SWISSFEL U15 PROTOTYPE DESIGN AND FIRST RESULTS

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Abstract

SwissFEL [1] has in its base line design two undulator lines for the hard- and soft x-ray, U15 in-vacuum and U40 / UE40 APPLE II type undulators with 12 respectively 15 modules of 4m length each. All undulators are equipped with the same frame and gap drive system to profit best from the series production. The frame is built up from two identical bases and side frames made of cast mineral. In this design, the frame transfers its stiffness to the I-beam through a backslash-free wedge based gap drive system. The interfaces to the inner I-beam for the in-vacuum undulator have been rearranged allowing a large reduction in the number of columns. Magnets and poles are carried by an extruded Aluminium block-keeper, which will allow an automatized shimming of the magnet structure. The prototype of the support structure has been built up in 2012 and first mechanical results are presented. The entire prototype shall be ready by the end of 2012.

SWISSFEL UNDUALTOR LINES

SwissFEL will have two undulator lines. The one for hard X-rays from, 7 Å (2 keV) to 1 Å (12.4 keV), with an electron energy of 5.8 GeV, is named Aramis. The second one, covering the entire soft X-ray range, from about 200 eV to 2 keV with full polarization control, is named Athos. In the baseline design, the Aramis line has 12 in-vacuum undulators U15's with 15mm period. However, there are free slots, which can be used i.e. for (self)-seeding. An overview of the Aramis undulator line is given in [2], the magnet array is discussed in detail in [3].

The Athos line will follow in 2020 and has a self-seeding design with 6 planar U40's and 9 APPLE II type UE40's, both with 40mm period. This sums up to 27 undulators. All undulators are 4m long each and have an identical intersection length of 75cm. The design large number of identical undulators for linac driven FELs is well suited for a consequent industrial based small series production.

SPECS AND DESIGN GUIDELINES

The specifications for the SwissFEL undulators can be summarized as follows:

- Short period undulators for Aramis beamline
- Variable polarization for Athos beamline
- Low beam height
- Low costs

SwissFEL has in the pool of hard x-ray FELs with 5.8GeV the lowest electron energy. To achieve photon energies of 12.4keV (1Å wavelength), the undulator period length has to be very small. For SwissFEL it has been optimized to a 15mm period. At a gap of 4.3mm a magnetic flux density of 0.85T provides the design K-value of 1.2. The low electron energy requires in addition small tolerances in all parts of the accelerator and the undulators .

As all forms of transport in SwissFEL tunnel are on the floor (no crane) a common floor level in the entire tunnel is foreseen. The beam height is determined by the undulators and needs to be reduced with respect to the 1.4m beam height at Swiss Light Source. And, of course the costs had to be optimized and as a consequence there is no technical gallery accompanying the undulator hall.

The basic design ideas for the SwissFEL undulators are:

- Modular undulator concept
- O-shape structure
- Use of cast and extruded materials
- Drive system on board
- Remote controlled alignment
- High stability and precise gap drive system.

SUPPORT AND GAP DRIVE

The most demanding undulators with respect to the support structure are the APPLE II type undulators which, when operated in anti-symmetric mode to produce linear inclined polarization, bring in not only vertical forces but also longitudinal and horizontal forces. Therefore the design for a modular undular concept in which the support and gap drive is identical for all types of undulators and only the magnet array with its vacuum system is adapted to the specific undulator type i.e. planar in and out of vacuum and APPLE II. The benefit is reduced engineering, larger series and a common transport concept which overcomes the drawback of partly oversized components.

Support Structure

For maximum stiffness the support structure is not the classical C-structure but a closed O-shape structure. Experience with cryogenic in-vacuum undulators where magnetic measurements inside the vacuum chamber are mandatory lead in recent years to the development of smarter measurement systems where the magnet structure tightly encloses the vacuum chamber a remote alignment required the vacuum chamber to be supported by the undulator itself. Best for series production is cast material, either cast iron or cast mineral which is used in many machine beds. For the SwissFEL undulator supports cast mineral is chosen: it has good internal damping characteristics, is non-magnetic, is cheap in series production and integrated channels for weight reduction can be used as cable traces.

