BEAM DIAGNOSTICS WITH COHERENT SP RADIATION

Towards a single-shot, non-destructive, compact and inexpensive device?

The present group

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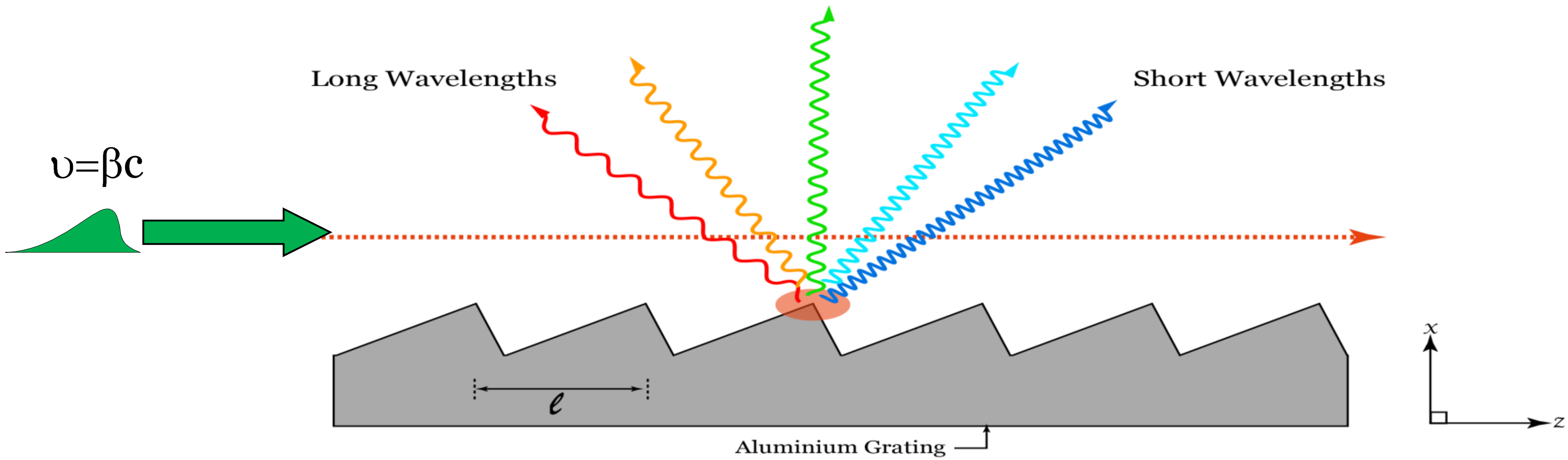
- SLAC: Vinod Bharadwaj, Christine Clarke
- IFIC (Valencia): Angeles Faus Golfe, Nuria Fuster, Javier Resta-Lopez

…and the past…

- John Walsh^{+} , J.H. Brownell (Dartmouth)
- John Mulvey, Colin Perry, Victoria Blackmore, Scott Stevenson (Oxford)
- Gunther Korschinek et al (Munich)
- G. P. Gallerano, A. Doria, E. Giovenale (Frascati)
- Lex van der Meer, B. Redlich (FOM)
- Mike Woods (SLAC)
- Maurice Kimmitt, Essex
- Rutherford Lab. -UK: P. Huggard

What is Smith-Purcell (SP) Radiation?



SP radiation is created, with wavelengths (λ) dispersed according to:

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

Wavelength depends upon grating period (*l*)

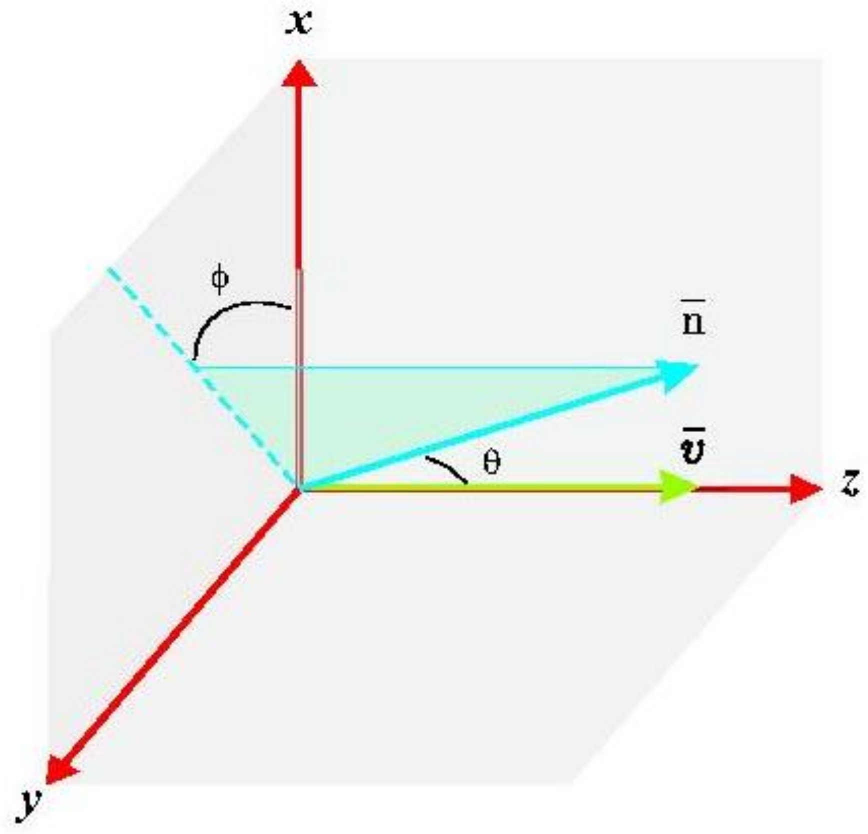
Typically, in the **far infrared**.

Period can be chosen, hence:

Coherent regime: When bunch length is shorter than, or equal to, emitted wavelengths.

Increases emitted intensity $\propto N_e^2$

Coordinate system



Coherent enhancement

- For a bunch of N_e electrons:

- But $$\left(\frac{dI}{d\Omega}\right)_{N_e} \approx \left(\frac{dI}{d\Omega}\right)_{1,x_0=0} N_e^2 S_{coh}$$

$$S_{coh} = \left|\frac{1}{\sigma_x\sqrt{2\pi}}\int_0^\infty e^{-\frac{x}{\lambda_e}} e^{-\frac{(x-x_0)^2}{2\sigma_x^2}} dx\right|^2 \left|\frac{1}{\sigma_y\sqrt{2\pi}}\int_{-\infty}^\infty e^{-ik_y y} e^{-\frac{(y-y_0)^2}{2\sigma_y^2}} dy\right|^2 \left|\int_0^\infty e^{-i\omega t} T(t) dt\right|^2$$

where the term:

$$\left|\int_{-\infty}^{\infty} e^{-i\omega t} T(t) dt\right|^2 = \rho^2(\nu)$$

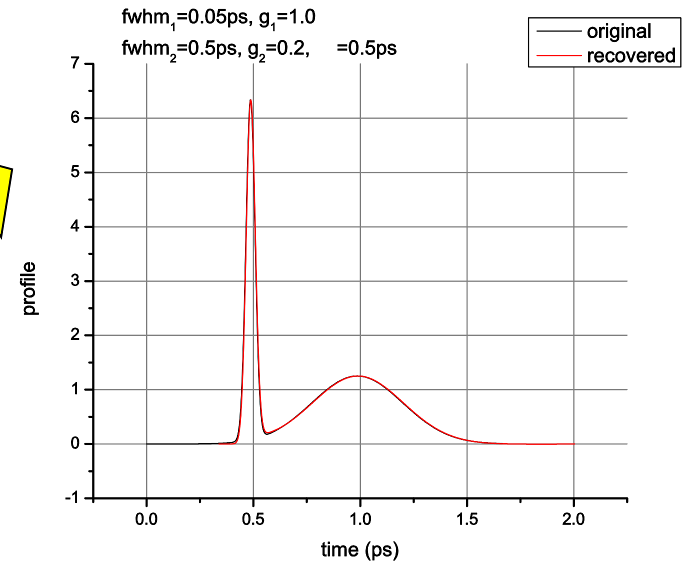
is the Fourier Transform of the time profile *T(t)* of the bunch.

