The Cockcroft Institute
of Accelerator Science and Technology

UNIVERSITY OF
LIVERPOOL

Beam Diagnostics

Prof. Carsten P. Welsch

Accelerator Beam Diagnostics

‹‹ novel **DI**agnostic **T**echniques for future particle **A**ccelerators:
A Marie Curie Initial Training **NET**work ››

What is/was DITANET ?

- Largest-ever EU funded training network in beam instrumentation and diagnostics (4.2 M€);
- Aim: Training of early stage researchers *(18 ESRs, 3 ERs)*
- Gives industry an important role;
- Presently 32 partners *(and growing...)*
- Recognized importance of beam diagnostics at European level !
  (only 68 from 905 selected - with 11 in physics)

C.P. Welsch, Proc. BIW 2010, IPAC 2011

DITANET Schools and Workshops

Schools on beam diagnostics: RHUL and Stockholm, Sweden
CERN Indico: 55242 and 112220

Cover all aspects of beam diagnostics and instrumentation.
Also: 9 Topical Workshops plus many more in oPAC and LA^3NET

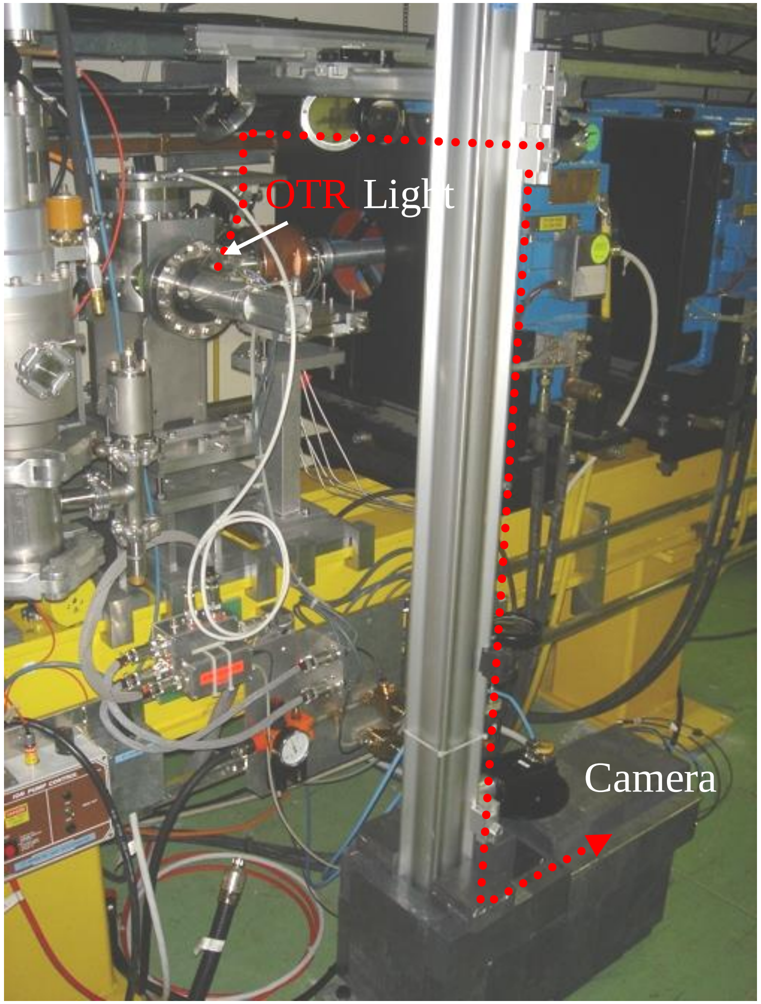
Today: General overview; focus on e^- beam diagnostics and CI R&D projects.

http://www.liv.ac.uk/ditanet

Outline

- Why diagnostics ?
- What do we need to know about the beam ?
  - Example: A compact storage ring
- Discussion of different instrumentation needs:
  - Beam position monitoring (capacitive pickups),
  - Beam current monitoring
  - Beam profile monitoring
  - Emittance
  - Longitudinal Profile
  - Energy (spread)
- Limitations, open questions.

A ‘typical’ Accelerator Diagnostics



- Material sciences
- Thermodynamics
- Electro-Magnetism
- Optics
- Mechanics
- Electronics
- Nuclear Physics
- …Optimization critical

➡ Multi-disciplinary field !

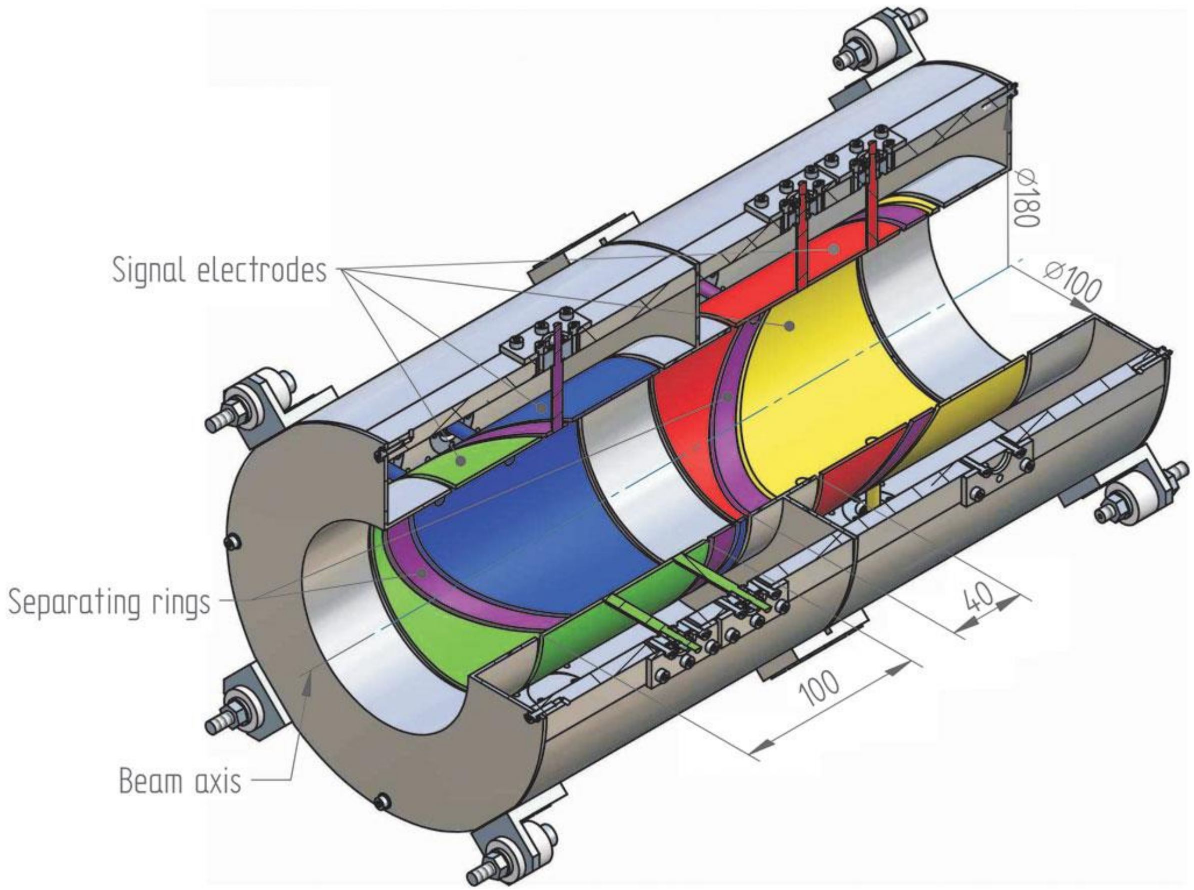
Challenges in Diagnostics

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

- Advantages of Optical Diagnostics:
  - Fast response
  - Parasitic use possible in some cases

Beam Position Monitoring

Capacitive Pickups

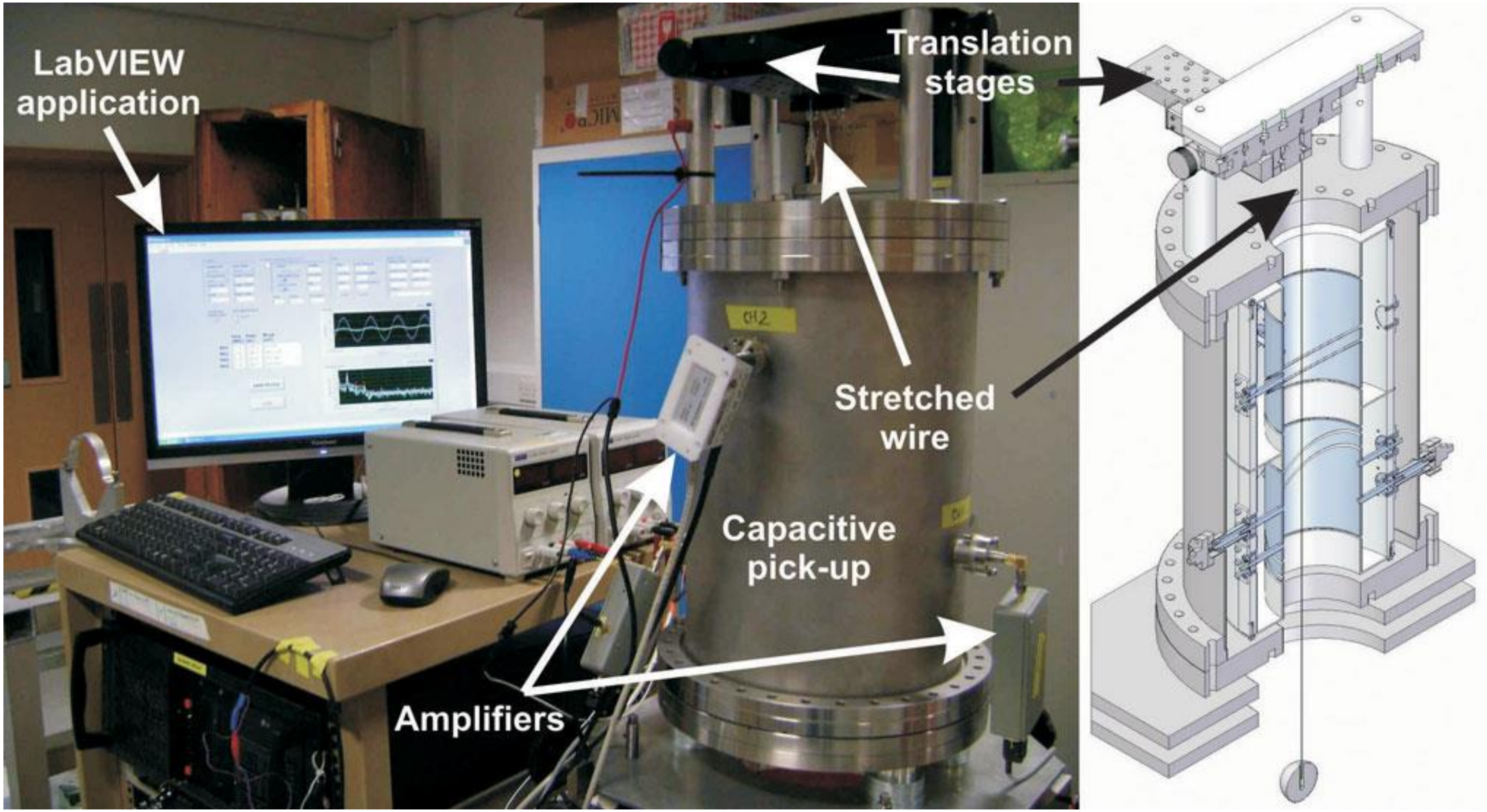


$$x = k \cdot \frac{\Delta U}{\Sigma U} + \delta,$$

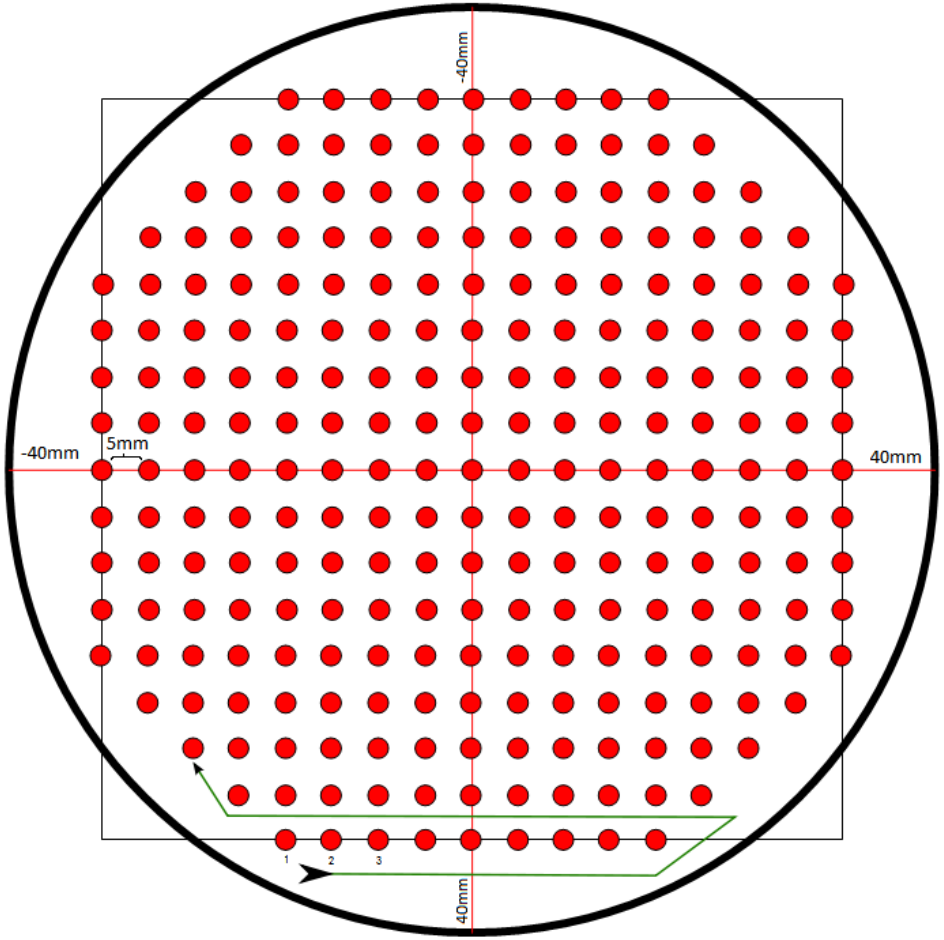
- Shoebox type
- Buttons
- Stiplines
- Etc.

J. Harasimowicz – PhD project at CI
J. Harasimowicz et al., Phys. Rev. STAB **15**, 122801 (2012)

Monitor Calibration



Experimental Results *(example)*

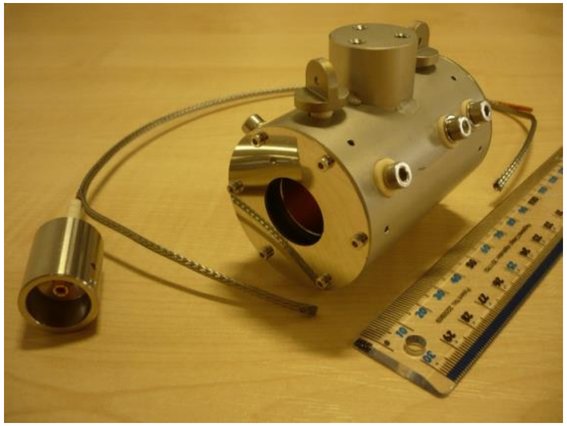


- 2D calibration of monitor;
- Can easily modify pickup geometry;
- Flexible test stand automation possible.

Beam Current Monitoring

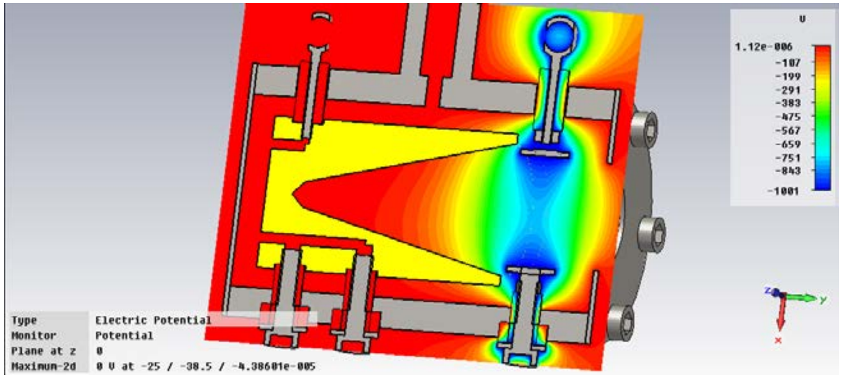
Beam Intensity

- Classic Solution: Faraday Cup



- Idea:
  - Stop beam,
  - Capture all charges,
  - Measure total charge.

