STATUS OF THE SWISSFEL FACILITY AT THE PAUL SCHERRER INSTITUTE

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Abstract

SwissFEL is a X-ray Free-Electron Laser facility with a soft and hard X-ray beamline, planned to be built at the Paul Scherrer Institute and to be finished in 2016. It covers the wavelength range from 1 Angstrom to 7 nm. In addition to the SASE operation at the entire wavelength, seeding is foreseen down to a wavelength of 1 nm.

We report in this presentation the status of the SwissFEL facility, including the layout, the timeline of the project, the different operation modes and the expected performance of the FEL beamlines.

INTRODUCTION

The Paul Scherrer Institute is currently planning the Free-Electron Laser facility SwissFEL to provide high brilliant radiation pulses to light source users in the wavelength range from 1 to 70 Ångstrom. The primary goal is the design of a compact facility without any compromise in the performance at the shortest wavelength. The foundation is a high brightness electron source with a slice emittance of less than 0.45 mm mrad at 200 pC. This allows for a compact undulator design with a period of 15 mm and a beam energy of up to 5.8 GeV, which is the lowest in comparison to all Ångstrom FEL facilities (e.g. LCLS, EuXFEL, SACLA). Contacts have been established to potential research groups within Switzerland, resulting in the conceptional design report for the user case [2]. The layout of the facility is documented in the conceptional design report for the machine [3] and the current design effort is progressing towards the technical design report, to be released at the beginning of next year.

In this paper we give an overview over the key design strategies, chosen technologies, expected performances and time schedule towards the expected start of the user operation in mid 2017.

LAYOUT OF THE FACILITY

The SwissFEL facility follows the generic layout of a X-ray FEL facility. A high brightness electron bunch is generated and accelerated while the emittance is kept small. A laser heater, placed at 130 MeV, controls the micro-bunch instability of the succeeding linac. The bunch is compressed and accelerated in two stages to reach the required peak current to drive the FEL at its shortest wavelength. A collimation system in the transverse dimension and in energy protects the undulator against any unexpected beam losses and thus degradation of the field quality.

The facility foresees two FEL beamlines, one hard X-ray beamline Aramis with a tuning range between 1 to 7 Å and a soft X-ray beamline Athos with a wavelength range of 7 to 70 Å. The beam distribution of the switchyard into the individual beamlines is placed in the midpoint of the linac at 3 GeV. Both have additional RF stations for tuning the FEL by energy (Athos: 2.5 - 3.5 GeV, Aramis: 2.1 - 5.8 GeV). The baseline design of SwissFEL includes a two bunch operation per RF pulse with a repetition rate of 100 Hz. The bunch spacing is 28 ns and a fast kicker in the switchyard separates the bunches.

Figure 1 shows the schematic layout of the SwissFEL facility. In the following the different section of the machine are discussed in more detail.

Gun and Booster

The injector of SwissFEL consists of a 2.5 cell S-band RF photo-electron gun, two 4 m long S-band accelerating structures with overlaid solenoids for emittance compensation, followed by a laser heater section and 4 additional S-band structures to accelerate the beam and generate the chirp for pulse compression. Two 0.75m short X-band structures linearize the longitudinal phase space for the succeeding bunch compression. The injector part ends with a diagnostic section [4] to measure bunch length, bunch profile, longitudinal phase space, projected and slice emittance, utilizing a transverse deflecting cavity, high resolution cameras and a spectrometer arm, which will also be used as a tune-up dump for normal operation of SwissFEL.

Currently the SwissFEL injector test facility [5] is under commissioning at PSI to demonstrate the required beam parameters for successful operation of SwissFEL and to test key components of the machine. When the existing injector is moved into the SwissFEL tunnel, it will be reconfigured to the layout described above. Right now, the test facility has fewer RF structures and no laser heater. Simulations have shown that the longer diagnostic section is less than optimal due to a higher sensitivity to microbunch instability after compression and will be reduced in length when moved to the SwissFEL building. Also, the injector facility is currently operating the CTF3 gun [6], though it is planned to replace it with a newly designed gun (SwissFEL gun) in the forthcoming years [7].

