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

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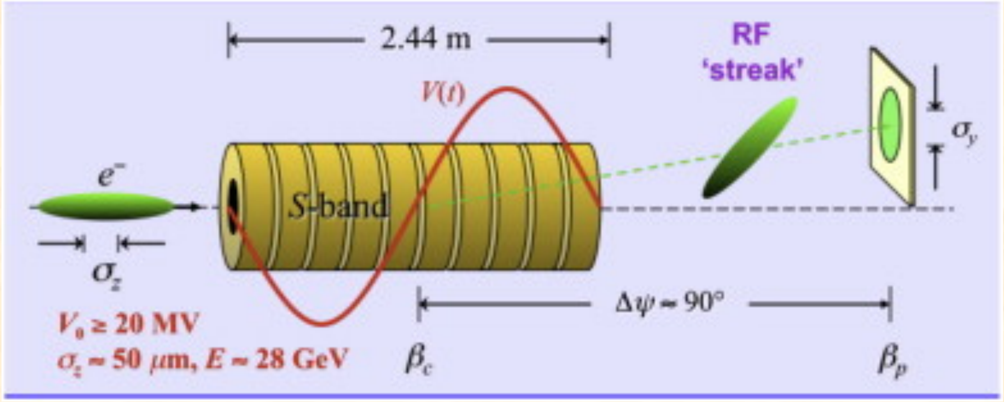
Motivation

- Modern accelerators such as Free Electron lasers need accurate measurement of the bunch length in the 100s fs regime.
- Deflecting cavities are the most popular tool to perform such measurement but they are expensive and destroy the beam.



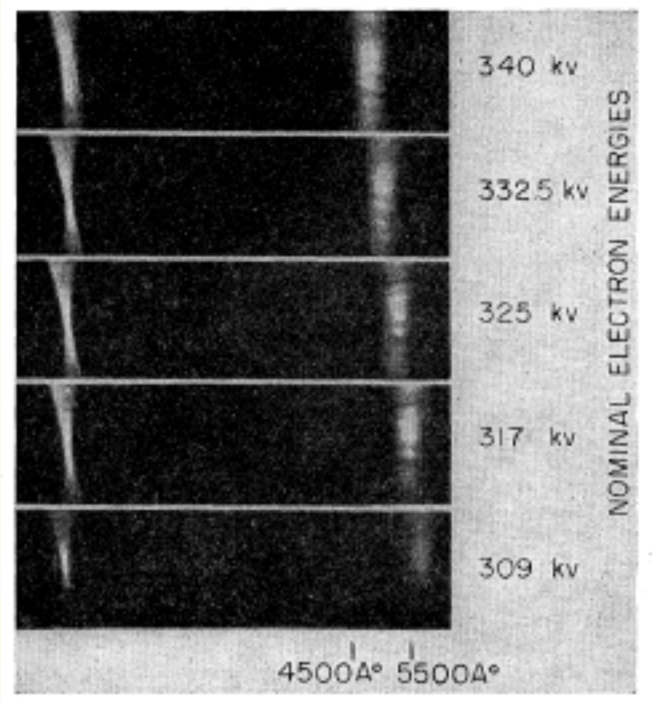
- Measurements of radiation emitted by the bunch can give this information in a non destructive way.

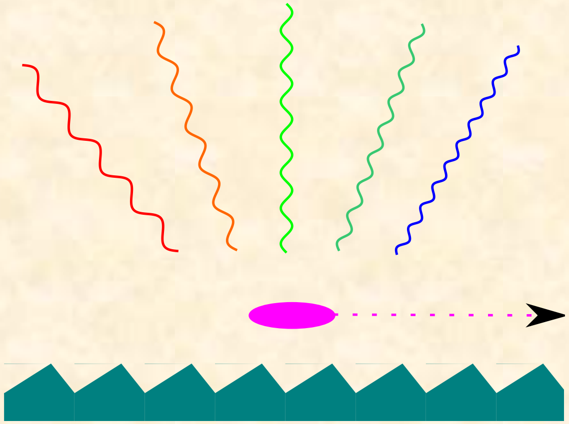
Radiation based bunch length measurements

- Several techniques use radiation to measure bunch lengths:
  - Transition radiation scans
  - Electro-optics sampling
  - Smith-Purcell radiation
- Smith-Purcell radiation has the advantage of giving a better yield and spectrally dispersed radiation.

Smith-Purcell radiation

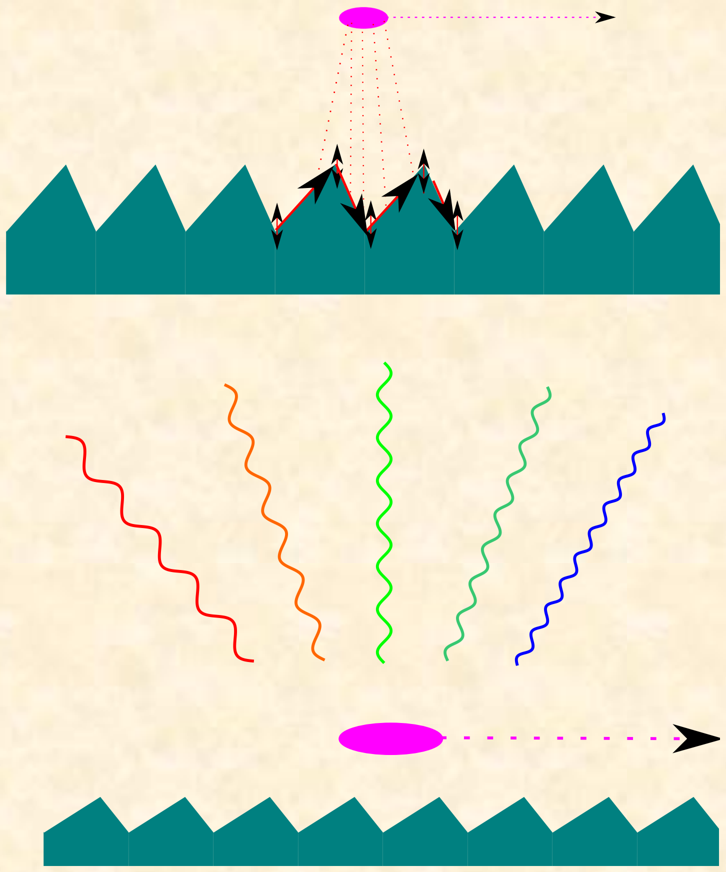
- Discovered experimentally in 1953 by Smith and Purcell.
- Electrons passing near a grating induce the emission of (visible) radiation.
- S.J. Smith and E.M. Purcell, Phys. Rev. **92**, pg. 1069, (1953)
- 300 keV electrons to emit in the visible wavelengths (d = 1.67 um)





