Particle Beam Diagnostics

Prof. Carsten P. Welsch

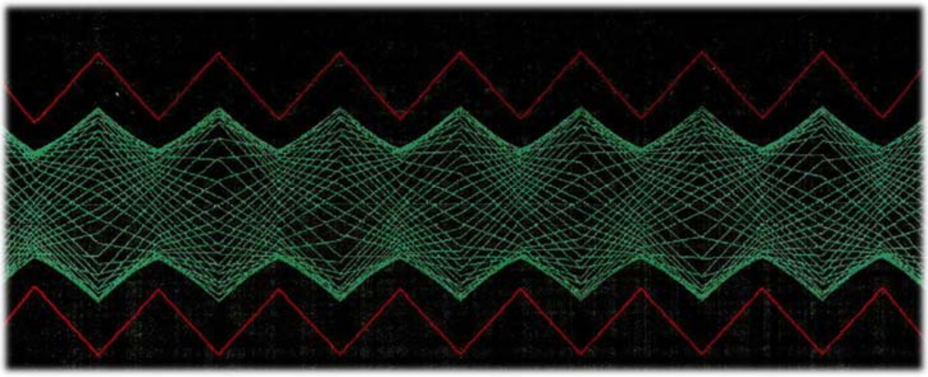
Overview

- Lecture 1 *(„the basics“)*
  - Transverse beam profile
  - Longitudinal beam profile
  - Beam position
  - Beam energy
- Lecture 2 *(„advanced topics“)*
  - Beam emittance
  - Beam halo
  - Non-invasive beam profile measurements

This school covers wide range of charged particle beams in terms if their time structure, profile, energy and other characteristics. Diagnostics suitable for essentially and particle beam will be presented and specific challenges in a *novel accelerators* context highlighted.

Emittance measurements

- Yesterday, we have talked about the beam profile or beam size.
- However, beam size changes as the 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:

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

Misleading, as *ΔE* and *x‘* can be very large in our case.

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

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

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

Attention !!

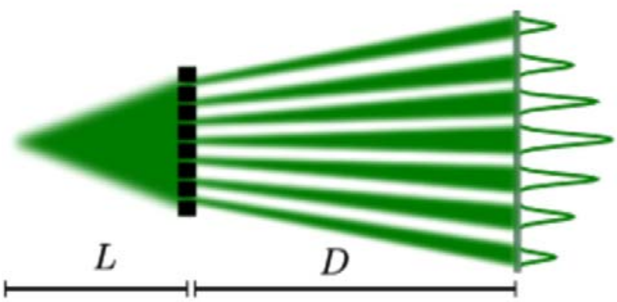
$$\varepsilon_n{}^2 = \langle\gamma\rangle^2 \sigma_E{}^2 \langle x^2\rangle\langle x'^2\rangle + \langle\beta\gamma\rangle^2(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2)$$

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

- Here: Focus on geometrical part.

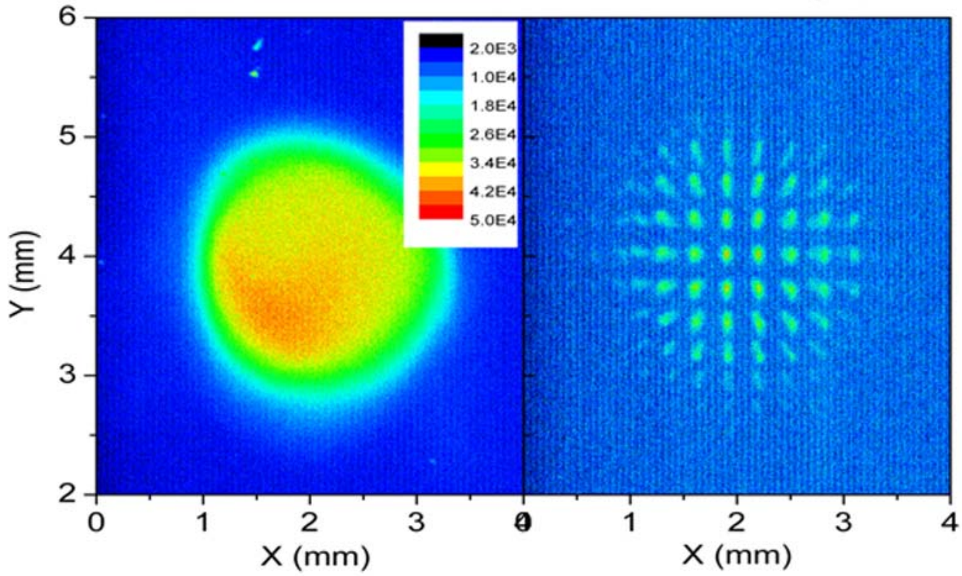
Emittance measurements

- 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.



