# Determination of the time profile of fs long bunches by means of coherent Smith-Purcell radiation


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**and**
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**on behalf of**
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IPAC11,
San Sebastian, 7 September 2011

# Outline

- Introduction

  Motivations

  A brief introduction to Smith-Purcell (SP) radiation

  SP radiation as diagnostics tool for bunch length measurements

- Experimental equipment

  SP detection and data analysis

- Toward fs bunch length measurements

  FACET experiment – August 2011

- Future perspectives

# Motivations (I)

High brightness linacs or Plasma Wakefield Accelerators (e.g. driving X-rays FELs or colliders) naturally produce ultra-short electron bunches

- high brightness linacs

  short pulses (100's to few fs)

  possibly low charge (100's to few pC)

- Laser Plasma Wakefield Accelerators (or beam driven PWA)

  short pulses (down to 10's fs)

  charge (1 nC to 100's pC)

# Motivations (II)

Diagnostics for ultra short (10's fs or below) bunches measurements are needed

- Streak cameras
- Transverse deflecting cavities (LOLA type)
- Electro Optical Sampling
- Coherent radiative processes (e.g. Smith Purcell, TR)

None of these techniques is simultaneously:

non-invasive, single shot, easy to extend to below 10's of fs, fully proven, requiring minimal extra hardware, cheap.

# What is Smith-Purcell radiation (I)

## Visible Light from Localized Surface Charges Moving across a Grating

S. J. SMITH* AND E. M. PURCELL
*Lyman Laboratory, Harvard University, Cambridge, Massachusetts*

(Received September 25, 1953)

IT occurred to one of the authors (EMP) that if an electron passes close to the surface of a metal diffraction grating, moving at right angles to the rulings, the periodic motion of the charge induced on the surface of the grating should give rise to radiation. A simple Huygens construction shows the fundamental wavelength to be $d(\beta^{-1} - \cos\theta)$, in which $d$ is the distance between rulings, $\beta$ stands for $v/c$ as usual, and $\theta$ is the angle between the direction of motion of the electron and the light ray. If $d = 1.67$ microns, as in a typical optical grating, and if electrons of energy around 300 kev are used, the light emitted forward should lie in the visible spectrum. As for intensity, if we assume that the surface

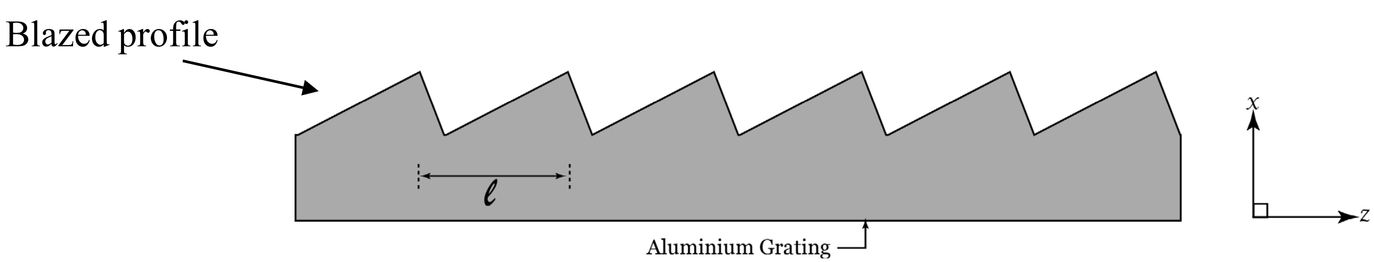
S.J. Smith and E.M. Purcell, Phys. Rev. **92**, pg. 1069, (1953)

300 keV electrons to emit in the visible wavelengths (d = 1.67 um)

# Smith-Purcell radiation (II)

An electron bunch grazing a metallic corrugated surface emits radiation

Within the surface current model, the emission of radiation is due to the acceleration of the surface charge induced on the grating surface



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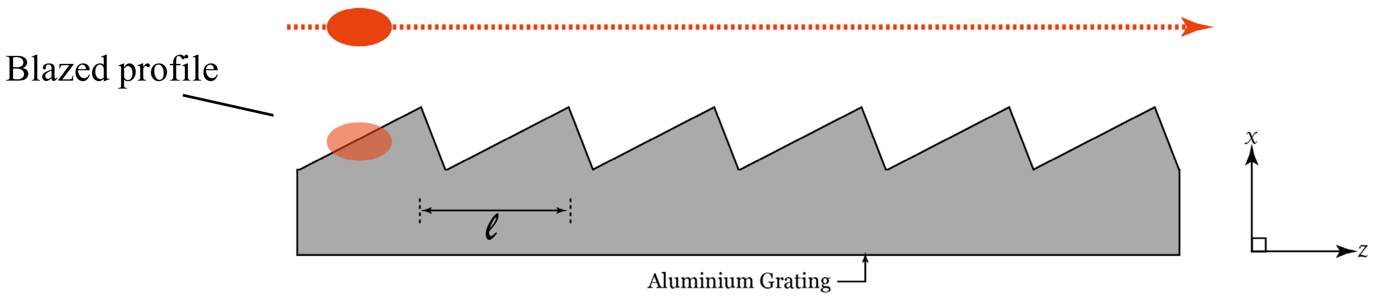

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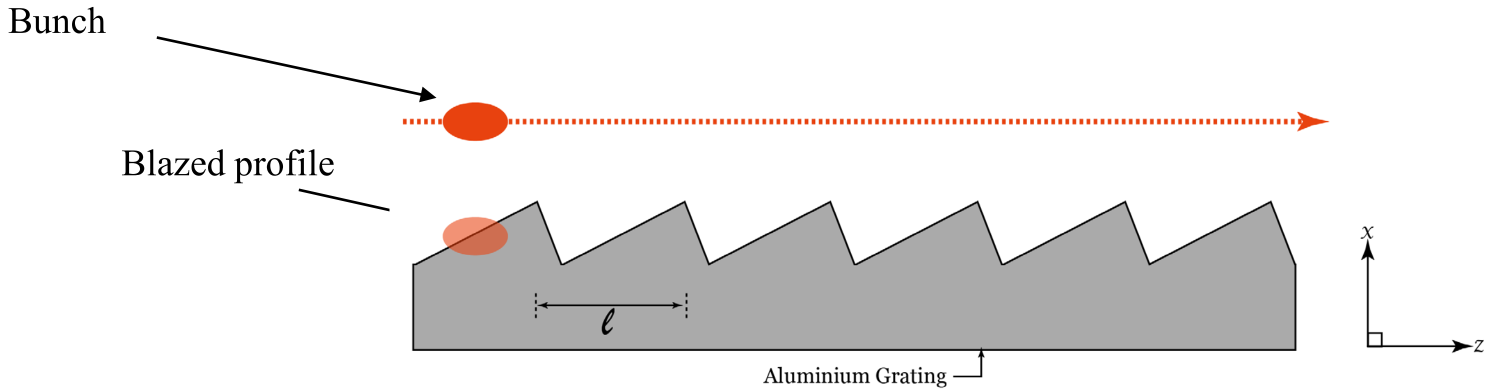

