CHARACTERIZATION OF COMPRESSED BUNCHES IN THE SwissFEL INJECTOR TEST FACILITY

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Abstract

The quality of the beam transverse emittance at the cathode and the uniformity of the longitudinal compression of the electron bunch are essential for the lasing efficiency of a Free Electron Laser. In SwissFEL the longitudinal compression of the electron beam is performed by means of two magnetic chicanes and an off-crest acceleration scheme. The curvature induced on the beam longitudinal phase-space during the compression can be compensated by means of an X-band cavity. The longitudinal phase-space of the beam can be experimentally characterized by means of a Transverse Deflecting Cavity (TDC) and a profile monitor in a dispersive section. Longitudinal phase-space measurements at the SwissFEL Injector Test Facility under compression with and without X-band linearizer are presented. In addition, energy spread measurements done by monitoring the Synchrotron Radiation (SR) emitted by the electron beam in the dispersive section of the chicane are shown. A comparison with numerical simulations is presented.

INTRODUCTION

The SwissFEL will provide a coherent X-rays source in the wavelength region 7-0.7 nm (phase-2) and 0.7-0.1 nm (phase-1) accelerating 200/10 pC electron beams up to an energy of 5.8 GeV [1]. For such a goal, the high brilliance features of the electron beam (normalized emittance 0.4/0.2 mm.mrad) has to be preserved during the acceleration - operated by a RF S-band Travelling Wave (TW) injector up to 330 MeV and, finally, by a RF C-band TW linac - and during the linear compression of the bunch length from 3/1 ps (RMS) up to 20/3 fs (RMS). The linear compression of the electron beam is provided by two magnetic chicanes downstream two X-band RF cavities compensating the quadratic distortion of the longitudinal phase space due to the off-crest accelerating scheme of the S-band structures and of the non-linear contribution of the magnetic dispersion. After the linear compression and a further linear acceleration, the electron beam - emitted at a repetition rate of 100 Hz with a 28 ns two-bunches temporal structure from a Copper photocathode illuminated by a Ti:Sa laser with a flat-top longitudinal profile (3.6/10 ps, FWHW) - is splitted via a magnetic switchyard to simultaneously supply two different undulator lines: the hard X-ray undulator line (ARAMIS) and the soft X-ray undulator line (ATHOS).

The 250 MeV SwissFEL Injector Test Facility (SITF) is the test-bed of the SwissFEL [2], see Fig.1. The Gun section is composed of a Ti:Sa laser extracting photo-electrons from a Copper cathode and a Standing-Wave (SW) S-band 2.5-cell RF gun accelerating a 200/10 pC electron bunch up to 7.1 MeV/c at a repetition rate of 10 Hz. The booster section is composed of four S-band TW RF structures accelerating the beam up to a maximum final energy of 250 MeV. The bunch linear compression section is composed of a X-band cavity upstream a magnetic chicane. Finally, a SW S-band 5-cell Transverse Deflecting Structure (TDS) upstream a FODO section, which is equipped with several beam profile monitors, and an energy spectrometer allow the experimental characterization of the longitudinal and transverse phase space of the beam.

Main goals of the SITF are: to demonstrate that the high brilliance quality of the electron beam - as required by the SwissFEL specifications - can be preserved during the acceleration and the linear compression; to test diagnostic solutions and measurement techniques to be adopted for SwissFEL. The experimental work so far carried out at SITF confirmed the achievement of the specifications imposed by the SwissFEL [3, 4, 5] and the reliability of the diagnostic solutions foreseen for SwissFEL [6]. A report on the bunch-compression operations and on the related beam longitudinal phase-space characterization, which has been carried out at SITF with and without the X-band linearizer, will be presented in the following.

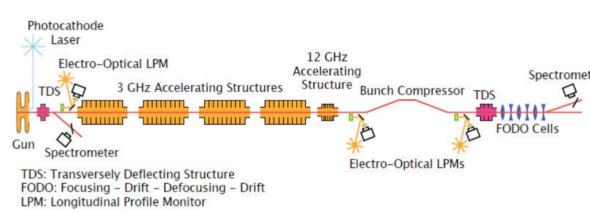

Figure 1: SITF schematic layout.

