INSTRUMENTATION ACTIVITIES AT THE SwissFEL INJECTOR TEST FACILITY

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Abstract

The SwissFEL Injector Test Facility has been equipped with numerous prototype diagnostics (BPMs, screen monitors, wire scanners, optical synchrotron radiation monitor, compression (THz) monitor, bunch arrival time monitor, EO spectral decoding monitor, charge and loss monitor) specifically designed for the low charge SwissFEL operation modes. The design of the diagnostics systems and recent measurement results will be presented.

THE SWISSFEL INJECTOR TEST FACILITY

The SwissFEL Injector Test Facility (SITF) [1] is a 230 MeV electron linear accelerator that has been built to test concepts and components for SwissFEL, the upcoming X-ray free electron laser at Paul Scherrer Institut [2]. Instrumentation installed at this test facility serves two purposes:

- Provide a stable baseline diagnostics for beam development and test of acceleration and beam compression concepts
- Test diagnostics designed for SwissFEL

To fulfill the first requirement, the Diagnostics Section has implemented a series of standard position, profile and charge monitors. These monitors do not meet the specifications for SwissFEL, but they provide a stable basis to set up the linear accelerator and to test more advanced concepts.

Figure 1 shows an overview of the monitors installed in the SwissFEL Injector Test Facility. In the following sections, the instrumentation is described in detail, starting with transverse position and profile measurements, longitudinal measurements and test of advanced concepts.

There are several requirements for SwissFEL instrumentation:

- *Low-charge operation.* The design charge for SwissFEL is between 10 and 200 pC, depending on the operating mode. It is foreseen that all diagnostics can be operated within this range.
- *Low emittance.* SwissFEL is being designed with a normalized core slice emittance of 180 to 430 nm. This results in beam sizes down to 10 μm rms and requires diagnostics with corresponding resolution.
- *Pulse length.* The design electron bunch length varies between 1 to 3 ps rms at the cathode to 6 to 30 fs rms at the undulators. Longitudinal diagnostics for such bunches have to be developed.
- *Stability requirements.* The transverse and longitudinal parameters of the machine must be stabilized.
- *Two-bunch operation.* The diagnostics for SwissFEL should be capable of distinguishing two bunches, separated by 28 ns. This is foreseen for a future upgrade of SwissFEL to a second beamline for soft X-rays.

BEAM POSITION MONITORS

The beam orbit in the SwissFEL Injector Test Facility (SITF) is measured by 19 resonant stripline beam position monitors (BPMs)[3]. The monitor pickups have four strips parallel to the beam, where each strip has an open and a shorted end, thus acting as lambda/4 resonator. The beam excites 500 MHz decaying sine signals on each of the strips. The signals are coupled out via antennas close to the shorted end of the strips. After filtering and amplification in an RF front-end (RFFE) electronics, the signals are digitized by a 5 GSample/s waveform digitizer. The digitized waveform is then processed by an FPGA carrier board to calculate beam position and amplitude. The single bunch resolution of this electronics that was developed by PSI is 7 μm rms for the beam position for charges between 5 and 1000 pC (dominated by digitizer noise) and still 35 μm rms at 1 pC (dominated by thermal RFFE noise). The charge resolution is 0.3% of the charge at 1-1000 pC and typ. 3-4 fC rms for charges 1 pC. Due to their robustness and low noise especially at low charge, the stripline BPMs are used for most charge measurements at SITF. However, dedicated charge monitors like ICTs or wall current monitors (see below) are still required for absolute charge calibration of the BPMs. Figure 2 shows the comparison of three adjacent beam position monitors.

While the stripline BPMs satisfy the requirements of SITF, SwissFEL will use only cavity BPMs, thus providing a homogeneous BPM system along the whole accelerator [4]. A BPM test section at SITF with five cavity BPMs is being used for tests of cavity BPM prototypes for SwissFEL and E-XFEL, where sub-micron resolution of the cavity BPM electronics developed by PSI has already been demonstrated [5].

