COMMISSIONING STATUS OF THE SwissFEL INJECTOR TEST FACILITY

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Abstract

The SwissFEL injector test facility at the Paul Scherrer Institute has been in operation since August 2010. Its primary goal is the demonstration of a high-brightness electron beam as it will be required to drive the SwissFEL main linac. The injector further serves as a platform for the development and validation of accelerator components needed for the SwissFEL project. We give an overview of recent commissioning activities at about 130 MeV beam energy, with particular emphasis on results from optics matching studies and emittance measurements, the latter obtained with different optics-based methods. A five-cell transverse-deflecting cavity allows studies of the longitudinal bunch charge distribution and slice emittance. Bunch length measurements will become the focus of interest after the installation of a magnetic compression chicane, completed in the summer of 2011.

INTRODUCTION AND MOTIVATION

The SwissFEL project at the Paul Scherrer Institute (PSI) foresees the realization of a SASE X-ray Free Electron Laser (FEL) operating at 0.1–7 nm photon wavelength by 2016 [1]. To minimize the facility length, and thus cost, the concept aims at relatively low electron beam energy. For the extensive study of the generation, transport and compression of high brightness electron beams and for developing the necessary components, PSI is commissioning the SwissFEL injector test facility, a highly flexible 250 MeV linear electron accelerator [2].

The commissioning of the test facility proceeds in three phases: in a first step (phase 1), the gun section with some dedicated diagnostics was put into operation [3]. In this paper we report on the results of the second commissioning phase, lasting from August 2010 to May 2011. For this phase, assembly of the full accelerator was essentially completed, with the exception of the bunch compression chicane, which was installed in July 2011. Also, only two out of four S-band accelerating structures were available for operation due to delays in the delivery of the RF hardware systems. The bunch compressor chicane will be put into operation during the third commissioning phase, starting later in 2011.

Concurrently performed simulation work is reported in a separate contribution [4].

BEAMLINE SETUP

The SwissFEL injector test facility consists of a laser-driven RF gun followed by an S-band booster section, a bunch compression section and a diagnostics section featuring an RF deflector and a series of FODO cells for emittance measurements.

Laser System

Two laser systems are used during the commissioning of the injector test facility: a compact, turn-key Nd:YLF amplifier suitable for basic commissioning tasks and a more sophisticated Ti:Sapph amplifier allowing longitudinal pulse shaping and wavelength tuning for detailed emittance studies.

The Nd:YLF amplifier [5] delivers 2.2 mJ at 1048 nm wavelength. Frequency quadrupling and transfer to the beamline results in an available pulse energy at the cathode of about 70 µJ at 262 nm wavelength. The UV temporal pulse intensity, measured with a cross-correlator is Gaussian with 6 ps FWHM.

The primary laser system [6] consists of an oscillator and a chirped pulse amplifier. After pre-amplification and temporal stretching the laser pulses are injected into three amplifier stages. The pulse energy reaches 20 mJ after the temporal recompression down to 100 fs. Frequency-conversion from the near-IR to the UV is achieved by third harmonic generation in two BBO crystals. The temporal pulse shaping is realized by cascading several birefringent α-cut BBO crystals. Each crystal generates two identical replicas of the input pulse delayed in time. After passing through 5 crystals some 32 pulses, with appropriate delay and duration, approximate the desired flat-top intensity profile. The resulting UV profile is measured to have 10.3 ps FWHM and 0.9 ps rise time. This passive shaping method is relatively simple and efficient (energy losses are about 30%).

The Ti:Sapph laser system together with an optical parametric amplifier allows wavelength tuning from near-IR to UV at 240 nm. In the near future, this feature will permit thermal emittance and quantum efficiency studies.

Spatial shaping is used for both lasers to reduce spatial nonuniformities and approximate a top-hat transverse profile. The laser beams are focused into a conical capillary of 100 µm diameter, which suppresses higher-order spatial modes. An aperture selects the central part ($\approx$50%) of the Gaussian-like output profile. A lens is then used to image the hard-edge profile at the mask onto the cathode.

