STATUS OF THE PSI X-RAY FREE ELECTRON LASER “SWISSFEL”

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Abstract

The Paul Scherrer Institut is planning to construct a free electron laser covering the wavelength range of 1 – 70 Å. This project “SwissFEL” will use a C-band radio-frequency linac of variable energy, 2.1 GeV to 5.8 GeV. The laser will be equipped with two undulator lines. A short period (15 mm) in-vacuum undulator, ‘Aramis’, will provide hard X-ray radiation in the range 1 Å to 7 Å. A 40 mm period APPLE-type undulator, ‘Athos’, will provide wavelengths from 7 Å to 7 nm. The accelerator will employ an S-band RF photo-gun and an S-band injector providing a low normalised slice emittance (~ 0.3 mm-mrad @ 200 pC) beam of 450 MeV. The initial photo-current of 22 Amperes is increased to 2.7 kA through the use of two magnetic chicane bunch compressors. Acceleration to full energy is provided by twenty-six C-band RF “modules” each consisting of four, 2 m long, C-band structures. We will describe the status of the project and in particular the design of the accelerator. The beam dynamics simulations which have led us to our base-line design will be discussed and a description of the basic RF module will be given. A schedule for the project realization will also be presented.

INTRODUCTION

PSI is currently planning the construction of an x-ray free electron laser in order to provide researchers with a source of intense, ultra-short pulses of transversely coherent radiation in the wavelength range of 1 to 70 Å. The design is based on a low emittance electron source and would use novel, short-period undulators in order to reach Angstrom wavelengths using a linear accelerator of relatively modest energy (5.8 GeV) in comparable to other Angstrom FEL’s. The machine could then be reasonably compact and economical while still providing FEL performance competitive with other X-ray FEL projects world wide. Indeed, the present design requires only 713 m for the entire facility length. The scientific case for the facility has been established in consultation with the Swiss research community and is documented in a PSI report [1]. In this paper we give a brief description of the radio-frequency (RF) linac and undulators. A detailed description of critical features of the facility (beam diagnostics, controls, orbit correction, timing system, magnets, vacuum and mechanical engineering, technical infra-structure) can be found in the SwissFEL Conceptual Design Report (CDR) [2].

THE FACILITY

The SwissFEL linac must satisfy two requirements: (i) acceleration of the beam to an energy of 5.8 GeV, (ii) longitudinal compression of the bunch, coming from the electron source, to the peak current needed to reach saturation in the undulators. It is convenient to divide SwissFEL into the following parts:

- Gun and booster
- Bunch compressors 1 and 2
- Linacs 1, 2 and 3.
- Switchyard and collimator
- Aramis undulator line
- Athos undulator line

Different modes of bunch charge operation are foreseen. The highest charge would have electron bunches of 200 pC. However, we are also planning a ‘low’ charge mode (10 pC) to produce ultra-fast “single-spike” photon pulses. The linac would be built with normal conducting (copper) RF structures and pulsed at 100 Hz. Each RF pulse would accelerate two electron bunches separated by 50 ns.

Gun and Booster

We have been developing a low emittance electron gun based on photo-assisted field emission for SwissFEL. However it has been shown at LCLS that an RF photo-injector is capable of providing sufficiently bright electron beams to drive a hard X-ray FEL [3]. Consequently, we have adopted an RF gun as our electron source. The gun is an S-band (2998.8 MHz) 2-1/2 cell cavity operated in the familiar standing wave π mode. It will operate at a peak accelerating gradient of 100 MV/m to reduce the detrimental effects of space charge on the beam emittance over the first few centimetres of acceleration. Excitation of the π/2 mode by the short RF pulse is suppressed by choosing a sufficiently large iris diameter to ensure a large frequency separation (16 MHz) between the two modes. In common with the LCLS and PHIN guns, the SwissFEL gun is fed by dual input waveguide on the output cell in order to reduce the effects of dipole kicks on the beam [4,5]. Quadrupole field components are reduced by machining the coupling cell to have a race-rack shape. The photo-emitting surface is simply the back plane of the ½ cell of the copper cavity.

With a typical quantum efficiency for copper of ~ 10^{-5} one requires ~ 100 μJ of VUV laser energy to generate pulses of 200 pC. These energies are easily available today from commercial lasers. SwissFEL will use a frequency tripled titanium-sapphire laser providing mJ energies tuneable over the range 260 nm to 283 nm. Tuneability of the laser has been shown to allow reduction of the intrinsic emittance on the gun test stand at PSI [6]. A complete description of the laser can be found in [7].

