Bunch Length Measurements Using a Martin-Puplett Interferometer at the VUV-FEL

VUV-FEL
Vacuum-Ultraviolet Free-Electron Laser

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Coherent Radiation as a Diagnostic Tool

The linac-driven Vacuum-Ultraviolet Free Electron Laser (VUV-FEL) at DESY, Hamburg produces short pulses of intense radiation with a wavelength of about 30 nm. Since the high gain FEL process depends strongly on a high peak current of the electron bunches, it is necessary to measure and control the bunch length. For this purpose, coherent synchrotron radiation (CSR) from a bending magnet of bunch compressor BC2 is analyzed with a Martin-Puplett interferometer.

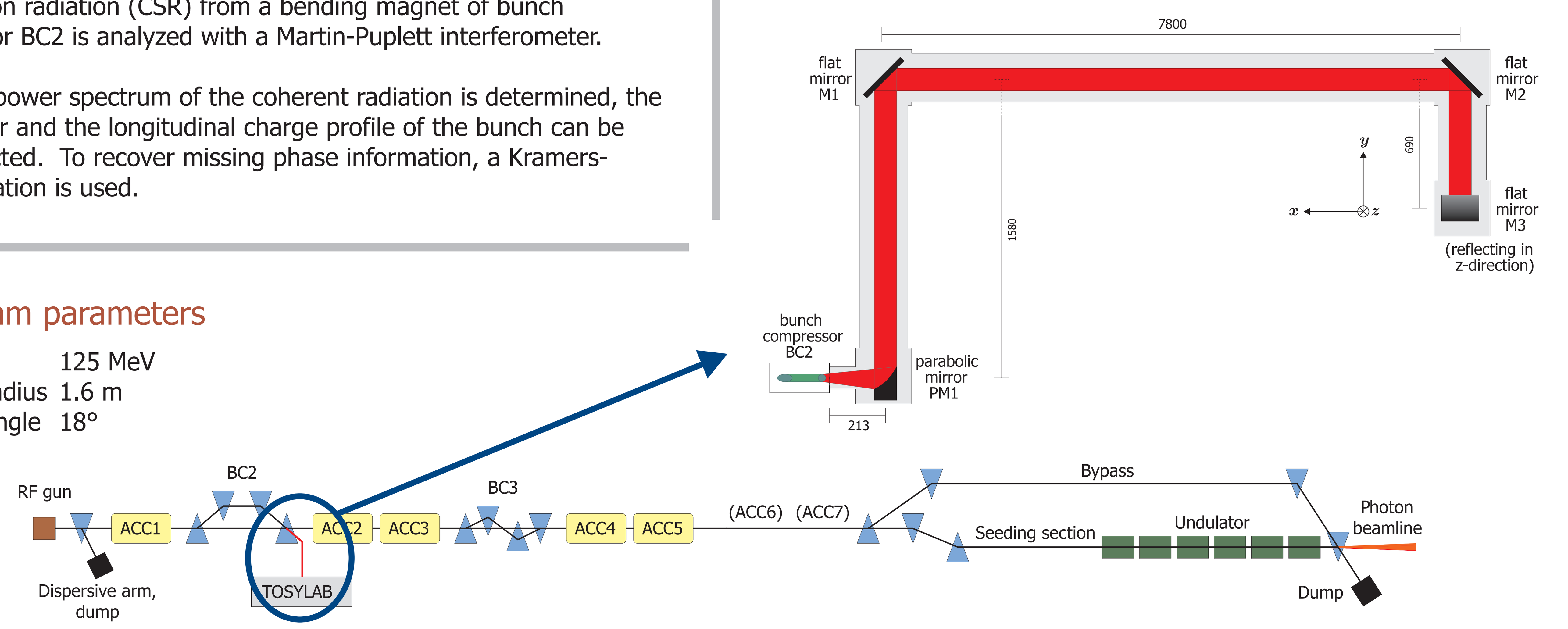
Once the power spectrum of the coherent radiation is determined, the form factor and the longitudinal charge profile of the bunch can be reconstructed. To recover missing phase information, a Kramers-Kronig relation is used.

