Smith-Purcell radiation as a bunch length diagnostic

Nicolas Delerue
LAL (CNRS and Université de Paris-Sud)

In collaboration with:
- E-203 (SLAC, JAI/Oxford,…)
- Synchrotron SOLEIL
- Joint France-Ukraine Laboratory (Kyiv and Kharkiv National Universities)

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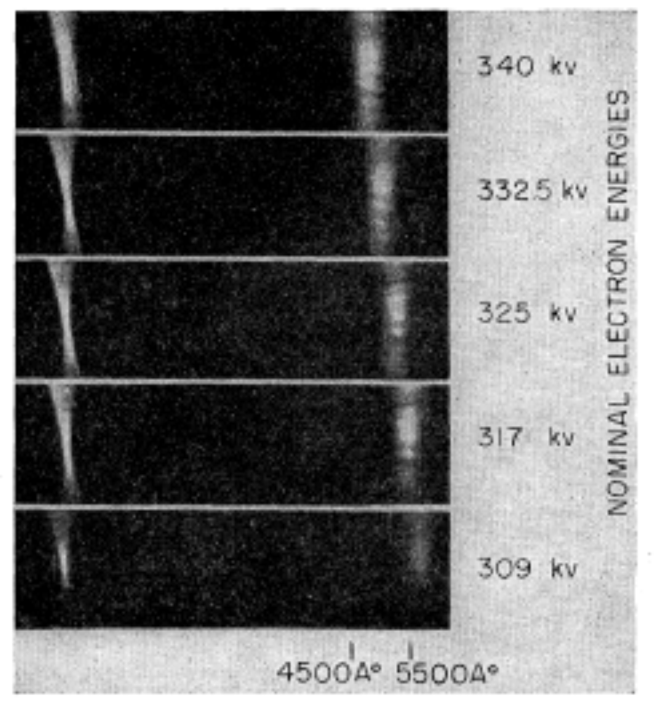
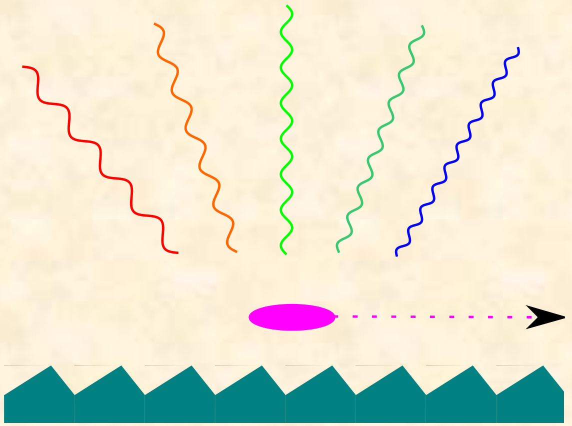
Content

- Introduction to Smith-Purcell radiation
- Model dependence & Pre-wave/near field effects
- Smith-Purcell Radiation as a bunch length Monitor
- E-203
- SPESO
- The future: single shot

Smith-Purcell radiation

- Discovered experimentally in 1953 by Smith and Purcell.
- Electrons passing near a grating induce the emission of (visible) radiation.
- *Radiation is dispersed spectrally.*
- 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)
- Theta is the azimuthal angle.

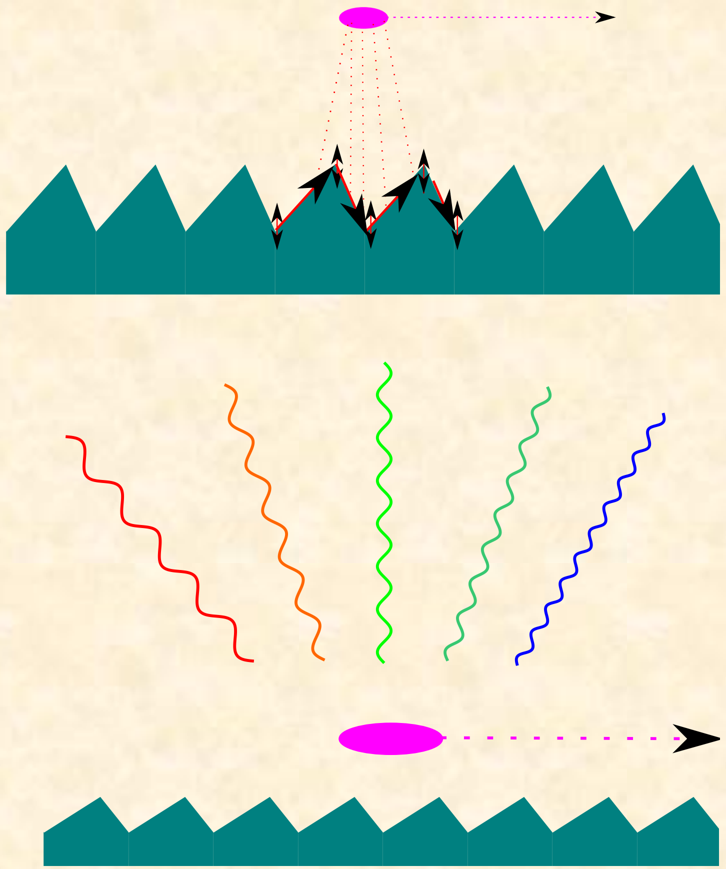




$$\lambda = \frac{\ell}{n}\left(\frac{1}{\beta} - \cos\theta\right)$$

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.

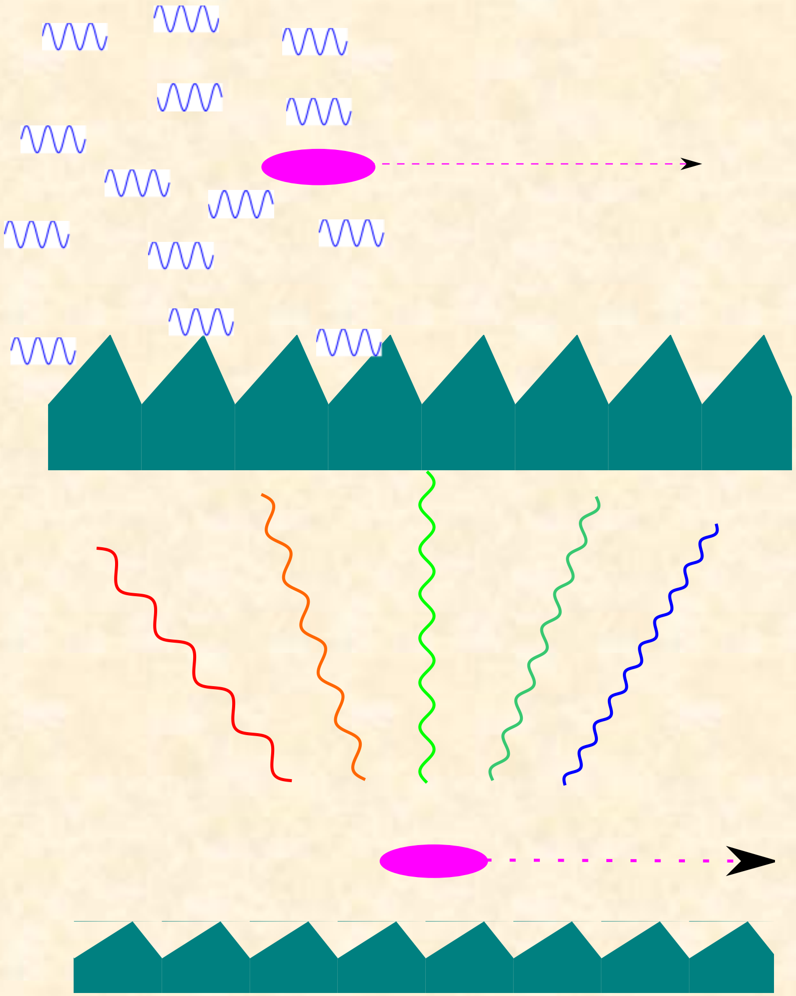


Ishiguro and Tako, Optica Acta (GB) 8 1961 25

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



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

Understanding grating yields

- The diffraction by a grating is very complicated! Neither model seem to fully take into account the grating theory…
- Anomalies…
- Polarisation…

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

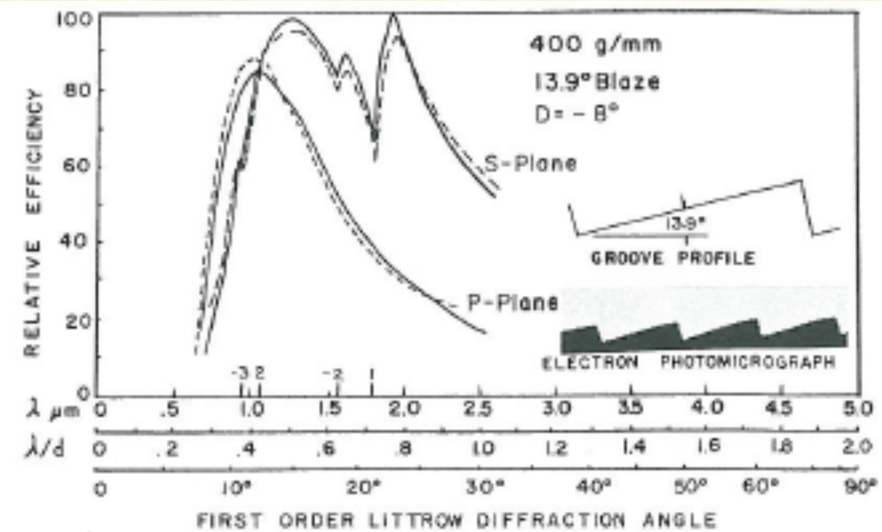


Fig. 4. Relative efficiencies in first order of odd generation aluminum replica (---) from master …ared with theoretical values derived from finite conductivity theory (—) based on …file shown. Actual profile photomicrograph is seen below profile sketch. Grating …ooves/mm, 13.9° blaze angle and $D = -8°$.

