Electron Diagnostics for plasma accelerators

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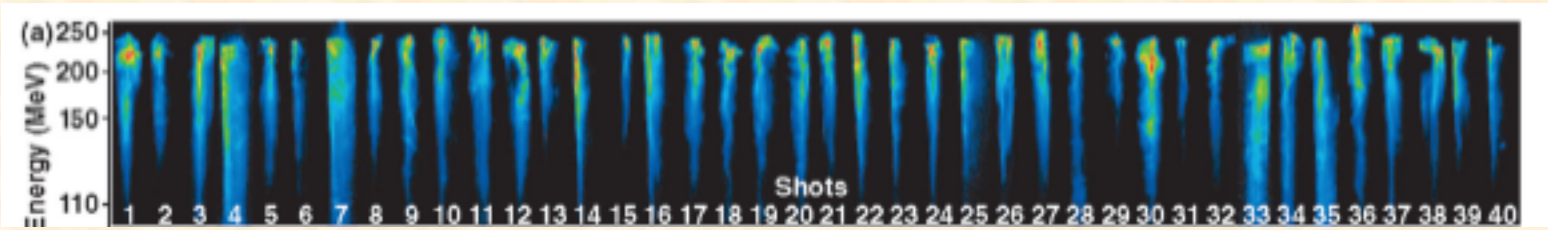
Diagnostics for plasma accelerators

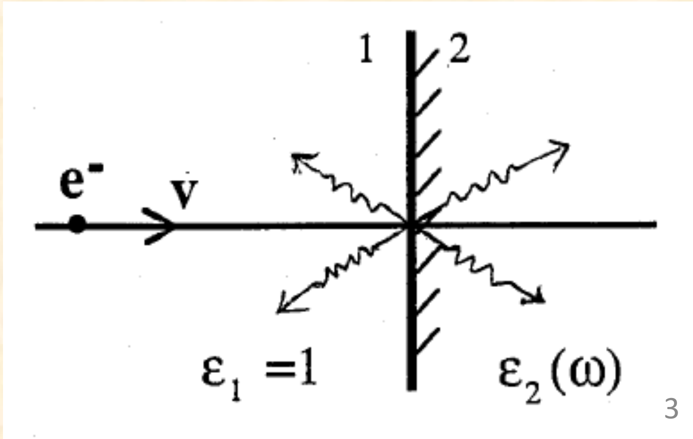
- Plasma based accelerators have a tremendous potential.
- However the beams they produce needs to be characterised accurately.
- This must be done on a shot to shot basis as repeatability is not always good.
- Such beam are typically very short (fs) but with a high energy.
- Example of diagnostics developed recently:
  - Single shot OTR based emittance measurements
  - High Energy Pepper-Pots
  - Longitudinal profile reconstruction using Smith-Purcell radiation



J.Osterhoff et al., PRL 101,085002(2008)

Multiple Optical Transition Radiation profile measurements

- When an electrically charged particle experience a change of medium it radiates => Transition Radiation
- Optical Transition Radiation is commonly used at accelerators to image high energy beams but it scatters the beams.
- Unlike phosphorescence, OTR is a surface effect, independent of the screen thickness.
- The scattering induced by an ultra-thin screen may be acceptable.

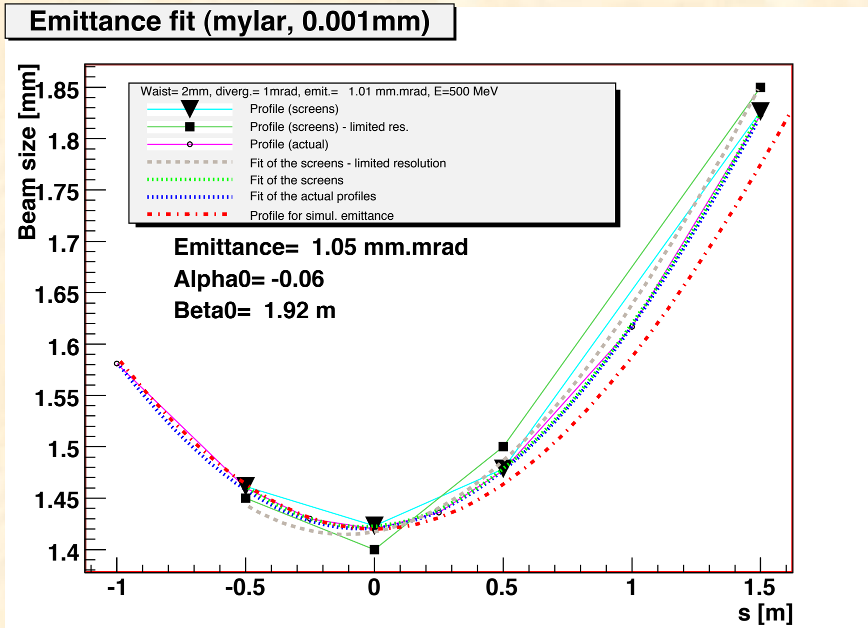


Effect of the scattering

- The condition for the scattering to be negligible can be derived:

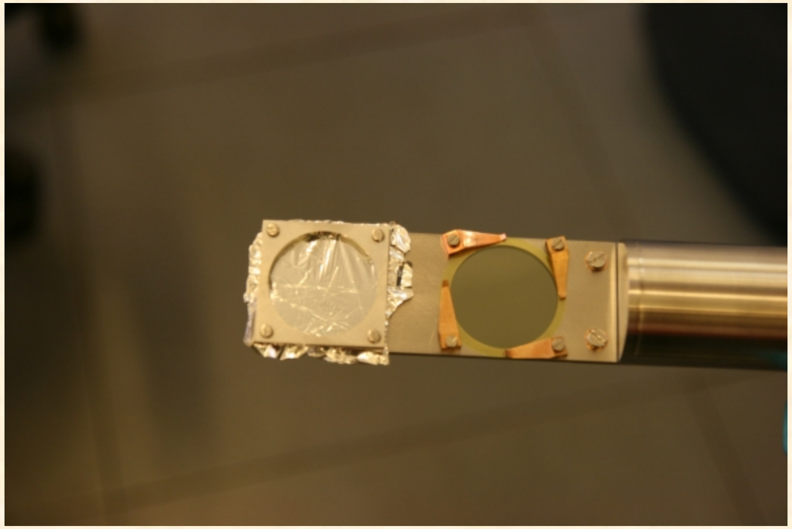
$$\sigma_0 << N_{\text{screens}} \frac{mc\epsilon_n}{p\theta_0}$$

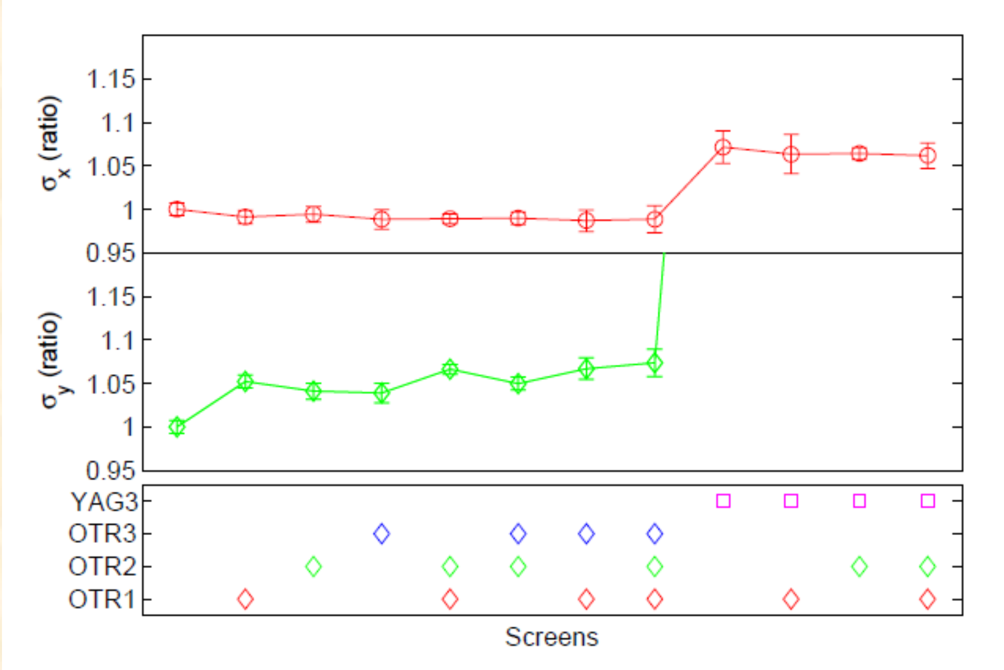
- For a small (focussed) beam the natural divergence will dominate the effect of the scattering whereas for a collimated beam the scattering will dominate.
- GEANT4 simulations were used to validate these calculations.



