RECAP: BEAM DIAGNOSTICS

Hao Zhang (hao.zhang@Cockcroft.ac.uk)

Outline

- Why beam Diagnostics?
- Challenges in Diagnostics?
- Instrumentation type
  - Beam position monitoring
  - Beam profile monitoring
  - Emittance measurement
  - Beam current monitoring
  - Beam energy monitoring
  - Beam halo monitoring

hao.zhang@cockcroft.ac.uk

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

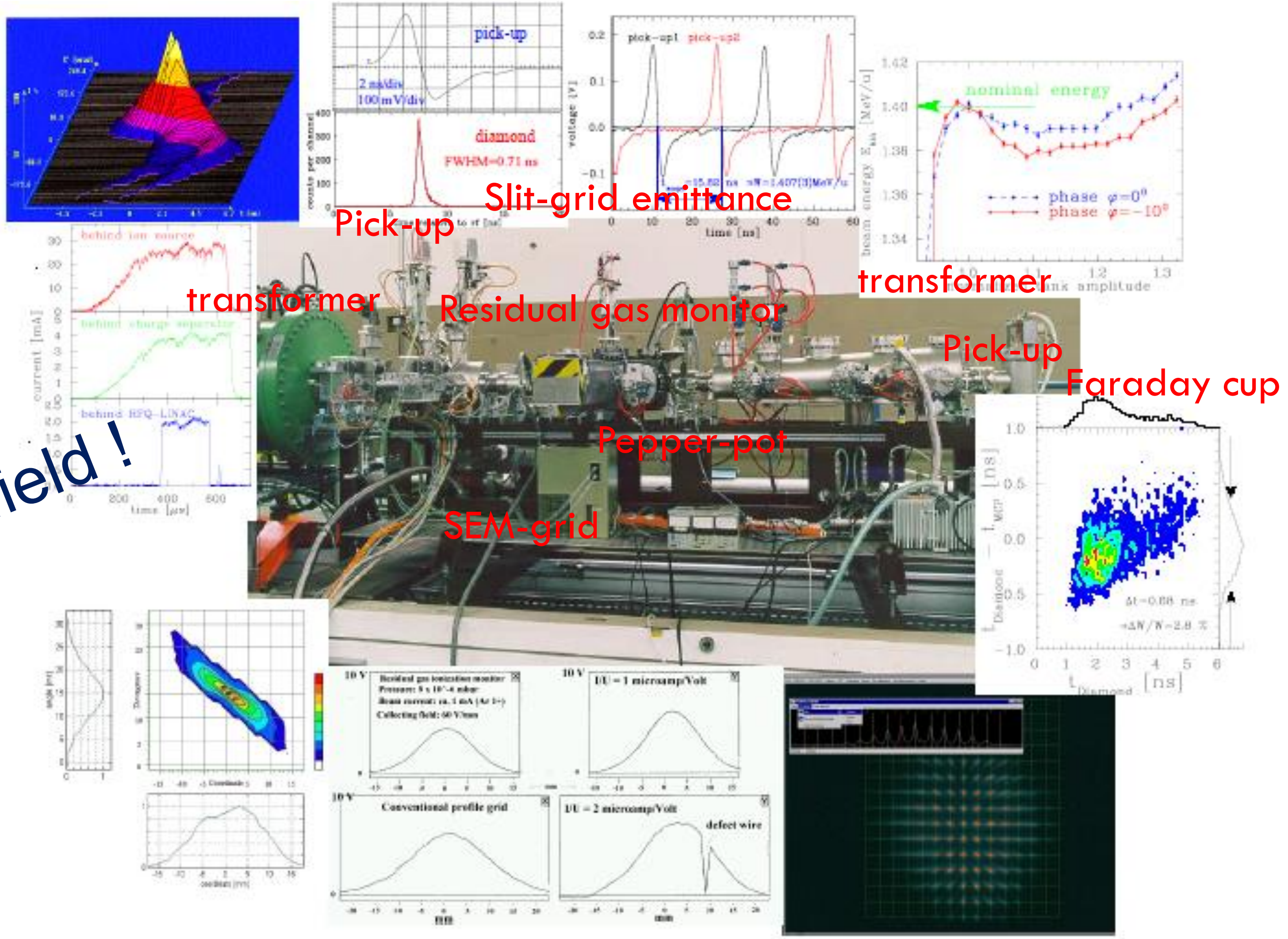
Beam quantity		LINAC, transfer line	Synchrotron
current I	*general*	transformer (dc, pulsed) Faraday cup	transformer (dc)
	special	particle detector (Scint. IC, SEM)	normalized pick-up signal
position $\overline{x}$	*general*	pick-up	pick-up
	special	using profile measurement	cavity excitation (e^-)
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.

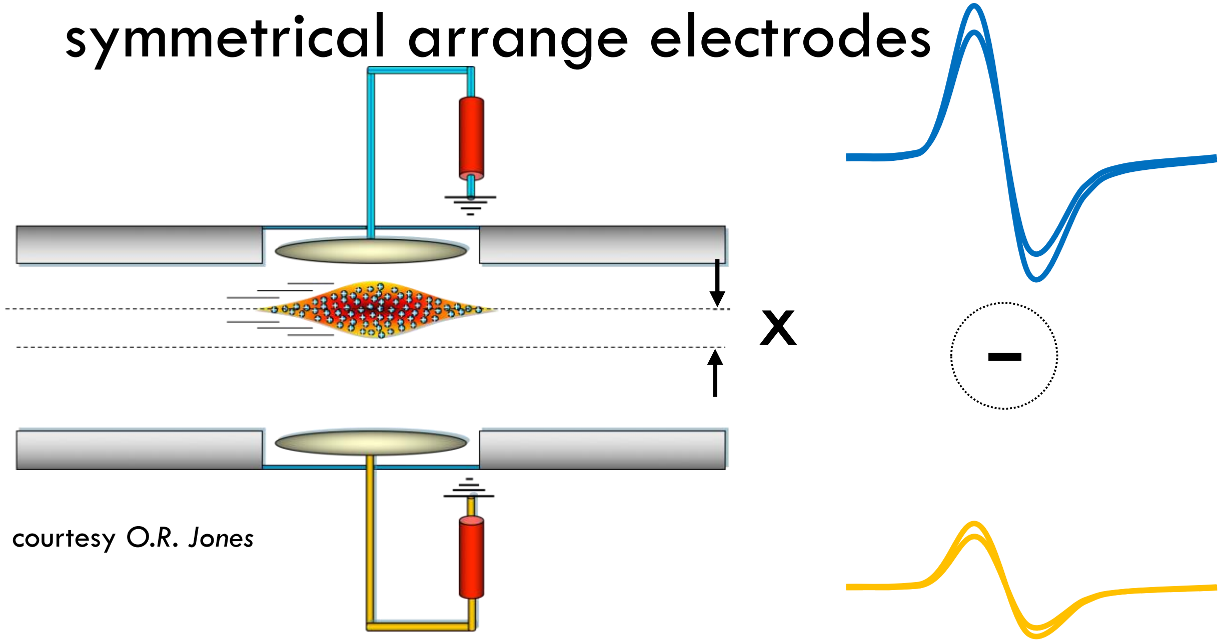
Challenge in beam diagnostics

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

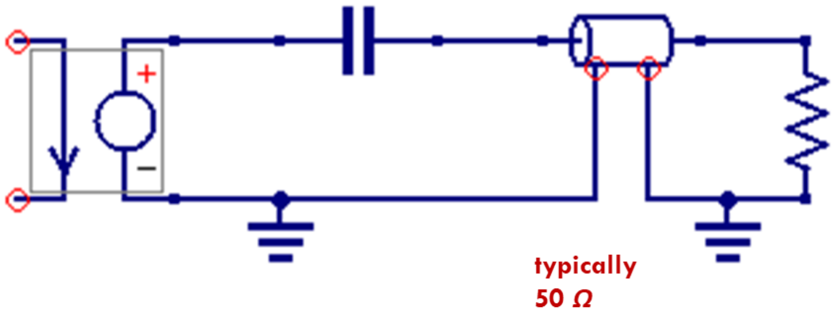
Beam Position Monitoring

Capacitive Pickups

- The Capacitive Pickups are based on symmetry
  - The beam displacement *x* is detected by a pair of symmetrical arrange electrodes



courtesy O.R. Jones



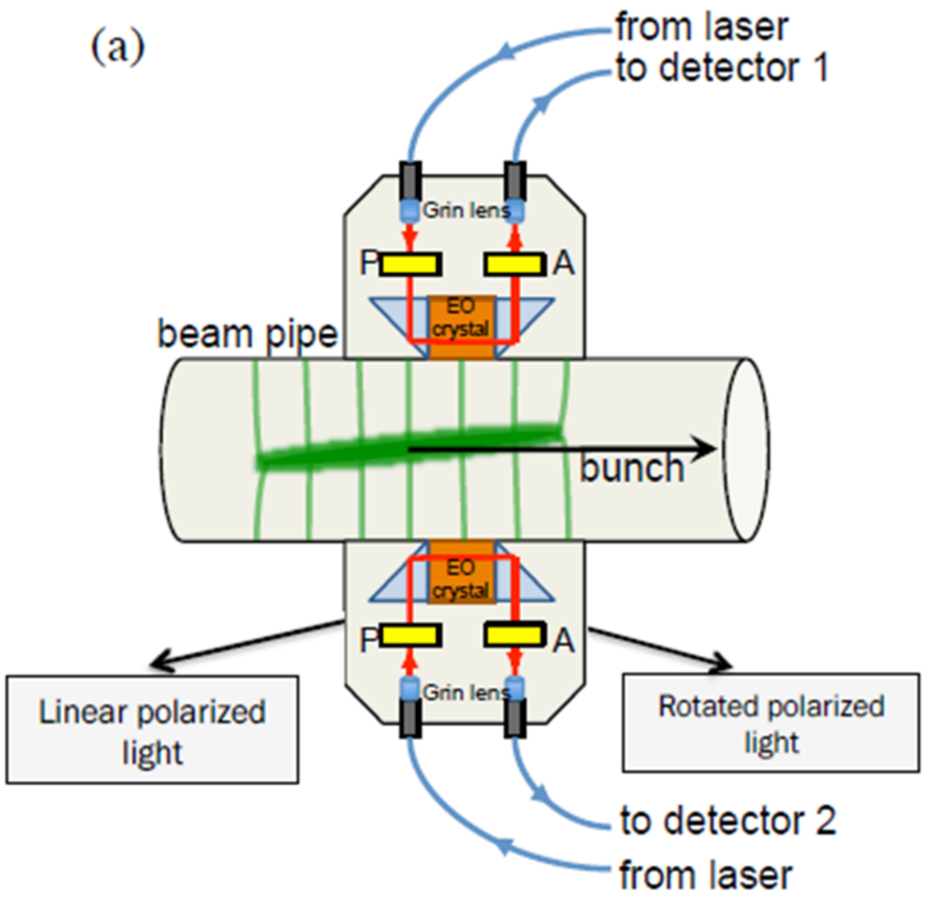
Examples:

- Shoebox type
- Buttons
- Striplines

$$x = k \cdot \frac{\Delta U}{\Sigma U} + \delta,$$

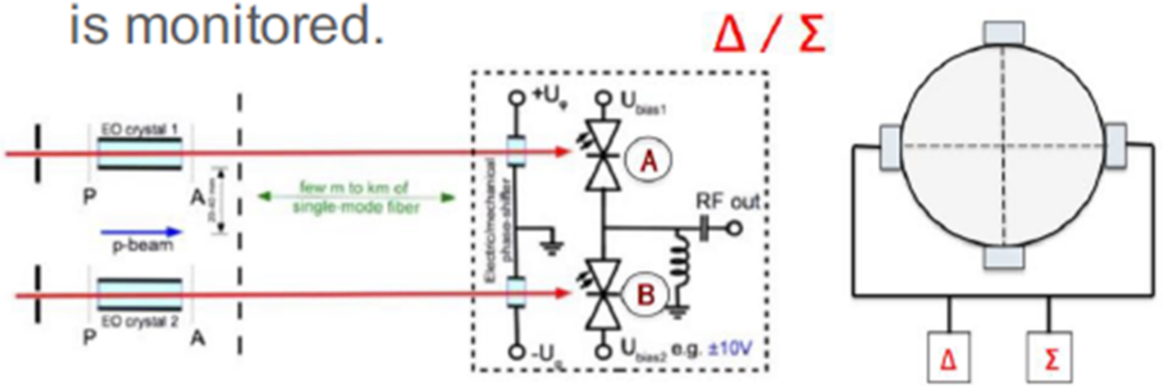
Electro-Optic Beam Position Monitors

Aim to develop fast, intra-bunch diagnostics to monitor crab-rotation of bunches.



courtesy *S. Gibson*

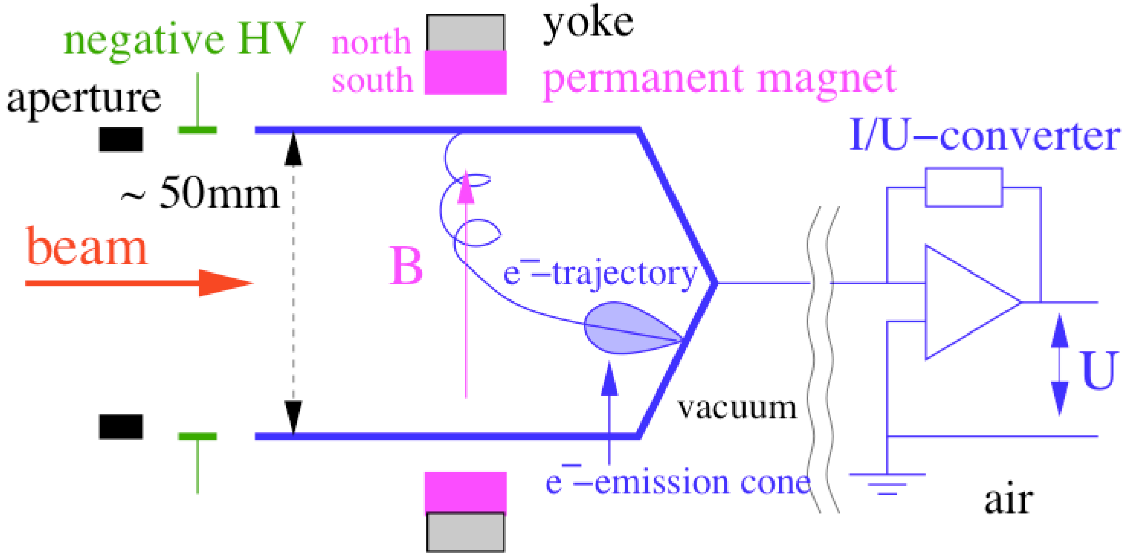
- Replace pick-ups in a button BPM with electro-optic crystals.
- The electric field from a passing bunch induces a ***polarization change*** of light through the crystal.
- Fibre-coupled design with laser and detectors 160 m away from accelerator tunnel.
- Transverse position along the 1ns LHC bunch is monitored.



