# STATUS OF SwissFEL UNDULATOR LINES

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*Abstract*

SwissFEL [1] will start operation with the so-called Aramis FEL line which lases in the hard X-ray wavelength range from 1 to 7 Angstroem. First photons are foreseen for the end of 2016. In this first phase of the project only the transfer line (a dog-leg section) to the soft X-ray line will be assembled. The soft X-ray undulator line, Athos, will be completed at a later stage after 2018. The civil construction of SwissFEL has started in spring 2013 and will be completed by December 2014. Aramis line has 12 undulator segments but can host up to 20 segments. Tests of an undulator prototype have been recently completed and are described in a companion paper [2]. The layout and the design status of components are presented.

## LAYOUT ARAMIS LINE & TRANSFER LINE

The overall layout of SwissFEL is shown in Fig. 1. In order to tune the FEL wavelength of Aramis between 1 and 7 Angstroem, the electron beam energy can be varied between 2.1 and 5.8 GeV. This is achieved with Linac 3 which either accelerates or decelerates the beam. This enables the energy at the extraction point towards Athos (end of Linac 2) to stay always constant and equal to 3 GeV. The Aramis line (Fig. 3) has 20 half FODO period of 4.75 m length that is to say a total length of 95 m for a maximum saturation length around 50 m (Fig. 2). This additional length in Aramis allows installation of more segments in case the electron beam quality is worse than expected but it also reserves space in the building for a future integration of an X band deflecting cavity downstream undulators like recently built at LCLS [3]. The Aramis line is located in a single floor building (Fig. 4) and most of the electronic infrastructure is situated in the gallery beside the tunnel. The vacuum tank of the in-vacuum undulator will be assembled in the SwissFEL building (see U15 assembly area in Fig. 4) just after the final magnet optimization which is done in the insertion device laboratory (ID lab in Fig. 4). The transport of undulators to their final destination is done thanks to an air cushion vehicle because of small tunnel height and in order to limit mechanical shocks.

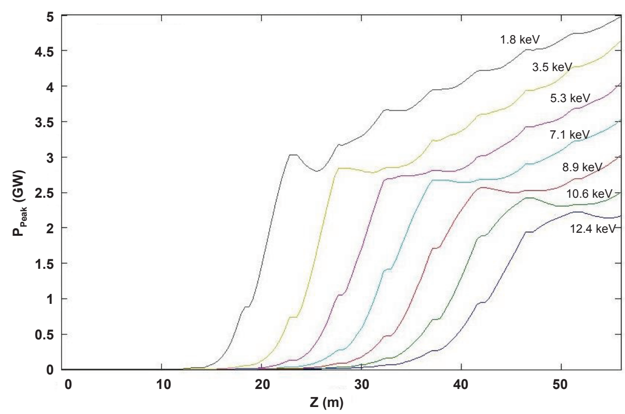


Figure 2: Genesis simulation of FEL power growth for the nominal design parameters of SwissFEL: 200 pC; 3 kA; 0.45 µm slice emittance.

At the end of the undulator line, electrons are bent vertically down towards a 240 tons beam dump shielding. Such massive beam dump can absorb 288 µC/h allowing the area situated 5 m above to stay a public zone [4]. The base plate for the beam dump is already poured on construction site (Fig. 5).

