BROADBAND SINGLE SHOT SPECTROMETER

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Abstract

This paper summarizes the ongoing activities at DESY for the longitudinal phase space studies on ultra short bunches of VUV-FEL using infrared spectroscopy.

INTRODUCTION

FEL facilities are pushing to achieve higher peak currents mainly by means of compressing bunches longitudinally. This process defines a machine parameter, longitudinal charge distribution that has to be fine-tuned empirically. Among the operational types of diagnostic tools for longitudinal phase-space are those based on infrared (IR) spectroscopy. The most commonly used IR spectrometers (e.g. Martin-Puplett interferometer) at the FEL facilities are inherently operating in a scanning mode and are not fast enough to be applicable for monitoring bunch compression versus machine settings on a bunch by bunch basis. On the other hand, any non-scanning single bunch spectrometer may suffer from the low amount of intensity that is available from Coherent Synchrotron Radiation (CSR) or Coherent Transition Radiation (CTR) or Coherent Diffraction Radiation (CDR) in short time intervals in different wavelengths.

The proposed single shot spectrometer is based on using gratings as dispersive elements. Pioneering tests with a Transmission Grating (TG) have shown the feasibility of the concept. The results of these measurements are in agreement with simulations that have been made using “THz-Transport”, a code which is developed at the FLA-group at DESY to simulate the radiation transport based on scalar diffraction theory [1].

In a second step, a version with Reflective Blazed Gratings (RGB) will be tested and should allow getting the maximum available signal for the whole spectrum and improved resolution.

Parallel to the study of optical parts, an array of pyroelectric detectors with integrated multi-channel readout is under development.

SIMULATION CODES

THz-Transport as simulation tool-box

THz Transport generates the transition radiation from a single particle for a specified target geometry and frequency. It can propagate all kinds of radiations, including transition radiation, to optical elements using Fourier transformation optics. Optical elements which can be described include parabolic, elliptical, toroidal, spherical and flat mirrors, windows of different materials, and transmission gratings. The code provides the complex electric field amplitude at any plane perpendicular to the optical axis and allows simulating complex optical beam lines with respect to transmission functions or propagation of THz pulses. It is written as a set of Mathematica routines and is able to handle frequencies in the range of a few GHz up to about 50 THz.

GSolver as simulation code for gratings

It is a well known result that for a ratio of wavelength over grating pitch larger than 0.4, scalar diffraction theory doesn’t model the grating well. GSolver is a code which is based on a rigorous vector diffraction theory [2]. For all calculations for RBGs we have used this code [3].

OPERATIONAL DIAGNOSTIC TOOLS AT TTF2

Martin-Puplett Interferometer

Two Martin-Puplett interferometers are currently operational at VUV–FEL at DESY. One equipped with DTGS pyroelectric detectors looks to CSR at Bunch Compressor 2 (BC2) [4]. The second interferometer that uses Golay-cell detectors looks at CDR at BC3. A routine which is integrated in the machine control system scans over path length of one arm and derives the interferogram and thereby the frequency spectrum.

Bunch Compression Monitor (BCM)

First-generation BCMs use pyroelectric detectors looking to polychromatic IR. Signal amplitude is dependent on the degree of compression. While this device is a good tool for an approximate tuning of the off-crest phase in the accelerating cavities preceding the bunch compressor chicane, it is not sensitive enough to adjust the optimum bunch compression.

GRATINGS AS DISPERSIVE ELEMENTS

When a bunch of electrons is forced to radiate, electrons in the bunch radiate coherently at wavelengths longer than the bunch length. Therefore the range of the coherent radiation spectrum extends to shorter wavelengths as bunches become shorter, demanding for an efficient detection system that specifically covers this part of the spectrum. At VUV-FEL at DESY the bunch length is in the range of a few tens of fs, therefore coherent radiation extends from far-infrared to mid-infrared. One way to disperse such a polychromatic radiation to different components is based on gratings. TG and different types of RG (Reflective Gratings) are under study. RBG can be designed to give a very efficient (~90%) dispersive element that can reach the maximum possible signal for different components via appropriate optics. In the same conditions TGs can reach efficiencies as large as 20% (equal to the half of the lamellar reflective grating).

