UPDATE ON THE COMMISSIONING EFFORT AT THE SwissFEL INJECTOR TEST FACILITY

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Abstract

The SwissFEL Injector Test Facility at the Paul Scherrer Institute is the principal test bed and demonstration plant for the SwissFEL project, which aims at realizing a hard-X-ray Free Electron Laser by 2017. Since the spring of 2012 the photoinjector facility has been running with all RF cavities in full operation, allowing beam characterization at energies around 230 MeV with bunch charges between 10 and 200 pC. We give an overview of recent commissioning efforts with particular emphasis on efforts to optimize the emittance of the uncompressed beam.

INTRODUCTION AND MOTIVATION

The Paul Scherrer Institute (PSI) is planning an X-ray Free Electron Laser (FEL) user facility, which is to deliver ultrashort coherent photon pulses with wavelengths ranging between 0.1 and 0.7 nm by the year 2017 [1]. For cost and space reasons the driving linac is foreseen to feature a relatively modest end energy, thus calling for very low emittance to still achieve lasing at the target wavelengths. In preparation of SwissFEL, PSI is commissioning a 250 MeV photo-injector, which allows gaining experience with high-brightness electron beams and serves as a realistic test bed for crucial components in development for SwissFEL.

The SwissFEL Injector Test Facility [2] has been in operation in various configurations since 2010 [3]. Only recently the RF system was completed and the design energy of 250 MeV could be reached. At the same time, a flexible magnetic chicane, designed to compress the electron bunch longitudinally, was put into operation. The results of the first beam characterization around this energy as well as the first experience with the bunch compressor were reported in an earlier note [4]. In this paper we report on the ensuing work on emittance optimization with uncompressed beam, performed in a high-charge (about 200 pC) and low-charge (about 10 pC) mode.

MACHINE SETUP

Electrons are extracted from a copper cathode by a TW class drive laser, which is based on a frequency tripled Ti:sapphire chirped-pulse amplifier [5]. A pulse-stacking method, where the laser beam is sent through several birefringent BBO-crystals, is applied to approximate a flat-top longitudinal intensity profile. In the high-charge mode (typically 200 pC), the FWHM pulse length is 10.3 ps, in the low-charge mode (10 pC) it is 3.6 ps. Figure 1 shows a comparison of the two pulse shapes, as measured with a cross-correlation method. Transverse pulse shaping is performed with an aperture mask. The laser spot diameter on the cathode is about 0.84 mm for the high-charge mode and about 0.38 mm for the low-charge mode. A smaller back up laser system based on a Nd:YLF amplifier is used for simple tasks not requiring high beam quality.

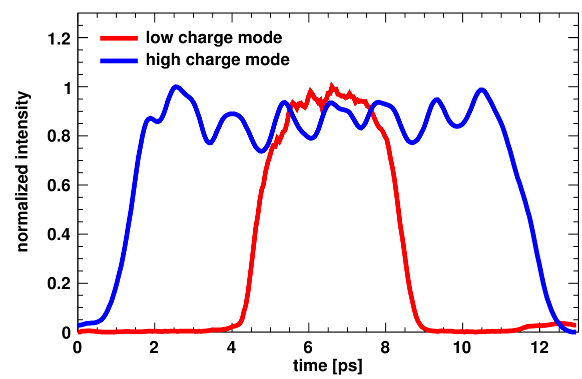

Figure 1: Laser longitudinal profile measurement for the two charge modes.

The first acceleration of the electrons to 7.1 MeV/c momentum is provided by the CTF3 Gun Nr. 5, an S-band RF gun originally built for the CLIC test facility at CERN [6].

A movable gun solenoid is used for initial focusing and optimization of the projected emittance. Energy and energy spread of the electrons emitted by the gun can be measured with a small dispersive beamline upstream of the booster.

The booster consists of four S-band travelling-wave structures, each surrounded by four solenoids for additional focusing. A fifth accelerating structure, operating at a harmonic frequency (X-band), was recently installed. Its purpose will be the approximate linearization of the longitudinal electron phase space for optimal bunch compression in the magnetic chicane following the booster. The bunch compressor was not in use (left in the straight position) during the measurements presented here, i.e., all results shown were obtained with uncompressed bunches.

An extensive diagnostic section equipped with a series of quadrupoles allows various kinds of optics-based emittance measurements. A transverse-deflecting RF cavity (S-band, five cells) is used for bunch length and slice-resolved measurements (resolution 20 fs). Transverse beam profiles are obtained by imaging the beam with either, for overview images, scintillating crystal screens (YAG or LuAG) or, for precision measurements, OTR screens (thin metal foils emitting optical transition radiation). The beam orbit is tracked by a series of resonant strip-line beam-position monitors. The absolute bunch charge is measured by means of a wall current monitor with an uncertainty of 10–15%.