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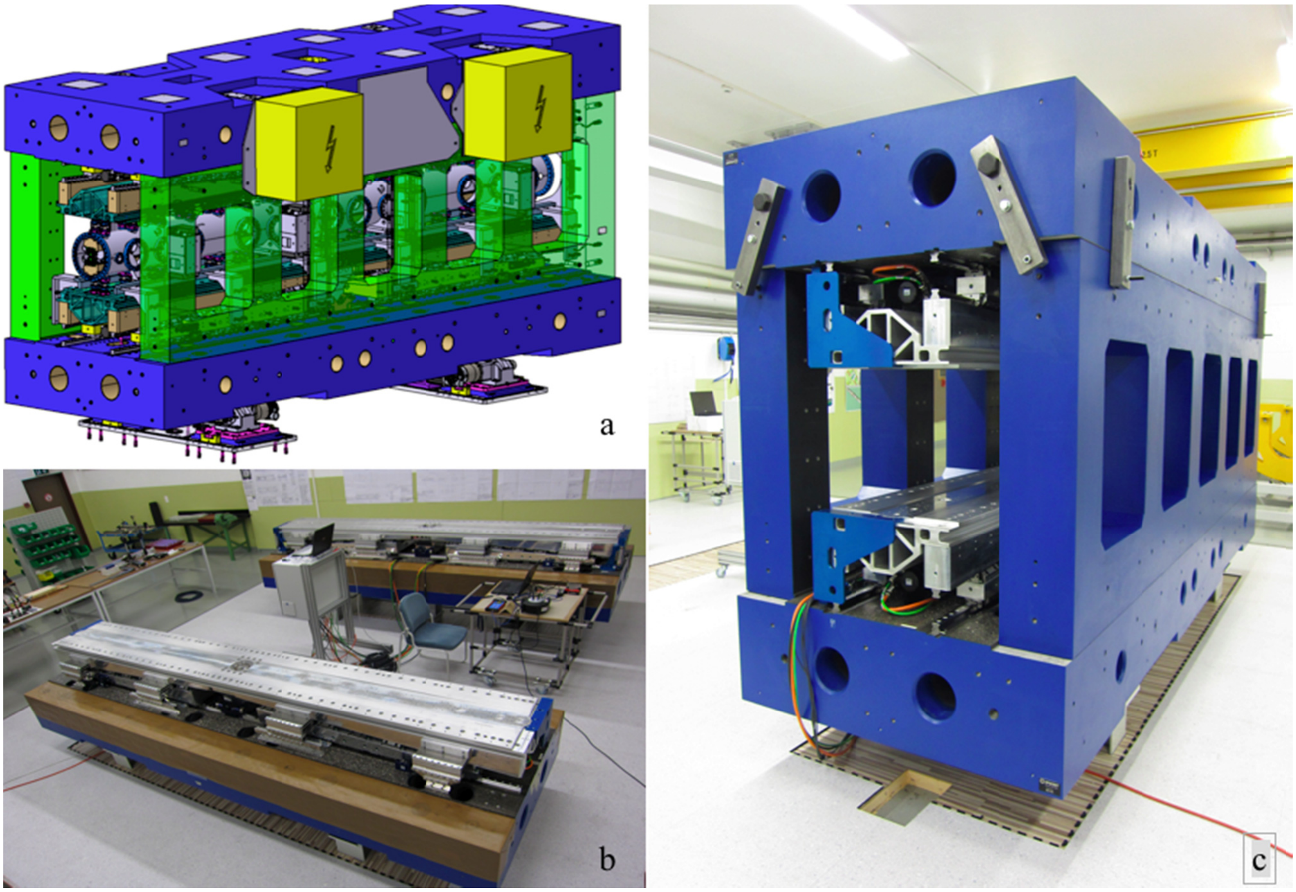

Figure 1: U15 in-vacuum prototype undulator: a) 3D CATIA sketch, b) assembling of top and bottom bases, c) completed support structure before the final gluing of the top bases with the side parts at MDC Max Daetwyler Corporation in Ursenbach, Switzerland.

