A MULTICHANNEL WAVELENGTH RESOLVED COHERENT RADIATION DETECTOR FOR BUNCH PROFILE MONITORING AT FLASH

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INTRODUCTION

The electron bunches in high-gain free-electron lasers are longitudinally compressed to achieve peak currents in the kA range which are necessary to drive the FEL gain process in the undulator magnets. Due to their high charge density, space charge forces and coherent synchrotron radiation have a profound influence on the time profile and internal energy distribution of the compressed bunches. The resulting complex longitudinal charge distribution can be studied using a transverse deflecting microwave structure (TDS) converting the temporal charge profile into a transverse streak on a view screen by a rapidly varying electromagnetic field. Frequency-domain techniques provide a complementary access to the femtosecond regime. The spectral intensity of the coherent radiation emitted by a bunch is determined by the spectrum of a single particle and the form factor of the bunch squared. The form factor is given by the Fourier transform of the normalized spatial density distribution of the particles. A measurement of the coherent radiation spectrum thus yields the absolute magnitude of the form factor as a function of wavelength and bares detailed information about the bunch structure if a sufficiently wide wavelength range is covered. At DESY, a novel type broad-band spectrometer with single-shot capability [1] has been developed. The present version has two sets of five consecutive gratings, which can be interchanged by remote control, either the far-infrared wavelength range from 45 μm to 430 μm or the mid-infrared range from 5.1 μm to 43.5 μm is covered. The spectral intensity is recorded simultaneously in 120 wavelength bins. In this paper, we describe the design of the spectrometer, the detectors, amplifiers and readout electronics. Test measurements at a coherent transition radiation (CTR) beamline are presented which were carried out on bunches whose time profile was determined simultaneously using the transverse deflecting microwave structure TDS.

DESIGN AND REALIZATION OF THE SPECTROMETER

Multiple Grating Configuration

Coherent radiation from short electron bunches extends over a wide range in wavelength, from a few micrometers up to about 1 mm, thus a large spectral range has to be covered simultaneously. In our device we make use of the fact that reflective blazed gratings of appropriate geometry can be used as dispersive elements and wavelength filters simultaneously. In a well defined wavelength range, the radiation is dispersed with very high efficiency to the first dispersive order while longer wavelengths are totally reflected in zero order as from a mirror (Fig. 1). Using this effect, the radiation can be distributed in distinct wavelength bands with high efficiency over several grating stages and thus analysed simultaneously.

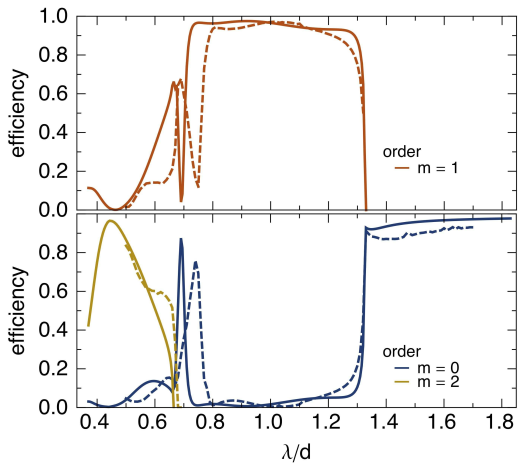

Figure 1: Efficiency curves of a gold-plated reflection grating for radiation polarized perpendicular to the grooves, computed with the codes *PCGrate* (solid curves) and *GSolver* (dashed curves). Top graph: first-order diffraction $m = 1$. Bottom graph: diffraction orders $m = 0$ and $m = 2$.

Our spectrometer is equipped with five consecutive reflection gratings, G0 to G4 (see Fig. 2). Each grating exists in two variants, for the mid-infrared (MIR) and the far-infrared (FIR) regime. The MIR and FIR gratings are mounted on top of each other in vertical translation stages. Between the gratings is either a mirror (G1, G2, G3) or a pyroelectric detector (G0, G4) for alignment purposes. The incident radiation is passed through a polarization filter (HDPE thin film THz polarizer by TYDEX) to select the polarization component perpendicular to the grooves of the gratings, and is then directed towards grating G0 which acts as a low-pass filter: the high-frequency part of the radiation is dispersed and guided to an absorber, while the low-frequency part is specularly reflected by G0 and sent to grating G1. This is the first grating stage of the spec-

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trometer. The subsequent gratings work similarly dispersing consecutive wavelength intervals.