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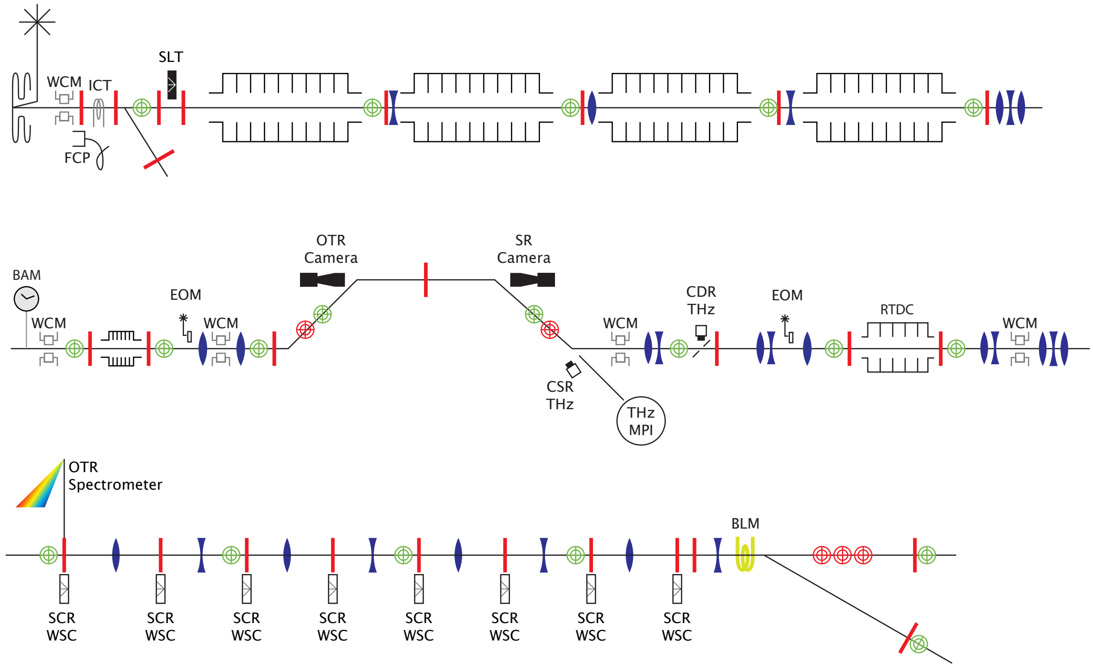

Figure 1: Overview of the diagnostics installed in the SwissFEL Injector Test Facility. Quadrupole magnets are represented by blue lenses, beam position monitors by crosshairs (green: resonant strip line BPMs, red: cavity BPMs), and screens are represented by red bars. BAM: bunch arrival monitor, BLM: beam loss monitor CDR: coherent diffraction radiation monitor, CER: coherent edge radiation monitor, EOM: electro-optical monitor, FCP: Faraday cup, ICT: integrating current transformer, MPI: Martin-Puplett interferometer, OTR: optical transition radiation, RTDC: radiofrequency transverse deflecting cavity, SCR: screen, SLT: slits, SR: synchrotron radiation, WCM: wall current monitor, and WSC: wire scanner.

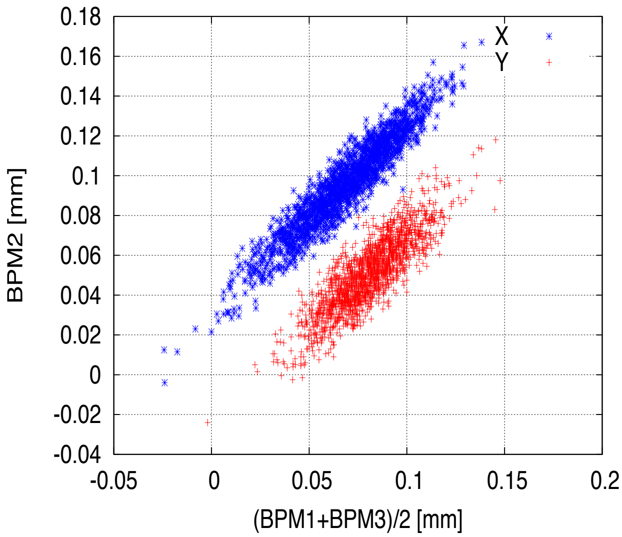

Figure 2: Comparison of the position calculated from three adjacent stripline BPMs.

