COHERENT MICRO-BUNCHING RADIATION FROM ELECTRON BUNCHES AT FLASH IN THE 10 MICROMETER WAVELENGTH RANGE

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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 [1].
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) [2]. 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 [3]. 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. This is of special importance to detect possible substructures, or "microbunching", resulting from amplification of parasitic density and energy modulations [4, 5].

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 0.5 mm diamond window offering a flat transmission from the visible to the far infrared regime. The radiation is guided by a system of focussing mirrors through a 20 m long evacuated beam pipe to the spectrometer outside the accelerator tunnel [6]. Since the expected CTR spectrum extends over several decades and the bunch profile fluctuates considerably from shot to shot, a broad band single-shot IR spectrometer has been developed [7]. 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.

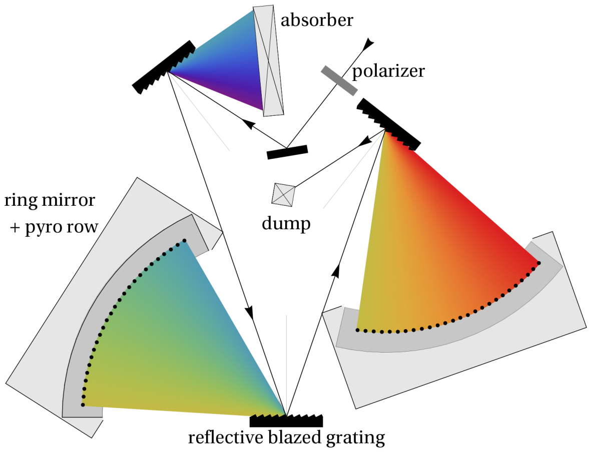

Figure 1: Schematic layout of the two stage single shot spectrometer.

EXPERIMENTAL DATA

Fig. 2 shows the average spectrum of coherent transition radiation from a single bunch in the range of 3 μm$<\lambda<$65 μm under normal FEL operation conditions of the linac. The bunch charge was 0.8 nC. The spectrum is rather flat down to about 10 μm with average spectral intensities of 100 nJ/μm and extends with significant intensity down to 3 μm, the shortest wavelength recorded here. The spectrum has been corrected for the transmission function of the beam-line, the diamond window, the polarizer, the grating efficiency 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 between $20\,\mu\mathrm{m}$

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and $40\,\mu\mathrm{m}$ are 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 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.

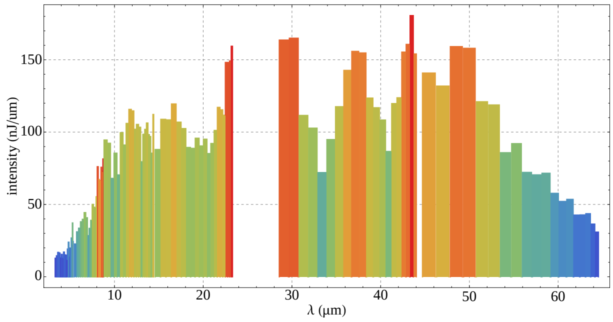

Figure 2: Intensity of coherent transition radiation from electron bunches with 0.8 nC charge for normal FEL-mode operation. The spectrum was recorded with 6 different grating stages and averaged over 300 shots.

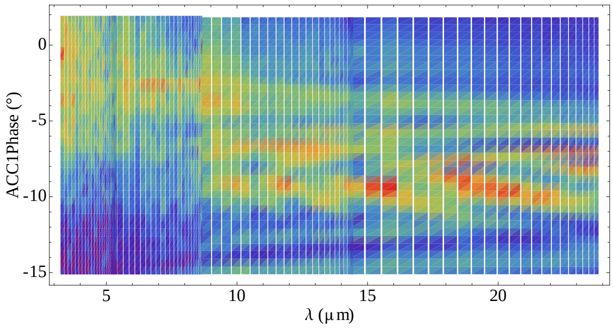

Figure 3: Normalized spectral intensity for $3\,\mu\mathrm{m} < \lambda < 24\,\mu\mathrm{m}$ as function of the off-crest phase of the first acceleration module. Each wavelength bin is normalized to its maximum value individually. A typical FEL operation point is at $-4°$ to $-6°$ off-crest.

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 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 dependencies on the off-crest phase. Wavelengths above about $10\,\mu\mathrm{m}$ occur predominantly for compression phases around $-5\,°$

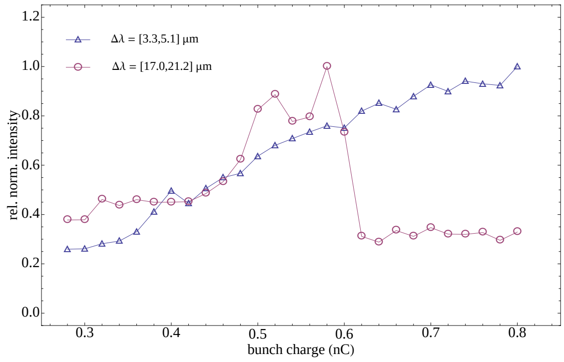

Figure 4: Normalized spectral intensity for two wavelength bands as function of the bunch charge. The band $3.3 - 5.1\,\mu\mathrm{m}$ is dominated by microstructures while the band $17 - 21\,\mu\mathrm{m}$ results predominantely from the leading current spike of the compressed bunches.

