Recent results from E-203 at FACET (SLAC): Longitudinal profile measurement of ultra-short electron bunches

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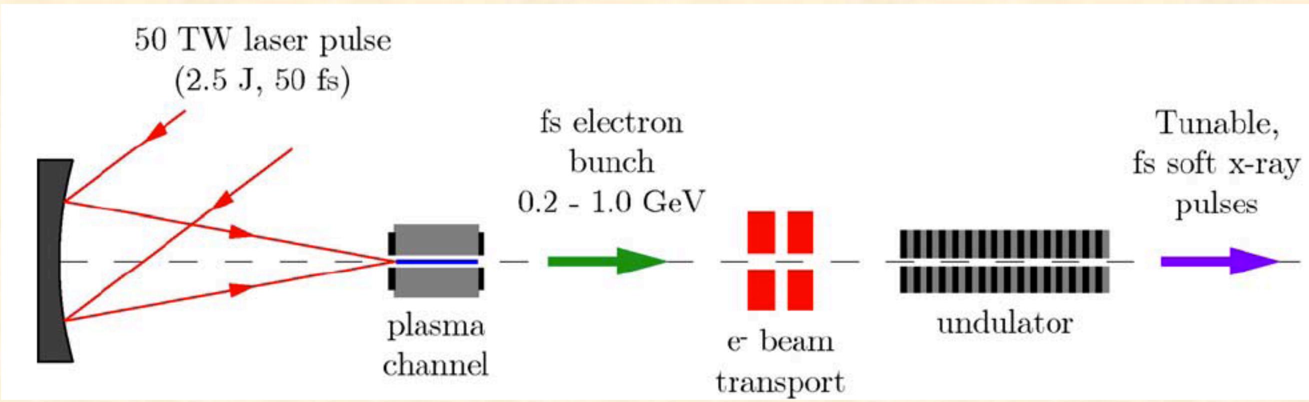
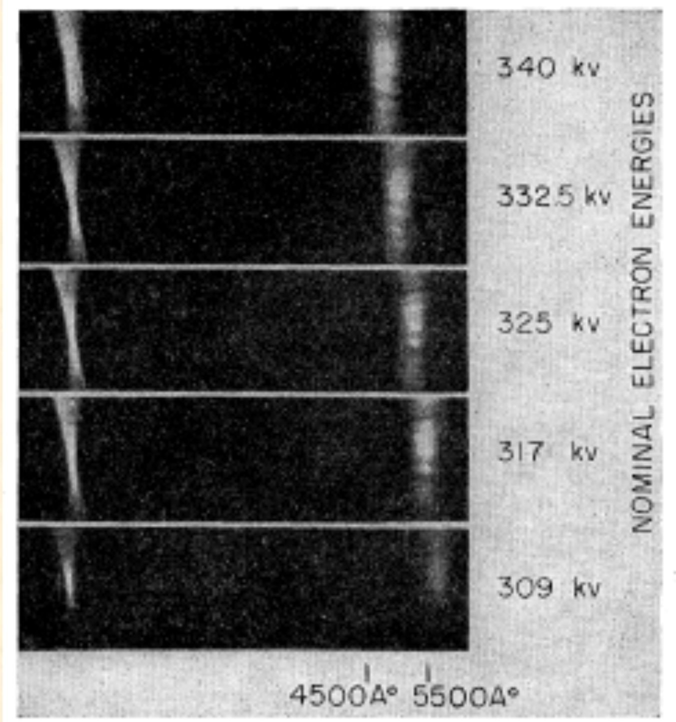
Motivations

- In particle accelerators some effects (eg: coherent effects) depends on the bunch current (charge/time), not the bunch charge.
- Laser-driven plasma accelerators (LPA) use fs laser pulses to produce ultra-short bunches of electrons.
- To use LPA as drivers for FEL it is important to be able to measure the longitudinal profile of the bunch.
- This can be attempted using Smith-Purcell radiation.

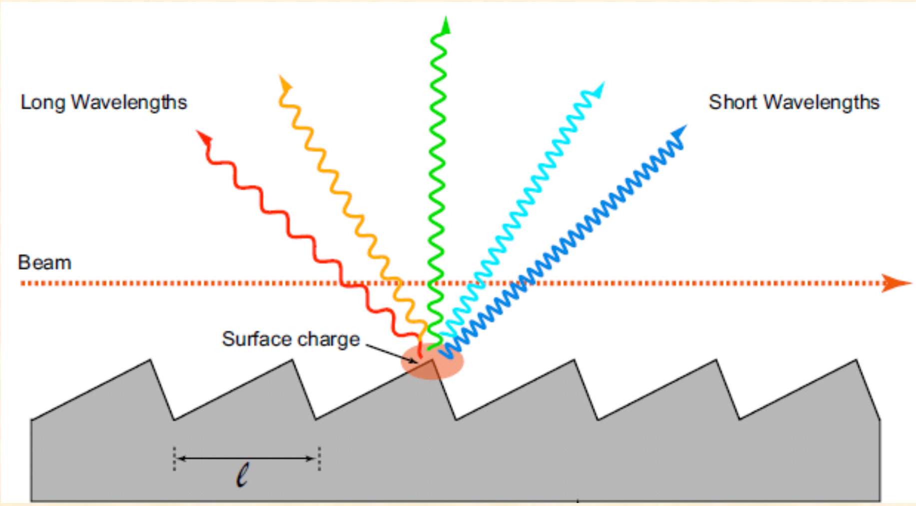


Smith-Purcell effect

- Discovered 1953 by Smith and Purcell.
- Surface charges induced in a grating emit light.
- This can be explained by the accelerating of the induced charges at the teeth of the grating.
- This light is spectrally dispersed by the grating.
- When the charges are induced by a short bunch there can be coherent emission.



$$\lambda = \frac{l}{n}\left(\frac{1}{\beta} - \cos\theta\right)$$



Coherent emission

- Like most radiative processes SPR has an incoherent and a coherent component.
- The coherent component is the product of N^2 and the Fourier transform of the bunch shape squared.

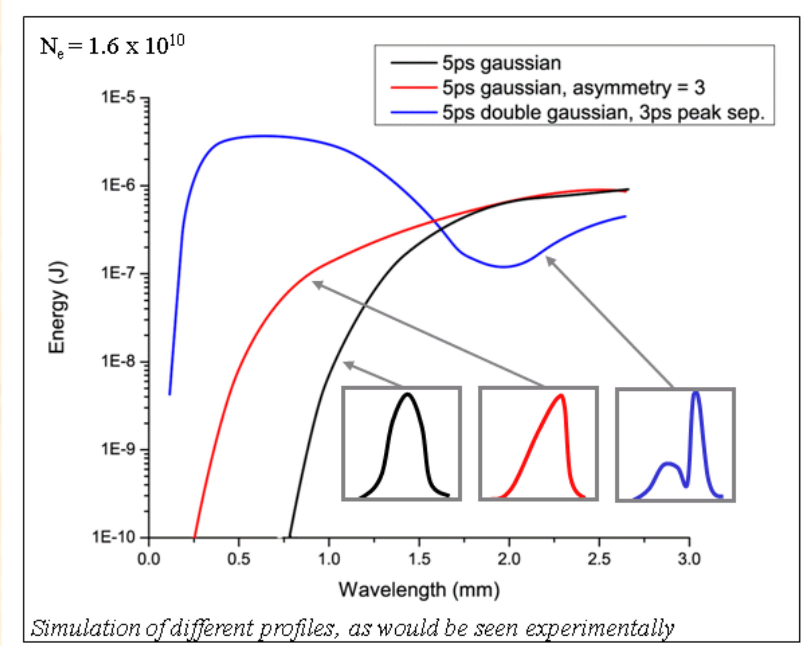
$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e}(\Omega,\omega) = \left(\frac{dI}{d\Omega d\omega}\right)_{sp}(\Omega,\omega)\cdot[N_e + N_e(N_e+1)\,|\,F(\omega)\,|^2]$$

$$\left(\frac{dI}{d\Omega}\right)_{sp} = 2\pi q^2 \frac{Z}{\ell^2}\frac{n^2\beta^3}{(1-\beta\cos\theta)^3} R^2 \exp\left(-\frac{2x_0}{\lambda_e}\right)$$

$$\lambda_e = \frac{\lambda}{2\pi}\frac{\beta\gamma}{\sqrt{1+\beta^2\gamma^2\sin^2\theta\sin^2\phi}}$$

- A measure of the SPR therefore gives a measure of the Fourier transform of the bunch shape.

