REALIZATION OF A COMPACT APPLE X UNDULATOR*

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Abstract

The APPLE X is a compact, elliptically polarizing undulator with a small round magnetic gap that provides full polarization control of synchrotron radiation at a lower cost and in less built-in space than comparable devices (Fig. 1). The APPLE X will be the source for MAX IV's potential future Soft X-ray Laser (SXL) Free Electron Laser (FEL). The mechanical design, finite element analysis optimization, assembly process, magnetic measurements, and shimming of a full-scale 2 m, 40 mm-period Samarium-Cobalt (SmCo) permanent magnet undulator are presented.

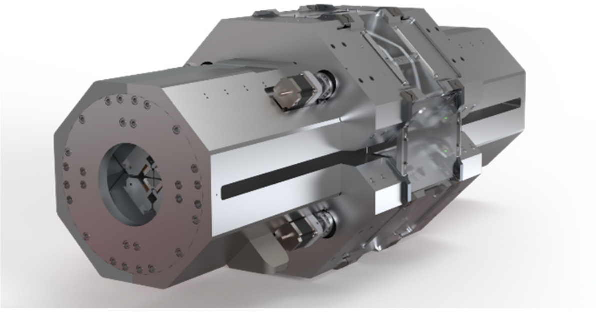

Figure 1: MAX IV APPLEX X prototype.

INTRODUCTION

A Soft X-ray Laser (SXL) beamline utilizing MAX IV Linear accelerator and the FEL technology is being designed at the MAX IV Laboratory and in collaboration between several Swedish Universities [1]. The baseline goal of the SXL beamline is to generate intense and short pulses in the range of 250 eV-1000 eV, and the conceptual design was reported in [2]. The set of features the undulator needs to fulfil includes being compact and light-weight, provide for independent gap- and phase adjustment, enable full polarization control, and K-value tuning via a radial gap operation. As a byproduct of the design, the undulator has the ability to create transverse field gradients as well as to neutralize its transverse field in a fixed-gap operation. An additional requirement is the ability to shim every individual magnet in the fully assembled undulator for magnetic fine-tuning. After a design review, in particular the shortening of the undulator length from 3 m to 2 m due to optimizations in the FEL design, prototyping of the APPLE X undulator is ongoing since late 2021 and has recently entered the assembly phase. The most recent key figures of the APPLE X undulator as it is being build are summarized in Table 1.

Table 1: Key Figures

Magnet Type	SmCo ($B_r = 1.12$ T)
Period Length	40 mm
Photon Energy	0.25-1 keV
Magnetic Gap Range	8.0-17.3 mm
Effective K range	3.9-1.51
Max. gap / min. eff. K	28 mm / 0.55
Undulator Magnetic Length	2 m
Weight	2800 kg

DESIGN

The main concept of the design is to handle the magnetic forces with an as tight and short mechanical circuit as possible. The reason being to reduce the lever arms and thus also the forces experienced by the structure of the device. Focus in the detailed design has therefore been to keep the size down on each step from magnet to keeper, shimming wedge, girder, motion wedge and strongback (Fig. 2).

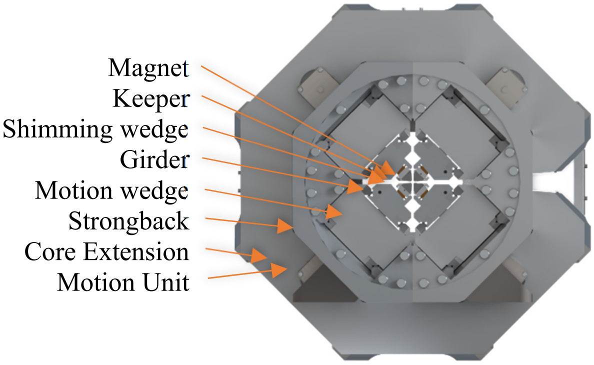

Figure 2: Outline of component stack

Nestled in through this is then the motion units (Fig. 3) one for each girder controlling radial motion and longitudinal motion on each individual girder. At first the design was a closed strongback in two half-moon parts forming a full circle around the inner parts, but due to a limitation in current magnetic measurement techniques the device is required to have a lateral opening on one side for access of a Hall-probe mounted on an arm moving along the device measuring the magnetic field. Initially the design was aiming at measurements being performed with a pulsed-wire system but will in the prototype accommodate a lateral opening for hall probe measurements and gives us the opportunity to commission a pulsed-wire system for magnetic measurements [3]. When successful, this new set-up will allow us to remove

