A monitor for single shot longitudinal profile measurement based on Coherent Smith-Purcell radiation

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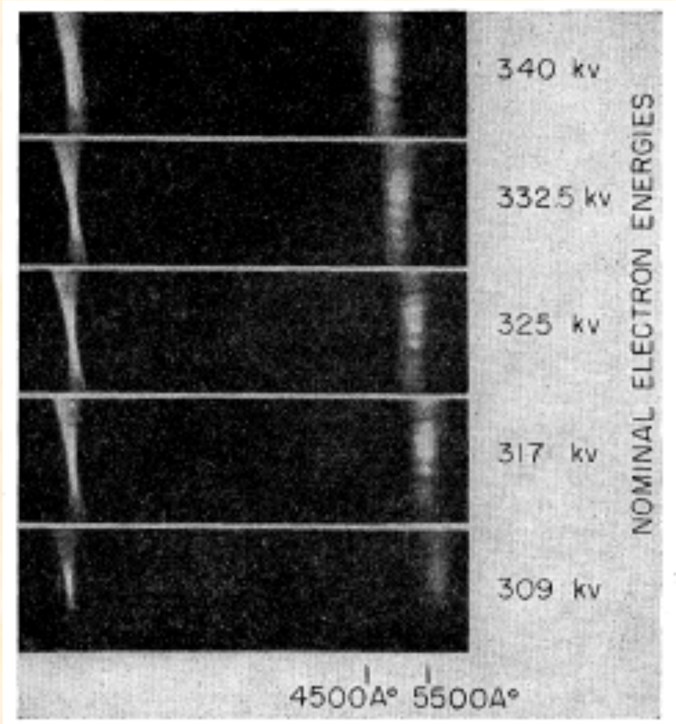
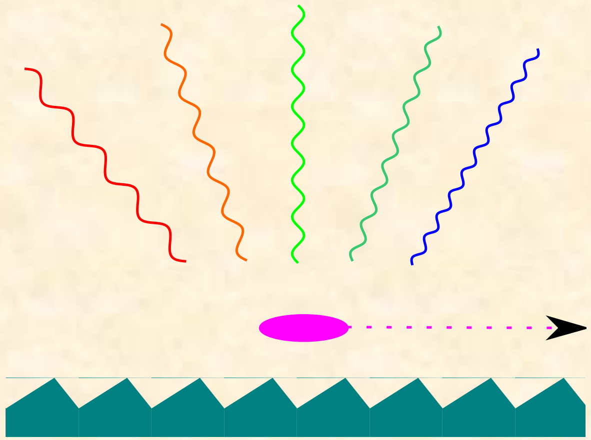
Smith-Purcell radiation

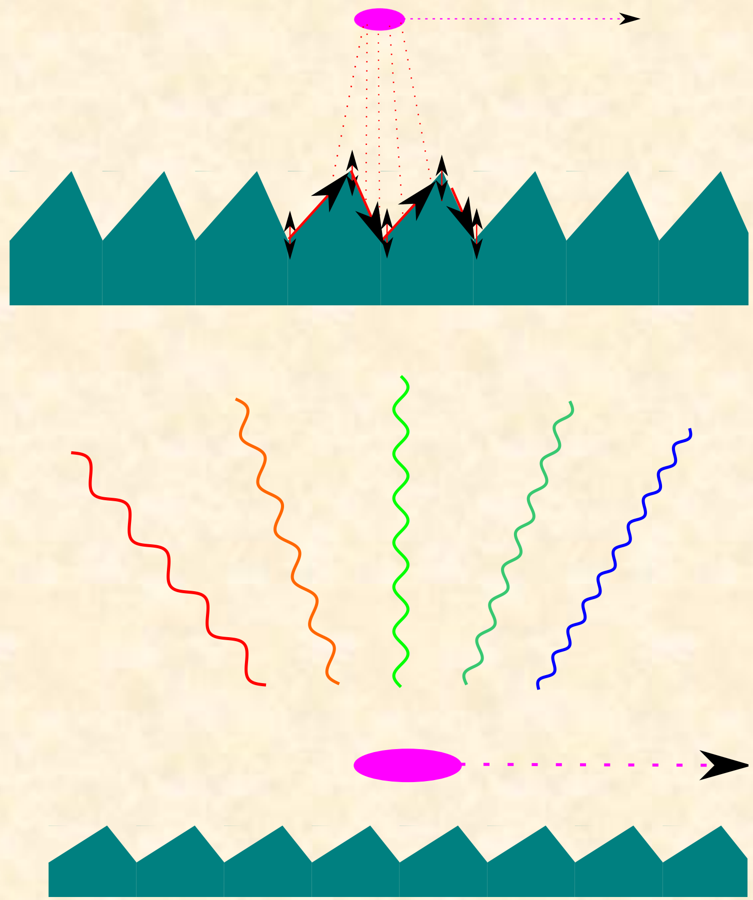
- Discovered experimentally in 1953 by Smith and Purcell.
- Electrons passing near a grating induce the emission of (visible) radiation.
- S.J. Smith and E.M. Purcell, Phys. Rev. **92**, pg. 1069, (1953)
- 300 keV electrons to emit in the visible wavelengths (d = 1.67 um)





Explanation: dipole radiation

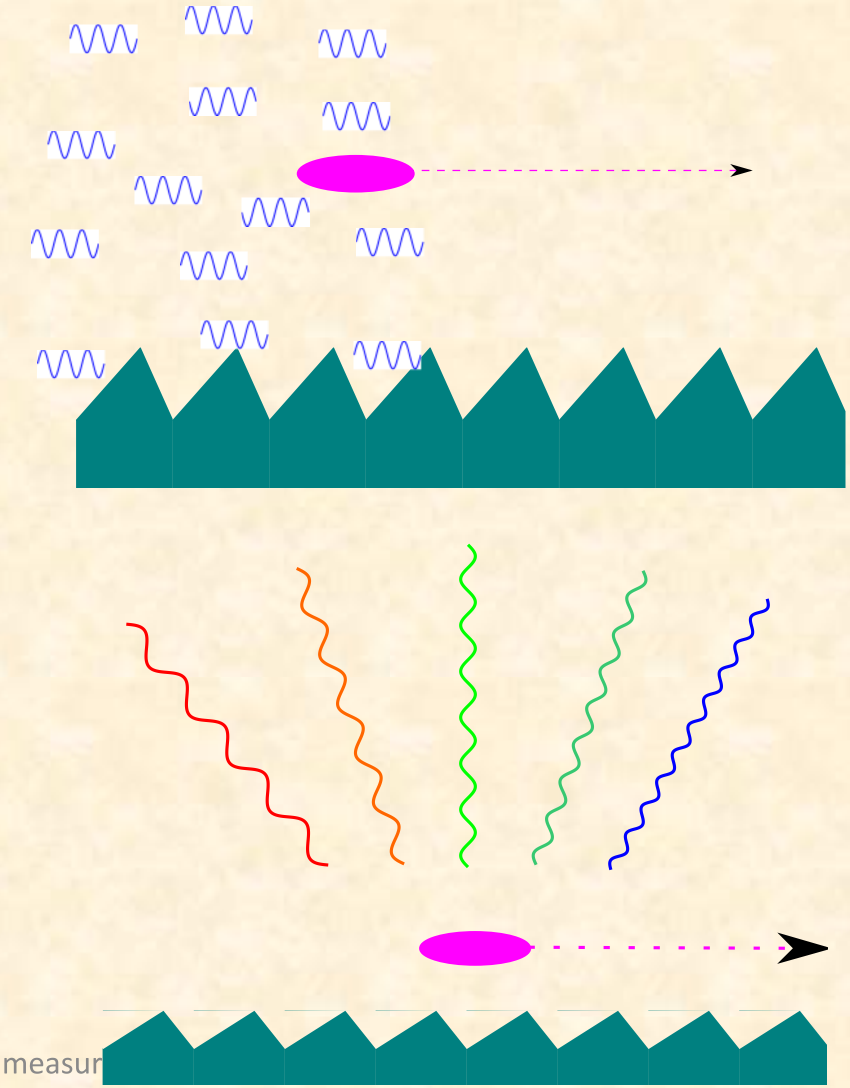
- Smith-Purcell radiation can be interpreted as the dipole radiation of the current induced by the beam in the conducting grating.
- This radiation then interfere constructively with different wavelength propagating in different directions.



Ishiguro and Tako, Optica Acta (GB) 8 1961 25

Explanation: EM field at grazing angle

- Another interpretation suggest that evanescent waves from the EM field arrive at grazing angle on the grating and are then diffracted by the grating.



G. Toraldo di Francia, Nuovo Cimento, 16 (1960) 61

SP radiation and bunch profile

- The intensity of the radiation depends on the distance between the bunch and the grating.
- It depends also on the pitch of the grating.
- For relativistic electrons the beam energy is not very important.