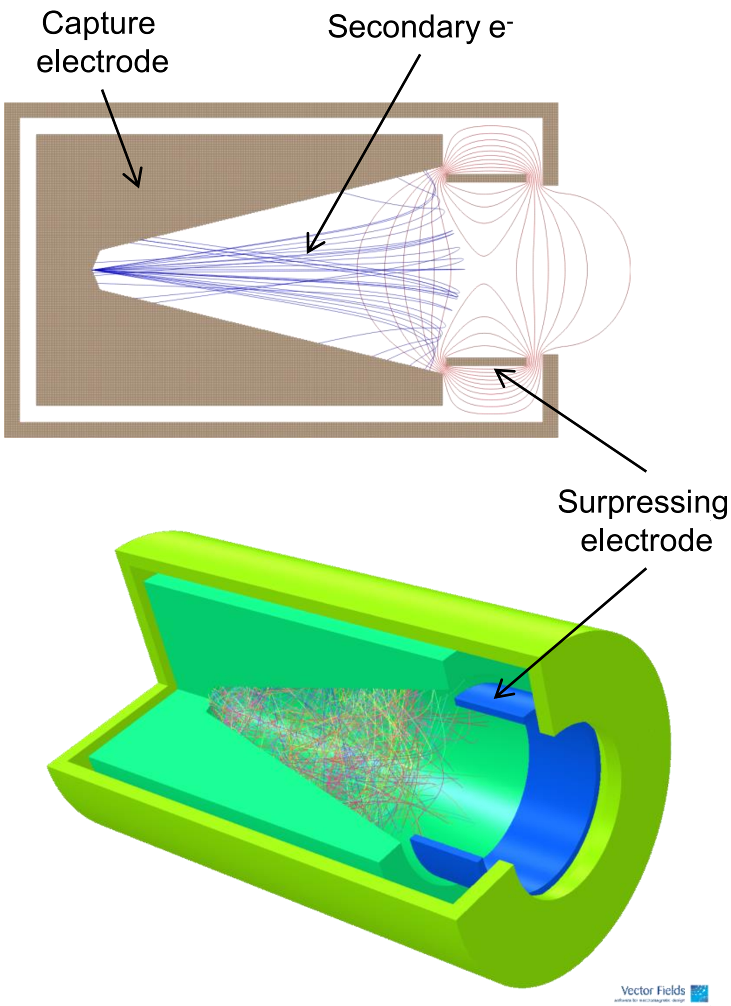
➡ Total intensity.



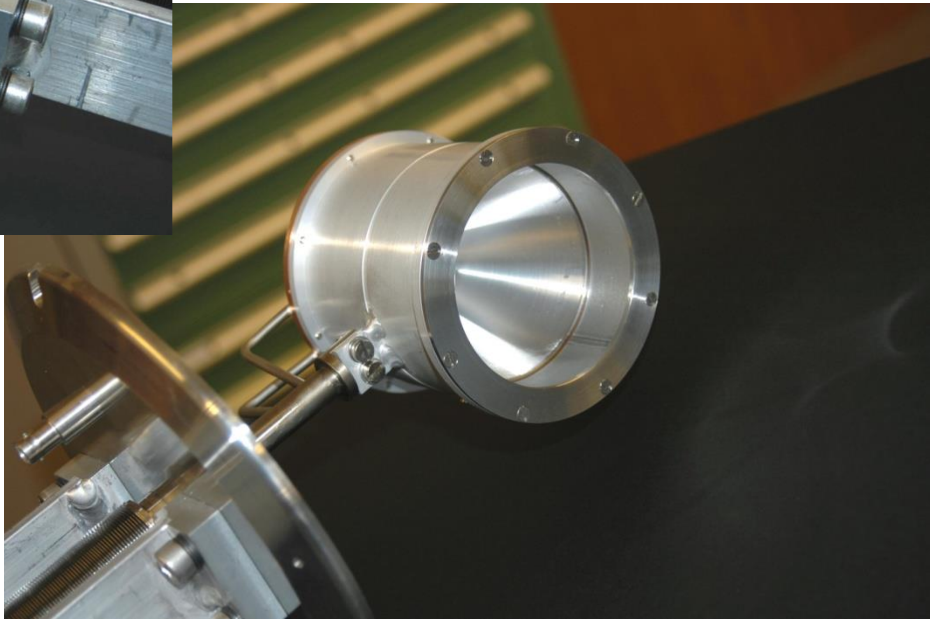
J. Harasimowicz and A. Sosa – PhD projects at CI
J. Harasimowicz et al., Phys. Rev. STAB **15**, 122801 (2012)
E. Cantero, et al., Nucl. Instr. Meth. A (2015)

Generic Layout of a Faraday Cup

- Stop main beam in capture electrode,
- Secondary electrons are generated,
- Repelling electrode pushes secondary electrons back onto the electrode,
- Very low intensities can be measured, USR: fA !
- Limitations:
  - Beam energy ?
  - Sensitivity/noise ?
  - Antimatter ?



Faraday Cup with Water Cooling



For higher intensities
water cooling may be needed

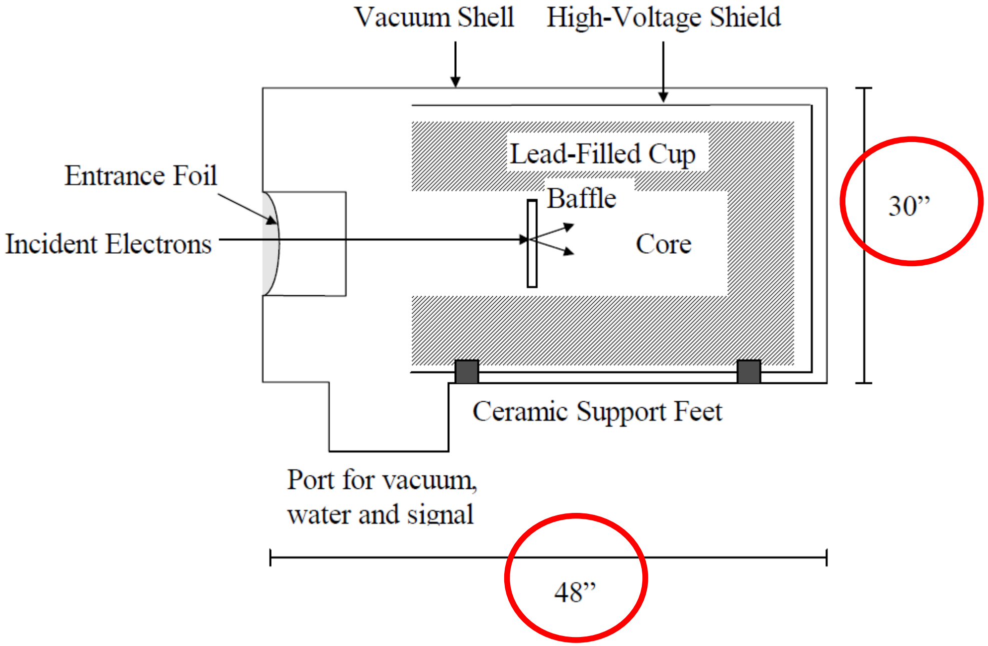
Source: U. Raich, CERN.

Excursion: High Power Beams

- 1 GeV @ 50 μA

- Need to dissipate 50 kW heat load !

- Error source ?



Cryogenic Current Comparator (CCC)

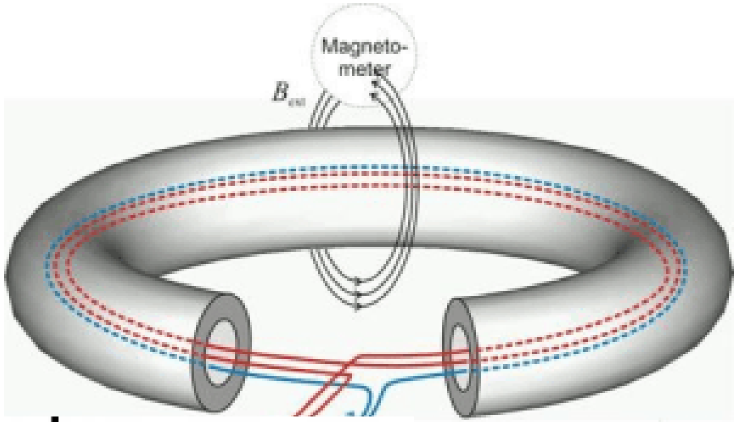
Absolute Current Measurement

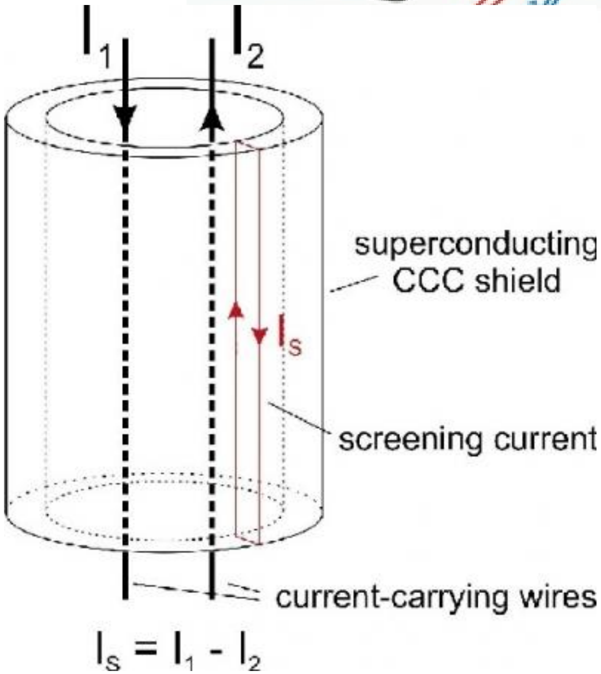
- Highly desirable !
  - Callibration of other monitors,
  - Direct link to experimental output.
- Challenges:
  - Signal levels VERY low,
  - Signal/noise critical,
  - Isolation against vibrations, rf noise
  - ...many more...
- PhD project Miguel Fernandes

Cryogenic Current Comparator

The CCC consists of:

- SC pickup coil,
- High efficient SC shield,
- High performance SQUID measurement system.





Harvey, Rev. Sci. Instrum. **43** (1972)
F. Kurian, DITANET fellow at GSI

SQUID

Superconducting QUantum Interference Device

- Most sensitive magnetic flux detector,

The working principle makes use of:

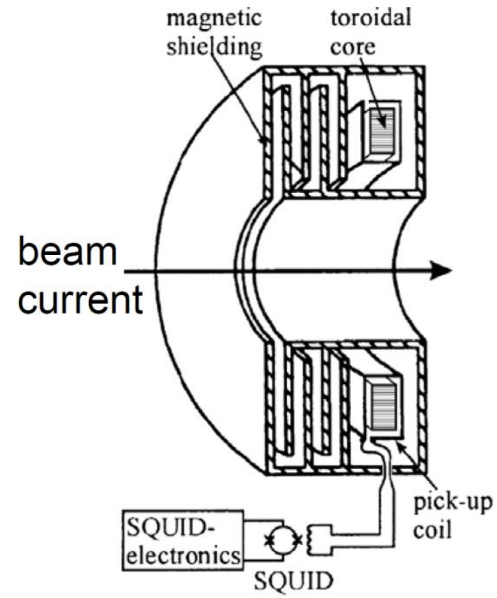
- Superconductivity,
- Flux quantization in SC rings,
- Josephson effect.

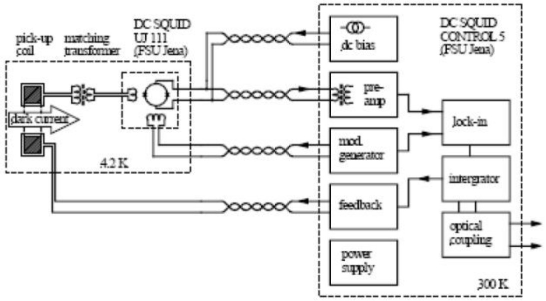
A SQUID consists of a SC ring with one or two weak links (*Josephson tunnel junctions*).

Measurement Principle

- Couple to azimuthal magnetic field,
- Screening current induced in SC coil with ferromagnetic core,
- DC SQUID for sensitive detection of coil magnetic field,
- Strong shielding against magnetic noise is key !

(14 ring cavities give 200 db shielding factor)

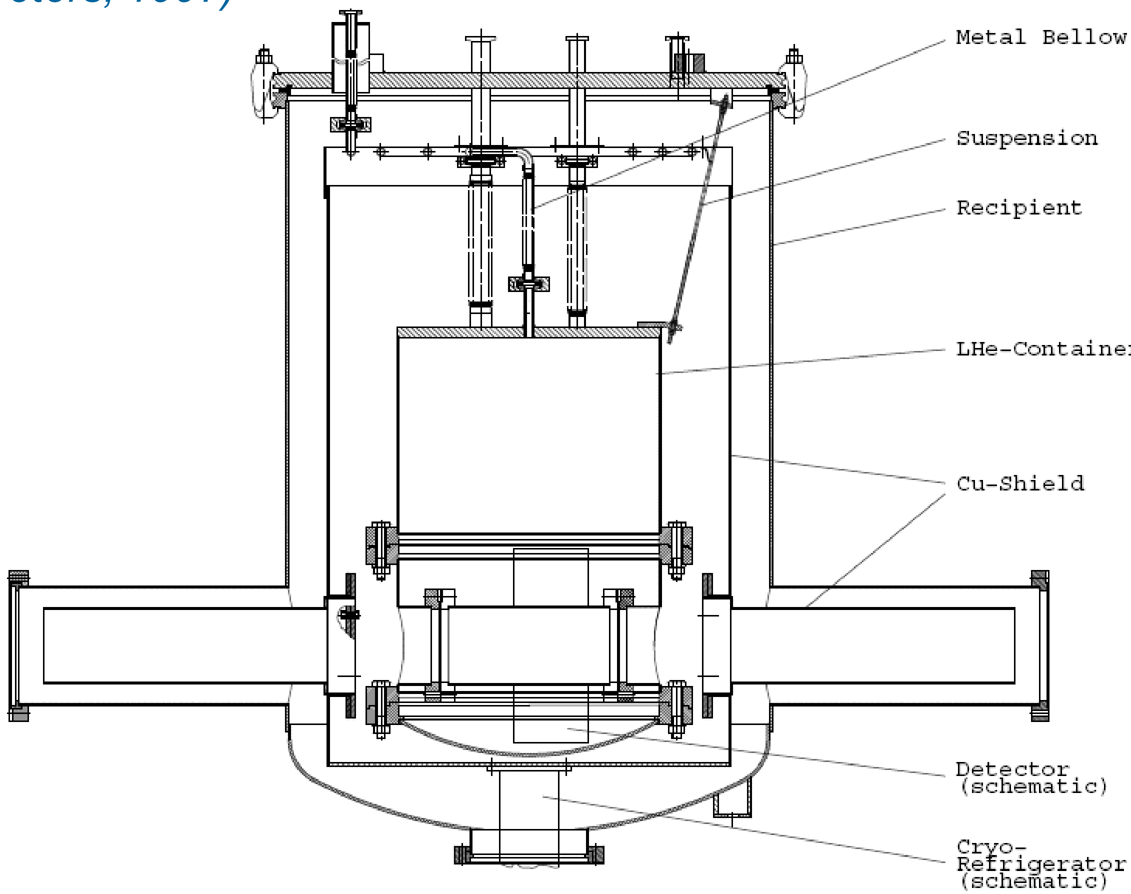




M. Schwickert

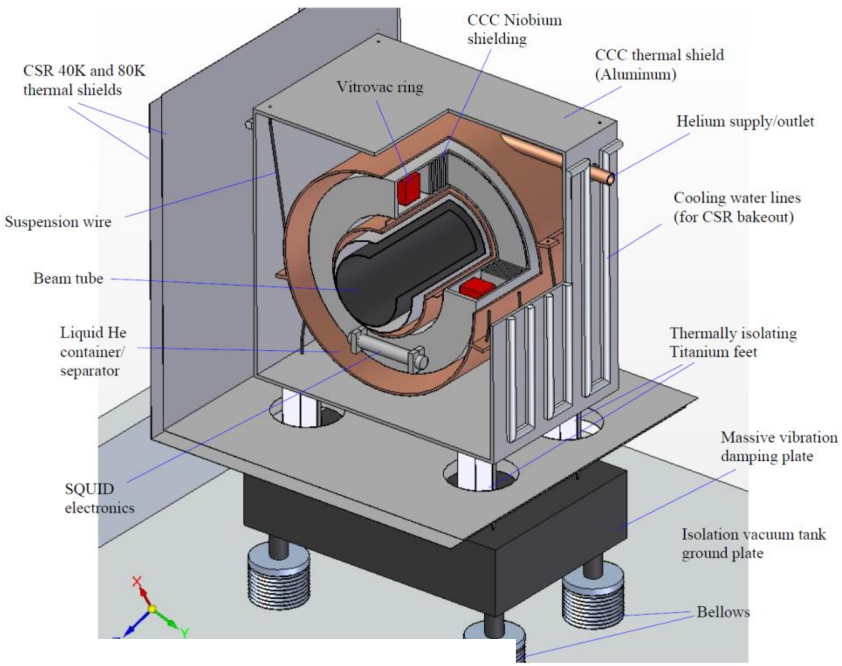
Prototype @ GSI

- GSI prototype *(A. Peters, 1997)*



Resolution:
250 pA/√Hz
→ **8 nA (1 kHz readout)**
→ **2×10^9 U^{28+}/s**

More recently...