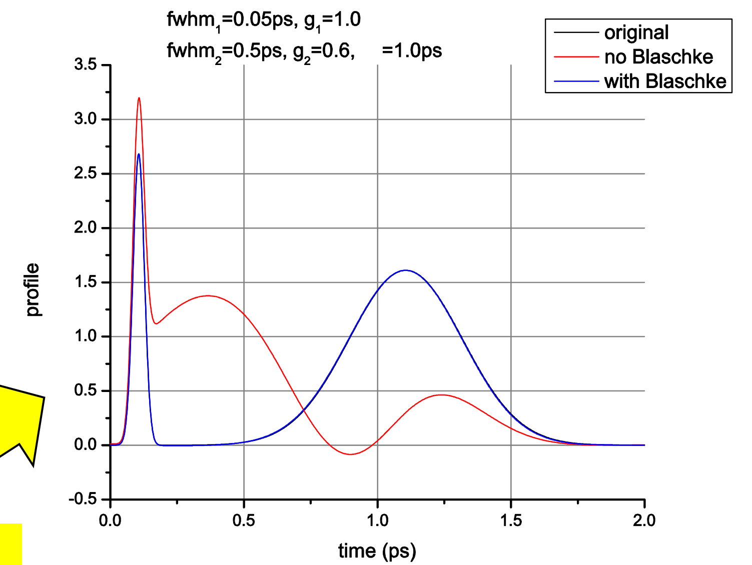
- *The grating acts as its own spectrometer.*
- *Radiation can be made coherent by suitable selection of the grating period.*
- *A measurement of the spectral yield gives the FT of the time profile T(t).*
- *Therefore, the time profile of the bunch is 'encoded' in the spectral yield $\rho(\nu)$.*
- *… from which the profile can be reconstructed, but…*
- *There is no information about the phase.*

Minimal phase

- Can be recovered by the Kramers-Kronig method.
- May (or may not) be equal to the true phase.
- Blaschke phase contributions?
- Not known *a priori*.
- Need information over ‘all’ frequencies.
- Multiple gratings extend the range of measured points.
- Even so, interpolation & extrapolation are necessary.

good





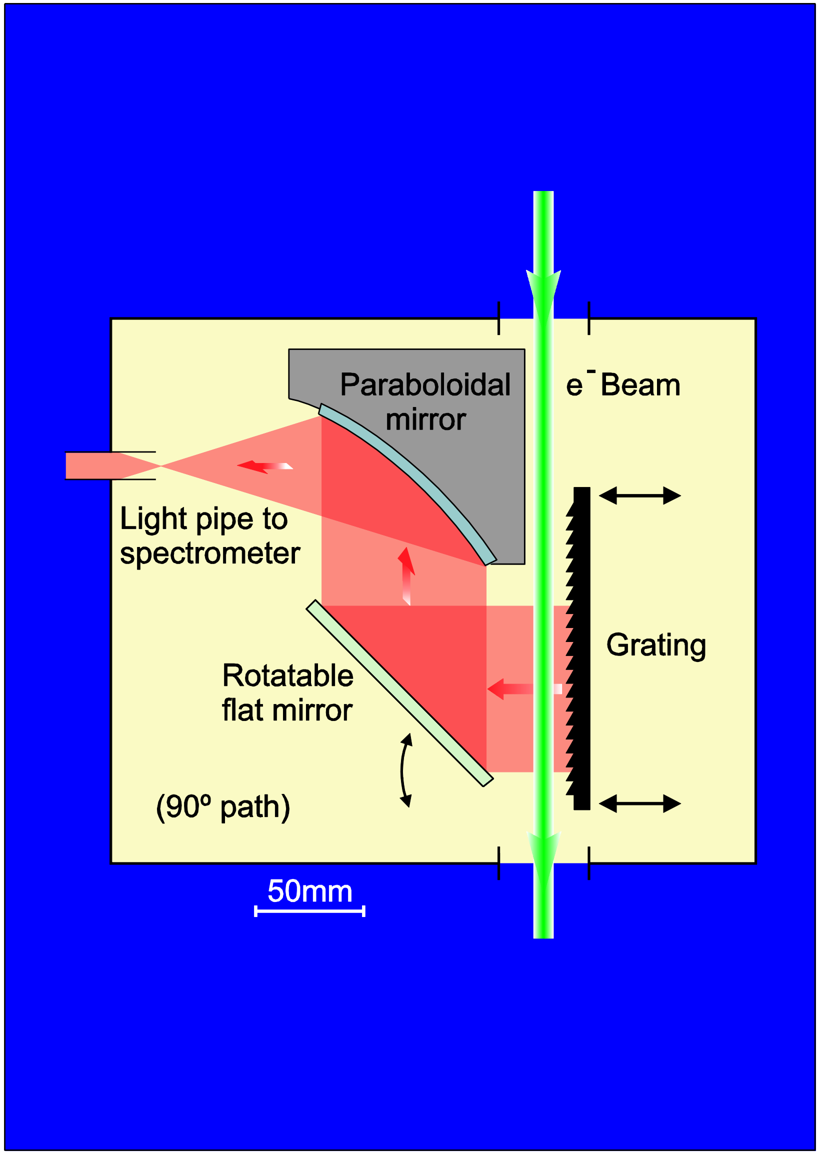
Not good

Basic assumptions

- The charge distribution $q(x,y,t)$ can be expressed by three uncorrelated distribution functions, i.e. $q(x,y,t)= X(x)Y(y)T(t)$ ★
- Moreover, the transverse distributions are assumed to be Gaussian. ★
- SP radiation is coherent but the 'background' is incoherent. ★
- The detectors are not located at 'infinity' relative to the grating, hence need to estimate interference effects, esp. at short wavelengths. ★
- Must determine what is the background (i.e. non-SP) radiation, which can be quite intense. ★
- The grating surface is a perfect conductor. ★

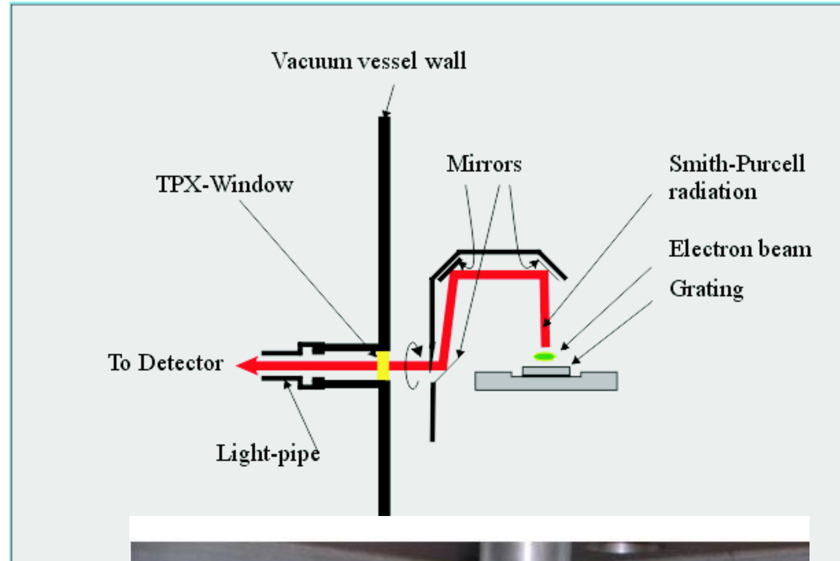
History (as seen from Oxford…)

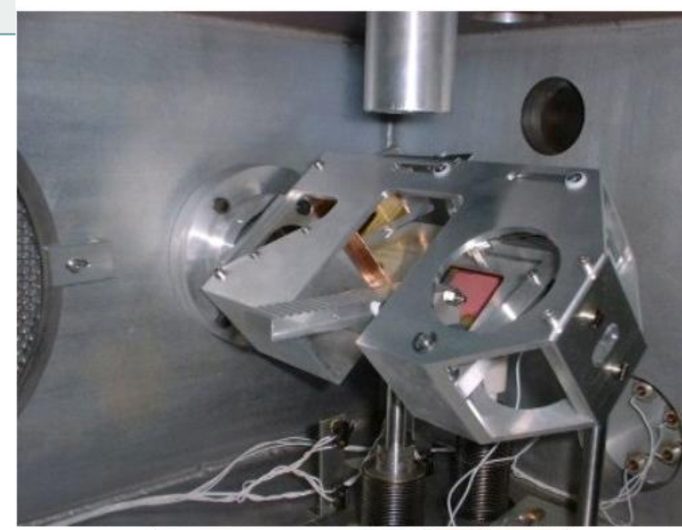
- First experiment by Smith & Purcell in 1953 using 300keV beam.
- Long gap, with minimal activity, until 1991 when Oxford + Dartmouth carried out the first experiment with relativistic (3.6MeV) electrons. *Phys. Rev. Lett* ***69****, 1761, (1992)* .
- Based on Van de Graaff accelerator.
- <u>Very long bunch, hence no coherence effects</u>.
- Cryogenic detector.



