# Introduction to Smith-Purcell radiation

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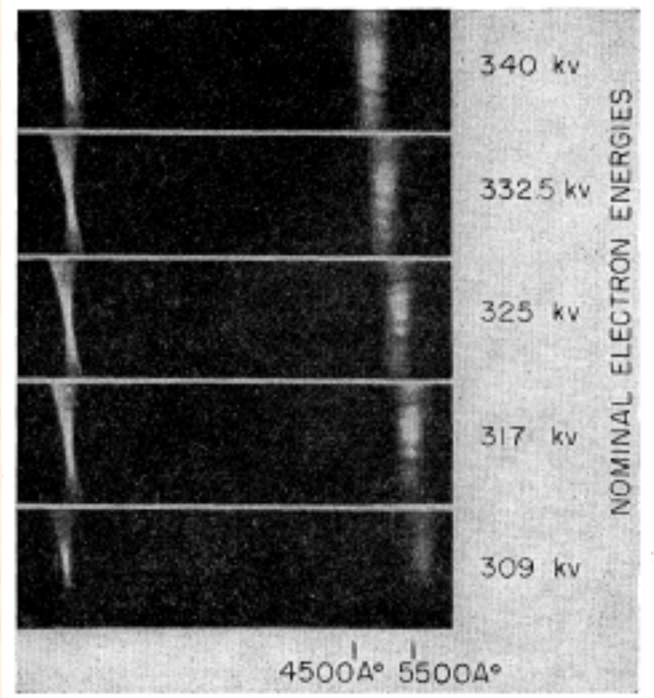
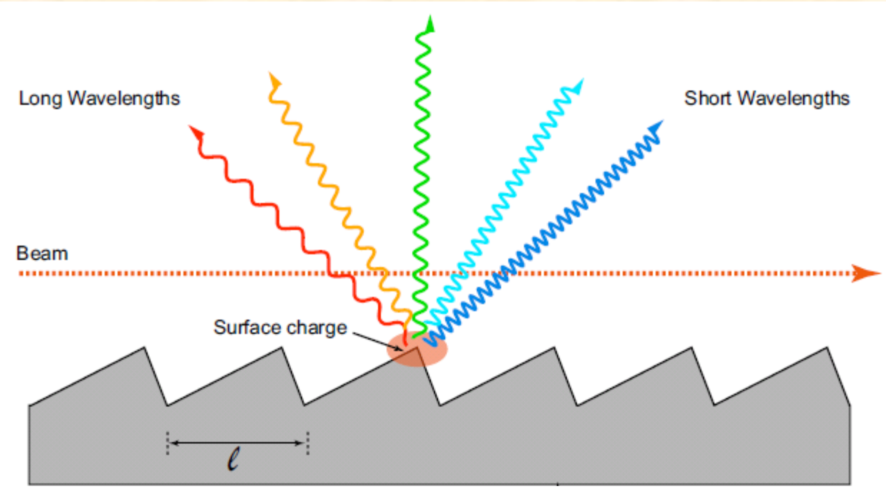
# Smith-Purcell radiation

- Discovered 1953 by Smith and Purcell.
- Surface charges induced in a grating by an electron bunch emits light.
- This can be explained by the dipole radiation of the charges induced as they travel along the grating.
- This light is spectrally dispersed by the grating.
- When the charges are induced by a short bunch there can be coherent emission => Coherent SP radiation.