RF Gun and Solenoid

In the early commissioning phases, the injector test facility relies on the CTF3 gun number 5, a 2.6-cell standing wave S-band cavity originally developed for high-current operation at the CLIC test facility at CERN. The gun is run at a nominal gradient of 100 MV/m with 21 MW peak power, which results in an electron momentum of 7.1 MeV/c. Degradations in the quantum efficiency of the copper cathode, probably due to contaminants, prompted a replacement of the cathode in January 2011. The available cooling limits the repetition rate to 10 Hz. A new gun, optimized for operation at the final SwissFEL facility, is currently under construction at PSI and will be installed in the injector test facility sometime during 2013.

Initial beam focusing and emittance optimization is achieved by a movable solenoid located immediately after the gun. The solenoid contains additional wires providing regular and skew quadrupole fields to correct for possible quadrupole terms in the solenoid field.

Booster Linac

The design of the main accelerating section of the injector foresees four S-band travelling-wave structures, each 4.15 m long and operating at nominal gradients of about 20 MV/m, with the exception of the first structure, which runs at a lower gradient to ensure emittance compensation at the earliest stage of acceleration. The accelerating structures are surrounded by solenoids for additional focusing. For the commissioning phase described here, only two of the four accelerating structures were in operation, as a result of delays with several RF hardware components.

Diagnostics

The transverse beam profile is measured by a series of screen monitors distributed along the accelerator. Beam images are obtained with either (for overview images) YAG scintillating crystal screens (200 µm thickness) or (for precise measurements) thin metal-foil screens emitting optical transition radiation (OTR). The transverse beam position (orbit) is monitored by a series of 500 MHz resonant stripline beam-position monitors.

Measurement of the bunch length and, more generally, characterization of the longitudinal charge distribution is performed by “streaking” the electron bunch with a transverse RF deflecting structure at its zero-crossing phase followed by imaging after a suitable distance. The RF deflector used at the injector test facility is a 5-cell S-band cavity providing a deflecting voltage of up to 5 MV, resulting in a temporal resolution of 20 fs.

Typical beam parameters throughout the commissioning period were 130 MeV/c for the final momentum and 160–200 pC for the bunch charge. The laser spot size at the cathode was kept at about 1 mm diameter.

OPTICS MATCHING

The focusing solenoids around the S-band accelerating structures leave considerable freedom to the β-function of the beam after the booster. Therefore, an extremely robust method was chosen for the first optics matching [7]. In this method, the settings of two appropriately chosen quadrupoles needed to minimize the beam size at some downstream observation point are determined by two independent scans. The constraint of minimum beam size alone then uniquely determines the Twiss parameters α and β, without knowledge of the absolute beam size.

The final matching is then performed with the help of a matching routine based on a suitable online model. In Fig. 1 we show the measured beam sizes along the beamline in comparison with the values predicted by the online model for the matched injector.

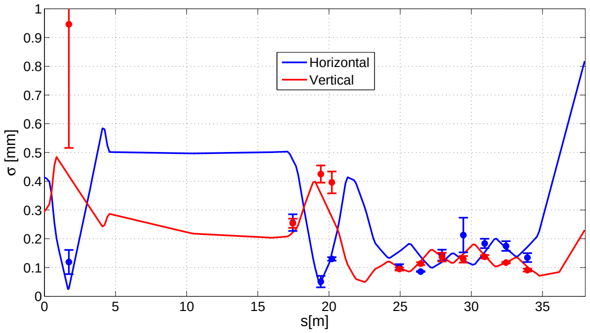

Figure 1: Predicted (solid lines) and measured (data points) beam sizes along the injector test facility.

EMITTANCE MEASUREMENTS

The emittance of the electron beam is a key quantity in view of the FEL application of the injector. It is measured in the diagnostics section with so-called optical methods, i.e., the beam size is measured as a function of varying phase advance.[1] The Twiss parameters including the emittance are then reconstructed from the known relationship between the beam envelope and the lattice parameters for a given set of Twiss parameters. Two approaches were pursued: In the first, the focusing strengths of three quadrupoles are varied according to a predefined sequence, which provides a step-wise increase in phase advance. The use of three (or more) quadrupoles ensures that the beam size at the observation point can be kept within a relatively small range, which reduces systematic effects arising from measurements of strongly varying beam sizes (e.g., small focal points). In the second approach, the beam is matched into a section of three and a half FODO cells, which by their design provide a phase advance of 22.5° per half-cell. Measurement of the beam size in each half-cell again allows the reconstruction of the Twiss parameters and the emittance. Most of the emittance measurements

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[1] For the measurements presented here the beam sizes were obtained from Gauss fits to background-subtracted beam profiles.

were performed with the first method ("triple-quad scan") since it was found to be simpler and faster (only one screen needed for beam size measurement), while the more involved FODO measurements served as an occasional cross-check [8].