Frascati (2000-2002)

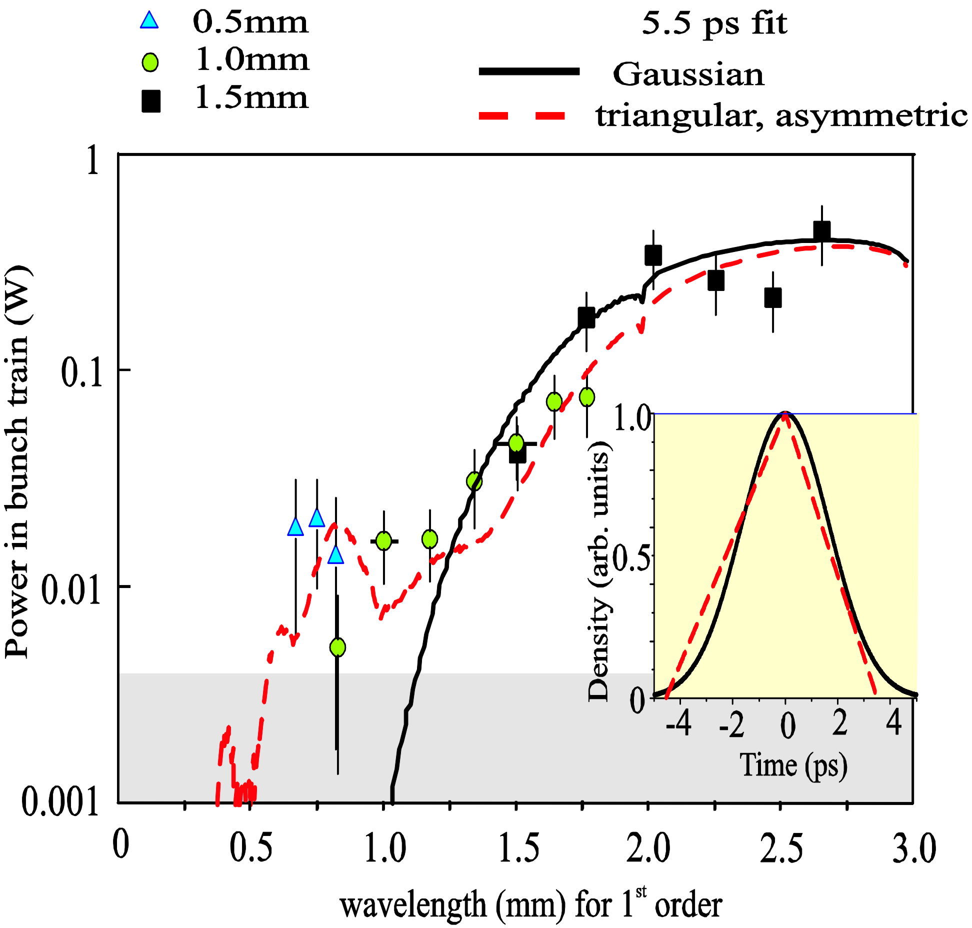
- E=1.8MeV (up to 5MeV), from a Microtron.
- 14ps long bunches, spaced 333ps apart, in a 5μs bunch train.
- Charge= 4.2x10^8 electrons/ bunch
- One grating, with period of 2.5mm and a blaze angle=14^0
- *<u>Determination of bunch profile was done by comparing spectral yield with various 'template' profiles</u>*.
- Not enough attention was paid to the 'background' problem.
- Cryogenic detector.





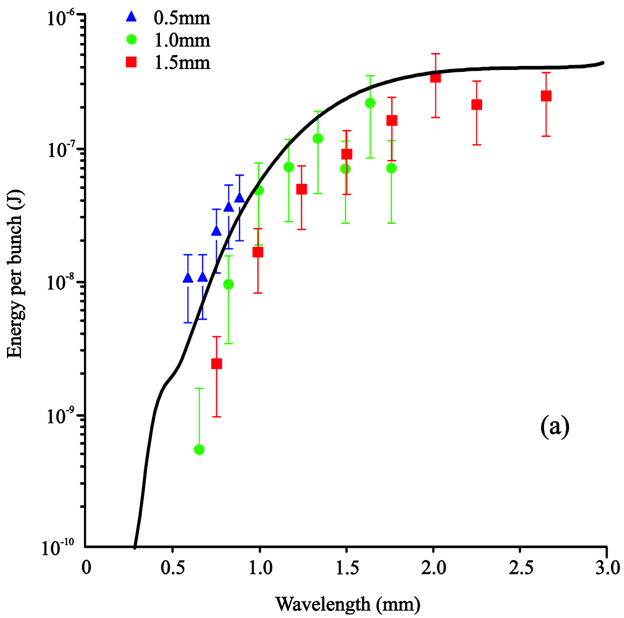
FOM (2004-2006)

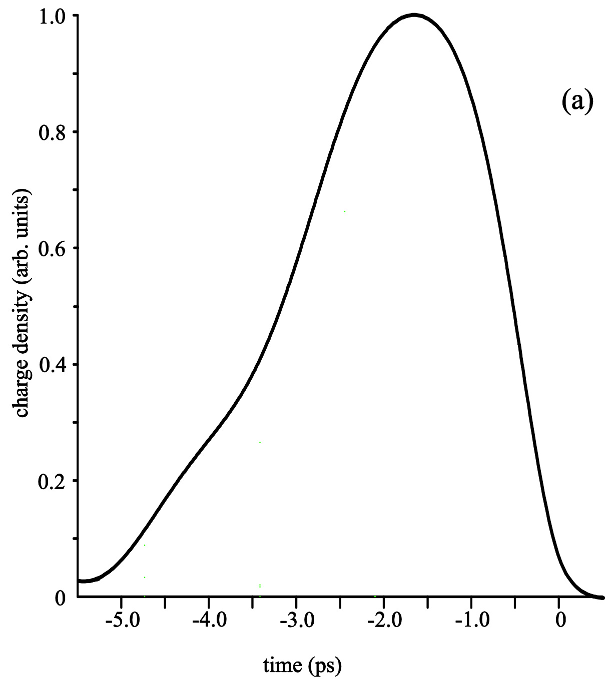
- Energy=45MeV, 5μs bunch train, 1ns bunch spacing.
- Charge= 1x10^9 electrons/bunch
- First use of multiple gratings and 'blank' (to determine background).
- First use of 11 room-temperature pyroelectric detectors
- Simultaneous measurement of yield at 11 different wavelengths.
- No external spectrometer, but filters used in order to suppress background.
- Use of Winston cones.
- Measured spectral yields fitted with various 'template' profiles.



SLAC-ESA (2007)

- E= 28.5GeV
- Single bunch, 0.9-1.4x10^{10} electrons/bunch, 10Hz.
- Apparatus very similar to that used at FOM.
- <u>Profiles reconstructed by the Kramers-Kronig method</u>.





E-203 Experimental set-up

•Vacuum chamber, contains 3 gratings and one ‘blank’.