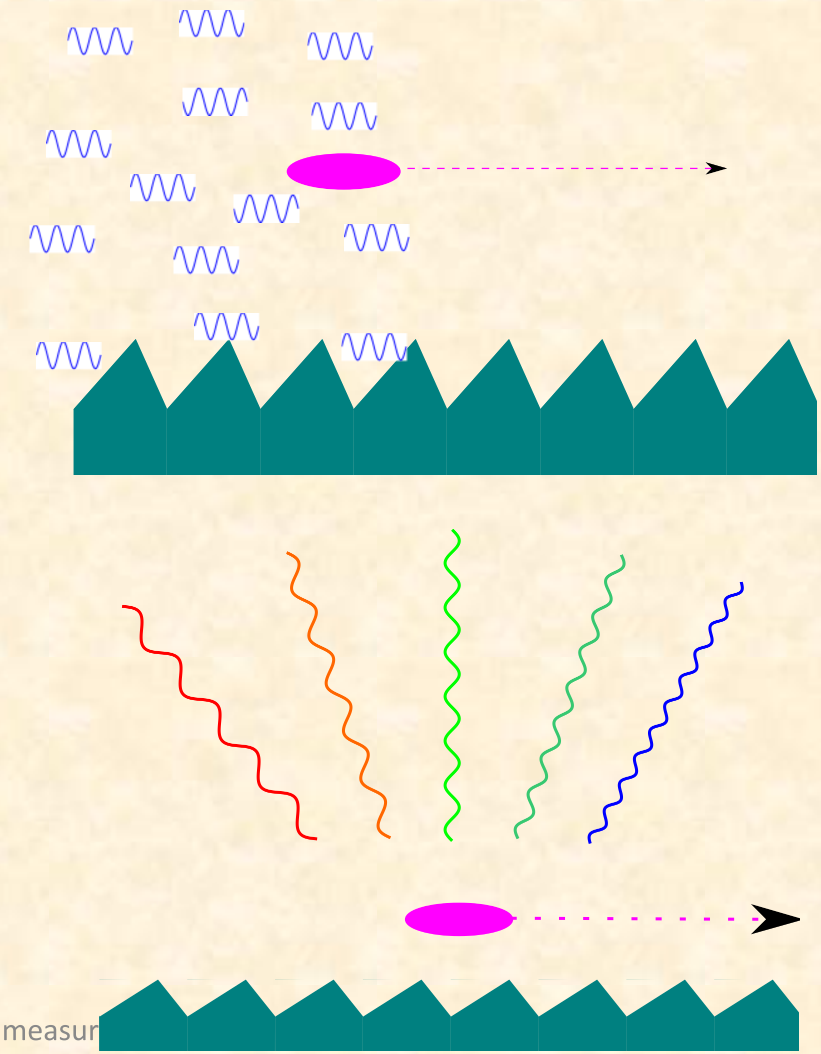
Explanation: dipole radiation

- 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.

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

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

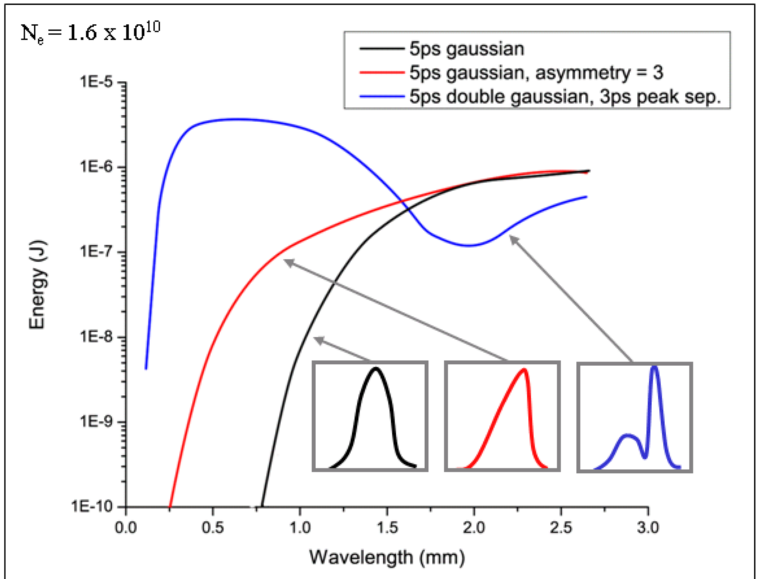
Coherent SP radiation

- 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.

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

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.

