SASE FEL PERFORMANCE AT THE SWISSFEL INJECTOR TEST FACILITY

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Abstract

A 4 m long prototype of the SwissFEL undulator module with an undulator period length of 15 mm was installed at the SwissFEL Injector Test Facility and tested with a 200 MeV electron beam in the beginning of 2014. We observed FEL lasing in SASE mode in the wavelength range from 70 to 800 nm, tuning the wavelength by energy and gap. The measurements of the FEL performance are reported.

INTRODUCTION

Hard X-ray FEL facilities rely very heavily on cutting-edge technology for RF, diagnostics, insertion devices, and X-ray optics such that building these facilities would represent a high risk without a prior test of the key components. This was the main purpose of various test facilities around the world, such as GTF [1] for LCLS, PITZ [2] for the European XFEL, or SCSS [3] for SACLA. The SwissFEL [4], currently under construction at the Paul Scherrer Institute (PSI), is based on the results of the SwissFEL Injector Test Facility [5], also hosted by the PSI. The test facility has been in operation since August 2010 and will be decommissioned in fall 2014 to move parts over to the SwissFEL building for installation. The start of commissioning of SwissFEL is foreseen for 2015 with a duration of two years.

Like SACLA, SwissFEL will utilize in-vacuum undulators to minimize the undulator period and thus the required electron energy to reach one Angstrom as the resonant wavelength of the FEL. Due to the technical challenge to construct 12 modules of 4 m each a test with an electron beam is highly beneficial to discover possible limitations in the performance of the undulator prototype module. For that an undulator module was installed at the test facility in the early months of 2014. Demonstrating SASE performance was one of the goals for this measurement series and the results are reported in this paper.

THE SWISSFEL INJECTOR TEST FACILITY

The SwissFEL Injector Test Facility (SITF) is a platform to test key components for SwissFEL as well as to demonstrate the beam parameters of the electron beam to successfully operate SwissFEL at its shortest wavelength of 1 Angstrom.

The RF gun is a 2.5 cell photo RF gun [6], operating at European S-band frequency of 2.998 GHz, which has recently replaced the 3rd generation CLIC Test Facility (CTF3) Gun in spring 2014. The former CTF3 gun was sufficient to demonstrate the key beam parameters for a 200 pC beam and a slice emittance of about 200 nm [7]. The gun is followed by two 4 m long S-band traveling wave accelerating structures, boosting the electron energy up to 130 MeV. They are enclosed by focusing solenoids to keep the beam size and Twiss parameter within reasonable limits. An additional S-band RF station feeds two S-Band structures to increase the energy up to 250 MeV and to apply a chirp for compression. However running off-crest to generate the chirp yields less beam energy at a level of about 220 MeV. An X-band RF structure linearizes the energy chirp for a better control on the current profile after compression.

The 11 m long bunch compressor is movable to have variable R_{56} from 0 to 70 mm while keeping the vacuum chamber small. This allows for precise BPM readings in the dispersive section of the bunch compressor as well as the installation of quadrupoles and skew quadrupoles to correct for linear tilts in the electron beam distribution in both transverse planes [8].

A diagnostic section follows the bunch compressor for current profile, projected and slice emittance, and longitudinal phase space measurements (the last in the dispersive part of the beam dump). The key component is a S-band transverse deflecting cavity, streaking the beam in the vertical direction. Initially a FODO section was foreseen to measure the beam size at various positions along several cells of the FODO lattice and reconstruct the beam emittance values from it. In practice quad scans and multi-knob measurements with a dedicated high resolution YAG screen at the end of the beam line were more robust and easier to use [9]. The center part of the FODO section could therefore be modified for other tests.

One important test involved the in-vacuum undulator prototype: a 4 m long undulator with a period length of 15 mm and a tunable undulator parameter K between 1.0 and 1.7. The main study was the entrance and exit kick of the undulator on the electron beam and the alignment strategy of the module by means of alignment quadrupoles [10]. The orbit within the undulator is checked with the spontaneous radiation (or FEL beam) on various screens after the undulator and compared to the electron BPM reading.

With the installation of an undulator the expectation for a SASE signal comes naturally. In particular the narrow opening angle of the FEL signal would yield better resolution in the angle between light cone and electron beam than the rather broad and weak signal of the spontaneous undulator radiation.

The general layout of the SwissFEL Injector Test Facility is shown in Fig. 1.