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the lateral opening in coming design reviews and thereby increase the structural integrity of the strongback. The lateral opening makes the device asymmetric and the strongback has become larger than the initial design but can possibly shrink again if the opening is removed in a future version. Actions to mitigate the deflection were introduced in the ends of the device where there was enough space for additional material in the form of stainless-steel rings. In the centre C-shaped external structures was introduced providing additional support and encapsule the motion units. These are referred to as core extension.

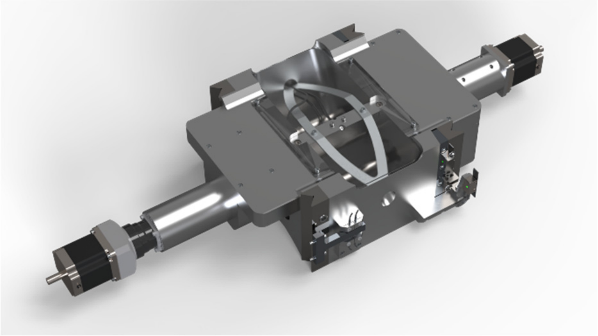

Figure 3: Motion Unit.

MATERIALS

The innermost parts were designed to be made of stainless-steel 316L to keep the strength up, the size down and the magnetic permeability close to 1.00. The strongback was due to its size and large cutouts designed to be made out of aluminium. The linear guides in the device are made out of tool steel 90MnCrV8 and provide additional stiffness to the parts but affects the magnetic field. This was simulated and the influence was determined to be low enough. During manufacturing the material Nitronic 50 was chosen as we had difficulty keeping the permeability low with 316L steel in the keepers. Initial test was promising but during mass production the permeability rose to as high values as 1.04. All keepers have due to this been annealed in vacuum oven and successfully been reduced to below 1.01.

It proved to be difficult to machine a 2 m long girder out of stainless steel that kept an overall straightness below 0.4mm. Due to delayed deliveries and failure to achieve the required tolerances and some errors in the machining of the girders new ones made of aluminium EN-AW 5083 was made which to a much higher degree fulfilled the required tolerances. In analysis additional deflection is estimated to be 5µm due to change of material.

MOTION

Each of the four girders holding an array of magnets can make radial and longitudinal motion. The longitudinal motion is supported by linear guides between the girder and the motion wedges. The longitudinal motion is performed by an arm extending through the strongback out to the motion unit where a roller screw adjust the position. The radial motion is performed by the two motion wedges supported by linear guides to the strongback with an inclination of 1:10. The position of the wedges is adjusted in towards each other and away from each other to perform the radial move of the girder attached to them. With this configuration they provide additional support in the centre when the gap is smallest (Fig. 4). The motion is performed with arms extending out to the motion and a pair of roller screws connected with a gearbox to a single stepper motor. The motion unit moves radially together with the girder locked radially by the arms to girder and wedges. It is connected to the strongback by linear guides allowing the radial motion. Feedback of the radial position is also made at this interface between motion unit and strongback whilst longitudinal position is measured between the arm from the girder in respect to the motion unit.

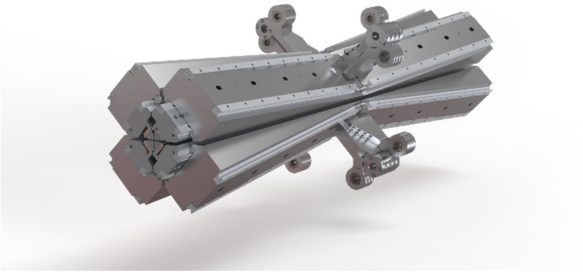

Figure 4: Motion wedges pulled together.

