Beam Instrumentation & Diagnostics Part 2

CAS Introduction to Accelerator Physics

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2nd part of this lecture covers:

- **Transverse profile techniques**
- **Emittance determination and transfer lines**
- **Diagnostics for bunch length and momentum spread**

Measurement of Beam Profile

The beam width can be changed by focusing via quadruples.

Transverse matching between ascending accelerators is done by focusing.

→ Profiles have to be controlled at many locations.

Synchrotrons: Lattice functions ***β (s)*** and ***D(s)*** are fixed ⇒ width ***σ*** and emittance ***ε*** are:

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

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

Typical beam sizes:

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

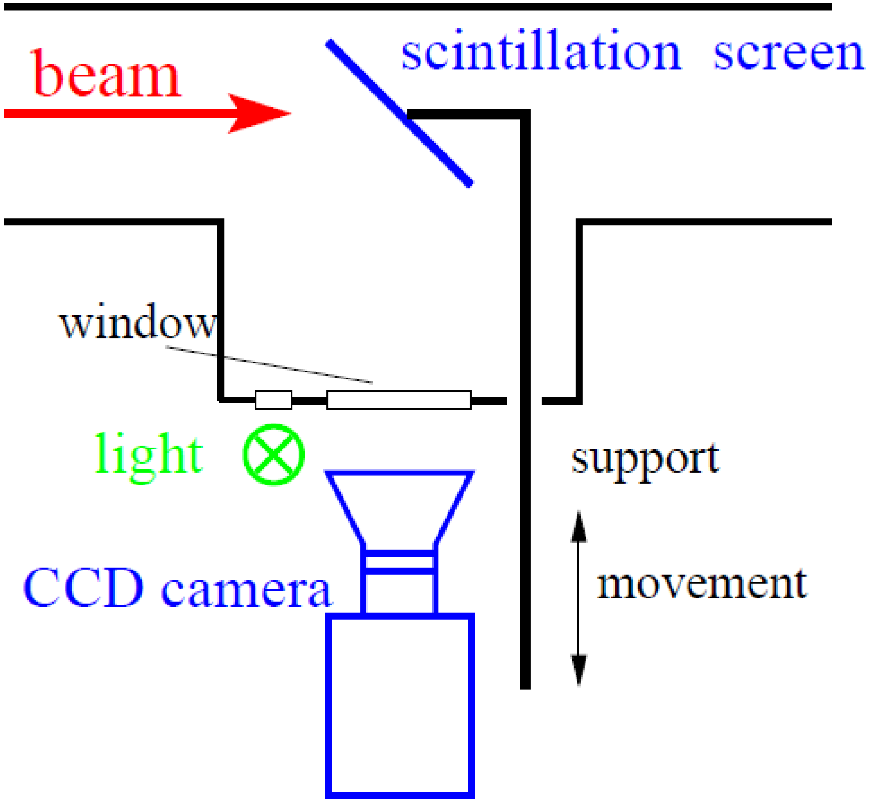
A great variety of devices are used:

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

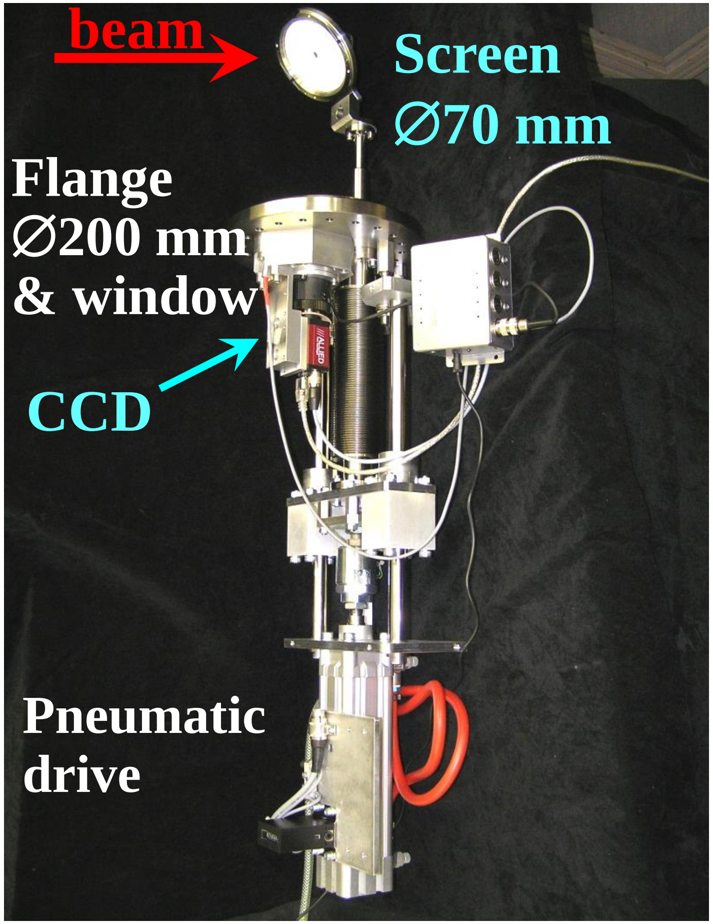
Scintillation Screen

Particle's energy loss in matter produces light

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



Pneumatic feed-through with Ø70 mm screen:



Example of Screen based Beam Profile Measurement

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

Advantage of screens:

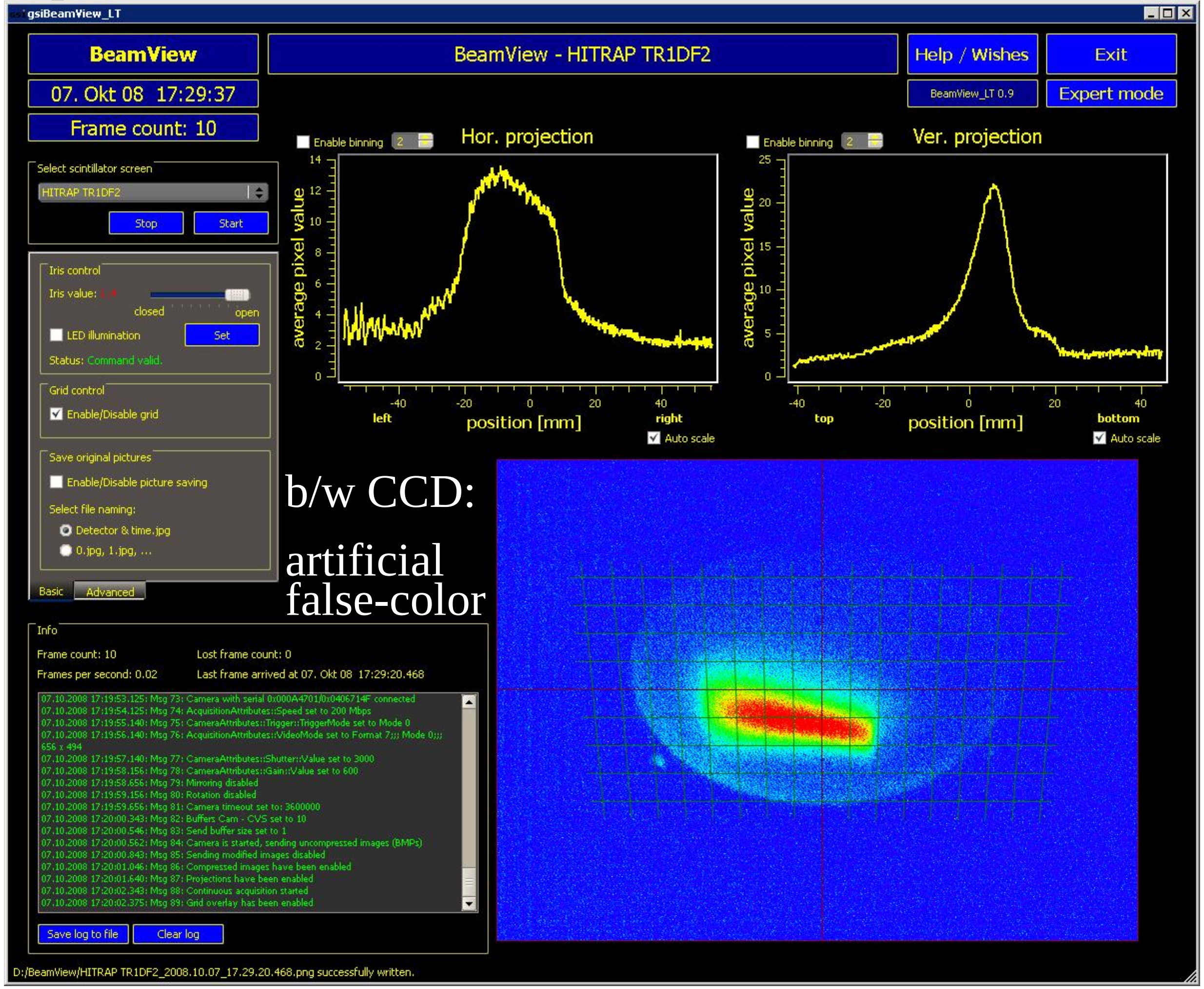
- ➢Direct 2-dim measurement
- ➢High spatial resolution
- ➢Cheap realization

⇒ widely used at transfer lines

Disadvantage of screens:

- ➢Intercepting device
- ➢ Some material might brittle
- ➢ Low dynamic range
- ➢Might be destroyed by the beam

Observation with
a CCD, CMOS or video camera



07. Okt 08 17:29:37

Frame count: 10

Select scintillator screen: HITRAP TR1DF2

Iris control
Iris value:
closed — open
☐ LED illumination
Status: Command valid.

Grid control
☑ Enable/Disable grid

Save original pictures
☐ Enable/Disable picture saving
Select file naming:
● Detector & time.jpg
○ 0.jpg, 1.jpg, ...

b/w CCD:

artificial false-color

Info

Frame count: 10 Lost frame count: 0
Frames per second: 0.02 Last frame arrived at 07. Okt 08 17:29:20.468

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

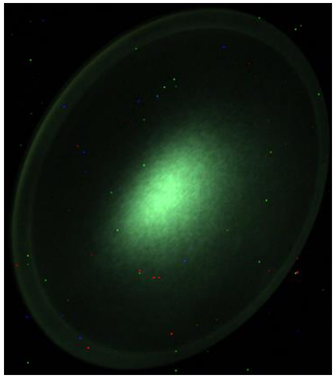
D:/BeamView/HITRAP TR1DF2_2008.10.07_17.29.20.468.png successfully written.

Scintillation Screen (beam stopped)

Light output from various Scintillating Screens

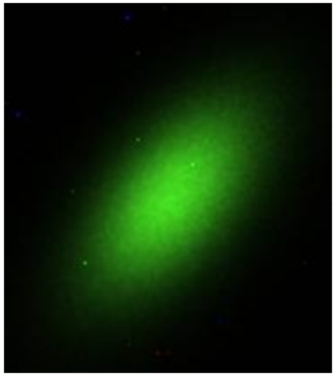
Example: Color CCD camera: Images at different particle intensities determined for U at 300 MeV/u

Alumina: Al_2O_3

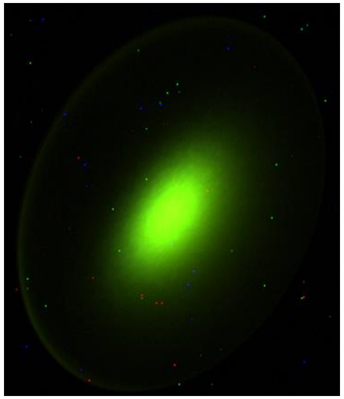


CsI:Tl

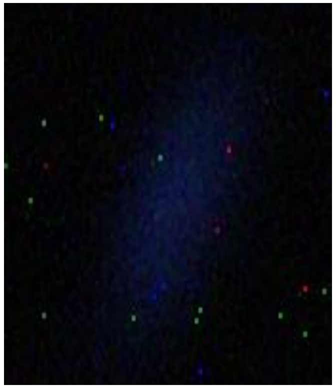
Chromox: Al_2O_3:Cr



P43

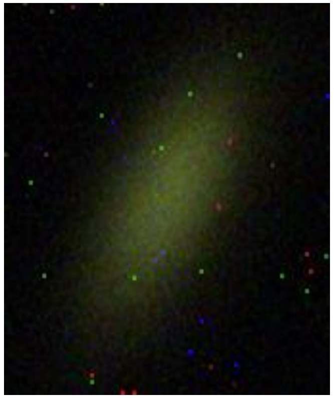


YAG:Ce



Quartz

Quartz:Ce



ZrO_2:Mg

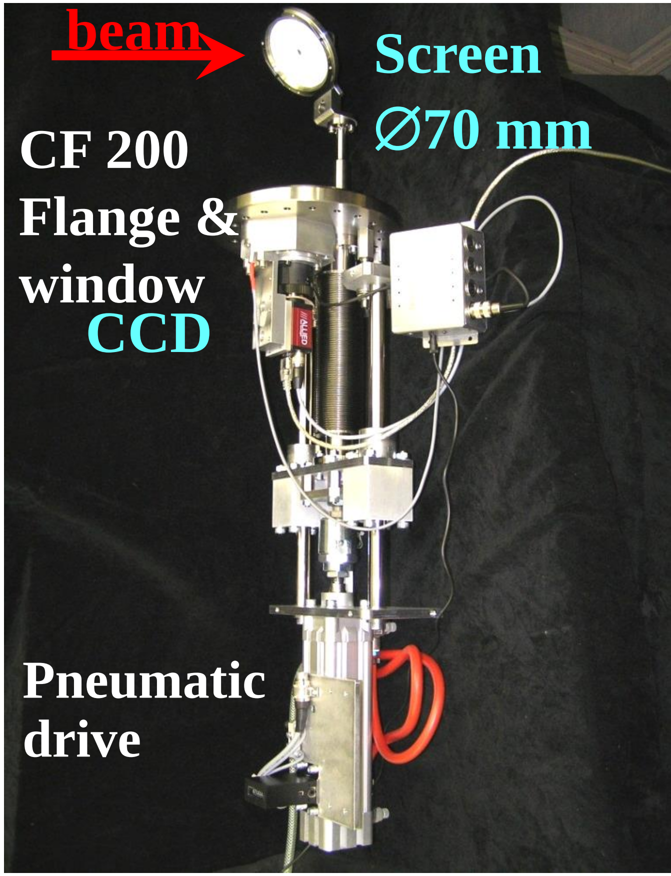
- ➢ Very different light yield i.e. photons per ion‘s energy loss
- ➢ Different wavelength of emitted light

Material Properties for Scintillating Screens

Some materials and their basic properties:

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

Standard drive with P43 screen



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).

Measurement of Beam Profile

Outline:

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

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

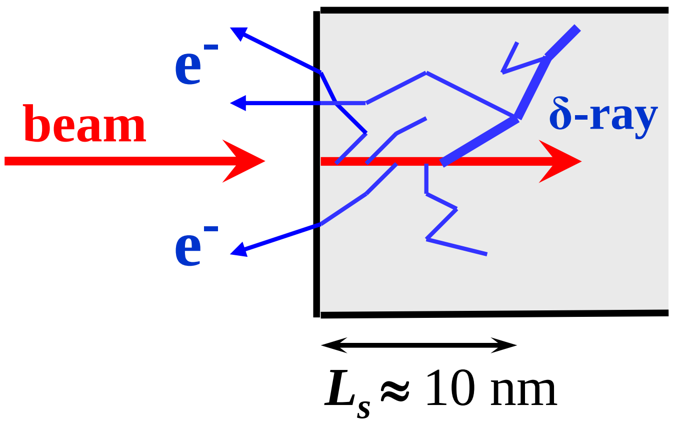
Distant collision with low energy transfer → slow e$^-$ with $E_{kin} \lesssim$ 10 eV

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

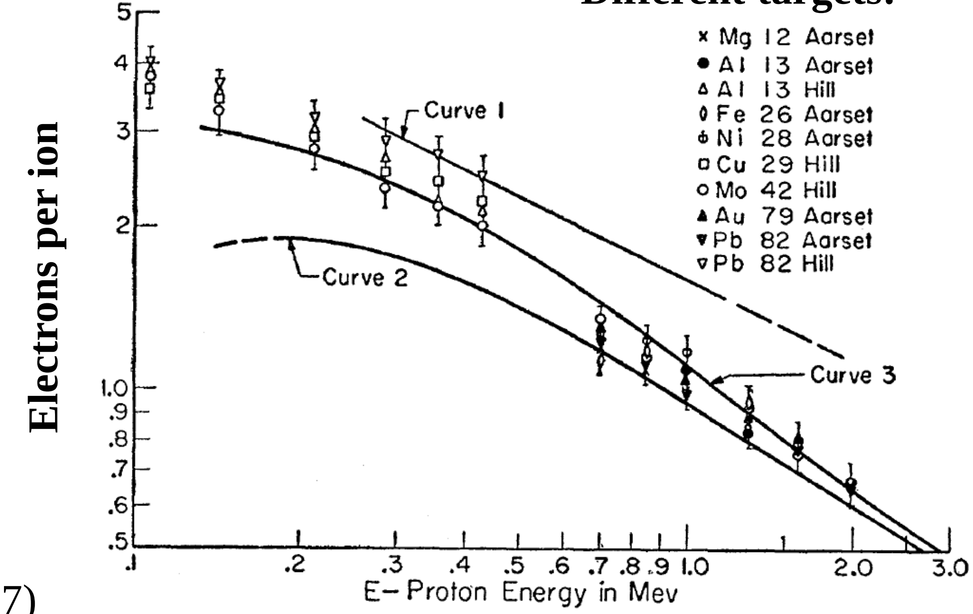
→ at surface ≈ 90 % probability for escape

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

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



Different targets:

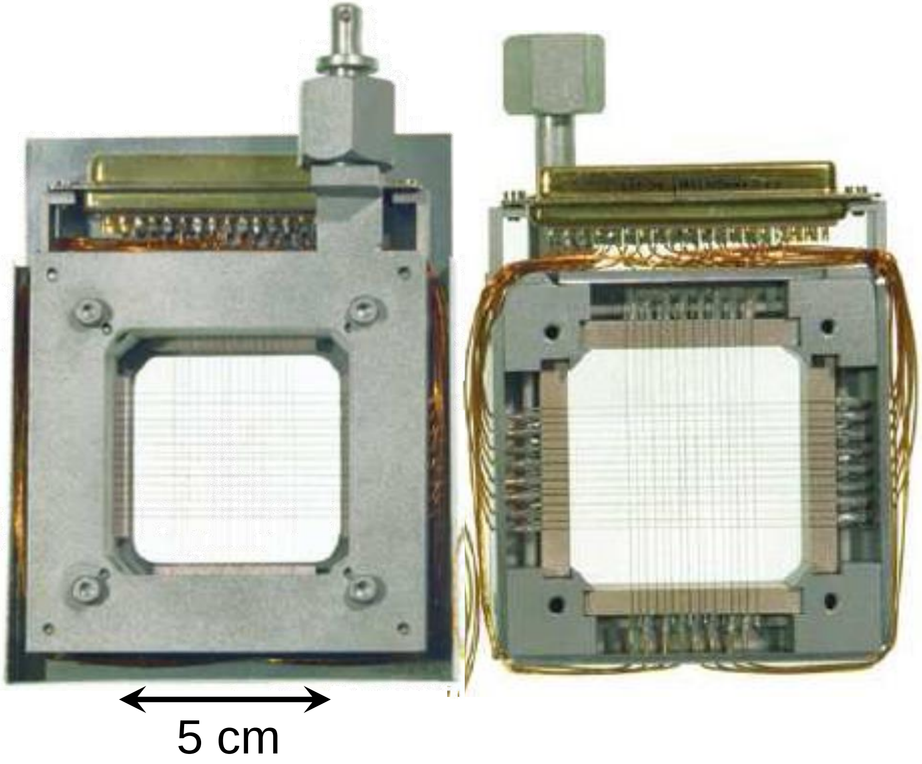


From E.J. Sternglass, Phys. Rev. 108, 1 (1957)

Secondary Electron Emission Grids = SEM-Grid

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

Example: 15 wire spaced by 1.5 mm:



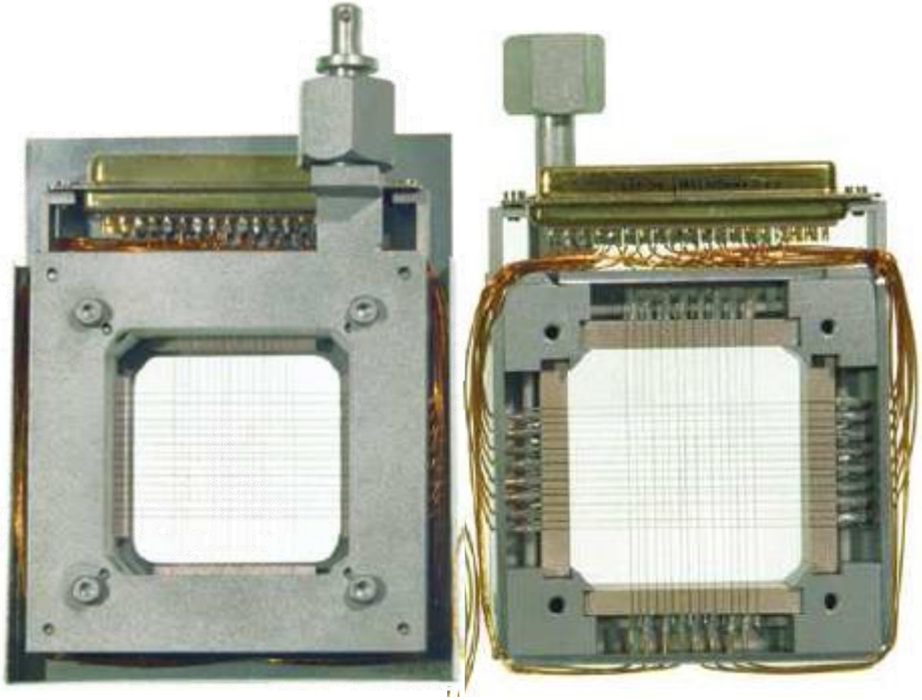
SEM-Grid feed-through on CF200:

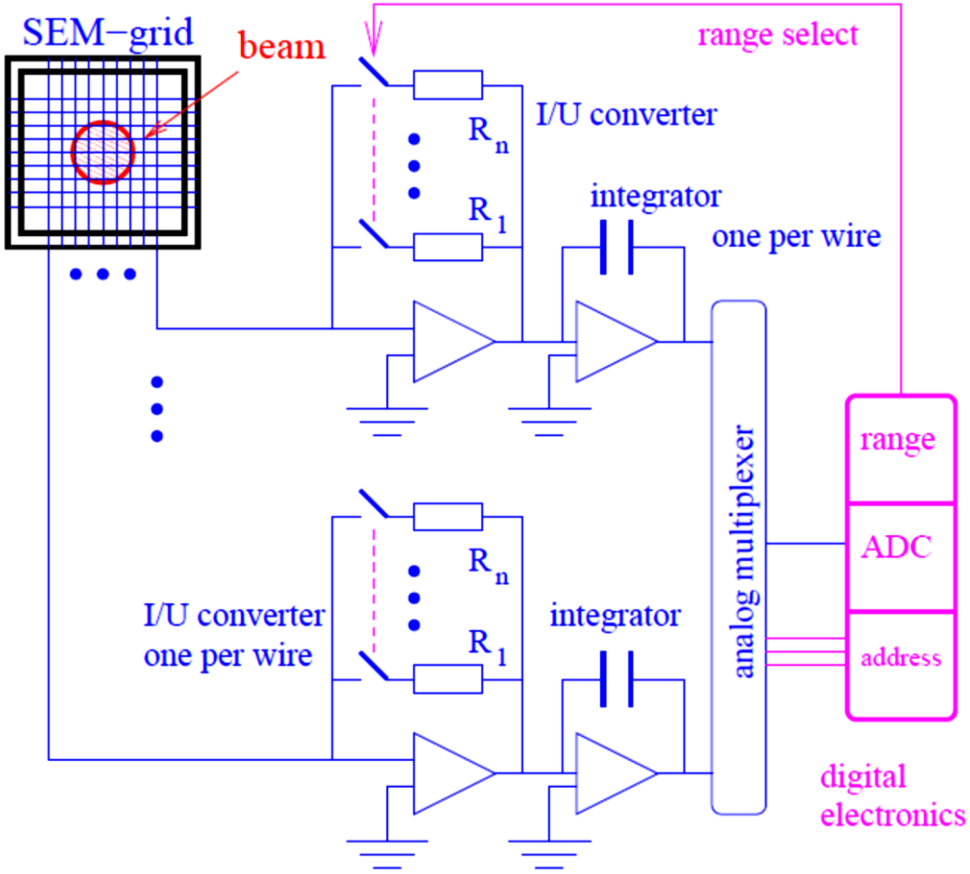
Parameter	Typ. value
# wires per plane	10 ...100
Active area	$(5...20\ \text{cm})^2$
Wire ∅	25....100 μm
Spacing	0.3...2 mm
Material	e.g. W or Carbon
Max. beam power	1 W/mm

Secondary Electron Emission Grids = SEM-Grid

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

Example: 15 wire spaced by 1.5 mm:





Each wire is equipped with one I/U converter

different ranges settings by R_i

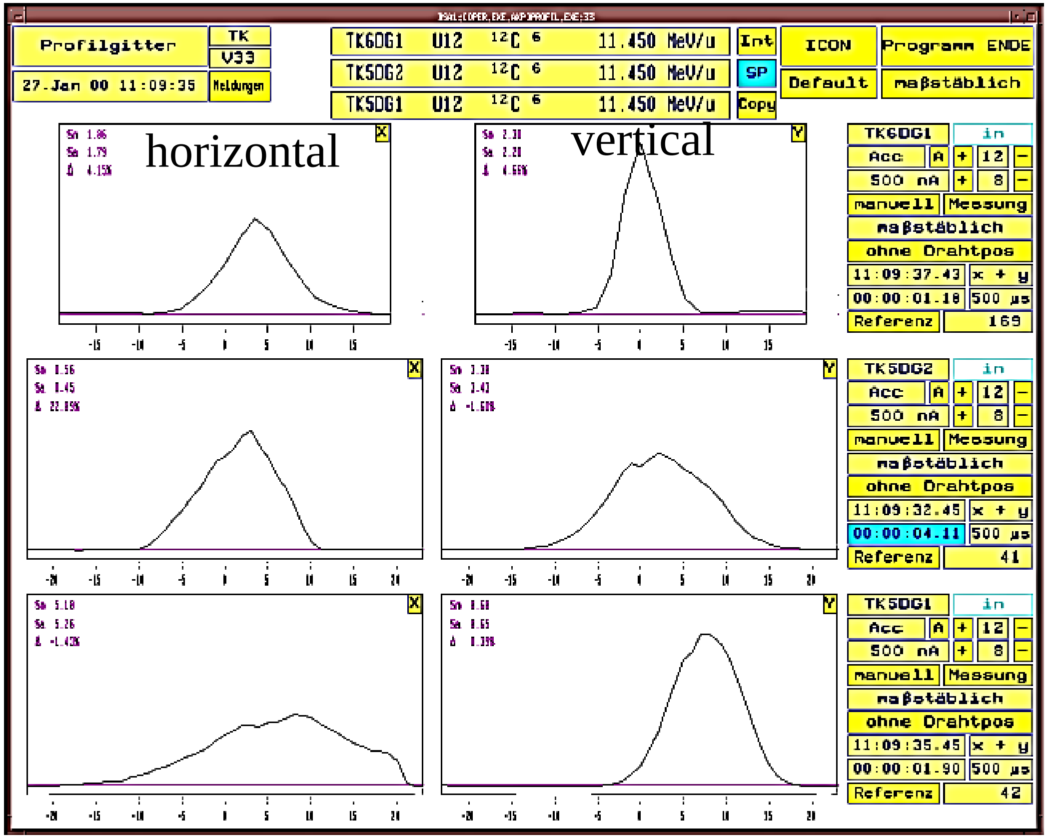
→ very large dynamic range up to 10^6.

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



Profilgitter TK V33

27.Jan 00 11:09:35

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

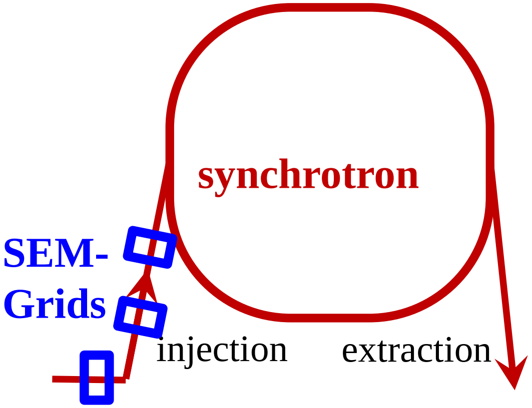
TK5DG2 U12 ^{12}C 6 11.450 MeV/u

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

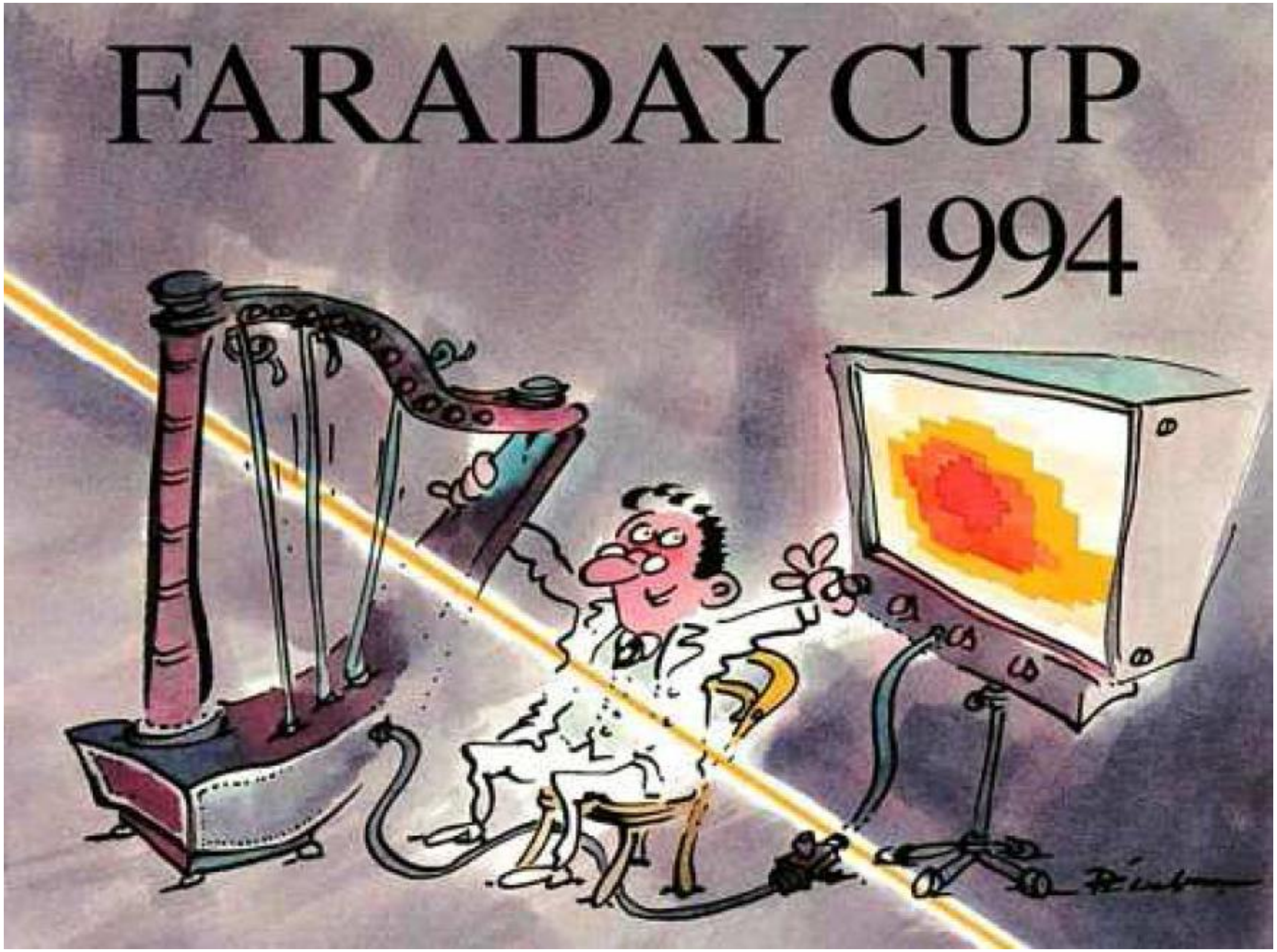
TK6DG1 in, Acc A 12, 500 nA 8, manuell Messung, maßstäblich, ohne Drahtpos, 11:09:37.43 x + y, 00:00:01.18 500 µs, Referenz 169

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

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



The Artist view of a SEM-Grid = Harp



Measurement of Beam Profile

Outline:

- Scintillation screens:
  emission of light, universal usage, limited dynamic range
- SEM-Grid: emission of electrons, workhorse, limited resolution
- Wire scanner: **emission of electrons, workhorse, scanning method**
- Ionization Profile Monitor
- Optical Transition Radiation
- Synchrotron Light Monitors
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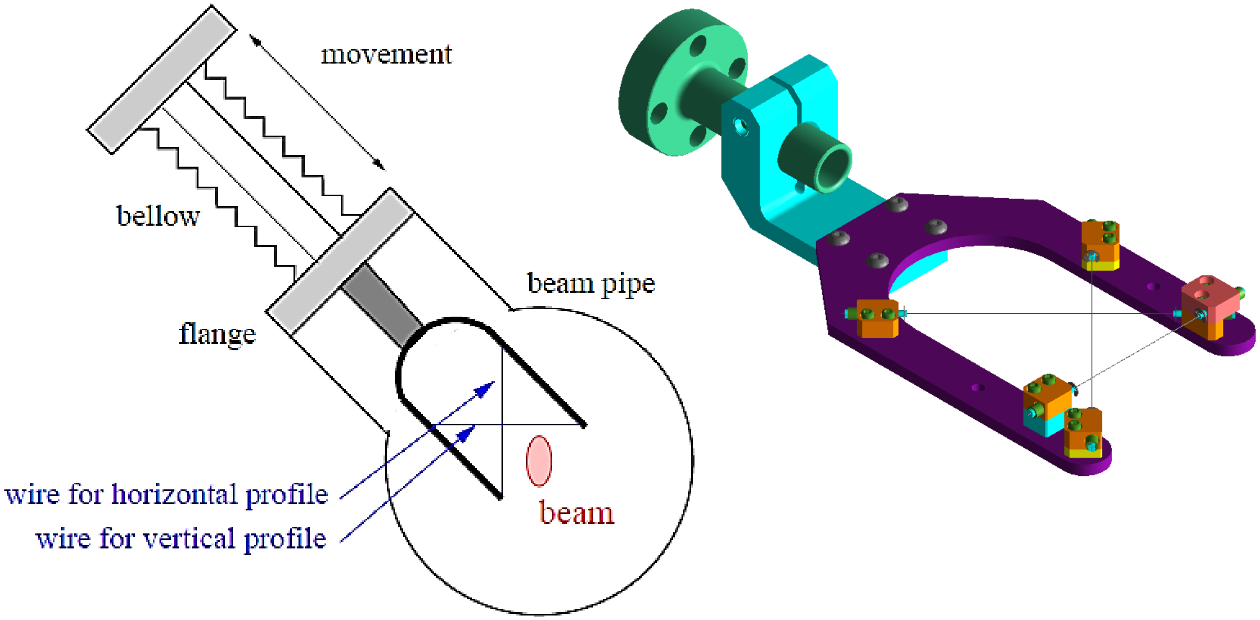
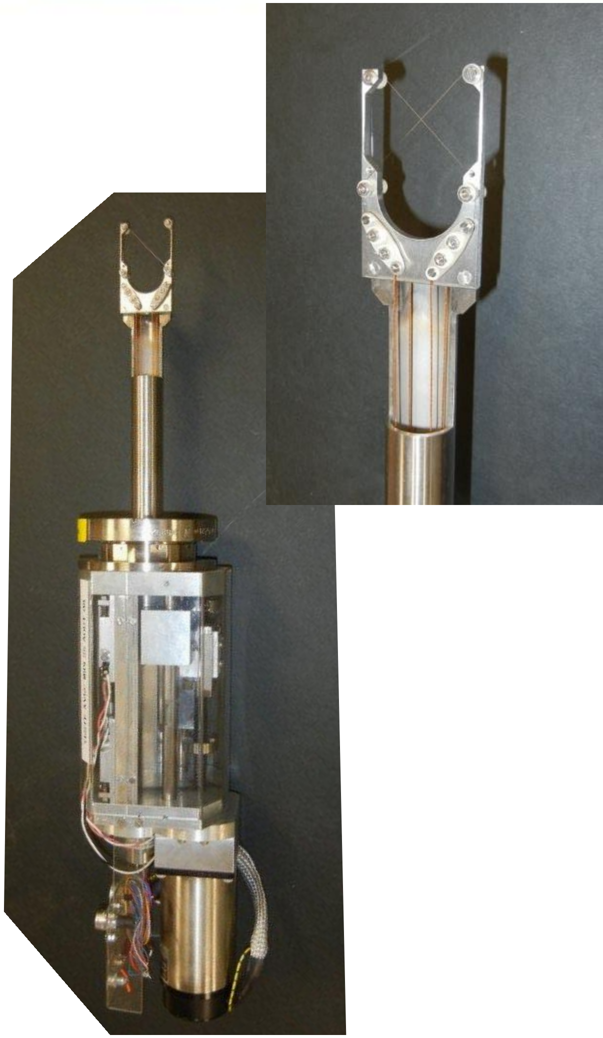
Slow, linear Wire Scanner

Idea: One wire is scanned through the beam!

Slow, linear scanner are used for:

- low energy protons
- high resolution measurements e.g. usable at e^+-e^- colliders
  by de-convolution $\sigma^2_{beam}=\sigma^2_{meas}-d^2_{wire}$
  $\Rightarrow$ resolution down to 10 μm range can be reached
- detection of beam halo.





The Artist view of a Beam Scraper or Scanner

principle plus another article describing the performance.

Eligibility

Nominations are open to candidates of any nationality for work done at any geographical location. There are no restrictions for candidates, with the only exception that they cannot be members in charge of the BIW Program Committee. In the event of deciding between works of similar quality, preference will be given to candidates in an early stage of their beam instrumentation career. The award may be shared between persons contributing to the same accomplishment. Once accepted by the Award Committee a

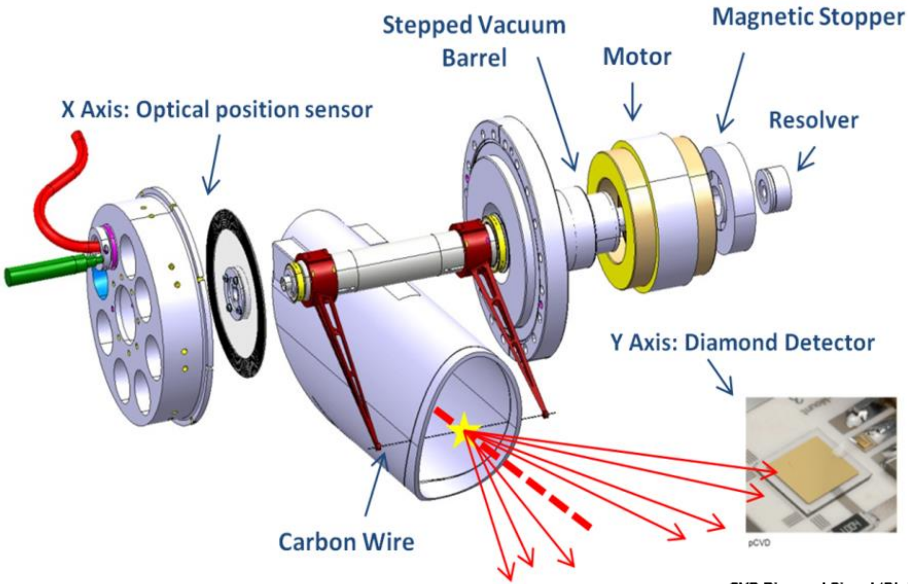
Disclosure:

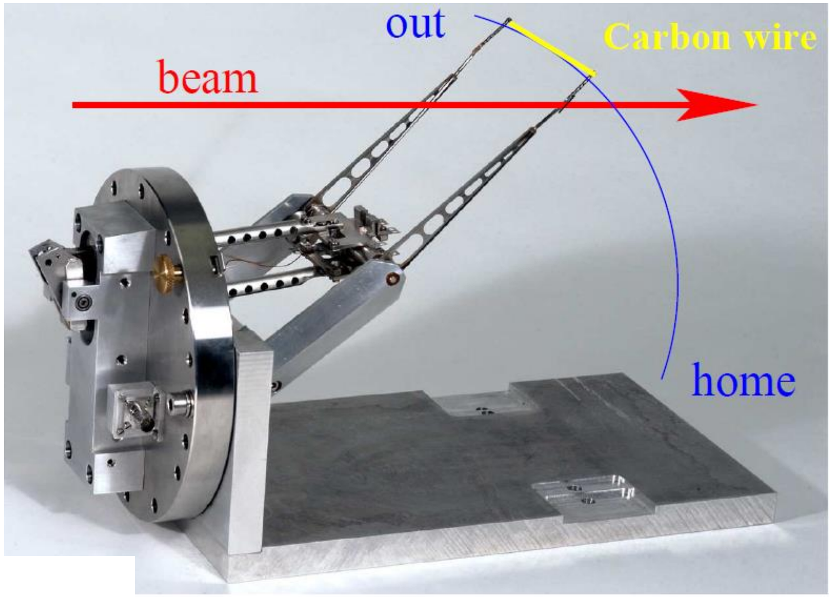
The Award Committee may release the names of entrants and a list of publications related to an entry if requested by a third party. Unpublished supporting material will not be disclosed nor will the names of persons supporting a nomination. Discussion regarding individual entries,

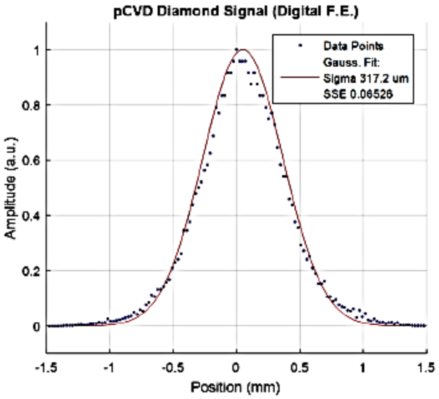
Fast, Flying Wire Scanner

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***’:







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.

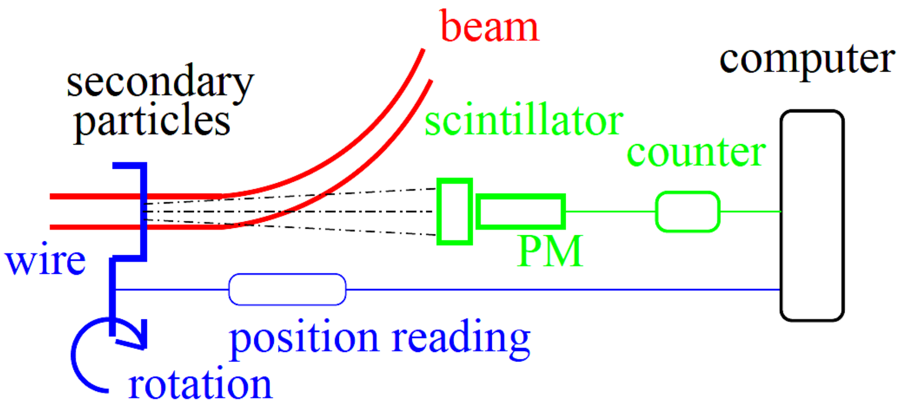
Thickness: down to 10 μm → high resolution.

Detection: Either the **secondary current** (like SEM-grid) or
high energy **secondary particles** (like beam loss monitor)
flying wire: only sec. particle detection due to induced current by movement.

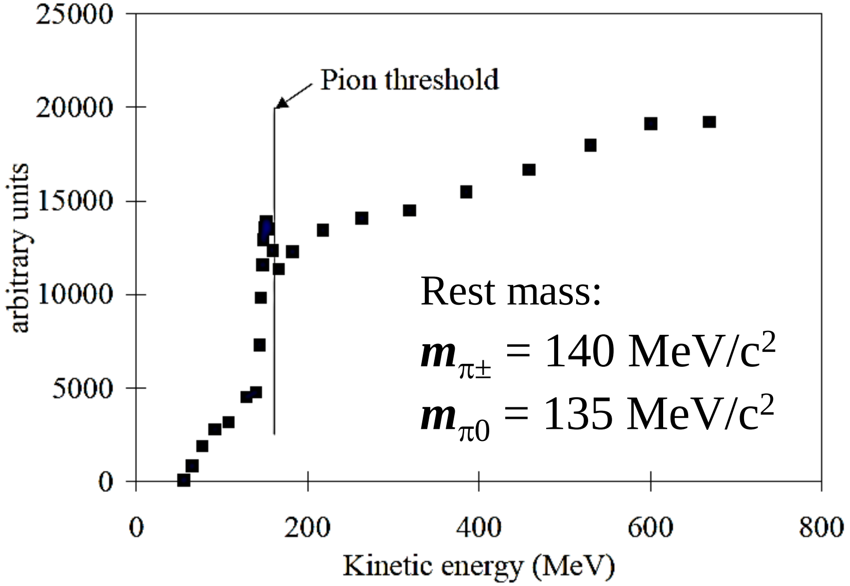
Secondary particles:

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

Electron beam → Bremsstrahlung photons.



Proton impact on scanner at CERN-PS Booster:



Rest mass:

$m_{\pi\pm} = 140$ MeV/c^2

$m_{\pi 0} = 135$ MeV/c^2

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 View of a Wire Scanner

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

Award The award consists of a $5000 prize and a certificate to be presented at the next US Beam Instrumentation Workshop which will be held at Fermi National Laboratory on May 1 - 4, 2006. Winners participating in the BIW will share a $1,000 travel allowance. The selection of recipients is the responsibility of the BIW Organizing Committee.