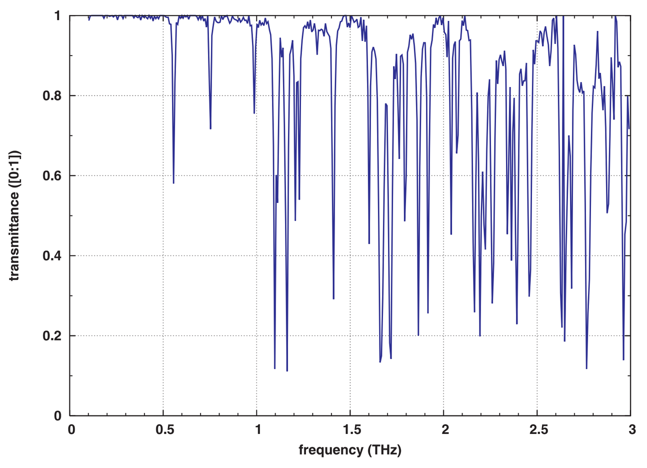
BC2 beam parameters

energy 125 MeV
bending radius 1.6 m
bending angle 18°

Experimental Setup at the VUV-FEL

Coherent synchrotron radiation from a bending dipole at bunch compressor BC2 is reflected out of the accelerator tunnel by a series of mirrors, facilitating interferometer adjustment and installation of additional filters or detectors. The beam line can be flushed with dry nitrogen to minimize absorption by water vapor.



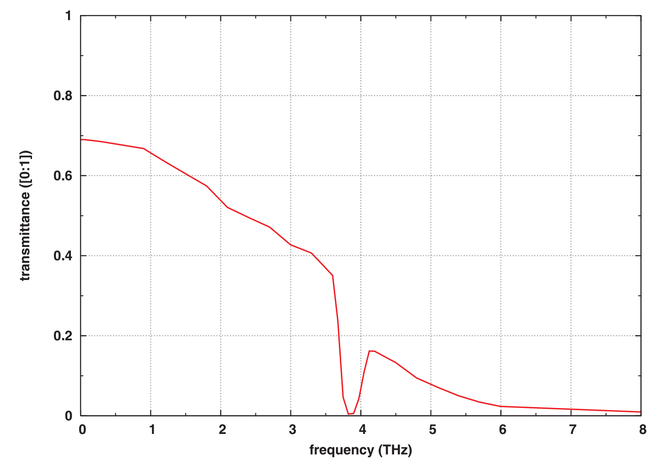


Residual water vapor (after 1 day of flushing with medium nitrogen flow)

Transfer functions

To facilitate a good reconstruction of the bunch form factor, the influence of various elements along the beam line has to be taken into account.

It takes at least 1 day to achieve sufficient suppression of water absorption effects by nitrogen purging. Therefore, preparations are underway to evacuate the transfer line. Transfer functions describing the sensitivity of the DTGS detectors and diffraction effects along the optical path are currently under investigation.

