BEAM DIAGNOSTICS (DESTRUCTIVE METHODS)

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Outline

- Demands for beam diagnostics
- Beam profile measurement
- Emittance measurement
- Beam Current measurement

Demand for beam diagnostics

- Essential for any accelerator
- ‘Organ of sense’
- Deal with real beam with imperfections

- Three categories
  - Reliable, quick measurements for general functionality, e.g. current transformer
  - For a daily check of performance and stability, e.g. profile determination
  - Complex instrumentation, e.g. Emittance measurement

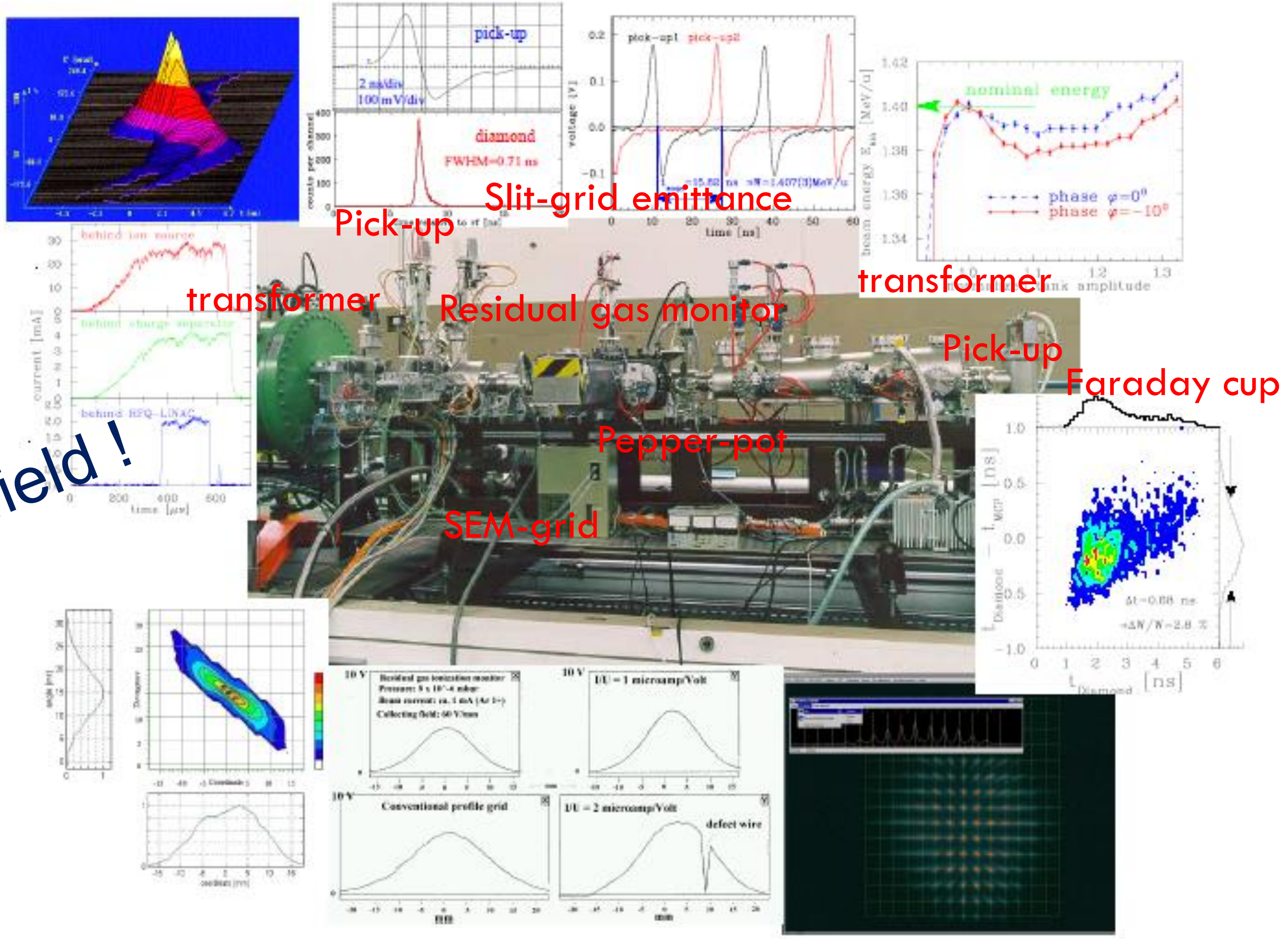
Beam quantity		LINAC, transfer line	Synchrotron
current I	*general*	transformer (dc, pulsed) Faraday cup	transformer (dc)
	special	particle detector (Scint. IC, SEM)	normalized pick-up signal
position $\overline{x}$	*general*	pick-up	pick-up
	special	using profile measurement	cavity excitation (e^-)
profile x_{width}	*general*	SEM-grid, wire scanner viewing screen, OTR-screen	residual gas monitor synch. radiation (e^-) wire scanner
	special	grid with ampl. (MWPC)	
trans. emittance ϵ_{trans}	*general*	slit grid quadrupole scan	residual gas monitor wire scanner
	special	pepper-pot	transverse Schottky pick-up wire scanner
momentum p and $\Delta p/p$	*general*	pick-up (TOF) magn. spectrometer	pick-up
	special		Schottky noise pick-up
bunch width $\Delta\varphi$	*general*	pick-up	pick-up wall current monitor
	special	particle detector secondary electrons	streak camera (e^-)
long. emittance ϵ_{long}	*general*	magn. spectrometer buncher scan	
	special	TOF application	pick-up + tomography
tune, chromaticity Q, ξ	*general*	—	exciter + pick-up (BTF)
	special	—	transverse Schottky pick-up
beam loss r_{loss}	*general*	particle detector	
polarization P	*general*	particle detector	
	special	Compton scattering with laser	
luminosity $\mathcal{L}$	*general*	particle detector	

P. Forck, Lecture Notes on Beam Instrumentation and Diagnostics, Joint University Accelerator School, January – March 2012

A 'typical' Accelerator Diagnostics

- Material sciences
- Thermodynamics
- Electro-Magnetism
- Optics
- laser technology
- Mechanics
- Electronics
- Nuclear Physics
- Vacuum science
- …

Multi-disciplinary field !



A picture of the mobile test bench including some measurements, as provided for the commissioning of the high current injector at GSI in 1999.

Challenge in beam diagnostics

- Better resolution (time/space)
- (single) photon resolution
- Improved radiation hardness
- Least invasive
- Able to cover variety of beams

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Beam Profile Monitoring

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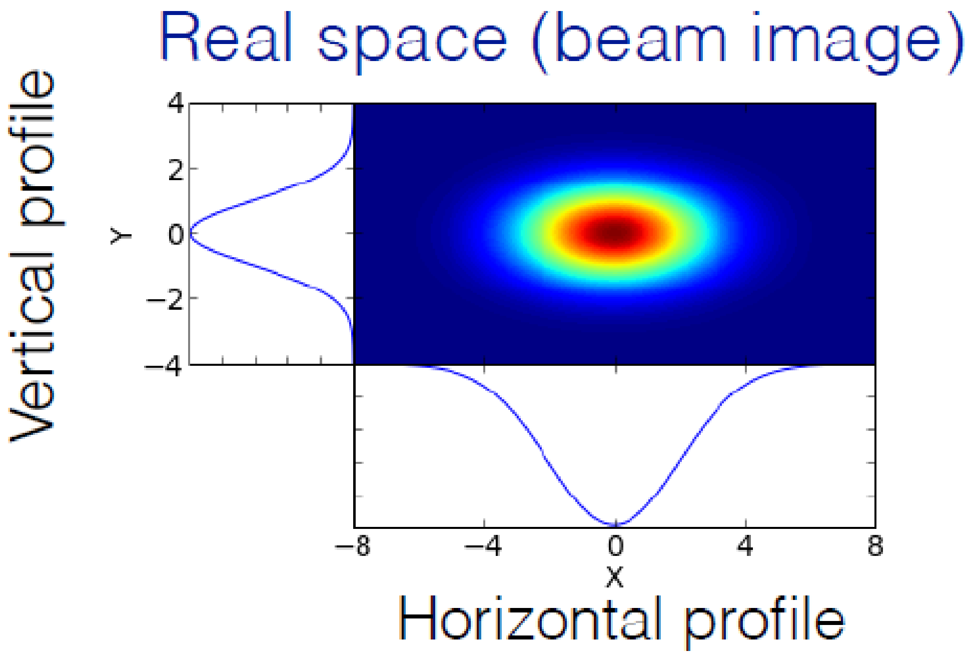
Beam profile



General distribution:

$$f(x,y)$$

Profile:

$$f(x) = \int_{-\infty}^{+\infty} f(x,y)dy$$

$$f(y) = \int_{-\infty}^{+\infty} f(x,y)dx$$

Rms beam size:

$$x_{rms}{}^2 =< x^2 > = \frac{1}{N_0}\int_{-\infty}^{+\infty} x^2 f(x)dx$$

$$y_{rms}{}^2 =< y^2 > = \frac{1}{N_0}\int_{-\infty}^{+\infty} y^2 f(y)dy$$

Example: Gaussian distribution

General distribution:

$$f(x,y) = \frac{N_0}{2\pi\sigma_x\sigma_y}\ e^{-(\frac{x^2}{2\sigma_x{}^2}+\frac{y^2}{2\sigma_y{}^2})}$$