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

Criteria Interpretation Beam Diagnostic Instrument: A device to measure the properties of charged elementary particle, atomic or simple molecular beams during or after acceleration, or the properties of neutral particle beams produced in an intermediate state of charged particle acceleration. The device may operate by detecting secondary beams of charged, neutral, massive or mass less particles. But its purpose should be to diagnose the primary charged particle beam. The mass of primary beam particles shall be no greater than the order of 1000 atomic mass units.

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

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

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

Comparison between SEM-Grid and slow Wire Scanners

Grid: Measurement at a single moment in time

Scanner: Fast variations can not be monitored

→ for pulsed LINACs precise synchronization is needed

Grid: Not adequate at synchrotrons for stored beam parameters

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

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Grid: Resolution of a grid is fixed by the wire distance (typically 1 mm)

Scanner: For slow scanners the resolution is about the wire thickness (down to 10 µm)

→ used for e−-beams having small sizes (down to 10 µm)

Grid: Needs one electronics channel per wire

→ expensive electronics and data acquisition

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

Measurement of Beam Profile

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  emission of light, universal usage, limited dynamic range
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- Wire scanner: emission of electrons, workhorse, scanning method
- Ionization Profile Monitor:

  secondary particle detection from interaction beam-residual gas
- Optical Transition Radiation
- Synchrotron Light Monitors
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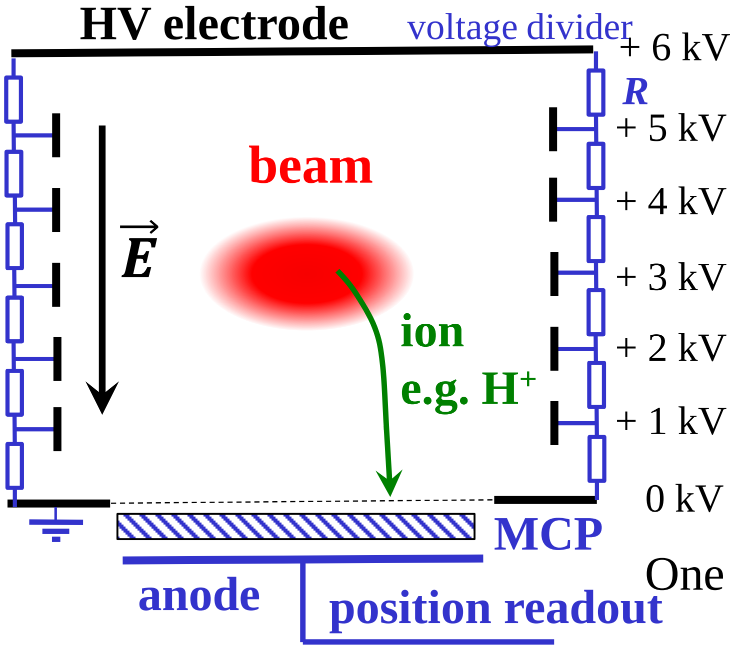
Ionization Profile Monitor at GSI Synchrotron

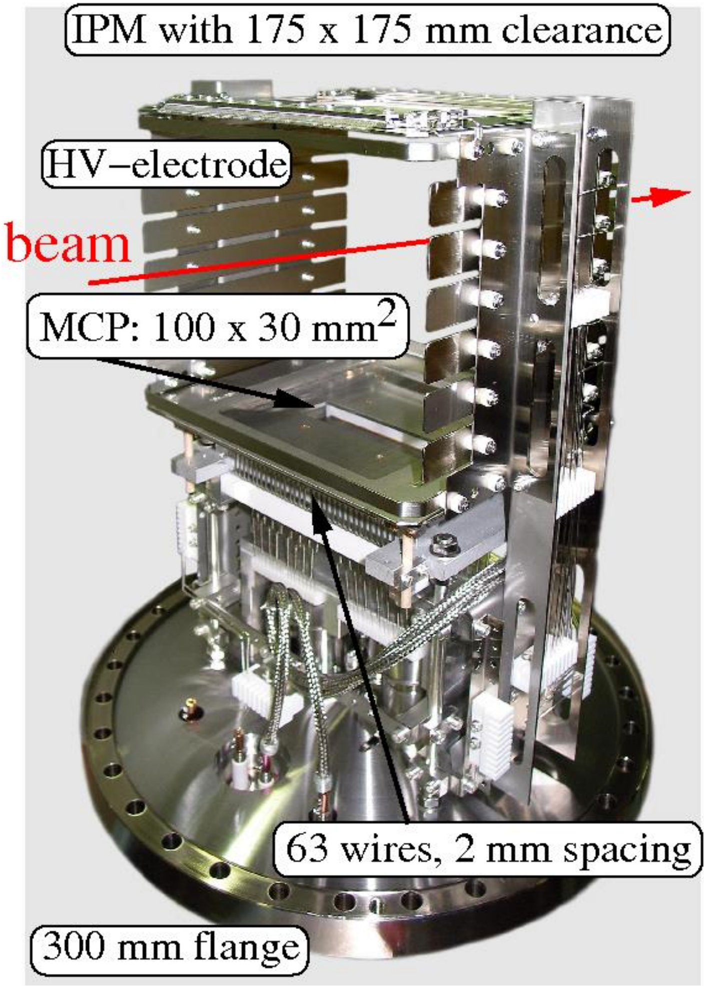
Non-destructive device for proton synchrotron:

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



One device per plane

Realization at GSI synchrotron:



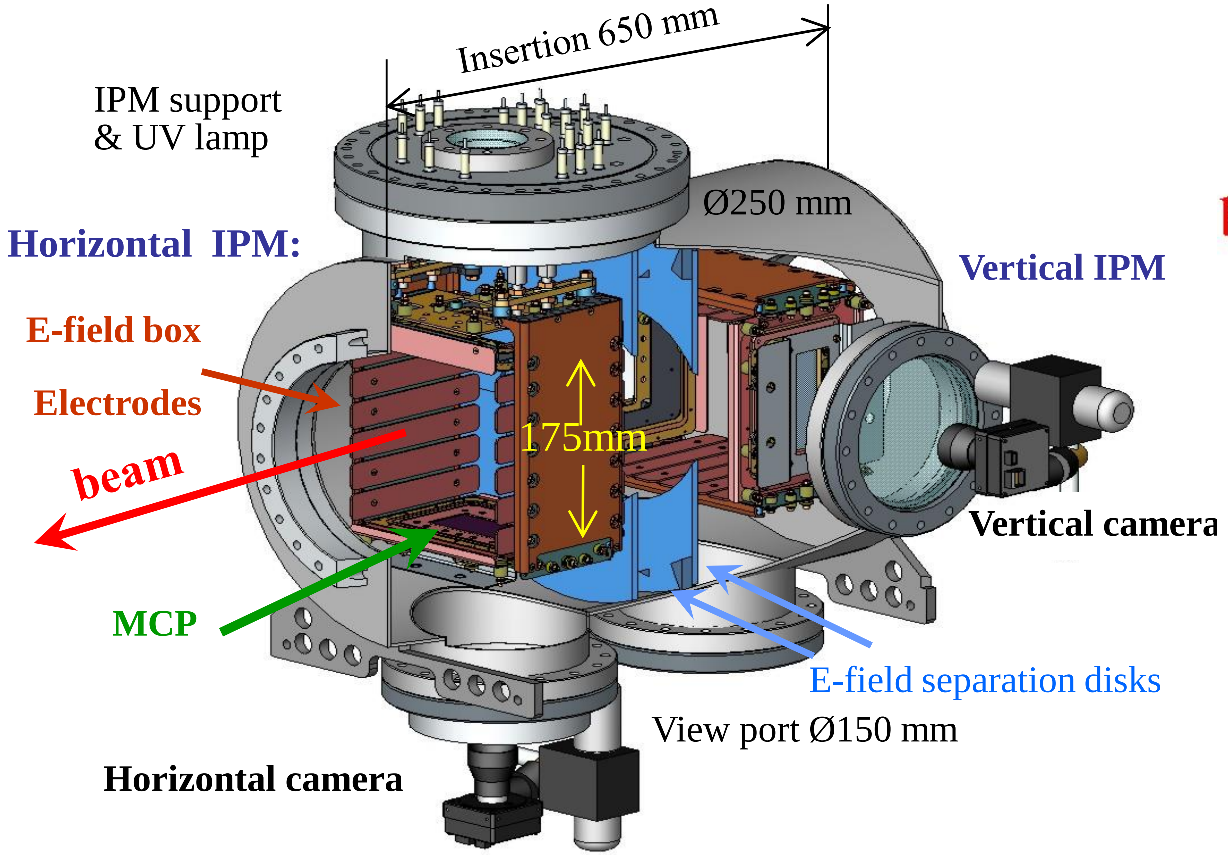
Typical vacuum pressure:

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

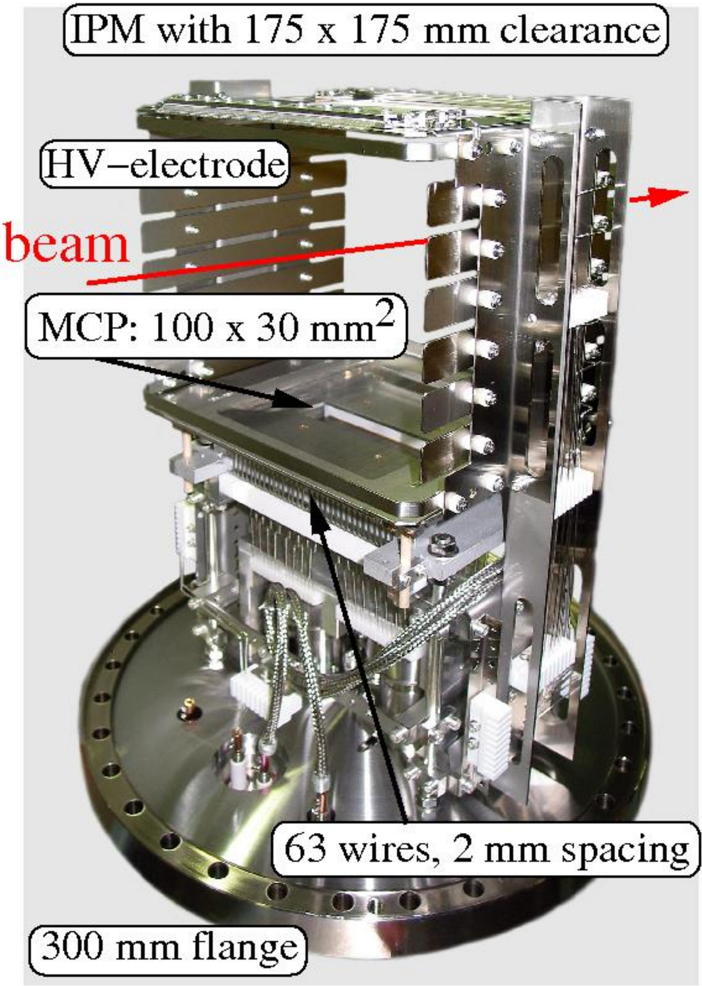
Synchrotron: H_2 $10^{-11}...10^{-9}$ mbar $\simeq 3\cdot10^5...3\cdot10^7$cm^{-3}

Ionization Profile Monitor Realization

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



Realization at GSI synchrotron:



Ionization Profile Monitor Realization

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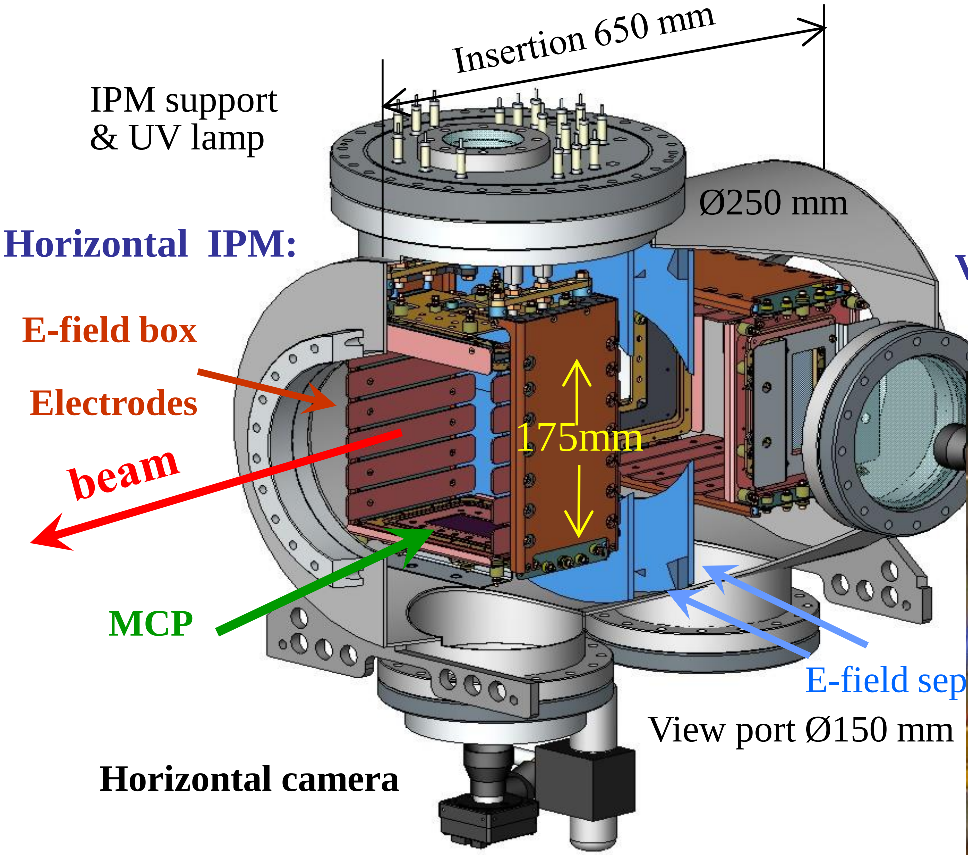


Insertion 650 mm

IPM support
& UV lamp

Ø250 mm

Horizontal IPM:

Vertical IPM

E-field box

Electrodes

beam

175mm

MCP

E-field sep

View port Ø150 mm

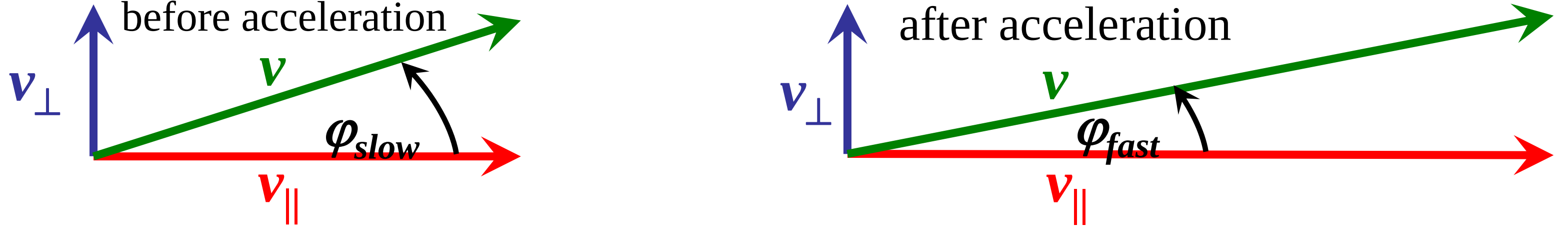
Horizontal camera

Realization at GSI synchrotron:

→ IPM measure

'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 ⇒ angle φ is smaller

The angle is expressed in momenta: $x' = p_\perp / p_\parallel$ the emittance is $\langle xx' \rangle = 0$: $\varepsilon = x \cdot x' = x \cdot p_\perp / p_\parallel$

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

⇒ normalized emittance $\varepsilon_{norm} = \beta\gamma \cdot \varepsilon$ is preserved with the Lorentz factor γ and velocity $\beta = v/c$

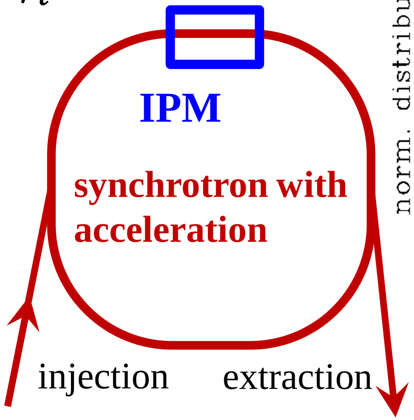
Example: Acceleration in GSI-synchrotron for C^{6+} from 6.7 → 600 MeV/u (β = 12 → 79 %) observed by IPM

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

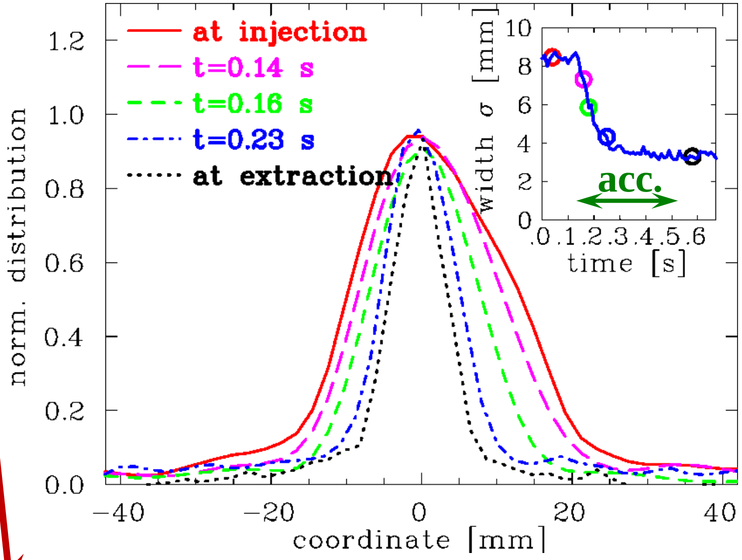
IPM is well suited
for long time observations
without beam disturbance
→ mainly used at proton synchrotrons.



IPM

synchrotron with acceleration

injection extraction



→ OTR

Injection Matching into a Synchrotron: Phase Space Mismatch

Ideal case of injection matching:

Orientation of injected beam matches phase space as given by synchrotron Twiss parameters α, β, and γ i.e. 'machine emittance'

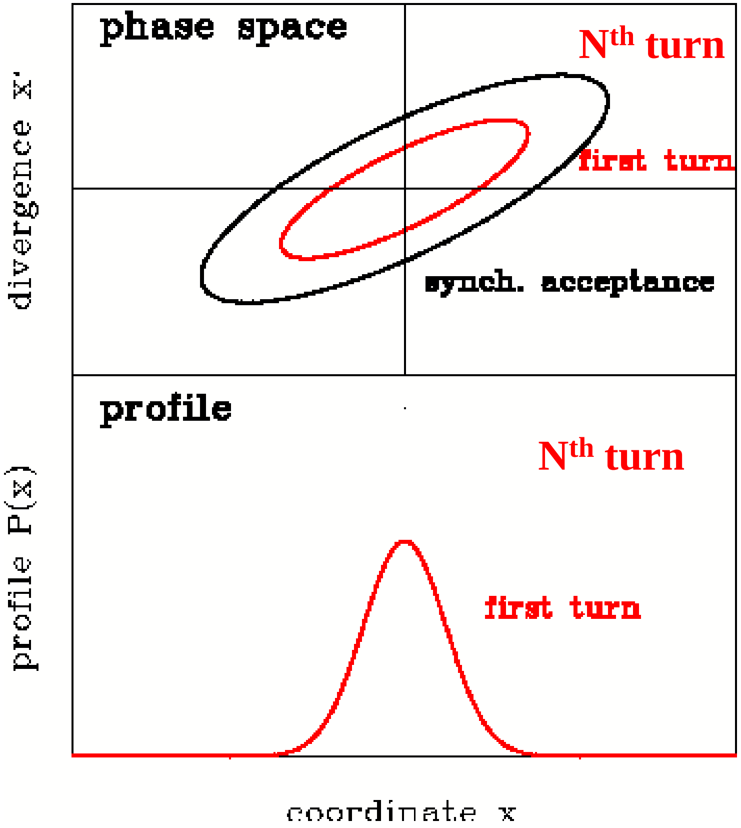
⇔ no change after each turn ⇔ stable storage

⇔ The beam ellipse $\boldsymbol{\sigma}_{beam}$ correspond to the machine ellipse at injection point for ***N***=0 i.e.

$$\boldsymbol{\sigma}_{beam}(N=0) = \varepsilon_{beam}\begin{pmatrix} \beta_{synch} & -\alpha_{synch} \\ -\alpha_{synch} & \gamma_{synch} \end{pmatrix}$$

⇒ **only in this case stable storage** (math: $t \rightarrow \infty$)

$$\boldsymbol{\sigma}_{beam}(N=0) = \boldsymbol{\sigma}_{beam}(N \rightarrow \infty)$$



Injection Matching into a Synchrotron: Phase Space Mismatch

Ideal case of injection matching:

Orientation of injected beam matches phase space as given by synchrotron Twiss parameters α, β, and γ i.e. 'machine emittance'

⇔ no change after each turn ⇔ stable storage

Mismatched case:

- The beam ellipse $\boldsymbol{\sigma}_{beam}$ has different orientation as machine ellipse at injection point for N=0 i.e.
- Transformation after one turn

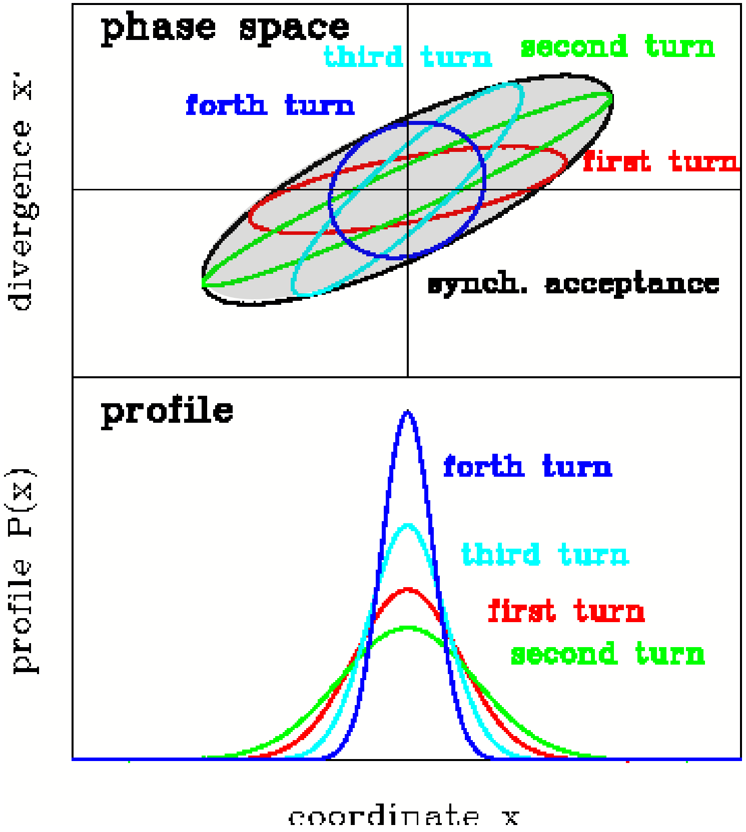
$$\boldsymbol{\sigma}_{beam}(N=1) = \mathbf{M}\boldsymbol{\sigma}_{beam}(N=0)\,\mathbf{M}^T$$
$$\neq \quad \boldsymbol{\sigma}_{beam}(N=0)$$

i.e. rotation in phase space by the tune

i.e. phase advance per turn

Depictive argument: A particle on both ellipses

Observable quantity: Beam profile oscillates



After many turns:

Particle have different tunes e.g. by longitudinal momentum deviation and chromaticity $\frac{\Delta Q}{Q_0} = \xi \cdot \frac{\Delta p}{p_0}$

or space charge ΔQ_{incoh} ⇒ Entire transverse phase space is filled i.e. beam with enlarged emittance

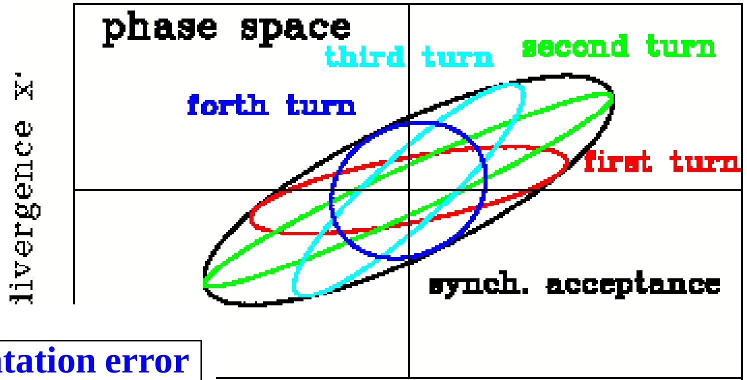
Injection Matching into a Synchrotron: Phase Space Mismatch

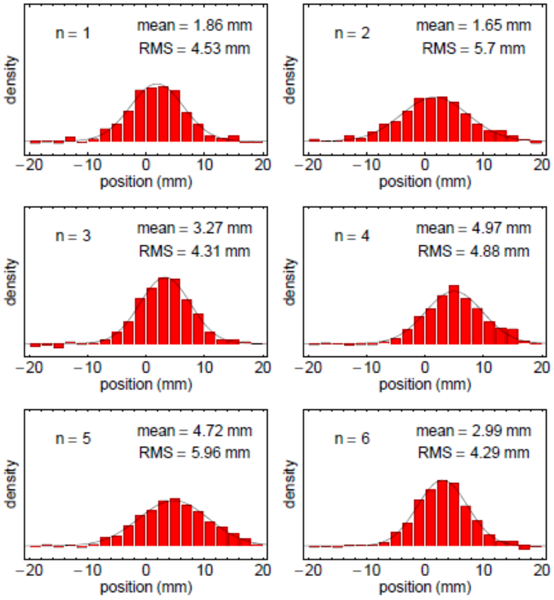
Mis-matched injection into a synchrotron:

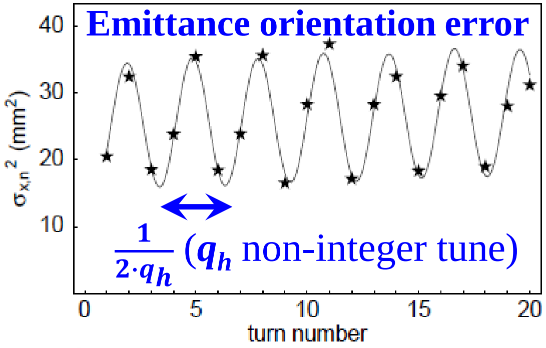
Can be monitored by beam profile measurement:

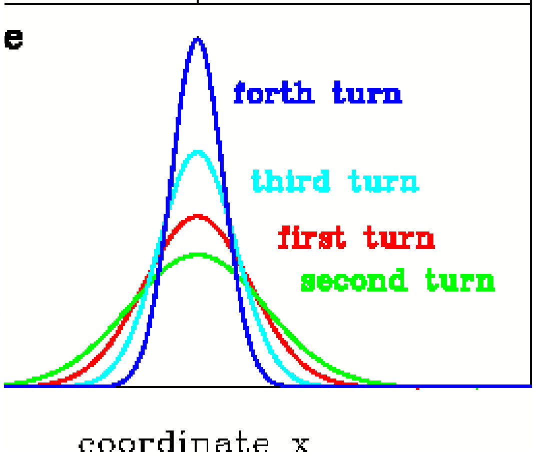
Example: Injection of a 80 ns bunch of protons into CERN PS at 1.4 GeV/u (2.2 μs revolution time)
Profile measurement by SEM-Grid

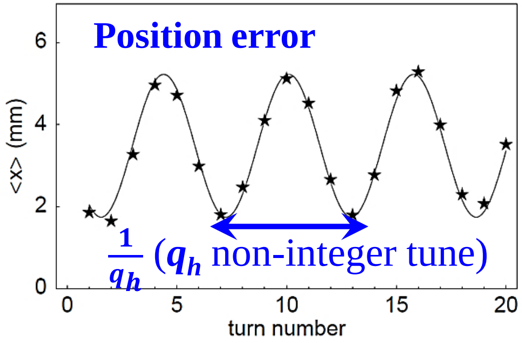
- Turn-by-turn profile variation related to tune
- Used for improvement of injection parameters











From M. Benedikt et al., DIPAC 2001

Measurement of Beam Profile

Outline:

- Scintillation screens:

  emission of light. universal usage, limited dynamic range
- SEM-Grid: emission of electrons, workhorse, limited resolution
- Wire scanner: emission of electrons, workhorse, scanning method
- Ionization Profile Monitor:

  secondary particle detection from interaction beam-residual gas
- Optical Transition Radiation:

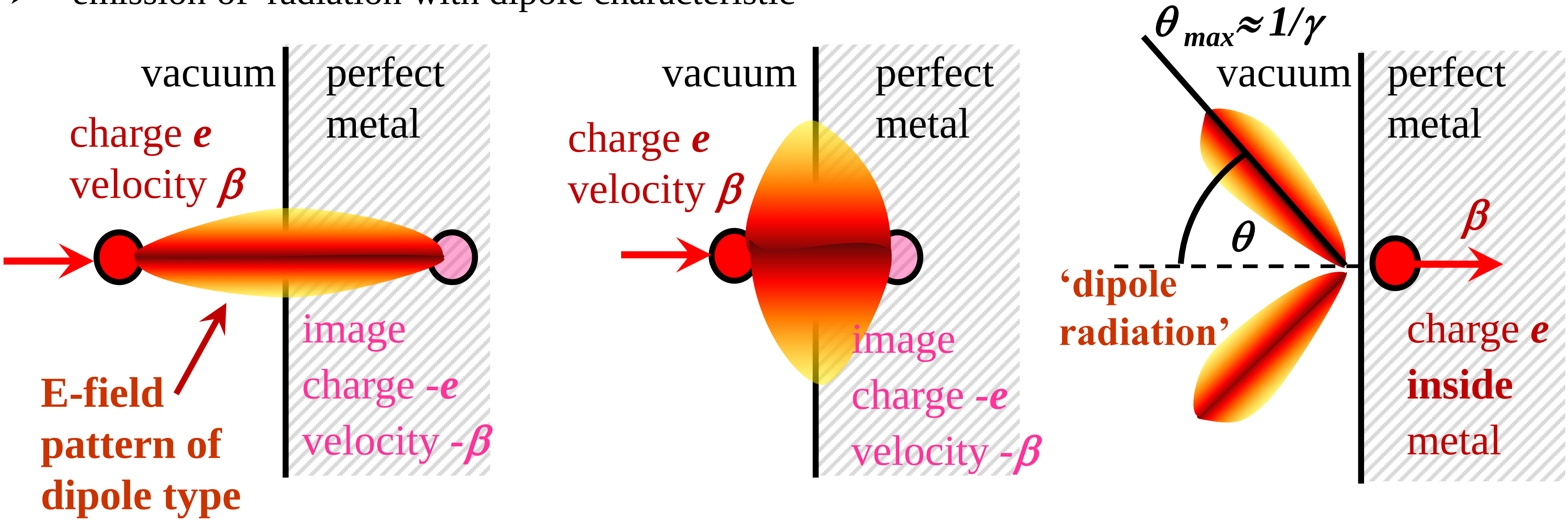
  crossing material boundary, for relativistic beams only
- Synchrotron Light Monitors
- Summary

Optical Transition Radiation: Depictive Description

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

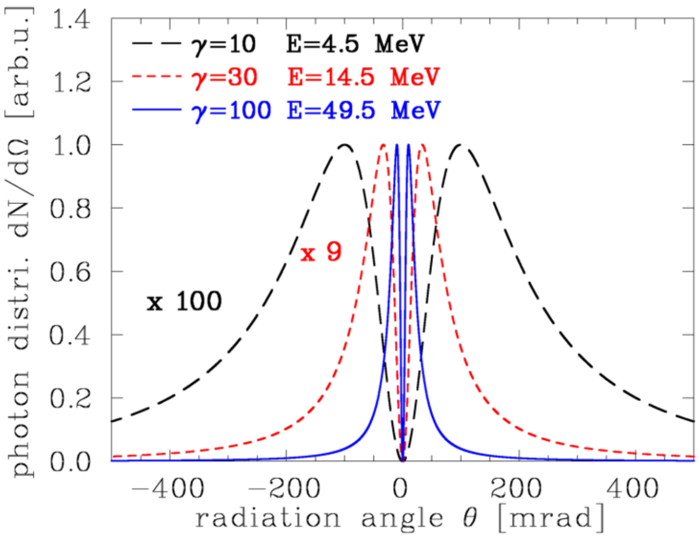
Optical Transition Radiation OTR can be described in classical physics:

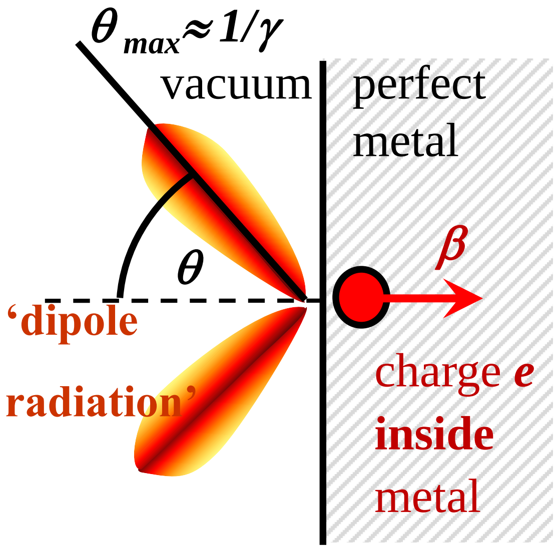
approximated formula
for normal incidence
& in-plane polarization:

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

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 $\boldsymbol{\theta \approx 1/\gamma}$
- emitted energy i.e. amount of photons scales with $\boldsymbol{W \propto \beta^2}$
- broad wave length spectrum (i.e. no dependence on $\boldsymbol{\omega}$)

→ suited for high energy electrons

sudden change charge distribution
rearrangement of sources ⇔ radiation

Technical Realization of Optical Transition Radiation OTR

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}

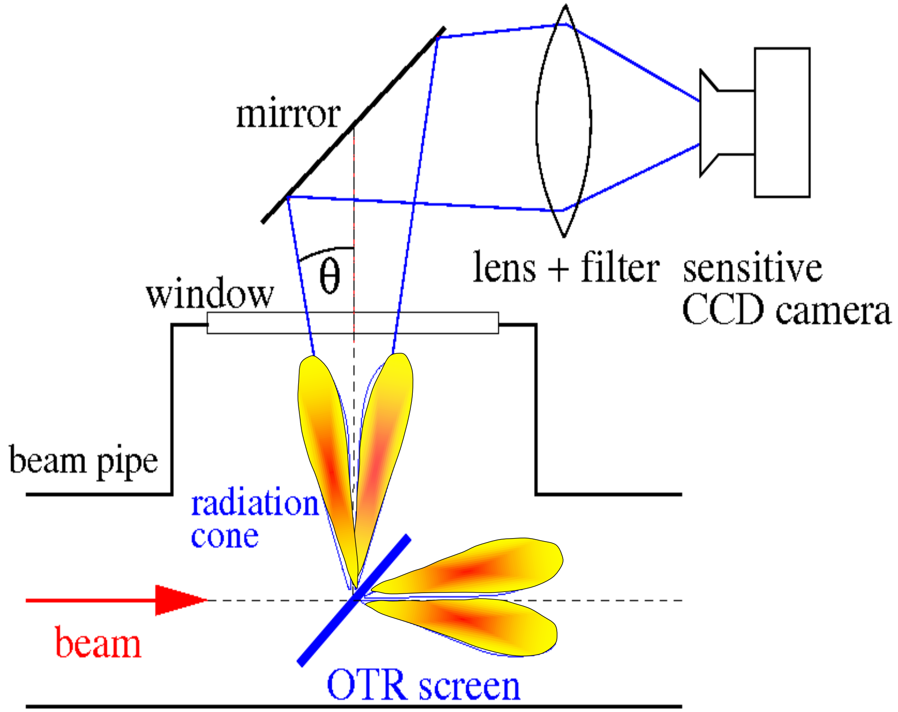
$$\frac{dN_{photon}}{d\Omega} = N_{beam} \cdot \frac{2e^2\beta^2}{\pi c} \cdot \log\left(\frac{\lambda_{begin}}{\lambda_{end}}\right) \cdot \frac{\theta^2}{\left(\gamma^{-2}+\theta^2\right)^2}$$

- Detection: Optical 400 nm < λ < 800 nm

  using image intensified CCD
- Larger signal for relativistic beam $\gamma >> 1$
- Low divergence for $\gamma >> 1 \Rightarrow$ large signal

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

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



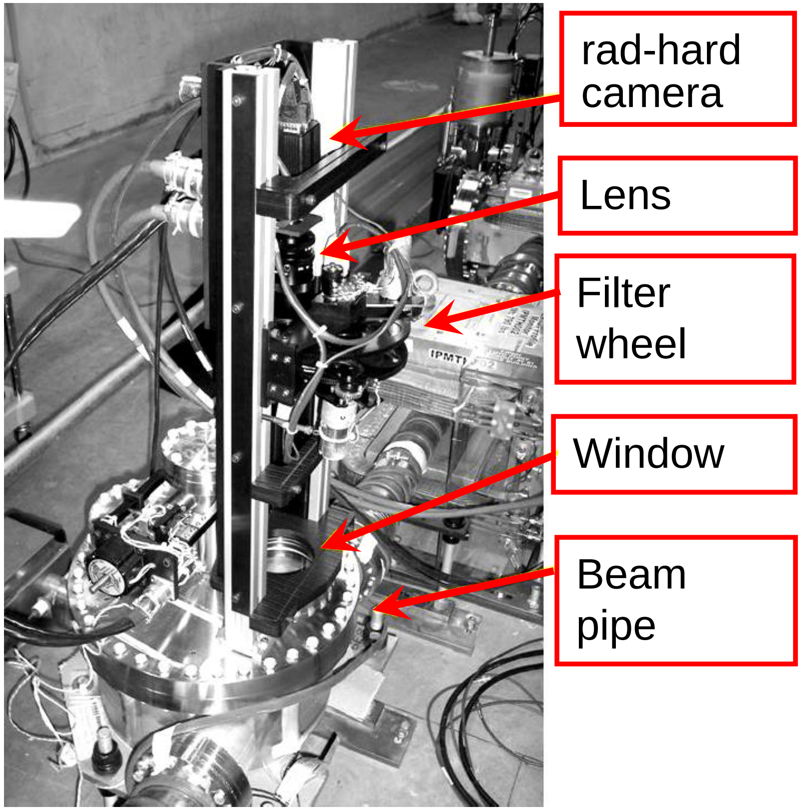
- Insertion of thin Al-foil under 45^o
- Observation of low light by CCD.

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



rad-hard camera

Lens

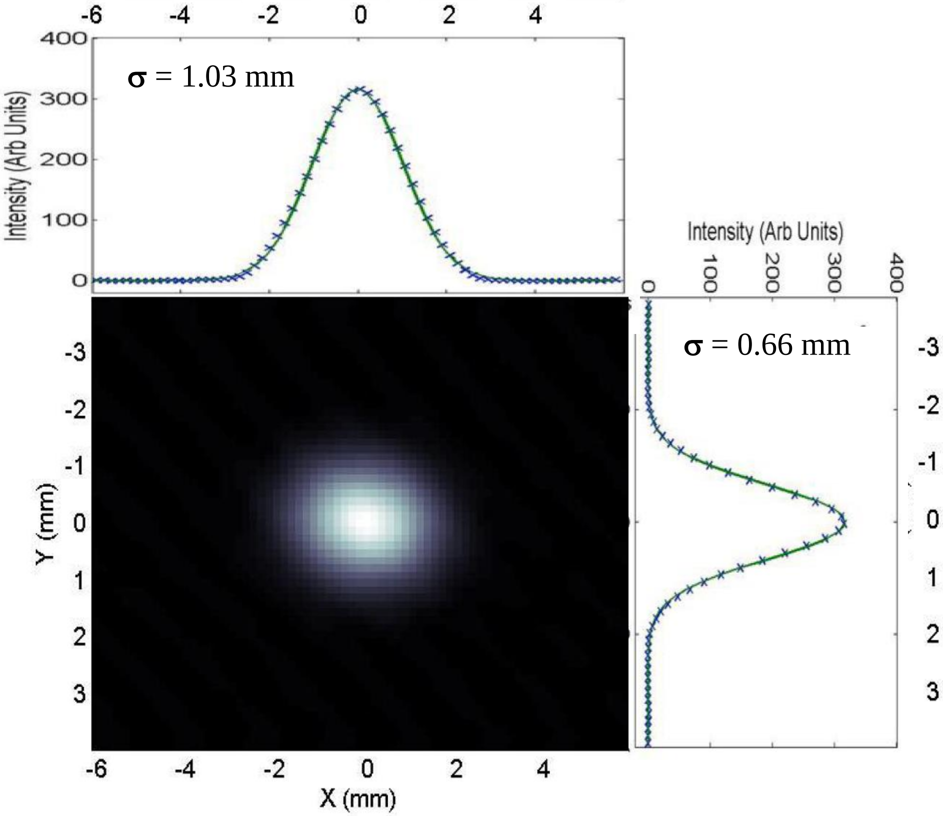
Filter wheel

Window

Beam pipe

Results at FNAL-TEVATRON synchrotron with 150 GeV proton

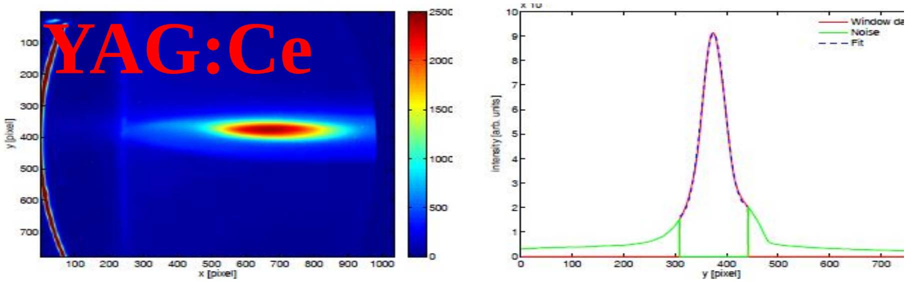
Using fast camera: Turn-by-turn measurement

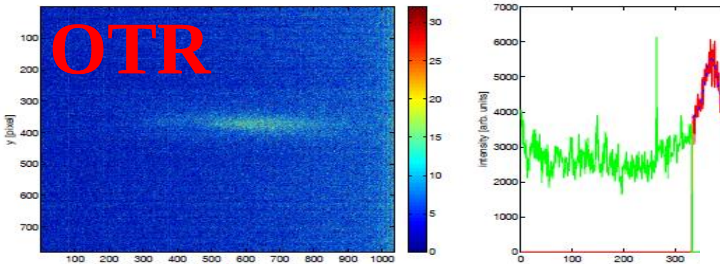


Courtesy V.E. Scarpine (FNAL) et al., BIW’06

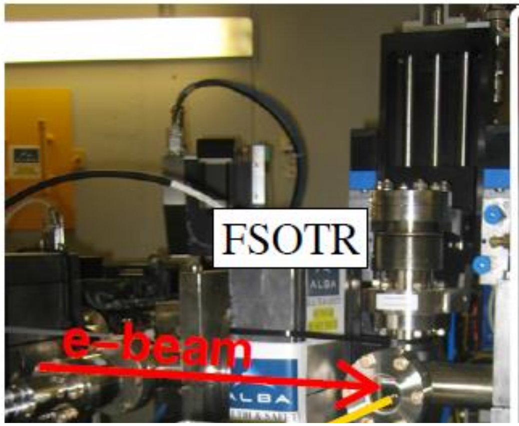
Optical Transition Radiation compared to Scintillation Screen

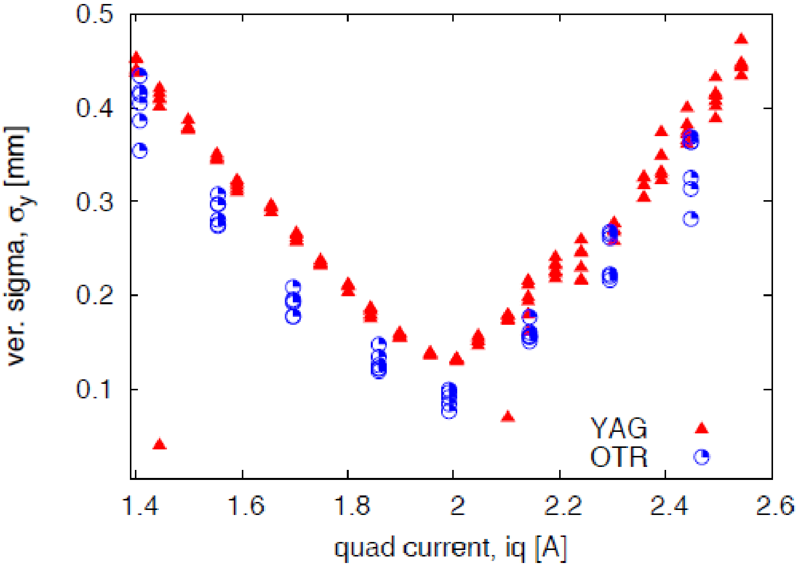
Installation of OTR and scintillation screens on same drive :





Example: ALBA LINAC 100 MeV





Results:

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

Courtesy of U. Iriso et al., DIPAC’09

Comparison between Scintillation Screens and OTR

OTR: electrodynamic process → beam intensity linear to # photons, high radiation hardness

Scint. Screen: complex atomic process → saturation possible, for some low radiation hardness

---

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

Measurement of Beam Profile

Outline:

- Scintillation screens:

  emission of light, universal usage, limited dynamic range
- SEM-Grid: emission of electrons, workhorse, limited resolution
- Wire scanner: emission of electrons, workhorse, scanning method
- Ionization Profile Monitor:

  secondary particle detection from interaction beam-residual gas
- Optical Transition Radiation:

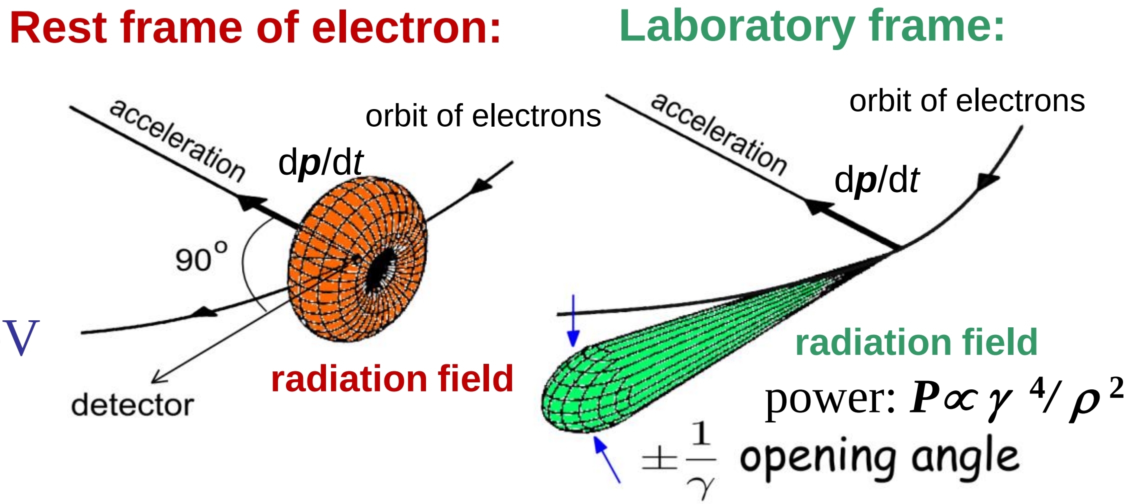
  crossing optical boundary, for relativistic beams only
- Synchrotron Light Monitors

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

Synchrotron Light Monitor

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

This light is emitted
into a cone of
opening 2/γ in lab-frame.
⇒Well suited for rel. e^-
For protons:
Only for energies $E_{kin} > 100$ GeV

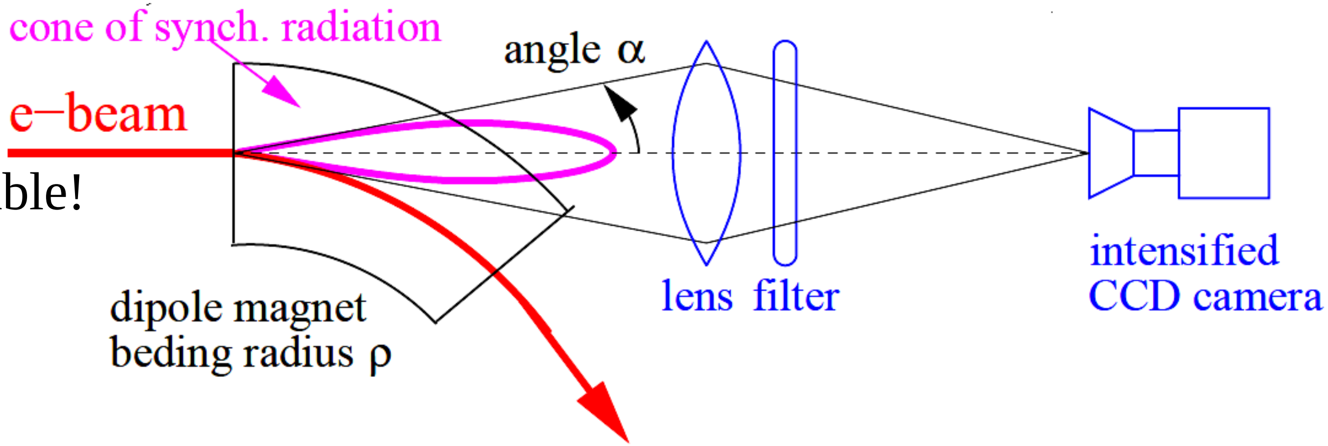

Rest frame of electron:

Laboratory frame:

The light is focused to a intensified CCD.

Advantage:

Signal anyhow available!



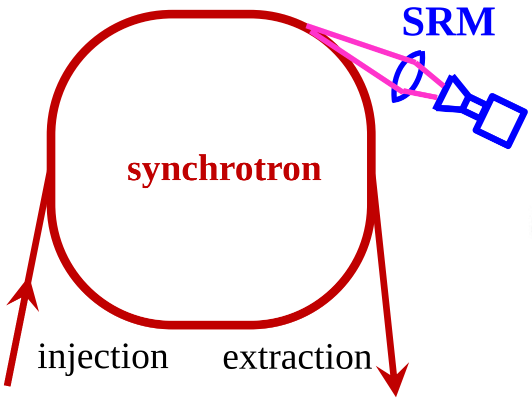
Realization of a Synchrotron Light Monitor

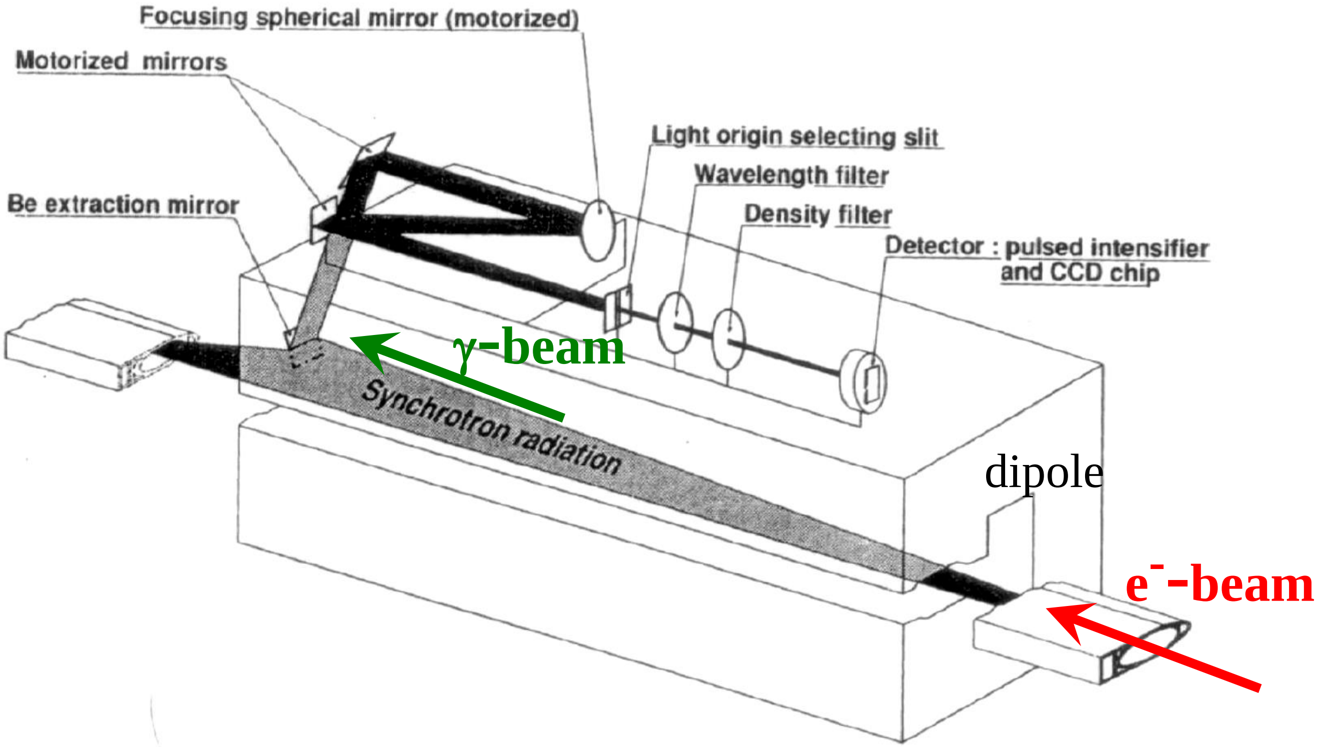
Extracting out of the beam’s plane by a (cooled) mirror

→ Focus to a slit + wavelength filter for optical wavelength

→ Image intensified CCD camera

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

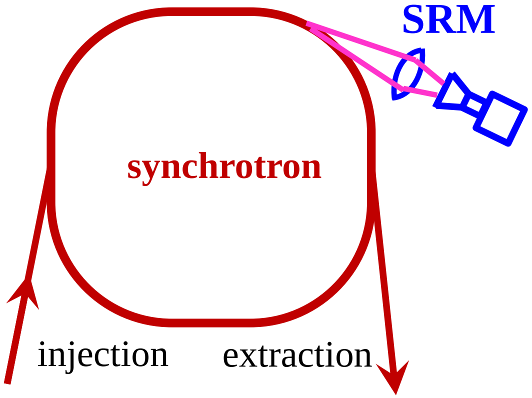


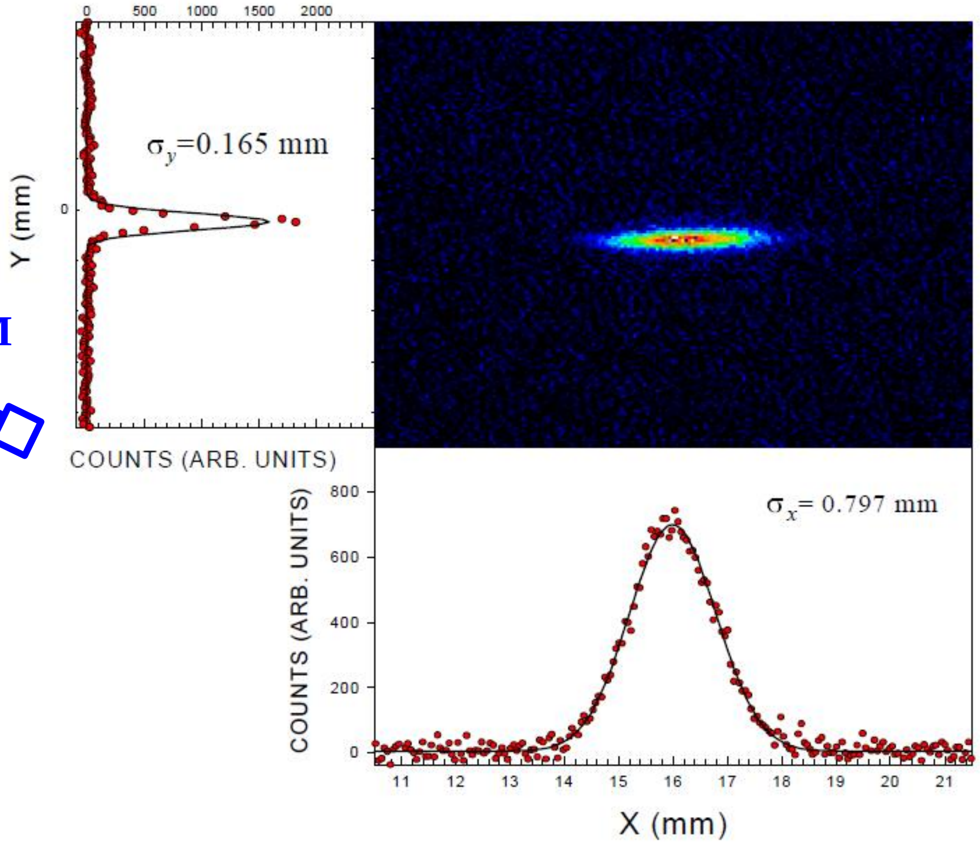


Courtesy C. Bovet (CERN) et al., PAC’91

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

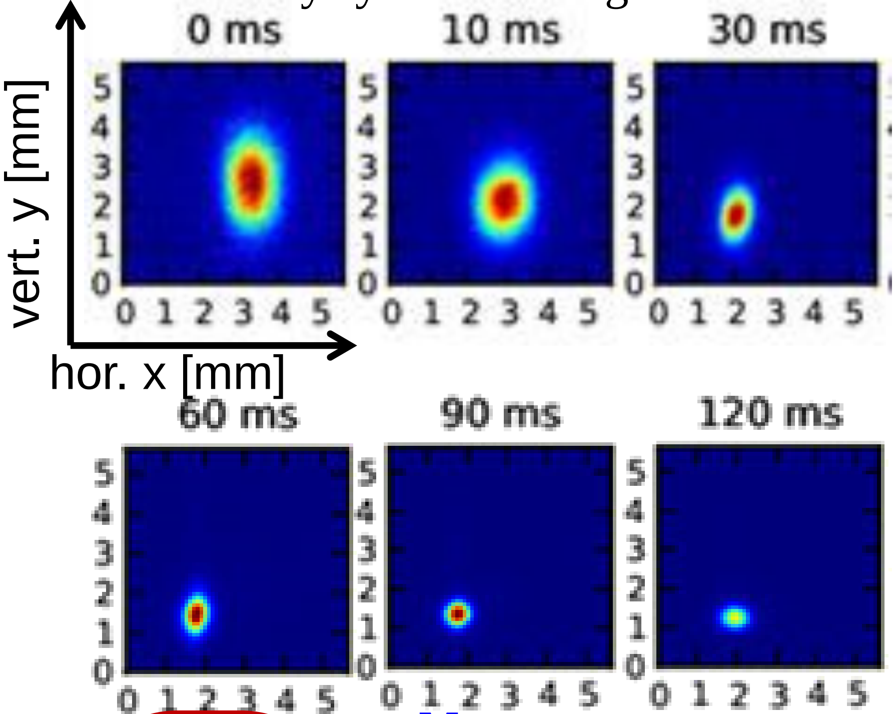
Realization: Optics outside of vacuum pipe

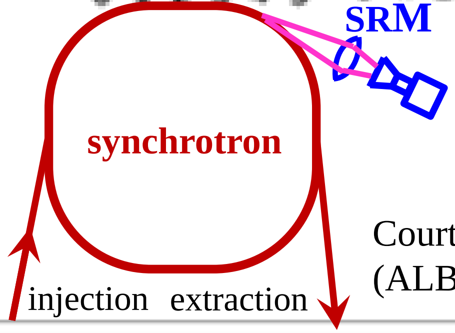
Disadvantage: Resolution limited by the diffraction due to finite apertures in the optics.

Adiabatic Damping for an Electron Beam

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

Profile measure by synchrotron light monitor:



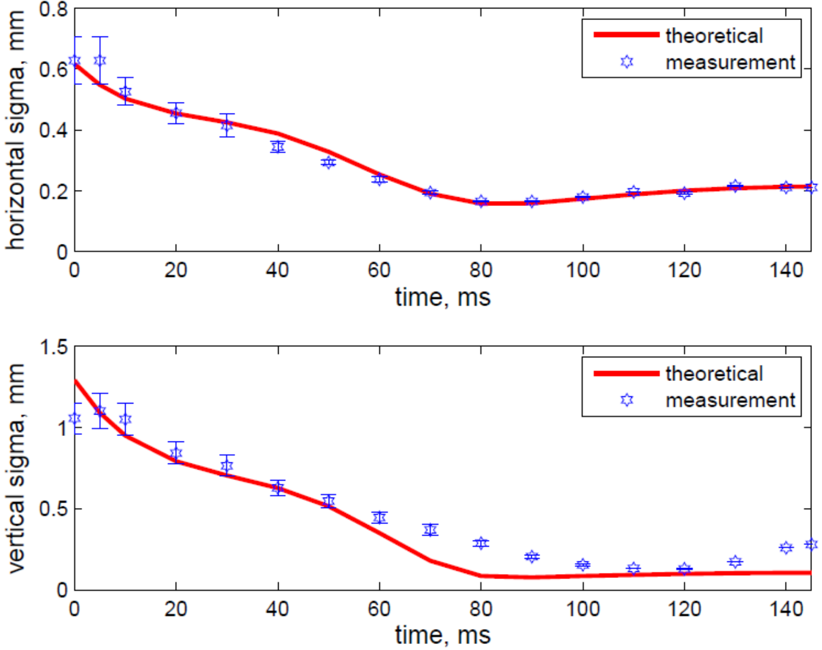


Courtesy U. Iriso & M. Pont (ALBA) et al. IPAC 2011

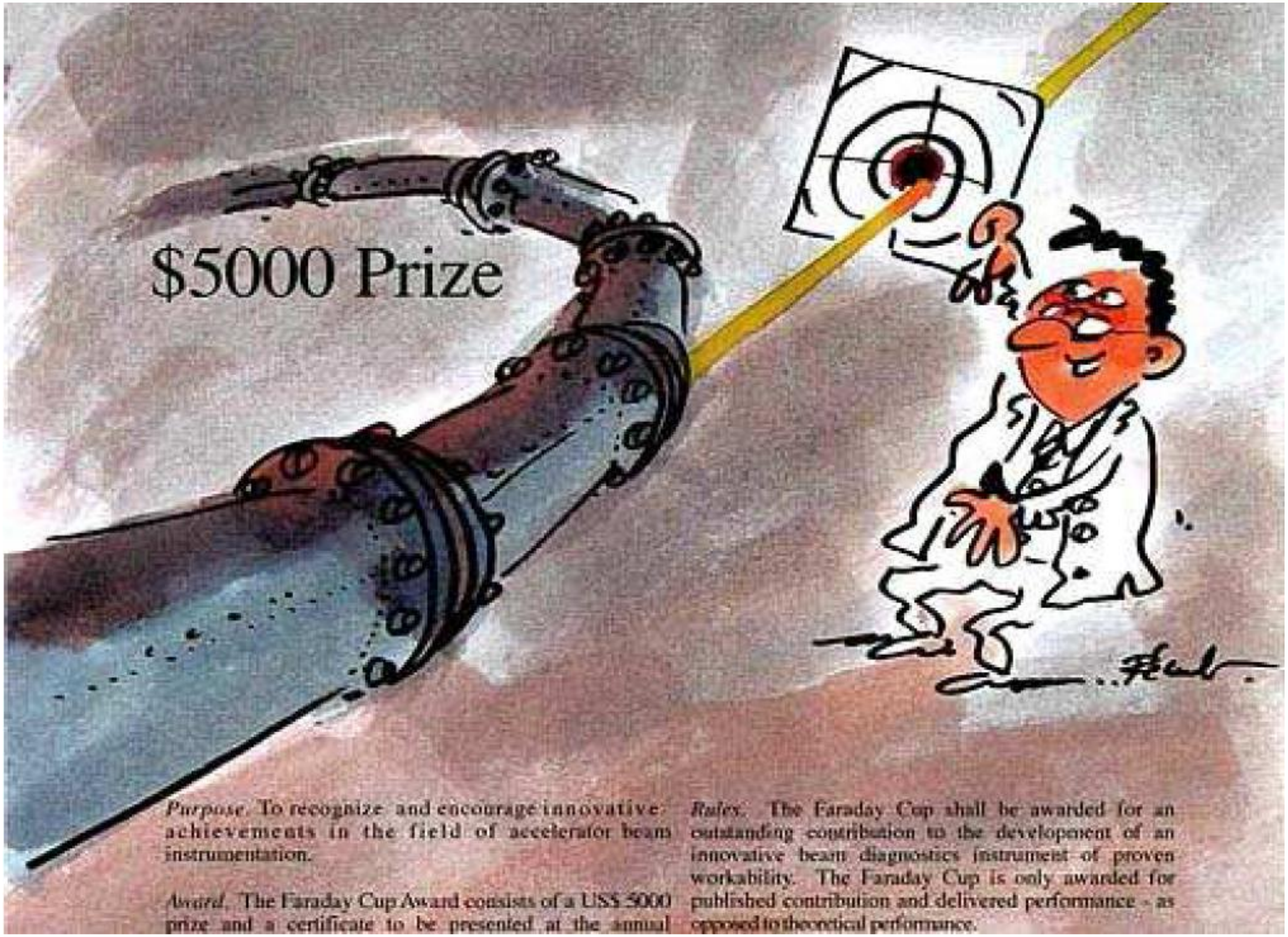
The beam emittance in influenced by:

- Adiabatic damping
- Longitudinal momentum contribution via dispersion $\Delta x_D(s) = D(s)\cdot\frac{\Delta p}{p}$

  total width $\Delta x_{tot}(s) = \sqrt{\varepsilon\beta(s) + D(s)\cdot\frac{\Delta p}{p}}$
- Quantum fluctuation due to light emission



The Artist View of a Synchrotron Light Monitor



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

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

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

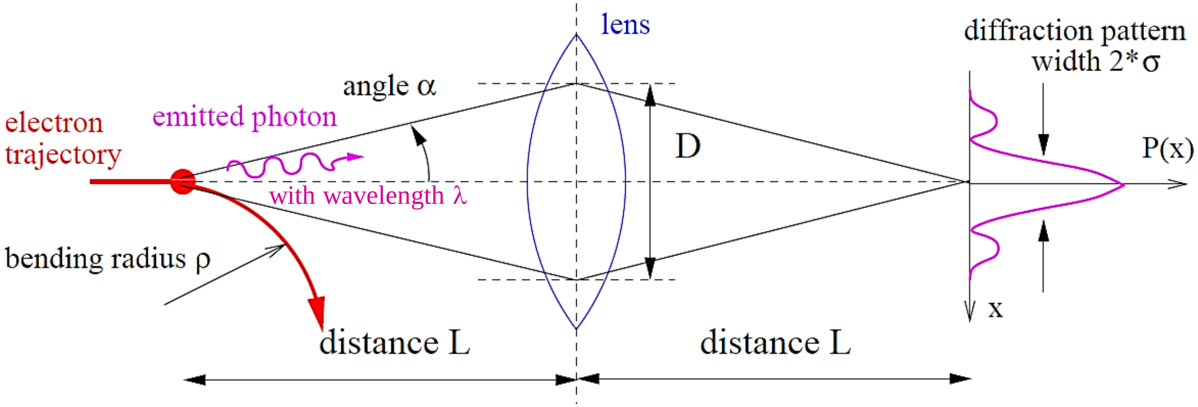
Diffraction Limit of Synchrotron Light Monitor

Limitations:

Diffraction limits the resolution due to Fraunhofer diffraction

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

$$\approx 100\ \mu\text{m for typical case}$$



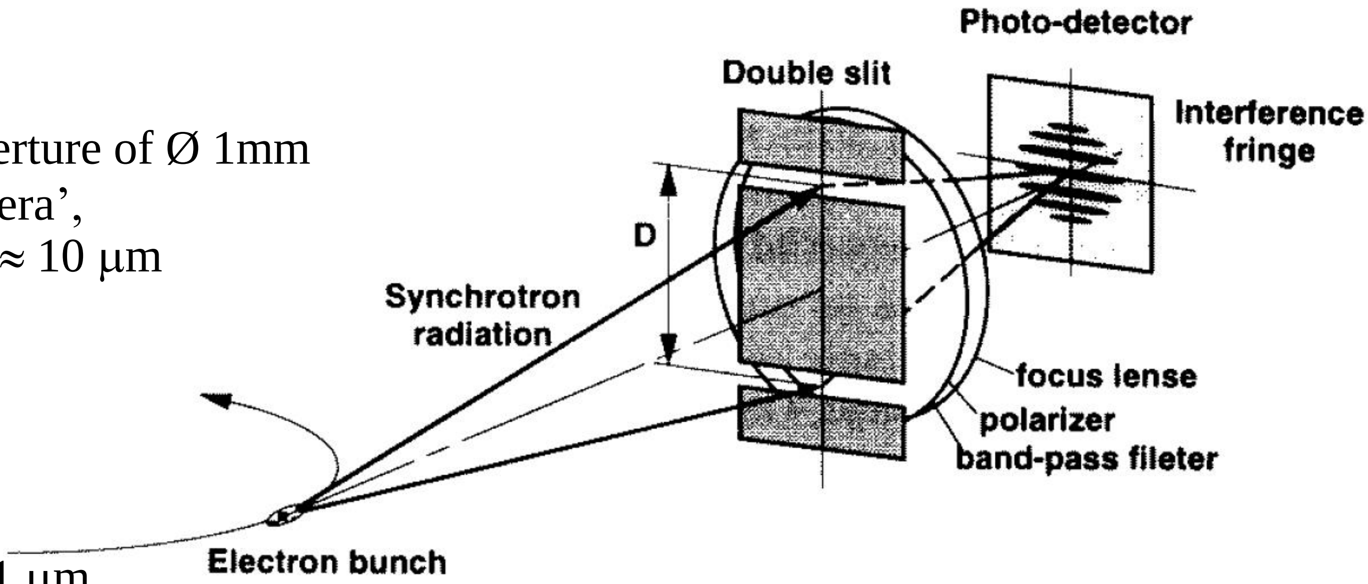
Improvements:

- ***Shorter wavelength:***

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

- ***Interference technique:***

  At optical wavelength using a double slit → interference fringes achievable resolution $\sigma \approx 1\ \mu$m.