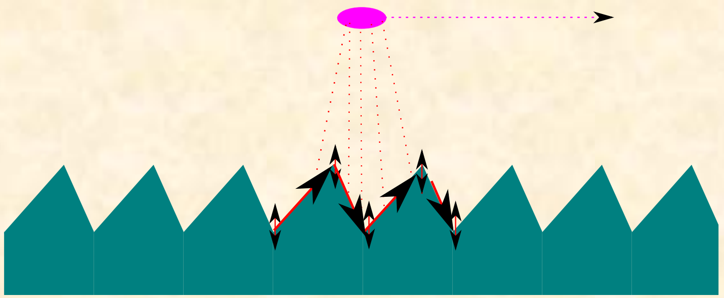
Proc. ICO Conf. Opt. Methods in Sci. and Ind. Meas., Tokyo, 1974
Japan. J. appl. Phys. 14 (1975) Suppl. 14–1

Correlation between Efficiency of Diffraction Gratings and Theoretical Calculations over a Wide Range

Erwin G. Loewen, Daniel Maystre†, Ross C. McPhedran†* and Ian Wilson*

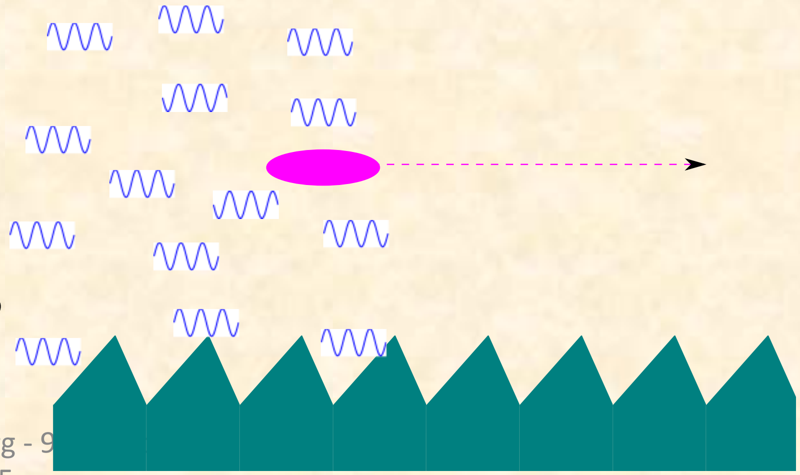
Smith-Purcell models: comparison

- Several developments of both models since 1960… (including by people present at this conference).



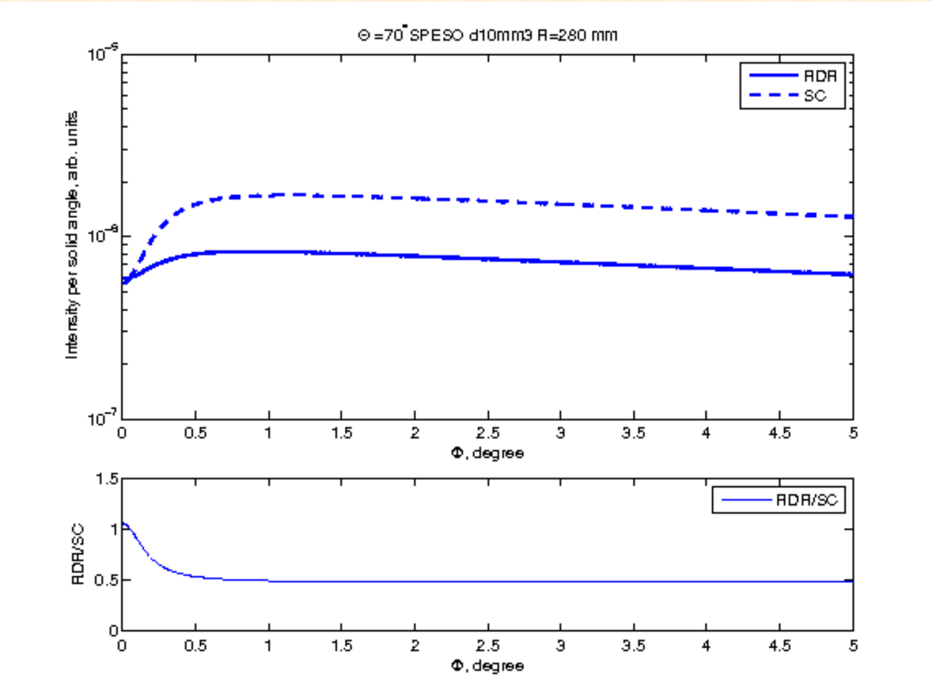
- Most recent comparison (mostly at low gamma):

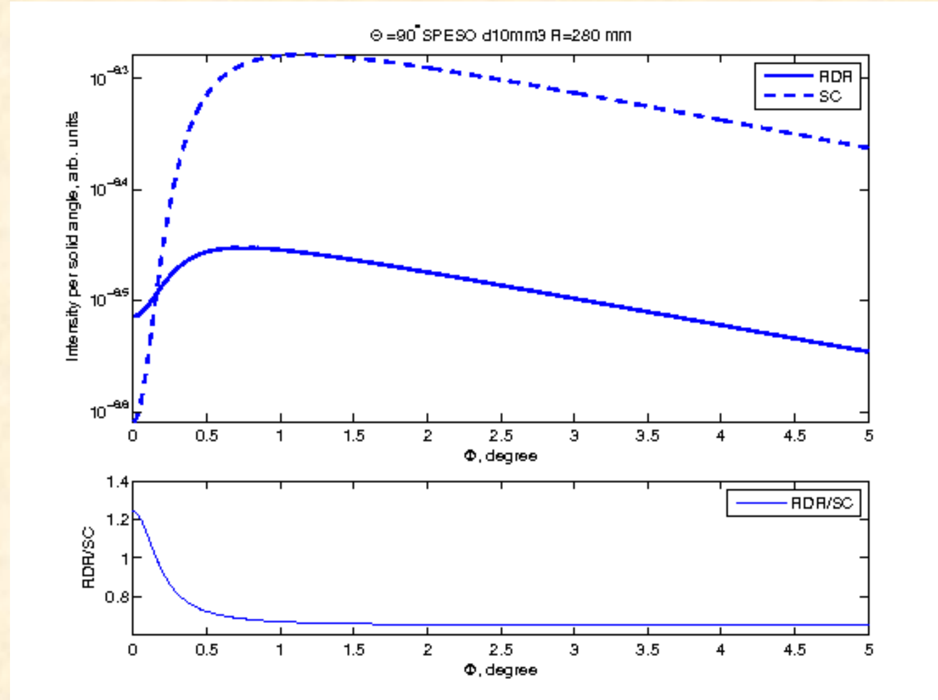
D.V. Karlovets and A. P. Potylitsyn
Phys. Rev. ST Accel. Beams 9, 080701 (2006)



Model comparison at high gamma

- Comparison at gamma=200 (SOLEIL linac)





- RDR predicts a more intense signal with a larger drop at phi (polar) = 0º.
- Overall slope is similar. Intensity within 50%.

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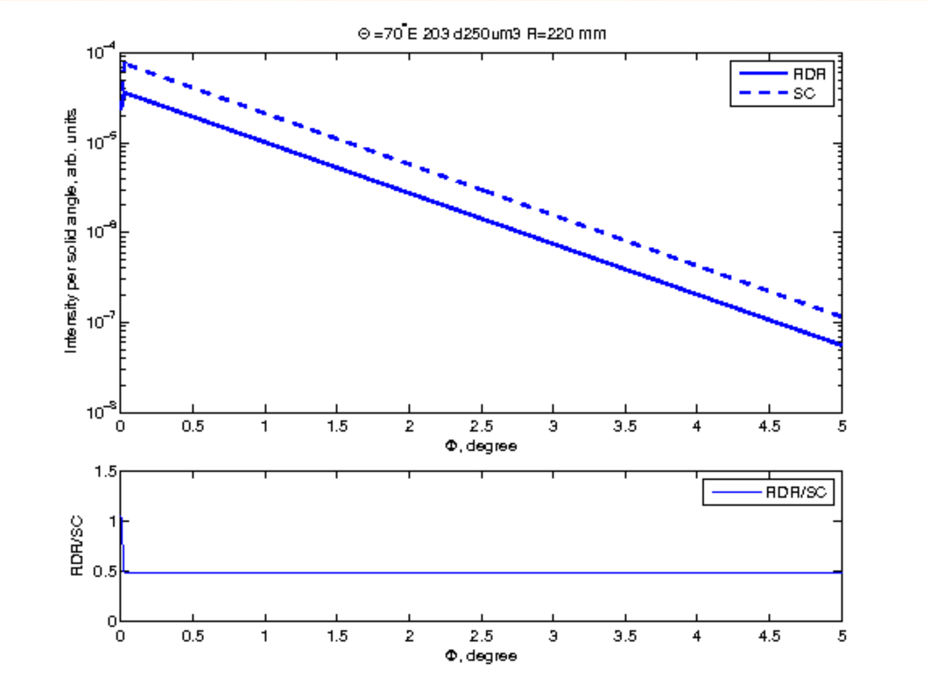
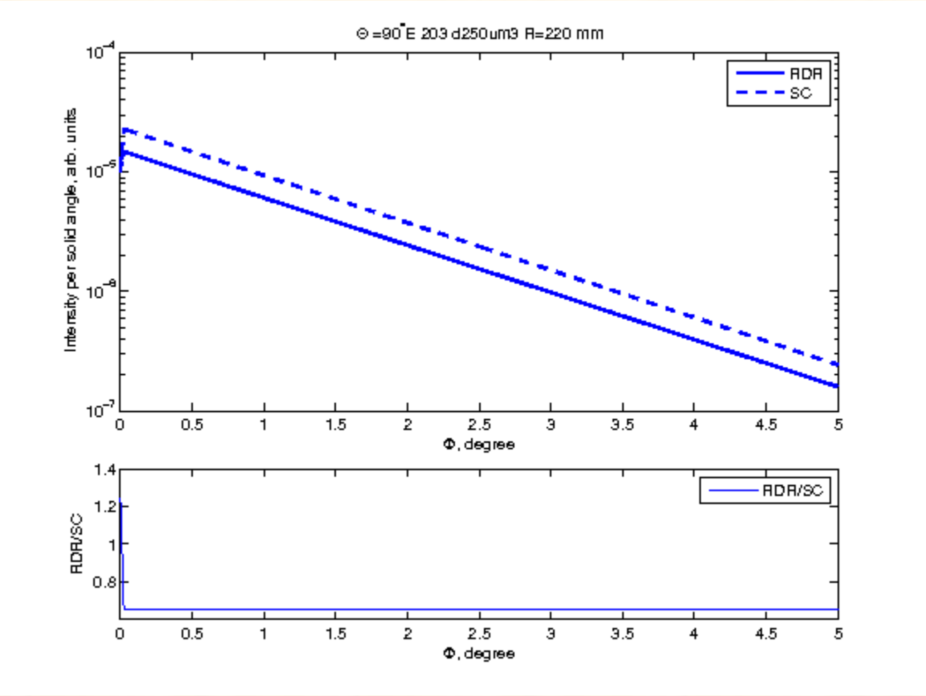
Model comparison at high gamma

- Comparison at gamma=40000 (FACET)





- Now SC predicts a more intense signal with a larger drop at phi (polar) = 0º!
- Once again overall slope is similar. Intensity within 50%.