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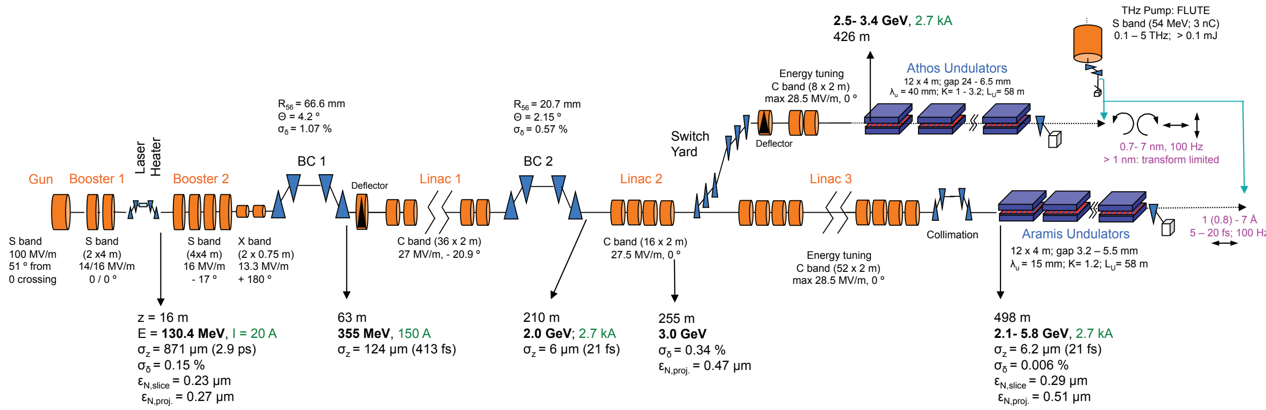

Figure 1: Schematic layout of the SwissFEL facility.

Bunch Compressors

Two magnetic chicanes at 350 MeV and 2.1 GeV compress the electron bunch by roughly a factor of 150 to yield a peak current of around 3 kA. Both chicanes are D-type chicanes with movable inner dipoles. This allows for a narrow vacuum chamber and thus the implementation of a high resolution BPM for energy measurement. In addition, both legs of each bunch compressor have correcting quadrupoles and sextupoles to control the overall dispersion and the orientation of the electron bunch, which gets rotated due to CSR effects in the chicane [8]. Also a skew quadrupole is placed in the chicane as a "cheap" streaking device utilizing the strong correlation between energy, longitudinal position and transverse position within the chicane. The lengths of the chicanes are 14 and 17 m, respectively.

Linacs

The SwissFEL linac consists of C-band travelling wave structures with an effective length of about 2 m per structure. Four structures are combined and fed by a 50 MW C-band RF station. To provide sufficient power, the RF pulse is compressed with a BOC[9] pulse compressor before being split and distributed to the RF structures. In total 28 RF station are used: 9 before the second bunch compressor, 4 stations before the switchyard, 13 for the acceleration towards the Aramis beamline and 2 to alter the beam energy for the Athos beamline. Space is reserved for 2 additional RF stations in the Aramis beamline to extend the wavelength range towards higher photon energies covering the Iron-Moessbauer line.

The tapered irises along 113 cells provide a constant field gradient of about 27.5 MV/m along each structure. The resulting wakefields are strong and partially used to remove the energy chirp after compression. Both bunches in the two bunch operation require the same RF phase and amplitude for identical compression. This is achieved by a phase feed-forward table and the resulting response from the pulse compressor. After the last compression some difference in phase and energy between the two bunches can be tolerated for a higher accelerating gradient. The difference in energy can be fully compensated by the individual tuning capabilities of the undulators.

Switchyard

The SwissFEL generates 2 bunches per RF pulse. The first bunch is accelerated up to 5.8 GeV and injected into the Aramis undulator beamline while the second gets extracted at 3 GeV for Athos in the switchyard. Because the bunch separation is only 28 ns a resonant kicker will apply different kicks for each bunch in the vertical direction. A static kicker cancels the kick of the first bunch but doubles the kick of the second. The actual separation is done with a Lambertson septum, deflecting the second bunch by 2 degrees [10]. The main purpose of the switchyard is to generate a beamline separation of 3.75 m for space reasons between the two FEL beamlines in the undulator hall. However it is also designed to provide controllable decompression of the bunch, to close the dispersion in the vertical plane from the resonant kicker, to compensate the CSR kick in the two double bend systems with a 360 degree phase advance between the kicks and to allow for energy collimation.