Transmission Grating (TG)-spectrometer at Bunch Compressor-2 (BC2)

Assuming plane waves illuminating a TG, it is not difficult to deduce a surprisingly simple relation between slit and pitch size that suppresses spectral orders above 1 and thus allows for broad free spectral range [5]. Based on this principle, a set of TGs were designed and manufactured at DESY. A collimating optics puts CDR at BC2 onto the TG, a paraboloid focuses the dispersed radiation into a line representing the wavelength spectrum. Since no fast multi-channel sensors of the required size exist for this wavelength range at the moment, we scan the spectrum with a single pyrodetector. The detector itself and the readout is fast enough to resolve individual bunches in the first spectroscopic order, that is selecting a specific, narrow wavelength range given by the diffractive power of the set up and the size of the detector element. An example is shown in Fig. 1. The achievable resolution in the focal plane is basically diffraction limited and the size of the detector element has to be properly adjusted.

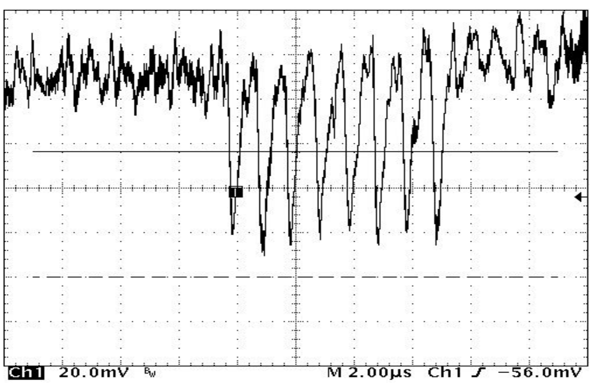

Figure 1: Signal from a Pyroelectric sensor for 8 subsequent bunches of 1nC charge in first spectroscopic order. The wavelength range covered by the detector is about 40 µm.

Fig. 2 shows a picture of the TG spectrometer set up. Fig. 3 shows a reference spectrum using a CDR. In the front of the detector a 357 µm band-pass filter is used to calibrate the wavelength axis. Position, width and intensity of the first order maxima are in agreement with the simulations using THz-Transport.

Figure 2: TG spectrometer at BC2 (Top view).

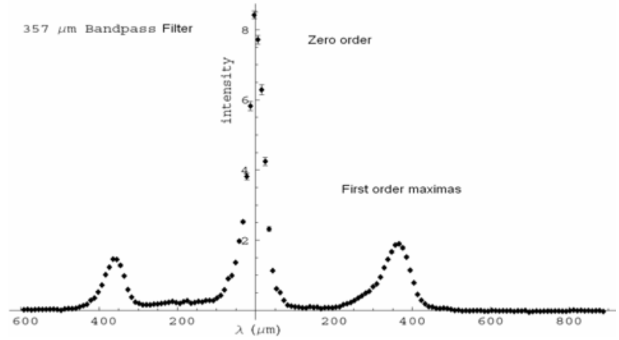

Figure 3: TG-Spectrometer is illuminated by CDR and a 357 µm band-pass filter is in the front of the detector.

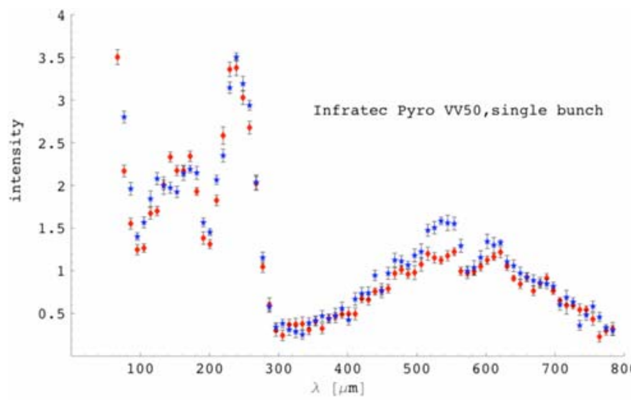

Figure 4. TG-Spectrometer is illuminated by CDR, no filters.

