Diagnostics for plasma accelerators

-> Plasma acceleration

-> Diagnostics for PA

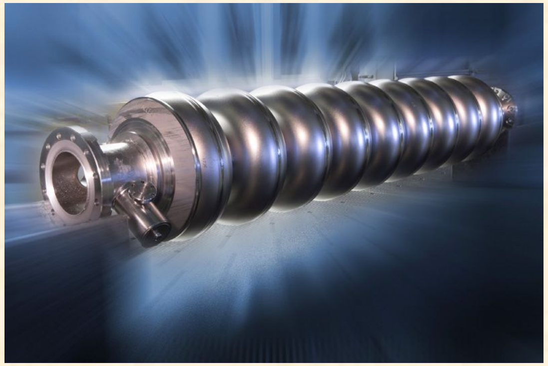
-> Toward PA applications

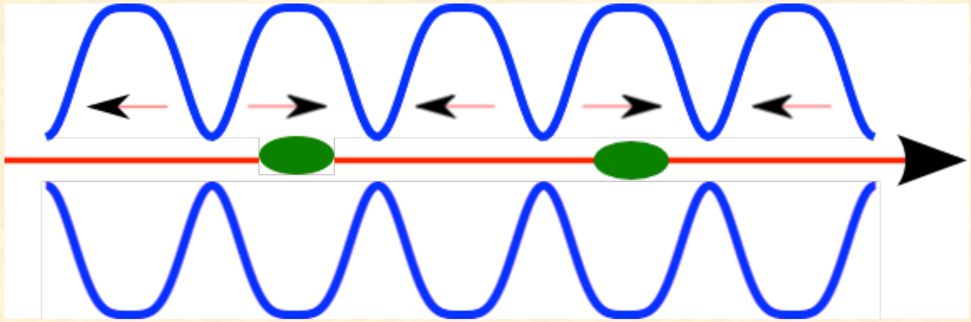
Nicolas Delerue, LAL

(Work done at the University of Oxford)

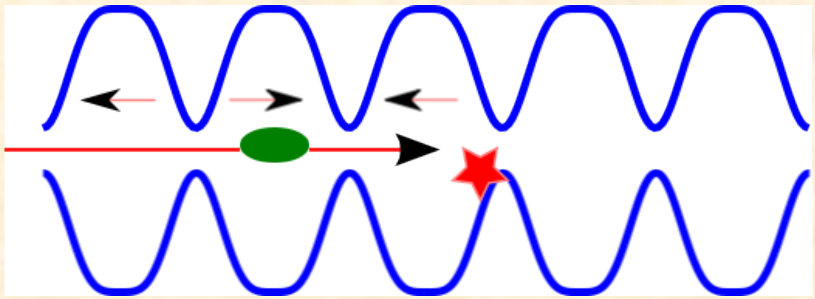
Limitations of current acceleration techniques

- In an accelerator particles are accelerated by an electromagnetic wave creating an accelerating gradient when the particles pass.





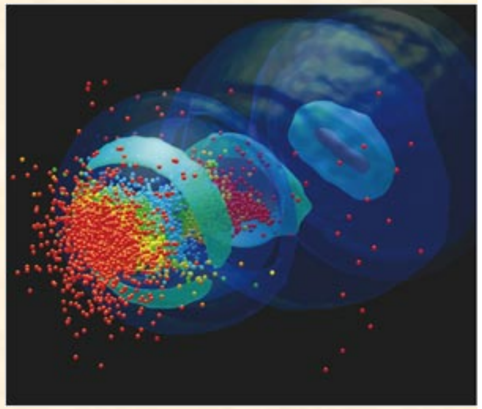
- If the gradient is too high an imperfection in the cavity may concentrate too much EM power and create a spark (breakdown) leading to the loss of the beam and possible damages to the cavity.
- So far accelerating cavities are limited to less than 100MV/m.



Plasma acceleration

- If the cavity is replaced by something that can not be damaged, much higher accelerating gradients can be reached.
- This can be done by creating a wakefield in a plasma.
- Different tools are used to create such plasma accelerator:
  - Lasers (Tajima and Dawson, PRL, 1979)
  - Electron beams (Hogan et al., PRL, 2005)
  - Proton beams (Caldwell et al., Nature Phys., 2009)

Example of wakefield
Source: http://www.arwenmarine.com

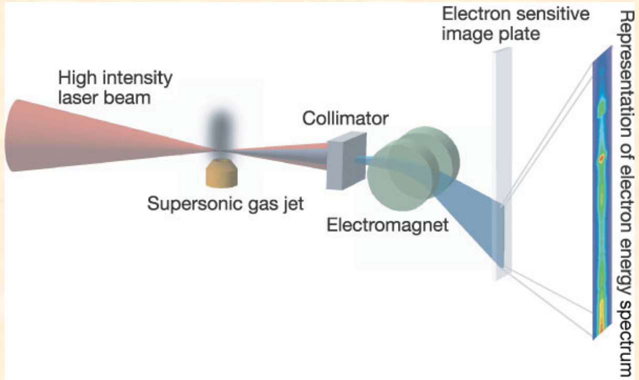


Wakefield in a plasma
Source: CERN Courier

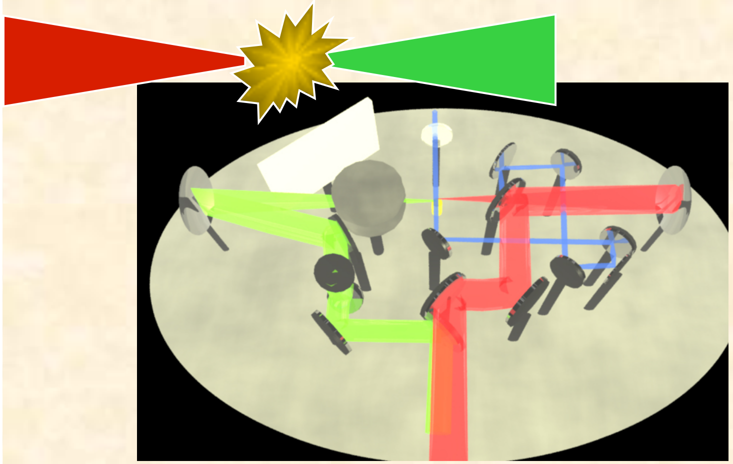
Laser-driven plasma acceleration

- First proposed in 1979 (Tajima and Dawson)
- In the 90s LULI demonstrated that injected electrons can be accelerated from 3 MeV to 4.5 MeV (Amarinoff et Al., PRL, 1998).
- Significant progress in 2004:
  Nature: "dream beam"
  - RAL/IC/UK: Mangles et al.
  - LOA/France: Faure et al.
  - LBNL/USA: C.G.R. Geddes et al.

Laser-driven plasma acceleration: "dream beam"



Mangles et al, doi:10.1038/nature02939

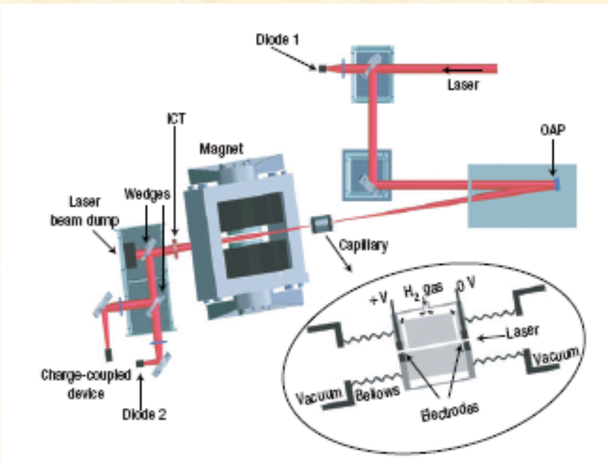


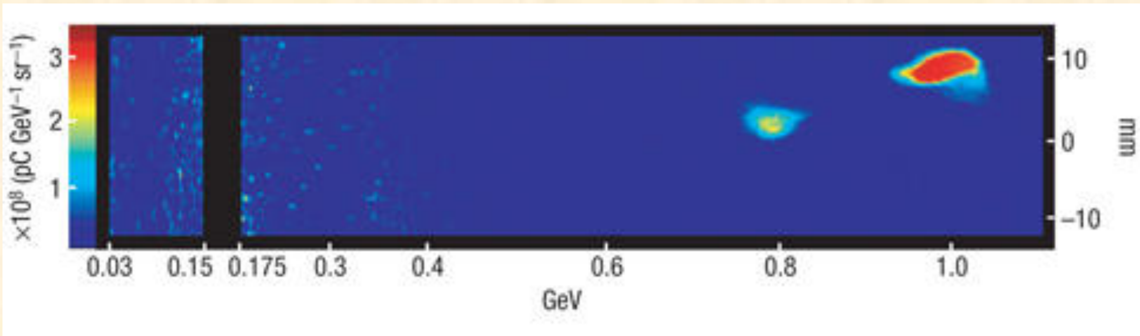
Faure et al., doi:10.1038/nature05393

- In the "dream beam" experiments the plasma was created in a gas jet.
- In this case the electrons are taken from the ions inside the plasma.
- In 2008 a beam of 800 MeV was produced using this technique (Kneip,..., ND, et al., PRL, 2009)

GeV LPA beam

- Another breakthrough occurred in 2005 when a Berkeley + Oxford collaboration reached an energy of 1 GeV.
- To do so they used a 33mm long capillary to extend the length over which the plasma has the right properties to accelerate electrons.
- The field created during this experiment was of the order of 100 GV/m!