There are two identical bases and side parts. The reference surfaces have been grinded with an accuracy of 20µm. The 4 parts are assembled by glue to form a 2m height, 1.36m wide and 4m long box with very high stiffness (see figure 2). For a proper adjustment of the top part with reference to the bottom one a Leica lasertracker could be used, where the laser head was positioned at the middle of the bottom I-beam.

The undulator is placed on 5 camshaft movers which allow a remote alignment in 5 degrees of freedom. They were designed at SLAC [4] and already used for SLS girders and in-vacuum undulators.

The gap drive system consists of a servo motor, satellite roller screws with a pitch of 1mm only. This, together with the reduction of the wedge with its 3° allows a gearbox-free drive system with minimized backlash. The entire drive system is built up with Beckhoff components, which allow the entire motion control system to be kept in three small cabinets which are attached to the undulators. One box for each, gap drive, shift drive for the APPLE II undulators and cam shaft movers.

At each end is an absolute linear encoder (Heidenhain). The gap ranges for the U15 undulator from 3 to 18mm and can vary maximum by 32mm for the out of vacuum undulators. For highest precision the Aluminium wedges and its counterpieces are grinded in one clamping. Each wedge is connected to the mineral base and the counterpieces by 4x7 highly preloaded bearings. The I-beam is laterally fixed in the center by a massive bearing, which is glued into the cast mineral base.

Gap Drive System

To guide the stiffness of the frame to the I-beam a wedge-based drive system was designed. Two wedges are moved synchronously against each other, lifting up and down the outer I-beam. The I-beam, from extruded Aluminium, couples mechanically the two wedges. For small gaps the wedges move towards the outside in order to minimize the deflection curve of the I-beam.

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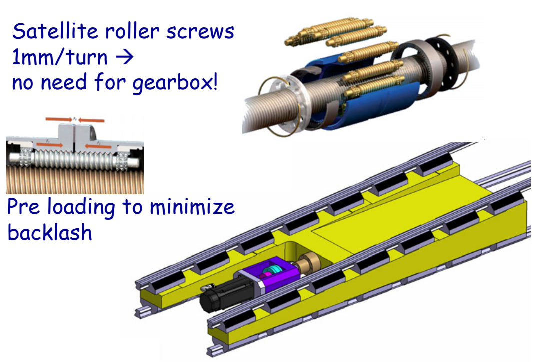

Figure 2: SwissFEL undulator drive system with servo motor, satellite roller screw and wedge sandwiched by bearings.

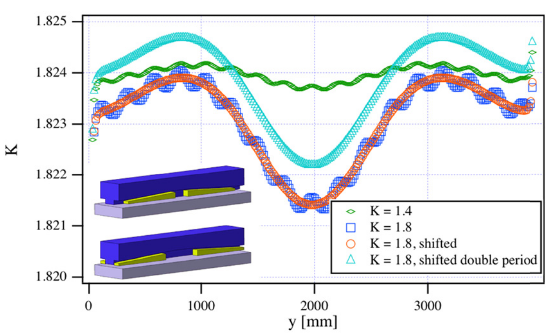

Figure 3: Simulated K-variation with gap change based on FEM and RADIA calculations. At K=1.2 (gap=4.4mm) the ID will be optimized, the different forces at K=1.4(1.8), gap=3.8(3)mm, lead to deformations in the outer and inner I-beam (long range and short range variations). A shifted arrangement of the columns (see next section) flattens the high frequency oscillations, even with reduced number of columns. The sketch shows the wedge settings for open (top) and closed gap (bottom).