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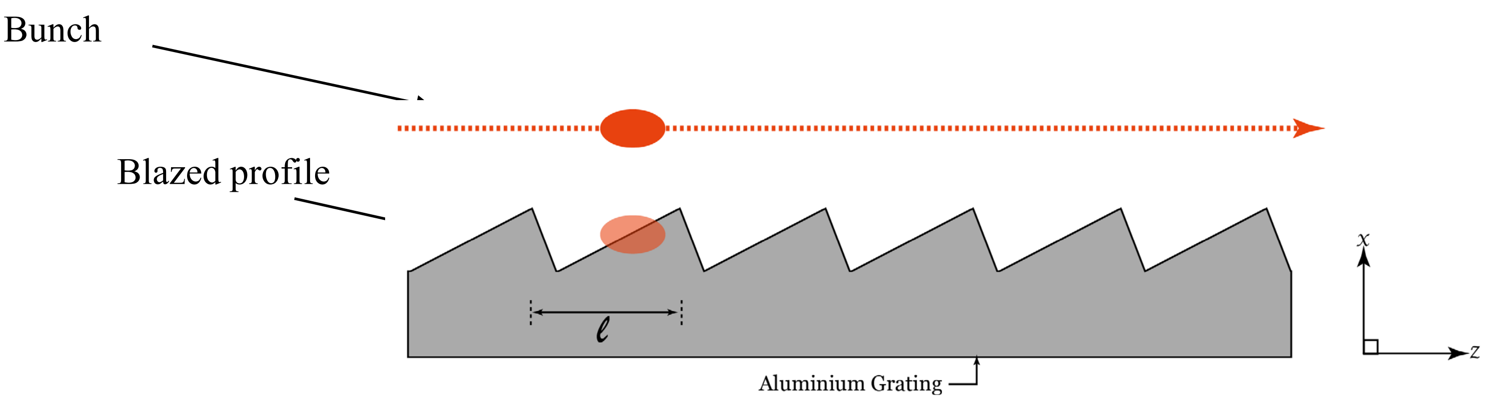

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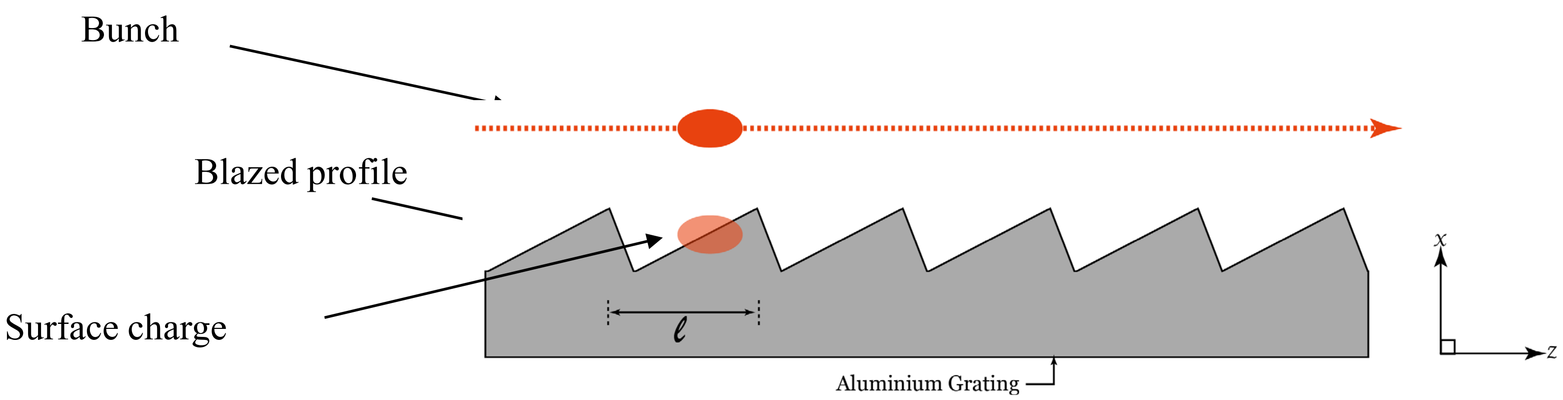

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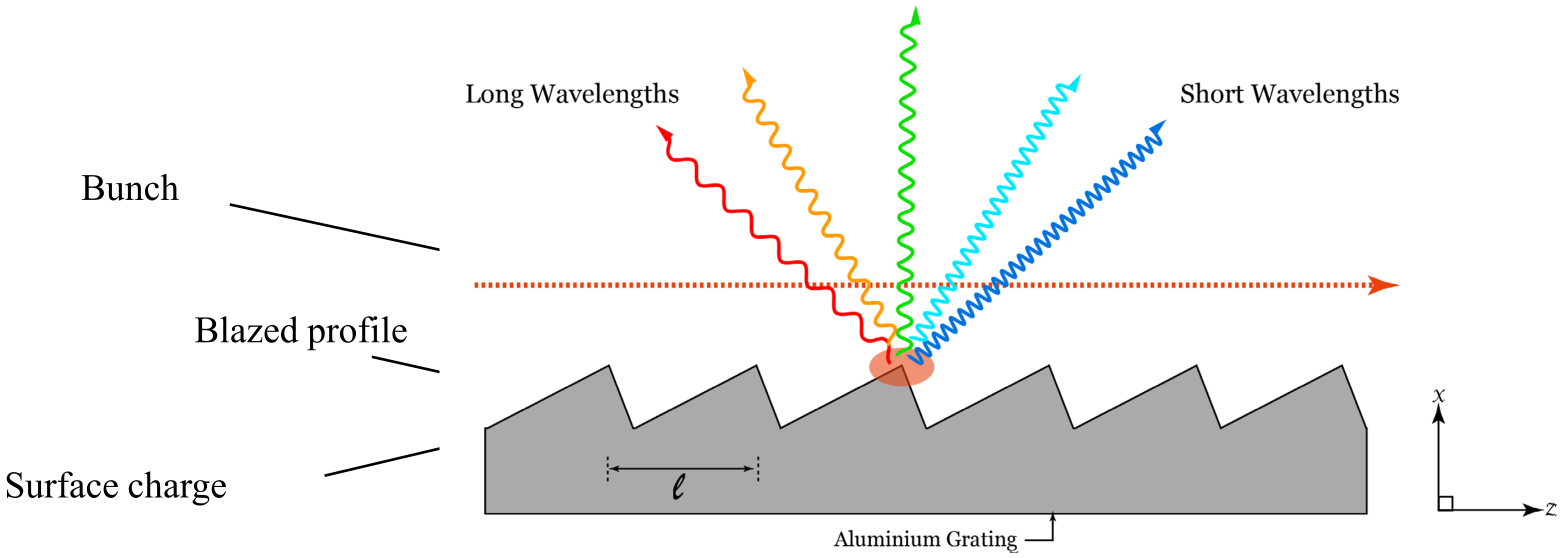
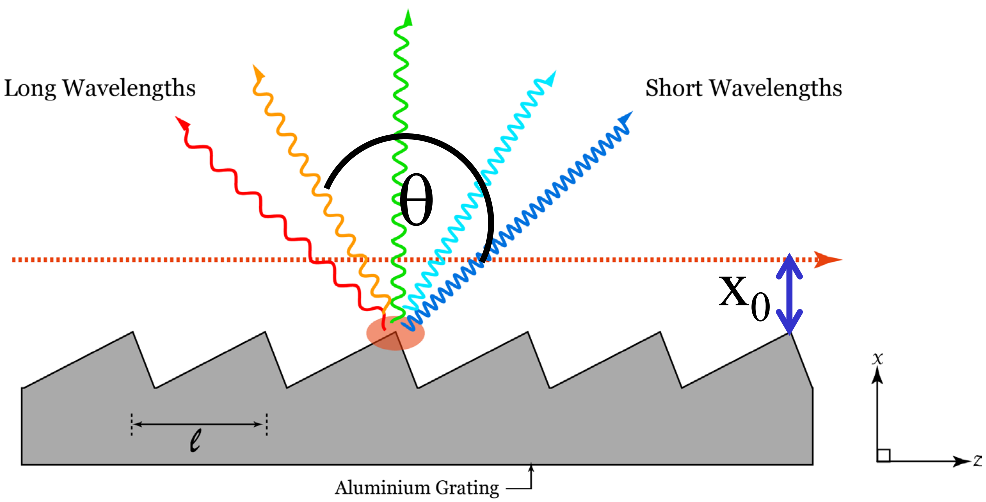