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

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

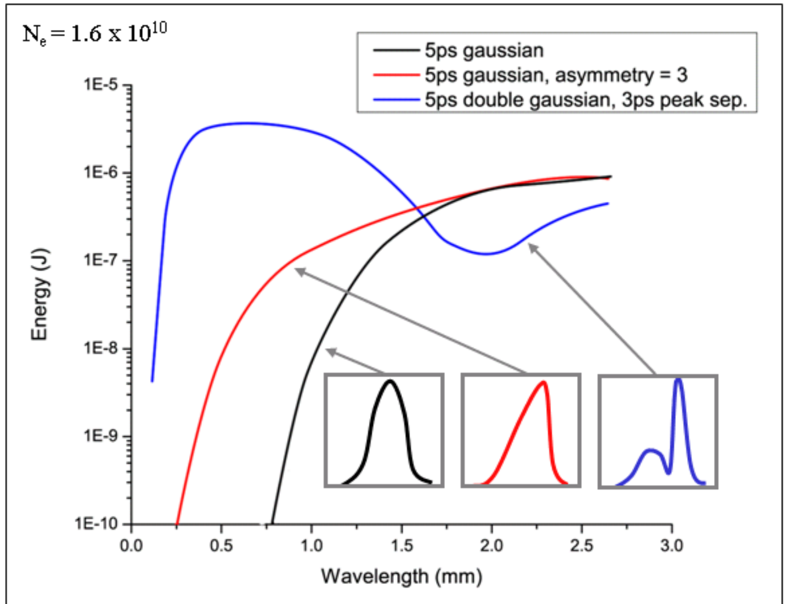
Coherent SP radiation

- Like many other radiative phenomena in EM, SP radiation can also be coherent at wavelength sufficiently longer than the bunch length.
- In both interpretation SP radiation depends on the shape of the electron bunch and the wavelength of the photons emitted encodes the Fourier transform of the electron bunch longitudinal profile.
- This means that for sufficiently short bunches the signal intensity is proportional to the square of the beam charge.

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

Coherent SPR as a longitudinal profile diagnostic

- Because Coherent SPR encodes the Fourier transform of the longitudinal profile, it can be used as a diagnostic.
- Such diagnostic requires a measurement of the SPR spectrum.



Simulation of different profiles, as would be seen experimentally

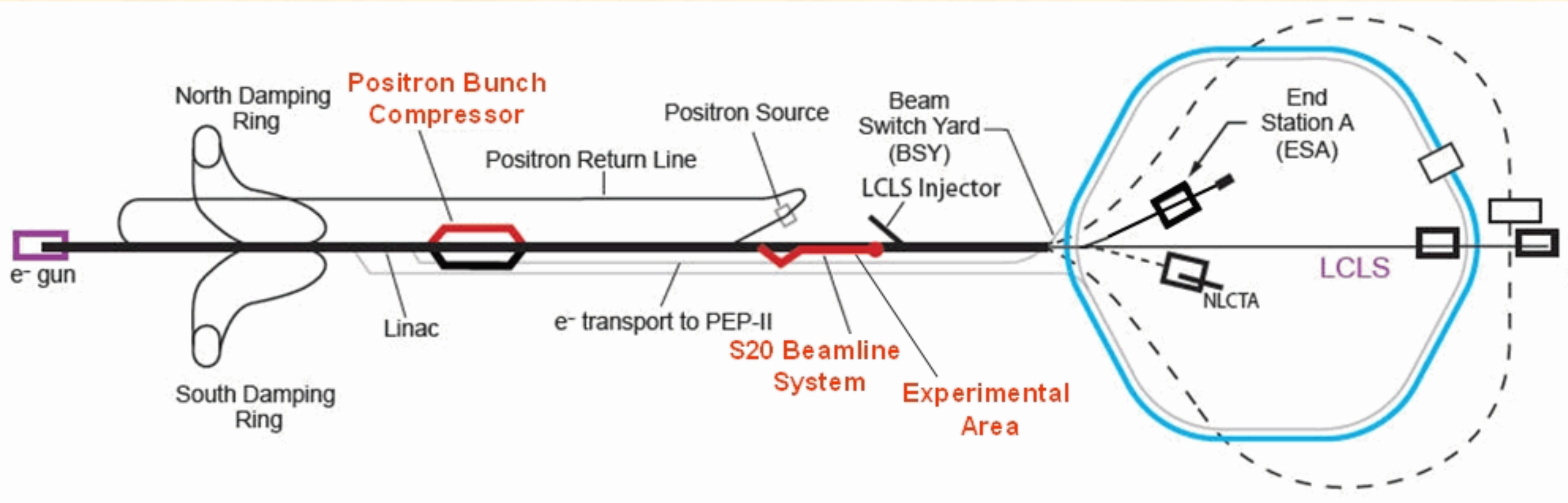
$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e}(\Omega,\omega) = \left(\frac{dI}{d\Omega d\omega}\right)_{sp}(\Omega,\omega)\cdot[N_e + N_e(N_e+1)\,|\,F(\omega)\,|^2]$$

CSPR as a longitudinal diagnostic: Work so far

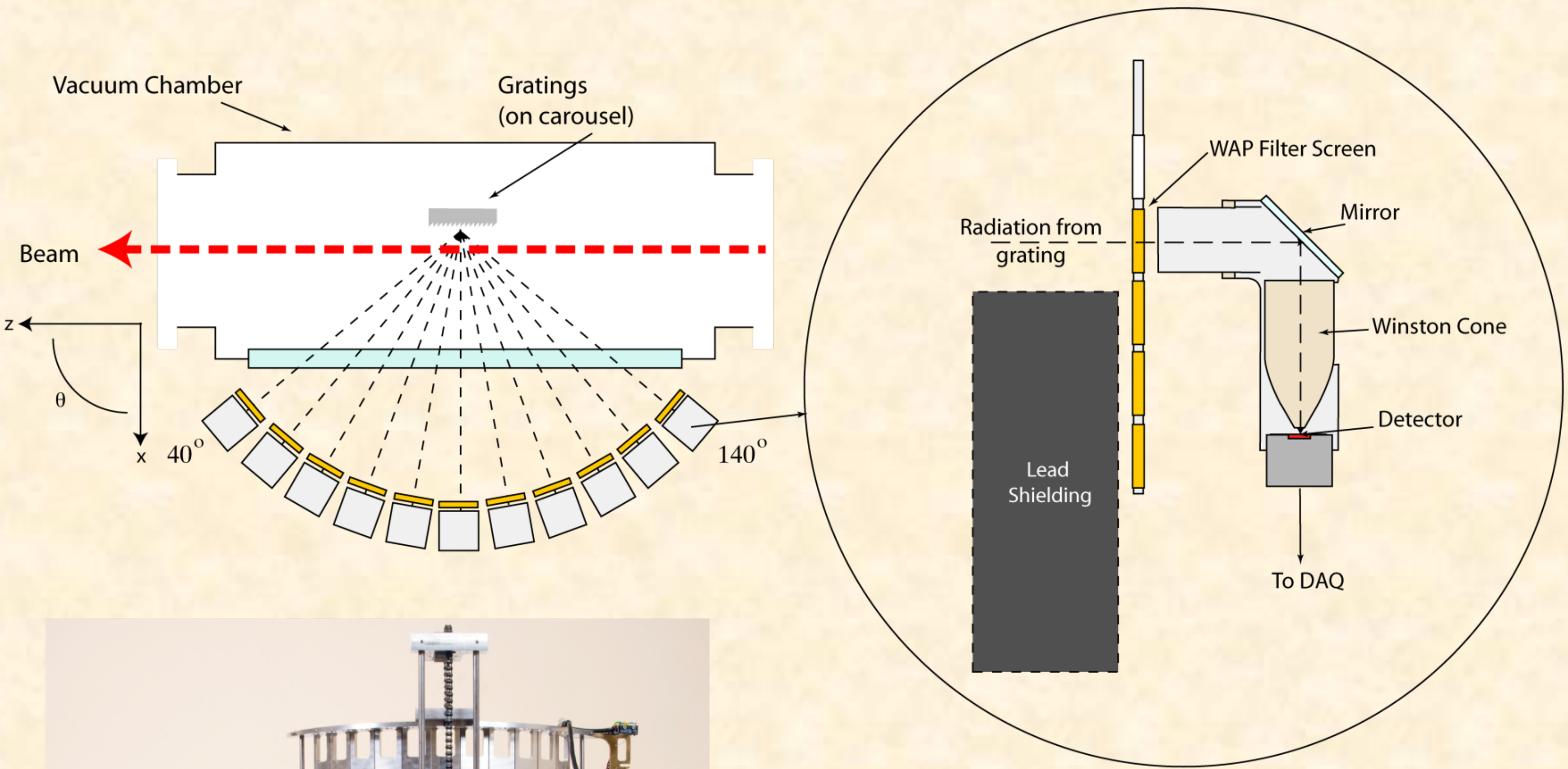
- George Doucas from Oxford has been investigating CSPR as a longitudinal diagnostic for several years.
- Initial work on picosecond bunches
  => Test at FELIX (45MeV) in the Netherlands
  Phys. Rev. ST Accel. Beams 9, 092801 (2006)
  => Test at End Station A at SLAC (28.5 GeV)
  Phys. Rev. ST Accel. Beams 12, 032803 (2009)
- Extension to the femtoseconds range started in 2009 with seed funds from the Fell fund of the University of Oxford.
  => E-203 collaboration (Oxford, LAL, LANL, SLAC,…) to perform tests at FACET