• ‘Blank’ is *identical* to the gratings, but without any corrugations.

• Grating periods= 1.0, 0.5 and 0.25mm, for FACET experiments.

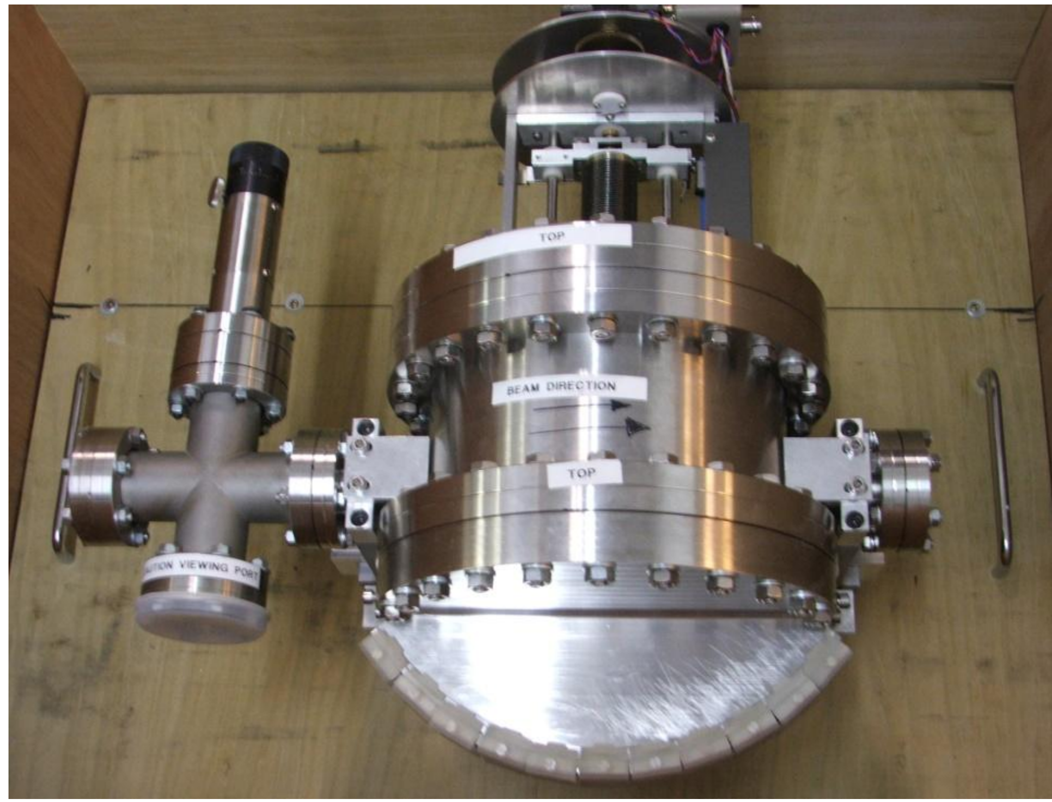
• Changeover by remote control.

•Each grating has its own set of filters.

• Filters must change when changing the grating.

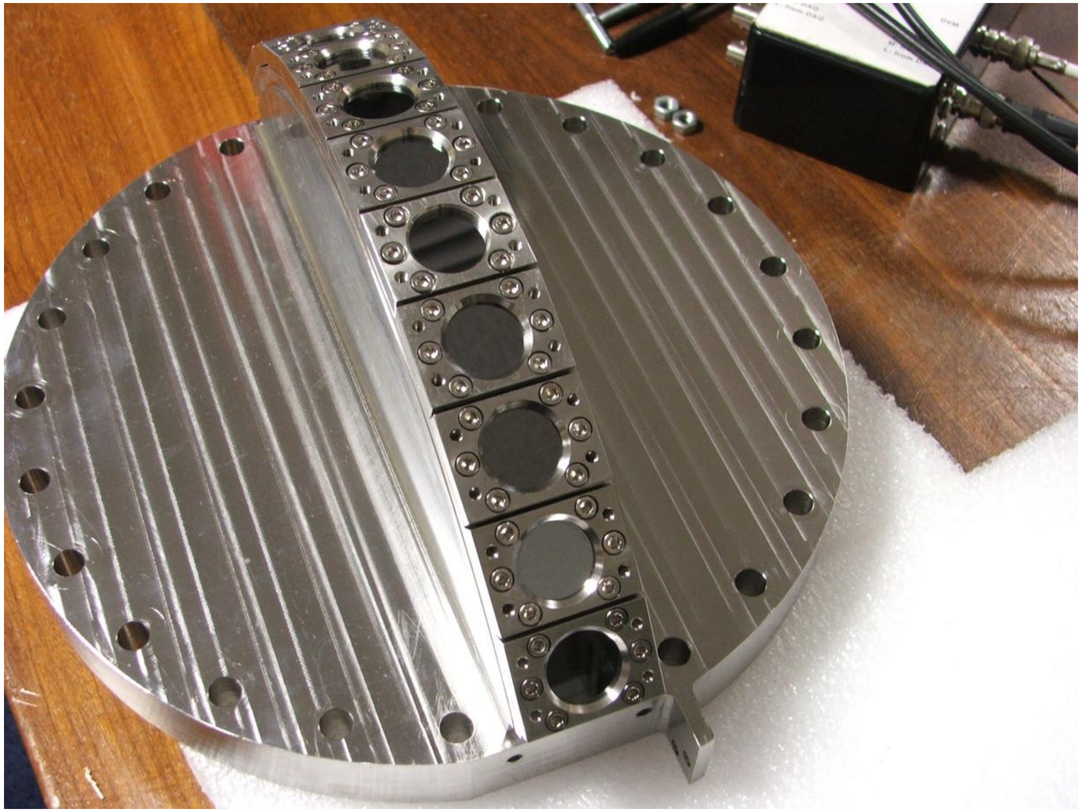
•Overall insertion length in the beam line is $\sim$ 0.6m.

• This is not a single-shot device!