Profile:

$$f(x) = \int_{-\infty}^{+\infty} f(x,y)dy = \frac{N_0}{\sqrt{2\pi}\sigma_x}\ e^{-\frac{x^2}{2\sigma_x{}^2}}$$

$$f(y) = \int_{-\infty}^{+\infty} f(x,y)dx = \frac{N_0}{\sqrt{2\pi}\sigma_y}\ e^{-\frac{y^2}{2\sigma_y{}^2}}$$

Rms beam size:

$$x_{rms}{}^2 =< x^2 > = \frac{1}{N_0}\int_{-\infty}^{+\infty} x^2 f(x)dx = \sigma_x{}^2$$

$$y_{rms}{}^2 =< y^2 > = \frac{1}{N_0}\int_{-\infty}^{+\infty} y^2 f(y)dy = \sigma_y{}^2$$

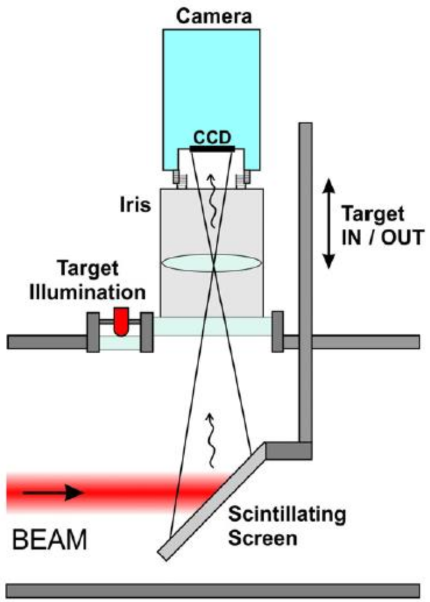
Measure the beam profile

- **Intercepting methods**
  - Scintillating screen
  - Optical transition radiation (OTR)
  - Wire scanner
  - Scraper

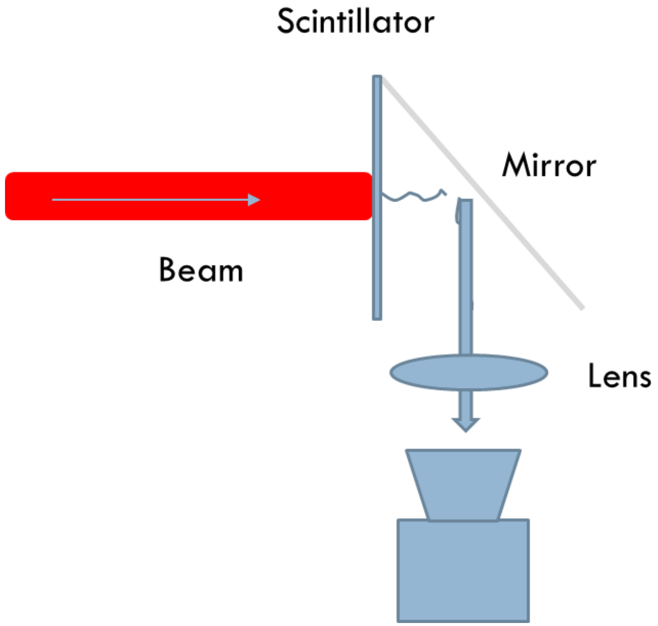
- **Non intercepting methods**
  - Synchrotron radiation
  - Laser wire
  - Rest gas ionisation
  - Beam induced fluorescence
  - Gas jet beam profile monitor

Scintillating screen

- Simply
- Cheap
- Effective



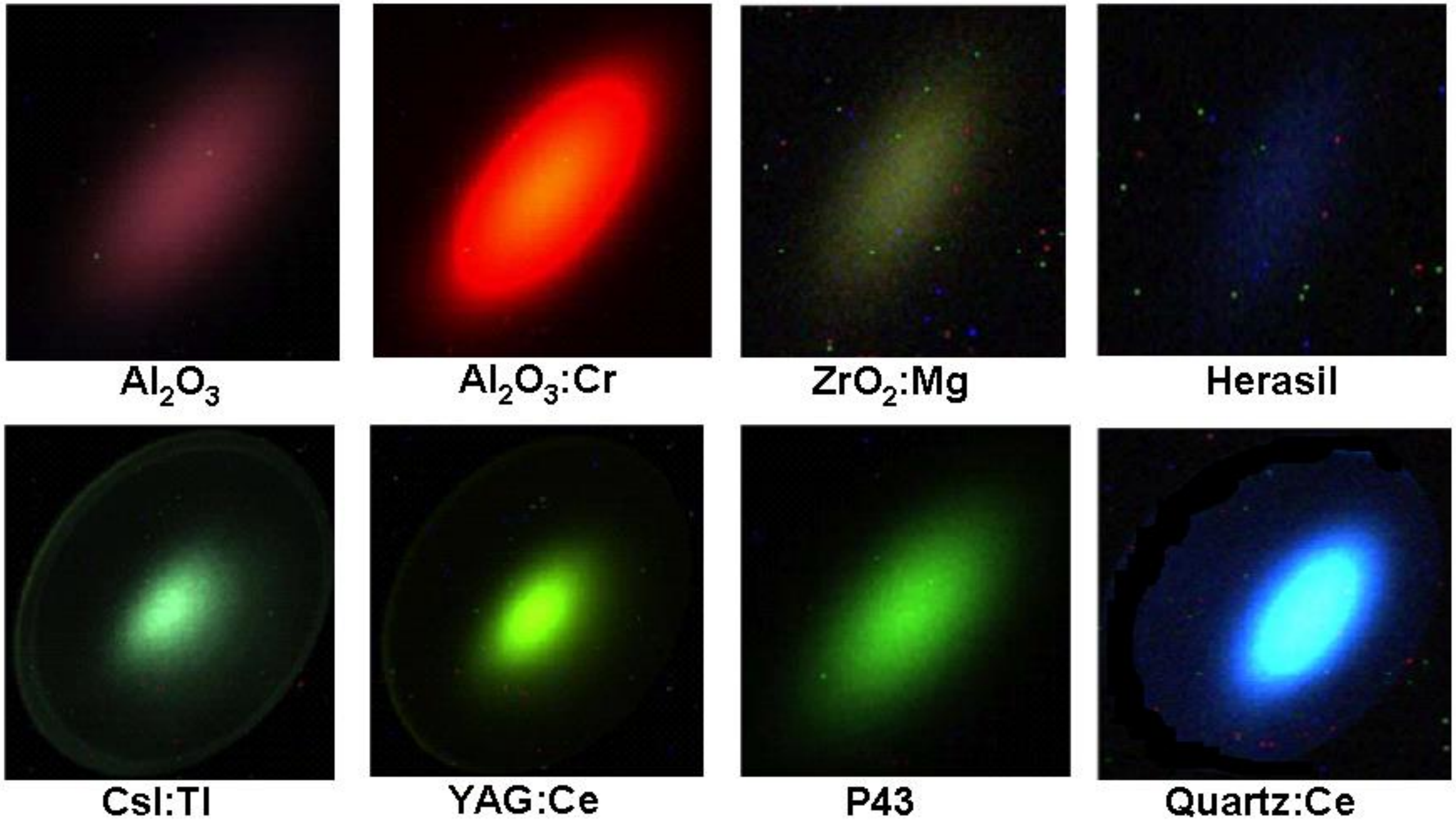
Credit: B. Walasek-Höhne, GSI and G. Kube, DESY



Scintillating materials

Abbreviation	Material	Activator	max. emission	decay time
Quartz	SiO_2	none	optical	< 10 ns
	CsI	Tl	550 nm	1 μs
	ZnS	Ag	450 nm	0.2 μs
Chromolux	Al_2O_3	Cr	700 nm	100 ms
	Li glass	Ce	400 nm	0.1 μs
P43	Gd_2O_2S	Tb	545 nm	1 ms
P46	$Y_3Al_5O_{12}$	Ce	530 nm	0.3 μs
P47	$Y_2Si_5O_5$	Ce	400 nm	50 ns