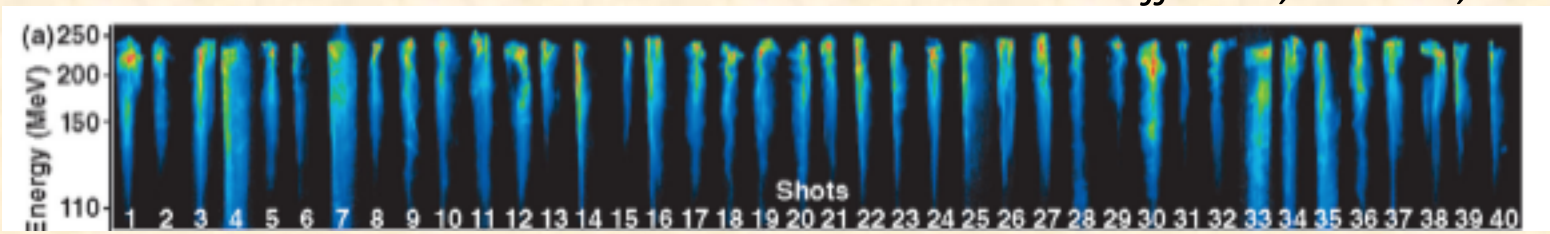


Leemans et al, doi:10.1038/nphys418

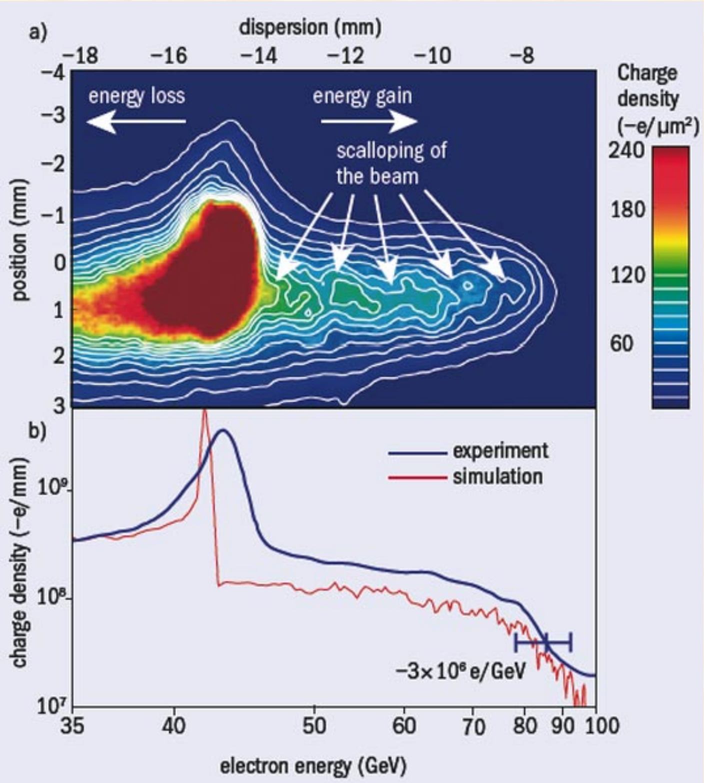
Typical features of LPA beams achieved so far

- Energy 50 MeV – 1 GeV
- Energy spread: from very large to a few percent
- Low repetition rate: 1Hz and less
  (eg: 1 shot every 20s at GEMINI)
- Low charge: 10-50pC
- Ultra-short pulses: 5-30fs (measure very difficult)
  => High peak current
- Shot to shot reproducibility is poor.
- Very small footprint for the "accelerator", laser included (few rooms).
- Simulations are difficult (particle in cell on large computers)
- Not all plasma acceleration experiments produce the beam predicted/ expected…

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

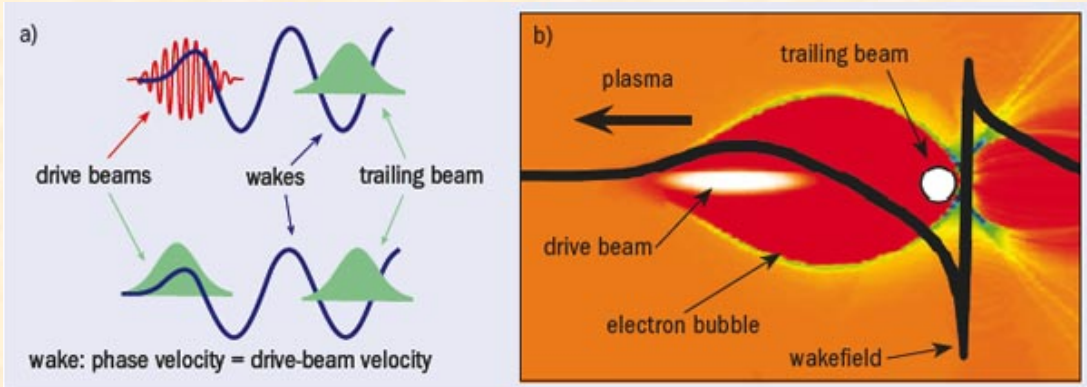


Electron driven plasma acceleration

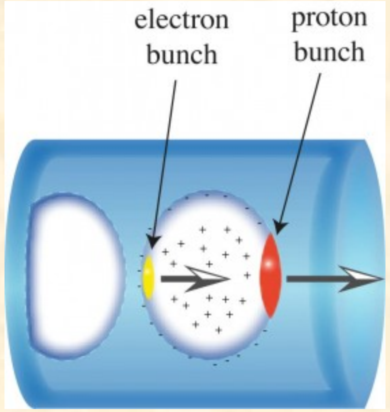


- Electrons can also be used to generate the wakefield required to accelerate other electrons.
- This has been demonstrated using the SLAC LINAC when the energy of some electrons of a bunch was doubled from 42 to 85 GeV.
- The field was about 50 GV/m.

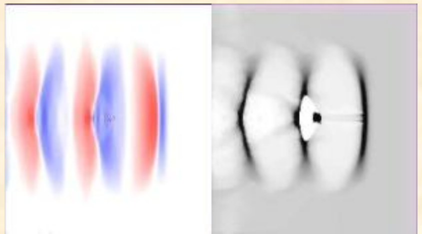
I Blumenfeld *et al.* 2007 *Nature* **445** 741
See also CERN Courier, May 2007 and CERN Courier, June 2007



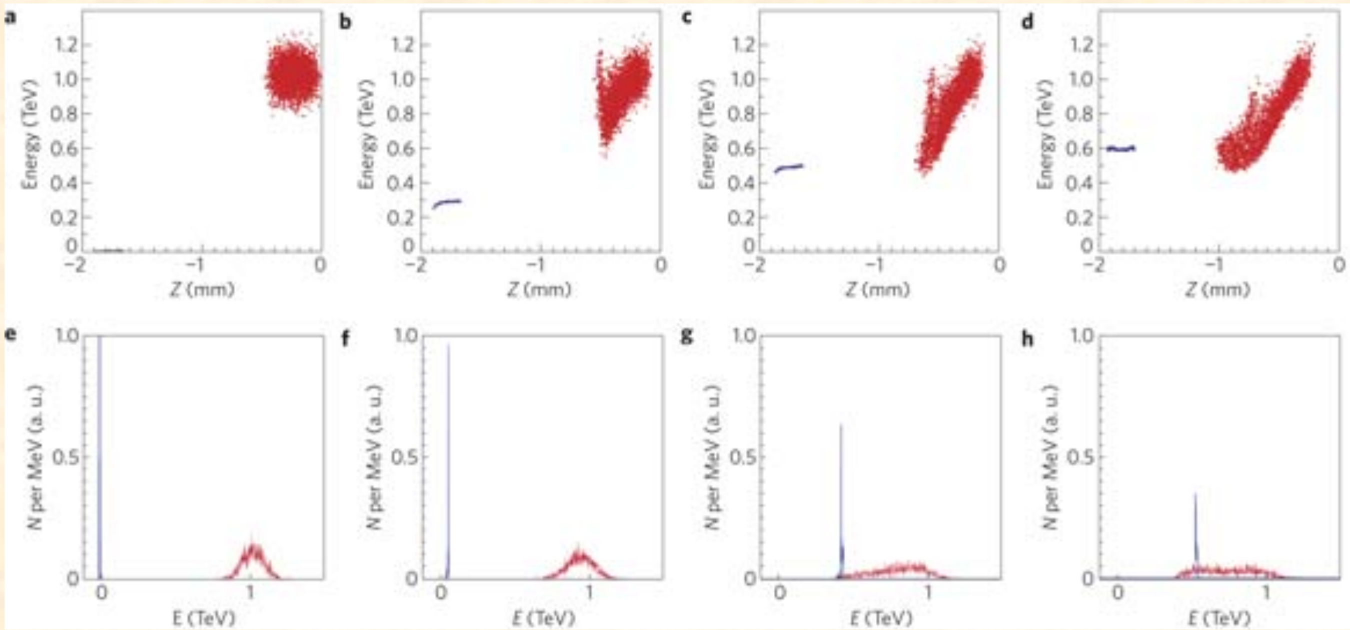
Proton driven plasma acceleration



- More recently there has been a proposal to use protons as drive beam to accelerate electrons.
- Simulations indicate that the CERN SPS beam could be used to accelerate electrons to 600 GeV.

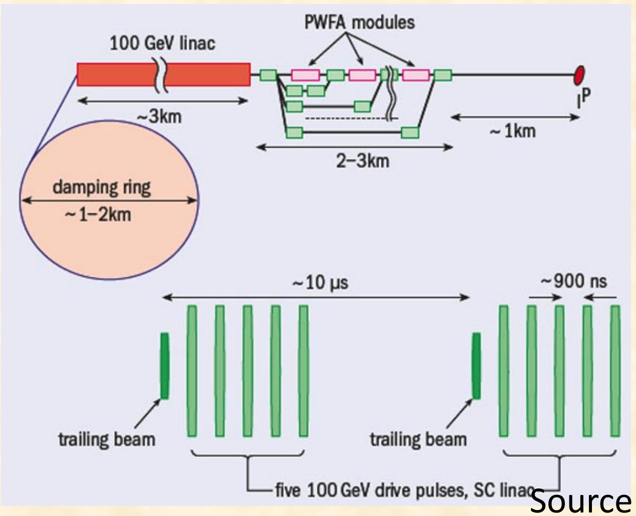


Caldwell et al.,
Nature Physics 5, 363 - 367 (2009)

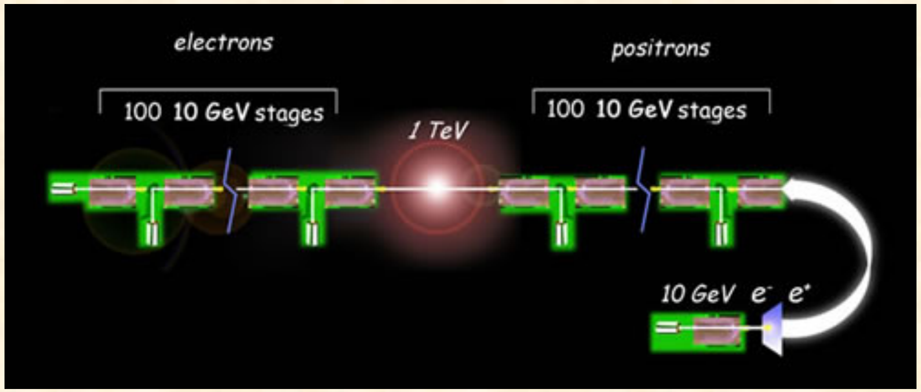


Toward a plasma-based collider

- The next electron collider will require beams with an energy of between 500 GeV and a TeV.
- The production of such beam by a plasma-based collider has not yet been demonstrated, however there are proposal to stage several “accelerating sections” to achieve this.