BEAM POSITION IN X-BAND ACCELERATING STRUCTURE

In SITF and SwissFEL an X-band cavity is required to linearize the longitudinal phase space for optimal compression [6]. The beam orbit in this accelerating structure is of particular interest due to the strong short range transverse wake fields induced by bunches that have a transverse offset, which deteriorate the beam emittance. Depending on the transverse alignment of the beam the wake fields couple to the high order modes (HOM) of the structure, which can be measured directly with a suitable coupler system. In SITF we monitor the beam alignment along the X-band cavity via two HOM couplers placed respectively upstream and downstream of the accelerating structure. The HOM have frequencies above 10 GHz, which requires special care in couplers and cables. In a first experiment performed at the SITF, these signals were digitized by a fast sampling oscilloscope. Figure 3 shows the signal strength as a function of offset, measured by resonant strip line beam position monitors.

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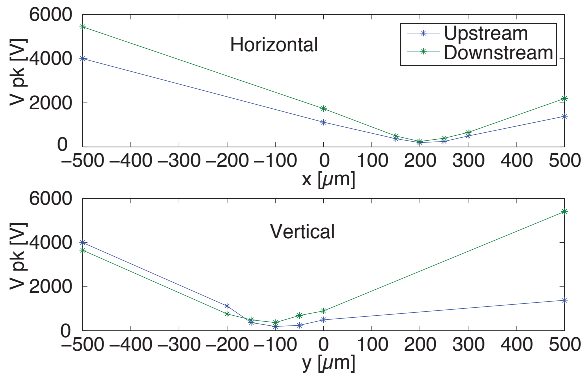

Figure 3: Signal from the wakefield monitor as a function of offset in the X-band cavity.

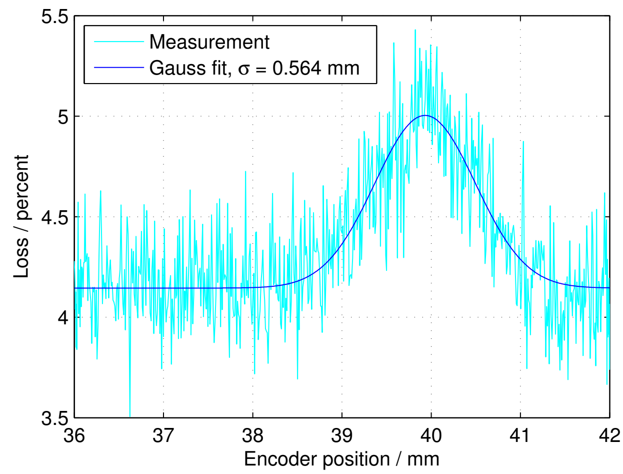

Figure 4: Vertical beam size measurement, using a wire scanner.

CHARGE MONITORS

Two types of dedicated charge monitors are installed in SITF, integrating current transformers (ICT) and wall current monitors (WCM).

In an ICT, the beam current induces a magnetic flux in a ferrite core, which is picked up by a secondary winding. ICTs are factory calibrated and can be used for absolute charge measurements. They are however not fast enough to distinguish between the actual beam and dark current. For this reason, we have started a collaboration with Bergoz Instrumentation to develop fast integrating charge transformers for SwissFEL. First results from this prototype show a resolution of 1% at a charge of 120 pC [7].