Some example of scintillating light



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Scintillating light yield

- Materials
- Energy

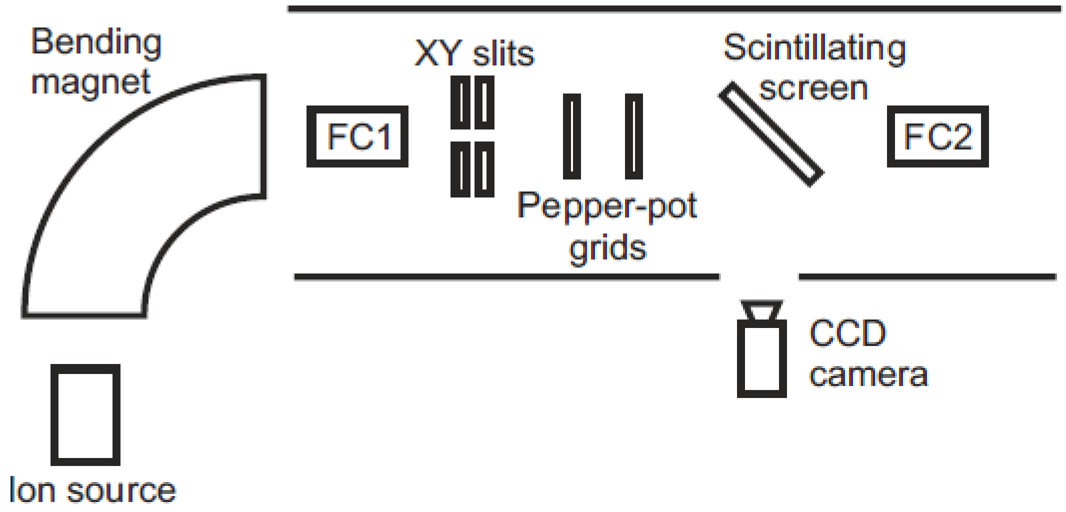
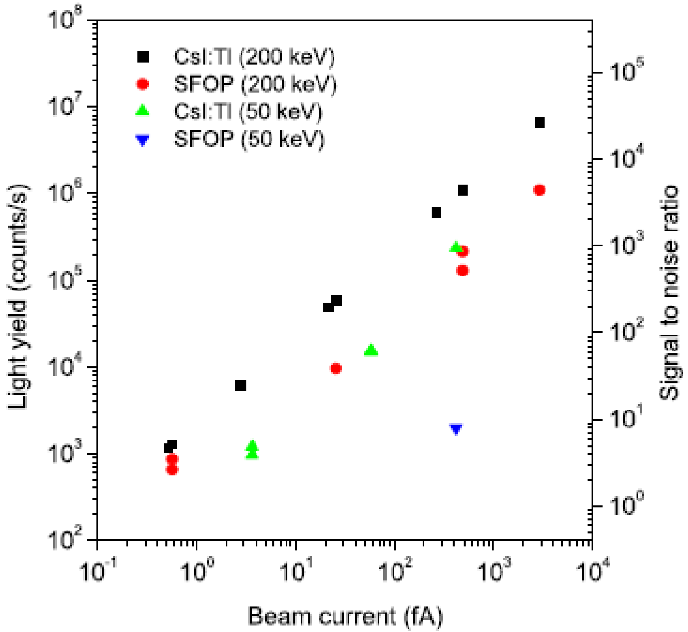


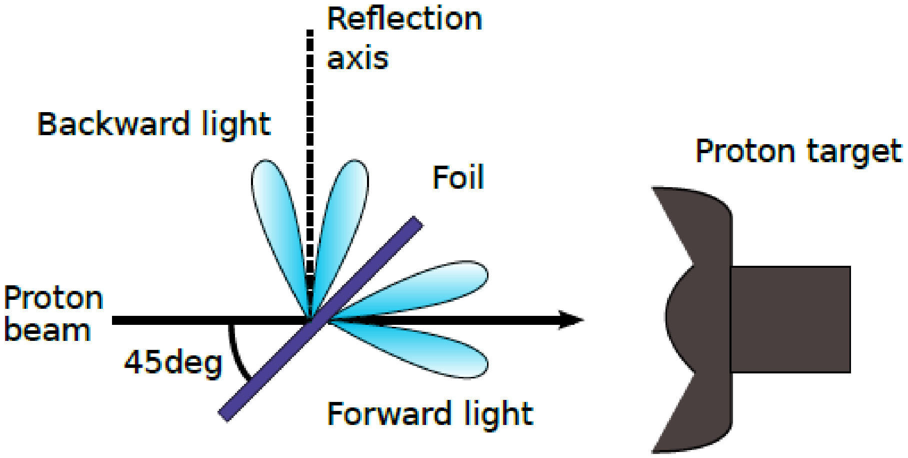
FIG. 1. Experimental setup at INFN-LNS.



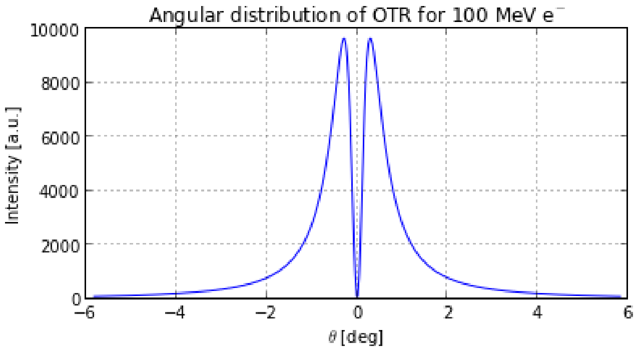
J. Harasimowicz et al.,
Rev. Sci. Instr. 81 (10), 2010

Shows sub femtoampere range for 200 keV proton beam
Much smaller in the 50 keV range

Optical Transition Radiation



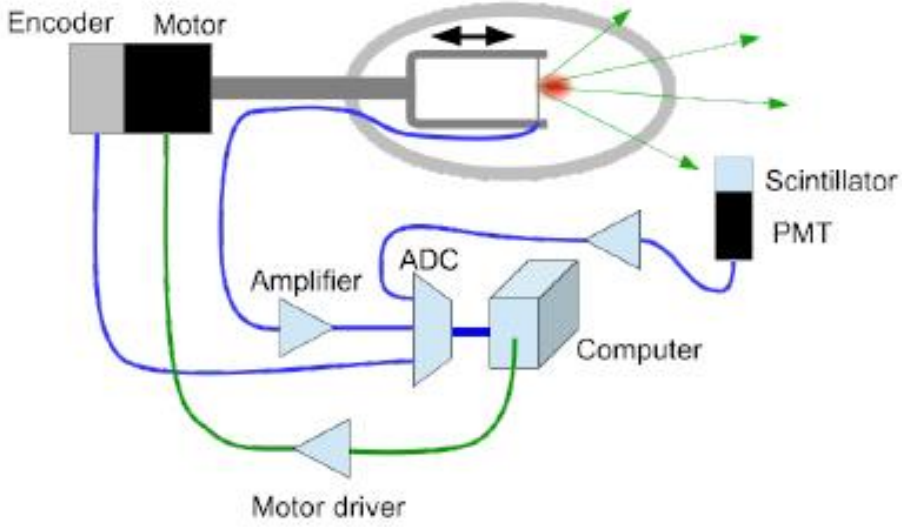
Credit: D. Morris, et al., TRIUMF

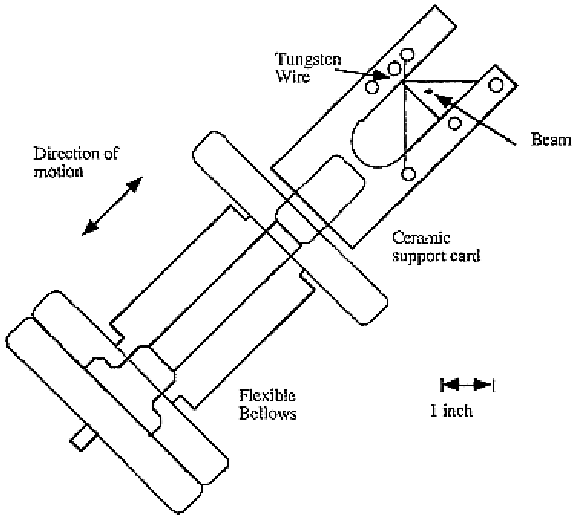


E. Bravin, Cern Accelerator School on Beam Instrumentation
2-15 June 2018, Tuusula, Finland

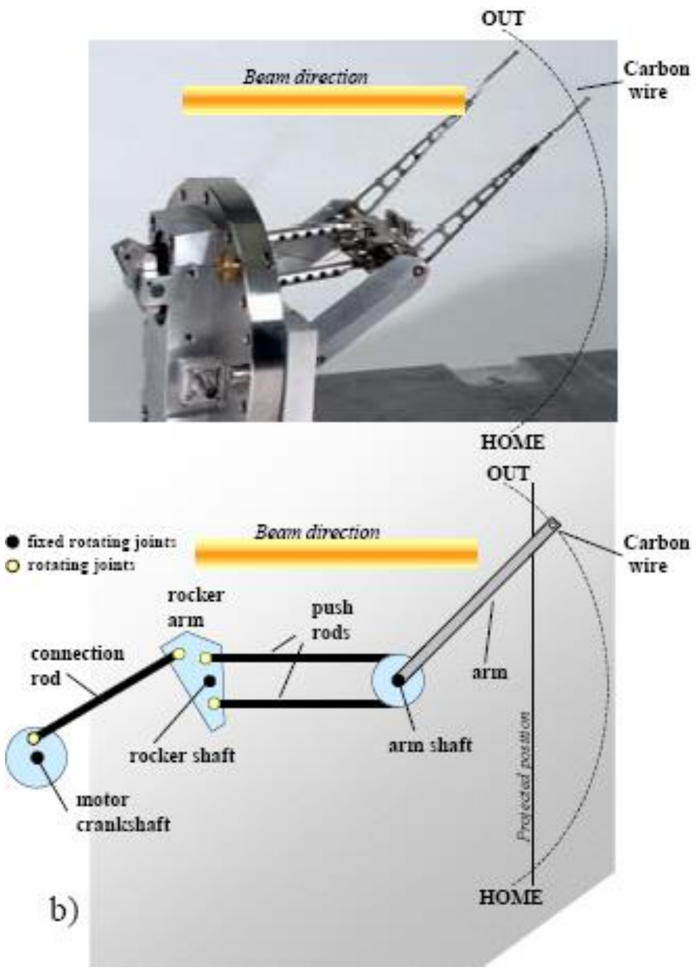
- Radiation is emitted when a charged particle crosses the boundary of different dielectric properties
- Radiation has defined angular distribution
- Radiation is radially polarised

Wire scanner





SLAC SLC high resolution 3 axis scanners



Scans a thin wire or a needle across the beam. Detects secondary emission current or high energy secondary particles (scintillator + PMT)

CERN “flying wires”