Source:CERN Courier



Source:LBL

Limits

- Several important steps need to be made before such collider can be built.
- Plug to beam power efficiency is very low. In the case of laser-driven accelerators, fibre lasers may improve this but it may not be enough.
- Beam stability is another issue: at the moment each shot is different and goes in a slightly different direction…
- Very little is know about the quality (emittance) of such beam.

Getting involved

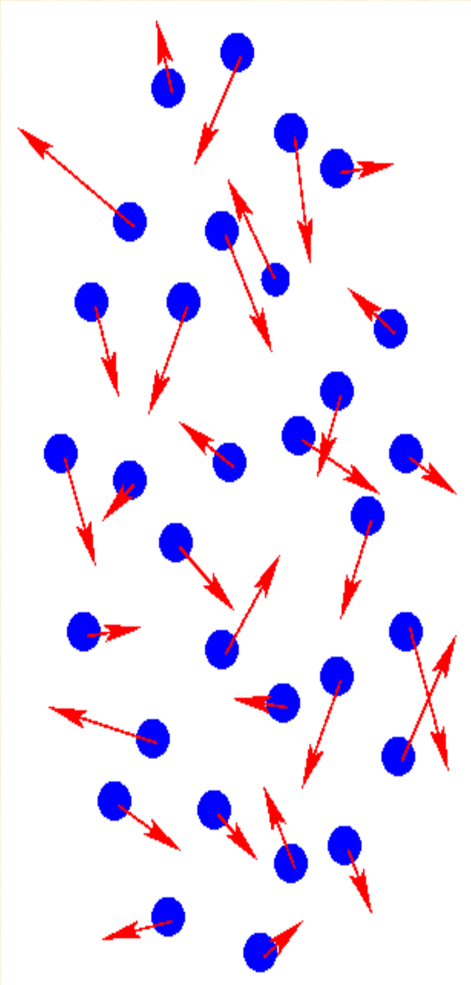
- Although a significant fraction of the developments require laser physics and plasma physics skills, particle and accelerator physicists can help by addressing several questions:
- What are the beam properties? (Energy, Energy spread, transverse emittance, longitudinal profile…)
- What happens when the beam propagates in matter?
- Etc…

Diagnostics for plasma accelerators

- Although the energy/energy spread measurement techniques are well understood (magnet + screen), other diagnostics are not so trivial.
- They must be able to measure the beam properties in a single shot at high energy.

  In Oxford we focussed on:
  - Transverse emittance measurement
  - Longitudinal profile measurement

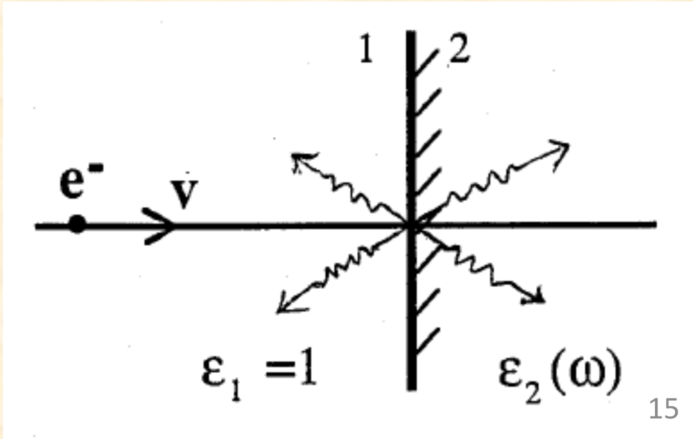
Transverse emittance



- The emittance of a beam is a measure of its quality (“temperature”).
- It is the volume occupied by the beam in the phase space.
- The transverse emittance tells how strongly the beam can be focussed
 => Luminosity.
- Typical high energy techniques average over several bunches.
- We studied 3 different transverse emittance measurement techniques:
  - Multi-OTR measurement
  - High energy pepper-pot
  - Nuclear emulsions based tracking

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.

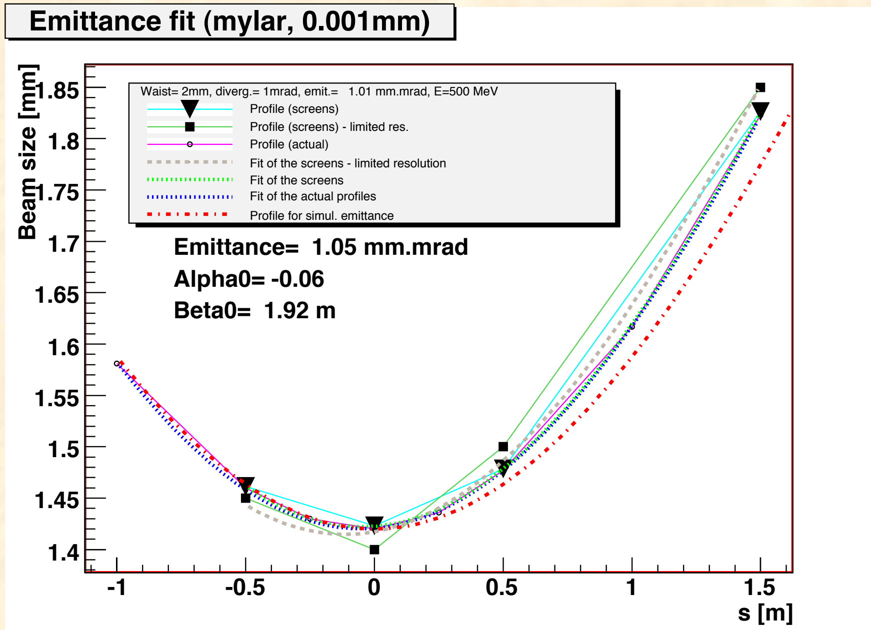


Effect of the scattering

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

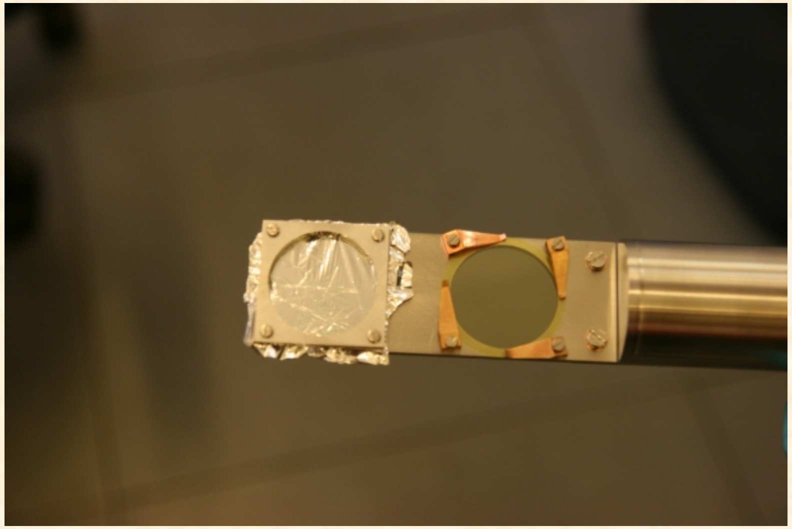
$$\sigma_0 << N_{\text{screens}} \frac{mc\epsilon_n}{p\theta_0}$$

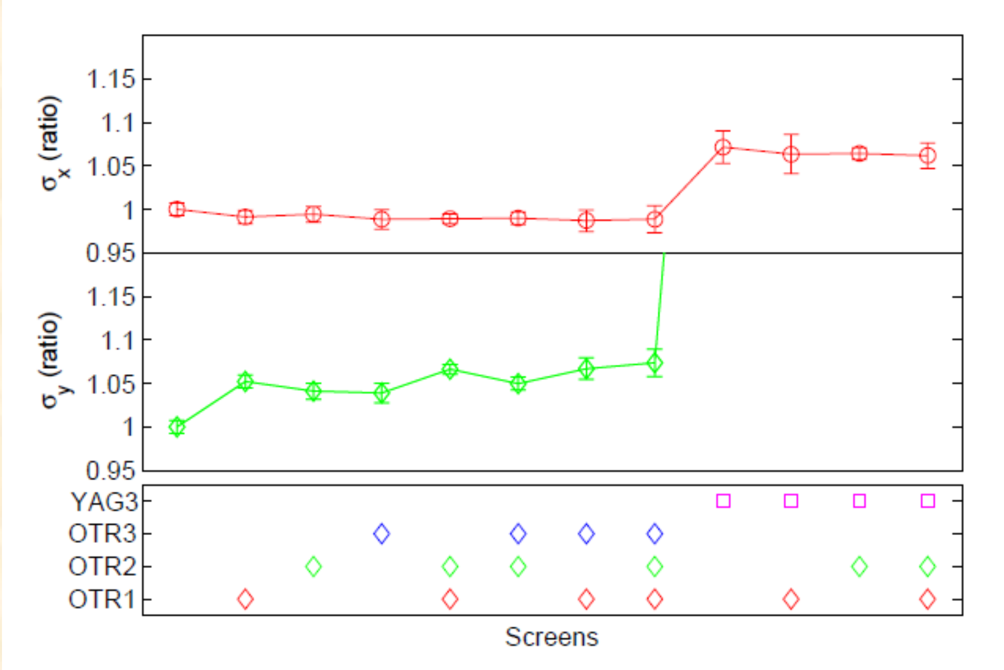
- For a small (focussed) beam the natural divergence will dominate the effect of the scattering whereas for a collimated beam the scattering will dominate.
- GEANT4 simulations were used to validate these calculations.