In a wall current monitor, the beam pipe is interrupted by a ceramic gap. Resistors around the circumference of this gap provide a means for the wall current to flow across the gap, and the voltage across this resistors is measured. At charges foreseen for SwissFEL, this voltage is very small, and thus the readout noise is equivalent to about 10 pC bunch charge. The WCMs installed in SITF have a bandwidth of several GHz and thus allow distinguishing the signal of the beam and the dark current.

LOSS MONITORS

Beam losses are detected outside the vacuum chamber. In the SwissFEL Injector Test Facility, two types of monitors are tested: scintillation monitors and field effect transistors that degrade due to radiation (RadFETs) [8].

The scintillation monitors are based on optical fibers and are read out by vacuum photomultiplier tubes (PMT). Two options are being evaluated: organic scintillators in a polymethylmethylacrylate (PMMA) fibers coupled to plastic optical fibers (POF) with a diameter of 1 mm, and inorganic scintillators coupled to quartz fibers with 300 μm diameter. The PMMA is inexpensive and has a large sensitivity, but it may degrade due to radiation exposure. Tests are underway to determine this degradation. The scintillator system is fast and will be used for wire scanners as well as for the SwissFEL machine protection system. An absolute calibration is not foreseen.

WIRE SCANNERS

The vertical profile of the electron beam can be measured with wire scanners installed in the diagnostics section after the bunch compressor. For simplicity, these wire scanners are integrated with the screen monitors. Three tungsten wires with a diameter of 25 μm are installed, one horizontal, and two at $\pm 45°$. Figure 4 shows a measurement of vertical beam size. The losses are determined with charge monitors before and after the wire scanner. A Gauss fit to the losses results in a vertical beam size of 564 μm, which is compared to a beam size of 585 μm measured with optical transition radiation. The two results agree within the error of the measurement, which is estimated to be 5 to 10%.

SCREEN MONITORS

The two-dimensional transverse profile can be measured at 27 locations using screen monitors. These combine scintillating crystals with optical transition radiation (OTR) screens. It was initially foreseen to use scintillators only for overview and beam finding purposes during the initial commissioning, and to use the OTR screens for beam size measurements. The resolution of the scintillator screens is limited by the crystal thickness and the orientation of the crystal to the optical axis to about 200 μm [9].

The occurrence of coherent optical transition radiation, together with the low signal-to-noise of OTR from low-charge beams, has lead to the decision to develop a new type of scintillating crystal transverse profile imager that overcomes the limitation of the resolution due to the crystal thickness. This is demonstrated in Figure 5, where a beam of 41 μm rms is shown. The sensitivity of the monitor is sufficient to measure the slice emittance of beams of a charge of 10 pC. Tests to determine the immunity to coherent optical transition radiation are underway.

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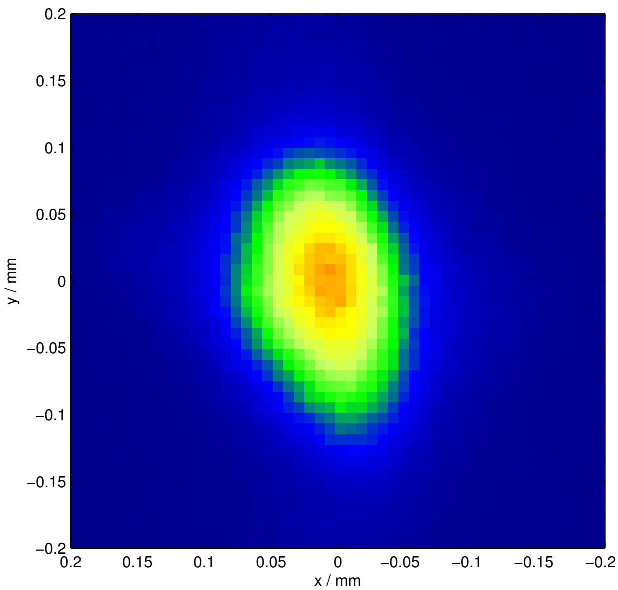

Figure 5: Electron beam with a size of 41 μm rms, measured with a scintillating screen of 100 μm thickness.

