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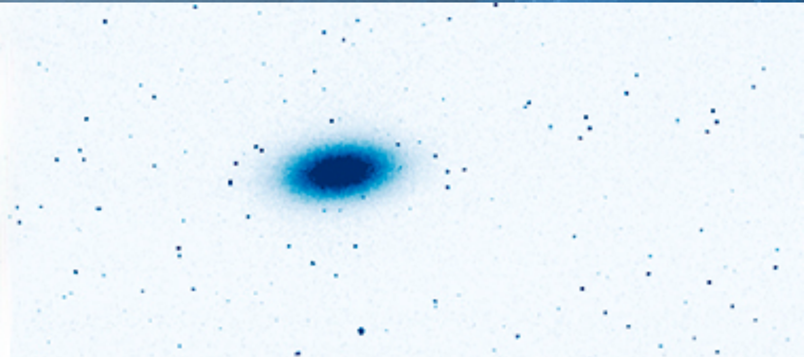
Nicolas Delerue, LAL (CNRS and Univ. Paris-Sud)

Single shot emittance measurement at 3 GeV using pepper-pots and OTR screens.

Alba, January 2018



Motivation

- Laser-driven plasma accelerator produce high energy beams that are significantly unstable.
- The transverse emittance must be measured in a single shot.
- Two different techniques were investigated:
  - High energy pepper-pots
  - Single shot OTR measurement
- Work done in collaboration with Riccardo Bartolini (DLS) and Cyrille Thomas (DLS, now at ESS).

Motivations (2)

- From this morning's introduction

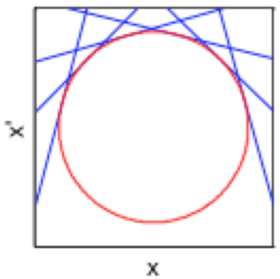
Optics-based emittance measureme

$$\begin{cases} \langle x^2 \rangle = R_{11}^2 \cdot \langle x^2 \rangle_{s_0} + R_{12}^2 \cdot \langle x'^2 \rangle_{s_0} + 2R_{11}R_{12} \cdot \langle xx' \rangle_{s_0} \\ \langle y^2 \rangle = R_{33}^2 \cdot \langle y^2 \rangle_{s_0} + R_{34}^2 \cdot \langle y'^2 \rangle_{s_0} + 2R_{33}R_{34} \cdot \langle yy' \rangle_{s_0} \\ \langle xy \rangle = R_{11}R_{33} \langle xy \rangle_{s_0} + R_{12}R_{33} \cdot \langle x'y \rangle_{s_0} + R_{11}R_{34} \cdot \langle xy' \rangle_{s_0} + R_{12}R_{34} \end{cases}$$

What w measu

What we v reconstru

- At least 3 (4) transformations are needed for 2D (4D) parameters, but more measurements improve the robustness of the reconstruction
- The best 2D reconstruction is when the phase-advance is covered regularly between 0 and π
- There are 2 general strategies to scan the phase advance: fixed optics and variable position (FODO), fixed position and variable optics (quadrupole scans).



Alternatives:

- OTR screens can be used to measure the beam size and divergence at the same time. In a beam waist, this is sufficient to obtain the emittance. *[F. Bisesto et al, JP 874, 012035, 2017]*
- Pepperpot at high energies *[C. Thomas et al, NIMA 729, 554, 2013]*
- Others?

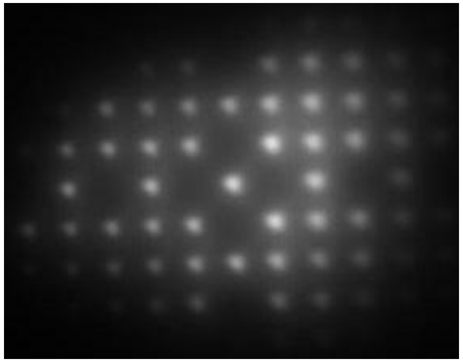
Future challenges

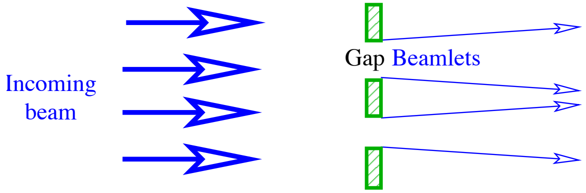
- **Ideal profile monitor** (best from screen + best from WS)
  - Can measure charges from 1 pC to 1 nC
  - Resolution down to 1 µm
  - Non-invasive
  - Fast
  - Can obtain 2D information
- **Time-resolved measurements:**
  - Demonstrate slice emittance measurements with fs resolution
  - TDS with variable polarization to streak in both planes (X-band collaboration project going on between CERN, DESY and PSI)
  - Develop better (non-invasive) streaking methods to reach sub-fs resolution
- **Single-shot emittance measurements?**

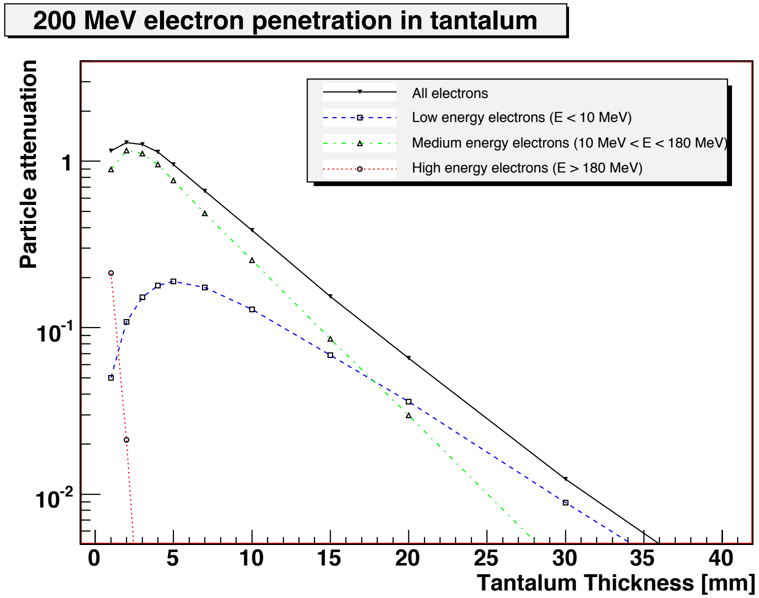
From Eduard's Prat talk this morning.

