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FABRICATION PROGRESS OF A SUPERCONDUCTING HELICAL UNDULATOR WITH SUPERIMPOSED FOCUSING GRADIENT FOR HIGH EFFICIENCY TAPERED X-RAY FELs*

S. M. Lynam†, R. Agustsson, I. I. Gadjev, A. Y. Smirnov, RadiaBeam, Santa Monica, CA, USA
F. H. O'Shea, Elettra-Sincrotrone Trieste S.C.p.A., Basovizza, Italy

Abstract

The Advanced Gradient Undulator (AGU) represents a potentially significant advancement in x-ray conversion efficiency for x-ray FELs. This increase in efficiency would have broad implications on the capabilities of x-ray light sources. To achieve this high conversion efficiency, the inner diameter of the undulator coil is a mere 7 mm, even with the use of superconducting coils. To accommodate the beamline at the Advanced Photon Source this yields in a chamber with a wall thickness of 0.5 mm fabricated from Aluminum. With a period of 2 cm and a conductor position tolerance of 100 µm over a length of 80 cm at 4.2 K, the engineering and fabrication challenges for the undulator alone are substantial. We will discuss these fabrication challenges and present solutions to meet the tolerances required for desired performance, and provide an update on current progress of the construction of a section of the AGU insertion device.

BACKGROUND

One of the largest difficulties facing self-amplified spontaneous emission (SASE) free electron lasers (FELs) is that of efficiency; because amplification must occur in a single pass of the electron bunch, radiation amplification is limited by the FEL parameter ρ. Current conversion efficiencies of beam power to radiation are approximately 0.1%, limiting x-ray brightness and creating a requirement for expensive high brightness electron sources to be used [1]. To reduce the requirement for immense beam power at FEL facilities, insertion devices must be made more efficient.

As noted above the AGU uses a combination of extremely small bifilar helical undulator design with an overlaid quadrupole field, both wound with He-cooled Nb-Ti superconducting wire. The quadrupole is critical to the design, supplying the 26.6 T/m gradient field which allows the conversion efficiency to surpass the FEL parameter.

ENGINEERING DESIGN

Strongback

The strongback will serve as both the structural member for the mandrel, as well as the epoxy mold. Once the mandrel has been wound, it will be placed in the strongback and epoxied in place. Once epoxied the mandrel will not be removed from the strongback, so cryogenic considerations must be made for its design. The passages delivering liquid Helium (LHe) will be gun drilled along the length of the strongback.

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† slynam@radiabeam.com

Mandrel Beam Pipe and Vacuum Chamber

A significant concern in manufacturing is the surface roughness of the beam pipe through the centre of the mandrel, as well as wall thickness of the vacuum vessel which will be on the beam line. Gun drilling the beam pipe was considered, however this approach was discarded due to unpreferable cutting fluids required as well as inability to reliably achieve the required geometric tolerancing. The mandrels will be extruded as raw stock from a preferred vendor, with several samples destructively tested to ensure proper beam pipe straightness and concentricity relative to the outer diameter [2]. See Fig. 1 for sample cross section of a segment of the undulator assembly.

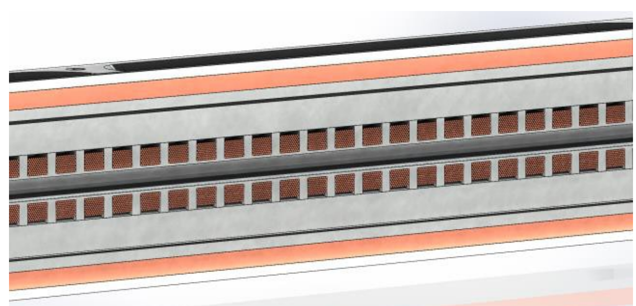

Figure 1: Cross section of bifilar undulator assembly with conductor, quadrupole, and strongback.

Conductor Pitch Angle and Grooves

Early in the design phase of the mandrel it was realized that the pitch angle of the conductor would play a major factor in the geometry of the mandrel. Due to the extremely small diameter of the inner conductor on the helix, and high aspect ratio between the inner diameter and the outer diameter, there is a significant change in pitch angle of the conductor as it is wound from the inner layer to the outermost layer. As a result the overall width of the filament layers changes significantly, by approximately 0.12 mm from inner conductor layer to outer as seen in Fig. 2. Failure to account for this change would result in considerable difficulty in conductor packing, as each location error compounds in the winding above it, causing the undulator to fail to meet its tolerance budget.

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Mandrel Manufacturing Approach

To address this problem a slightly dovetail-like profile was chosen, which will be machined on a swiss screw machine. This type of machine is well-suited to achieve the tolerance budget required of the AGU, as it is typically used to make high-precision screw-like pieces on scales under approximately 30 mm in diameter.