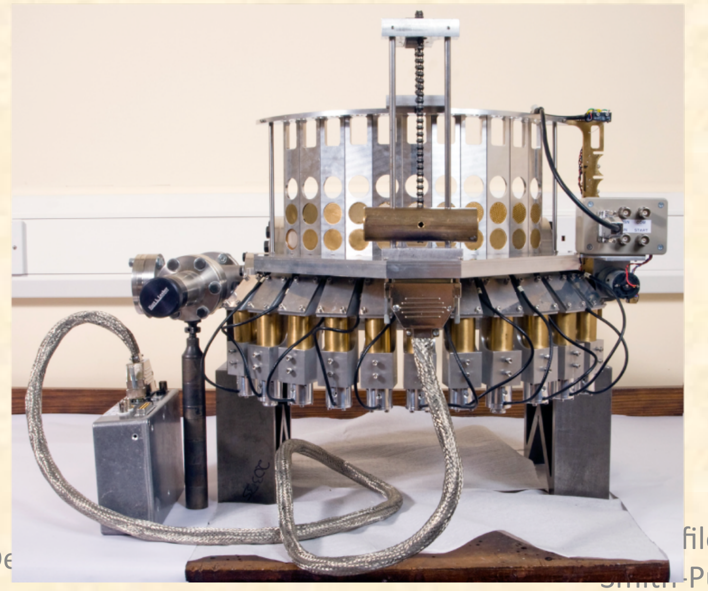
E-203 at FACET

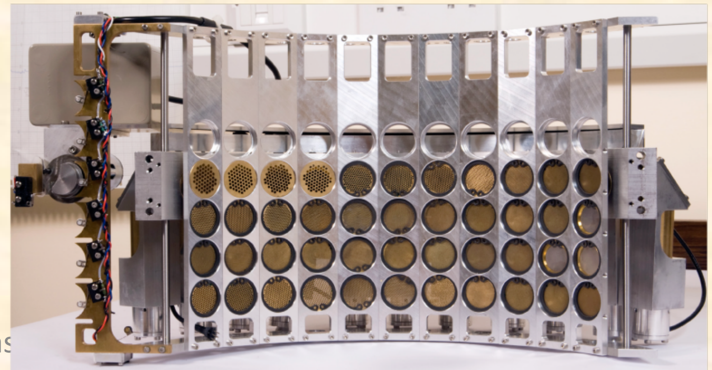
- FACET at SLAC is a test facility offering access to 100s femtoseconds long electron bunches.
- Electrons energy is 22.5 GeV (gamma=45000)
- Collaboration E-203 approved with rating “excellent” to develop longitudinal profile monitor in the fs range.
- Schedule: 2 runs/year (approval must be confirmed yearly)



Experimental apparatus (schematic)

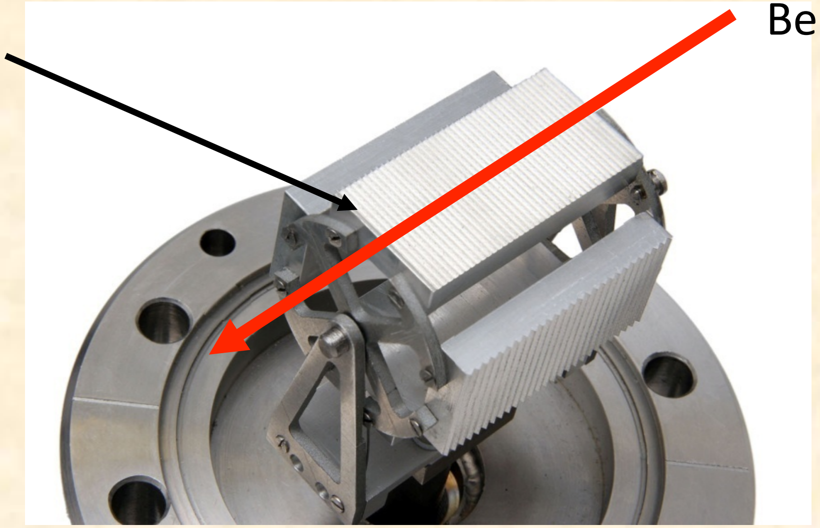






Experimental apparatus: gratings carousel

3 gratings
1 blank piece of aluminium



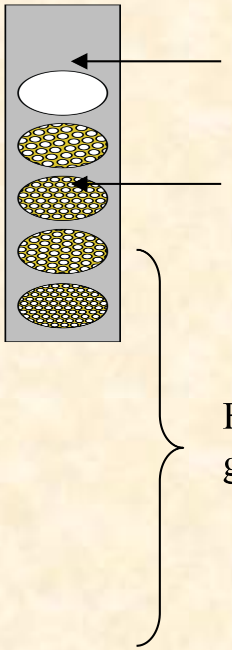
Expected SP radiation at FACET in the wavelength range 10 μm to 1 mm

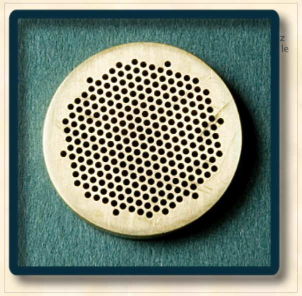
A carousel can rotate and offer three different gratings or one blank to the beam. Rotation is controlled remotely.

Detection of FIR SP radiation

Filters of many varieties remove background radiation. Suitable filters for each grating are moved in front of silicon windows

Winston cones collect the radiation toward the pyroelectric detectors and provide additional filtering





Wire mesh: 117 µm, 175 µm; Δλ = 10-20 µm
Wave guide array plates: 175 < λ < 1000;
Mylar based thin films: 20 < λ < 117; Δλ = few µm
Silicon based thin films : 10 < λ < 20; Δλ = few µm

After data taking: Profile reconstruction techniques

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

- The measured signal is the square of the Fourier transform of the bunch.
- To reconstruct the profile, the phase of each Fourier components must be recovered.
- Several techniques are available; we rely mostly on Kramers Kronig phase recovery technique

Kramers Kronig phase recovery technique

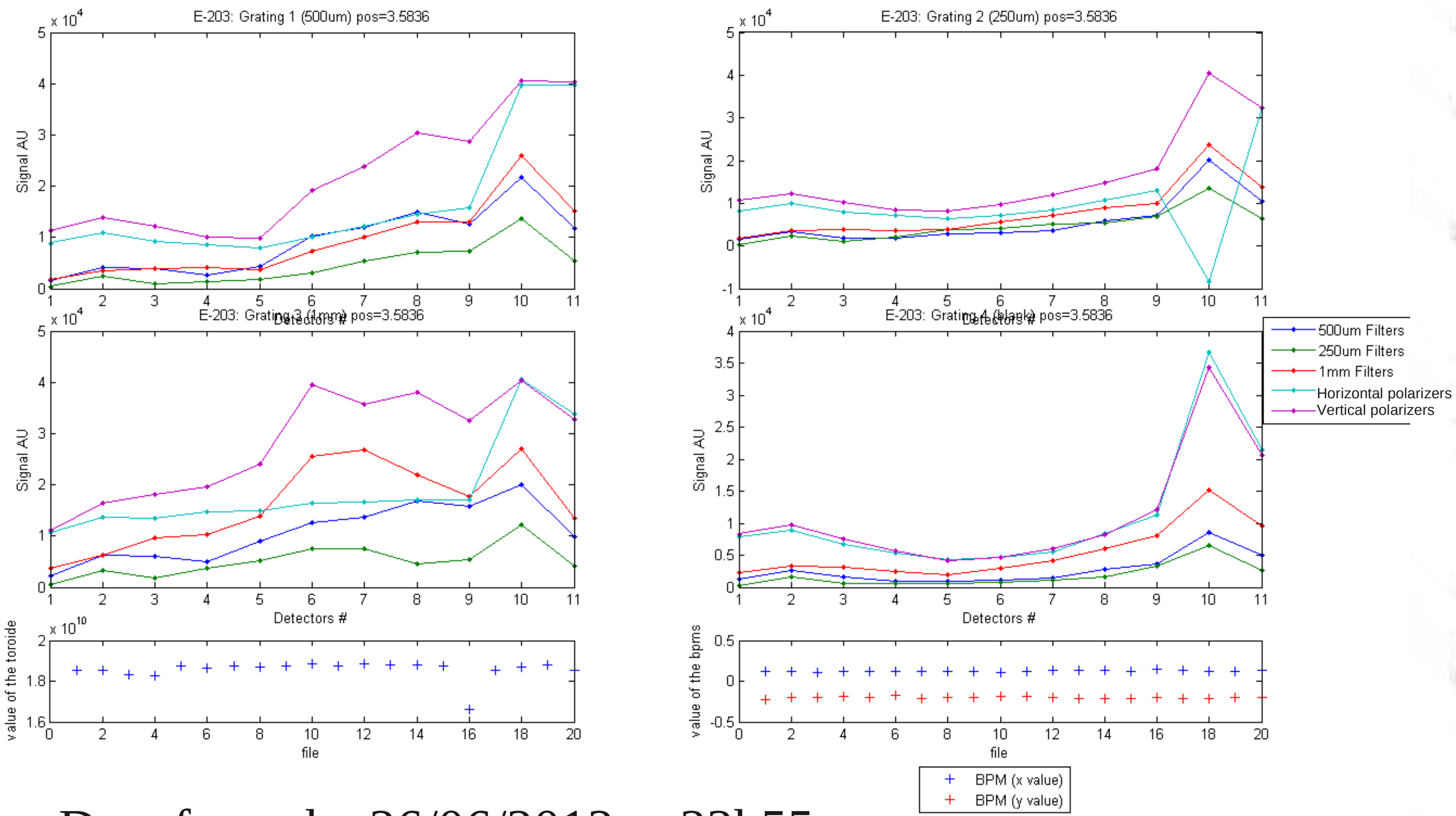
- The Kramers Kronig phase recovery technique assumes that the system has the minimum phase difference.
- The phase is recovered from the relation between the amplitudes of the observables.