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

# Original Smith & Purcell paper

## 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)

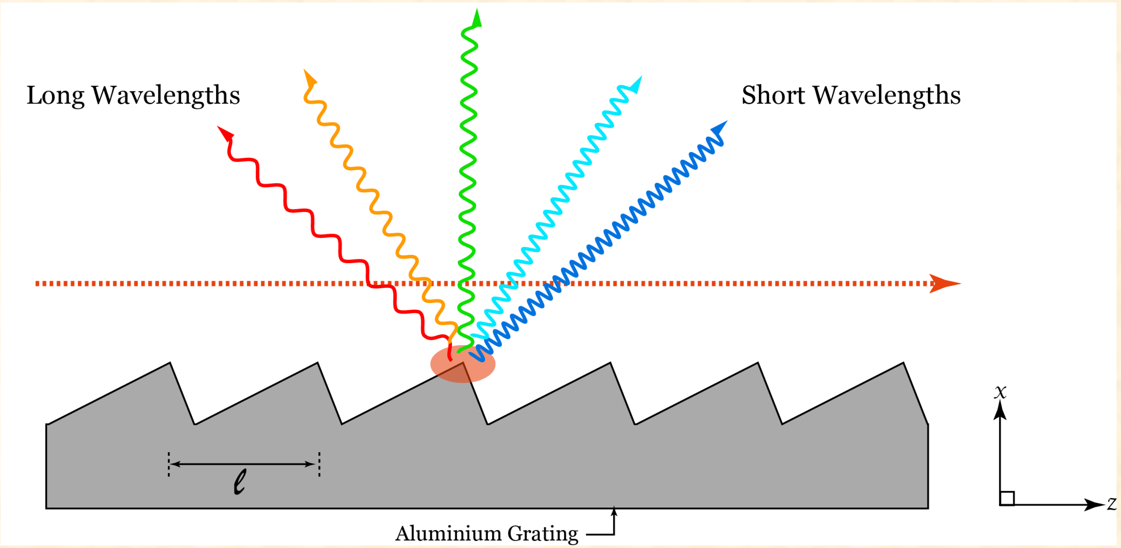
IT occurred to one of the authors (EMP) that if an electron passes close to the surface of a metal diffraction grating, moving at right angles to the rulings, the periodic motion of the charge induced on the surface of the grating should give rise to radiation. A simple Huygens construction shows the 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

- Smith Purcell radiation is emitted when a charge passes near a grating.



# Coherent emission

- Like most radiative processes SPR has an incoherent and a coherent component.
- The coherent component is the product of $N^2$ and the Fourier transform of the bunch shape squared.

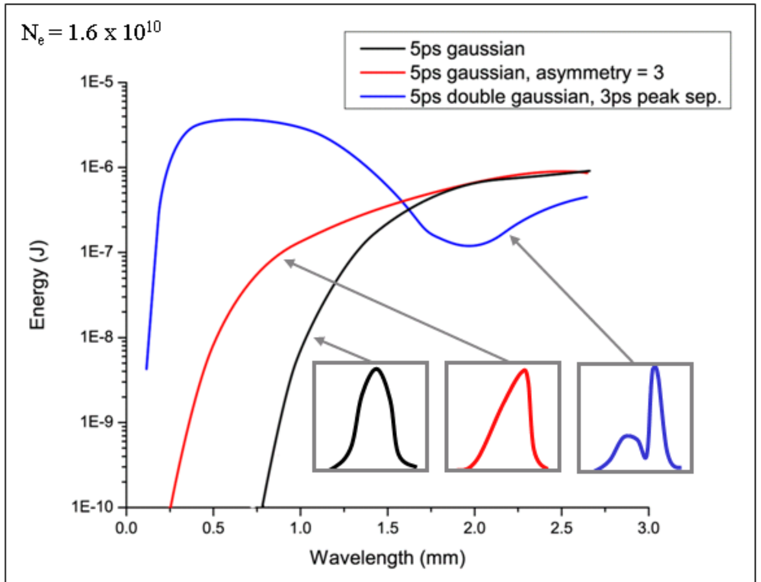
$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e}(\Omega,\omega) = \left(\frac{dI}{d\Omega d\omega}\right)_{sp}(\Omega,\omega)\cdot[N_e + N_e(N_e+1)\,|\,F(\omega)\,|^2]$$

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

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

- A measure of the SPR therefore gives a measure of the Fourier transform of the bunch shape.

