LONGITUDINAL STRUCTURE OF ELECTRON BUNCHES AT THE MICROMETER SCALE FROM SPECTROSCOPY OF COHERENT TRANSITION RADIATION

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INTRODUCTION

At the free electron laser FLASH, the electron bunches are compressed using two successive magnetic chicanes. The longitudinal energy chirp needed for this purpose is produced by operating the RF modules in front of the magnetic chicanes (ACC1 and ACC2/3) at off-crest phases. The non-linear time dependence of the RF field results in a time profile of the bunch charge with a very narrow leading spike with peak currents of the order kA which are necessary to drive the SASE process in the undulators. The high charge density in this spike leads to a complicated beam dynamics with strong contributions from collective effects like space charge and emission of coherent synchrotron radiation which critically depends on the details of the bunch compressor operation [5].

To study the longitudinal charge distribution experimentally, several techniques have been implemented at FLASH. Single shot electro-optic experiments are non-invasive but intrinsic properties of the electro-optic crystals limit their resolution to about 50 fs (15 μm) (rms) [1]. The most comprehensive and direct visualization of the bunch profile is achieved with a transverse-deflecting structure (TDS) with a time resolution of 15 - 20 fs (5-7μm) (rms) depending on machine optics [2]. Spectroscopy of coherent transition radiation (CTR) is an indirect method, not allowing for a direct reconstruction of the longitudinal profile, but has the unique feature of being capable to detect the presence of structures in the bunches down to optical wavelengths.

EXPERIMENTAL SET UP

Coherent transition radiation (CTR) is produced on an off-axis screen by single electron bunches, picked out of the bunch train by a fast kicker 10 m upstream the screen. The CTR leaves the electron beam pipe through a 0.5mm CVD diamond window offering a flat transmission from the visible to the FIR regime. The radiation is guided by a system of mirrors through a 20 m long evacuated beam pipe to the spectrometer outside the accelerator tunnel [4]. Since the expected CTR spectrum extends over several decades and the bunch profile fluctuates considerably from shot to shot, a novel broad band single-shot IR spectrometer has been developed [3]. As shown in Fig. 1, the radiation is dispersed by a sequence of reflecting blazed gratings and detected by pyroelectric line arrays with fast readout. The special geometry and blaze angle of the gratings allows to use them as filters (separating the consecutive grating stages) and dispersive elements simultaneously, each grating covers a spectral range of about ± 0.4 times the central wavelength with high efficiency. With two consecutive stages and three selectable grating sets, the wavelength range from $3\,\mu\mathrm{m}$ to $65\,\mu\mathrm{m}$ can be explored. The pyroelectric line detectors have a detection threshold of about 200 pJ and a parallel read-out with 1 MHz clock rate.

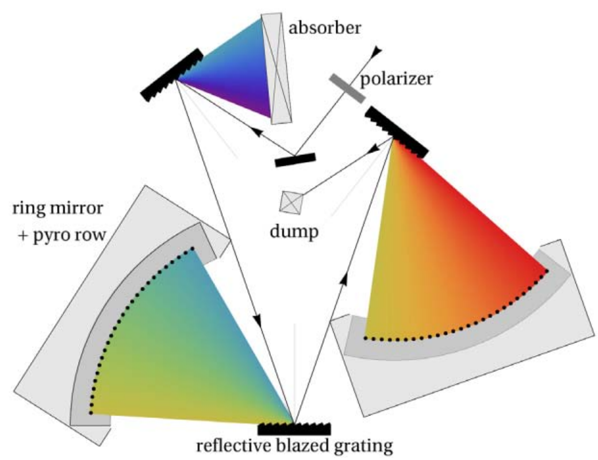

Figure 1: Schematic layout of the two stage single shot spectrometer.

EXPERIMENTAL DATA

Fig. 2 shows the average spectrum of coherent transition radiation from a single bunch in the range of $3\mu\mathrm{m} < \lambda < 65\mu\mathrm{m}$ under normal FEL operation conditions of the linac. The bunch charge was 0.8 nC. The spectrum is rather flat down to about $10\,\mu$m with average spectral intensities of $100\,\mathrm{nJ}/\mu\mathrm{m}$ and extends with significant intensity down to $3\,\mu$m, the shortest wavelength recorded here. The spectrum has been corrected for the transmission function of the beam-line and the windows as well as for the response function of the detectors as far as it is presently known to us. Below $35\,\mu\mathrm{m}$, the detector response still has considerable uncertainties due to lack of calibration data, especially the pronounced structure around $24\,\mu\mathrm{m}$ is most likely due to a sensitivity enhancement of the pyroelectric detectors. Despite the fact that these unresolved calibration problems prevent a detailed analysis of the spectral structures, the general shape, the

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extension to short wavelengths and the dependence of the intensity on machine parameters reveals some information about the structure of the bunches on a scale which is not accessible to other more direct diagnostic techniques.