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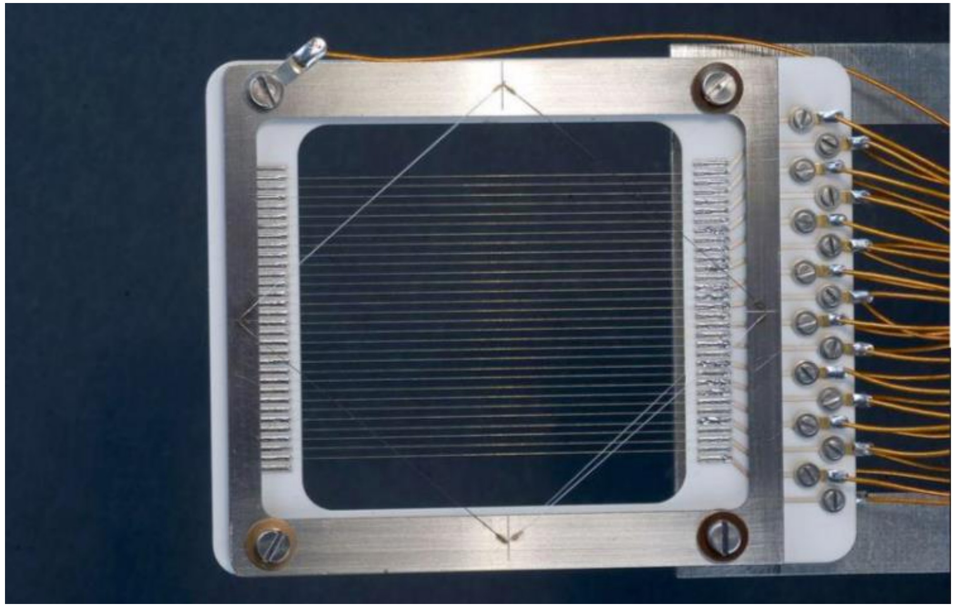
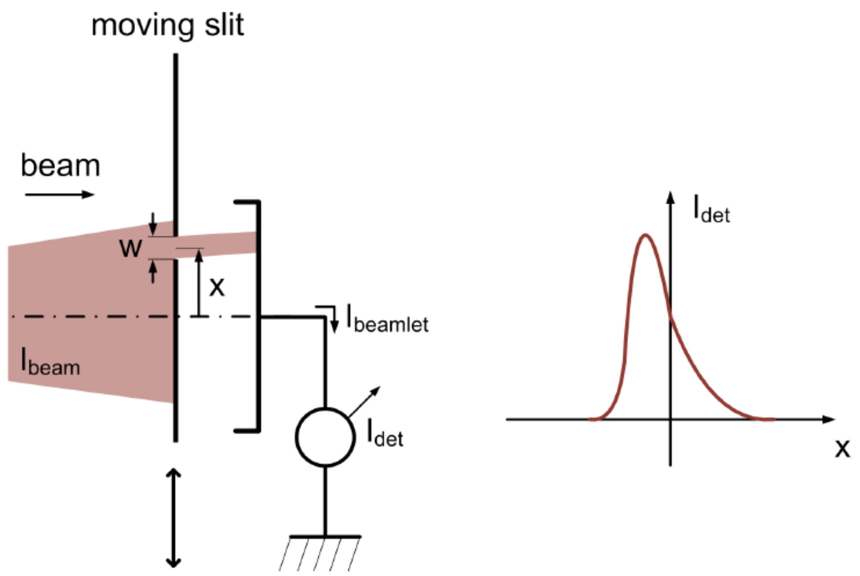
SEM Grid

- Similar to wire scanner
- The SE current from each wire or strip is acquired independently
- Wire spacing down to a few hundreds microns
- Single shot measurement



slit scanner



- Similar to wire scanner
- Beam pass through a slit and then the intensity is measured by faraday cup or scintillator.
- Slit could be vertical or horizontal
- Useful for low energy and low intensity ($I >> I_{SEM}$)

Scraper

- Similar to wire scanner
- But deal with lower intensity
- Measured CDF instead of PDF

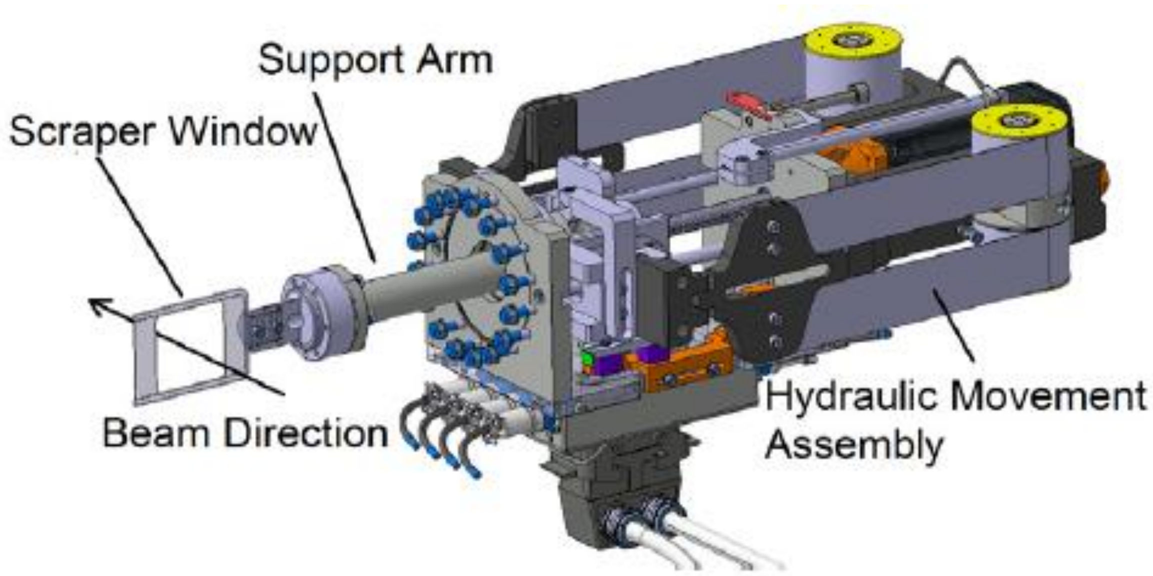
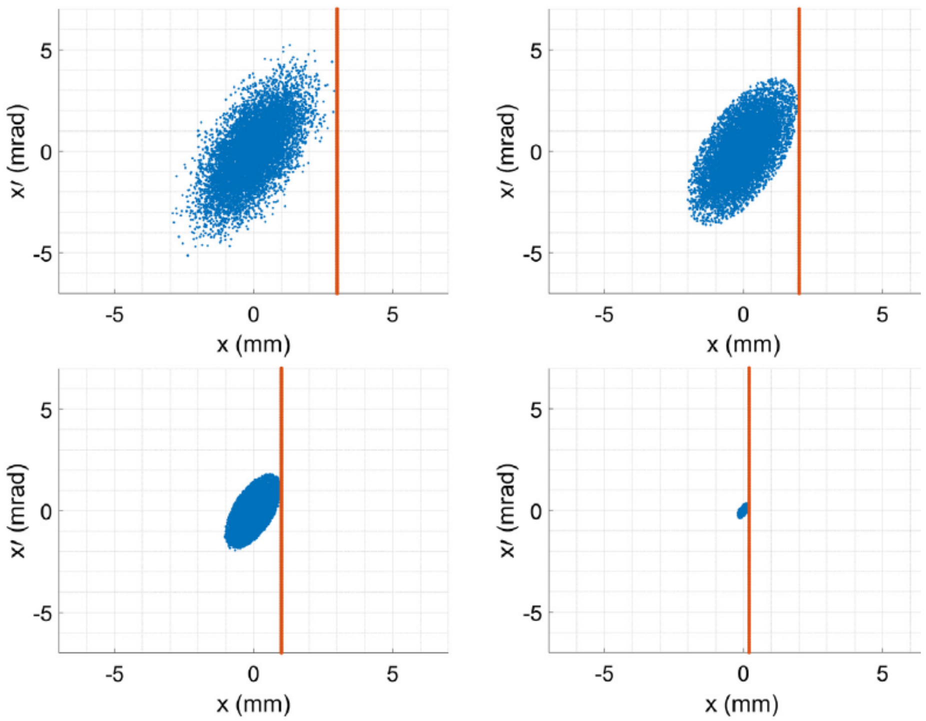


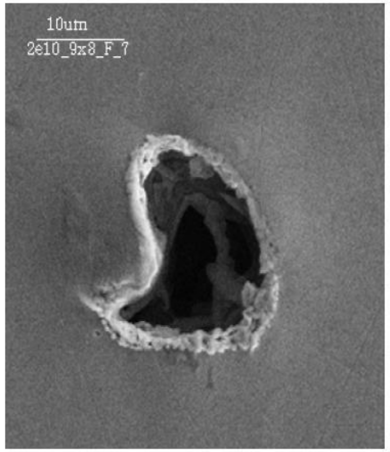
Fig. 4. A model of the horizontal scraper blade window in the extended position for use in ELENA [17].

