BUNCH COMPRESSION MONITOR

H. Delsim-Hashemi[2], O. Grimm[1], A.F.G. van der Meer[3], J. Rossbach[2],
H. Schlarb[1], B. Schmidt[1], P. Schmüser[1,2]
[1] Deutsches Elektronen-Synchrotron DESY
[2] Institut für Experimentalphysik, Universität Hamburg
[3] FELIX/FOM Institute 'Rijnhuizen', Nieuwegein, The Netherlands

Abstract

The longitudinal charge distribution in the electron bunches has a strong impact on the lasing process in a Free-Electron Laser based on the principle of Self Amplified Spontaneous Emission of radiation. For the ultraviolet and soft X ray FEL FLASH at DESY, structures in the range of ten to hundred micrometers play a crucial role. The investigation of the longitudinal charge distribution in the electron bunches on a bunch-by-bunch basis is an important issue for optimizing the bunch compression and improving the performance of the machine. This paper introduces a new tool for longitudinal diagnostics based on THz spectroscopy of coherent radiation. A novel spectrometer has been designed which permits to analyze the radiation of single electron bunches in a broad spectral range and with high resolution. Preliminary measurements with this spectrometer are presented. A strong variation of the CTR intensity in the $40\ \mu$m regime is observed when the off-crest phase in the accelerating cavities preceding the first magnetic bunch compressor is changed in small steps. This variation in the CTR intensity is found to be correlated with a similar variation in the pulse energy of the FEL light. Hence the THz spectrometer appears to be a very sensitive device for controlling the parameters of the bunch compression scheme.

INTRODUCTION

FEL facilities in the vacuum-ultraviolet (VUV) and X-ray regime require kA peak currents which are usually achieved by several stages of bunch compression. FLASH, the VUV and soft X ray FEL at DESY, has recently been upgraded to a maximum electron energy of 700 MeV, allowing to cover the wavelength range from 13 to 80 nm. A schematic view of FLASH is shown in Fig. 1. The FEL is based on the principle of Self Amplified Spontaneous Emission (SASE) which opens the way to powerful FELs in the X - ray regime. The 1 nC electron bunches are generated in an RF photocathode with an rms length of 4.5 ps and are rapidly accelerated to relativistic energies to reduce the emittance dilution due to internal space charge forces. At energies of typically 127 resp. 360 MeV the bunches are longitudinally compressed.

The longitudinal bunch compression works as follows: the phase in the accelerating cavities is chosen off-crest
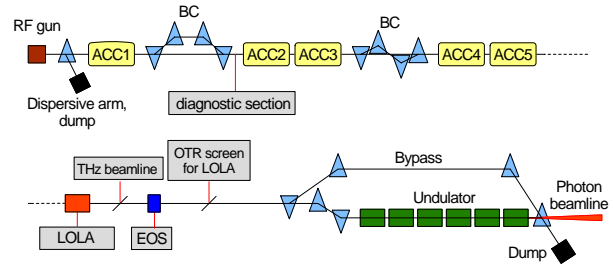

Figure 1: Schematic layout of the VUV-FEL FLASH. The beam is accelerated to a maximum energy of 700 MeV in five acceleration modules ACC1 to ACC5, each containing eight superconducting cavities. The two bunch compression stages are denoted by BC. The transition radiation screen of the THz beamline is located between the transverse deflecting RF structure LOLA and the electro-optic experiment EOS.

such that the leading electrons in the bunch recieve a smaller energy gain than the trailing electrons. In a magnetic chicane the lower-energy leading electrons travel on a longer path that the higher-energy trailing electrons, so the particles at the tail of the bunch can catch up with those at the head. FLASH uses two bunch compression stages. Due to the curvature of the RF wave it is presently not possible to squeeze all electrons into a narrow spike. The bunch shape after the two compressors is characterized by a narrow leading peak with a FWHM of < 100 fs which is followed by a long tail. In the future it is foreseen to install a third-harmonic cavity in FLASH in order to linearize the RF wave and improve the compression efficiency.

The longitudinal charge distribution of the compressed bunches has to be measured with high precision in order to fine-tune the off-crest phase in the accelerating section preceding the magnetic bunch compressor chicanes and to optimize the SASE performance.

THZ BEAMLINE AND GRATING SPECTROMETER

In order to facilitate longitudinal bunch diagnostics with high-resolution electro-optic or spectroscopic devices we have designed a THz beamline which guides coherent transition radiation (CTR) from the accelerator tunnel over a distance of 18 m to an experimental hut [1]. A special

ultrahigh vacuum chamber housing several transition and diffraction radiation screens is located between the last acceleration module and the collimator section in front of the undulator. The radiation is coupled out the UHV chamber of the linac through a 0.5 mm thick diamond window and is transported by an optical system consisting of five focusing and four plane mirrors to the experiment. The THz beam is transported in a tube of 190 mm inner diameter which is evacuated (pressure < 0.1 mbar) to avoid absorption in humid air. The computed THz energy transmission is plotted in Fig. 2 as a function of frequency resp. wavelength. The
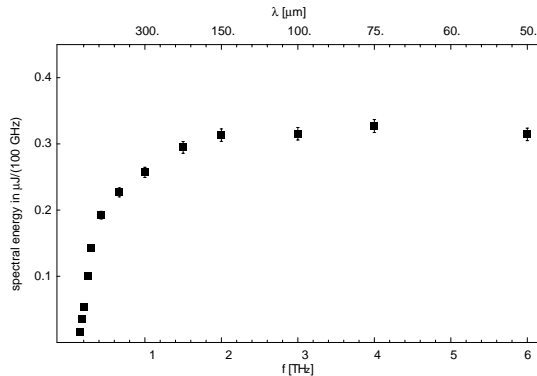