Delerue et al., arXiv:1005.2417

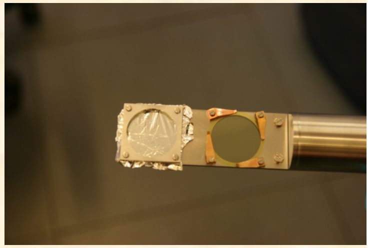
Experimental validation

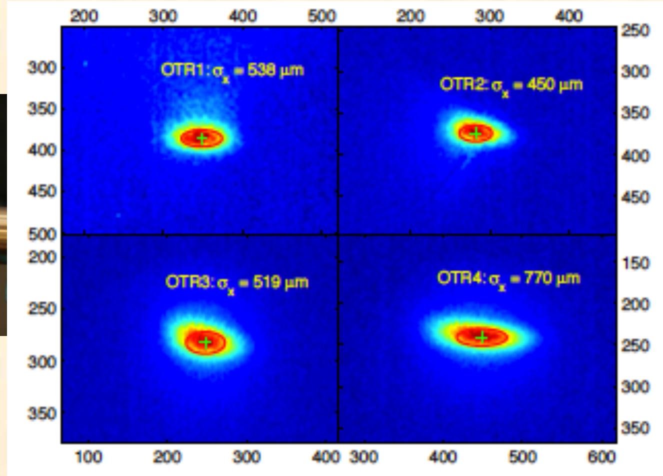


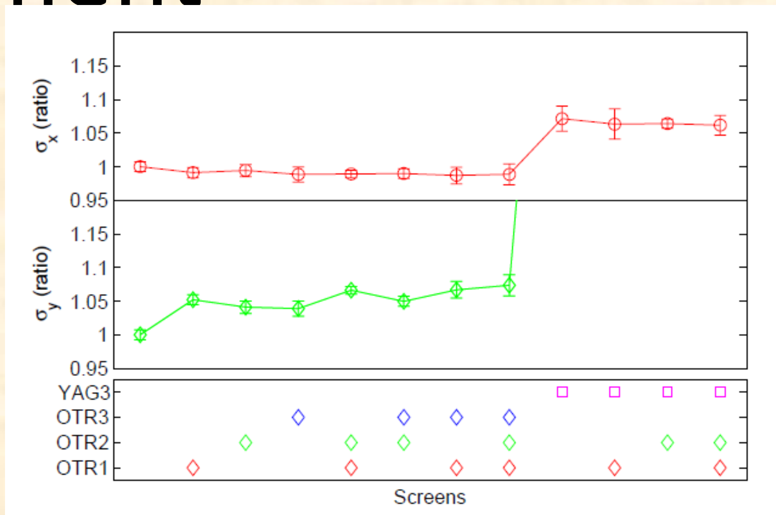


- This was verified experimentally using the DIAMOND (UK) BTS (3 GeV electrons).
- The beam optics validates the condition on x and is close to it in y.
- Scattering with OTR screens is seen in y and not in x.

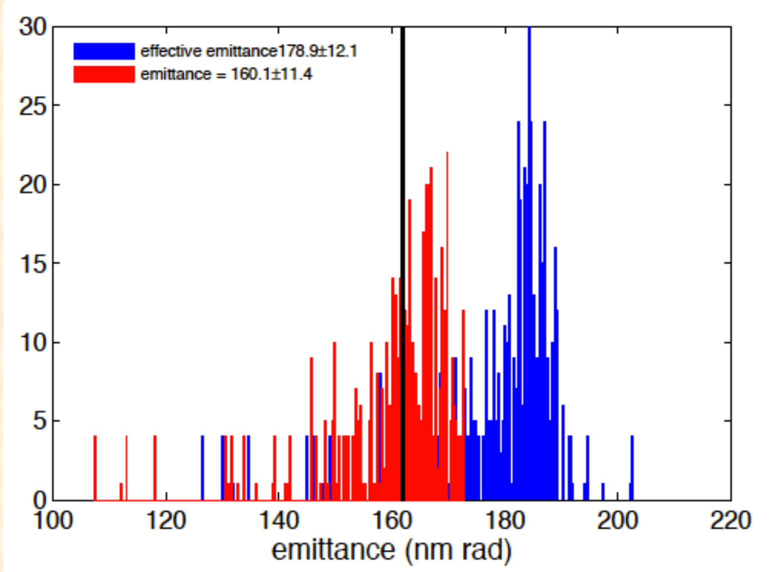
Single shot beam envelope measurement







- Tested at DIAMOND
- Beam dispersion correction required.
- Good agreement with quadrupole scan.



Thomas, Bartolini and Delerue, Jinst 6 p07004 (2011)

OTR summary

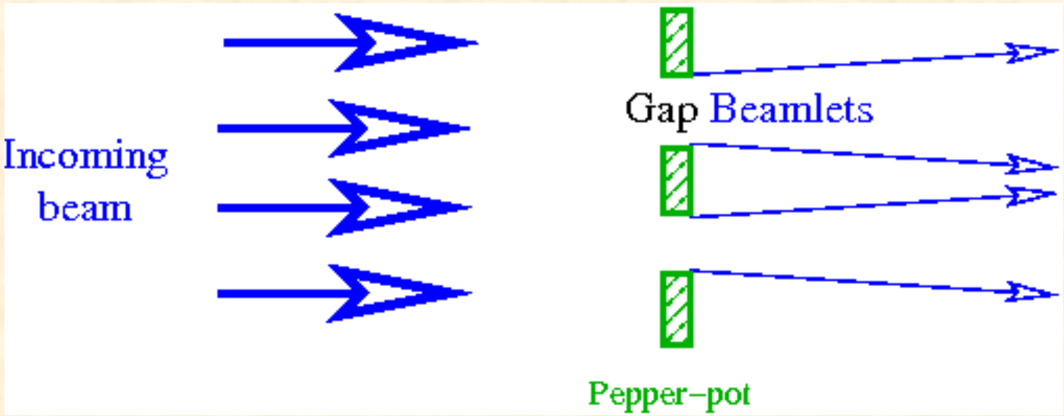
- We have shown that thin OTR screens can be used to measure the emittance of a high energy beam in a single shot.
- An attempt was made to make a similar measurements at a plasma accelerator last June but was hampered by coherent effects. => more R&D needed to address those.

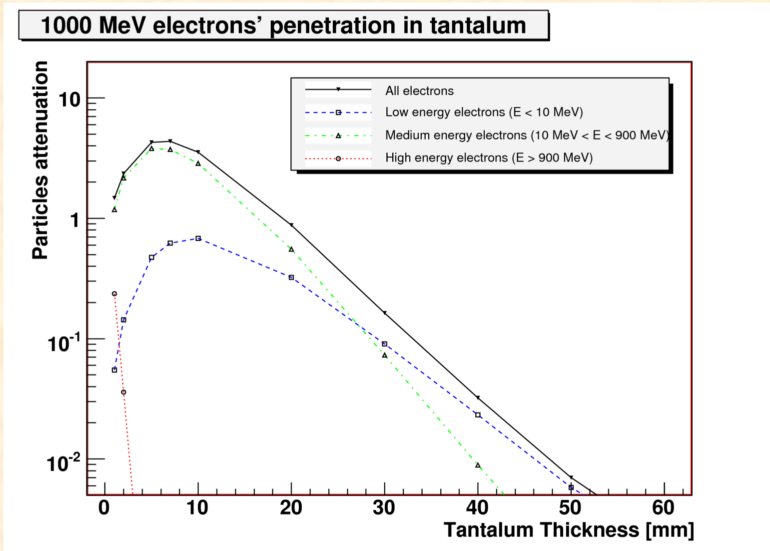
Issues with COTR

- Several accelerators using shorts bunches have seen problem with OTR becoming (partially) coherent.
- This issue needs to be investigated, for example by making measurements at shorter wavelength.
- Issue is worse with laser-driven plasma accelerators.
- This problem could be addressed at a test facility with short bunches.