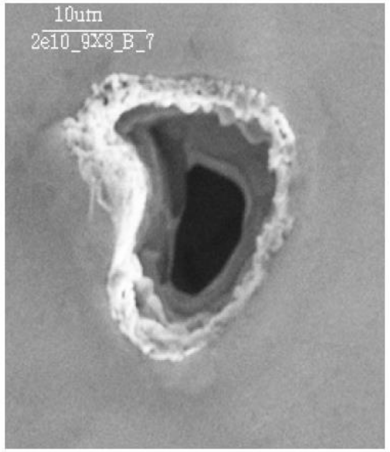


J. Hunts, et al., NIMA, Vol 896, Pages 139-151.

Beam profile of high intensity beams

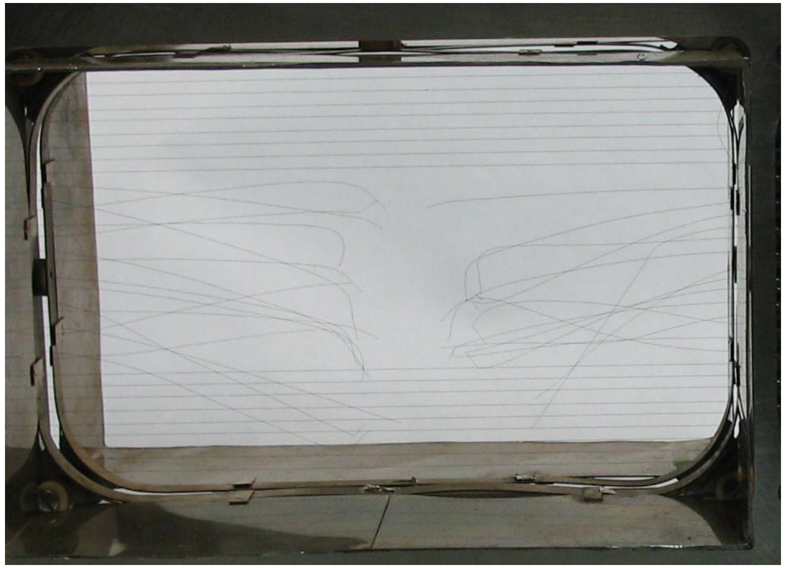
- Energy deposition
  - Signals are often proportional to the deposited energy
  - Energy deposition can cause damage to the instrument





Damaged screen

Damaged SEM Grid



Damaged OTR screen

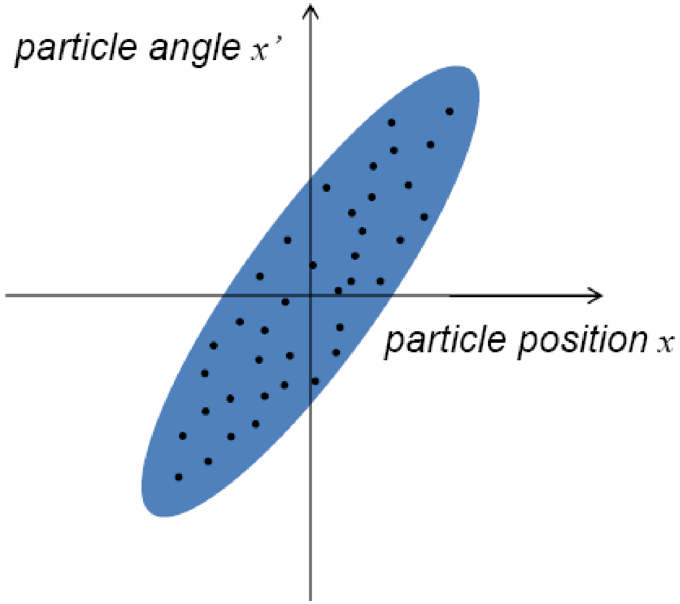
- Ideally: Non-invasive.

Emittance measurement

Emittance

- The emittance describes the beam quality, assuming linear behavior due to second order differential equation.
- It is defined as the area in phase space where the particles occupied (generally an ellipse).
- Commonly used Definition in horizontal plane (RMS Emittance):

$$\varepsilon_x = \sqrt{< x^2 >< x'^2 > - < xx' >^2}$$



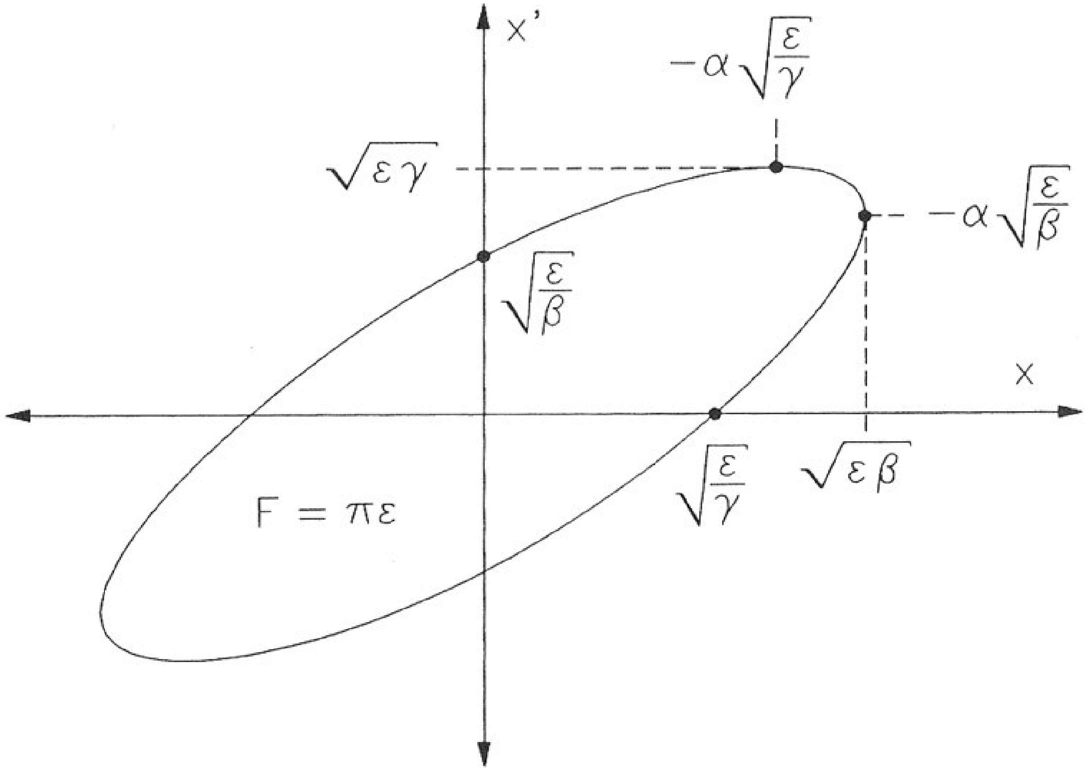
Emittance measurement

- Why measuring emittance?

  Emittance is one of the key parameter in accelerator
  - Luminosity of colliders for particle physics
  - Brightness of synchrotron radiation sources
  - Wavelength range of free electron lasers
  - Resolution of fixed target experiments
- Methods
  - Quadrupole scan
  - 3 screen method
  - Pepper pot
  - Tomography

Beam optics

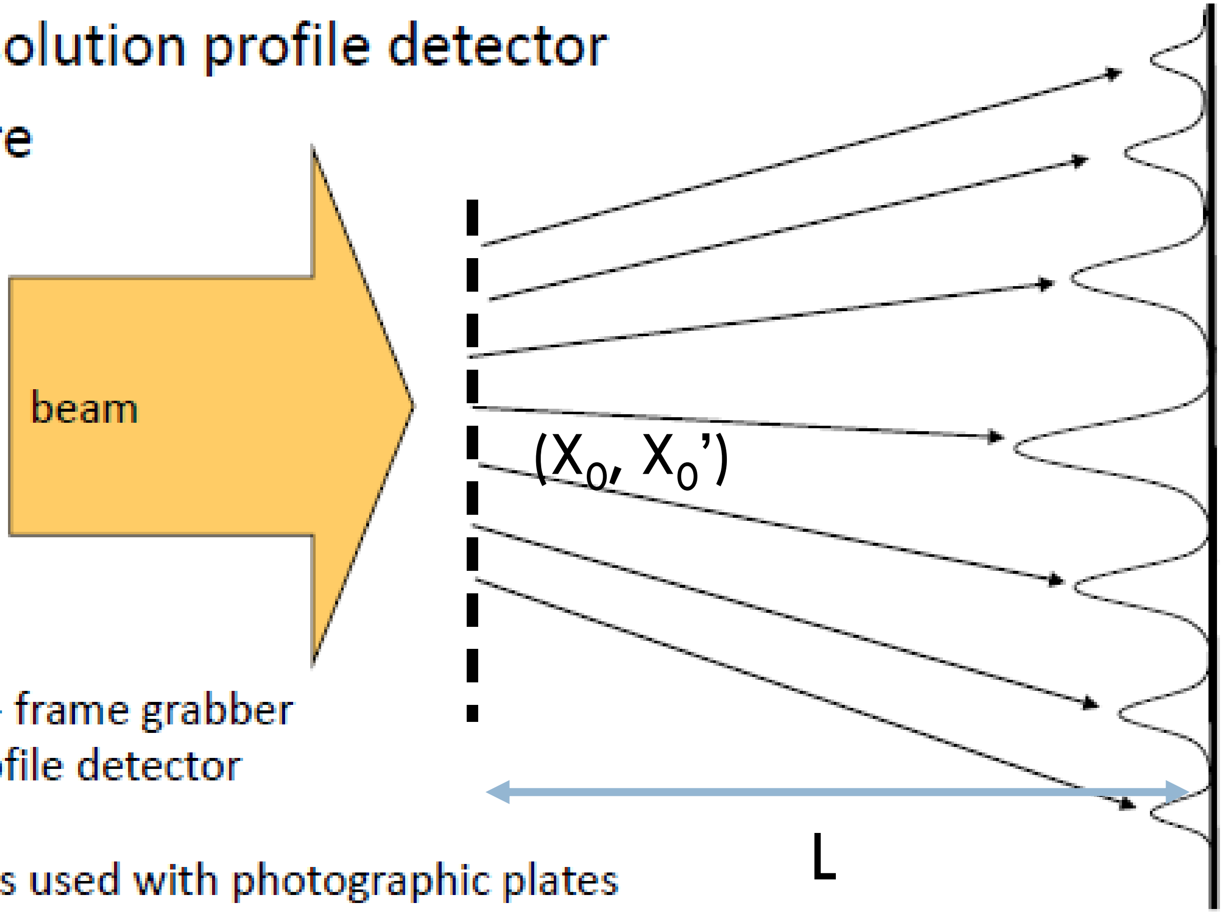
- If you know the beam optics, you can get the emittance from your profile measurement.