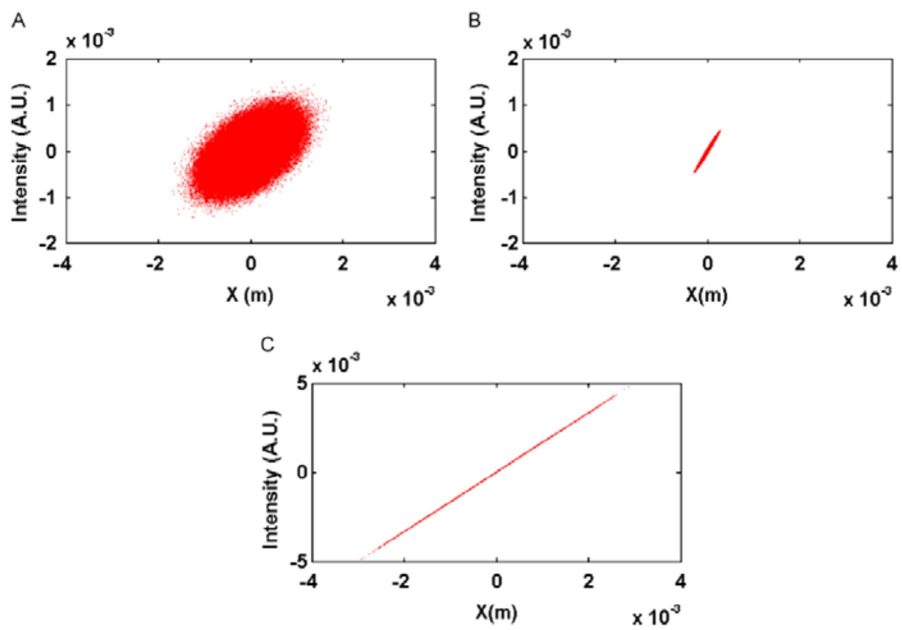
Emittance measurements

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



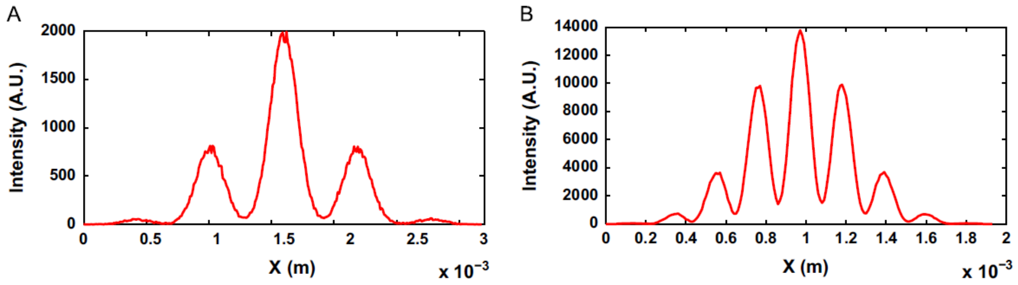
Pepperpot in Plasma Accelerators

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



Pepperpot in Plasma Accelerators

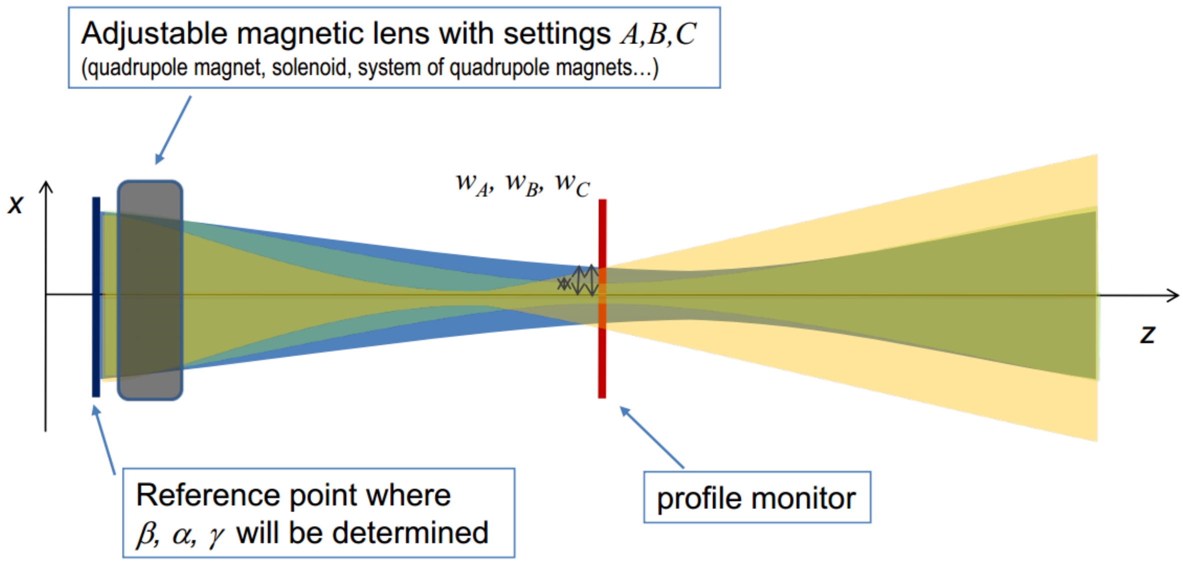
- Error estimation



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:

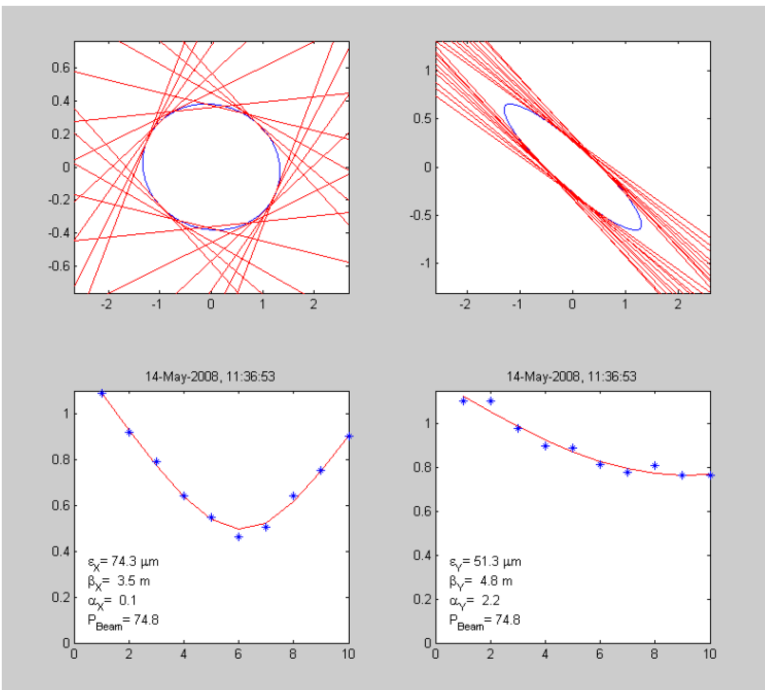
$$w_A^2 = c_A^2 \beta\,\varepsilon - 2c_A s_A\;\alpha\,\varepsilon + s_A^2\;\gamma\,\varepsilon$$
$$w_B^2 = c_B^2 \beta\,\varepsilon - 2c_B s_B\;\alpha\,\varepsilon + s_B^2\;\gamma\,\varepsilon$$
$$w_C^2 = c_C^2 \beta\,\varepsilon - 2c_C s_C\;\alpha\,\varepsilon + s_C^2\;\gamma\,\varepsilon$$

$\Downarrow$ 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

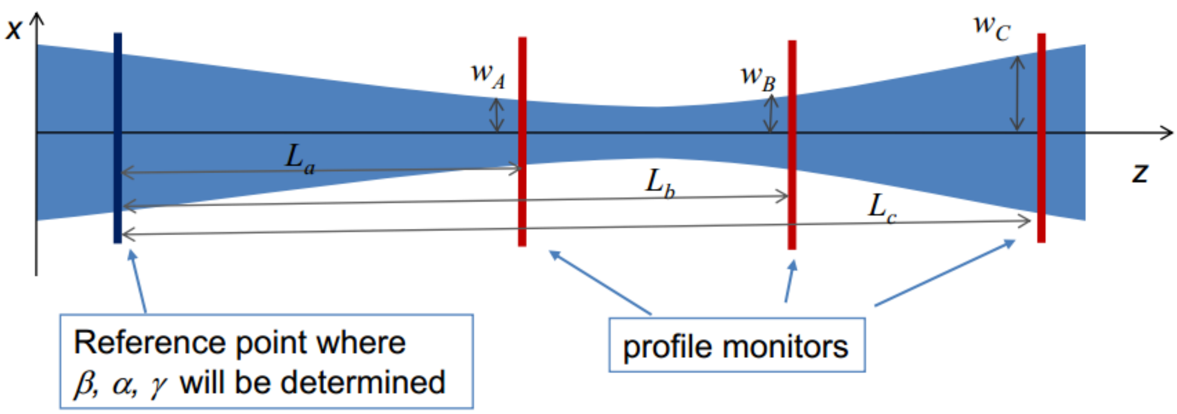
➡ Distance between quad – waist rather short.

- Can be an issue in actual experimental setup.

- However, good candidate.

Three Screen Method

- Determine α, β and γ and hence 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

Find TWISS parameters

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

$\Downarrow$ can be rewritten in Matrix notation

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

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

Challenges

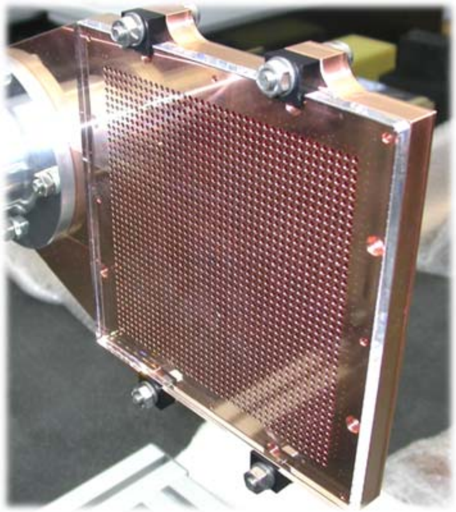
- Access to single shot measurements
- Requires thin foils
- Multiple scattering in foils needs to be carefully assessed