# Smith-Purcell radiation (III)

The grating has a dispersive effect: the angular distribution of the wavelength is given by

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

At 90 degrees in first order the wavelength is equal to the period $\ell$ of the grating




R: coupling strength of grating to radiation

The angular distribution of the power emitted by a single electron is computed from the radiation integral

**Infinite grating:**

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

**Evanescent wavelength:**

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

# Coherent Smith-Purcell radiation

Two electrons will emit in phase over the wavelengths which are longer than their separation in the longitudinal direction

The power radiated by a bunch of electrons is given by

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

$F(\omega)$ is the form factor of the electron bunch, i.e. the square modulus of the Fourier transform of the longitudinal bunch distribution

For a bunch length $\sigma_\tau$ the form factor $|F(\omega)|^2$ is different from zero up to $\omega \leq \frac{2\pi c}{\sigma_\tau}$

50 ps $\Rightarrow$ $\lambda$ coherence >15 mm    microwaves
50 fs $\Rightarrow$ $\lambda$ coherence > 15 $\mu$m    FIR

# Smith-Purcell radiation as a diagnostic tool (I)

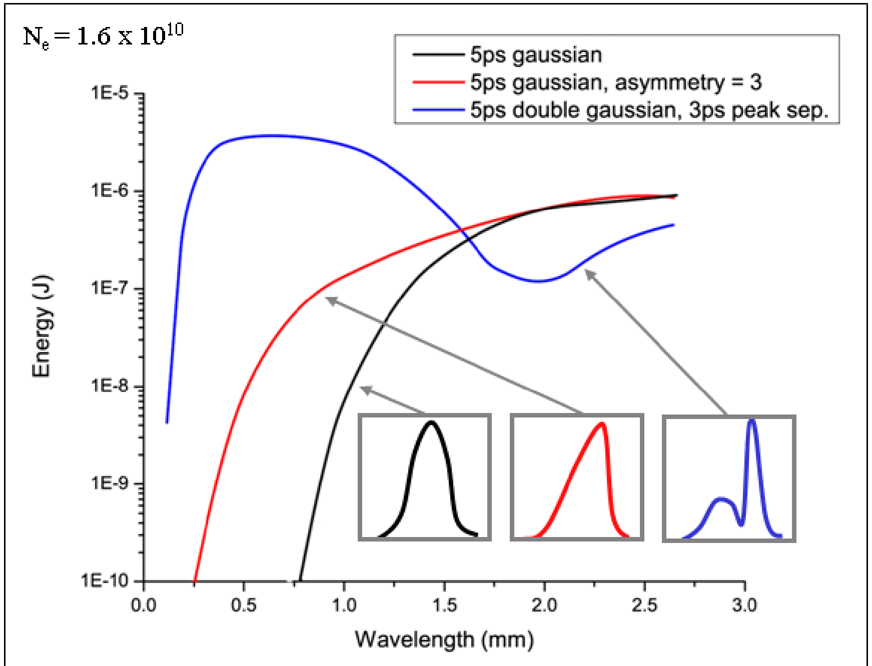
SP Radiation is emitted **away** from beam direction (i.e. out of the beam pipe).

**Unlike other techniques wavelengths are emitted over a large angular spread. Different SP wavelength at each observation angle!**

Different bunch profiles = different radiation distributions.

Measuring emitted energy in coherent SP radiation carries information ***not only to bunch rms length but also on the bunch profile.***

Can measure multiple angles at once for a single-shot measurement.




*Simulation of different profiles, as would be seen experimentally*

# Smith-Purcell radiation as a diagnostic tool (III)

Disadvantages: indirect profile reconstruction

Measurement of the emitted energy as a function of frequency
Measurement the square of the amplitude of the form factor

Loss of phase information in the form factor

Possible approaches to recover the phase factor

Recover phase information with a **Kramers-Kronig** technique.

**Shrinkwrap** technique adapted to 1D longitudinal profile s
H. Chapman, S. Marchesini et al, Nature Phys. **2**, 830, (2006)

However these techniques do not fully overcome the missing phase issues

# KK reconstruction of the bunch profile (I)

Assume the relation

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

is the FT or the response of a time invariant, causal system to a given input

$$\mathrm{out}(\omega) = \mathrm{in}(\omega)\cdot\mathrm{G}(\omega) \qquad \mathrm{G}(\omega) \approx \mathrm{N_e^2}\,|\,\mathrm{F}(\omega)\,|^2$$

$$\mathrm{G}(\omega) = \rho(\omega)\cdot\exp[\mathrm{i}\phi(\omega)]$$

The phase $\phi$ is determined from the amplitude $\rho$ as

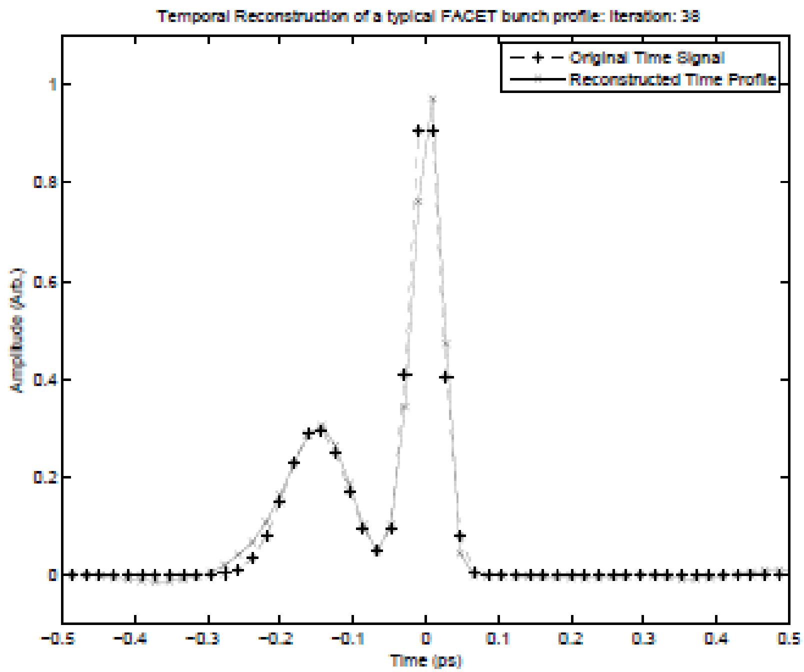
$$\phi(\omega) = \frac{2\omega}{\pi}\int_0^{\omega}\frac{\ln[\rho(\omega)/\rho(\omega_0)]}{\omega_0^2-\omega^2}\,\mathrm{d}\omega$$