After exiting the gun the beam is accelerated by six 4.3 m long travelling wave (TW) S-band accelerating structures (Fig. 1). The optimisation of the gun and the first two sections, leading to an energy of 130 MeV, has

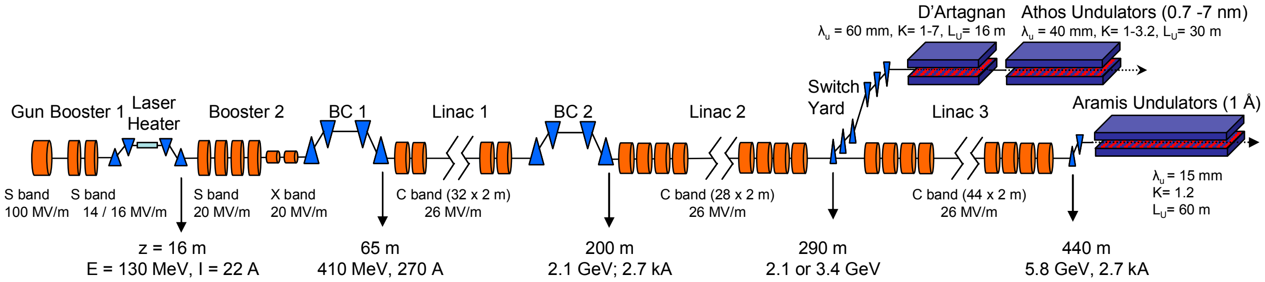

Figure 1: Schematic layout of the SwissFEL accelerator and undulator lines.

been performed using ASTRA simulations [8]. The goal is to use the emittance compensation technique whereby the gun solenoid setting, the position of the first structure iris and the cell gradient are chosen to accelerate the beam on the invariant envelope [9]. This results in conservation of the low emittance produced by the gun. Figure 2 shows the calculated emittance variation from the gun through the first two S-band sections.

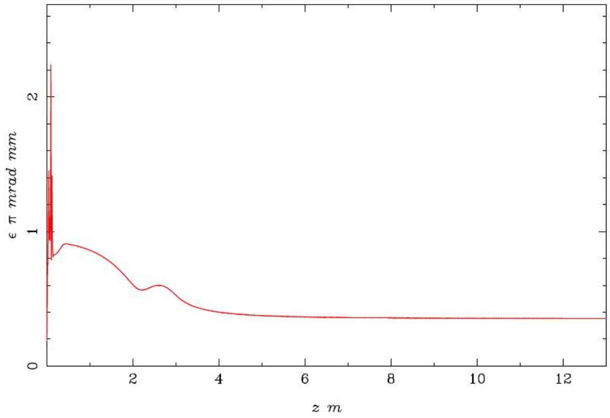

Figure 2: Variation of the projected beam emittance illustrating the compensation principle.

At the time of writing, a 250 MeV S-band injector is under commissioning on the PSI-west site and has produced a first beam. It will later be used for SwissFEL. This injector will be an important resource in demonstrating component performance for the project.

Our design also foresees the use of a laser heater as employed at LCLS [3]. This would combat micrbunching instabilities excited on the highly mono-energetic electron beam, which in turn could lead to strong coherent synchrotron radiation (CSR) effects.

Bunch Compressors

SwissFEL employs a strong longitudinal compression of the electron bunch in order to reach the high peak current (2.7 kA) needed to drive the FEL. This is performed in two stages by two magnetic-chicane type bunch compressors (BC1 and BC2). The first is situated at the output of the Booster while the second is placed downstream of Linac-1. The energy chip required to allow the chicanes to compress the electron beam is applied by off-crest acceleration in the Booster and in Linac-1. The resulting energy-phase distribution is linearised with the aid of two harmonic X-band structures (11.995 GHz) placed downstream of the Booster. This structure, being developed in collaboration with CERN, is a 72 cell, constant gradient TW structure with a cell to cell phase advance of 5π/6 [10]. It will be tested on the SwissFEL injector. The small iris of the structure (4.1 mm), which is 750 mm in active length, means that even small transverse misalignments can result in severe emittance dilution. For this reason two of the cells are coupled to four waveguide arms to extract dipole mode signals and provide information on structure alignment