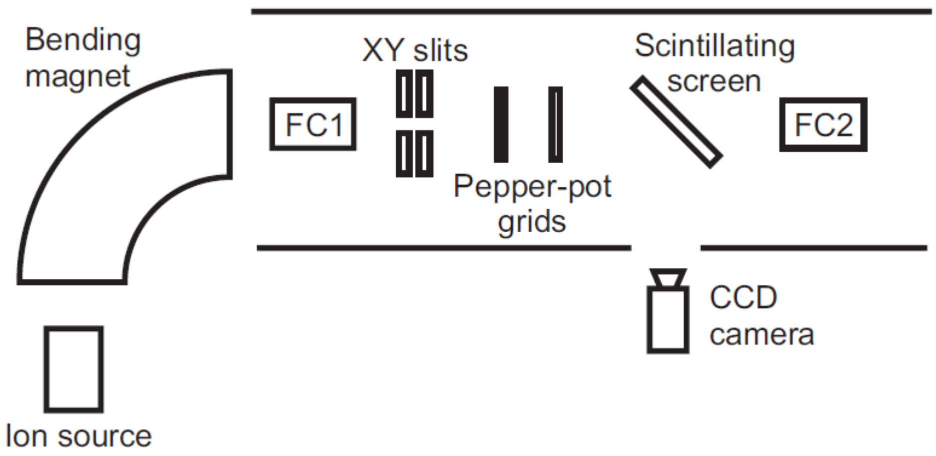


F. Kurian, DITANET Fellow at GSI

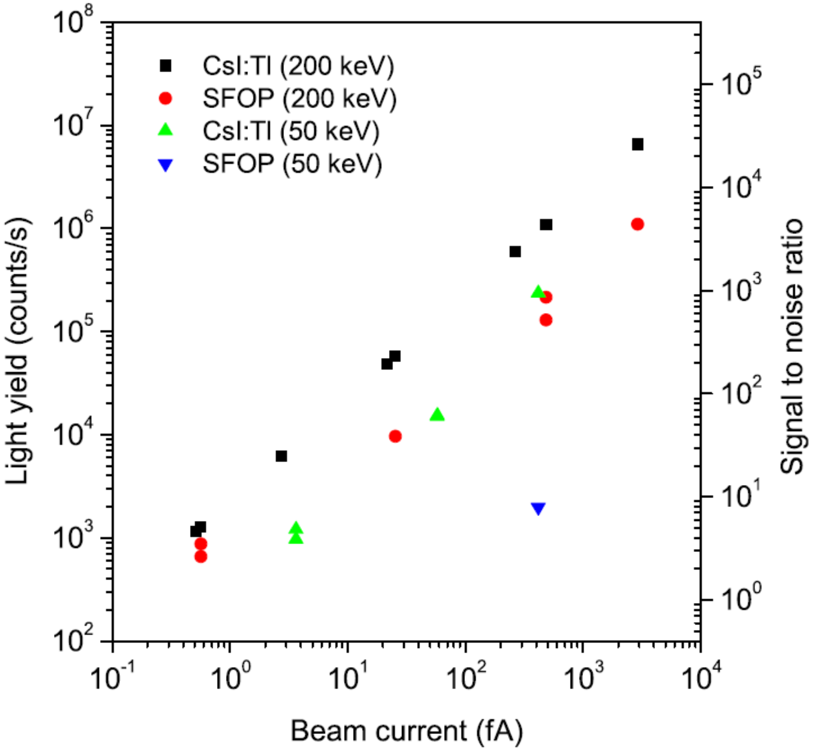
Beam Profile Monitoring

Screens *(scintillator, OTR, DR, etc.)*

- Realized in close collaboration with INFN-LNS



Various Options!

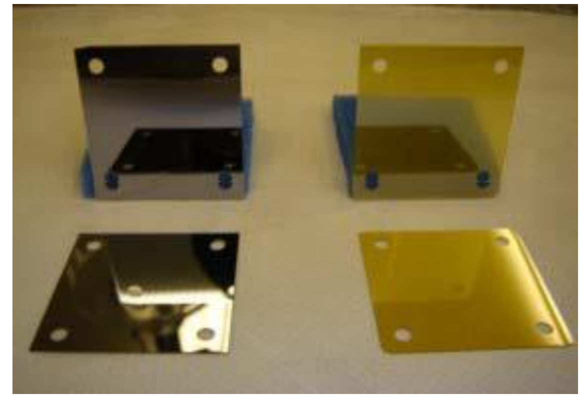


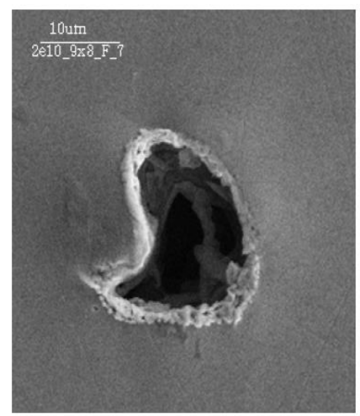
J. Harasimowicz et al.,
Rev. Sci. Instr. 81 (10), 2010

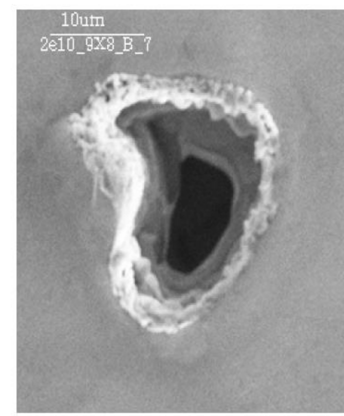
DITA-IIF

Beam profile of high intensity beams

- Damage caused by the beam
- Ideally: Non-invasive.

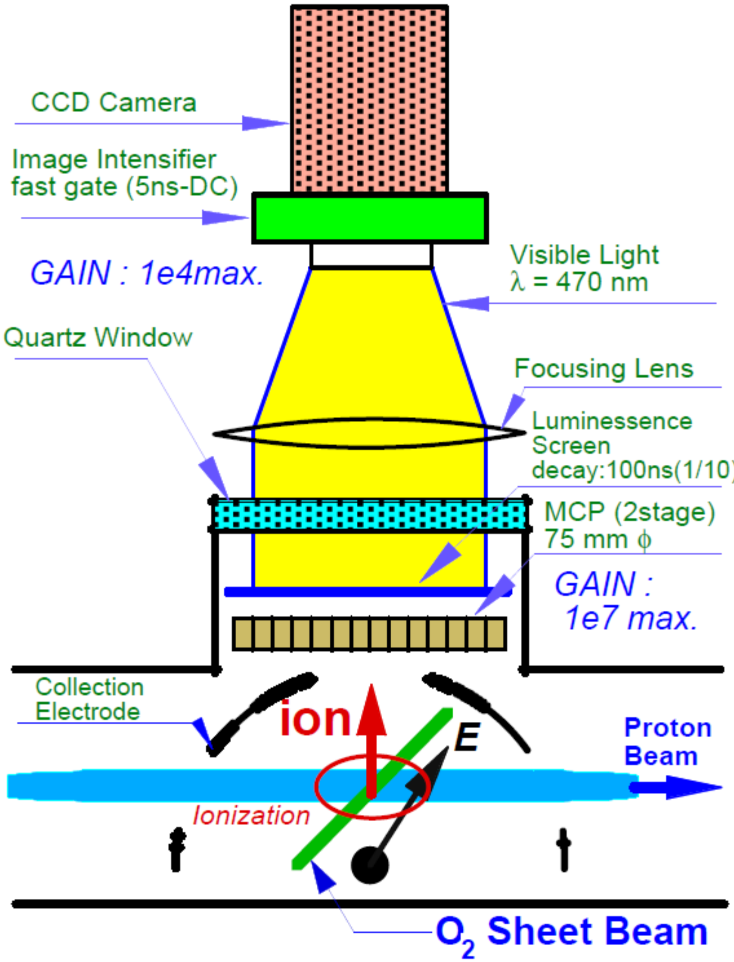






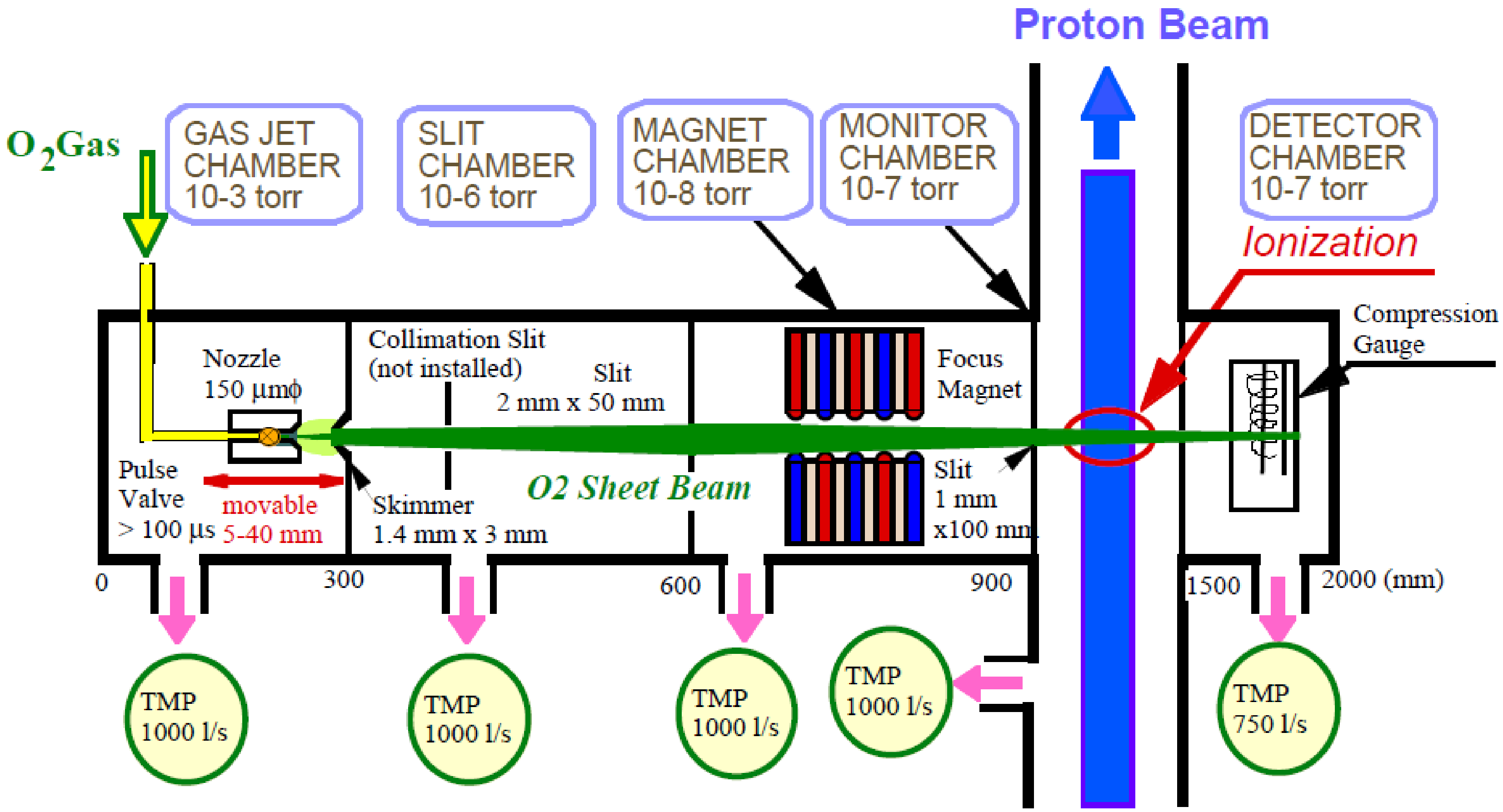
Gas Sheet Monitor

- Generate thin atom gas curtain,
- Ionize atoms with primary particle beam,
- Extract ions via electric field,
- Monitor on MCP, P screen.



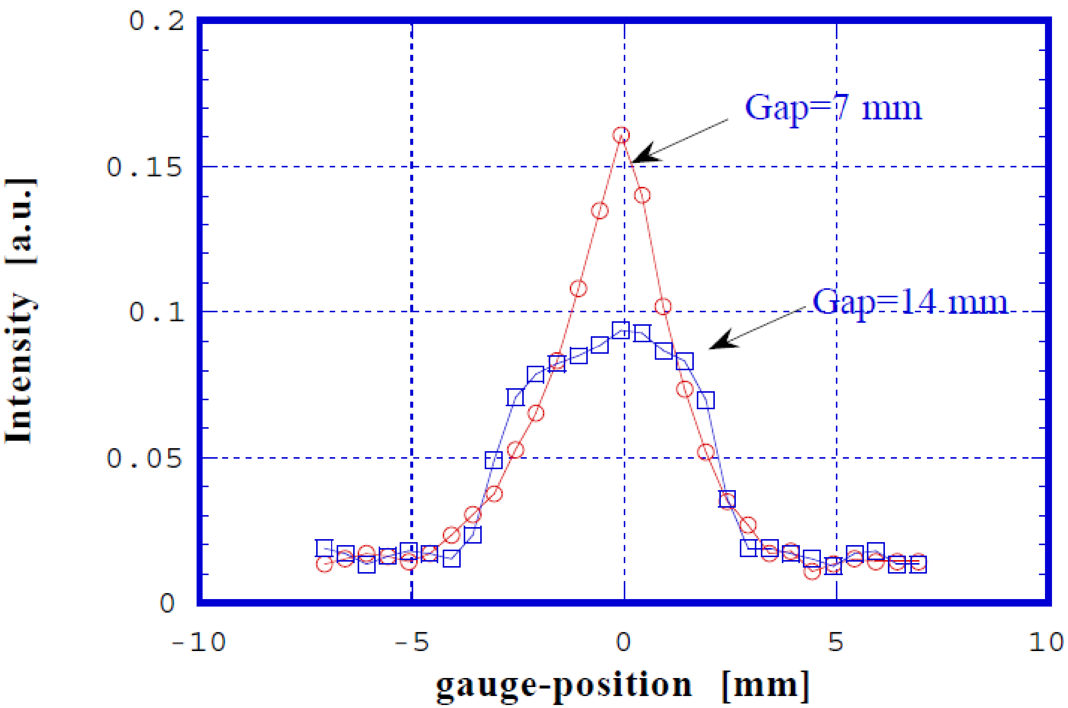
Y. Hashimoto et al., Proc. Part. Acc. Conf., Chicago (2001)

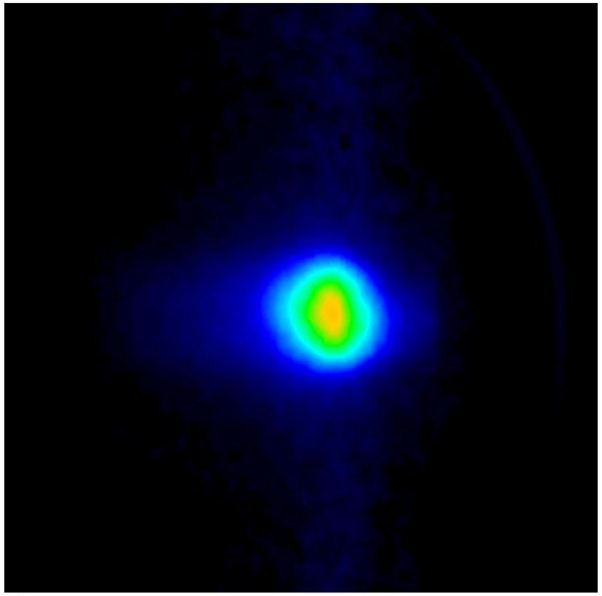
How to Generate the Jet ?