Delerue et al., arXiv:1005.2417 (submitted to JInstr)

Experimental validation

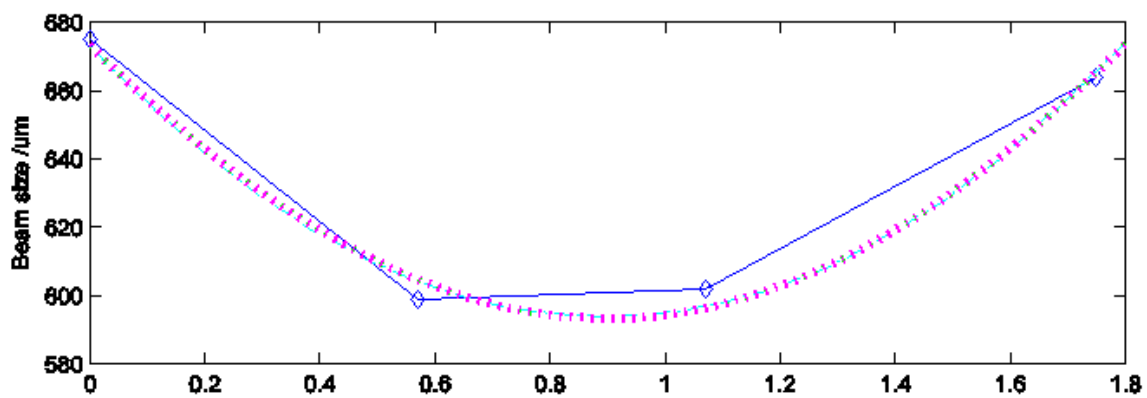


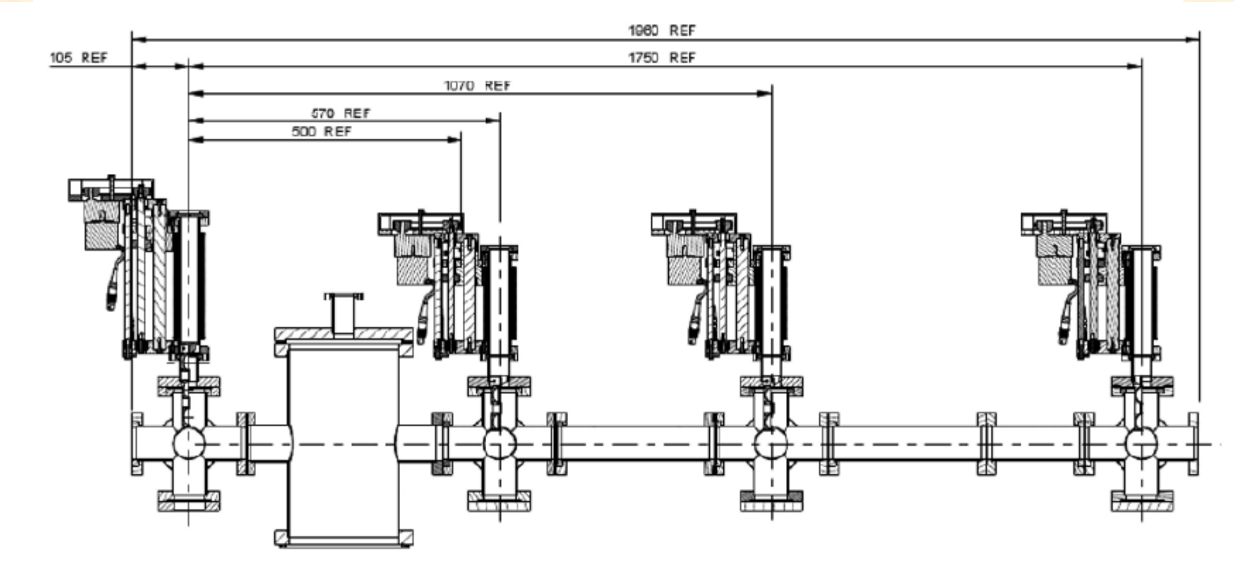


- This was verified experimentally using the DIAMOND (UK) BTS (3 GeV electrons).
- The beam optics validates the condition on x and is close to it in y.
- Scattering with OTR screens is seen in y and not in x.

Thomas, ND et al., IPAC'10 MOPE080

Single shot transverse emittance measurement at 3 GeV





$$\sigma(s) = \sqrt{\epsilon\beta_0 + \frac{\epsilon}{\beta_0}s^2}$$

Measured value close from the DIAMOND predictions.

Shot to shot variations observed…

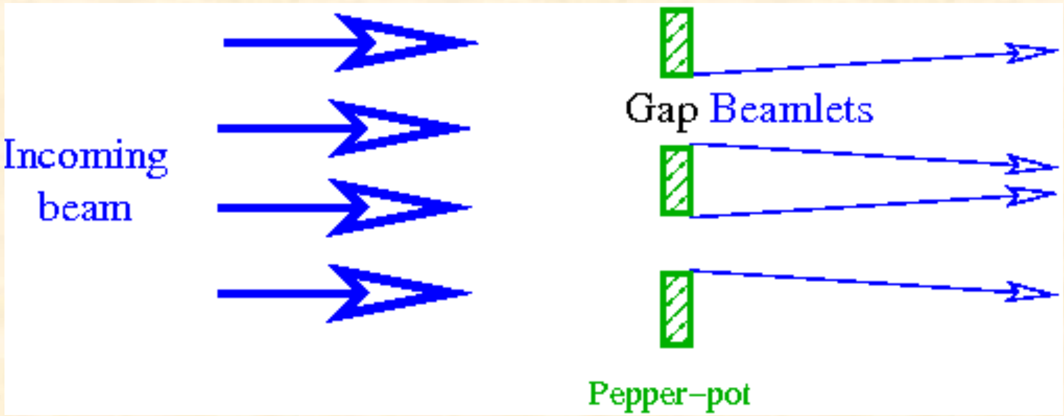
Thomas, ND et al., IPAC'10 MOPE080

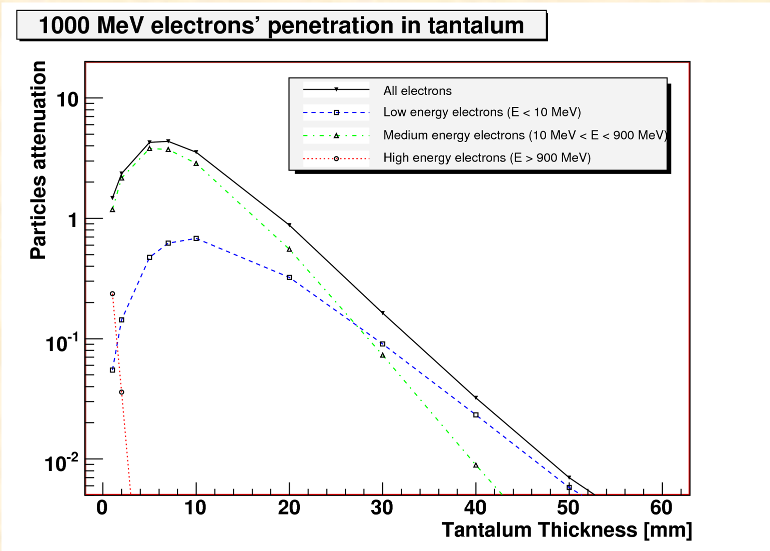
OTR summary

- 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.

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…





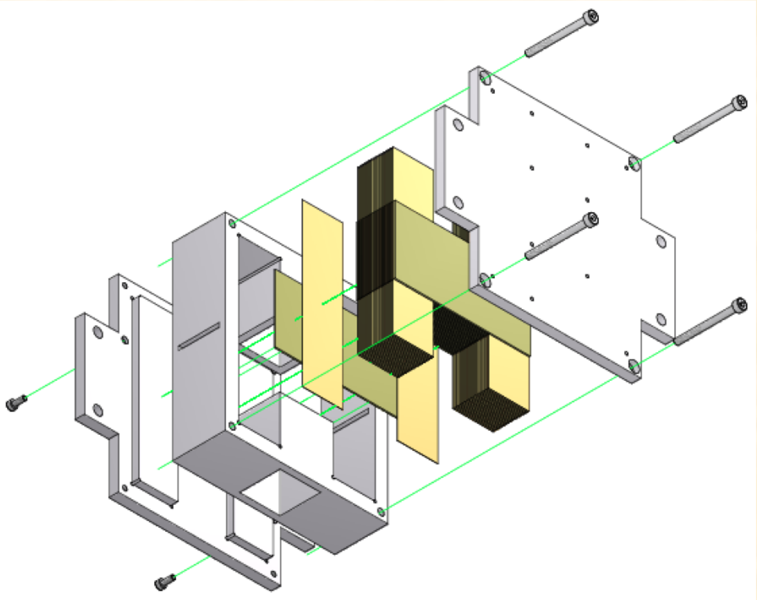
Extended pepper-pots

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

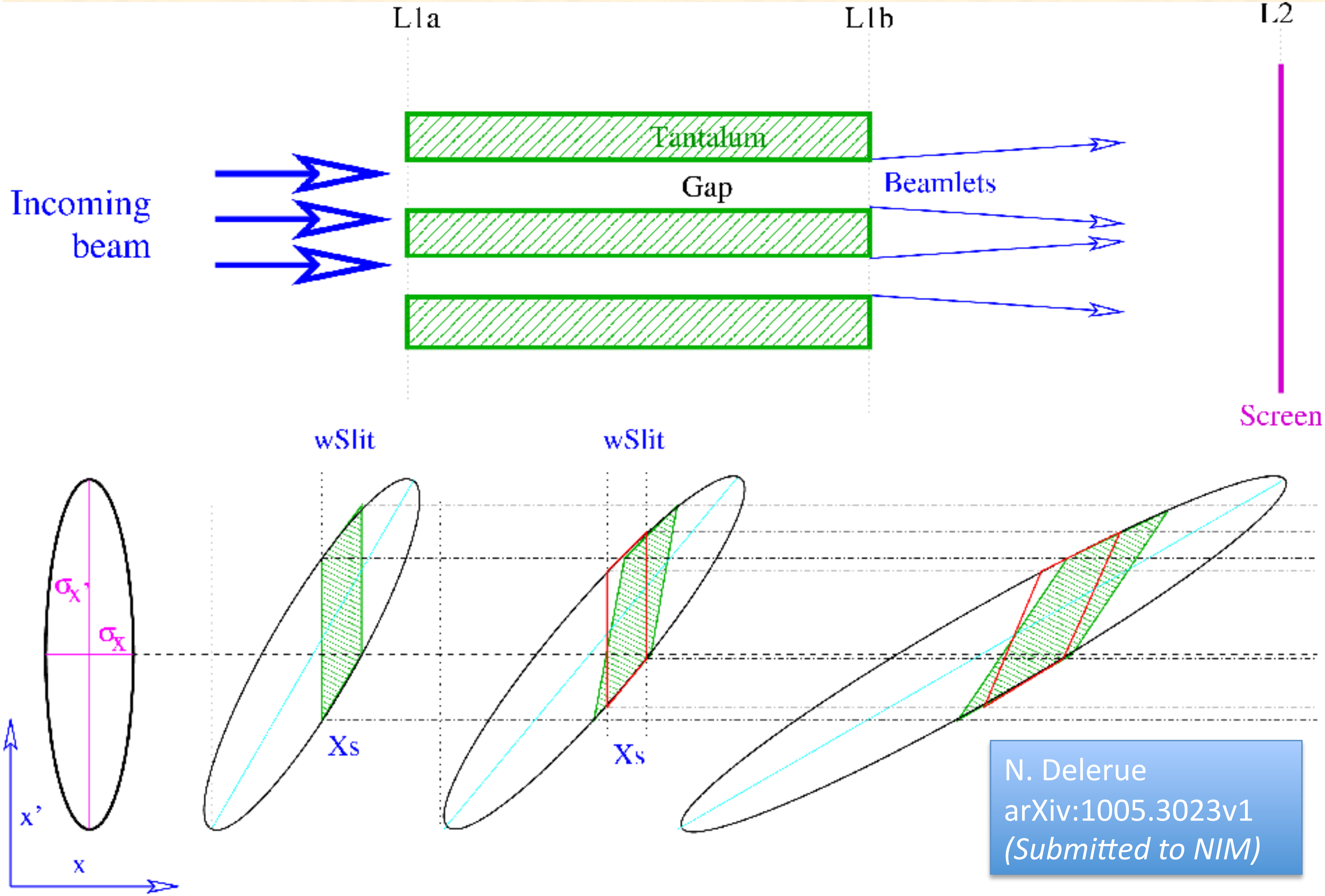
- Two challenges:
  - Mechanical assembly
  - Phase-space preservation

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.