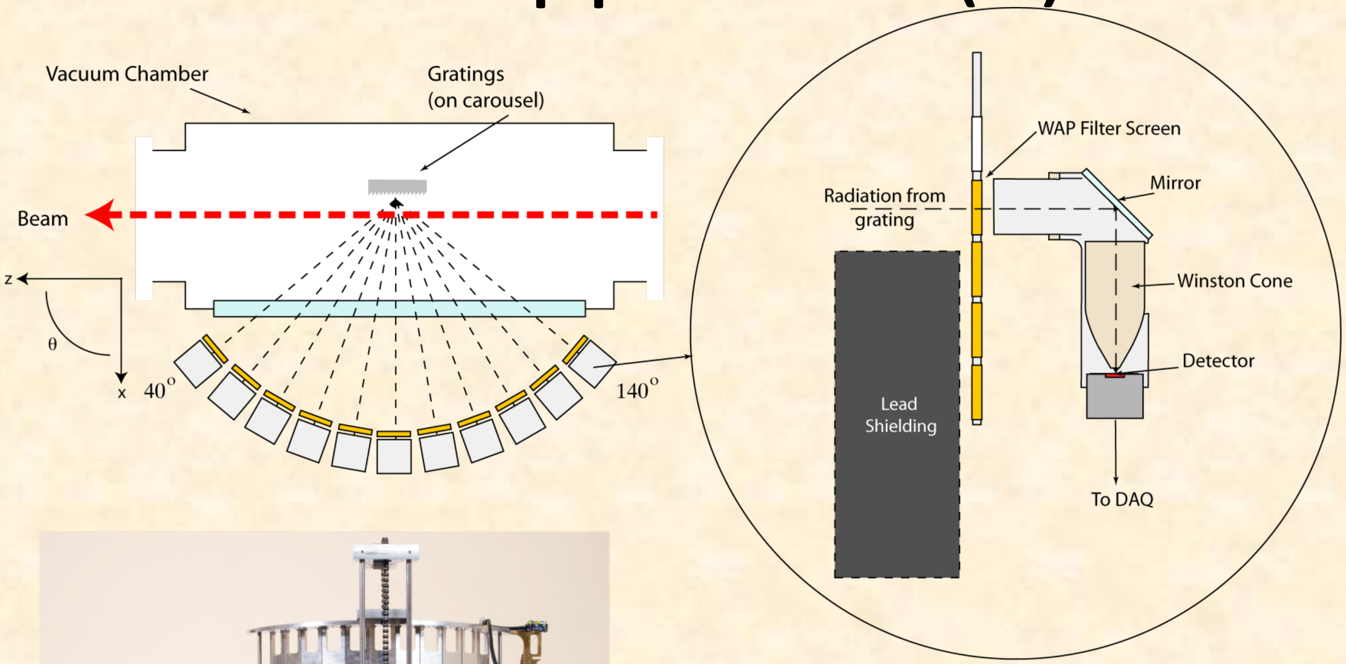
Effect of the profile on the emitted spectrum

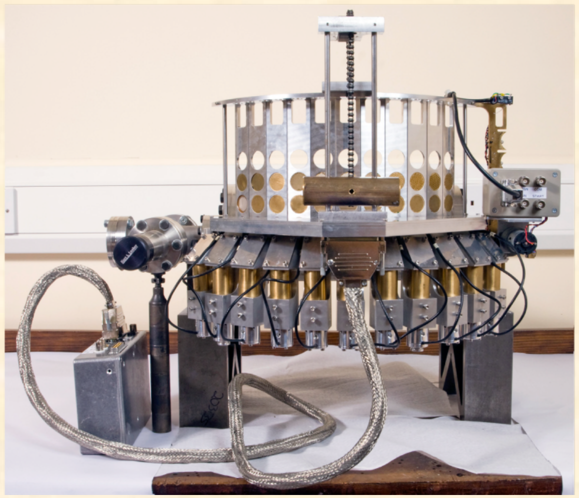


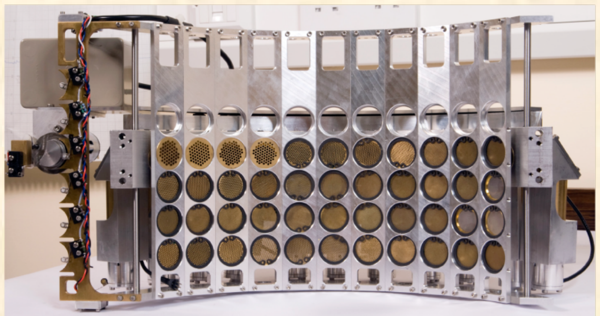
$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e}(\Omega,\omega) = \left(\frac{dI}{d\Omega d\omega}\right)_{sp}(\Omega,\omega)\cdot[N_e + N_e(N_e+1)|F(\omega)|^2]$$

- Pulses with the same "length" but different shapes will produce different SPR spectrum.
- A device able to measure the emitted radiation at different angles is therefore needed.

The apparatus (1)

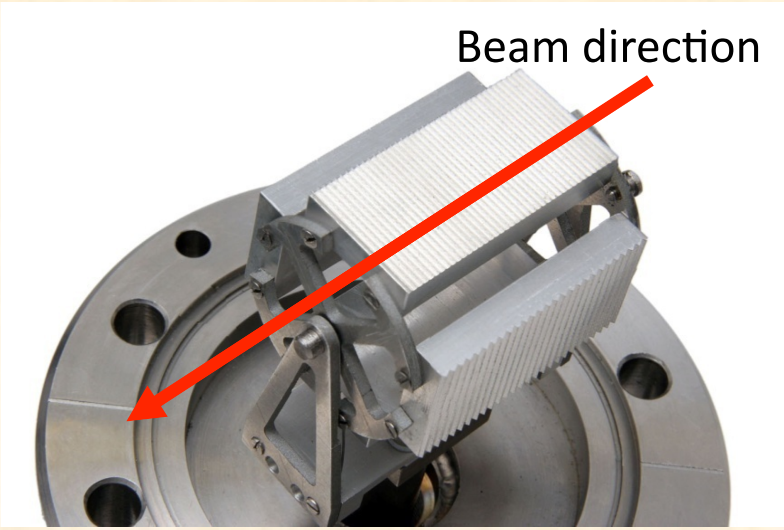


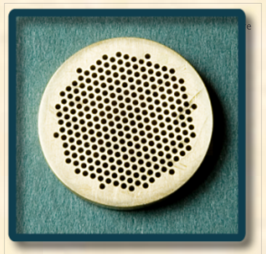


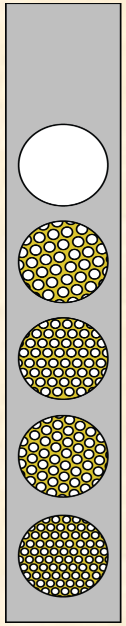


- Ability to switch between 3 gratings (sets of wavelengths)

The apparatus (2)