Pepper-pots

- At low energy the usual transverse emittance measurement methods uses an array of slits or holes to split the incoming beam into several beamlets.
- For each hole the position of the beamlet is known.
- A screen located downstream measures the divergence of each beamlet.
- At HE e- penetrate in matter…





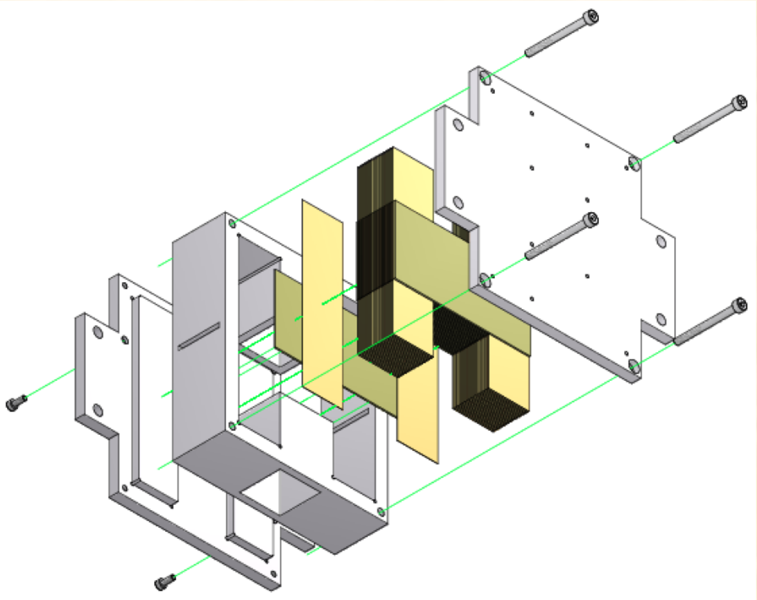
Extended pepper-pots

- Instead of a thin foil deep channels can be used to form the beamlets.

- Two challenges:
  - Mechanical assembly
  - Phase-space preservation

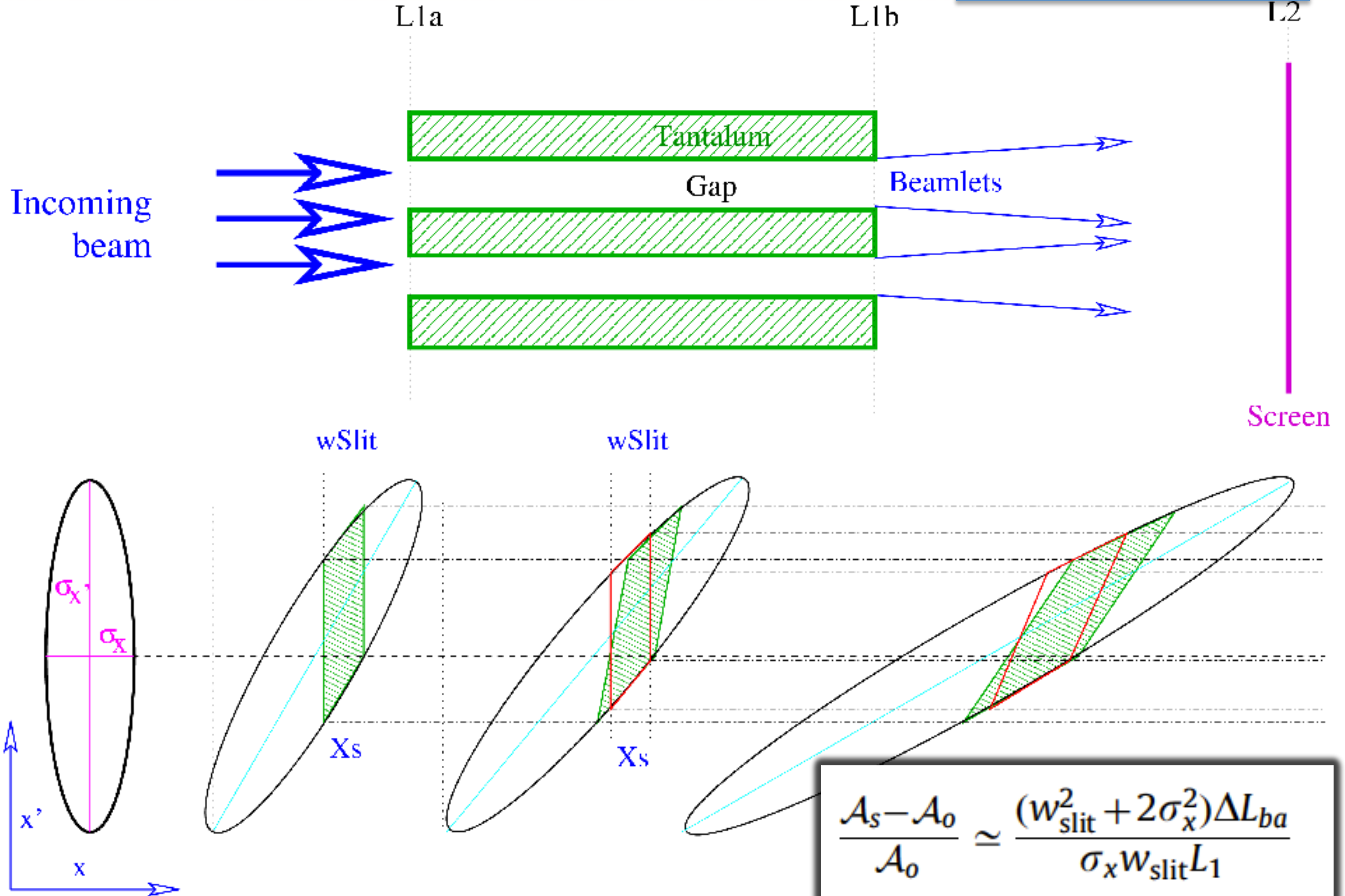
High energy pepper-pots (extended pepper-pots)

- Creating thin channels is quite challenging from a mechanical point of view.
- We form them by stacking absorbers and shims.
- Require ultra-flat Tantalum (or Tungsten) => industrial collaboration.