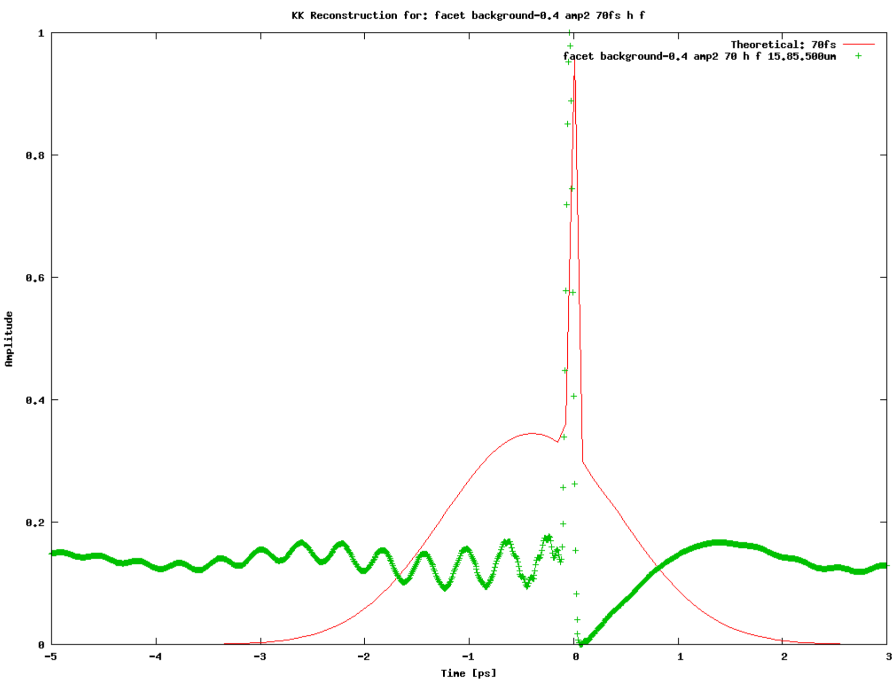
$\phi$ is unique for a causal system. G($\omega$) is non-zero in the upper half complex plane.

The KK profile reconstruction however does not always provide a good solution

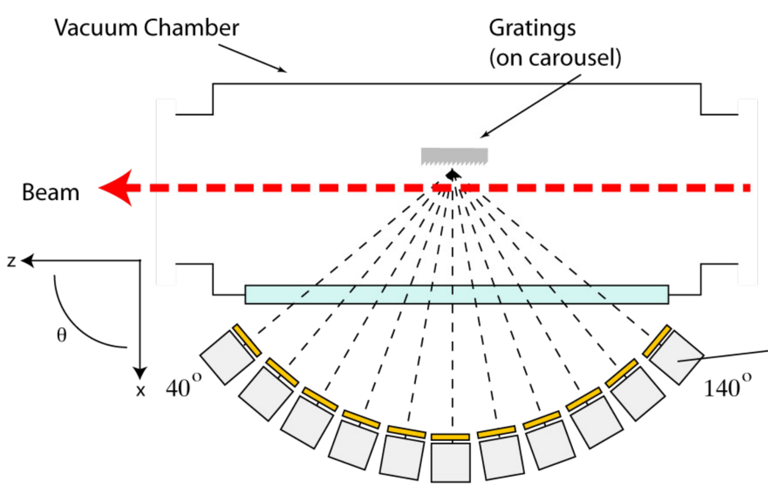
# KK reconstruction of the bunch profile (II)

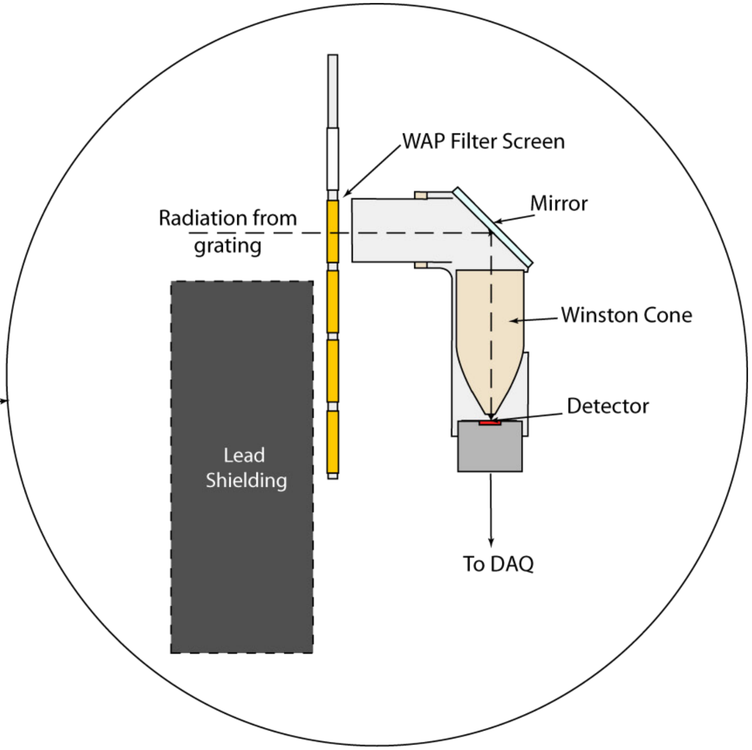
We have numerical evidence that the KK profile reconstruction works well for well behaved profiles. It fails with pathological profiles

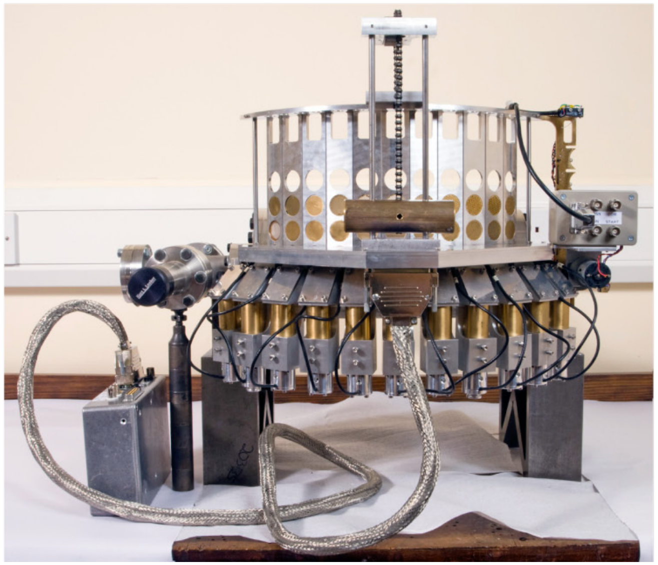


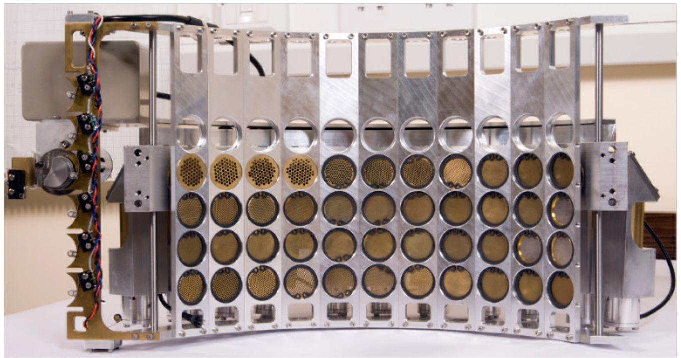



# Experimental equipment





# Detection of FIR SP radiation (I)

Challenges:

- eliminating background radiation

  IR filters, use of a blank grating as reference

  true SP signal = total signal – blank background

- collecting sufficient IR power

  Winston cones concentrators

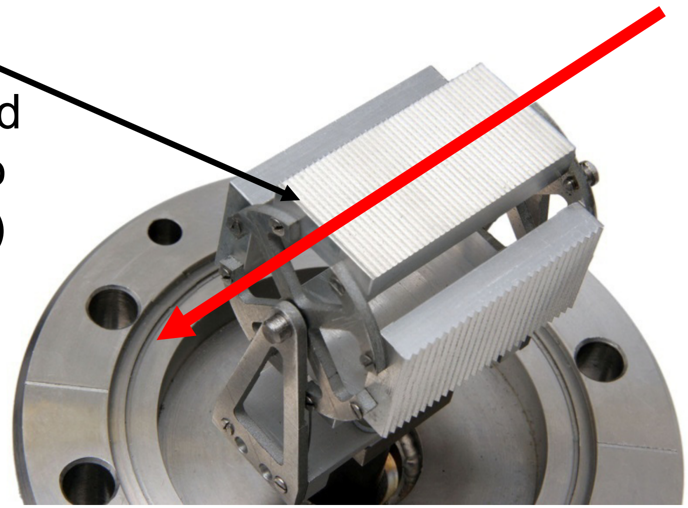
- collecting sufficient discrete frequencies

  use 3 gratings and collect radiation at 11 angles of observations from 40 degrees (forward) to 140 degrees (backward)

  use room temperature pyroelectric detectors (almost BB)

# Detection of FIR SP radiation (II)

3 gratings (50, 250, 500 $\mu$m)
1 blank piece of aluminium
The grating periods are tailored to the bunch length we want to measure at FACET (60 fs rms)




Expected SP radiation in the wavelength range 10 $\mu$m to 1 mm

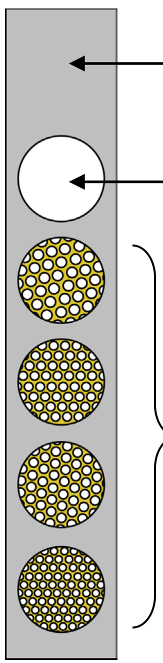
A carousel can rotate and offer three different gratings or one blank to the beam. Rotation is controlled remotely

For a true single shot measurements the gratings should be located in series.

# Detection of FIR SP radiation (III)

Various filters remove background radiation. Suitable filters for each grating are moved in front of the silicon windows. BW tailored to the expected SP wavelength

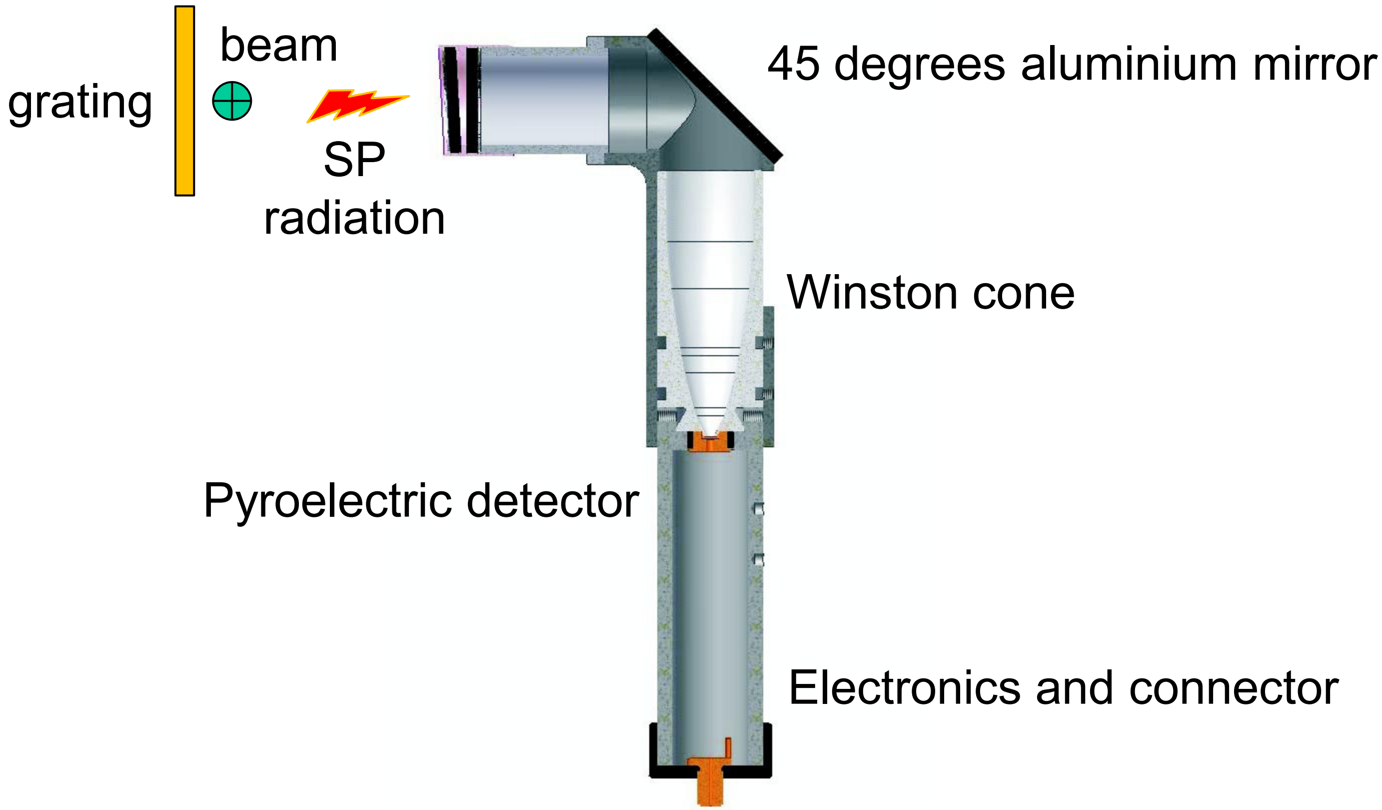
Winston cones collect the radiation toward the pyroelectric detectors and provide additional filtering





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

# FIR detector assembly




**Calibration of detectors** (and loss measurements in the system) is a crucial issue
**done at RAL and at the IR beamline B22 at Diamond**

# How short bunch profiles can we measure?

Test coherent SP technique to 60 fs rms at FACET

a factor 20 shorter than presently proven results (**~1 ps at ESA 2007**)

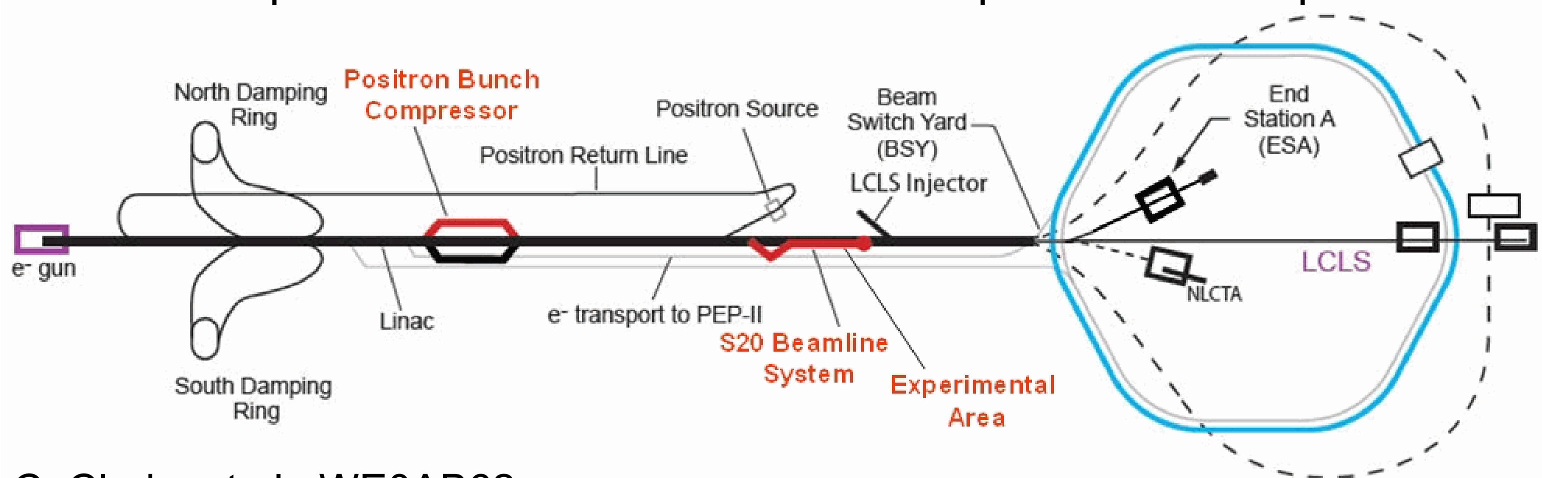
as proof of principle that might open the path to few fs range bunch length measurements