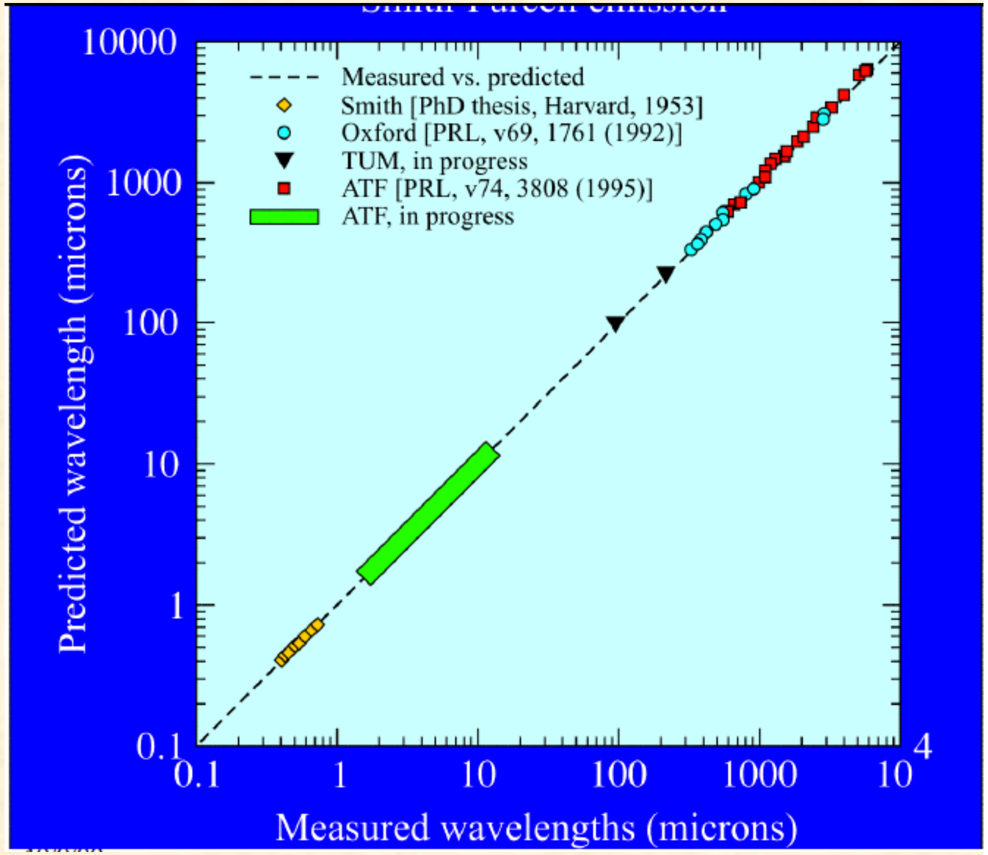




- Gratings carrousel, filters, filters ladder and winston cones.

Early experiments

- In the early 1990s Smith-Purcell radiation (SPR) was seen as a possible seed for FELs.
- After that several experiments were done by G. Doucas to assess its potential as a longitudinal profile monitor in the ps range:
  - FELIX (Netherlands) 45 MeV, 5.5 ps
  - End station A, SLAC (US) 28 GeV, 5 ps

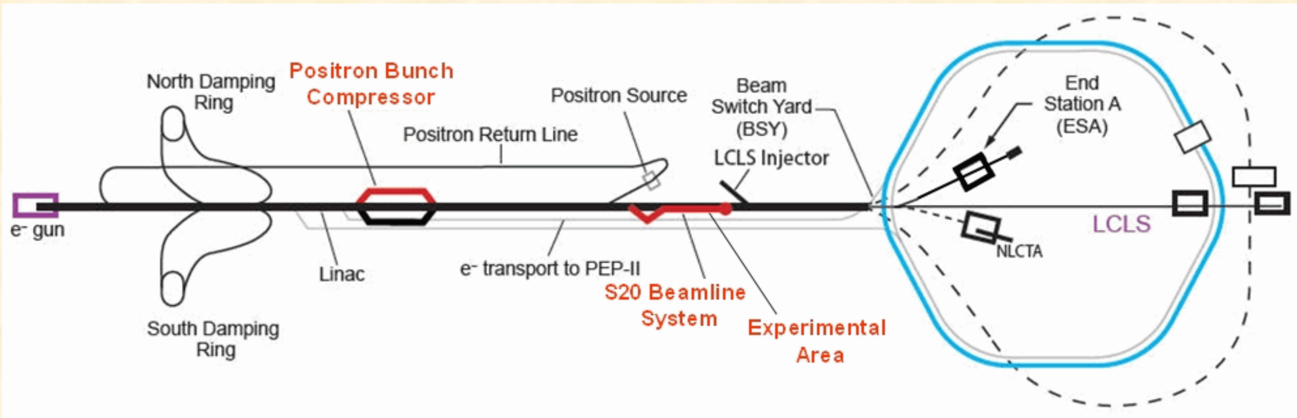


5ps => mm wave

Application to LPA

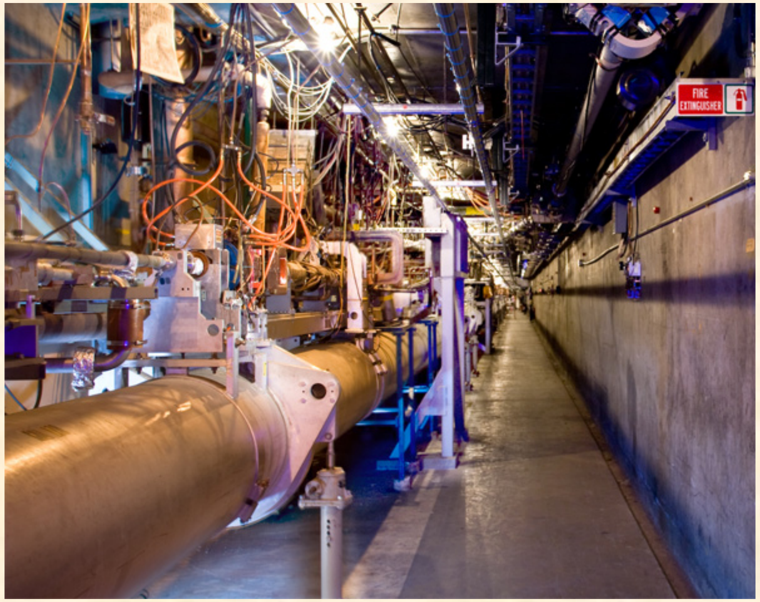
- In 2008, studies started to use SPR at LPA.
- LPA have very short bunches: less than 100fs (some claim just a few fs).
- Such short bunches become coherent near the THz range (50fs => wavelength=15um)
  - Gap between microwaves and optics.
  - In the THz range many materials are absorbing radiation.
  => Measurement is more complicated.
- Before trying at a LPA where there are many other unknown parameters we applied for beam time at a conventional accelerator: FACET

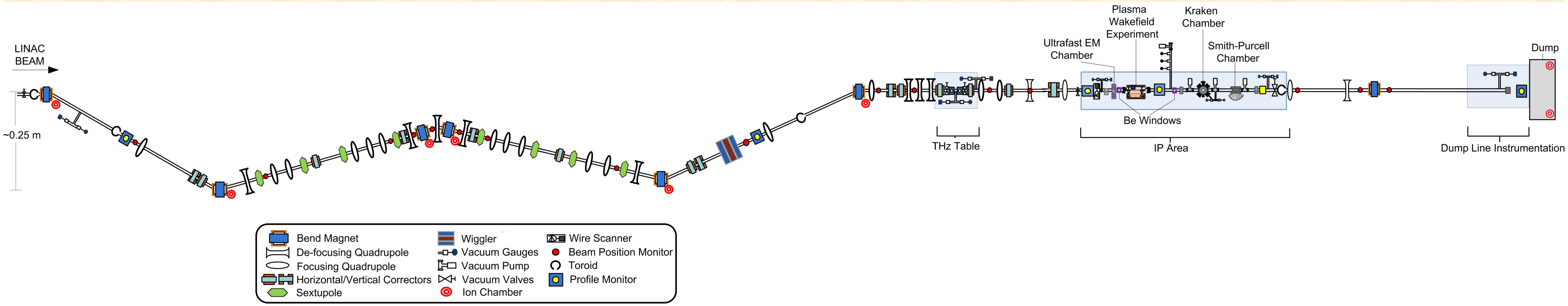
$$\lambda = \frac{l}{n}\left(\frac{1}{\beta} - \cos\theta\right)$$



FACET

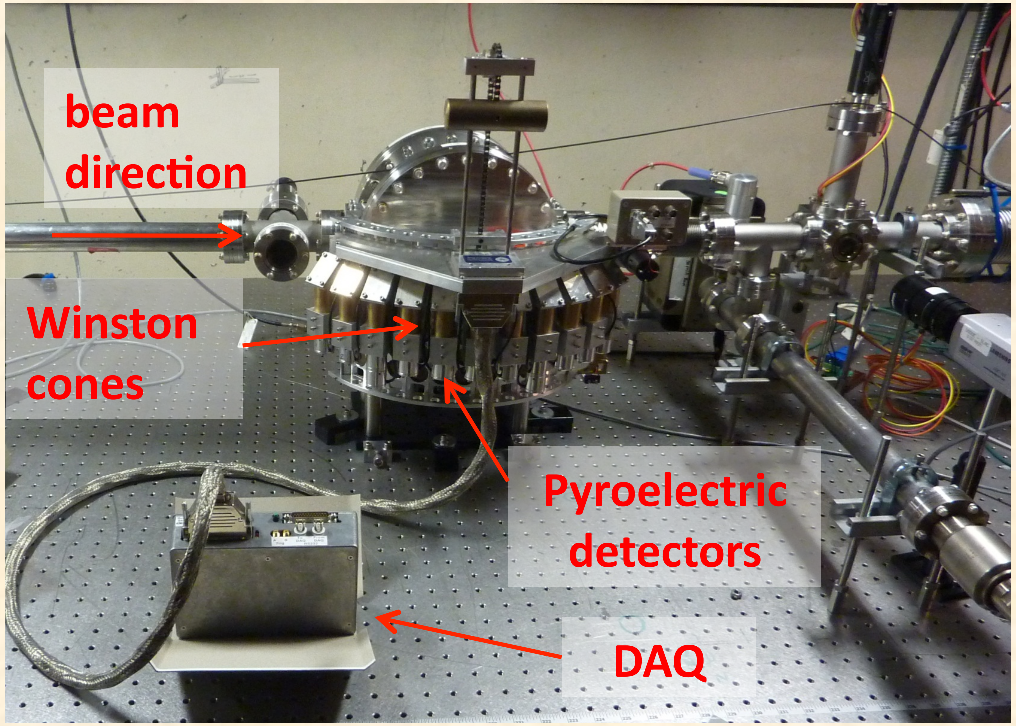
- Facility for Advanced Experimental Tests
- Part of the SLC Linac (2/3) not used by LCLS
- Goal: advanced experiments on beam driven plasma acceleration but open to other R&D.
- Very short bunches (design 60fs) at 20 GeV.
- Up to 3nC/bunch
- 1-30 Hz
- Now under commissioning…