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 an off-crest phase, no sharp structures are produced, for phases below $-8\,°$ the compression of the first stage is too high and collective effects between the compressors and in BC3 disrupt the bunch head [3]. In contrast to this wavelength regime, radiation below $10\,\mu\mathrm{m}$ has a different dependence 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 (Fig. 4). For wavelengths above $15\,\mu\mathrm{m}$, the radiation exhibits a very pronounced maximum between $0.5\,\mathrm{nC}$ and $0.6\,\mathrm{nC}$, for larger bunch charges the intensity is strongly reduced due to space charge effects preventing the formation of a well defined leading spike. In the wavelength regime around $5\,\mu\mathrm{m}$, the intensity increases monotonically with the bunch charge.

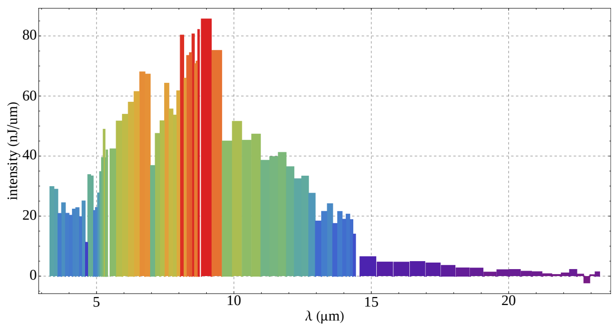

Figure 5: Intensity of coherent transition radiation from electron bunches with 0.8 nC charge for both bunch compressors set to on-crest operation.

Looking into this spectral range in more detail, it was found that the electron bunches emit coherent radiation

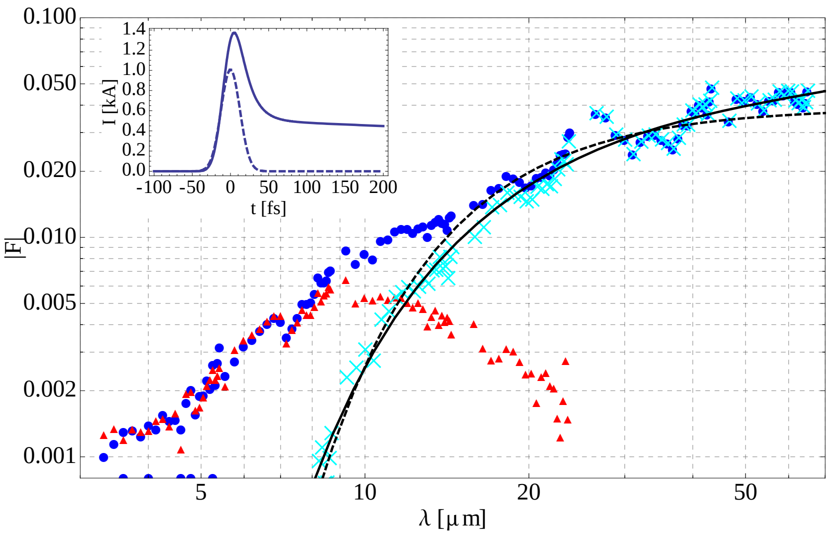

Figure 6: Modulus of the form factor of the electron bunches derived from the CTR spectra. Circles : FEL operation, triangles : on-crest operation, crosses: difference . Solid line : fit with asymmetric profile, dashed : fit with Gaussian profile. The fitted current profiles are shown as inset.

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 $8\,\mu\mathrm{m}$ wavelength and with peak intensities around 80 nJ/μm. The radiation vanishes completely if *one* of the two magnetic chicanes is switched off. The difference of both types of spectra (compressed and un-compressed bunches) becomes most clearly visible looking at the form factor of the electron bunches derived from the CTR spectra (fig. 6). In FEL operation mode (compressed bunches), the form factor at wavelengths above $10\,\mu\mathrm{m}$ shows the expected behavior of a short current spike with about 15 fs RMS. For uncompressed bunches (RF phases on-crest), the non-vanishing short wavelengt component indicates the presence of substructure (microbunching) at the 0.5% level.

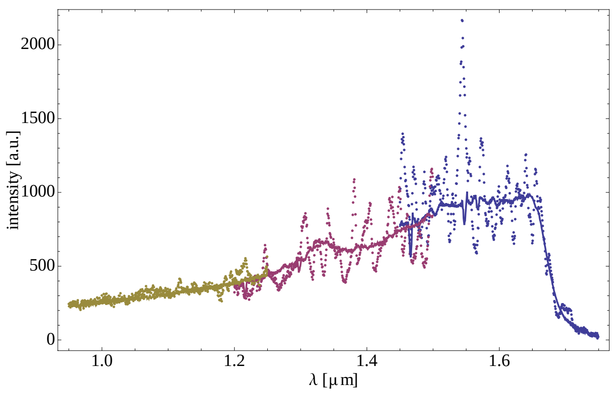

Figure 7: Single shot (dots) and averaged (line) CTR spectrum between 0.95 μm and 1.7 μm measured with a commercial InGaAs spectrograph. The response of the detector is basically flat between 1.0 μm and 1.7 μm.