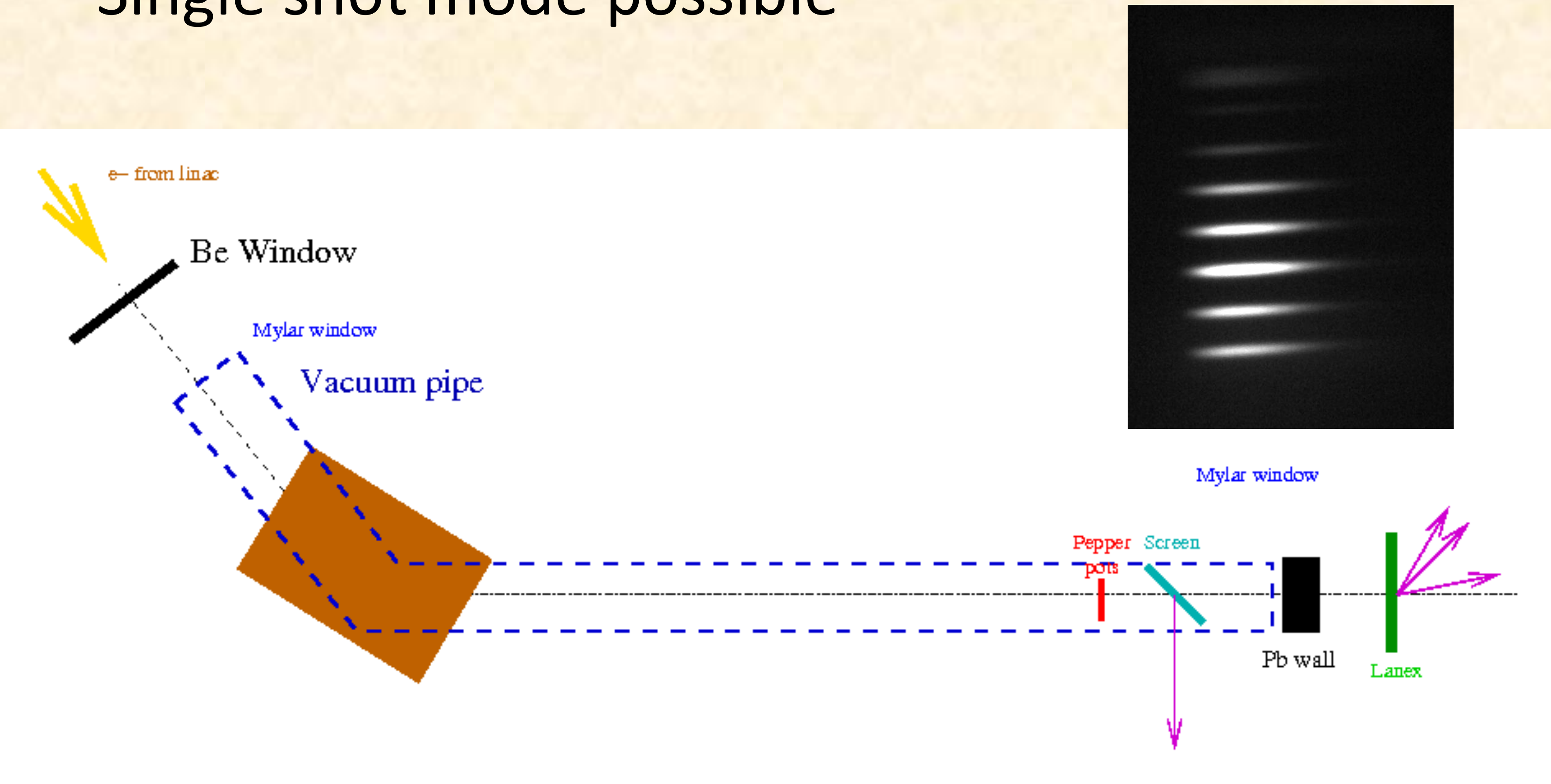
Phase space preservation



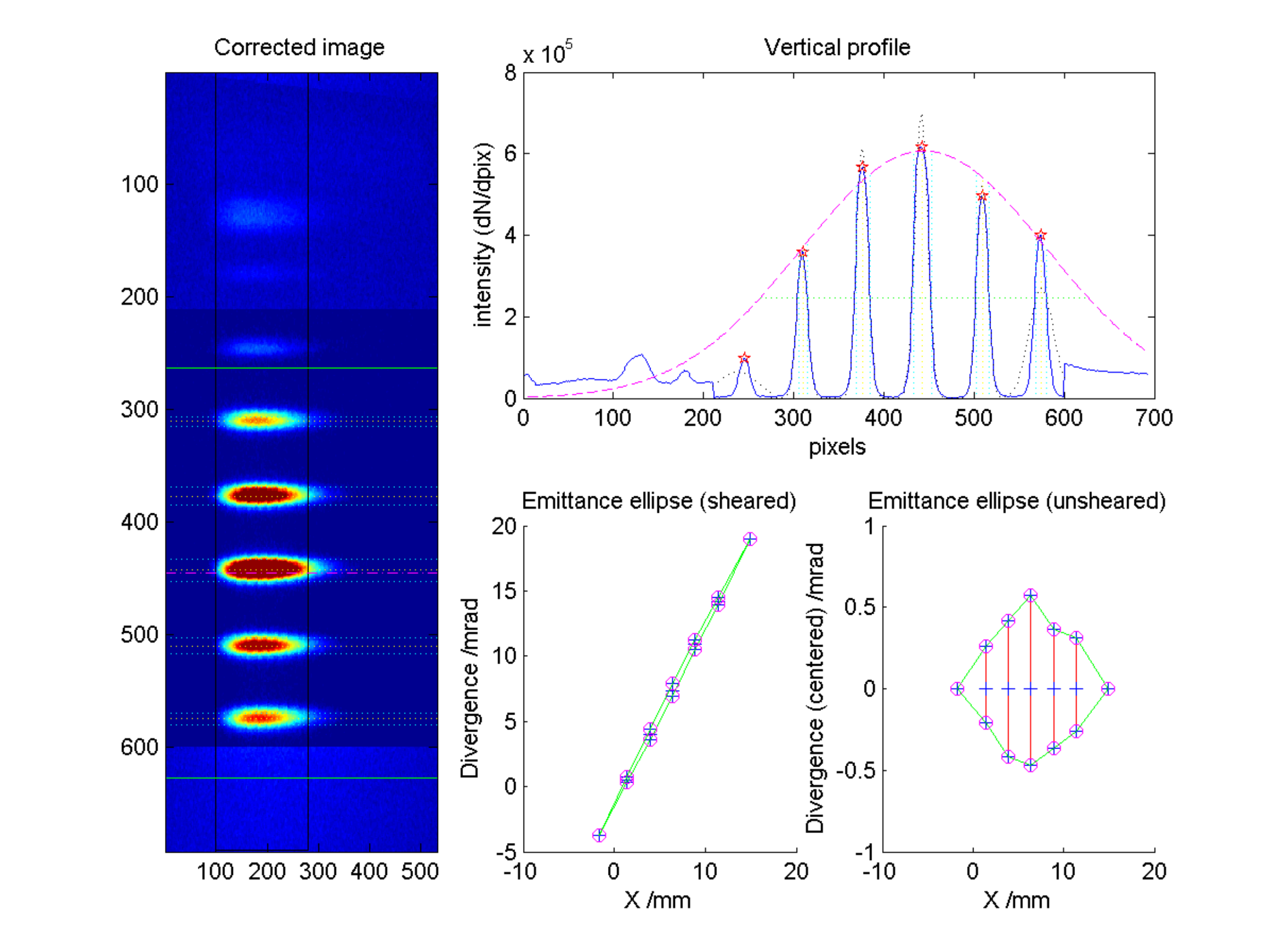
N. Delerue
arXiv:1005.3023v1
(Submitted to NIM)

