PROGRESS REPORT ON THE SwissFEL INJECTOR TEST FACILITY

T. Schietinger, M. Aiba, S. Bettoni, B. Beutner, M. Csatari Divall, K. Doshekenov, Y.-C. Du, M. Guetg, C.P. Hauri, R. Ischebeck, F. Le Pimpec, N. Milas, G.L. Orlandi, M. Pedrozzi, P. Peier, E. Prat, S. Reiche, B. Smit, A. Trisorio, C. Vicario
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

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. The RF photoinjector facility has been in operation since 2010 and has recently reached its design energy of 250 MeV. A newly installed movable magnetic chicane allows longitudinal bunch compression studies. We report on the first experience with the bunch compressor and present the latest results of projected and slice emittance measurements.

INTRODUCTION AND MOTIVATION

The SwissFEL project at the Paul Scherrer Institute (PSI) aims at realizing an X-ray Free Electron Laser (FEL) user facility by 2017, delivering ultrashort coherent photon pulses in the wavelength range between 0.1 and 0.7 nm [1]. The linac design calls for a relatively low electron beam energy to minimize facility length and therefore cost. As a first step towards SwissFEL, PSI is commissioning a highly flexible 250 MeV photo-injector, the SwissFEL Injector Test Facility. Its purpose consists in extensive studies of the generation, transport and compression of high-brightness electron beams as well as testing of crucial components for SwissFEL [2].

The operation of the test facility started in 2010, with successive commissioning of the gun section and the remaining linac [3]. In July 2011, a magnetic bunch compression chicane was installed downstream of the booster section. The following months were dedicated to the consolidation of the S-band RF system, as well as the integration of additional longitudinal diagnostics at the bunch compressor. Beam development resumed in early April 2012, with all accelerating RF structures in operation. The nominal beam energy of 250 MeV was reached for the first time on April 11. The first few weeks of operation were dedicated to optics matching, measurement of projected and slice emittance with uncompressed beam, and first bunch compression experiments. In this paper we give a brief overview of the very first results obtained within the first few weeks of running at or near design energy.

BEAMLINE SETUP

Electron bunches are produced and accelerated to 7.1 MeV/c momentum in a laser-driven S-band RF gun (CTF3 Gun Nr. 5, copper cathode). The drive laser is based on a TW class, frequency tripled Ti:sapphire chirped-pulse amplifier [4]. An approximate flat-top longitudinal intensity profile is achieved with pulse-stacking using a series of birefringent BBO-crystals (10 ps FWHM pulse length). A smaller Nd:YLF amplifier serves as a back up laser system. After initial focusing by a movable gun solenoid allowing for emittance compensation, the electron bunches are further accelerated up to 250 MeV/c by four S-band accelerating cavities, each surrounded by four focusing solenoids. The booster is followed by a dispersive magnetic chicane, which acts as a longitudinal bunch compressor if the bunch features a particle energy correlation along the bunch (energy chirp, induced by off-crest RF acceleration). An additional harmonic (X-band) RF cavity is foreseen to be installed in front of the bunch compressor later in 2012 to compensate the curvature in longitudinal phase space caused by the sinusoidal RF wave. The diagnostic section consists of a quadrupole lattice for optics-based emittance measurements as well as a five-cell S-band RF deflector for bunch length and slice-resolved measurements (resolution 20 fs). Transverse beam profiles are measured with a series of screen monitors (YAG or LuAG crystals and thin metal-foils emitting optical transition radiation, OTR), orbit information is provided by a series of resonant strip-line beam-position monitors.

The measurements shown below were performed at a beam energy of 230 MeV and a bunch charge of 200 pC. The laser spot size at the cathode was kept at 1.07 mm diameter.

BUNCH COMPRESSION CHICANE

Bunch compression is achieved with a four-bend magnetic chicane, where the two central dipole magnets are installed on a movable girder to allow different deflection angles. The four dipole magnets are connected in series to ensure equal field in each dipole, with small corrector dipoles to compensate for field imperfections. Two small quadrupoles attached to the outer arms are used to correct for residual dispersion. Figure 1 shows a 3D drawing of the compression chicane, Table1 lists a few relevant parameters.

EMITTANCE MEASUREMENTS

Low emittance is one of the key requirements for the electron beam in view of its application as a FEL driver. While the eventual lasing in the undulator section will mainly depend on a small slice emittance of the core bunch, the optics matching of the linear accelerator calls for a reasonably small projected emittance. We measure both projected and slice emittance with optical methods, where the

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Table 1: Some Bunch Compression Chicane Parameters

Parameter	**Nominal**	**Maximal**
R_{56}	–46.8 mm	–68.9 mm
Displacement	0.333 m	0.404 m
Deflection angle	4.1°	5.0°
Bend magnetic field	0.18 T	0.22 T
Total length		11.16 m
Inner drift length		0.75 m
Outer drift length		4.39 m
Dipole length (effective)		0.25 (0.303) m