Limitation

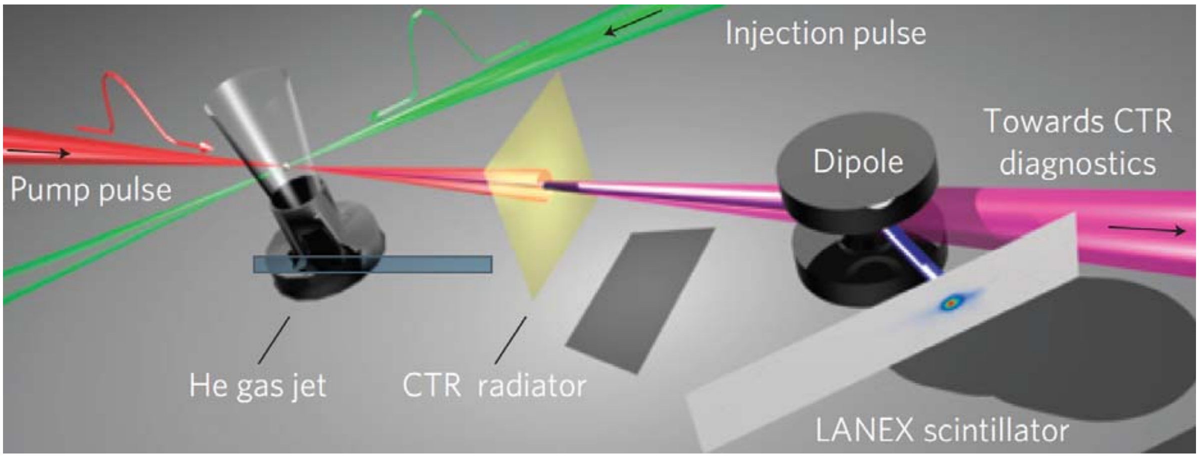
- Probably only suitable if beam energy > 1 GeV.

Pitfalls with Emittance Measurements

- Beam width determination
- Space charge
- Chromatic effects
- Calibration errors
- Scattering effects
- Is mask good enough to block the beam ?



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).

Diagnostics 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

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

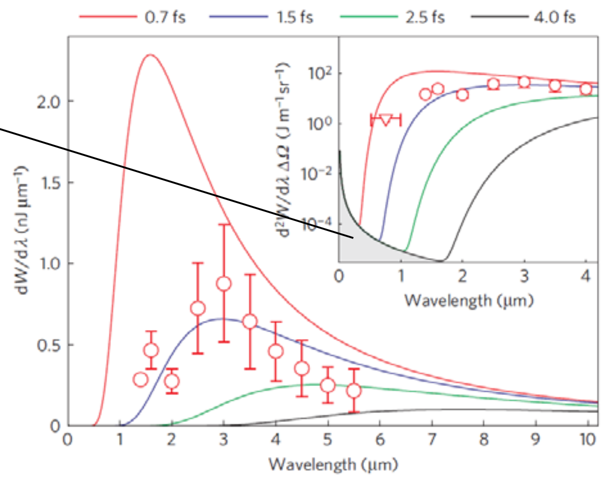
$$\frac{d^2W}{d\omega d\Omega} = [N + N^2 F(\omega,\theta)] \frac{d^2w}{d\omega d\Omega}$$

- 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.

Coherent part;
7 orders Δ in brightness !

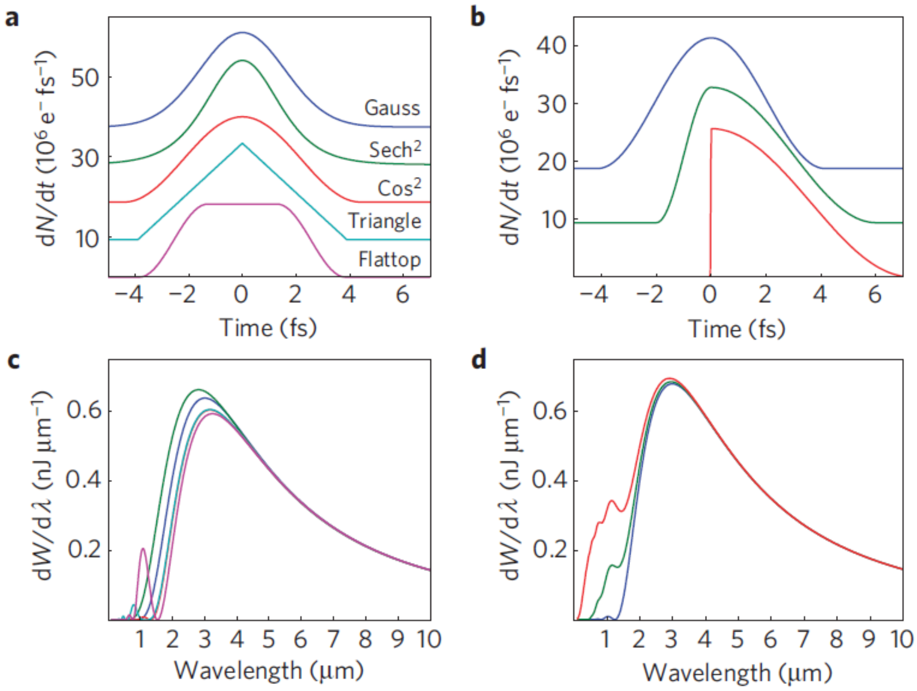


<u>Assumption</u>:

- Gaussian shape
- Vary σ, find good fit

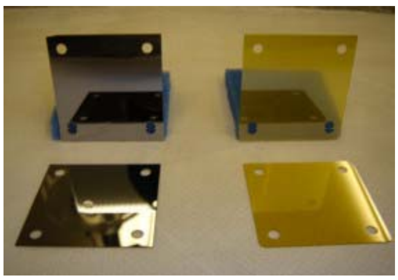
➡ *σ = 1.5 fs*

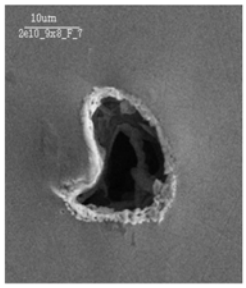
Impact of Bunch Shape ?