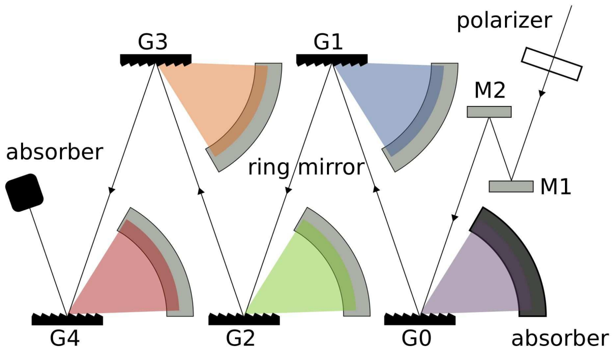

Figure 2: Principle of the staged spectrometer equipped with five reflection gratings. Explanations are given in the text. To avoid FIR absorption in humid air, the spectrometer is mounted in a vacuum vessel (not shown).

Each grating spreads the first-order dispersed radiation over an angular range from $27°$ to $80°$. To focus the light onto a cicular arc passing through the 30-channel detector array, a ring-shaped parabolic mirror has been designed with an angular acceptance of $60°$. The grating is located in the center of the ring mirror which deflects the radiation by $90°$ and has a focal length of $f = p = 150$ mm.

Detector Array

The first-order diffracted radiation is recorded in a specially designed detector array equipped with 30 pyroelectric detectors which are arranged on a circular arc covering $57°$.

A special pyroelectric detector has been developed by an industrial company (InfraTec) according to our specification. This sensor possesses sufficient sensitivity for the application in a coherent transition radiation spectrometer and has a fast thermal response. A special combination of crystal thickness and top and front electrodes greatly reduces internal reflections which are the origin of the strong wavelength-dependent efficieny oscillations observed in conventional pyroelectric detectors.

The pyroelectric detector is connected to a charge-sensitive preamplifier (Cremat CR110). This combination has been calibrated [2] with picosecond infrared pulses of selectable wavelength at the infrared FEL user facility FELIX [3]. While the wavelength dependence of the sensitivity has been determined on the few percent level, the absolute calibration is uncertain by at least 50%.

The complete electronics diagram is depicted in Fig. 3 where also the pulse shape at various stages can be seen. The shaped signals are digitized with 120 parallel ADCs with 9 MHz clock rate, 14 bit resolution and 50 MHz analog bandwidth. The electronics used at the THz beamline (see below) is equipped with long integrating pre-amps and shaping to 4 μs which is sufficient since only one bunch per bunch train is kicked to the TR screen. A fast version of the electronics with 250 ns shaping time will be used for an identical spectrometer inside the FLASH tunnel which is presently being commissioned.

Response Function

The computed overall response function of the multichannel spectrometer as installed at the CTR beamline is shown in Fig. 4. The output signal as a function of wavelength depends critically on the emission characteristics of the radiation source and is different for transition and synchrotron radiation. A dedicated Mathematica code, *THz-Transport*, was developed to generate coherent transition radiation by an infinitely short electron bunch (longitudinal form factor $F_\ell \equiv 1$) with an rms radius of $\sigma_r = 200\,\mu$m and a charge of 1 nC. The same code was applied to transport the radiation through the CTR beamline, taking near-field diffraction effects into account. detailed description of the numerical procedures is found in Ref. [4]. Additionally, the following wavelength-dependent effects were taken into consideration: transmission of polarization filter, grating efficiencies, pyroelectric detector sensitivity, and wavelength acceptance of the sensors as a function of grating constant and sensor number.

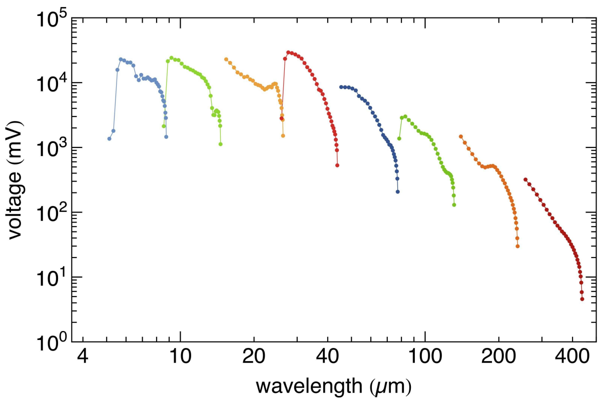

Figure 4: Computed overall response function of the multichannel spectrometer as installed at the CTR beamline at FLASH. The expected voltage in the ADCs is plotted as a function of wavelength. For details see text. The enhancement around 30 μm is due to an enhanced pyroelectric detector sensitivity in this range.

COMMISSIONING OF THE SPECTROMETER AND BENCHMARKING RESULTS

The instrument has been tested at the soft X-ray FEL facility FLASH, a detailed description of the design criteria and the layout of this accelerator can be found in Refs. [5, 6].