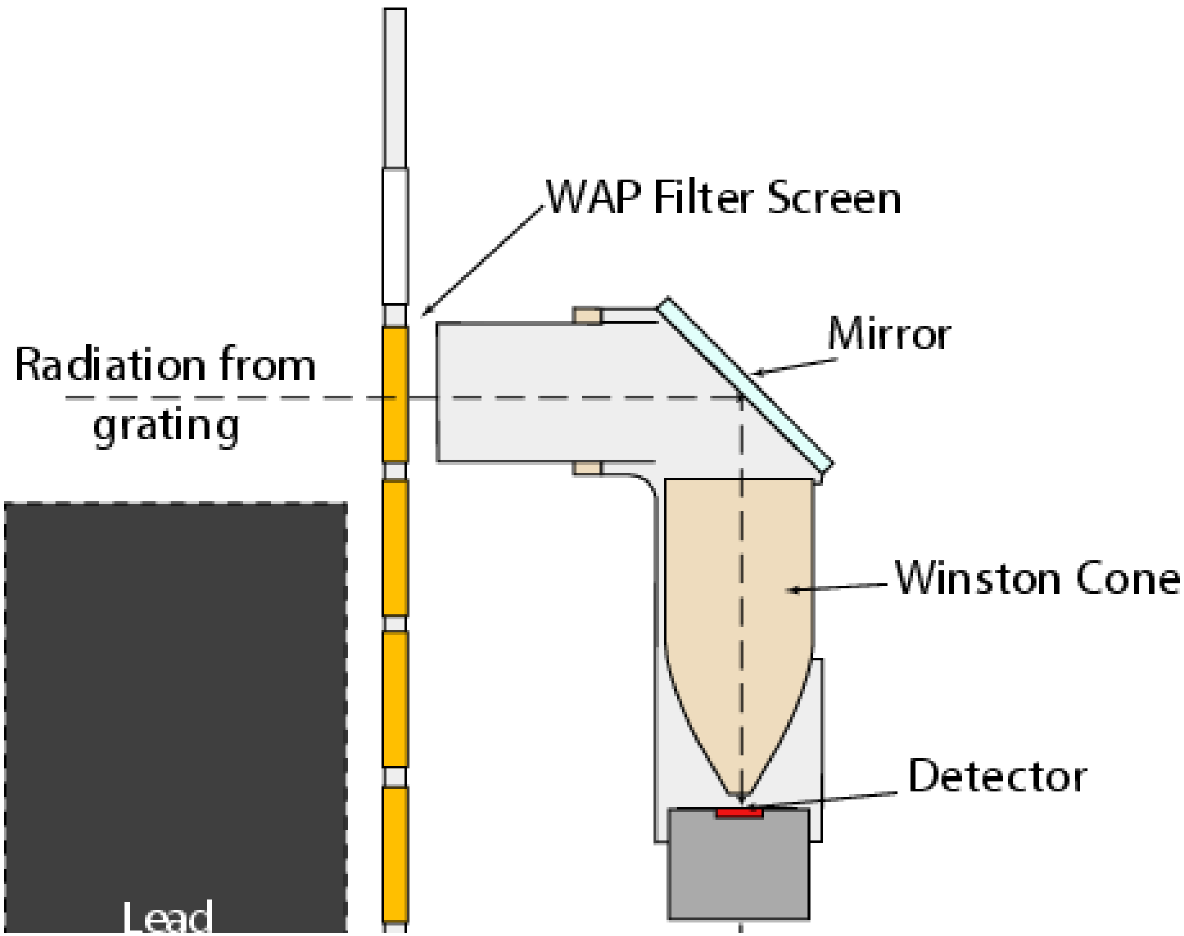


Experimental set-up

- The whole of the optical system is on the atmospheric side.
- Radiation emerges through 11 high-resistivity Si windows.
- Detection by an array of 11 pyroelectric detectors…
- …arranged between 40-140^0 relative to the beam direction.

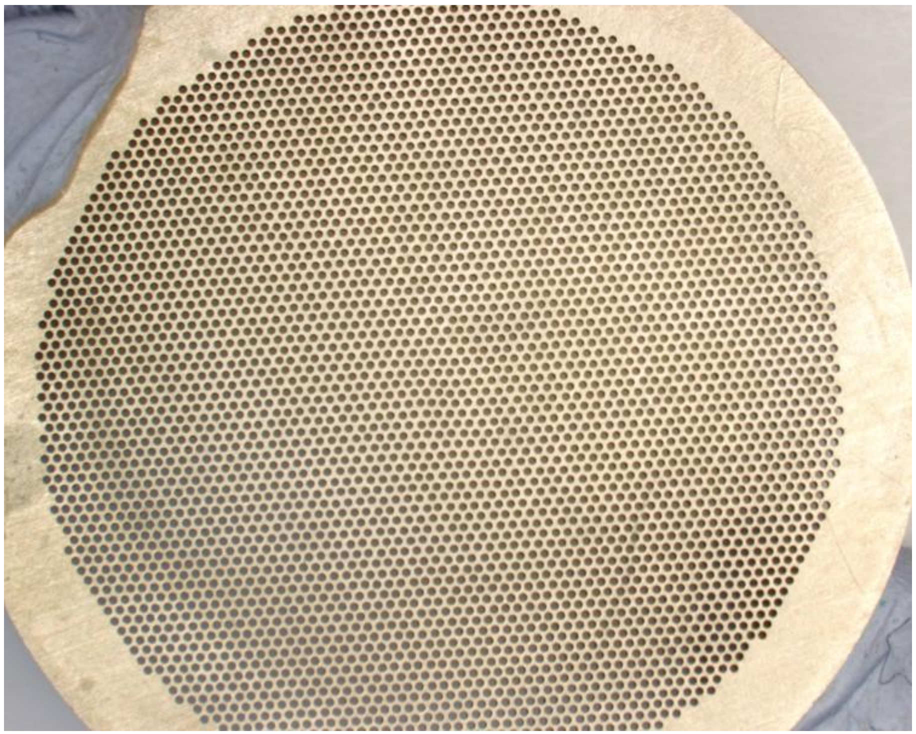


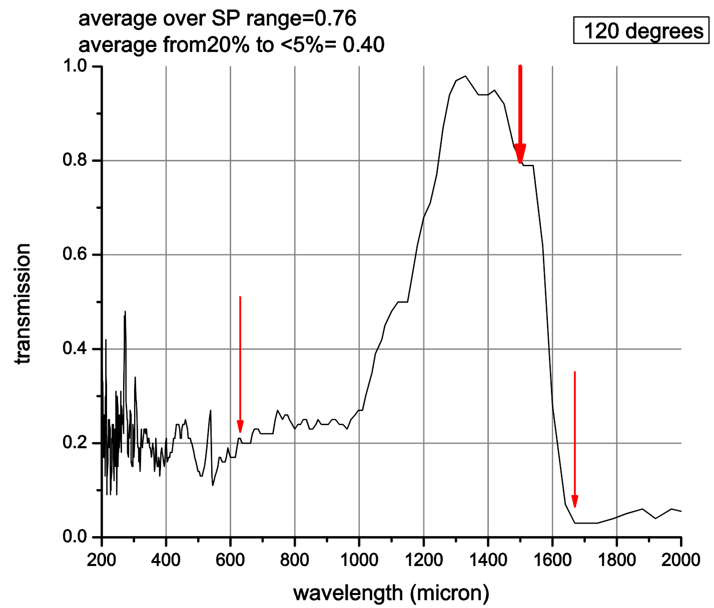
Installed on the FACET beam line



Optical system

Waveguide Array Plate (WAP) filters





approx. blocking wavelength= 1670 m

Experimental procedure

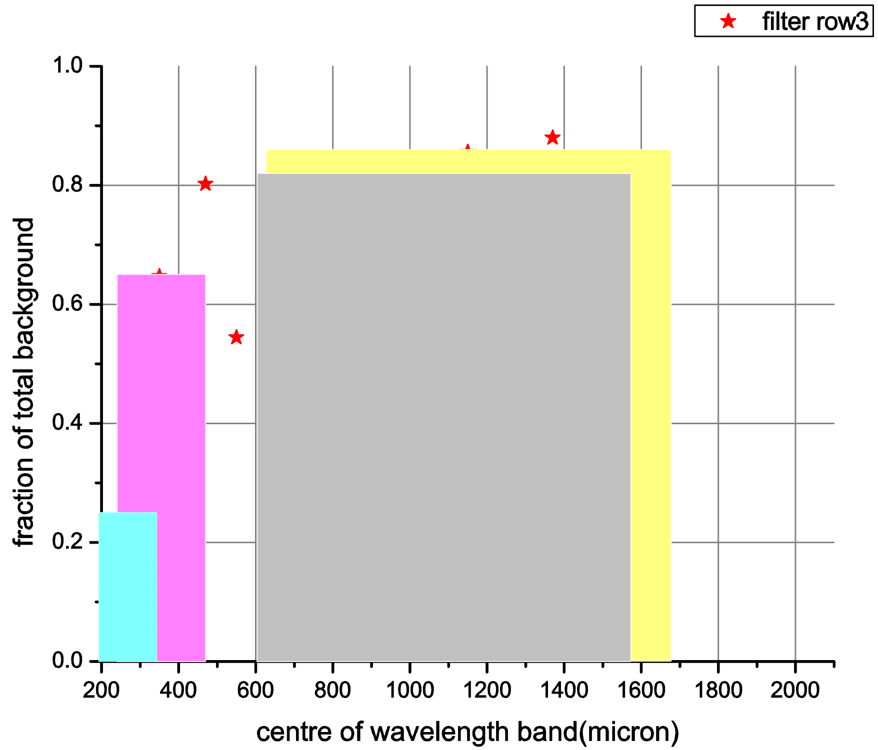
- FACET parameters: 20GeV, 1.5-2.0x10^{10} electrons/bunch, single bunch at 10Hz.
- Insert grating to about 2mm from beam and count for $\sim$10s.
- Determine the background radiation by inserting the blank, in the same position and using same set of filters.
- Correct for any differences in charge.
- Take net counts, divide by overall transmission efficiency and translate into Joule.
- New! Since observation is not taking place at an 'infinite' distance from the grating, interference may have a significant effect at short wavelengths.
- Extract the magnitude of the Fourier Transform (ρ).