Beam Current Monitoring

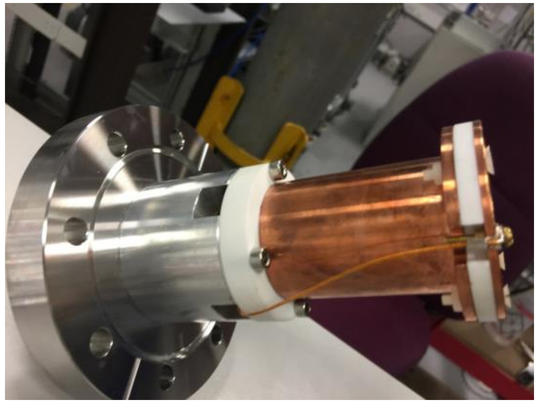
hao.zhang@cockcroft.ac.uk

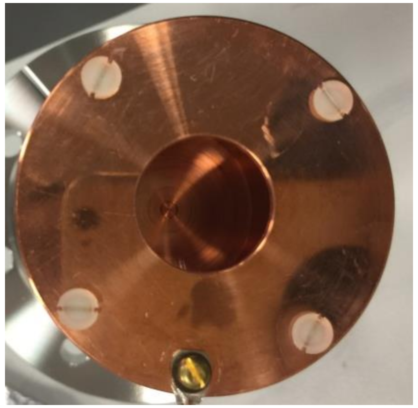
Faraday cup

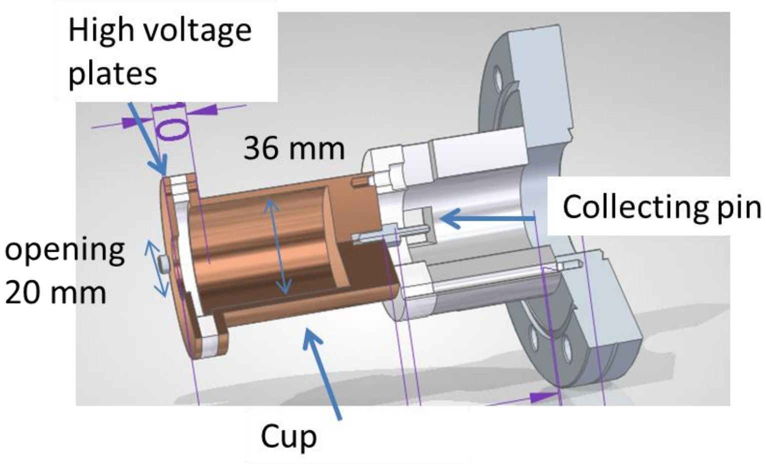


- The Faraday Cup destructively intercepts the beam
- DC coupled! (With just a resistor the signal is Vout = Ibeam*R)
- Low current measurements possible e.g., USR fA!
- Problem with secondary electrons:
  - Use long cup or voltage suppression or magnetic field
- If not properly terminated -> very high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

Faraday cup examples





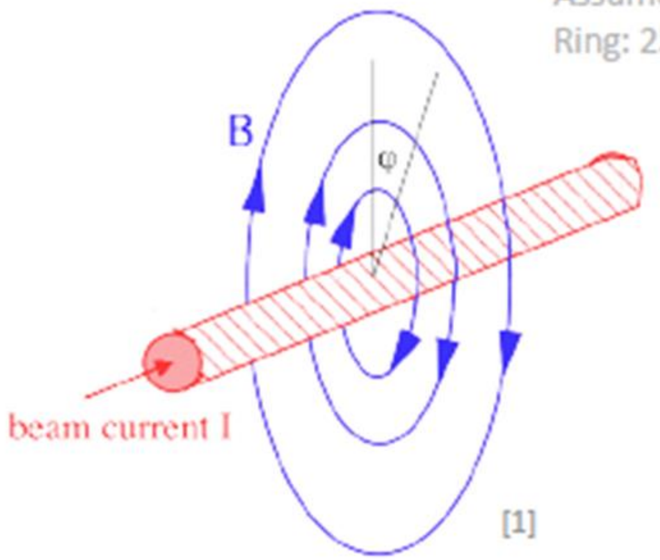


Simple faraday cup in my lab

For higher intensities
water cooling may be needed

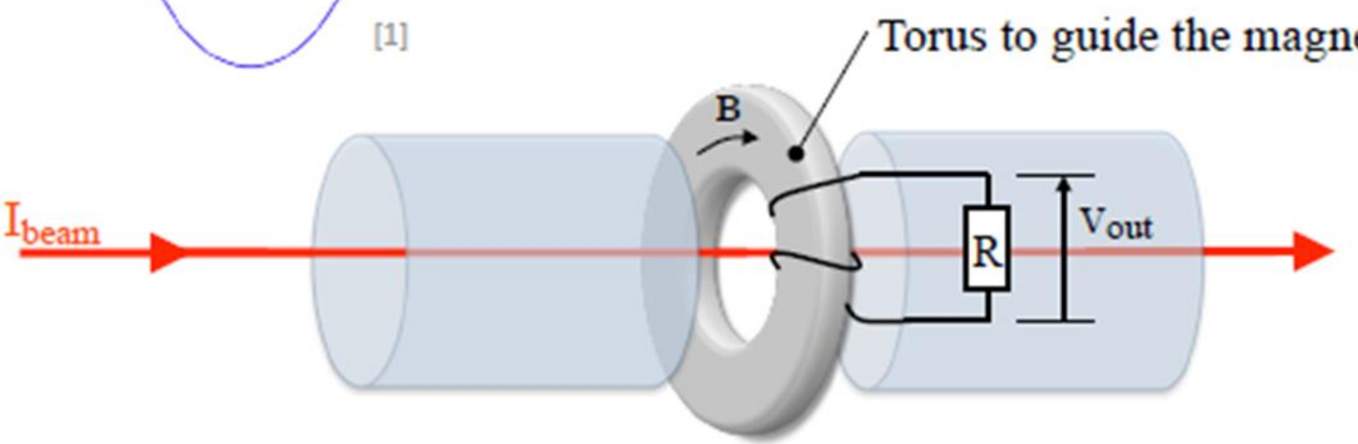
Beam transformer

Measure the beam current through the magnetic field of the beam.



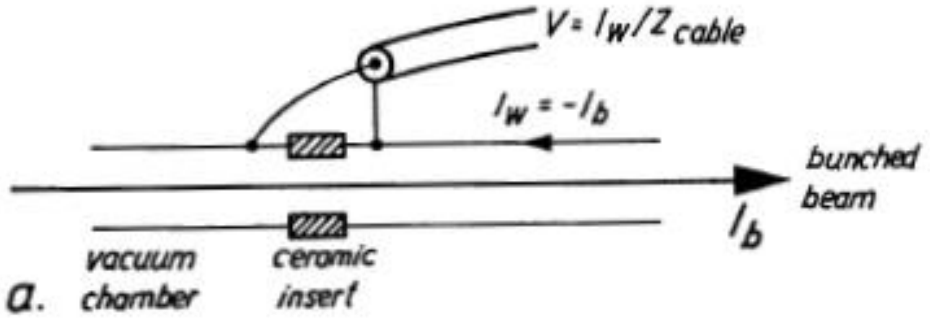
Assume the beam is long enough to be regarded as a line current. E.g. SNS Ring: 250 meters for 1usec

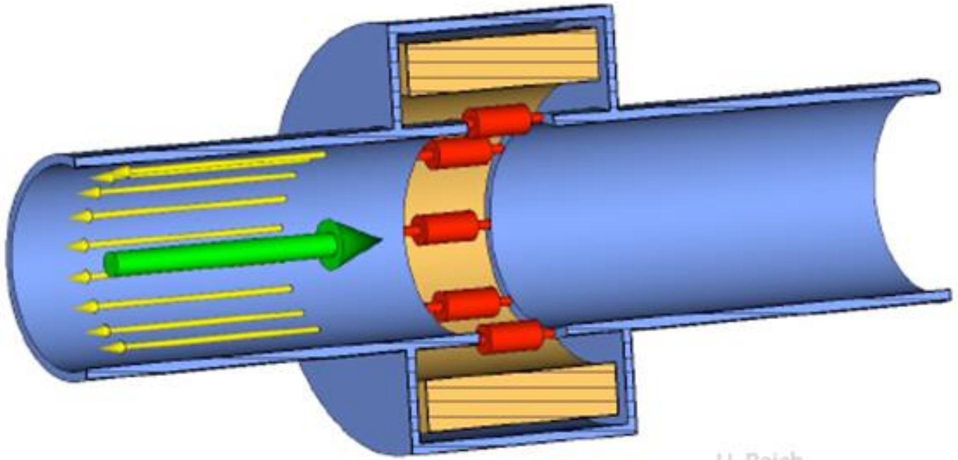
$$\text{Line current field:} \quad \vec{B} = \mu \cdot \frac{I_{beam}}{2\pi r} \vec{a}_{\varphi}$$



Courtecy: W. Blokland

Wall-Current Monitors

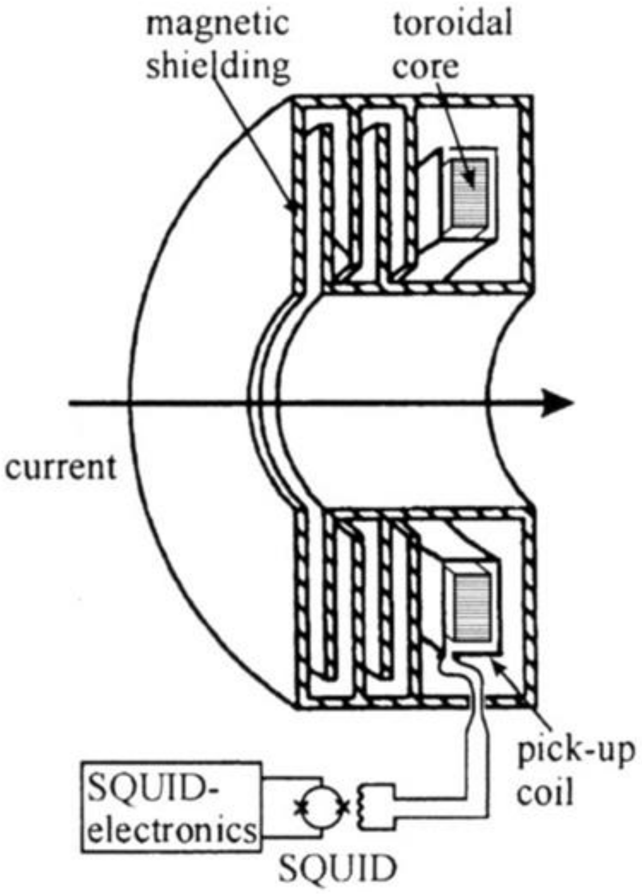




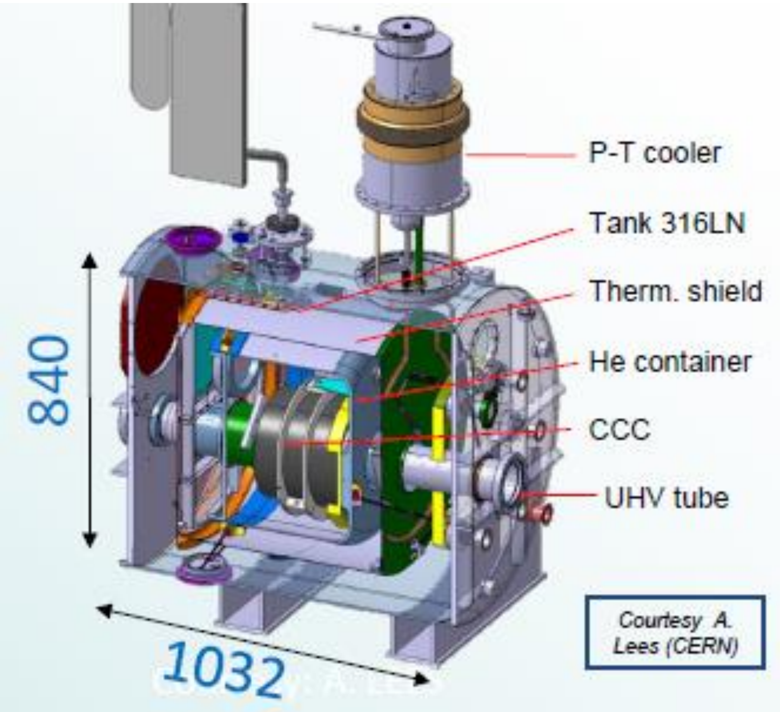
- The image current accompany the beam current.
- A voltage proportional to beam current can be measured across the resistors
- Also the noise issue will limit the resolution

Cryogenic Current Comparator (CCC)

- Non-destructive measurement device for low intensity beams (between 1 nA to 10 µA)



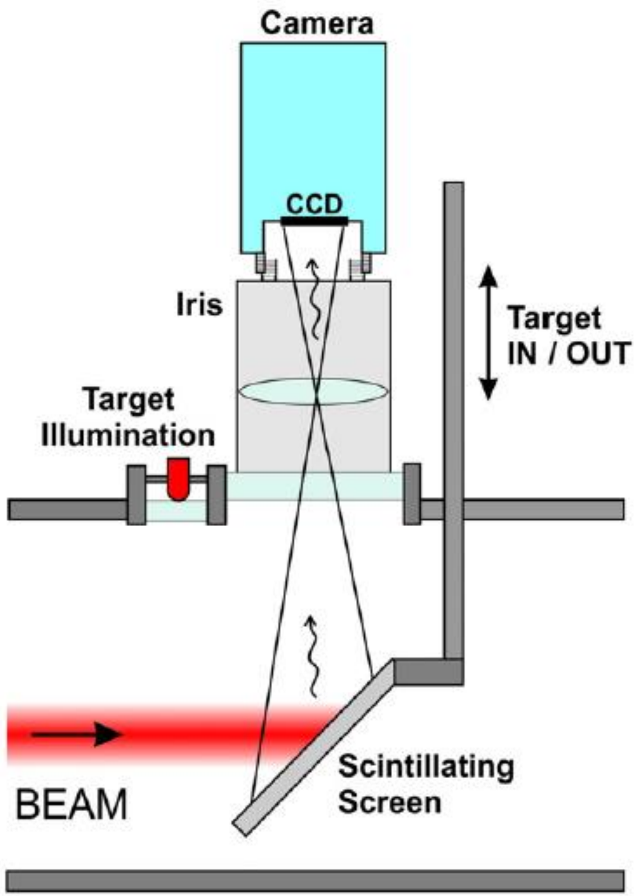
- The CCC consists of:
  - Cryogenic device
  - SC pickup coil,
  - Highly efficient SC shield,
  - High performance SQUID measurement system.

