Possibilities for the Realization of Porthos (Machine-side perspective)

During the design of SwissFEL and the space allocation for the building, the possibility to include a third Free-electron laser (FEL) beamline – named Porthos - next to the initial hard X-ray beamline Aramis and the soft X-ray beamline Athos was considered. The present building allows to place Porthos parallel to Aramis with an electron beam distribution system at full energy after the final linear accelerator. An extension of the experimental hall is already integrated in the global construction permit of SwissFEL.

The existing hard X-ray beamline Aramis uses in-vacuum undulator modules with a length of 4 m each and a period of 15 mm. It operates mostly in self-amplified spontaneous emission (SASE) mode with a pulse energy of about 500 uJ and a pulse duration of about 50 fs (RMS) in the photon energy range between 2 and 12.4 keV. Shorter pulses can be produced at the cost of less pulse energy, e.g. pulses below 1 fs duration and a pulse energy of around 5 microJ. Another special mode is the generation of a chirped pulse with a strong correlation between the instantaneous photon pulse energy and its arrival time at the sample.

As a substantial improvement in terms of capability and opportunities, Porthos should offer more than a duplication of the Aramis beamline opening the path for new, unique experiments at SwissFEL.
There are two different but compatible approaches to define the capability of Porthos. A possible layout of SwissFEL with all three beamlines is shown below:

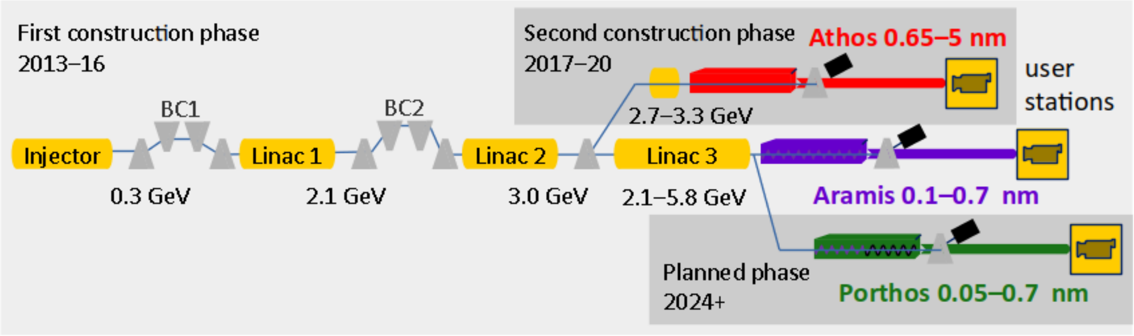
SwissFEL Layout

Athos:

Soft X-ray FEL, λ=0.65–5.0 nm

Variable polarization, Apple-X undulators

First users 2021



Linac:

Pulse duration : 1–20 fs

Electron energy : up to 5.8 GeV

Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz (2-bunches)

Aramis:

Hard X-ray FEL, λ=0.1–0.7 nm

Linear polarization, variable gap, in-vacuum undulators

First users 2018

Porthos:

Hard X-ray FEL, λ=0.05–0.7 nm

Linear polarization, fix gap, super conducting undulators

Start of construction: 2025+

Design

1. Advanced operation modes with interleaved delaying chicanes (CHIC modes)

The soft X-ray beamline Athos has a key feature, which allows controlling the FEL process beyond the standard SASE operation mode. This feature is enabled by the placement of short delaying chicanes at each intra-undulator break section, allowing advanced operation modes that can be transferred from the soft to the hard X-ray regime.

1.1. High Brigthness SASE (HB-SASE)

The most basic mode is the distributed optical klystron, accelerating the formation of bunching in the FEL process and thus reducing the saturation length. In the spectrum the appearance of a modal structure around the central frequency is expected. However this can be mitigated if the beamline is configured as a compact **High-Brightness (HB) SASE**. While the formation of micro-bunching is slightly reduced, yet still faster than normal SASE FEL operation, the delays increase the temporal coherence and cancel out the side bands. Adjusting the delays properly, the resulting single line in the spectrum is narrow. In comparison to standard SASE, the output of this compact HB-SASE is brighter while requiring less undulator length.

1.2 . Short Pulse, High Power (SPHP)

The natural limit of an FEL is the saturation power, which is for SwissFEL parameters around 10 GW. With a pulse length of 50 fs this yields 500 uJ while a sub-femtosecond pulse, as demonstrated by slicing or full compression at Aramis, has a pulse energy of around 10 uJ. A way to overcome the limitation of low pulse energies for very short pulses is the superradiant regime, where the radiation field is overlapped with an unspoiled part of the bunch. Due to the electron-field dynamics, different to the FEL process, the radiation power is further amplified and grows quadratically from the point on where the superradiant regime starts. In the same time a shortening of the pulse exists which goes as the inverse square root of the distance since the starting point.

The main challenge is to provide unspoiled (“fresh”) beam for the superradiant amplification. This can be provided by a spatially tilted beam since only the part (“slice”) aligned to the undulator axis will amplify the field. Once the slice is exhausted the electron beam is delayed by the chicanes, pushing the radiation field forward with respect to the electron beam. It requires also a local realignment of the fresh slice to the undulator axis. Simulations for Athos have shown that TW peak power with a pulse length around 1 fs or less are feasible. Similar performance can be expected for Porthos and thus increasing the pulse energy yield of short pulses by a factor of around 100.

