ISBN: 978-3-95450-220-2 ISSN: 2673-5474 doi: 10.18429/JACoW-FEL2022-TUP64

EEHG SEEDING SCHEME AT SwissFEL ATHOS FEL

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Abstract

In order to improve the brightness and coherence of the soft x-ray FEL line of SwissFEL (Athos), components for an Echo Enabled Harmonic Generation (EEHG) scheme are currently being installed. The first components have been installed to allow ESASE operation test in spring 2022. This first stage consists in a 10 mJ class seed laser, a U200 modulator with individual control of each half period gap and a four electromagnet dipole chicane (R_{56} ~ 850 µm). The large magnetic chicane and the second modulator are still in preparation for an installation by the end of 2022. This paper describes the different components as well as preliminary results of the commissioning with beam.

ATHOS MODES OF OPERATION

Athos is the second Free Electron Laser (FEL) of SwissFEL which had its first lasing in December 2019 [2-4]. It covers the soft x-ray wavelength range extending from 0.65 nm to 5 nm. It is complementary to Aramis, the FEL already in operation since 2016, which operates in the hard x-ray wavelength range from 0.1 to 0.7 nm. Both FELs share the same photoinjector and linac in which two electron bunches are accelerated with only 28 ns time separation at a repetition rate of 100 Hz [5]. A series of fast kicker magnets followed by a DC septum magnet situated about 300 m downstream the photocathode are deflecting the second bunch towards Athos as the first bunch continues towards the Aramis FEL (Fig. 1). Being the second FEL of SwissFEL, the design of Athos was more ambitious than Aramis and the choice was made at the very early stage to have a very versatile FEL line with different operation modes to control as many parameters as possible of the generated FEL pulses. The ultimate goal is to offer the users a full control of the main light parameters and to push the performances beyond the state of the art. To achieve these goals a few key technologies and design choices had to be made [3]. From day one, Athos has been equipped with small chicanes (CHIC chicanes) between subsequent undulator segments (Fig. 1, top) speeding up the SASE process by about 20 % (optical klystron mode of operation [6]). The undulator design is a so-called APPLE X design [7] where the four magnet arrays can move radially and independently such that a transverse magnetic field gradient can be obtained [8]. Recently a seed laser has been commissioned and is the main ingredient required to do enhanced SASE (ESASE) [9], mode-locked lasing [10] or Echo Enabled Harmonic Generation (EEHG) [11].

With the introduction of an external seed laser, it becomes possible to manipulate the time structure of the generated FEL pulse. For example in the ESASE scheme, a train of attosecond pulses can be generated. Overlapping the seed laser and the electron bunch in a modulator (U200) introduces an energy modulation in the electron bunch, this energy modulation is converted in a density modulation when the bunch passes through an electromagnetic chicane. The obtained electron density peaks will dominate the lasing and generate a train of sub-femtoseconds pulses with a regular periodicity. These peaks are not phase locked but phase locking can be obtained with the mode locking scheme which requires to use the small chicanes situated between every undulator segment. In fact, when the sum of the chicane delay and the radiation phase slippage after one undulator segment is exactly equal to the seed laser period, then it becomes possible to reduce the bandwidth of individual pulses and to propagate the phase information over many pulses of the train. The pulses are then phase locked.

With the EEHG scheme very high harmonics of the seed laser wavelength can be amplified and the bandwidth of the radiated pulses is further reduced close to the Fourier Transform limit. Also, the shot to shot wavelength jitter is reduced which is a very important parameter for experiments. The produced pulses are then almost fully coherent, both transversally and longitudinally.