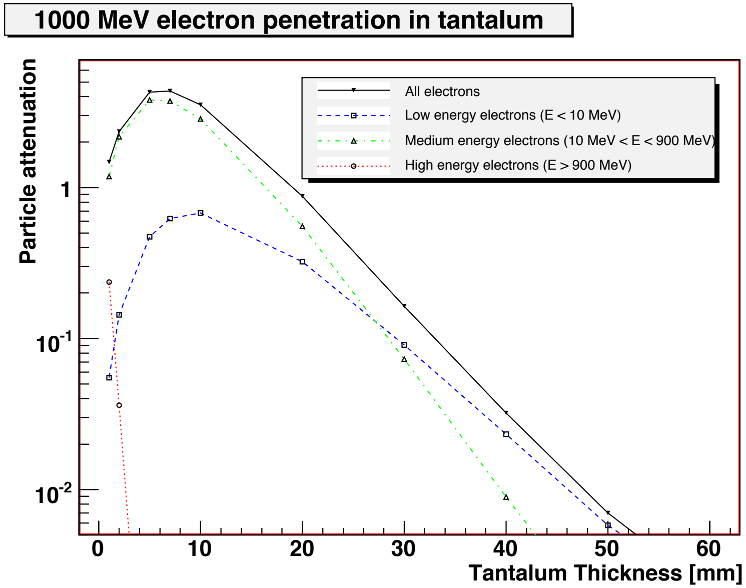
Pepper-pots at high energy

- Pepper-pots are commonly used to measure the transverse emittance of low energy beams.
- However at high energy the beam may go through the plate unaltered or even regenerate the beam!



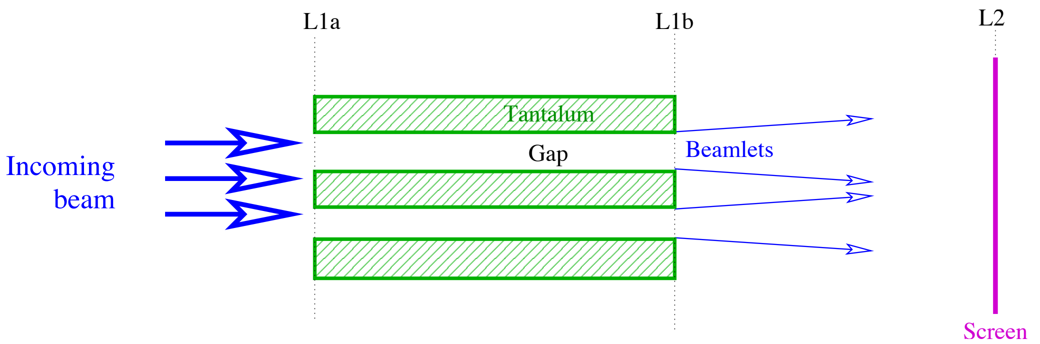


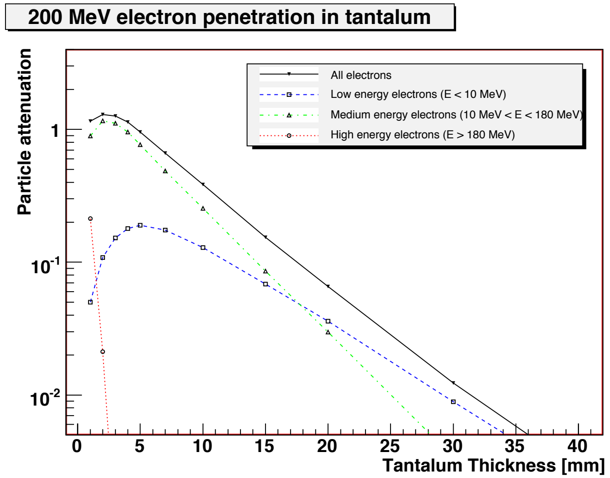


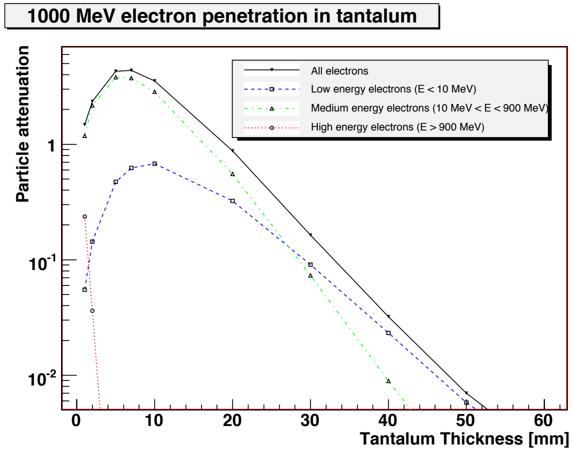


Extended pepper-pots

- To avoid this one can use an “extended” pepper-pot made of thick material (Tungsten, Tantalum,…) to absorb the beam.
- The length then depend on the energy and on the charge.





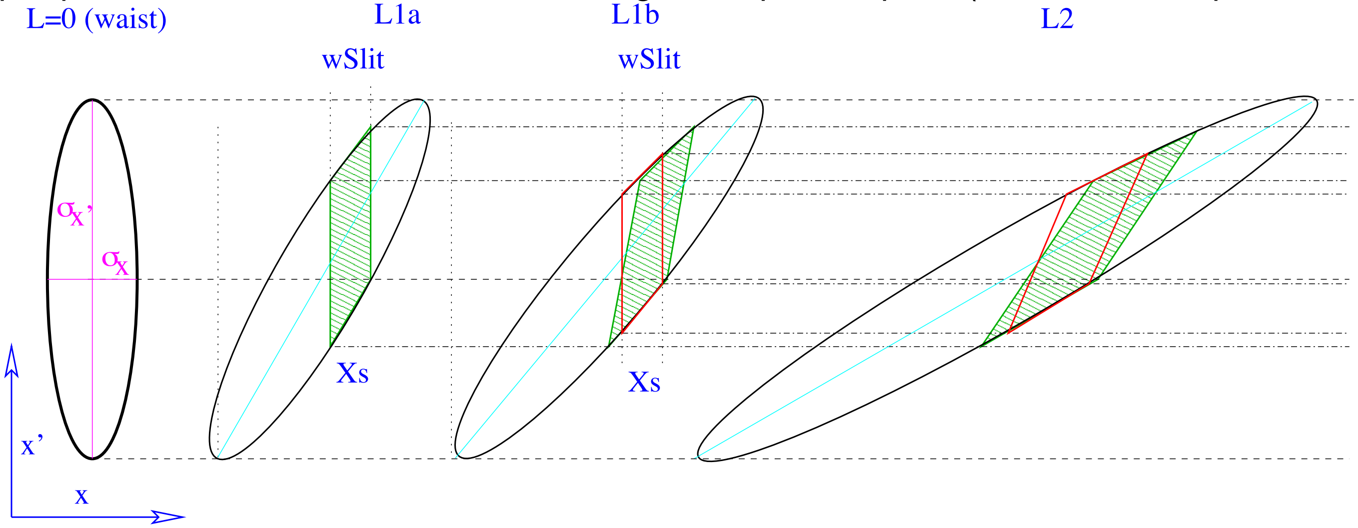


Extended pepper-pots (2)