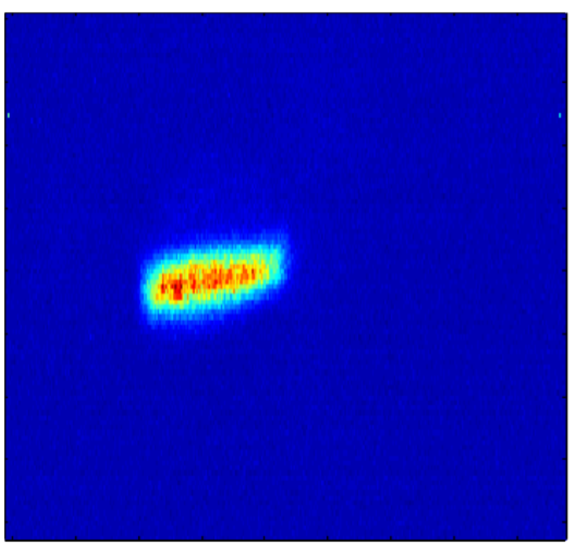

Figure 6: Image of optical radiation generated in the third bunch compressor magnet. Due to the periscope setup, the beam is rotated by 4.1°.

SYNCHROTRON RADIATION IMAGER

In the dipole magnets of the bunch compressor, synchrotron radiation is generated. This can be used both for transverse and longitudinal profile measurements.

Optical radiation from the third dipole magnet is imaged onto a CMOS sensor [10]. The camera is focused on the entrance of the magnet, and the edge radiation generated by the beam at this location can be clearly distinguished over the streak of synchrotron radiation generated along the trajectory through the magnet (Figure 6).

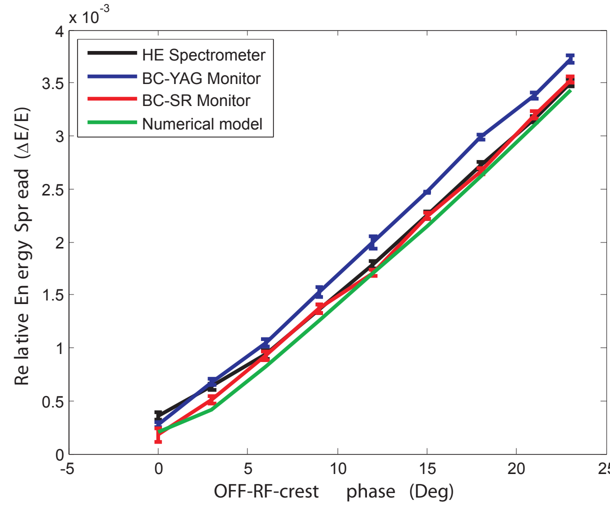

Figure 7: Comparison of energy spread measurements performed with high-energy spectrometer, scintillator in the bunch compressor, and synchrotron radiation imager with a numerical simulation. Beam Energy 230 MeV, bunch charge 12 pC.

From the dispersion and the horizontal size of the edge radiation, the energy spread of the beam can be determined. Figure 7 shows a comparison of energy spread measurements using scintillators in the bunch compressor and in the high-energy spectrometer with the synchrotron radiation imager. All three measurements agree with the numerical model.

ARRIVAL TIME MEASUREMENT

The arrival time of the electron bunches can be measured before and after the bunch compressor [11]. Button pickups are connected to electro-optical modulators that measure the arrival time with respect to the pulses of the reference laser. To achieve the best possible time resolution, the electro-optical modulators are installed in a shielded and temperature-controlled box inside the accelerator tunnel.

The resolution of the BAM is 18 fs rms. This has been determined by scanning the reference laser pulse across the pickup signal, and by taking into account the amplitude jitter of the reference laser. Figure 8 shows the measured arrival time before the bunch compressor, as a function of accelerating phase in the gun.