Very recently, we used a commercial InGaAs spectrometer to verify that this coherent radiation extends to almost the visible wavelength range, see Fig. 7. The single shot spectra typically consist of a smooth background with strongly fluctuating narrow spectral lines superimposed. The measured width of these spectral lines is determined by the resolution of the spectrometer.

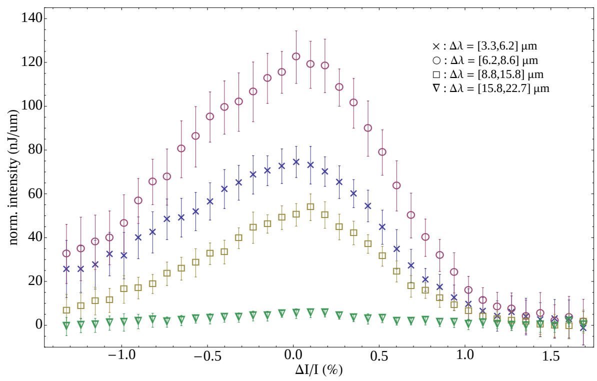

Figure 8: Intensity of coherent transition radiation in on-crest mode in different wavelength bands as function of the relative deviation of the gun solenoid current from the normal operation point. The radiation intensity is normalized to constant bunch charge.

The intensity of the microbunching radiation is strongly affected by the parameters of the photo injector gun, especially by the focal length of the coaxial solenoid field (fig. 8). From measurements and simulations it is well known, that the solenoid field is a crucial parameter for the emittance of the beam [8]. In fig. 9, the spectral intensity in the wavelength regime $6.2 - 8.6\,\mu\mathrm{m}$ is shown as function of the beam emittance expected from ASTRA simulations

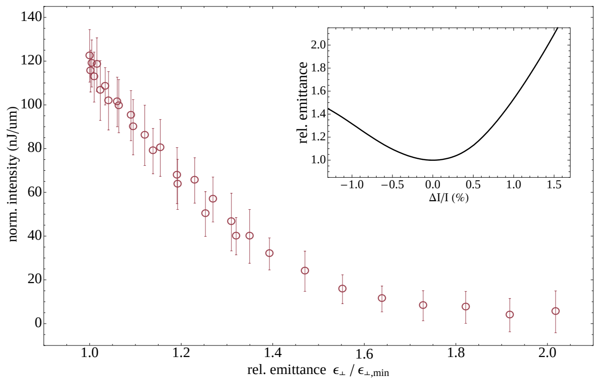

Figure 9: Intensity of coherent transition radiation for $6.2 < \lambda < 8.6\,\mu\mathrm{m}$ as function of the expected beam emittance. The emittance as function of the solenoid current was determined by ASTRA simulations [8] as shown in the plot inset.

for the corresponding setting of the solenoid current. The radiation intensity shows an unambiguous correlation with the emittance and it increases strongly with decreasing emittance without any sign of saturation.

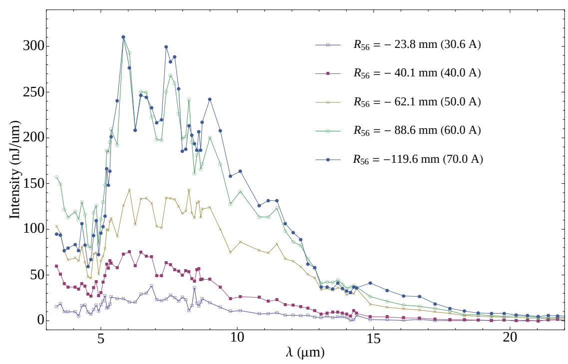

Figure 10: Intensity of coherent transition radiation in on-crest mode of both bunch compressors. The first magnetic chicane is set to nominal operation conditions while the dipol strength of the second chicane is varied.

Fig. 10 finally shows the spectra of the coherent microbunching radiation for different settings of the dipole strength in the second bunch compressor resulting in different R_{56} values of the magnetic chicane. The first bunch compressor was kept at the nominal operation point ($R_{56} = -180$ mm). Increasing the dipole current from 30 A to 60 A forces the intensity up by about a factor of 10 without notably changing the spectral composition. At 70 A, the physical limit of the magentic chicane is reached. Models describing the appearance of microbunching resulting from amplification of parasitic density modulations driven by CSR and space charge effects [4, 5] predict such a behaviour for reasonable parameter settings. A detailed comparison with the model predictions is yet not meaningful since simplifications and constraints are used which are not fully applicable in this wavelength regime. A more detailed analysis based on model calculations and rigorous simulations is under way.

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 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. The dependence of the intensity and spectral shape of the microbunching radiation on various machine parameters and beam settings has been studied. It could be shown, that a small beam emittance and a large longitudinal dispersion in the second magnetic chicane are crucial for the formation of the micro structures in the beam.

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