- The pepper-pot will trim the beam at the slits.
- However, while the beam travel in the pepper-pots length, its ellipse shears.
- So the phase space sampled at the entrance and the exit are not exactly the same.
- The measurement is slightly modified to take into account an extra contribution from the slit depth:

$$C_{sw} = \frac{w_{slit} L_2}{2\sigma_x (L_2 - L_1) + w_{slit} L_2} = \frac{w_{slit}}{2\sigma_x \left(1 - \frac{L_1}{L_2}\right) + w_{slit}}$$

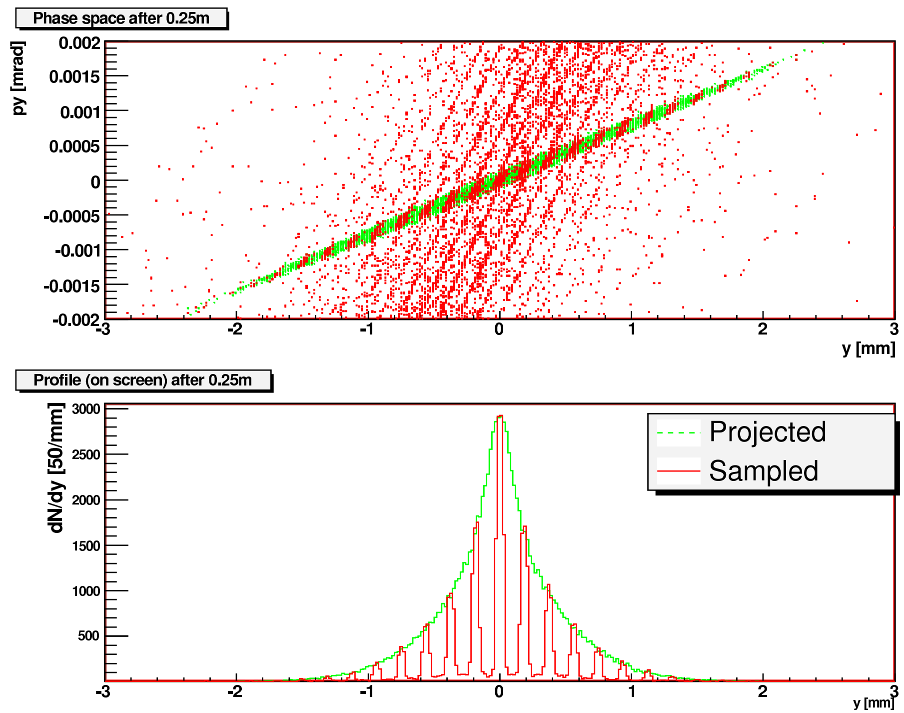
- Pepper-pot also allow to measure the shearing of the phase space (distance to the previous waist).



Single Shot Transverse Emittance Measurement of multi-MeV Electron Beams Using a Long Pepper-Pot. *Nucl. Instrum. Meth.*, A644:1–10, 2011.

Extended pepper-pots (3)

- The calculations have been confirmed with Geant4 simulations.

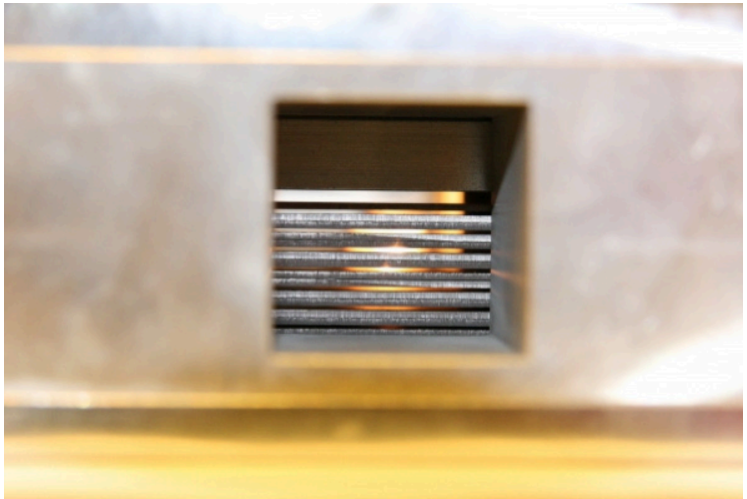


Single Shot Transverse Emittance Measurement of multi-MeV Electron Beams Using a Long Pepper-Pot. *Nucl. Instrum. Meth.*, A644:1–10, 2011.

Prototype

- Next step was the experimental verification.
- We could not get such structure machined as the slits were too deep and too thin.
- The prototype was built using tantalum plates separated by shims.

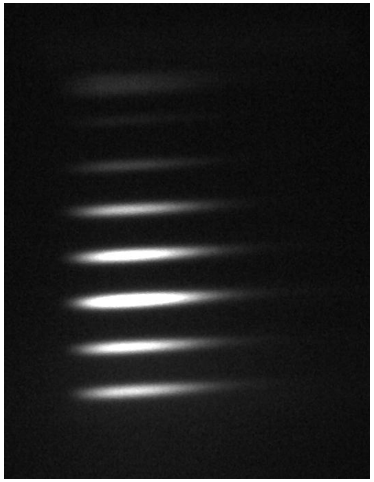
Layer	Material	Thickness
1	Aluminium	$1 \times 10\,\text{mm}$
2	Gap (Al shims)	$1 \times 1\,\text{mm}$
3	Gap (steel shims)	$5 \times 100\,\mu\text{m}$
4	Tantalum	$1 \times 1\,\text{mm}$
5	Gap (steel shims)	$5 \times 100\,\mu\text{m}$
6	Tantalum	$2 \times 1\,\text{mm}$
7	Gap (steel shims)	$5 \times 100\,\mu\text{m}$
8	Tantalum	$2 \times 1\,\text{mm}$
9	Gap (steel shims)	$5 \times 100\,\mu\text{m}$
10	Tantalum	$2 \times 1\,\text{mm}$
11	Gap (steel shims)	$5 \times 100\,\mu\text{m}$
12	Tantalum	$2 \times 1\,\text{mm}$
13	Gap (steel shims)	$5 \times 100\,\mu\text{m}$
14	Tantalum	$2 \times 1\,\text{mm}$
15	Gap (steel shims)	$5 \times 100\,\mu\text{m}$
16	Tantalum	$2 \times 1\,\text{mm}$
17	Gap (steel shims)	$5 \times 100\,\mu\text{m}$
18	Tantalum	$2 \times 1\,\text{mm}$

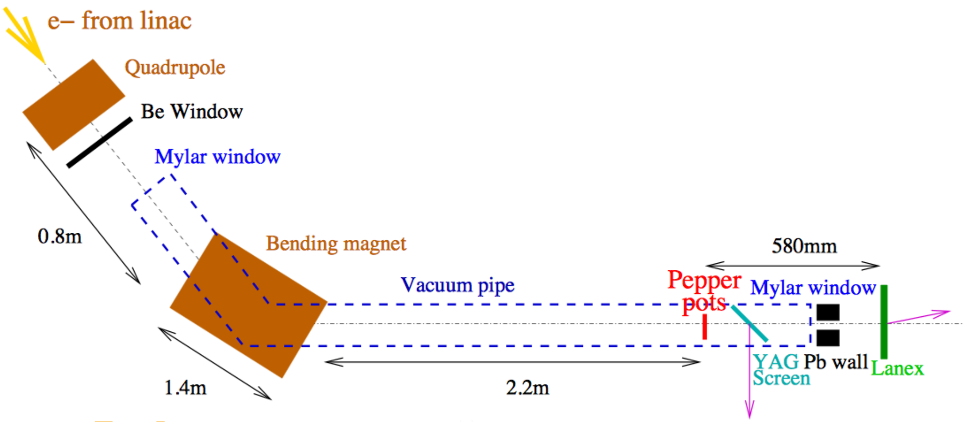


Can we use nanofabrication like at SwissFEL?