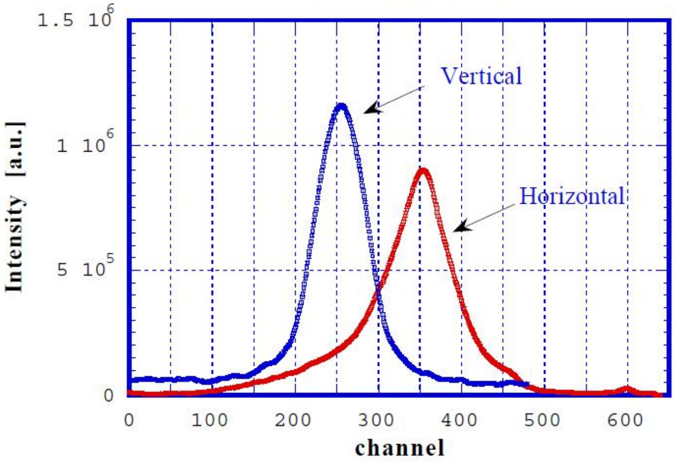


Y. Hashimoto et al., Proc. Part. Acc. Conf., Chicago (2001)

Experimental Data

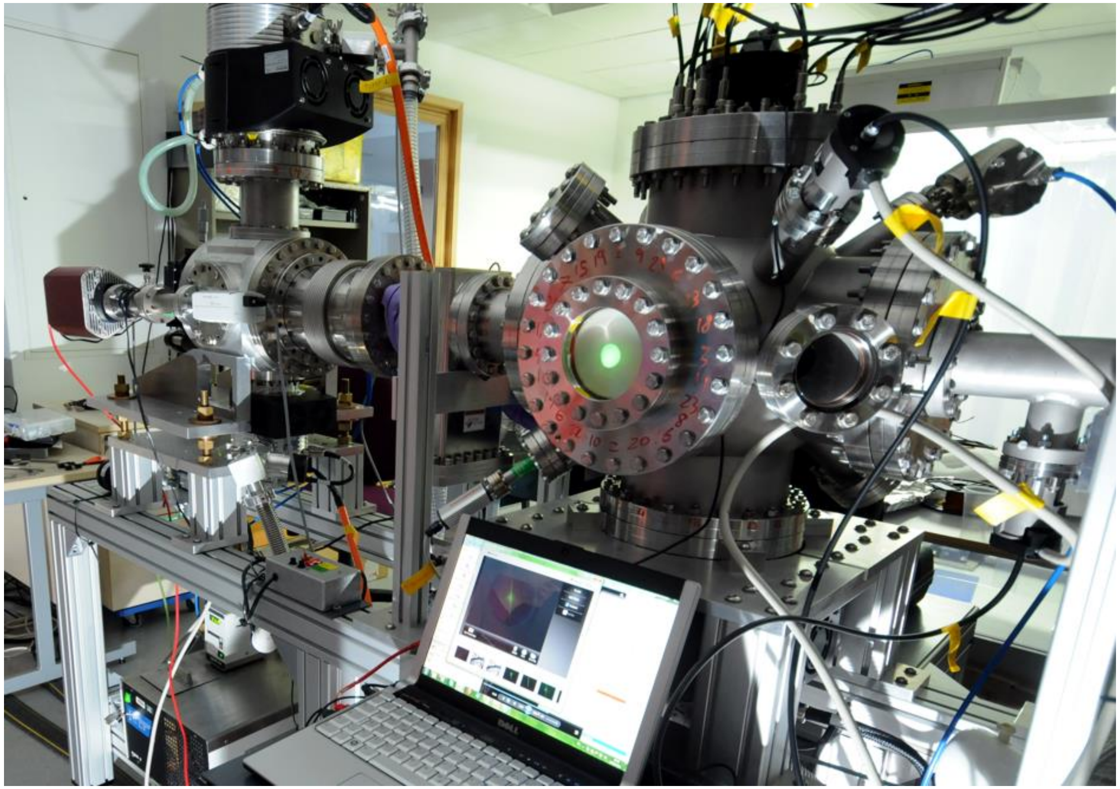




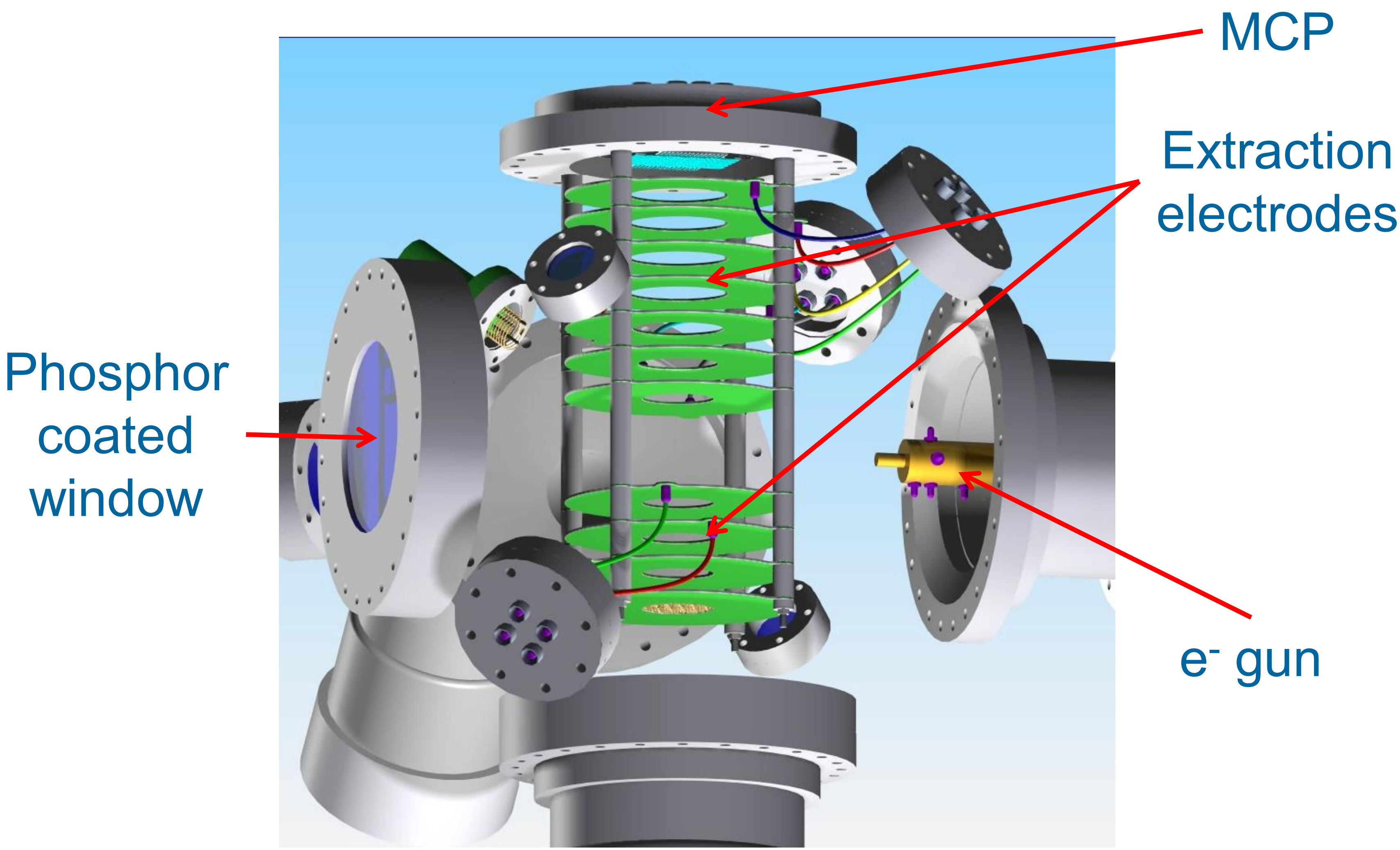


Y. Hashimoto et al., Proc. Part. Acc. Conf., Chicago (2001)

Setup @ Cockcroft Institute

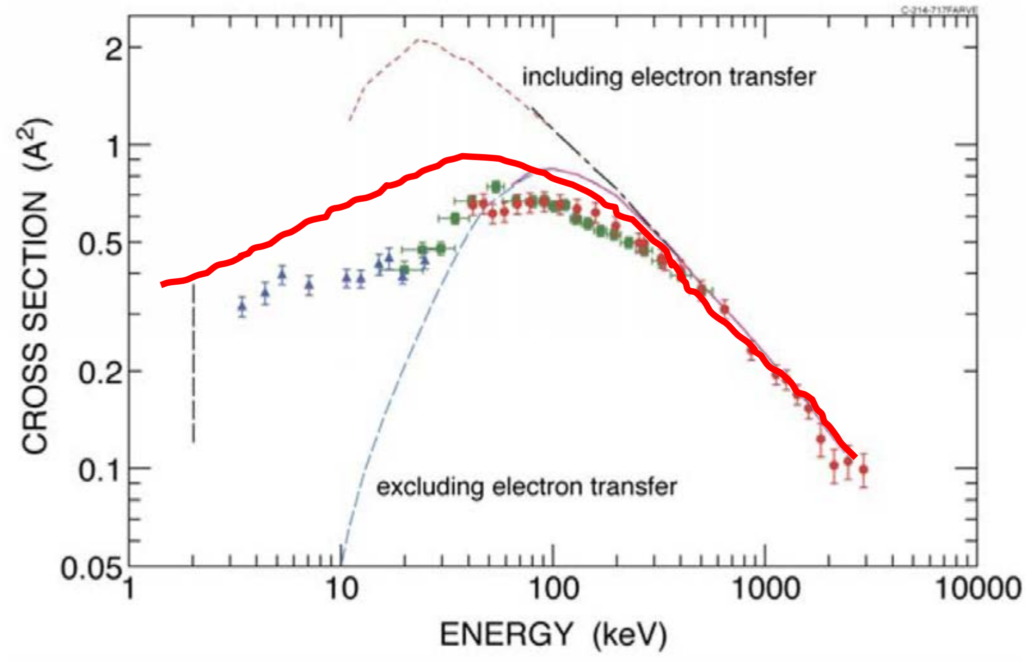


Zoom: Main chamber



Ionization Cross Sections

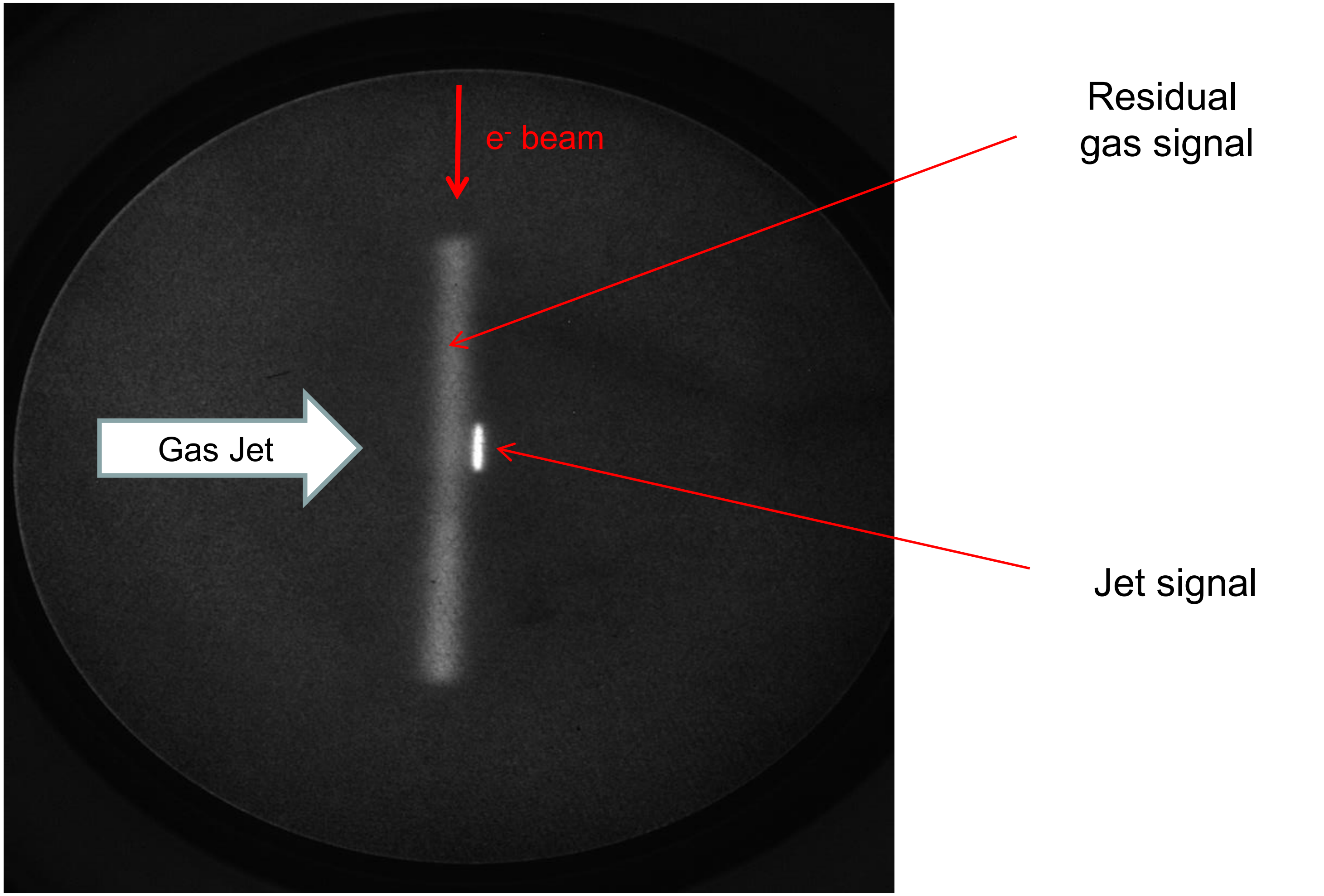
- Can be exotic, e.g. single ionization of helium by antiproton impact



$$\#_{Events} = \frac{\#_{ions}}{C} \cdot v \cdot \sigma(E) \cdot \rho_{target} \cdot w_{target}$$

H. Knudsen, Hyperfine Interactions **109** (1997) 133–143
H. Knudsen, Journal of Physics:Conf. Series **194** (2009) 012040

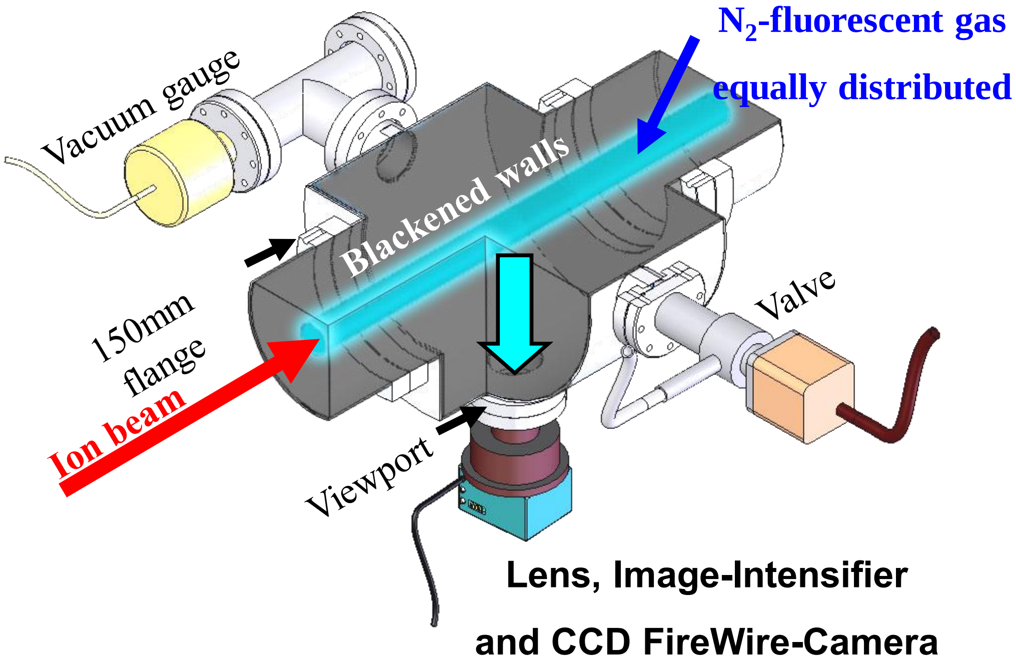
Results @ CI

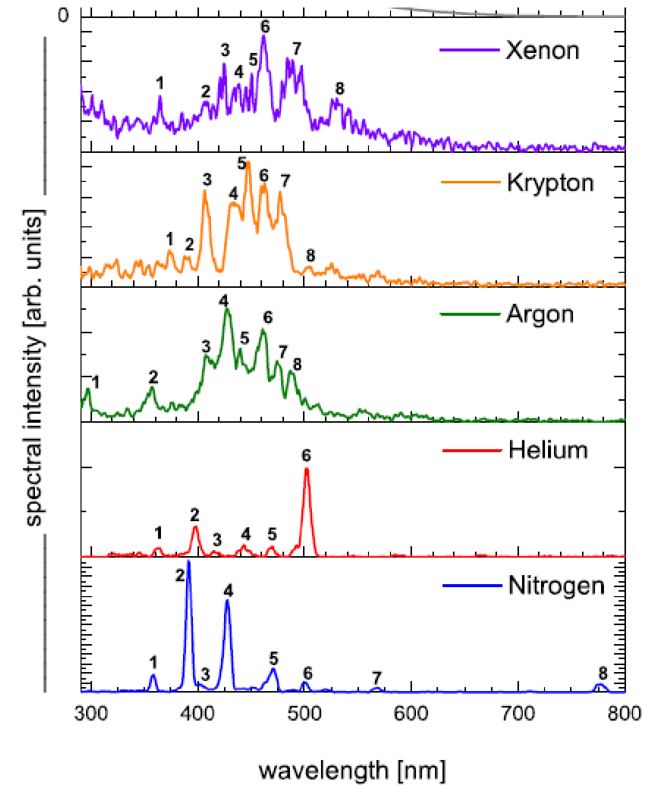


V. Tzoganis, et al.,
APL **104** 204104 (2014)

V. Tzoganis, et al.,
VACUUM (2015)

Fluorescence Monitor Principle





P. Forck et al., *Beam induced fluorescence profile monitor developments*, Proc. HB2010

- Gas molecules are excited by the beam and emit a photon when returning to the ground state.
- Emission wavelength is determined by the gas species
- The relaxation time is typically 10s or 100s of ns.

Benefit from both methods !

- Generate electrons/ions or light in collisions between gas jet and beam to be measured
- Detect electrons/ions or photons and measure profile
- R&D challenges:
  - Monitor integration (location, EM fields, cryostat,…)
  - Optimum location, e.g. do we have to measure inside the solenoid?
  - Gas condensation, space charge issues,…
  - Achievable resolution of optics and signal levels
- Optimize towards medical, HLLHC, etc. Applications

Beam Halo Monitoring

Definition: What is 'Halo' ?