EEHG COMPONENTS

Layout

ESASE and mode-locking modes of operation are using half of the components required for EEHG. Logically the project was then split in two phases. In the first phase, a completely new laser room with controlled air temperature, humidity and cleanness has been installed in a building room next to Athos. The seed laser was installed together with an UHV vacuum line to transfer the laser pulses over about 13 m from seed laser room to a laser table near the incoupling electromagnet dipole (Fig. 1-Bottom). This dipole is in fact the last dipole of the SwissFEL dogleg allowing easy incoupling onto Athos axis. About two meters downstream from the in-coupling window, a modulator U200 has been installed where the electron bunches and the seed laser pulses should overlap.

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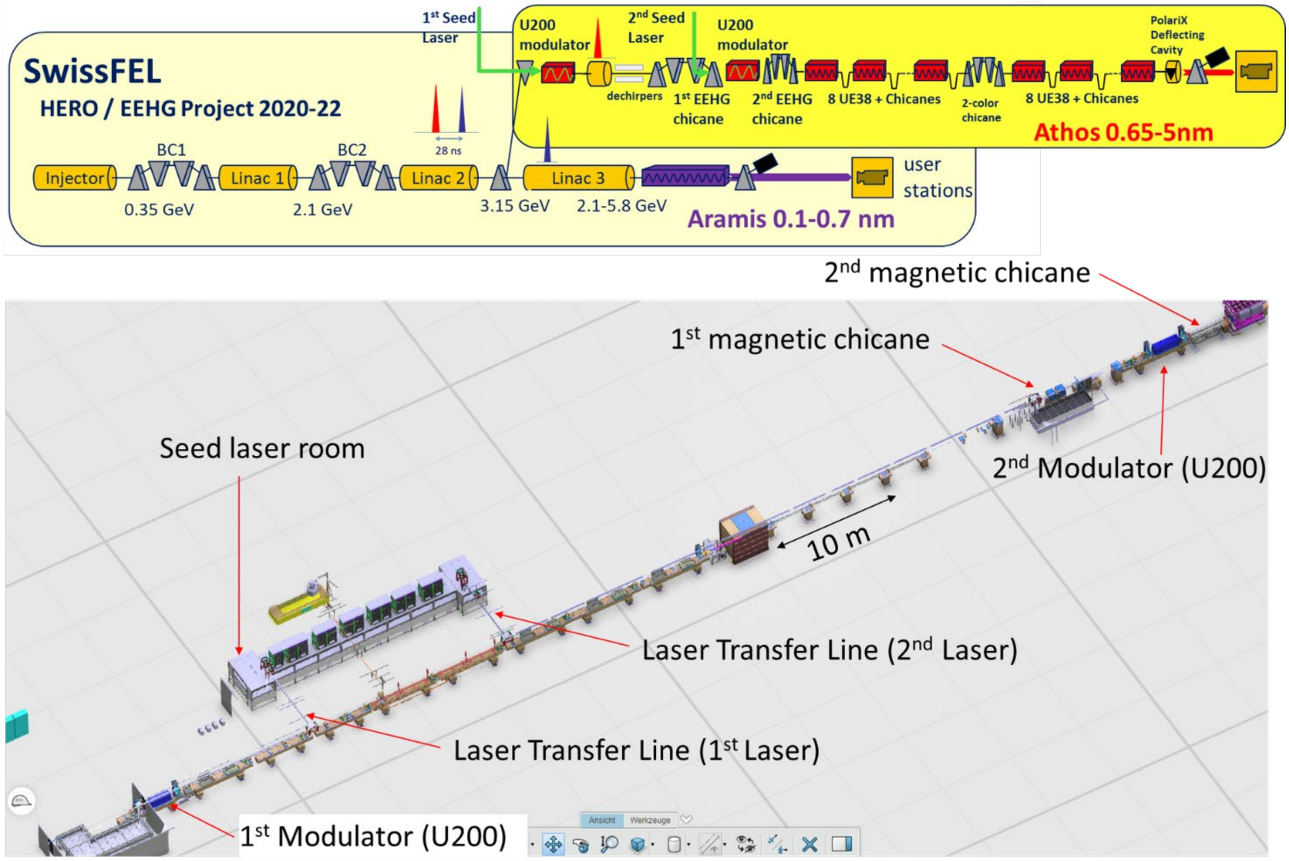

Figure 1: Schematic of SwissFEL with the Athos line and the main components required for EEHG (top). 3D illustration of the Athos areal where the EEHG are installed giving an idea of the scale (bottom).

