# BEAM COMMISSIONING PLAN FOR THE SwissFEL HARD-X-RAY FACILITY

T. Schietinger on behalf of the SwissFEL team,
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

*Abstract*

The SwissFEL facility currently being assembled at the Paul Scherrer Institute is designed to provide FEL radiation in the photon wavelength range between 0.1 and 7 nm. The commissioning of the first phase, comprising the electron injector, the main electron linear accelerator and the first undulator line, named Aramis and dedicated to the production of hard X-rays, is planned for the years 2016 and 2017. We present an overview of the beam commissioning plan elaborated in accordance with the installation schedule to bring into operation the various subsystems and establish beam parameters compatible with first pilot user experiments in late 2017.

## INTRODUCTION

SwissFEL is an X-ray Free-Electron-Laser facility under construction at the Paul Scherrer Institute (PSI) in Switzerland [1]. Its two undulator lines, named Aramis and Athos, are designed to deliver hard X-rays in the wavelength range between 0.1 and 0.7 nm and soft X-rays between 1 and 7 nm, respectively. Figure 1 shows a schematic overview of the facility, annotated with relevant machine and beam parameters. In a first phase, only the Aramis beamline will be realized, with Athos to be completed in a second phase, currently foreseen for the period 2018–20. After an extensive design and development phase, including beam development work [2] and component tests [3] at a dedicated injector test facility [4], the SwissFEL-Aramis facility is currently in the installation phase, with first beam commissioning scheduled for early 2016. The commissioning phase is foreseen to extend over two years, with installation activities continuing in parallel or in between. First pilot user experiments are expected for late 2017.

We give an overview of the various commissioning steps. While the sequence of commissioning tasks will remain the same apart from further refinements or small rearrangements due to possible changes, the dates are subject to change depending on the overall progress of component delivery and installation. The SwissFEL commissioning plan is part of a global project plan (dubbed Planning-Installation-Commissioning, or PIC, plan), which ensures the overall consistency of the project schedule taking into account all dependencies. It is updated on a regular basis reflecting progress achieved on building construction, component delivery and installation. The dates presented here have been derived from the latest PIC plan update (July 2015).

## COMMISSIONING OVERVIEW

The SwissFEL commissioning, up to the end of the first project phase, can be split into three phases: the injector phase (first acceleration stage, up to a beam energy of 320 MeV), the linac phase (transmission through the full accelerator and undulator line, but no intentional generation of X-rays yet) and the FEL phase (final phase with X-rays from the undulators). The SwissFEL commissioning objectives have been formulated in terms of a set of milestones, specifying electron beam energy and bunch charge, repetition rate, and photon wavelength and pulse energy to be achieved for three specific dates, see Table 1.

The start of beam development activities is usually dictated by the installation and start-up schedule of the necessary infrastructure. In particular in the later stages of commissioning, progress towards reaching the final beam energy, and thus the final photon wavelength, will be driven entirely by the deployment schedule of the RF stations powering the main linac.

The special location of SwissFEL in a freely accessible forest outside the PSI site requires particular consideration to radiation issues. As a consequence, every commissioning step involving a significant change in beam parameters is followed by extensive radiation mappings of the building and the surrounding areas.

The commissioning work will be performed in eight-hour shifts, following the existing PSI shift schedule for simplicity. Due to the limited manpower available, only two shifts per work day will be staffed, with the third shift (during the night) being used for long-term stability tests and the like. On weekends it is foreseen to staff one shift per day on average. Shift crews will consist of a shift leader (typically a beam dynamics expert) a shift expert (from a PSI expert group, such as diagnostics, RF, controls etc., but also beam dynamics, depending on the specific commissioning task or issue), and, as far as available, a member of the PSI operation section. For all the critical hardware systems, on-call services will be maintained by the expert groups. The absence of scheduled, dedicated night shifts considerably simplifies both the organizational aspects of shift work and the associated formal approval procedure.

The numbers of shifts needed during each commissioning phase to reach the milestones have been estimated as 155 for injector commissioning, 135 for linac commissioning and 204 for FEL commissioning. In addition, some 28 weeks are needed for the commissioning of the photonics infrastructure in the optical and experimental hutches.