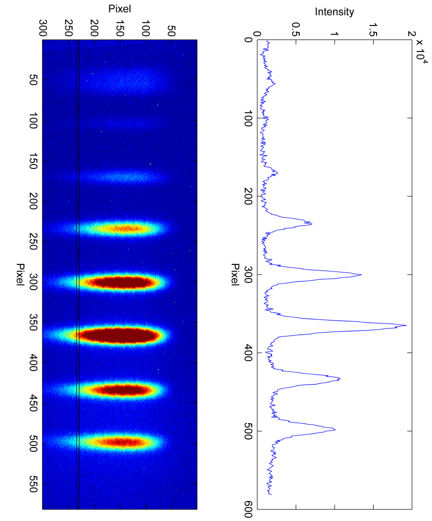
Tests at Frascati's BTF

- To test the prototype we got beam time at at the Daphne Beam Test Facilty at Frascati.
- The beam had an energy of 508MeV and a charge of 500pC electron beam.
- We reconstructed a transverse emittance of 4.mm.mrad, compatible with the expectations.
- Using the shearing of the transverse emittance ellipse we were also able to accurately reconstruct the position of the previous waist.



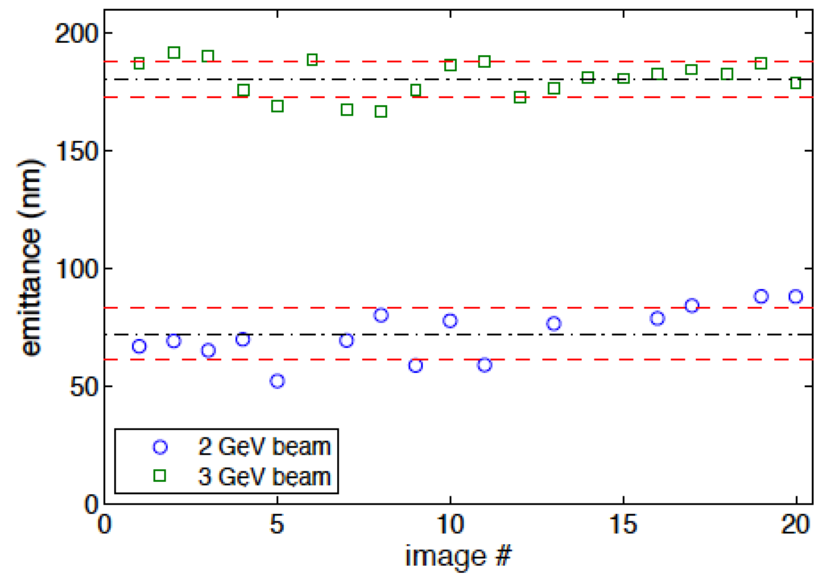


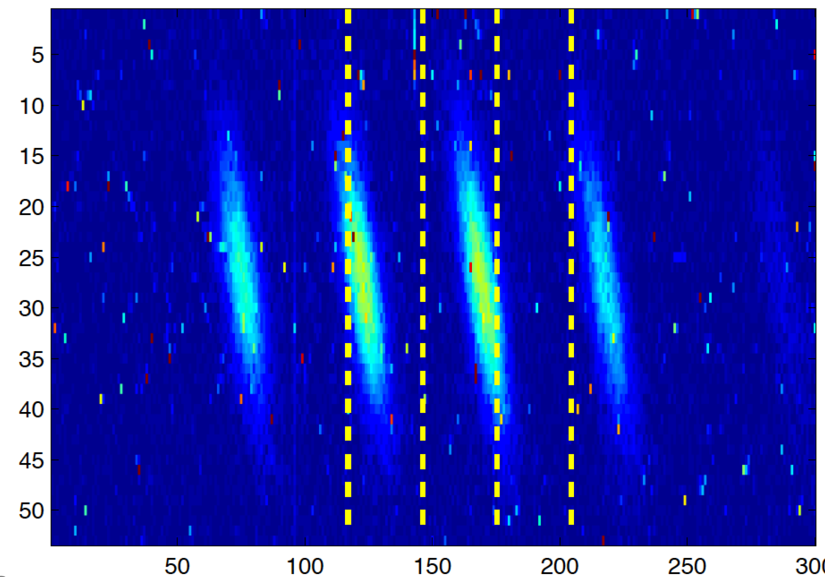
PAC'09 – TH5RFP065



Tests at Diamond Light Source

- The next tests were done at Diamond's booster to synchrotron line at 2 GeV and later at 3 GeV.
- The measurements gave a transverse emittance that was constant from shot to shot.
- Tilt of the beamlets is due to the extraction kicker of the booster.