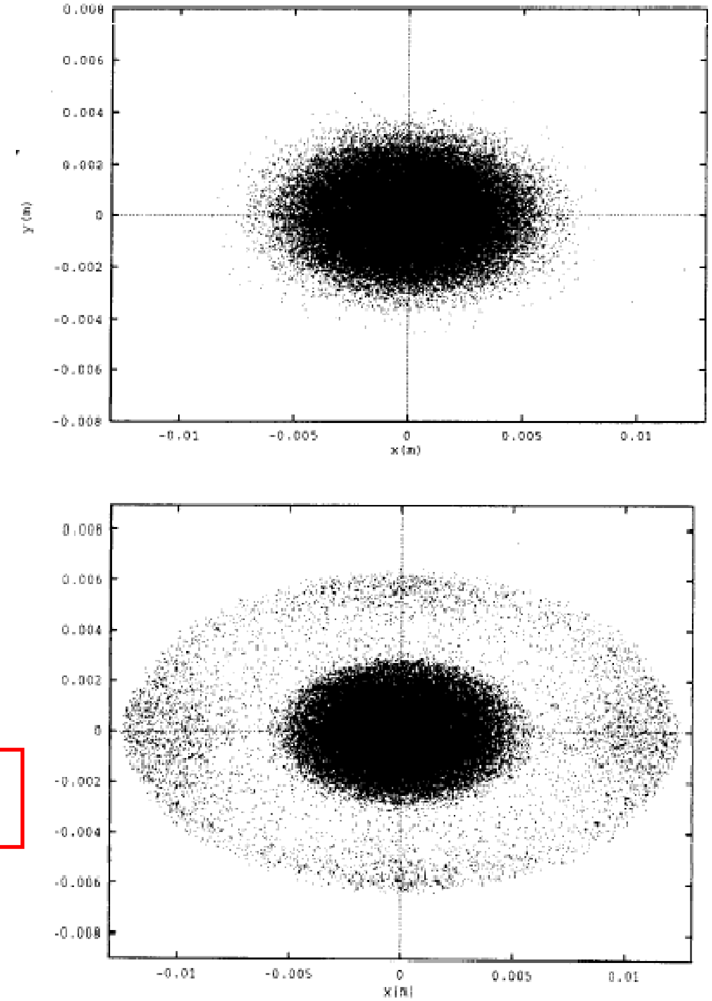
General definition difficult to make:

Accelerator physicists

↕

Instrumentation specialists

➡ Low density / difficult to measure

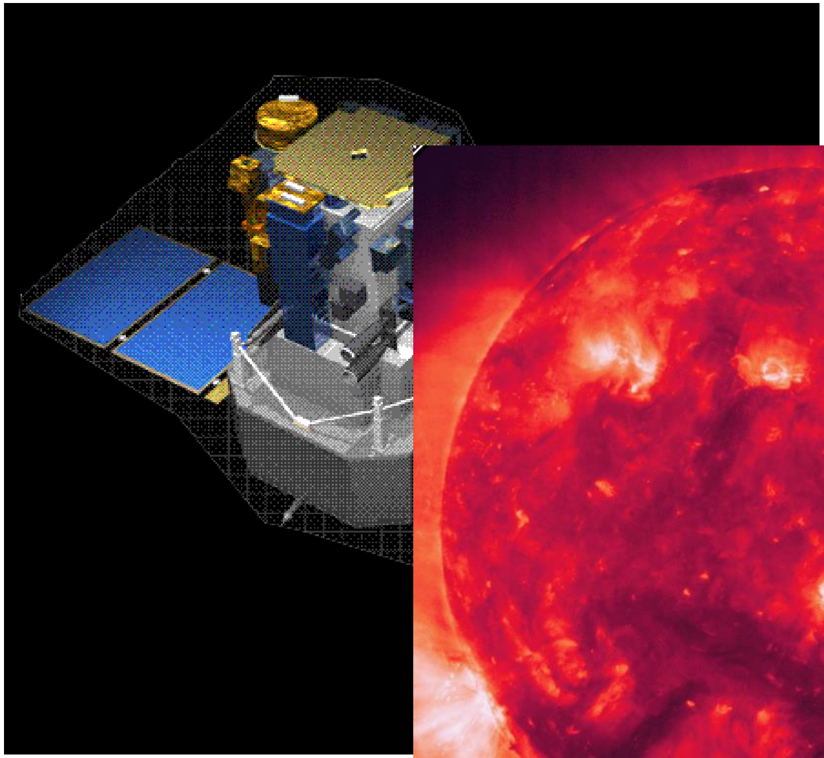


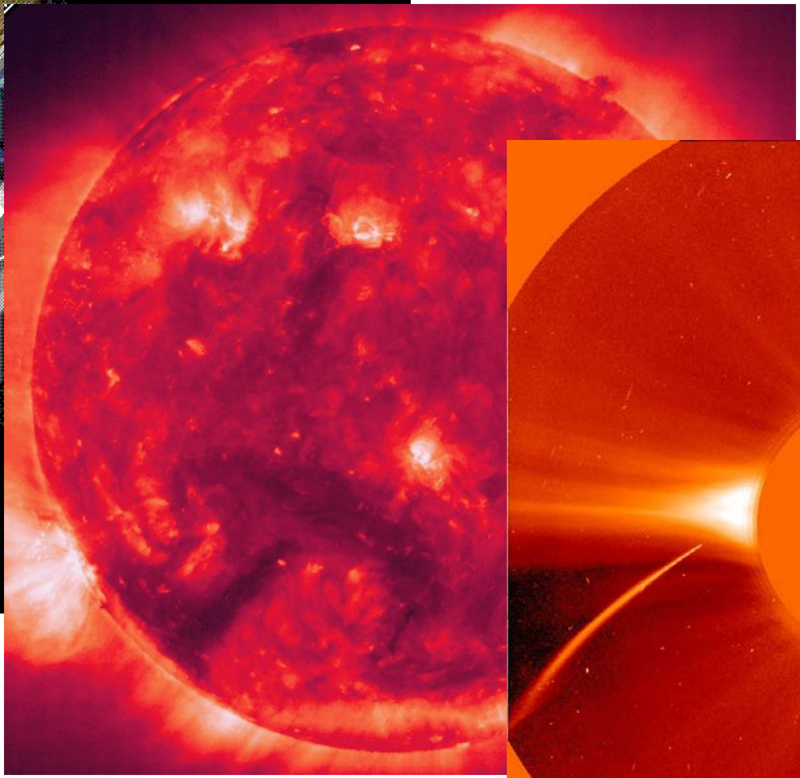
Problem

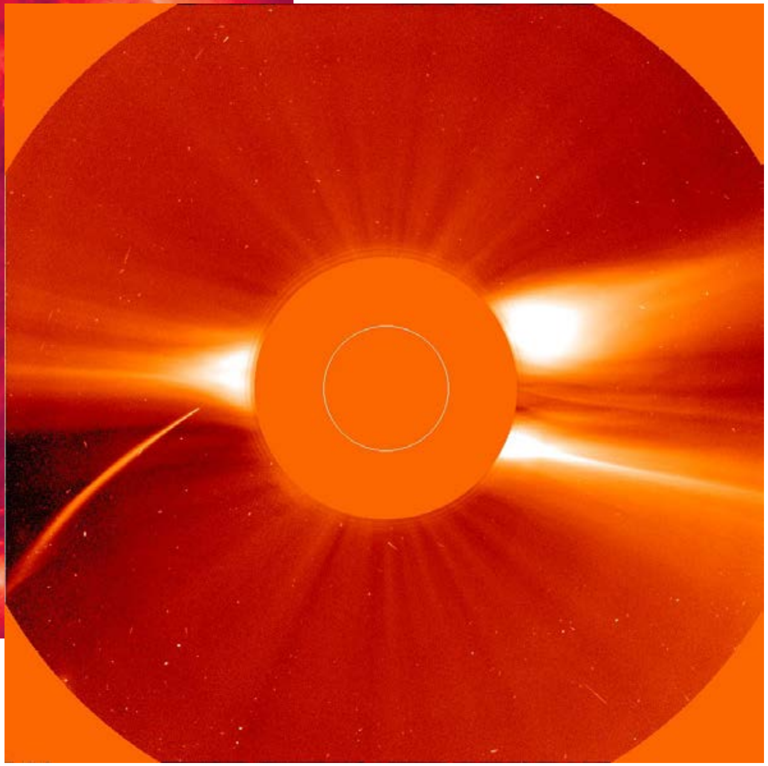
- Very high intensity in core:
  - Saturates pixels
  - Signal overflow to neighbouring pixels
  - Tail regions are being modified, wrong measurement.

- Concentrate measurement on tail region ONLY as this is the interesting part !

SOHO



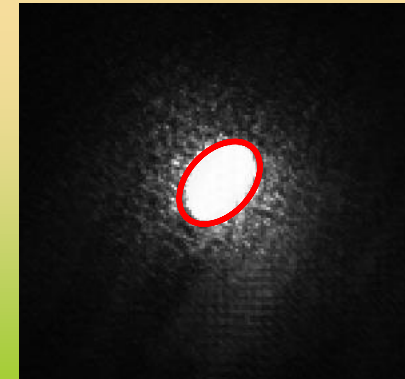




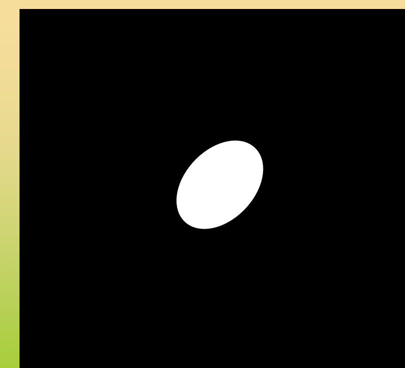
*__So__lar and __H__eliospheric __O__bservatory

Halo Monitoring: Core Masking

(1) Aquire profile



(2) Define core



(3) Generate mask

(4) Re-Measure

C.P. Welsch et al.,
Proc. SPIE (2007)

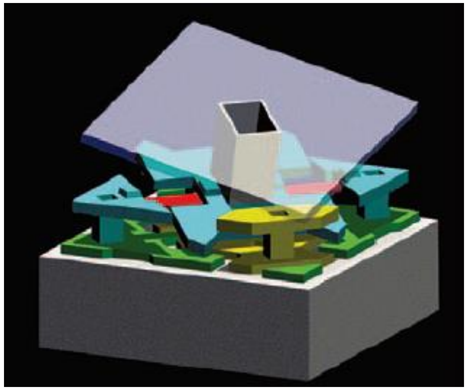
J. Egberts, et al.,
JINST **5** P04010 (2010)

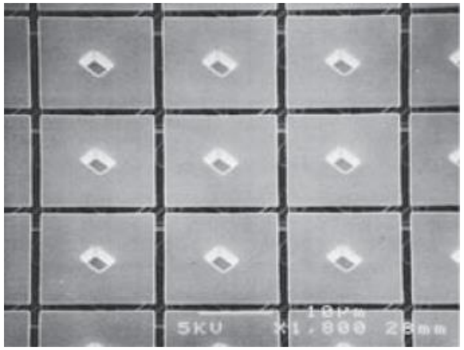
H. Zhang, et al.,
Phys. Rev. STAB 15 (2012)

B. Lomberg, et al.
Proc. IBIC (2013)

Basis: Micro Mirror Array (TI)

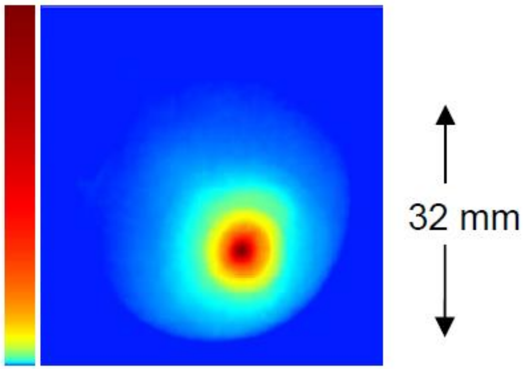
- 1024 x 768 pixels (XGA)
- USB Interface
- high-speed port 64-bit @ 120 MHz for data transfer
- up to 9.600 full array mirror patterns / sec (7.6 Gbs)
- 16 μm in size
- +/- 12° tilt angle
- Switch of 15 μs physically, 2 μs optically

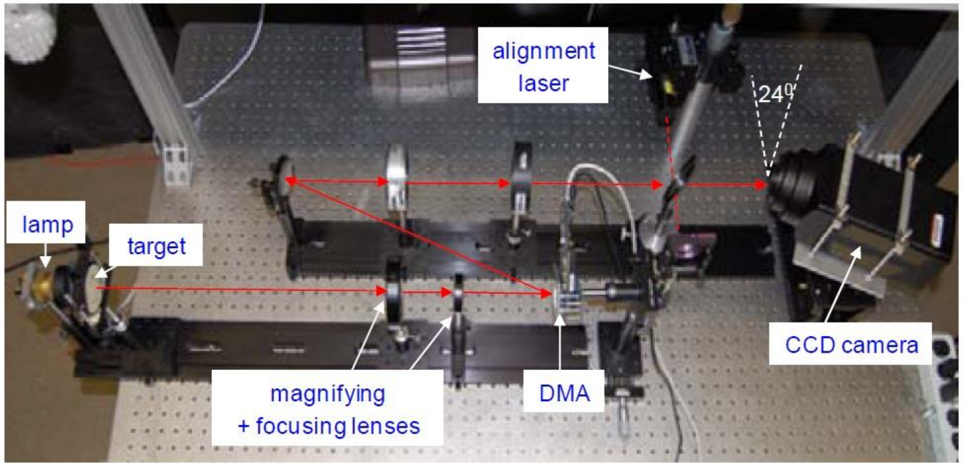




Measurements at UMER

- 10 keV e^- beam, Phosphor screen
- iCCD camera
- Verification of earlier lab measurements
- Reconstruction of beam profile with DR of 10^5
- Effects from diffraction on DMA are minimal



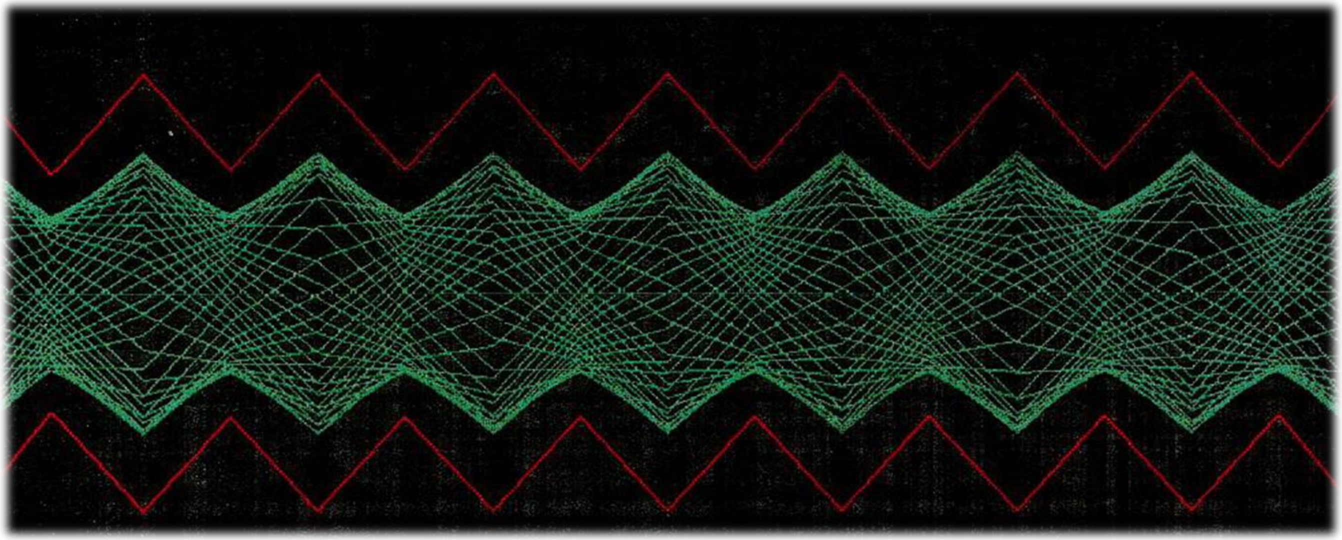


R. Fiorito, et al., Proc. BIW
H. Zhang, et al.,
Phys. Rev. STAB **15**, 072803 (2012)

Emittance Measurement

Emittance measurements

- Beam size changes as a beam is focused and defocused.



- Emittance describes 'inherent' size of the beam
- It allows determining the beam size at any point.

Definition of the Emittance

- Commonly used:

$$\varepsilon_n{}^2 = \langle x^2\rangle\langle\beta^2\gamma^2x'^2\rangle - \langle x\beta\gamma x'\rangle$$

Misleading, as *ΔE* and *x'* can be very large.

Assume a drift, where there is no correlation between energy and transverse position:

$$\varepsilon_n{}^2\, A = \langle\gamma\rangle^2\sigma_E{}^2\,\langle x^2\rangle\langle x'^2\rangle + \underbrace{\langle\beta\gamma\rangle^2(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2)}_{\text{Geometrical emittance}}$$

A. Cianchi, et al., Nucl. Instr. Meth. A 720 (2013)

Attention !!

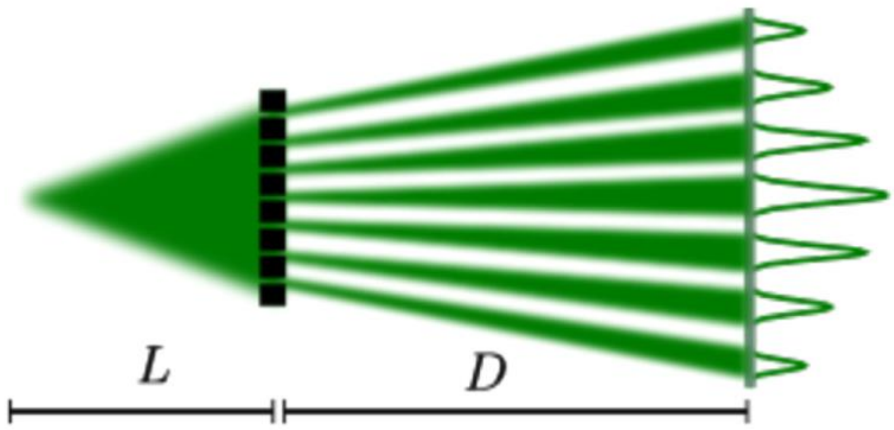
$$\varepsilon_n{}^2\ A = \langle\gamma\rangle^2\sigma_E{}^2\ \langle x^2\rangle\langle x'^2\rangle + \langle\beta\gamma\rangle^2(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2)$$

- is usually negligible
- For example in plasma accelerators:
  large *ΔE* and *x'*.
- Normalized emittance depends on position of measurement !

- Here: Focus on geometrical part.