COMPRESSION MONITOR

Edge radiation from the fourth dipole magnet in the bunch compressor is used to monitor the compression of the bunches [12]. The spectral content varies as a function of bunch length, and it is foreseen to equip SwissFEL with a monitor that compares radiation in several spectral bands [13]. It is expected that the sensitivity on the bunch length can be increased by comparing the different frequency components [14].

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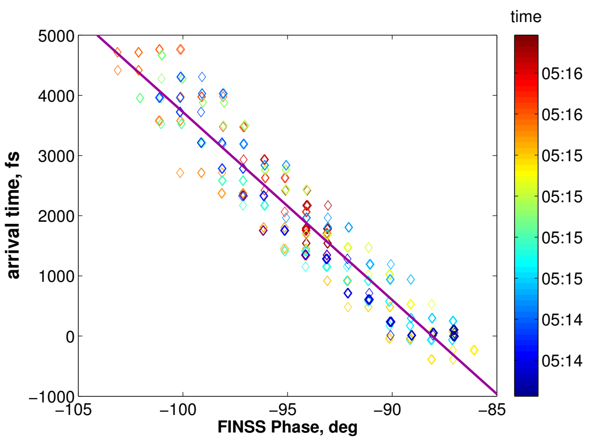

Figure 8: Measurement of the arrival time of electron bunches as a function of gun phase. Gaussian electron bunches with a length of 3 ps, a particle energy of 245 MeV, and a bunch charge of 84 pC were used.

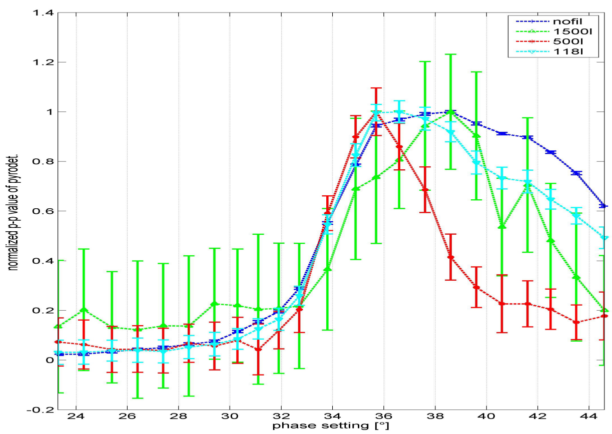

Figure 9: Spectral response to bunch compression in several spectral bands.

The selection of spectral bands can be achieved by filtering the terahertz radiation with suitable bandpass or highpass filters. First tests with bandpass filters were disappointing due to the low rejection outside the passband. Highpass filters with a good suppression of low-frequency radiation can be achieved by building a sieve with high aspect ratio in the holes. A measurement with three different filters is shown in Figure 9.

Sensitivity and noise level are of particular interest for SwissFEL, because of the low charge and the stringent stability requirements. In addition, the sensor should be fast enough to distinguish the two bunches separated by 28 ns. We are therefore evaluating several sensors for terahertz frequencies, based on different operating principles. Some of these sensors have to be operated at cryogenic temperatures. Figure 10 shows the signal of the compression monitor as a function of RF phase.

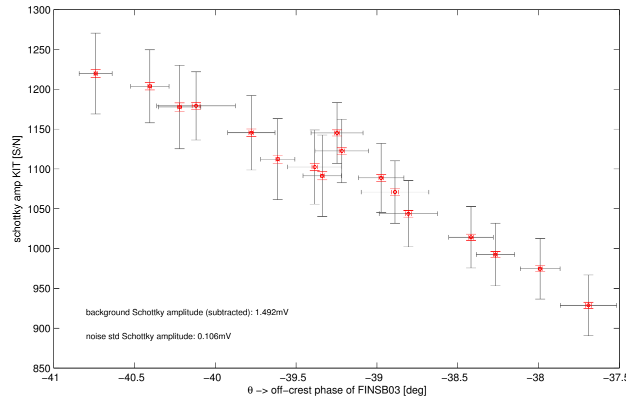

Figure 10: Measurement of compression. Beam parameters: energy 200 MeV, bunch charge: 10 pC, bunch length around 500 fs.