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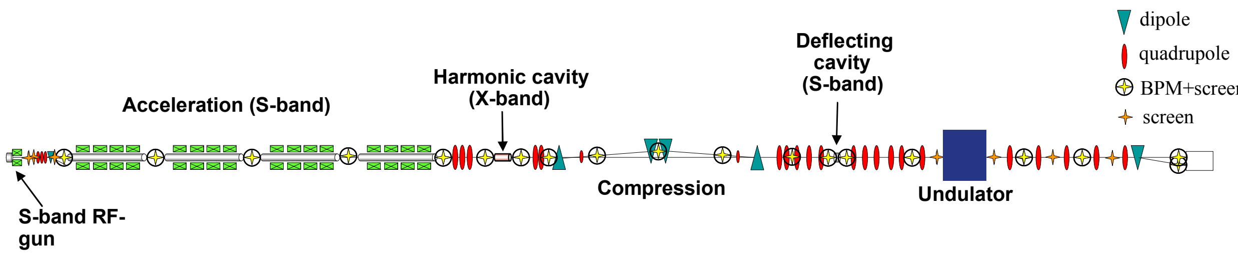

Figure 1: Schematic Layout of the SwissFEL Injector Test Facility.

SASE FEL MEASUREMENTS

In this section we report the measurements of the FEL performance. In the same measurement period from January to April 2014 other studies have been carried out, such as the orbit response measurement of the U15 undulator module, which are reported elsewhere [10] and not directly related to the FEL performance.

Within two days of restarting the test injector after shutdown we observed a bright signal on a YAG screen after the undulator in addition to the electron spot. However the spot exhibited diffraction like patterns and could not be propagated beyond the first screen. Also the statistical distribution of the FEL pulse intensity didn't follow the expected Gamma distribution [11] but had a significant enhancement at very low pulse energies. The suspicion that we have observed only a reflection of the FEL beam was confirmed by increasing the aperture of the vacuum chamber after the undulator

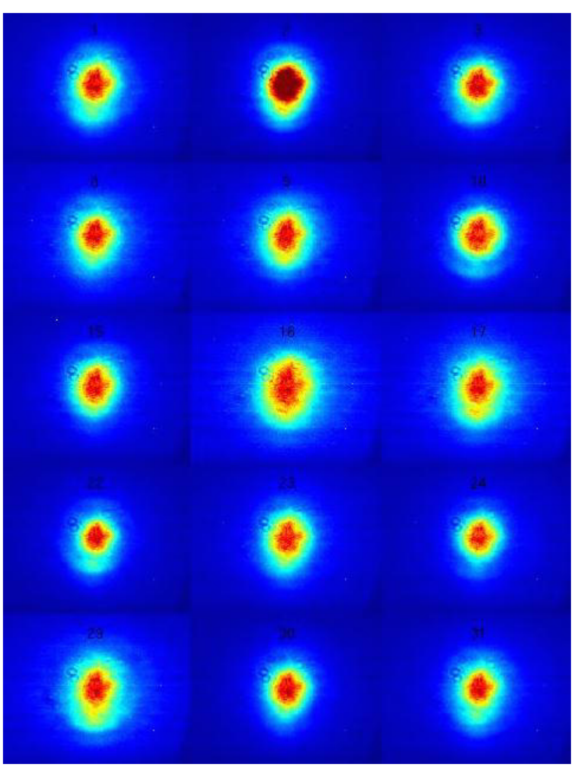

Figure 2: Various FEL spots on a YAG screen 1 m after the undulator.

and the analysis of the orbit response measurements indicating a very strong downward kick of the electron beam by the fringe fields of the undulator field [10].

After the modification we observed an almost round spot on various screens after the undulator. With a pair of corrector magnets right after the undulator module the FEL signal was separated from the electron beam. A special YAG screen with a hole in the lower half allowed bypassing the electron beam without generating scintillating light in the case that the FEL signal would be weak. However the intensity of the spot was bright enough that a normal YAG screen could be used. Figure 2 shows a series of FEL spots on the YAG screen, 1 m behind the undulator module, taken for the statistical analysis of the FEL energy.

The measurement of the intensity fluctuation can give information on the pulse length of the FEL pulse. The less it fluctuates the longer the FEL pulse is because more spikes are present in the pulse reducing the fluctuation in the summation over all spikes per pulse. To check the behavior we configured the FEL for two different electron bunch lengths and compared with numerical simulations, using the FEL code Genesis 1.3 [12]. For the simulations we didn't fit any beam parameter. Instead the beam properties were derived from the measurement of the electron beam parameters at the test facility, such as bunch length, charge, emittance and energy chirp.

