SWISSFEL INJECTOR TEST FACILITY – TEST AND PLANS

M. Pedrozzi, T. Schietinger, M.Aiba, S. Bettoni,B. Beutner, A.Falone, R. Ganter, R. Ischebeck, F. Le Pimpec, N.Milas, G.L. Orlandi, E. Prat, S. Reiche, A. Trisorio, C. Vicario
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

Abstract

In August 2010 the Paul Scherrer Institute inaugurated the SwissFEL Injector Test Facility as a first step towards the Swiss hard X-ray FEL planned at PSI. The main purpose of the facility is to demonstrate and consolidate the generation of high-brightness beam as required to drive the 6 GeV SwissFEL accelerator. Additionally the injector serves as a platform supporting development and test of accelerator components/systems and optimization procedures foreseen for SwissFEL. In this paper we report on the present status of the commissioning with some emphasis on emittance measurements and component performances. The scientific program and long-term plans will be discussed as well.

INTRODUCTION

To operate in the wave length range between 0.1 and 7 nm the compact X-ray FEL planned at PSI relies on low emittance electron beam and short period undulator [1,2]. To investigate the generation, the acceleration, the transport and the stability of a high brightness beam sufficient to drive the main SwissFEL linac a flexible 250 MeV injector facility was built at PSI. The goal beam parameters for this test facility are summarized in Table 1.

As described schematically in Figure 1 the injector layout starts with a 2.6 cells S-band RF photo-cathode followed by four S-band travelling wave (TW) accelerating structures surrounded by solenoid magnets. A magnetic chicane with bending angle adjustable between 0 and 5 degrees allows extensive studies and optimization of the bunch compression parameters. The chicane is preceded by a 4th harmonic cavity [2] for linearization of the longitudinal phase space.

A long diagnostic section including a 5-cell deflecting cavity follows for the projected and slice beam characterization. A detailed description of the SwissFEL Injector Test Facility can be found in [3,4].

COMMISSIONING PROGRESS

The SwissFEL Injector Test Facility has been in progressive commissioning since the beginning of 2010. The official inauguration ceremony with first beam down to the beam dump took place in August 2010 after an earlier commissioning and characterization of the electron source performed in parallel with the assembly of the acceleration and transport line [5].

Table 1: SwissFEL Injector Test Facility Beam Parameters

Parameter	Goal	Test facility
Charge – operation mode (pC)	10	200
Projected norm..Emittance (mm.mrad)	0.15	0.5
Slice norm. emittance (mm.mrad)	0.11	<0.43
Uncorrelated energy spread (keV)	<50	<50
Peak current (A)	100	300
Energy (MeV)	250	250

The second commissioning phase between October 2010 and May 2011, reported here, was principally dedicated to consolidate the matching procedure in the diagnostic line and the measurement techniques for the projected emittance. The RF plants available during this first phase (RF-gun, first and second TW accelerating structure) were usually adjusted near the expected conditions for the invariant envelope matching [6] generating a beam of 130 MeV and up to 200 pC [7]. The third commissioning phase will start late in 2011 after the summer shutdown dedicated to the integration of the magnetic chicane and to the consolidation of the RF systems.

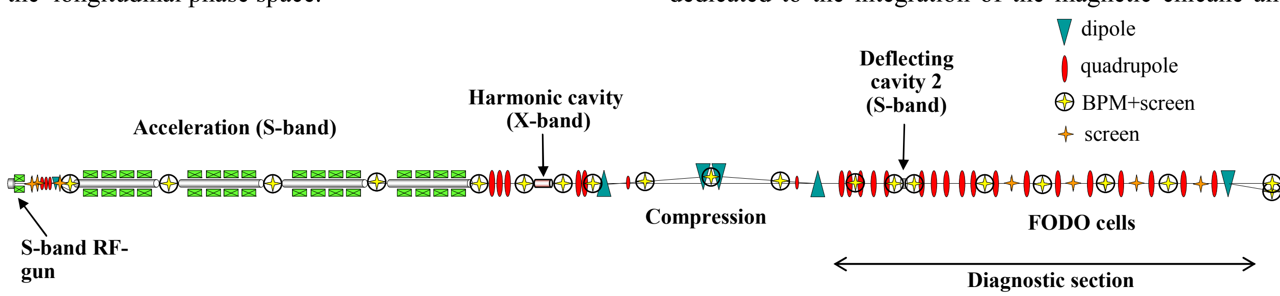

Figure 1: Schematic layout of the SwissFEL Injector Test Facility.