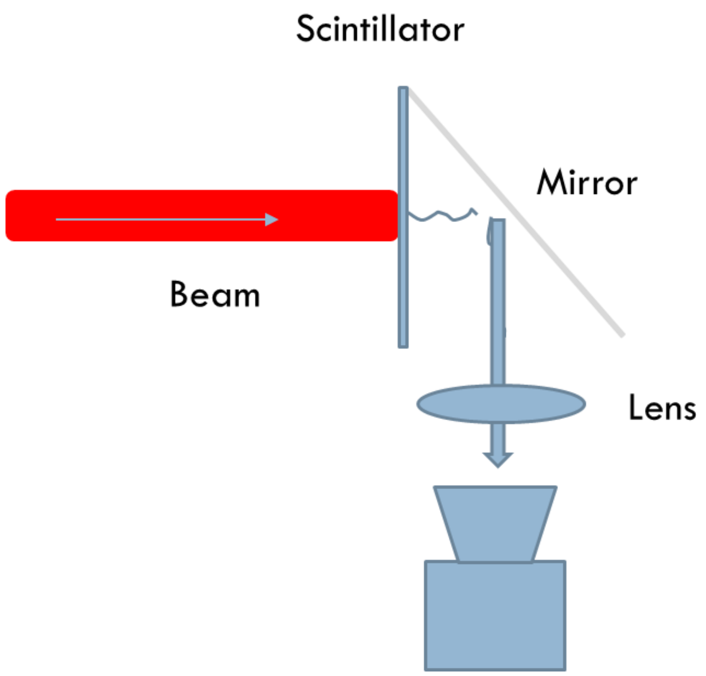


Beam Profile Monitoring

Scintillating screen

- Simply
- Cheap
- Effective



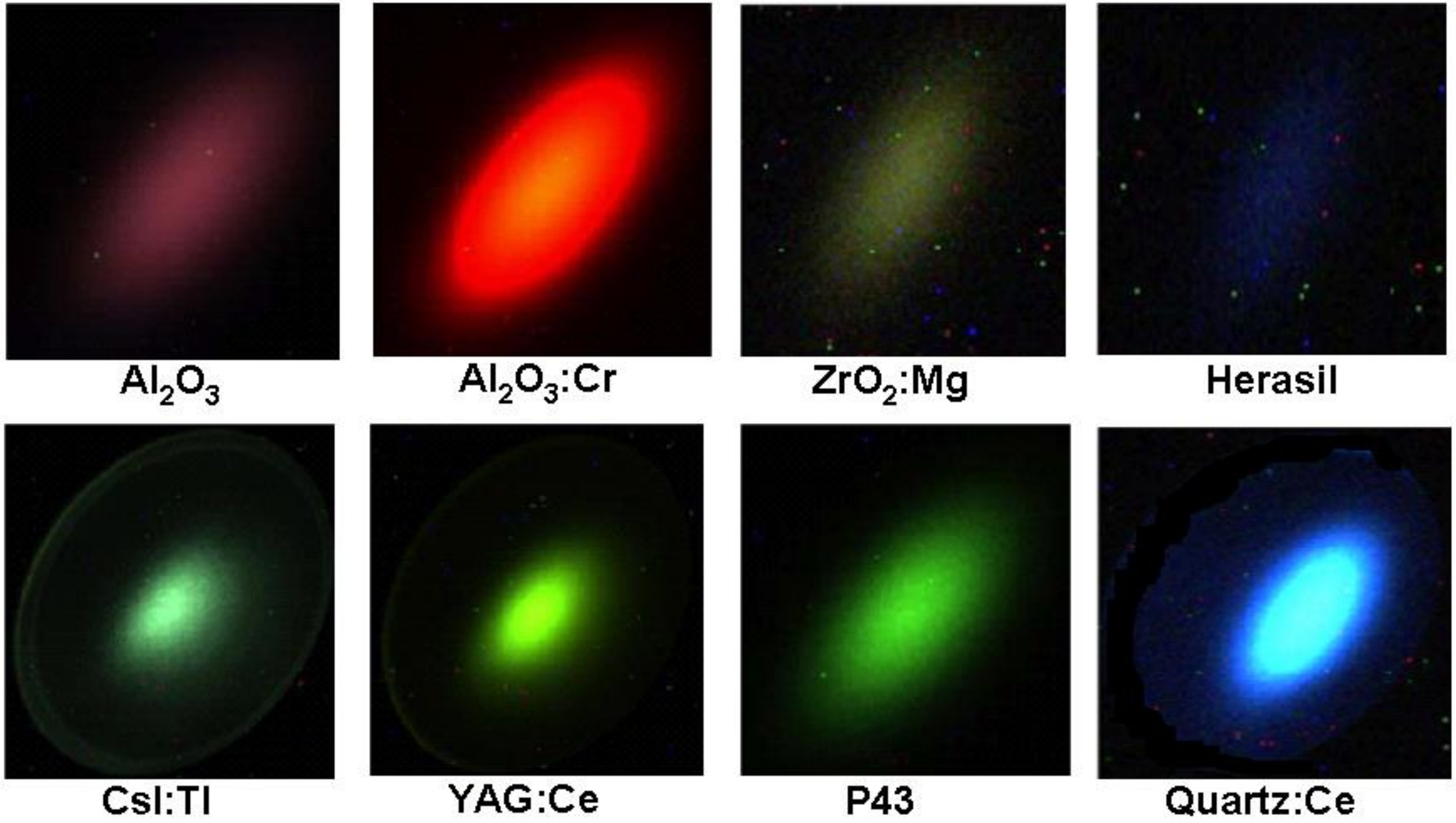


Credit: B. Walasek-Höhne, GSI and G. Kube, DESY

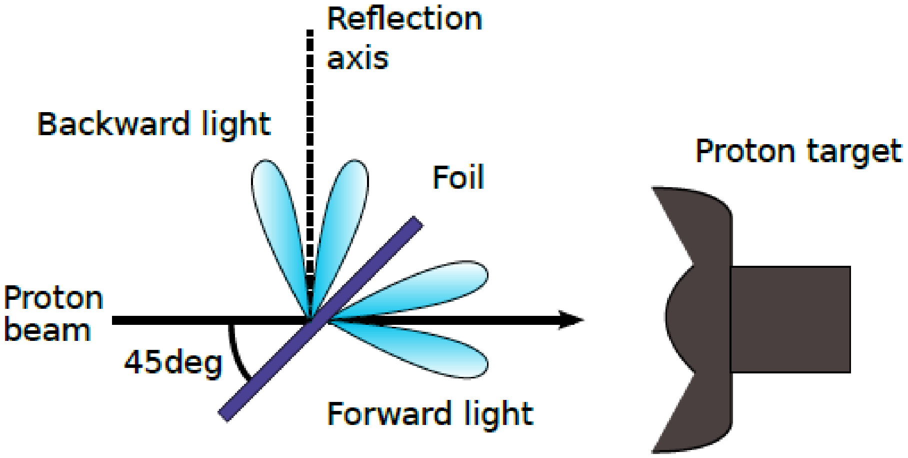
Scintillating materials

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

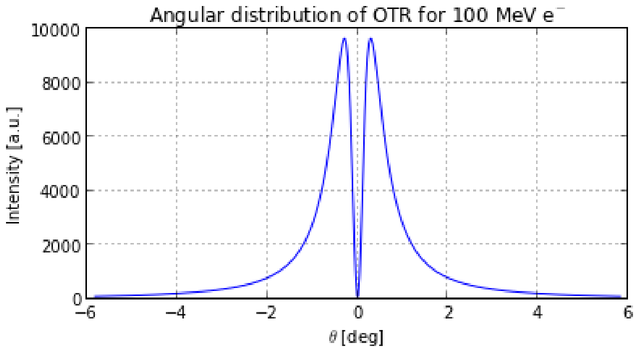
Some example of scintillating light



Optical Transition Radiation



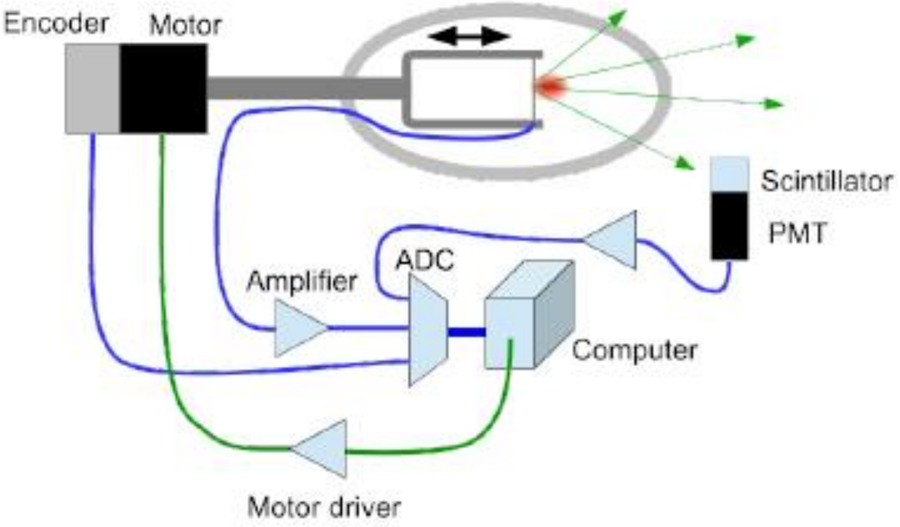
Credit: D. Morris, et al., TRIUMF

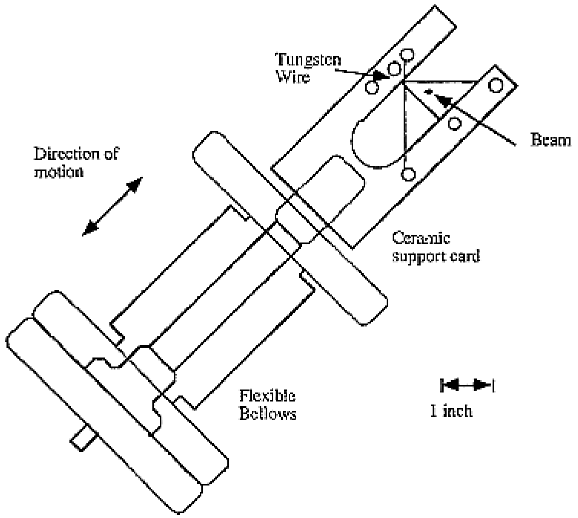


E. Bravin, Cern Accelerator School on Beam Instrumentation
2-15 June 2018, Tuusula, Finland

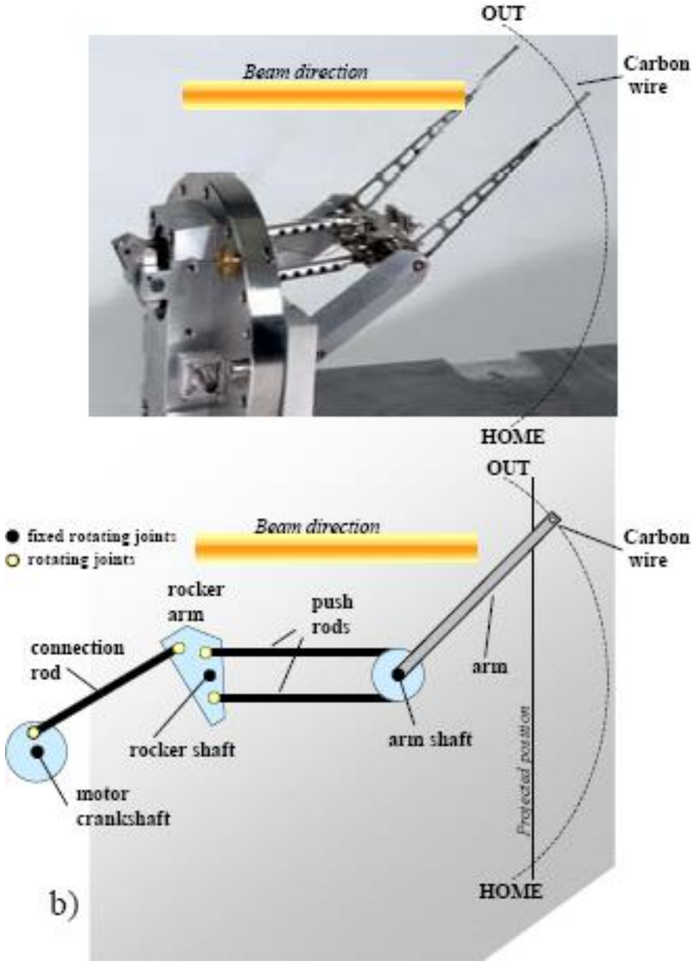
- Radiation is emitted when a charged particle crosses the boundary of different dielectric properties
- Radiation has defined angular distribution
- Radiation is radially polarised

Wire scanner





SLAC SLC high resolution 3 axis scanners



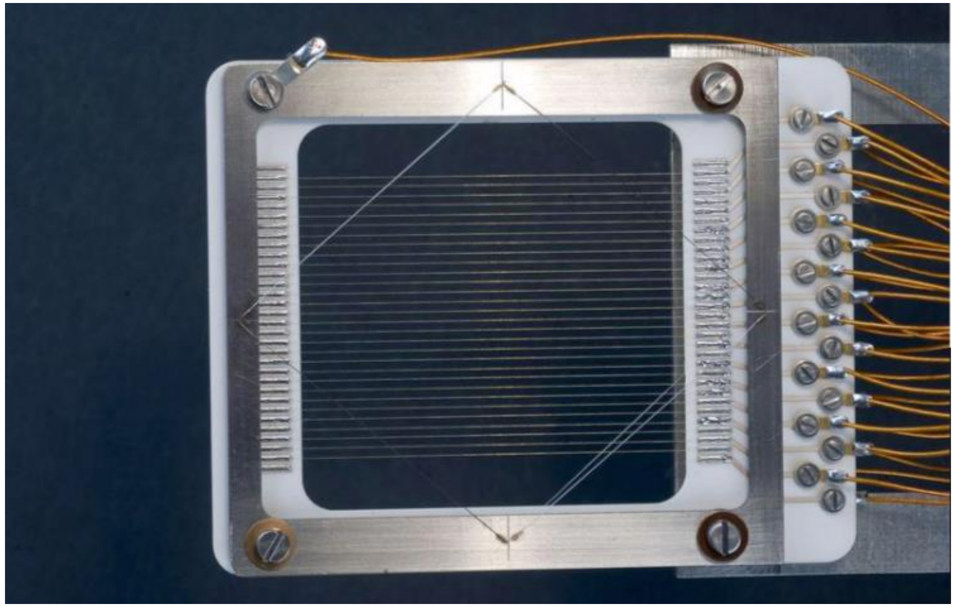
CERN “flying wires”

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

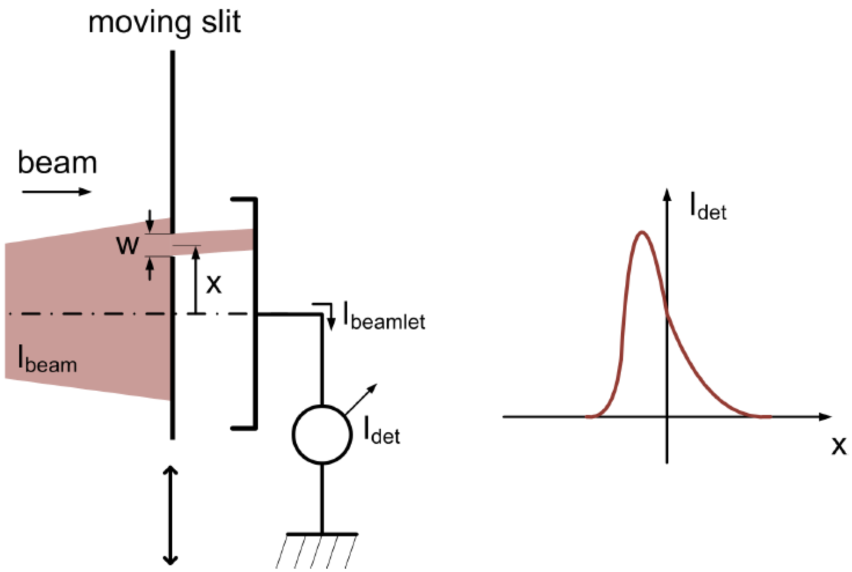
E. Bravin, Cern Accelerator School on Beam Instrumentation 2-15 June 2018, Tuusula, Finland

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

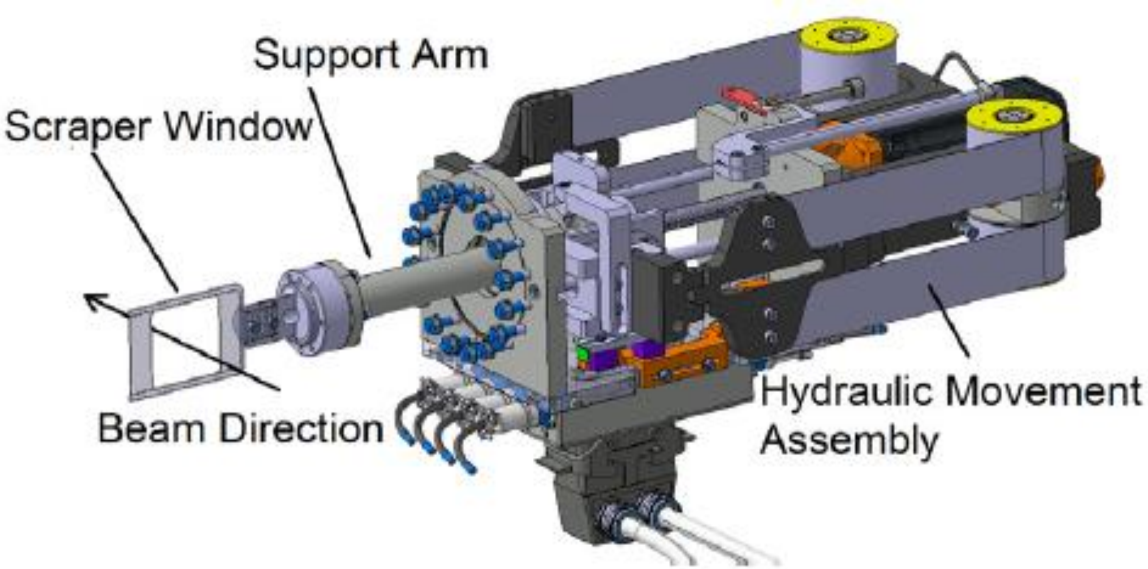
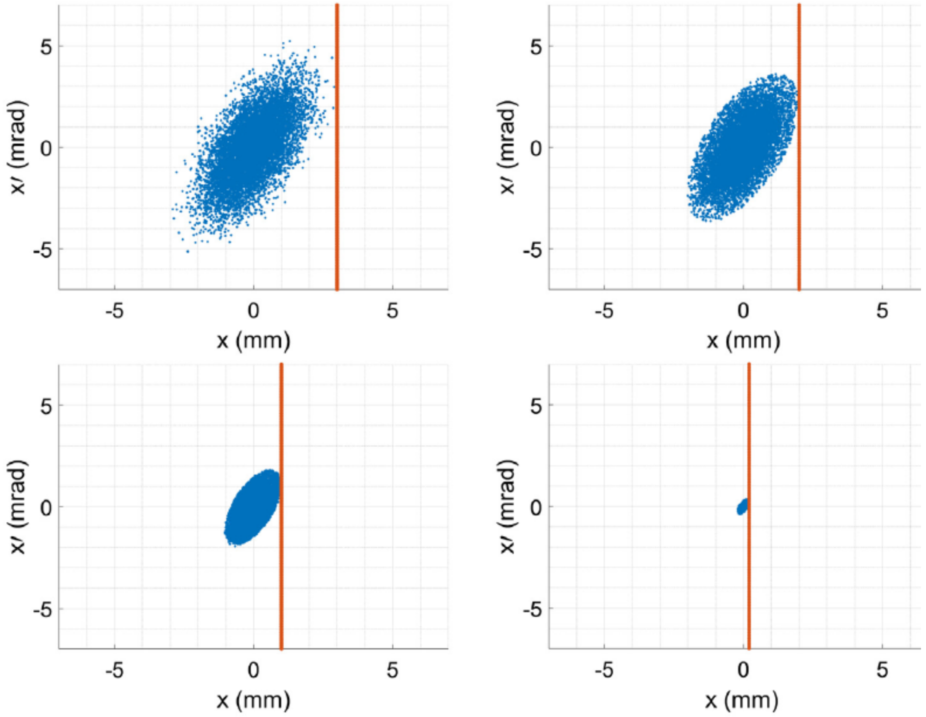


Fig. 4. A model of the horizontal scraper blade window in the extended position for use in ELENA [17].