With the emittance measurement established, the injector was matched to the invariant envelope condition, mainly by adjusting the gun solenoid strength. In Fig. 2 we show the measured emittance as a function of gun solenoid current (Ti:Sapph laser). The emittances measured at the optimal setting are $\varepsilon_{n,x} = 0.61 \pm 0.02$ mm mrad and $\varepsilon_{n,y} = 0.38 \pm 0.03$ mm mrad, where the errors are statistical (obtained from the evaluation of 10 images per set point). The reason for the observed x/y asymmetry is not fully understood. Attempts at symmetrizing the emittance by using the skew quadrupole integrated in the gun solenoid result in scans as shown in Fig. 3. In this scan, the optimal solenoid setting yields $\varepsilon_{n,x} = 0.55 \pm 0.01$ mm mrad and $\varepsilon_{n,y} = 0.52 \pm 0.01$ mm mrad.

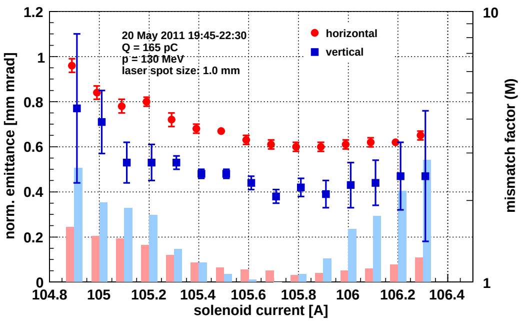

Figure 2: Measured emittance as a function of gun solenoid current. Also shown (bars, right-hand scale) is the mismatch factor determined by the fit to the optics as a measure for the matching quality (optimum value is 1).

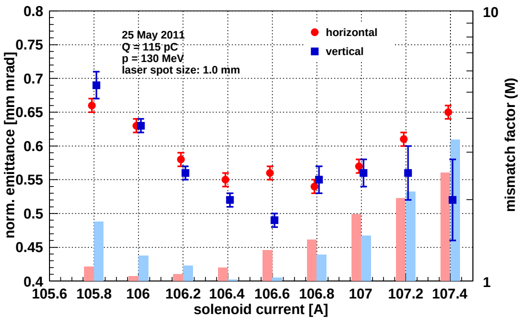

Figure 3: Example of a gun solenoid scan after symmetrization using the skew corrector quadrupole in the gun solenoid (note the zero-suppressed scale).

BUNCH LENGTH MEASUREMENTS

First bunch length measurements using the RF deflector were performed with the Nd:YLF laser, which provides, at the cathode, a Gaussian beam profile with $\sigma_t = 2.6$ ps. To control systematic effects the measurements were performed at deflecting voltages varying between 1 and 2 MV. Combining the results we find an rms bunch length of 2.6 ± 0.2 ps, close to the initial bunch length.

Using the RF deflector in combination with the dispersive spectrometer arm allows the characterization of the electron distribution both in terms of energy and arrival time. As an example we show in Fig. 4 an image of the streaked beam in the spectrometer obtained with the first S-band accelerating structure running at on-crest phase. The distribution clearly shows the RF curvature in the longitudinal phase space.

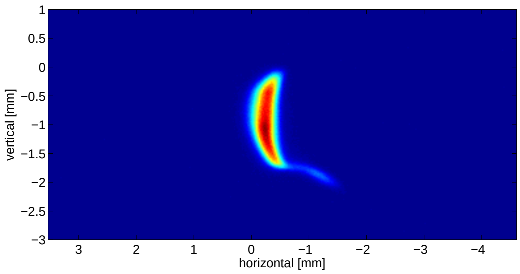

Figure 4: Image of the streaked beam in the spectrometer, revealing the RF curvature.

CONCLUSION AND OUTLOOK

During the second commissioning phase of the SwissFEL injector test facility between August 2010 and May 2011, we established procedures for optics matching, emittance measurement and bunch length measurement using an RF deflector. A first optimization of the emittance gave encouraging results.

Recently, the magnetic bunch compression chicane was integrated in the test facility, which will resume operation later in 2011. In 2012, the injector test facility will be completed with the installation of a harmonic X-band cavity for phase-space linearization in front of the bunch compressor.

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