The ‘background’ problem

- We use the blank grating to get a good indication of the magnitude of the b/g signal.
- We want some indication about its wavelength distribution (*does it overlap with SP signal*?)
- Is it polarised? *May be useful later.*
- We assume that it is incoherent but is it? (*needs testing*).
- Start by measuring the ‘total’ background, i.e. without using any filter at all.
- Repeat with a filter, but need to know the properties of that filter…

Approx. wavelength distribution

- Define an approx. transmission band for the filter.
- Get an average transmission for this band.
- Compare the signal to what is measured without a filter.
- Only a small fraction of the background radiation is in the 200-350μm band (cyan-coloured block).
- Most of the background lies in a band extending from approximately 600μm to 1550μm (grey block)
- Extending the filter band to about 1700μm causes a very small increase in the transmitted fraction (yellow block).



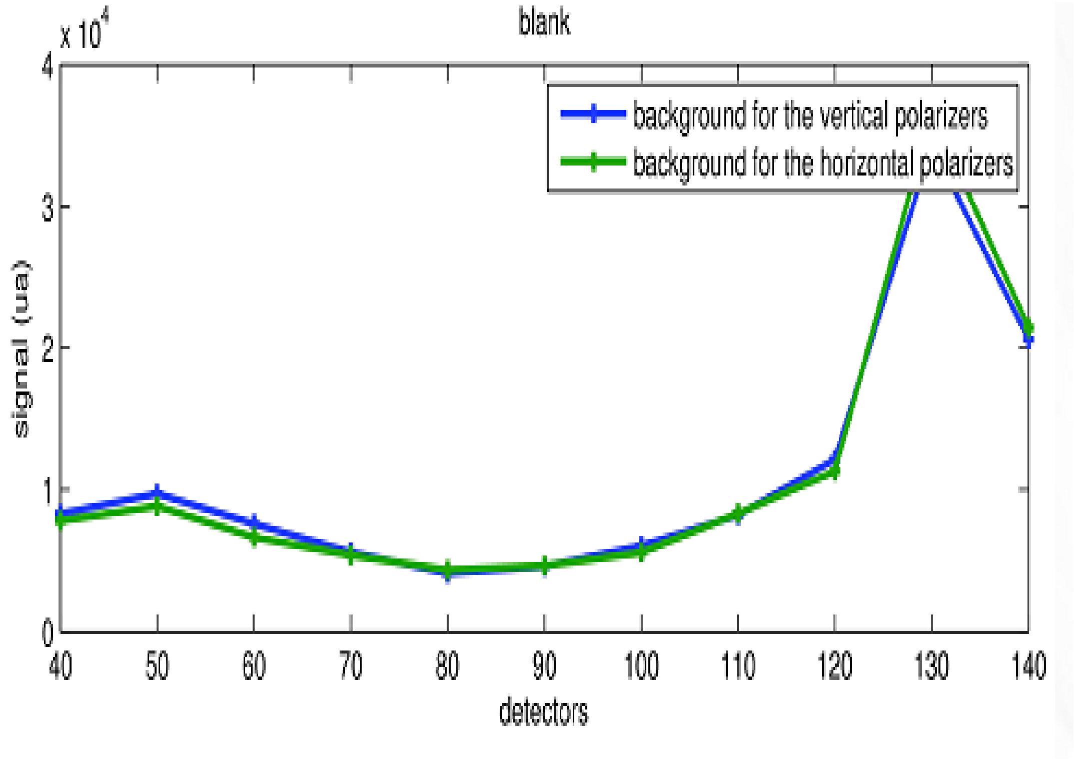
Seems to overlap with the range of SP wavelengths !

Polarisation of background signal

- Degree of polarisation defined:

$$p = \frac{p_1 - p_2}{p_1 + p_2}$$

- p1 is the energy in the *n-z* plane and p2 is perpendicular to that.
- Wire polarisers, good to about 200μm, approximately.
- Orientation of the wires judged by eye.
- *Background radiation appears to be un-polarised.*



Polarisation of SP radiation

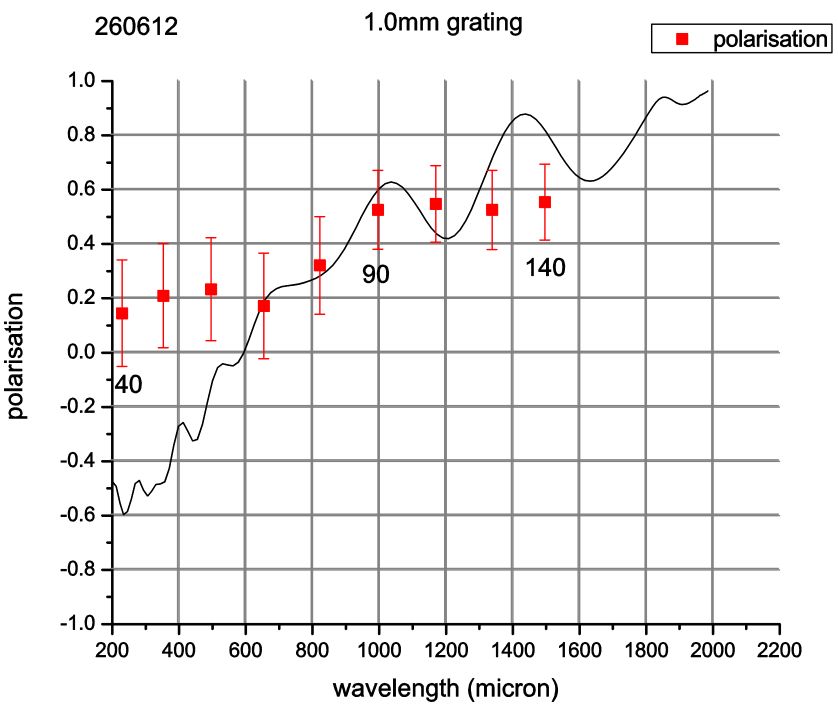
- Needs 4 separate measurements, two with the blank to get b_1 & b_2, the background signals in the two polarisation directions
- … and then another two with the grating to get ($g_1 + b_1$) and ($g_2 + b_2$).
- Then