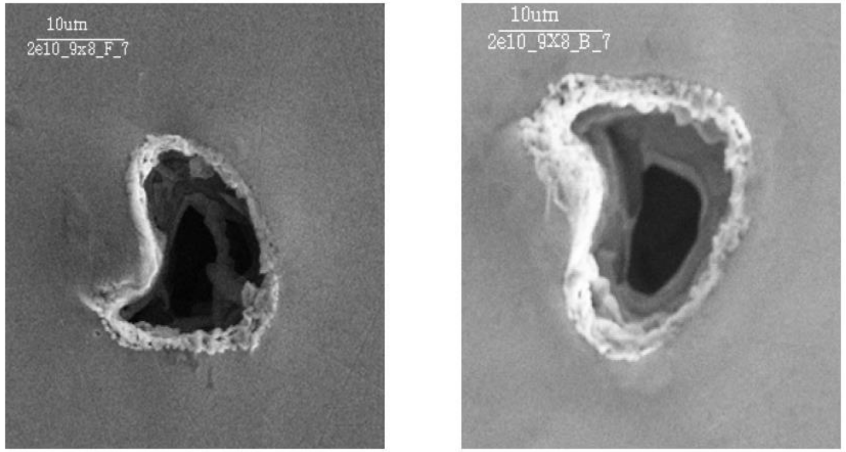


J. Hunts, et al., NIMA, Vol 896, Pages 139-151.

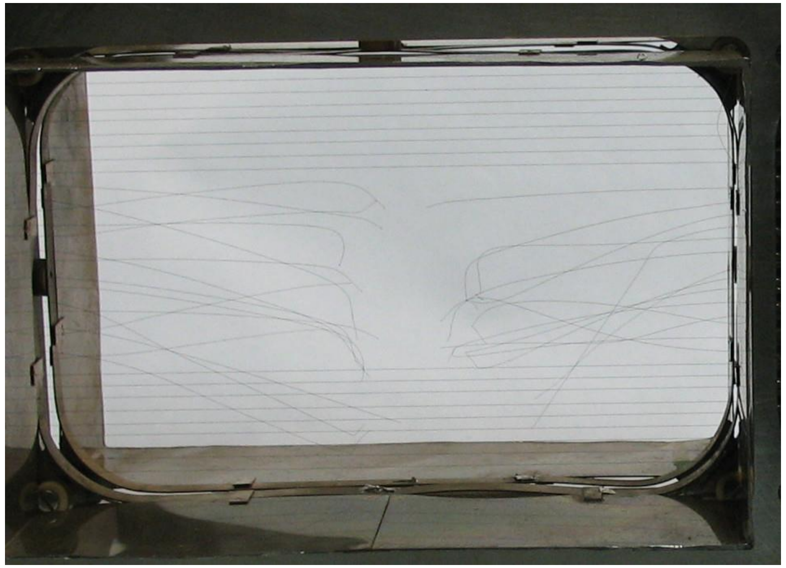
Beam profile of high intensity beams

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

Damaged SEM Grid



Damaged screen

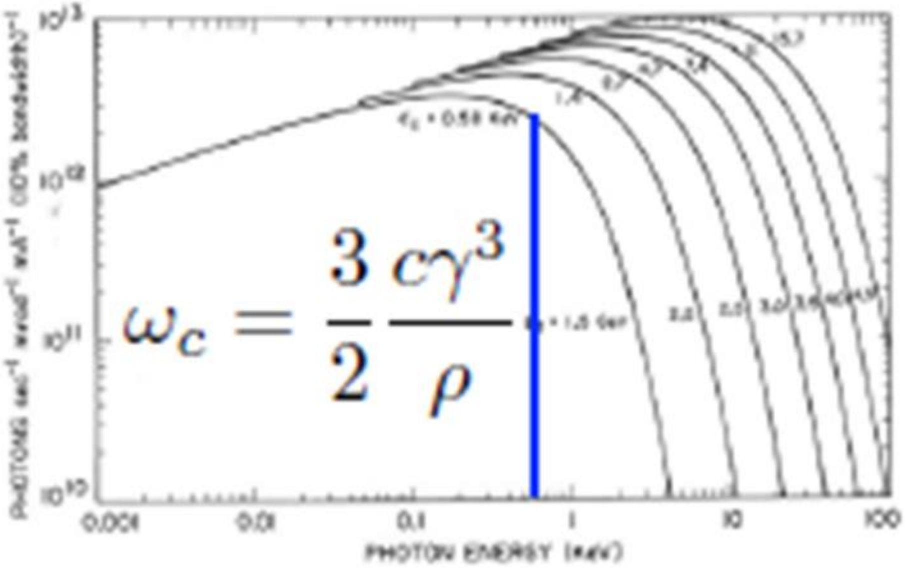


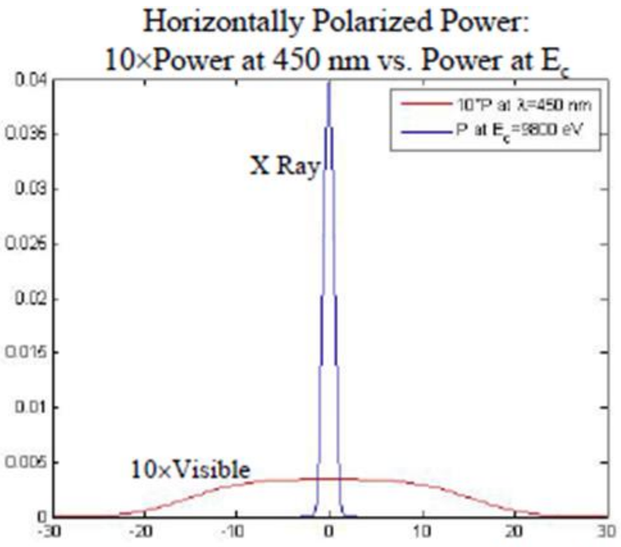
Damaged OTR screen

- Ideally: Non-invasive.

Synchrotron radiation

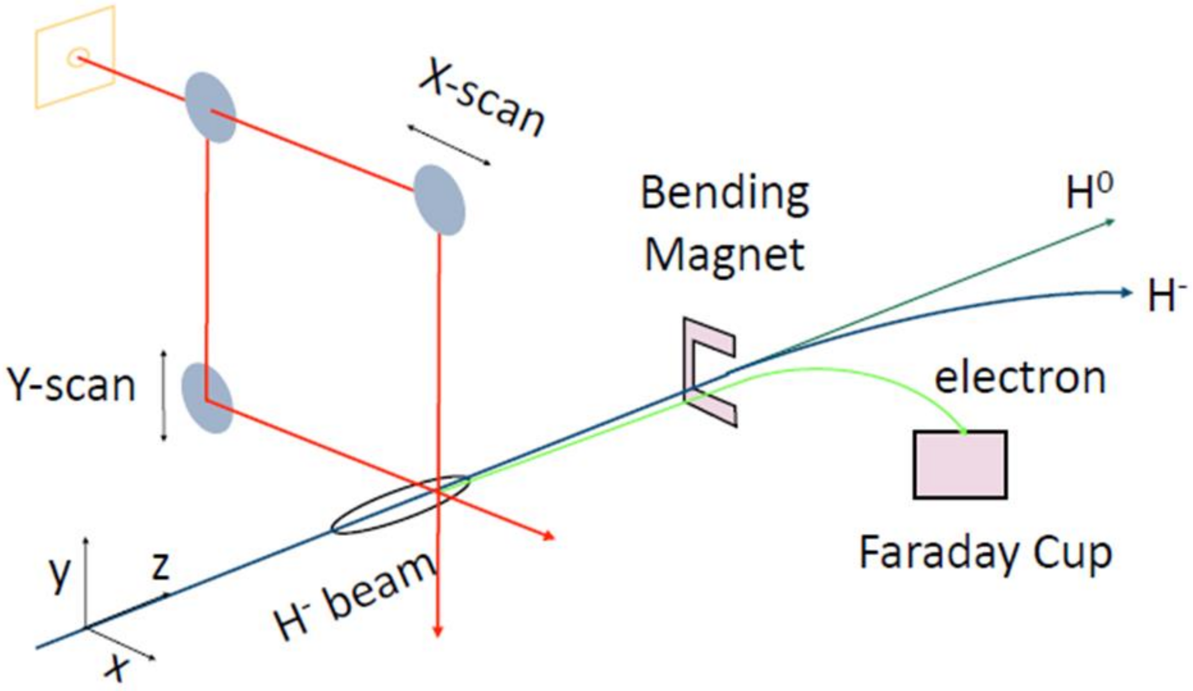
- Synchrotron radiation is broad band.
- Visible wavelength
  - Optical component is easy to implement.
  - diffraction limits the resolution at longer wavelengths when the beam is small
- X-ray
  - Better resolution
  - Hard to form an image
    - Pinhole camera
    - Zone plates





hao.zhang@cockcroft.ac.uk

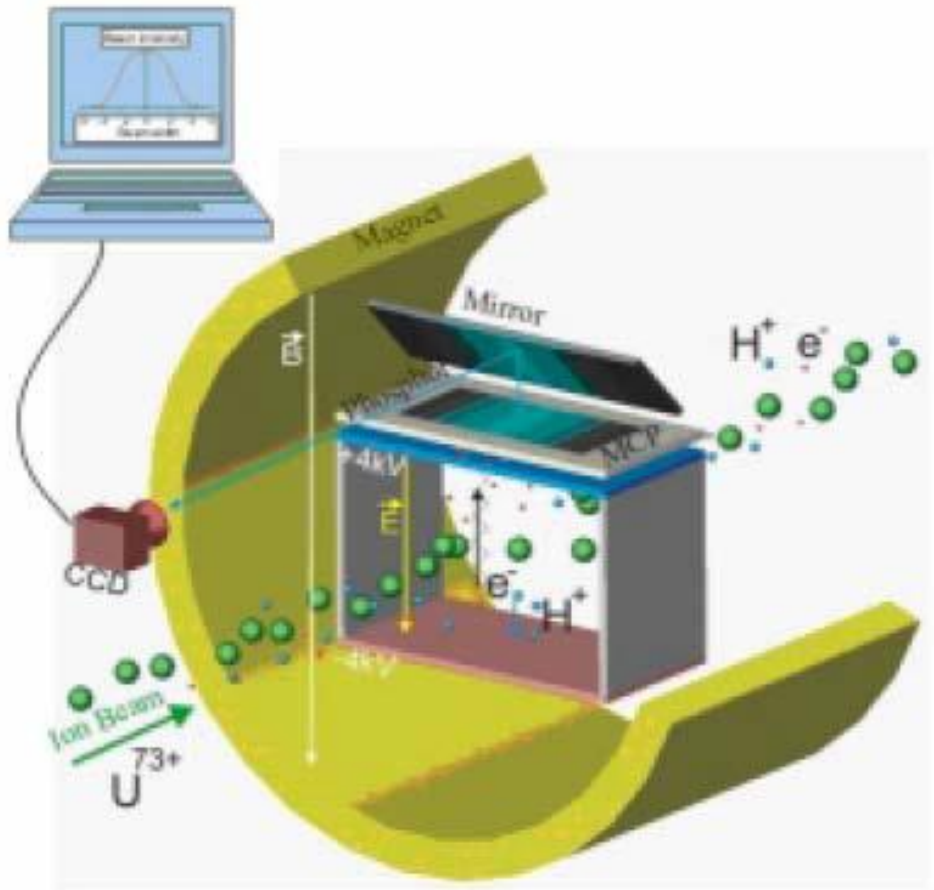
Laser wire

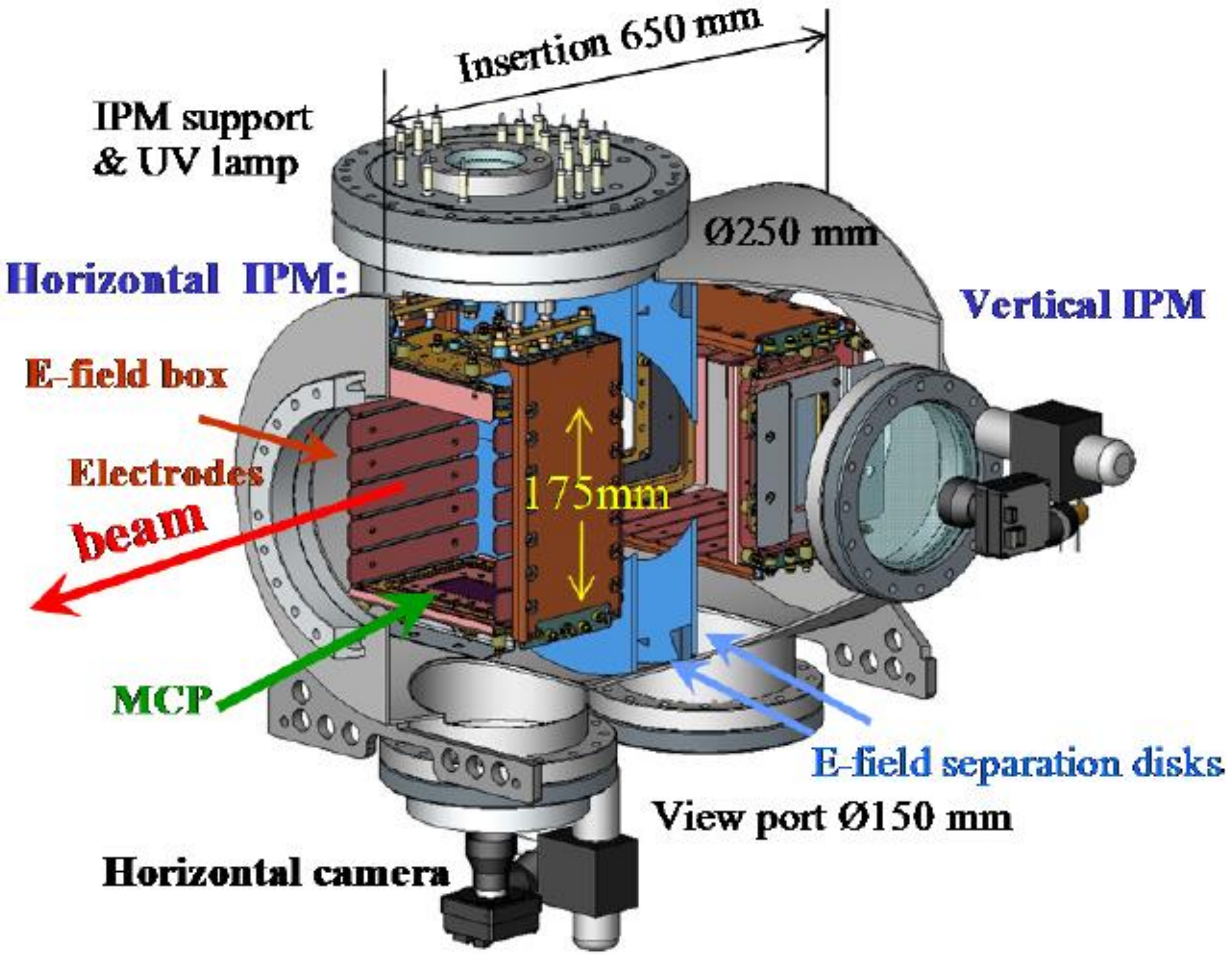


T. Shea, Laser Diagnostics for H- beams, , Accelerator Beam diagnostics, USPAS 2009

- First ionization potential for H- ions is 0.75eV.
- Photons with λ<1500nm can separate H^- ion into free electron and neutral H.
- The H^- ion has no excited states so the electron is removed into the continuum.
- **Laser can be used to mark a portion of beam by neutralization.**
- Once a porton of the beam is marked, measurements can be made on the neutral beam, the removed electrons, or the reduced beam current with beam current transformer or BPM stripline.