$$G^2(\omega) \simeq N_e^2 |F(\omega)|^2$$

$$G(\omega) = \rho(\omega) \exp\left[i\phi(\omega)\right]$$

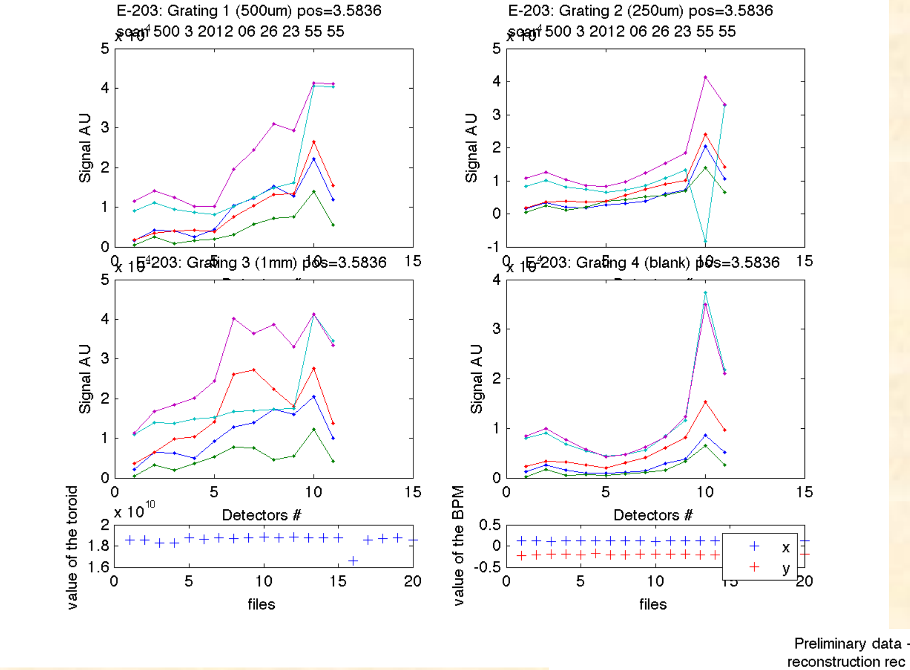
$$\phi(\omega) = \frac{2\omega}{\pi} \int_0^\omega \frac{\ln\left[\rho(\omega)/\rho(\omega_0)\right]}{\omega_0^2 - \omega^2} d\omega$$

