TECHNICAL OVERVIEW OF THE SWISSFEL UNDULATOR LINE

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Abstract

SwissFEL [1] is a hard X-ray FEL facility currently being designed at PSI. It uses a photocathode gun, S-band injector and C-band main linac to drive a hard X-ray undulator line with 100 Hz repetition rate. Beam commissioning of the hard X-ray undulator line called Aramis is scheduled to start in 2016. The Aramis line extends over a length of 177 m, from an energy collimator after the main linac to the electron beam dump. Electrons enter the Aramis line with a maximum energy of 5.8 GeV, a normalized slice emittance below 0.43 µm and a peak current of 3 kA at 200 pC bunch charge. A prototype of an in-vacuum undulator (U15) is currently being assembled. Most of the other beamline components have been designed and for some of them prototypes are already ordered. This paper describes the main beamline components of Aramis (quadrupoles, phase shifters, alignment quadrupoles, mechanical supports, safety components) with particular emphasis on constraints like temperature drifts, stray magnetic field, wakefields and costs. Undulators are however described in details in a companion paper [2].

ENERGY COLLIMATOR AND BEAM STOPPER

At the entrance of Aramis, the electron bunch has a momentum spread of 350 keV for the 200 pC normal operation mode of SwissFEL [1]. The repetition rate is 100 Hz. In order to protect the undulator from beam losses, the electron bunch will pass through an energy collimator (at z= 454 m) having an energy acceptance of 2 % peak to peak. Downstream of the energy collimator chicane the electrons will go through a matching section, where the electron bunch transverse profile is checked with a screen and a wire scanner. During the tuning of the machine the beam is deflected horizontally towards a beam stopper upstream of the 1st undulator (z = 501 m).

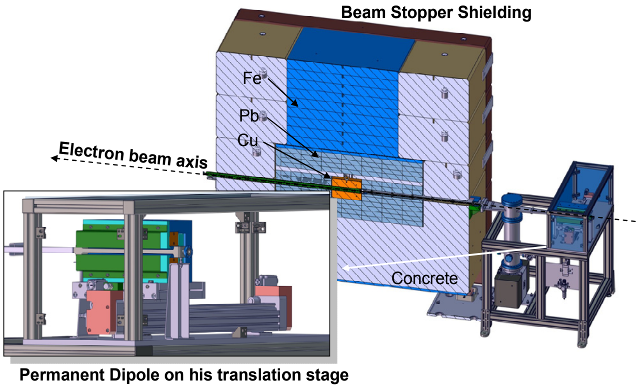

Figure 2: Beam stopper layout assembly: the 5.8 GeV beam is deflected by 0.7 º when the dipole is inserted.

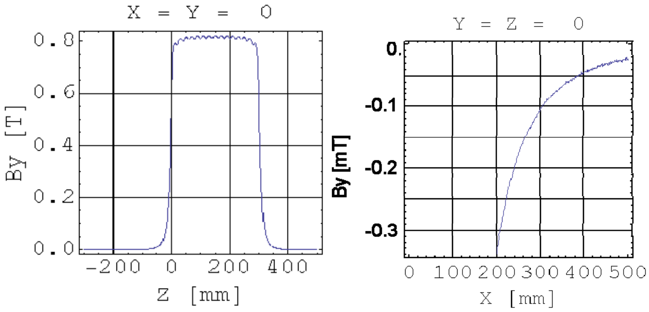

Figure 3: Permanent dipole field profile along axis (left) and transverse stray field at Z=150 mm; Y=0 (right).

This deflection is generated with a permanent dipole magnet. This magnet (which slides transversally) can be moved remotely into the beamline (Fig. 2). When the dipole is retracted 400 mm out of axis the remaining dipole field on axis is less than 0.5 G (Fig. 3), so that the electrons can continue straight to the undulators, with perturbations on the earth magnetic field level. Using an electromagnet instead of a permanent one would have required more space as well as a degauss procedure.

