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OPERATION MODES OF THE SwissFEL SOFT X-RAY BEAMLINE ATHOS

S. Reiche*, E. Ferrari, E. Prat, T. Schietinger, Paul Scherrer Institut, Villigen PSI, Switzerland

Abstract

The SwissFEL linac drives the two FEL beamlines Aramis and Athos, a hard and soft X-ray FEL, respectively. The layout of Athos extends from a simple SASE FEL beamline with the addition of delaying chicanes, external seeding and beam manipulation with wakefield sources (dechirper). It also reserves space for a possible upgrade to self-seeding. This presentation gives an overview on the detailed layout enabling the unique operation modes of the Athos facility.

INTRODUCTION

Since the first demonstration of Free-electron Lasers (FEL) [1], based on SASE [2] – the amplification of the spontaneous undulator radiation – several user facilities became operational worldwide [3–7] to extend the wavelength down to the hard X-rays. While there has been significant progress to overcome the limited longitudinal coherence of the SASE pulse or to control the pulse length and peak power, only FERMI [8] can be considered a user facility, which deviates significantly from basic SASE operation by providing a fully seeded signal with an external seed laser.

The soft X-ray beamline Athos of SwissFEL [9], which is currently realized as a second step after the commissioning of the hard X-ray beamline Aramis, features a layout optimized away from basic SASE operation at the cost of shorter undulator modules, more focusing quadrupoles and delaying chicanes about 1000 times stronger than phase shifters. It has also sufficient space to host additional hardware such as external seeding.

So far simulations have shown better performances than SASE in terms of saturation length or brilliance but also a more direct control on the FEL output pulse characteristics. This leads to a catalog of various operation modes, depending on the specific needs of user experiments. In the following we give a very brief description of the capabilities of the Athos soft X-ray FEL beamline.

DESIGN AND LAYOUT CONSIDERATIONS

The aim to operate the soft X-ray beamline Athos at SwissFEL independently of the hard X-ray beamline Aramis, whose wavelength is mostly tuned by the electron beam energy between 2.1 GeV and 5.8 GeV, resulted in an optimum solution to extract a second bunch at the intermediate energy of 3 GeV to drive Athos. Up to that point the machine is fixed in its energy profile and only the succeeding linac changes the beam energy for Aramis. The two FEL beamlines share the same infrastructure, they are installed parallel to each other with a shift of 50 m to accommodate the layout of the end stations, see Fig. 1. Also the experimental stations are in the same building. The Athos undulator modules are 2 m long and interlined with dispersive chicanes, thereby offering new modes of operation, as explained in more detail in the next section. A re-optimization of the undulator length resulted in a reduction from 4 m to 2 m [10]. This change did not compromise the baseline SASE operation of Athos, but it allowed for a reduction of the total undulator length since the optical klystron (OK) effect [11] reduces the saturation length. Currently there are 16 modules of 2 m each in the baseline layout with a chicane of 2 m length and a delay of 500 fs in the middle, splitting the undulator beamline in two halves for two-color operation based on tilted beams [12].

An additional grant now allows financing the interaction of the electron beam with a laser. This will be realized in two stages. The first is an energy modulation and conversion into a current modulation (ESASE) [13] by means of a chicane identical to that of the two-color operation. The second phase adds another modulator and a larger chicane for an Echo-Enabled Harmonic Generation (EEHG) [14] set-up to provide seeded pulses to the users at least for the low photon energy range of Athos. The required infrastructure is placed directly in front of the main undulator with the exception of the first modulator, which is located all the way upstream at the end of the out-coupling switchyard to eliminate the need for an additional chicane. The modulator is resonant in the wavelength range between 250 to 1500 nm.

Self-seeding [15] was considered a possible upgrade option for Athos but the decision for shorter undulator modules makes a simple implementation difficult, since the filtering of the FEL signal by a monochromator does not fit into the 2.8 m periodicity of the Athos lattice, much shorter than the implementation at LCLS [16]. Also, self-seeding requires a rather uneven split of the 16 undulator modules for best performance, which is not compatible with two-color operation. Therefore, self-seeding is no longer part of the baseline design. However, the large chicane in the first stage of EEHG is upgradable to include a spectrometer, and the available space before can host up to 5 undulator modules, providing the SASE signal for self-seeding.

Figure 1 shows the final layout with a total length of about 80 m for the FEL beamline, split into 50 m for the main undulator line, 15 m for the EEHG chicanes and modulator and another 15 m for the first stage in a possible self-seeding upgrade. In addition to the standard SASE operation, this arrangement allows control of the bandwidth via either external seeding, self-seeding or HB-SASE [17], as well as the possibility to achieve extremely short pulses. A summary of the Athos parameters are given in Table 1.