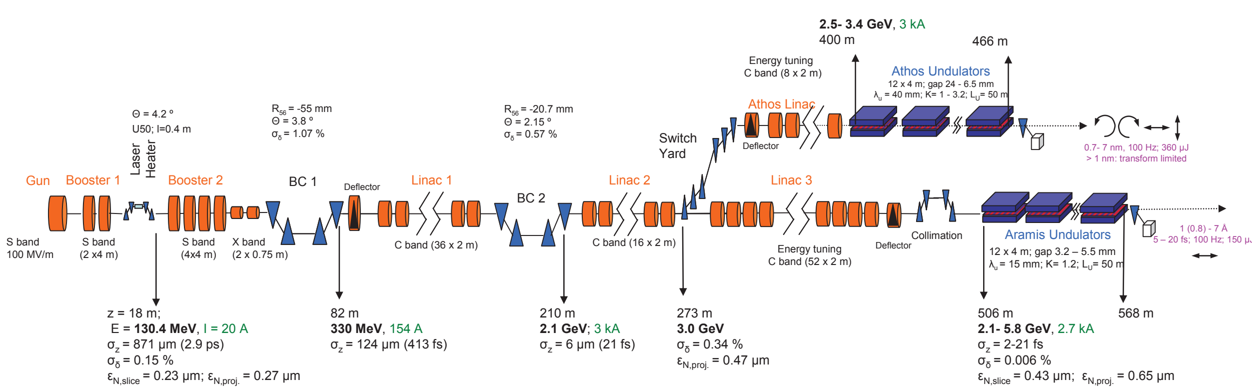


Figure 1: Layout of SwissFEL with the hard X-ray FEL line Aramis and the future Athos line to be built after 2018 (some parameters are just indicative and only valid for a specific mode of operation).



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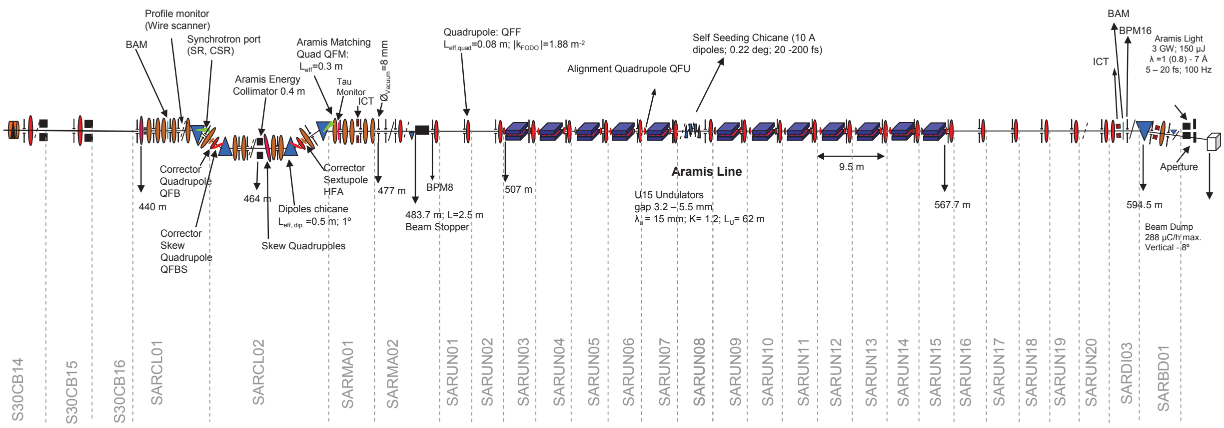


Figure 3: The Aramis hard X-ray SwissFEL undulator line starting with the energy collimator chicane to the beam dump.

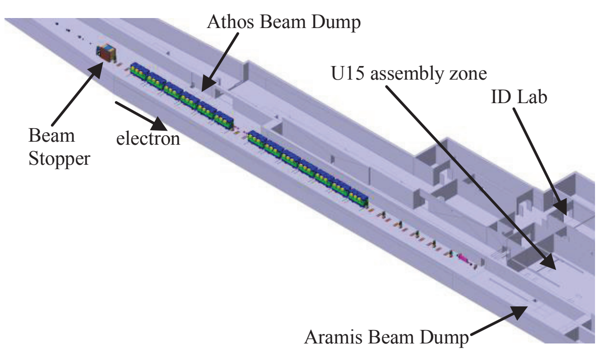


Figure 4: 3D drawing of the Aramis FEL line in the building.

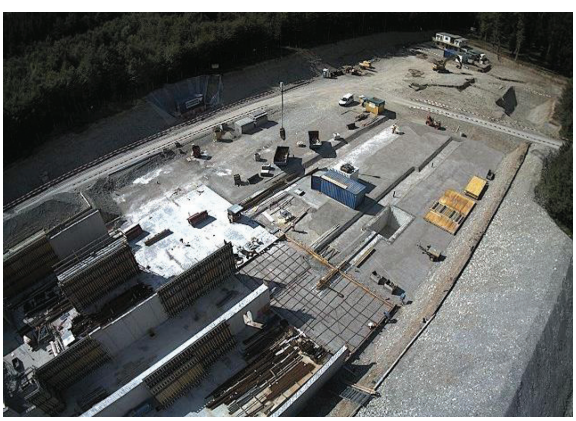

Figure 5: Picture of the SwissFEL construction site with the Aramis beam dump groove clearly visible.