Model comparison at high gamma

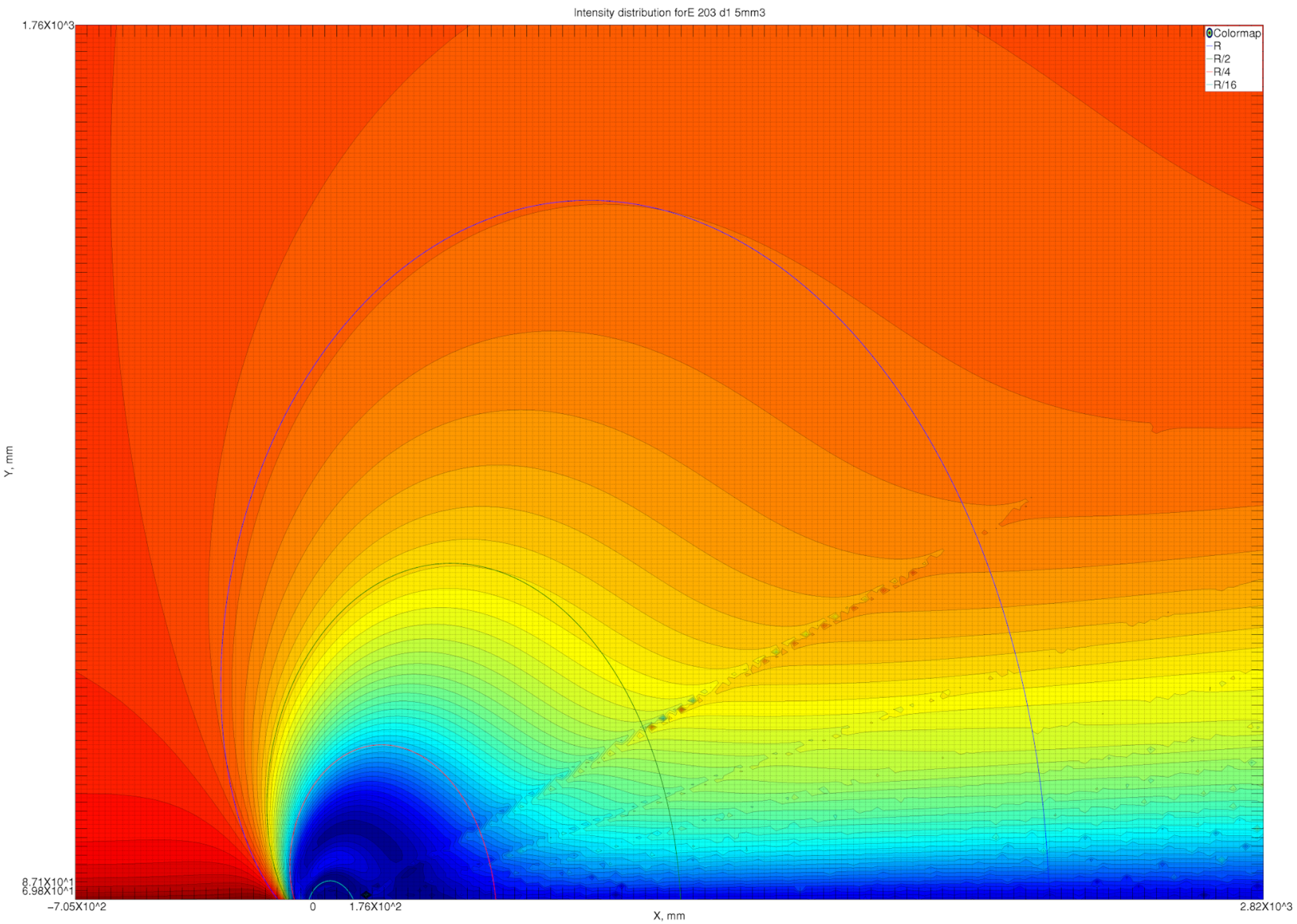
- To discriminate between the models one needs a good polar resolution and/or good detectors/ beam calibration.
- There is no obvious measurement that could allow an easy discrimination between the two models.
- **Neither are available at the moment at these facilities.**

=> Within the experimental accuracy available both models predict compatible single electron yield.

Near field (Pre-wave) effect

- At large wavelength corrections must be applied to the grating yield as the rays do not perfectly build an interference pattern:
  Near field / pre-wave effect.
  => Signal yield is modified
- Most advanced study: D.V. Karlovets and A. P. Potylitsyn, JETP Letters Vol 84 No 9 (2006).

Pre-wave signal intensity
Gamma=40000 d=1.5mm



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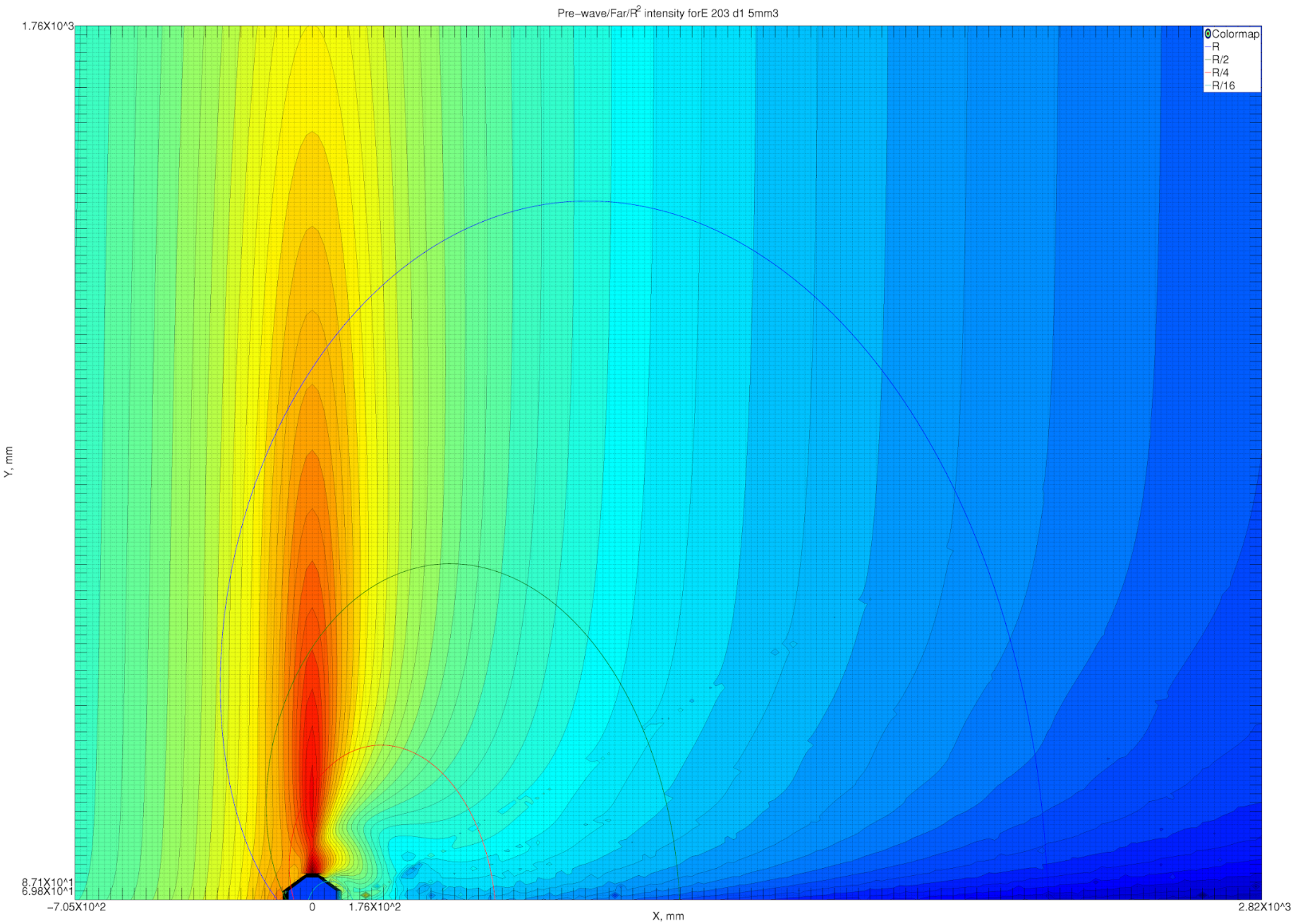
Pre-wave signal intensity Gamma=40000 d=1.5mm I/R^2