The Linacs

The SwissFEL linac will be composed of one hundred and four 2 m long C-band (5712 MHz) travelling-wave structures to accelerate the beam from the injector energy of 410 MeV to the final energy of 5.8 GeV. The choice of C-band is based essentially on considerations of electrical power consumption. A C-band linac would require less power than an S-band version. The higher effective gradients achievable with C-band structures also result in a reduced active linac length and thus reduced civil engineering costs. In contrast, the smaller iris diameter of a C-band structure results in increased wake-fields with respect to S-band. Simulations show that the effects of the transverse wake-fields on the emittance are tolerable. In addition, by suitably phasing Linacs-2 and 3 the longitudinal wake can be used to reduce the energy chirp imparted in Linac-1 thus contributing to the spectral purity of the FEL. The basic RF "module" is composed of four structures powered by a solid-state modulator and a 50 MW klystron whose power is amplified by an RF pulse compressor (Fig. 3). The twenty-six modules are distributed over the three linacs as shown in Fig. 1. The space available for the modules is somewhat longer than is needed, allowing for the possibility of a future energy extension to 6.5 GeV. The design of the C-band structure remains to be fixed. Three options for the cell topology are being considered. They are similar in terms of the power requirements to establish a gradient of 26.5 MV/m. The final decision will be dictated by manufacturing issues and overall module efficiency.

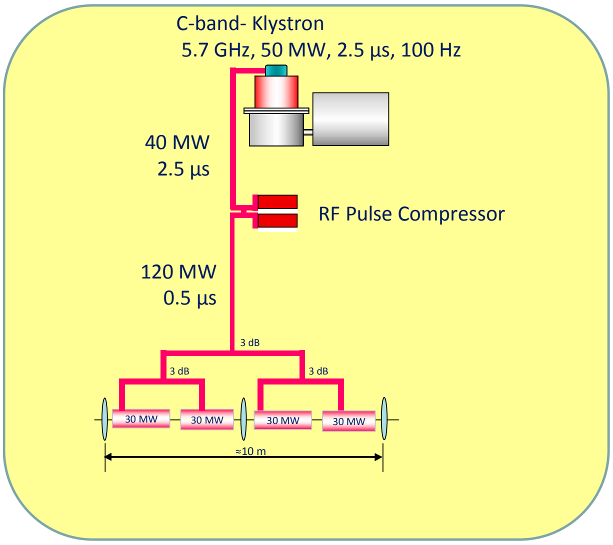

Figure 3: Basic RF accelerating module of SwissFEL consisting of 1 modulator, 1 klystron, a pulse compression system and 4 C-band structures.

The Switchyard

The second electron bunch within each RF pulse will be sent to the Athos undulator after emerging from Linac-2. At the entrance to the switchyard a fast kicker followed by a septum magnet will deviate the second of the two bunches. The bunch is then deviated by two double bend achromats. The net bending is zero making the two undulator lines parallel and separated by 4 m. The length required for the switchyard is 77 m. Emittance and beam size changes have been studied through the switchyard using the PTC model embedded in MAD-X [11]. The input phase-space parameters were taken from the output of an ELEGANT simulation for the high charge case [12]. CSR effects are not included but these have been evaluated separately using CSRTrack and are found to be negligible. The beam size remains suitably small throughout the switchyard and the slice emittance and bunch length are both conserved. The full design of the switchyard is still in progress and further details can be found in [13] along with some initial thoughts on the subject of collimation.