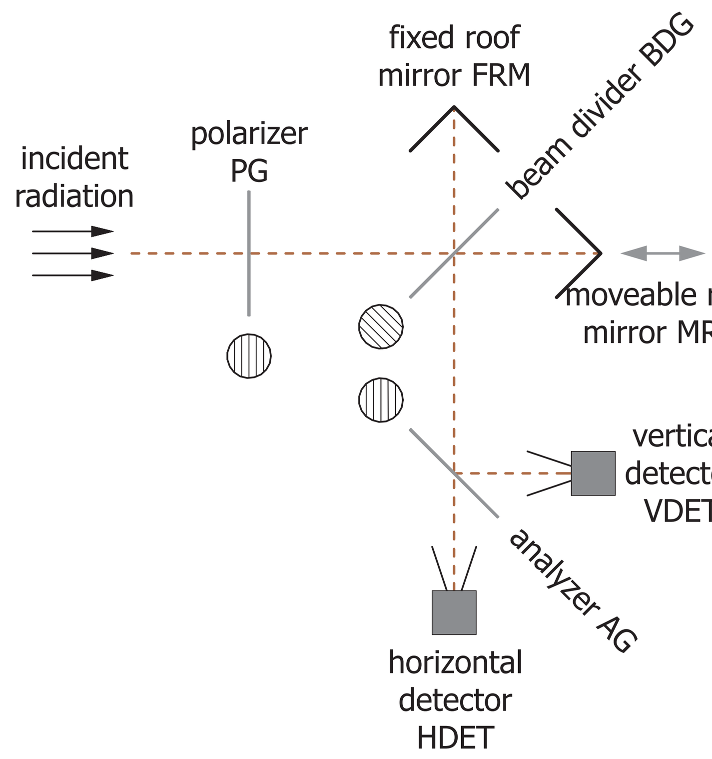


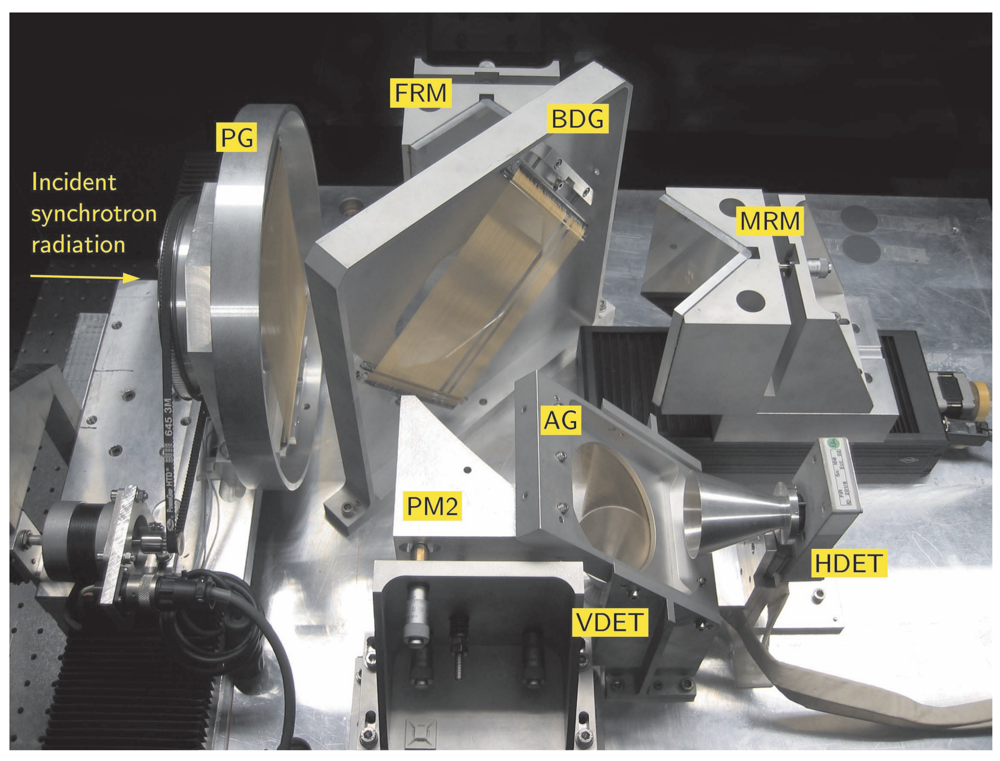
Vacuum chamber window (4.5 mm, z-cut crystalline quartz)

Interferometer Setup

The Martin-Puplett interferometer is a polarizing version of the Michelson type.

Grids of gold-coated tungsten wires (thickness 15 μm, distance 45 μm) are used as polarizers, pyroelectric DTGS detectors monitor the FIR/IR radiation intensity.
(Grids and mirrors manufactured at RWTH Aachen.)





Measurement Results

The measured spectra show no significant intensity contribution above a frequency of 2 THz, and the reconstructed bunch shape is found to be independent of the acceleration phase in the accessible range, with a full width at half maximum of about 1 ps. No evidence for the formation of a narrow charge spike with an extent below 400 fs can be established. However, critical factors of the measurement need further investigation.

Resolution limits

The **maximum length** of reconstructable bunch features is defined by the low-frequency cutoff of the vacuum chamber:

$l_{\max} \approx (275\ \mathrm{GHz})^{-1} \approx 1.8\ \mathrm{ps}$ (or 550 μm)

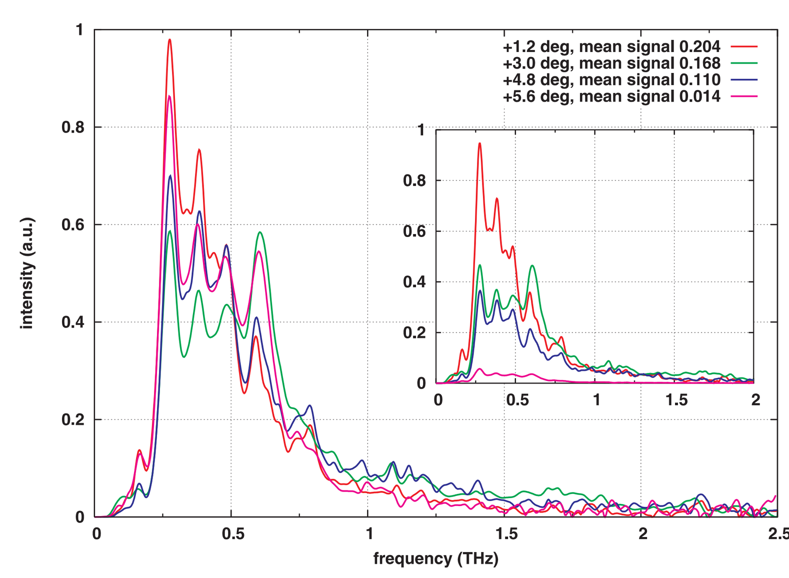
The **minimum length** of reconstructable bunch features is defined by limitations towards high frequencies, e.g. absorption by the quartz window:

$l_{\min} \approx (3.6\ \mathrm{THz})^{-1} \approx 140\ \mathrm{fs}$ (or 42 μm)

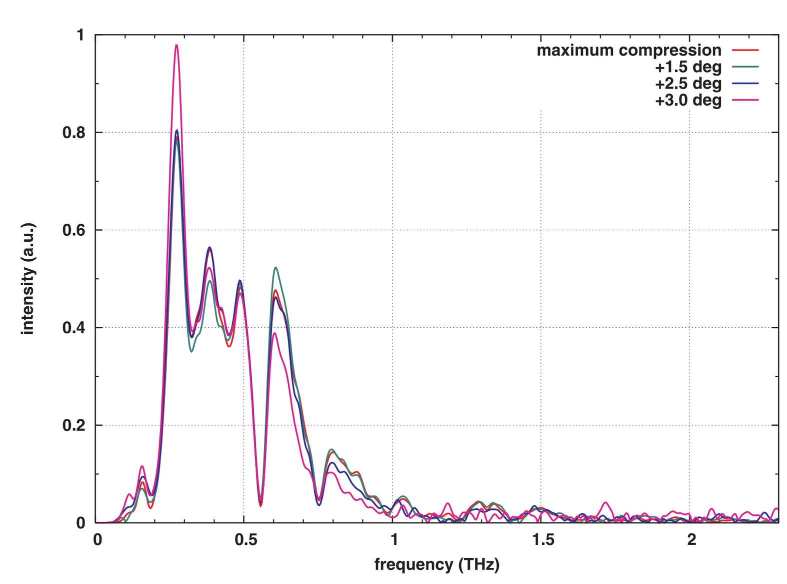
Variation of the acceleration phase

The phase of acceleration module ACC1 is the main parameter for tuning the compression of the electron beam.

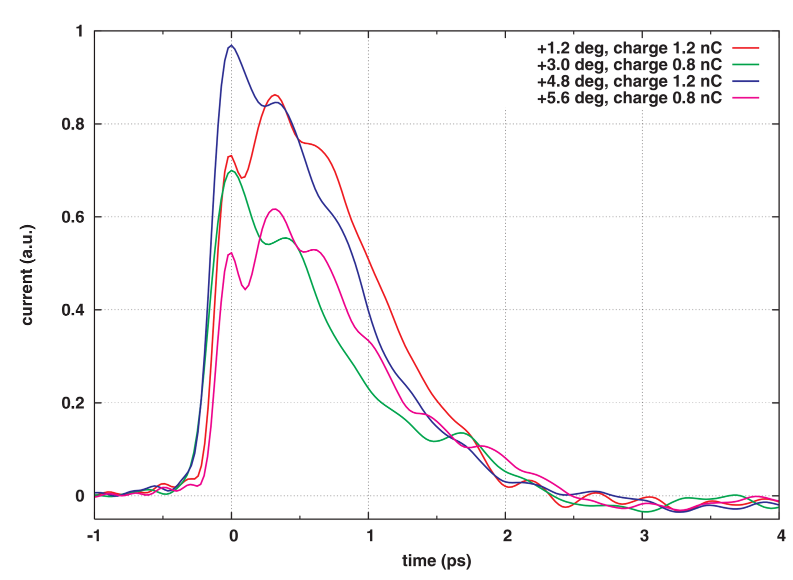
While variation of the phase causes a strong change of the total coherent radiation power, the spectral power distribution remains largely unchanged.