SwissFEL injector will produce two bunches separated by 28 ns at a repetition rate of 100 Hz. The second bunch is deflected after linac 2 in the transfer line (Fig. 6) towards the soft X-ray Athos line. This dog leg line is designed such that it can also act as a compression chicane depending on the operation mode. So called "de-chirper" components, which removes energy chirp thanks to wakefields, can be installed in the first bending section of +5 degrees (SATSY03 in Fig. 6). An energy collimator will be installed in the second section (-5 degrees) in SATCL01. The distance between Athos and Aramis line is 3.75 m [5]. The installation of the transfer line will start in the first half of 2017 during short shutdowns of 2 weeks planned every 1.5 months.

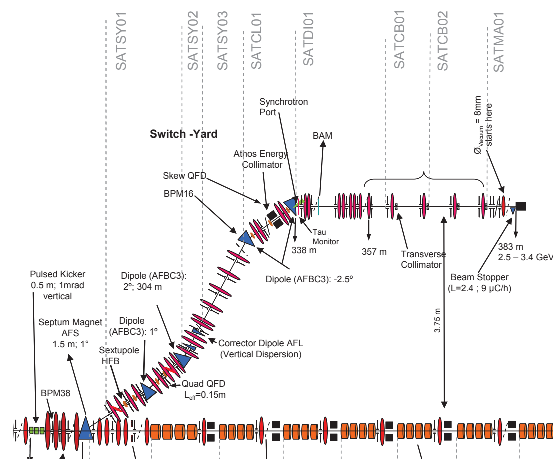


Figure 6: Layout of the transfer line to the future Athos soft X-ray FEL line.

## MATCHING SECTIONS & ENERGY COLLIMATORS

Linac 3 ends with a transverse deflecting cavity just upstream the energy collimator chicane of Aramis (SARCL01-02 in Fig. 3) [6]. In consequence, several screens and wire scanners are installed in this chicane to characterize the electron bunch phase space transversally and longitudinally before it enters the undulator line. A first matching section (SARCL01 in Fig. 3) with 5 water cooled quadrupoles (Fig. 7) is used to vary the phase advance for phase space measurements and / or to match the beam into the 4 dipole chicane. Design of these magnets is completed and production has started (Fig 7). Additional quadrupoles between dipoles in the chicane can adjust the dispersion (for example in the case of the large bandwidth mode of operation for which the electron bunch has a large energy spread) to make sure that the beam goes always between the collimator blocks (Fig. 8).



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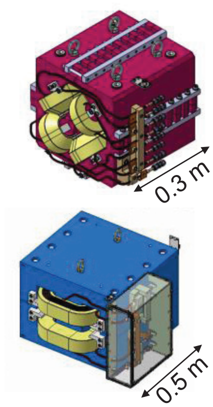
With a gap of 2 mm and a dispersion of 0.1 m the collimator has an energy acceptance of 2%. This is enough to block the full beam in case of failure of a RF module which would lead to a 4% energy drop at minimum.




| Matching Quadrupole specifications (water cooled) | |
|---|---|
| Aperture | 22 mm |
| Gradient max. | 50 T/m |
| Yoke length | 30 cm |
| Maximum Current | 50 A |
| **Delivery of 18 Units** | **End 2013** |

| Collimator chicane (& Transfer Line) dipoles | |
|---|---|
| Gap | 22 mm |
| Integrated field max. | 0.46 T.m |
| Yoke length | 50 cm |
| Maximum Current | 150 A |
| **Delivery of 12 Units** | **Mid 2014** |

Figure 7: Matching quadrupole magnets (top) and energy collimator dipole magnets (bottom).

Downstream the 4 dipole chicane, another 5 quads section (SARMA01) insures the matching of the beam into the FODO lattice of the Aramis undulator line. Three wire scanners located at equivalent positions of the ½ FODO periods (in SARMA02, SARUN08 and SARUN20) can be used to check transverse beam size periodicity.