BUNCH-COMPRESSION OPERATIONS

Bunch-compression at SITF is obtained by a longitudinal dispersive path, a so called chicane, in combination with an energy chirped electron beam. The energy chirp of the electron beam is provided by off-crest acceleration in the last two S-band injector modules. An X-band system, which is operated at 180°, can be used to linearize the

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dynamics. Without initial linear and quadratic correlations in longitudinal phase space, the approximate longitudinal dynamics of such a system reads:

$$\Delta s = R_{56}\left(\frac{E_X}{E}\frac{k_X^2}{2}s^2 - \frac{E_S}{E}\left(\sin(\phi)k_S s + \frac{\cos(\phi)}{2}k_S^2 s^2\right)\right) + T_{566}\left(\frac{E_S^2}{E^2}\sin^2(\phi)k_S^2 s^2\right), \quad (1)$$

with the total energy after compression E, the energy gain of the S and X-band systems E_S and E_X, the off-crest RF phase ϕ, the longitudinal dispersion parameters R_{56} and T_{566}, and the wave numbers of the two RF-systems k_S and k_X. The linear term in s is the linear energy chirp used for uniform compression. The X-band voltage E_X is chosen to compensate the other quadratic terms. Compression is implemented by setting the off-crest RF phase in the last two S-band accelerating structures, which determines the compression factor and matches the X-band voltage accordingly. Energy loss generated by the X-band system is compensated with more S-band acceleration. In the following, a description of the main machine components involved in the bunch-compression operations at SITF is given.

The X-band cavity foreseen for the SwissFEL resonates at the forth harmonic of the European S-band (11.992 GHz). The RF power is supplied by the SLAC XL5 klystron, which is developed in the framework of a SLAC-CERN-PSI-Sincrotrone-Trieste collaboration. The RF structure has a length of 75 cm (RF active length), constant gradient, phase advance per cell of $5/6\pi$ and an average iris diameter of 9.1 mm. The geometry adopted, similar to NLC type H75, is a good compromise between a high shunt impedance, associated with small apertures, and a low transverse kick, associated with larger iris apertures. It is composed of 73 cells and integrates two alignments monitors for accurate beam steering and trajectory correction [7]. The cavity is placed on a rigid support that can be remotely motorized for fine 3D mechanical adjustments (maximum deviation of 2 mm with a resolution less than 2 μm and a reproducibility of the positioning better than 5μm).

Downstream the the bunch-compressor (BC) a Transverse Deflecting Structure (TDS) permits to make absolute measurements of the bunch length and to calibrate the near and far-field longitudinal beam diagnostics. The TDS at SITF is an S-band 5-cell $\beta\lambda/2$ RF structure resonating to the π-mode TM_{110} with a length of 45 cm (flange-to-flange). For a maximum input RF power of 5 MW (repetition rate of 10/100 Hz), the TDS integrated voltage is 4.89 MV. Resolution of about 15/10 fs can be reached by the TDS at 250MeV in the two operation modes (200/10 pC).

The movable magnetic chicane (BC) is designed to accept - with a sub-millimeter precision - a beam horizontal dispersion in the range 0-404 mm, corresponding to a BC bending angle between 0° and 5°. The fine adjustment of the horizontal dispersion of the beam trajectory in the BC can be achieved thanks to the flexible design of the chicane vacuum chamber - composed of two arms and a central part whose rigid components are joined together by vacuum-bellows - and a movable girder, where the two inner dipoles of the chicane are mounted, which can be stiffly translated horizontally by means of a micro-meter stepping-motor. The BC is equipped with diagnostics measuring: charge and beam center-of-mass [BPM: Resonant Strip Line (7 μm resolution 5-500 pC) and Cavity BPM]; beam phase jitter (BAM, resolution better than 5 fs); bunch length [Electro-Optical monitor (resolution of 200 fs), THz pyrodetector monitors of coherent synchrotron radiation from the fourth dipole of the chicane and of the coherent diffraction radiation emitted by a diffraction radiation iris [8] just after the magnetic chicane].