ISBN 978-3-95450-134-2

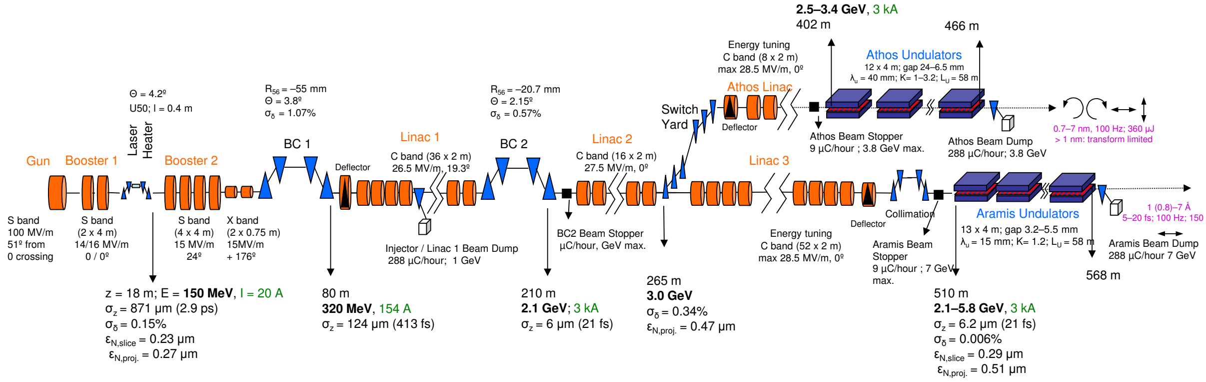


Figure 1: SwissFEL schematic overview showing the two beamlines Aramis (hard X-rays) and Athos (soft X-rays). The latter beamline will only be realized in a second phase and is shown here for information only.

Table 1: SwissFEL Aramis principal milestones with target dates according to current planning.

| **Parameter** | **Milestone I**<br>30 June 2017 | **Milestone II**<br>30 Sept. 2017 | **Milestone III**<br>30 Dec. 2017 |
|---|---|---|---|
| Electron beam energy [GeV] | 3.0 | 3.8 | 5.8 |
| Electron bunch charge [pC] | 200 | 200 | 200 |
| Repetition rate [Hz] | 50 | 50 | 100 |
| Photon wavelength [Å] | 3.7 | 2.3 | 1.0 |
| Photon pulse energy [μJ] | 400 | 400 | 400 |

## RF CONDITIONING

Every beam commissioning phase is preceded by a period of RF conditioning, during which the accelerating structures of newly installed RF stations are slowly brought up to their nominal accelerating gradients and somewhat further to ensure smooth operation with beam. The procedure is needed to remove remaining surface impurities as well as dust and humidity directly with RF power and may take from a few hours up to several weeks, depending on the state of the cavities. While this conditioning is done without beam, i.e., no electrons are injected during the conditioning RF pulses, it may proceed in parallel to beam operation, which would make use of already conditioned cavities only. In this case the timing of the electron bunches is set in a way that ensures their undisturbed passage through cavities under conditioning, i.e., between two RF pulses. Also, to prevent the acceleration of dark current electrons (from field emission at the cavity surface) produced in the cavities of one RF station by any of the following cavities, the RF conditioning pulses are all shifted, not only with respect to the electron bunch, but with respect to all other RF stations under conditioning as well.

## INJECTOR COMMISSIONING

The commissioning of the SwissFEL injector proceeds in four main stages, summarized in Table 2. The first two stages after the RF conditioning are dedicated to the commissioning of the gun and booster sections of the injector, whereas the last two stages deal with the setup of the two chicanes (bunch compressor and laser heater). The stages typically include a few shifts for the beam-based commissioning of the diagnostics components involved in the new machine part. After every stage, the stability and reproducibility of the beam parameters will be verified before proceeding to the next stage. Provided that the first C-band RF station of linac 1, situated between the end of the booster and the injector spectrometer, is in operation at the time of completion of the injector commissioning, a further commissioning stage is foreseen to test and characterize this RF module with beam, taking advantage of the injector spectrometer for beam measurements.