* sven.reiche@psi.ch

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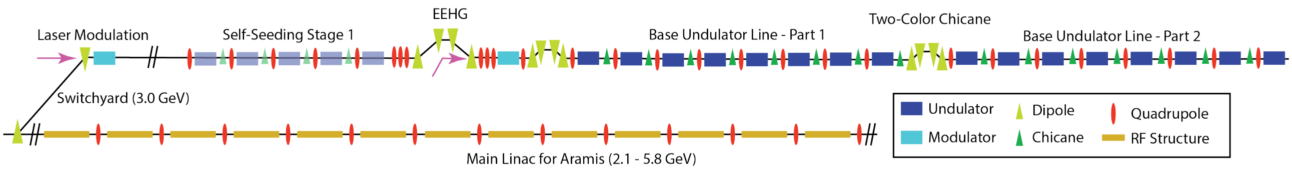

Figure 1: Layout of the Athos beamline.

Table 1: Athos Design Parameters

Parameter	**Value**	**Unit**
Photon Energy Range	250–1900	eV
Beam Energy	2.9–3.4	GeV
Current	2–6 kA	
Charge	10–200	pC
Emittance	100–430	nm
Energy Spread	500	keV
Undulator K-Value	1.1–3.4	
Undulator Period	38	mm
Undulator Module Length	2	m
Number of Modules	16	

OPERATION MODES

The majority of the operation modes for Athos are based on SASE amplification, using the 16 undulator modules interlined with delaying chicanes. To achieve the maximum pulse energy, we plan to operate at the maximum possible K value giving the required resonance at a beam energy of 3.4 GeV. To cover the full tunability range of the beamline, see Table 1, we will have to lower the K value from its maximum above 400 eV final emission. If the optical klystron scheme is not utilized the total length of the undulator is sufficient to reach saturation at 1900 eV photon energy with a K value of 1.1 and the nominal electron beam parameters. This leaves us some safety margin.

Given the limited scope of this conference proceedings, not all modes can be presented in detail. For a summary, see Table 2 where we list the expected performance of the most prominent modes at the reference wavelength of 1 nm.

Chic Modes

Dispersive chicanes of 20 cm length are installed between the undulators. They can act both as phase shifters and/or an electron beam line up to 5 femtoseconds. The longitudinal position of the magnetic arrays of the undulators can also be adapted to compensate for small phasing errors between successive modules. This is particularly important since for large delays the chicanes do not need to have a sub-wavelength tuning precision. The chicanes are also more robust against fluctuations as they are based on permanent magnets. Unavoidable fluctuations in the beam energies are taken into account in the simulations.

A straight-forward application is the distributed optical klystron (OK) [11], where the growth in the micro-bunching is enhanced by the longitudinal dispersion of the chicanes. This is particularly effective in the linear amplification regime. The benefit is a significant reduction in the saturation length of about 30%. The OK effect can also be used to measure the slice energy spread of the electron beam with high precision [18].

The chicanes can also act as small delay lines, retarding the electrons with respect to the radiation field. If the imposed delay is larger than the slippage in one module, the spectro-temporal profile of the output radiation will exhibit mode-coupling. In the case of the Athos undulators, the maximum slippage occurs for emission at the lowest photon energies and is on the order of 200 nm per module, while the maximum delay from the chicanes is 1.5 µm. Another possible approach is to distribute different delays over the entire undulator to increase the slippage. This suppresses the appearance of the modal structure, while at the same time increasing the longitudinal coherence, in the so-called "high-brightness SASE" scheme [17]. In this configuration it is in principle possible to achieve bandwidths comparable to self-seeding, with the only drawback that the electron beam energy jitter causes a jitter in the central wavelength of the FEL radiation. In the original proposal for high-brightness SASE, the delays were supposed to be non-dispersive. Yet, this is very difficult to achieve in a compact design. Therefore, Athos features a compromise between the high-brightness SASE operation and the optical klystron effects, which on the one hand reduces the total saturation length, but on the other hand limits the overall achievable delay before overbunching occurs. We refer to it as the compact high-brightness mode [19]. Its performance is better than standard SASE, as the saturation length is reduced, the power levels are similar to SASE and the final radiation bandwidth is reduced by a factor 7 to 10 depending on the wavelength.

The chicanes can also be used to implement the fresh slice technique [20], in which the radiation is superimposed with different parts of the electron beam that were not involved in the FEL process in previous undulator modules. In this mode, the radiation growth can be superradiant [21] and the FEL amplification can overcome the SASE saturation, while the pulse duration is reduced. Preventing the beam from lasing before it overlaps with the radiation field is achieved by tilt generation [22]. Transversally misaligned slices undergo betatron oscillation disrupting the overlap between electron beam and radiation field, effectively preventing lasing of all slices except the aligned one. The final requirement for achieving superradiant growth is the realignment of the fresh slice. To this end the initial and final magnets of the chicanes are independently tunable, giving control of the transverse

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Table 2: Expected Performances for the Athos Operation Modes at 1 nm