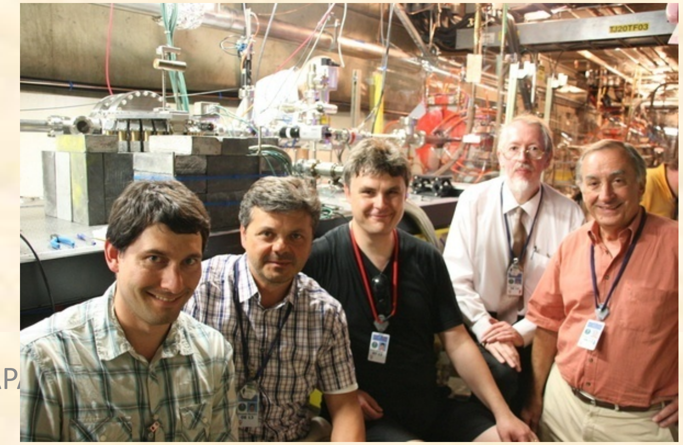




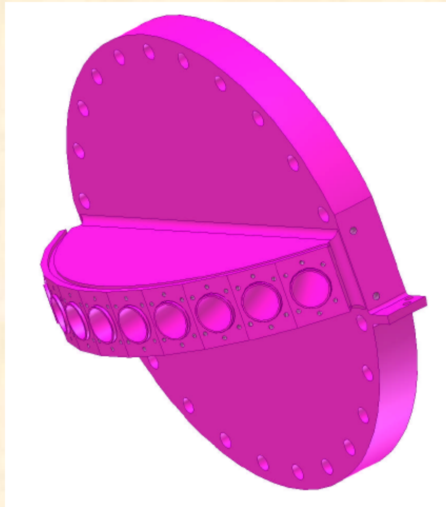
E-203

- Longitudinal profile measurements using Smith-Purcell radiation.

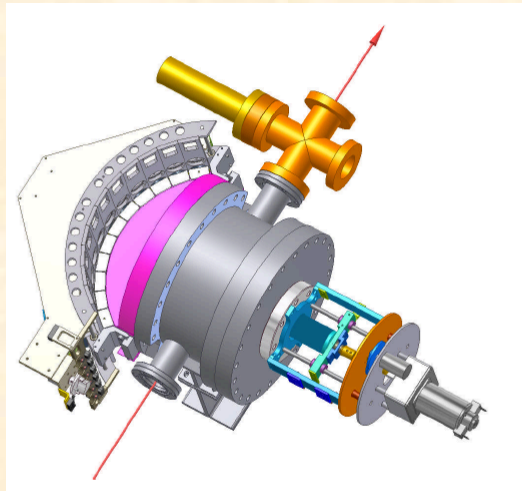




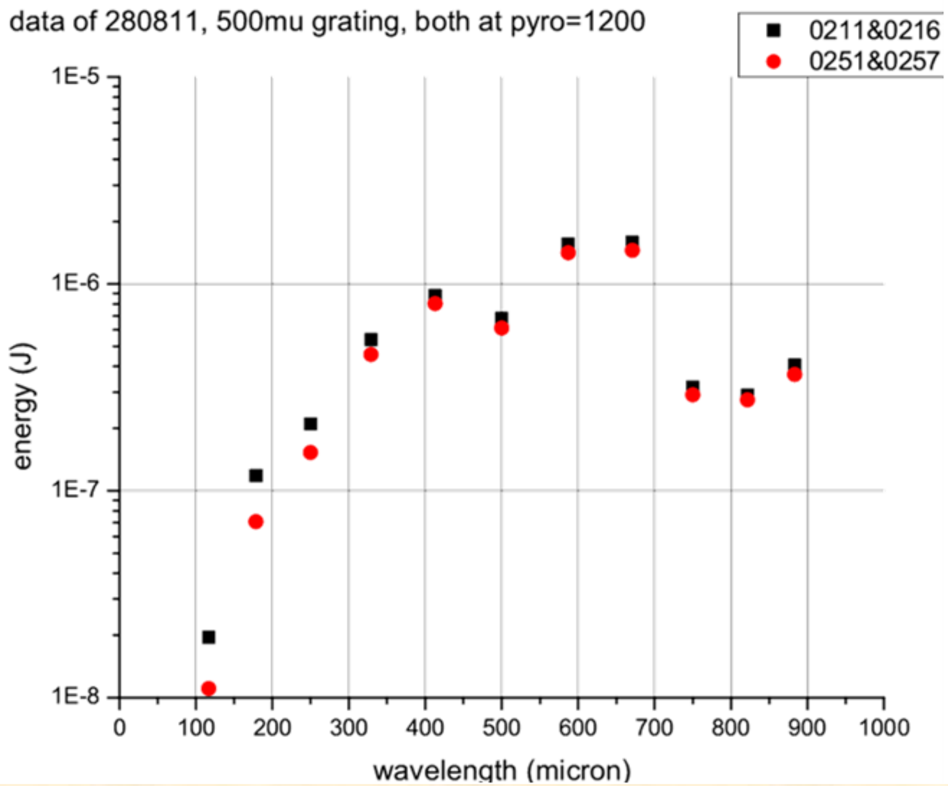
SPR in the THz gap

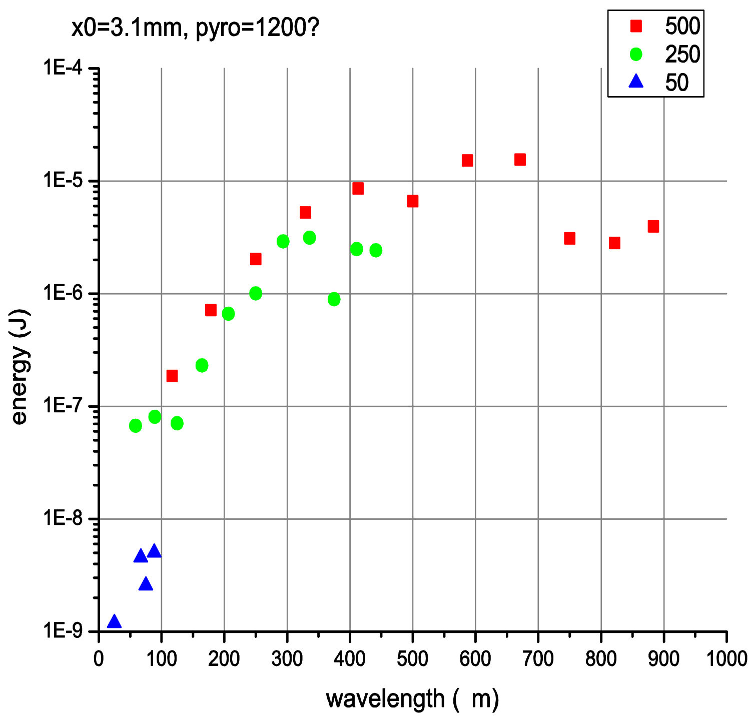


- Moving from mm-wave to micrometric/THz wave was not easy.
- With mm-wave Band pass filters were easy to build: a plate with holes drilled in the workshop!
  Filters in the THz rang are complicated and much more expensive arrays of mesh.
- The new gratings (50um and 250um pitch) were also more difficult to manufacture (requires high precision).
  Regular optical grating are not suitable as they are made of glass.
- Fused silica absorbs radiation on part of the THz range. We had to find a new window type. Synchrotron beam lines use synthetic diamond, but at £5-10000 a piece it was out of price => We decided to use special Silicium (2 suppliers worldwide).
- However silicium is strongly birefringent
  => the signal needs to be orthogonal to the window
  => partial redesign of the chamber.
- It was not possible to braze the new windows and silicium is very brittle
  => Vacuum sealing was complicated