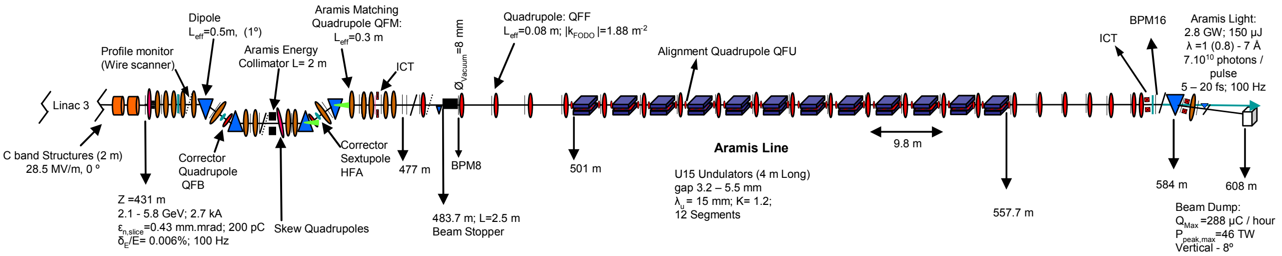

Figure 1: The Aramis hard X-ray SwissFEL undulator line.

The beam stopper shielding can absorb up to 9 μC / hour of beam at 7 GeV. This corresponds to a dose rate below 0.25 mSv/h on shielding surface, as shown by FLUKA simulation on Figure 4 (purple contour line). The electrons are stopped by a copper block surrounded by 0.5 m of lead followed by iron and concrete.

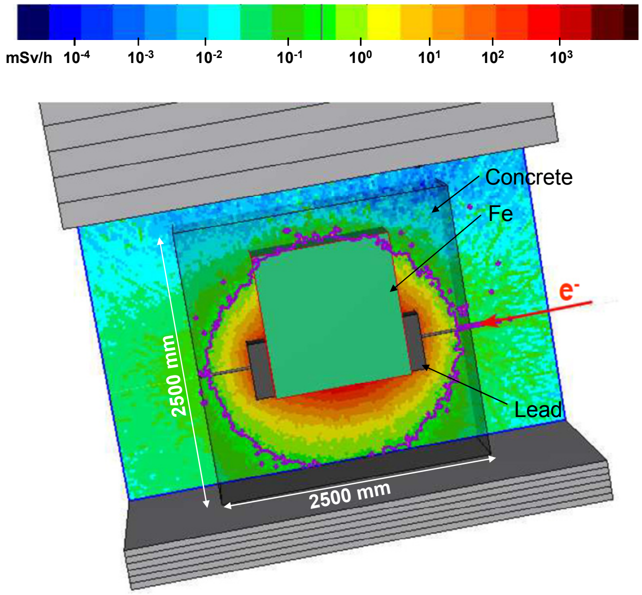

Figure 4: Dose rate distribution (mSv/h) around the beam stopper shielding.

UNDULATORS U15

The Aramis line has 12 in-vacuum undulator magnets called U15 with a period of λ_U= 15 mm (Fig. 5).

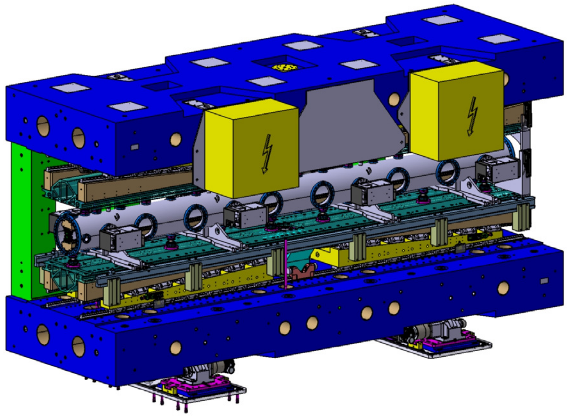

Figure 5: U15 undulator with in-vacuum magnets and gap adjustment mechanics based on wedge systems.

The U15 gap can be adjusted during operation via a precise wedge system [2]. The nominal gap is 4.7 mm corresponding to a K value of 1.2. Wavelength tuning from 7 to 1 Å is achieved by varying the electron beam energy from 2.2 to 5.8 GeV. Only small, but fast, wavelength scans within a few percents will be done by changing K. The undulator frame sits on 4 eccentric cam shaft movers for adjustment of the undulator position relative to the electron beam axis.

INTER-UNDULATOR SECTION

The beam trajectory in the Aramis line should not deviate from an ideal straight line by more than a few micrometers. This is achieved by beam based alignment of the FODO quadrupoles that have motorised supports (Fig. 6) [3]. The alignment of each undulator segment on this straight line is done with the so called alignment quadrupoles (Q_{AI}) (Fig. 7).