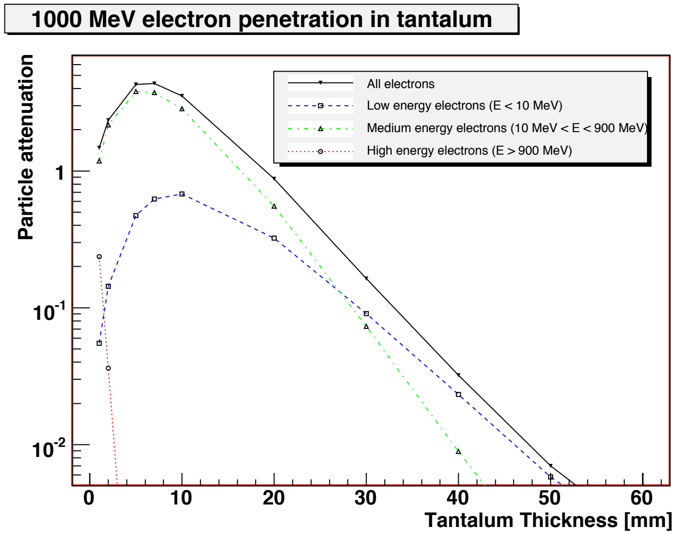


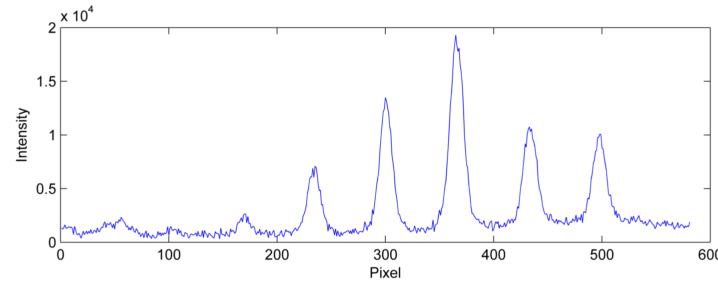


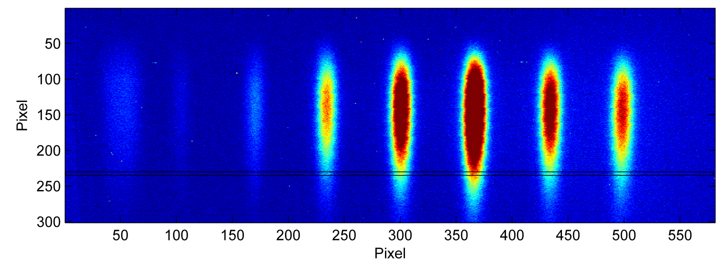
Single shot 3 GeV electron transverse emittance with a pepper-pot NIM. A 2013
10.1016/j.nima.2013.07.017

About the pepper-pot length

- Some lessons learnt from these tests:
  - It is not necessary to build pepper-pots that fully absorb the shower:
    - After a few mm all particles have undergone scattering => they won't reach the screen.
    - If some limited background remains the profile of the beamlets can be obtained by fits.
  - Tantalum is often produced rolled. For thin sheets it is better to use Tungsten.







Multiple OTRs

- Another single shot transverse emittance measurement technique that was investigated is the use of several OTRs.
- As the beam energy increase the scattering on a thin screen decreases.
- For a small enough beam, the scattering introduced by the screen(s) is negligible.

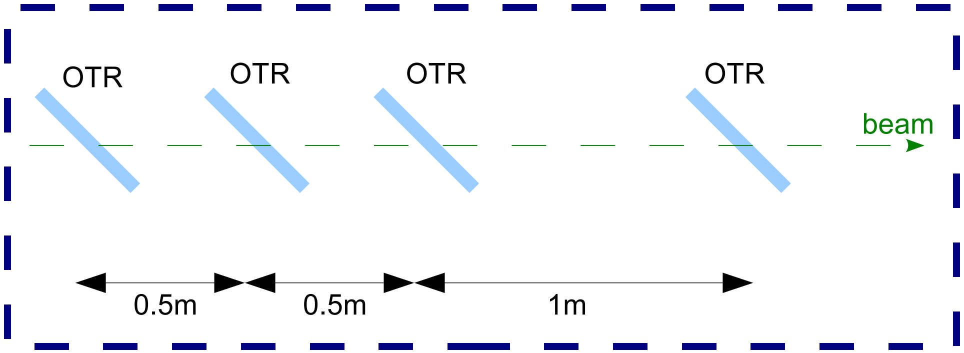
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\sqrt{\frac{x}{X_0}}\left[1 + 0.038 ln\left(\frac{x}{X_0}\right)\right]$$

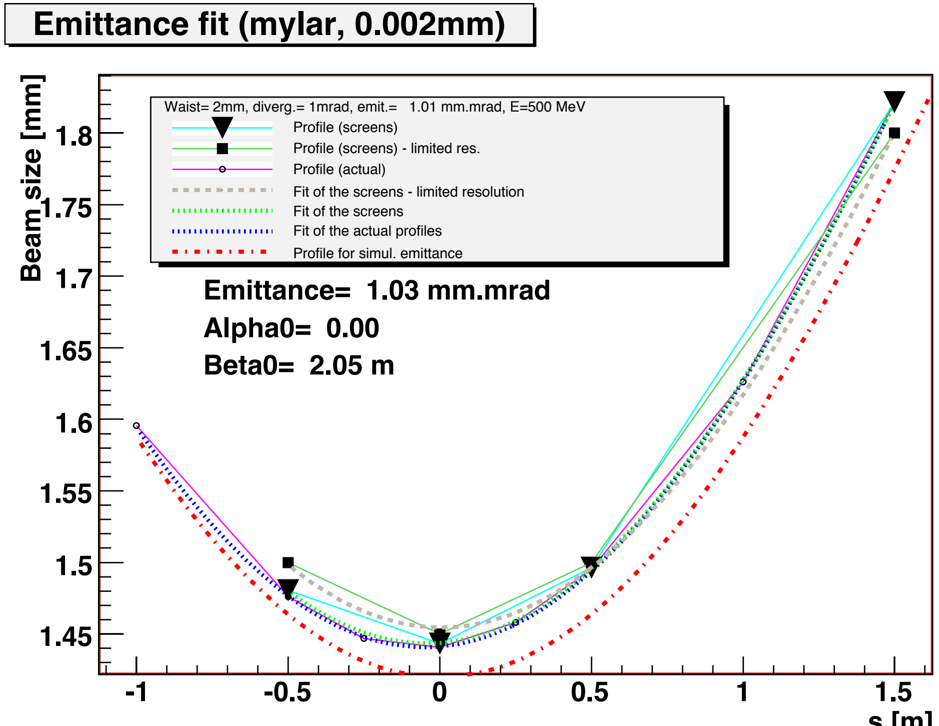
Material	Radiation Length (X_0)	Thickness $10^{-4}\ X_0$	Scattering $p\theta_0$	Limit σ_0 (eq. 7.13) $\frac{1\mathrm{mm.mrad}}{\theta_0}$
Aluminium (10 μm)	8.9 cm	1.12	139 MeV.mrad	0.9 mm
Aluminium (30 μm)	8.9 cm	3.37	242 MeV.mrad	0.5 mm
Mylar (2 μm)	28.6 cm	0.069	34 MeV.mrad	3.7 mm
Mylar (5 μm)	28.6 cm	0.17	55 MeV.mrad	3.7 mm
Polyimide film (7.5 μm)	28.6 cm	0.26	66 MeV.mrad	1.9 mm
Polyimide film (10 μm)	28.6 cm	0.34	77 MeV.mrad	1.6 mm
Mylar (10 μm)	28.6 cm	0.34	77 MeV.mrad	1.6 mm
Air (2 m), 1 atm.	$3\ 10^4$ cm	66.67	1089 MeV.mrad	-
Air (2 m), 0.01 atm.	$3\ 10^6$ cm	0.67	107 MeV.mrad	-

Adapted from:
Single shot transverse emittance measurement from OTR screens in a drift transport section
Journal of Instrumentation, Volume 6, July 2011

Multiple OTRs (2)

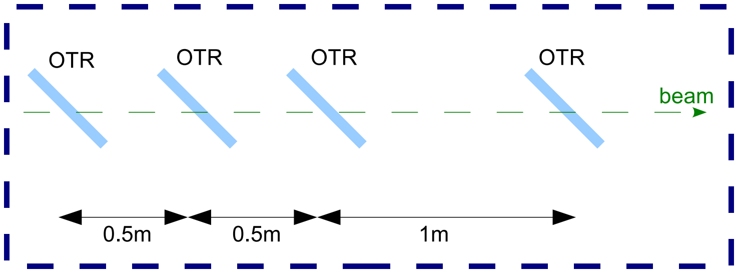
- By placing several OTRs on a beamline one can reconstruct the beam transverse emittance.
- To get the best fit the waist should be located near the 2nd screen with a 4th screen as far as possible.
- For our demonstration we wanted to show that the measurements could fit within 2m.
- If the measurement is made in a drift space it is more model-independent.

