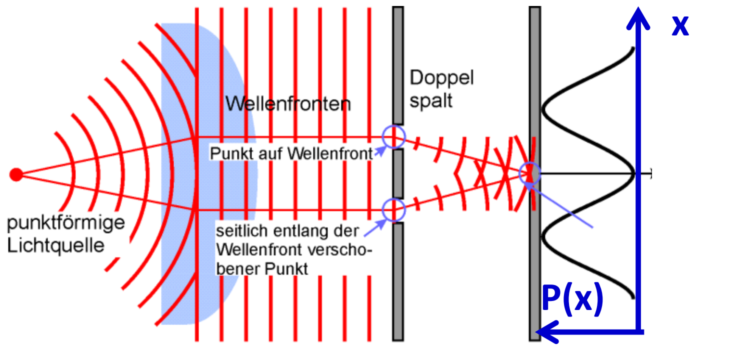
i.e. 'de-convolution' of blurred image!

→ highest resolution, but complex method

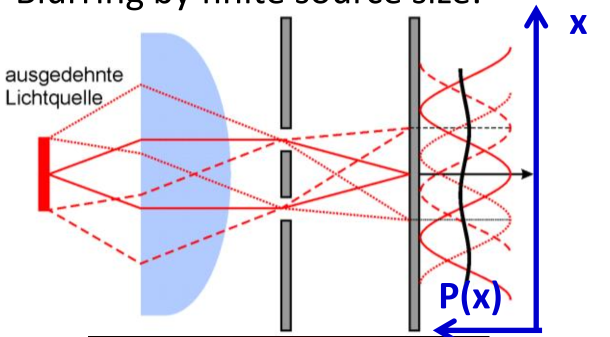
Typical resolution for three methods:

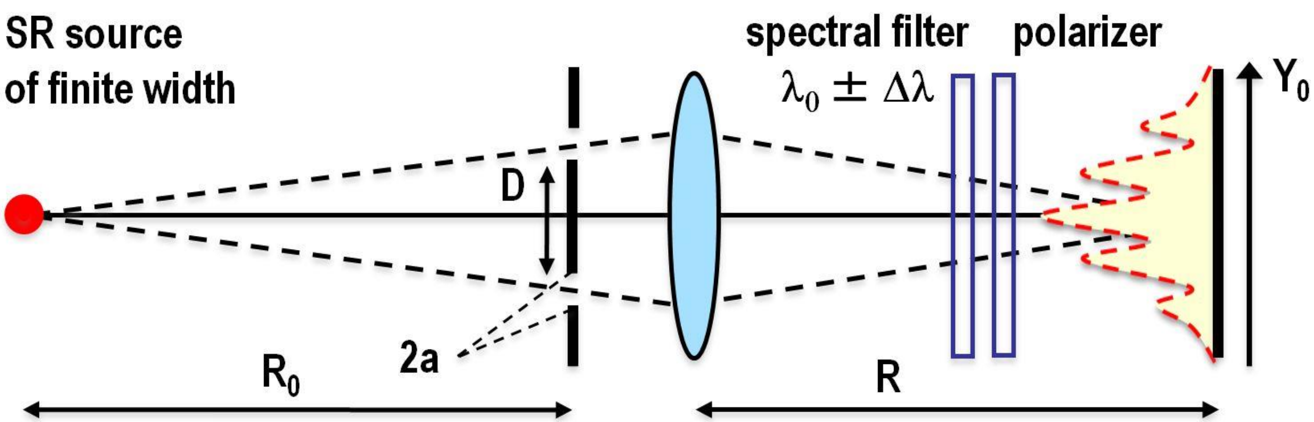
- Direct optical observation: $\sigma \approx$ **100 µm**
- Direct x-ray observation : $\sigma \approx$ **10 µm**
- Interference optical obser: $\sigma \approx$ **1 µm**

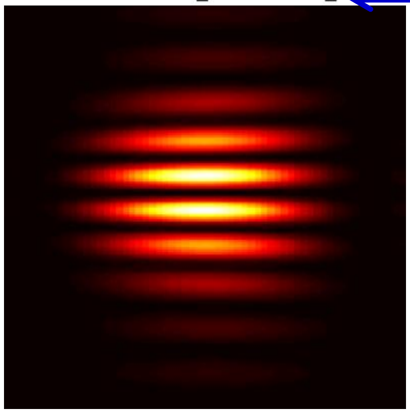
Ideal double slit interference pattern:



Blurring by finite source size:







Courtesy of V. Schlott PSI

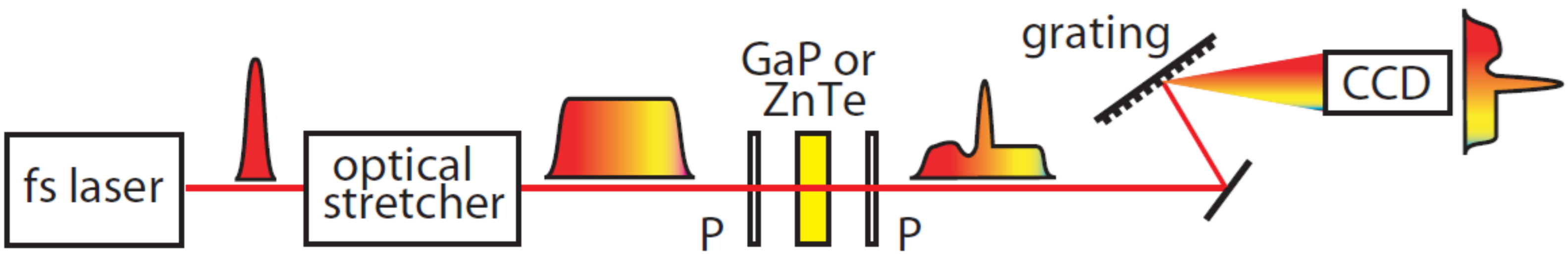
Optical Strecher for electro-optical Method

For Free Electron Lasers → bunch length below 1 ps is achieved

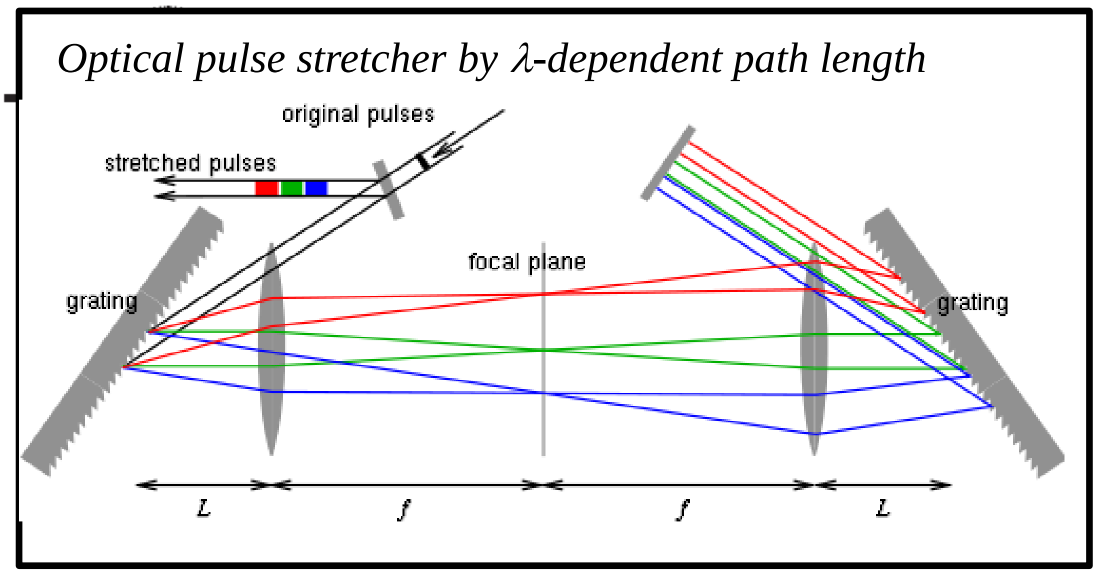
Short laser pulse ⇔ broad frequency spectrum (property of Fourier Transformation)