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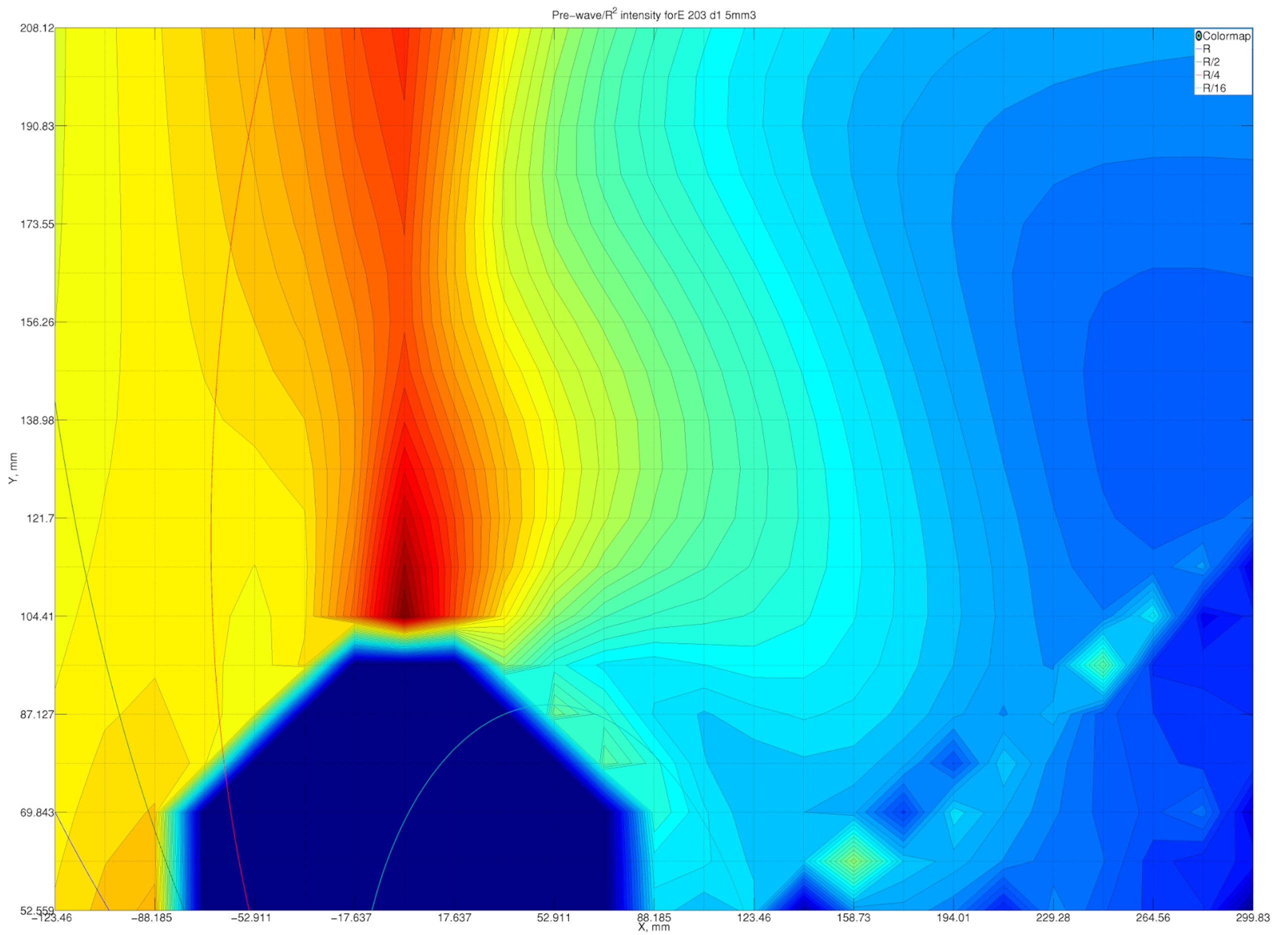
Pre-wave signal intensity Gamma=40000 d=1.5mm I/R^2



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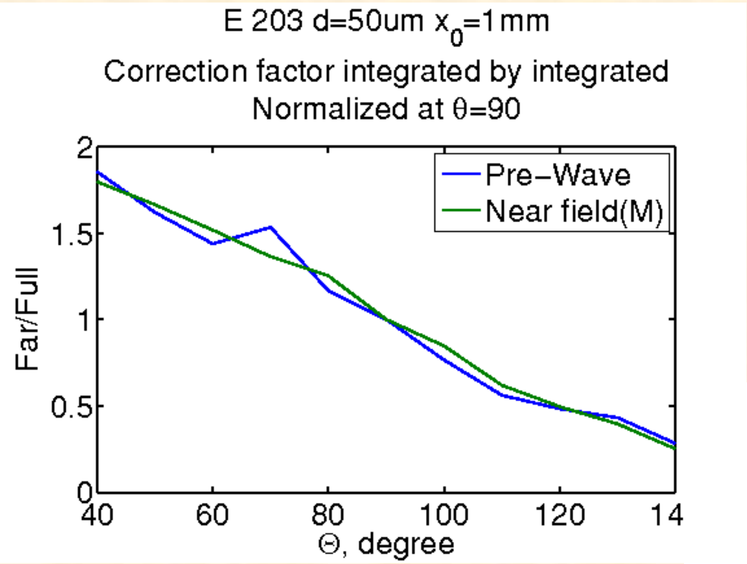
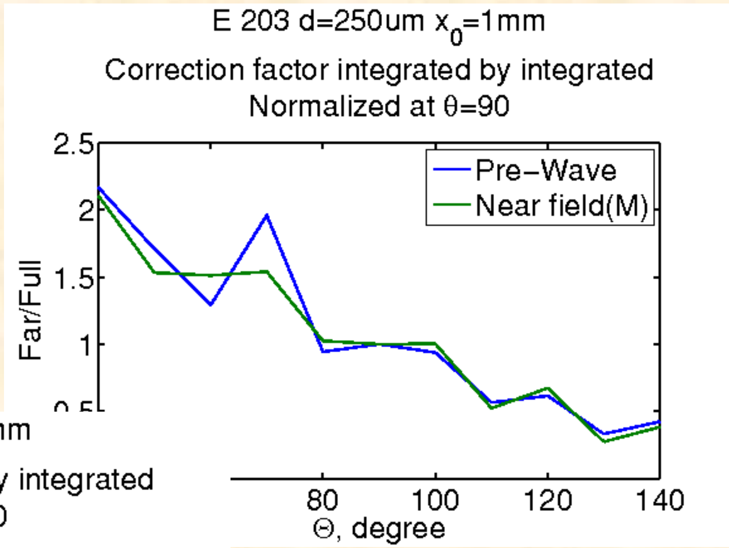
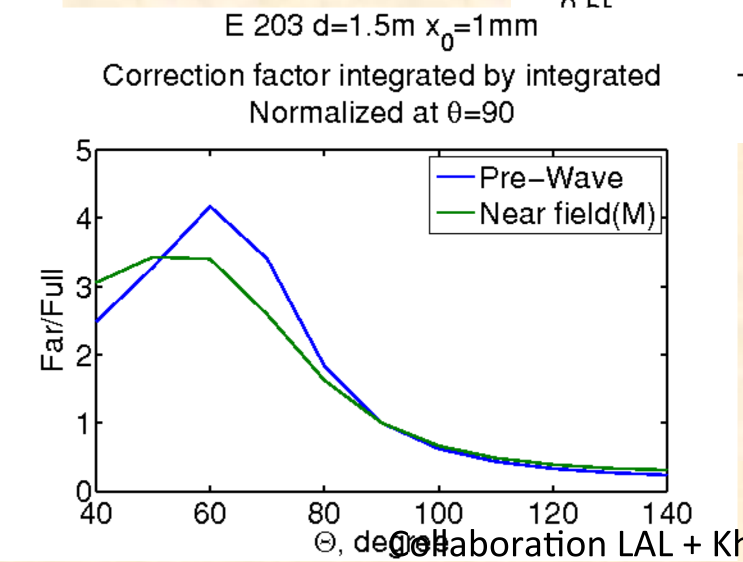
Pre-wave/near field corrections comparisons

- The E-203 collaboration uses a different method to calculte the corrections but the results are similar.







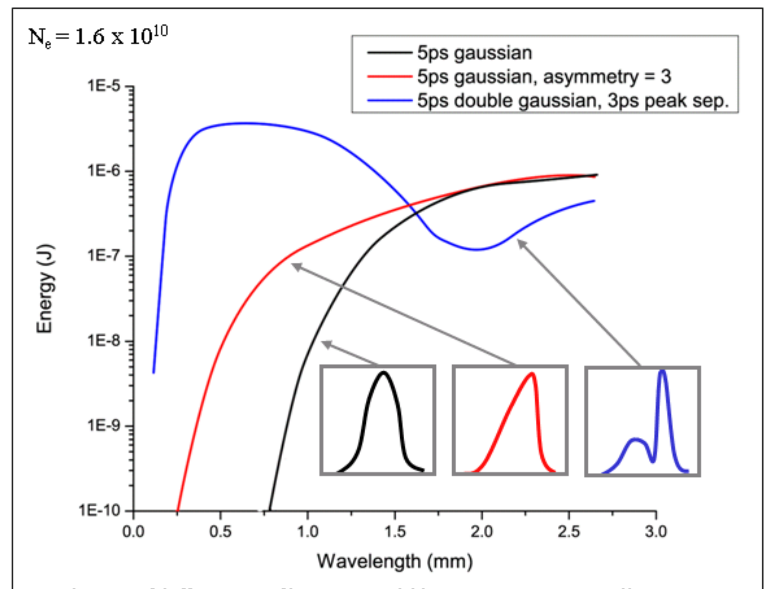
Coherent SP radiation

- Like many other radiative phenomena in EM, SP radiation can also be coherent at wavelengths sufficiently longer than the bunch length (form factor).
- 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

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

After data taking: Profile reconstruction techniques

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

- The measured 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 Hilbert or 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.

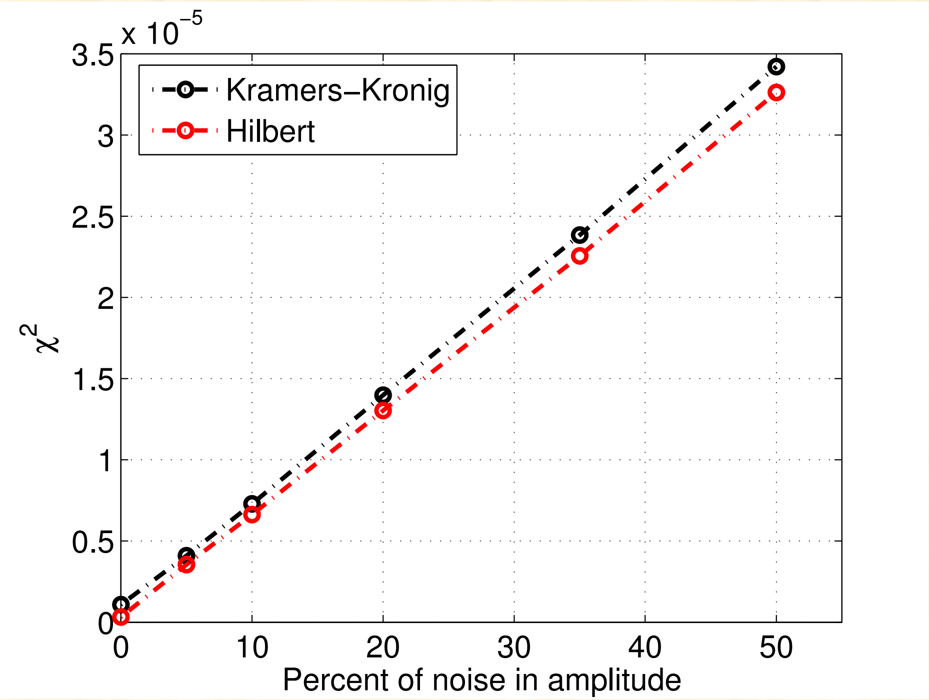
$$G^2(\omega) \simeq N_e^2 |F(\omega)|^2$$