Sixty meters further downstream in the line a chicane made out of four electromagnets (2nd magnetic chicane in Fig. 1) was recently commissioned. With these elements it became possible to perform first ESASE tests as well as mode locking tests as described below. The rest of the components (the 2nd Laser Transfer Line, the 2nd modulator and the strong magnetic chicane (1st magnetic chicane in Fig. 1)) with laser in coupling are still in preparation.

Seed Laser

Laser pulses of a few mJ at 800 nm (266 nm for EEHG) are focused to a spot size of 400 um rms in the modulator. The detailed description of the seed laser is given in a companion paper [1].

Modulator U200

The modulator design was inspired by the pre-existing permanent magnet CHIC chicanes installed between the undulator segments of Athos and which have a total length of 200 mm with 4 permanent magnets in a row [5]. The U200 consists in fact of a series of 9 such CHIC chicanes placed on a granite girder (Fig. 2). Only the magnetic polarisation configuration of the 4 permanent magnets differs to the chicanes and is here ++/-- as it is +-/-+ in an Athos undulator chicane.

With this ++/-- magnetic arrangement there is the nice feature that every half period of the U200 is independently motorized with two motors per half period for the upper and lower magnets (Fig. 2). As a consequence the undulator shimming can easily be done directly with the motors and the relation between local K and gap for every half period was recorded during a Hall probe measurement campaign. Figure 3 illustrates the beam trajectory within the undulator assuming a beam energy of 3 GeV, the end magnets are set such that the beam enters and exits on axis. This setting of the end magnets can easily be changed with the motors. From Fig. 3, we see that the trajectory horizontal oscillation (x direction) is about 400 μm at maximum for K=36 which corresponds to a gap of 11.5 mm. The vacuum chamber is made out of copper with an elliptical cross section (8 x 16 mm inside dimensions) and 0.5 mm wall thickness allowing an absolute minimum gap of 10.8 mm.

For a laser wavelength around 800 nm, the resonance will be at K=24.6 such that the orbit transverse motion amplitude will be rather 200 um and then smaller than the laser spot size (400 um rms) in the modulator.

During first modulator assembly it was found out that due to the repulsive force of two adjacent magnet blocks of same half period (++ or --), the blocks were not perfectly parallel despite the clamping system. It was then decided to glue together the two magnet blocks of the same half period. In addition, two guiding rails are holding the half period magnet keeper instead of one in the original CHIC

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design. This is to avoid any mechanical tilt of the keepers when having different gaps between adjacent half periods.

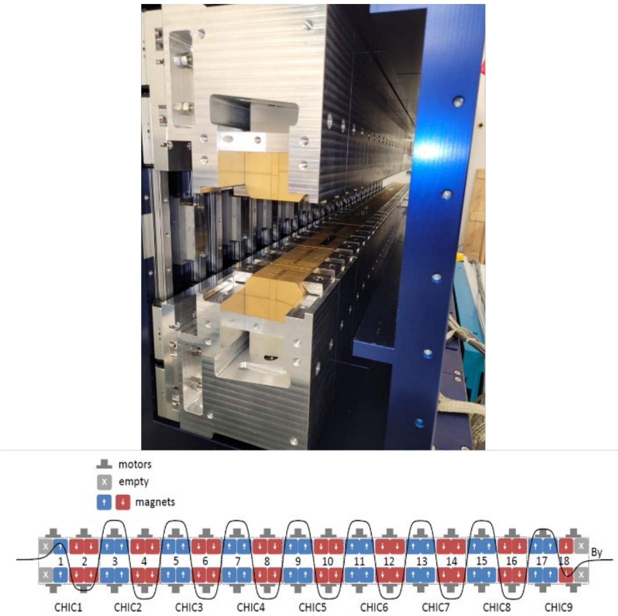

Figure 2: Picture of the U200 gap where every half period can be motorized independently (top) as depicted in the bottom schematic (bottom)