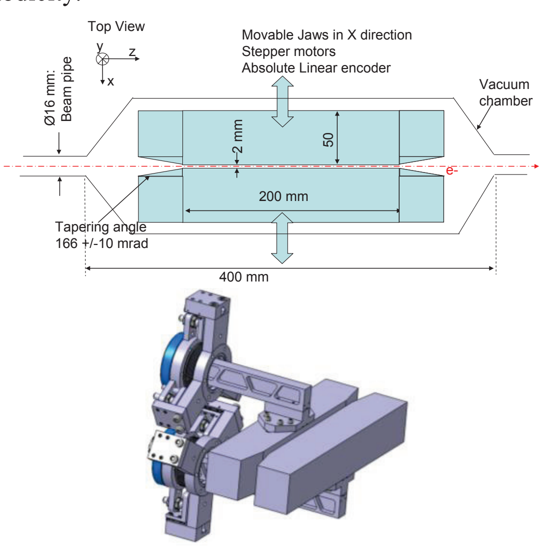



Figure 8: Collimator block system to intercept electrons having the wrong energy in order to protect undulator magnets from radiation.

During commissioning of the linac the beam is deviated into a beam stopper (SARMA02) thanks to a retractable permanent magnet (Fig. 9). Once the electron beam quality is adequate, the dipole will be retracted to let the beam go through the undulator line.

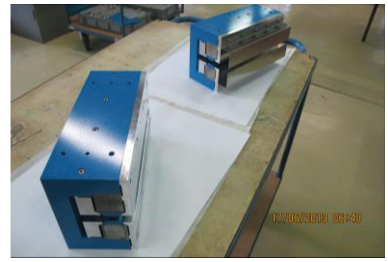


Figure 9: Permanent dipole magnets (0.22 T.m) used to deflect the beam into a beam stopper or into the shielding wall (safety dipole upstream of user area ).

A set of 3 BPM cavity (1 µm resolution) will be placed in front of the undulator line in order to determine, and later check, the injection angle of the electron beam into the undulator line.

## INTER-UNDULATOR SECTION

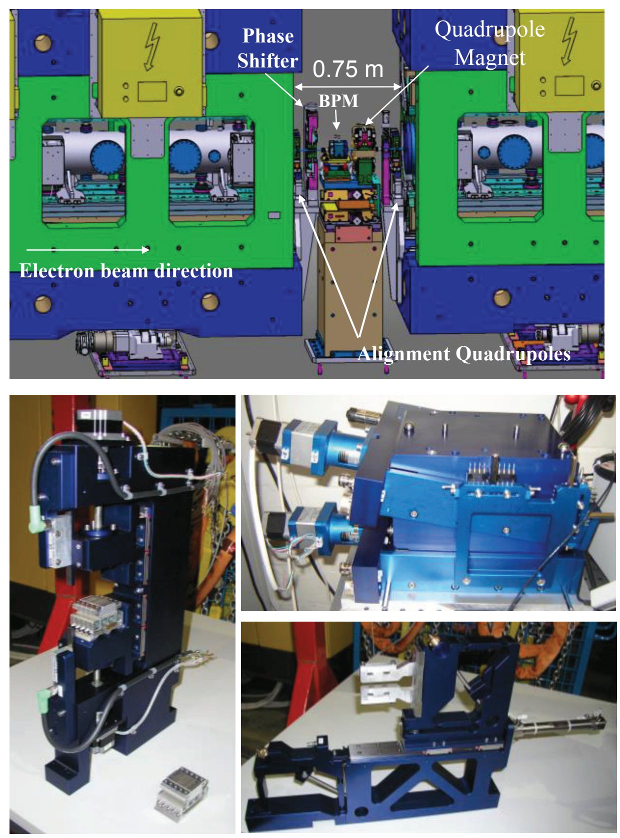



Figure 10: Inter-undulator section (top), phase shifter (bottom left), X-Y table and alignment quadrupole (bottom right).