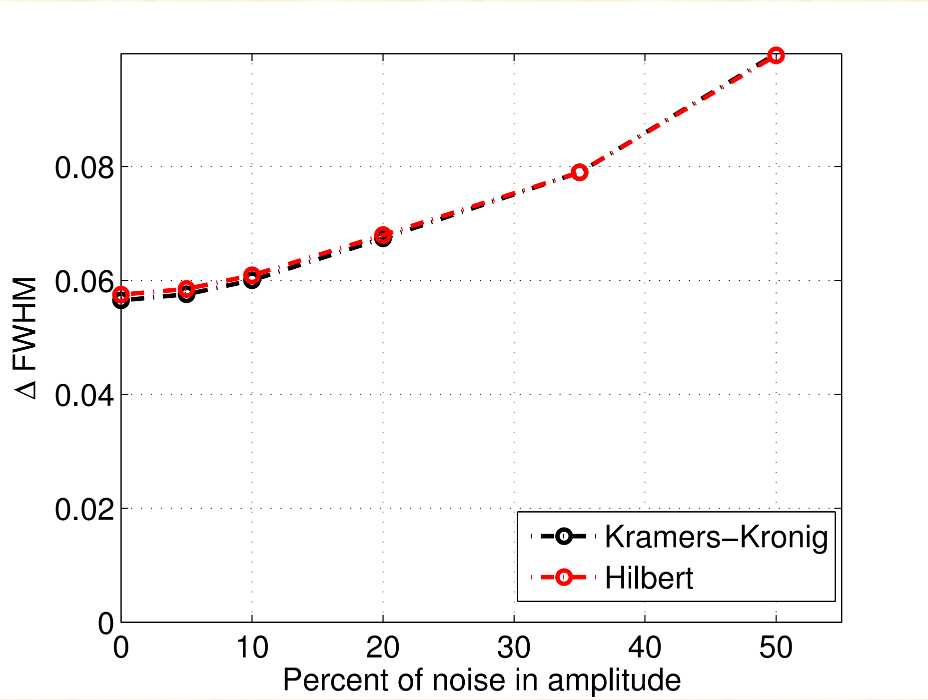
- The phase is recovered from the relation between the amplitudes of the observables.

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

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

Performance of the Hilbert and Kramers Kronig phase recovery techniques



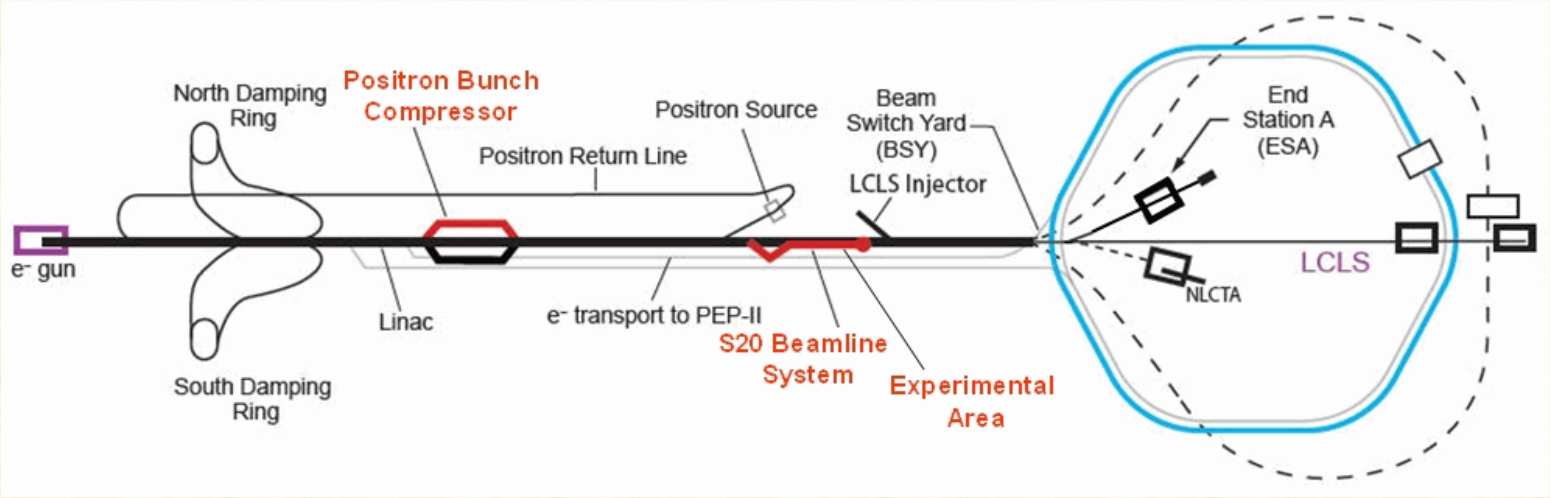


- We simulated more than a 1000 profiles and showed that the reconstruction performances were acceptable for both Hilbert and Kramers Kronig methods.
- Hilbert is faster and easier to implement in Matlab.
- IPAC'14 THPME088 / arXiv.org 1407.0741; Full paper in preparation.

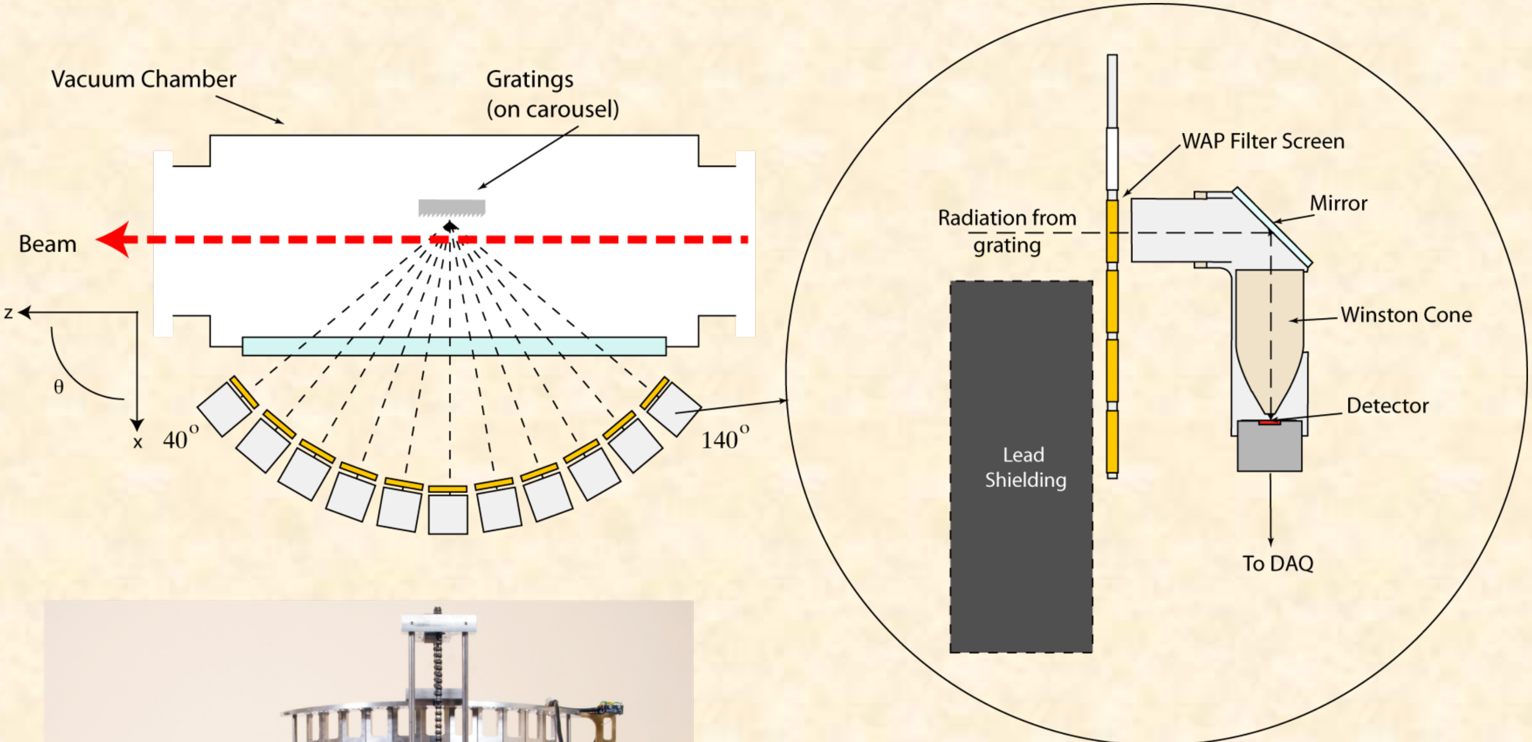
Collaboration LAL + Kyiv National University

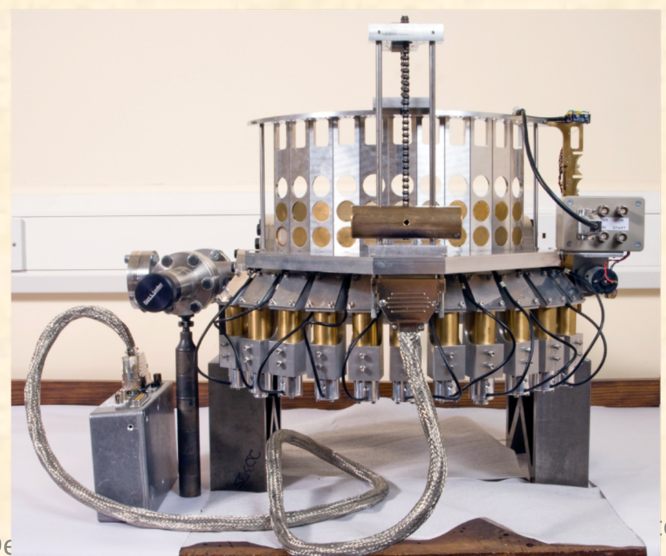
E-203 at FACET

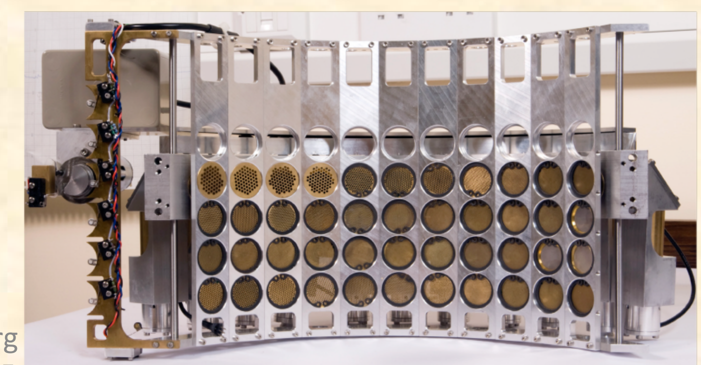
- FACET at SLAC is a test facility offering access to 100s femtoseconds long electron bunches.
- Electrons energy is 22.5 GeV (gamma=45000)
- Aim of the E-203 collaboration: development of a longitudinal profile monitor in the fs range.