# Effect of the profile on the emitted spectrum




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

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

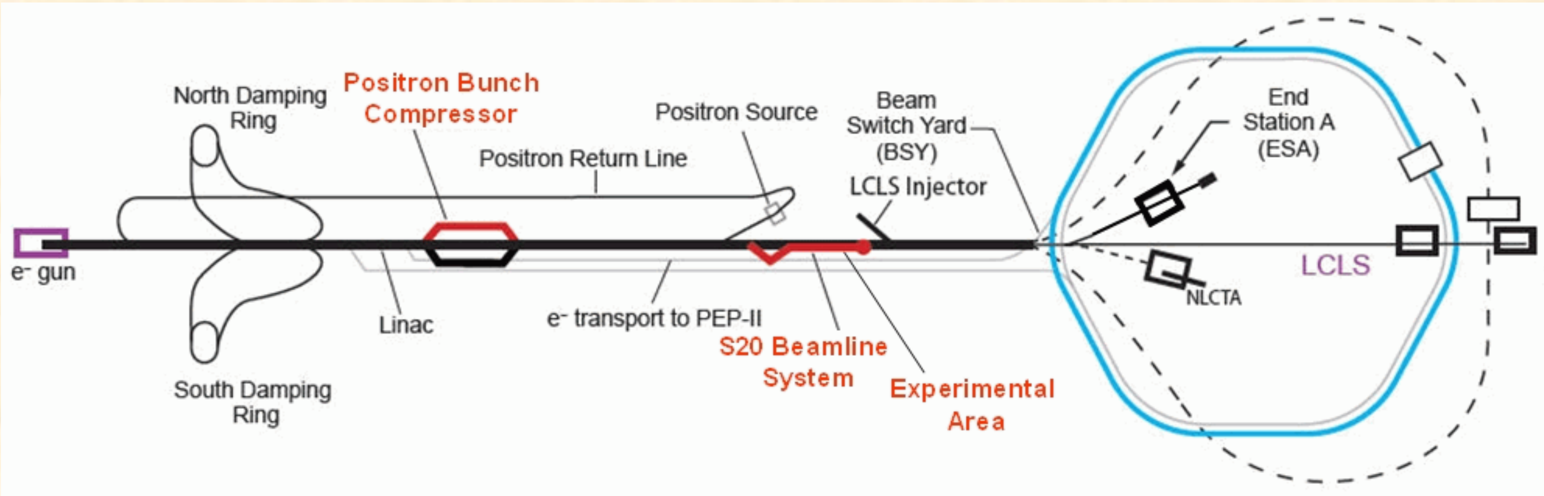
- Pulses with the same "length" but different shapes will produce different SPR spectrum.
- A device able to measure the emitted radiation at different angles is therefore needed.