$$p_g = \frac{t_1 - t_2 - p_b b}{t - b}$$

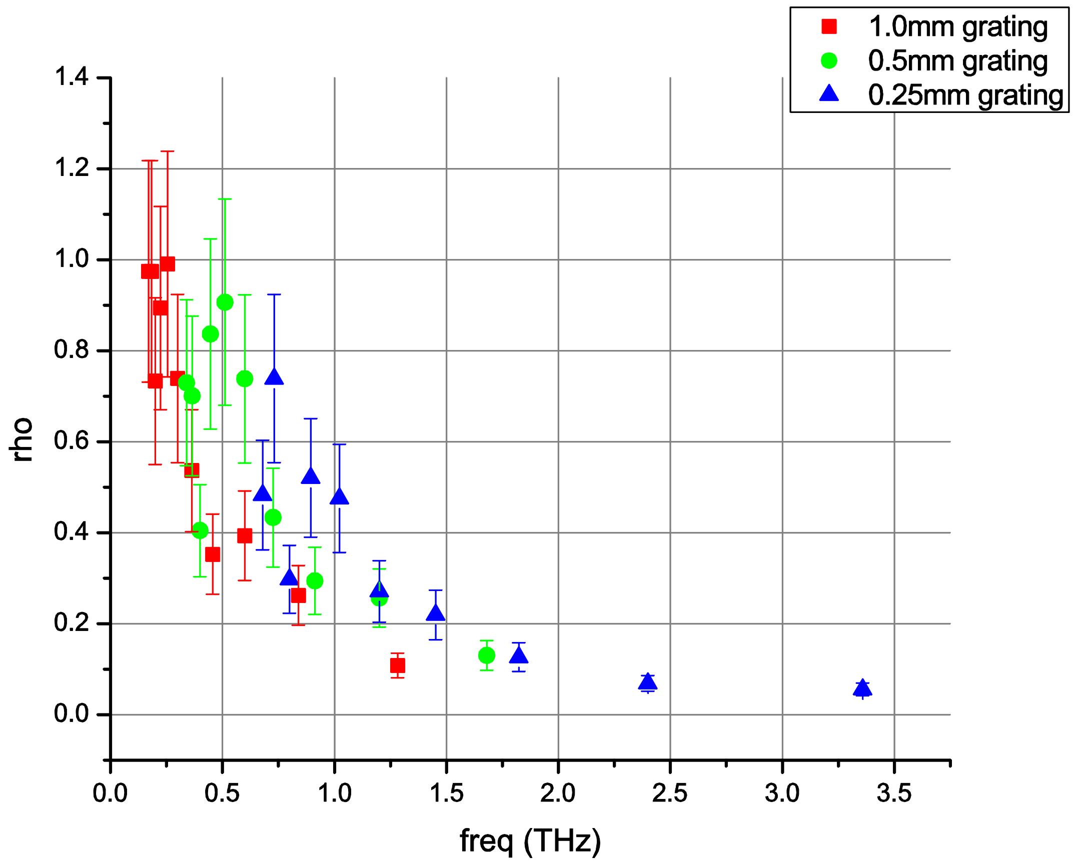
Where $t = t_1 + t_2$

And $b = b_1 + b_2$

- *Significant systematic uncertainties and not conclusive*.
- However, worth knowing!

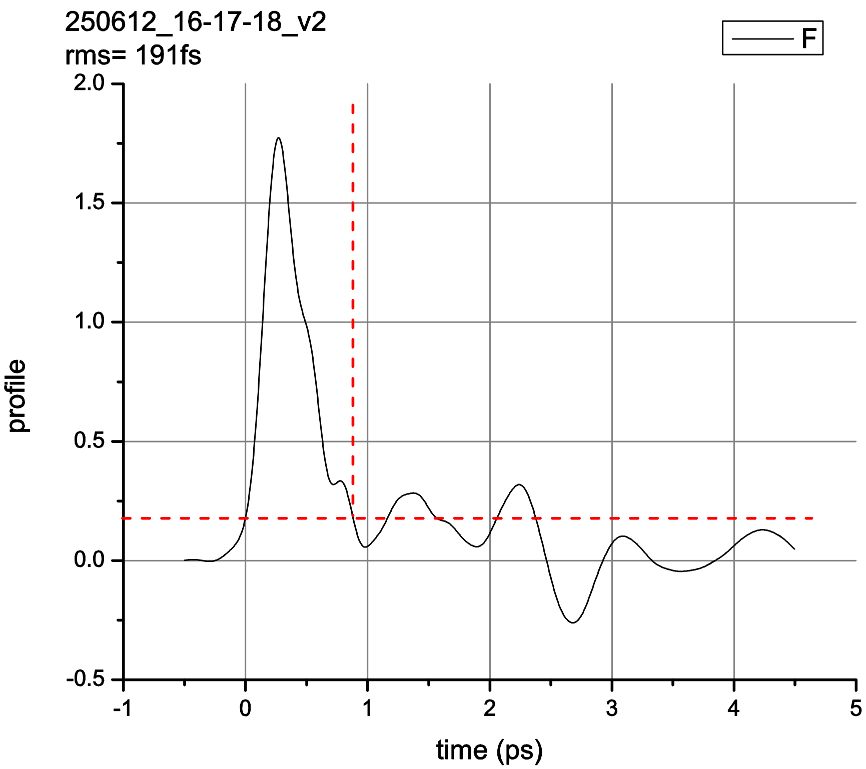


Frequency spectrum

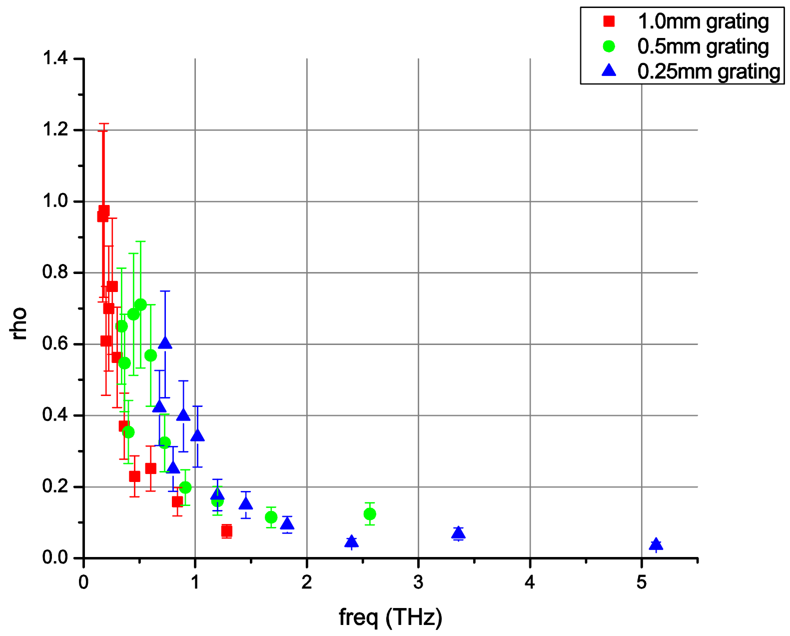


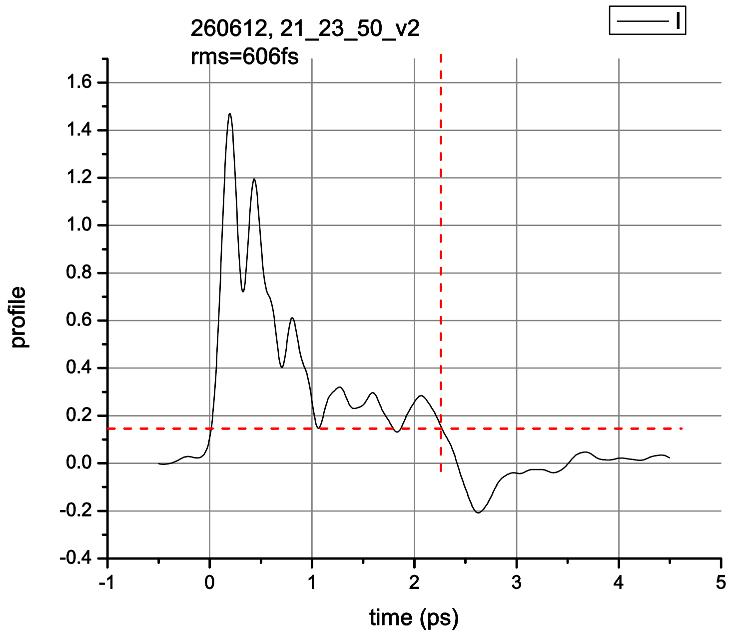
Reconstructed profile- provisional!

- Expand the 33 measured spectral yield points to create a table of ρ vs. f with total of 1500 points.
- Use KK to determine the minimal phase.
- Recover the temporal profile.
- *The weighted rms value is determined for points >10% of the peak value.*
- Fluctuations beyond ~2.5ps are meaningless.