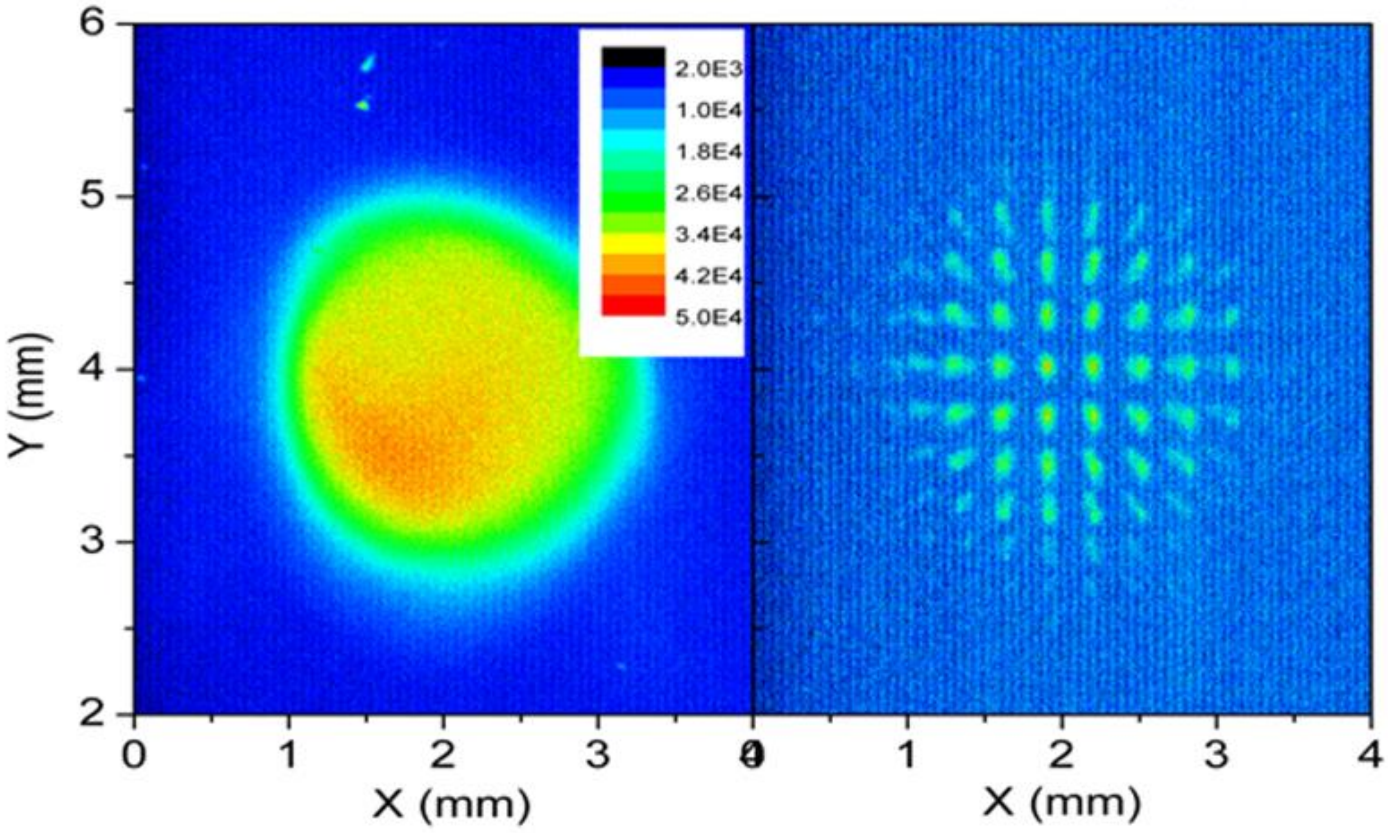
Emittance measurements

- Measure angular spread of the beam and beam profile at the same time.
- One option: ‘pepperpot’ and screen.
- Block the beam apart from a few small holes.
- Reduces space charge dominated beam to emittance-dominated beamlets that drift to screen.



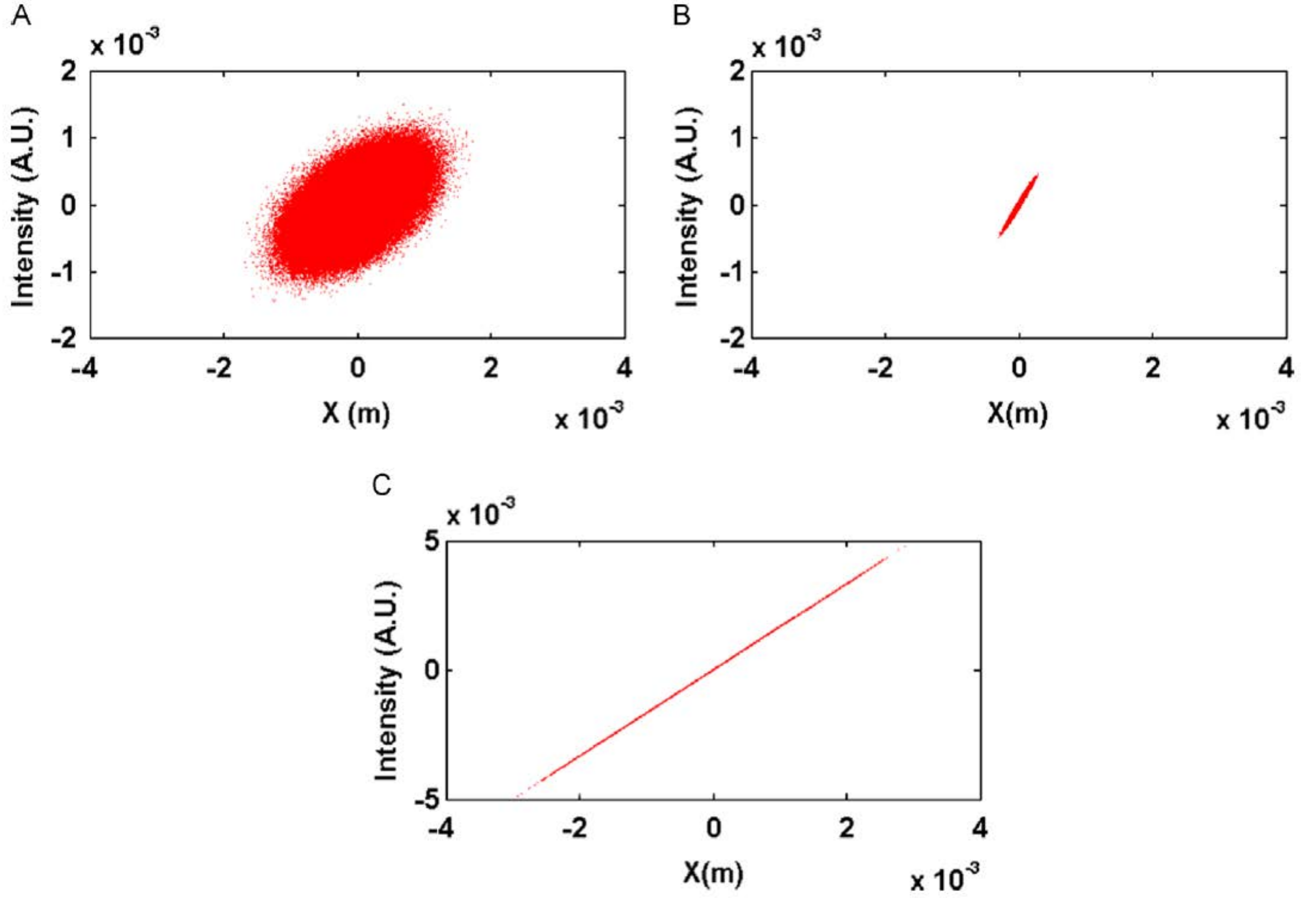
Emittance measurements

- Use a ‘pepperpot’ mask and a screen.
- Block the beam apart from a few small (well-defined) holes.



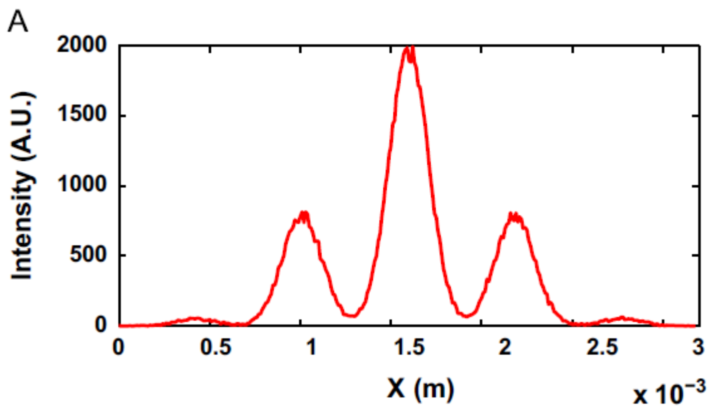
Pepperpot in Plasma Accelerators

- 5 MeV with size 1 mm; 500 MeV with 10 μm; 500 MeV with 1 μm

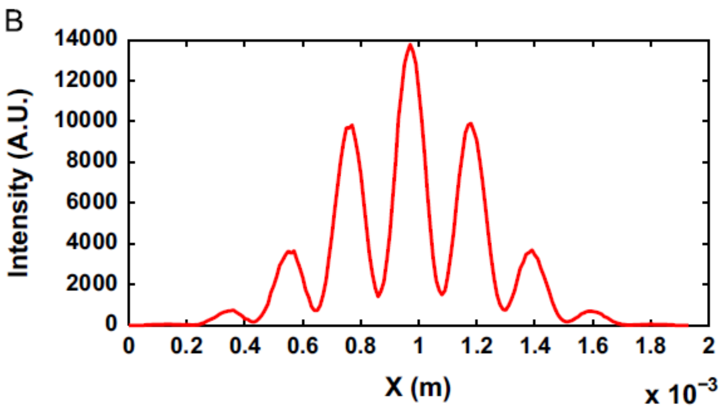


Pepperpot in Plasma Accelerators

- Error estimation



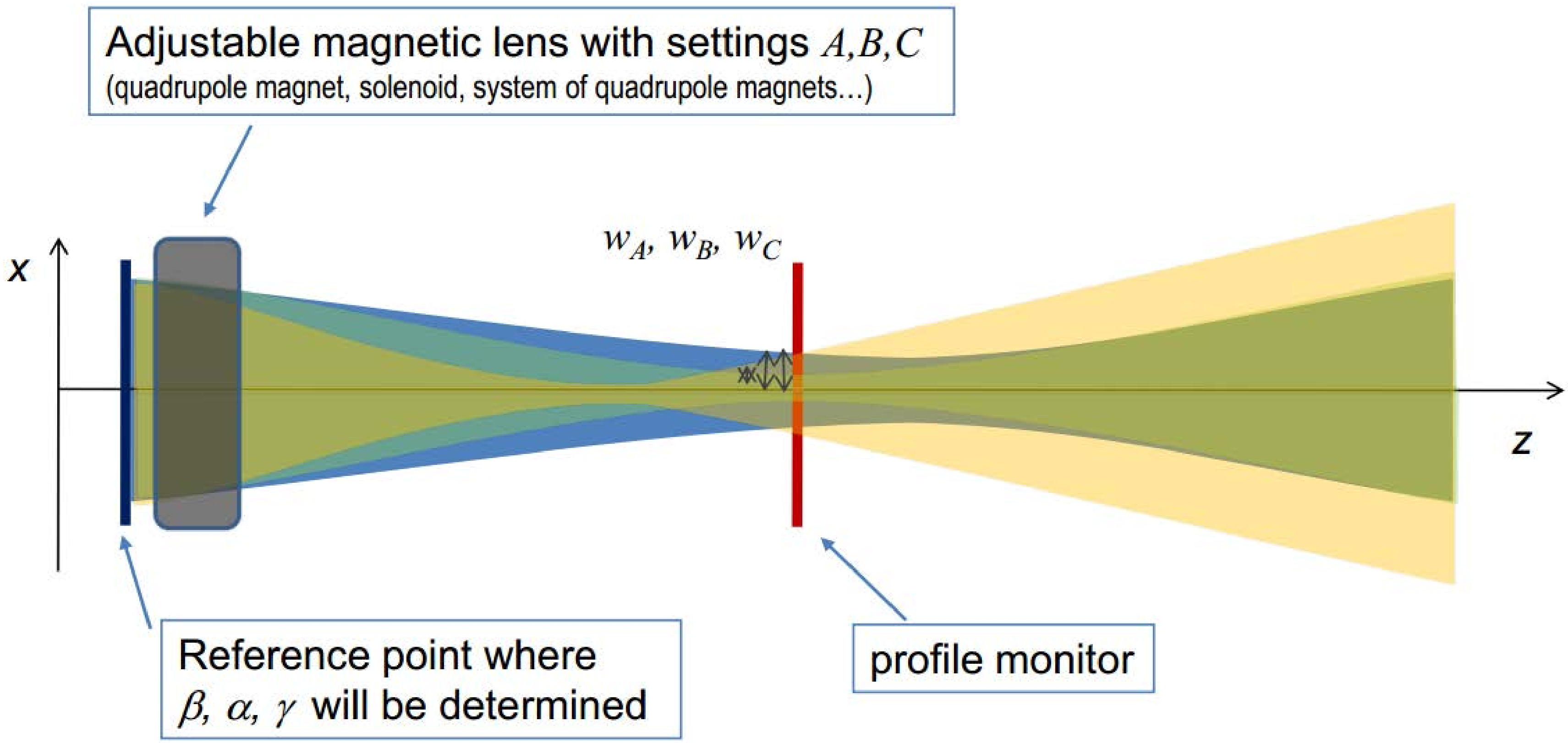
around 1 %



around 47 %

- For case C – this would be 20x more:= 1000 % ➡ not suitable !

Quadrupole Scan



$$w^2 = c^2\,\beta\varepsilon - 2cs\,\alpha\,\varepsilon + s^2\,\gamma\,\varepsilon, \qquad \begin{pmatrix} c & s \\ c' & s' \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} m_{11}(I_{mag}) & m_{12}(I_{mag}) \\ m_{21}(I_{mag}) & m_{22}(I_{mag}) \end{pmatrix}$$

Change quad strength:

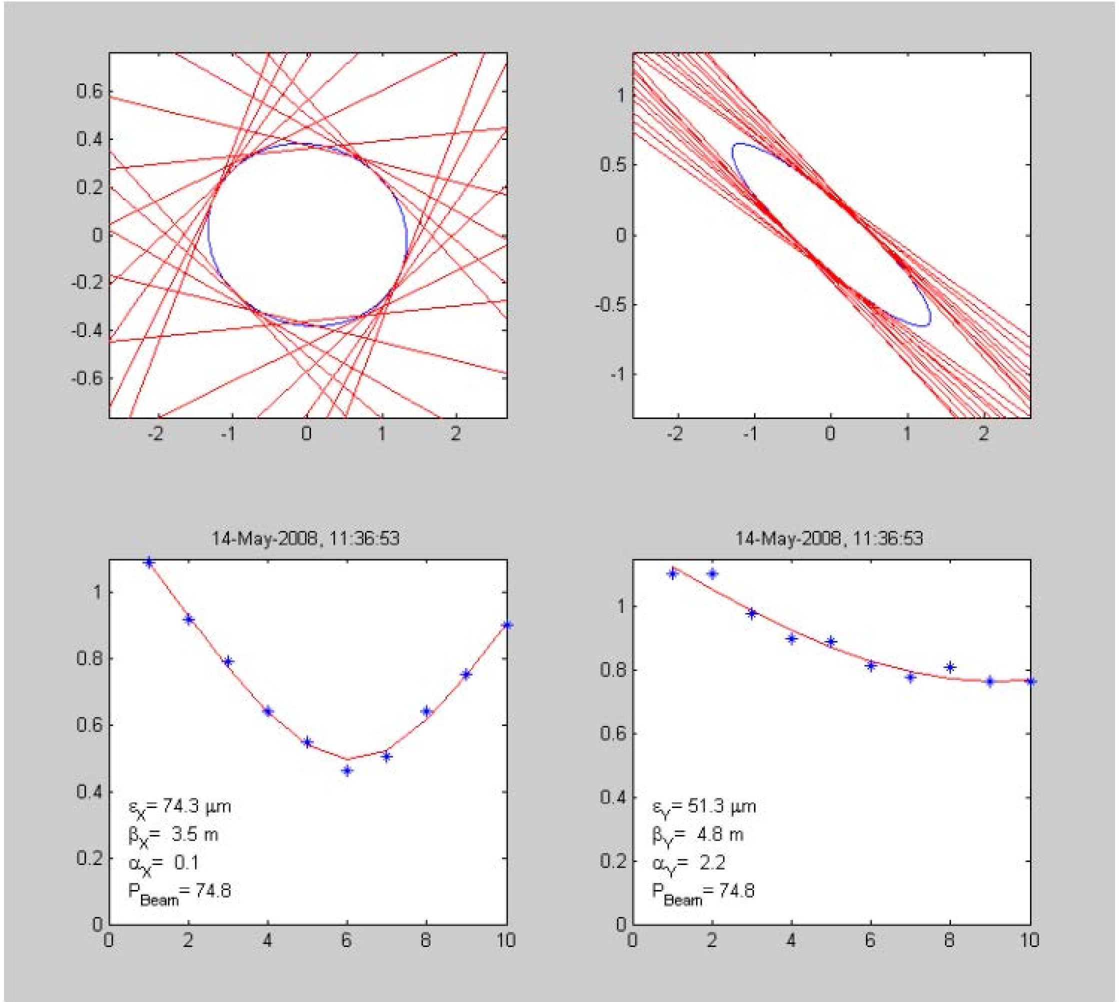
$$w_A^2 = c_A^2 \beta\,\varepsilon - 2 c_A s_A\ \alpha\ \varepsilon + s_A^2\ \gamma\,\varepsilon$$
$$w_B^2 = c_B^2 \beta\,\varepsilon - 2 c_B s_B\ \alpha\ \varepsilon + s_B^2\ \gamma\,\varepsilon$$
$$w_C^2 = c_C^2 \beta\,\varepsilon - 2 c_C s_C\ \alpha\ \varepsilon + s_C^2\ \gamma\,\varepsilon$$

$\Downarrow$ can be rewritten in Matrix notation

$$\begin{pmatrix} w_A^2 \\ w_B^2 \\ w_C^2 \end{pmatrix} = \begin{pmatrix} c_A^2 & -2c_A s_A & s_A^2 \\ c_B^2 & -2c_B s_B & s_B^2 \\ c_C^2 & -2c_C s_C & s_C^2 \end{pmatrix} \cdot \begin{pmatrix} \beta\varepsilon \\ \alpha\varepsilon \\ \gamma\varepsilon \end{pmatrix} \Rightarrow \begin{pmatrix} c_A^2 & -2c_A s_A & s_A^2 \\ c_B^2 & -2c_B s_B & s_B^2 \\ c_C^2 & -2c_C s_C & s_C^2 \end{pmatrix}^{-1} \cdot \begin{pmatrix} w_A^2 \\ w_B^2 \\ w_C^2 \end{pmatrix} = \begin{pmatrix} \beta\varepsilon \\ \alpha\varepsilon \\ \gamma\varepsilon \end{pmatrix}$$

$$\beta\varepsilon \cdot \gamma\varepsilon - (\alpha\varepsilon)^2 = \varepsilon^2\left(\beta \cdot \gamma - \alpha^2\right) = \varepsilon^2 \quad \Rightarrow \quad \sqrt{\beta\varepsilon \cdot \gamma\varepsilon - (\alpha\varepsilon)^2} = \varepsilon, \quad \beta = \frac{\beta\varepsilon}{\varepsilon}, \quad \alpha = \frac{\alpha\varepsilon}{\varepsilon}$$

Example: Quad scan @ CTF3



Quad scan: A candidate ?