$$\varepsilon_x = \frac{1}{\beta_x(s)}\left[\sigma_x^2 - \left(D(s)\frac{\Delta p}{p}\right)^2\right] \text{ and } \varepsilon_y = \frac{\sigma_y^2}{\beta_y(s)}$$

Multi-slit measurement

- Needs high resolution profile detector
- Must make sure that profiles don't overlap



Scintillator + TV + frame grabber often used as profile detector

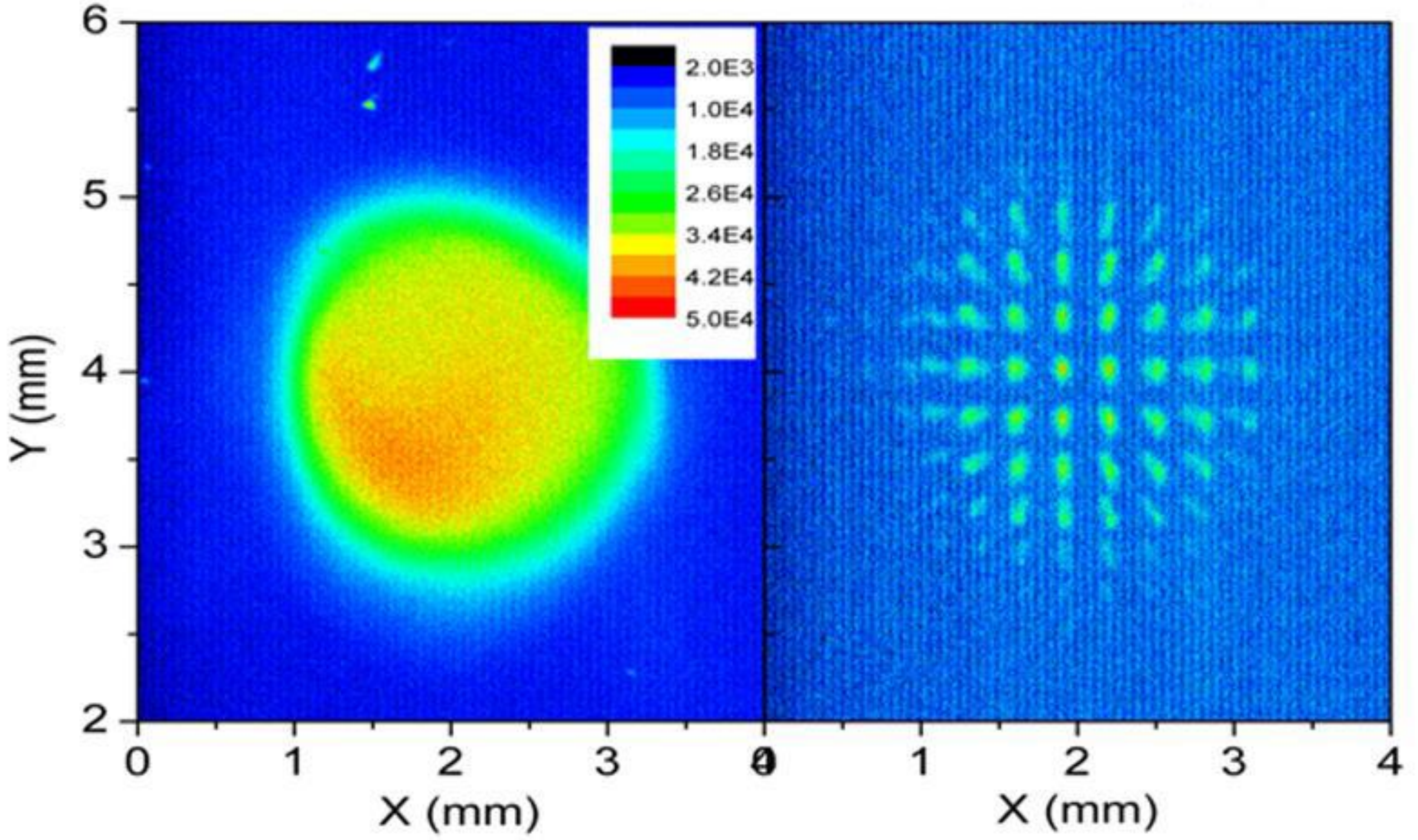
Very old idea, was used with photographic plates

$$X_0' = \frac{2\sigma - d}{L}$$

Slit size = d

Beamlet rms size = σ

Pepper pot

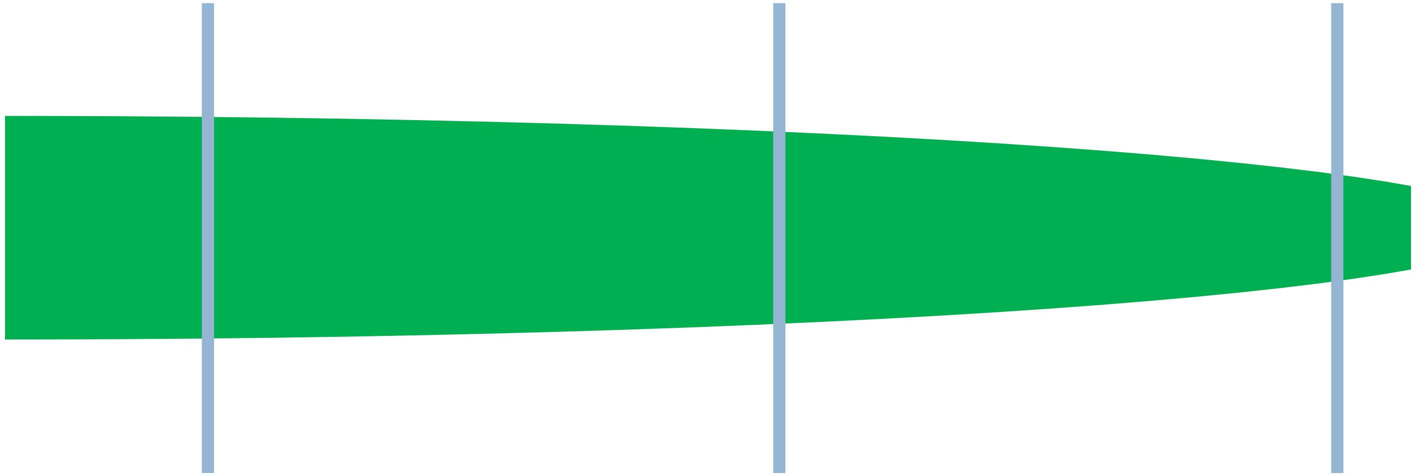

6
5
4
3
2
Y (mm)
0
1
2
3
4
X (mm)
2.0E3
1.0E4
1.8E4
2.6E4
3.4E4
4.2E4
5.0E4
0
1
2
3
4
X (mm)

3 profile measurement

- Transfer matrix

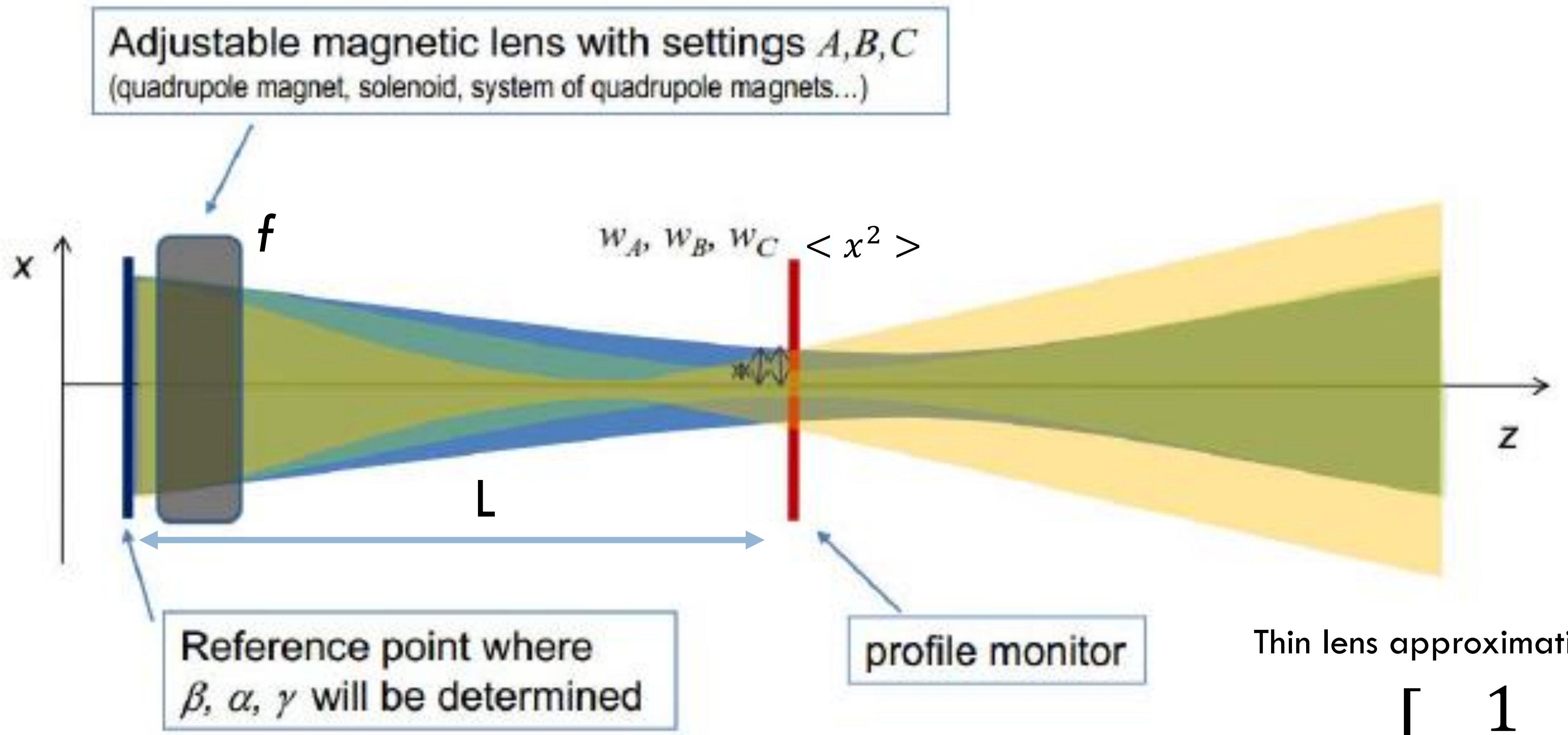
$$\begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}$$