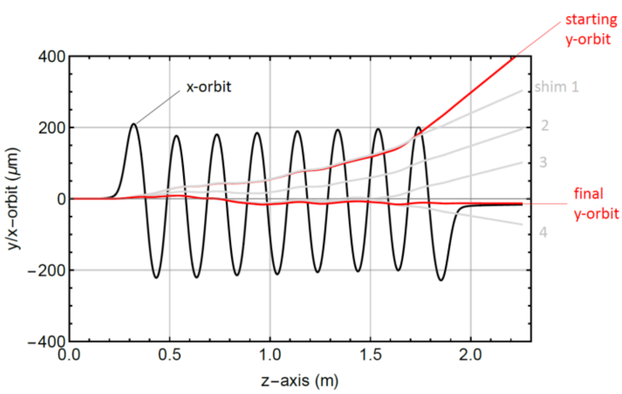

Figure 3: Beam trajectory for K = 36 (minimum gap of 11.5 mm) in horizontal plane (black) and in vertical plane (red). The grey curves show the effect of steel corrections strips.

Finally small steel correction strips have been glued directly on some magnets, within the gap, to correct the vertical orbit (dark strips visible on the magnet surface in Fig. 2 top picture). Indeed, vertical magnet pointing errors of individual blocks were not negligible and had to be compensated to obtain a flat vertical orbit (red and grey curves in Fig. 3).

Overlap Diagnostic

In order to overlap the seed laser pulses with the electron bunches, screens were installed upstream and downstream of the U200 for spatial and temporal overlap. For transversal overlap a Cromox Al_2O_3 or a YAG screen can be inserted depending on seed laser wavelength. The downstream screen feedthrough is also equipped with an OTR screen (50 um Si + 200 nm Al) which will direct the transition radiation of the electron bunches as well as the seed laser pulses on a photodiode or photomultiplier. The diode resolution (rise time of 15 ps) will only allow a coarse overlap of the laser pulses (about 500 fs FWHM) and electron bunches (50 fs rms). The fine tuning has to be done by scanning a seed laser delay stage over typically 50 ps with 0.1ps increment and looking for a decrease in SASE intensity. During the first test the SASE intensity decreased by almost 80%, clearly indicating the temporal overlap. The photomultiplier (500 ps rise time) with a larger acceptance window was finally not used since the photodiode could easily capture some signal.

Compression Chicanes

For the EEHG scheme, two compression chicanes with different R_{56} values are required. Their parameters are summarized in Table 1. The “strong” chicane serves also as in-coupling point for the second (not yet installed) seed laser. It is almost 10 m long and its main particularity is that the vacuum chamber between the 3rd and 4th dipole is movable transversally to the beam propagation by 100 mm (see Fig. 4) such that one can either couple the seed laser onto the Athos axis (Chicane ON and Position IN) or leave the electron beam orbit straight (chicane OFF and Position Out).

Table 1: EEHG Compression Chicane Parameters

EEHG Weak Chicane	**Max.**
Deflecting angle	1.55 deg (27 mrad)
Transverse beam offset at central dipoles	18.4 mm
R_{56}	849 µm
Delay in ps	1.41 ps at 3.15 GeV
Chicane Total length	2.12m
EEHG strong Chicane	
Deflecting angle (at 3.15 GeV)	2.79 deg (48 mrad)
Transverse beam offset at central dipole	193 mm
R_{56}	18 mm
Delay in ps	30 ps
Chicane Total length	9.15 m

FIRST ESASE RESULTS

The detection of time overlap was found by detecting an FEL pulse energy drop by almost 80% while scanning a delay stage. The Athos line is equipped with a transverse deflecting cavity (with variable polarisation) downstream the undulator line [12]. This diagnostic device gives the possibility to streak the bunch horizontally and then in a vertically oriented dispersion section (like the beam dump section) to observe the bunch energy distribution along its length. The electron energy spread gets larger when the seed laser is activated. So far the streaking resolution was not enough to observe a train of sub-fs pulses but the deflecting cavity was not yet conditioned to its full power.