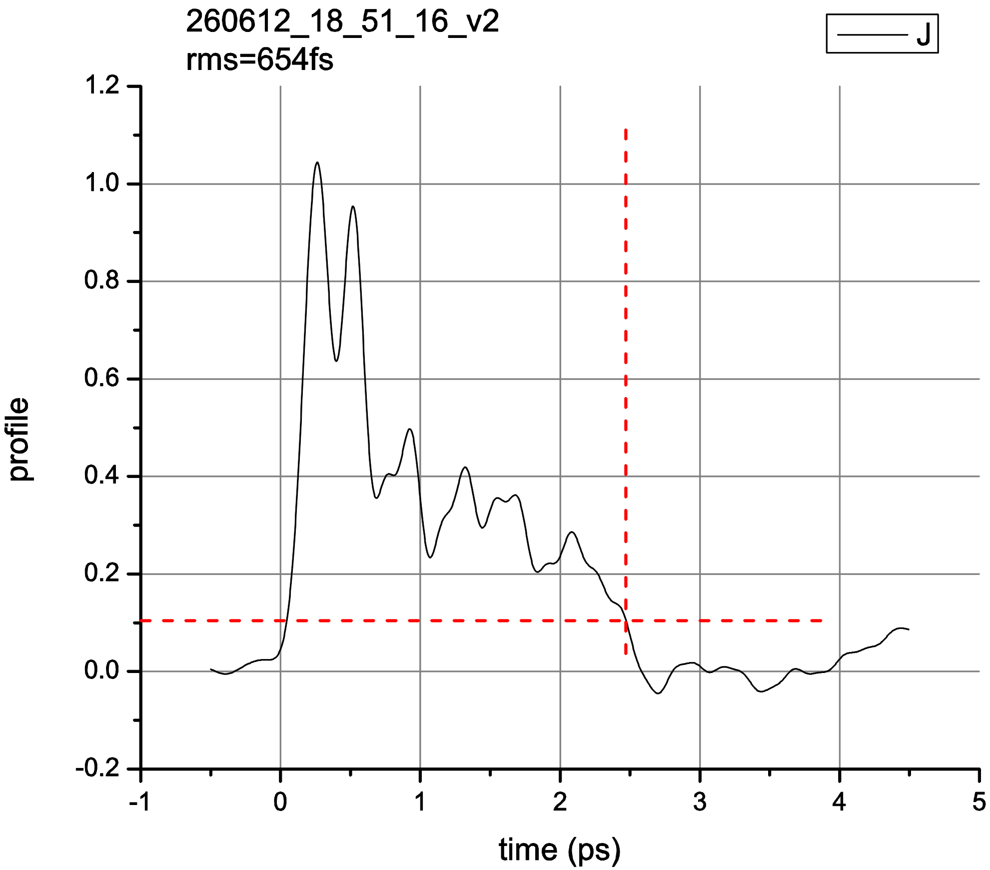


… another case, again provisional





and a 'low compression' case, provisional



Uncertainties

- Pyroelectric detectors do not have a flat response over all wavelengths.
- Must know the response curve of each detector over the whole wavelength range.
- …otherwise comparison of spectral yields is meaningless.
- In the 2007 calibrations we saw variations between detectors of ±50% in the 1.0-2.5mm range.
- Detectors have spent 6 years exposed to atmosphere → ??
- <u>Need for re-calibration</u>, i.e. access to a well-equipped infrared-laboratory.

Overview

1. Is the theory the appropriate one?
2. Are the experiments reliable and do we interpret them correctly?
3. What other information do we need?
4. Is the analysis the best we can do?
5. What is the shortest length one can hope to measure?
6. Is a single-shot device desirable? Feasible?

Is the theory the appropriate one?

- Originally suggested by Ed Purcell himself.
- Reasonably ‘transparent’.
- Do we apply it correctly? Yes, I believe.
- Unlikely to hold any surprises.
- Have just started using PIC codes.

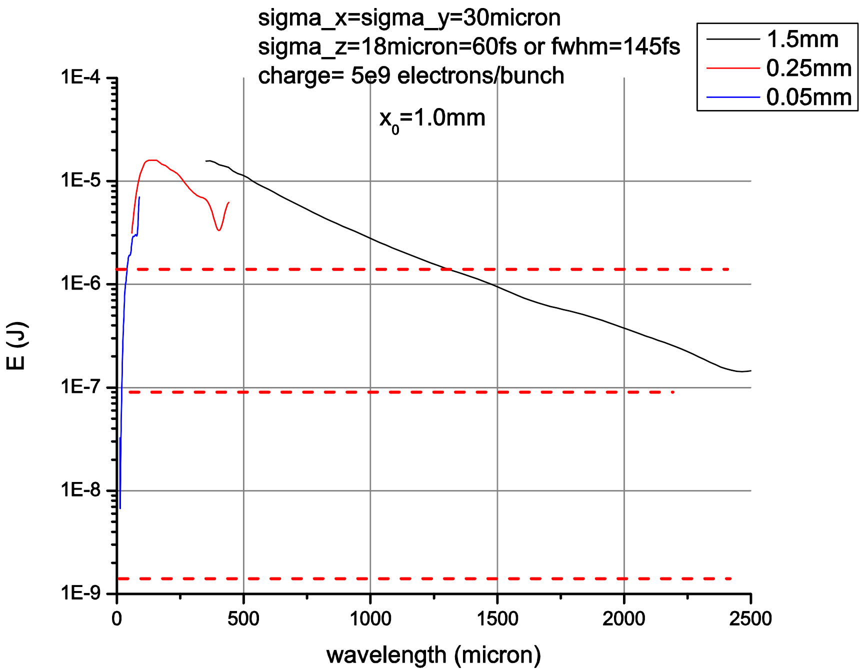
What is the shortest length one can hope to measure?

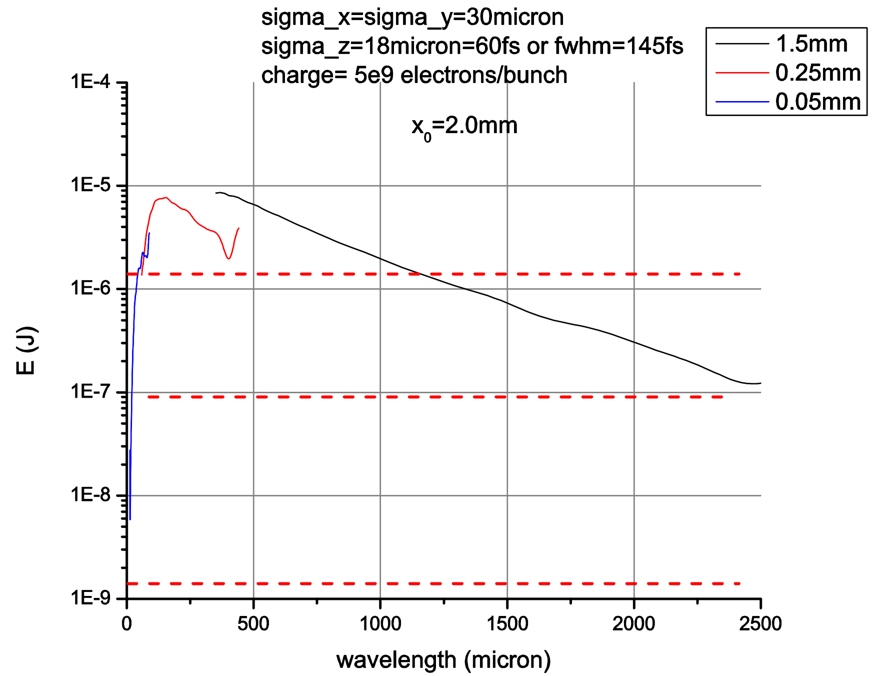
- Short bunch lengths mean short wavelengths, but…
- … below 4μm, approx., the assumption of perfect conductivity will start to break down; how does that affect the calculation of the yield?
- Potentially more important are the experimental issues: the beam needs to be close to the grating in order to couple effectively to the short wavelengths.
- The quality of the beam itself would be an important parameter.
- *There is always a danger of being swamped by the background radiation*.
- A general comment :

The SP diagnostic device needs to be seen as part of a suite of diagnostics, especially BPMs and charge monitors, operating close to each other.

- The shorter the bunch length, the more important the above statement would become.

E-203, predictions for the April run





Is a single-shot device desirable? Feasible?

- The answer to the first part must be 'yes', especially in connection with plasma wake-field acceleration.
- It is also feasible, within a timeframe of about 2 years, at least for the specification of such a device.
- There are a number of ideas about what such a device would look like, but nothing specific.
- I hope that we can avoid the unimaginative idea of 'multiplying' the existing device by 3.
- Needs effort, both on the mechanical side and, also, on the electronics.
- An intermediate step would be the construction of a Smith-Purcell based detector for the experiments of the IFIC Group at ESTB (SLAC).
- The current experiments at FACET are the first measurement of the time profile of sub-ps long bunches with coherent SP radiation and, hopefully, a significant step in the realisation of our objectives.