$$< {x_1}^2 > = < (x_0 + L_1 x_0')^2 > = < x_0^2 + 2L_1 x_0 x_0' + x_0'^2 >$$
$$= < x_0^2 > + 2L_1 < x_0 x_0' > + < x_0'^2 >$$



Tutorial: Can you derive the emittance?

Quadrupole scan

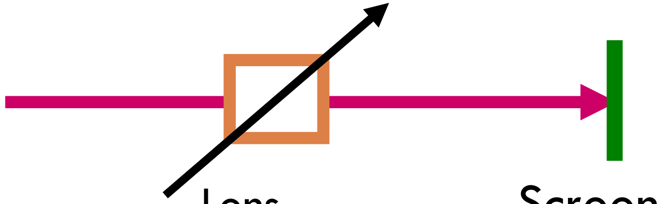


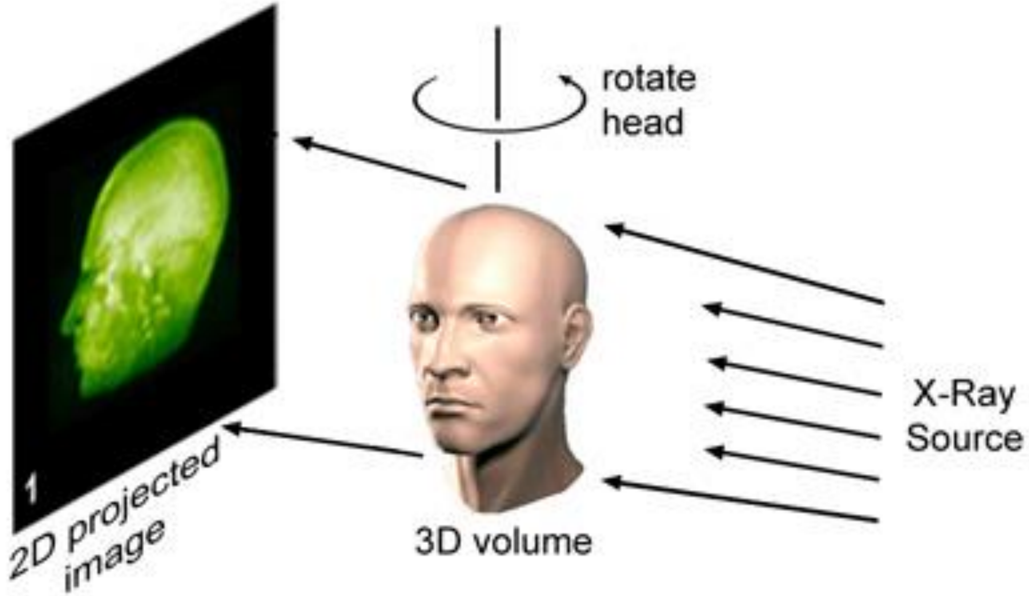
Thin lens approximation

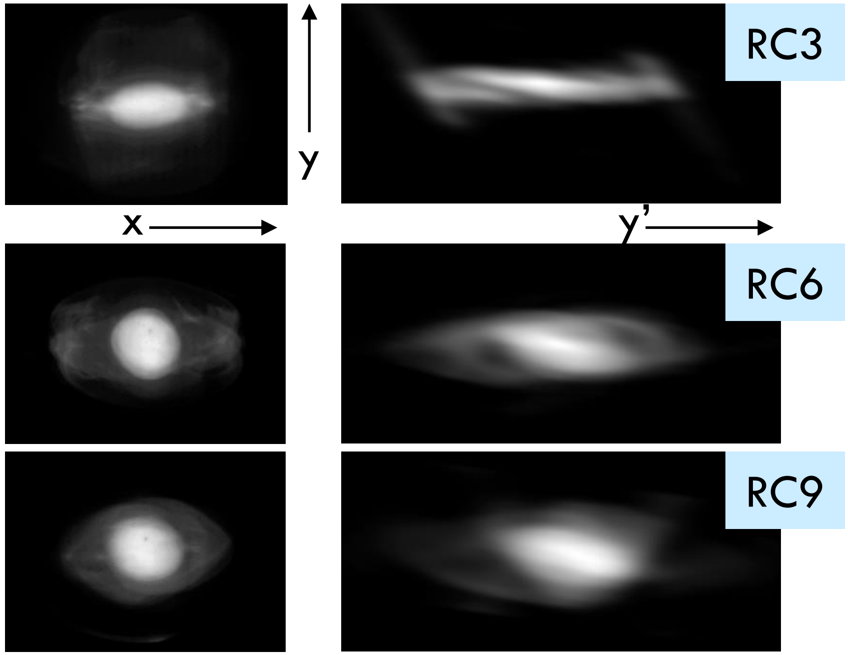
$$\begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}$$

Tutorial: Can you derive the emittance?

Tomographic Phase Space Reconstruction



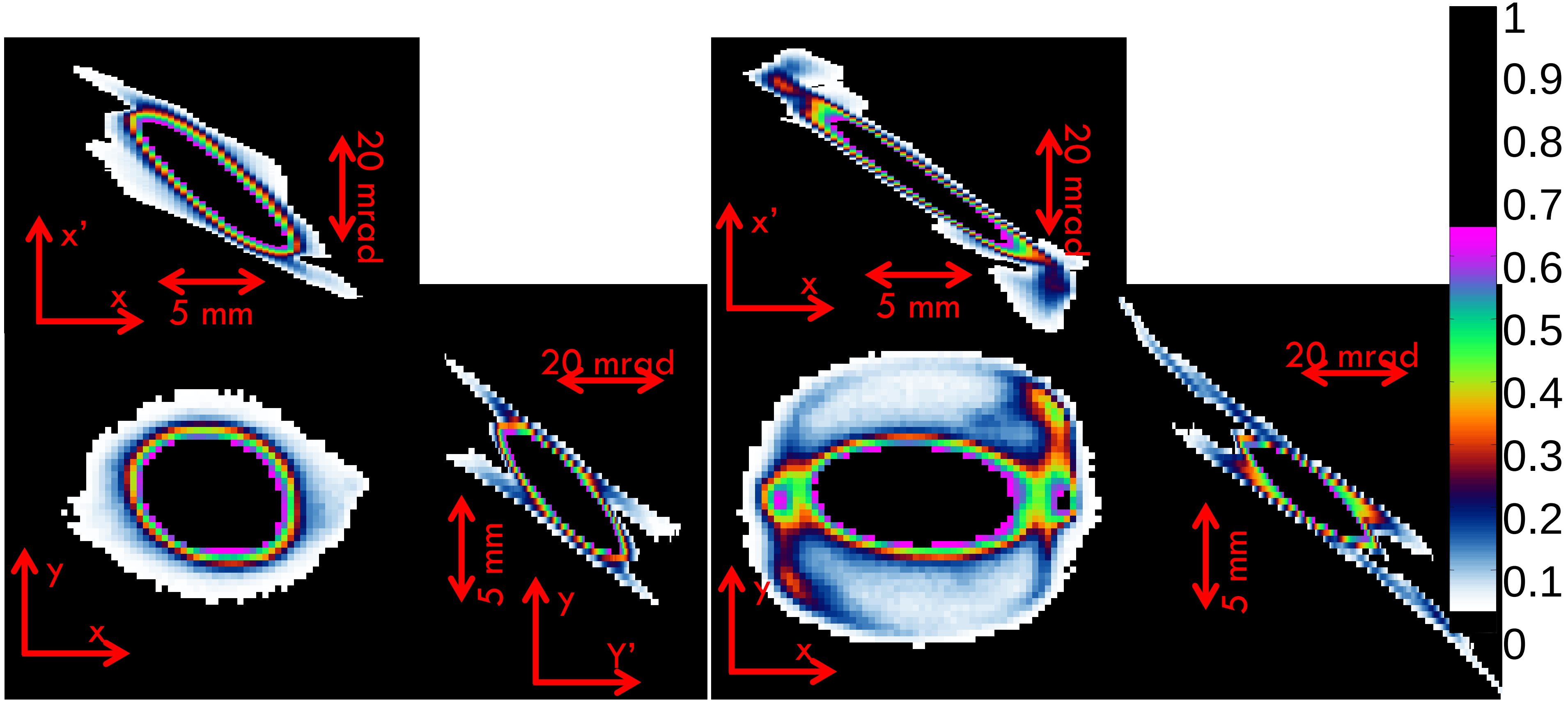




Projected / Slice, using Quadrupoles / Solenoids
with Space Charge

*D. Stratakis, R.A. Kishek, S. Bernal, et al., Physics of Plasmas **17**, 056701 (2010).*