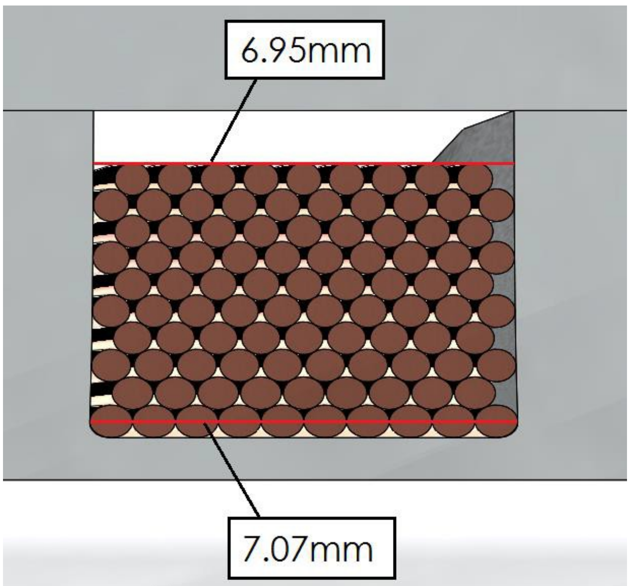

Figure 2: Cross-section of single filament indicating conductor pitch angle changes as a function of radius from beamline.

Conductor End Windings

The end windings of the conductor also posed a considerable design problem. Due to the mandrel's small size and thin wall thickness, strength during winding becomes a considerable concern. Significant effort has been made to ensure all bossed features and end windings have adequate material to prevent deformation of the mandrel during the winding process, while preventing the conductor from deviating substantially from the correct packing geometry. In addition, a geometry more suitable for winding was selected to reduce the risk of the conductor dislodging from the end winding features.

Further considerations include ensuring the superconducting wire is not bent beyond its 1 mm bend radius, as well as keeping the conductor as constrained as possible throughout the end windings to minimize as much as possible higher order field effects.

Fabrication Approach

The general fabrication approach of the AGU is as follows:

1. Machine the mandrel for the NbTi wire, which also serves as the vacuum chamber for the beam-line.
2. Using a precision CNC winding machine, wind the mandrel with NbTi superconducting wire.
3. Install the mandrel in the strongback, which also serves as the mandrel's epoxy mold. Once epoxied, the mandrel will not be removed from the strongback.
4. Complete assembly of the quadrupole magnets and install on the strongback.

By incorporating the mandrel and the vacuum chamber into one piece, the conductor can be brought much closer to the beam-line than in similar designs. Similarly, by using the strongback as the epoxy mold, rigidity of the undulator is maximized and tight positional tolerances can be maintained.

One of the largest challenges facing production of the AGU is the very tight tolerance budget (see Table 1). With careful analysis, the requirement on the relative position of the conductors has been relaxed to the regime of hundreds of microns, which allows for the manufacture of drel.

Table 1: Tolerance Budget for the Advanced Gradient Undulator

Parameter	**Tolerance**	**Units**	**P/P_0**
Injection Angle	2×10^{-6}	rad	0.969
Und. Current ($\Delta I/I$)	1×10^{-6}		0.991
Und. Offset (Δx)	1×10^{-4}	m	0.967
Und. Offset (Δy)	1×10^{-4}	m	0.967
Und. Pitch	1×10^{-4}	rad	0.999
Und. Yaw	1×10^{-4}	rad	0.999
Und. Phase	5	deg	0.990
Und. Roll	1×10^{-3}	rad	0.974
Relative P.S. Error	1×10^{-4}		0.984
Drift Error	5×10^{-5}	m	0.960
Quad. Current ($\Delta I/I$)	1×10^{-2}		1.000
Quad. Roll	1×10^{-4}	rad	0.996
Quad. Offset (Δx)	1×10^{-6}	m	
Quad. Yaw	1×10^{-6}	rad	
I_y	5×10^{-5}	T·m	
II_y	1×10^{-4}	T·m²	0.970
Quad. Offset	1×10^{-6}	m	
Quad. Pitch	1×10^{-6}	rad	
I_x	5×10^{-5}	T·m	
II_x	1×10^{-4}	T·m²	0.970
Total			**0.765**

FUTURE WORK

The next phase of construction includes short section prototype mandrel manufacturing to validate that the required tolerances can be achieved. Further design for manufacture considerations are likely required to achieve the required coil geometry.

Significant effort is still required to refine the AGU's quadrupole magnet positioning and mounting. The field at the centre of the quadrupole needs to be zero to "few micron" precision [1], which has not yet been refined. See Fig. 3.

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Figure 3: Current design of the AGU strongback and quadrupole configuration.

In addition, the final epoxy regimen must be worked out to ensure good positioning and thermal contact of the mandrel within the strongback. This is critical since the strongback would also serve to supply the undulator with LHe for cooling to cryogenic temperatures.

CONCLUSION

The Advanced Gradient Undulator represents a potentially significant step in FEL efficiency. Such a significant step expectedly comes with design and fabrication challenges which must be surmounted to achieve the desired device performance [3, 4].

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