Collimation System

The collimation system protects the undulator against beam losses and a possible degradation in the field quality. The transverse collimation, which scrapes off halo particles of the electron beam as well as residual dark current (most of the latter is lost in the bunch compressors) is integrated into the main linac by inserting a vertical or horizontal aperture, depending on the polarity of the adjacent quadrupole. The total phase advance in the linac and the Athos transport line is more than 180 degree and sufficient for collimation.

The collimator operates typically as a double dogleg system with no further momentum compaction but a

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change in the optics converts the collimator into an ordinary magnet chicane. At the location of the collimator the sign of the dispersion function has opposite signs, depending on the configuration, but the same magnitude. Therefore protection for the undulator line against an uncontrolled change in the beam energy is not affected by the operation mode.

For Athos the energy collimation is integrated into the switchyard of the transport line in a double bend system. A slight decompression occurs due to the nature of the double bend configuration but it is compensated by a magnetic chicane, used for seeding of Athos.

Undulator Lines

The facility has two undulators lines, Athos and Aramis. Both consists of several modules of 4 m length each. A common support frame is used in both beamlines. The modules are separated by an intersection of about 90 cm, where a phase shifter, BPM and quadrupole is placed.

Aramis consists of an in-vacuum undulator with a period of 15 mm and a nominal undulator parameter value of 1.2. The planar hybrid undulator uses the novel material of a Dy-diffused NdFeB for the permanent magnets [11]. The nominal gap of 4.2 mm can be varied for each module to compensate for the beam losses by the incoherent undulator radiation and the undulator wakefields as well as to increase the output performance with a post-saturation taper.

In contrast, Athos is a variable gap APPLE Type II undulator to address the particular demand of the users for variable polarization in the soft X-ray region. The undulator is out of the vacuum and the vacuum chamber has an inner diameter of about 5 mm. The Athos beamline also has a preceding seeding section to seed the FEL with a longitudinally coherent signal down to 1 nm. Currently echo-enabled harmonic generation [12] is the preferred choice for the seed signal though the beamline also allows one to seed with an external high harmonic generation signal.

OPERATION MODES

The SwissFEL Facility operates with a bunch charge in the range between 10 and 200 pC. Strong wakefields in the undulator define the upper limit while the resolution of the diagnostics becomes less reliable for a stable operation below the lower limit. To keep the emittance compensation scheme unchanged a different charges requires a scaling in the RF gun laser pulse size in all three dimensions. However the different bunch charges alter the wakefield, which has a significant contribution to the energy chirp for the compression of the bunch. Thus the linac phases and R_{56} of the chicanes need to be adjusted to provide the same flat current profile at the undulator entrance.

Beside this standard operation, the SwissFEL can operate in two special modes. One mode utilizes maximum compression for a 10 pC bunch. To avoid the transport of a high peak current, short bunch through the main linac of SwissFEL, the energy collimator in front of the hard X-ray FEL Aramis is reconfigured to allow for a final compression stage.

Table 1: Beam Parameters at Aramis for the Different Operation Modes: nominal 200 pC (A), nominal 10 pC (B), large bandwidth (C), and attosecond pulse (D)

Mode	A	B	C	D
Charge [pC]	200	10	200	10
Peak Current [kA]	2.7	1.6	3.0	15
Length [fs]	25	2	22	0.3
Emittance [μm]	0.43	0.18	0.43	0.25
Energy Spread [MeV]	0.35	0.5	25	1

The other special mode results in a large energy chirp in the electron beam. For this the electron bunch is over compressed in the second chicane without a significant degradation of the slice emittance. In the succeeding linac the strong wakefield adds up to the inverted chirp instead of "eating up" the chirp as in normal operation. In comparison to S-band and L-band machines the wakefields are much stronger in SwissFEL and the relative chirp can build up despite the adiabatic damping of the chirp due to acceleration. Initial simulations have shown a chirp of about 1.5 % FWHM at 6 GeV, which provides a 3 % chirp of the FEL pulse (see Fig. 2). The FEL performance is hardly affected because the co-operation length is still significantly smaller than the bunch length and slippage will see only a negligible fraction of the chirp. One necessity for this operation mode is the correction of the electron slice alignment due to the very strong CSR kick in the second bunch compressor. This is done by correction quadrupoles and sextupoles in the dispersive regions of the second bunch compressor and energy collimator.