Phase space preservation

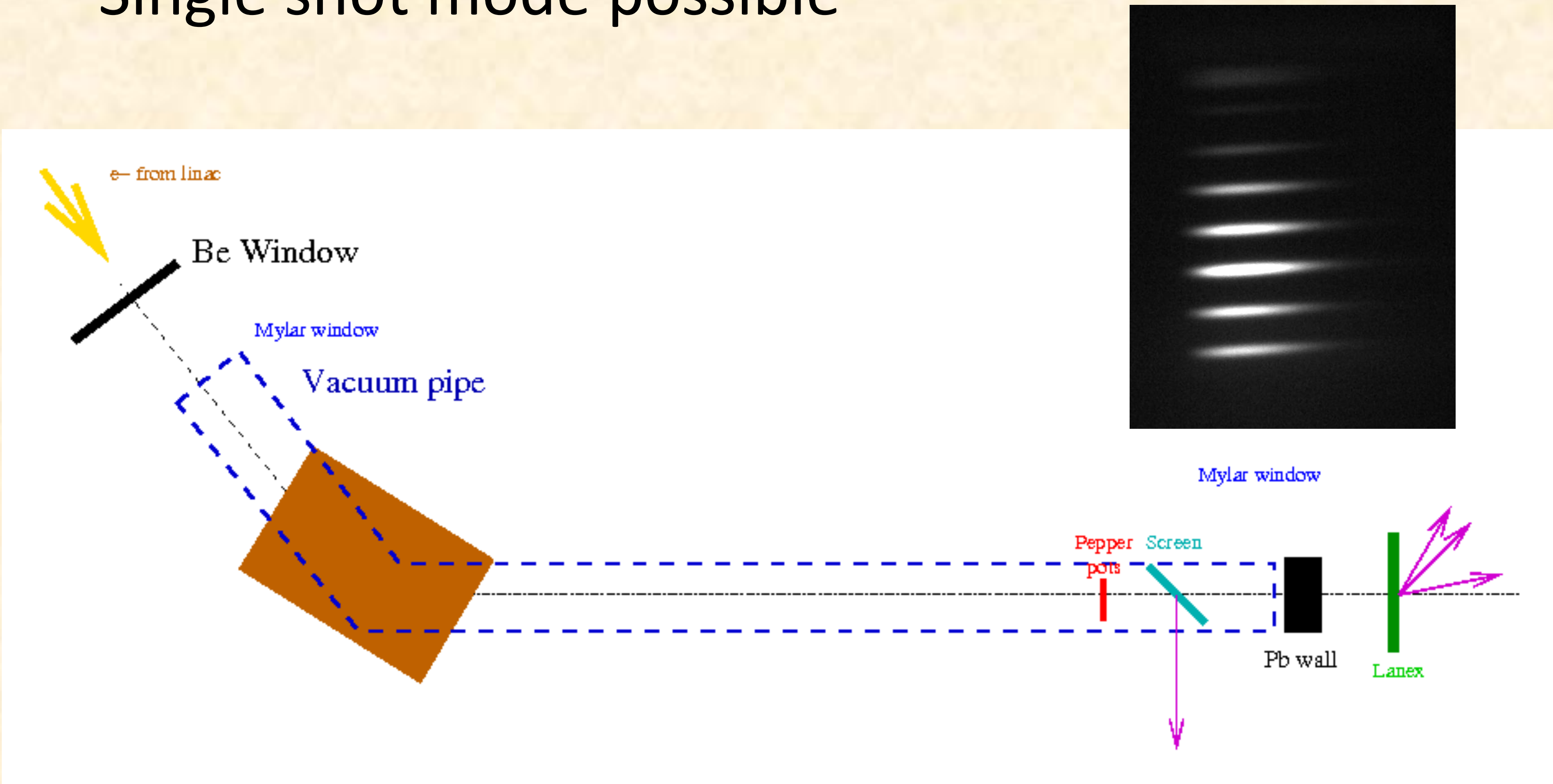
N. Delerue
NIM A 644 (2011) 1-10



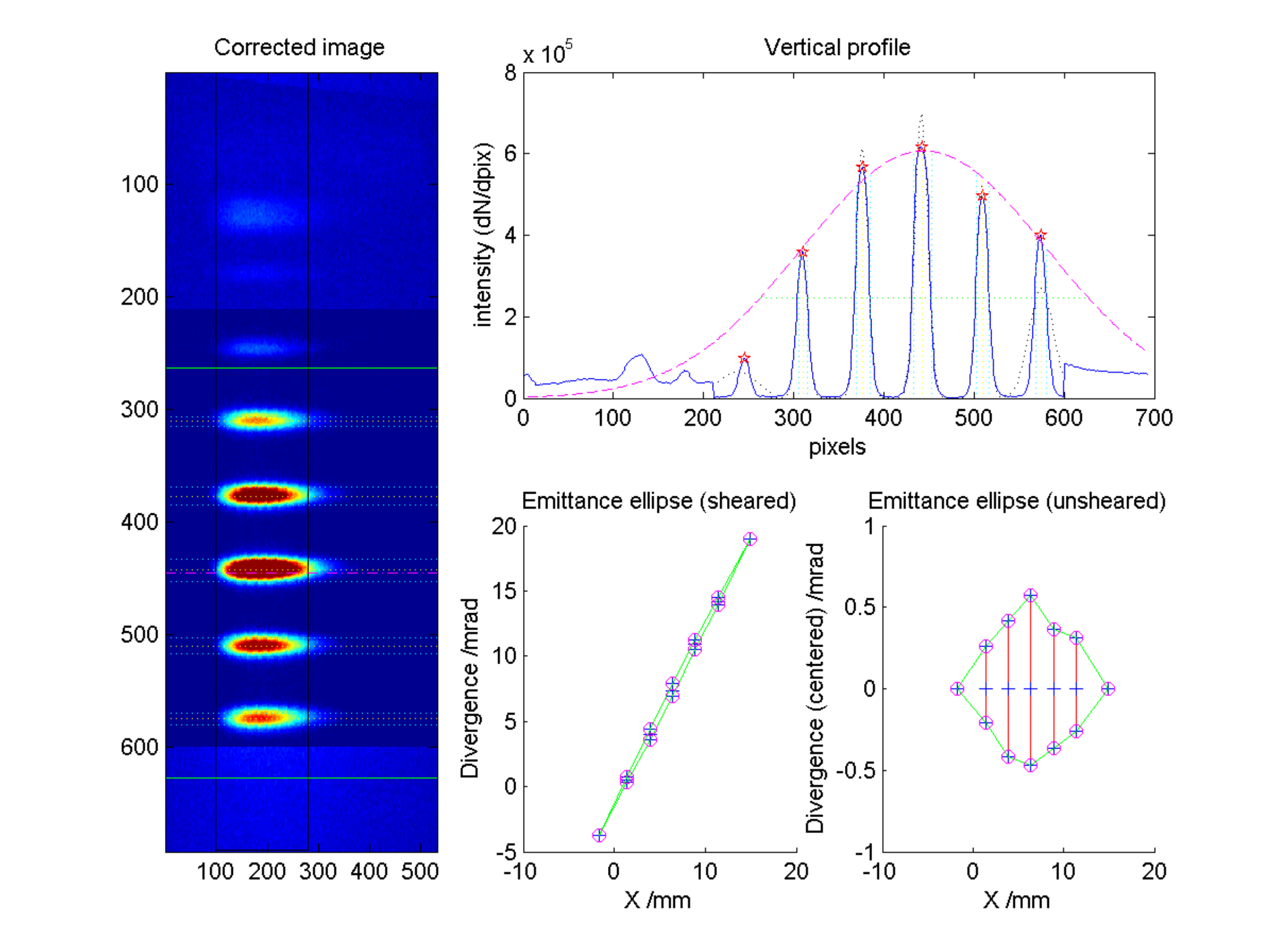
$$\frac{\mathcal{A}_s - \mathcal{A}_o}{\mathcal{A}_o} \simeq \frac{(w_{\text{slit}}^2 + 2\sigma_x^2)\Delta L_{ba}}{\sigma_x w_{\text{slit}} L_1}$$

Extended PP:
Beam tests at DAFNE

- Beam tests at DAFNE BTF: 508 MeV electrons
  Single shot mode possible



High energy pepper-pots (extended pepper-pots)



RMS Emittance= 4.0 mm.mrad

(geometric)