Optical stretcher: Separation of colors by different path length

⇒ different colors at different time ⇒ **single-shot observation**



Spectral Decoding



Courtesy S.P.Jamison et al., EPAC 2006

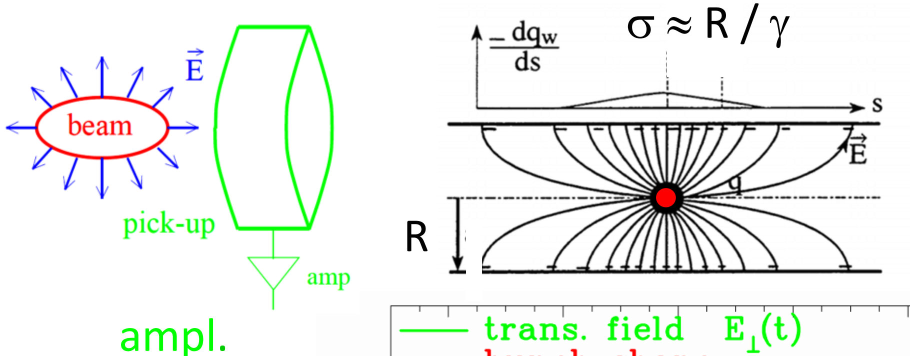
Pick-ups are used for:

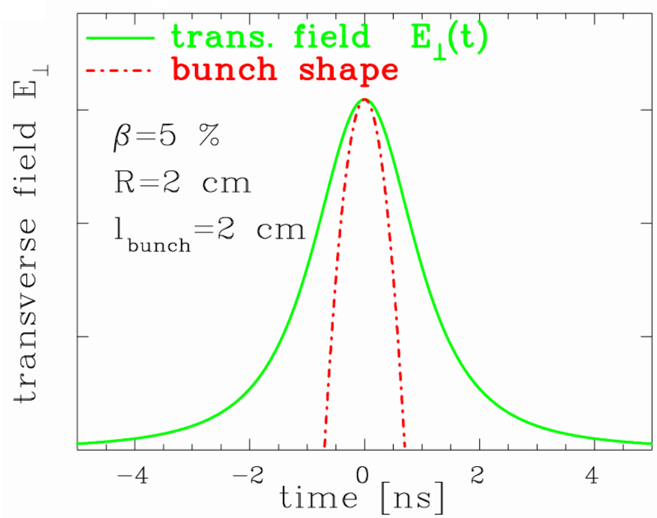
- precise for bunch-center relative to rf
- course image of bunch shape

But:

For $\beta << 1 \rightarrow$ long. E-field significantly modified:

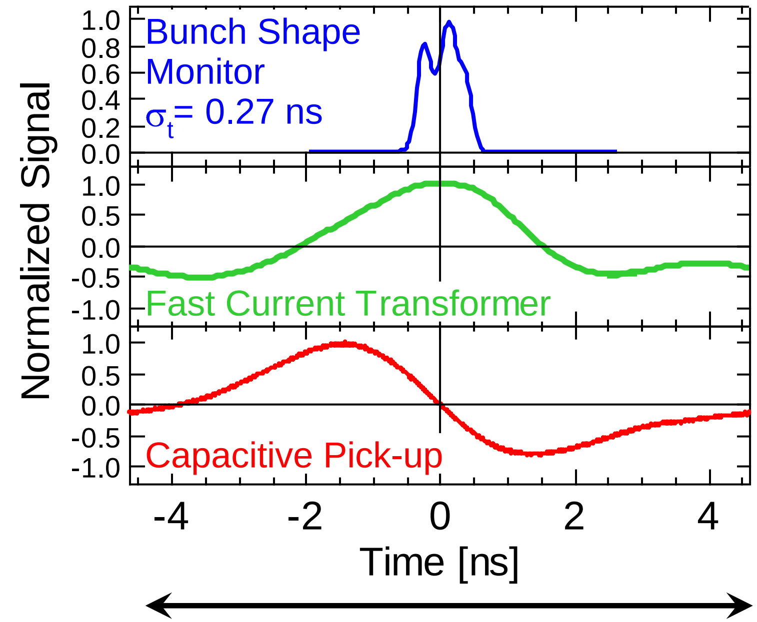
$\sigma \approx R / \gamma$





Example: Comparison pick-up – particle counter:

Ar beam of 1.4 MeV/u (β = 5.5%) , f_{rf} = 108 MHz



$1/f_{rf}$ = 9.2 ns

$\Rightarrow$ the pick-up signal is insensitive to bunch 'fine-structure'

Bunch Structure using secondary Electrons for low E_{kin} Protons

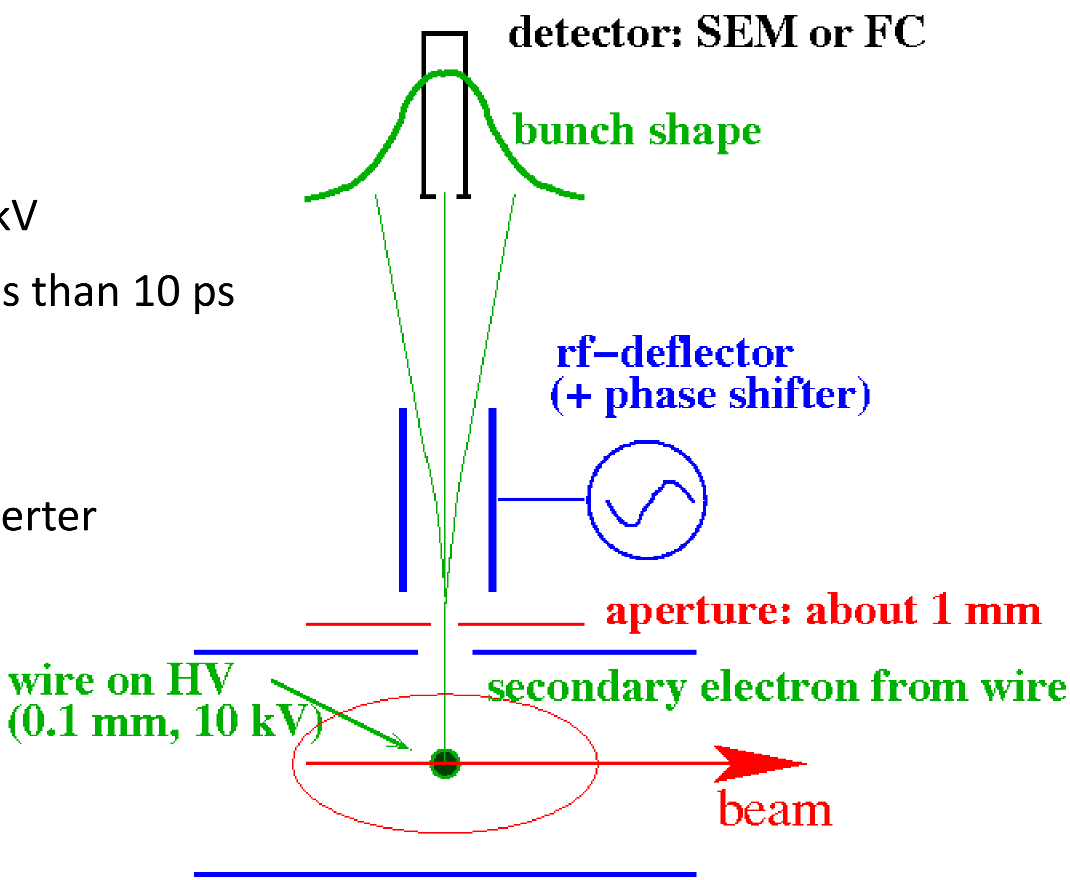
Secondary e^- liberated from a wire carrying the time information.