FACET is a unique test facility for high energy electron beam

Charge up to few nC

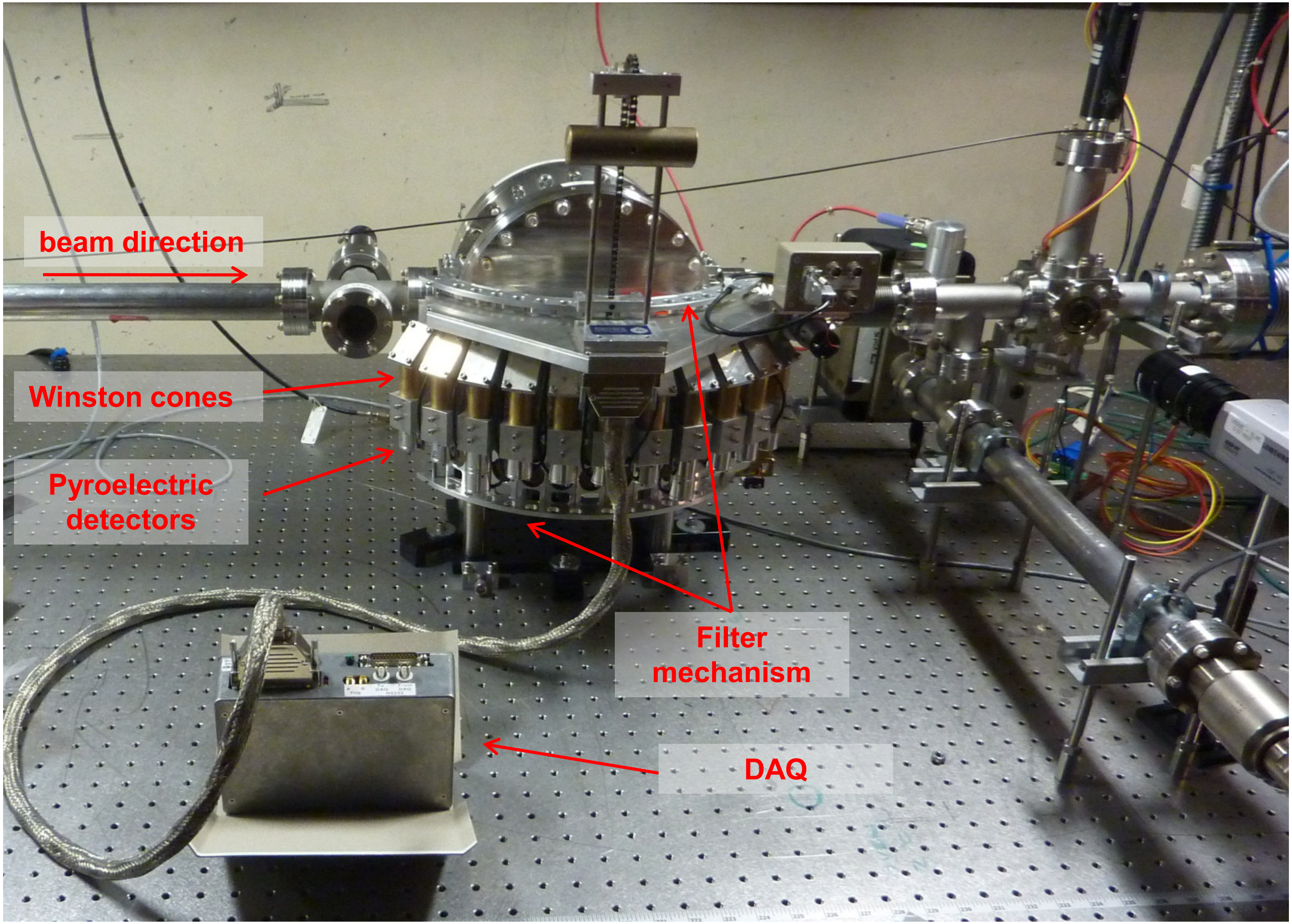
Bunch length controllable with bunch compressors (down to 60 fs rms)