The results of measurements and simulations are shown in Fig. 3 and are in reasonably good agreement. Assuming a Gamma distribution as the underlying distribution the only free parameter is M and has fit values of $M = 136$ and $M = 208$ for the measurement and simulation, respectively. The beam energy was 100 MeV and a peak current of 20 A, resulting in a radiation wavelength of 300 nm.

The pulse was compressed by applying a chirp with the X-band cavity because at the time of the measurement the RF station for the last two accelerating S-band structures, controlling the chirp and boosting the beam energy to 250 MeV, was not operational. The values in the fluctuation of the FEL energy in measurements and simulations were $M = 28$ and $M = 20$, respectively.

The fitting of the Gamma distribution to the measurement results were challenging because a background value has to be subtracted. A slight change in that value has a strong impact on the fit value, in particular for distributions, where the spread is small compared to the mean value (e.g. the long

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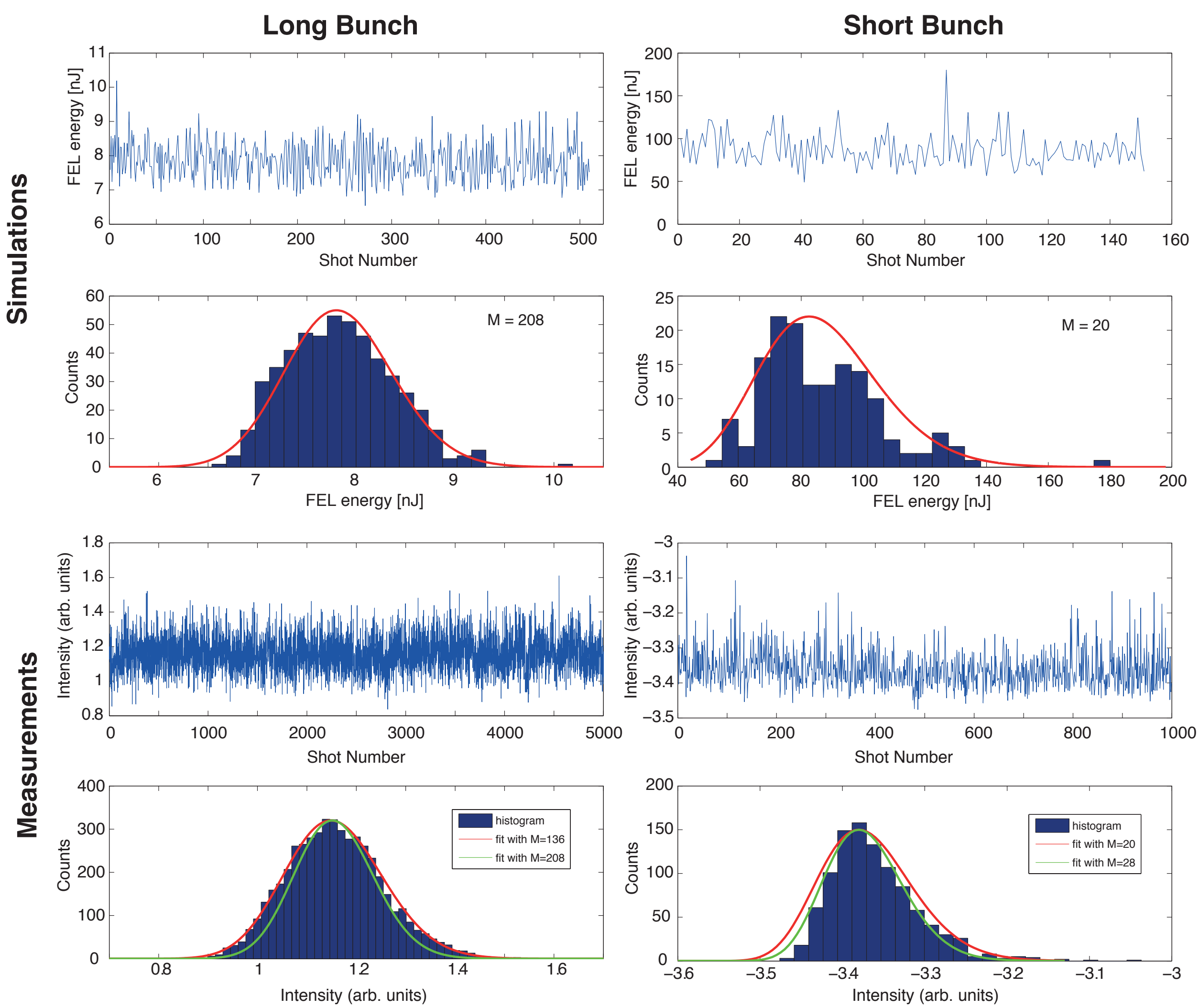