→ Bunch Shape Monitor (BSM)

Working principle:

- insertion of a 0.1 mm wire at ≈ 10 kV
- emission of secondary e^- within less than 10 ps
- secondary e^- are accelerated
- toward an rf-deflector
- rf-deflector as 'time-to-space' converter
- detector with a thin slit
- slow shift of the phase
- resolution ≈ 10 ps ≈ 1° @ 280 MHz
- Measurements are comparable

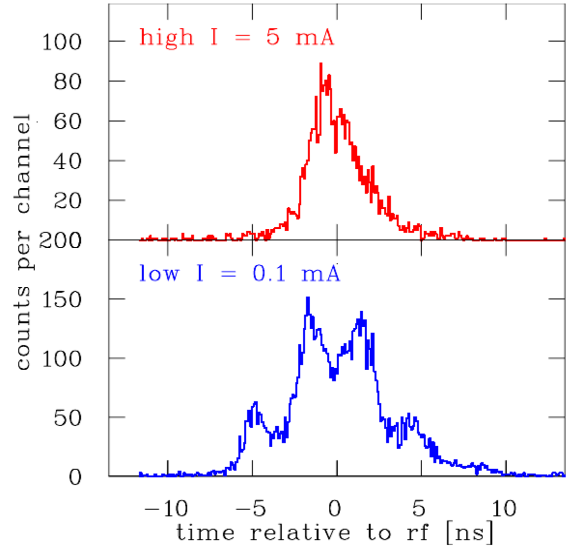
  to that obtained with particle detectors.

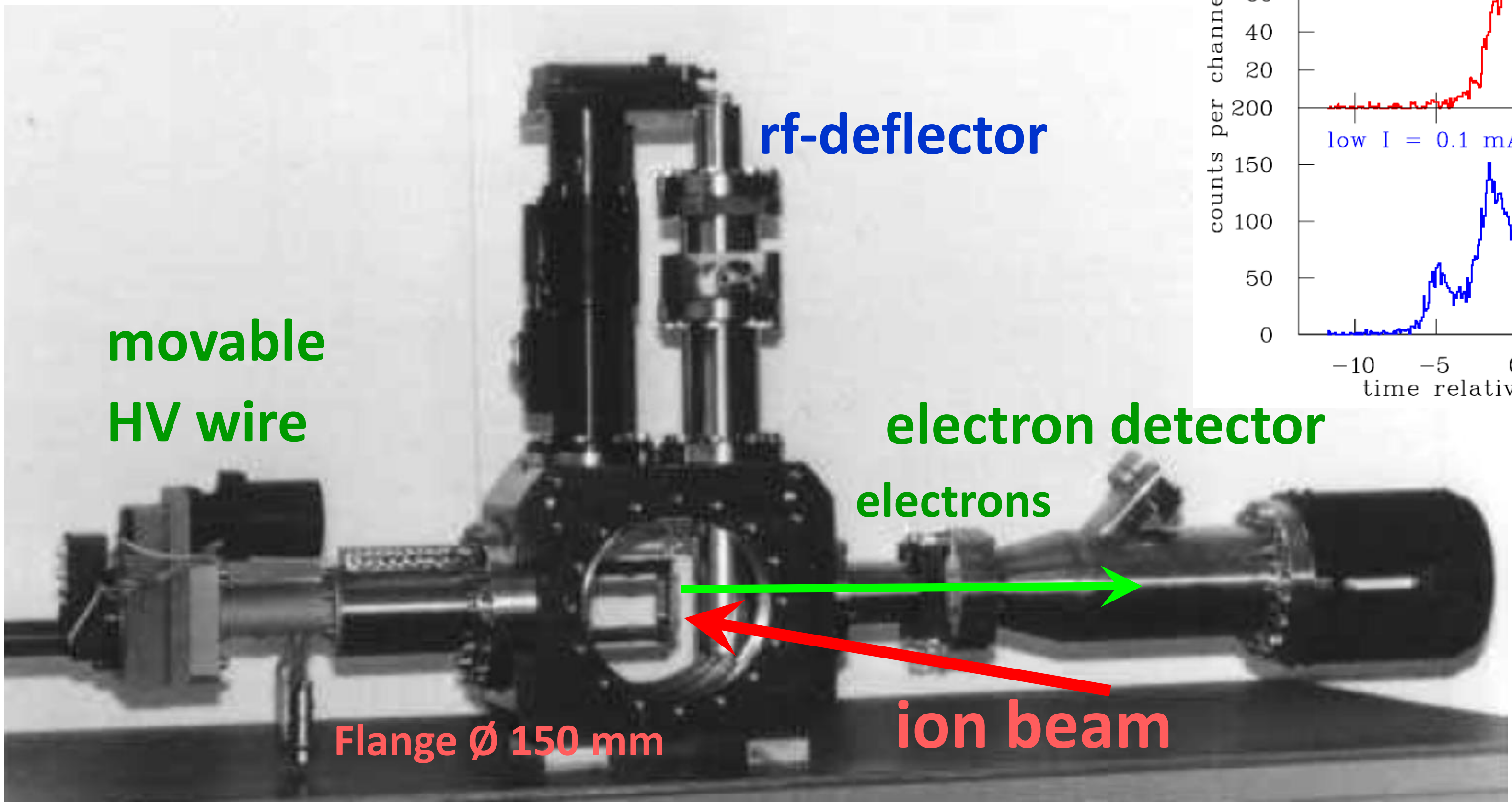


SEM: secondary electron multiplier

Realization of Bunch Shape Monitor at CERN LINAC2

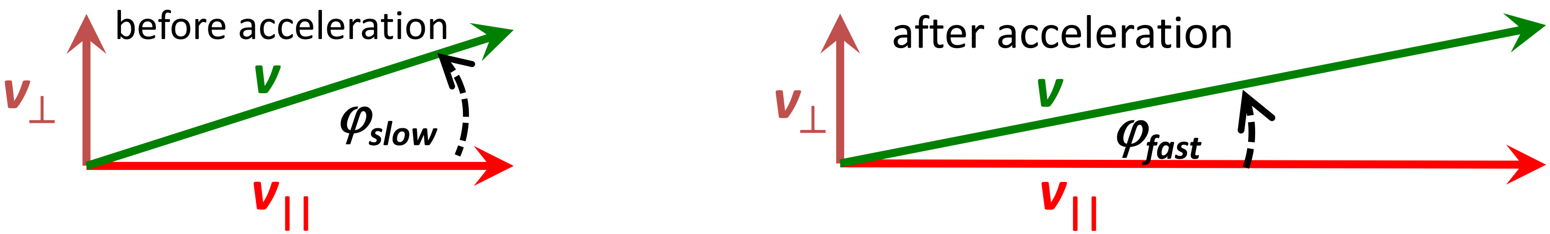
Example: The bunch shape behind RFQ with120 keV/u:





‘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 $\langle xx' \rangle = 0$: $\varepsilon = x \cdot x' = x \cdot p_\perp / p_{||}$

$\Rightarrow$ 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 γ and velocity $\beta = v/c$

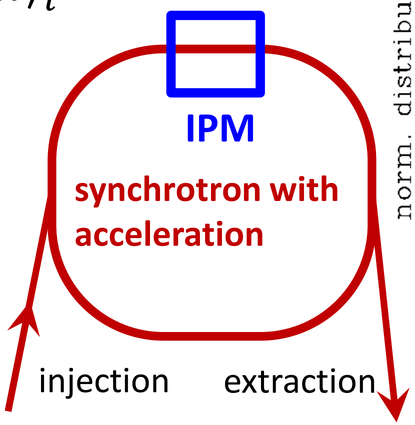
Example: Acceleration in GSI-synchrotron for C^{6+} from 6.7 → 600 MeV/u (β = 12 → 79 %) observed by IPM

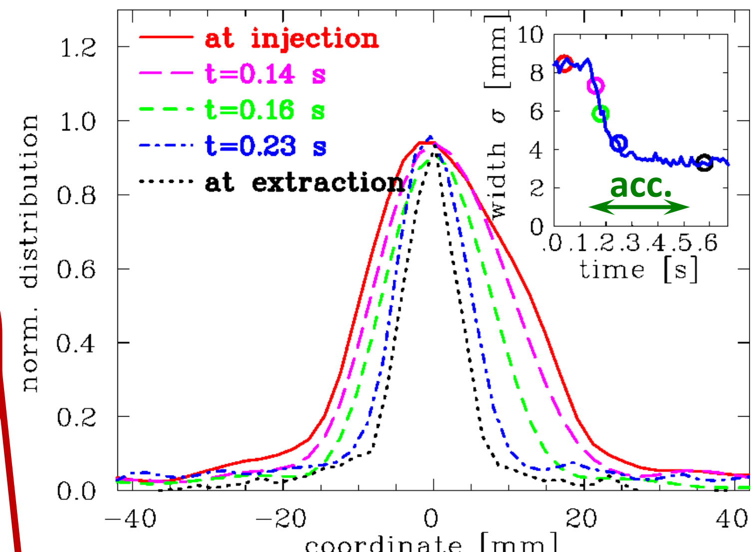
theoretical width: $\langle x \rangle_f = \sqrt{\frac{\beta_i \cdot \gamma_i}{\beta_f \cdot \gamma_f}} \cdot \langle x \rangle_i$

$= 0.33 \cdot \langle x \rangle_i$

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

IPM is well suited
for long time observations
without beam disturbance
→ mainly used at proton synchrotrons.