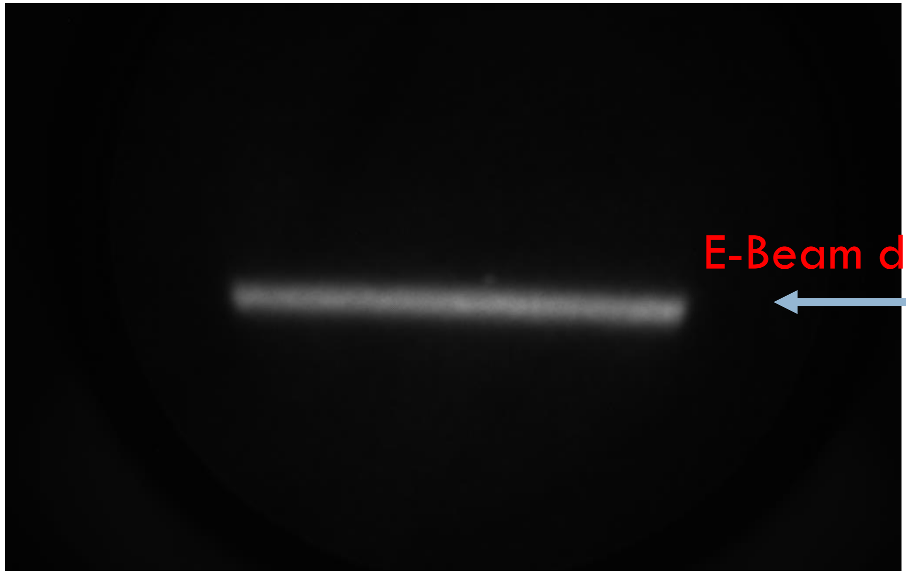
Residual gas based Ionization Profile Monitor





Credit: P. Fork, GSI

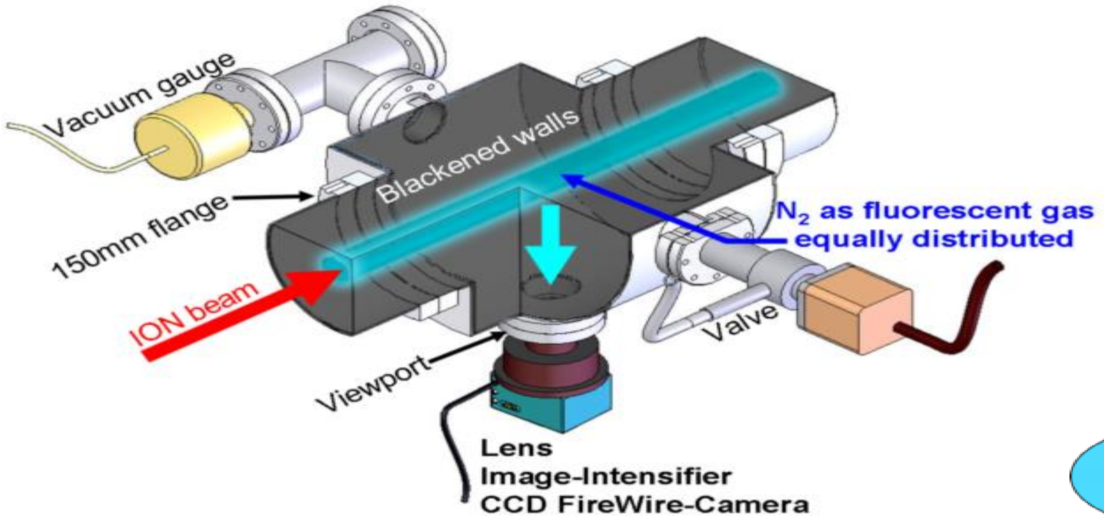
Residual gas image of a electron beam



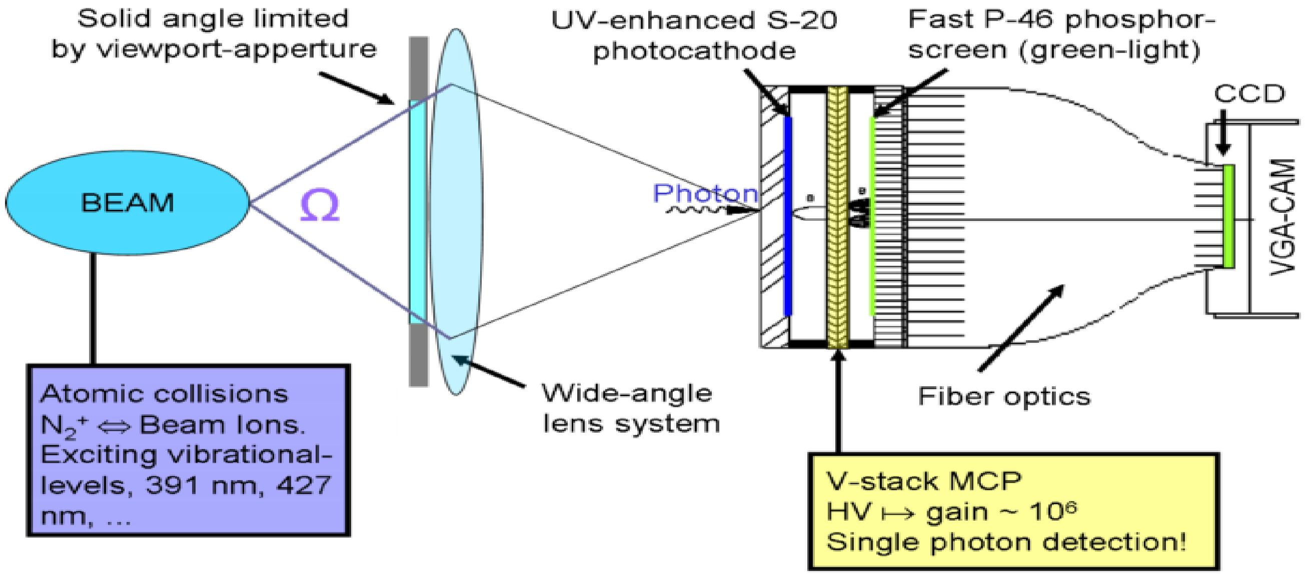
Give you a one-dimensional profile!

- Secondary ions or electrons are collected.
- Magnetic field are used to compensate the profile distortion by self space charge force or wake fields.
- Secondary particles are collected by electronics or optical (scintillator plus MCP)

Beam induced fluorescence (BIF)



Schematic drawing of the BIF-monitor as installed at GSI UNILAC. *



BIF detection principle - How the beam induced fluorescence light is imaged, intensified and detected.*

*Credit: GSI, http://www-bd.gsi.de/dokuwiki/doku.php

IPM and BIF

- The cross section for impact ionization and fluorescence dependent on the beam energy, residual gas species, and certain fluorescent wavelength.
- BIF has longer integration time due to lower cross section and viewed at certain solid angle.
- Might need gas injection using a leaking valve to increase the local pressure.
- Normally N_2 has higher cross section, other gases such as Ne, Ar has been used.

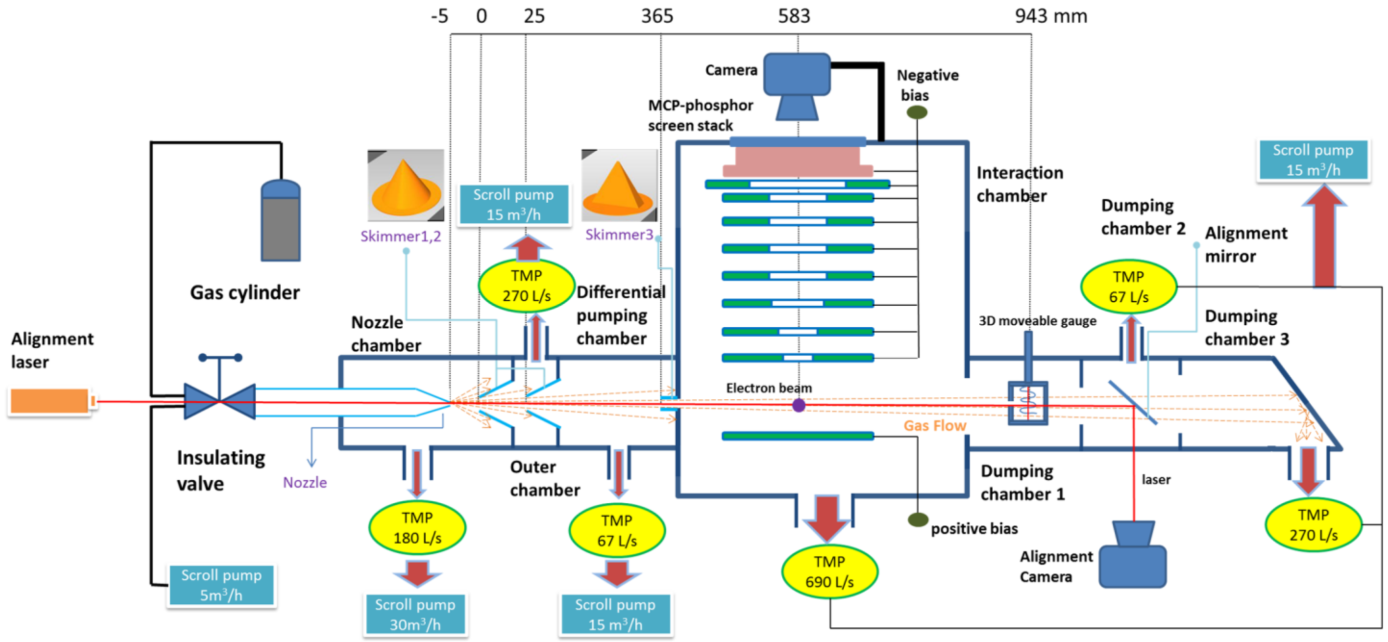
→ **Using Supersonic gas jet !**

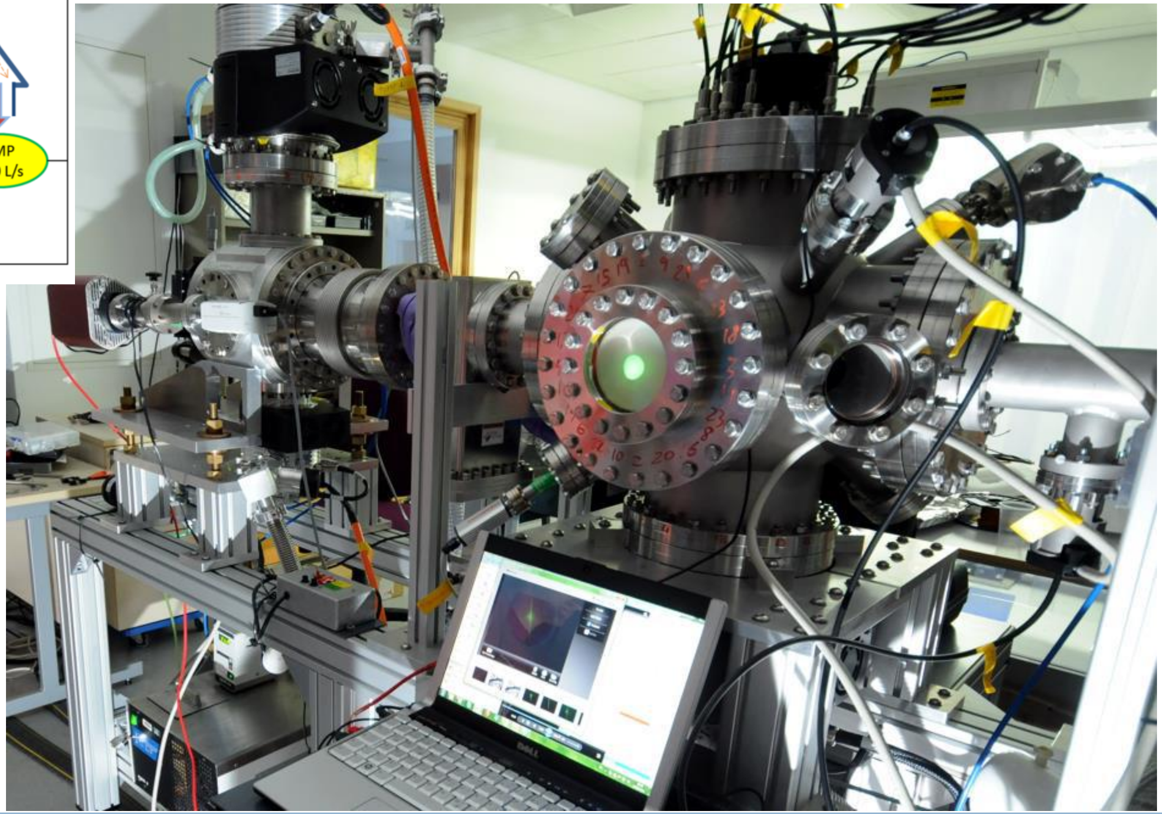
Motivation to use gas jet

- Low temperature
- High directional jet
- Non-invasive or minimum-invasive
- Not dependent on beam species, energy and intensity
- No damage threshold
- Not affect the vacuum very much