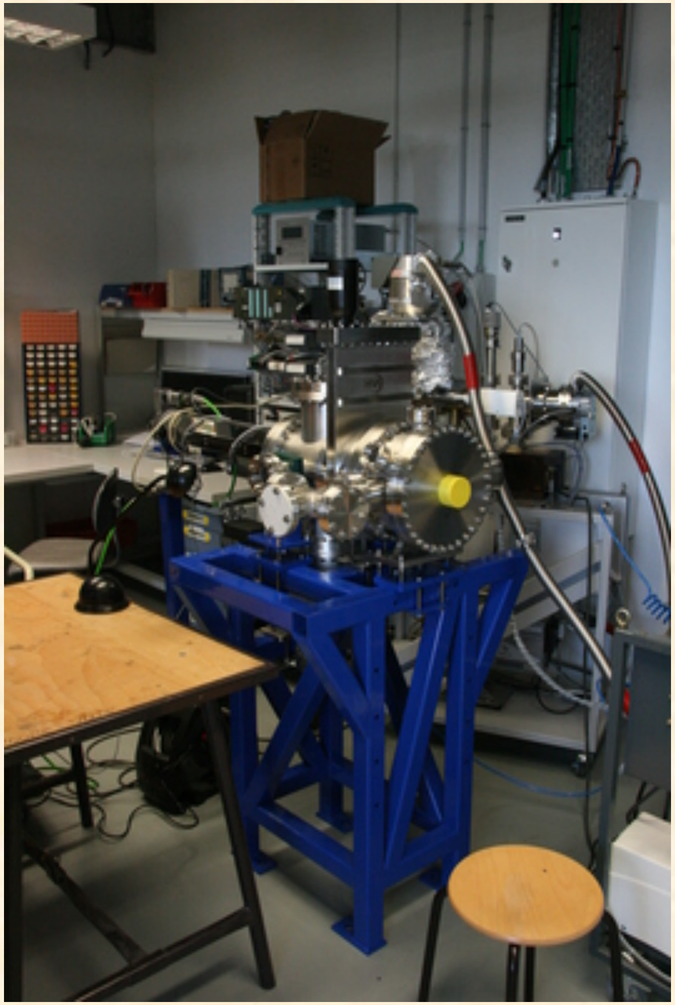


Simulation of different profiles, as would be seen experimentally

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

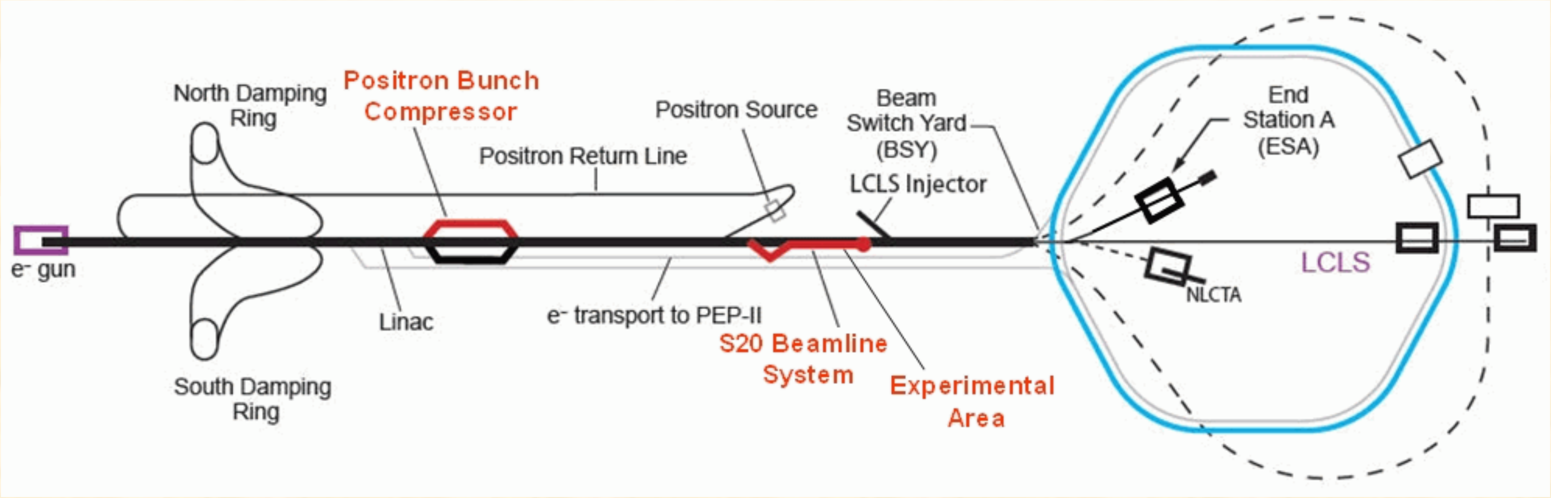
CSPR as a longitudinal diagnostic: Current R&D

- Work is currently ongoing to establish Coherent Smith-Purcell radiation as a longitudinal profile diagnostic.
- E-203 collaboration (Oxford, LAL, LANL, SLAC, IFIC…) to perform tests at FACET (SLAC)
- SPESO: Smith-Purcell Experiment at SOLEIL
=> installed last month