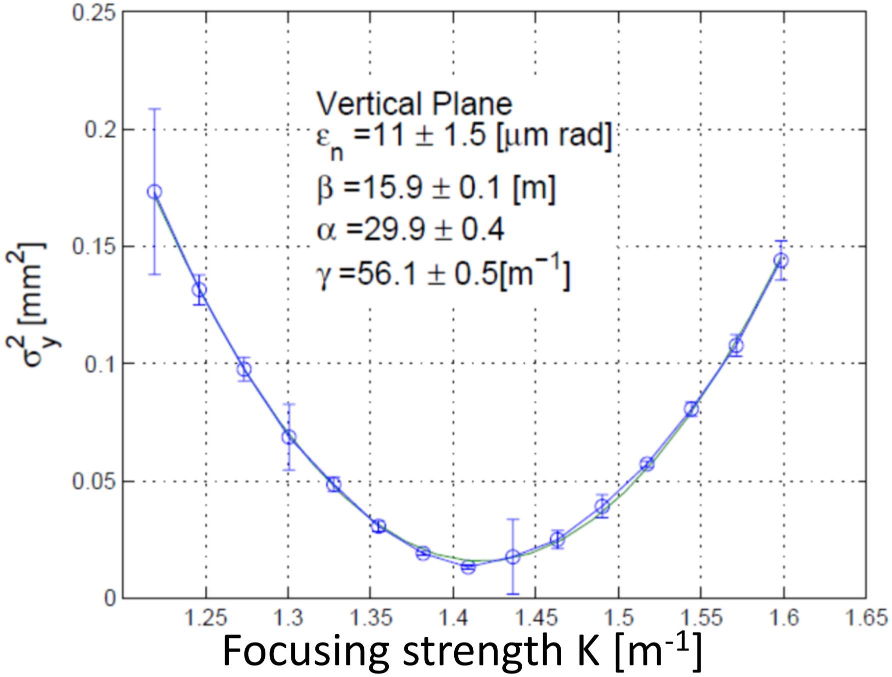
Measurement of transverse Emittance

Using the 'thin lens approximation' i.e. the quadrupole has a focal length of ***f***:

$$\mathrm{R}_{focus}(\boldsymbol{K}) = \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ -\mathbf{1}/\boldsymbol{f} & \mathbf{1} \end{pmatrix} \equiv \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \boldsymbol{K} & \mathbf{1} \end{pmatrix} \Rightarrow \mathrm{R}(\boldsymbol{L},\boldsymbol{K}) = \mathrm{R}_{drift}(\boldsymbol{L}) \cdot \mathrm{R}_{focus}(\boldsymbol{K}) = \begin{pmatrix} \mathbf{1}+\boldsymbol{LK} & \boldsymbol{L} \\ \boldsymbol{K} & \mathbf{1} \end{pmatrix}$$

Measurement of matrix-element $\boldsymbol{\sigma}_{\mathbf{11}}(s_1, K)$ from matrices $\boldsymbol{\sigma}(s_1,K_i) = \mathbf{R}(K_i) \cdot \boldsymbol{\sigma}(s_0) \cdot \mathbf{R}^{\mathbf{T}}(K_i)$

Example: Square of the beam width at ELETTRA 100 MeV e⁻ Linac, YAG:Ce:



G. Penco (ELETTRA) et al., EPAC'08

For completeness: The relevant formulas

$$\begin{aligned}\boldsymbol{\sigma}_{11}(\mathbf{1},\boldsymbol{K}) = {} & \boldsymbol{L}^2\boldsymbol{\sigma}_{11}(\mathbf{0}) \cdot \boldsymbol{K}^2 \\ & + 2 \cdot (\ \boldsymbol{L}\boldsymbol{\sigma}_{11}(\mathbf{0}) + \boldsymbol{L}^2\boldsymbol{\sigma}_{12}(\mathbf{0})\ ) \cdot \boldsymbol{K} \\ & + \boldsymbol{L}^2\boldsymbol{\sigma}_{22}(\mathbf{0}) + \boldsymbol{\sigma}_{11}(\mathbf{0}) \\ \equiv {} & \boldsymbol{a} \cdot \boldsymbol{K}^2 - 2\boldsymbol{ab} \cdot \boldsymbol{K} + \boldsymbol{ab}^2 + \boldsymbol{c} \\ = {} & \boldsymbol{a} \cdot (\boldsymbol{K} - \boldsymbol{b})^2 + \boldsymbol{c}\end{aligned}$$

The three matrix elements at the quadrupole:

$$\boldsymbol{\sigma}_{11}(\mathbf{0}) = \frac{\boldsymbol{a}}{\boldsymbol{L}^2}$$

$$\boldsymbol{\sigma}_{12}(\mathbf{0}) = -\frac{\boldsymbol{a}}{\boldsymbol{L}^2}\left(\frac{\mathbf{1}}{\boldsymbol{L}} + \boldsymbol{b}\right)$$

$$\boldsymbol{\sigma}_{22}(\mathbf{0}) = \frac{\mathbf{1}}{\boldsymbol{L}^2}\left(\boldsymbol{ab}^2 + \boldsymbol{c} + \frac{2\boldsymbol{ab}}{\boldsymbol{L}} + \frac{\boldsymbol{a}}{\boldsymbol{L}^2}\right)$$

$$\boldsymbol{\varepsilon}_{rms} \equiv \sqrt{\det \boldsymbol{\sigma}(\mathbf{0})} = \sqrt{\boldsymbol{\sigma}_{11}(\mathbf{0}) \cdot \boldsymbol{\sigma}_{22}(\mathbf{0}) - \boldsymbol{\sigma}_{12}^2(\mathbf{0})} = \sqrt{\boldsymbol{ac}} / \boldsymbol{L}^2$$

The Emittance for Gaussian and non-Gaussian Beams

The beam distribution can be non-Gaussian, e.g. at:

- Beams behind ion source
- Space charged dominated beams at LINAC & synchrotron
- Cooled beams in storage rings

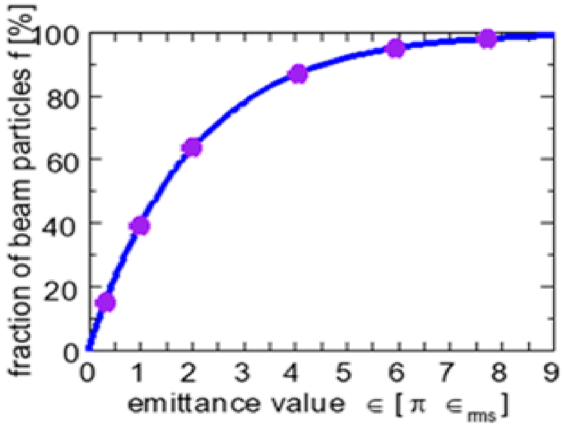
General description of emittance by statistical moments of 2-dim distribution:

$$\varepsilon_{rms} = \sqrt{\underbrace{\langle x^2\rangle\langle x'^2\rangle}_{\text{Variances}} - \underbrace{\langle xx'\rangle^2}_{\text{Covariance i.e. correlation}}}$$