The beam trajectory through the Aramis line, should not deviate from an ideal straight line by more than 3 µm rms over a length of the order of the gain length (gain length ~ 1.8 m) to limit deterioration in FEL power to 5%. This will be achieved by beam based alignment (BBA) of the BPMs with an algorithm proposed in [7]. The BPMs are situated in every inter-undulator section, mounted on a motorised X-Y supports (Fig. 10) having less than 0.3 µm

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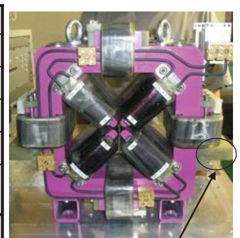
encoder resolution. FODO quadrupole magnets share the supports with BPMs. They are air cooled and they will slightly heat up and deform (dilatation) when going from 0 A to the nominal operation current of 6 A. Vibrating wire measurements on a prototype quad [8] have shown that the quadrupole axis moves by less than 4 µm vertically when current rise from 0 to 7 A (Fig. 11) as expected from simulation [9]. The corresponding temperature rise is only about 5 degrees C and dilatation stops after 8 hours once the steady state temperature is reached.

| FODO Undulator Quadrupole | |
|---|---|
| Aperture | 12 mm |
| Gradient max. | 50 T/m |
| Yoke length | 8 cm |
| Maximum Current | 10 A |
| Steering Dipoles maximum angle (@ 5.8 GeV, bandwidth 1 kHz) | 200 µrad |
| **Delivery of 24 Units** | **Spring 2014** |



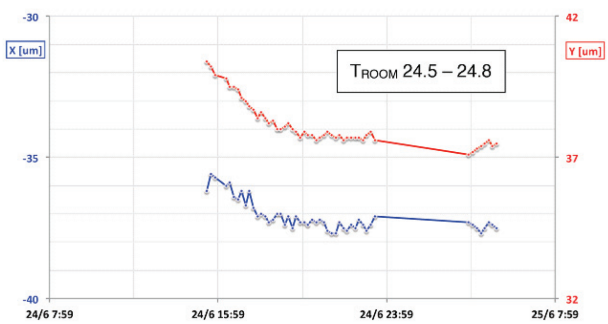




Figure 11: Parameters and picture of the quadrupole magnet located between undulator segment (top). Measurements of quadrupole axis position versus time after current was set to 7 A (vertical scale is inverted, axis is going up during dilatation).

The complete alignment strategy for the undulator line is summarized in Table 1.

Table 1: Undulator Line Alignment Strategy

| |
|---|
| 1. Pre-alignment of quadrupole & U15 < 100 µm (laser tracker method) |
| 2. Beam based alignment (Undulator Gap Open) *BBA method: Minimization of steerer strength deviation [7].* Goal: e-beam straightness < 3 µm over gain length |
| 3. Alignment of U15 on e-beam axis using Alignment Quadrupoles. Undulator axis aligned on electron beam < 10 µm |
| 4. K- value discrepancy & Phase mismatch (using photonic diagnostics) |

After achieving an alignment of the BPMs onto a straight line with the electron beam (within 3 um over the gain length), each undulator segment will be aligned on this beam axis with the so called alignment quadrupoles ($Q_{AI}$) (Fig. 10) which deflects the beam when the trajectory does not corresponds to its centre. Finally the series of 11 phase shifters (Fig. 10, left) which insure the time overlap between electrons and radiation are currently assembled at PSI.Not shown on Fig. 10, are the corrector air coils which will be wrapped around the beam pipe (Fig. 12) at each undulator end. These correctors have to compensate the kicks (< 5 µrad at 5.8 GeV) produced by end magnets of the undulator magnet arrays. These end magnets compensate kicks only for a given operating gap. Additional coils realize a local correction of the gap-dependent kick for the full gap range (3.5 to 6 mm). Correction fields (up to 120 µT.m) will be measured in the lab and a look-up table will be prepared for a use during operation. The table will be updated based on beam if necessary.

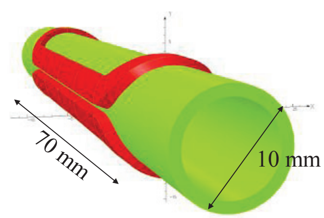



Figure 12: Corrector coils (230 µT.m for 10A) which will be installed at each extremity of an undulator segment to compensate end magnets kicks.

## CONCLUSION

Preparation of components for the Aramis Hard X-ray FEL line of SwissFEL is progressing in order to start assembly in January 2015. Most of magnets are designed and are currently in production. After successful characterization of the undulator U15 prototype (see companion paper [2]), the production of the full series of 12 undulators will start in a few months. Components of the inter-undulator section are designed and first mechanical parts have arrived at PSI. Civil construction has already started and will be completed by January 2015, but heavy components like beam dumps will already be installed in 2014.

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