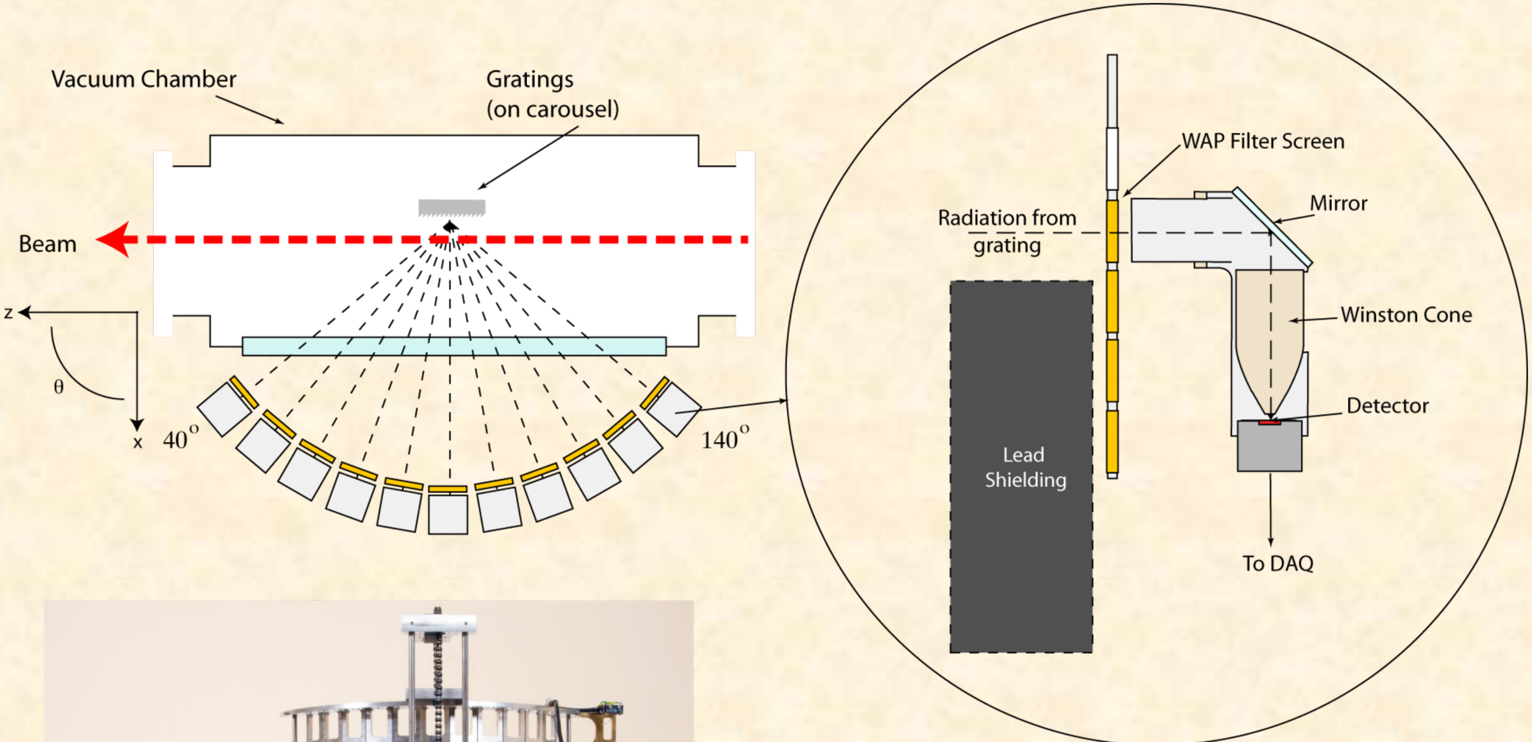


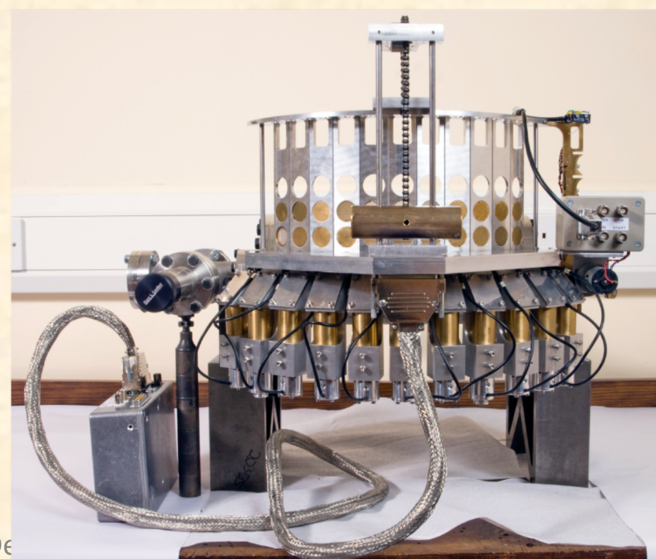
E-203 at FACET

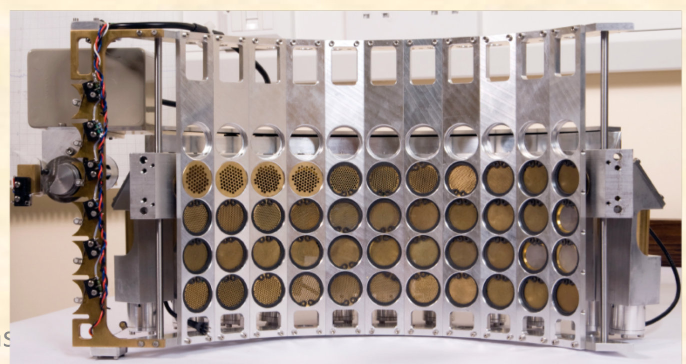
- FACET at SLAC is a test facility offering access to 100s femtoseconds long electron bunches.
- Electrons energy is 22.5 GeV (gamma=45000)
- Collaboration E-203 approved with rating "excellent" to develop longitudinal profile monitor in the fs range.
- Schedule: 2 runs/year (approval must be confirmed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



Experimental apparatus (schematic)