beam parameters and their control adequate for our experiments




See C. Clarke et al., WE0AB62

# SPR at FACET (August 2011) before lead shielding installation



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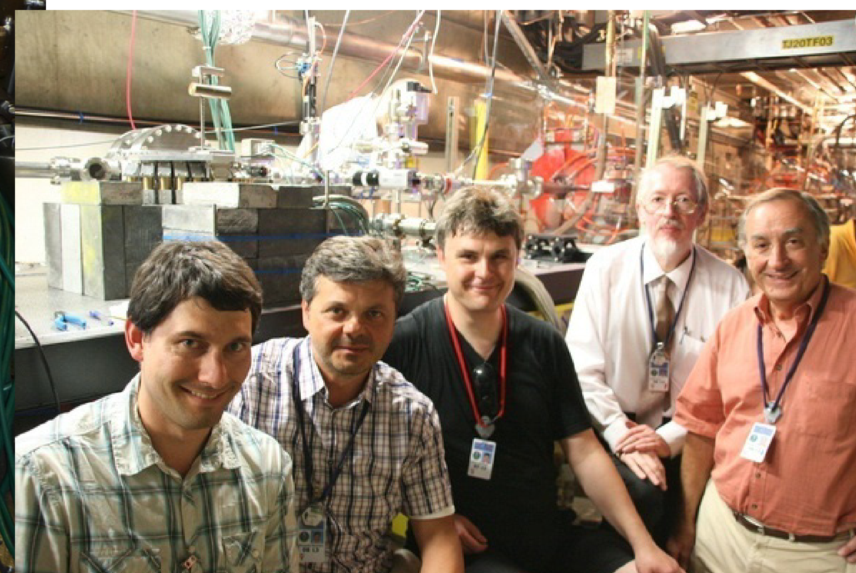
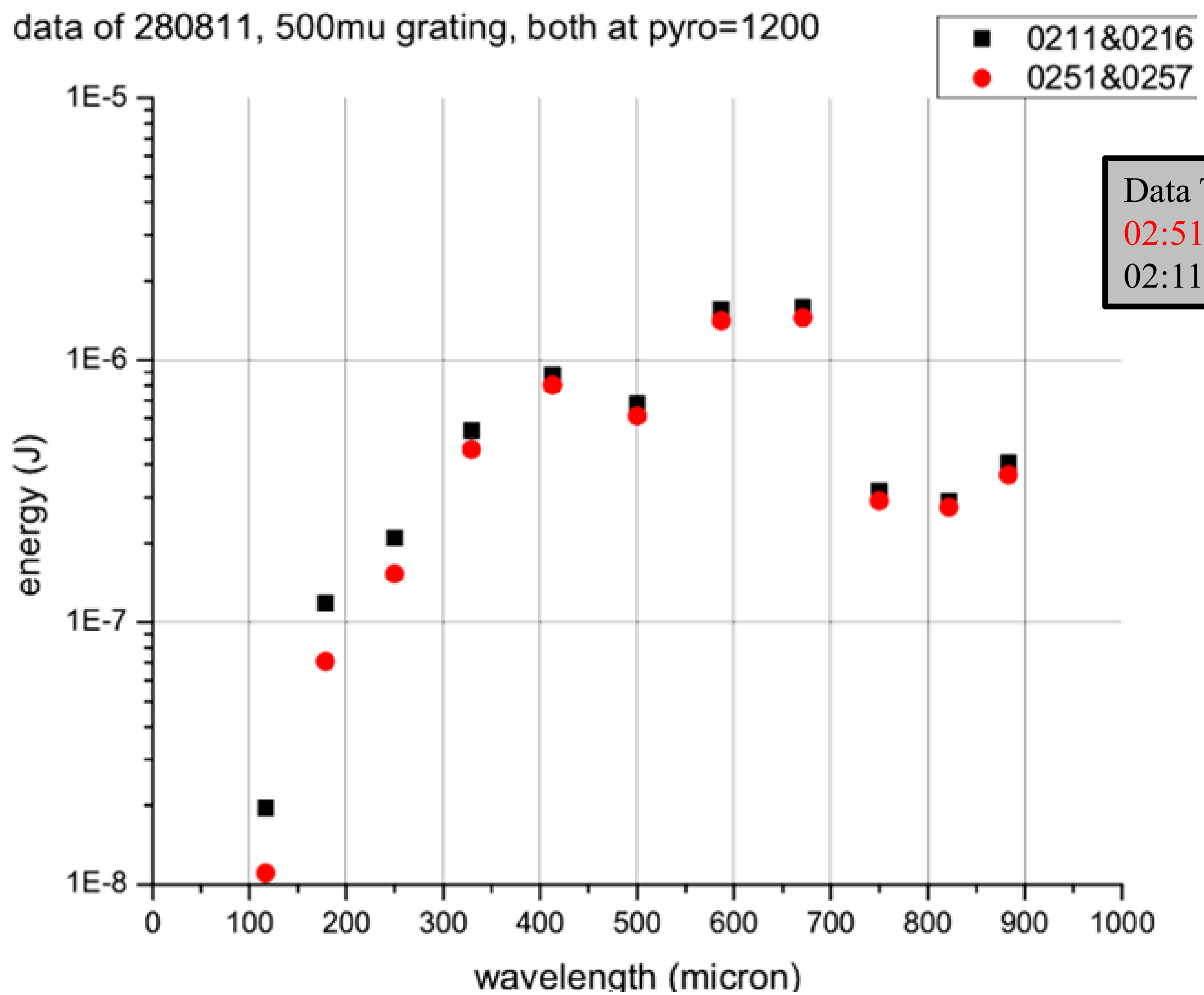


# First preliminary data (28/08/2011)

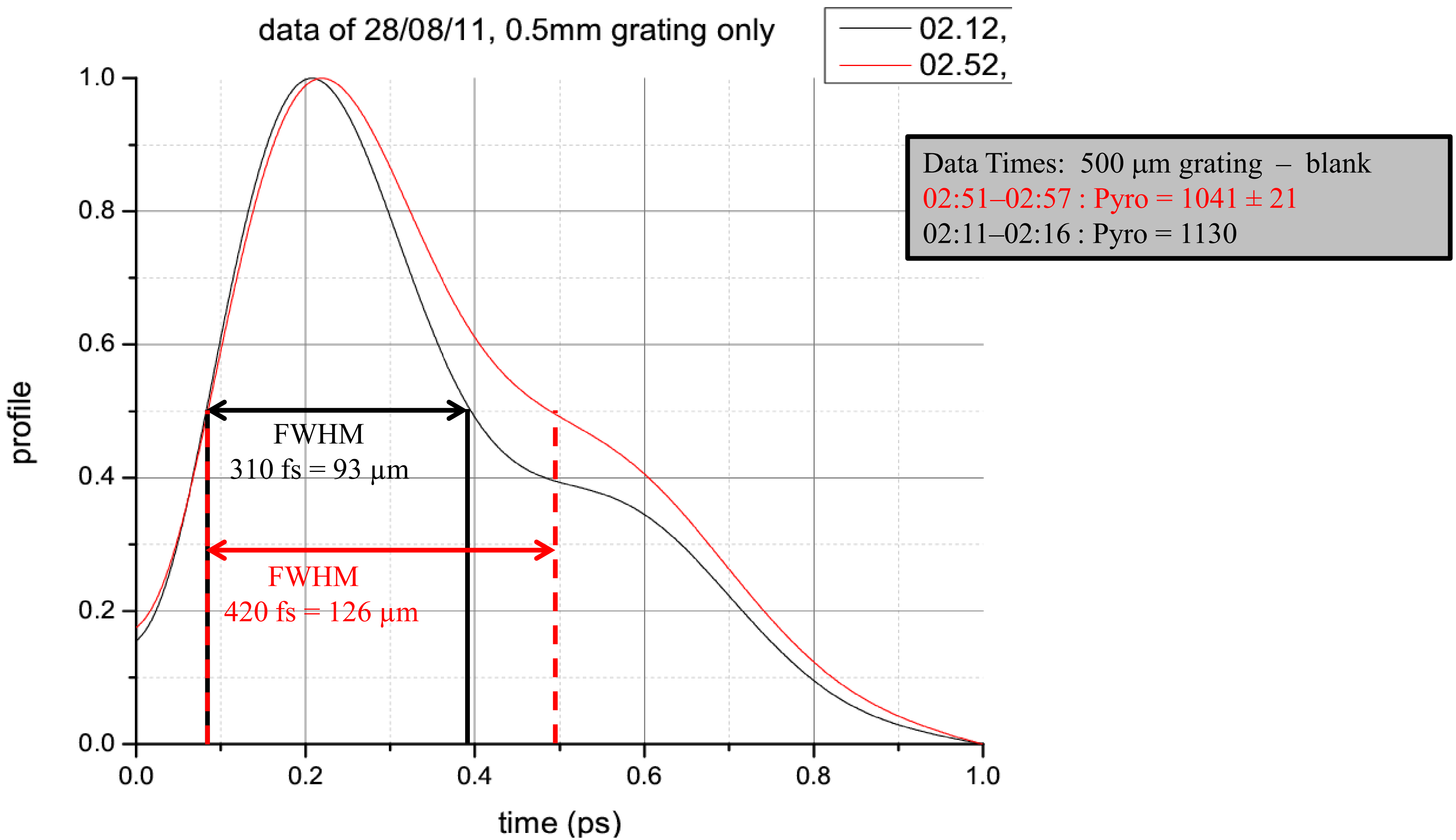
Partially corrected Smith Purcell Spectrum (500 μm grating only)




Data Times: 500 μm grating – blank
02:51–02:57 : Pyro = 1041 ± 21
02:11–02:16 : Pyro = 1130

# First preliminary data (28/08/2011)

Reconstructed temporal profile (KK method)