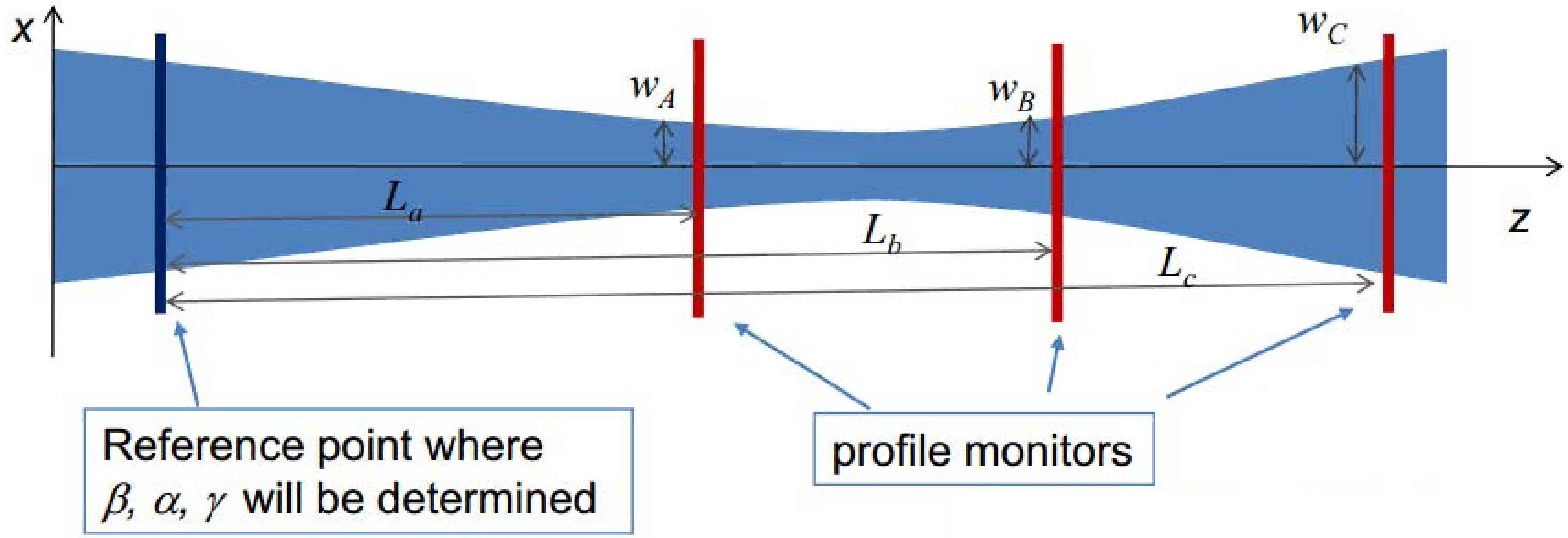
- Spot size dominated by large angular divergence;
- Chromatic effects should not affect results

➡ Distance between quad – waist rather short.

- Can be an issue in actual experimental setup.
- However, good candidate.

Three Screen Method

- Determine α,β and γ together with ε.



$$w^2 = c^2\,\beta\varepsilon - 2cs\,\alpha\,\varepsilon + s^2\,\gamma\,\varepsilon,\text{ for drift } \begin{pmatrix} c & s \\ c' & s' \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

$$\Rightarrow \quad w^2 = \beta\,\varepsilon - 2\,L\,\alpha\,\varepsilon + L^2\,\gamma\,\varepsilon$$

H. Braun

Derivation of TWISS parameters

$$w_A^2 = \beta\,\varepsilon - 2\,L_A\,\alpha\,\varepsilon + L_A^2\,\gamma\,\varepsilon$$
$$w_B^2 = \beta\,\varepsilon - 2\,L_B\,\alpha\,\varepsilon + L_B^2\,\gamma\,\varepsilon$$
$$w_C^2 = \beta\,\varepsilon - 2\,L_C\,\alpha\,\varepsilon + L_C^2\,\gamma\,\varepsilon$$

⇓ can be rewritten in Matrix notation

$$\begin{pmatrix} w_A^2 \\ w_B^2 \\ w_C^2 \end{pmatrix} = \begin{pmatrix} 1 & -2L_A & L_A^2 \\ 1 & -2L_B & L_B^2 \\ 1 & -2L_C & L_C^2 \end{pmatrix} \cdot \begin{pmatrix} \beta\varepsilon \\ \alpha\varepsilon \\ \gamma\varepsilon \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} 1 & -2L_A & L_A^2 \\ 1 & -2L_B & L_B^2 \\ 1 & -2L_C & L_C^2 \end{pmatrix}^{-1} \cdot \begin{pmatrix} w_A^2 \\ w_B^2 \\ w_C^2 \end{pmatrix} = \begin{pmatrix} \beta\varepsilon \\ \alpha\varepsilon \\ \gamma\varepsilon \end{pmatrix}$$

$$\beta\varepsilon \cdot \gamma\varepsilon - (\alpha\varepsilon)^2 = \varepsilon^2\left(\beta \cdot \gamma - \alpha^2\right) = \varepsilon^2 \quad \Rightarrow \quad \sqrt{\beta\varepsilon \cdot \gamma\varepsilon - (\alpha\varepsilon)^2} = \varepsilon, \quad \beta = \frac{\beta\varepsilon}{\varepsilon}, \quad \alpha = \frac{\alpha\varepsilon}{\varepsilon}$$

Emittance measurement: Challenges

- Access to single shot measurements
- Requires thin foils
- Multiple scattering in foils needs to be carefully assessed

Limitation

- Probably only suitable if beam energy > 1 GeV.

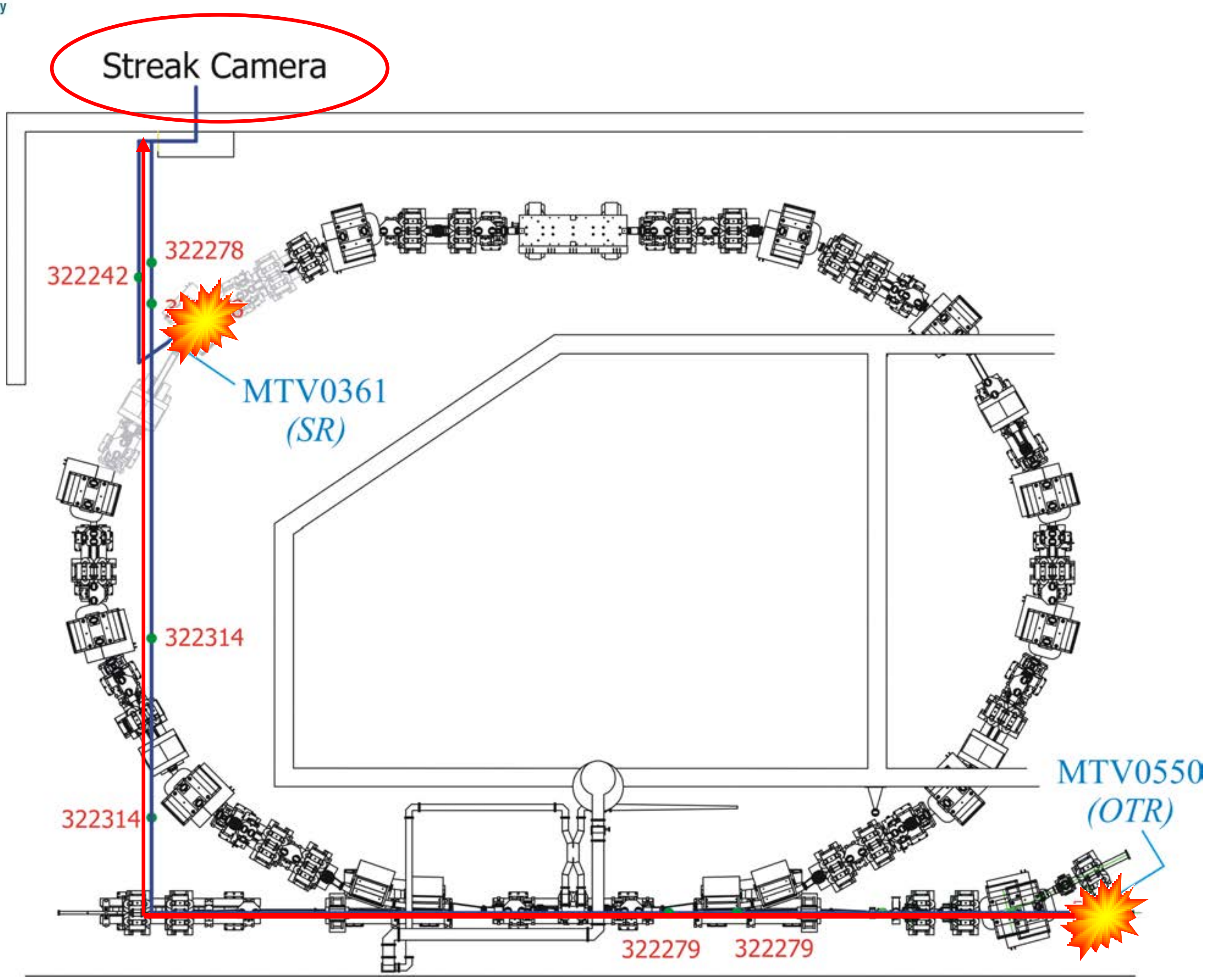
Longitudinal beam profile measurement

Bunch length measurement

- Desirable: good/excellent time resolution
- Non/least invasive

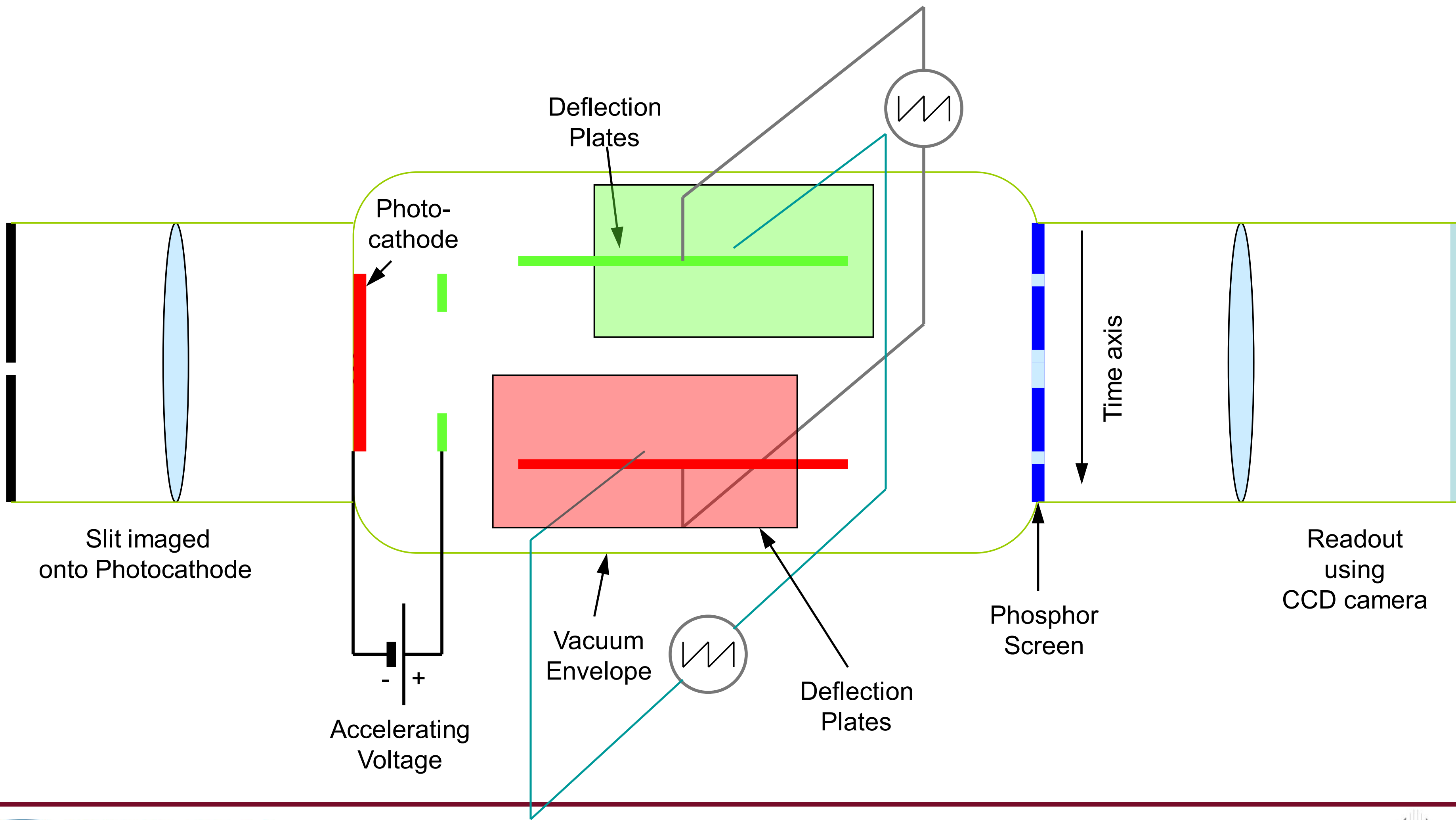
- Alternatives:
  - EO Techniques *(not today)*
  - RF measurements (deflectors/streak camera)
  - CTR measurements
  - CDR measurements *(future R&D)*

Bunch structure: Optical Lines



CTF3 Note 072

Long. Profile: Streak Camera

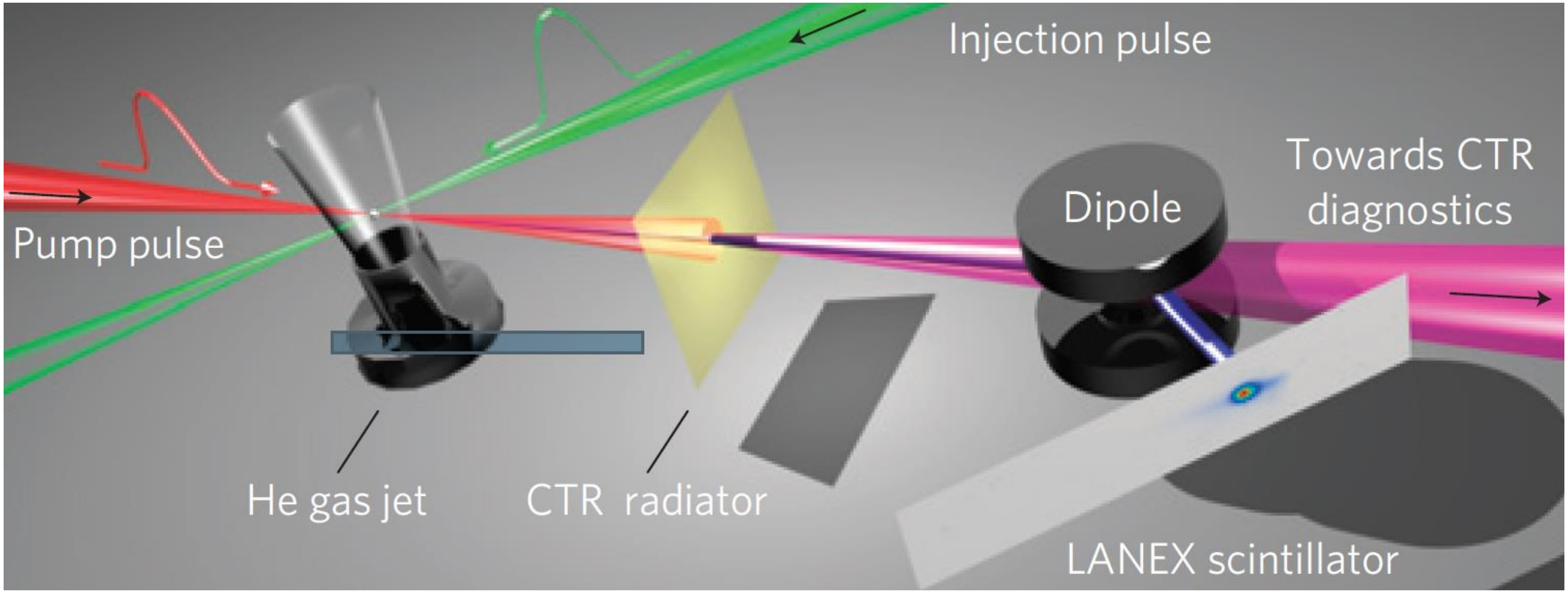


Used for…

- Monitoring of phase switch using sub-harmonic bunchers
- Monitoring of the RF bunch combination
- Monitoring of track length modification with a wiggler
- Bunch length measurements
- Similar principle: RF deflecting cavity !