Fig.4 shows a full spectrum and its reproducibility in the range of device acceptance. The detector responsivity i not flat over far-infrared and it is the main reason fo structures.

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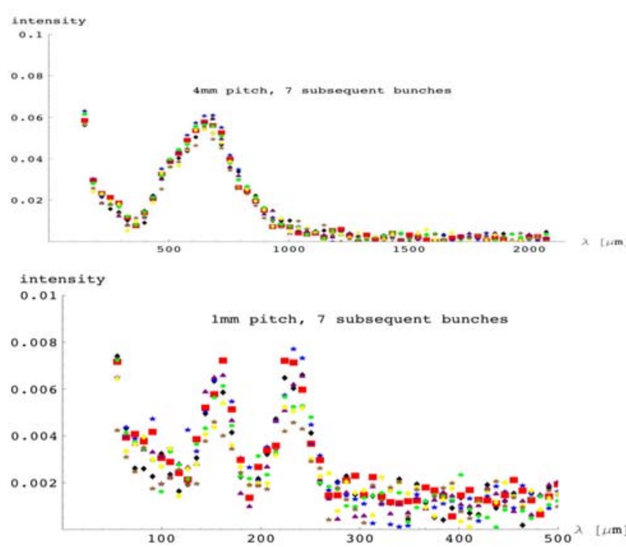

Figure 5. Bunch to bunch spectra made by TG spectrometer.

Fig. 5 shows two examples for spectra of the unfiltered CDR with TG of 4mm and 1mm pitch. The 0-order maximum and the left side of the spectra are suppressed.

The different symbols (colours) refer to 7 subsequent bunches from the same bunch train recorded simultaneously. The prominent structures at 260µm and 150 µm wavelength seen in the short wavelength spectrum do not reveal bunch structures but are caused by the resonant behaviour of the responsivity for this specific pyroelectric sensor.

As a result of this pioneering measurement at VUV-FEL, the efficiency of TG turned out to be sufficient to get a detectable signal even from a single bunch of intermediate charge (using CDR).

Reflective Blazed Grating (RBG) versus Transmission Grating (TG)

Efficiency curve of a properly designed RBG is illustrated in Fig.6. It is clear form that plot that the higher orders become exited below 45 µm wavelengths but above 45 µm all reflected power goes to zero and/or first orders. The 45 to 85 µm wavelength window is the dispersive region for this grating and for longer wavelengths it acts like a mirror. With as sequence of different such gratings, it is possible to cover a broad band of wavelengths without loss of intensity. The gain in intensity as compared to the best TG is at least a factor of four.

For calculation of the RBG efficiency curves, vector diffraction theory is used. The validity of calculations based on this theory for reflective grating has been widely proven. In fact the region of our interest, IR, is the safest region of electromagnetic spectrum for this theory [6].

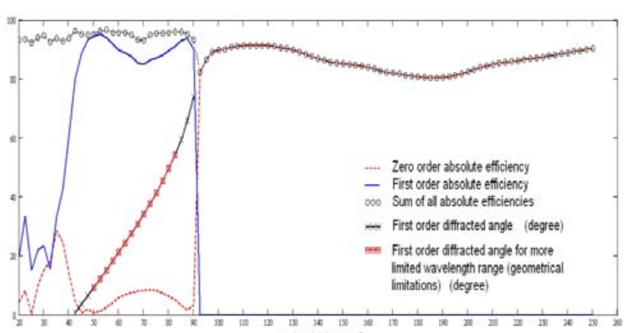

Figure 6. First and zero order efficiencies and first order diffracted angles for a RBG with 20 grooves/mm and blaze angle of 26.75° for S-polarization.