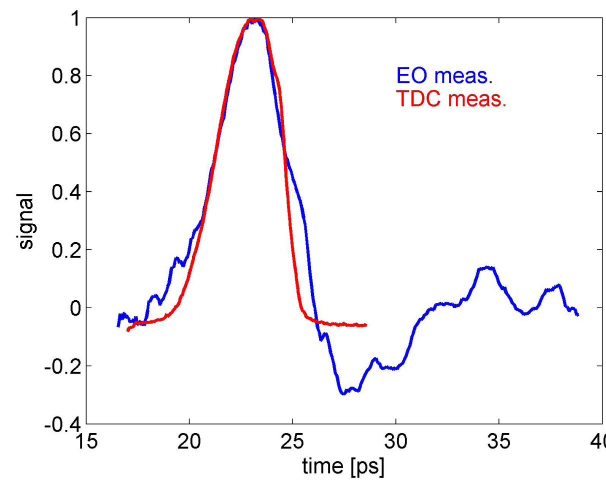

Figure 11: Measurement of the longitudinal bunch profile with an electo-optical monitor. This measurement agrees well with a measurement performed with the RF transverse deflecting structure.

ELECTRO-OPTICAL MONITORS

Two electro-optical (EO) monitors are installed in SITF for a direct time-domain measurement of the longitudinal profile. These monitors are non-invasive and can be operated during routine operation [15].

Similarly to the bunch arrival monitors, EO monitors make use of the Pockels effect to modulate an external reference laser with a signal from the electron beam. A transmission of the beam profile through an electrical pickup is not possible, therefore the electro-optical crystal is installed directly in the accelerator vacuum. The Coulomb field of the relativistic bunch passes through the crystal, and the bunch profile can be reconstructed from the laser pulse, applying the spectral decoding technique.

Figure 11 shows a measured profile.

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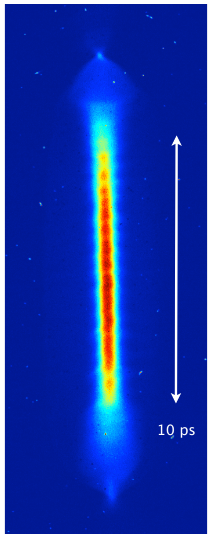

Figure 12: Image of an electron beam streaked by the transverse deflecting RF cavity.

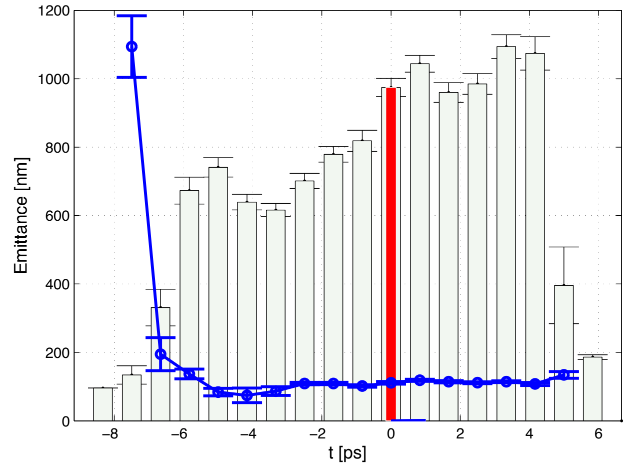

Figure 13: Measurement of the slice emittance. Slice emittance as a function of time is shown in blue; current in arbitrary units is shown in grey. The red bar indicates the center of the bunch.