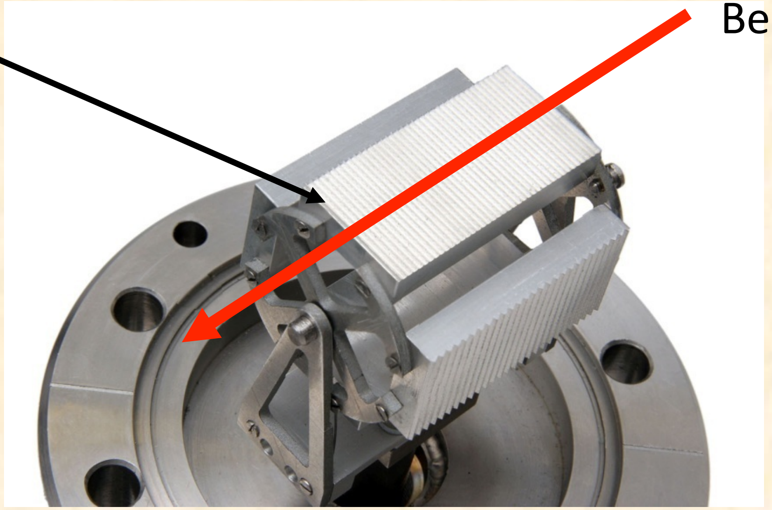






Experimental apparatus: gratings carousel

3 gratings
1 blank piece of aluminium

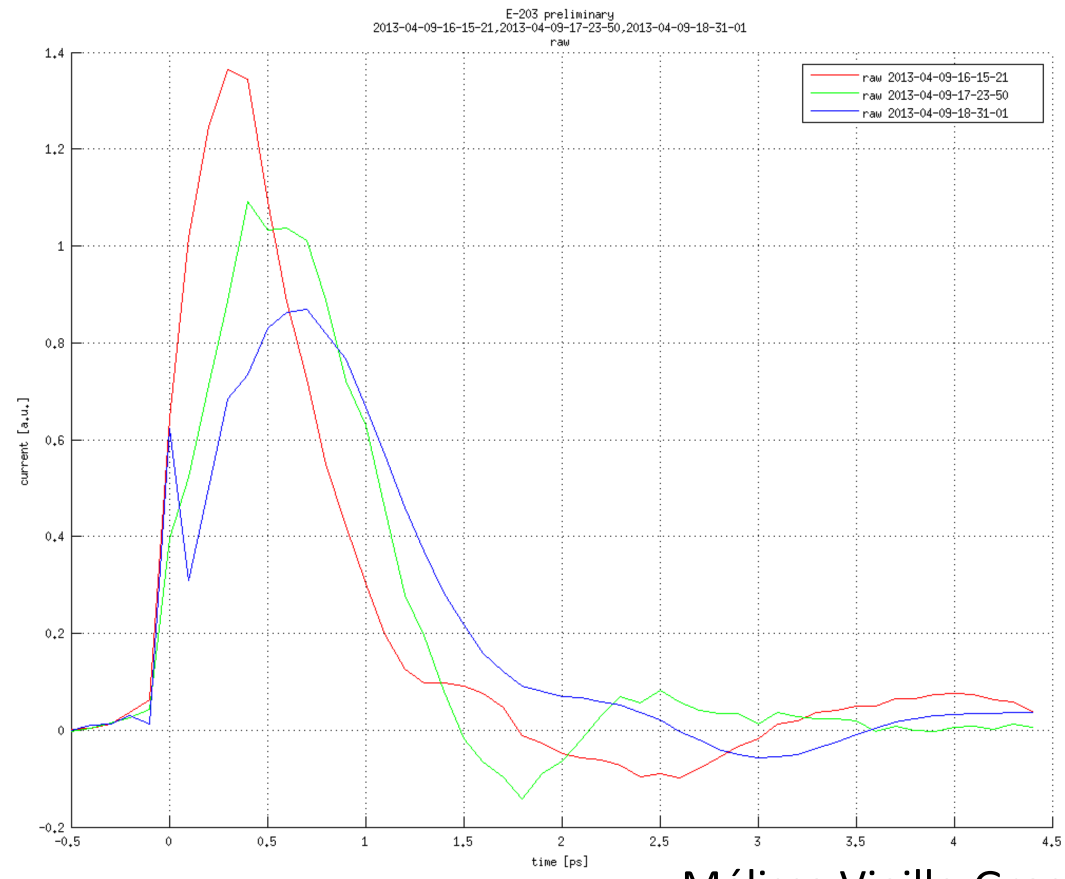


Expected SP radiation at FACET in the wavelength range 10 μm to 1 mm

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

Installed on the FACET beam line

Very preliminary result: Comparison of different compression settings



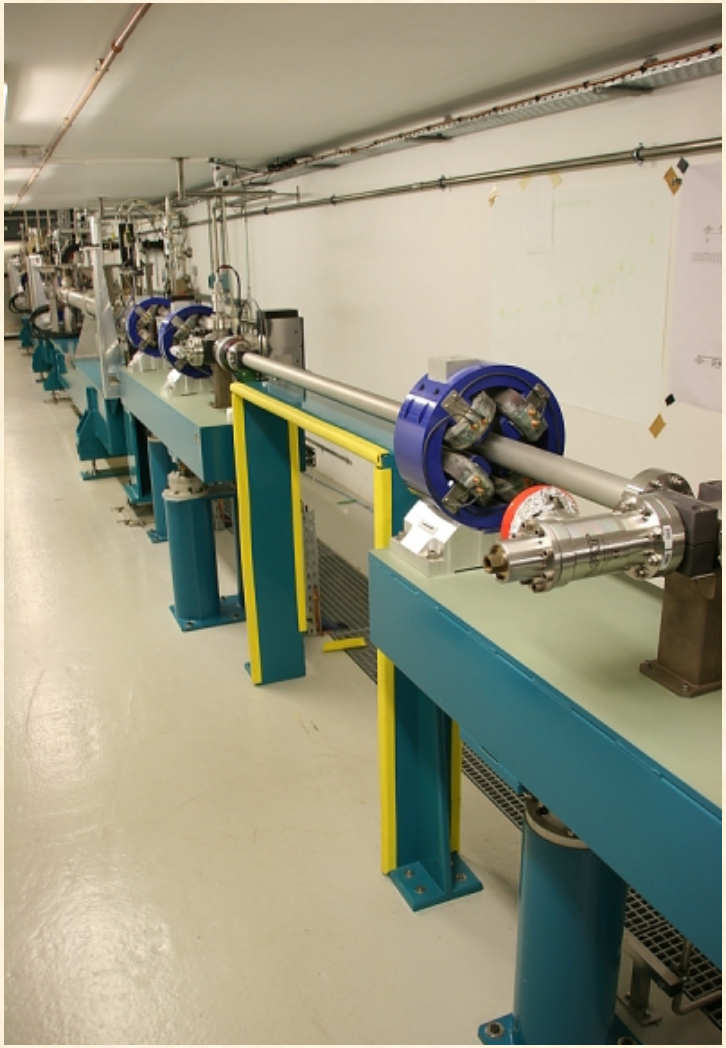
Mélissa Vieille-Grosjean

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)