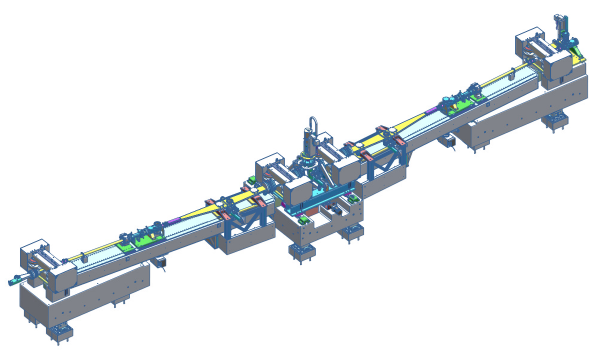

Figure 1: 3D drawing of the bunch compression chicane. The two central dipoles can be moved laterally.

beam size is measured as a function of varying phase advance. The beam sizes are determined from Gauss fits to background-subtracted beam profiles using the OTR screens.

Two strategies are used to generate phase advance for the measurement of *projected emittance.* In the first, the strengths of three matching quadrupoles are varied in a predefined sequence, which ensures successive phase advance in steps of 5°, 10° or 15° at a screen further downstream while keeping the beam size within some limits suitable for measurement. The phase advance is first scanned in the horizontal (x), then in the vertical (y) plane. In the second approach, a single quadrupole is used to generate phase advance simultaneously in x and y. This is possible if the beam optics at the scanning quadrupole are equal in both planes, with α given by the product of β and L, the distance to the observing screen, i.e., $\beta_x = \beta_y = \beta_0 = \alpha_0 L$ where $\alpha_0 = \alpha_x = \alpha_y$. In this case the waist occurs in both planes for zero quadrupole gradient and is equal to $\beta_{\min} = L^2/\beta_0$ (thin lens approximation). In both methods, the beam is first matched to the measurement optics by means of a matching tool based on a suitable online model.

Measurements of normalized projected emittance after an adjustment of the gun solenoid field typically yield values of around 0.4 mm mrad in x and 0.6 mm mrad in y. The x-y asymmetry has been the subject of investigation and can probably be attributed to component misalignment in the low-energy section of the beamline, to be adjusted in the immediate future. Meanwhile the effect can be partially compensated by individually tuning the current of the solenoids surrounding the S-band cavities. The smallest symmetric emittance achieved so far is $\varepsilon_{n,x} = 0.448 \pm 0.013$ mm mrad and $\varepsilon_{n,y} = 0.442 \pm 0.026$ mm mrad, where the errors are statistical only and obtained from the evaluation of 10 images per set point. In Fig. 2 we show the details of this measurement (single-quadrupole scan, uncompressed bunch).

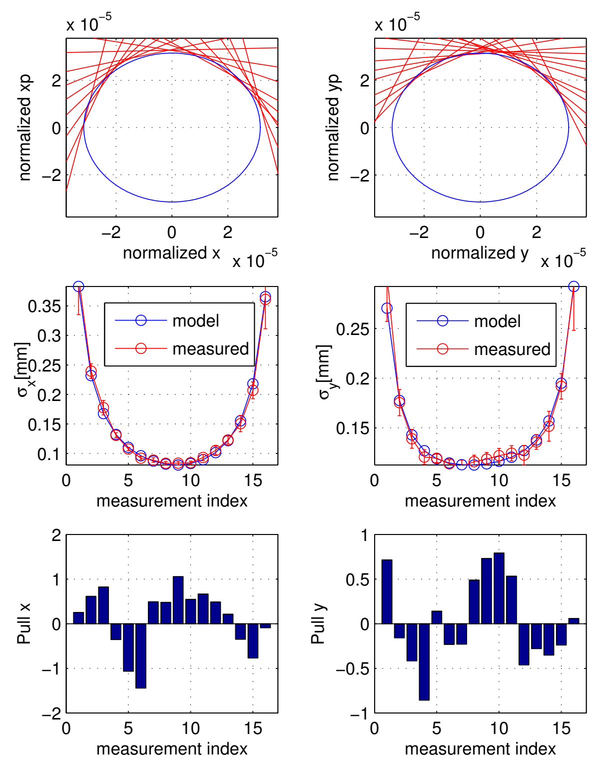

Figure 2: Single-quadrupole emittance measurement showing normalized phase space with beam size measurements under different phase advance as tangential lines (top plots), measured beam sizes in comparison to the model expectation (middle plots), and the corresponding statistical pulls defined as the difference between measurement and model normalized by the measurement error (bottom plots).

In the *slice emittance measurement,* beam optics parameters and emittance are measured for individual bunch slices. The transverse deflecting RF cavity is used to “streak” the beam vertically, providing the necessary longitudinal resolution of the bunch on a subsequent observation screen. Phase advance (in the horizontal plane only) is again generated with a set of quadrupoles downstream of the deflecting cavity. The quadrupole settings are optimized to control the beam size in both planes and to keep the longitudinal (slice) resolution constant, in addition to providing phase advance.