The repetition rate for injector commissioning will generally be limited to 10 Hz to minimize beam losses. Exceptions are occasional gun tests at 100 Hz and overall booster tests at 50 or 100 Hz towards the end of injector commissioning, when orbit and optics are well understood. Some linac installation work is planned in parallel with injector operation in the linac 3 and undulator areas ($z > 245$ m). For the time of the injector commissioning, a temporary beam stopper, consisting of a 50 cm $\times$ 30 cm $\times$ 30 cm iron block, will prevent the direct propagation of the electron beam beyond the injector area.

The commissioning of the injector will mainly be performed at a nominal bunch charge of 200 pC. For first passes through machine sections, however, the bunch charge will be reduced to about 50 pC to minimize radiation losses. The charge will only be raised once a stable orbit and a reasonable optics have been established for a given section.



ISBN 978-3-95450-134-2

Table 2: Commissioning stages for the SwissFEL injector. Beam conditions refer to the nominal conditions during a given stage; $E$ is the electron beam energy, $Q$ the bunch charge and $R$ the repetition rate.

| Commissioning Stage | Approx. Dates | Beam Conditions | Main Tasks |
|---|---|---|---|
| RF Conditioning | Jan./Feb. 2016 | | Conditioning of gun and S-band booster cavities beyond nominal accelerating gradient. Conditioning of first C-band module as soon as available. |
| **Gun Commissioning** | Feb./March 2016 | $e^-$ to gun dump<br>$E$ = 7.1 MeV<br>$Q$ = 50–200 pC<br>$R$ = 10–100 Hz | Initial setup of the electron gun, commissioning of diagnostics in gun section, detailed characterization of the gun. |
| **Booster Commissioning** | April–June 2016 | $e^-$ to inj. dump<br>$E$ = 320 MeV<br>$Q$ = 50–200 pC<br>$R$ = 10 Hz | Transmission to injector beam dump, beam-based commissioning of diagnostics, RF commissioning of booster cavities, setup of beam orbit and optics, radiation mapping, beam emittance optimization. |
| **BC1 Commissioning** | June/July 2016 | $e^-$ to inj. dump<br>$E$ = 320 MeV<br>$Q$ = 50–200 pC<br>$R$ = 10 Hz | Setup of bunch compressor (orbit and optics), longitudinal phase space measurement (compression verification), commissioning of X-band cavity, emittance optimization of compressed beam. |
| **Laser Heater Commissioning** | July/Aug. 2016 | $e^-$ to inj. dump<br>$E$ = 320 MeV<br>$Q$ = 50–200 pC<br>$R$ = 10 Hz | Basic setup of the laser heater chicane (final setup will be done based on FEL signal). |
| C-band Module Test | Aug. 2016 | $e^-$ to inj. dump<br>$E$ = 590 MeV<br>$Q$ = 50–200 pC<br>$R$ = 10 Hz | Beam-based test and characterization of first C-band module. |

## LINAC COMMISSIONING

The goal of the linac commissioning phase, summarized in Table 3, is the safe transport of electrons through all linac sections as well as the transfer and undulator lines at a nominal beam energy of 2.1 GeV. The reduced beam energy reflects the fact that at this stage of the commissioning, only linac 1 will be equipped with operational power RF stations. (Linacs 2 and 3 will have cavities installed, but no RF power to drive them.) The final beam energy of 5.8 GeV, requiring all RF power stations, will only be achieved during the FEL phase of commissioning.

Once stable beam delivery from the injector has been established and the linac beamline has been fully assembled the commissioning of the linac stage can start. It is foreseen to perform a first pass of the machine up to the beam stopper installed in front of the Aramis undulator at the injector energy of 320 MeV. This approach will expose any obvious problems with the beamline at low beam power and allow for first diagnostics checks still in parallel to the conditioning of the linac-1 RF stations. In the subsequent commissioning stage, the beam energy will be raised gradually to the linac-1 energy of 2.1 GeV, followed by the setup of the second bunch compressor and the energy collimator chicane.