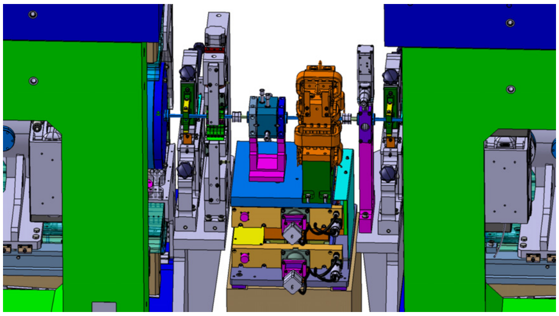

Figure 6: Inter-segment girder with (from left to right, electron direction): Alignment quadrupole (Q_{AI}); phase shifter; BPM pickup; FODO quadrupole; gate valve and Q_{AI}.

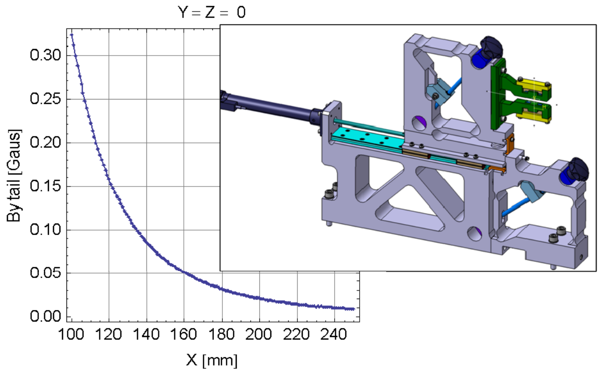

Figure 7: Alignment quadrupole Q_{AI} (retractable) and the corresponding stray dipole field when retracted.

Two Q_{AI} are attached at each extremity of the undulator module frame. The magnetic axis of the Q_{AI} is aligned to the undulator magnetic axis in the laboratory before the installation in tunnel. The Q_{AI} is then used as a beam finder with 10 μm resolution. The complete undulator frame is moved until both Q_{AI} at each extremity are aligned to the beam corresponding to the steering free position. The Q_{AI} are made from permanent magnets with an integrated gradient (G.L) of 0.44 T [4]. After alignment, the Q_{AI} are pneumatically retracted by 150 mm and the remaining stray field $B_{y,tail}$ is then less than 0.1 G (Fig. 7, left).

Phase shifter

Phase shifters between the undulator segments are used to synchronise the electrons with the phase of the FEL light at the entrance of each undulator segment. The

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magnet array of the phase shifter is shown in Figure 8 [5]. By changing the gap of the phase shifter one can control the phase delay with typically 0.2 degree / µm. The end magnets (C & D) minimize the kick angle and transverse offset of the out coming beam.

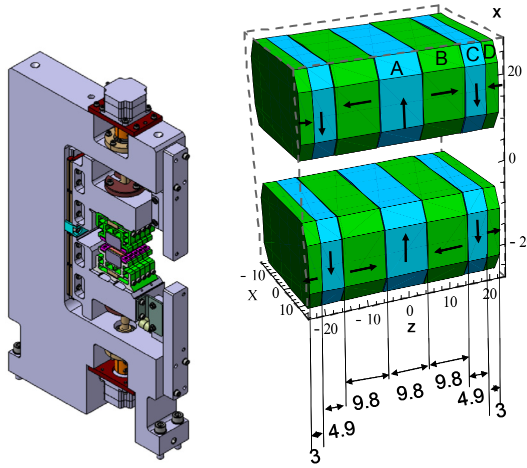

Figure 8: Phase shifter support with adjustable gap and the corresponding magnet array design.

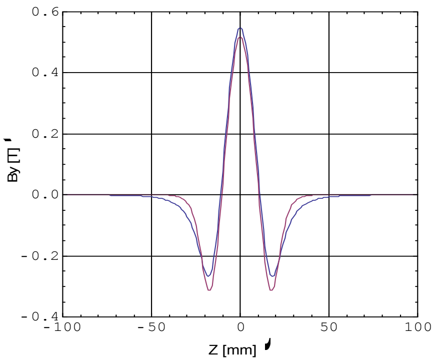

Figure 9: Magnetic longitudinal field profile in the phase shifter (gap = 14 mm; 5.8 GeV; Br=0.95; X=Y=0) with magnet D (red curve) without (blue curve).