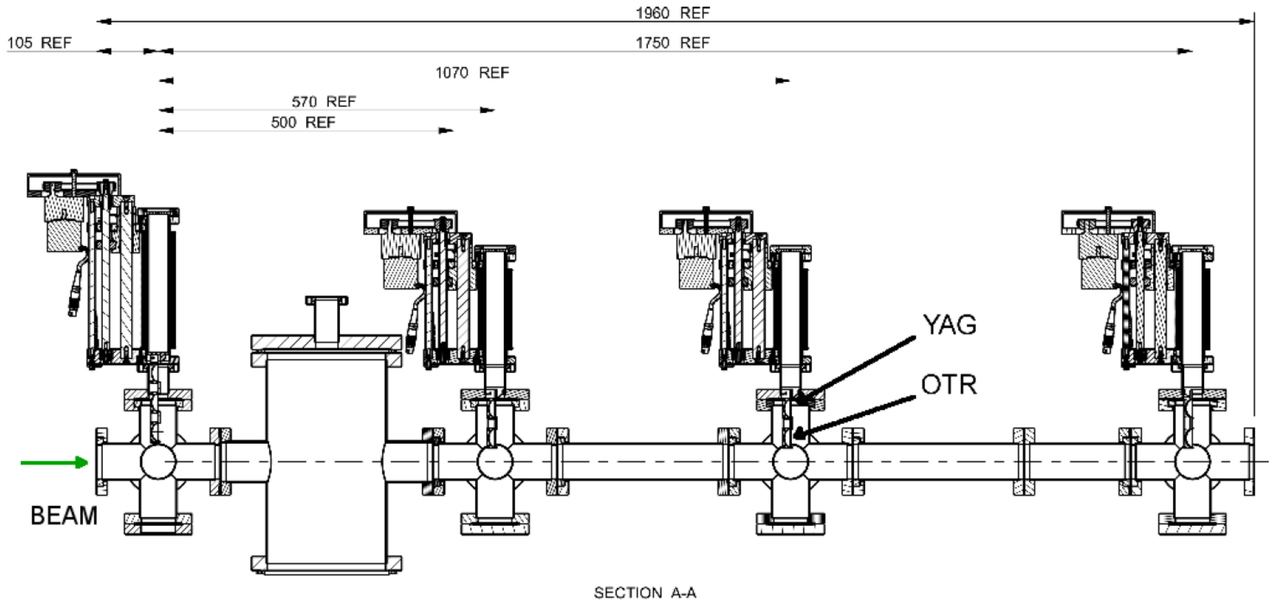




Tests at DLS

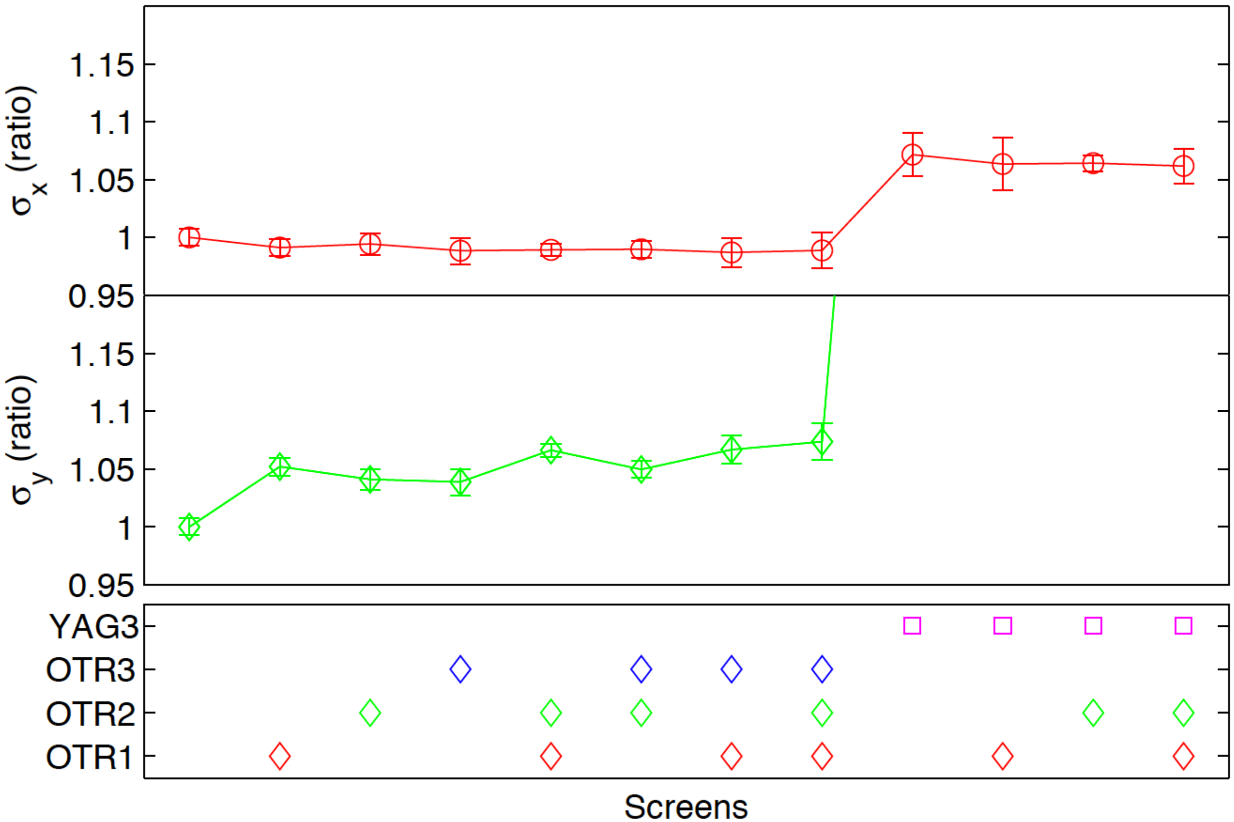
- We also tested that solution on the DLS Booster to Synchrotron test stand.