SPR data



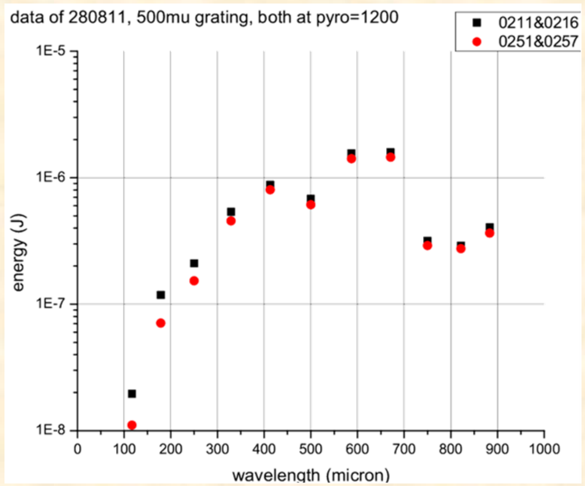


- Very preliminary data!
- We had some experimental issues at the beginning but we observed a nice once we understood our system.
- Data with 3 gratings still under investigation
- Relation between the gratings not as expected.

Going from the data to the bunch profile

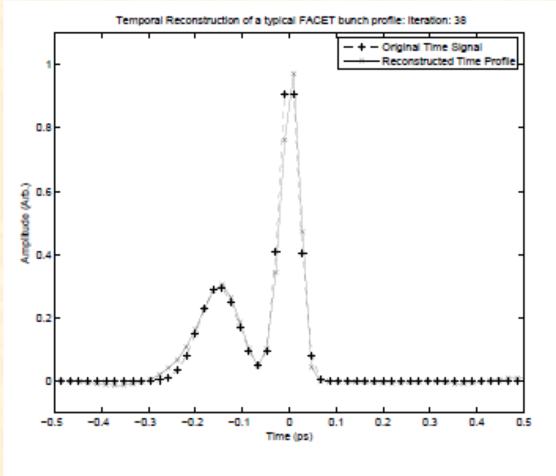
$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e}(\Omega,\omega) = \left(\frac{dI}{d\Omega d\omega}\right)_{sp}(\Omega,\omega)\cdot[N_e + N_e(N_e+1)\,|\,F(\omega)\,|^2]$$

- The measured spectrum gives only the square of the Fourier Transform of the bunch profile.
- Some phase information has been lost in the process.
- It is necessary to "reconstruct" this missing information.



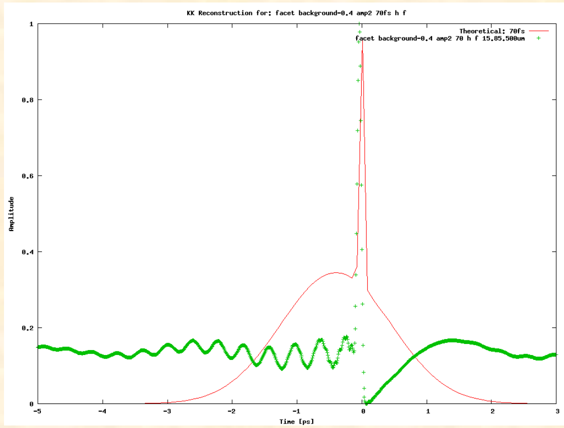
Phase recovery: Kramers-Kronig

- Several methods exist to recover missing phase information (this is done every day by crystallographers at SOLEIL):
- In the Kramers-Kronig methods one tries to find the minimal phase satisfying all the constraints set by the measurement:



$$G(\omega) \approx N_e^2 \, |F(\omega)|^2 \qquad G(\omega) = \rho(\omega) \cdot \exp[i\phi(\omega)]$$

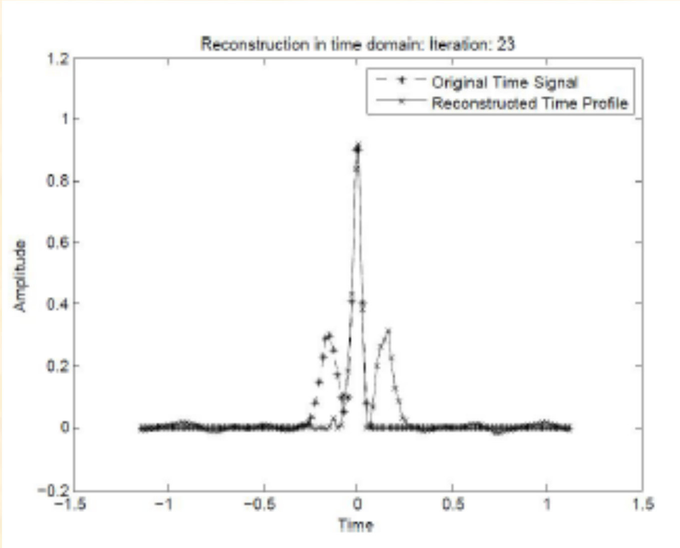
$$\phi(\omega) = \frac{2\omega}{\pi} \int_0^{\omega} \frac{\ln[\rho(\omega)/\rho(\omega_0)]}{\omega_0^2 - \omega^2} \, d\omega$$

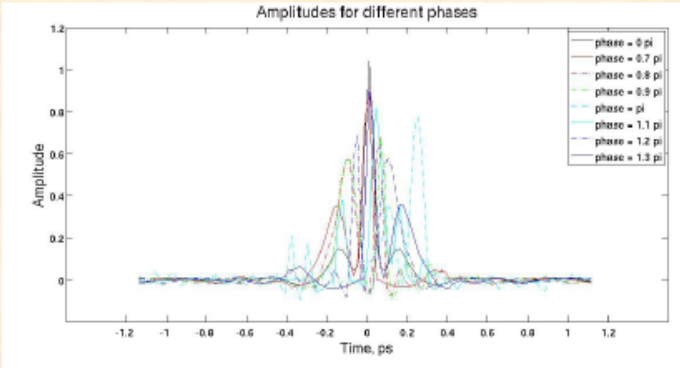


- However the results produced by this methods are sometimes non physical.