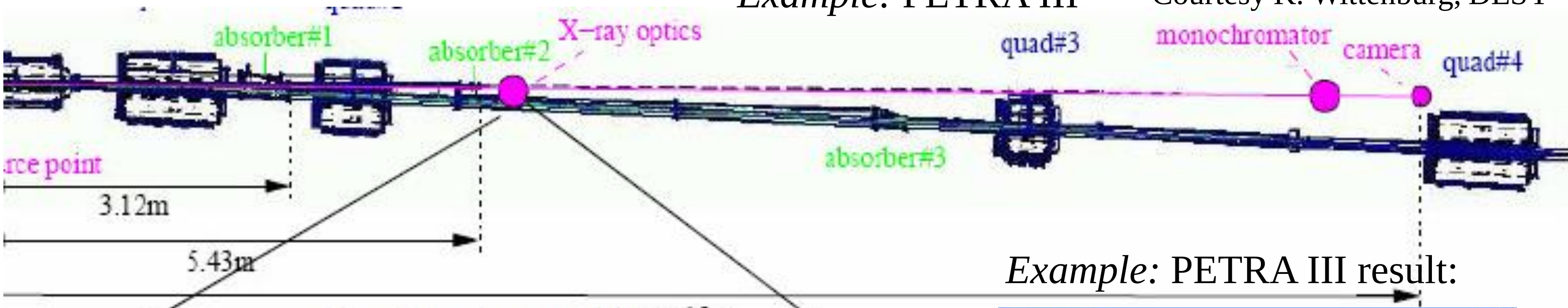


→ emi-concl.

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***.

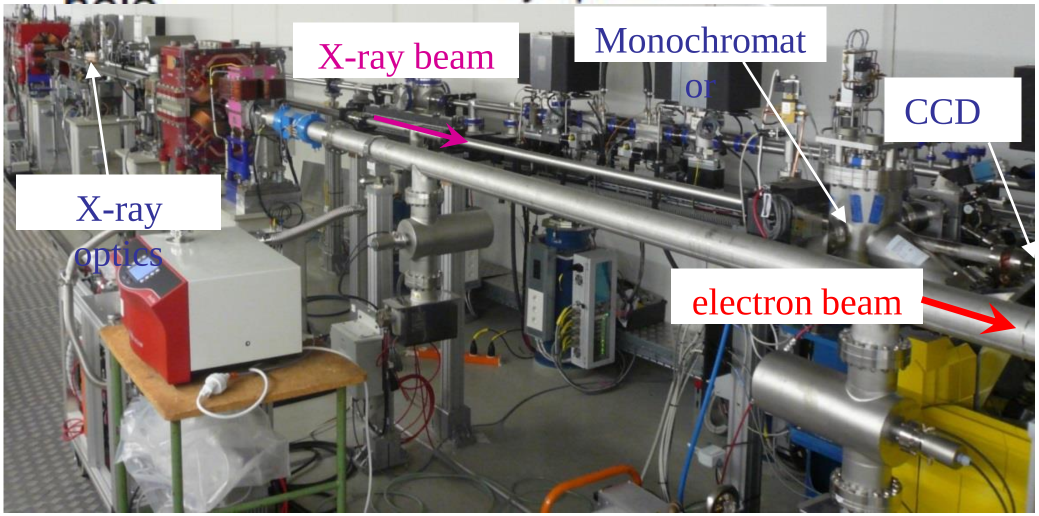
Example: PETRA III Courtesy K. Wittenburg, DESY

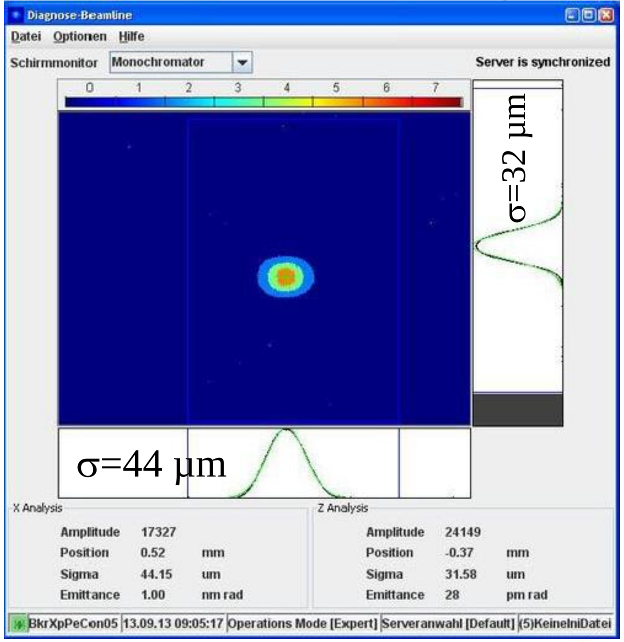


Example: PETRA III result:

ca. 15m

Two interchangeable X-ray optics:





Schirmmonitor Monochromator

Server is synchronized

X Analysis

Amplitude	17327	
Position	0.52	mm
Sigma	44.15	um
Emittance	1.00	nm rad

Z Analysis

Amplitude	24149	
Position	-0.37	mm
Sigma	31.58	um
Emittance	28	pm rad

BkrXpPeCon05 | 13.09.13 09:05:17 | Operations Mode [Expert] | Serveranwahl [Default] | (5)KeineInIDatei

Summary for Beam Profile Measurement

Different techniques are suited for different beam parameters:

e^--beam: typically Ø 0.1 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 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.

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 $\boldsymbol{\sigma_x}$ at different locations and linear transformations.

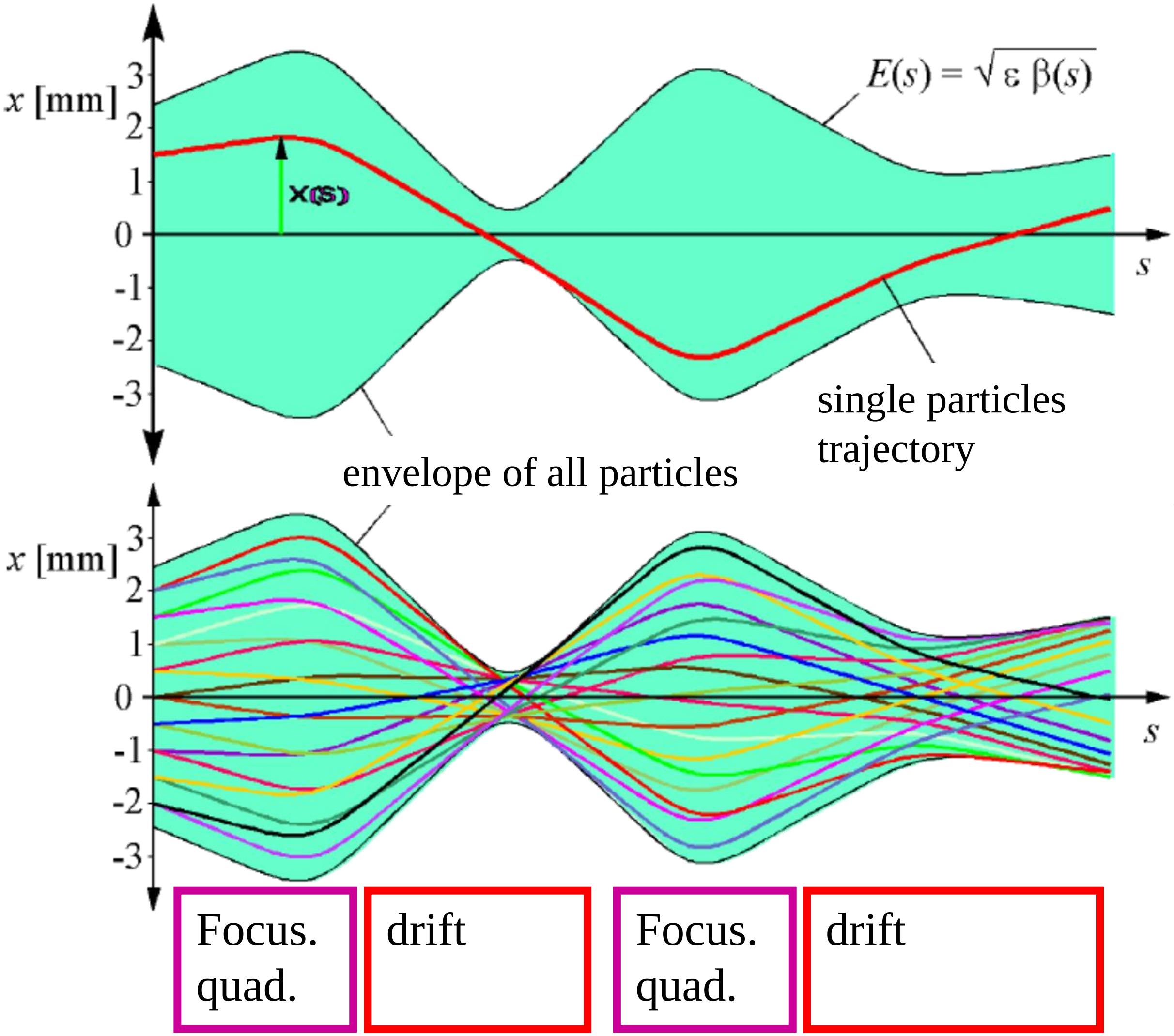
Different devices are used at transfer lines:

- Lower energies $\boldsymbol{E_{kin}}$ < 100 MeV/u: slit-grid device, pepper-pot (suited in case of non-linear forces).
- All beams: Quadrupole variation, 'three grid' 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



- ➢ 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

Courtesy K.Wille

Definition of Coordinates and basic Equations

The basic vector is 6 dimensional:

$$\vec{x}(s) = \begin{pmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{pmatrix} = \begin{pmatrix} \text{hori. spatial deviation} \\ \text{horizontal divergence} \\ \text{vert. spatial deviation} \\ \text{vertical divergence} \\ \text{longitudinal deviation} \\ \text{momentum deviation} \end{pmatrix} = \begin{pmatrix} [\text{mm}] \\ [\text{mrad}] \\ [\text{mm}] \\ [\text{mrad}] \\ [\text{mm}] \\ [‰] \end{pmatrix}$$

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 *<u>decoupled</u>* hor. & vert. plane:

$$\boldsymbol{\sigma} = \begin{pmatrix} \boxed{\sigma_{11}} & \sigma_{12} & 0 & 0 & \sigma_{15} & \sigma_{16} \\ \sigma_{12} & \sigma_{22} & 0 & 0 & \sigma_{25} & \sigma_{26} \\ 0 & 0 & \boxed{\sigma_{33}} & \sigma_{34} & 0 & 0 \\ 0 & 0 & \sigma_{34} & \sigma_{44} & 0 & 0 \\ \sigma_{15} & \sigma_{25} & 0 & 0 & \boxed{\sigma_{55}} & \sigma_{56} \\ \sigma_{16} & \sigma_{26} & 0 & 0 & \sigma_{56} & \sigma_{66} \end{pmatrix}$$

horizontal
vertical
longitudinal
hor.-long. coupling
→ 13 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:

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

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

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

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 using terms of 2-dim distribution:

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

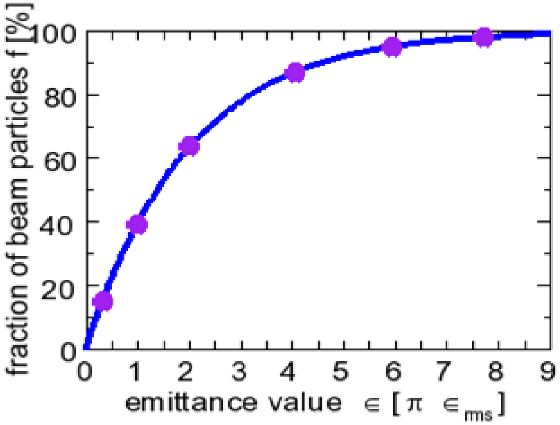
It describes the value for 1 standard derivation

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

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

Care:

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



Emittance $\varepsilon(f)$	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 %

Measurement of transverse Emittance

Outline:

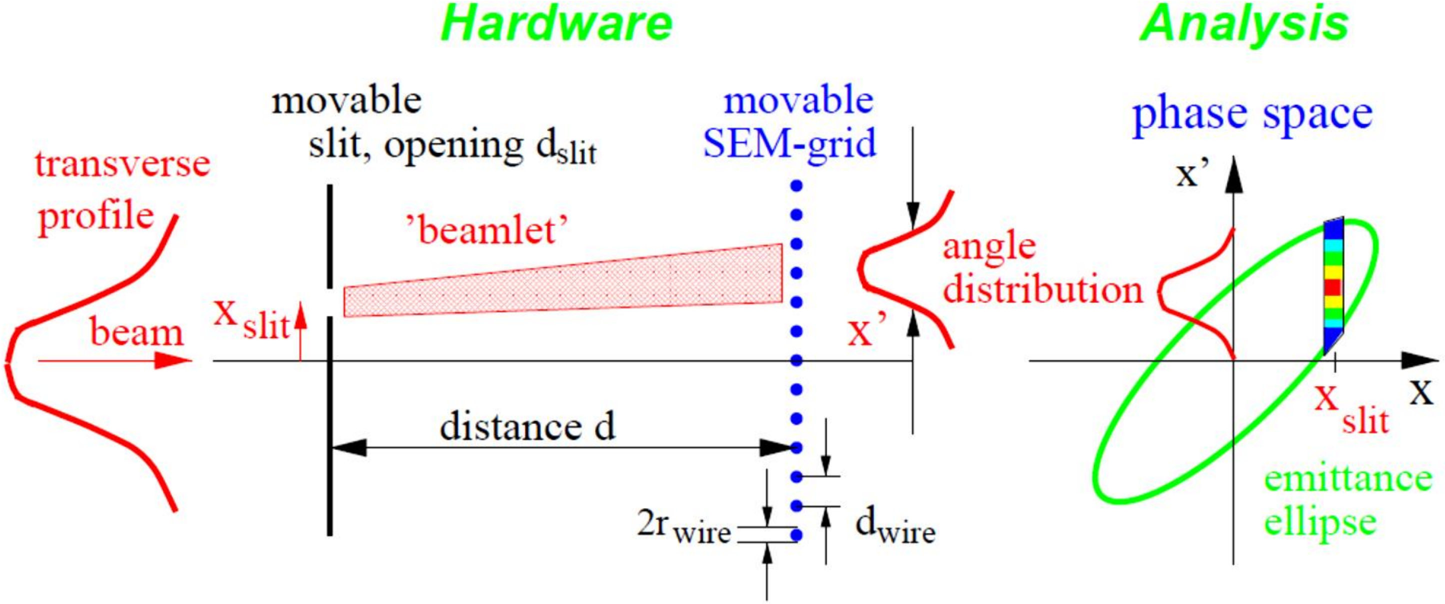
- Definition and some properties of transverse emittance
- Slit-Grid device: scanning method

  scanning slit → beam position & grid → angular distribution
- Quadrupole strength variation and position measurement
- Summary

The Slit-Grid Measurement Device

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

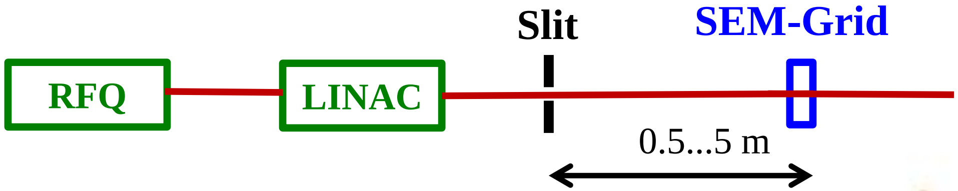
Used for protons with $E_{kin} < 100$ MeV/u ⇒ range $R < 1$ cm.



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 $<x^2>$, $<x'^2>$ & $<xx'>$

Emittance value ε_{rms} from

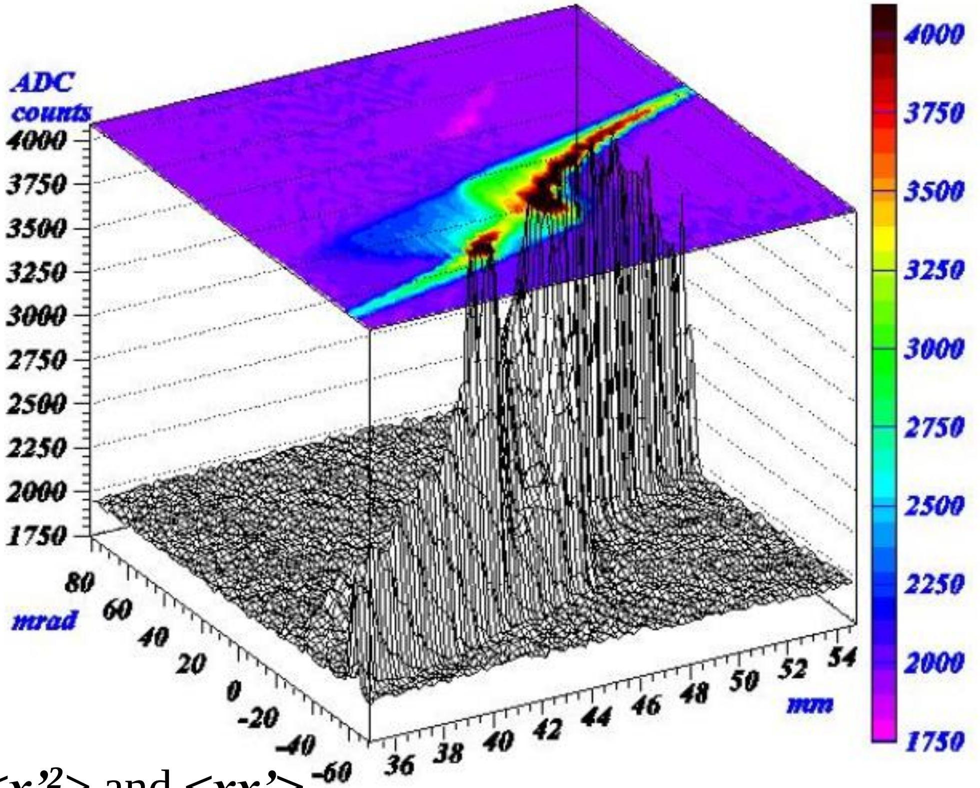
$$\varepsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

⇒ **Problems:**

- Finite **binning** results in limited resolution
- **Background** → large influence on $<x^2>$, $<x'^2>$ and $<xx'>$

Or fit of distribution with an ellipse

⇒ **Effective emittance only**



Beam: Ar^{4+}, 60 keV, 15 μA

at Spiral2 Phoenix ECR source.

P. Ausset, DIPAC 2009

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

Measurement of transverse Emittance

Outline:

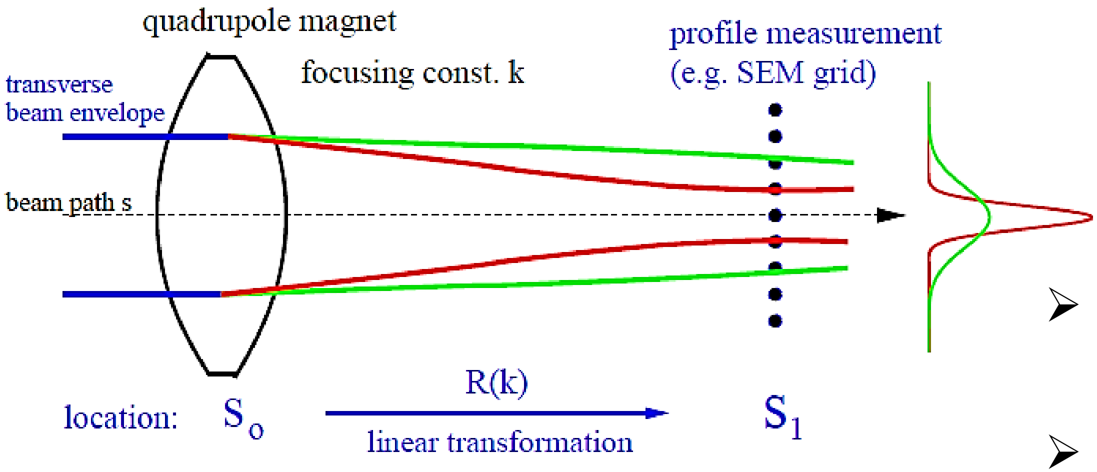
- ➢ Definition and some properties of transverse emittance
- ➢ Slit-Grid device: scanning method

  scanning slit → beam position & grid → angular distribution
- ➢ Quadrupole strength variation and position measurement

  emittance from several profile measurement and beam optical calculation
- ➢ Summary

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.