First measurements of slice emittance with uncompressed bunches gave values between 0.25 and 0.30 mm mrad for the central slices. Figure 3 summarizes the result of such a measurement.

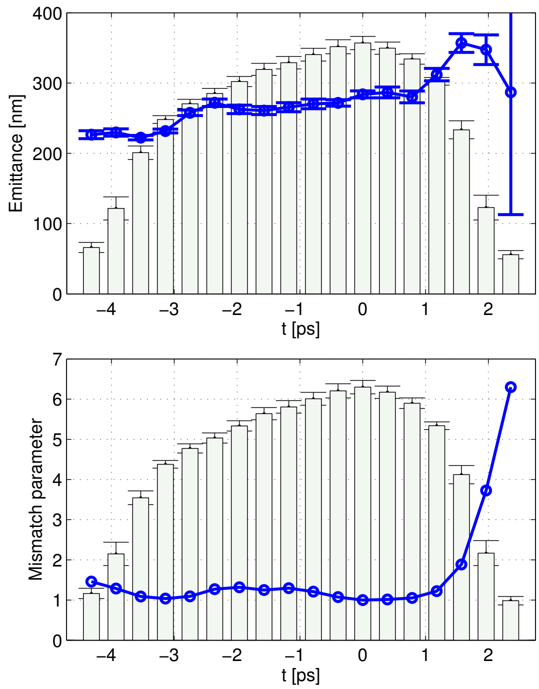

Figure 3: Slice emittance measurement: charge profile (bars) in comparison to slice emittance (top) and relative mismatch parameter (bottom) as a function of position along the bunch.

FIRST BUNCH COMPRESSION STUDIES

First experiments using the bunch compression chicane resulted in a reduction of the rms bunch length from 3.6 to 0.2 ps. Figure 4 shows a series of images demonstrating the compression of the bunch as the phase of the last two S-band RF cavities is successively moved from on-crest to 46° off-crest, where maximal compression occurs (this measurement was performed with the Nd:YLF laser featuring a Gaussian longitudinal profile). Preliminary measurements of the R_{56} parameter under various bending angles using the RF deflector to measure arrival time are consistent with expectation. A coherent synchrotron radiation monitor picking up radiation in the THz range emitted by the compressed bunch in the last dipole of the chicane was successfully tested during these first bunch compression studies.

CONCLUSION AND OUTLOOK

The SwissFEL Injector Test Facility has recently reached its design energy of 250 MeV. First measurements of projected and slice emittance in this energy range gave values well below 0.5 mm mrad and 0.3 mm mrad, respectively, thus validating the SwissFEL injector design. First experiments with the bunch compressor show a reduction of the bunch length by about a factor of 20. Later in 2012, the facility will be completed with the installation of a harmonic X-band cavity enabling linear bunch compression.

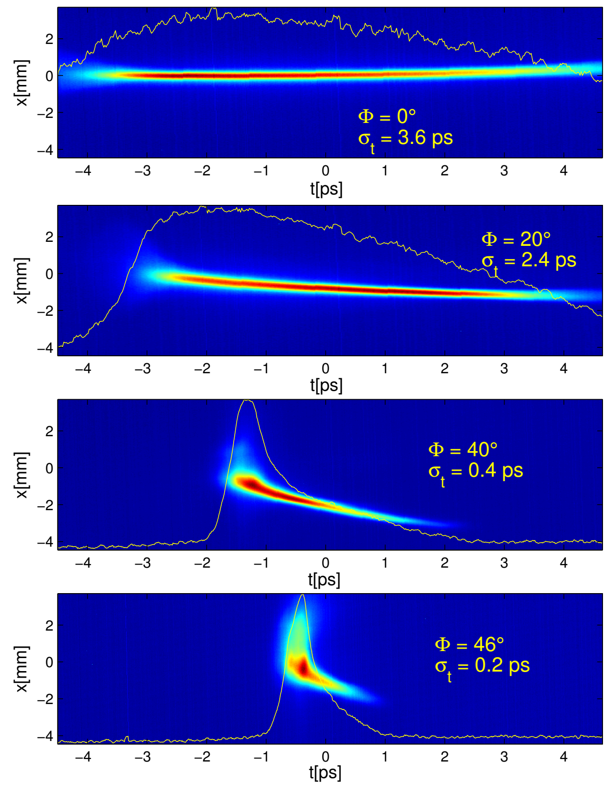

Figure 4: Series of images illustrating the compression of the bunch as a function of the phase of the last two S-band RF cavities. The rotated images show the bunch after it is streaked vertically by the RF deflector, therefore, the horizontal axis corresponds to the longitudinal coordinate along the bunch whereas the vertical axis corresponds to the horizontal bunch coordinate.

ACKNOWLEDGMENT

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