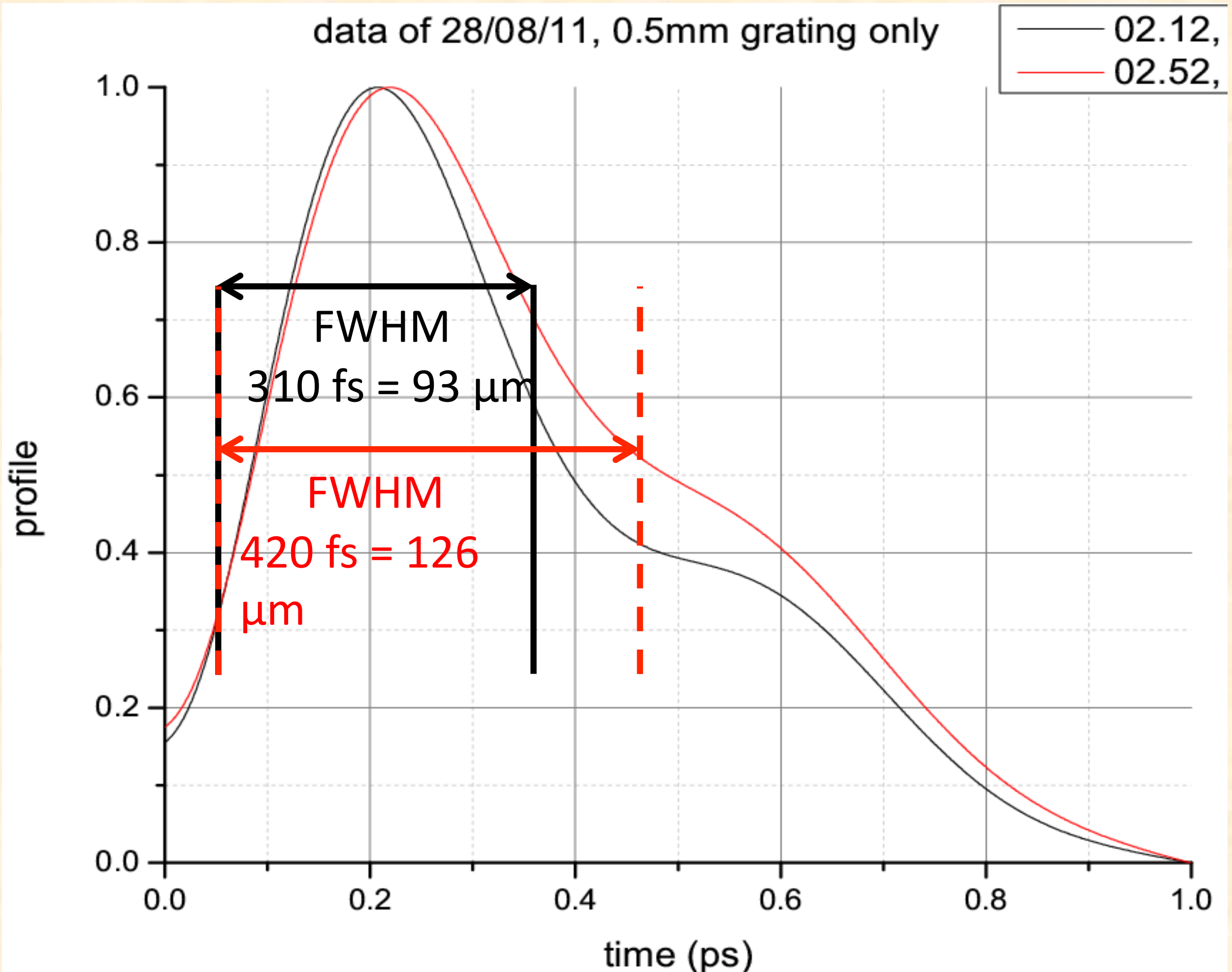
Shrink wrap method

- To address the problems of the KK methods we also use another method inspired from crystallography: the shrink wrap method.
- In that method an initial phase is chosen and used to reconstruct the profile.
- Tests are then applied on the reconstructed profile. If the profile fails the tests, then the phase of one parameter is slightly changed and the tests are applied again.
- However this method may lead to a large number of solutions/profiles.
  => The reconstructed profile is not necessarily unique.
  (R.Tovey / C.Santamaria)



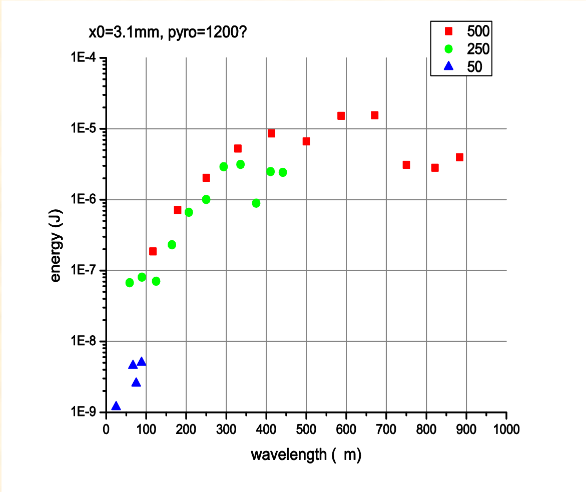


Reconstructed profiles (KK method) Very preliminary



Remaining issues

- At the moment we do not understand the data produced by the shorter grating: the signal intensity is much mower than expected.
- We are still comparing the results obtained with the Shrink wrap method and the KK method.
- We identified several operational problems (data alignment, grating/ filters mismatch, …) that we need to address.

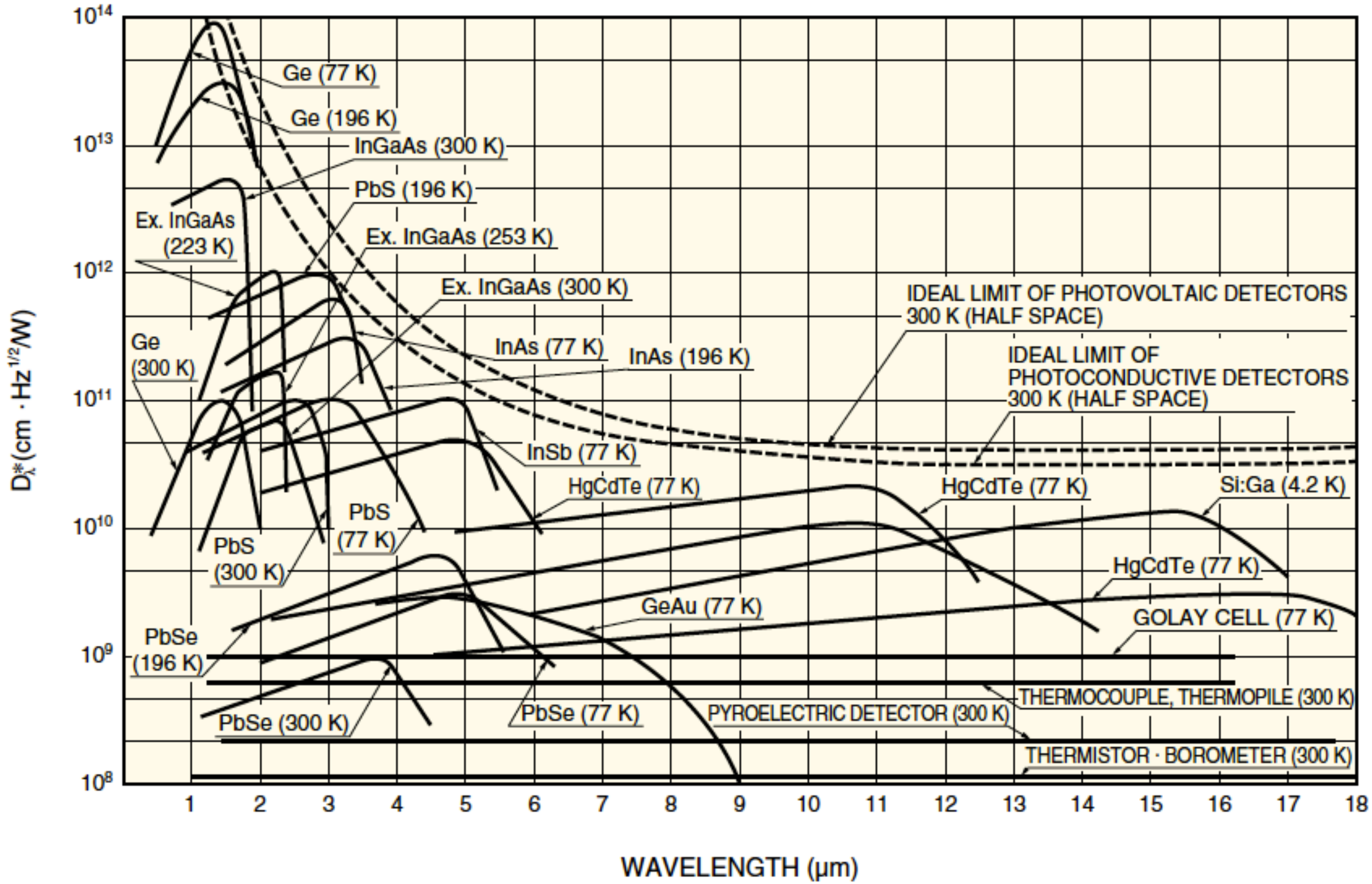


Further developments

- E-203 is currently approved until Summer 2012.
- We have applied this week for an extension until summer 2013.
- Our preliminary results have triggered a lot of interest from the community.
- To reach our goal and deliver a device suitable for a LPA we need several improvements:
  - Make it single shot (3 gratings in a row? Gratings around the beam pipe?…)
  - Increase the sensitivity of the detectors (Bolometers???)
  - Extend the ability to shorter pulses (1-50fs), deeper in the THz gap and reaching the water absorption band.