In order to evaluate our specific gratings and to compare their behaviour with theory, measurements were done at FELIX (Fig.7). The transition from dispersive to reflective behaviour (see Fig.6) for two different pitch size gratings in air and vacuum were tested. The incident radiation illuminates the grating with an angle of 57° from the normal to the grating plane (Fig. 8). For the lattice used for this test, grating equation shows that only zero and first orders are possible. Therefore measuring the zero order in the reflection (with much sharper peak, thus easier to measure) for different wavelengths seems sufficient to verify calculations. The prediction for the propagation direction of the first orders as a function of wavelength found to be in complete agreement with calculations. For the zero order efficiency the agreement with theory is excellent. Furthermore, in the dispersive window region and for several wavelengths, the dispersed first order efficiencies were measured and they are in good agreement with the expected values.

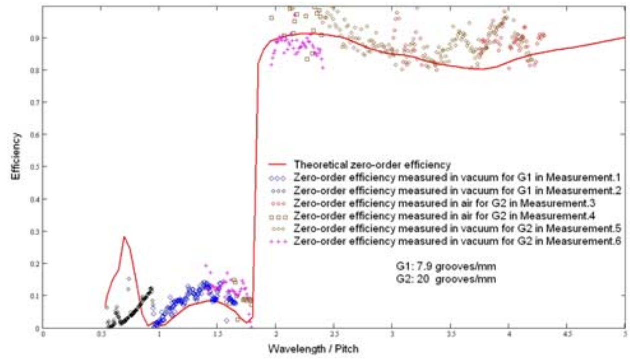

Figure 7. Theoretical zero-order (solid-red) and measured zero-order for two different gratings in air and vacuum.

Further studies with a non-scanning device were made. A large enough paraboloid with short focal length was focusing the dispersed first orders to an array of pyro-electric detectors. It was possible to see the narrow spectrum of the FELIX radiation and, changing the FEL wavelength, the spectrum was sliding on the array of detectors accordingly. No quantitative measurements made with this device yet.

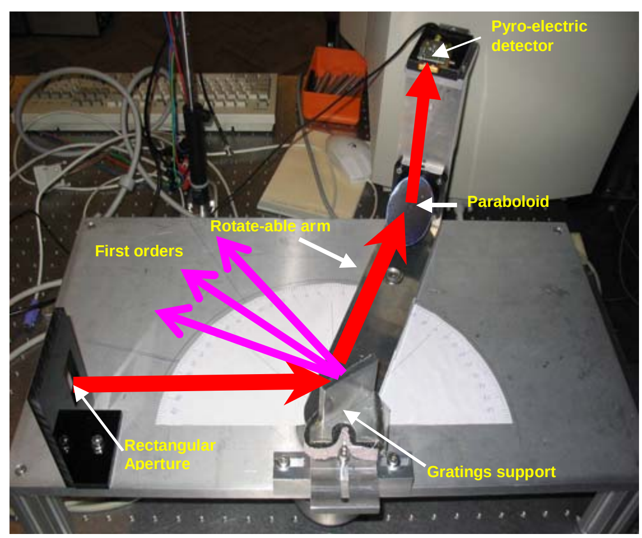

Figure 8. The mounting used for studies on distribution and efficiency of different orders at FELIX.

CONCLUSION

A single shot spectrometer based on the grating as dispersive elements can give a full spectrum of the IR radiation of an individual bunch of intermediate charge. We were able to measure CDR spectra for individual successive bunches from a 7 bunch train with a scanning pyrodetector to demonstrate the feasibility of such a set up. The extension to a single shot device by developing a fast multi-channel far-infrared detector is in preparation. First measurements have shown the power of the concept of RBG for this wavelength range and proven the validity of our simulation tools. A set of properly designed RBG together with multi-channel detectors should be able to cover a broad wavelength band for single bunches with high sensitivity.

REFERENCES

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