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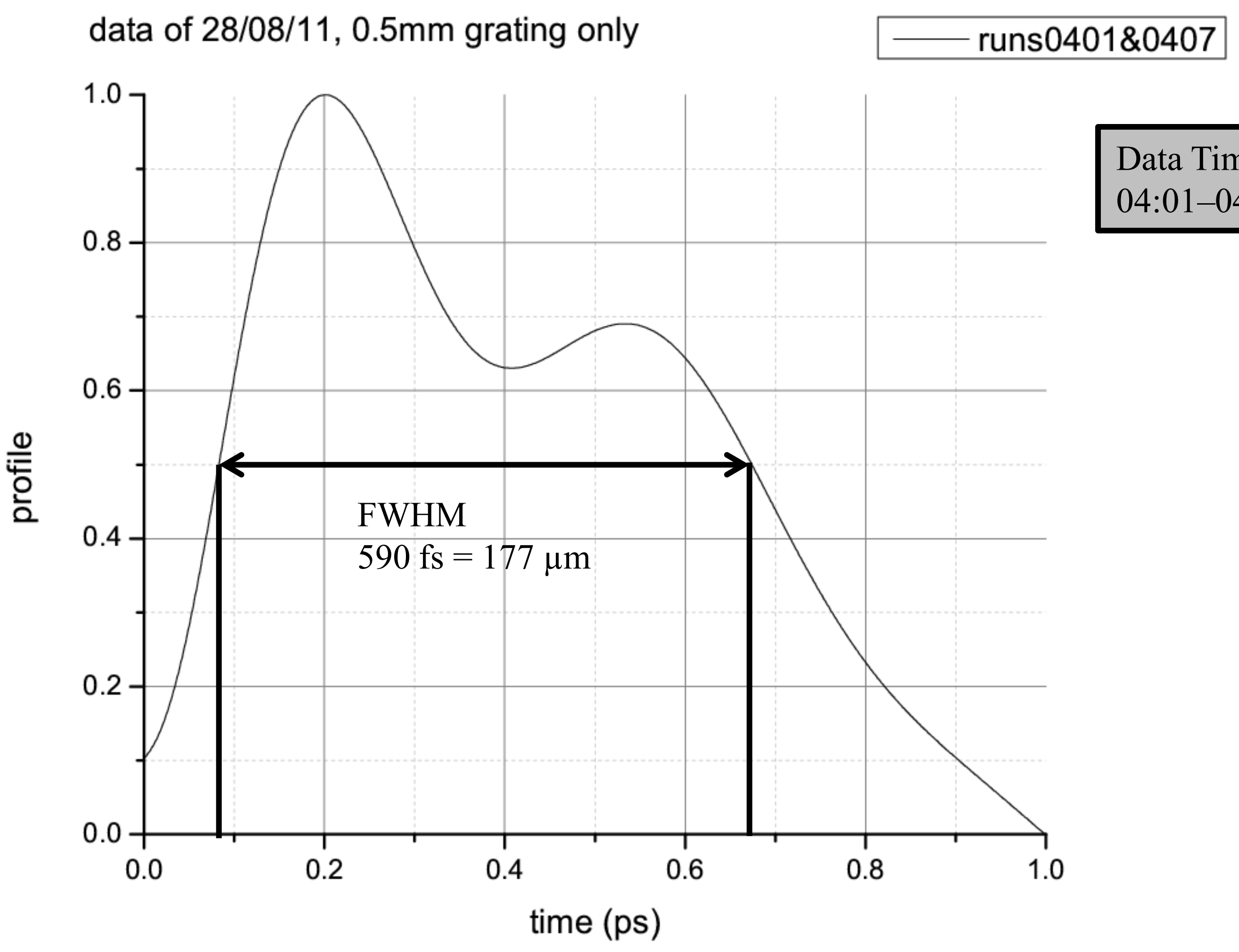
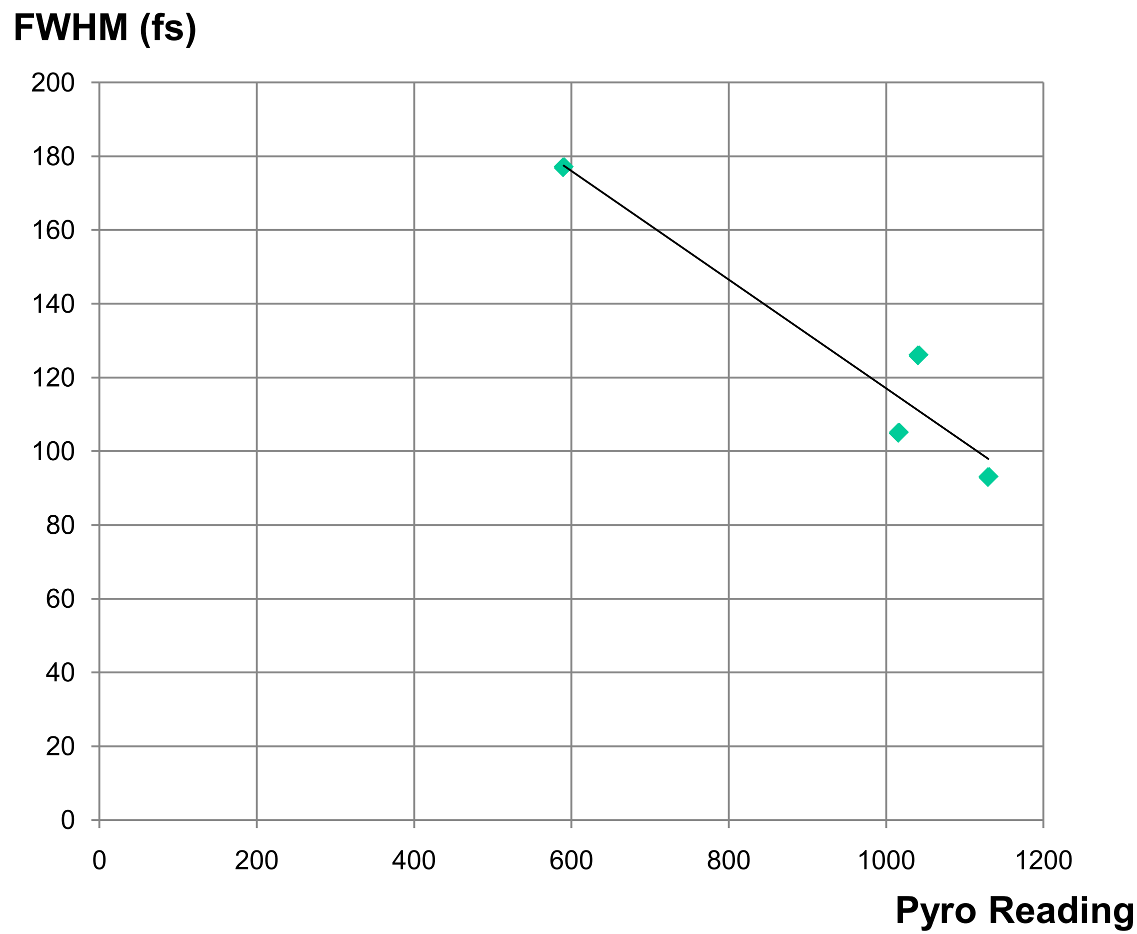



Data Times 500 μm grating – blank
04:01–04:07 : Pyro=585

# First Preliminary Data at FACET (August 2011)

| Pyro A007 reading | FWHM from SP spectrum |
|---|---|
| 590 | 177 microns |
| 1016 | 105 microns |
| 1041 | 126 microns |
| 1130 | 93 microns |



# Conclusions and ongoing work

Coherent Smith Purcell is an promising candidate to provide a diagnostics system for bunch length measurement which

- has the potential for very high resolution (tens fs or below)
- provide profile information not simply rms
- non-invasive (non-intercepting and no modification to operating parameters)
- single shot
- inexpensive

Preliminary results at FACET are very encouraging. No showstopper in extending this techinque to 100 fs FWHM which pave the way to applications to fs bunch lengths.

Future work will be the construction of a true single shot apparatus and improvement of profile reconstruction techniques.

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**Thanks to the FACET team**
**and**
**Thank you for your attention !**

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