The measurements presented here were performed at a beam energy of 230 MeV, with the phases of all travelling-wave structures set to their on-crest values.

EMITTANCE OPTIMIZATION

Given the moderate size of the SwissFEL main linac, low emittance is a key requirement for the SwissFEL electron beam to achieve lasing in the X-ray domain. In particular a small core slice emittance is crucial for the FEL process in the undulator section. For the matching of the beam optics, however, it is vital to keep the projected emittance under control as well.

The primary method used to measure emittance is a single-quadrupole scan, where the beam optics are set up in a way that allows the generation of phase advance simultaneously in the horizontal and the vertical plane. The precondition for this to work is that the beam optics are equal in both planes at the location of the scanning quadrupole, i.e., $\beta_x = \beta_y = \beta_0$ and $\alpha_x = \alpha_y = \alpha_0$, with $\beta_0 = \alpha_0 L$ where L marks the distance to the observing screen. Under these conditions, the beam waist occurs in both planes for zero quadrupole gradient and is equal to $\beta_{\min} = L^2/\beta_0$ in a thin-lens approximation. The method has the advantage that an operator can easily verify how well the beam is matched to the desired optics. The beam size is then measured as a function of phase advance from Gauss fits to background-subtracted beam profiles using the OTR screens. Figure 2 shows an example of an emittance scan at 10 pC charge. The plots show normalized phase space with beam size measurements under different phase advance as tangential lines (top), measured beam sizes in comparison to the model expectation (middle), and the corresponding statistical pulls defined as the difference between measurement and model normalized by the measurement error (bottom).

The emittance of a photo-injector at a given bunch charge is mainly determined by the laser spot size, the strength of the initial focusing at the gun solenoid, and the gradient of the first booster cavity. In our optimization procedure we set the laser spot size and the gradient of the first cavity to design values and scan the gun solenoid field strength for the lowest projected emittance. We then minimize the transverse couplings of the beam by adjusting two small corrector quadrupoles integrated in the coil of the gun solenoid. Further reduction of couplings is achieved by tuning the solenoids surrounding the first S-band cavity.

A sizable dependence of the emittance on the orbit through the S-band structures was observed after this first optimization. The next step was therefore a beam-based alignment of the orbit in the S-band section.

In this procedure an orbit feedback loop is closed to fix the beam orbit through the S-band section during a measurement. The optimal orbit is found empirically by measuring the emittance as a function of the reference BPM offsets used by the feedback.

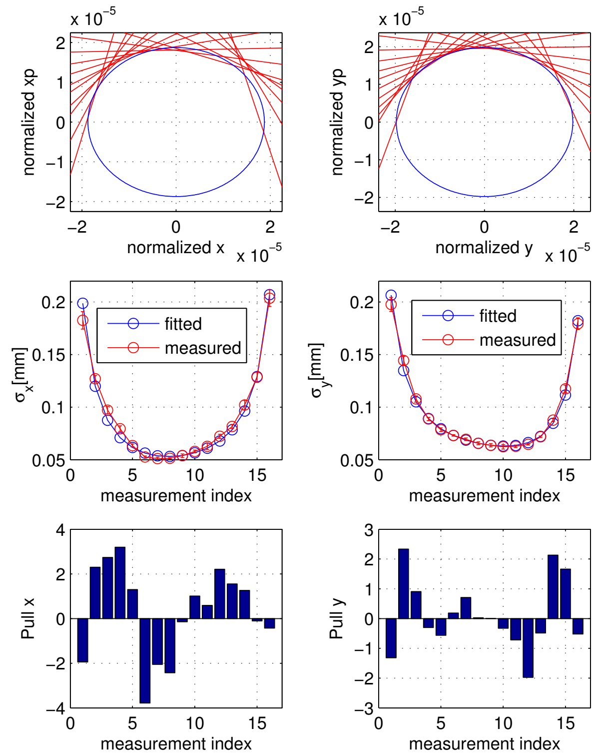

Figure 2: Example of a single-quadrupole emittance measurement performed at 10 pC charge. See text for details.