Phase space tomography to study halo



H. Zhang, PhD thesis, university of Maryland, 2014

Transverse emittance measurement methods

Technique	Pros	Cons
Basic Optics	Simple to implement. Linear space charge OK. Small or large beams.	RMS emittance only. No phase-space.
Pepper-pot	Simple to implement. Space charge OK. No beam optics.	Coarse phase-space. Impractical for small beams.
Quad Scan	Different schemes. Easy computation.	Space charge limits. No phase-space. Linear optics assumed.
Slit-Wire	Phase space info. Integrated or t-resolved. Space charge OK.	S/N problems. Hard to implement. Comp. intensive.
Tomography	Detailed phase space info. Linear optics/sp. charge.	More beam manipulation required. Computationally intensive.

Beam Current Monitoring

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Current measurement

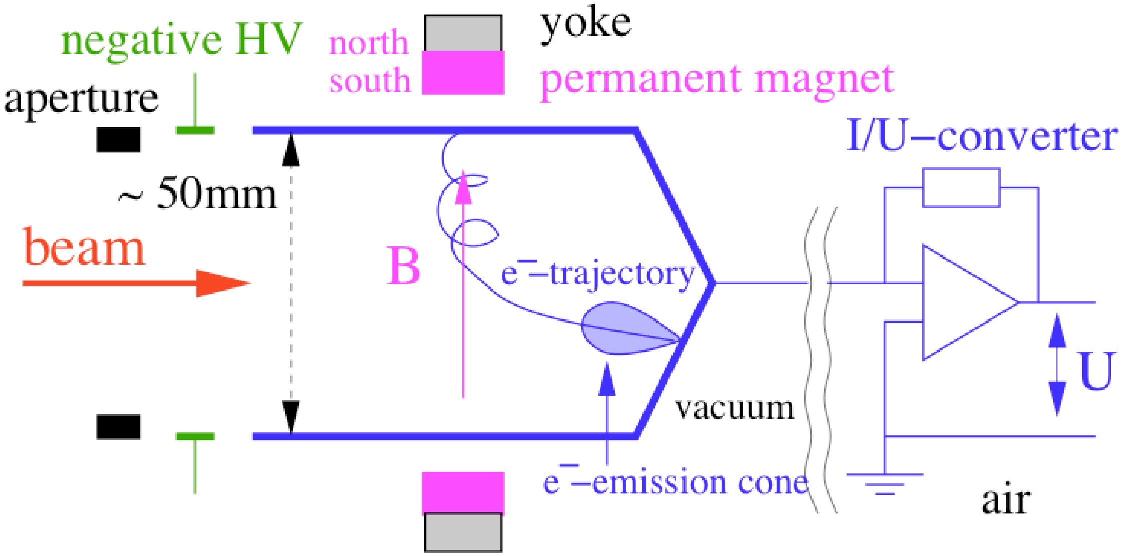
- What is the beam current?

$$I_{beam} = \frac{qeN}{t} = \frac{qeN}{l} \cdot \beta c$$

In an accelerator the current is formed by N particles of charge state *q* per unit of time *t* or unit of length *l* and velocity $\beta = v/c$.

- Measurement methods
  - Faraday cup
  - Wall current monitor
  - Current transformer
  - Cryogenic Current Comparator (CCC)

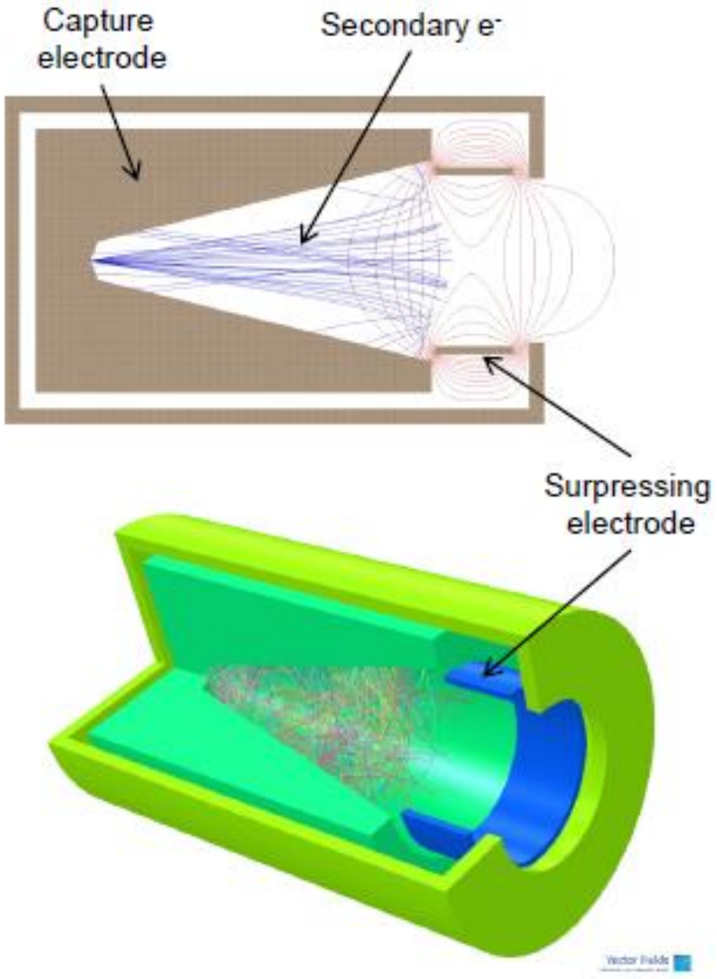
Faraday cup



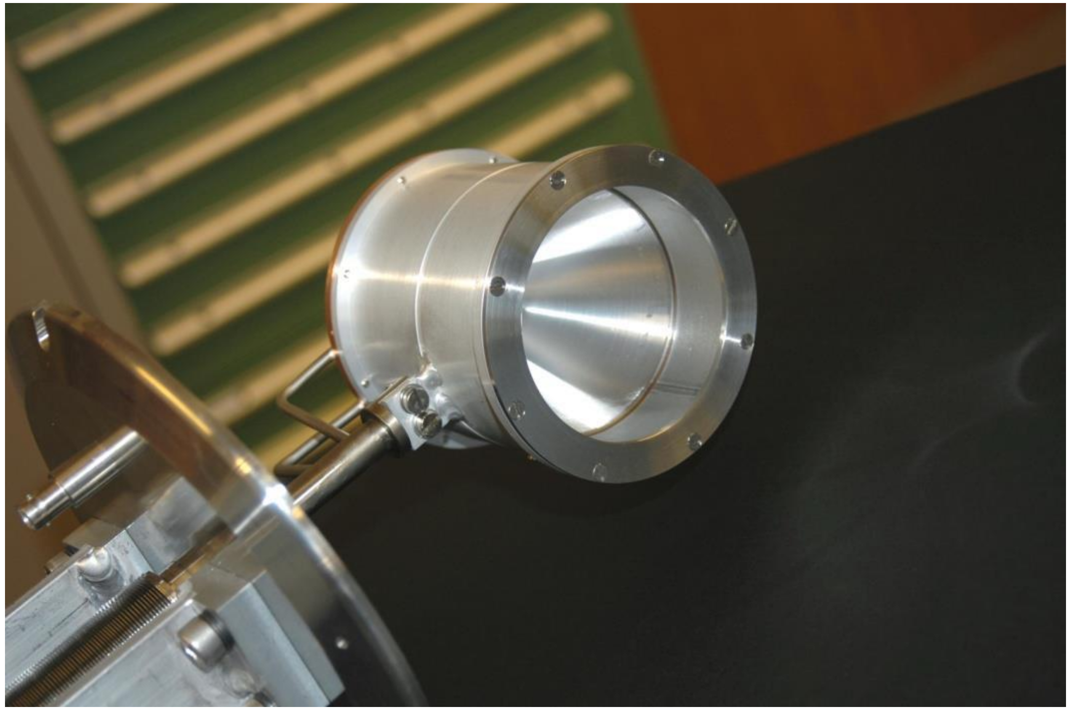
- The Faraday Cup destructively intercepts the beam
- DC coupled! (With just a resistor the signal is Vout = Ibeam*R)
- Low current measurements possible e.g., USR fA!
- Problem with secondary electrons:
  - Use long cup or voltage suppression or magnetic field
- If not properly terminated -> very high voltage (beam potential)
- Must process beam power

- Stop main beam in capture electrode,
- Secondary electrons are generated,
- Repelling electrode pushes secondary electrons back onto the electrode,

- Limitations:
  - Beam energy ?
  - Sensitivity/noise ?
  - Antimatter ?



Faraday cup with water cooling



For higher intensities
water cooling may be needed

Thank you for your attention

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Reference

- Workshops, conference and schools
  - BIW, IBIC
  - DITANET, OPAC, USPAS, JUAS, JAS, CAS

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