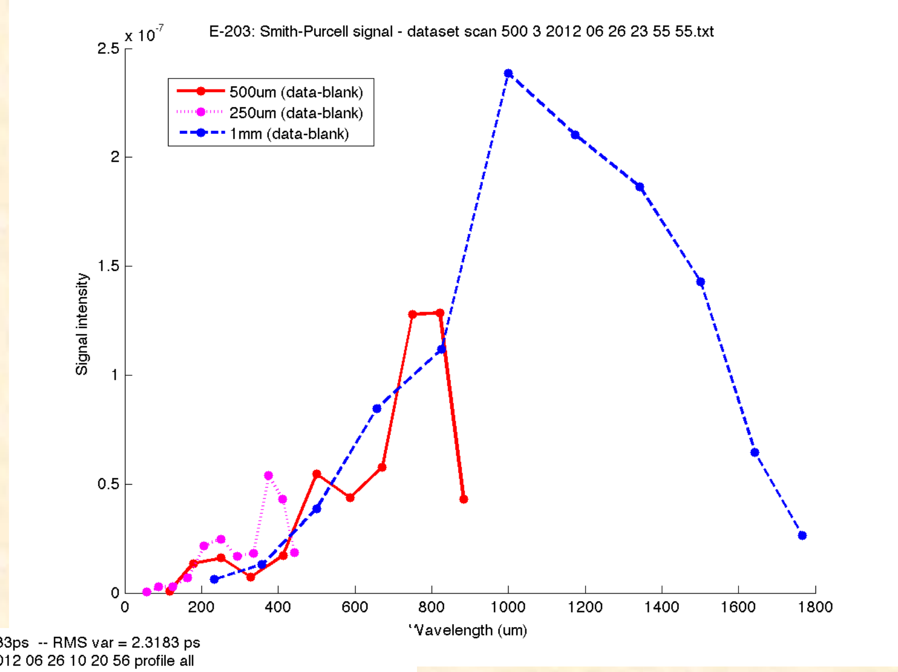
Example of data

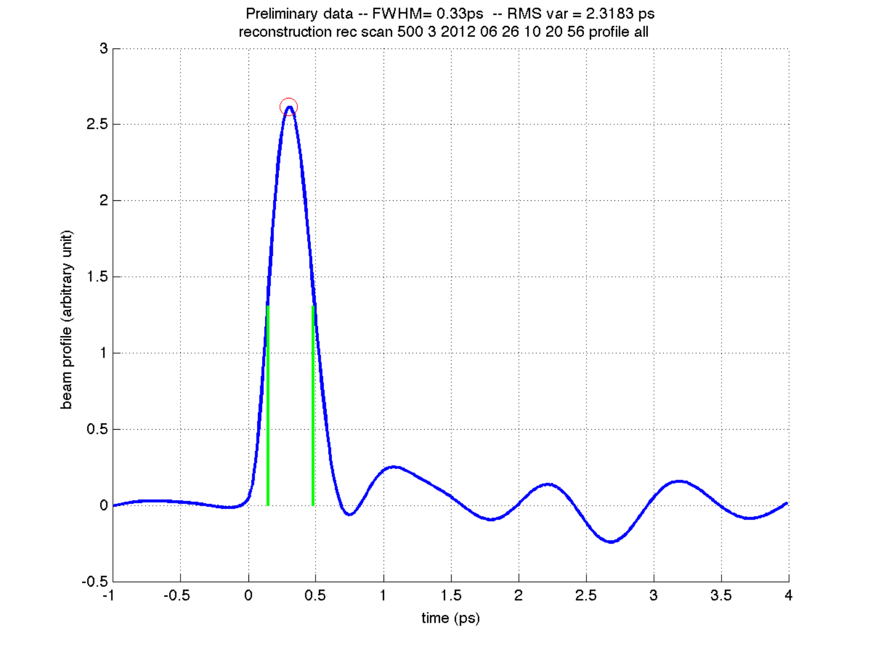


Data from the 26/06/2012 at 23h55

Example of data analysis



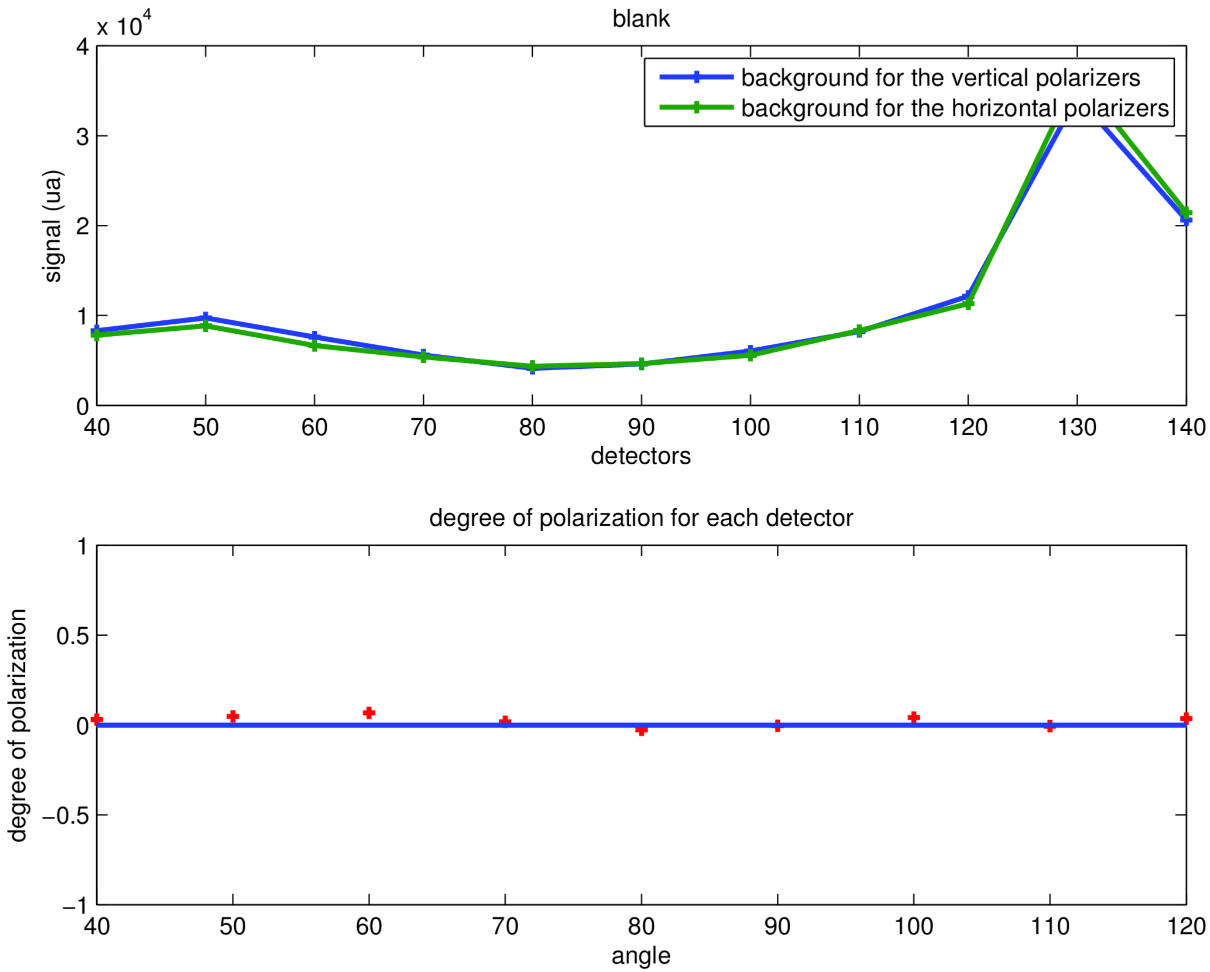




Recent results

- First E-203 paper published January 2012
JINST **7** P01009 (2012)
- More data taking in April and June 2012 (analysis still in progress):
- reconstructed profile vs compression setting
- comparison with THz scan and deflecting cavity
- Polarisation study

Background unpolarized



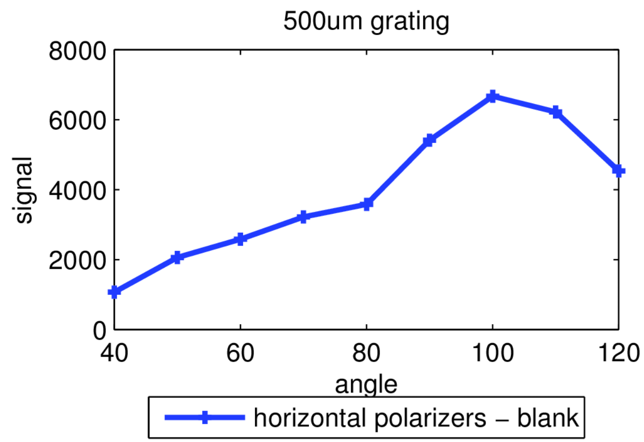
Degree of polarization d calculated with:

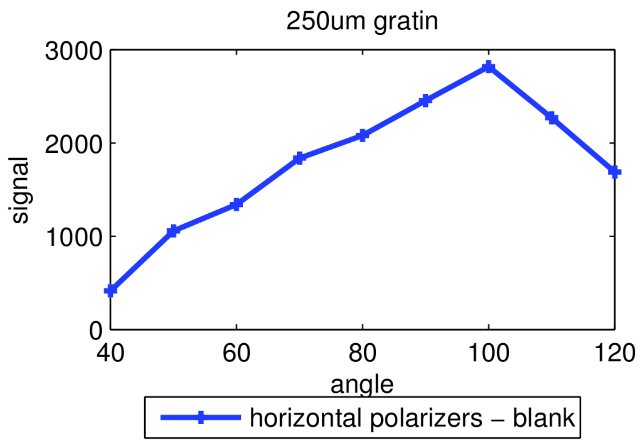
$$d = \frac{VP - HP}{VP + HP}$$

=> We can see that the background is unpolarized

Data from the 26/06/2012 at 23h55

Horizontal polarization



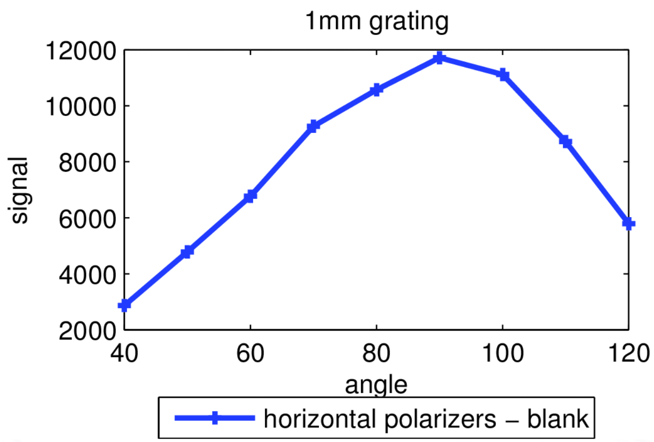


We were expecting:

HP ~ background

i.e.

HP – blank ~ 0



We clearly see on the graphs that HP – Blank ≠ 0

=> We can't neglect the horizontal component of polarization

Data from the 26/06/2012 at 23h55

Signal of Smith-Purcell radiation with horizontal polarization

- We measure the signal of polarization ($VP_{grating}$ and $HP_{grating}$) and the background ($Bckg_v$ and $Bckg_h$)
- Because the background is not polarized, we have:

$$Bckg_v = Bckg_h = B$$

- Taking into account horizontal polarization, we have:

$$SP = SP_v + SP_h = (VP_{grating} - B) + (HP_{grating} - B) \quad (1)$$

and, with α a fixed angle:

$$SP_v = \cos^2\alpha \; SP \qquad\qquad SP_h = \sin^2\alpha \; SP$$

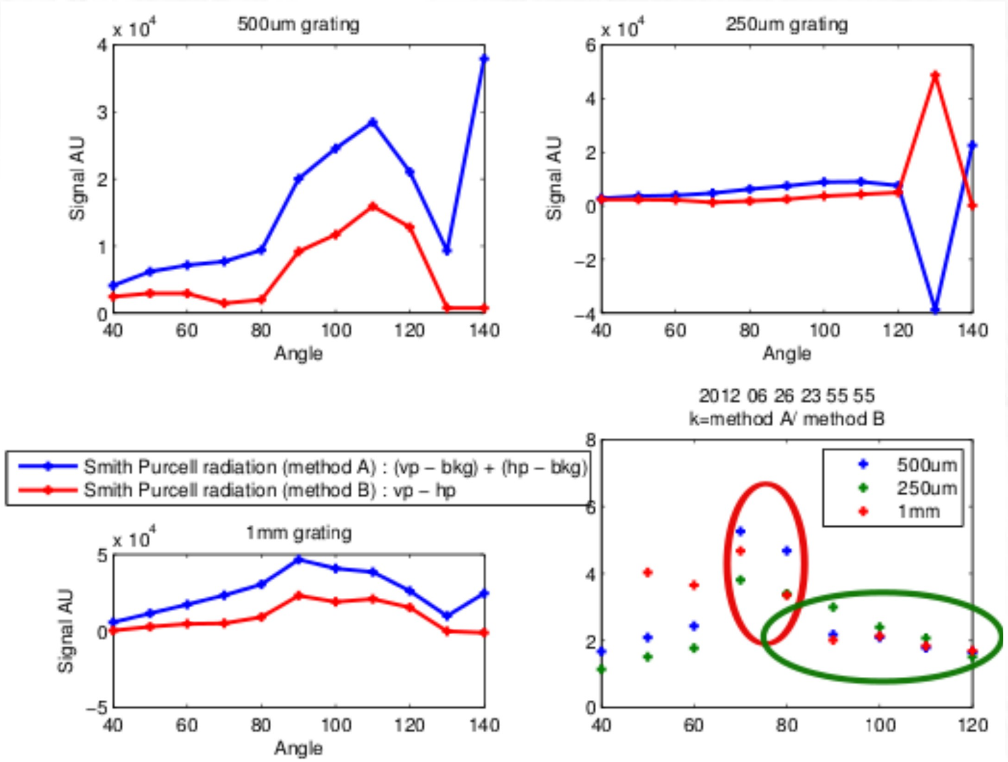
- Therefore we have: $VP_{grating} - HP_{grating} = SP_v - SP_h = \beta SP \quad (2)$