RF Photo Cathode Experience

Two different laser systems were used to drive the photo-cathode. The first one dedicated to basic commissioning purposes is based on a Nd-YLF amplifier [8] that delivers 200 μJ Gaussian impulses after frequency

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multiplication at 262 nm with pulse length of 6.2 ps FWHM. The second and more sophisticated system foreseen for SwissFEL is based on a wavelength tunable Ti-Sapphire oscillator and amplifier system capable of delivering up to 500 µJ after frequency multiplication in the wavelength range between 260 and 283 nm [9]. The temporal pulse shaping is realized via the pulse stacking method. To approximate a 10ps flat-top pulse (Fig. 2) 32 identical replica of the initial Gaussian pulse (~320 fs FWHM) are generated and stacked by cascading several birefringent α-cut BBO crystals

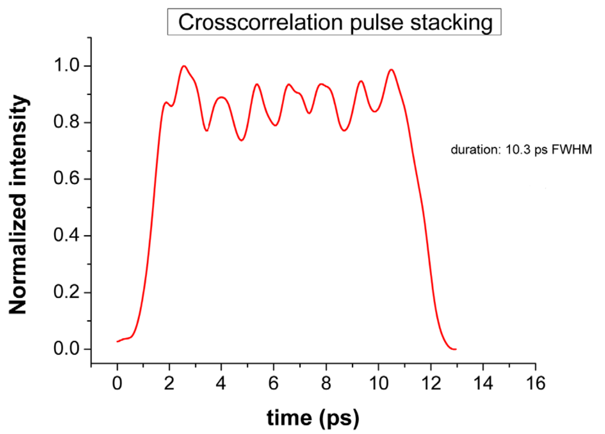

Figure 2: Measurement of the temporal profile of the UV laser pulse generated by pulse stacking.

The cathode consists of a diamond-milled copper plug of 18 mm diameter hosted by a 2.6 cell S-band RF-gun, which was developed in the framework of CTF3 [10]. Due to cooling limitation of the RF cavity the present repetition rate while operating at 100 MV/m peak gradient is 10 Hz. A new 2.6 cell RF-gun able to work at 100 Hz is presently in construction at PSI and will be ready for installation in the beginning 2013.

During phase 2 the RF gun was typically delivering up to 200 pC for a momentum of 7.1 MeV/c. In February 2011, the cathode was replaced as it was showing large non-homogeneities in the emission. Figure 3 shows the emission map obtained by scanning the cathode surface with a focused laser beam. On the map of the first cathode, besides the global non-homogeneity low quantum efficiency (QE) circular spots are clearly visible; these correspond to regions which were illuminated by the UV laser. The second cathode, which experienced a very smooth RF conditioning, was showing after installation a very smooth emission profile with typically ±15 % peak to peak QE fluctuations while on the first cathode it was exceeding ±50%. The initial measured QE was 4.2 10^{-5} for the first cathode and 9 10^{-5} for the second. A QE degradation to 7 10^{-5} after 3 Month of operation was observed on the second cathode in the region illuminated by the UV laser. Usually associated to contaminants it is the subject of further investigations.

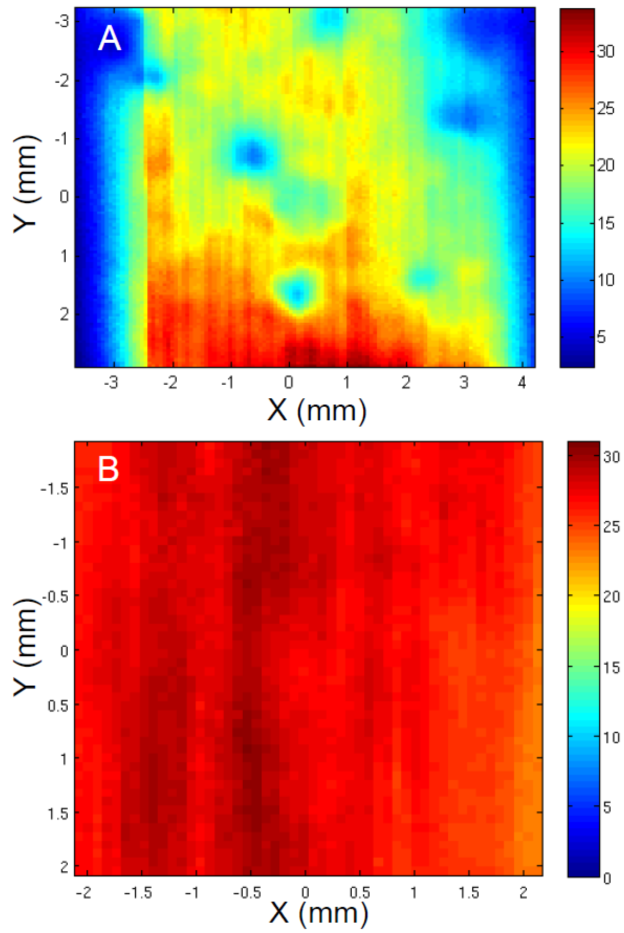

Figure 3: Cathode extracted charge - contour plot (a.u.). A) First cathode. B) Second cathode after installation