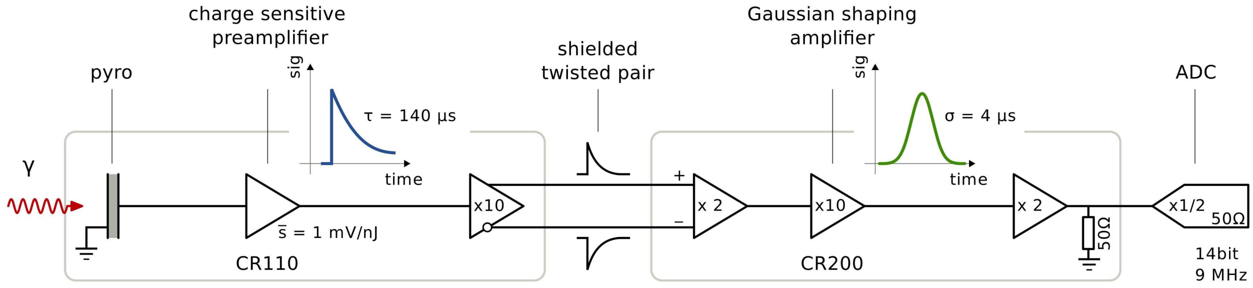

Figure 3: Electronics diagram. The preamplifier and the twisted-pair line driver amplifier are mounted on the electronics board inside the vacuum vessel. Line reciever, Gaussian shaping amplifier and ADC are located outside the the vacuum vessel.

To facilitate frequency domain experiments at FLASH, an ultra-broadband beamline for coherent transition radiation was built which transports electromagnetic radiation ranging from millimeter waves down to the optical regime and permits spectroscopic measurements in a laboratory outside the accelerator tunnel [4]. The radiation is produced on an off-axis CTR screen by single electron bunches that are picked out of the bunch train by a fast kicker magnet. The CTR leaves the electron beam vacuum chamber through a 0.5 mm thick diamond window featuring high transmission over a large wavelength range, from visible light to the far infrared (THz) regime. The radiation is guided through a 20 m long evacuated beam line equipped with 6 focusing mirrors to a vacuum vessel outside the accelerator tunnel which houses the spectrometer.

Test Measurements with Bunches of Known Shape

To verify the performance of the spectrometer, test measurements were carried out with bunches of different length and structure. The longitudinal profiles of the bunches were determined with high accuracy using the transverse deflecting microwave structure TDS mounted in front of the undulator. Three different bunch shapes with total lengths between 100 and $400\,\mu$m were realized by a proper choice of the RF phases in the acceleration modules ACC2 and ACC3. To eliminate systematic errors and to reduce statistical fluctuations, 40 bunches were recorded with the TDS setup for each shape. Two different projections of the longitudinal phase space were applied to minimize systematic errors in the determination of the longitudinal charge distribution.

The averaged longitudinal profiles are shown in Fig. 5. The form factors were computed by Fourier transformation of the averaged longitudinal profiles. They are shown as solid curves in Fig. 6.

The rms time resolution of the TDS system depended on the total bunch length to be covered and varied between $\sigma_t = 27$ fs for the shortest bunches and $\sigma_t = 43$ fs for the longest ones. The finite time resolution of the TDS system leads to a suppression of the formfactor towards small wavelengths. The suppression factor is $\exp(-\lambda_{\rm cut}^2/\lambda^2)$

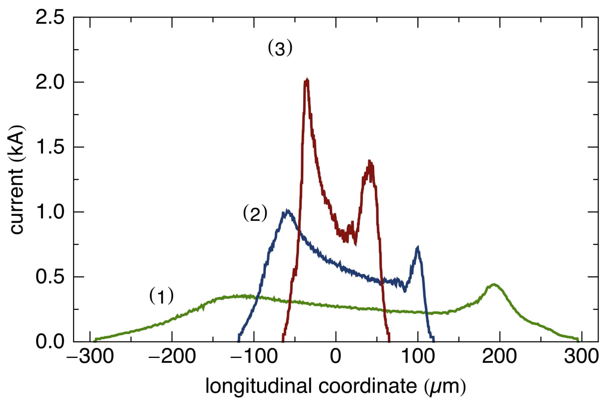

Figure 5: Longitudinal profiles of three different electron bunches in the FLASH linac as measured with the transverse deflecting microwave structure.

with the "cutoff wavelength" $\lambda_{\rm cut} = \sqrt{2}\,\pi\,c\,\sigma_t$; here c is the speed of light. For the three bunch shapes shown in Fig. 5, the cutoff wavelengths are 58, 40 and 36 μm, respectively.