# SP as longitudinal profile monitor

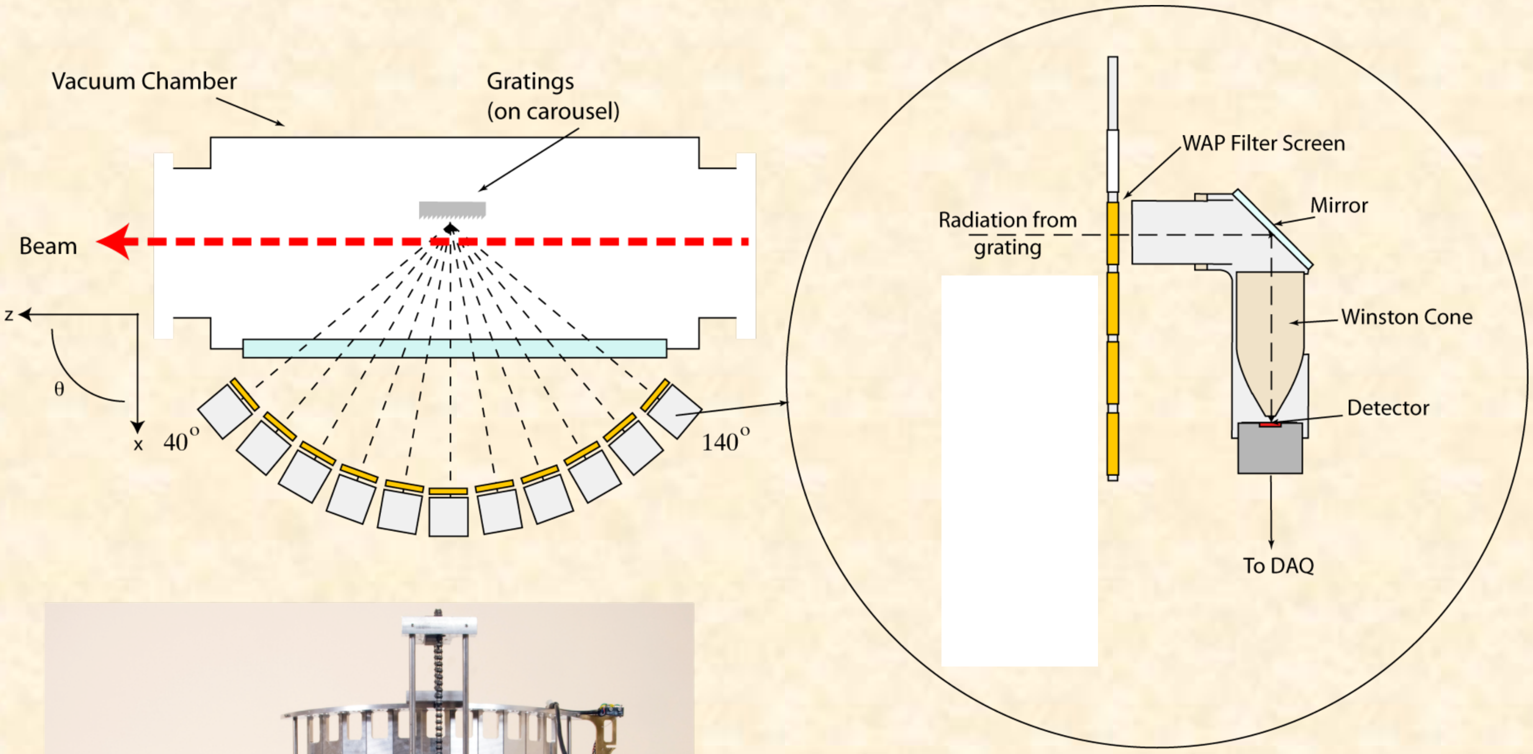
- The longitudinal dimension is the most difficult to measure in particle accelerators.
- Research has been on-going for about 20 years to use Coherent Smith-Purcell radiation as a longitudinal profile monitor.
- Work initiated in the picoseconds range by George Doucas (Oxford) at Frascati, Felix and SLAC (ESA).
- Extension to femto-seconds range more recent in collaboration with ND.