Signal of Smith-Purcell radiation with horizontal polarization

- We have therefore two different ways to obtain the signal of Smith-Purcell radiation:

$$SP = (VP_{grating} - B) + (HP_{grating} - B) \quad (method\ A)$$

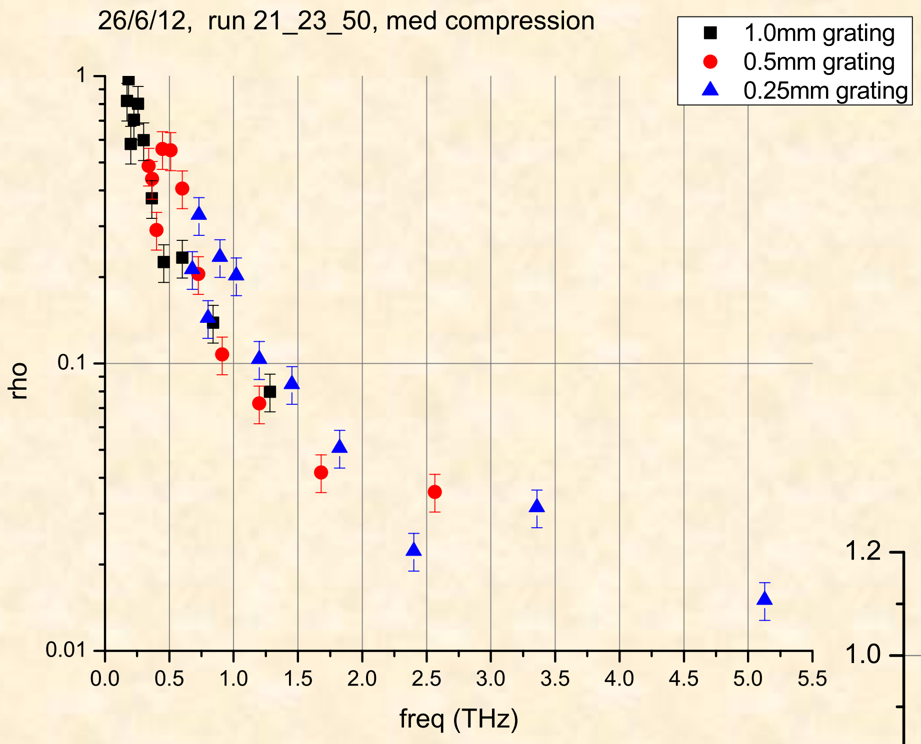
$$SP = \frac{1}{\beta}(VP_{grating} - HP_{grating}) \quad (method\ B)$$

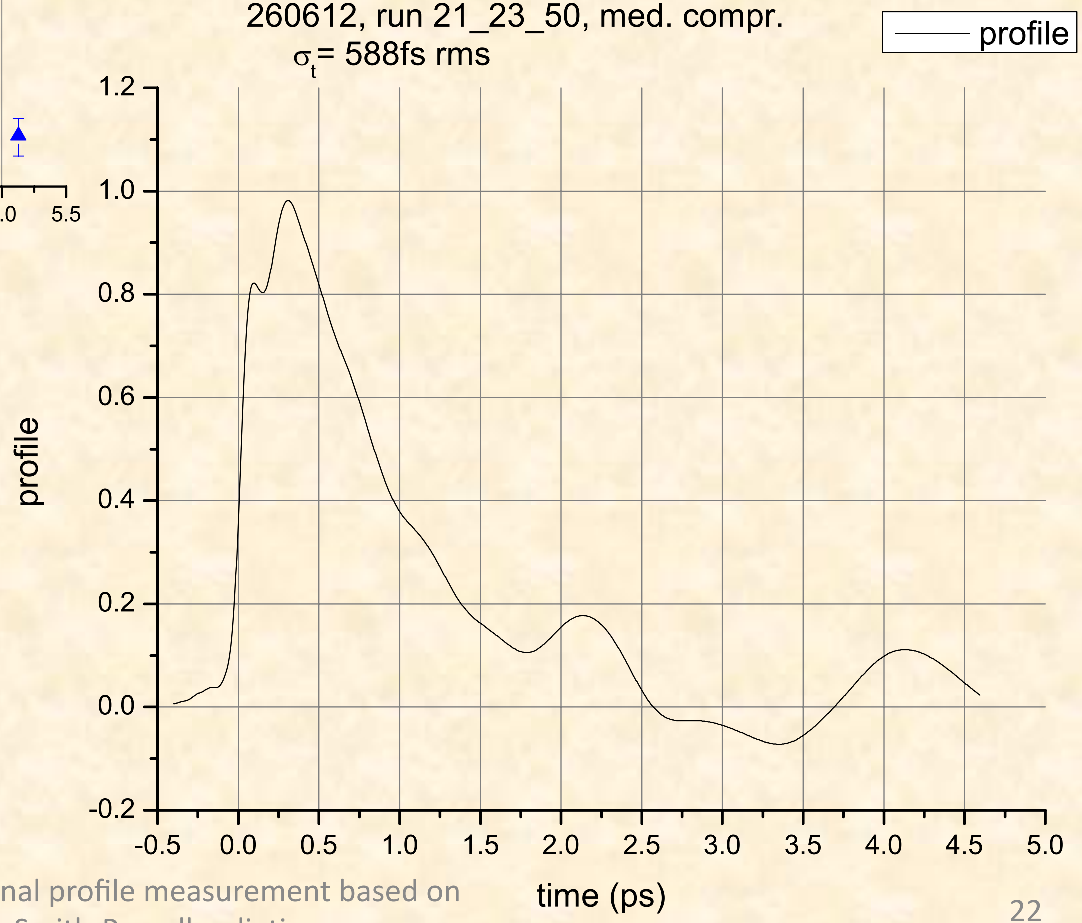


We plot each method for each grating.

The ratio (see bottom right) would be almost constant if the formulas are right. But we can see an anomaly for the detectors at 70/80 degrees.

Measured profile



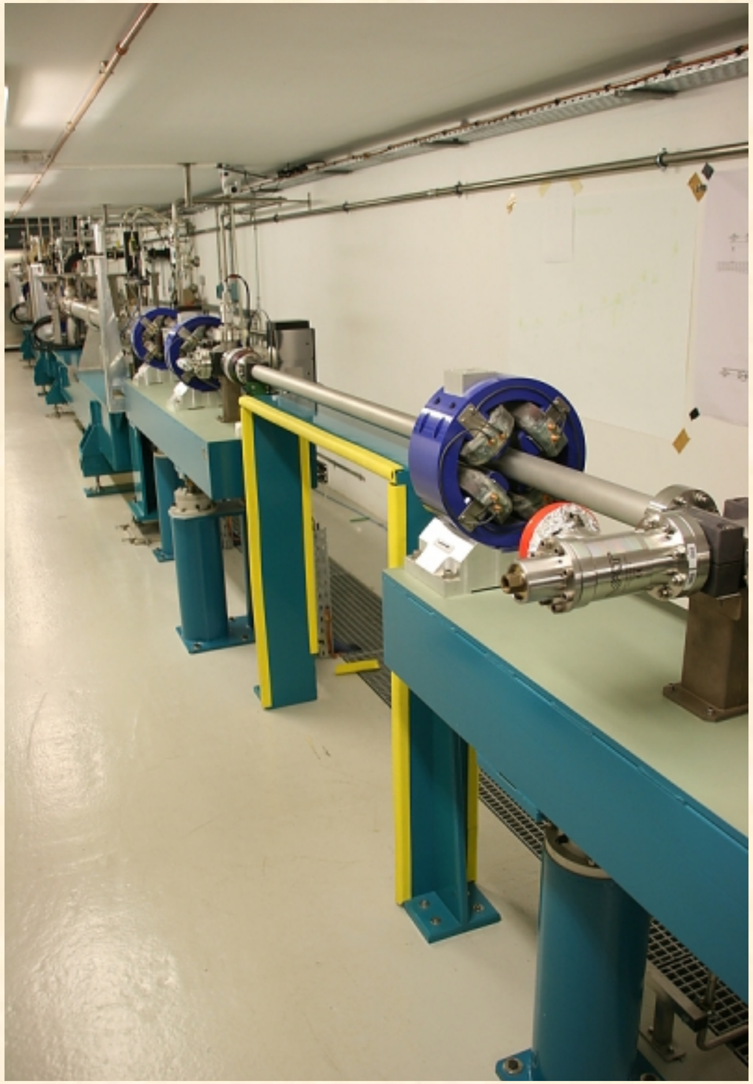


Some challenges

- So far one measurement requires 6 data taking runs of about 1 minute each.
  (3 gratings + 3 backgrounds)
- Ideally we would like to do single shot measurements:
  => use 3 (?) gratings at the same time? In parallel? In series?
- Need to measure the background at the same time.
  => most of the background is clearly induced by the insertion of the gratings
  => need to find direction where the gratings produce similar background but not SPR.
- Data taken at SLAC are limited in statistics (only a few runs per week, a few weeks per year) to address these issues.