The Undulators

The facility will have two permanent magnet undulator lines, named *Aramis* and *Athos*. Linearly polarised hard X-rays will be produced by Aramis, a novel short-period (λ_u = 15 mm) in-vacuum undulator composed of twelve sections of magnetic length = 4 m. The undulator will have a K of 1.2 which allows 1 Å lasing at the peak electron energy of 5.8 GeV. Small changes in K will allow fast tuning within 1% of the resonant wavelength. Changes in energy over the range 2.1 GeV to 5.8 GeV will allow wavelength tuning from 1 Å to 7 Å. The Athos undulator will be of the APPLE (Advanced Planar Polarised Light Emitter) type, thus allowing variable polarisation of the photon beam. Its wavelength range is 0.7 nm to 7 nm. The wavelength ranges from 0.7 nm - 2.8 nm and 1.8 nm - 7 nm are obtained by operation at beam energies of 3.4 GeV and 2.1 GeV respectively and by varying the undulator gap, and thus the K value (from 1 to 3.2). To improve on the longitudinal coherence of the soft X-ray beamline it is intended to seed Athos with an external coherent signal. For this purpose Athos is used with a companion undulator, *d'Artagnan*. The latter has a periodicity of 60 mm and a variable K (1 to 5). It is composed of three modules each 4 m long and spaced by 75 cm. It could be seeded by the technique of High Harmonic Generation in gas. An alternative scheme, Echo Enabled Harmonic Generation will also be investigated [14]. The engineering design of the undulators (support structures, choice of materials etc..) is under development.

SIMULATIONS

A number of different simulation tools have been employed to design the linac such that it meets the beam requirements to reach saturation at 1 Å. Beam dynamics simulations are performed for the RF gun and the first accelerating structures using the particle tracking code, ASTRA, along with detailed field maps of the RF cavities and solenoids. Tracking through the main linac is performed using ELEGANT after having matched the transverse optics with MAD-X. ELEGANT includes a 1-D CSR model which has been cross-checked against the code CSRTRACK. Thus CSR effects which might be of importance in the bunch compressors are included. Finally, the FEL performance is evaluated using GENESIS [15]. Care is needed to ensure that the design is robust against fluctuations in parameters about their nominal values. It is necessary therefore to perform many 'start-to-end' simulations through the linac to establish "tolerance" limits for parameter changes. Indeed such studies help to set specifications for machine components. Numerous parameters are varied in turn to ensure that they do not result in excessive changes of peak current (<5%), beam energy (0.05%) or beam arrival time (< 20 fs) at the entrance of the undulator. A detailed description of this work is not possible here but is given in a companion paper at this conference [15]. The study shows that the most sensitive parameters are the S-band and X-band RF phases. Phase stability for these systems is needed at the level of 0.015° and 0.06° respectively. A high performance low-level RF control system is under development to meet this challenge. Details can be found in the CDR [2].

FEL PERFORMANCE

As an illustration of the expected performance of the SwissFEL we show the calculated photon output parameters for the Aramis line operating at 5.8 GeV and 2.2 GeV for the high charge mode. These simulations are performed with the nominal design parameters. Beam dynamics calculations indicate that a smaller slice emittance (0.3 mm-mrad) may be possible resulting in a reduction in the saturation length. For the performance of the Athos beamline the reader is referred to the CDR [2].

Table 1: Performance of the Aramis Beamline

Beam energy	5.8 GeV	2.2 GeV
Peak current	2.7 kA	2.7 kA
Charge	200 pC	200 pC
Energy spread	350 keV	350 keV
Emittance	0.43 mm.mrad	0.43 mm.mrad
Undulator period	15 mm	15 mm
Undulator parameter	1.2	1.2
Undulator module length	4.00 m	4.00 m
Undulator section length	4.75 m	4.75 m
Average β-function	15 m	15 m
Wavelength	1 Å	7 Å
Saturation length	45 m	21 m
Saturation pulse energy	0.066 mJ	0.063 mJ
Effective saturation power	2.0 GW	1.9 GW
Photons at saturation	$3.32\cdot10^{10}$	$2.21\cdot10^{11}$
Bandwidth	0.034 %	0.144 %
Pulse length	13 fs	13 fs
Beam radius	22.2 µm	37.9 µm
Beam divergence	1.1 µrad	5.7 µrad

CONSTRUCTION SCHEDULE

R&D for system components such as high power RF and undulators is currently in progress. Low level RF and diagnostic issues will be studied on the injector which is currently being commissioned. A full C-band RF module will be installed and tested at PSI from the summer of 2011. We will seek funding approval in 2011 and, in the case of a positive decision, civil construction and component procurement could begin in 2012. we would complete construction of the tunnel, building and experimental halls by the end of 2013 so allowing installation of the accelerator components in 2014. Installation of the linac, the injector and the Aramis beam-line would be complete by the end of 2015 allowing commissioning of the facility early in 2016. Our goal would be to achieve lasing in Aramis by summer of 2016 and have regular user operation at the beginning of 2017. The Athos line would be installed during a shutdown early in 2018.

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