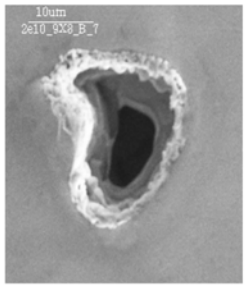


Screens and Wires

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

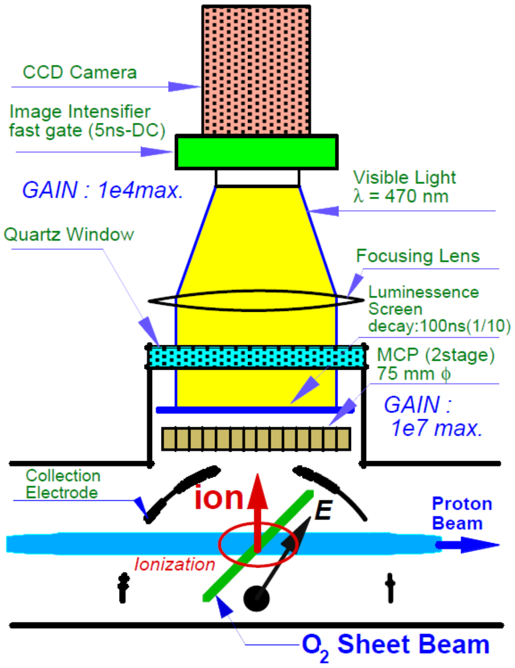






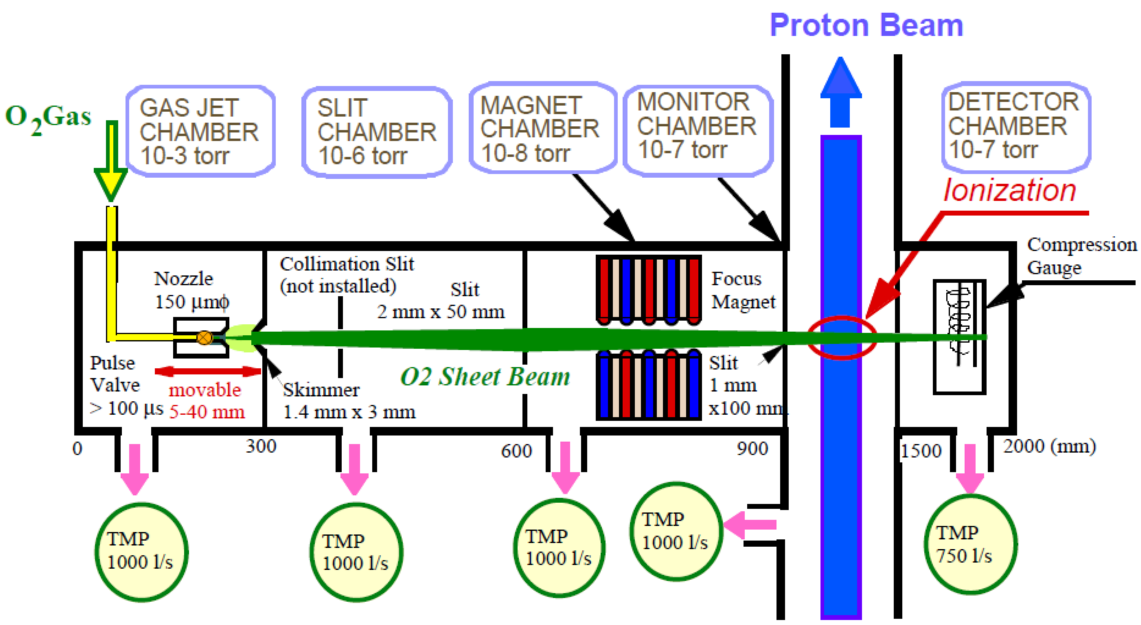
The idea: Gas Sheet Monitor

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



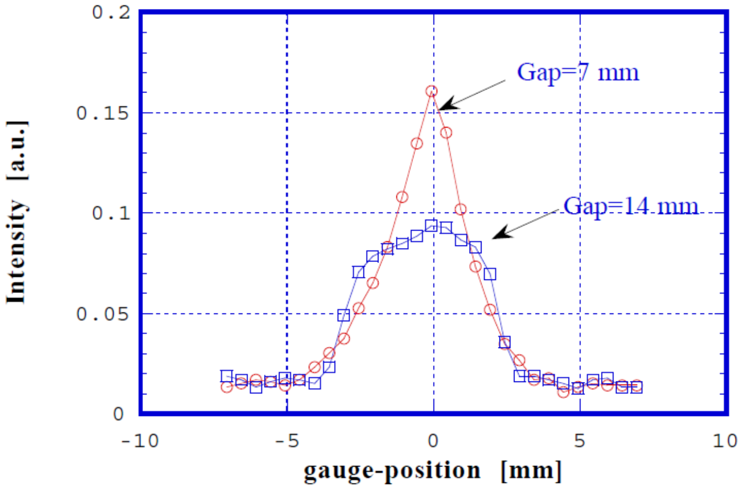
Y. Hashimoto et al., Proc. Part. Acc. Conf., Chicago (2001)

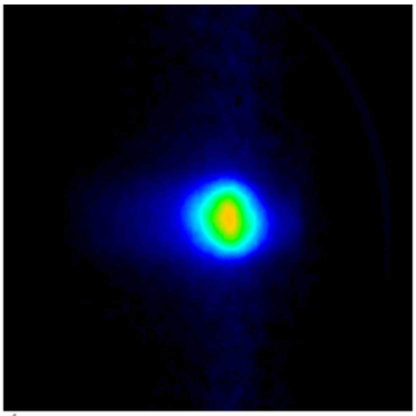
How to Generate the Jet ?

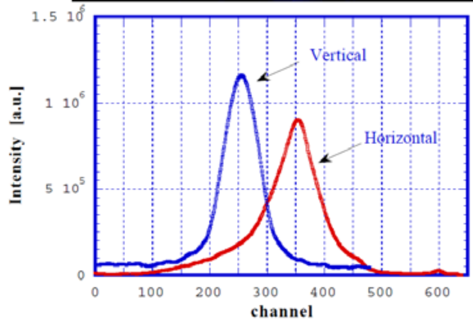


Y. Hashimoto et al., Proc. Part. Acc. Conf., Chicago (2001)

Experimental Data

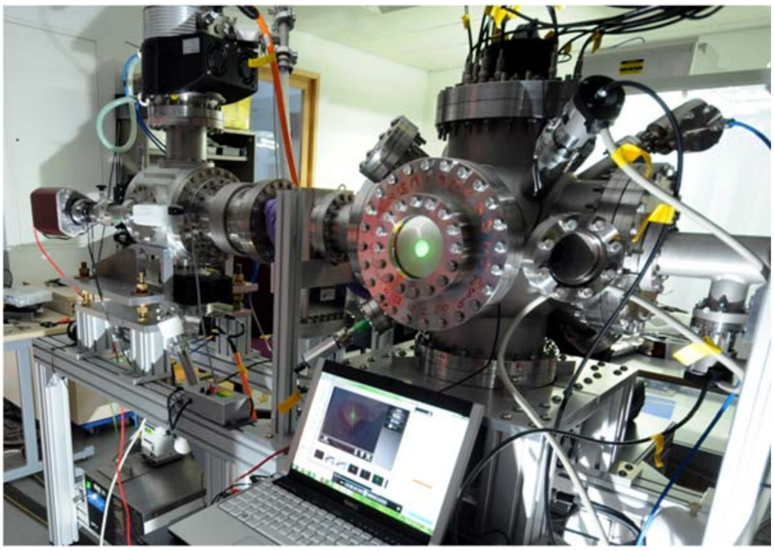






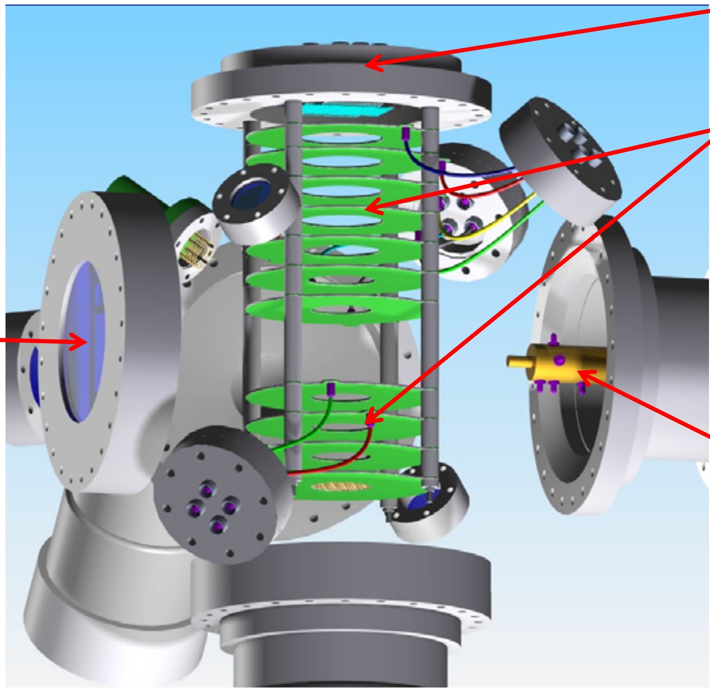
Y. Hashimoto et al., Proc. Part. Acc. Conf., Chicago (2001)