It describes the value for 1 standard derivation

For Gaussian beams only: ε_{rms} ↔ interpreted as area containing a fraction ***f*** of ions:

$$\varepsilon(f) = -2\pi\varepsilon_{rms} \cdot \ln(1-f)$$

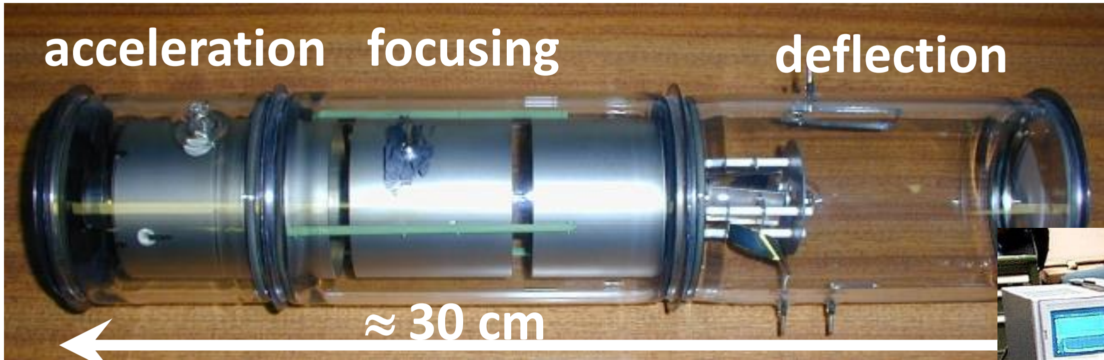


Emittance ε (*f*)	Fraction *f*
$1 \cdot \varepsilon_{rms}$	15 %
$\pi \cdot \varepsilon_{rms}$	39 %
$2\pi \cdot \varepsilon_{rms}$	63 %
$4\pi \cdot \varepsilon_{rms}$	86 %
$8\pi \cdot \varepsilon_{rms}$	98 %

Care:

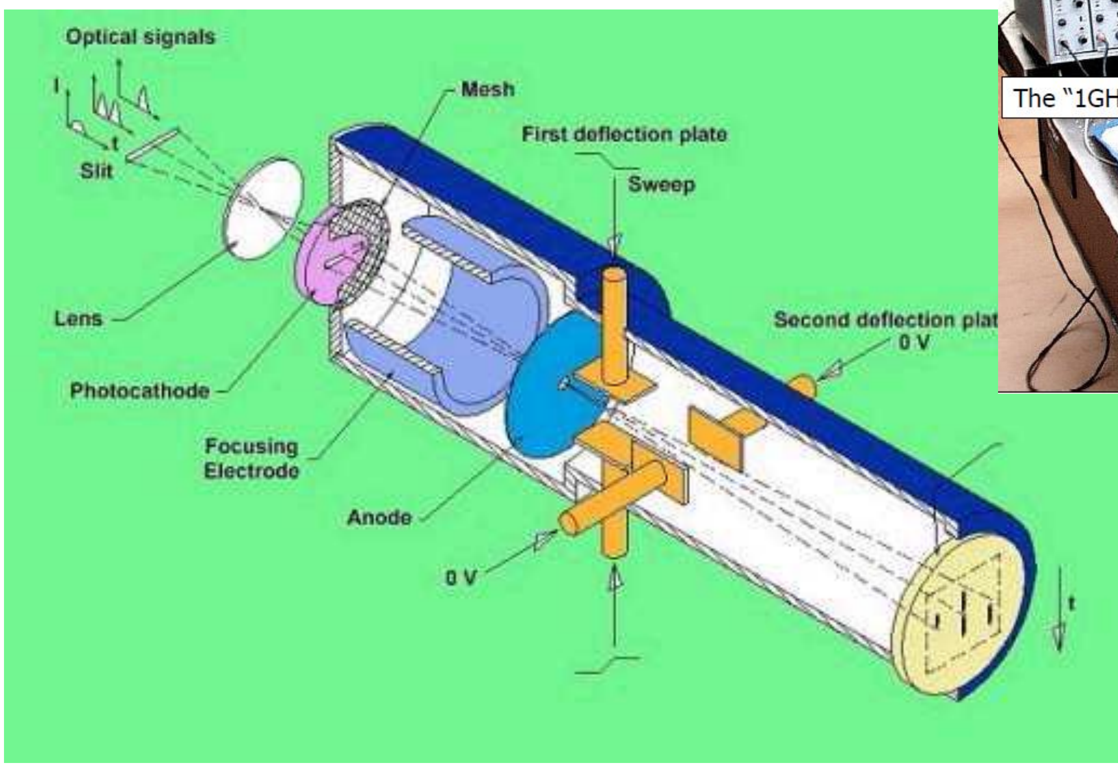
No common definition of emittance concerning the fraction ***f***

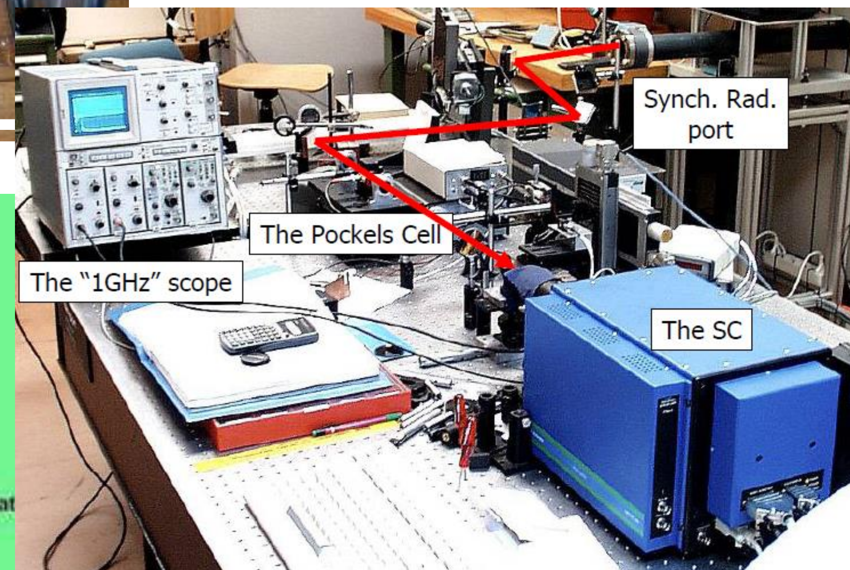
Technical Realization of a Streak Camera

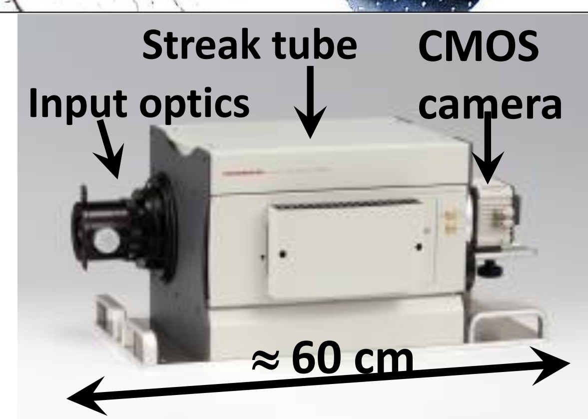


Hardware of a streak camera

Time resolution down to 0.5 ps







Diffraction Limit of Synchrotron Light Monitor

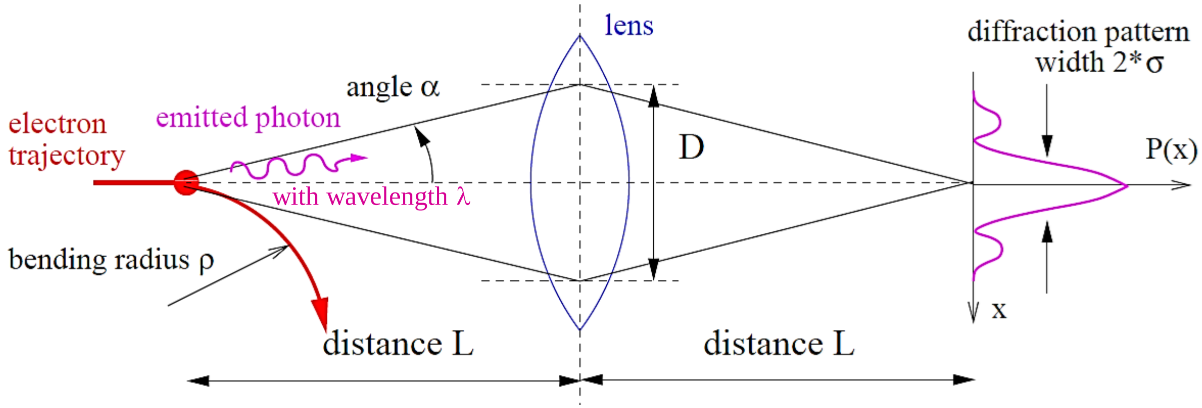
Limitations:

Diffraction limits the resolution due to Fraunhofer diffraction

Pattern width for 1:1 image:

$$\sigma \simeq \frac{\lambda}{2D/L} \simeq 0.6 \cdot \left(\frac{\lambda^2}{\varrho}\right)^{1/3}$$

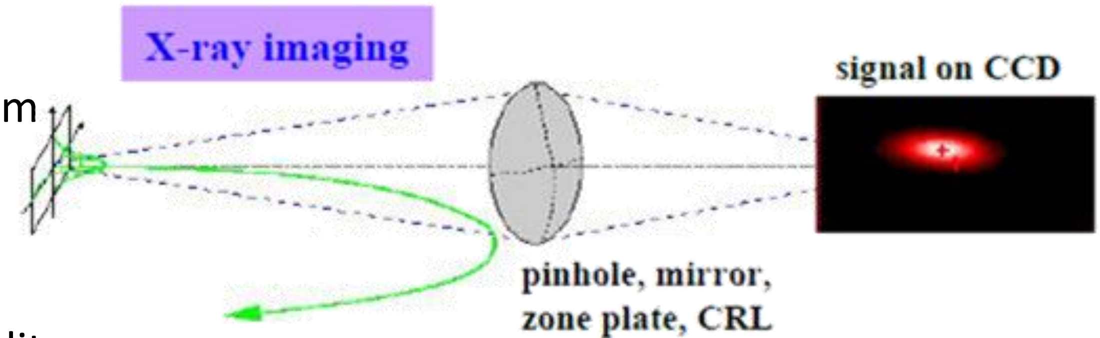
$\Rightarrow \sigma \simeq 100$ µm for typical cases



Improvements:

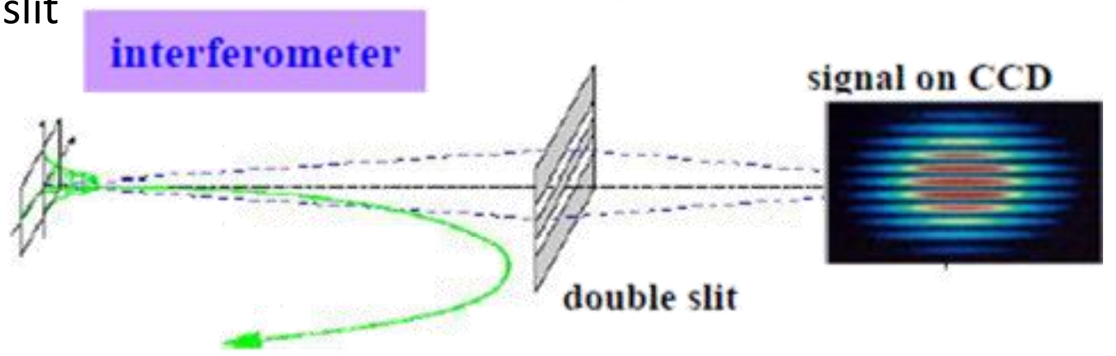
- ***Shorter wavelength:***

  Using X-rays and an aperture of Ø 1mm
  → 'X-ray pin hole camera',
  achievable resolution $\sigma \simeq 10$ µm



- ***Interference technique:***

  At optical wavelength using a double slit
  → interference fringe blurring
  compared to point source
  achievable resolution $\sigma \simeq 1$ µm.



Basic Idea of Beam Loss Monitors

Basic idea for Beam Loss Monitors BLM:

A loss beam particle must collide with the vacuum chamber or other insertions

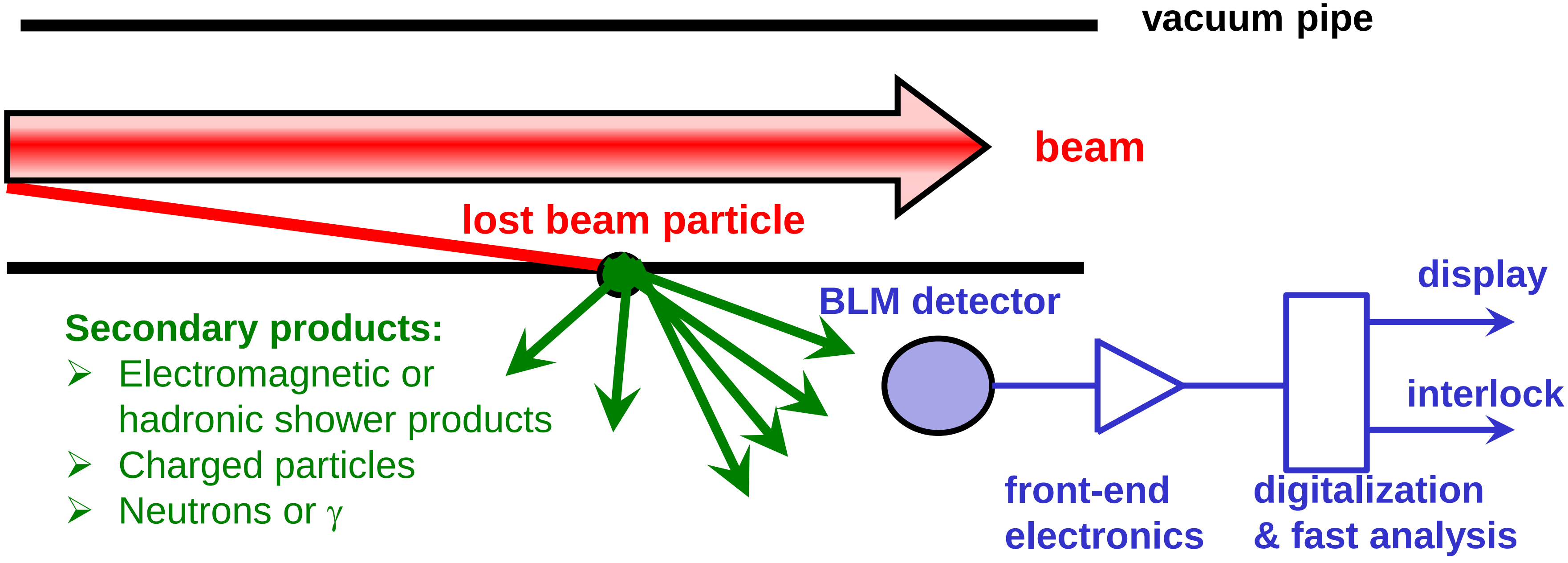
⇒ Interaction leads to some shower particle:

e⁻, γ, protons, neutrons, excited nuclei, fragmented nuclei

→ Detection of these secondaries by an appropriate detector outside of beam pipe

→ Relative cheap detector installed at many locations

Remark: Due to grazing angle a thin vacuum chamber might be a ‘thick target’



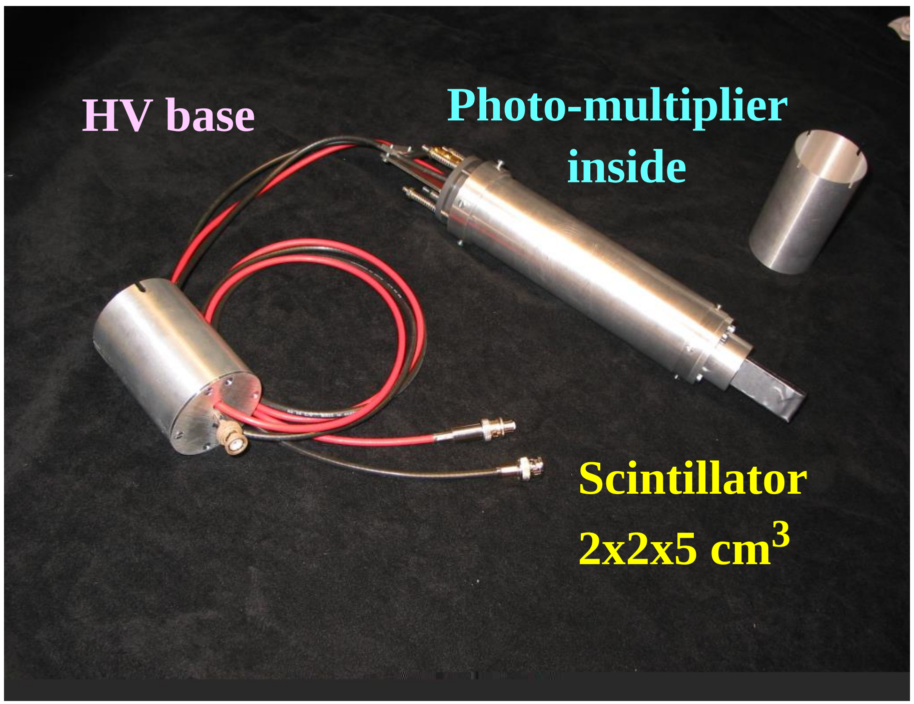
Scintillators as Beam Loss Monitors

Plastics or liquids are used:

- Detection of **charged particles** by electronic stopping
- Detection of **neutrons** by elastic collisions n on p in plastics and fast p electronic stopping.

