ELECTRON BEAM DIAGNOSTICS FOR THE EUROPEAN X-RAY FREE-ELECTRON LASER

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Abstract

To achieve and maintain stable operation of the European X-ray free-electron laser (XFEL) dedicated diagnostic sections are foreseen for the characterization and stabilisation of the electron beam. Especially the measurement and control of the longitudinal phase space during the bunch compression process is very demanding. Non-linear collective effects may degrade the slice emittance or energy spread during the bunch compression process. Moreover, a beam energy jitter transforms into a time jitter in the magnetic chicanes, and the beam arrival time is of particular importance for other synchronised sub-systems, e.g. seed lasers or pump-probe lasers for user experiments. Beam position monitoring with single bunch resolution in the sub-micron range is needed to establish and maintain the overlap of the electron and photon beam in the up to 250m-long undulators. The development status of various new diagnostic devices is discussed, and, where appropriate, experimental results obtained at the Free-electron LASer in Hamburg FLASH are presented.

INTRODUCTION

Future free-electron lasers (FELs) operating in the X-ray regime put tight tolerances on the beam quality of high-brightness electron bunches and their trajectory through the very long undulators. The beam properties vary over a wide range during the passage through a single-pass machine and need to be measured and controlled at various places. For stable long-term operation, they need to be monitored with sufficiently high precision to be able to detect deviations from the nominal values. Moreover, to serve as input signals for feedback systems, the detector systems have to be non-destructive to the electron beam in order to guaranty undisturbed FEL user operation.

As the FEL amplification process is based on exponential gain, the FEL radiation is extremely sensitive to variations of the peak current, transverse emittance and energy spread. Typically, only part of the beam fulfils the required conditions and the diagnostics has to be sensitive to this fraction of the beam. As an example, Fig. 1 shows the longitudinal phase space distribution and the corresponding slice energy width for a non-linear compression scheme as used at FLASH [1]. Since collective effects, such as coherent emission of synchrotron radiation (CSR) and longitudinal space charge (LSC), strongly influence the beam parameters it becomes obvious that projected values are of limited use.

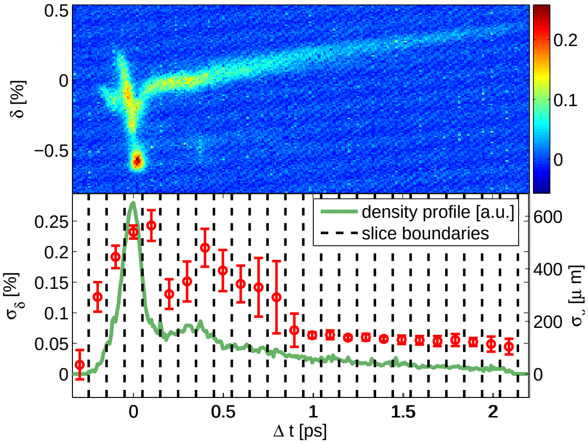

Figure 1: Longitudinal phase space distribution measured at FLASH under SASE conditions (top) and corresponding rms slice energy spread and density profile (bottom).

DIAGNOSTIC SECTIONS

The principle accelerator layout of the European XFEL [2], which will generate laser-like, femtosecond radiation down to the Ångstrom wavelength region, is shown in Fig. 2. In order to achieve high peak currents and ultra-short bunches whilst maintaining small slice energy spreads and emittances the electron beam is accelerated and compressed in several steps mitigating diluting CSR effects in the bunch compressors (BC1 and BC2) and space charge effects at low beam energies. The main beam parameters vary considerably during the compression process and are included in Fig. 2. Dedicated diagnostic sections (denoted as DS) are located in the injector and downstream of the two bunch compressors.

The major objectives of the diagnostic sections are the monitoring and stabilisation of the electron beam parameters with high accuracy and a well-defined matching into the subsequent linac sections. The super-conducting 1.3 GHz linac will be operated at a repetition rate of 10 Hz with 650 μs long bunch trains with 200 ns bunch spacing. Besides feedbacks that compensate for slow drifts, ultra fast detectors that act on a sub-microsecond timescale are required for intra bunch train feedbacks. Consequently, a suite of diagnostic devices for the measurement of the various beam parameters needs to be integrated in the lattice design which in turn should be kept short as the electron bunches need to be accelerated as quickly as possible after bunch compression to reduce LSC effects [3].