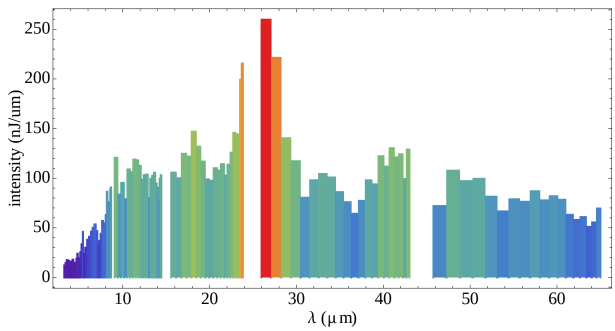

Figure 2: Intensity of coherent transition radiation from electron bunches with 0.8 nC charge for normal FEL-mode operation. The spectrum was recorded with 6 different grating stages and averaged over 300 shots.

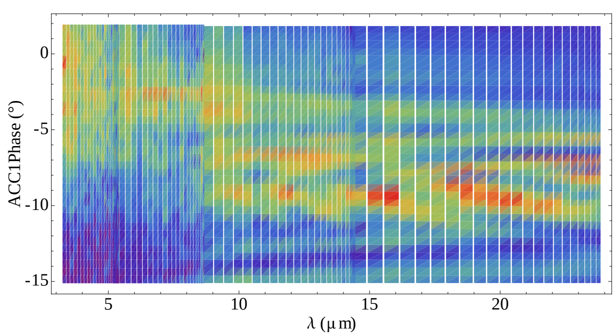

Figure 3: Normalized spectral intensity for 3 μm $< \lambda <$ 24 μm as function of the off - crest phase of the first acceleration module. Each wavelength bin is normalized to its maximum value individually. A typical FEL operation point is at $-4°$ to $-6°$ off-crest.

The most important parameter influencing the forming and the structure of the leading current spike is the off-crest phase of ACC1, the RF module upstream the first bunch compressor. As shown in Fig. 3, the spectral intensity varies considerably as function of the ACC1 phase in a highly complex way with pronounced structures changing on the a scale of a fraction of a degree. It has been verified that these structures are not due to machine fluctuations but can be reproduced in recurring measurements. As a very general feature, there seem to be two distinct regimes of wavelengths with completely different dependence on the compression phase. Wavelengths above about $10\,\mu$m occur predominantly for compression phases around $-5°$to$-10°$ off-crest, they result from the leading current spike which is produced in a delicate co-operation of the two compressor stages. For too small off-crest phase, no sharp structures are produced, for phases below $-8°$ the

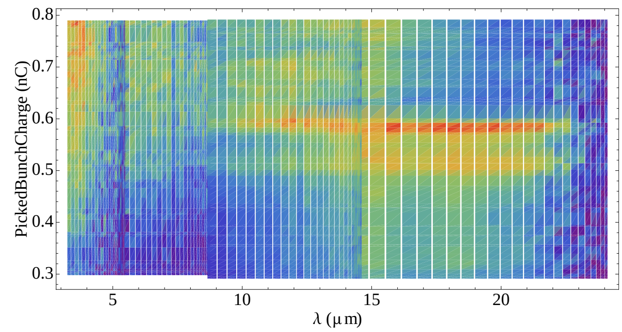

Figure 4: Normalized spectral intensity for 3 μm $< \lambda <$ 24 μm as function of the bunch charge. Each wavelength bin is normalized to its maximum value individually. The compressors were set to normal FEL operation mode.

compression of the first stage is too high and collective effects between the compressors and in BC3 disrupt the bunch head [2]. In contrast to this wavelength regime, radiation below $10\,\mu$m has a different dependencies on the ACC1 phase, there are no distinct structures and maximum intensity is observed for on-crest operation of ACC1. A similar distinction in wavelength regimes is found when the charge of the electron bunches is varied between $0.4\,$nC and $0.8\,$nC (Fig. 4). For wavelengths above $15\,\mu$m, the radiation exhibits a very pronounced double-maximum between $0.5\,$nC and $0.6\,$nC, for larger bunch charges the intensity is strongly reduced. In the short wavelength regime, a component becomes visible which monotonically increases with increasing bunch charge.

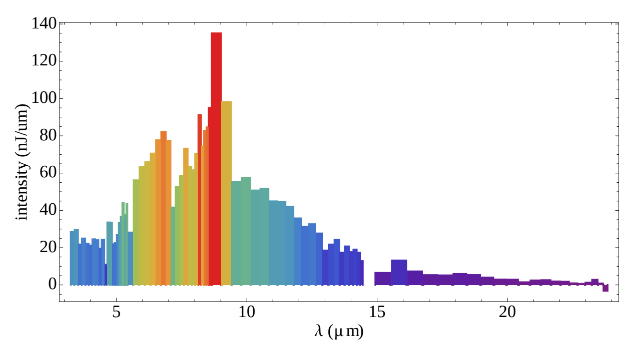

Figure 5: Intensity of coherent transition radiation from electron bunches with 0.8 nC charge for both bunch compressors set to on-crest operation.