Curtain Gas Jet Monitor



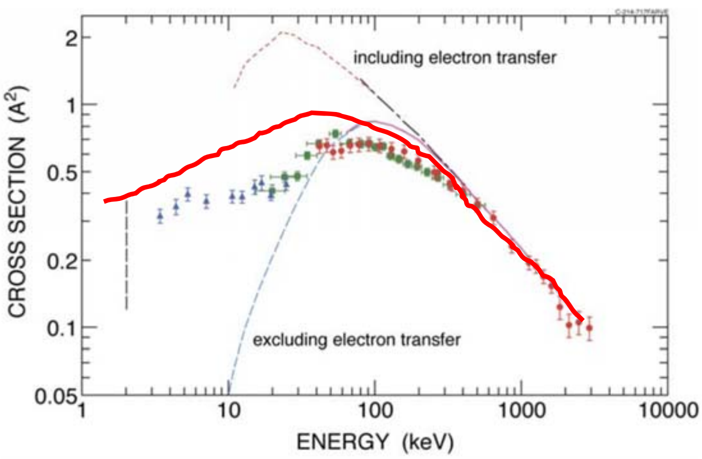
M. Putignano
PhD thesis, Liverpool (2012)

Zoom: Main chamber



Ionization Cross Sections

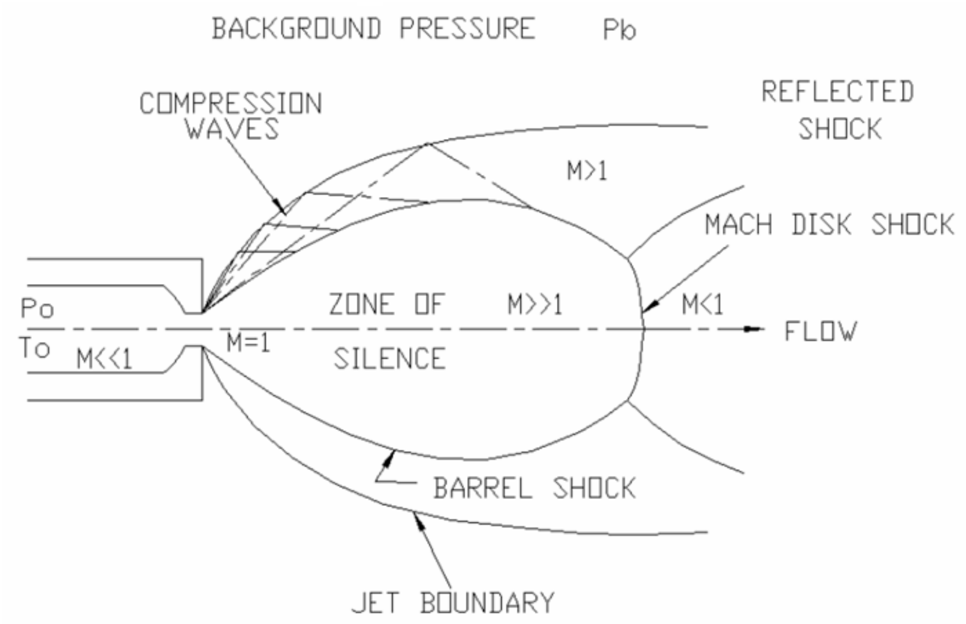
- Can be exotic, e.g. single ionization of helium by antiproton impact



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

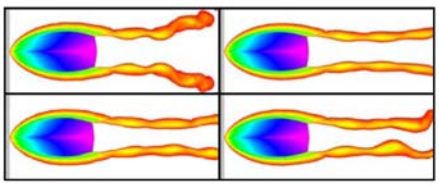
H. Knudsen, Hyperfine Interactions **109** (1997) 133–143
H. Knudsen, Journal of Physics:Conf. Series **194** (2009) 012040

Jet Generation

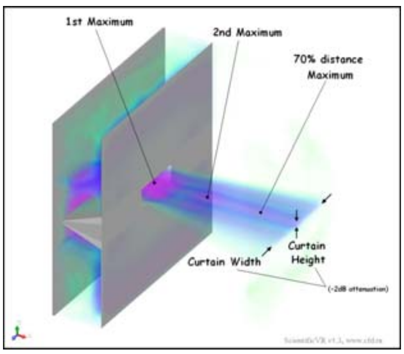


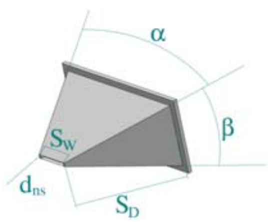
Y. Hashimoto et al., Proc. Asian Part. Acc. Conf., Beijing (2001)