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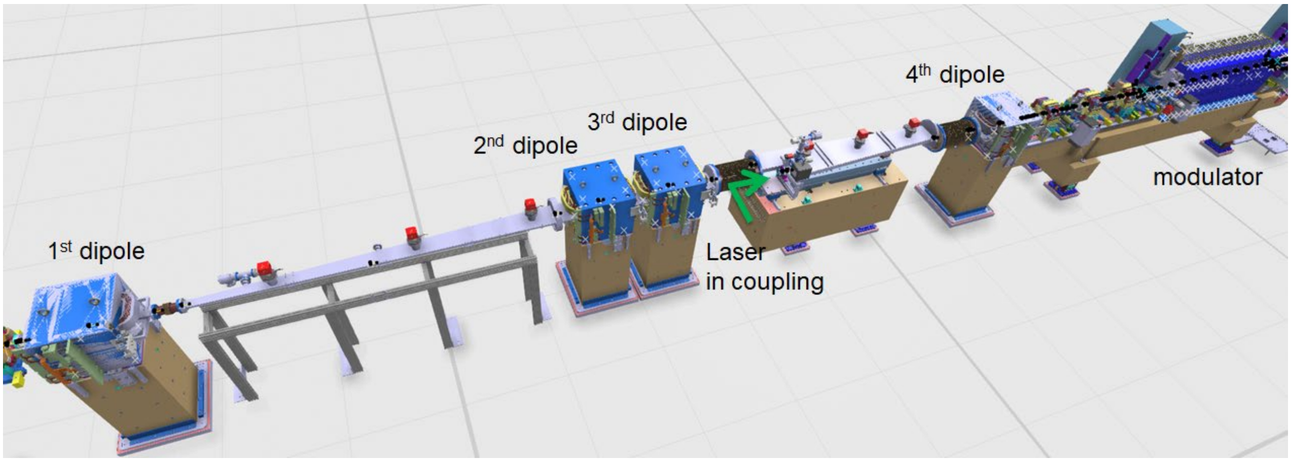

Figure 4 : 3D Layout of the « strong » EEHG chicane with a movable vacuum chamber between the 3rd and 4th dipole to allow laser in coupling.

Once the overlap between the electron bunch and the laser pulses is insured, the ESASE mode of operation is straight forward and best proven by looking at the FEL pulse spectrum. For this purpose, the single shot spectrometer of the Athos line has been used. Up to 100 spectra are acquired and a second order correlation analysis of these spectra revealed side band frequency peaks which are characteristic of a train of short pulses with regular periodicity. This periodicity is exactly equal to the seed laser period (800 nm or 2.7 fs or 1.55 eV). It is more difficult to determine whether mode locking could be reached. To achieve mode locking, the delays induced by the CHIC chicanes between the undulators together with the natural phase slippage of the radiation with respect to the electron bunch in each undulator segment should be equal to the seed laser period. When such a condition is fulfilled the individual pulses of the train should have the same phase and should be below one fs in duration. This would then be a train of sub-femtosecond long, phase locked pulses. Unfortunately, the autocorrelation plot does not exhibit much difference between the ESASE mode and the mode locked operation mode. Most probably this comes from spectral resolution limitations. Further measurements and analysis are planned on mode locking lasing even if an indirect measurement of phase conservation over individual pulses in a train might be difficult.