- Measurement of beam width

$$x^2_{max} = \sigma_{11}(1, k)$$

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

- With the drift matrix the transfer is

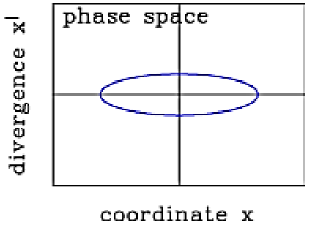
$$\mathbf{R}(k_i) = \mathbf{R}_{drift} \cdot \mathbf{R}_{focus}(k_i)$$

- Transformation of the beam matrix

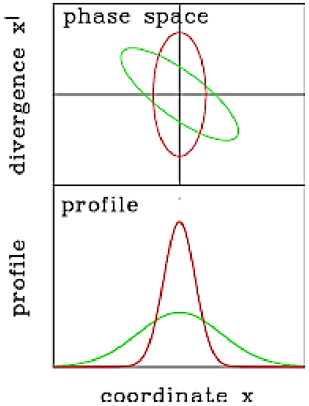
$$\sigma(1,k_i) = \mathbf{R}(k_i) \cdot \sigma(0) \cdot \mathbf{R}^T(k_i)$$

Task: Calculation of $\sigma(0)$

at entrance s_0 i.e. all three elements



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



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

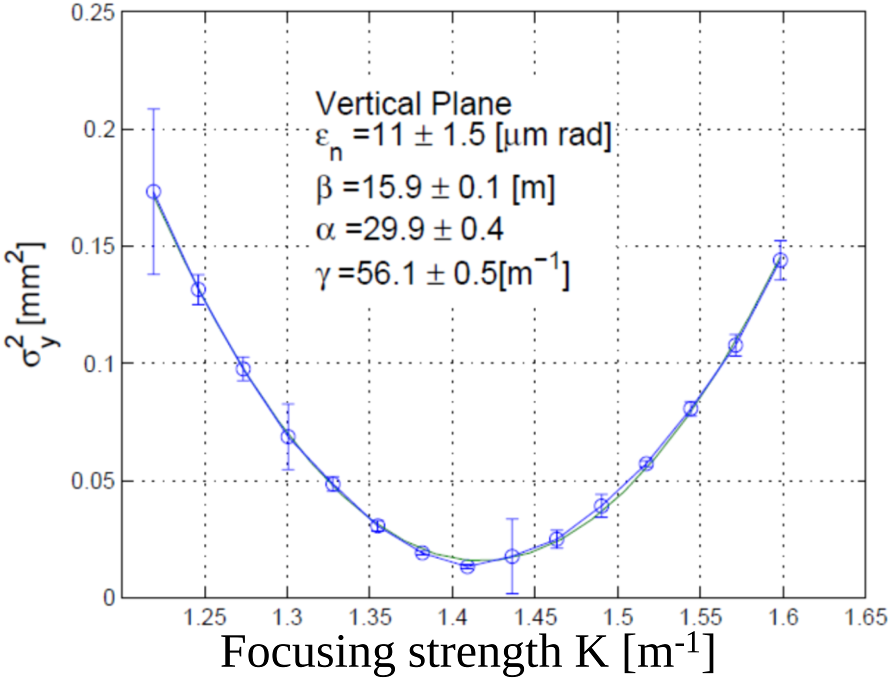
Measurement of transverse Emittance

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

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

Measurement of the matrix-element $\sigma_{11}(1,K)$ from **$\sigma(1,K) = \mathrm{R}(K)\cdot\sigma(0)\cdot\mathrm{R}^{\mathrm{T}}(K)$**

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

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

The three matrix elements at the quadrupole:

$$\sigma_{11}(0) = \frac{a}{L^2}$$

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

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

$$\varepsilon_{rms} \equiv \sqrt{\det\sigma(0)} = \sqrt{\sigma_{11}(0)\cdot\sigma_{22}(0)-\sigma_{12}^2(0)} = \sqrt{ac}\,/\,L^2$$

Summary for transverse Emittance Measurement

Emittance is the important quantity for comparison to theory.

It includes size (value of ***ε***) and orientation in phase space ($\boldsymbol{\sigma_{ij}}$ or ***α, β*** and *γ*)

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

assuming no coupling between horizontal, vertical and longitudinal planes

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

- ***Slit-grid:*** movable slit → ***x***-profile, grid → ***x′***-profile

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.

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

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

Measurement of longitudinal Parameters

Measurement of longitudinal parameter:

Bunch length measurement at

- **Synchrotron light sources**
- **Linear light sources**
- **Summary**

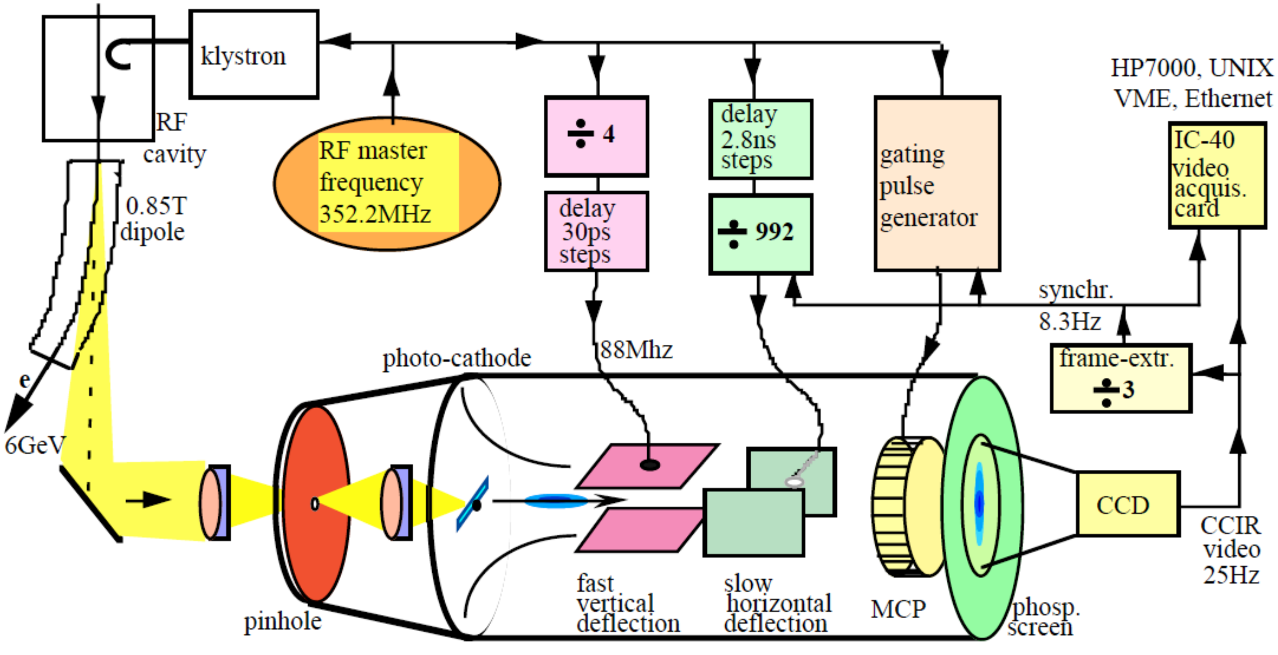
Longitudinal ↔ transverse correspondences:

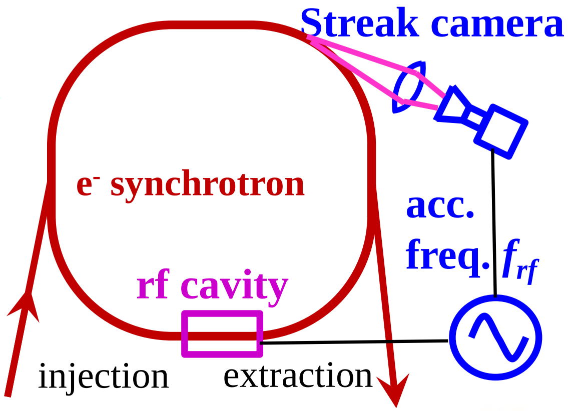
- position relative to rf ↔ transverse center-of-mass
- bunch structure in time ↔ transverse profile
- momentum or energy spread ↔ transverse divergence
- longitudinal emittance ↔ transverse emittance.

Bunch Length Measurement for relativistic Electrons

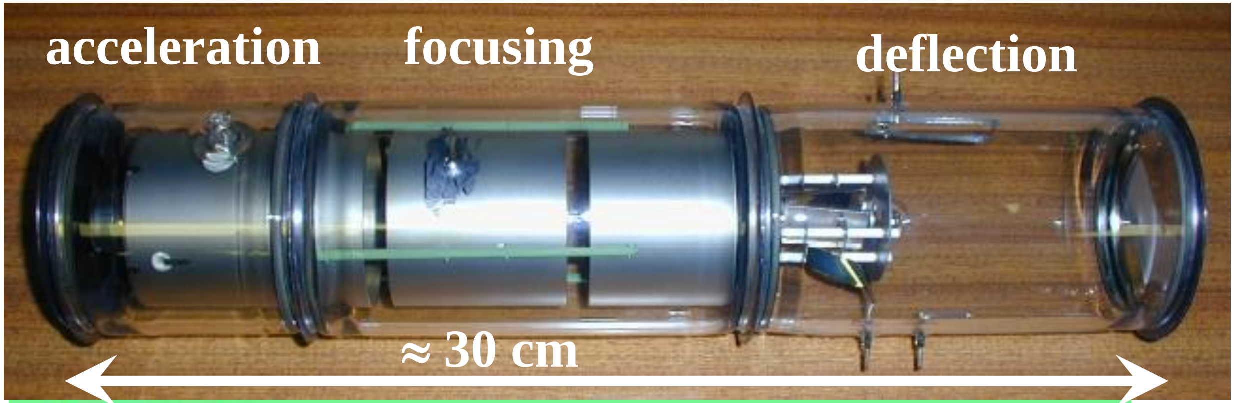
Electron bunches are too short (σ_t < 300 ps) to be covered by the bandwidth of pick-ups (f < 1 GHz ⇔ t_{rise} >300 ps) for structure determination.

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



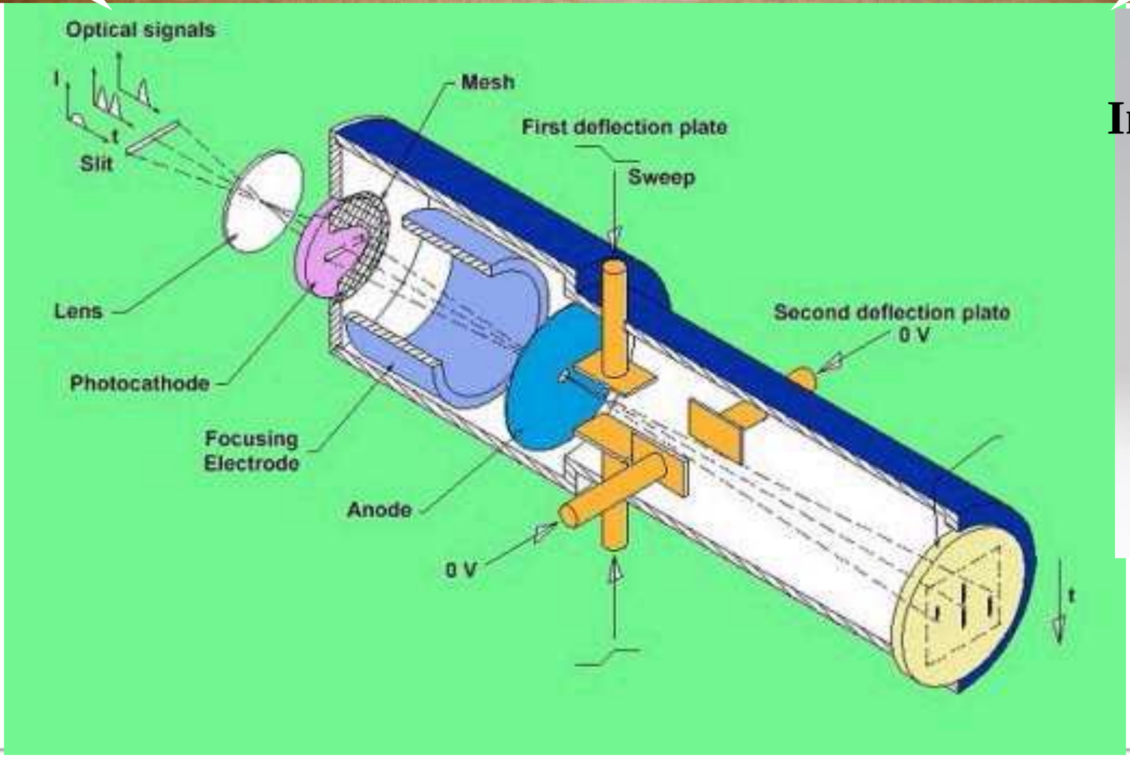


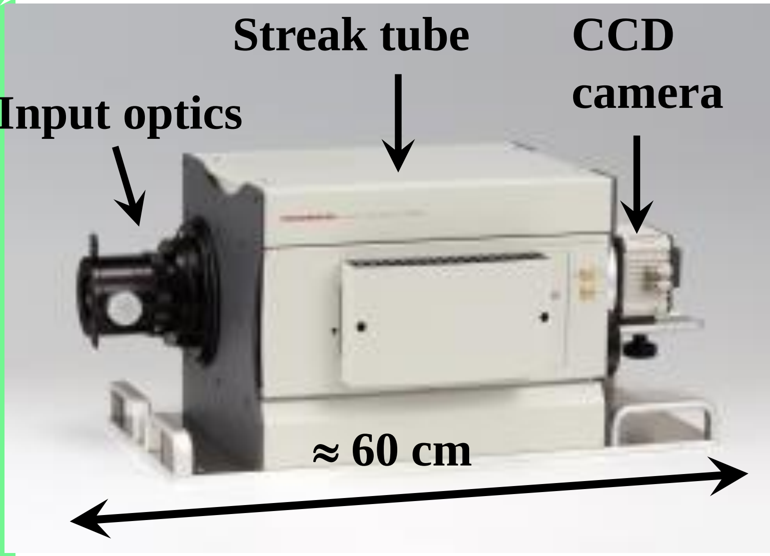
Technical Realization of Streak Camera



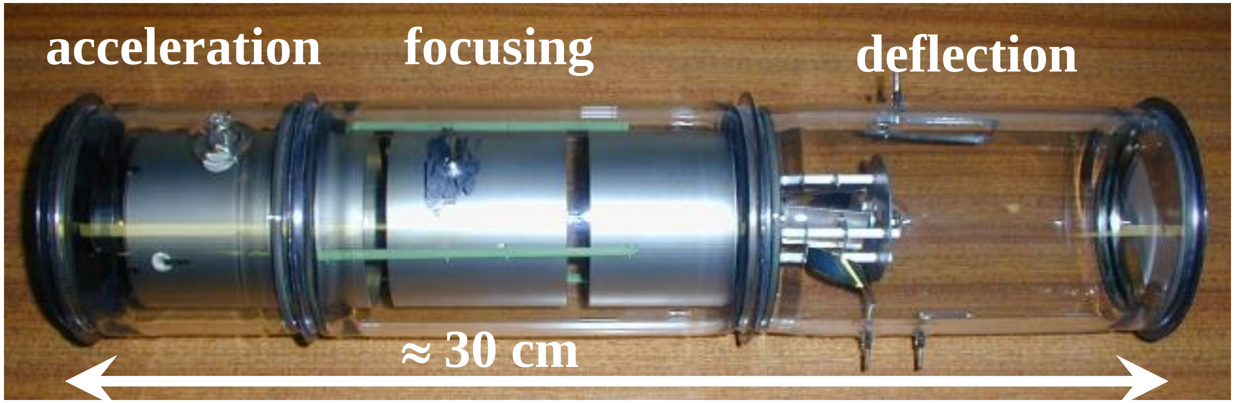
Hardware of a streak camera

Time resolution down to 0.5 ps:



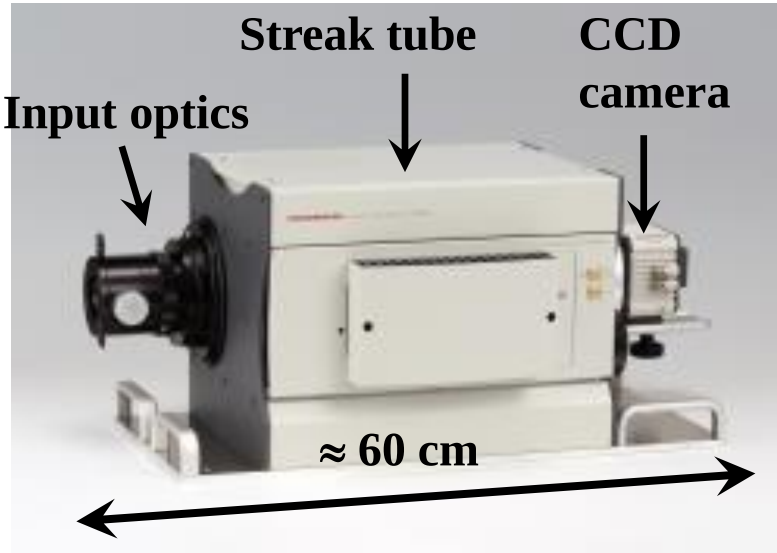


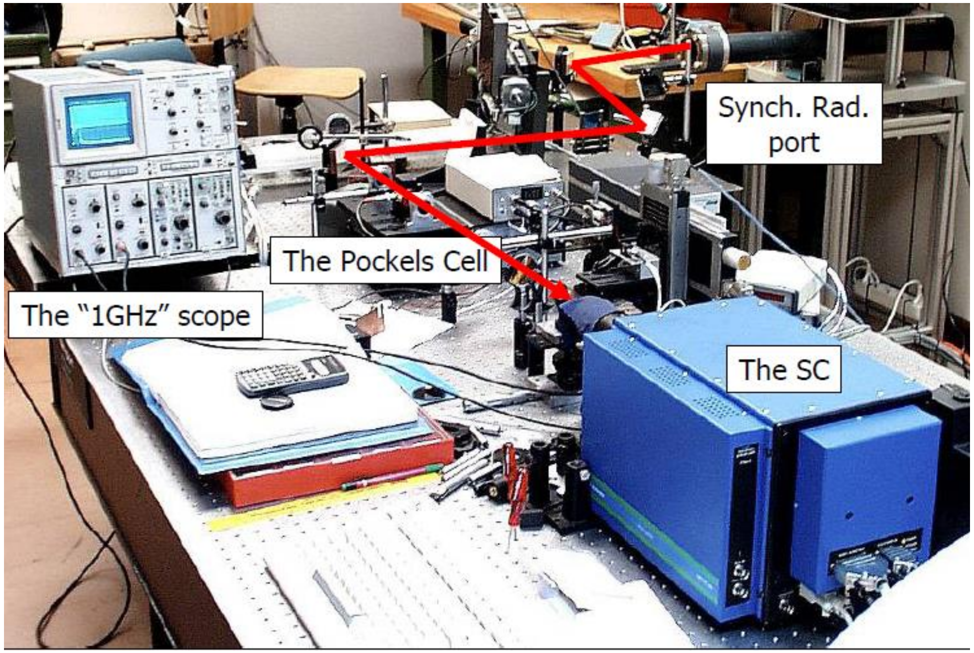
Technical Realization of Streak Camera



Hardware of a streak camera

Time resolution down to 0.5 ps:



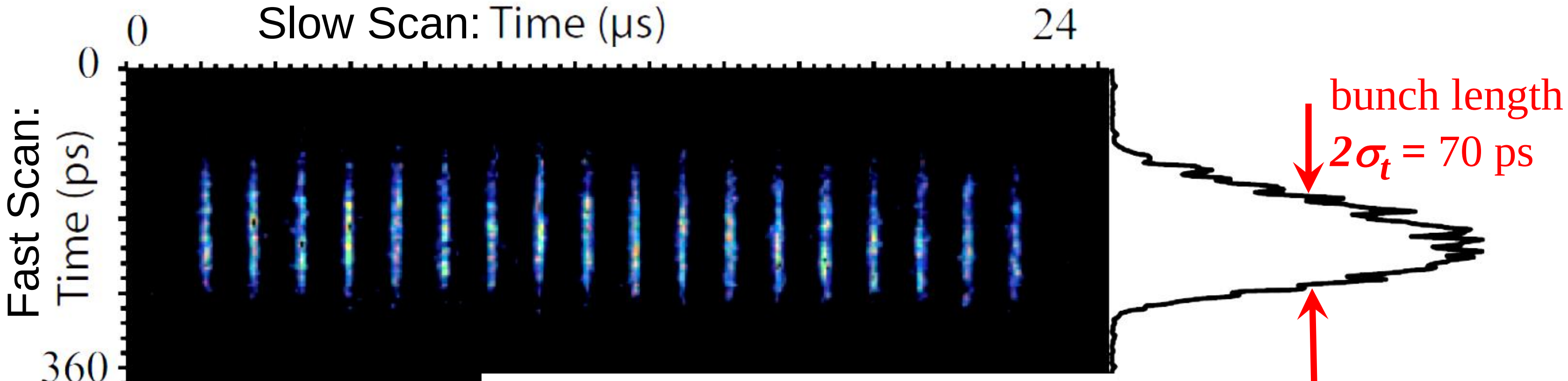


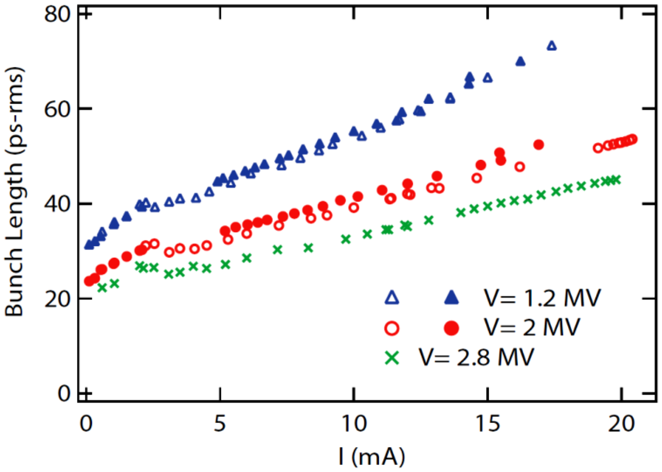
The Streak Camera setup at ELETTRA, Trieste, Italy

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 $\boldsymbol{U_{rf}}$ = 2 MV for slow direction 24 μs and scaling for fast scan 360 ps: measure $\boldsymbol{\sigma_t}$ = 35 ps.

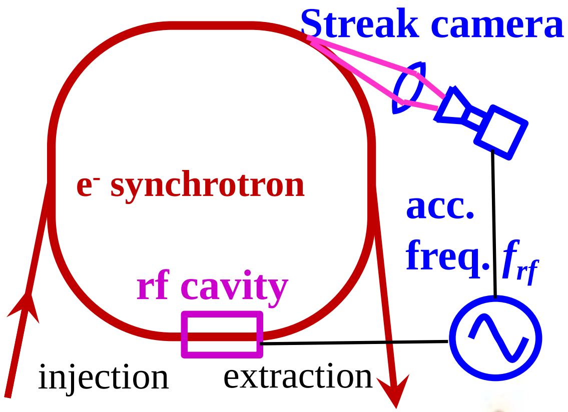




Short bunches are desired by the users

Example: Bunch length $\boldsymbol{\sigma_t}$ as a function of stored current (i.e. space charge de-focusing) at SOLEIL

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



The Artist View of a Streak Camera

FARADAY CUP
1998

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

Award. The Faraday Cup Award consists of a US$ 5000 prize and a certificate to be presented at the next Beam Instrumentation Workshop. Winners participating in the BIW will be given a $1000 travel allowance.