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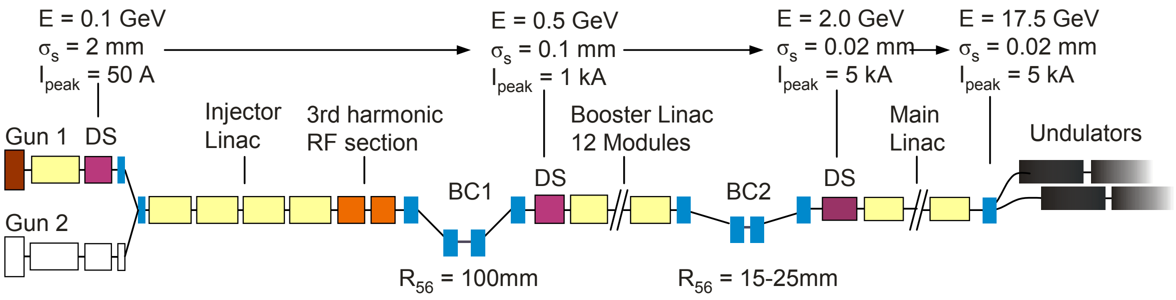

Figure 2: Accelerator layout of the European XFEL (BC: bunch compressor; DS: diagnostic section).

Beam Position Monitoring

The electron trajectory in a single-pass machine is not stabilized due to periodic boundary conditions and needs to be carefully monitored along the full length of the machine. From the injector to the main linac, the required accuracy of the order of a few tens of micrometers can be met by resonant stripline BPMs [4]. Four of these BPMs in combination with fast correction kickers will be used in the diagnostic section of BC1 for an intra bunch train feedback that stabilises actively the beam trajectory.

First start-to-end simulations indicate that a much higher accuracy of a few microns has to be reached in the up to 250 m long undulator sections to ensure stable SASE operation at X-ray wavelengths. C-band cavity BPMs working at 4.4 GHz with sub-micron resolution are being developed in collaboration with PSI, Villingen.

Longitudinal Phase Space

Manipulation of the longitudinal phase space is accomplished in the magnetic bunch compressors in combination with off-crest acceleration in both the injector linac and third-harmonic structures. Extremely challenging is the beam-based measurement and control of this compression process, which has a highly non-linear dependence on the rf settings. The rf amplitude and phase of the fundamental and third-harmonic plus the beam arrival time need to be measured. Different working points result in different tolerances for the phases and amplitudes [5] and it is desirable to find a working point for which one or more parameters are relaxed in order to reduce the number of rf parameters that need to be controlled.

Bunch compression monitors (BCM), which are based on an intensity measurement of the coherent synchrotron radiation emitted by the last dipole of the bunch compressor, can be used as input for fast feedbacks for the low-level rf for phase stabilization. Pyro detectors, which measure the integral radiation power, are used routinely at FLASH to correct the rf phase for slow drifts.

A new bunch arrival time monitor (BAM) has been developed [6] that uses the beam induced signals from button electrodes and modulates the amplitude of an Erbium-doped fibre laser pulse with electro-optical modulators based on $\mathrm{LiNBO_3}$. The timing information of the rf pulse is encoded in the amplitude of the laser pulse which is then detected by a fast photo diode. A first test setup has been installed at FLASH and an arrival time difference of two adjacent bunches of the same bunch train has been measured to be 50 fs which gives an upper limit for the resolution of 30 fs for the BAM.

A special BPM with a large horizontal aperture for a flat vacuum chambers [7] has been developed to measure the beam position and size in the dispersive section of the bunch compressors. The BPM consists of a long stripline pickup that is perpendicular to the electron path. The electron bunches induce broadband electrical signals that travel to the opposite ends of the stripline pickup where their arrival times can be measured with an optical technique as used for the BAM. An rf amplitude jitter transforms into a position jitter in first order transport theory via $\Delta x = R_{16}\Delta E/E$. An accuracy better than 30 μm is required to resolve the desired value of the relative beam energy stability of $1\cdot10^{-4}$ for a high beam arrival and peak current stability [5]. An alternative method to record the beam energy is a time-of-flight measurement utilising two BAMs: one upstream and one downstream of the magnetic chicane. To resolve the same relative energy stability an accuracy of better than 10 fs would be required.