Shearing: 0.32mrad/mm

Calculated distance to waist: 3.1m

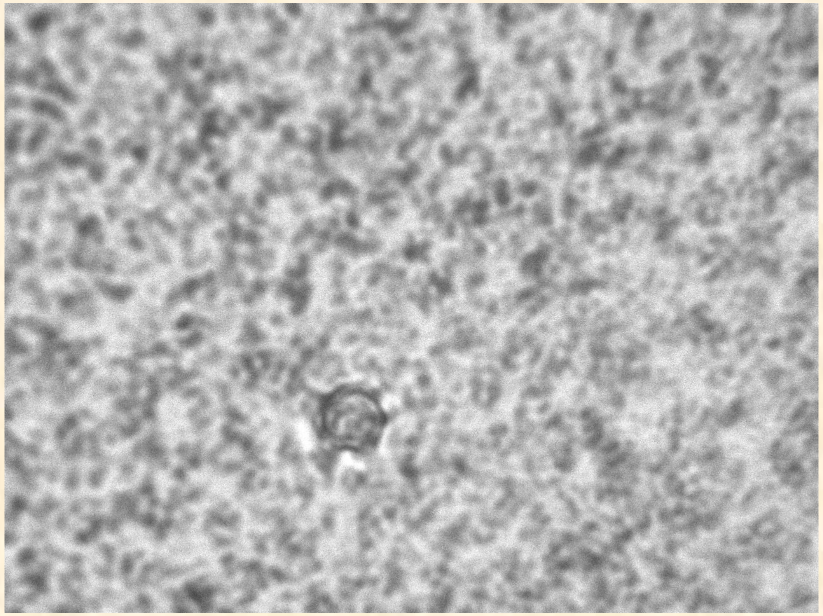
Delerue et al. PAC'09 TH5RFP065

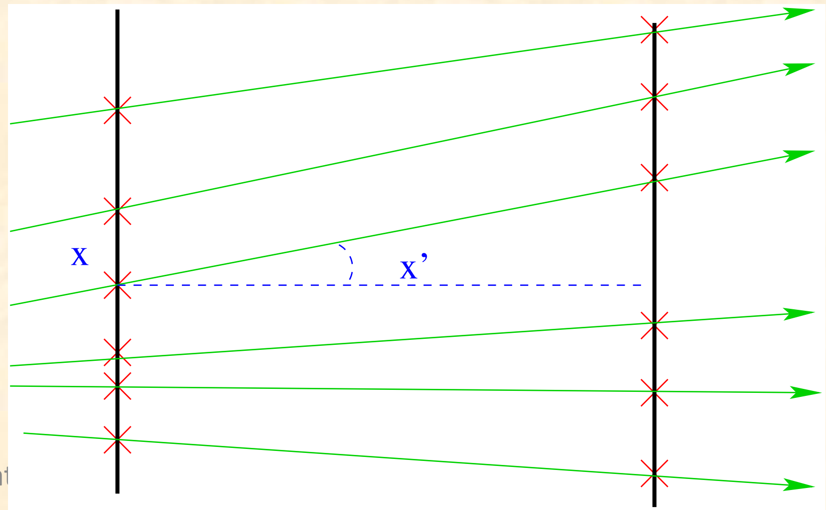
Pepper-pot summary

- We have demonstrated that extended pepper-pot can work when positioned correctly.
- We have shown that it is possible to measure the emittance and reconstruct the phase-space of a 508 MeV beam in a single shot.
- Tests are on-going at DIAMOND to extend this method to 3 GeV!

Nuclear emulsions based tracking

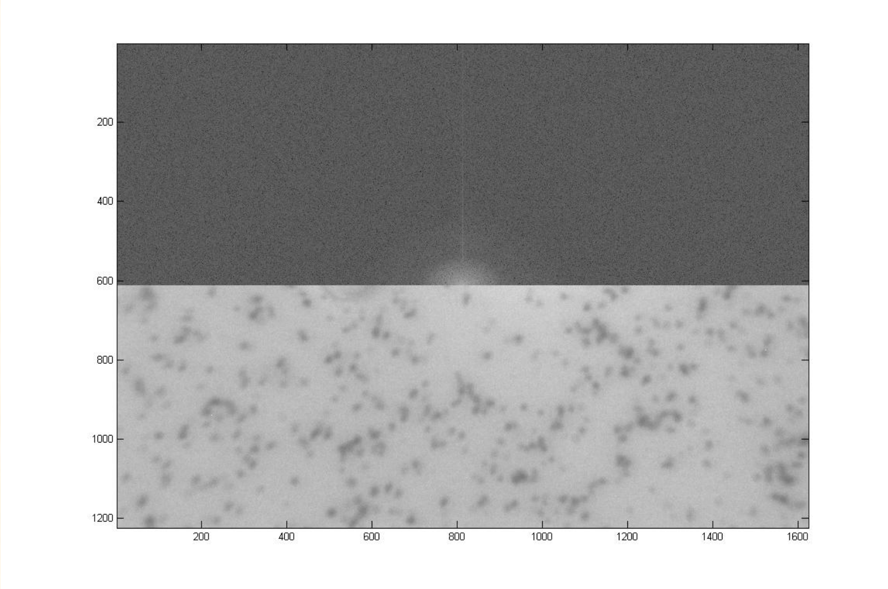
- Perfect emittance measurement
  => position + direction of each particle.
- Nuclear emulsions can resolve particles with a resolution of about 1um.
- Stacks of thin emulsions can resolve the direction and the position of a beam.
- Damaging an emulsion plate with a high power laser is less of a problem than damaging an expensive camera!





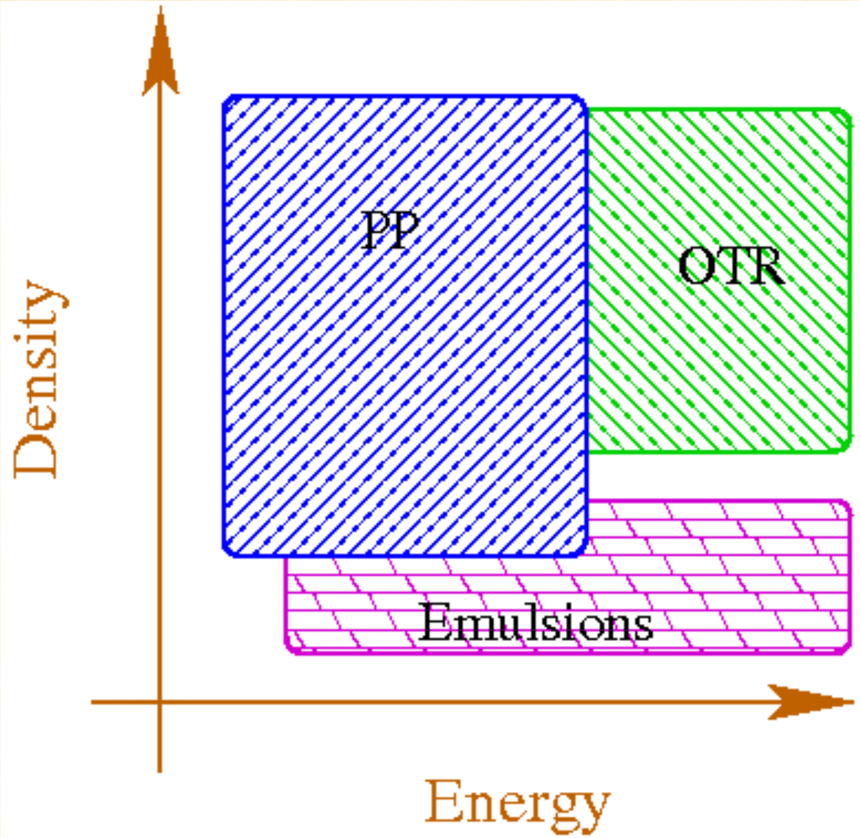
Particle tracking

- Electrons above 100 MeV are not significantly scattered by a thin layer of Nuclear Emulsions.
- We used a technique called "image registration" to match (rotate, scale,…) the simulated images from two consecutive emulsion plates.
- A motorised microscope allows the scanning of a large area.
- A low particle density is necessary. At a LPA this is usually achieved because the beam has a strong divergence.