J. of Instr. **1** P09002 (2006)
CLIC-Note 681

Bunch Length using CTR



- 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).

Transition Radiation

- Spectral radiation field at frequency ω and observation angle θ is:

$$\frac{d^2W}{d\omega d\Omega} = [N + \underbrace{N^2 F(\omega,\theta)}]\frac{d^2w}{d\omega d\Omega}$$

Dominates ? ➡ coherent

- Typically occurs if e^- bunch length < radiation wavelength λ.
- Form Factor *F* contains information on bunch shape !

Check: Is radiation really coherent ?

Coherent (?) Radiation

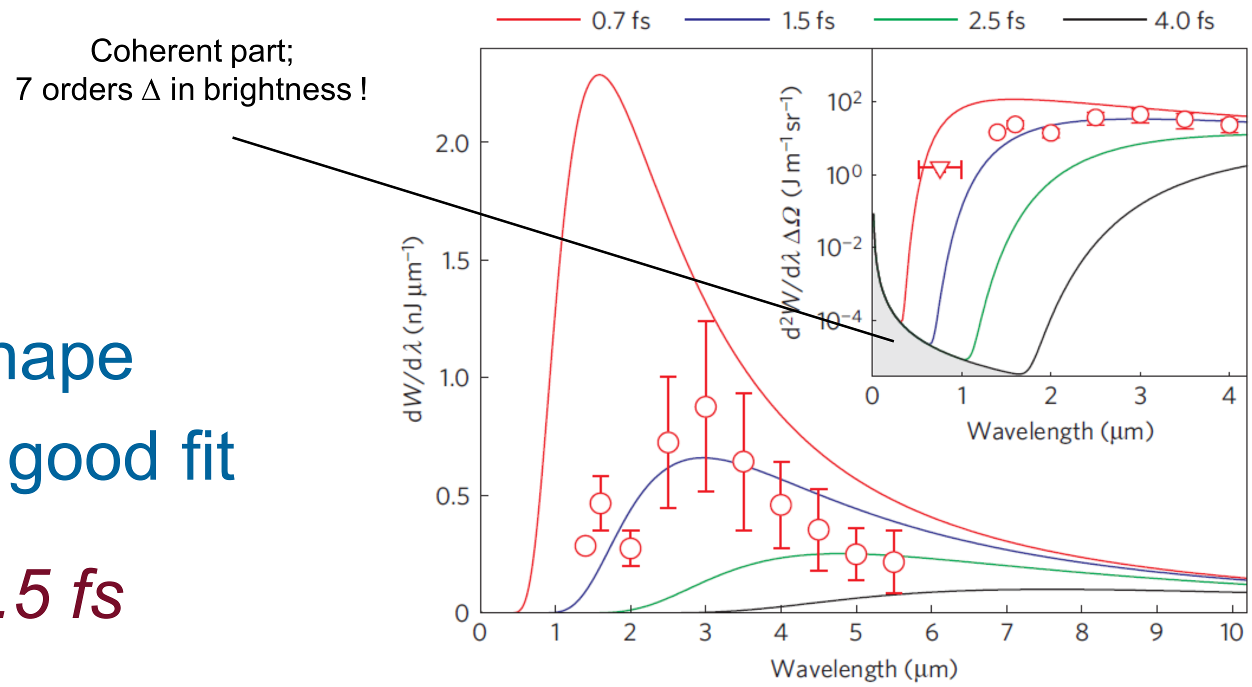
- Image spatial distribution on CCD
- Apply wavelength filter λ_0=546 nm, $\Delta\lambda$=10 nm.
- 17 mrad half-angle collection: $2 \cdot 10^7$ photons

$$\frac{d^2W}{d\omega d\Omega} = [N + N^2 F(\omega, \theta)] \frac{d^2w}{d\omega d\Omega}$$

- Integrating TR equation for 15 pC bunch charge yields: $5 \cdot 10^3$ photons.

CTR Spectrum: Measurement

- 1) Scanning Monochromator [1.4 - 5.5 μm], collection angle: 2 mrad.
- 2) Imaging Spectrometer [0.55 – 1.0 μm], collection angle: 17 mrad.



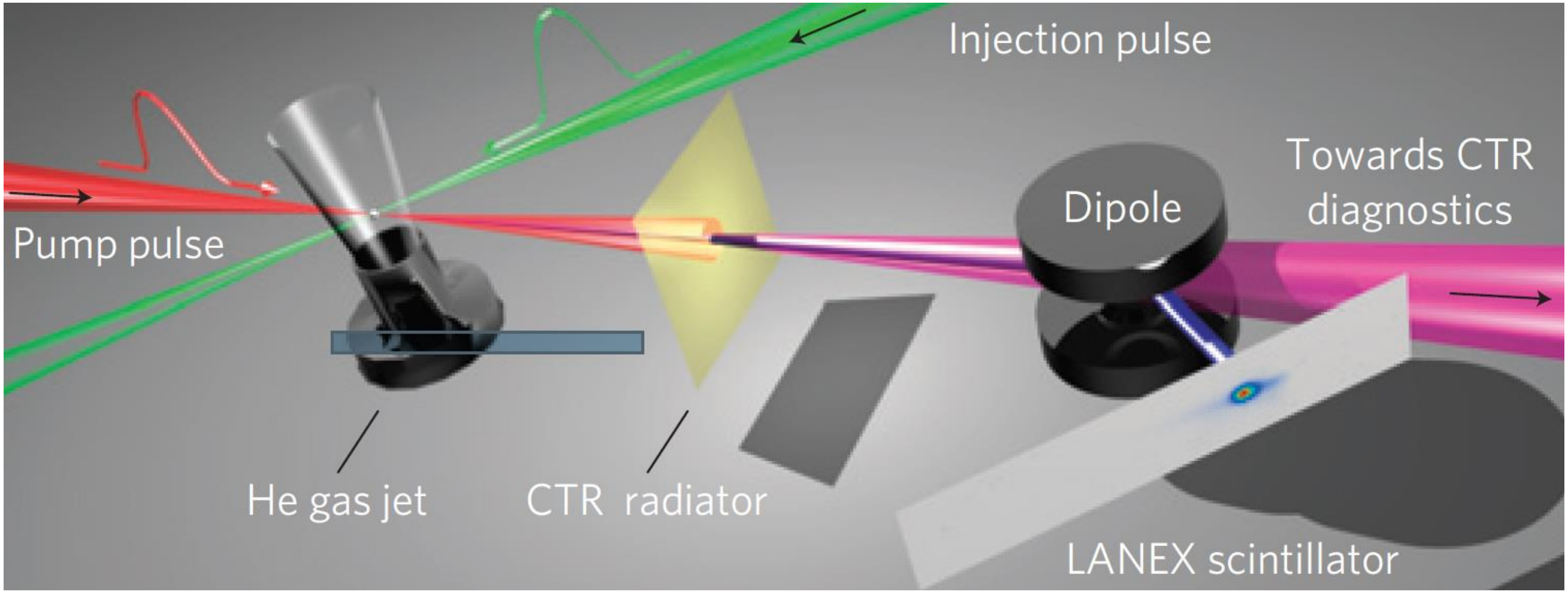
<u>Assumption</u>:

- Gaussian shape
- Vary σ, find good fit

➡ *σ = 1.5 fs*

Beam Energy Measurement

Energy measurement using magnets



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- 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).

Energy measurement - details

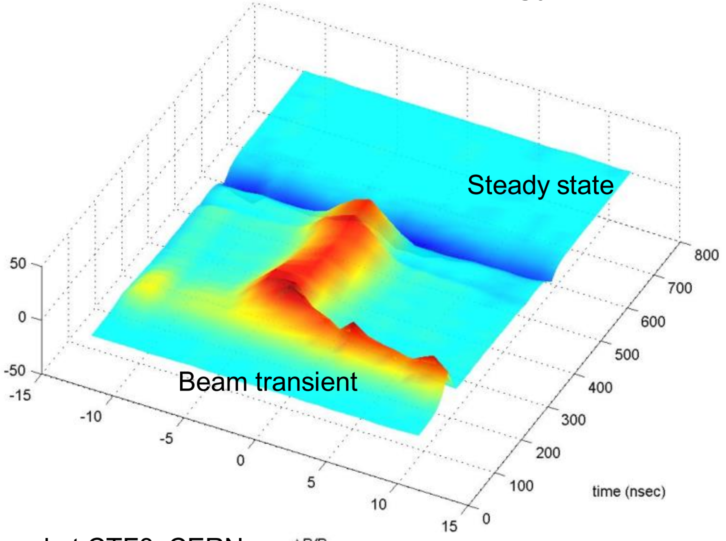
- 1.6 T dipole magnet, l=25 mm
- LANEX Phosphor screen
- Doublet lens images screen on 16 bit CCD

- Measure divergence with/without radiator

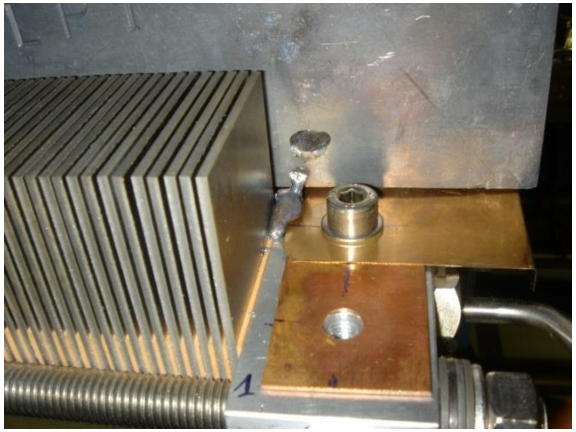
- Determine energy spread

Alternative: Segmented dump

<u>Time evolution of the beam energy spread</u>



Measured at CTF3, CERN.



Bandwidth limited (parasitic noise)

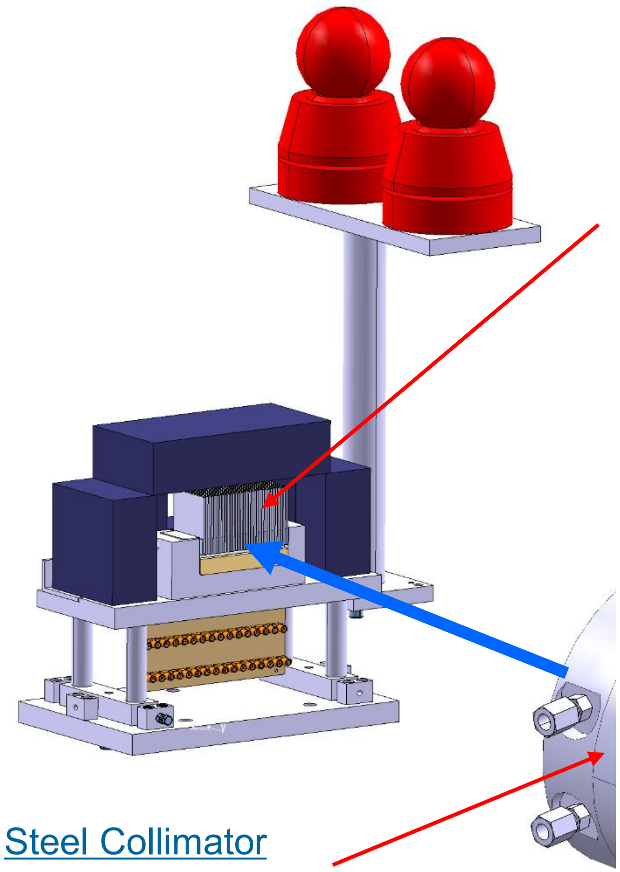
Destructive method (long term reliability)

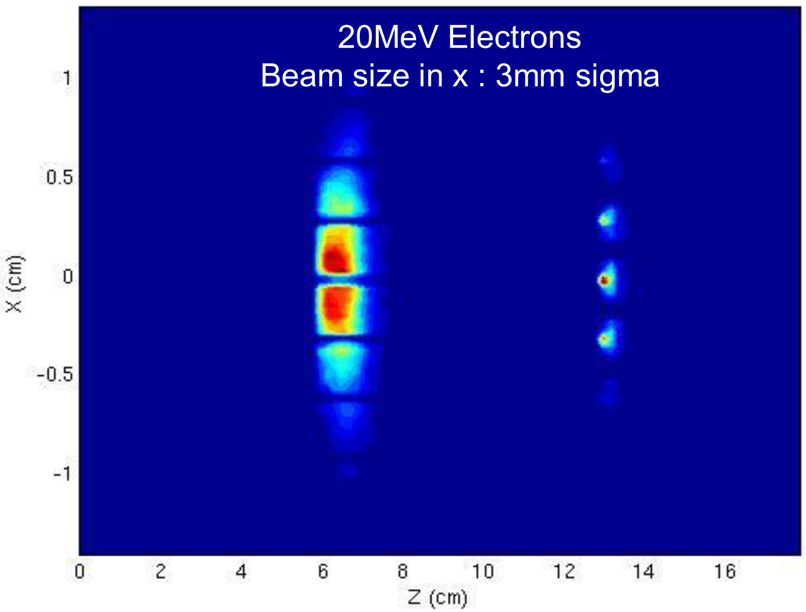
Non-radiation hard insulator

Segmented Dump

<u>Segmented DUMP</u>

- 32 Tungsten plates (2mm thick) spaced by ~ 1mm
- Alumina insulator (rad-hard)



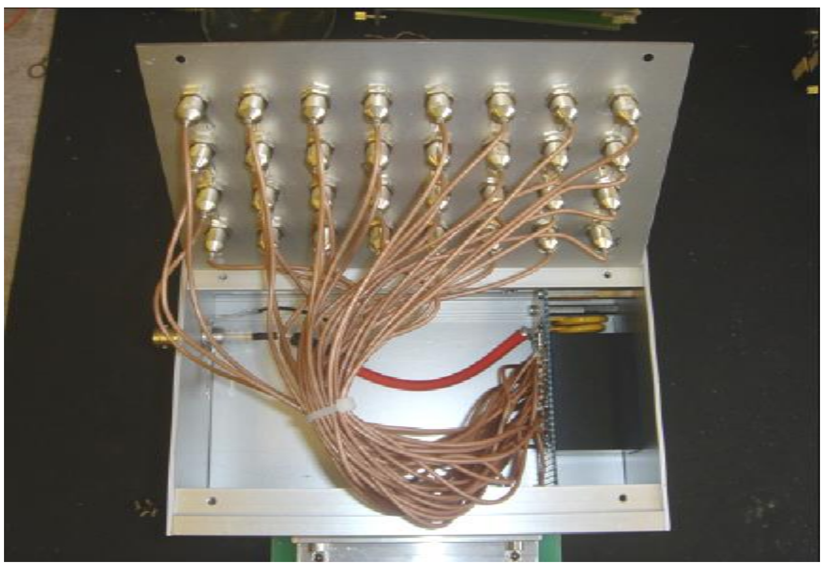


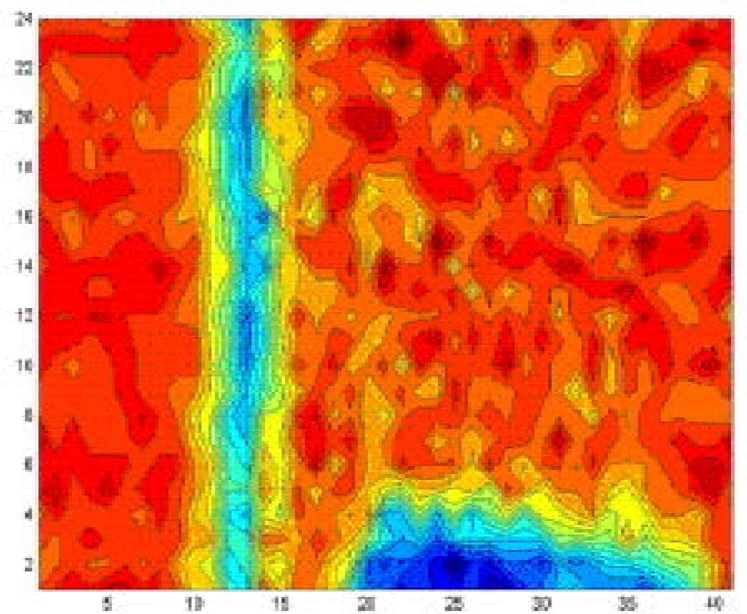
<u>Steel Collimator</u>

- Water cooled
- Mounted on the beam tube
- 32 vertical slits 400μm thick

Segmented PMT

- 32 channel PMT from Hamamatsu
- Observing OTR light from Al screen.
- Beam splitter: Camera PMT





Conclusion

- Without beam diagnostics...

  ...it is impossible to operate, let alone optimize any accelerator !

- Trend is towards non-invasive, online diagnostics
- High impact studies, relevant for many communities

Diagnostics R&D is key part of OMA, EuPRAXIA, EuroCirCol, AWAKE, HLLHC, etc. projects.

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