Numerical Investigations with GDT



- System optimization and trends analysis



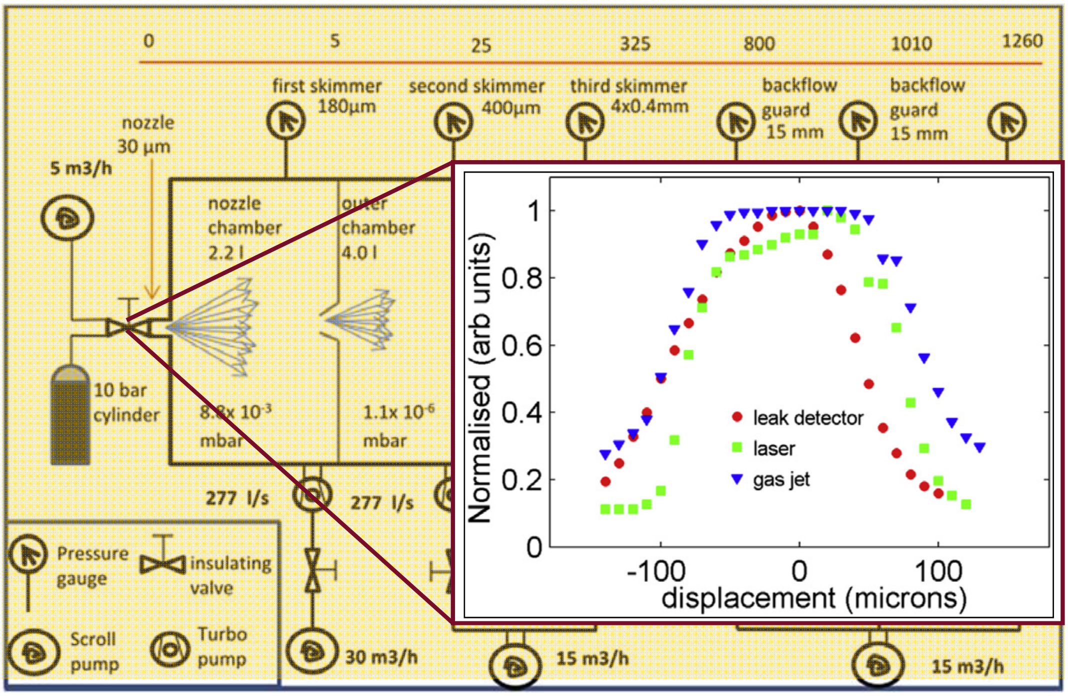


	Mach N.	D	W
α	↘	↘	↗
β	↘		→
SW	↘	↘	↗
SD	α		
Dist		α, β	α, β

M. Putignano et al.,
Nucl. Instr. Meth. A 667 (2012)

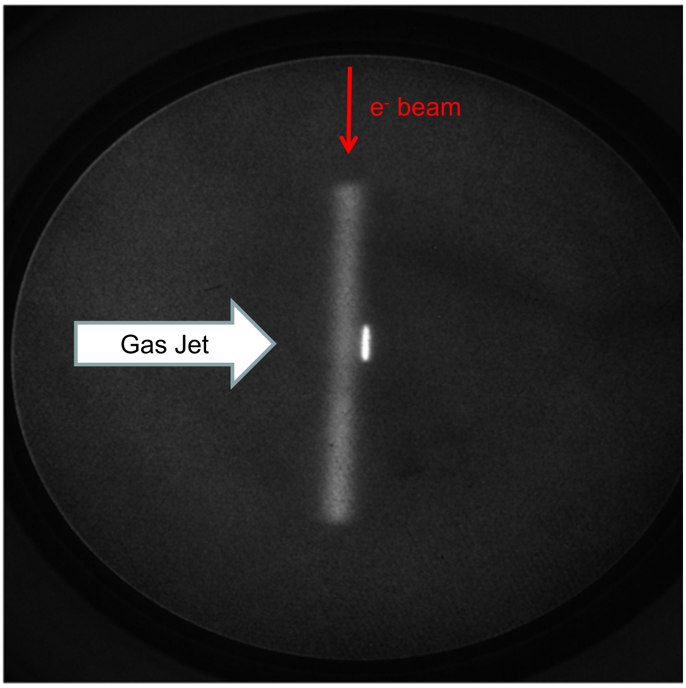
Challenge: Laser probing via self-mixing

Alignment and Vacuum Issues



V. Tzoganis, et al., Vacuum **109** ((2014)

Initial Results



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

Gas Jet Scanner

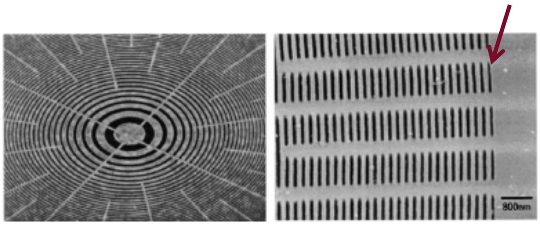
- Generate a thin pencil jet and scan it through the beam
- Like a wire scanner but non-interceptive
- Still collect ions but position not important: not affected by space charge
- Slow scan through halo region, fast through main beam

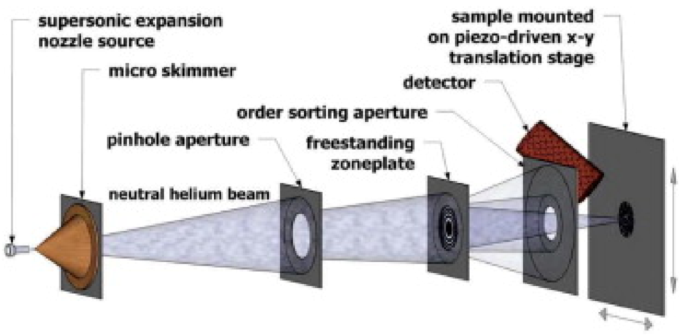
- Problem: needs a thin jet !

Matter-wave focusing

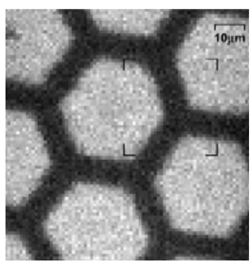
- Aim: Create a thin jet

Smallest zone 100 nm





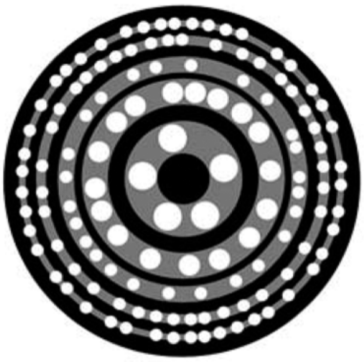
FWHM at focus 2µm !



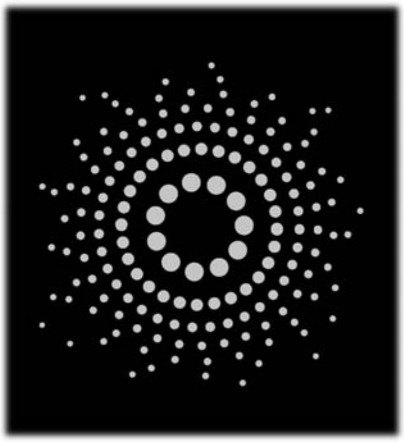
T. Reisinger, et al. Microelectronic Engineering **87** (2010)

Photon Sieve

Replaces clear zones of an FZP with a series of holes



+ Sharper focusing
+ Easier to manufacture
- Lower transmission



Apodized Photon Sieve reduces higher order diffraction, increases central maximum

A. Jeff

L. Kipp et al, Nature **414** (2001)

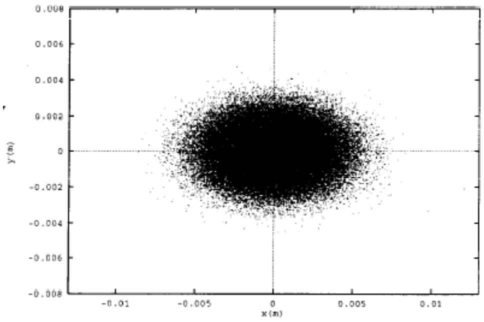
Definition: What is 'Halo' ?

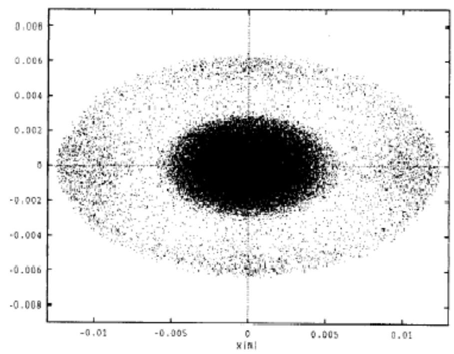
<u>General definition difficult to make:</u>

Accelerator physicists

Instrumentation specialists

Low density / difficult to measure



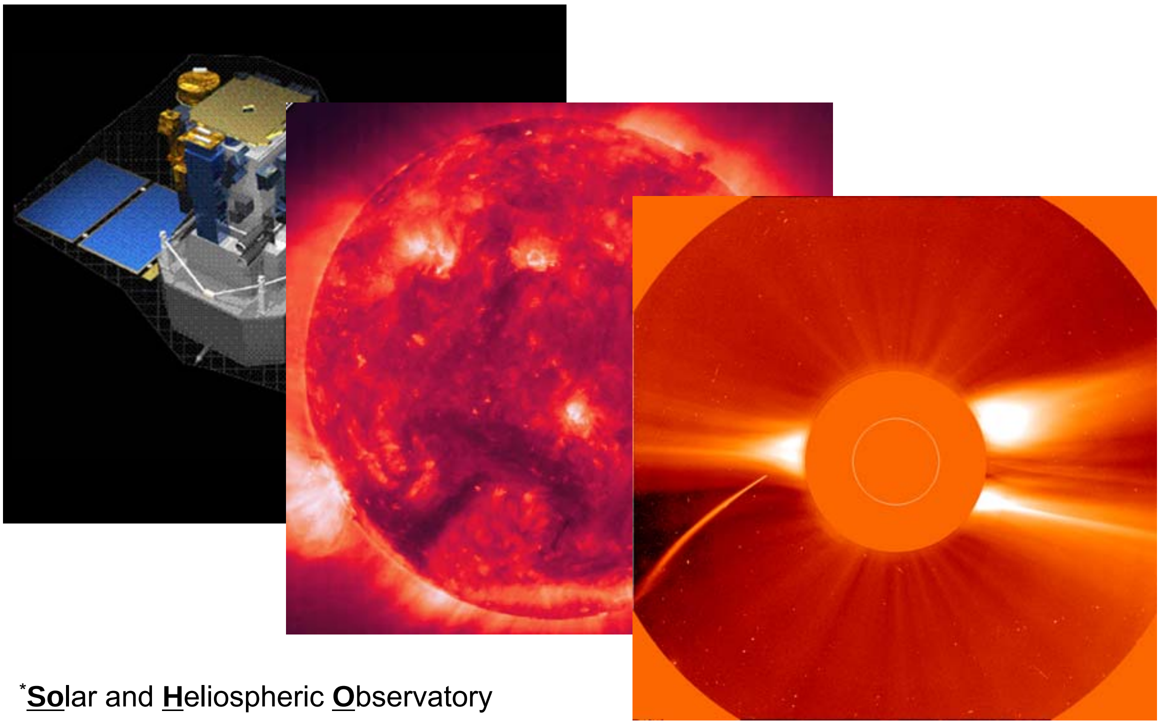


Problem

- 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 !