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

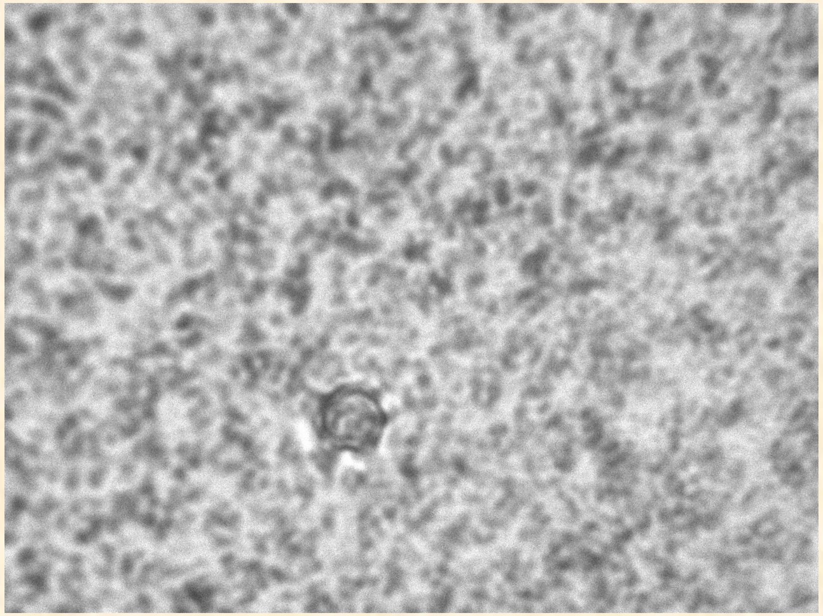
Delerue et al. PAC'09 TH5RFP065

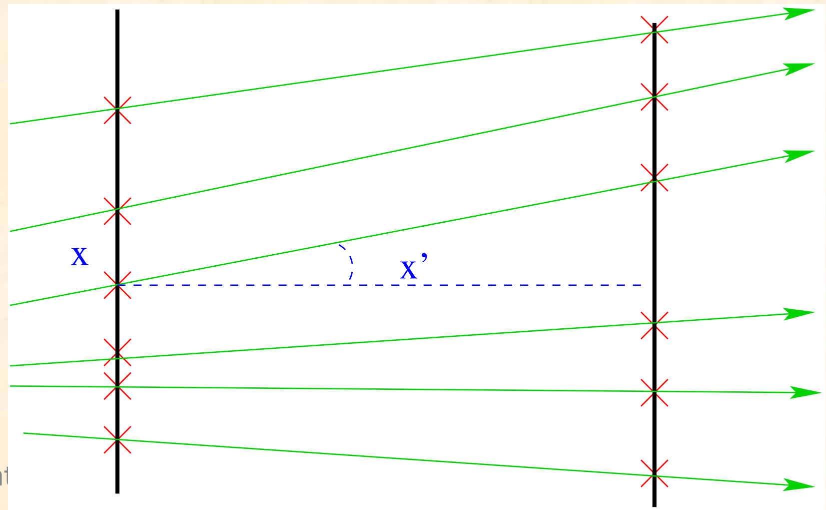
Pepper-pot summary

- 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

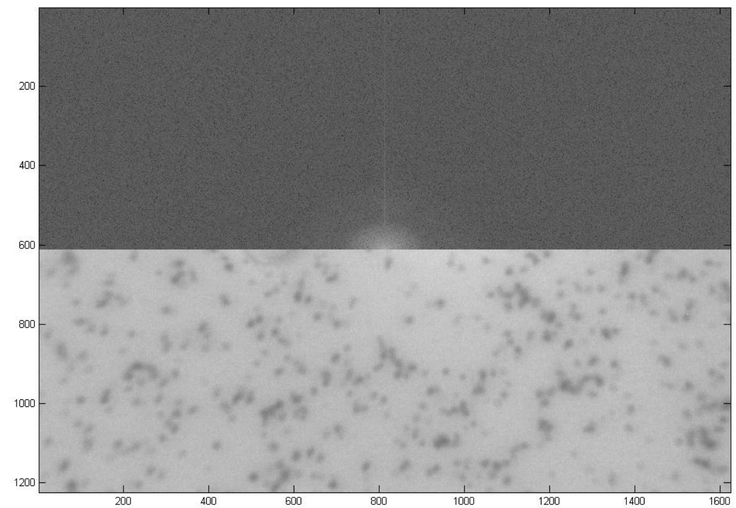
- Perfect emittance measurement
 => position + direction of each particle.
- Nuclear emulsions can resolve particles with a resolution of about 1um.
- Stacks of thin emulsions can resolve the direction and the position of a beam.
- Damaging an emulsion plate with a high power laser is less of a problem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





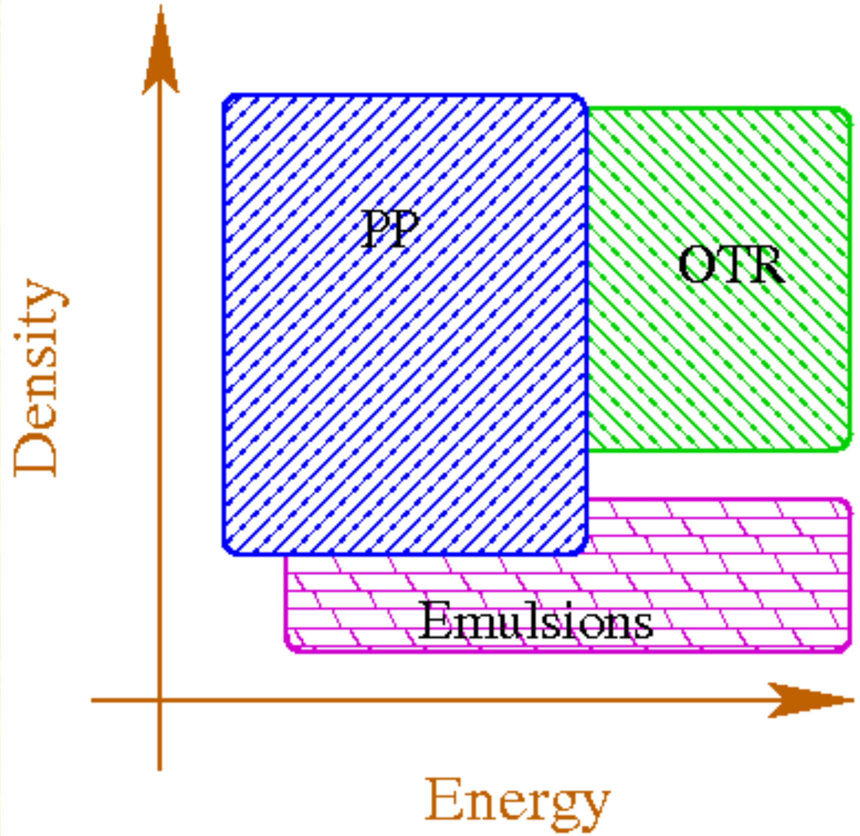
Particle tracking

- 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.



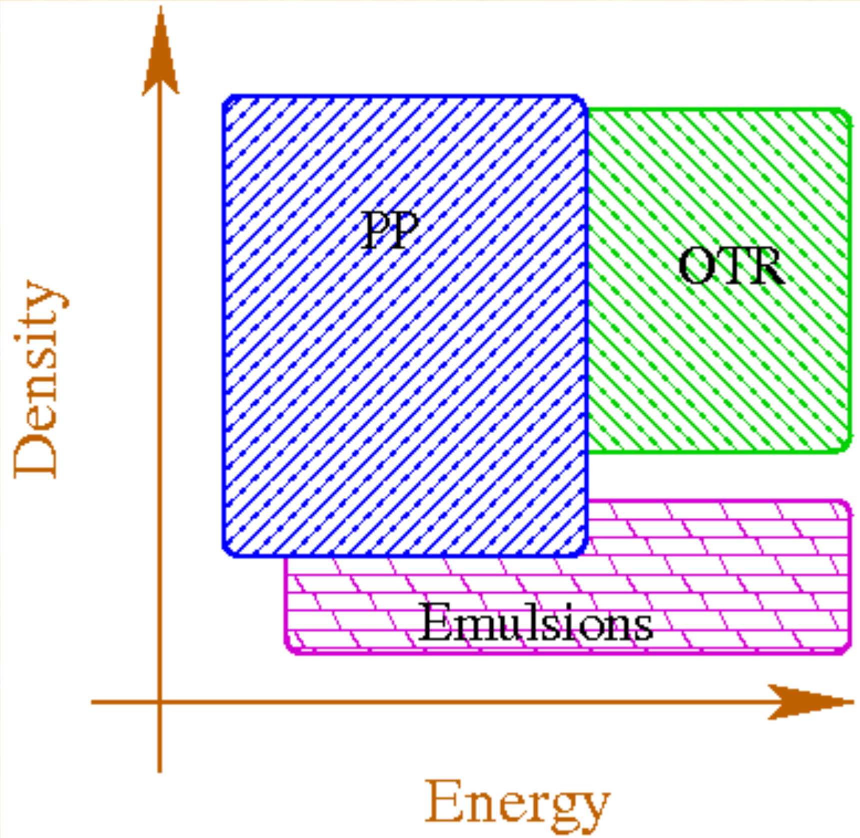
- We demonstrated that all the bits work but did not have time to put them together within the duration of the grant.
- There may be applications with ion beams.

Why 3 techniques



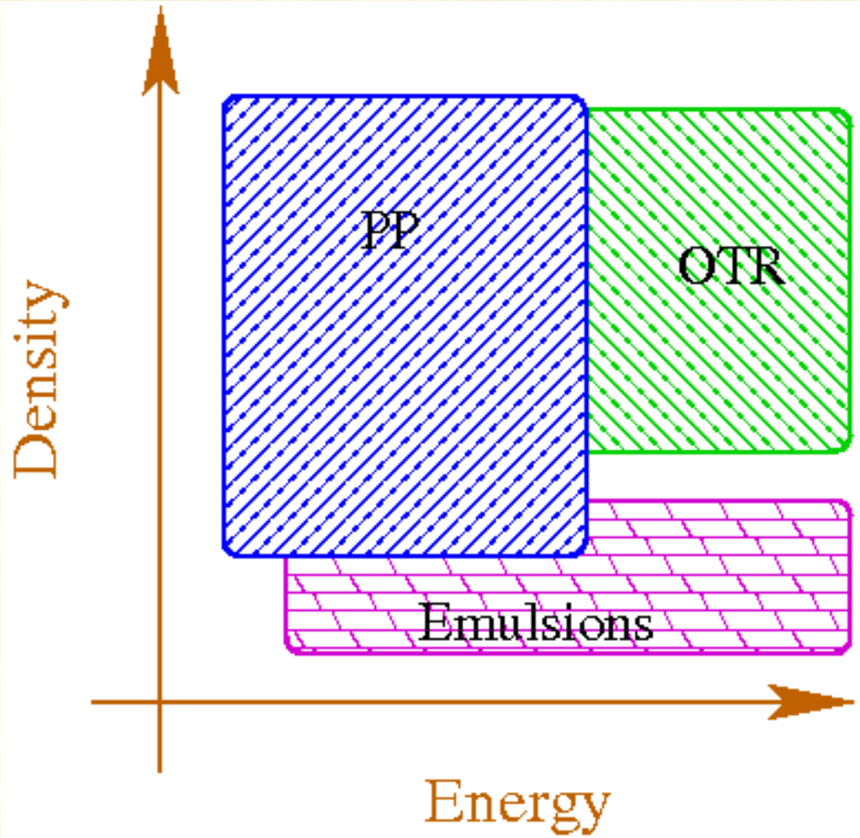
- The 3 techniques we studied are meant to be complementary:
  - Multi-OTR requires an intense beam to have enough OTR signal.
  - At low energy scattering is too intense.

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.