CSR spectra for various ACC1 phases
major graph: normalized to an equal integral
minor graph: normalized to the mean signal amplitude



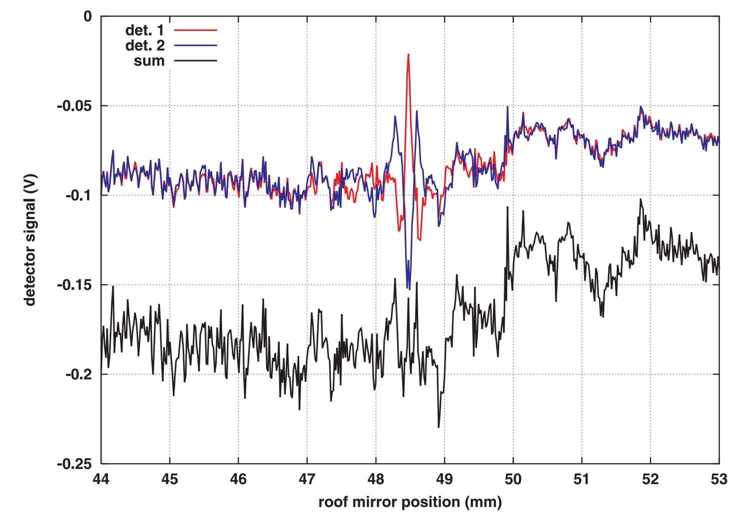
Spectra recorded under humid atmosphere



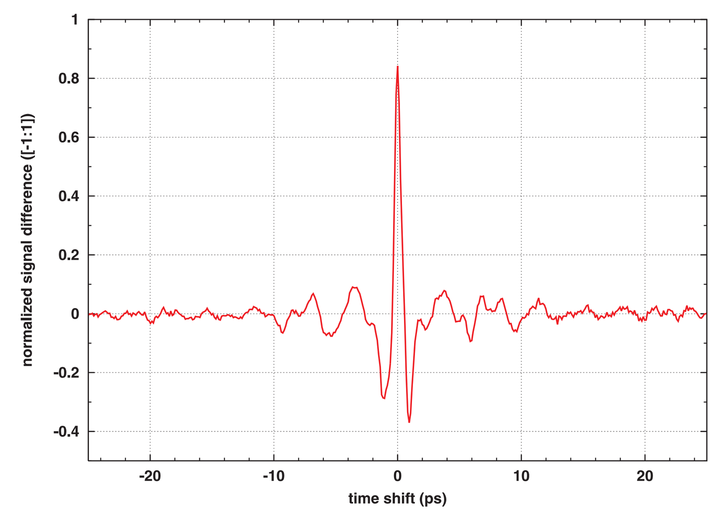
Reconstructed bunch shapes
FWHM: ~1 ps
RMS width: ~0.5 ps

From Raw Interferograms to the Bunch Shape

The Reconstruction Process

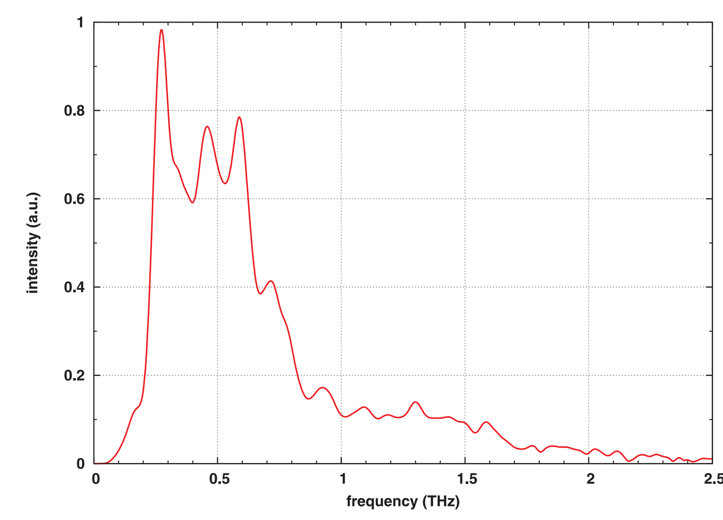


Drifts and fluctuations are visible in the **detector signal amplitudes** U_1, U_2.