Matching Techniques

Reliable and precise measurements of the phase space depend on a proper matching in the diagnostic section. The wide range of beta function at the accelerator exit is controlled via the focusing solenoids surrounding the S-band accelerating sections. To determine the unknown Twiss parameters α and β a robust method independent from any absolute beam size measurement was therefore developed [11]. The results were used to match the optics to the diagnostic section.

The method is essentially based on an independent scan of two quadrupoles. The quadrupole setting corresponding to the minimum beam size measured at an appropriate observation point downstream the magnet defines a set of possible solutions for α and β. Combining this result with a scan performed with a different quadrupole uniquely determines the Twiss parameters. The fine matching is then optimized via an on-line model.

Emittance Measurements

One of the main goals of the beam dynamics studies performed during phase 2 was to establish and automatize a robust method for measuring the projected emittance of the electron beam.

Two methods based on a series of beam size measurements, with defined phase advance of the optical parameters, were investigated and compared. 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 quadrupoles was chosen to keep the beam size at the observation point within a relatively small range, which alleviates 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 (see Figure 1), 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 were performed with the first method ("triple-quad scan") since it was found to be simpler and faster, while the more involved FODO measurements served as an occasional crosscheck [12].

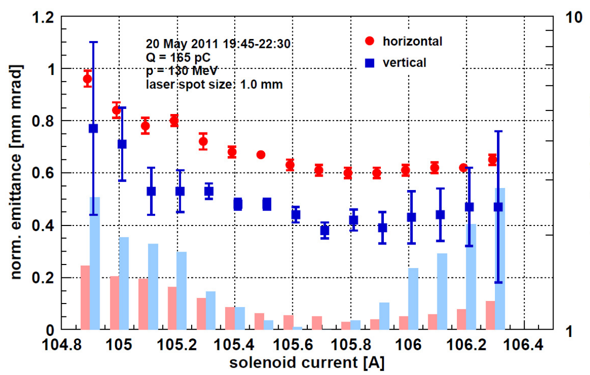

Figure 4: Emittance versus gun solenoid strength (165 pC, 130 MeV).

After establishing the emittance measurement the first attempt at matching the injector to the invariant envelope conditions was performed mainly by adjusting the gun solenoid strength. In Fig. 4 we show the measured emittance as a function of gun solenoid current (Ti:Sapph laser). At the optimal solenoid settings we observed the following emittances:

$$\varepsilon_{n,x} = 0.61 \pm 0.02 \text{ mm mrad}$$

$$\varepsilon_{n,y} = 0.38 \pm 0.03 \text{ mm mrad}$$

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 yet fully clear; one contribution could arise from quadrupole aberrations in the gun solenoid field without excluding other factors downstream. Attempts to compensate the transverse coupling was then performed using the corrector skew quadrupole integrated in the gun solenoid which results typically in scans as shown in Fig. 5. In this case at the optimum solenoid strength we have:

$$\varepsilon_{n,x} = 0.55 \pm 0.01 \text{ mm mrad}$$

$$\varepsilon_{n,y} = 0.52 \pm 0.01 \text{ mm mrad}$$

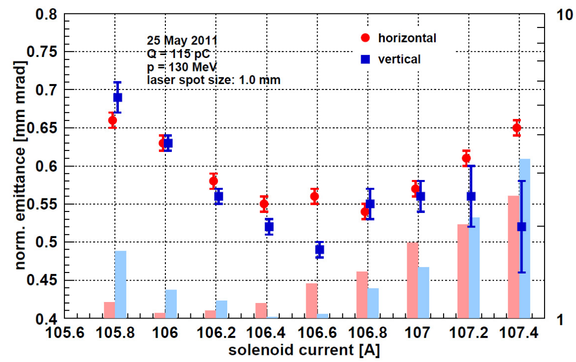

Figure 5: Emittance versus gun solenoid strength –after asymmetry correction via quad and skew quad integrated in the gun solenoid (115 pC, 130 MeV)

Bunch Length Measurements

The first bunch length measurements were performed using a 5-cell standing wave S-band RF deflector based on the SPARC cavity design [13] and manufactured for PSI by INFN-LNF in Frascati.