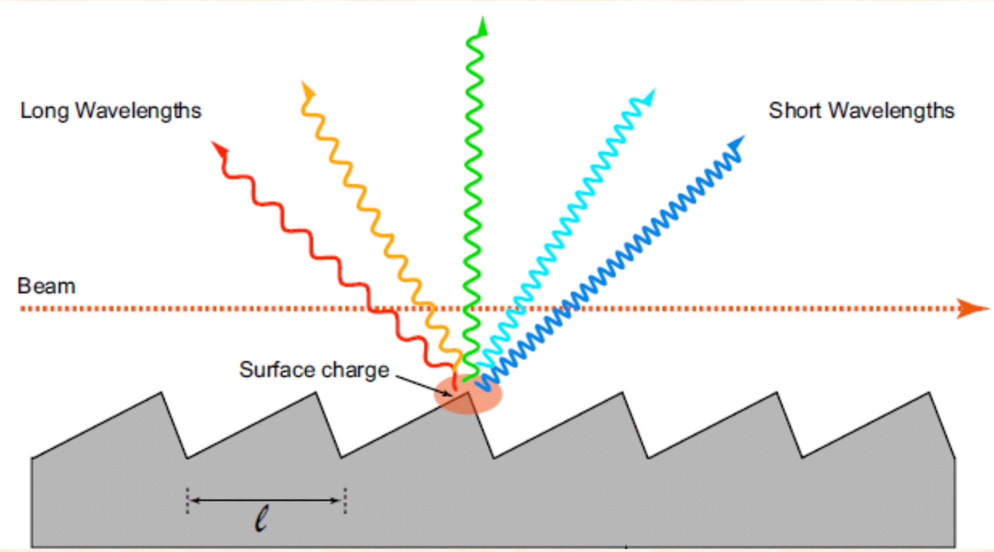
The information provided by the 3 methods is also slightly different.

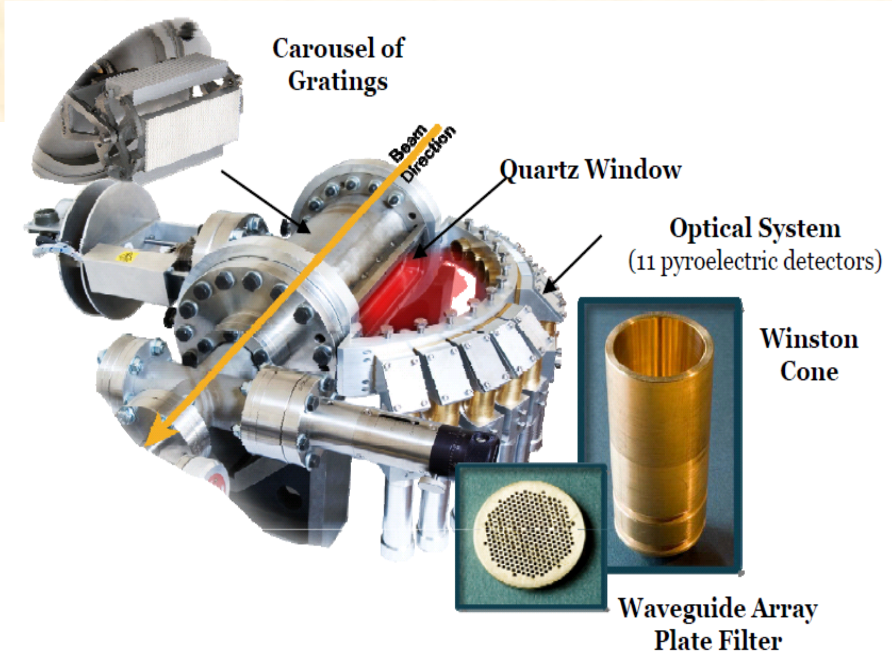
Longitudinal profile measurement

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 30fs)
- Several techniques (CTR, CDR, …) use the radiation emitted by a relativistic bunch when passing trough/near an interface.

Smith-Purcell radiation



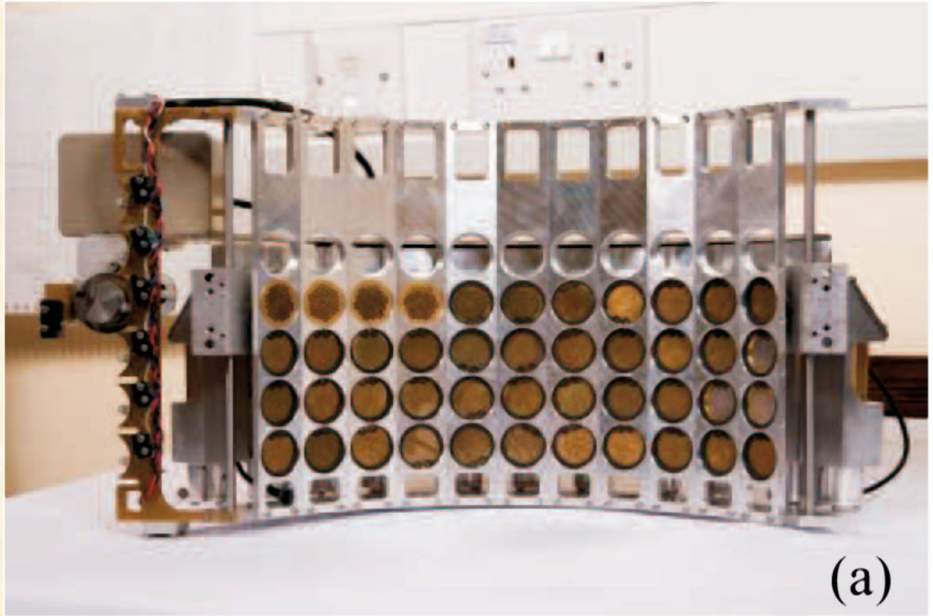


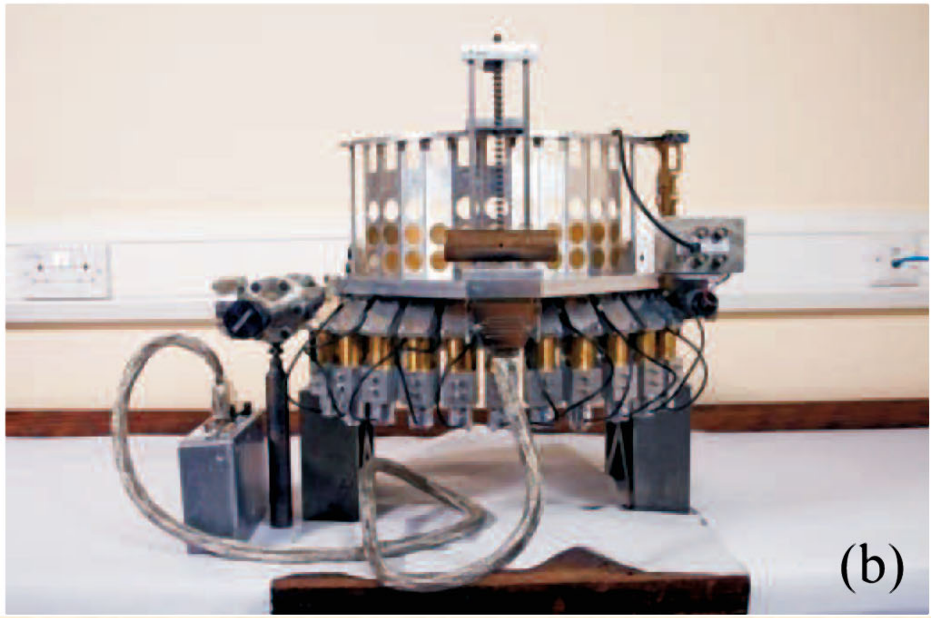
- Smith-Purcell radiation is emitted when relativistic charged particles pass near a grating.
- Pioneering work on its use as longitudinal profile monitor done in Oxford by George Doucas (in the picosecond regime).

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.