  => ANR

IR detectors sensitivity

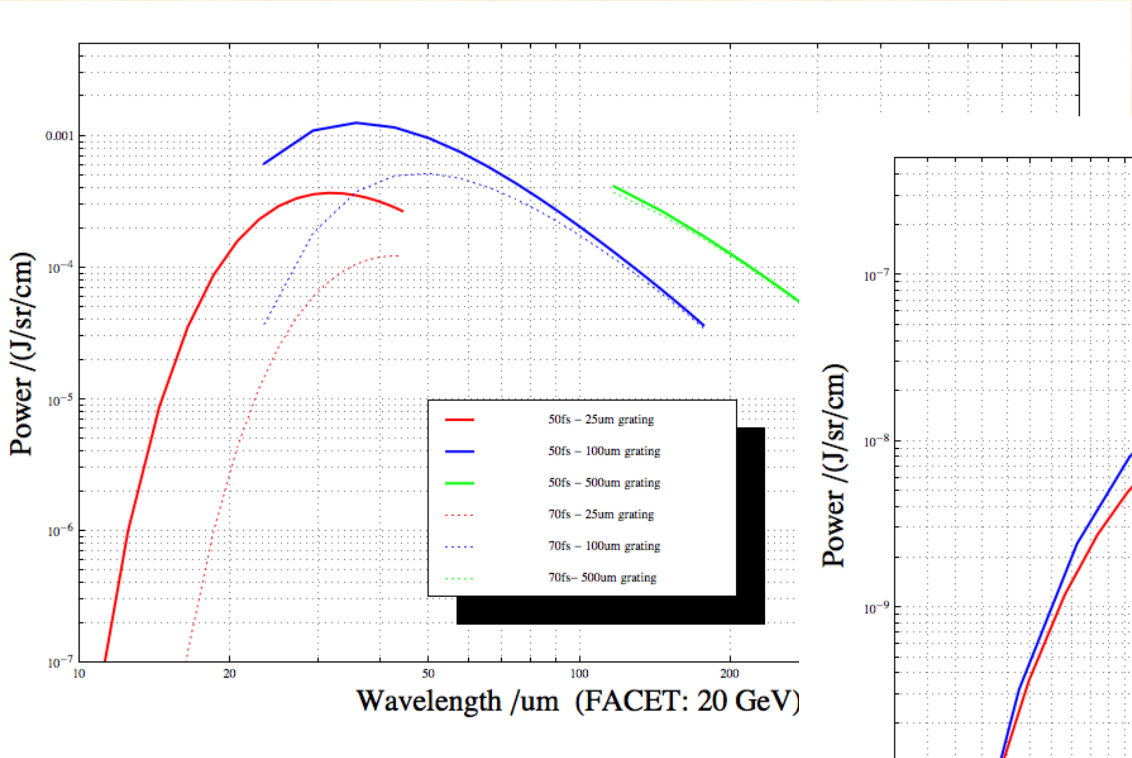


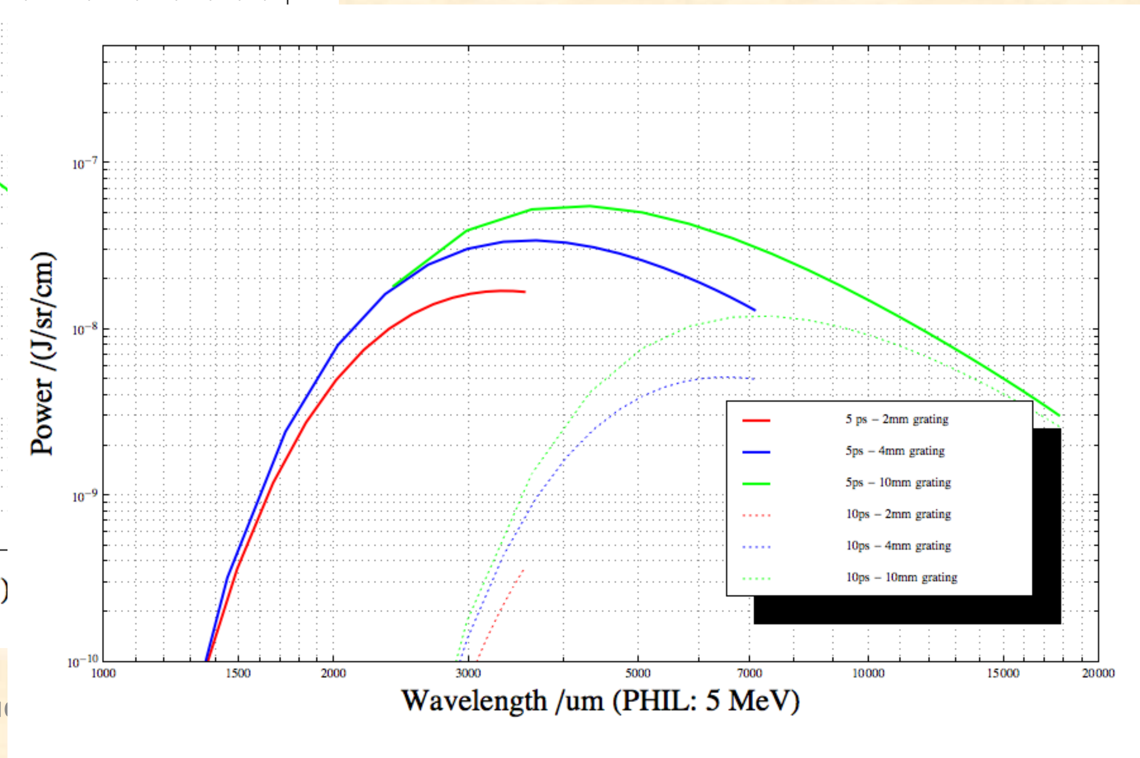
PHIL, ThomX, SOLEIL, LPA

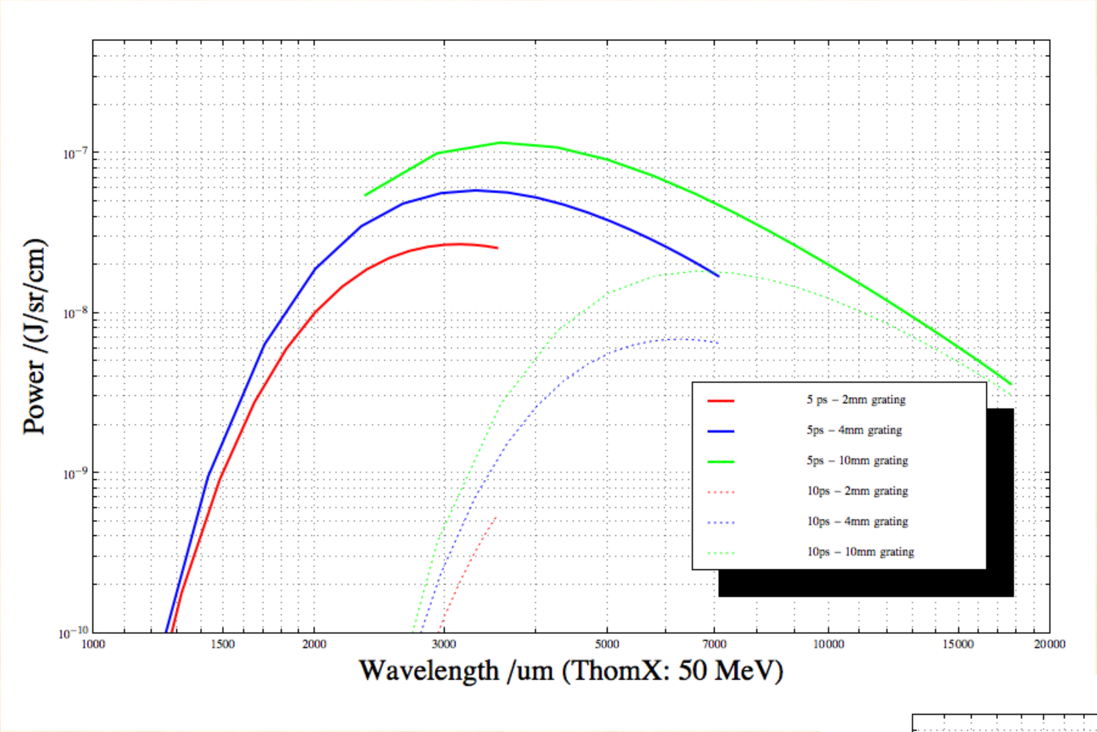
$$\left(\frac{dI}{d\Omega}\right)_{sp} = 2\pi q^2 \frac{Z}{\ell^2} \frac{n^2\beta^3}{(1-\beta\cos\theta)^3} R^2 \exp\left(-\frac{2x_0}{\lambda_e}\right)$$