Mode	Pulse Energy	Pulse Duration (r.m.s)	Bandwidth (r.m.s)	Comment
SASE	>1 mJ	30 fs	0.1–0.4 %	
HB-SASE	>1 mJ	30 fs	0.01–0.06 %	
High-power short-pulse	~ 300 µJ	~ 250 as	1% FWHM	20 modules assumed
Large-bandwidth	~ 100 µJ	30 fs	>10% FW	
Slicing	1 µJ per pulse	< 1 fs per pulse	0.1–0.4%	Number of pulses defined by laser pulse length
Self-seeding	~1 mJ	30 fs	$< 10^{-4}$	

offset of the electron beam. The corrector coils installed on the quadrupoles, also located between each undulator modules, allow for further angular correction. The transverse tilt can be generated either by leaking dispersion from the upstream electron beam transport line or the transverse wake of the dechirpers, which are placed in front of the undulator with the primary reason to remove the residual energy chirp needed for compression. The dechirpers are not indispensable for this mode as each undulator can be retuned for the corrected resonance condition.

The delaying chicanes allow Athos to provide either FEL pulses close to the TW level in the high-power short-pulse mode or with improved temporal coherence in the compact high-brightness configuration. We refer to these modes as “CHIC”, which stands for “Compact, High power and Improved Coherence” [10]. They can be also used in combination with laser-manipulated electron beams as discussed below.

Transverse-Gradient Undulator Modes

Athos also introduces a new type of undulator called APPLE-X [23] and derived from the APPLE-II/III layout. Here the 4-quarter arrays of permanent magnets can be moved longitudinally and radially. This avoids the problem of DELTA undulators reducing the effective K value of the undulator by guiding the magnetic field longitudinally and thus reducing the magnetic flux transversely. Since all four motions are controlled independently, two adjacent arrays can be moved out further resulting in a transverse gradient of the undulator field. This feature enables two operation modes. First, a transverse gradient together with a tilted beam, injected into the undulator beamline without external focusing, yields a spatially frequency-chirped pulse [24]. In comparison to alternative methods, such as over-compression, the direction and the amount of chirp can be easily controlled and FEL pulses with full-width spectra up to 20% are achievable. Second, a transverse gradient, together with a rotation of the undulator module around its yaw axis, converts effectively the transverse gradient into a longitudinal intra-module taper. This is needed when a very strong taper is required and the module-wise taper is not sufficiently smooth to maintain the FEL resonance condition within a single undulator module [25].

External Laser Manipulation Modes

With additional funding available, a manipulation of the electron beam by means of a laser field is currently under consideration. Starting with a modulator and a chicane, operation modes such as ESASE and slicing can be obtained, in particular for the case when the laser seed is shorter than the bunch length. This case results in a passive stabilization in the longitudinal arrival time of the FEL pulse with the laser pulse, if the same laser is used also as the pump for the experiments. While ESASE is preferred at shorter wavelengths due to the negative impact of the slippage, the preferred method for short pulses at longer wavelengths is slicing [25]. Here the resonance condition is adapted, while the field slips along the energy modulation. Because the required energy modulation amplitude is larger for slicing, the use of an intra-module taper, as described in the previous subsection, is beneficial.

A very attractive option unique to Athos is the combination of energy modulation with the delay of the intra-undulator chicanes to achieve mode-locked lasing [26]. This configuration is comparable to ESASE with the exception that the radiation spikes are correlated in phase, exhibiting a strong modal structure in radiation spectrum. Besides an energy modulation, we are currently studying also other means of modulation, for instance by current or energy spread.

A further extension of laser-based electron manipulation is echo-enabled harmonic generation, which seems promising for the low photon energy range of Athos. For this, a second modulator and a larger chicane of up to 10 mm R_{56} and a length of 7 m are foreseen. Finally, a possible extension to shorter wavelengths is under study, using either fresh-bunch techniques or staging.

Upgrade Options

Beside the above-mentioned modes, which are funded and currently planned, further upgrades will be still possible. One is self-seeding to provide a stable seed signal in the high photon-energy range, which cannot be covered easily by EEHG. As mentioned above, the large chicane of EEHG can be used to host the monochromator, while the 6 m distance between the end of the chicane and the beginning of the main SASE/CHIC undulator will enhance the resolution as the electron beam will act as an “aperture” for the monochromatized radiation. There is sufficient space

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to place up to 5 modules before the chicane to provide the initial SASE signal to the monochromator. To enhance the resolution, we plan to operate the self-seeding at a subharmonic and then tune to the final wavelength once the seed has introduced a sufficiently high coherent signal at higher harmonics [27].

CONCLUSION

The design of the soft X-ray beamline Athos goes beyond a simple SASE operation. It embeds small chicanes for delaying the electron bunch and the radiation, enhancing the induced bunching or shifting the radiation to a fresh part of the bunch. Together with the flexibility of the APPLE-X undulator design it offers many options to tailor the FEL pulse towards the user needs. This will be complemented by external seeding or slicing to provide narrow bandwidth or trains of attosecond pulses. In the upcoming months the beamline will be commissioned and, if these additional modes will resonate well with users' requests, it will demonstrate the next step in the design of X-ray facilities towards more individual control on pulse characteristics such as length, peak power and bandwidth.

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