The commissioning and calibration of the bunch length measurements were carried out with the Nd:YLF laser, which provides, at the cathode, a Gaussian beam profile with σ_t = 2.6 ps. To control systematic effects the measurements were repeated at deflecting voltages varying between 1 and 2 MV. In agreement with the initial laser pulse profile and setting the machine for "on crest" acceleration we measured as expected an rms bunch length of 2.6 ± 0.2 ps.

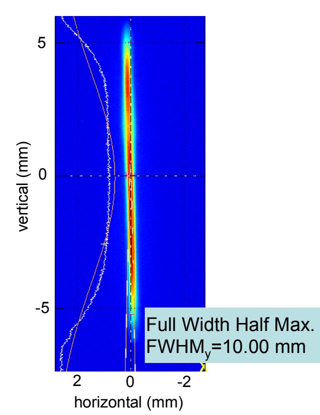

Figure 6: Streaked beam on the observation screen for "on crest" acceleration

A similar measurement was later performed with the Ti-Sapphire system. The typical image of the streaked beam behind the deflecting cavity is shown in Figure 6. The slight vertical tilt is a signature of the transverse wakes in the S-band TW structures which indicate a non-optimal alignment of the electron orbit. The bunch length

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evaluated with two different deflecting voltages are again consistent with the laser pulse profile at the gun as reported in Table 2.

Table 2: Pulse Length Measurements At 130 MeV With Ti-Sapphire laser

Deflecting voltage (MV)	Beam vertical size on screen FWHM (mm)	Pulse length FWHM (ps)
1.15	10.00±0.06	9.85±0.11
1.48	12.44±0.08	9.57±0.14

The RF deflector in combination with the dispersive spectrometer arm at the end of the facility allows the characterization of the electron distribution both in terms of energy and phase. As an example we show in Fig. 7 three images of the streaked beam in the spectrometer obtained with the first S-band accelerating structure running respectively in bunching mode (+10 degrees out of crest), on-crest and in de-bunching mode (-10 degrees out of crest). The on crest distribution clearly shows the RF curvature in the longitudinal phase space.

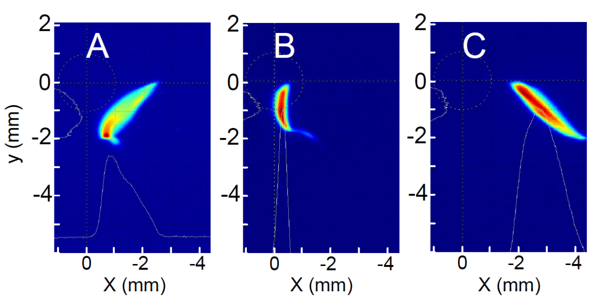

Figure 7: Streaked beam in the spectrometer harm (Vertical ∝ Time, Horizontal ∝ Energy). **A)** bunching mode +10 deg in first TW cavity , **B)** on crest, **C)** de-bunching mode -10 deg in first TW cavity. .

EXPERIMENTAL PROGRAM

The past operation period of the SwissFEL injector Test Facility was mainly dedicated to establishing the methods for measuring the beam emittance and commissioning to the first tool for accessing the longitudinal phase space. During the imminent third phase of the commissioning systematic optimizations of the machine aiming at reducing the projected emittance will be performed for both the high and low charge regimes. Although very similar to the procedure for measuring the projected emittance the method for measuring the slice emittance must be established and automatized.

To to understand the potential emittance dilution mechanisms in the magnetic compression chicane and to indentify the optimal settings for SwissFEL a wide range of beam and chicane parameters must be investigated. For this purpose in 2012 the X-band cavity will be finally integrated into the facility.

CONCLUSIONS

At PSI the SwissFEL Injector Test Facility is being progressively commissioned since the beginning of 2010. The first encouraging results with uncompressed electron beams shows that normalized projected emittances lower than 0.4 mm mrad at 200 pC are achievable. Although a systematic investigation of the emittance compensation and the mechanisms diluting the emittance are necessary, the machine can easily reproduce projected emittances between 0.5 and 0.6 mm mrad with uncompressed beams. The magnetic bunch compressor was integrated in the test facility during the summer shutdown. The commissioning of this component will be performed late in 2011, while the harmonic cavity for phase space linearization will be implemented in 2012.

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