hao.zhang@cockcroft.ac.uk

Gas jet profile monitor in Cockcroft institute

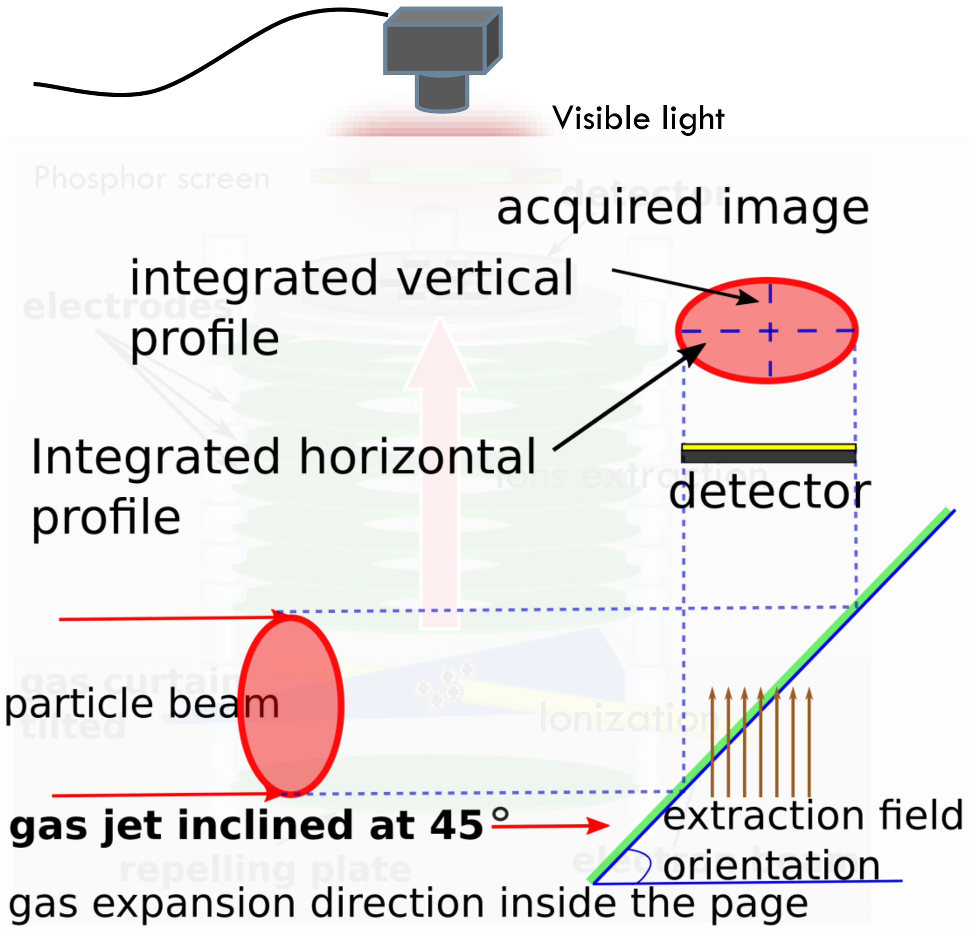




AVA school on Precision studies 23-27 March 2020

hao.zhang@cockcroft.ac.uk

Gas jet beam profile monitor

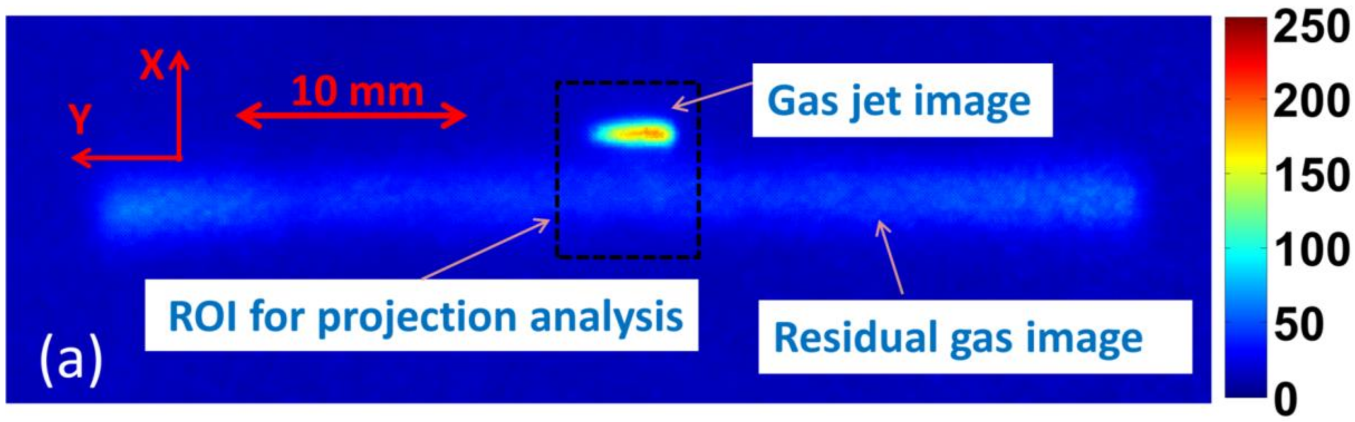


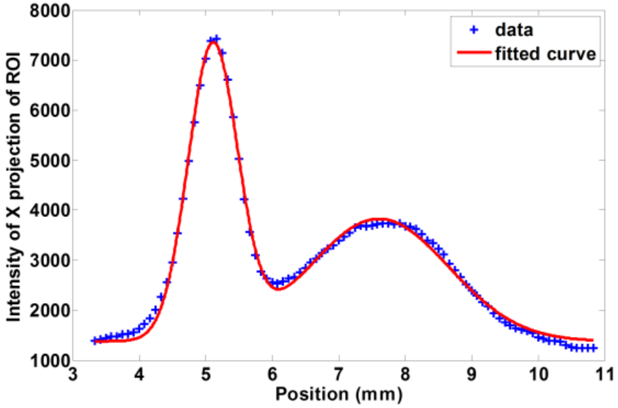
Estimated integration time = 1 ms

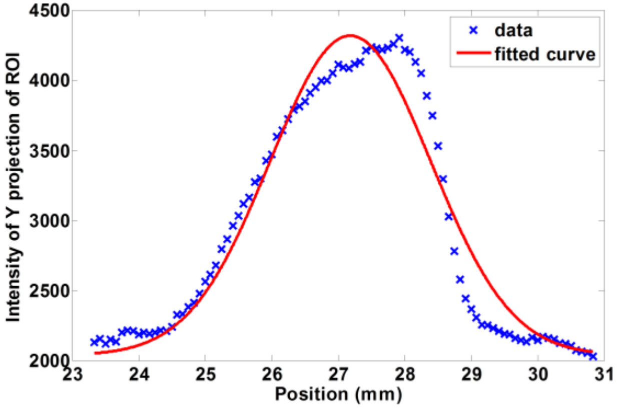
- Estimated jet property

Parameter	Value
Density	$2.5*10^{16}$ particle/m^3
Thickness	0.5 mm
Vertical size	5 mm

Typical results at CI



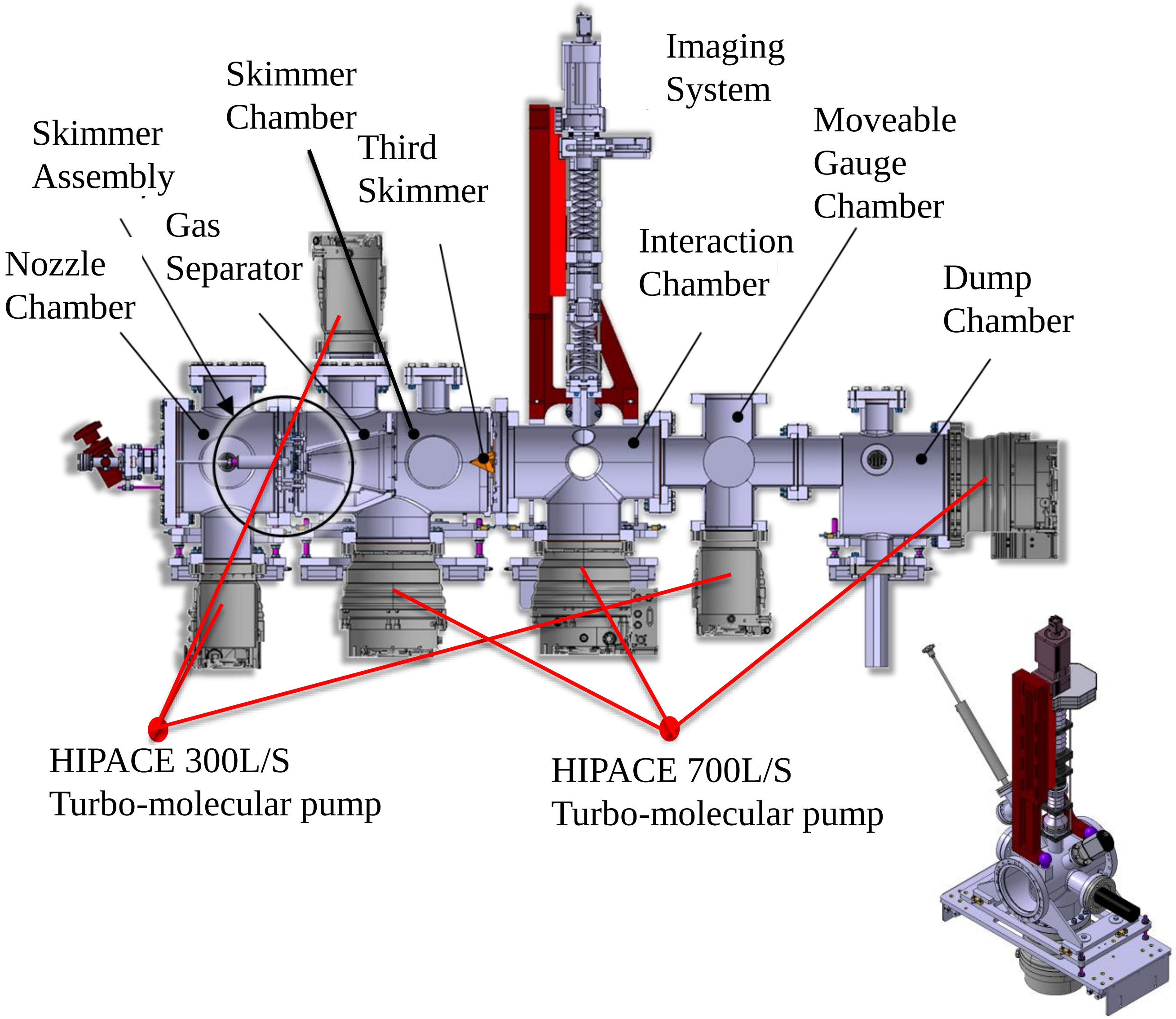


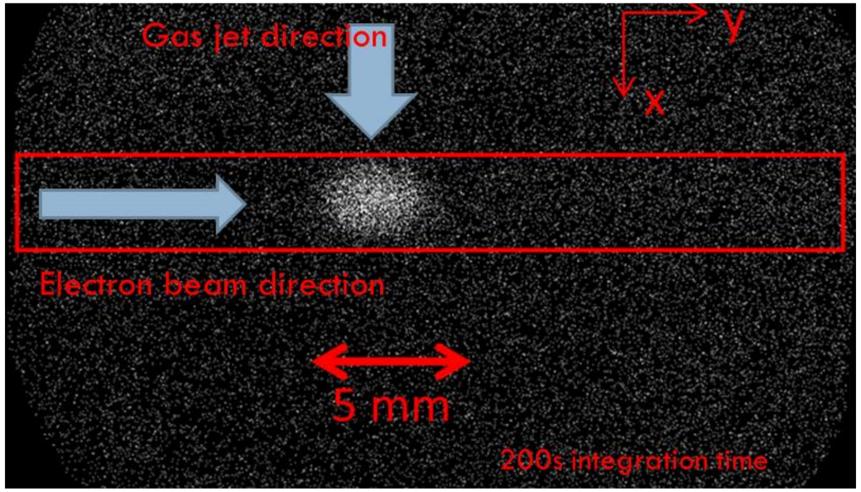


Setting	Value
Energy	3.75 keV
Current	~5.0 μA
External field	7.5 kV/m
Exposure	70 ms

size	Value
Xrms	0.42
Yrms	1.23
Xrms from residual	1.01

Using gas jet to measure LHC proton beam

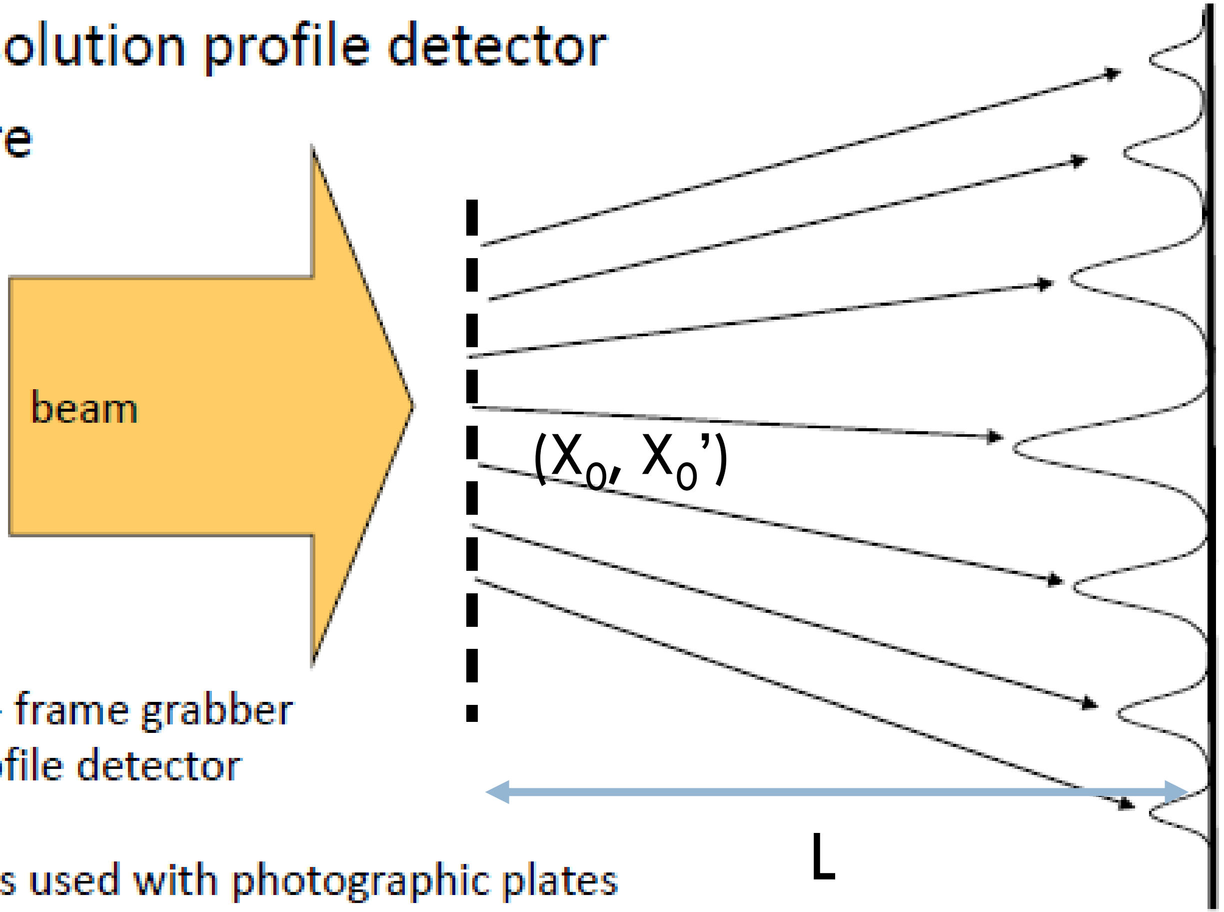




Emittance measurement

Multi-slit measurement

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



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

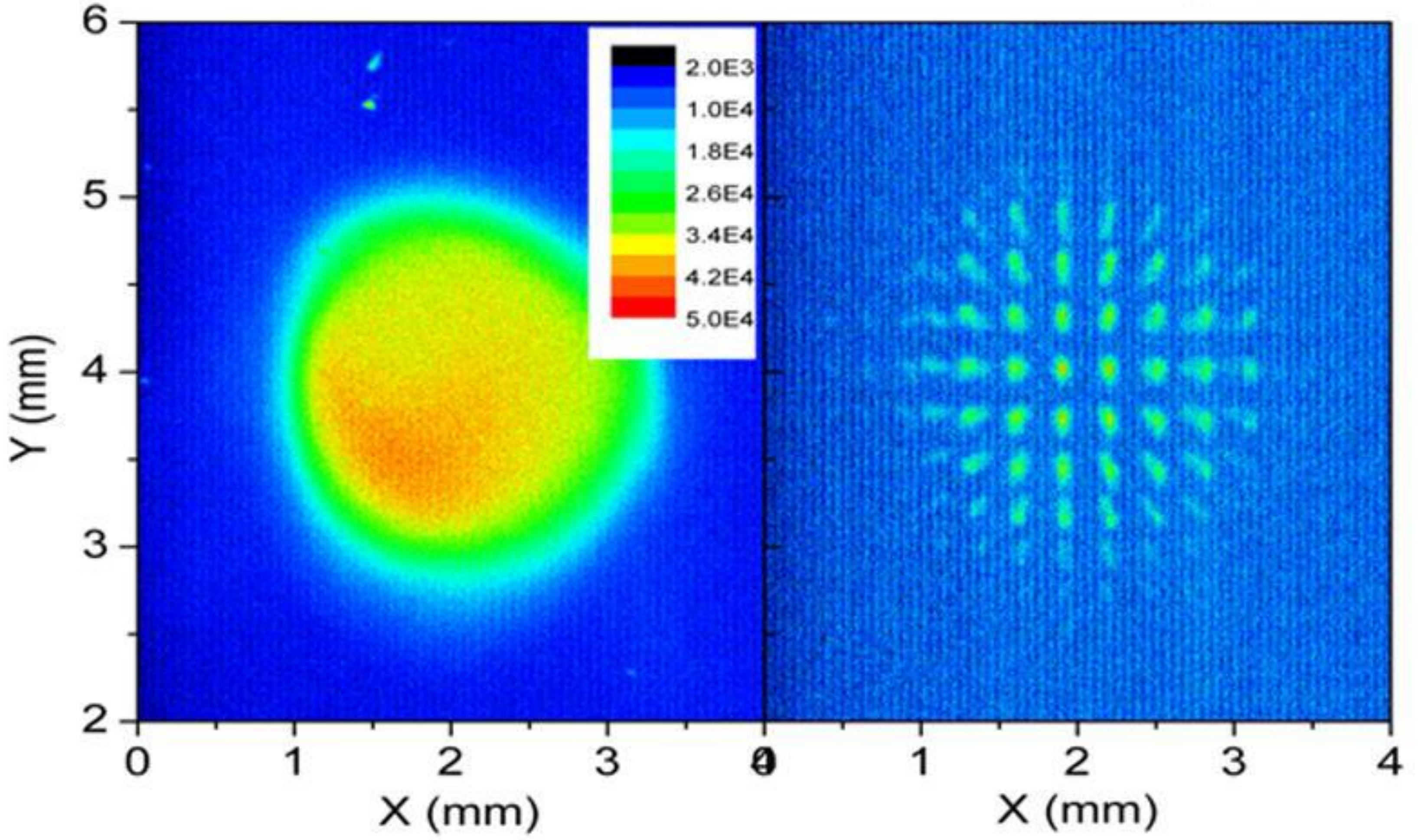
Scintillator + TV + frame grabber often used as profile detector