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Column Design

The columns which connect the outer I-beam with the I-beam in the vacuum vessel are adjustable so that the phase error can be adjusted even after installation into the vacuum vessel. To reduce the costs we tried to reduce the quantity: First, the two columns side by side are replaced by a central one with increased stiffness. Experience with the U14 cryogenic undulator at SLS showed that for the adjustment only one column is feasible. Second, the columns are arranged in a shifted way, so that the resulting gap is not oscillating but following a wave with roughly constant gap (see figure 3 and 4). So the gap variation with exponential field dependency is transferred to a virtual position change in the gap with only a cosine hyperbolic dependency. A reasonable end configuration could be found which allows for the prototype to work with standard setup and 32 columns or in the shifted setup with 20 columns only. This means less costs for columns and welding, less risk and less assembling work.

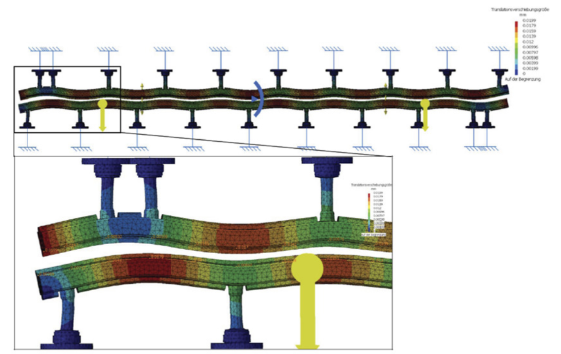

Figure 4: End design for the shifted column design.

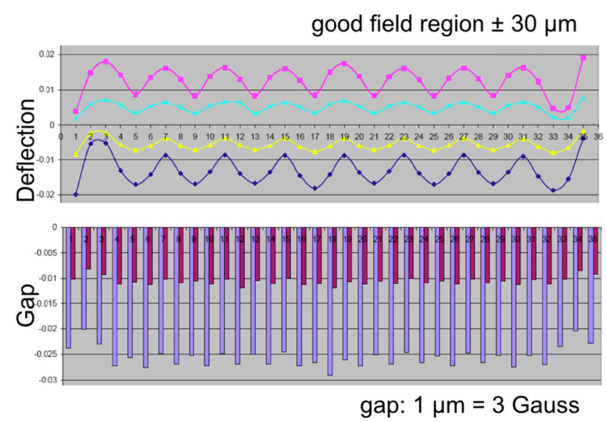

Figure 5: FEM calculations of deflections of top and bottom I-beam and resulting gap variation which is constant within 1µm for K=1.4 and 2µm for K=1.8.

UHV Design

The demands on the vacuum of the single pass FEL are relaxed compared to those in a storage ring. The magnet design allows no bake-out and hence the bearings which would allow an expansion at bake-out are skipped. Therefore, the production has to follow the same stringent UHV specifications as for storage ring undulators.

MEASUREMENT RESULTS

Important for the functionality of the undulator are the precision of the gap setting, the stiffness of the outer and inner I-beam under magnetic load and the gap change of the outer beam due to machining precision of the wedge and counterparts when changing the gap.

Gap Settings

The minimum step width of the gap is about 0.2µm. Measurements with an interferometer showed a hysteresis of the gap settings of 1µm. The reproducibility of the measurements was 0.5 µm.

Each of the 4 servo-motors has its own encoder, located at the end of the I-beam to be most sensitive to a

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taper of the I-beam and attached to the outer I-beam in the beam plane to minimize the Abbes projection error. However, as the I-beam is not supported for larger gaps by the moving wedge, a better position could be near to the end of the always supported part of the I-beam.

Flatness of I-beams

All parts have been machined and grinded down to better than 20µm over the 4m length. To verify the flatness of the reference surfaces on the cast mineral base and, the longitudinal bearings and the outer I-beam an electronic inclinometer (Wyler BlueLevel ™) with an accuracy of 1µm/m) has been used. With the help of this tool the sensitivity to temperature stability respectively gradients could clearly be seen. Problematic was reproducibility (we slide in longitudinal positions to not clearly defined positions) and that the measurements were very time consuming.