Magnet D also limits longitudinally the leaking stray field which could perturb adjacent components.

FODO Quadrupole

The FODO quadrupole (Fig. 10) has an aperture of 12 mm which allows to reach a maximum gradient of 50 T/m with only 10 A of current. The coils are air cooled, thus reducing infrastructure costs in comparison to a water cooled magnet. The magnet is 8 cm long, and the quadrupole function is combined with vertical and horizontal steerers to minimize space requirement between undulators. One drawback of this combination is the presence of a sextupole field component which has however negligible effect due to the small beam diameter (20 µm). The coupling between steerers and quadrupole through the yoke is limited thanks to a small pole tip field (0.3 T) and thanks to a special low hysteresis losses steel material (M270) for the magnet yoke. The yoke is laminated with 0.5 mm thick foils in order to limit eddy currents and allow fast beam orbit feedback.

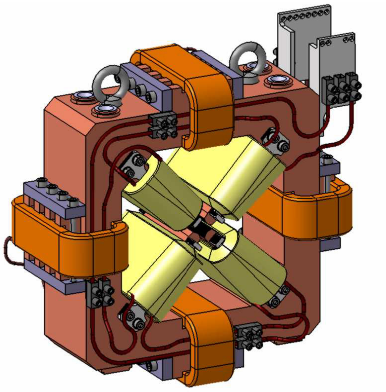

Figure 10: FODO quadrupole of the Aramis line combining steering and quadrupole functions.

At 1 kHz, the steering field is attenuated by 50% which fulfills the requirement of SwissFEL.

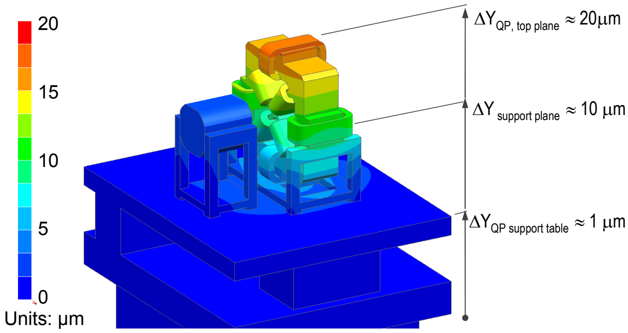

Figure 11: Mechanical deformation due to dilatation when magnet goes from 0 to 6 A (aluminium support).

One drawback of the air cooled quadrupole is the related heat up of the magnet coils (16 W of heat dissipation at nominal current of 6 A) and the related mechanical dilatation. Simulations of these effects have been carried out taking into account heat transfer through the air and through the aluminium support (Fig. 11). The results show that the axis of the quadrupole moves up to 10 µm vertically when changing the magnet current from 0 to 6 A [6]. The steady state is reached after 8 hours. Although such slow drifts could be compensated by beam based orbit feedbacks, the deformation will be reduced via a thermal insulating layer located between the quadrupole and the support to avoid temperature gradient along the support. In addition, the quadrupole current stays almost constant during SwissFEL operation.

Longitudinal Geometric Wakefields

In the Aramis vacuum chamber, the wakefield potential due to geometric transitions can deteriorate the longitudinal phase space of the bunch, which directly affects the FEL performance. Therefore the geometrical wakefield was quantified for each transition in order to determine the necessity of RF shielding. Geometric wakefields cumulated between two consecutive undulator segments have been simulated with ECHO [7] taking into account the different transition depicted in Fig. 12. Assuming a Gaussian beam profile with 6 µm rms bunch length, a peak wakefield of about 1200 V/pC (Fig. 13) was obtained where 90% are caused by the step-out transition. This wakefield amplitude is less than 1/3 of the resistive wall wakefield and roughness wakefield cumulated in the undulator gap [1].

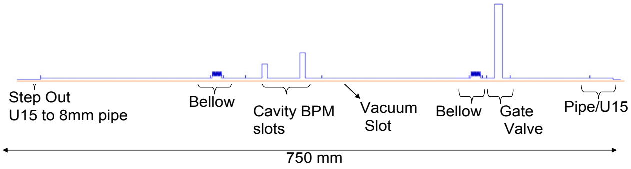

Figure 12: Geometrical transitions in the inter undulator section.