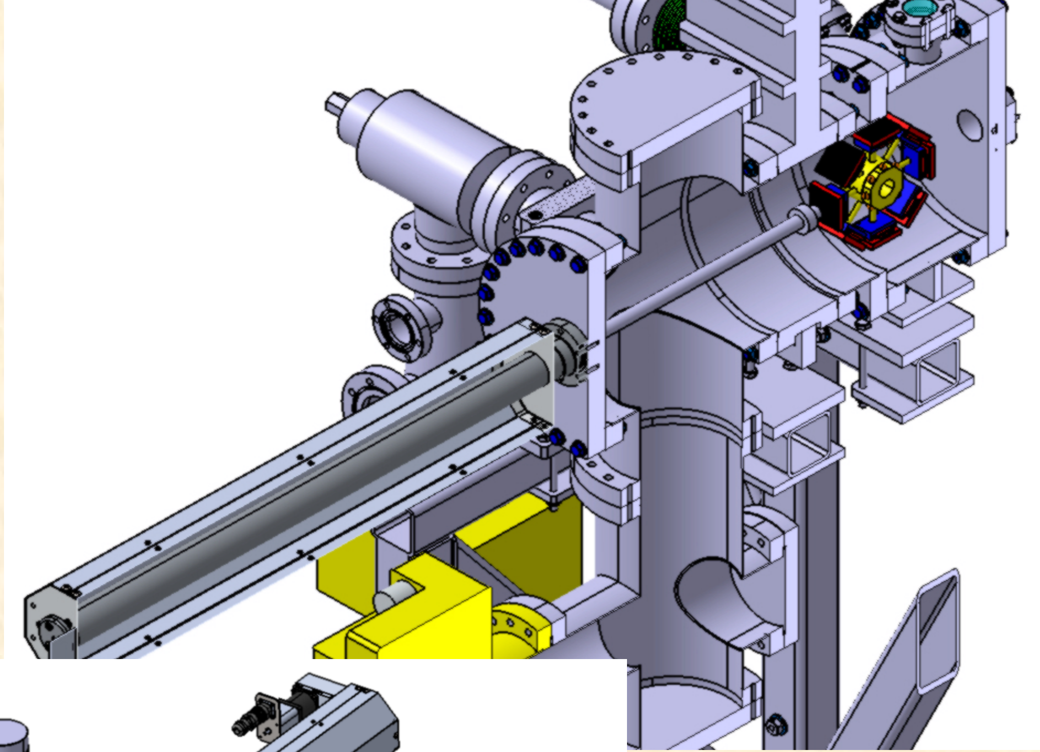
SPESO

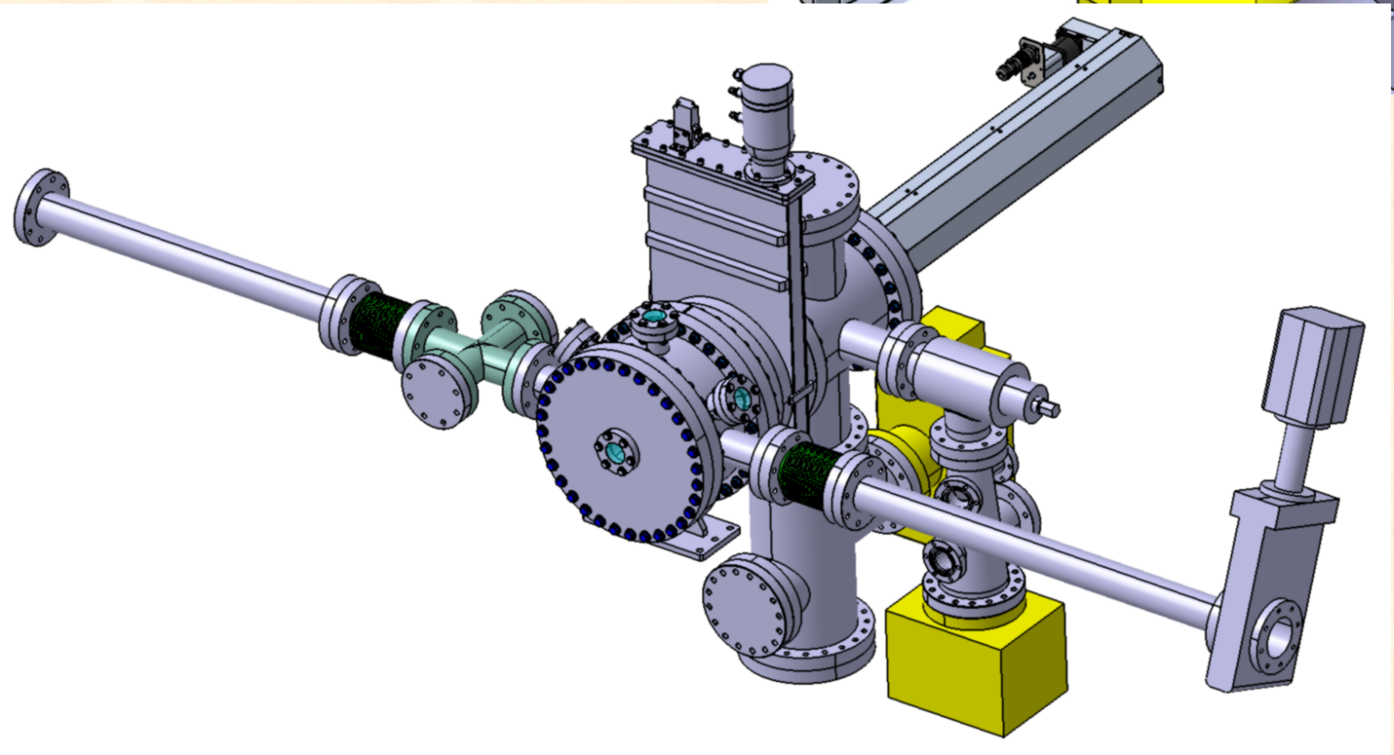


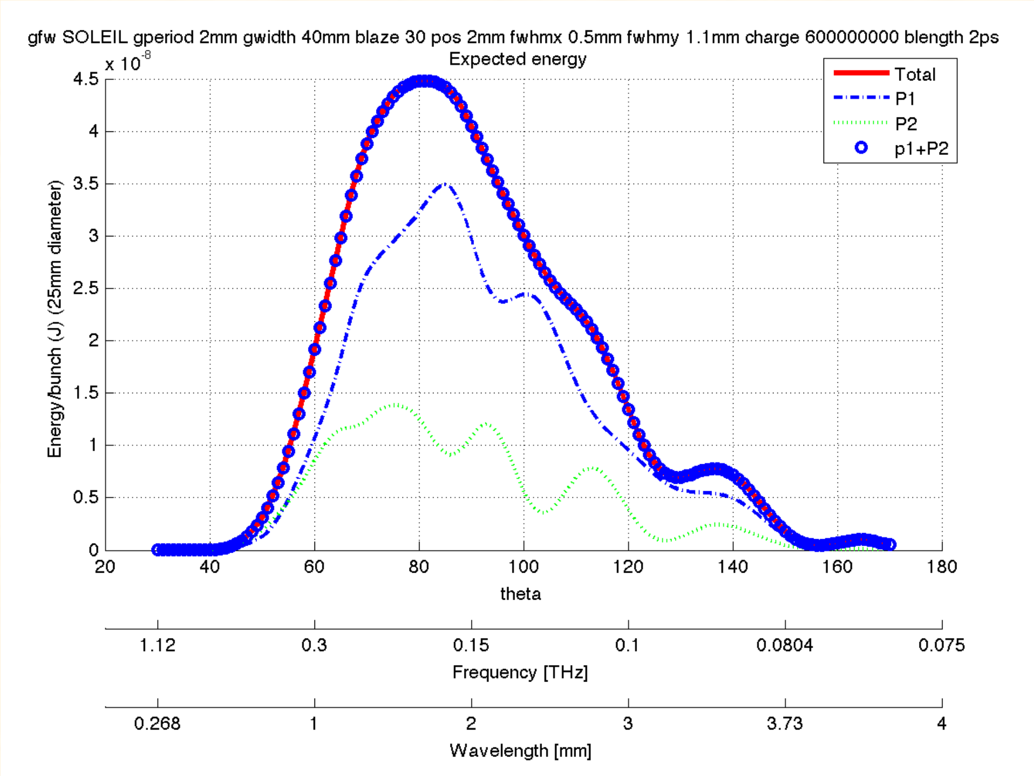
- Better understand the formation of CSPR (angular and spatial distribution, polarization, …).
- Check different grating geometries too minimise backgrounds.
- Effect of grating material (conductivity, surface quality,…)
- Compare experimental measurements with CSPR theories