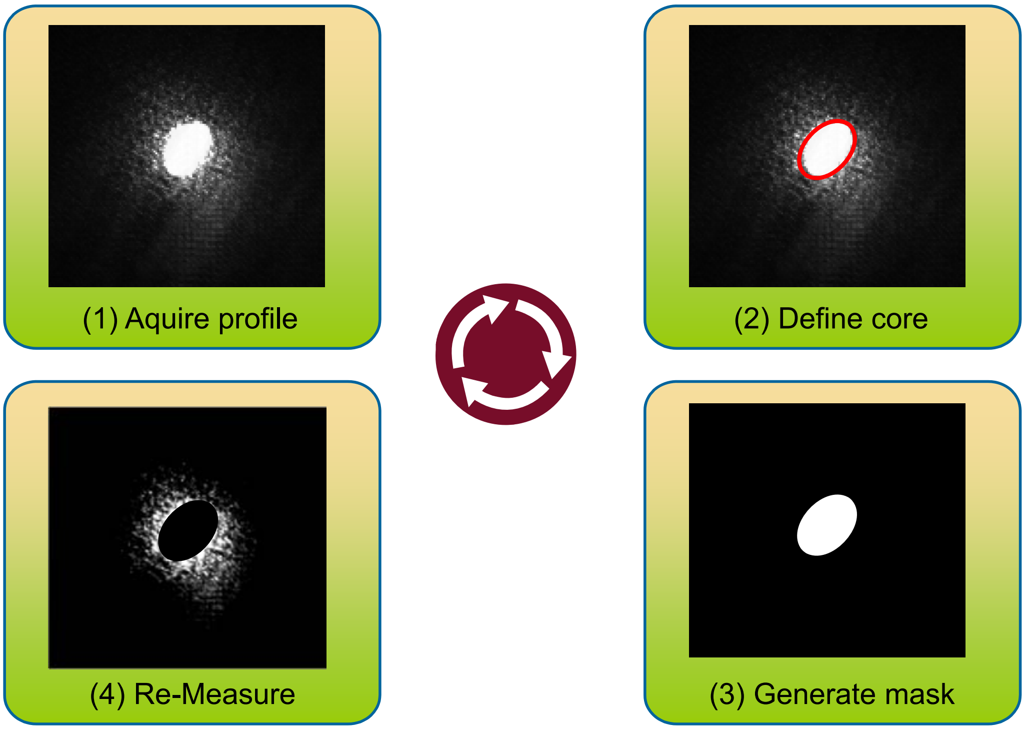
- How ??

SOHO



*__So__lar and __H__eliospheric __O__bservatory

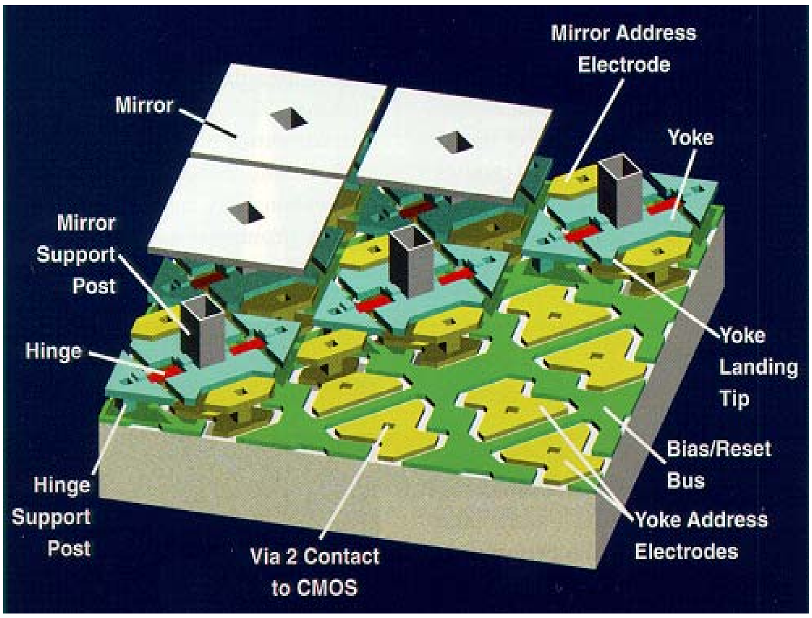
Halo Monitoring: Core Masking

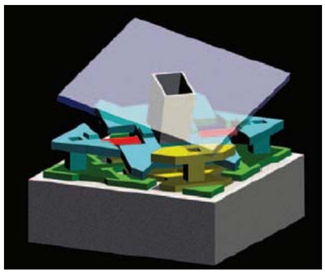


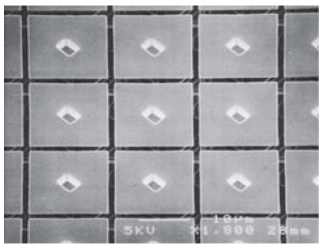
C.P. Welsch et al.,
Proc. SPIE (2007)

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

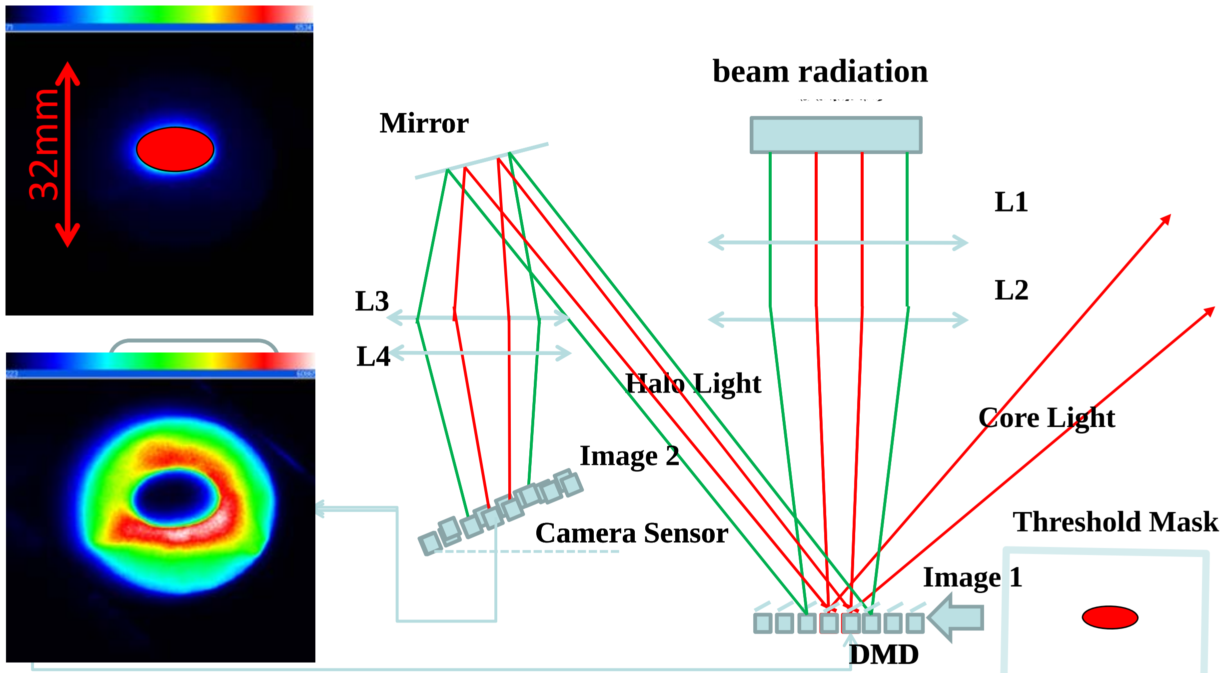
Basis: Micro Mirror Array (TI)