Eligibility. Nominations are open to contributors of all nations regardless of the geographical location at which the work was done.
The Award goes normally to one person, but may be shared by recipients having contributed to the same accomplishment. It will normally be awarded to scientists in the early stage of their career. Nominations of candidates shall remain active for 2 competitions.

Establishment and support. The Award was established in 1991 with the support of the Beam Instrumentation Workshop Organizing Committee.

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

Award Committee. The Beam Instrumentation Workshop Organizing Committee.

Nominations. The nomination package shall include the name of the candidate, relevant publications, a statement outlining his/her personal contribution and that of others, two letters from co-workers familiar with the candidate and his contribution. Two master copies suitable for photocopying of this package must be submitted not later than the 15th of November 1997 to Steven Smith c/o BIW'98 Secretariat, SLAC, Stanford University, Stanford CA 94305-4085, U.S.A..

→ conclusion

Bunch length measurement by electro-optical Method

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

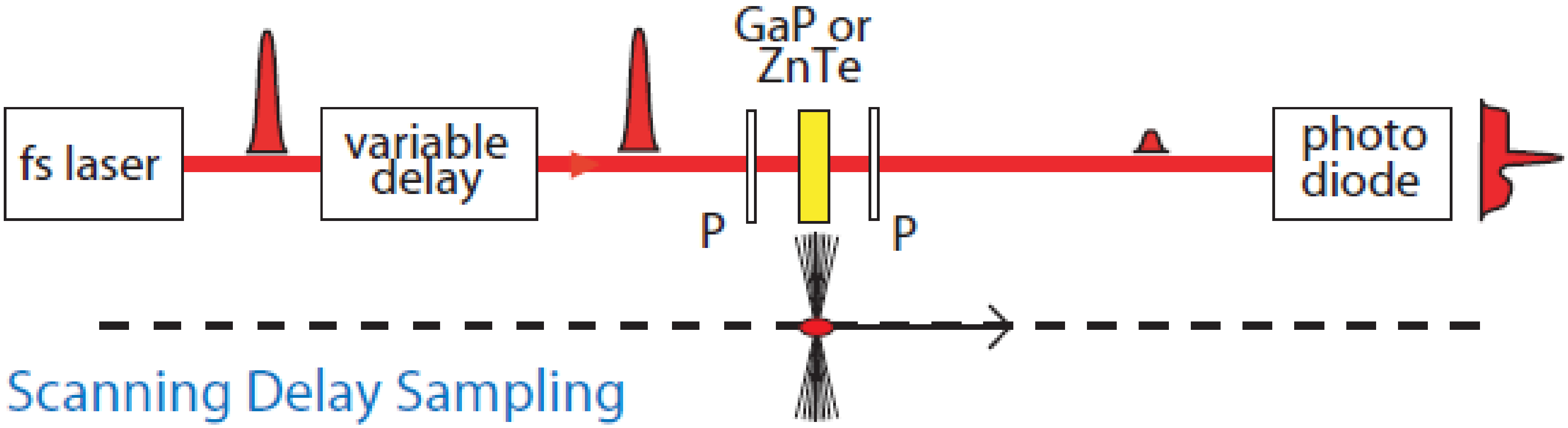
→ below resolution of streak camera

→ short laser pulses with $t \approx$ **10 fs** and electro-optical modulator

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

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

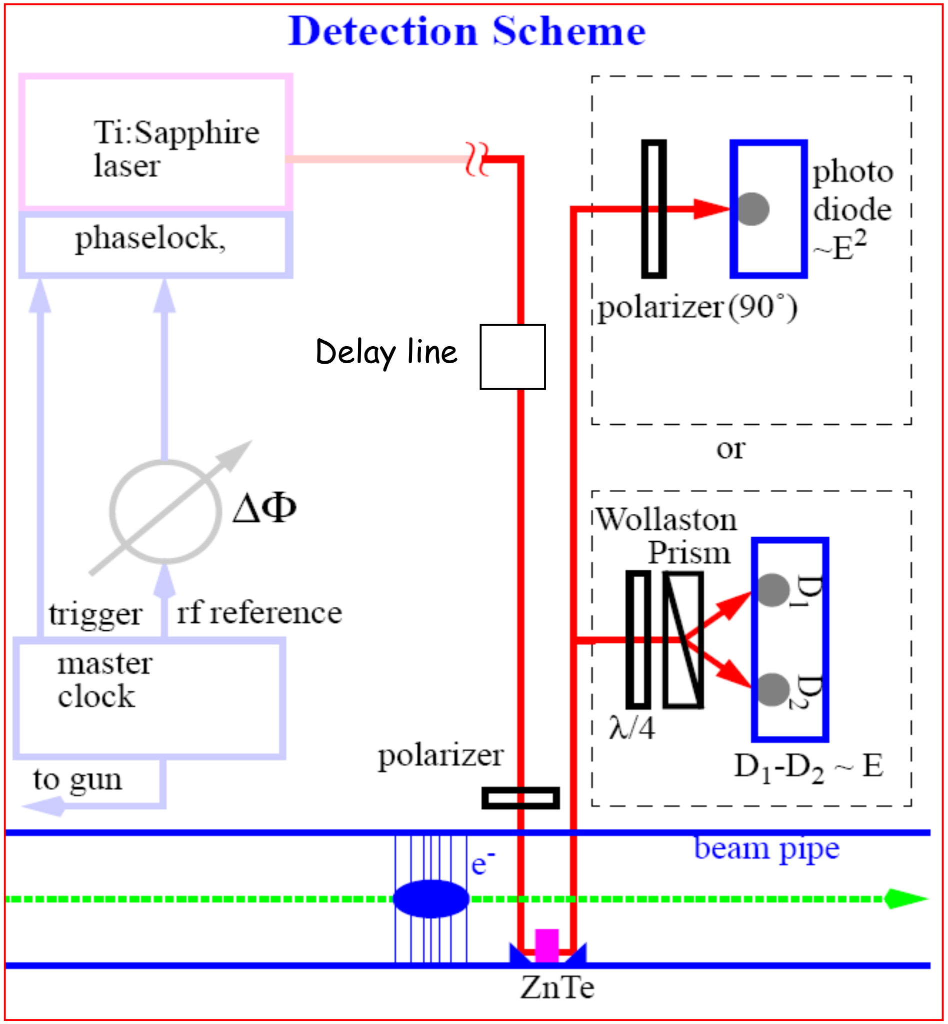
Scanning of delay between bunch and laser → time profile after several pulses.

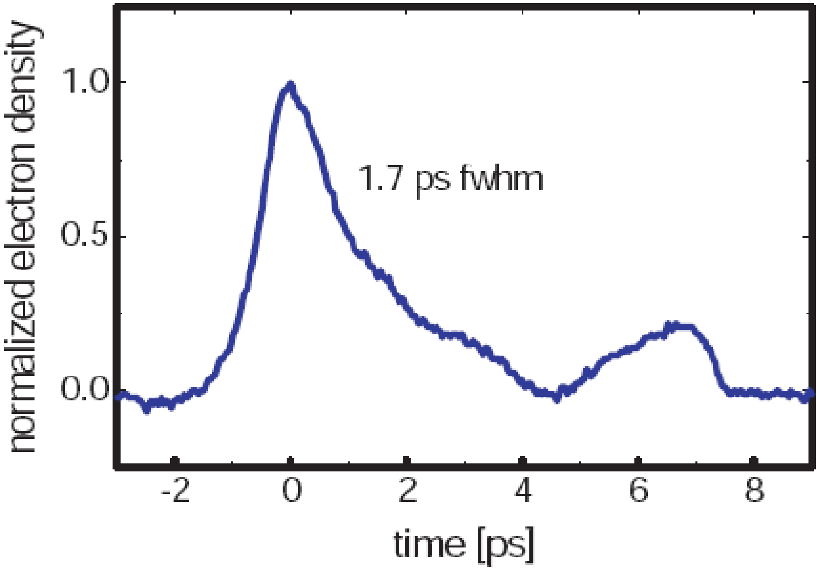


From S.P.Jamison et al., EPAC 2006

Realization of EOS Scanning

Setup of a scanning EOS method

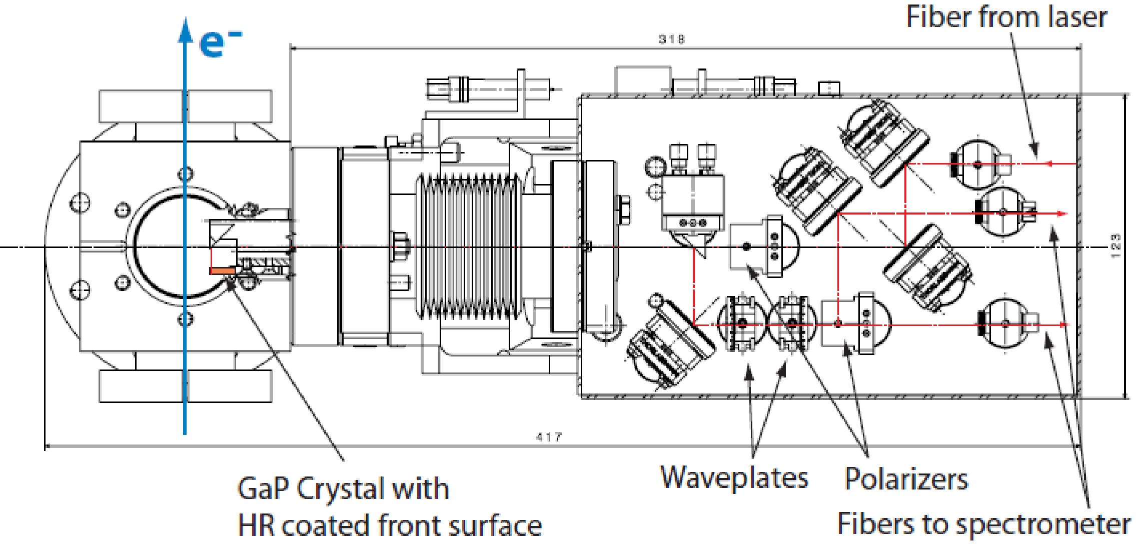




Using 12fs pulses from
$Ti:A_{l2}O_3$ laser at 800nm and
ZnTe crystal 0.5mm thick
with a e^- - beam 46MeV of 200pC

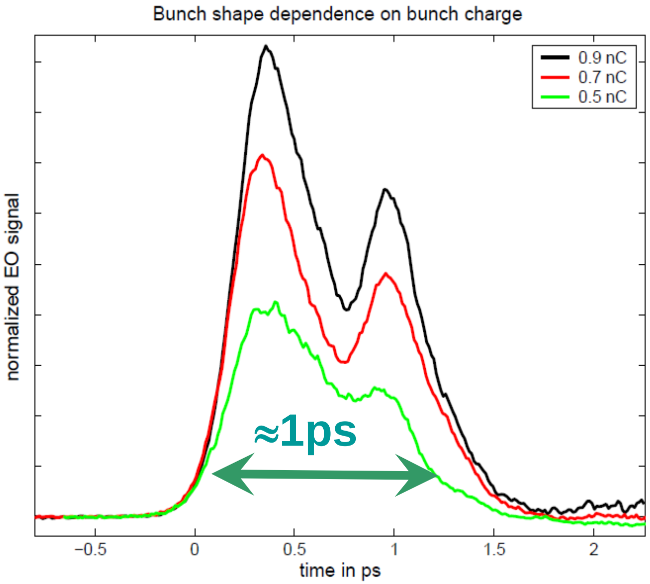
X. Yan *et al*, PRL 85, 3404 (2000)

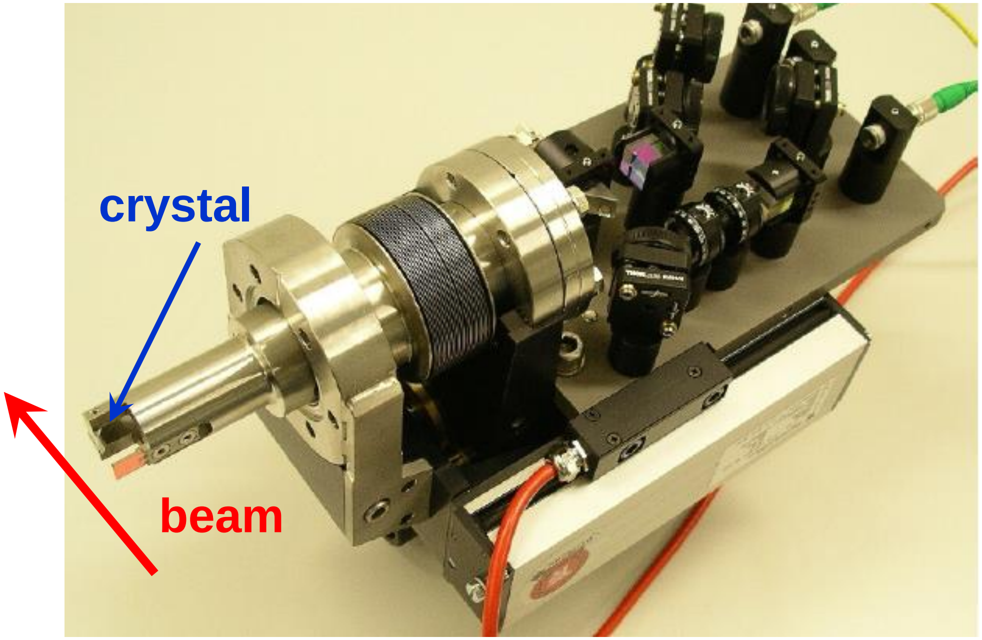
Hardware of a compact EOS Scanning Setup



Example: Bunch length at FLASH

(1 ps bunch duration = 300 μm length)





B. Steffen (PSI) et al, DIPAC 2009

B. Steffen et al., FEL Conf. 2005

Summary of longitudinal Measurements

Devices for bunch length at light sources:

Streak cameras:

- Time resolved monitoring of synchrotron radiation

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

  reason: too short bunches for rf electronics.

Laser scanning:

- Electro-optical modulation of short laser pulse

  → very high time resolution down to some fs

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:

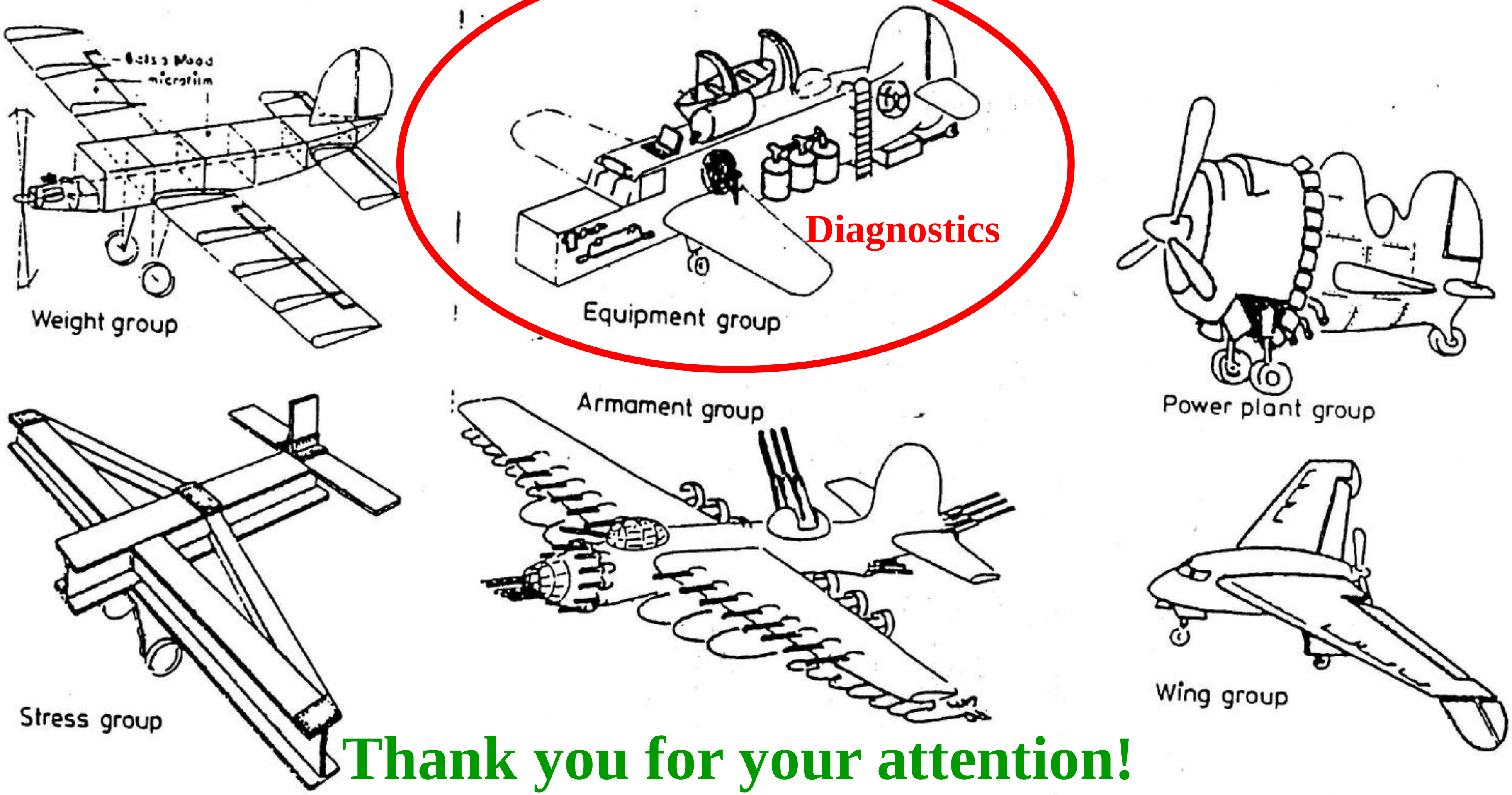
- Quick, non-destructive measurements leading to a single number or simple plots
- Complex instrumentation used for hard malfunction and accelerator development
- Automated measurement and control of beam parameters i.e. feedback

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

Conclusion for Beam Diagnostics Course



Thank you for your attention!

For a successful construction and operation of an accelerator,
the understand and right balance of all disciplines is required!

General Reading on Beam Instrumentation

- H. Schmickler (Ed.) *Beam Instrumentation*, Proc. CERN Accelerator School, Tuusula 2018 in prep.
- 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

Emittance Enlargement by Injection Mis-steering

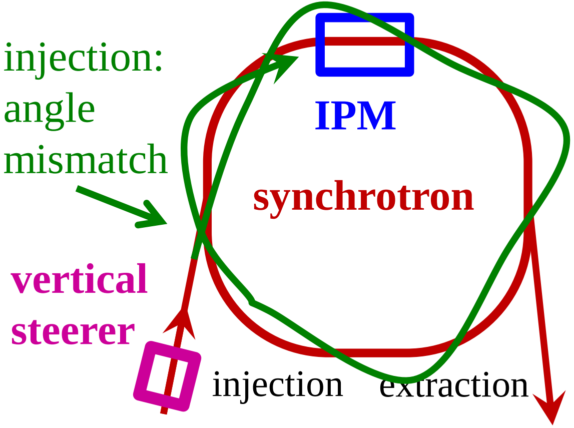
Emittance conservation requires precise injection matching

Wrong angle of injected beam:

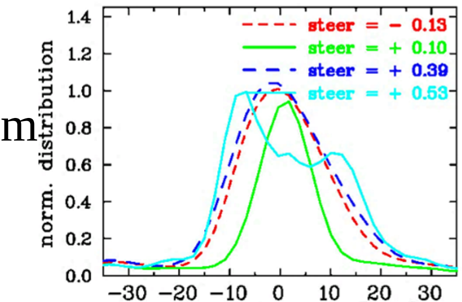
- injection into outer phase space → large β-amplitude i.e. large beam
- might result in 'hollow' beam
- filling of acceptance i.e. loss of particles

⇒ Hadron beams: larger emittance after acceleration

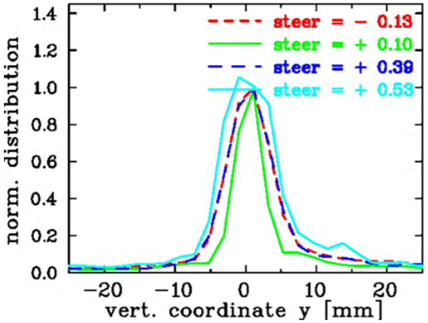
Example: Variation of vertical injection angle by magnetic steerer
Beam: C^{6+} at 6.7 MeV/u acc. to 600 MeV/u, up to $6\cdot10^9$ ions per fill with multi-turn injection, IPM integration 0.5 ms i.e. ≈ 100 turns

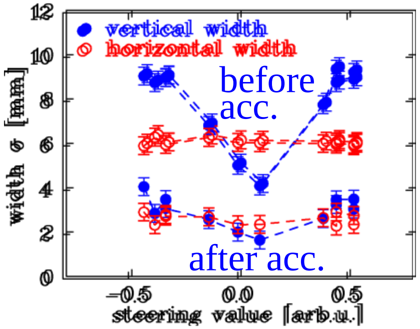


Vertical profile **at** injection:

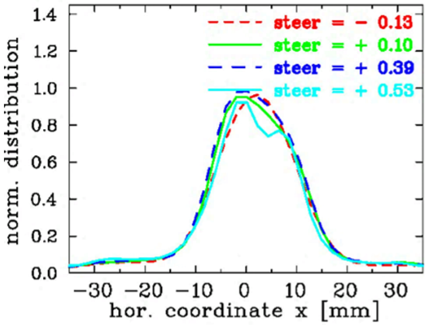


Vertical profile **after** acc.:

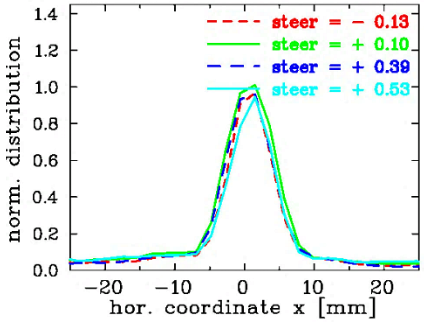




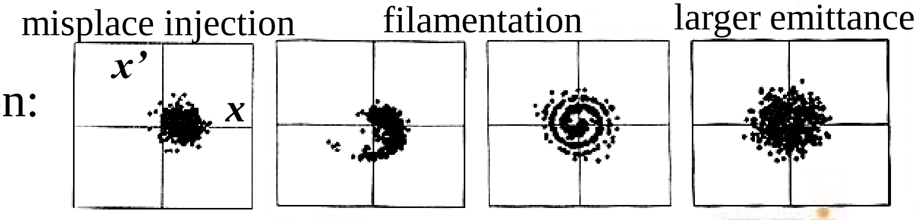
Horizontal profile **at** injection:



Horizontal profile **after** acc.:



Schematic simulation:
Courtesy M. Syphers



→ OTR