Scintillator + photo-multiplier:

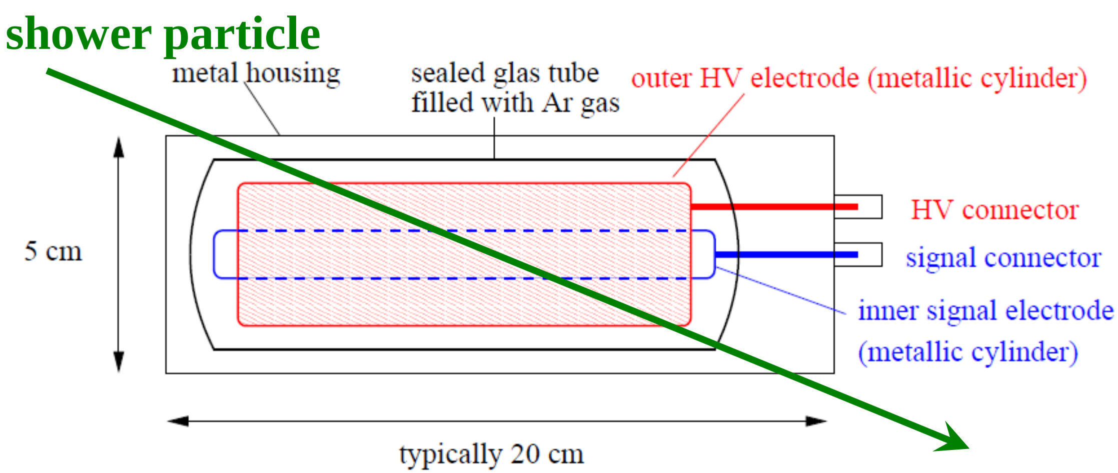
counting (large PMT amplification)
or analog voltage ADC (low PMT amplification)
Radiation hardness:
plastics 1 Mrad = 10^4 Gy
liquid 10 Mrad = 10^5 Gy



Ionization Chamber as Beam Loss Monitors

Energy loss of charged particles in gases → electron-ion pairs → current meas.

$$I_{\mathrm{sec}} \propto \frac{1}{W} \cdot \frac{dE}{dx} \Delta x$$

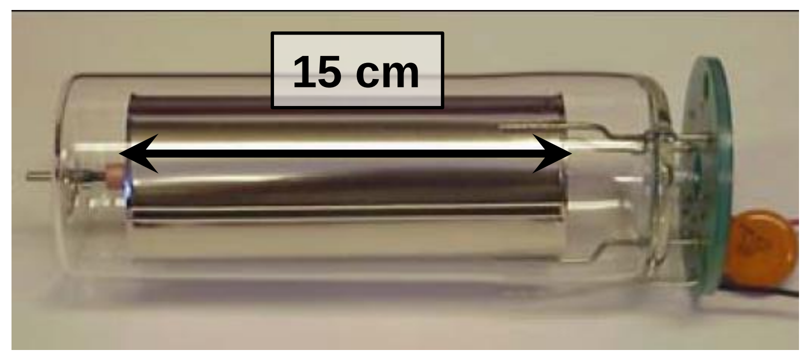


W is average energy for creation for one e^- -ion pair:

Gas	Ionization Pot. [eV]	W-Value [eV]
Ar	15.7	26.4
N_2	15.5	34.8
O_2	12.5	30.8
Air		33.8

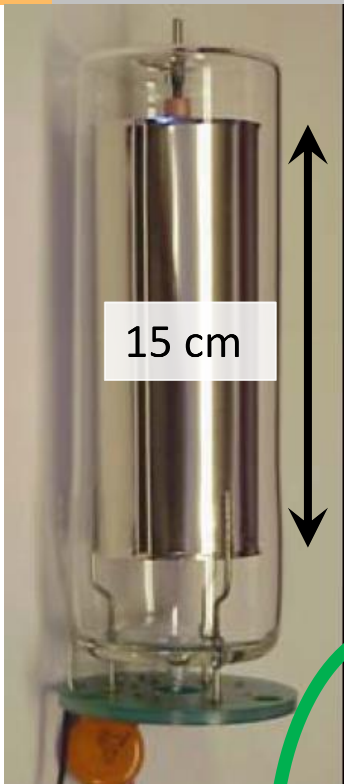
Sealed tube Filled with Ar or N_2 gas:

- Creation of Ar^+-e^- pairs, average energy ***W*** = 32 eV/pair
- measurement of this current
- Slow time response due to ≈ 10 μs drift time of Ar^+.



Per definition: Direct measurement of dose !

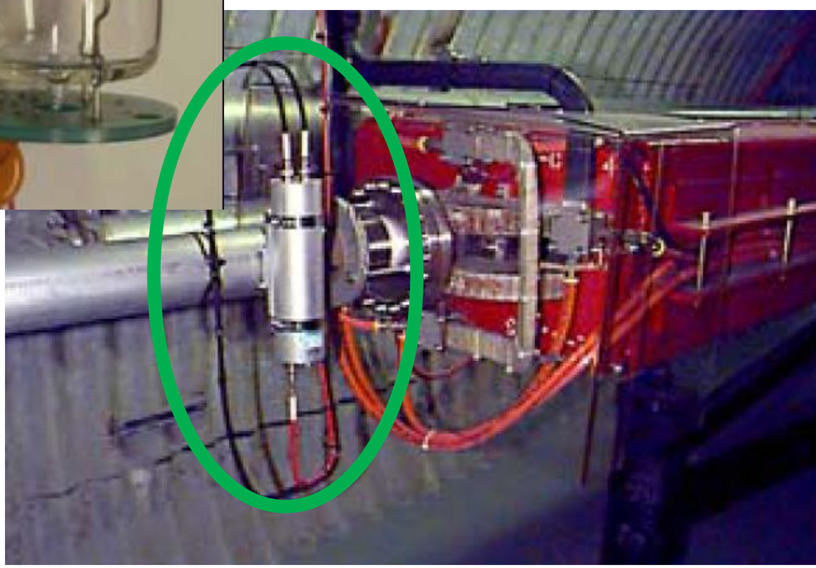
Ionization Chamber as BLM: TEVATRON and CERN Type



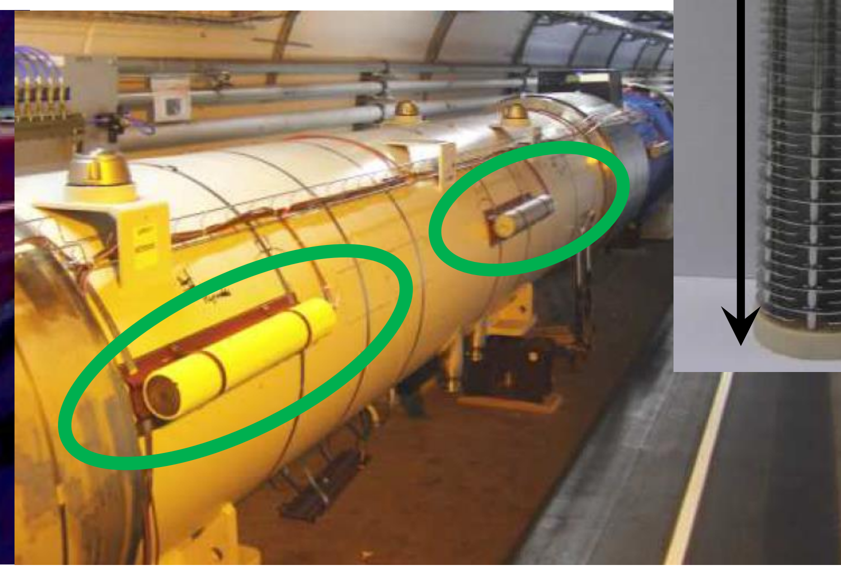
Parameter	TEVATRON, RHIC	CERN type
Size	15cm, ∅ 6 cm	50 cm, ∅ 9 cm
Gas	Ar at 1.1 bar	N_2 at 1.1 bar
# of electrodes	3	61
Voltage	1000 V	1500 V
Reaction time	3 µs	0.3 µs