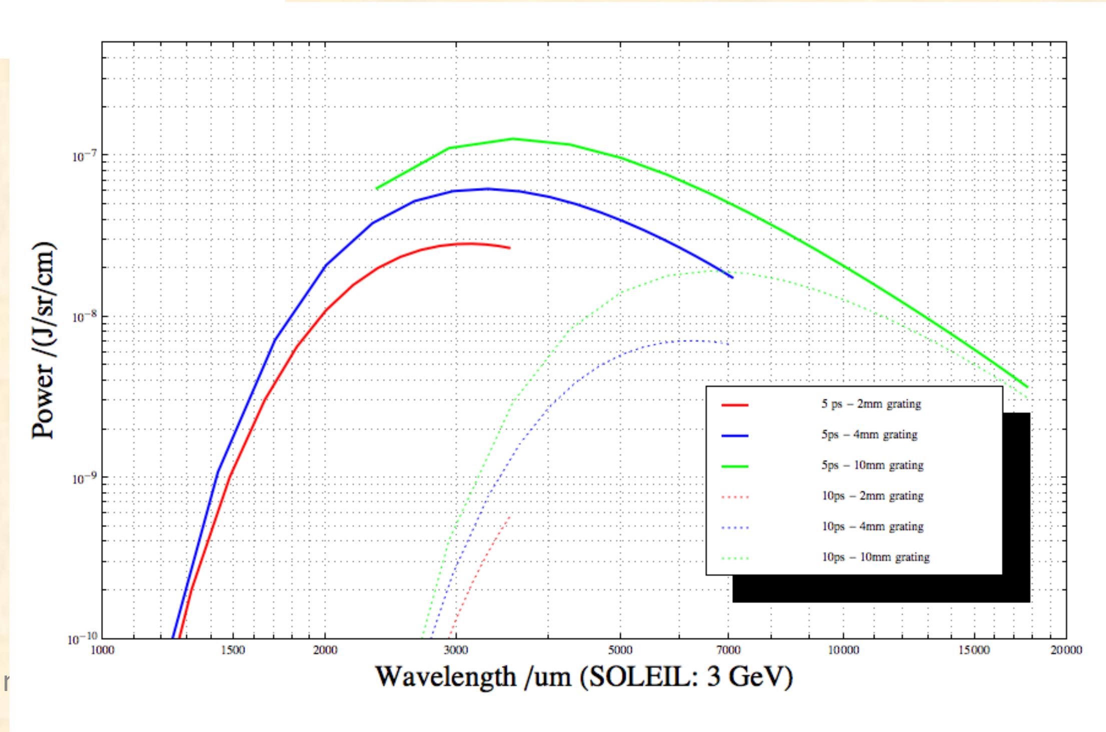
$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e}(\Omega,\omega) = \left(\frac{dI}{d\Omega d\omega}\right)_{sp}(\Omega,\omega)\cdot [N_e + N_e(N_e+1)\,|F(\omega)|^2]$$

- 45 MeV, few ps already tested at FELIX






Power /(J/sr/cm)
Wavelength /um (ThomX: 50 MeV)
5 ps – 2mm grating
5ps – 4mm grating
5ps – 10mm grating
10ps – 2mm grating
10ps – 4mm grating
10ps – 10mm grating


Power /(J/sr/cm)
Wavelength /um (SOLEIL: 3 GeV)
5 ps – 2mm grating
5ps – 4mm grating
5ps – 10mm grating
10ps – 2mm grating
10ps – 4mm grating
10ps – 10mm grating

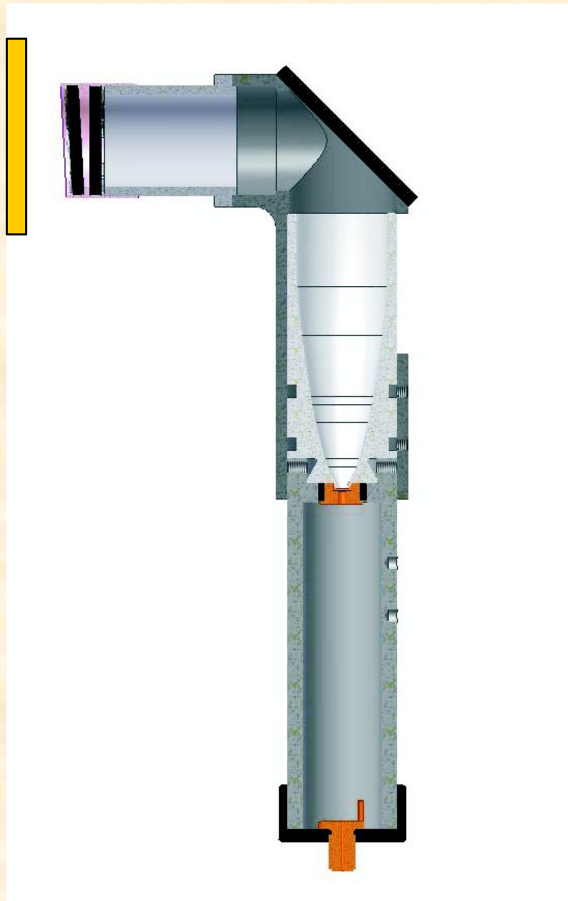
Summary

- We are investigating SPR as a diagnostic in the fs range.
- Most hardware difficulties have been addressed.
- Currently trying to understand the data.
- First results promising.
- Step toward SPR at a LPA.

Thank you for your attention

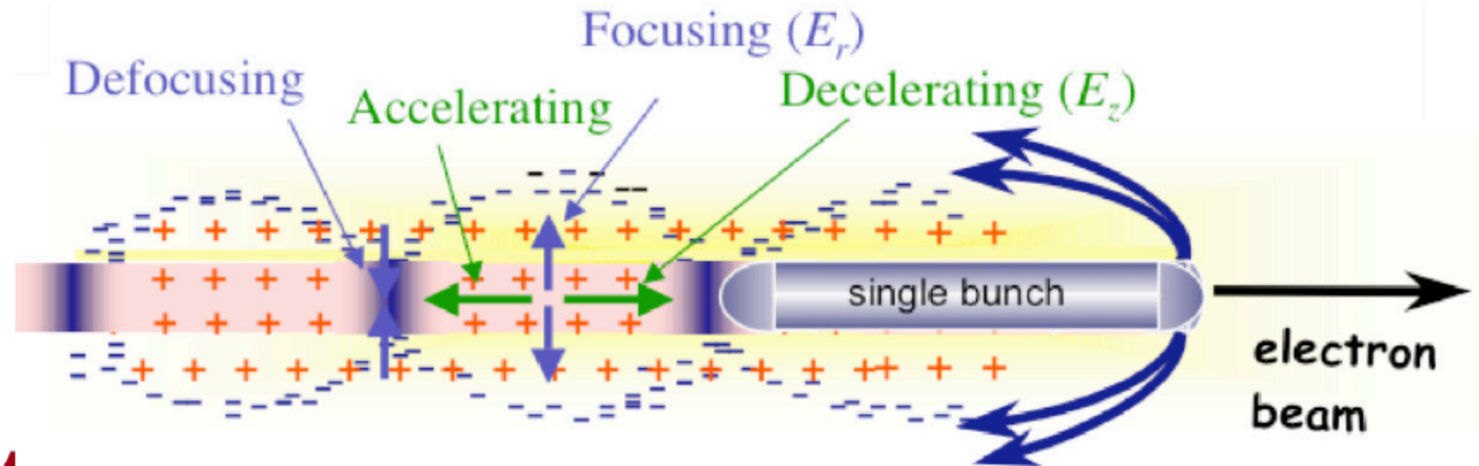
I am grateful to all those at LAL who have helped with the preparation of this experiment and in particular the design office and the vacuum group.

Detector assembly



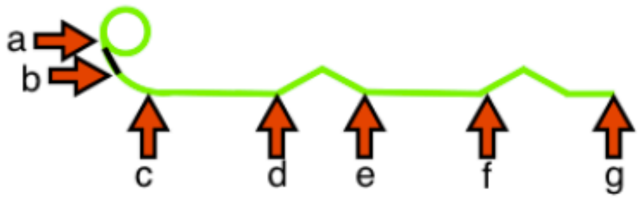
Plasma Wakefield Acceleration

- Continuation of very successful experiments at SLAC
  - Single electron bunch in field ionized lithium plasma
  - Single bunch in field ionized caesium plasma
  - Use Notch Collimator
  - Two electron bunches (drive and witness) in field ionized caesium plasma
- Second stage: pre-ionized plasma, positrons and electrons



Bunch Compression

- Three-stage bunch compression:



1. On entering linac from damping rings
2. Magnetic chicane in S10
3. Magnetic chicane in S20