Checking the effect of scattering

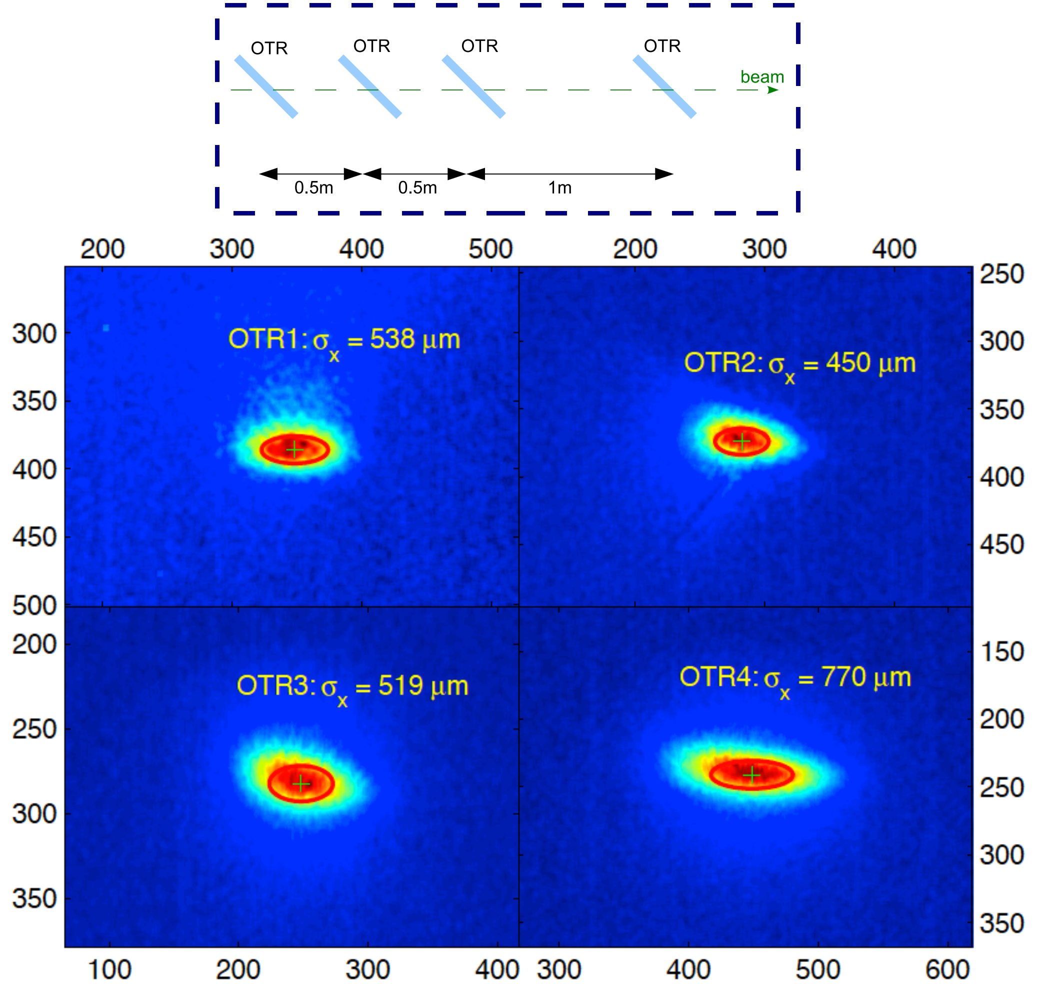
- To check that the contribution from scattering was negligible we inserted the screens one by one and observed the beam size on the 4th screen.
- We also inserted a YAG screen to compare the effect.



Single shot transverse emittance measurement from OTR screens in a drift transport section
Journal of Instrumentation, Volume 6, July 2011

Screen interferences (lack of)

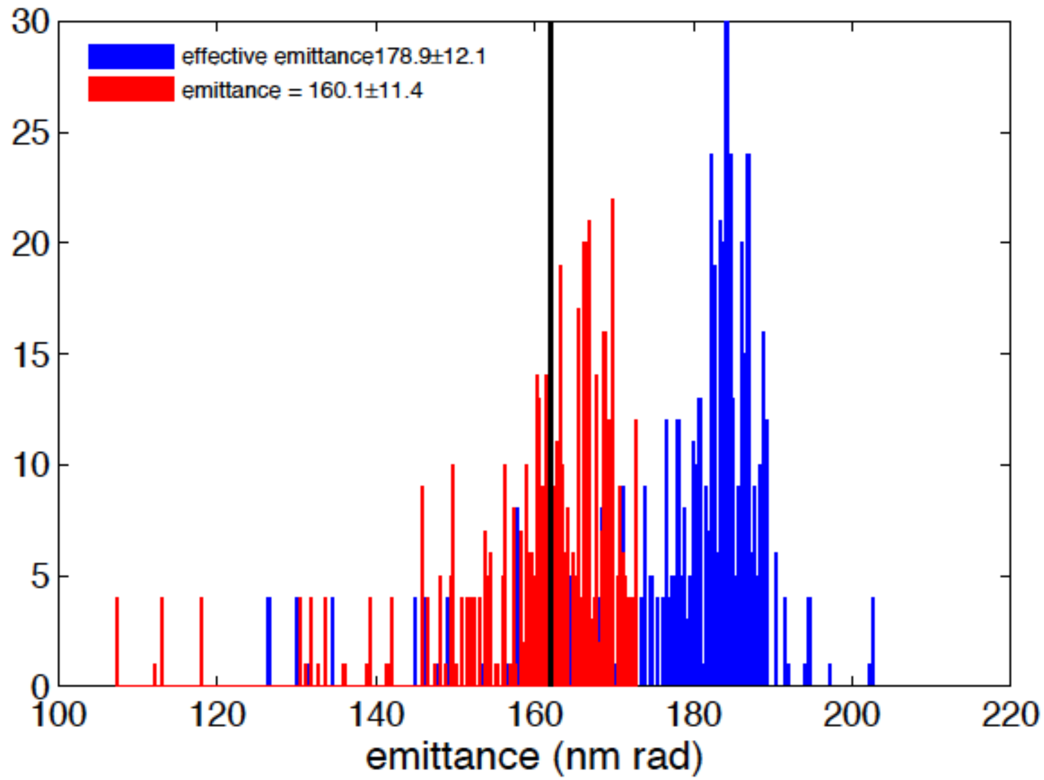
- Given the close distance between the screens and the high energy of the beam there were concerns that the forward OTR from one screen would interfere with the backward OTR of the next screen.
- This is true for each individual wavelength but because our camera integrated over a large optical bandwidth these interferences were smeared.