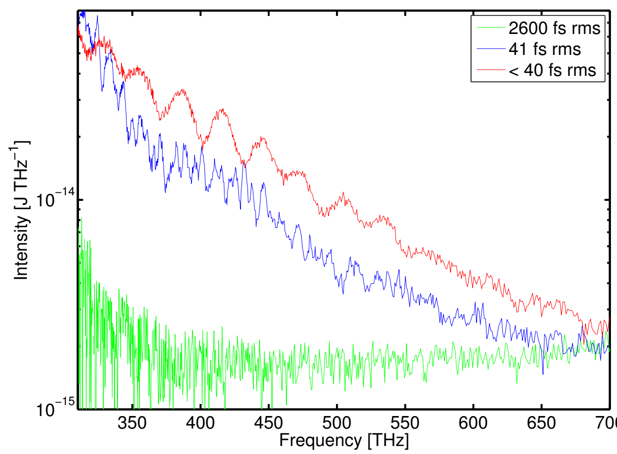

Figure 14: Spectra of optical transition radiation, for different bunch lengths.

TRANSVERSE DEFLECTING RF CAVITY

A transverse deflecting RF cavity is installed in the diagnostics section of SITF [16]. It is a Five-cell S-band 5-call $\beta\lambda/2$ standing-wave RF structure resonant to the π-mode TM_{110}. The integrated deflecting voltage is 4.89 MV at an input poser of 5 MW.

The electromagnetic field in the cavity gives the particles a vertical kick, depending on their arrival time with respect to the RF phase. To measure the bunch length, it is operated such that the middle of the bunch goes through the structure at zero crossing of the electromagnetic field. The net deflection is then zero, and the streak is maximized. The vertical beta function of the beam is adjusted to 40 m, and the phase advance to the measurement screen is 270°.

Together with a quadrupole magnet lattice, this transverse deflecting cavity is used for slice emittance measurements [17]. Figure 13 shows a representative example. The measurement is fully automated and is being performed routinely to assess the quality of the electron beam.

OPTICAL SPECTRUM OF TRANSITION RADIATION

Coherent radiation from the electron bunches can be used to assess their length, as used by the compression monitors. Moreover, also the incoherent part of the spectrum can be used to infer the bunch length. This is due to a convolution of the random noise spectrum of incoherent radiation with the form factor. This method has been successfully used with undulator radiation in synchrotrons[18].

The goal of our present effort is to extend the usage of this method to the ultra-short bunches from linear accelerators. We use optical transition radiation, due to the straightforward optical setup. The radiation is focused into a fiber, which is connected to a commercial spectrometer for radiation between 320 and 700 THz.

Figure 14 shows spectra recorded at three different bunch lengths. The difference in the correlation width is apparent, and we are presently evaluating whether such a monitor could be useful for SwissFEL.

X-RAY PULSE LENGTH MEASUREMENT

The final measurement of bunch length at SwissFEL will be done directly on the X-ray pulses. For this purpose, we are planning to install a terahertz streak camera. In this device, photoelectrons generated in a gas jet are streaked by a terahertz field that is sourced from the pump laser.

We are presently setting up such a chamber at the experimental laser hutch in the SwissFEL Injector Test Facility [19]. We have successfully measured spectra of high harmonics of the laser, and we are planning to introduce the terahertz streaking field in the next step.

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OUTLOOK TOWARDS SWISSFEL DIAGNOSTICS

We develop the instrumentation for SwissFEL based on the developments at SITF. For certain monitors such as beam position and profile monitors, a small series is built together with industrial partners. Longitudinal diagnostics are typically unique, because the bunch length changes significantly at very localized points.

All monitors for SwissFEL will be built during the next 18 months, to be ready for installation in Spring 2015. Most systems are well advanced and the implementation should be finished in time. The exception is an absolute bunch length measurement after the second bunch compressor S10BC02. It is foreseen to install a transverse deflecting structure, but it will not be available during initial commissioning of SwissFEL. We are presently evaluating alternative approaches to address this important issue.

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