During these first commissioning stages, the beam will be deflected (by a movable permanent dipole magnet) to a beam stopper placed in front of the Aramis undulator line. Another beam stopper is available further upstream after the second bunch compressor (BC2 beam stopper). It will be used only rarely in conjunction with a profile monitor at the same location (whenever the beam profile needs to be checked before entering linac 2).

As soon as the beam parameters, as measured after the energy collimator, fulfill a set of predefined requirements, electrons will be transported through the undulator line onto the Aramis beam dump. During this first beam setup in the transfer and undulator lines the undulator gaps will remain in their open positions, such that no X-rays will be produced. For the first commissioning of the linac, transfer and undulator sections, the bunch charge will be kept at the intermediate value of 50 pC or even below, in particular when going through the undulators, to limit potential radiation losses. For the same reason the repetition rate will remain at 10 Hz for the early linac commissioning, to be raised to 50 Hz at the later stage in preparation for the first SASE attempts. The RF stations will run at 100 Hz throughout, irrespective of the bunch frequency. The nominal bunch frequency of 100 Hz can only be realized in the later stages of commissioning, since the handling of two zero-crossings with respect to the 50 Hz mains

ISBN 978-3-95450-134-2

supply will require some additional work by the low-level radiofrequency (adaptation of the feed-forward algorithm) and beam diagnostics groups.

## FEL COMMISSIONING

In the last commissioning phase, the electron beam will finally be used to generate coherent X-ray radiation by having it pass through the undulators at closed gaps. After the alignment of the undulators and the verification of the nominal beam transport through the undulator section with closed gaps, the first goal will consist in the observation SASE radiation, thus establishing the distinctive signal of free-electron lasing.

The individual FEL commissioning stages, summarized in Table 4, essentially follow the installation progress of the linac RF modules. At every commissioning stage, a few weeks of beam operation are reserved for photonics commissioning. As the electron energy is increased, the accessible output photon wavelength decreases, down to the nominal 1 Å for the full linac energy of 5.8 GeV. At this stage, the very first pilot experiments are planned as a test of the facility under user operation conditions.

The bunch charge during FEL commissioning will vary between 50 and 200 pC depending on the specific commissioning task. The milestones defined for each FEL commissioning stage call for operation at 200 pC yielding photon pulse energies of 400 µJ. The repetition rate will remain at 50 Hz for the first FEL commissioning stages to avoid complications arising from the second mains zero-crossing, and will only be raised to 100 Hz during the very last commissioning stage.

## TRANSITION TO USER OPERATION

Once the first commissioning goals have been reached, the facility will cycle through distinct periods of user operation (beginning with so-called friendly users), end station commissioning, and machine development. Corresponding operation modes (including some additional ones for machine tuning, shutdown etc.) have been defined. The exact details of the transition to regular user operation as well as the long-term organization of user operation at SwissFEL are the subject of current discussions and will be defined in the coming months.

## CONCLUSION AND OUTLOOK

The SwissFEL Aramis hard-X-ray facility is approaching its commissioning phase, currently foreseen for the years 2016 and 2017. We have presented an overview of the main commissioning steps of the facility leading up to first pilot user experiments by the end of 2017. The commissioning plan is aimed at reaching a set of predefined milestones in accordance with the SwissFEL installation and system commissioning schedule, taking into account the available resources.

## ACKNOWLEDGMENT

It is a pleasure to thank the various PSI expert groups for providing the input necessary for drawing up the SwissFEL commissioning plan. Special thanks go to Sven Reiche and his team for numerous invaluable discussions on commissioning issues.

## REFERENCES

[1] R. Ganter (ed.), PSI Report 10-06 (2010).

[2] See, e.g., E. Prat, M. Aiba, S. Bettoni, B. Beutner, S. Reiche, and T. Schietinger, Phys. Rev. ST Accel. Beams **17**, 104401 (2014).

[3] See, e.g., R. Ischebeck *et al.*, in *Proc. 2nd Int. Beam Instrumentation Conference (IBIC'13),* Oxford, UK, Sep. 2013, p. 12.

[4] M. Pedrozzi (ed.), PSI Report 10-05 (2010).