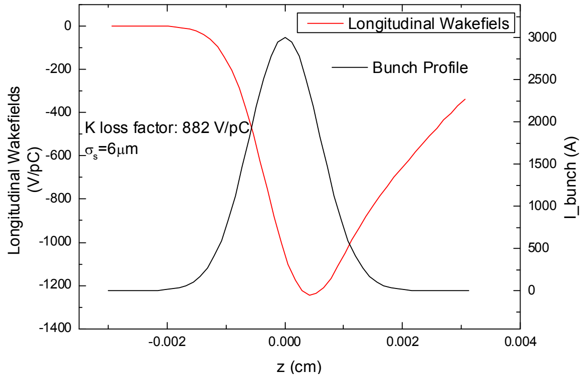

Figure 13: Longitudinal wakefield potential when an electron bunch (Gaussian profile, 6 µm) crosses the complete inter-segment section of Fig. 12.

To efficiently reduce the wakefield at the step out transition from undulator gap (nominal 4.7 mm) to round beam pipe (8 mm diameter), one would need a tapering transition with a slope smaller than 2.5 mrad. However this would almost double the distance between consecutive undulator segments, resulting in a large cost impact and negative effect on the beam – radiation overlap. The influence of the bellows, vacuum flange transitions and gate valve slots are all negligible, therefore no RF shielding that would increase costs and design complexity is required.

Finally, the simulation of Fig. 13 shows that the energy spread of the bunch will increase by less than 1.6 MeV leading to a relative energy spread of up to 0.03% which is still less than the FEL bandwidth of 0.05%.

BEAM DUMP AND SPECTROMETER

Aramis Beam Dump Spectrometer

An important function of the beam dump deflection arm is the electron bunch momentum and momentum spread characterisation. At position z = 584 m, the electron beam is deviated vertically down with an angle of 8 degrees.

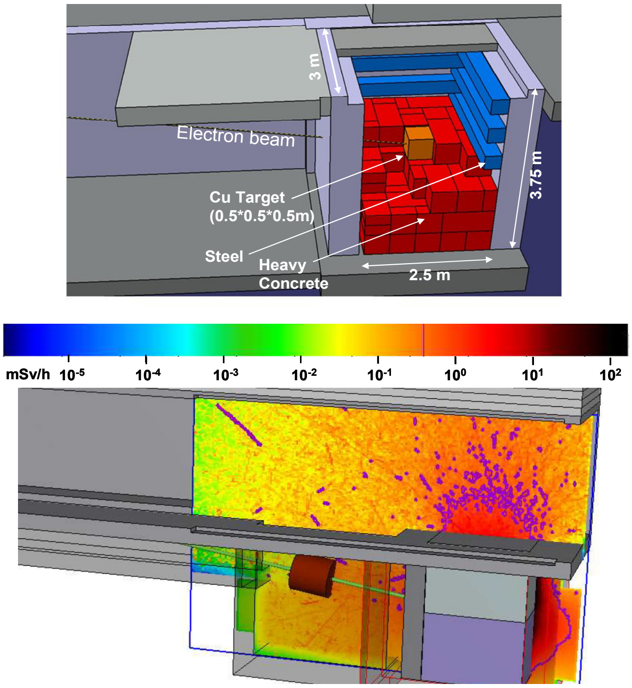

Figure 14: Beam dump shielding layout (top) and FLUKA simulation of 560 W of electrons at 7 GeV impacting the SwissFEL beam dump (bottom).

As shown in Fig. 1, a strong quadrupole (GL = 15 T) is located just after the dump dipole, thus avoiding a too large transverse beam size before the dump shielding by reducing the dispersion. In particular, one mode of operation of SwissFEL, the so-called large bandwidth mode with a relative momentum spread of about > 1% would lead to a too large beam size without this quadrupole magnet. The minimum resolution requirement for the spectrometer is 90 keV to be measured with both screens and BPMs. The electron bunches at SwissFEL will eventually hit a cubic copper target block (0.5 m side length) surrounded by 190 tons of steel and heavy concrete blocks as shown in Fig. 14. The shielding is design for a maximum of 288 µC per hour at 7 GeV. With this beam power the dose rate in the tunnel at photon beam height (ie. 3.2 m above the impact point) is below 500 µSv/h and below 0.5 µSv/h in the public zone outside tunnel (6.7 m above impact point).

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