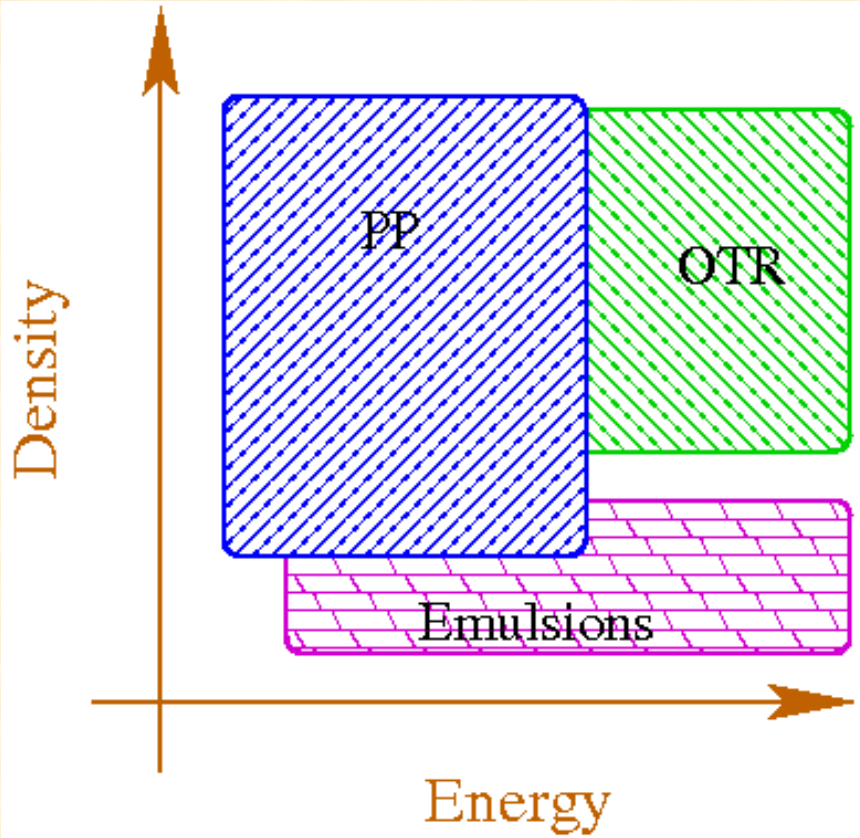
- We demonstrated that all the bits work but did not have time to put them together within the duration of the grant.
- There may be applications with ion beams.

Why 3 techniques



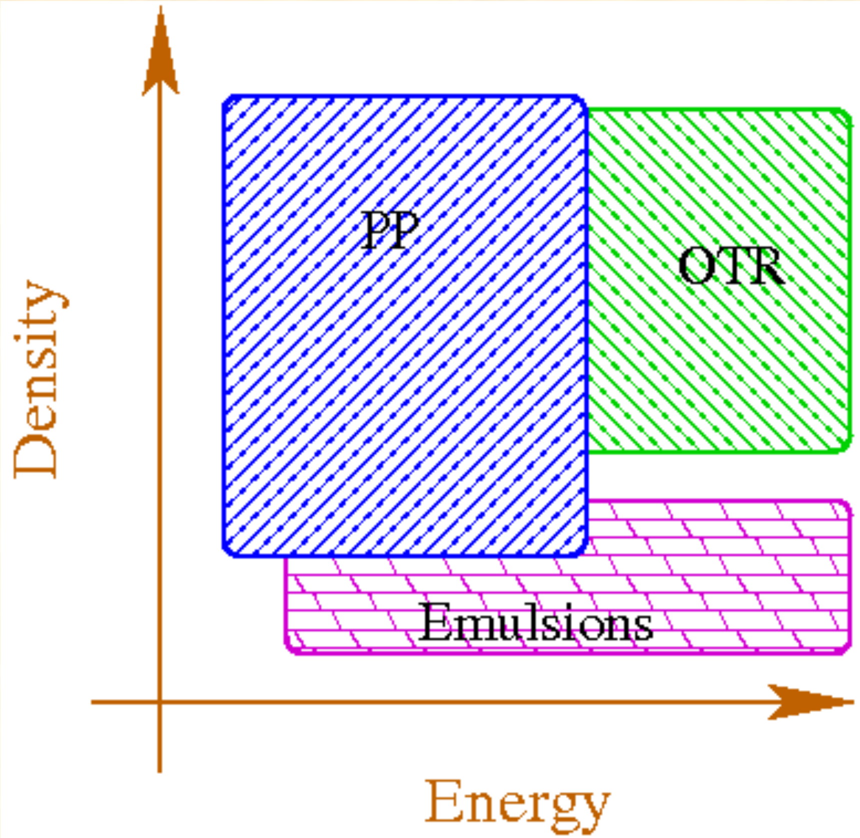
- The 3 techniques we studied are meant to be complementary:
  - Multi-OTR requires an intense beam to have enough OTR signal.
  - At low energy scattering is too intense.

Why 3 techniques



- Pepper-pots won't work with electron beams of several GeV
- but they can work with very high density beams.

Why 3 techniques



- Emulsions only work with low density beams.
- They work over a large range of energy.

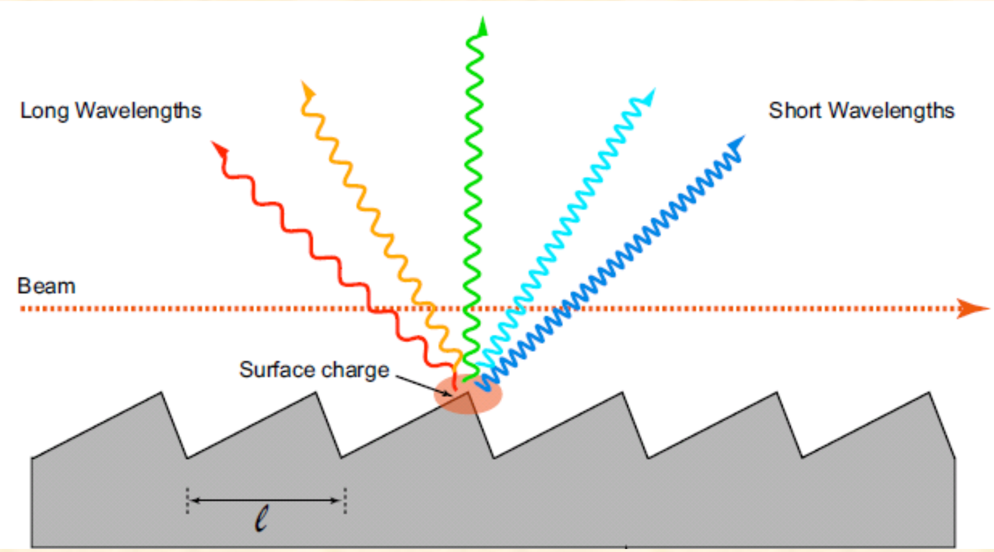
The information provided by the 3 methods is also slightly different.

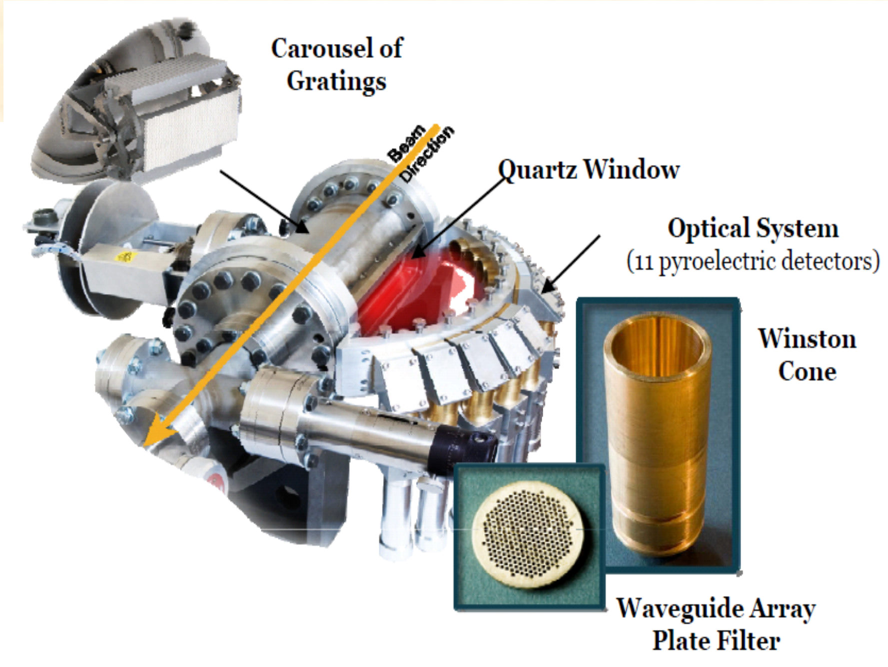
Longitudinal profile measurement

Longitudinal profile measurement

- There are several techniques to measure longitudinal profiles of electron bunches.
- The most straightforward is to use a RF deflecting cavity (or a streak camera) => but not suitable for ultra short beams.
- Electro-optic sampling uses the wakefield induced by the beam in a crystal to modulate the field of a laser.
  => but unable to reach ultra short bunches (below 30 fs)
- Several techniques (CTR, CDR, …) use the radiation emitted by a relativistic bunch when passing trough/near an interface.