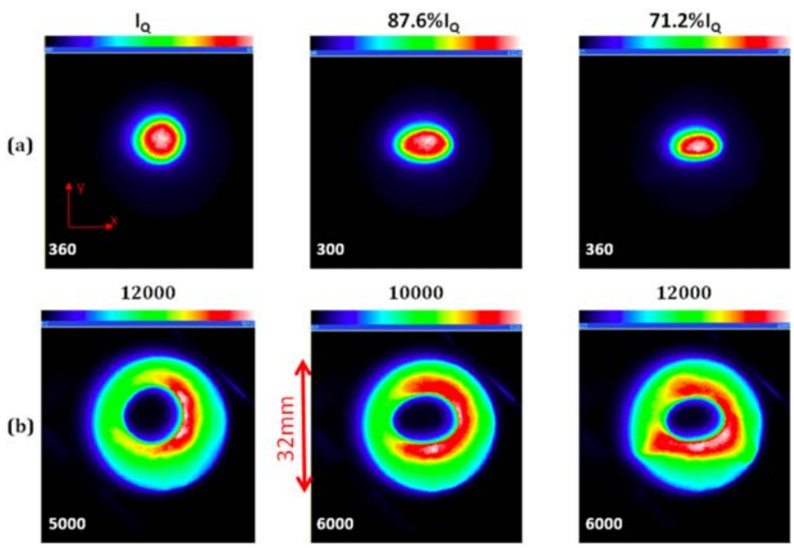


Overview: Imaging System



R. Fiorito, H. Zhang, et. al. Proc. BIW10

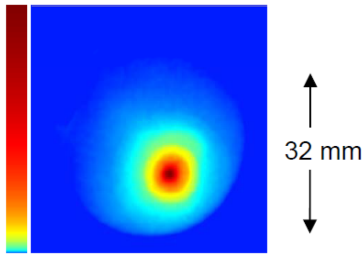
Masking at UMER (10 keV e⁻)



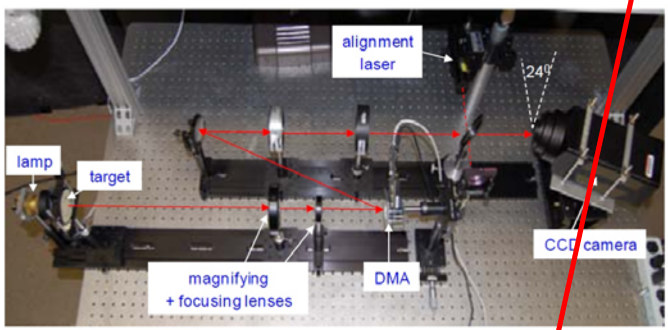
H. Zhang, et al.,
Phys. Rev. STAB 15, 072803 (2012)

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 DMD are minimal



!!

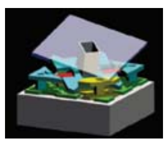


H. Zhang, et al.,
Phys. Rev. STAB 15, 072803 (2012)

Advantages

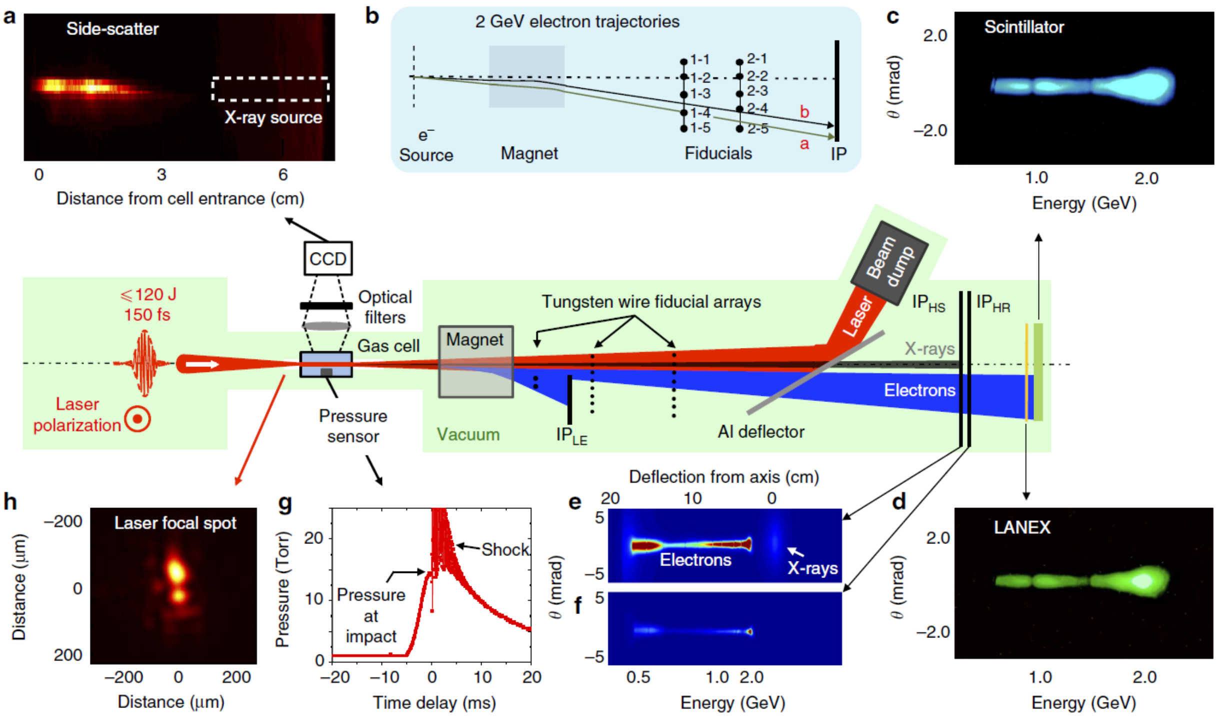
- Can be used with <u>any</u> raditiation (OTR, ODR, SR, Smith-Purcell, Cherenkov, etc.);
- Suitable for <u>any</u> charged particle beam;
- Advanced measurements possible: XDR, emittance, phase space mapping, injection optimization, etc.
- Significant achievements, more to come

- Problem: Needs minimum light intensity



Example Diagnostics

X. Wang, et al.,
Nature Communications(2013)



Summary

- Combined techniques give detailed insight into plasma and electron bunch evolution;
- A number of challenges due to specific beam characteristics and ‚noisy' environment (e.g. ICT);
- DLAs will require miniature-diagnostics, also embedded on-a-chip: New challenge !

Exciting field – still a lot to be done !