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

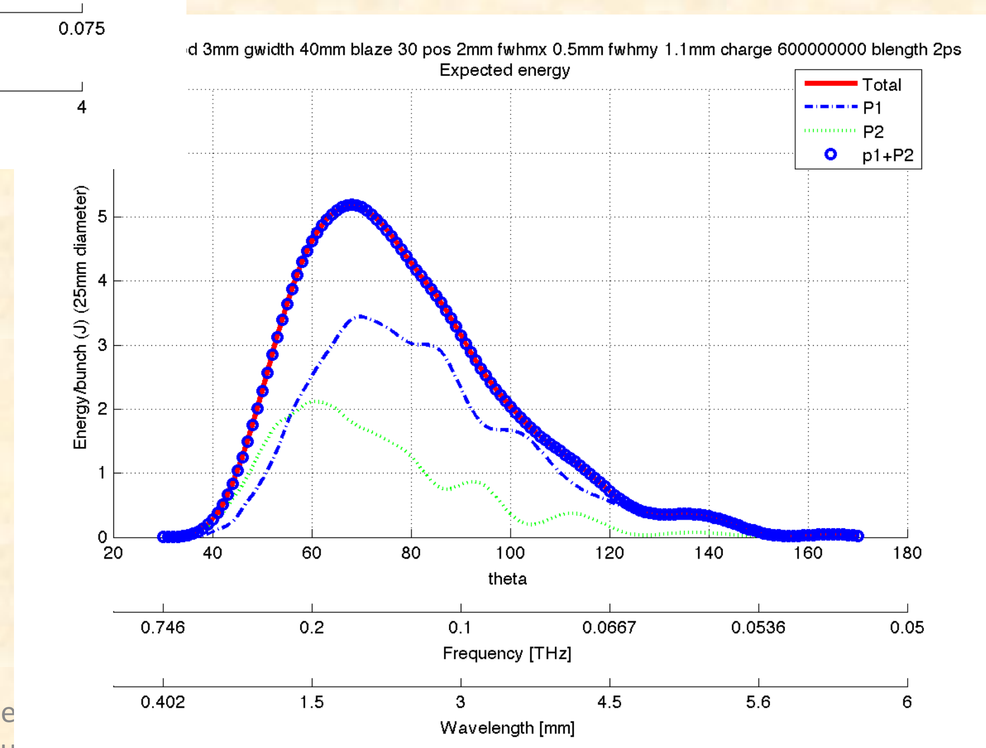
Layout





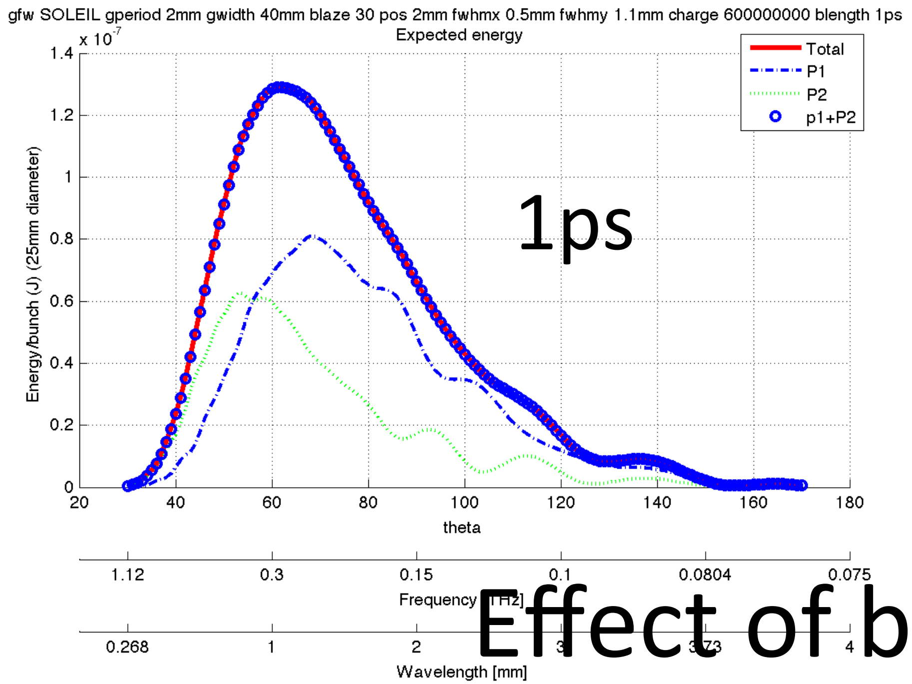


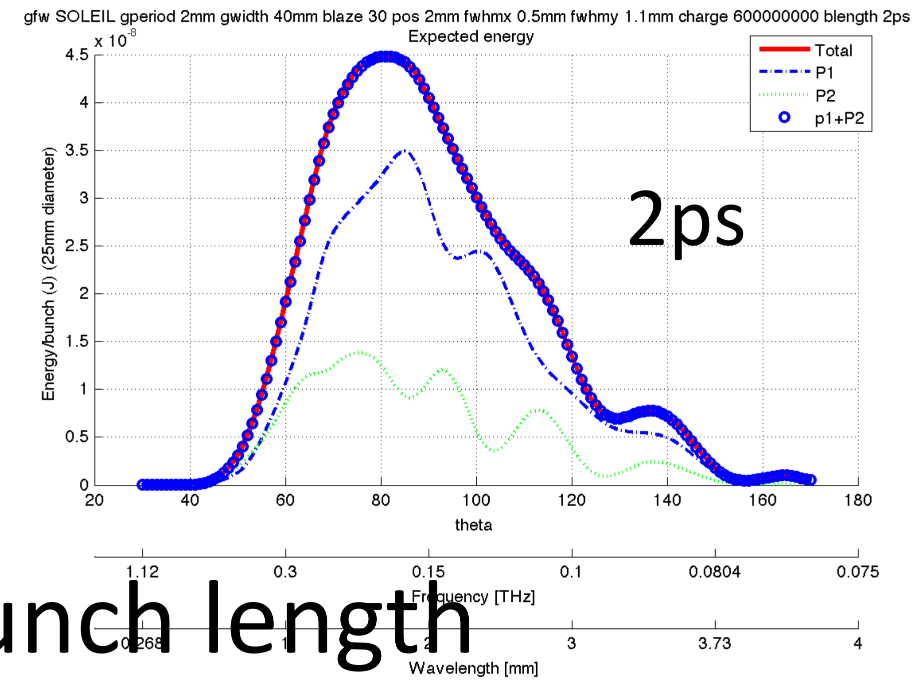
Predicted yield

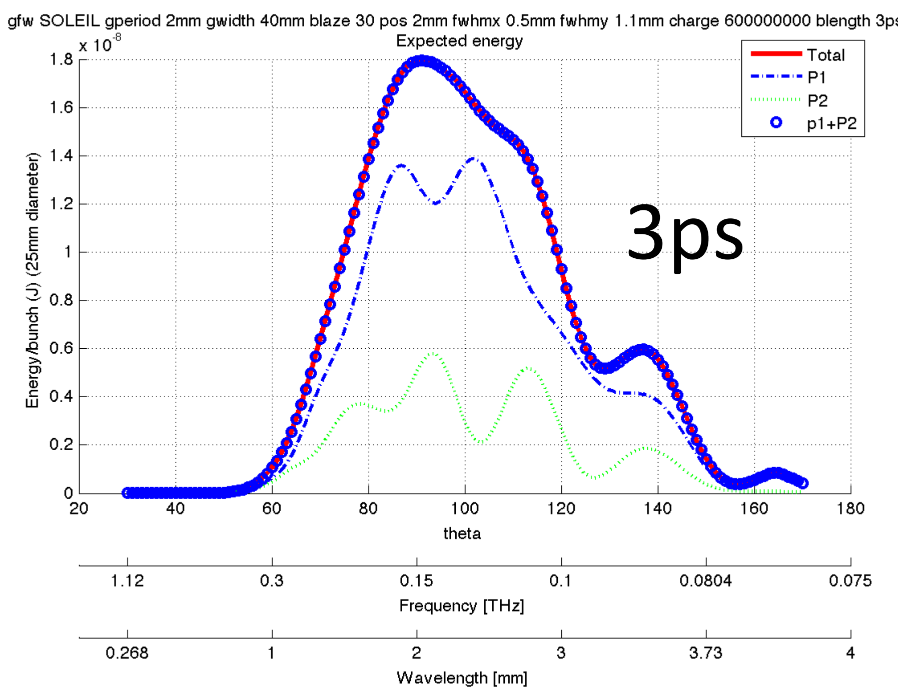


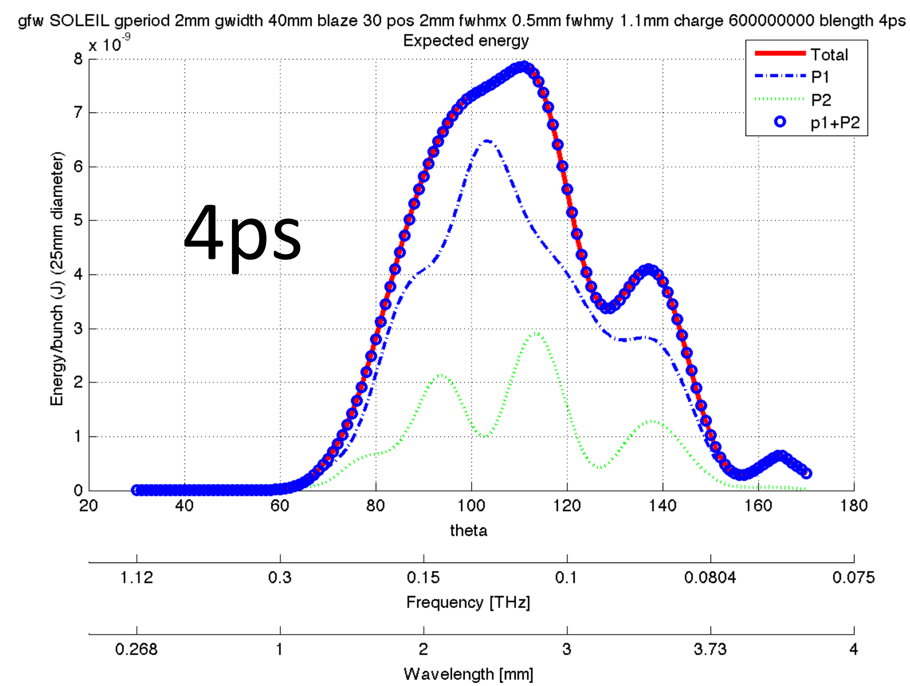
- Predicted yield is low
- Simulations: grating=2-3mm, bunch length 2ps FWHM, 37.5pC => ~45nJ/bunch => 4,5uJ/train

Effect of bunch length









Bunch length reconstruction

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

- After the measurement the Fourier transform must be inverted to reconstruct the bunch profile.
- However the phase of the Fourier transform is missing.
  => Phase recovery technique such as Jramers-Kronig

Kramers Kronig phase recovery technique

- Given that the profile we are trying to reconstruct is real and analytical there are some special relations between its phase and its amplitude.
- This can be used to recover the phase by assuming such relation.
- Currently we use an implementation of the Kramers Kronig relation that require the use of proprietary software.
- Work in progress on this topic for SPESO in collaboration with Oleg Bezshyyko and Vitalii Khodnevich to develop a better phase recovery tool.

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

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

Outlook

- Smith-Purcell radiation is one of the many coherent phenomena that encodes information about the bunch length.
- It offers the advantage of producing a spectrally dispersed radiation.
- It is non-destructive and has the potential to be single-shot.
- Tests are in progress at SLAC and at SOLEIL to validate it as a longitudinal bunch profile monitor.