Figure 2: Computed energy transmission of the THz beamline for coherent transition radiation. The spectral CTR pulse energy density in $\mu J/(100\ GHz)$ from a pointlike bunch with 0.1nC charge is plotted as a function of frequency resp. wavelength. The Lorentz factor of the electrons is $\gamma = 1000$.

acceptance of the THz beamline is small at frequencies below 500 GHz, due to diffraction effects, and rises steeply with frequency to a plateau which is practically constant between 2 THz and 50 THz (wavelength between 150 and 6 μm). Around $5 - 6$ μm the diamond window has an absorption band.

The coherent radiation of the compressed bunches in the FLASH linac covers a wide wavelength spectrum from the millimeter range down to a few micrometers. Diffraction gratings are well suited to disperse broad-band radiation to different detection channels. Reflectance blazed gratings (Fig. 3) yield high efficiency (90%). A single grating can of course only span a wavelength variation by a factor of two since one has to avoid a spatial overlap between first-order and second-order diffraction [2]. Simultaneous measurements in a larger wavelength range are possible if several gratings of different lattice constants are staged. A setup with three gratings has been realized at FLASH and is depicted in Fig. 3. The incident radiation with wavelengths larger than some minimum wavelength λ_0 is first guided to grating G1 which has the finest lattice constant. The wavelength interval $[\lambda_0, \lambda_1]$ (with $\lambda_1 \leq 2\lambda_0$) is dispersed in first-order, while all wavelengths $\lambda > \lambda_1$ are reflected into order zero and propagate to the next grating G2 with a larger lattice constant, matched to first-order diffraction
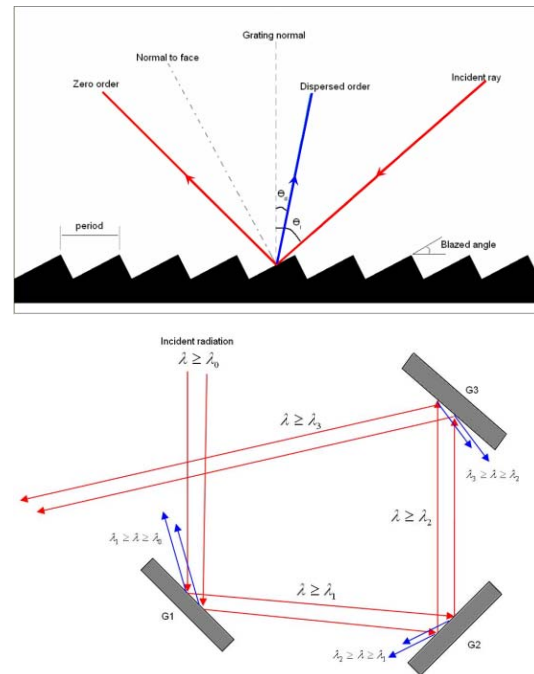

Figure 3: Top: Zeroth-order and first-order diffraction at a blazed grating. Bottom: A multichannel spectrograph consisting of three reflection gratings.

in the wavelength interval $[\lambda_1, \lambda_2]$. Grating G3 disperses the range $[\lambda_2, \lambda_3]$ and finally, radiation with $\lambda > \lambda_3$ leaves G3 in the zero-order direction. In the present setup one pyroelectric detector is placed behind each grating. Detector D1 (behing grating G1) accepts wavelength of 20 ± 1 μm, detector D2 accepts 40 ± 2 μm, detector D3 accepts 75 ± 4 μm, and the fourth detector D4 accepts all wavelength above 90 μm. A multichannel detection system containing more gratings and an array of pyroelectric detectors behind each grating is under construction.