Two beam profile monitors are in operation in the BC [9]. A YAG:Ce screen (BC-YAG-Screen) in the mid symmetry plane of the BC and a Synchrotron Radiation monitor (BC-SR-monitor) which, with an acceptance between 3° and 5° of the BC bending angle, can image the SR light spot emitted by the electron beam at the entrance of the third bending dipole of the magnetic chicane. A sCMOS-Camera(PCO.Edge, 100frame/s) equipped with a a 300 mm lens (projected pixel size resolution of 0.040 mm) and a CCD camera (Basler SCOUT) equipped with a 45 mm lens (projected pixel size resolution of 0.115 mm) are the sensors of the BC-SR-monitor and BC-YAG-screen, respectively. At the nominal BC bending angle (4.07°) the relative energy spread resolution ($\Delta E/E$) of the transverse profile monitor are: 1.2×10^{-4} (BC-SR-monitor) and 3.5×10^{-4} (BC-YAG-screen). The sCMOS cameras (PCO.Edge) are connected via a CAMERLINK-Fiber bridge to a PC with a Windows operation system. The CCD camera (Basler SCOUT) is connected via a direct GigE-Link to another PC. The cameras synchronization is done with a TTL-puls generated by the event based timing-system (Micro Research Finland). The software (IOC/EPICS) controls the camera via the vendor software interface and delivers the picture over EPICS or saves the pictures directly to a filesystem. An analysis C/C++ code directly running on the camera server and interfacing the IOC/EPICS channels of the camera allows to process the SR-camera single shot image within (8+/-2) ms. The camera setting and the relevant chicane parameters (the dispersion, for instance) needed for the analysis code as well as the IOC/EPICS flow of the analyzed data can be controlled by a Graphical User Interface (GUI) which displays - vs. time - the measured values of the horizontal centroid and RMS distribution of the single bunch SR light spot. The analysis tool of the BC-SR monitor, recently commissioned at SITF with a beam repetition rate of 10 Hz, meets already the 100 Hz timing constraints of SwissFEL.

MEASUREMENTS

Studies of bunch compression are currently carried out at SITF. Compression studies were already performed before the installation of the X-band cavity [9]. They are

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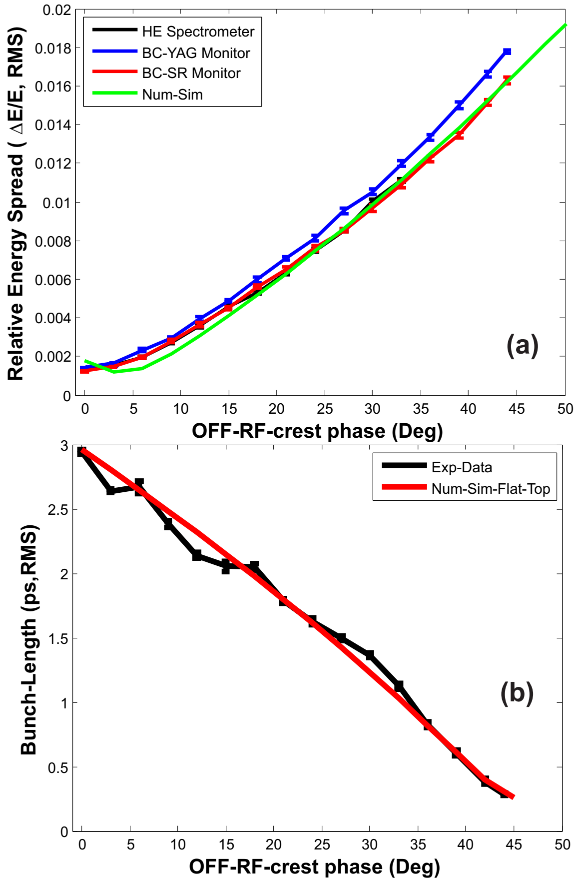

Figure 2: Beam energy of 200 MeV and charge of 180 pC (before Xband installation). (a) Relative energy spread measurements: BC-SR-monitor (red curve); BC-YAG-screen (blue curve); HE Spectrometer (black curve); numerical simulation (green curve). (b) Bunch length measurements: experimental data (black curve) and numerical simulation (red curve).