Experimental apparatus (schematic)

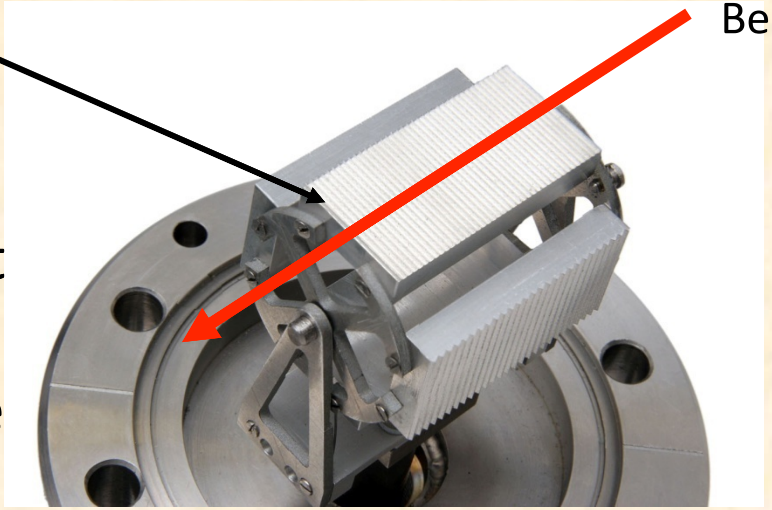






Experimental apparatus: gratings carousel

3 gratings
1 blank piece of aluminium



Beam direction

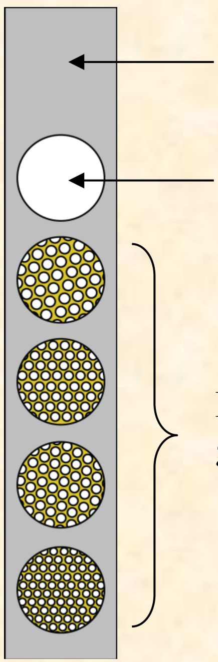
Expected SP radiation at FACET
in the wavelength range
10 μm to 1 mm

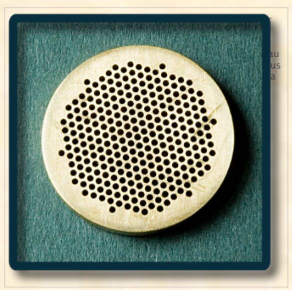
A carousel can rotate and offer three different gratings or one blank to the beam. Rotation is controlled remotely.

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; $\Delta\lambda$ = 10-20 µm
Wave guide array plates: 175 < λ < 1000;
Mylar based thin films: 20 < λ < 117; $\Delta\lambda$ = few µm
Silicon based thin films : 10 < λ < 20; $\Delta\lambda$ = few µm

E-203 Results

- Paper with profile reconstruction published in 2014.
- Further data taking in 2015 to study the polar distribution of the signal and its polarisation.

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Reconstruction of the time profile of 20.35 GeV, subpicosecond long electron bunches by means of coherent Smith-Purcell radiation

Phys. Rev. ST Accel. Beams **17**, 052802 – Published 27 May 2014

H. L. Andrews, F. Bakkali Taheri, J. Barros, R. Bartolini, V. Bharadwaj, C. Clarke, N. Delerue, G. Doucas, N. Fuster-Martinez, M. Vieille-Grosjean, I. V. Konoplev, M. Labat, S. Le Corre, C. Perry, A. Reichold, and S. Stevenson

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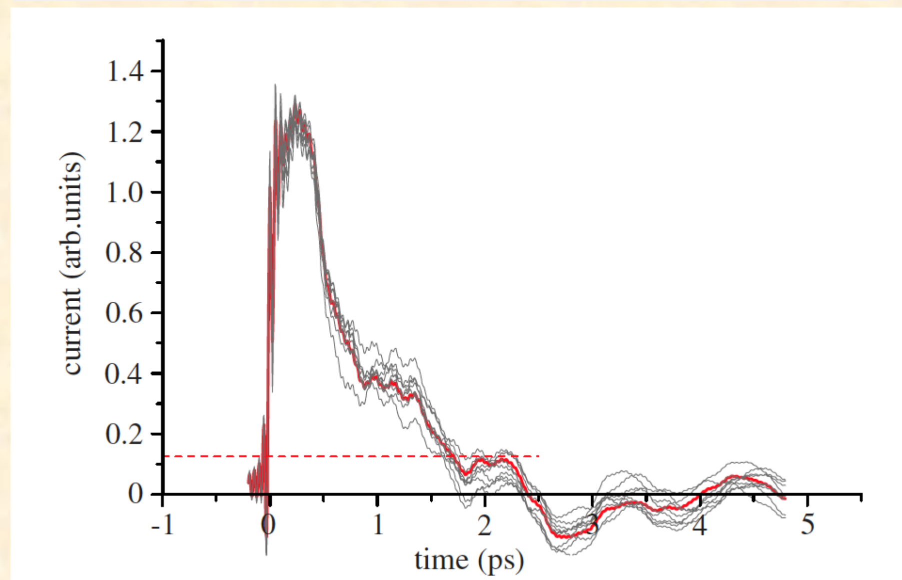
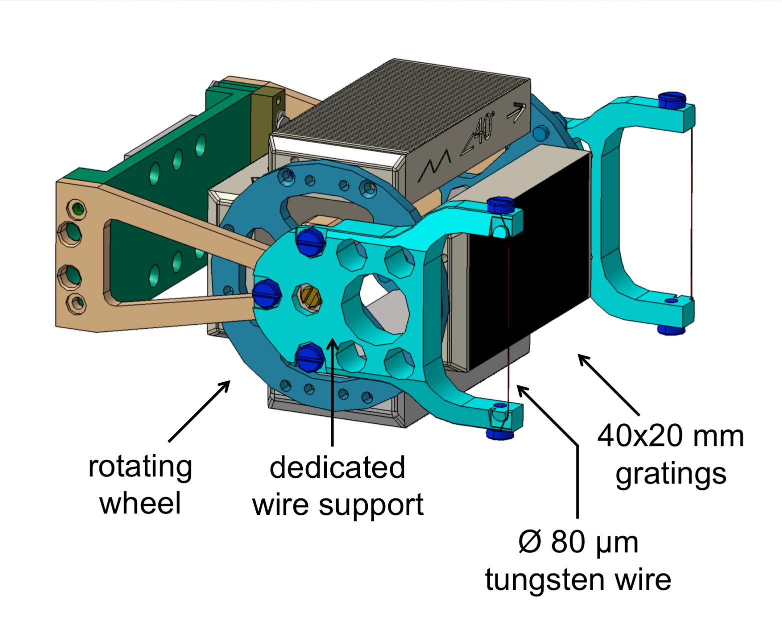
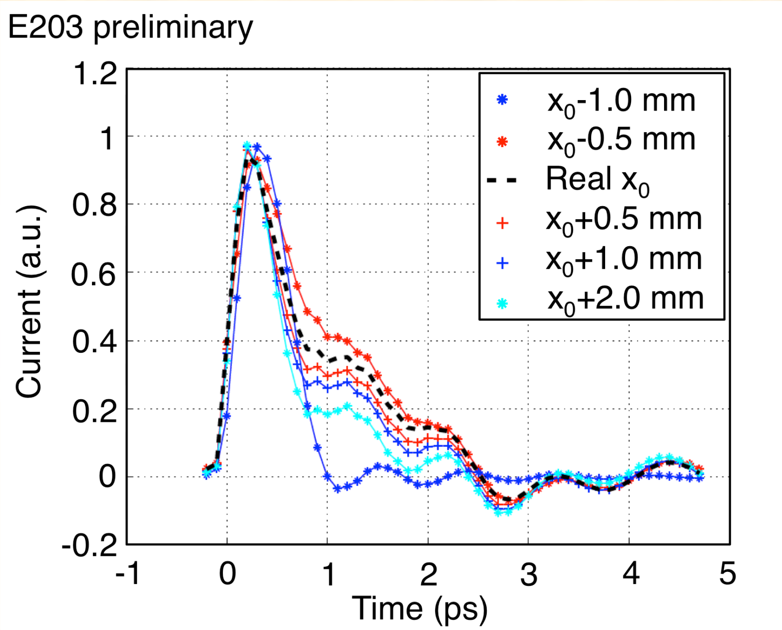


Position sensitivity

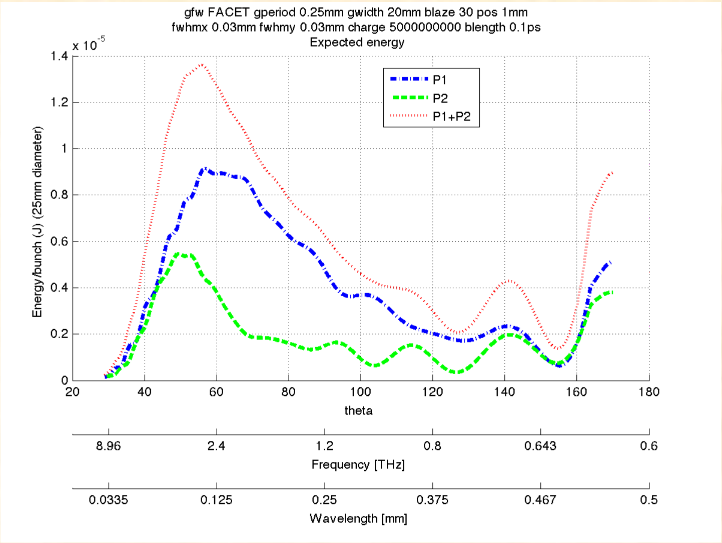
- The beam-grating is an important parameter of the measurement as the signal depends exponentially on it.
- To improve the position sensitivity we have added a wire-scanner to the experiment.