1.3 Mode-locked lasing. (MLL)

A similar scheme that should be further developed is mode-locked lasing, where the delay is applied to a periodic modulation of the electron beam. This can be done either by an external laser (like the implementation of the HERO laser and modulator at Athos), or a beatwave in the laser heater at the injector, generating periodic slices in the electron beam. The frequent pushing of the radiation field through the slices by the delaying chicanes settles the radiation field to a global phase for all slices and thus mode-locking the pulses. The model structure is very pronounced with very thin lines in the spectrum.

2. Advanced Undulator technology (Standard Design vs Superconducting Design)

2.1. Operation with standard undulators

One major challenge of a second hard X-ray beamline is the independent tunability of both beamlines . This is mostly driven by the limited tuning range through the undulator field of Aramis. The operation range of the undulator field is given by the undulator K-paramter with a value of 1.2 to 1.8, corresponding to a change of 30% in photon energy. The major parameter for changing the photon energy is the energy of the injected electron bunch, which ranges between 2 to 6 GeV for the whole tuning range of Aramis. Therefore a user requested photon energy at Aramis defines the energy of the electron beam within a narrow band.

If Porthos utilizes the same undulator type as Aramis the maximum separation would be identical to the tuning range of each undulator, hardly sufficient for a fully independent operation of both beamlines. Splitting the operation range mitigates this problems, since the electron beam energy can be restricted to a narrower range between 4 to 6 GeV for 4-12 keV photons at Aramis. The Porthos branch needs a longer undulator period of about 30 mm to reach the tender X-ray region and a maximum K-value of about 3. This approach does require little R&D on the FEL side with a rather conventional design of the undulator. However, the advantage lies mostly in the operation of the two beamlines. The user stations could be more dedicated and optimized for the specific photon range but in terms of FEL pulse parameters they are similar to the current Aramis operation with a slightly higher pulse energy at Porthos due to the higher K-value of the undulator.

2.2 Operation with super conducting undulators.

A different approach lies in a higher tuning range due to a higher magnetic field on axis, utilizing super-conducting technology for undulators. With the increase of the undulator field a reduction in the undulator period is needed to stay within the hard X-ray regime. An optimum parameter set is a period of 10 mm and a maximum K of about 2.5, compared to 15 mm and 1.2 for the Aramis design). These extreme parameters are challenging but still reachable with super-conducting undulator modules. Currently the ID group is developing such technology and constructing a short proto-type, with similar parameters. The plan is to install such SC undulator at SLS-II fextending the photon energy range and increasing the brightness of such insertion device.

The higher maximum K-value has two advantages. First, it reduces the coupling between Aramis and Porthos with the larger tuning range (as discussed above) but also allows for harmonic lasing, which is a more efficient way to extend the wavelength range in FELs. Instead of tuning directly to 24 keV with a low K-value and thus poor performance, the FEL is tuned to a sub-harmonic, in this example to 8 keV. Under normal condition there is a small, parasitic signal at the third harmonic for a sufficiently high K-values above 2.0, but remains on the percent level when the fundamental reach saturation and the electron beam quality is spoiled for further amplification.

Harmonic lasing avoids this limitation by disrupting the fundamental while the 3rd harmonic is amplified uninhibitedly. Phase shifters, when set to appropiate phase advances at 8 keV, will accomplish this, under the condition that about 4 times per gain length such phase shift occurs. For SwissFEL like parameters this corresponds to about 50 cm undulator sections with phase shifters.

Beside extending the photon energy range the new SC undulator technology improves the performance in the photon range between 2 – 12.4 keV, when compared to Aramis, due to the better coupling of the electron beam to the field.

(I propose to skip these parts for the roadmap document. They are however essential for the further development and should be integrated in an annex)

Evaluation of the the two options

It is possible to combine both options in the final design of Porthos. Depending on the technology choice for the undulator, the major parameters (undulator module length, maximum focussing strength, placement of possible phase shifters etc) needs to be optimized for the various operation modes. The special operation modes (CHIC for Porthos) would also suggest that the Cristalina user station would benefit more if it moves to the new Porthos line since it requests short pulses with high power, which are easier to realize with the new FEL beamline.

Upgrade of the SwissFEL Injector and Linac

With the addition of a third beamline comes the need to accelerate three electron pulses in the same RF pulse. Beside general multi-bunch consideration of all system (e.g. resolving 3 bunches with a fast BPM in the common beamline or adding the event for a third bunch in the control system) there are three major changes to the current configuration.

First it requires an addition gun laser, one for each electron bunch per RF pulse. Here the space requirement in the laser hutch must be evaluated.

Second, the three bunches has to be distributed into three beamlines. The Athos resonant kickers separates a second bunch into a different beamline, which arrives 28 ns after the first bunch. Placing the third bunch 28 ns after the second the resonant kicker has no effect on the bunch and it is transmitted into the third section of the linac. With a resonant kicker after the last RF structure in the section S30CB14, similar to the Athos kicker but with half the frequency one separates the Porthos bunch from the Aramis bunch. Currently the section S30CB15 and S30CB16 are empty and if not needed for an energy upgrade could be used to install the resonant kicker and the Lambertson septum.

Third, The linac has to provide acceleration and compression for all three bunches. In the current implementation the RF amplitude and phase is not constant over 28 ns but has only the same values at the time of the bunch arrivals, e.g. the Aramis and Athos bunch are currently accelerated before and after the peak in the RF field amplitude. Placing a third bunch in the RF pulse would require this for three points in time. A change in the low-level RF signal, controlling its amplitude and phase is needed and requires some R&D to find a technical solution for three bunch operation.

Is it possible to consider following distribution scheme?