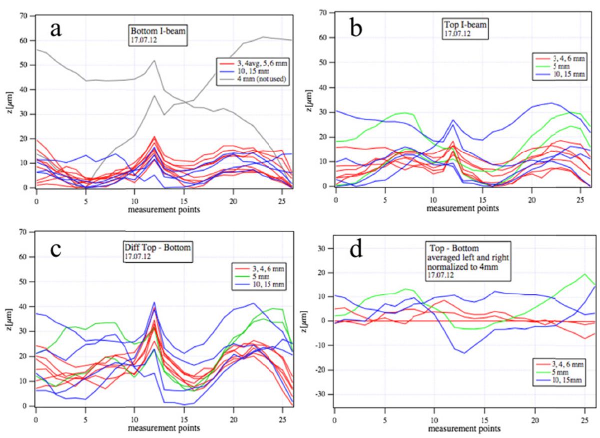

Figure 6: Flatness and calculated gap versus the longitudinal position of the outer I-beams (a,b), measured with the Wyler electronic inclinometer. The measurements show clearly the areas without direct support of the wedge bearing system. The variation with gap (d) is the remaining error.

The most important accuracy is that of the wedges in order to guarantee a homogenous gap variation all along the undulator (figure 6d). This has been measured in addition with an interferometer. The laser and the interferometer have been positioned on the lower I-beam and the reflector has been fixed vice versa at the top I-beam, longitudinally at all column positions. The results for the operating are are shown in figure 7 showing a variation of only ±2µm. Over the entire gap range 3 to 18mm, the variation is within ±6µm.

Force Simulation and Outlook

Mechanical simulation of the magnetic forces will be carried out with the help of pneumatic cylinders located at the column positions (see figure 8). The regulated pneumatic cylinders allow push and pull, so that in combination with additional lateral and longitudinal pneumatic cylinders also the APPLE II configuration can be studied. These studies are carried out in October. In November the support structure will be delivered to PSI where in the SLS ID laboratory the magnet array will be installed and the magnetic optimization will take place. The prototype U15 will be built in the 250MeV SwissFEL injector test facility in April 2013.

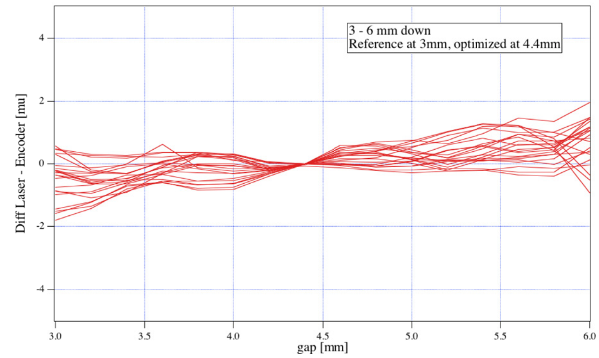

Figure 7: Gap variation versus Heindenhain encoder settings for gaps between 3 and 6mm in 0.2mm steps. The curves are referenced to a gap of 4.4mm (nominal K-value of 1.2) where the U15's will be optimized.

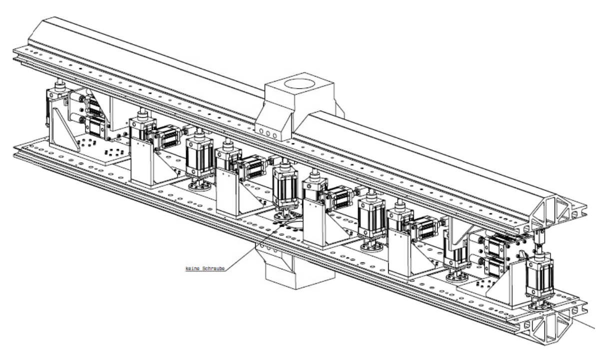

Figure 8: Pneumatic cylinder to simulate forces up to 3 tons in planar and APPLE II configuration.

CONCLUSION

For the SwissFEL undulators with in-vacuum, out of vacuum planar and APPLE II configurations a prototype has been built. With a closed cast mineral frame, a wedge-based drive system, the shifted column assembly and extruded I-beams the design has been optimized for series production. The measurements presented approve the expected performance.

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