Smith-Purcell radiation



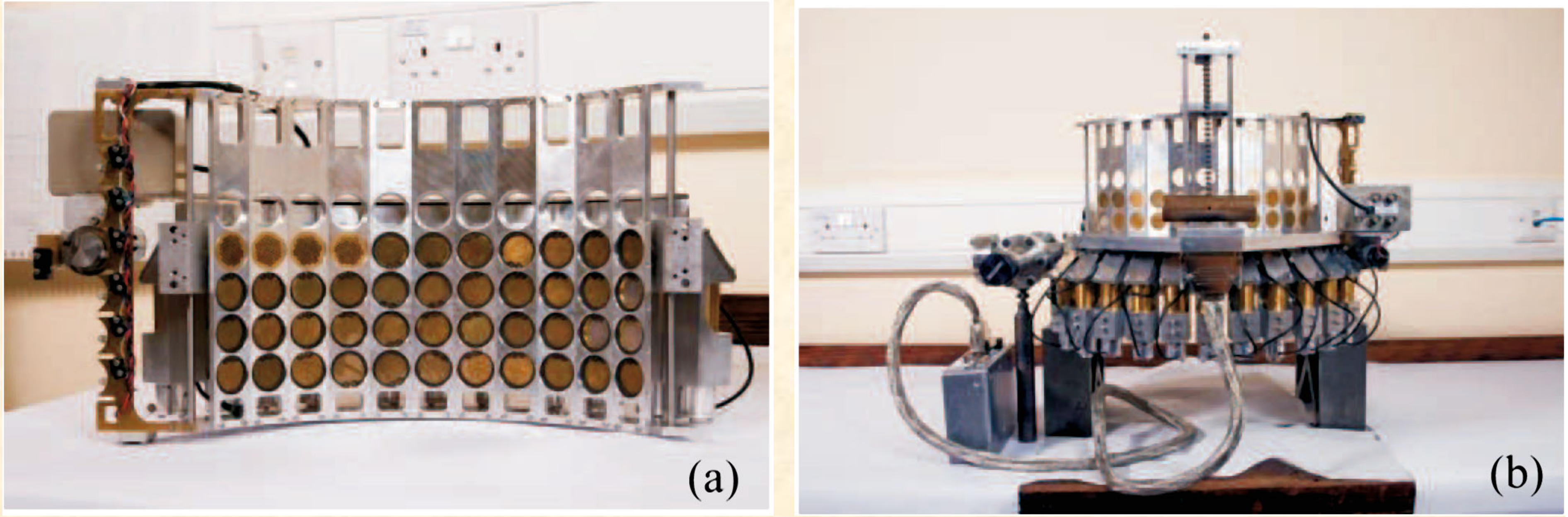


- Smith-Purcell radiation is emitted when relativistic charged particles pass near a grating.
- Pioneering work on its use as longitudinal profile monitor done in Oxford by George Doucas (in the picosecond regime).

Smith-Purcell radiation

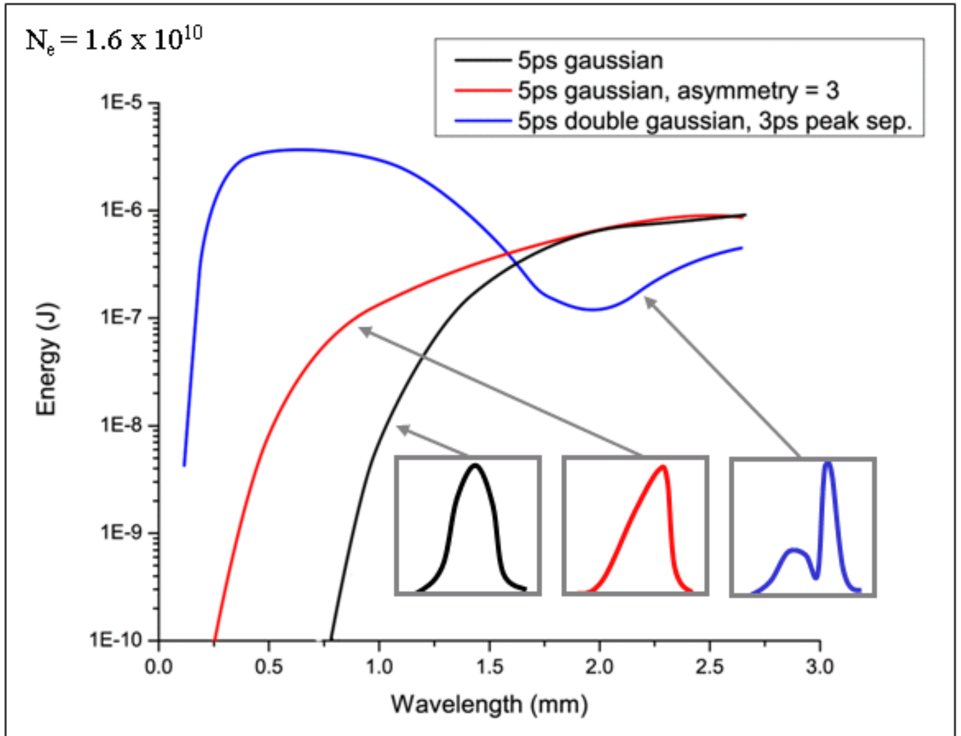
- In a Smith-Purcell detector, radiation of a certain wavelength is emitted in a fixed direction.
  => Allows to measure these different wavelength "easily" (the grating acts as spectrometer).
  => Give access to the Fourier transform of the bunch profile.
  => An inversion technique can then be used to reconstruct the bunch length but also the profile of the electron bunch.

Smith-Purcell detector



- The existing detector uses an array of 11 pyroelectric detectors able to detect far-infrared radiation.
- To increase the range of wavelengths that can be measured 3 sets of filters can be inserted in front of the detectors.

Bunch profile reconstruction



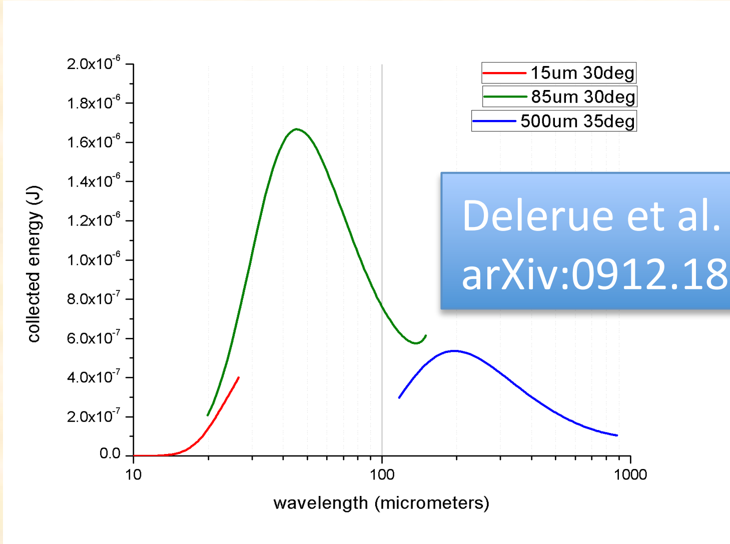
Simulation of different profiles, as would be seen experimentally

$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e}(\Omega,\omega) = \left(\frac{dI}{d\Omega d\omega}\right)_{sp}(\Omega,\omega)\cdot[N_e + N_e(N_e+1)\,|F(\omega)|^2]$$

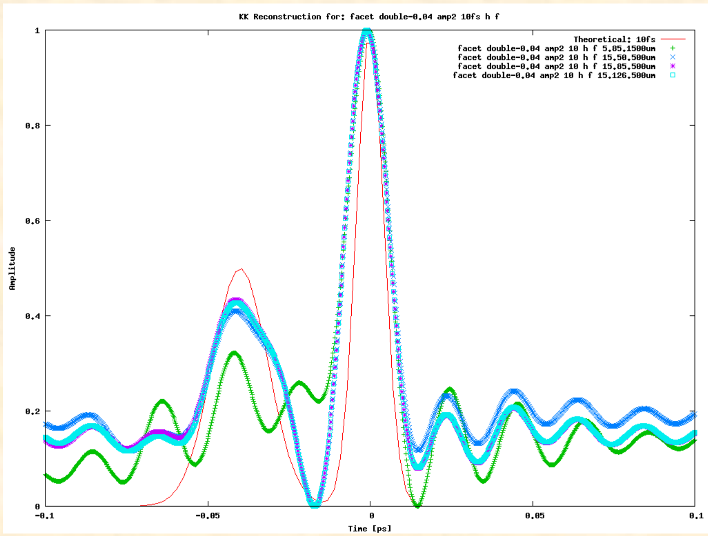
Different bunch profiles will give different radiation spectrums which can be reconstructed.