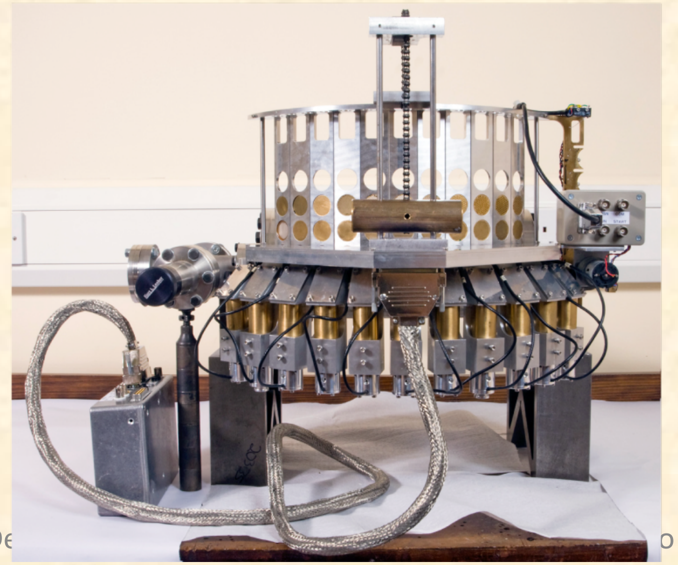
# E-203 at FACET

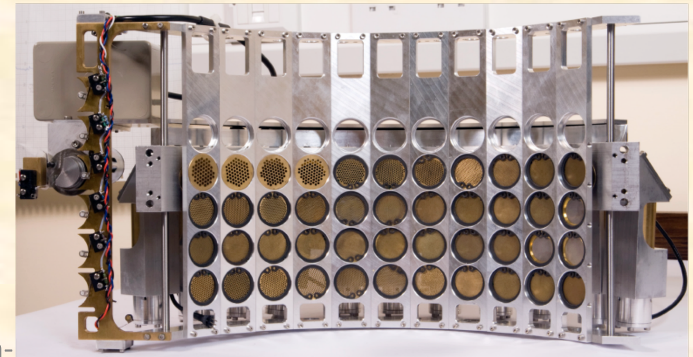
- FACET at SLAC is a test facility offering access to 100s femtoseconds long electron bunches.
- Electrons energy is 20 GeV (gamma=40000)
- Collaboration E-203 approved with rating “excellent” to develop longitudinal profile monitor in the fs range(Oxford, LAL, Los Alamos and SLAC).
- Schedule: 2 runs/year (approval must be confirmed yearly)