For each of the three bunch shapes spectroscopic measurements were carried out on 200 bunches. The form factors derived from the measured spectra are depicted as dotted curves in Fig. 6. For all three bunch shapes, there is an impressive overall agreement between the form factors derived by the two complementary methods. This is a convincing demonstration of the capabilities of the multichannel spectrometer. In the short-wavelength region below $20\,\mu$m the spectroscopically determined form factors are generally higher than the formfactors derived from the TDS measurements. This is evidence for the presence of a fine structure which cannot be resolved by the TDS system in its present configuration. The importance of the single-shot capability of the spectrometer is demonstrated in Fig. 7. The spectroscopically determined form factors of two successive bunches with identical RF setting exhibit both significant structures which however are shifted against each other. This shows that there exist substantial shot-to-shot fluctuations even if the accelerator parameters are kept as constant as technically feasible. Averaging over several bunches will wash out many of the structural details. Hence a perfect agreement between TDS and spectrometer data cannot be expected. With our present setup at the FLASH linac it is not possible to measure exactly the same bunch with both instruments.

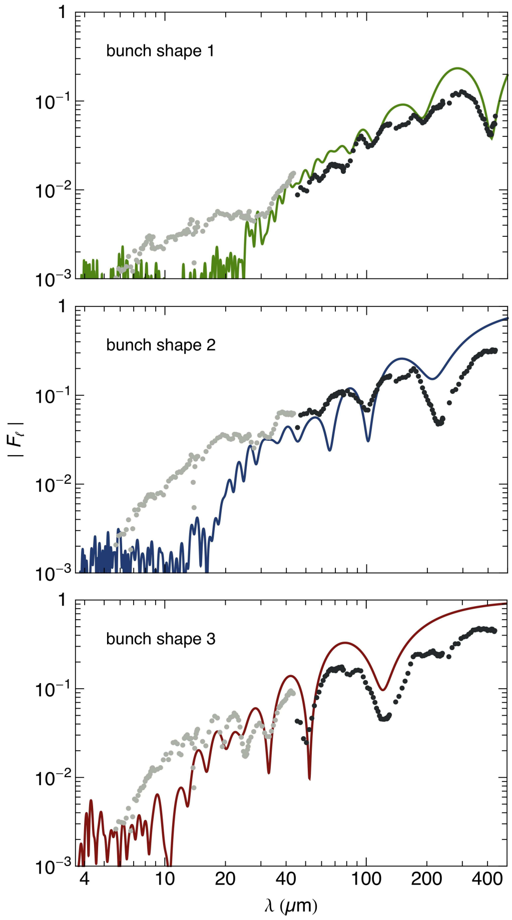

Figure 6: The magnitude $|F_\ell(\lambda)|$ of the longitudinal form factors of the bunch shapes shown in Fig. 5. Solid curves: form factors computed by Fourier transformation from the longitudinal bunch profiles. Dotted curves: form factors derived from the spectroscopic measurements (black dots: FIR configuration, gray dots: MIR configuration).

SUMMARY

A multi-channel single-shot spectrometer for the mid- and far-infrared range has been developed and successfully commissioned at the coherent transition radiation beamline at FLASH. The spectrometer covers a factor of 10 in wavelength with parallel readout. With two sets of remotely interchangeable gratings the wavelength ranges from $5.1 - 43.5\,\mu$m and $45.3 - 434.5\,\mu$m can be analyzed. Very good agreement is found between the spectroscopic longitudinal bunch form factors and the form factors derived from time-domain measurements using a transverse deflecting microwave structure. This is a proof that the instrument is well understood and calibrated.

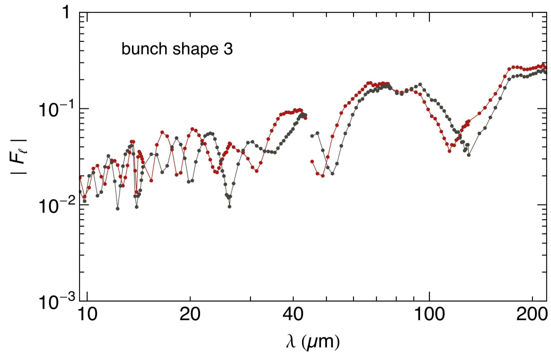

Figure 7: The form factor $|F_\ell(\lambda)|$ of two individual bunches, derived from two single-shot spectroscopic measurements.

The unique single-shot capability of the multi-channel spectrometer will allow to study and monitor the bunch profiles in great detail and will help to control the bunch compression process in view of an optimized FEL performance of the facility.

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