Table 1 lists the main beam parameters for the different operation modes.

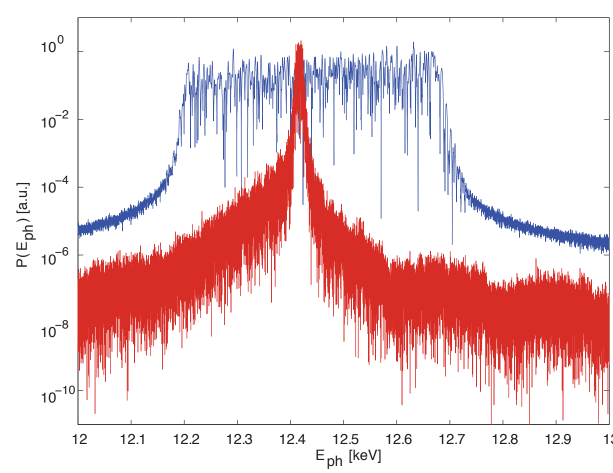

Figure 2: Simulated spectrum of the ARAMIS radiation output for normal and large bandwidth mode (red and blue line, respectively).

SIMULATIONS OF INJECTOR, LINAC AND FEL PERFORMANCE

In the current design phase we are using rather fast and efficient codes: for the injector the codes HOMDYN and ASTRA, for the transverse and longitudinal dynamic in the linac MAD-X and ELEGANT respectively, and for the FEL dynamics GENESIS 1.3. Some cases requires a more detailed study, such as the microbunch instability in the linac, mostly done with OPAL and CSRTrack. Most of the codes are executed on a 128 core computer cluster.

Transverse optics is designed and optimized mostly with MAD-X. The design strategy is to keep the values for the β-functions below 70 m to minimize the impact of chromaticity and thus the degradation of the slice emittance. The optics of the machine is very modular and only in very few places is some freedom in the optical functions allowed, mainly the diagnostic section behind the first bunch compressor.

The longitudinal dynamics and the compression scheme has been optimized with an iterative process [13], using ELEGANT and Lie-Track to track the beam, to provide a flat current profile and minimal residual chirp in the Aramis beamline, while relaxing the RF tolerances as much as possible for a robust operation. Tolerance studies [14] have shown that beam current fluctuation is the dominant source of the FEL performance jitter. It is mostly caused by a jitter in the X-band phase and charge fluctuation of the bunch at the cathode.

The FEL performance is simulated for the baseline design parameters (Table 1) as well as with start-end simulations using the code sequence of ASTRA-ELEGANT-Genesis 1.3. The FEL performance for the nominal 200 pC case is listed in Table 2.

Seeding of the soft X-ray beamline has been studied, starting with a simple 1D model and then verified and optimized with Genesis 1.3. Operating at 3 GeV and a final wavelength of 1 nm the seeding efficiency is sensitive to the quantum fluctuation in the incoherent synchrotron radiation and the effect of CSR. The impact of the latter has been significantly reduced by decompressing the bunch in the switchyard to a current of about 1.5 kA [15]. Energy modulation and strength of the dispersive section has been optimized for the best performance. Currently, we are studying the option of using a HHG signal at 50 nm as the second seeding stage of the EEHG seeding line, reducing the overall harmonic conversion by a factor of 5.

Table 2: Nominal FEL Performance at 200 pC

Electron Energy [GeV]	5.8	2.1
Wavelength [Å]	1	7
Pulse Energy [mJ]	0.08	0.15
Pulse Length [fs]	14	15.6
Beam Radius [μm]	25	43
Divergence [μrad]	1.5	5.3
Bandwidth [%]	0.04	0.1
Saturation Length [m]	47	25

CONSTRUCTION STATUS AND TIMELINE

The decision by the Swiss parliament is expected to be taken in summer 2012 with a start of the construction in January 2013. Civil construction (linac tunnel, experimental hall and technical buildings) will last till fall of 2014 and installation of beamline component starts in 2015. The commissioning starts in mid of 2016 and first light is expected early 2017.

In the initial phase only the hard X-ray beamline Aramis and the switchyard is constructed. The latter is used as a diagnostic beamline for the fully compressed bunch. A second phase will complete the facility (soft X-ray beam line Athos with seeding, 6 user stations in total), starting earliest in 2017. The SwissFEL test injector will operate until 2015.

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