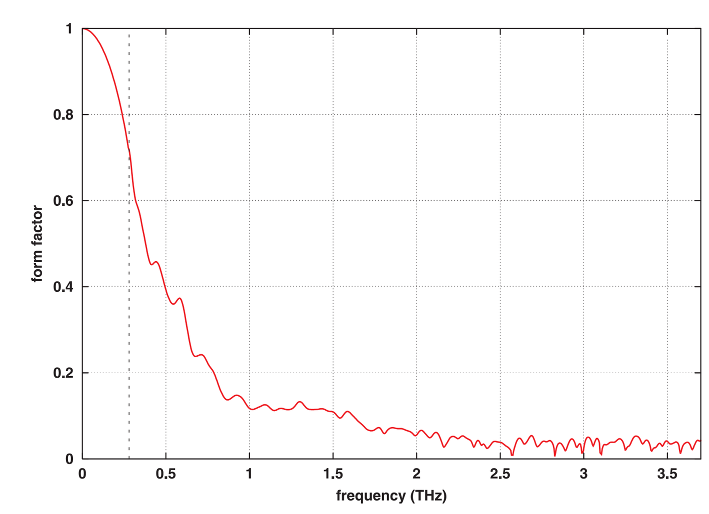


In the **difference interferogram**, the distortions are well suppressed.

$$\delta = \frac{U_1 - U_2}{U_1 + U_2}$$



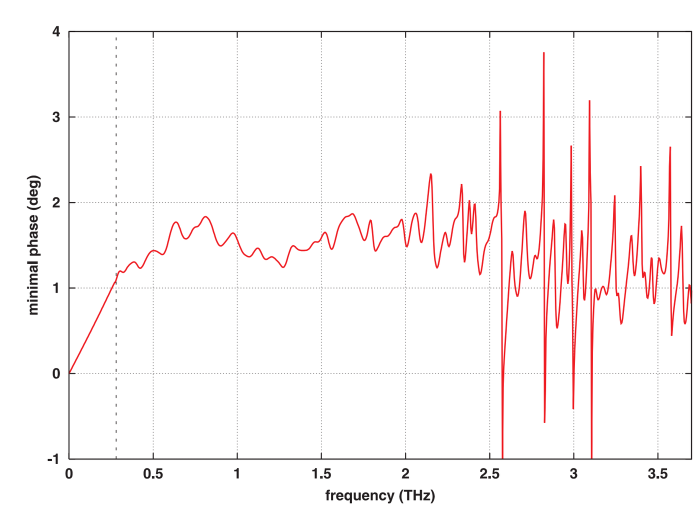
The **power spectrum** is obtained by a Fourier transform of the difference interferogram. Transfer functions for the optical elements are applied.



From the basic relation for coherent radiation

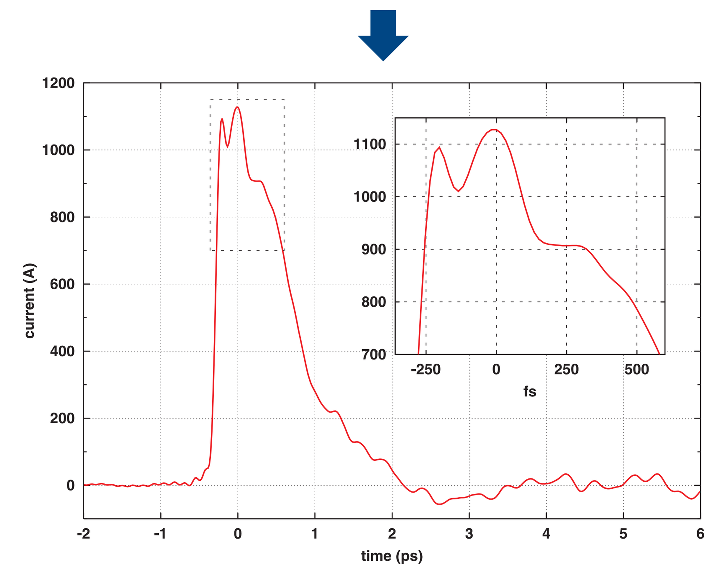
$$I(\omega) = I_1(\omega) \cdot \left(N + N(N-1)\,|F(\omega)|^2\right)$$

the **modulus of the form factor** is calculated; an asymptote is attached at low frequencies.



To recover the actual phase of the form factor, the **minimal phase** is calculated with a Kramers-Kronig relation:

$$\eta(\omega) = \frac{2\omega}{\pi} \int_0^\infty \frac{\ln \frac{|F(\omega')|}{|F(\omega)|}}{\omega^2 - \omega'^2}\, d\omega'$$



A Fourier transform of the complex form factor $F(\omega) = |F(\omega)| \exp(i\,\eta(\omega))$ yields the reconstructed **bunch shape**.