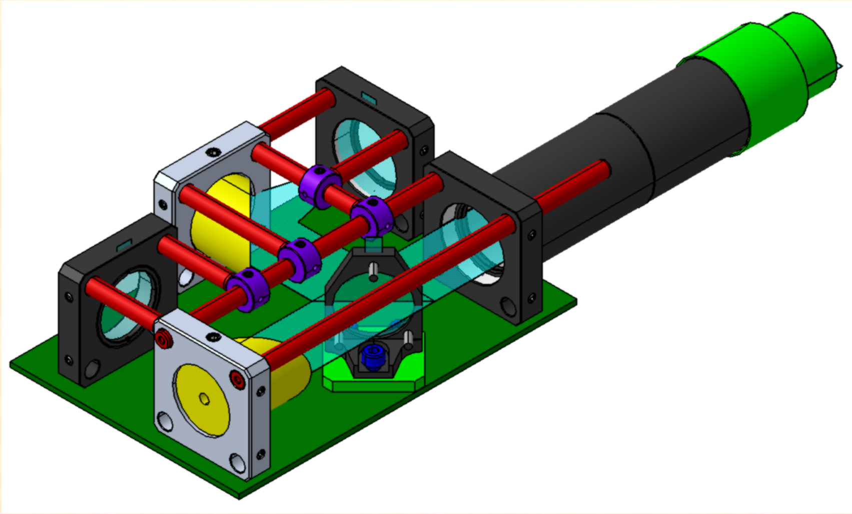


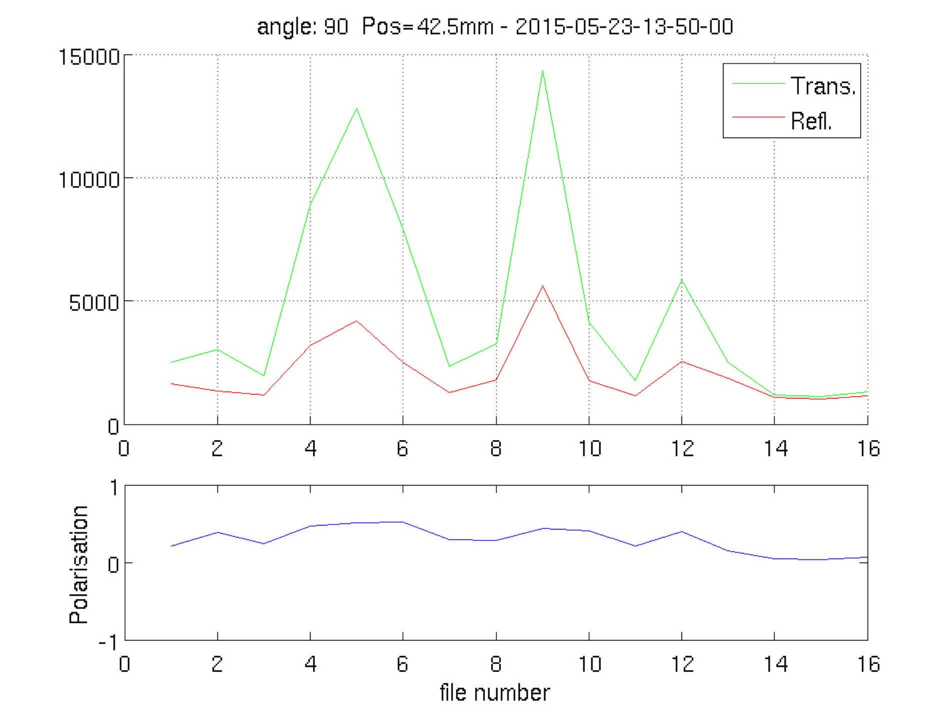


Polarisation

- We have shown that the background is not polarized.
- We made a preliminary measurement of the CSP polarization but this measurement does not agree with theory.
- => measurement repeated in 2015.
- Very preliminary analysis.

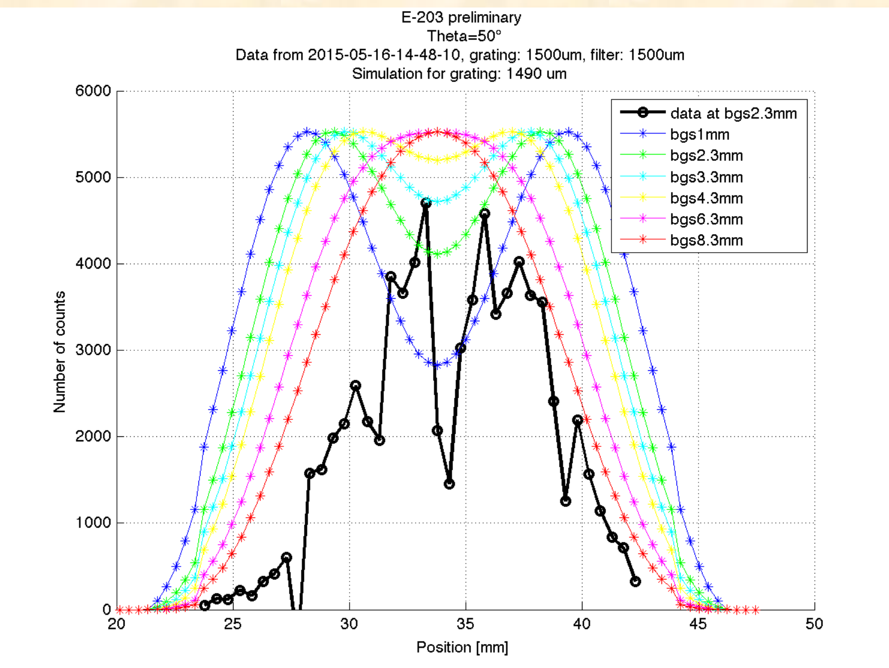


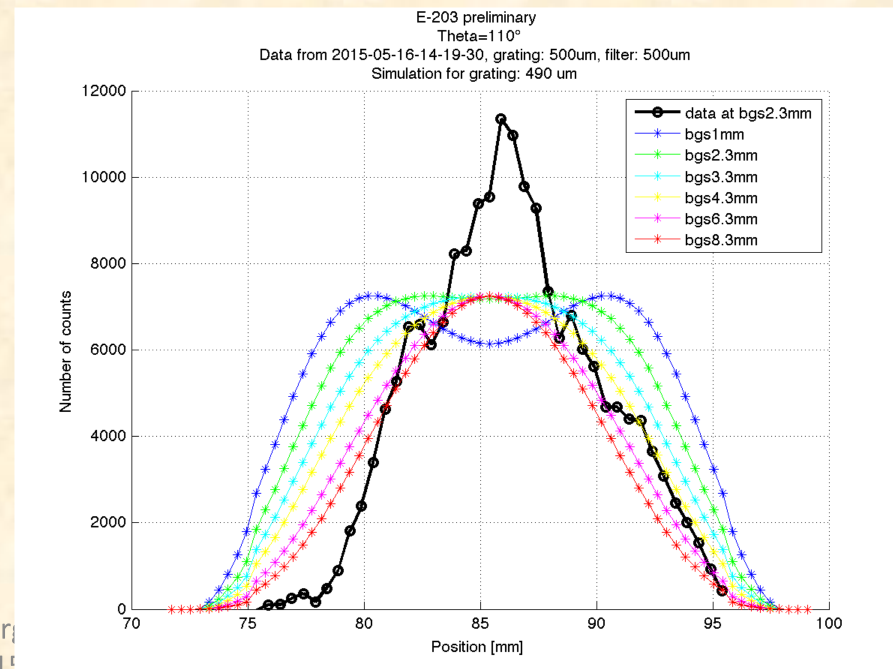




Polar distribution of the signal

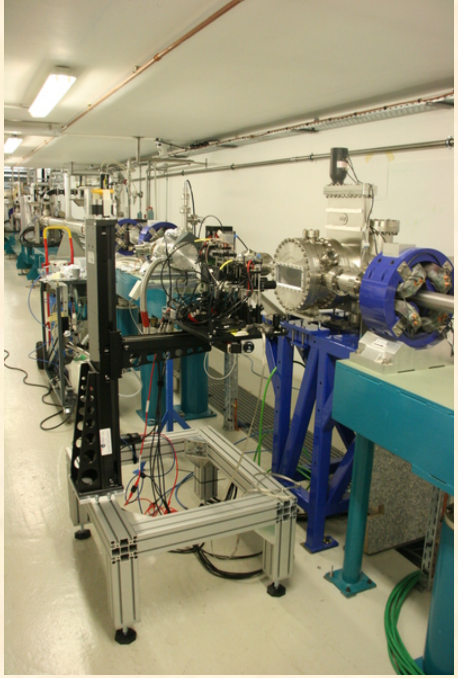
- En 2015 we also modified the E-203 setup to measure the polar (phi) distribution of the signal by adding slits in front of our detectors.
- Observation of a drop at phi=0 at some azimuthal angles but not all. Detailled analysis still in progress….