# Experimental apparatus (schematic)

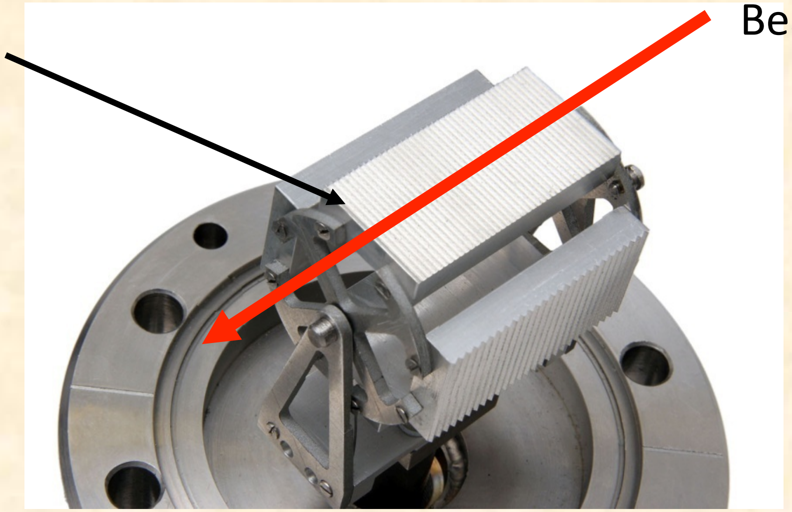




# Generation of FIR SP radiation

3 gratings (0.05, 0.25, 0.5mm)
1 blank piece of aluminium




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

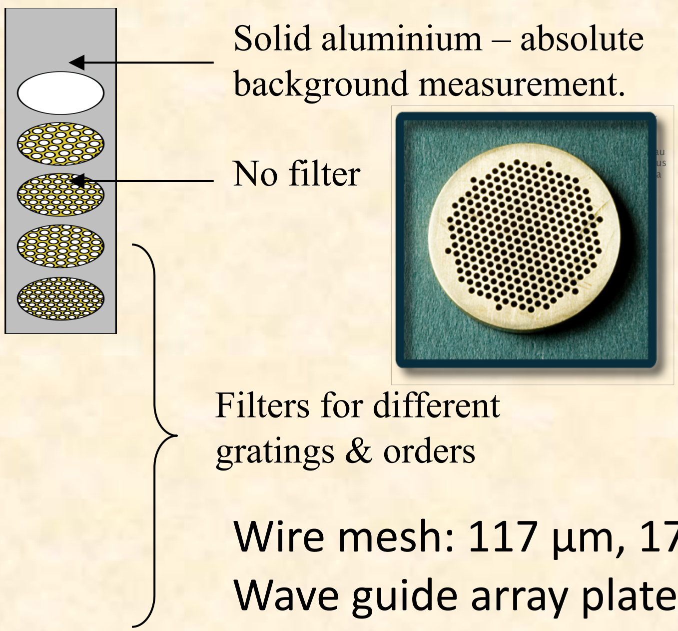
A carousel can rotate and offer three different gratings or one blank to the beam.
Rotation is controlled remotely but position is not registered

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

# Detection of FIR SP radiation (III)

Filters of many varieties remove background radiation. Suitable filters for each grating are moved in front of the 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: $175 < \lambda < 1000$;
Mylar based thin films: $20 < \lambda < 117$; $\Delta\lambda$ = few μm
Silcion based thin films : $10 < \lambda < 20$; $\Delta\lambda$ = few μm

# 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:
  - Kramers Kronig phase recovery
  - iterative “shrinkwrap” methods (used in crystallography but not necessarily suited to in 1D case)
- The Kramers Kronig method is the most popular in particle accelerators

# 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.

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

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

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

# Note on other methods to measure longitudinal profiles

- Coherent Transition Radiation:
  - A thin foil is used to trigger the production of coherent radiation.
  - This technique has a limited potential for single shot applications as all wavelengths are emitted in the same direction.
- Deflecting cavity:
  - A deflecting cavity ("crab cavity") is used to rotate the longitudinal dimension of the beam with one of its transverse dimensions and it is imaged on a screen.
  - Potential for single shot measurement but very difficult to get the phase right.
- Electro-optical sampling:
  - Crystals can be deformed by the wakefield on an electron bunch.
  - This deformation and its duration can be measured by sending a laser through the crystal.
  - Single shot measurement but limited by the crystal response time.
- COTR and Deflecting cavities are being tested concurrently with SPR at FACET.

# Recent results from E-203

- Polarisation studies:
  - Study of the polarisation of SPR shows unexpected results. This will help us refine our theoretical understanding of SPR emission.
- Beam compression studies:
  - We recorded data at various beam compression (length).
- Comparison with other longitudinal measurement techniques:
  - Data were taken during the same shift and with the same beam conditions by several groups (CTR, deflecting cavities and Smith-Purcell).

# Challenges

There are several challenges are to be addressed

- Grating shape: what is the optimal shape to get the best signal and the lowest background?
- Geometry of the apparatus: How to minimise the background coming from the accelerator and entering the detectors?
- Material: what is the best material for the gratings?
- Detectors: which detectors give us the best sensitivity? Do we need cryogenic detectors for low charge beams?
- Filters/polarizers: Those are very expensive (especially in the mid-IR). Can we find strategies where we do not need them or need fewer of them?
- Single shot: at the moment we need 6 shots to get a full spectrum (3 data and 3 backgrounds). Can we measure the background at the same time than the signal by looking elsewhere? Can we get the 3 data sets on the same shot?

=> Test stand at a conventional accelerator (SOLEIL) to address these issues.

# Applications

Knowing the length of a bunch is of general interest in all accelerators. It is especially important in the following cases:

- Plasma wakefield accelerators (laser-driven or beam-driven) where there is no easy way to predict the bunch length and it may change from turn to turn.
- Free Electron Lasers where the power emitted depends strongly on the bunch length *(Reminder: It is on one of LAL's accelerators that the first ever visible light FEL was operated).*