Very old idea, was used with photographic plates

Slit size = d

Beamlet rms size = σ

Pepper pot

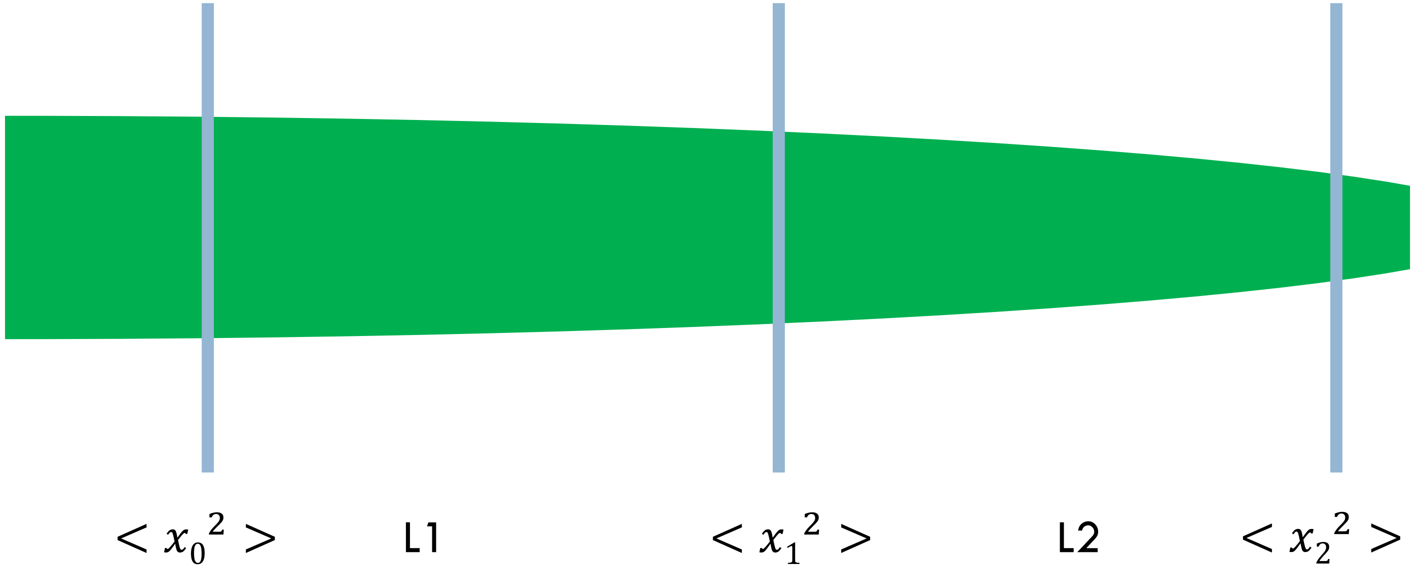

6
5
4
3
2
Y (mm)
2.0E3
1.0E4
1.8E4
2.6E4
3.4E4
4.2E4
5.0E4
0
1
2
3
4
X (mm)
0
1
2
3
4
X (mm)

3 profile measurement

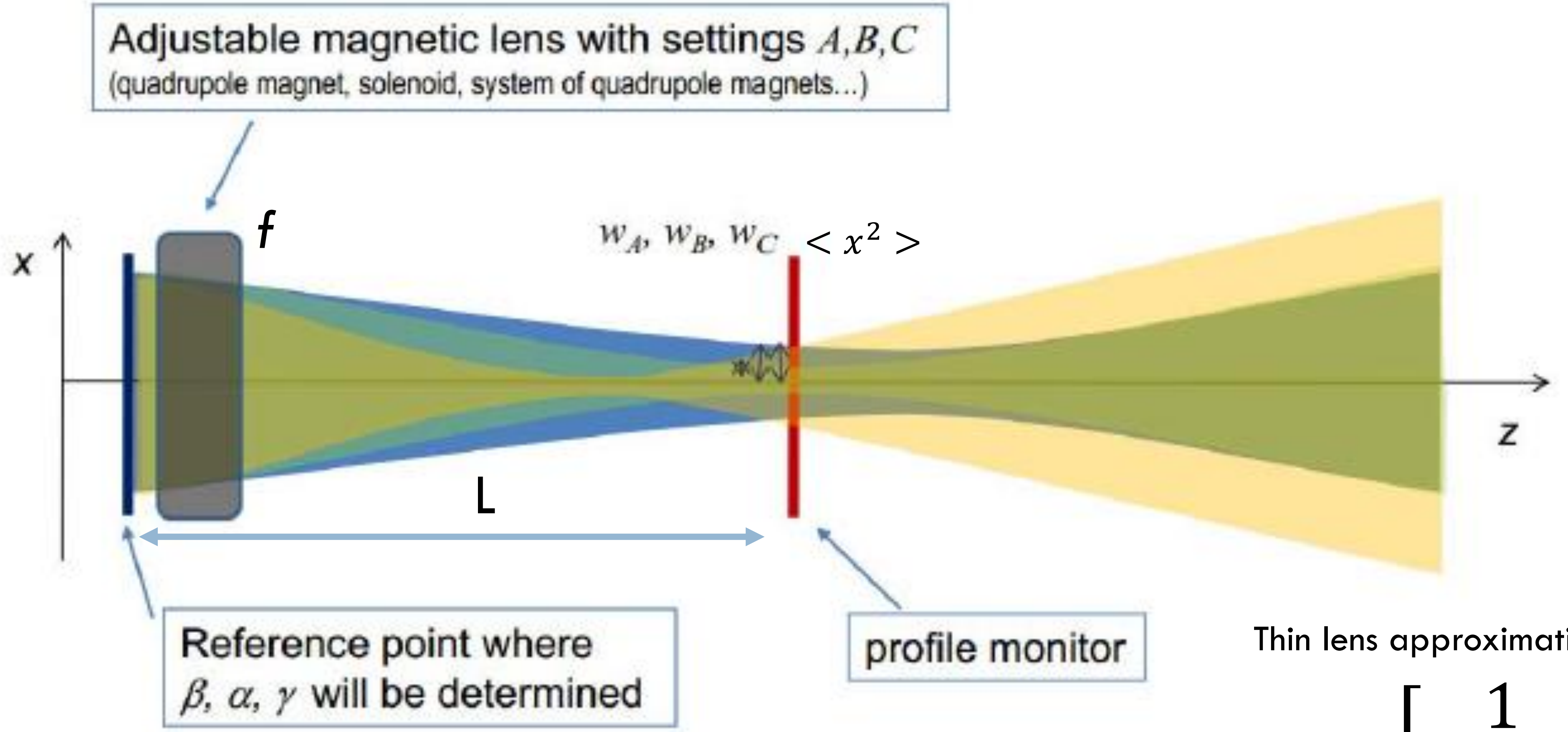
- Transfer matrix

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

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



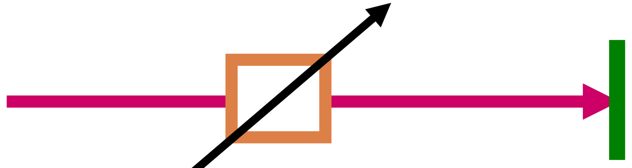
Quadrupole scan

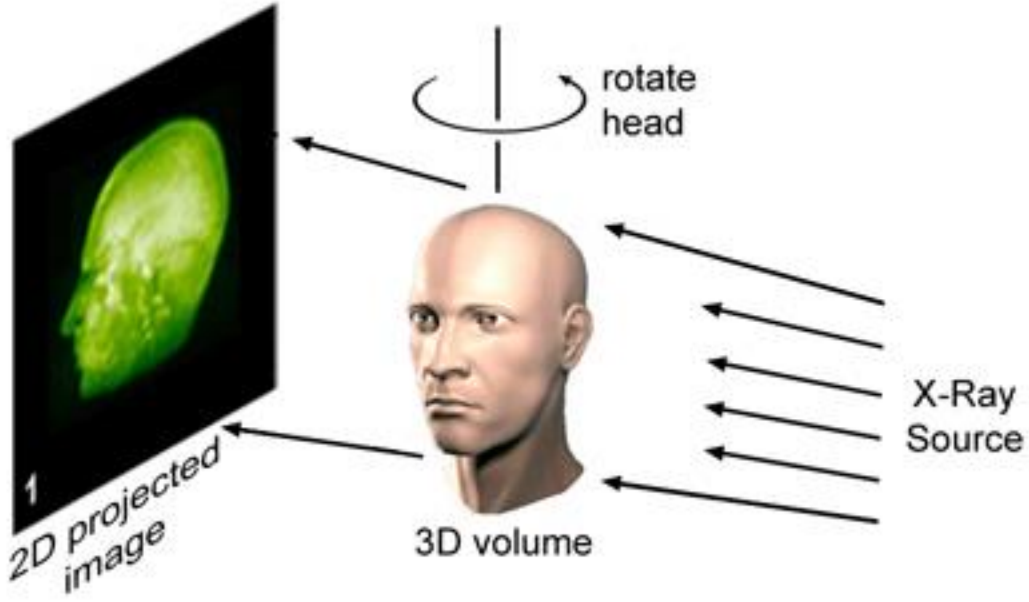


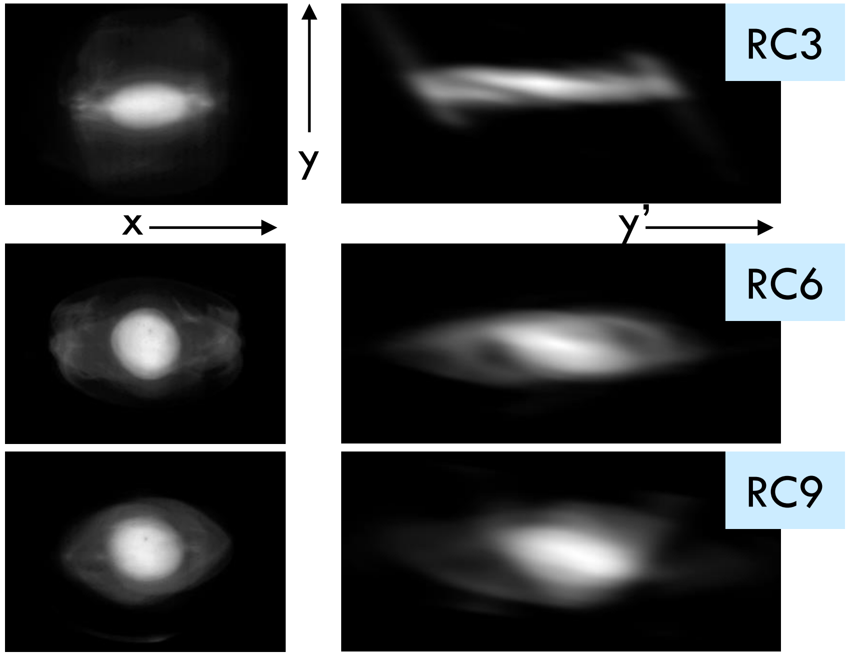
Thin lens approximation

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

Tomographic Phase Space Reconstruction





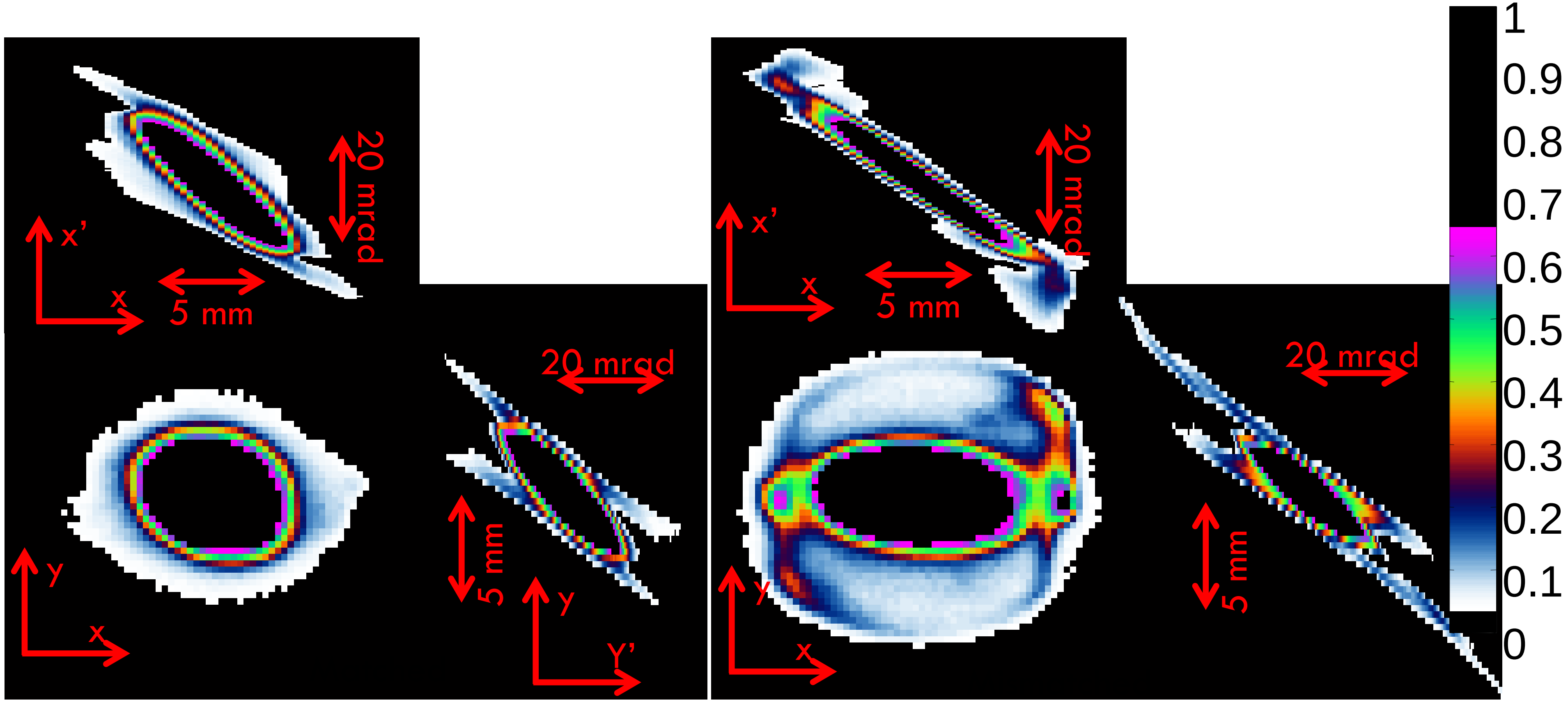


Projected / Slice, using Quadrupoles / Solenoids
with Space Charge

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

hao.zhang@cockcroft.ac.uk

Phase space tomography to study halo



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

hao.zhang@cockcroft.ac.uk

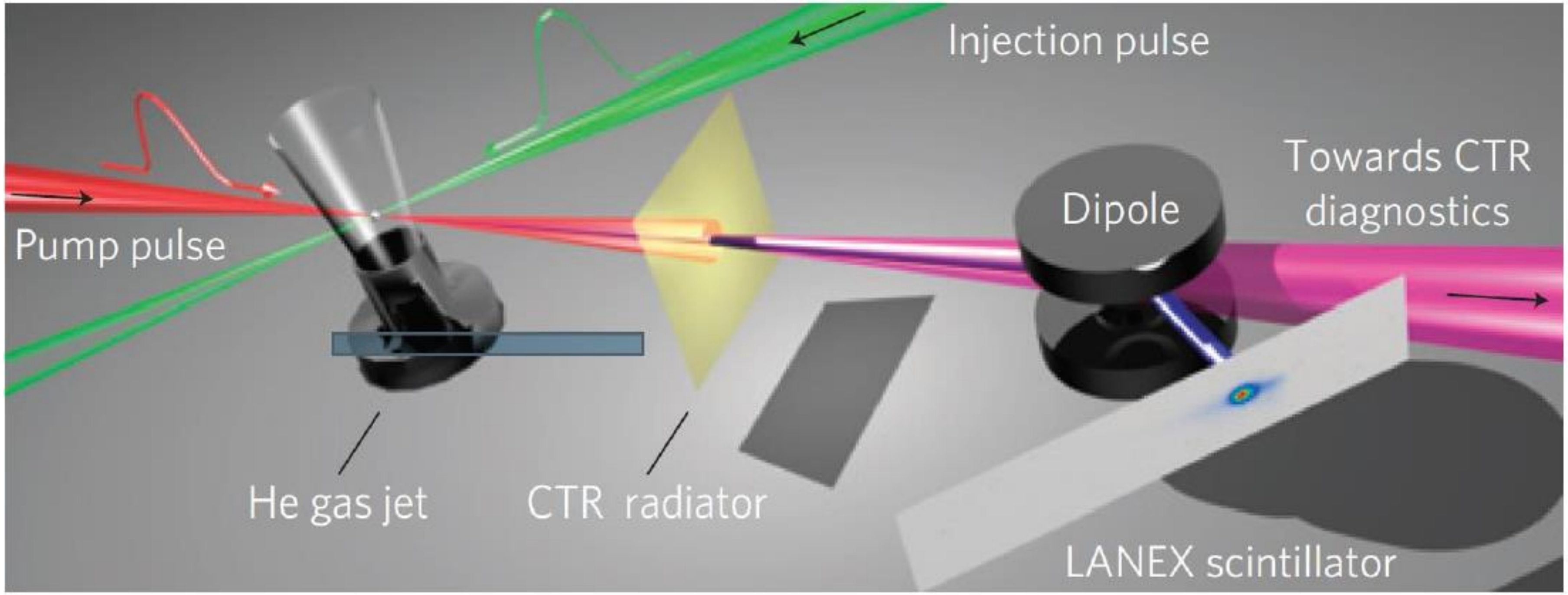
Transverse emittance measurement methods