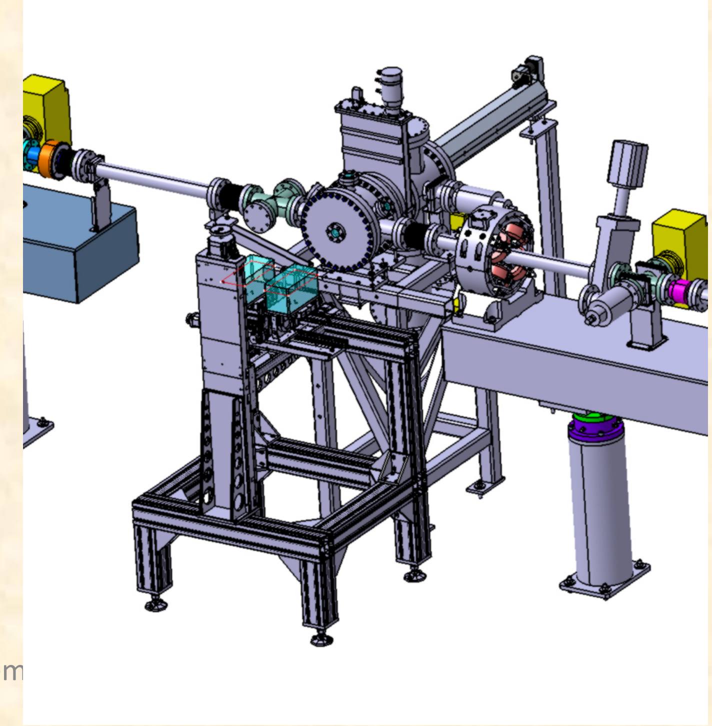




SPESO

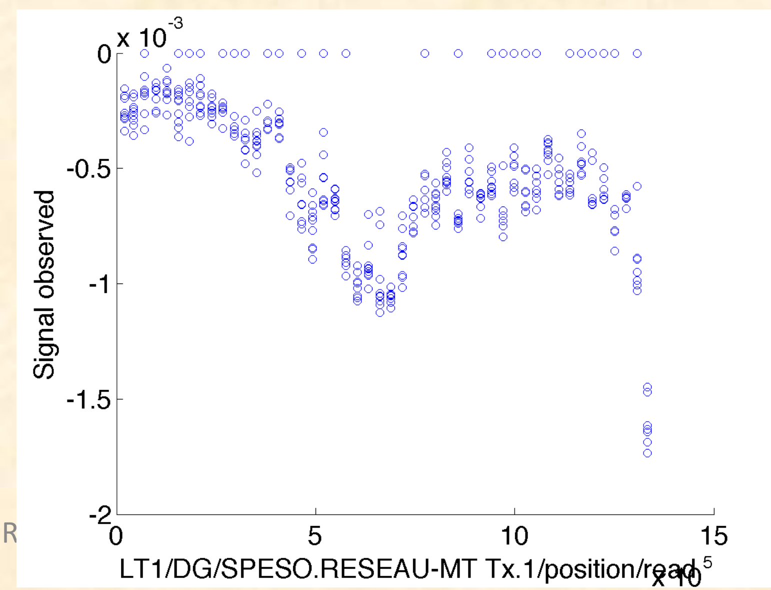
- To overcome the E-203 limitations, a Smith-Purcell test stand has been installed at the end of the SOLEIL Linac (gamma=200).
- A 5D robot can measure the radiation emitted at different positon and angles.
- Soon a polarisation measurement system will be added.





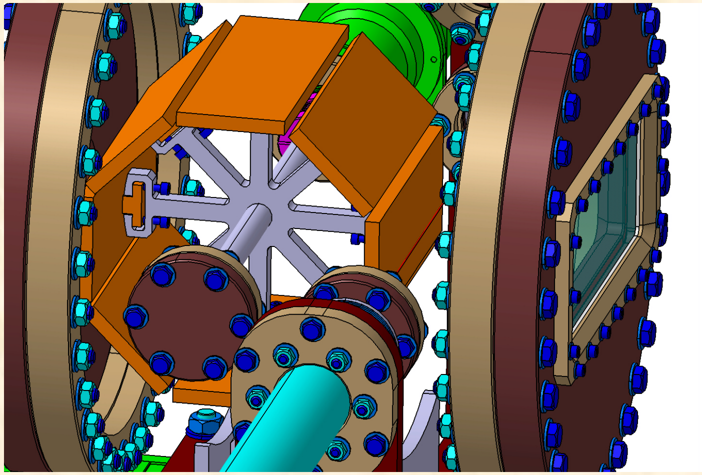
SPESO: first results

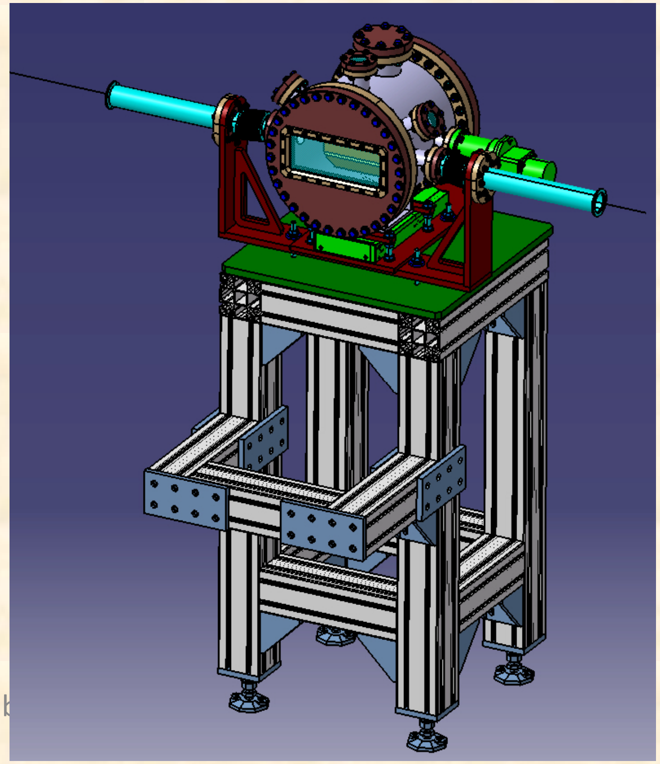
- Signal was difficult to find (bunch longer than expected).
- We now have a system that can measure the SP signal.
- Goal make 3D a map of SP emission (with polarisation).
- However this will be limited by the detectors (Gunn diodes).



The future: single shot?

- Further experiments are planned at SPARC and CLIO (french Free Electron Laser) to measure their bunch profile.
- The addition of several gratings should allow a larger wavelength coverage.
- We also plan to study more in detail the grating dependency.



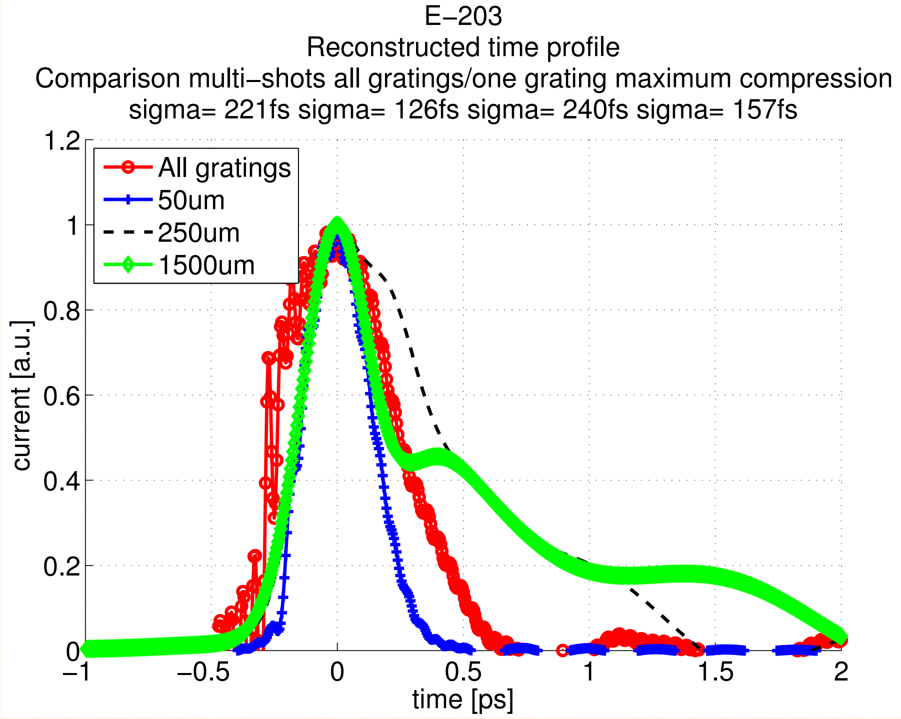


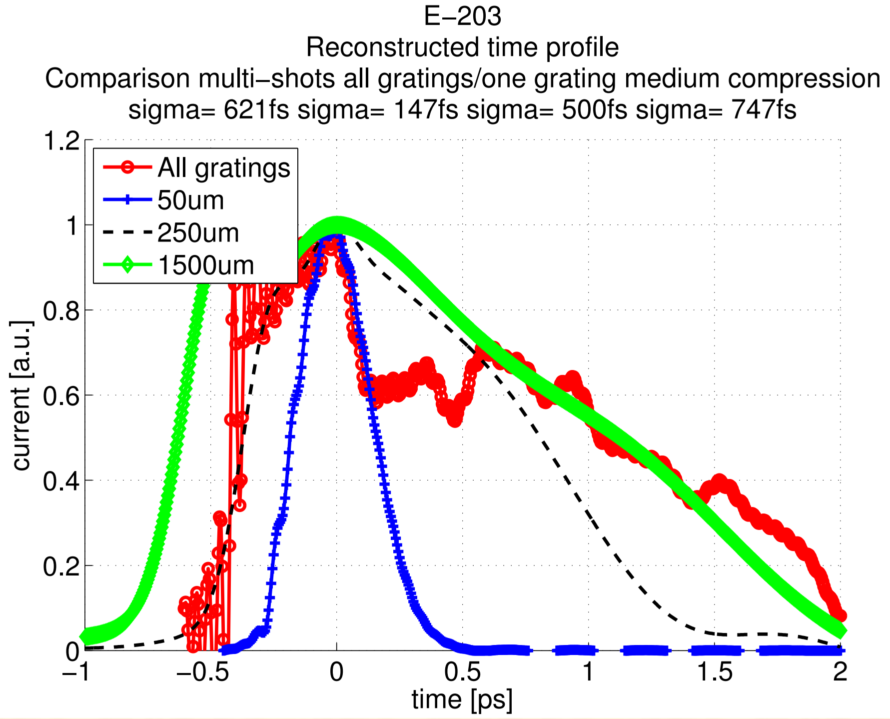
Outlook

- Smith-Purcell radiation can be used as a bunch length diagnostic.
- Model uncertainty on the signal yield are comparable to the (large) experimental uncertainties.
- R&D is in progress to better understand the signal distribution.
- The ultimate aim would be to use it as a single shot device.

Thank you!

Grating effect





Le nombre de réseau à utiliser dépend de:

- La précision de mesure désirée.
- La longueur du paquet attendue.