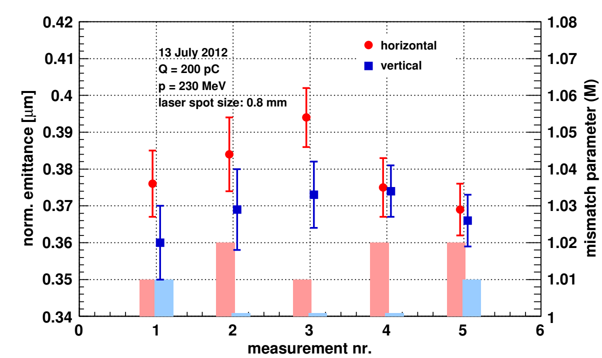

Figure 3: Stability of emittance measurement: the same single-quadrupole scan was repeated five times with 2 minutes between measurements. The measured emittance is shown in µm (left-hand scale), error bars are determined from the evaluation of 10 images per set point.. Also shown (bars, right-hand scale) is the mismatch parameter determined by the fit to the optics as a measure for the matching quality (optimum value is 1).

After adjusting the orbit some asymmetry between the horizontal and the vertical emittance remains (see also [4]). The asymmetry could be traced to dispersion effects dis-

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torting the beam at the observation point. A correction of the dispersion then results in symmetric emittance values as expected. Figure 3 shows the stability of the emittance measurement over a series of five measurements taken at intervals of two minutes.

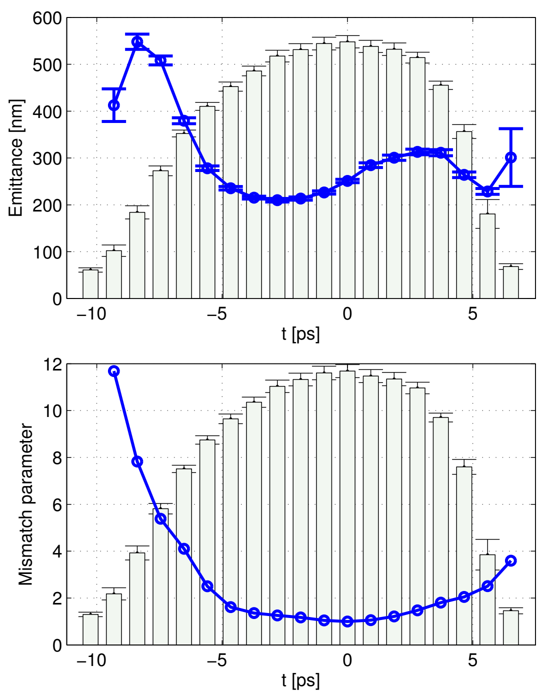

Figure 4: Slice emittance measurement at 200 pC: charge profile (bars) in comparison to slice emittance (top) and relative mismatch parameter (bottom) as a function of position along the bunch.

Once the projected emittance is optimized, we measure the horizontal emittance of individual longitudinal beam slices along the bunch by streaking the beam vertically with the RF deflector. Figure 4 shows an example measurement. For the low-charge mode, the slice emittance measurement is compromised by a weak signal-to-noise ratio on the observing screen. Improved diagnostics is currently being installed.

Table 1 summarizes the emittance values measured so far and compares them to design values. The reported errors are statistical; they are obtained by repeating the measurement a few times at a given setting.

OTHER MEASUREMENTS

Further commissioning work in the past few months mainly concerned the understanding and setup of the movable bunch compressor chicane. The activities include measurements of R_{56} and R_{16} as a function of the dipole current to obtain a complete characterization of the compressor. A setup procedure was worked out which ensures the correction of both the residual dispersion downstream of the bunch compressor and the effect of geomagnetism in the drift lengths of the chicane. First studies on mitigating the effect of coherent synchrotron radiation using the small quadrupoles inside the chicane have also been carried out, with encouraging results. The detailed findings of these studies will the subject of future reports.

Table 1: Measured normalized projected and core slice emittances in comparison to simulated values for the two different charge modes. Errors are statistical.

type	σ_{laser} [mm]	$\varepsilon_{n,x}$ [µm]	$\varepsilon_{n,y}$ [µm]	$\varepsilon_{n,\text{sim}}$ [µm]
high-charge mode (≈200 pC):				
proj.	0.21	0.379 ± 0.004	0.369 ± 0.004	0.350
slice	0.21	0.251 ± 0.004	–	0.330
low-charge mode (≈10 pC):				
proj.	0.10	0.161 ± 0.001	0.181 ± 0.002	0.096
slice	0.10	≤ 0.15	–	0.080

CONCLUSION AND OUTLOOK

The commissioning of the SwissFEL Injector Test Facility is progressing steadily towards the final characterization of the high-brightness beam required to drive SwissFEL. The last months were dedicated to emittance optimization with uncompressed bunches, yielding promising results.

During a recent shutdown, the last main component of the injector test facility was installed, a harmonic X-band (12 GHz) cavity in front of the bunch compressor, which will finally allow beam characterization after linear bunch compression, the crucial next step towards the demonstration of the validity of the SwissFEL design concept.

ACKNOWLEDGMENT

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