CONCLUSION

Components required for EEHG at SwissFEL are under preparation. Preliminary studies with the first stage involving only one modulator, a seed laser and a compression chicane showed are consistent with generation of a train of sub-femtosecond pulses. The mode locking scheme where `individual pulses of the train are also phase locked is more difficult to characterize. The installation of the rest of the EEHG components should be completed by April 2023.

ACKNOWLEDGEMENTS

The authors would like to thank all PSI technical staff that participated in designing and building this facility.

This project received funding from the European Research Council under the European Union’s Horizon 2020 research and innovation program, within the Hidden, Entangled and Resonating Order (HERO) project with Grant Agreement 810451.

REFERENCES

[1] A. Trisorio *et al.*, “Laser-Based Seeding of SwissFEL Athos”, presented at the FEL2022, Triest, Italy, Aug. 2022, paper TUP65, this conference.

[2] J. Alex *et al.*, "Athos Conceptual Design Report," Paul Scherrer Institut, PSI Villigen, 17-02, September 2017 2017.

[3] R. Abela *et al.*, "The SwissFEL soft X-ray free-electron laser beamline: AthosThis article will form part of a virtual special issue on X-ray free-electron lasers," *J. of Synchrotron Radiat.,* vol. 26, no. 4, pp. 1073-1084, 2019. doi: 10.1107/S1600577519003928.

[4] M. Yabashi, "Compact design delivers hard X-rays", *Nat. Photonics,* vol. 14, no. 12, pp. 715-716, 2020. doi: 10.1038/s41566-020-00721-7.

[5] R. Ganter *et al.*, "Status of Athos, the soft X-ray FEL line of SwissFEL", in *39th international free-electron laser conference. FEL2019*, Hamburg, H. S. In W. Decking, G. Geloni, S. Schreiber, M. Marx, & V. R. W. Schaa (Eds.), Ed., 2019, vol. 39, pp. 753-756. doi: 10.18429/JACoW-FEL2019-THP085.

[6] E. Prat, E. Ferrari, M. Calvi, R. Ganter, S. Reiche, and T. Schmidt, "Demonstration of a compact x-ray free-electron laser using the optical klystron effect", *Appl. Phys. Lett.,* vol. 119, no. 15, p. 151102, 2021. doi: 10.1063/5.0064934.

[7] T. Schmidt, & Calvi, M. , "APPLE X undulator for the SwissFEL soft X-ray beamline Athos", *Synchrotron Radiat. News,* vol. 31, no.3, pp. 35-40, 2018. doi: 10.1080/08940886.2018.1460174.

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[8] E. Prat, M. Calvi, and S. Reiche, "Generation of ultra-large-bandwidth X-ray free-electron-laser pulses with a transverse-gradient undulator", *J. Synchrotron Radiat.,* vol. 23, pp. 874-879, 2016. doi:10.1107/S1600577516007177

[9] A. A. Zholents, "Method of an enhanced self-amplified spontaneous emission for x-ray free electron lasers", *Phys. Rev. ST Accel. Beams,* vol. 8, no. 4, p. 040701, 2005, doi: 10.1103/PhysRevSTAB.8.040701.

[10] N. Thompson and B. McNeil, "Mode Locking in a Free-Electron Laser Amplifier", *Phys. rev. lett.,* vol. 100, p. 203901, 2008. doi:10.1103/PHYSREVLETT.100.203901.

[11] D. Xiang and G. Stupakov, "Echo-enabled harmonic generation free electron laser", *Phys. Rev. Accel. Beams,* vol. 12, no. 3, p. 030702, 2009. doi:10.1103/PhysRevSTAB.12.030702.

[12] P. Craievich *et al.*, "Novel X-band transverse deflection structure with variable polarization," *Phys. Rev. Accel. Beams,* vol. 23, no. 11, p. 112001, 2020. doi:10.1103/PhysRevAccelBeams.23.112001.