ISBN 978-3-95450-134-2

Table 3: Commissioning stages for the SwissFEL linac. Beam conditions refer to the nominal conditions during a given stage; $E$ is the electron beam energy, $Q$ the bunch charge and $R$ the repetition rate. The listed numbers of C-band modules do not include an additional module used to drive the transverse deflecting cavities.

| Commissioning Stage | Approx. Dates | Beam Conditions | Main Tasks |
|---|---|---|---|
| RF Conditioning | Feb.–Aug. 2016 | | Conditioning of C-band modules up to $z$ = 255 m beyond nominal accelerating gradient. |
| **0.32-GeV Linac** (no C-band modules) | Oct. 2016 | $e^-$ to Aramis stopper<br>$E$ = 320 MeV<br>$Q$ = 50 pC<br>$R$ = 10 Hz | Transmission through linac to Aramis beam stopper, beam-based commissioning of diagnostics, test of machine protection system, radiation mapping. |
| **2.1-GeV Linac** (9 C-band modules = linac 1) | Oct.–Dec. 2016 | $e^-$ to Aramis stopper<br>$E$ = 2.1 GeV<br>$Q$ = 50 pC<br>$R$ = 10 Hz | RF commissioning linac 1, beam-based commissioning of diagnostics, setup of beam orbit and optics, commissioning of transverse deflecting structures and bunch compressor 2, setup of energy collimator, global compression setup, radiation mapping. |
| **Transfer- and Undulator Lines** (9 C-band modules = linac 1) | Dec. 2016 | $e^-$ to Aramis dump<br>$E$ = 2.1 GeV<br>$Q$ = 50 pC<br>$R$ = 10–50 Hz | Transmission through undulator line, beam-based commissioning of diagnostics, orbit feedback, systematic beam-based alignment of quadrupoles and beam position monitors, final test of machine protection system, radiation mapping. |

Table 4: Commissioning stages for the SwissFEL Free-Electron Laser. Beam conditions refer to the nominal conditions during a given stage; $E$ is the electron beam energy, $Q$ the bunch charge and $R$ the repetition rate. The listed numbers of C-band modules do not include an additional module used to drive the transverse deflecting cavities.

| Commissioning Stage | Approx. Dates | Beam Conditions | Main Tasks |
|---|---|---|---|
| RF Conditioning | Aug. 2016– July 2017 | | Conditioning of all remaining C-band modules beyond nominal accelerating gradient. |
| **2.1–3.0-GeV FEL ($\lambda$ = 3.7 Å)** (9→13 C-band modules = linac 1&2) | Oct. 2016 | $e^-$ to Aramis dump<br>$E$ = 2.1–3.0 GeV<br>$Q$ = 50–200 pC<br>$R$ = 50 Hz | Undulator alignment, transport at closed gaps, first SASE, empirical SASE optimization, RF commissioning linac 2, linac energy management, FEL characterization and optimization, wavelength tuning, advanced diagnostics commissioning, routine operation studies. *Photonics:* optical hutch Aramis-2 and front-end. |
| **3.8-GeV FEL ($\lambda$ = 2.3 Å)** (17 C-band mod. = linac 1&2, and part of linac 3) | July–Oct. 2017 | $e^-$ to Aramis dump<br>$E$ = 3.8 GeV<br>$Q$ = 50–200 pC<br>$R$ = 50 Hz | RF commissioning linac 3 (first 4 modules), FEL characterization and optimization, wavelength tuning, radiation mapping, routine operation studies. *Photonics:* optical and experimental hutch, end-station for Aramis-1. |
| **5.8-GeV FEL ($\lambda$ = 1.0 Å)** (all 26 C-band mod. = linac 1–3) | Oct. 2017– Feb. 2018 | $e^-$ to Aramis dump<br>$E$ = 5.8 GeV<br>$Q$ = 200 pC<br>$R$ = 100 Hz | RF commissioning linac 3 (rest), FEL characterization and optimization, wavelength tuning, 100 Hz operation, radiation mapping, routine operation studies. *Photonics:* exp. hutch and end-station for Aramis-2. |

ISBN 978-3-95450-134-2