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 energy Monitoring

hao.zhang@cockcroft.ac.uk

Using magnets

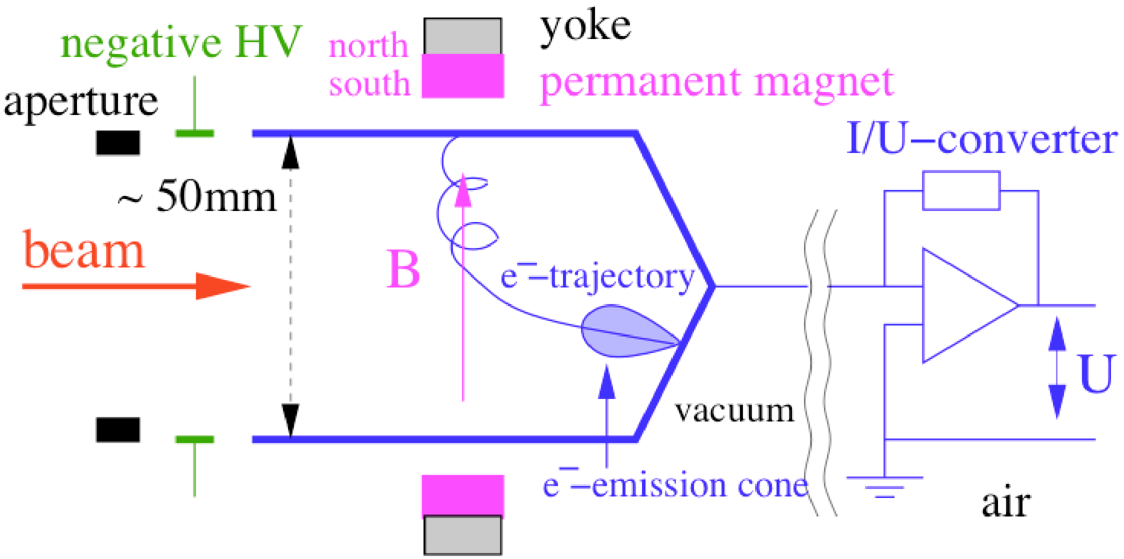


- 30 fs (FWHM) pump pulse and injection pulse collide at 135°
- 3 mm He gas jet target, beam diameter @ foil: 90 μm
- 100 μm Al foil generates radiation after 15 mm
- Peak charge: 15 pC and peak energy: 84 MeV

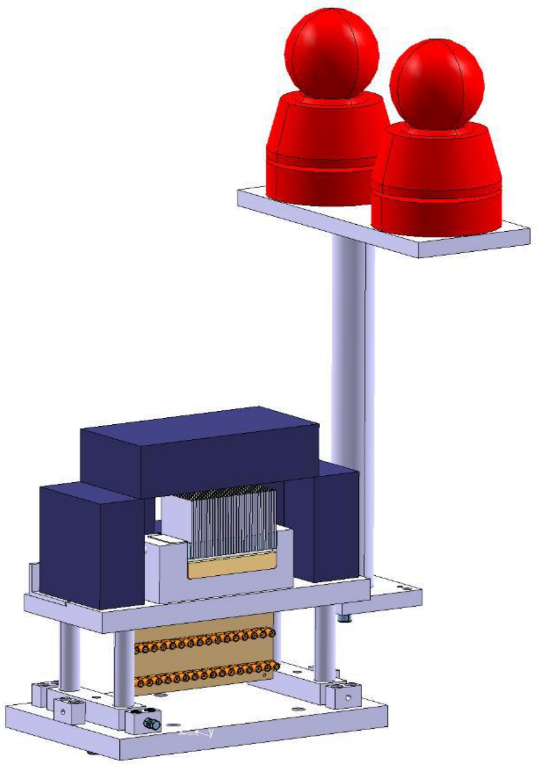
O. Lundh, et al., Nature Physics (2011).

Other methods

- Faraday cup

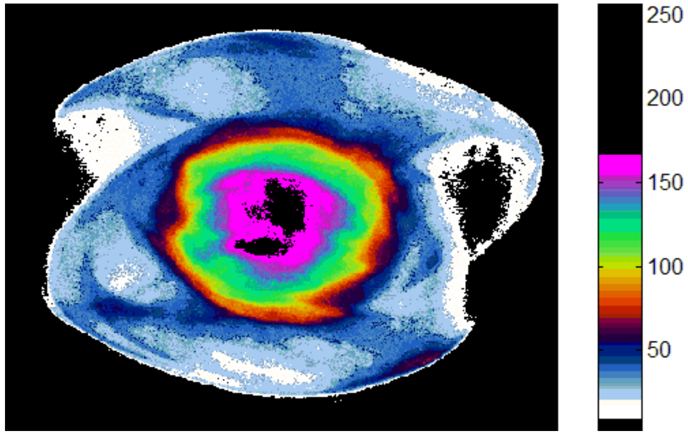


- Segmented Dump



Beam halo Monitoring

Halo Formation and Negative Effects



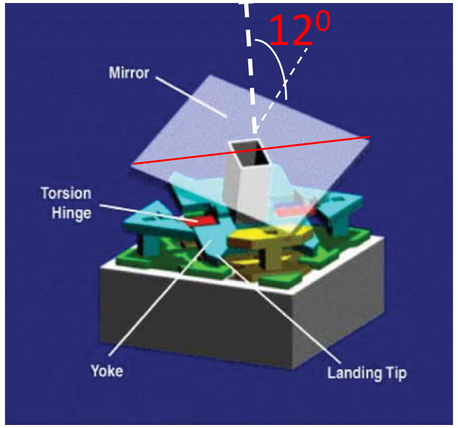
Causes of Beam Halo

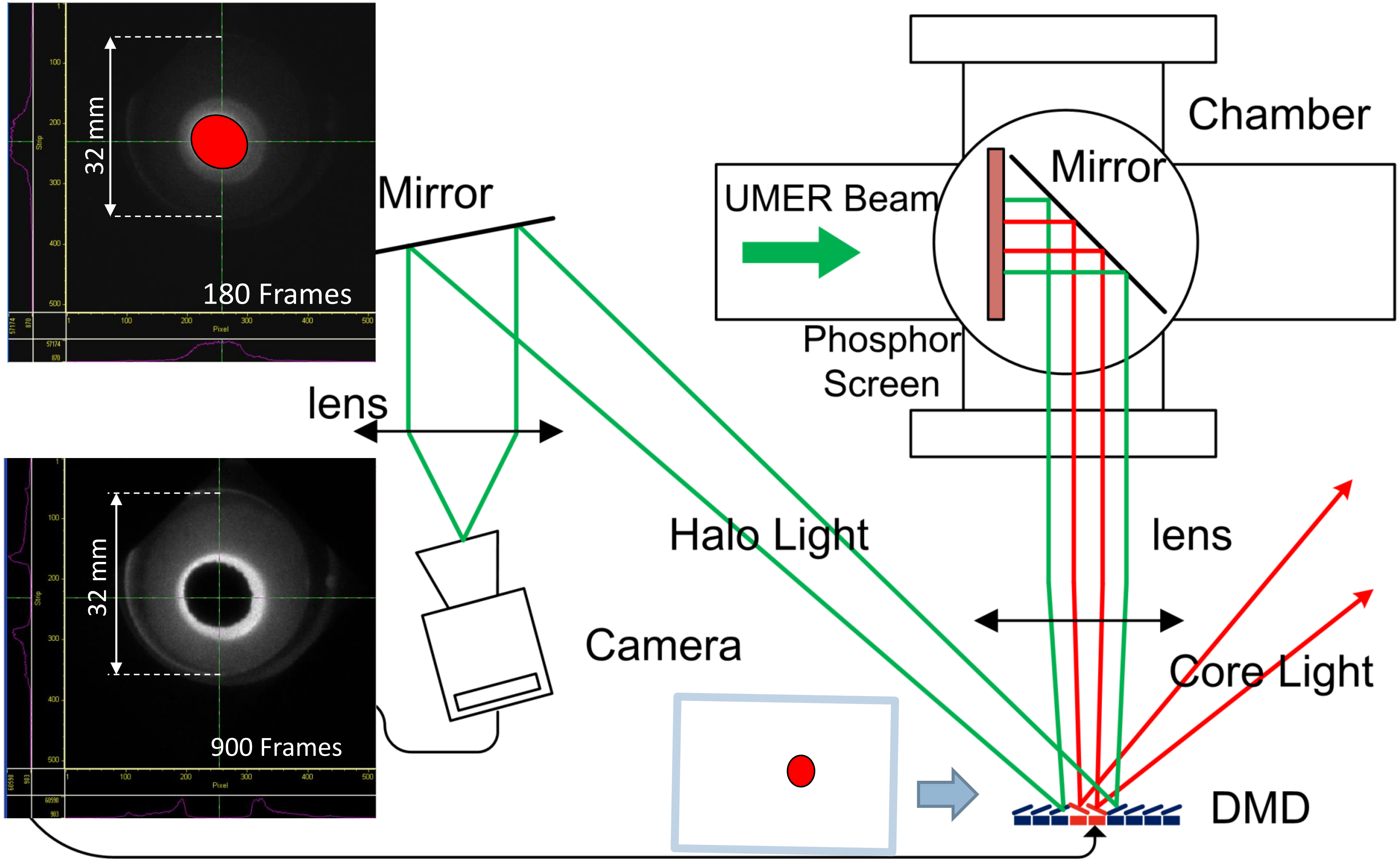
- Nonlinear forces due to space charge
- Parametric resonances
- Scattered Laser Light in Photo-cathodes:
- Misalignment, Magnet error, noise

- Beam Halo has many negative effects
  - Nuclear Activation of The Transport Channel
  - Emittance Growth
  - Emission of Secondary Electrons
  - Increasing Noise in The Detectors

hao.zhang@cockcroft.ac.uk

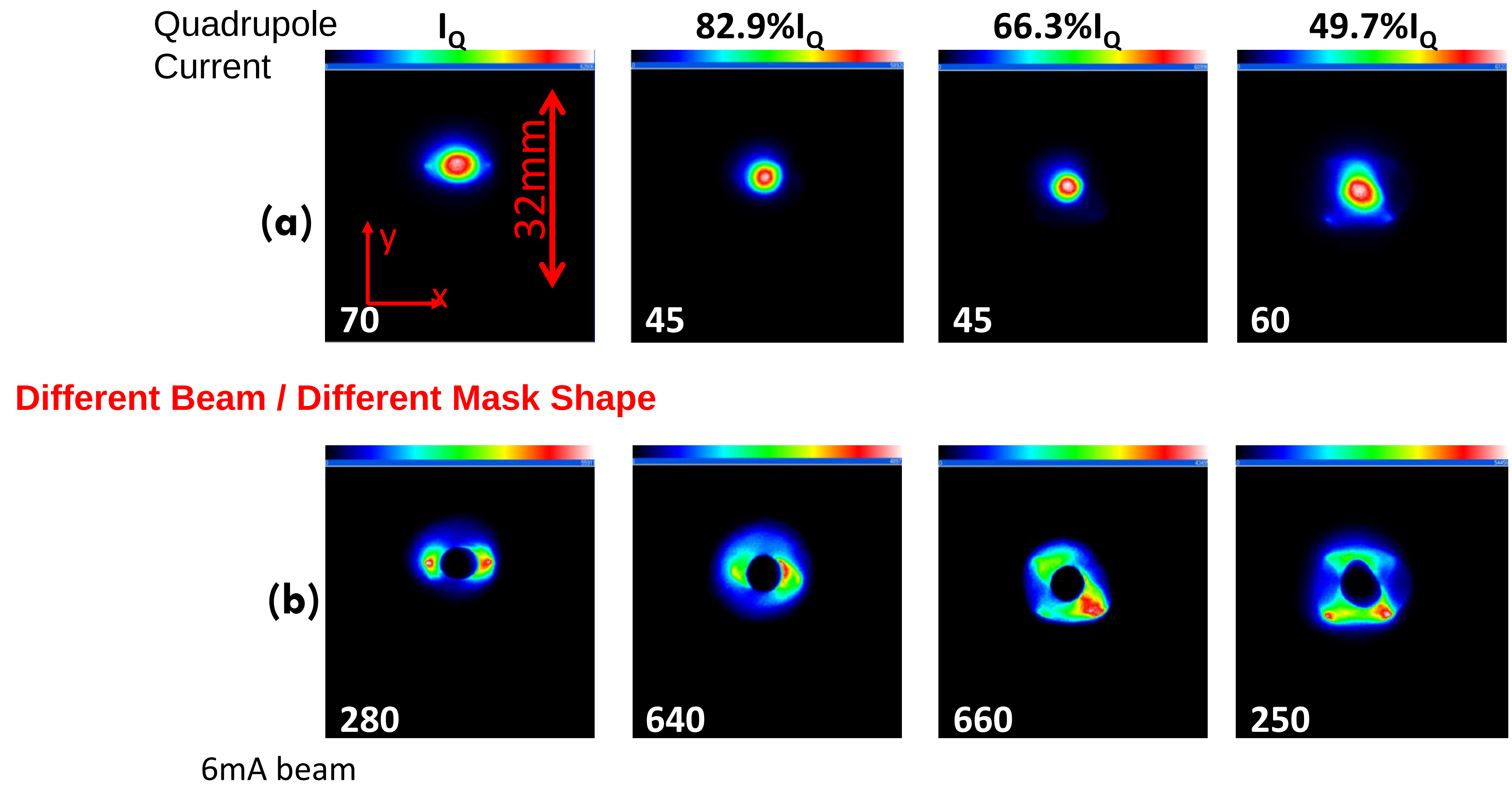
Optics System and Image process





C.P. Welsch et al., Proc. SPIE (2007)
J. Egberts, et al., JINST **5**P04010 (2010)
H. Zhang, et al., Phys. Rev. STAB 15 (2012)
B. Lomberg, et al. Proc. IBIC (2013)

Demonstration of Adaptive Masking on UMER



Conclusion

- Without beam diagnostics

  it is not possible to even operate a accelerator!!

- Non-invasive, single shot, real-time measurement is demanded.
- New concept adapted from other field is hugely popular
  - Example: laser, non-linear optics, advanced algorithm, machine learning,…
- User-based development specifically target to project
  - OMA, AWA, EuPRAXIA, EuroCirCol, AWAKE, HLLHC, etc. projects

Also: Good prospects for commercialization (D:Beam).

Any Question?

hao.zhang@cockcroft.ac.uk

Reference

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

- J. Harasimowicz et al., Rev. Sci. Instr. 81 (10), 2010
- H. Koziol, BEAM DIAGNOSTICS FOR ACCELERATORS
- P. Forck, Lecture Notes on Beam Instrumentation and Diagnostics, Joint University Accelerator School, January – March 2012
- J. Hunts, et al., NIMA, Vol 896, Pages 139-151.
- U. Raich, Accelerator Beam Diagnostics, USPAS, Albuquerque NM, June 23-26, 2009
- D. Stratakis, R.A. Kishek, S. Bernal, et al., Physics of Plasmas 17, 056701 (2010)
- H. Zhang, PhD thesis, university of Maryland, 2014
- E. Bravin, Cern Accelerator School on Beam Instrumentation 2-15 June 2018, Tuusula, Finland
- C. Welsch, Beam Diagnostics, CIPAS, 2015
- J. Harasimowicz, et al., PRSTAB, 15, 122801 (2012)
- S. Bernal, Emittance and Emittance Measurements, USPAS08, Beam Dynamics Experiments on the University of Maryland Electron Ring