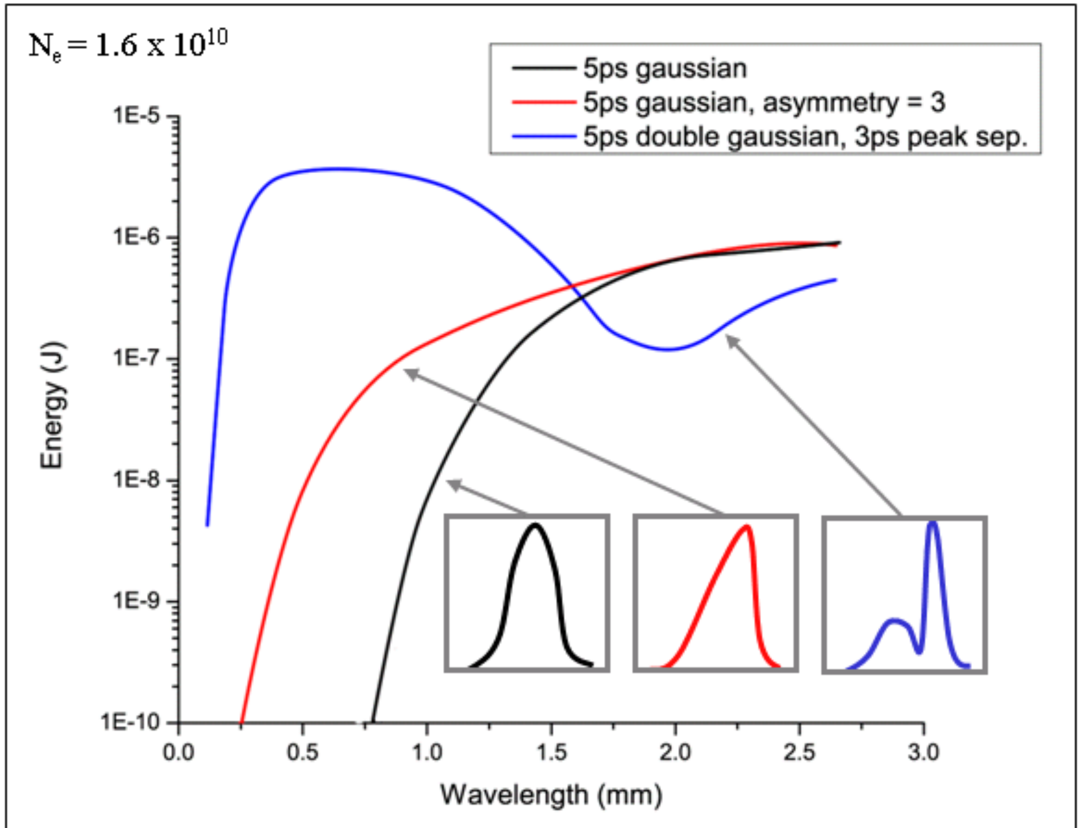
Smith-Purcell detector





- 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

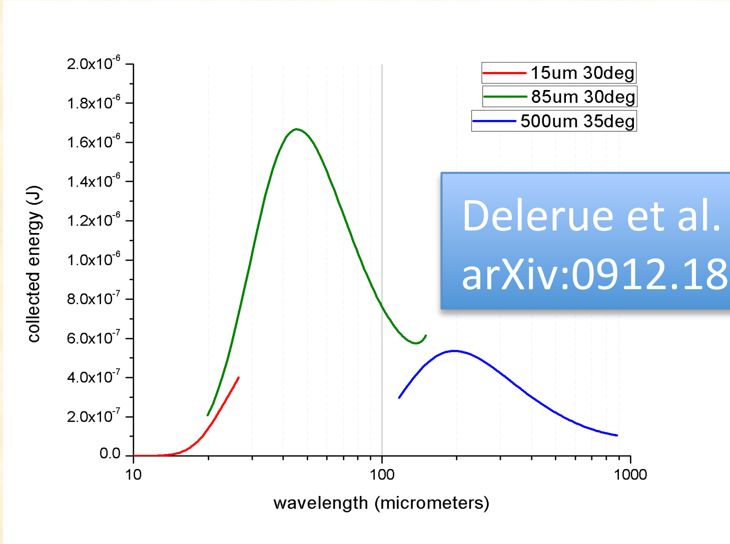


Simulation of different profiles, as would be seen experimentally

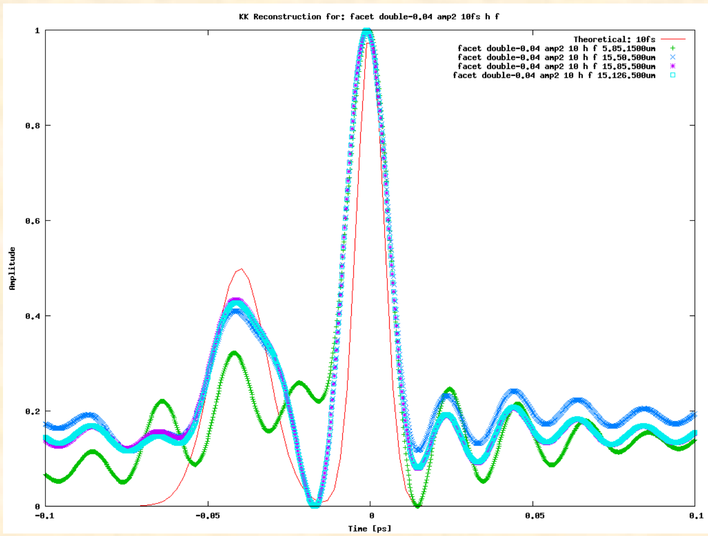
Different bunch profiles will give different radiation spectrums which can be reconstructed.

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.
- We have applied to do tests at FACET (SLAC) next summer.

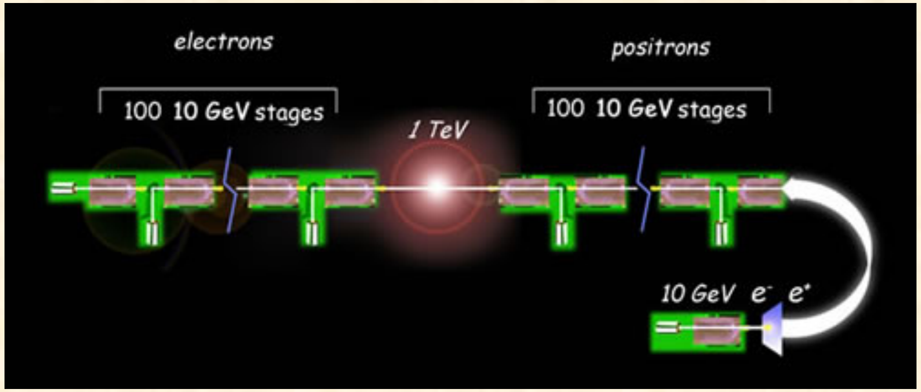


Delerue et al.
arXiv:0912.1863

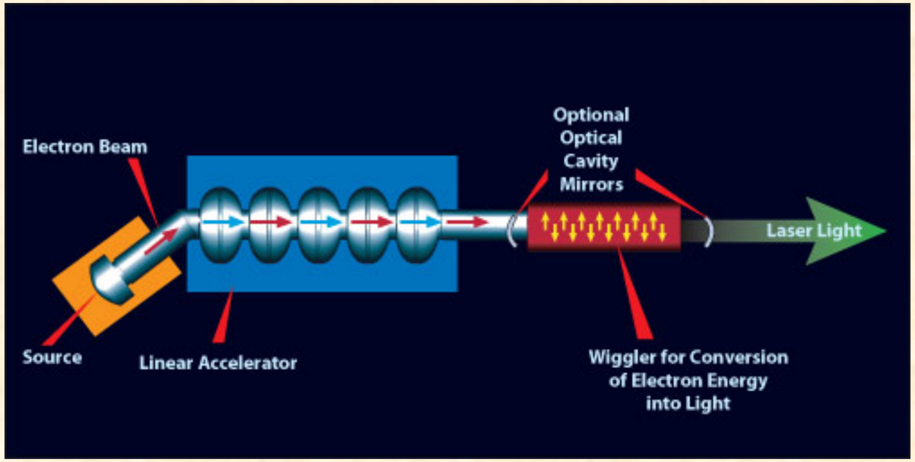


What to do with a plasma accelerator?

- Staging hundreds of plasma accelerators to build a “plasma based” linear collider is an interesting idea but there are still many challenges to solve before it can be done.
- However there are other applications for sources of electrons between 200 MeV and 1 GeV.
- The bunch energy and duration (10s of fs) are comparable to those required by free electron lasers (FELs).



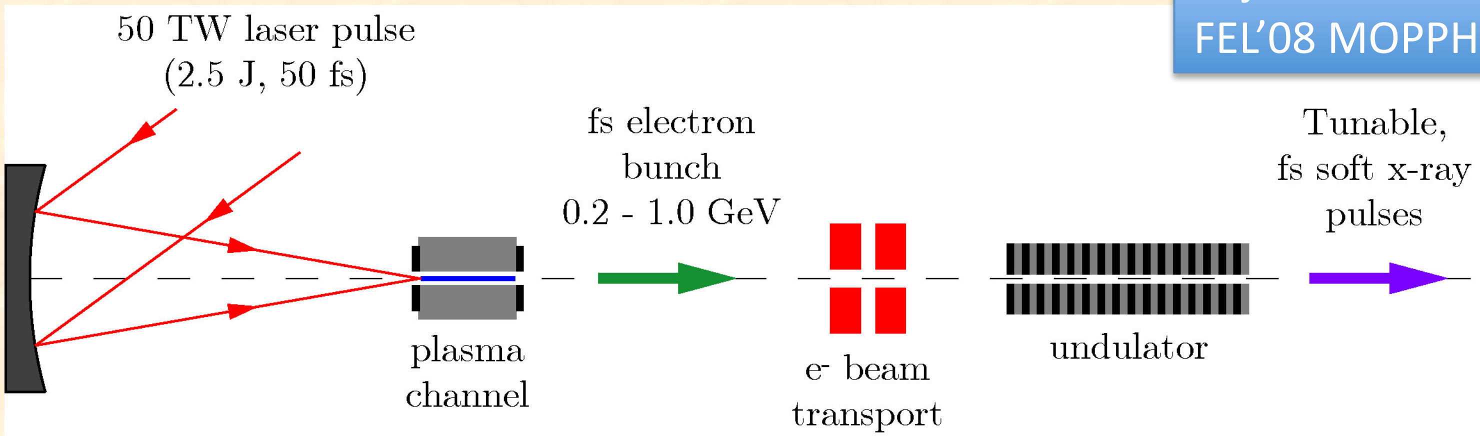
Source:LBL



Source:Lightsources.org

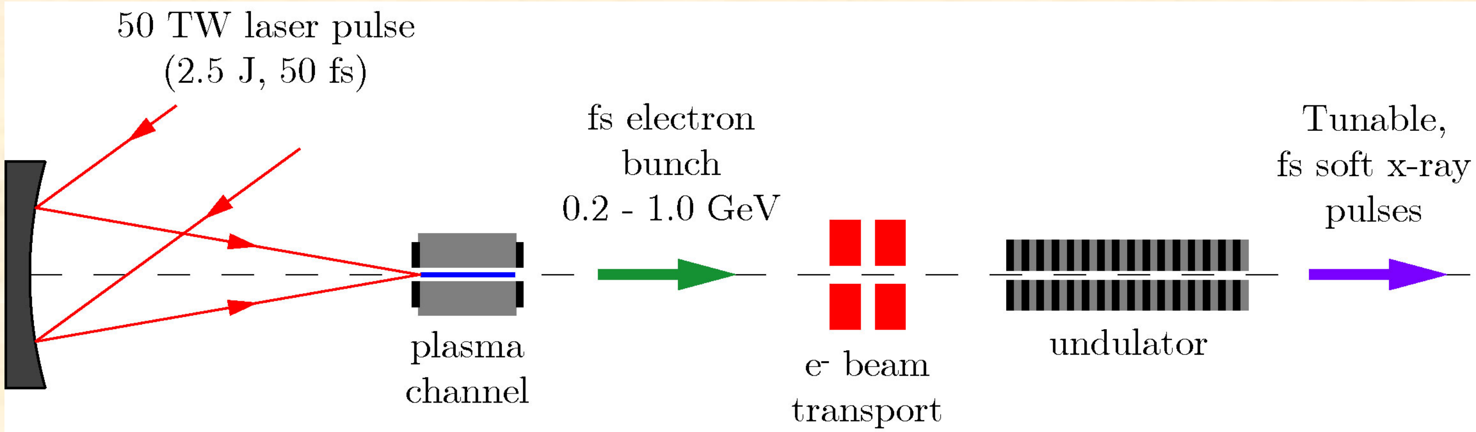
Toward a 5th generation light source

Bajlekov et al.
FEL'08 MOPPH081



- A 500 MeV beam can be used to shoot in an undulator and create X-rays.
- Very attractive source: low footprint (Fits in a university), high brightness,....
- Reasonably priced 5-10MEuros (much cheaper than a conventional X-rays FEL).

Toward a 5th generation light source



- BUT the output of a FEL is strongly correlated with the beam properties.
- To use plasma accelerators as 5th generation light sources one needs to be able to measure the beam's longitudinal profile and its transverse emittance!

Outlook

- Plasma accelerators have made tremendous progress since 1979.
- They have now reached a stage where applications can be considered.
- It is likely that in the coming few years there use a X-rays FEL will be demonstrated.
- Particle physics applications will have to wait longer…
- However they are many opportunities for particle physicists to help this date come sooner:
  - How to measure the properties of a multi-GeV beam?
  - In a multi stage accelerator, what happens when the incoming electrons pass through the laser injection mirror?
  - …

Thank you for your attention

Positrons acceleration

- The leading laser-driven plasma acceleration results ("dream beam", GeV beam,…) accelerated the electrons from the plasma.
  => Not possible for positron acceleration
- Other results (LULI,…) used externally injected electrons. In that case the acceleration gradient is usually smaller ("linear regime").
  => Suitable for positron acceleration
- Particle driven plasma accelerators use externally injected particles.
- In the case of proton driven acceleration, it may even be possible to accelerate electrons and protons in the same train (but at different phases).