MEASUREMENTS

The off-crest phase Φ_1 in the first acceleration module ACC1 has a strong influence on the longitudinal bunch profile that is obtained when the bunches have passed the two magnetic chicanes. Empirically it is found that the SASE efficiency depends very critically on Φ_1 and reaches its maximum at $\Phi_1 \approx -5°$ to $-6°$. A phase scan around this value is shown in Fig. 4. The signal of the so-called gas monitor detector (GMD), measuring the pulse energy of the FEL light, exhibits a pronounced maximum at $\Phi_1 = -5.7°$ with a width of $\pm 0.2°$. The CTR intensities in various wavelength channels are also plotted in Fig. 4. The remarkable observation is that at short wavelengths of 20 to 75 μm similar pronounced maxima are seen. This means that the pyroelectric detectors placed behind the gratings G1, G2 and G3 can be used to fine-tune the off-crest phase in ACC1 for optimum SASE performance.
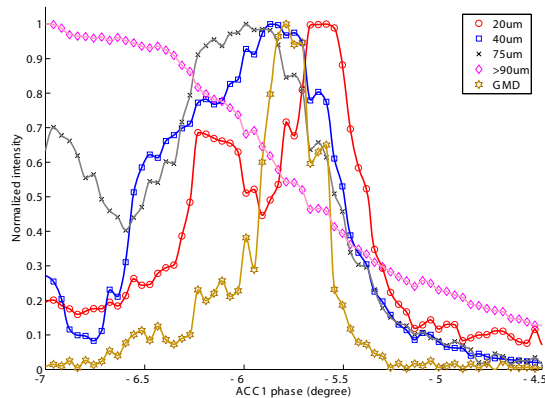
Figure 4: Amplitude of the SASE FEL signal (measured with the so-called gas monitor detector GMD) as a function of the off-crest phase Φ_1 in the acceleration module ACC1. Also shown is the intensity of coherent transition radiation as function of Φ_1 for wavelengths of $20 \pm 1\ \mu$m, $40 \pm 2\ \mu$m, $75 \pm 4\ \mu$m and for $\lambda > 90\ \mu$m. All distributions are individually normalized to a maximum value of 1.

Figure 5: Intensity of coherent transition radiation as a function of the off-crest phase Φ_1 for wavelengths of $40 \pm 2\ \mu$m, $75 \pm 4\ \mu$m and for $\lambda > 200\ \mu$m in comparison with the signal of the BCM detector which looks at coherent diffraction radiation at $\lambda > 75\mu$m.

Prior to the installation of the THz beamline and the grating spectrometer, a single pyroelectric detector has been used to optimize the bunch compression and to regulate the RF phase of the cavities in ACC1 in a feedback loop. This detector, named bunch compression monitor BCM, is mounted behind the first bunch compressor chicane and receives coherent diffraction radiation which is coupled out through a quartz window and is therefore restricted to wavelengths larger than $75\ \mu$m. From previous ACC1 phase scans it has been known that the maximum BCM signal is observed at an off-crest phase of $-11°$, about $5°$ to $6°$ away from the phase for optimum SASE performance. To compare the responses of the BCM and the grating spectrometer we have varied the ACC1 phase over a wider interval. The results are shown in Fig. 5.

One can clearly see that at long wavelength the intensity maximum is shifted to $\Phi_1 \approx -11°$. The short wavelength channels, on the other hand, exhibit two to three maxima but only the peak at $\Phi_1 \approx -6°$ is associated with good SASE efficiency. From this and the previous figure it is obvious that the regulation of the off-crest phase in ACC1 should in future be done using a detector looking at small wavelengths of 20 - 50 μm.

In a final measurement we have varied the RF phase in the acceleration modules ACC2 and ACC3. Under normal FEL operation the phase $\Phi_{2,3}$ is close to zero. The CTR intensity in various wavelength channels shows a comparatively weak dependence on $\Phi_{2,3}$ as can be seen from Fig. 6.

Figure 6: Intensity of coherent transition radiation as a function of the off-crest phase $\Phi_{2,3}$ in the modules ACC2 and ACC3 in four different wavelength ranges.

accelerating cavities used for bunch compression in a linac-driven Free Electron Laser.

CONCLUSION

We have demonstrated that frequency-selective detection of coherent transition radiation is a powerful tool for optimization and automatic regulation of the RF phase in the
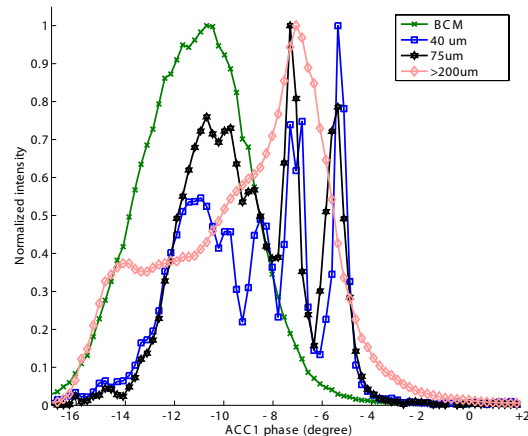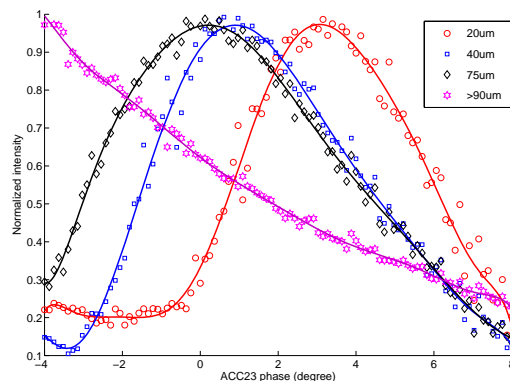
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