Single shot transverse emittance measurement from OTR screens in a drift transport section
Journal of Instrumentation, Volume 6, July 2011

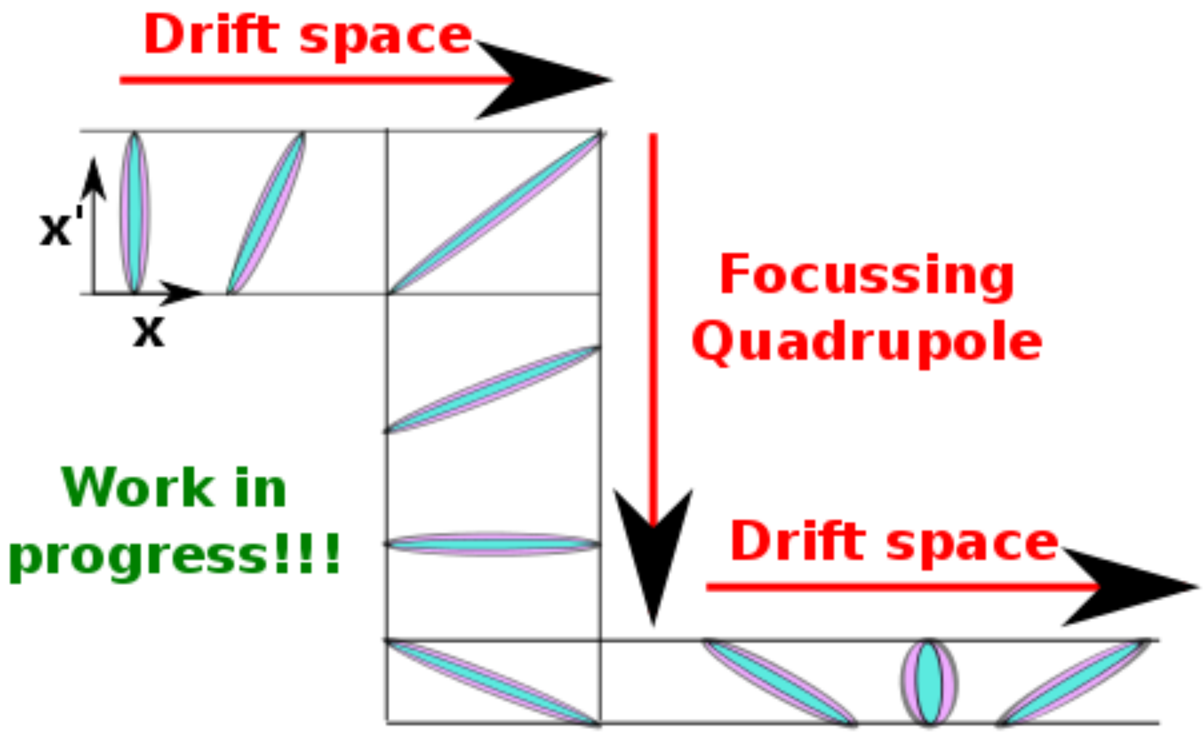
Transverse emittance measurement

- The measurements were done in a highly dispersive area, so this had to be taken into account to reconstruct the correct transverse emittance value.



Sheared phase space issue

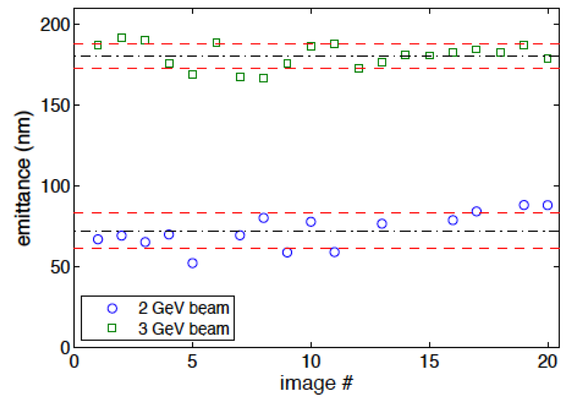
- In the case of laser-plasma beams, the beam size is very small (few micrometers) and strongly divergent (~10mrad).
- A transverse emittance measurement directly after the source is therefore difficult.
- A measurement after a focussing quadrupole is easier.

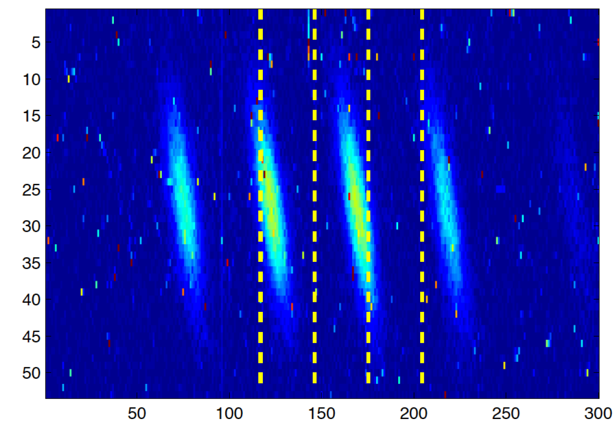


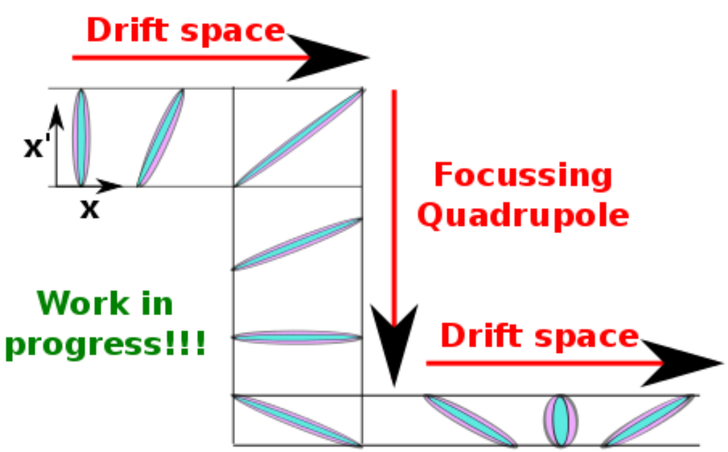
Thanks to A. Cianchi useful discussions on this.

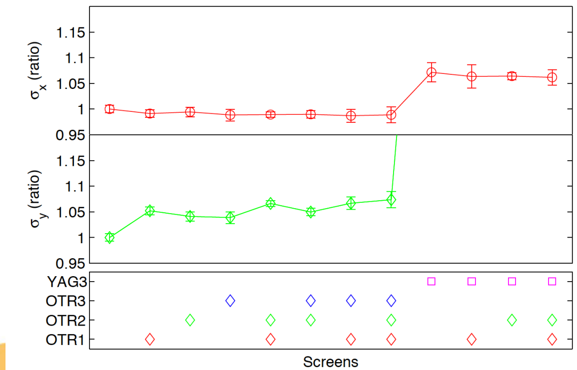
Outlook

- Pepper-pots and multiple OTRs offer two solutions for high energy single shot transverse emittance measurement.
- Issues related to heating not addressed here.
- Pepper-pots can give an instantaneous image of the beam phase space.
- The location where the measurement is done is also important.
- As shown by the SwissFEL colleagues, can we use nanofabrication?









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Thank you