Looking into this spectral range in more detail, it was found that the electron bunches emit coherent radiation at very short wavelengths even and especially when both bunch compressors are set to on-crest operation. Fig. 5 shows this "on-crest spectrum", maximum emission occurs at about $8\,\mu$m wavelength and with peak intensities around $100\,$nJ/μm. The radiation vanishes completely if *one* of the

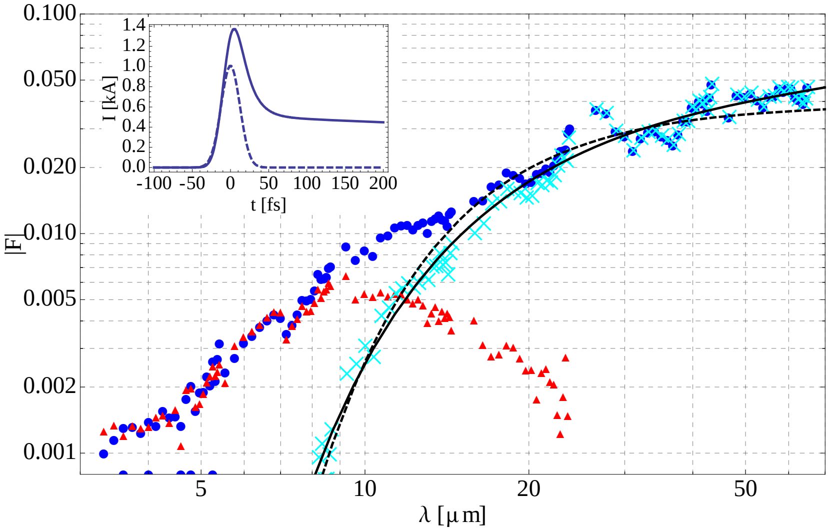

Figure 6: Modulus of the form factor of the electron bunches derived from the CTR spectra. Circles : FEL operation, triangles : on-crest operation, crosses: difference . Solid line : fit with asymmetric profile, dashed : fit with Gaussian profile. The fitted current profiles are shown as inset.

two magnetic chicanes is switched off. Very recently, we used a commercial InGaAs spectrometer to verify that this coherent radiation extends to almost the visible wavelength range, see Fig. 7.

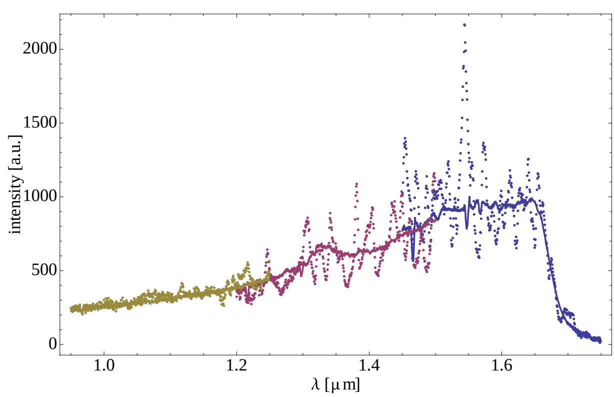

Figure 7: Single shot (dots) and averaged (line) CTR spectrum between 0.95 μm and 1.7 μm measured with a commercial InGaAs spectrograph. The response of the detector is basically flat between 1.0 μm and 1.7 μm.

DISCUSSION

The most astonishing finding is the pronounced emission of coherent radiation at short wavelengths for uncompressed electron bunches passing the magnetic chicanes. From TDS measurements it is known, that under these conditions the bunches are about $10\,\mathrm{ps}$ long with no visible short scale substructure. The nevertheless emitted radiation suggests that the passage of the magnetic chicanes introduces micro-bunching structures with characteristic length scales of a few μm. Comparing the modulus of the form factors for normal FEL operation and on-crest operation (Fig. 6) the two contributions can be separated and subtracted. As a first analysis of the form factor of the current spike, we fitted a simple model for a asymmetric charge distribution as well as an (unrealistic) Gaussian shape to this form factor difference (Fig. 6, inset). In both cases the length of the spike can be consistently determined to be of the order 13-15 fs (rms). The resulting current of 1.4 kA is in good agreement with simulations. A more detailed analysis will follow after a more rigorous calibration of the spectrometer response. An analysis of the microbunching structure in terms of a conversion into the time domain would be entirely model dependent since the phase of the form factor is not known. From the fact that the modulus vanishes for long wavelengths it can nevertheless be concluded that the radiation cannot be produced by a singular, very short spike but must be due to an extended ”modulation” in the charge distribution.

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