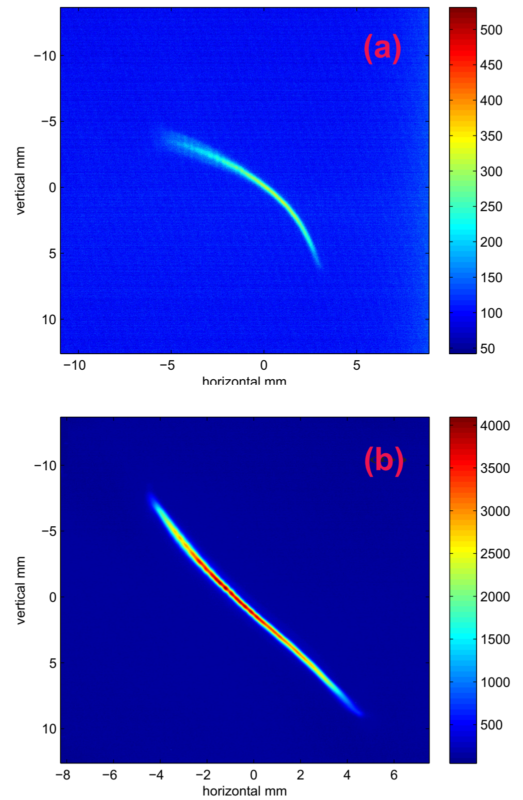

Figure 3: Image of the beam streaked onto the view screen of the HE Spectrometer by means of the TDS (beam longitudinal phase space) for a compression factor 2 (26.8° off-RF-crest): (a) Xband OFF and TDS(0.07MW); (b) Xband ON (4.68MW) and TDS (0.20MW). Horizontal axis is the energy axis, vertical axis is the longitudinal axis.

on-going now after the commissioning of the X-band cavity. A new campaign of measurements with X-band linearizer has been recently carried out. Measurements of the longitudinal phase space under compression with and without X-band linearizer are in the following presented, see Figs.(2,4). During compression operations, the X-band cavity was operated with a RF power in the range 4.7-7.0 MW. For a compression factor 2 and for two different X-band RF power - zero and a "linearizing" power of 4.7 MW - the images of the longitudinal phase space of the beam have been reproduced in the view screen of the High Energy (HE) spectrometer by vertically streaking the beam with the TDS, see Fig.(3). In Fig.(2,4), measurements of the relative energy spread and bunch length vs. compression phase are compared with results of numerical simulations obtained by means of beam tracking codes ASTRA, ELEGANT and LiTrack.

At SITF, the high energy characterization of the electron beam in a horizontal dispersive path can be done in the magnetic chicane - with the BC-SR-monitor and BC-YAG-screen - and in the HE spectrometer thanks to a view screen. For a bending angle of 4.07° the nominal value of the horizontal dispersion in BC is about $\eta_x = 331\ mm$. The nominal horizontal dispersion of the HE spectrometer is about $\eta_x = 275\ mm$ (relative energy spread resolution 8×10^{-5}). From the determination of the RMS horizontal size of the measured beam transverse profile in the dispersive sections, the relative energy spread can be finally evaluated. From the analysis of the reported data, a good agreement between expected and measured values characterizes both measurement campaigns. This agreement is particularly significative for the measurements done before the installation of the X-band cavity, see Fig.(2). In the measurements with the X-band linearizer - see Fig.(4) - a mismatch between the relative energy spread measured by the BC-SR monitor and the HE spectrometer can be observed at a very high compression factor. This discrepancy can be in part explained as the result of a non-homogeneity of the energy spread distribution (filamentation) observed in the HE Spectrometer, see Fig.(5). The BC-SR-monitor images indeed the beam profile at the mid point of the magnetic chicane when the bunch compression is still not com-