Smith-Purcell radiation at a LPA

- To extend the range of the detector from ps to fs the wavelength sensitivity needs to be modified.
- The previous experiment used mm radiation whereas fs electron will emit micrometric radiations.
- Simulations show that we are also sensitive to small satellites.
- Test done at FACET (SLAC) last summer.

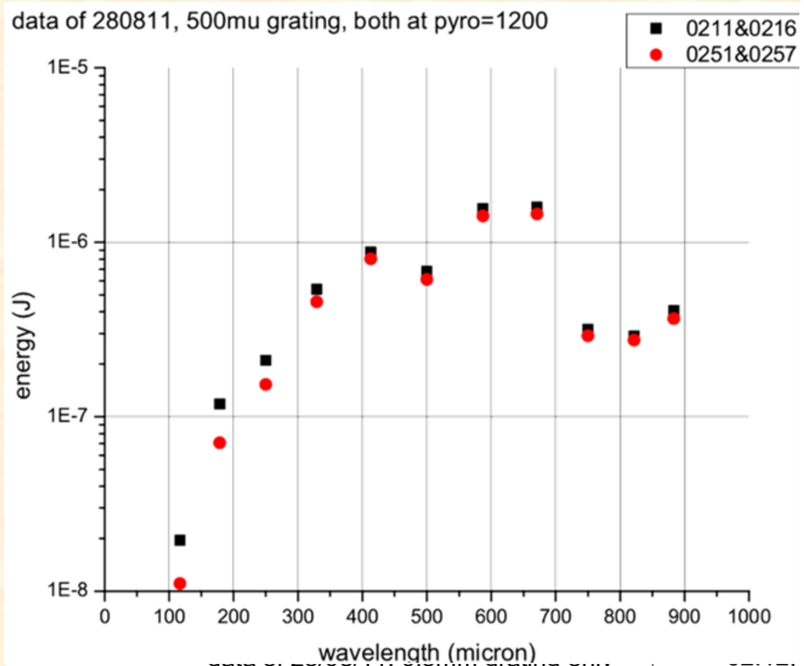


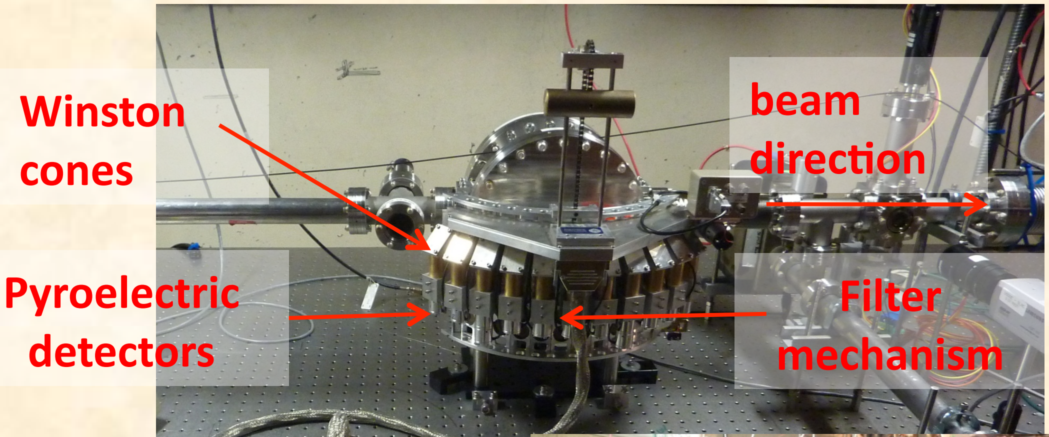
Delerue et al.
arXiv:0912.1863

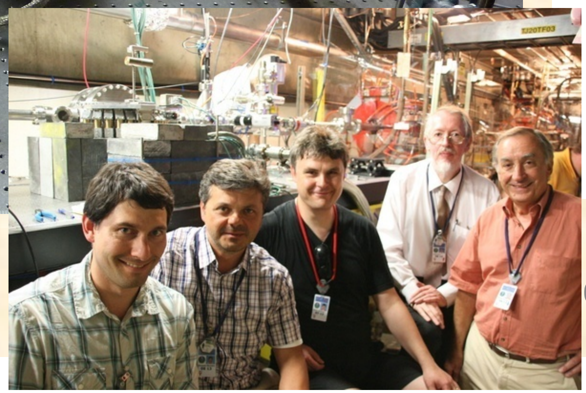


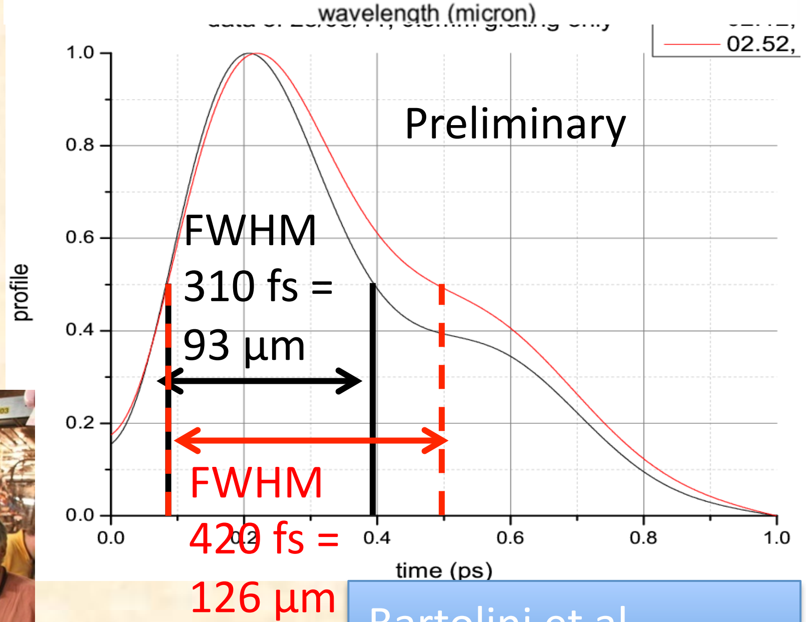
E-203 experiment at FACET

- FACET is the new test facility at SLAC (20 GeV, ~200fs).
- Preliminary measurements in August 2011
- Next data taking in March 2012.









Bartolini et al.
IPAC'11 WEOBB03

Outlook

- Single shot diagnostics are necessary to measure the beam produced by plasma accelerators.
- Two emittance measurement techniques suitable for plasma accelerators have been validated on conventional accelerators.
- Preliminary tests at FACET show that Smith-Purcell radiation can be used to measure longitudinal profile in the 100fs range.

- *Disclaimer:*
  Any involvement of LAL needs to be approved by its science board (next meeting in January).

Thank you for your attention

Other activity at LAL: Compton scattering

- Mighty Laser:
  Fabry-Perot cavity (gain 1000 -> 10000) with digital feedback for Compton scattering. Tested at the KEK ATF.