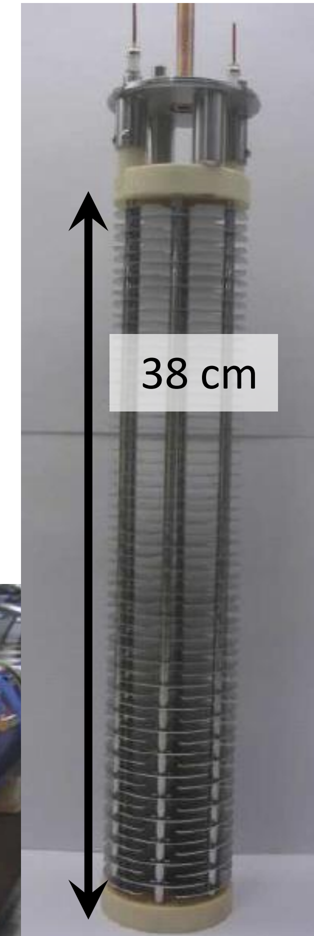
4000 BLMs at LHC⇔ each ≈ 6m

TEVATRON, RHIC type



CERN type





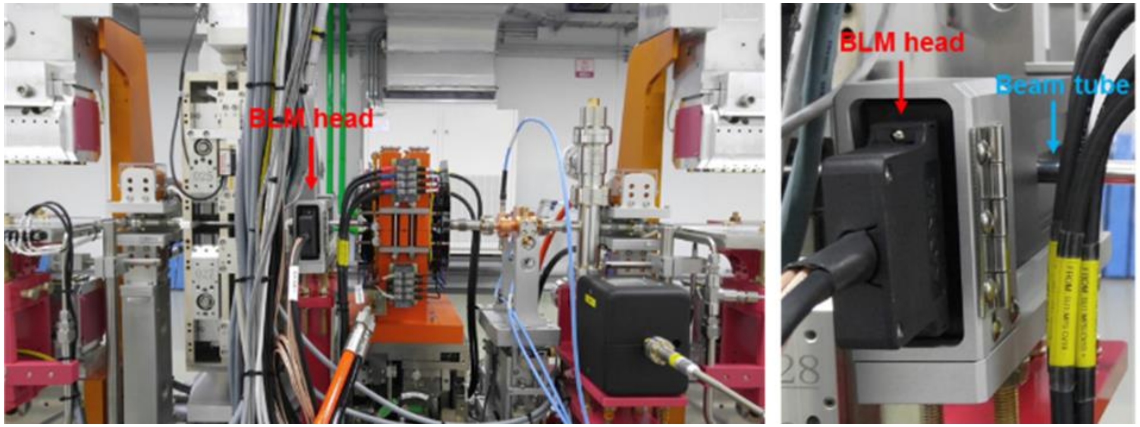
Cherenkov Light Detectors as Beam Loss Monitors

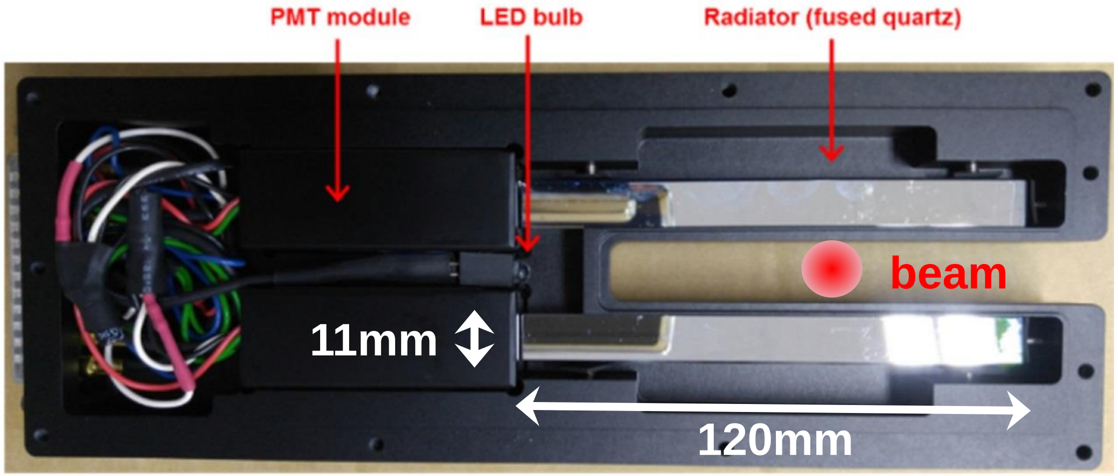
Cherenkov detectors:

Passage of a charged particle v faster than propagation of light $v > c_{medium} = c/n$

Technical: Quartz rod n=1.5 & photomultiplier

Example: Korean XFEL behind undulator



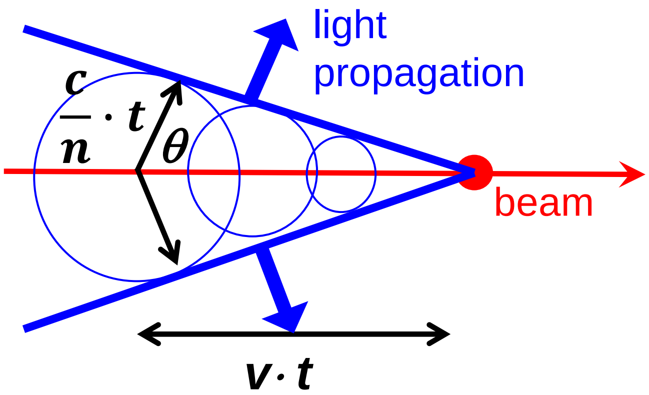


Cherenkov light emission:

For $v > c_{medium} = c/n$

light wave-front like a wake

broadband light emission



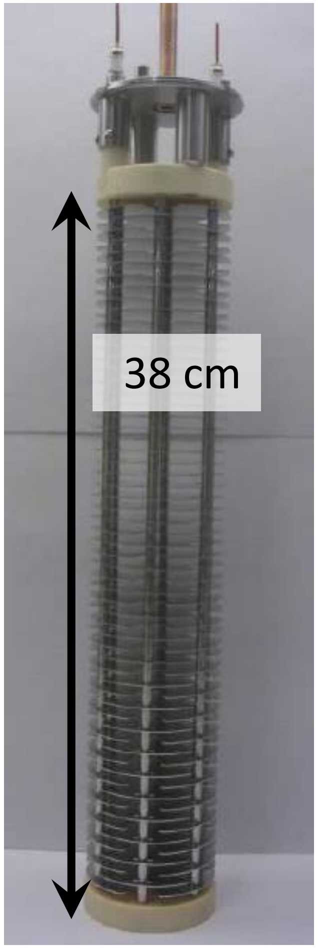
Advantage:

- **Detection of fast electrons only**
  not sensitive to γ & synch. photons
- No saturation effects
- Prompt light emission

Usage: Mainly at FELs for short and intense pulses

H. Yang, D.C. Shin, FEL Conf. 2017

Different detectors are sensitive to various physical processes very different count rate, but basically proportional to each other



Typical choice of the detector type:

- **Ionization Chamber:**

  Advantage:

  - Measurement of absolute dose

  Disadvantage:

  - Low signal (low γ, eff, no neutron detection),
  - Sometimes slow, ion drift time 10 ... 100 µs

  $\Rightarrow$ Often used at **proton** accelerators

- **Scintillator, Cherenkov detector:**

  Advantage:

  - Fast current reading or particle counting
  - Can be fabricated in any shape, cheap

  Disadvantage:

  - Need calibration in many cases
  - Might suffer from radiation

  $\Rightarrow$ Often used at **electron** accelerators