  => Smith-Purcell Experiment at SOLEIL (SPESO)

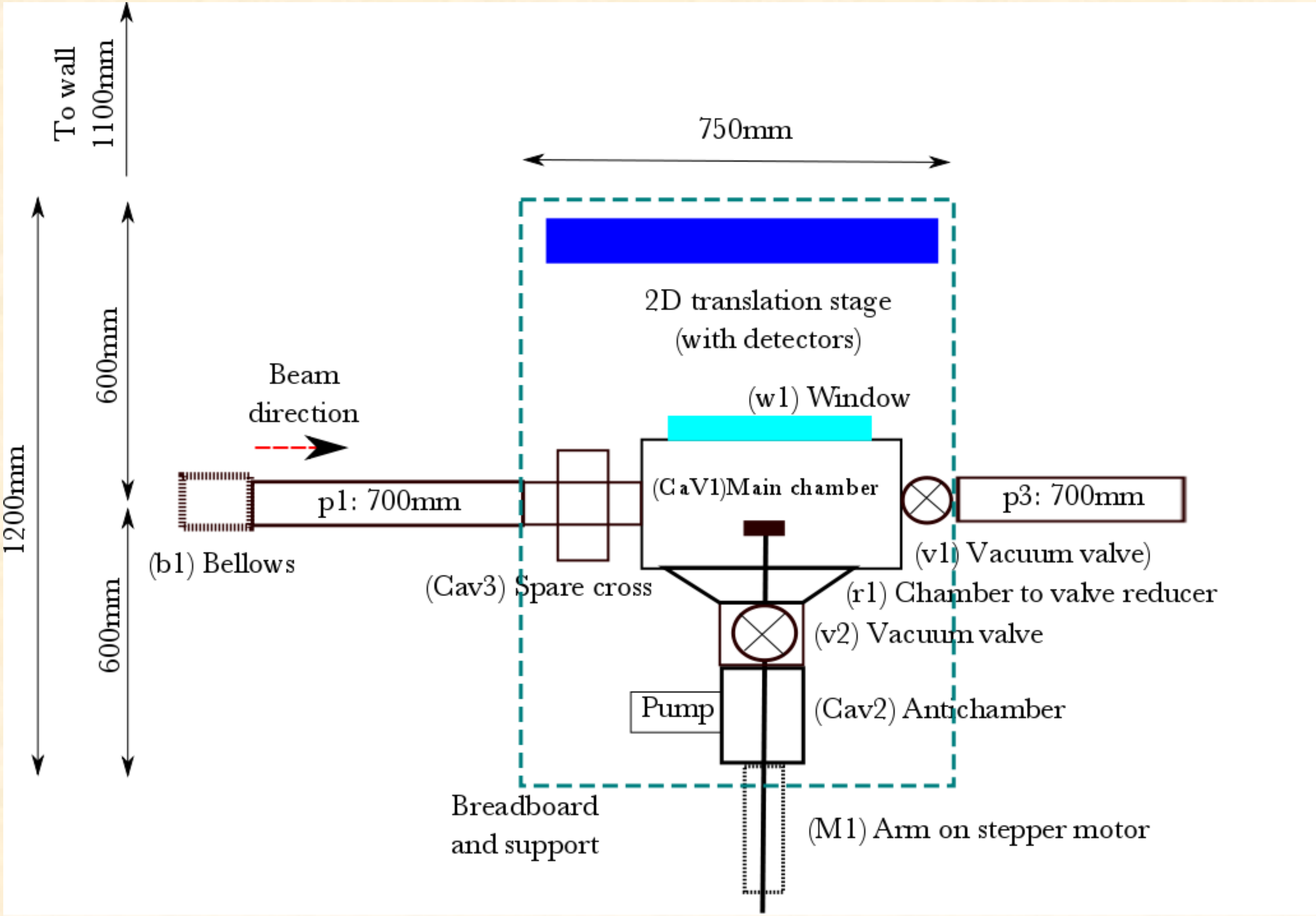
SPESO



- Better understand the formation of CSPR (angular and spatial distribution, polarization, …).
- Check different grating geometries too minimise backgrounds.
- Effect of grating material (conductivity, surface quality,…)
- Compare experimental measurements with CSPR theories

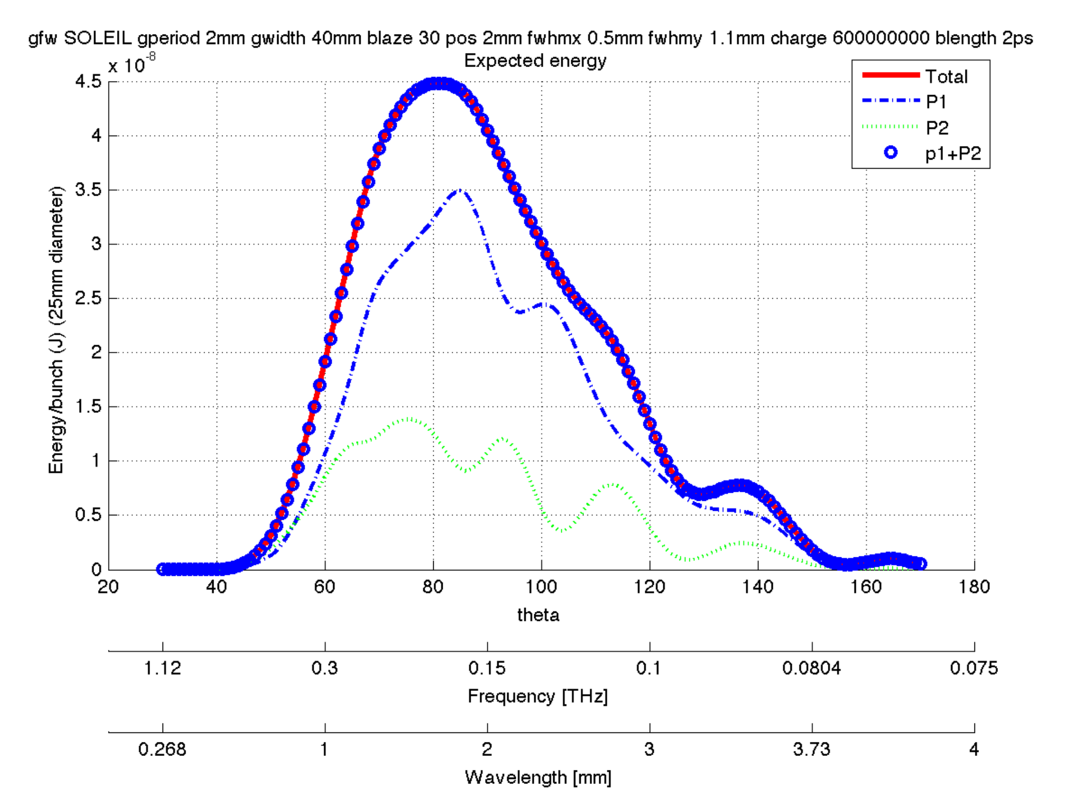
- Design a single shot longitudinal profile monitor suited for ps-beams.

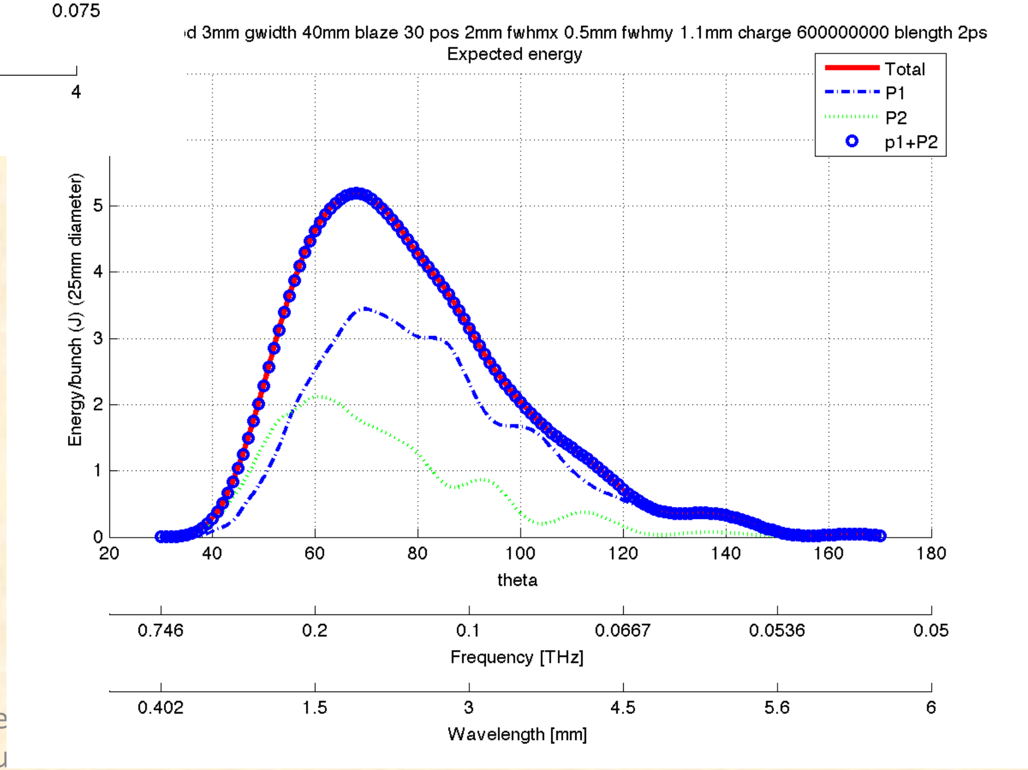
Layout



To wall
1100mm
750mm
1200mm
600mm
600mm
2D translation stage
(with detectors)
Beam
direction
(w1) Window
(CaV1)Main chamber
p1: 700mm
p3: 700mm
(b1) Bellows
(v1) Vacuum valve)
(Cav3) Spare cross
(r1) Chamber to valve reducer
(v2) Vacuum valve
Pump
(Cav2) Antichamber
Breadboard
and support
(M1) Arm on stepper motor