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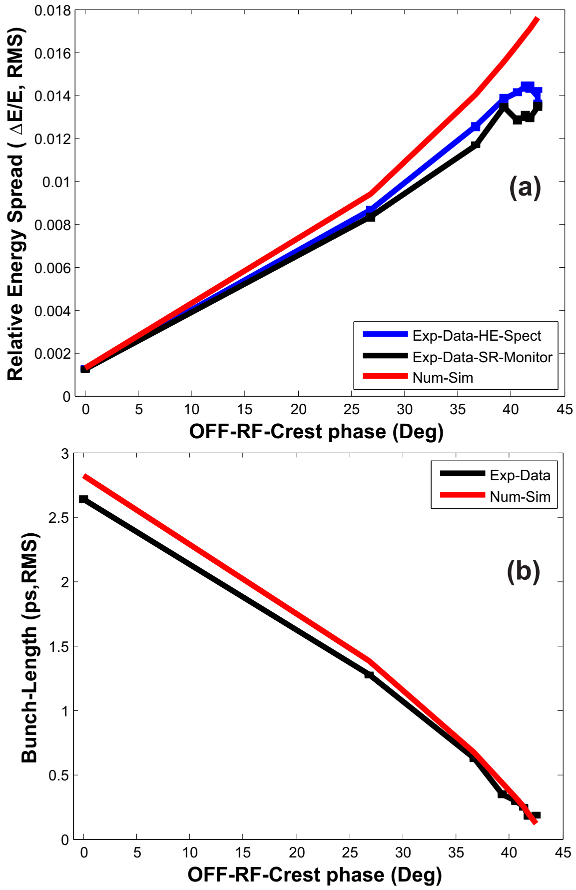

Figure 4: Beam energy of 160 MeV and charge of 160 pC (Xband in operation). (a) Relative energy spread measurements: BC-SR-monitor (black curve); HE Spectrometer (blue curve); numerical simulation (red curve). (b) Bunch length measurements: experimental data (black curve) and numerical simulation (red curve).

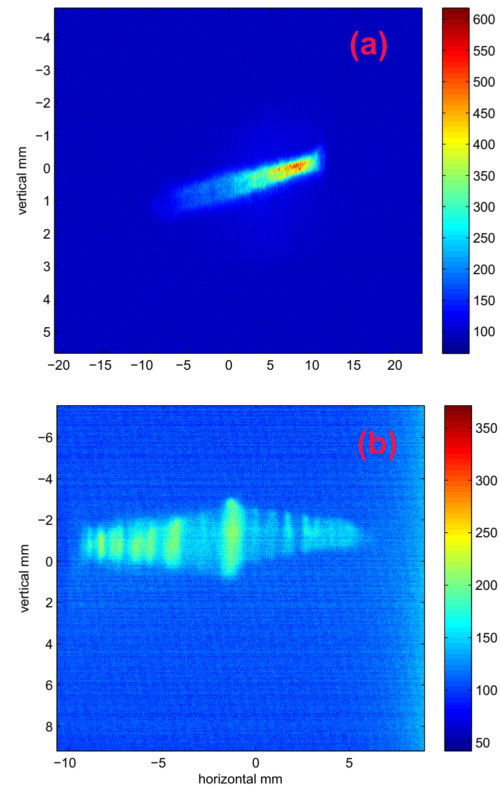

Figure 5: Compression factor 12 (41.8 deg off-RF-crest):(a) BC-SR-monitor; (b) HE Spectrometer. The beam energy distribution shows a non-homogeneity (filamentation) more pronounced at the HE spectrometer than in BC. The horizontal axis is the energy axis.

pletely accomplished. The increase of the correlated energy spread observed between the mid point of the magnetic chicane and the high energy spectrometer can be thus in part explained in terms of a longitudinal space charge effect originated by a longitudinal density modulation which become relevant at a very high compression factor. Further experimental and simulation studies - including a calibration check of the monitors - are foreseen to better understand the longitudinal phase space dynamics under a high compression regime.

CONCLUSIONS

Results on the experimental characterization of the longitudinal phase space vs. compression are here reported for two different SITF machine configurations: before and after the installation of the X-band cavity. The analysis of the experimental data shows a good agreement between measurements and numerical simulations. Further bunch compression studies with X-band linearizer are foreseen for a deeper understanding of the beam dynamics at a high compression regime where a non-homogeneous increase of the correlated energy spread was observed.

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