FEA

Static structural analysis has been made for the design looking at the deflection of the magnet arrays due to the forces they expose each other to. We have looked at three main cases. One with a strong pulling vertical force, one with a strong pulling horizontal force and one with a medium horizontal and vertical force (see Table 2).

Iterations of the analysis has been made to find a balance between the size and thickness of the girder keeping the lever arms short and then tuning the size of the strongback to an economical size where the performance is still within the required scope.

The deflection is worst for the first case where the vertical deflection of the magnet array is 32 µm concentrated in the centre of the device. It is on this case the focus of the analysis/design iterations has been (Fig. 5).

Table 2: Magnetic Forces per Girder

	Horizontal Fx [kN]	Fy [kN]	Fz [kN]
Girder 1	1,1	0	-15,7
Girder 2	-1,1	0	-15,7
Girder 3	1,1	0	15,7
Girder 4	-1,1	0	15,7
	Circular Fx [kN]	Fy [kN]	Fz [kN]
Girder 1	-7,5	0	-7,5
Girder 2	7,5	0	-7,5
Girder 3	-7,5	0	7,5
Girder 4	7,5	0	7,5
	Vertical Fx [kN]	Fy [kN]	Fz [kN]
Girder 1	-15,6	0	1,1
Girder 2	15,6	0	1,1
Girder 3	-15,6	0	-1,1
Girder 4	15,6	0	-1,1

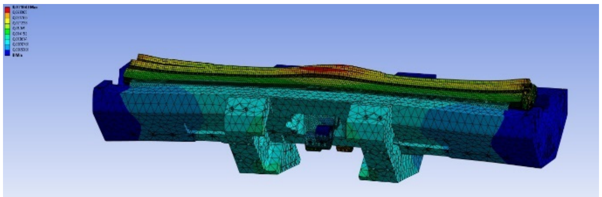

Figure 5: Deflection by magnetic forces.

The second case is very similar to the first case but have a slightly lower deflection due to that the strongback is stronger in this direction. The third case has medium radial forces. Between these cases we have low to medium longitudinal forces the deflection during these transfer cases is primarily dictated by the backlash of the motion unit which is expected to be low but have not been measured yet.

ASSEMBLY AND SHIMMING

The assembly of the device started slowly in the autumn of 2022 [4] and has due to delayed deliveries of the girders only recently passed the stage where all magnets has been mounted and received an initial magnetic shimming on the girders.

The assembly consists of three substages.

The motion units are mounted last on the finished device but is a self-contained unit with roller screws, gearbox and motors for radial and longitudinal motion. Four of these were assembled first as we awaited the delivery of the girders.

The girder is prepared with magnets mounted on keepers according to a sorting previously done. The nominal position of the magnets is first shimmed according to its physical position and then shimmed according to its magnetic position.

The strongbacks are prepared with motion wedges.

The final assembly is then performed by mating two girders in a jig sliding them into the strongback together as to avoid the alternating longitudinal forces between them. When both halves of the strongback are prepared the two are mated and then the C-shapes is slid in from each side. Last the motion units are attached and the device will receive a final tuning of the magnets as the field are now affected by the deflections of the total shape error and deflection. Since the shimming screws for the magnets are now embedded in the device a special couple of sticks has been developed which reach in to engage the screws in the small passages longitudinally present in the assembled device.

CONCLUSIONS

The design and analysis of the APPLE X undulator has been innovative and thorough. Manufacturing of the parts has been a rough experience with many delays but have at last been completed. The assembly of the APPLE X undulator is nearing completion. Initial shimming has been performed to a satisfactory level (Fig. 6). Tools and components have been manufactured assembled and tested. Ready for the final steps of the assembly which will take place in the end of 2023.

Figure 6: Shimmed girder.

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