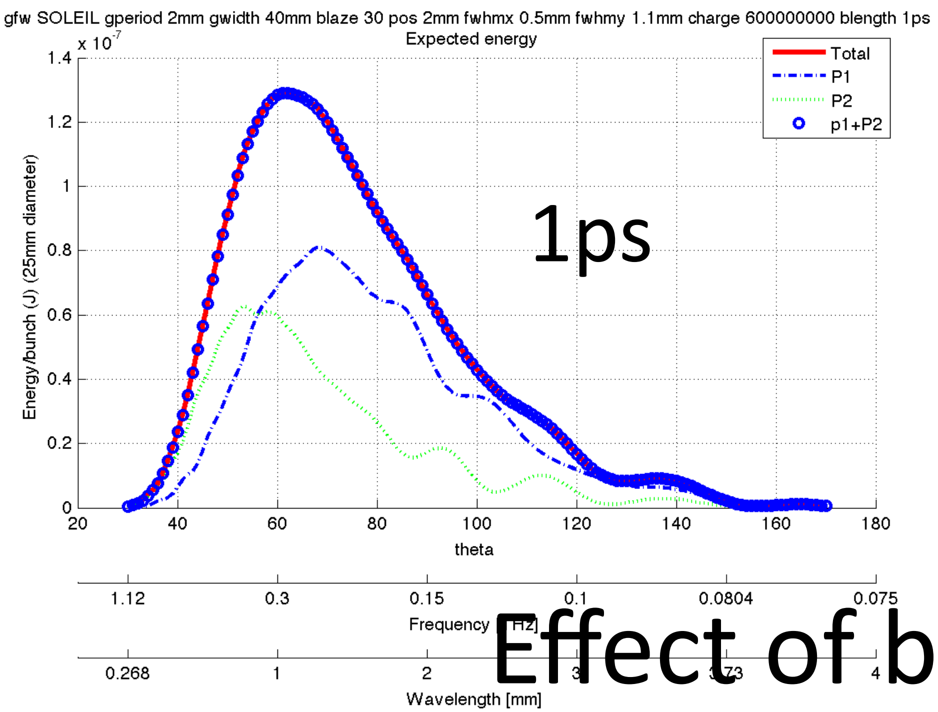
Predicted yield

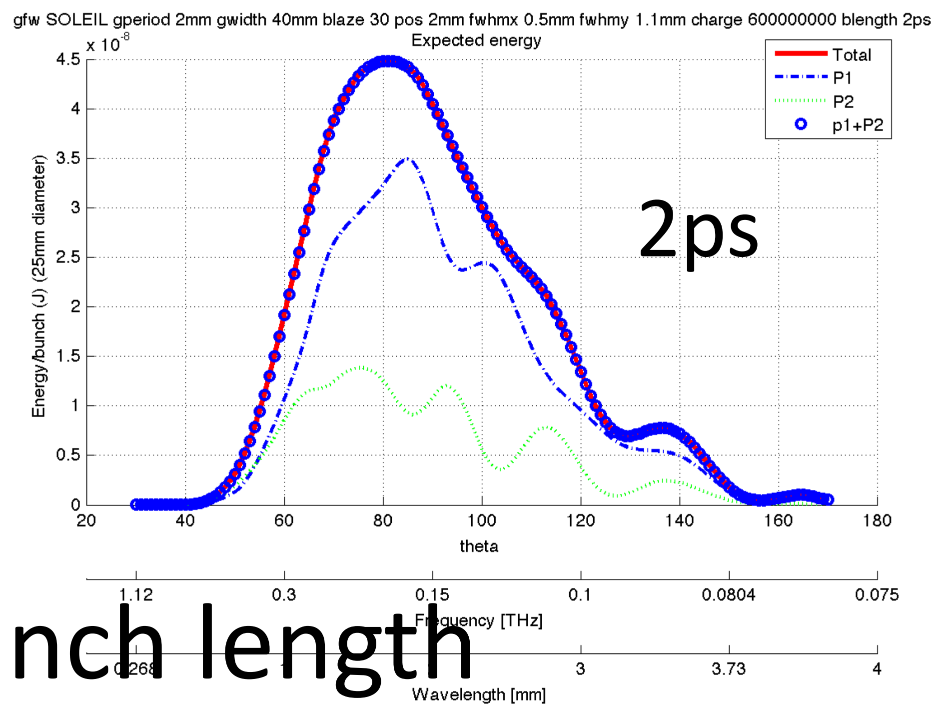


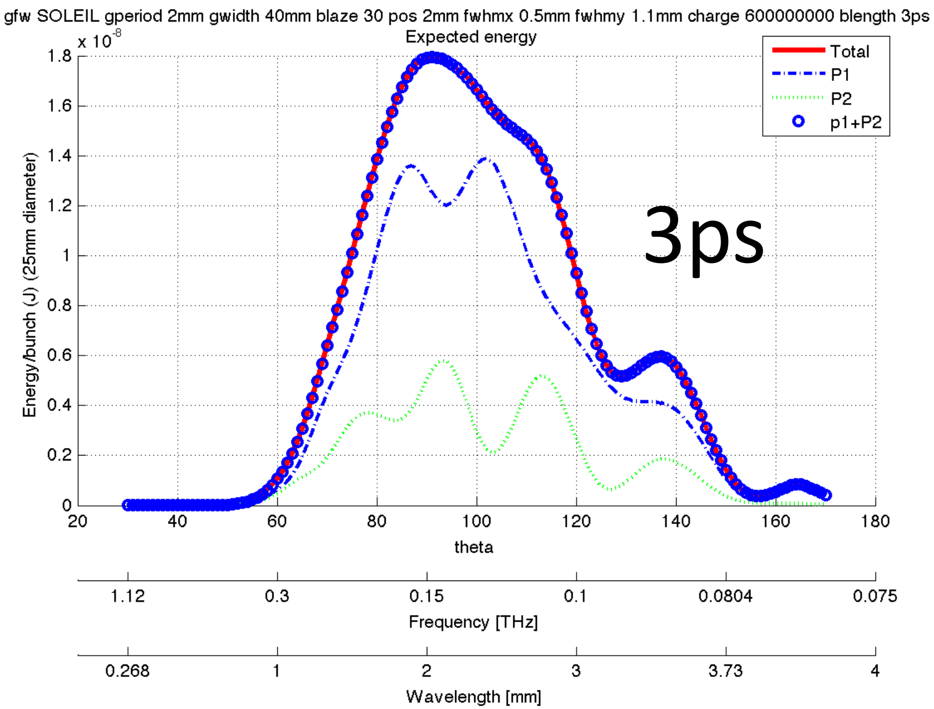


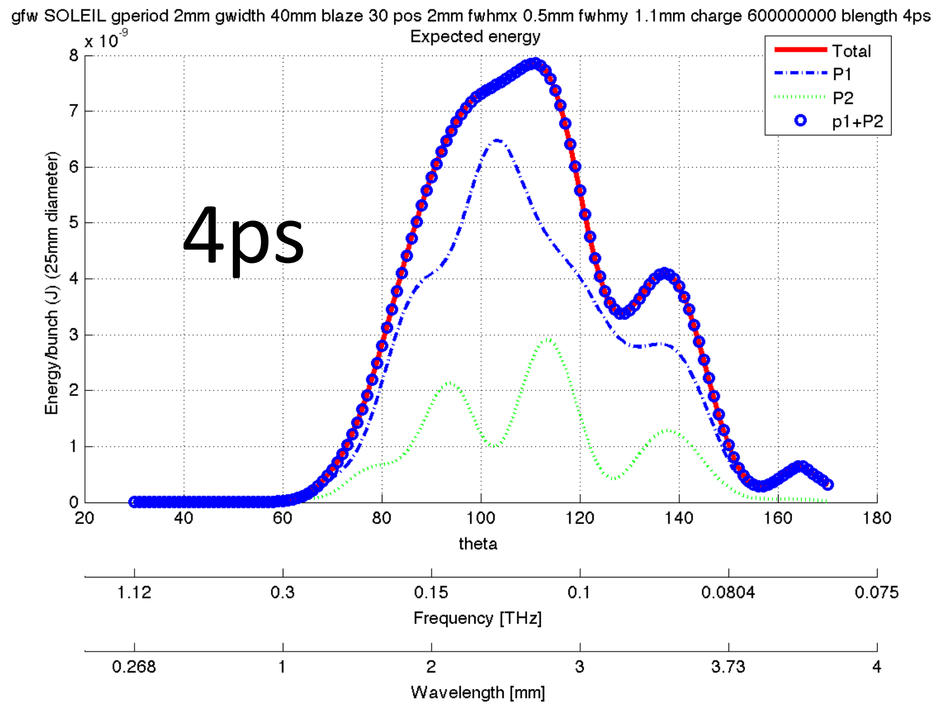
- Predicted yield is low
- Simulations: grating=2-3mm, bunch length 2ps FWHM, 37.5pC => ~45nJ/bunch => 4,5uJ/train

Effect of bunch length









Status

- All UHV parts have been ordered.
  Delivery expected for December/January.
- Supplier reported this week that crystal quartz windows broke during brazing…
- Currently investigating pyroelectric detectors & thermopiles to check that we can extract enough signal.

Beyond SPESO: SPARC and plasma accelerators

- SPESO will explore SPR in the ps range.
- After the experiment will be moved to SPARC to work in the fs range.
- The final goal is to produce a single shot longitudinal profile monitor in the few fs to use it at plasma accelerators.