Figure 3: Statistical fluctuation of the FEL signal in simulations and measurements for a long and short bunch (left and right plots, respectively). For comparison the fit from the simulation has been overlaid in the distribution of the measurements.

bunch case with a value of $M = 136$). We measured the base

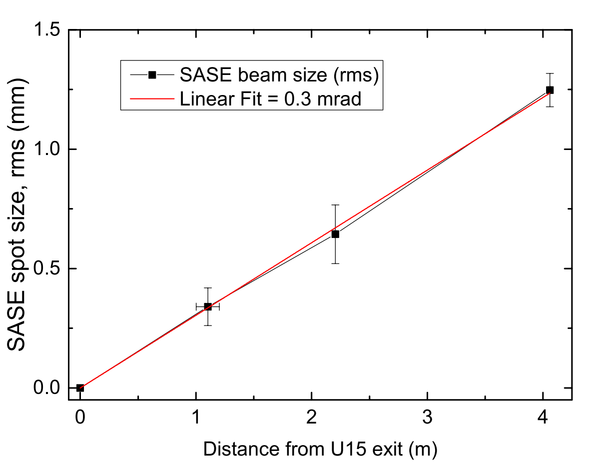

Figure 4: RMS FEL beam size at various screens after the undulator.

level by disabling the electron bunch generation and thus the FEL pulse, while keeping the region of interest constant. The fit of the Gamma distribution to the measurement is reasonably good although the base level may have been influenced by the stray light of the YAG screen, generated by the electron beam itself.

With the ability to measure the FEL spot on three different screens the divergence of the FEL beam can be determined and compared to simulations (see Fig. 4). The measurements yield a value of 0.3 mrad while the simulations produce a divergence of 0.38 mrad. As for the fluctuation of the FEL pulse energy the simulations are based on measured electron beam parameters and not matched to fit the result. For this measurement the beam was compressed to a peak current of 200 A at a beam energy of 130 MeV. The lower value in the measurement indicates that the FEL amplification was lower than in simulation and that gain guiding is weaker. The resulting larger FEL mode size yield less diffraction and thus smaller divergence.

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Tunability of the SASE FEL wavelength can be achieved by opening and closing the gap with a tuning range up to a factor 2 with respect to the shortest wavelength. This corresponds to undulator parameter values of 1.0 and 1.7. The measurements were done at a low beam energy of around 120 MeV with a resonance wavelength in the visible spectrum, because a spectrometer was available for that spectral range. In Fig. 5 two different spectra are shown. The overall tuning range in this measurement was between 500 and 1000 nm. There is also a visible signal of the 3rd harmonic, which shifts according to the resonance condition of the FEL. Note that the spectrometer hasn't been calibrated so that the shown signals do not correspond to the spectral intensity. A calibration would indicate much higher intensities towards longer wavelengths and the ratio between first and third is on a percent level at maximum. The spectrum is broader because the electron beam has a residual chirp due to compression. The measurement of the actual SASE bandwidth would have required an uncompressed beam with low beam current, resulting in a theoretical bandwidth smaller than the resolution of the spectrometer.

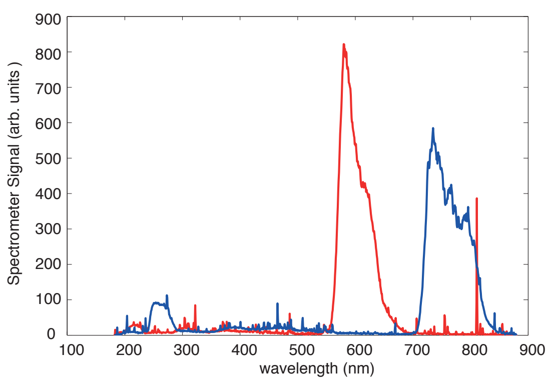

Figure 5: FEL spectra for an undulator gap of 4 and 5 mm (blue and red curve, respectively).

CONCLUSION

Installing a 4 m long in-vacuum undulator in the SwissFEL Injector Test Facility has successfully demonstrated SASE operation, though no saturation has been achieved. The measurements of the divergence angle and the SASE fluctuation agree quite well with simulation based on the measurements of the slice electron beam parameters using a transverse deflector.

Besides some strong kicks in the entrance and exit of the undulator, which had not been anticipated but could be compensated with a larger aperture succeeding the undulator, the field quality of the undulator is sufficient for operating a VUV and visible undulator. The more stringent undulator field requirements for a hard X-ray FEL could not be verified experimentally.

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