Yet another approach to measure the beam energy is the imaging of synchrotron radiation (SR) emitted in the bunch compressor dipoles. To achieve the desired resolution, the wavelength range used for the imaging needs to be optimised for a given beam energy and bend angle. A synchrotron radiation monitor (SRM) [8] that operates in the visible has been installed successfully at FLASH: the SR emitted at the entrance of the third dipole is imaged by a commercial photo-lens and recorded by a gated, intensified CCD camera. Figure 3 shows the bunch-to-bunch energy stability of a single bunch over a period of 120 s: the measured rms energy jitter is $2\cdot10^{-4}$ which includes the resolution of the SRM. By adjusting the timing of the gate, single bunches can be picked out of the bunch train and the energy slope on the bunch train can be measured. This procedure has been used to help adjust the low-level rf [9] and the results are in good agreement with BAM measurements [6].

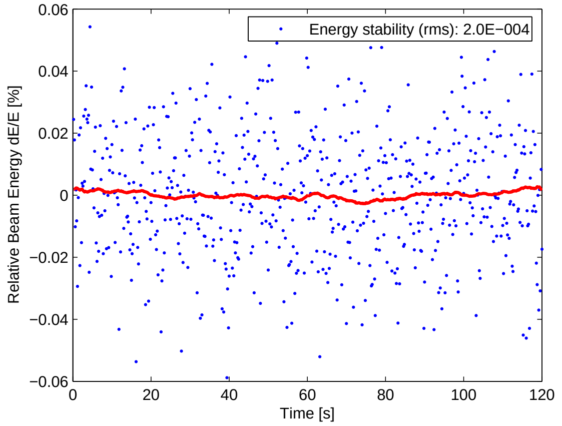

Figure 3: Bunch-to-bunch beam energy jitter measured with a SR monitor in the first bunch compressor at FLASH during SASE operation.

Slice Emittance

The goal is to monitor on-line the slice emittances with an accuracy in the percentage range. A promising solution appears to be a transverse deflecting structure (TDS) in combination with fast kickers that deflect individual bunches in a non-disruptive pulse stealing mode onto multiple off-axis optical transition radiation (OTR) screens. The screens are located in a FODO lattice and measurement of the time-sliced beam width on at least three screens allows the determination of the slice emittance and Twiss parameters (usually referred to as the standard multi-monitor method). The deflected off-axis bunches are then dumped in an absorber upstream of the subsequent accelerating module.

Figure 4 shows the normalised horizontal slice emittance measured with a TDS in combination with a quadrupole scan at FLASH [10]. The measurements were done at on-crest acceleration phases in all modules. The slice emittance varies along the bunch and the mean slice emittance amounts to 2.4 μm. A longitudinal tilt, which is apparent in the image of a bunch during the scan in the upper part of Fig. 4, is the origin of a considerably larger total projected emittance of 3.4 μm.

Slice Energy Spread

A spectrometer magnet followed by a high dispersion section will be located at the end of each diagnostic section and used for slice energy spread measurements in combination with the corresponding TDS. The goal is to resolve the uncorrelated energy spread of the order of several keV utalising an OTR screen. Assuming a resolution of about $\sim$ 10 μm for the optical imaging system a dispersion of 2-3 m is required. Figure 1 shows the slice energy width measured at FLASH under SASE conditions [1].

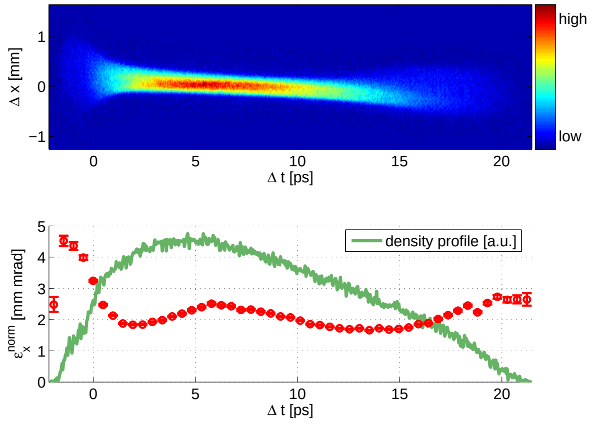

Figure 4: Image of a horizontally streaked bunch during a quadrupole scan (top) and the corresponding slice emittance and density profile (bottom).

CONCLUSIONS

Several diagnostic sections for the monitoring and stabilization of the electron beam are an integral part of the accelerator layout of the European XFEL. A continuous development of new and existing diagnostic techniques is ongoing to meet the demands on accuracy and timing. Not all recent developments could be covered in this conference proceeding and, especially, for an overview on electro-optical methods the reader is referred to Ref. [11].

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