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THE DESIGN AND MANUFACTURING OF SUPERCONDUCTING UNDULATOR MAGNETS FOR THE ADVANCED PHOTON SOURCE UPGRADE*

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Abstract

The Advanced Photon Source Upgrade (APS-U) will include 4 full length Superconducting Undulators (SCU). These SCUs require new undulator magnets to achieve the required performance of the new machine. The magnets are fabricated from low carbon steel and wound with NbTi superconductor. To meet the needs of the users, the magnets will be manufactured in different lengths and magnetic periods to accommodate SCUs in both inline and canted configurations. Because their operational conditions do not allow for shimming or other tuning adjustment, the magnets used in the APS-U SCUs require very tight tolerances for the poles and winding groves that push the extents of their manufacturability. This paper will cover the design of the 1.9m long magnets for the inline SCUs, their measurement data, lessons learned from manufacturing, and an overview of design changes that were made for the magnets to be used in the canted SCU configurations.

INTRODUCTION

The Advanced Photon Source (APS) located at Argonne National Laboratory (ANL) is currently undergoing an upgrade (APS-U) including a new storage ring and new insertion devices (IDs). Among the new IDs are four new Superconducting Undulators (SCUs) that will occupy the entire space provided in a straight section (~5.3 m) of the new storage ring. The SCUs required new magnets to be designed and manufactured to fit inside the new devices while achieving the magnetic performance required by the new accelerator. The new magnet designs aim to preserve desired features and functionality from past magnet designs, while also integrating new features to make the design more universal and easier to manufacture.

INITIAL DESIGN

The APS-U SCU magnet designs are an evolution of previous magnet designs used in past SCUs [1]. The previous designs (Fig. 1) consisted of a low-carbon steel core with G-10 spacers on top that were held in place with spring pins and low carbon steel poles on the bottom held in place with screws. These spacers and poles created grooves that would be used to wind the conductor around the magnet. The magnets also included holes drilled into the top of the magnet core so turn-around pins could be inserted during the winding process.

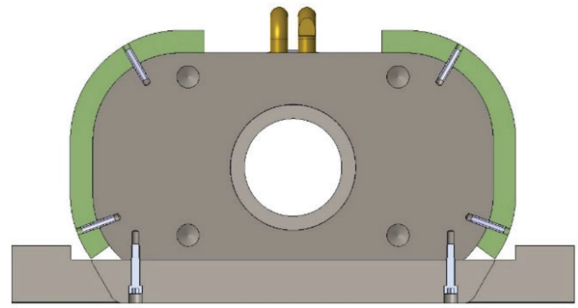

Figure 1: Previous SCU magnet core design that encompassed G-10 spacers and individual pole inserts.

The new SCU magnet designs for APS-U vary in length from 1.3 m - 1.9 m and have magnetic periods of 16.5 mm and 18.5 mm. This is the longest magnet that has been manufactured and wound by the SCU team at the APS. Features retained from previous designs include holes on top of the magnet core for the turn-around pins, helium channels that pass through the magnet, and a modified footed pole to be used during the resin impregnation (potting) process that extends out of the sides near the bottom of the magnet.

The magnets were modified from previous designs by changing the overall height and width of the magnet to have a better fit inside of the new cryostat [2]. Another benefit of a wider magnet is that the region of the magnet influencing the electron beam would be expanded and allow for a looser alignment tolerance of the magnets.

Other modifications include the removal of the G-10 spacers and individual poles on the magnet. The magnets now consist of a single piece with the grooves machined directly into the core, replacing the individual poles and spacers. This new magnet design can be seen in Fig. 2. This dramatically reduced the number of holes being drilled and tapped into the magnet core and reduced the overall number of pieces in the magnet assembly. The magnets still need to incorporate an extended pole insert at specific locations along the length of the core to be used in the potting process. Instead of using individual inserts like previous designs the inserts were changed to a single machined piece that included three poles and two grooves fastened by two 4-40 screws.

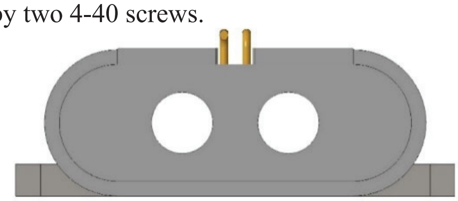

Figure 2: Magnet design used on the APS-U 1.9 m SCUs showing single piece core and footed poles.

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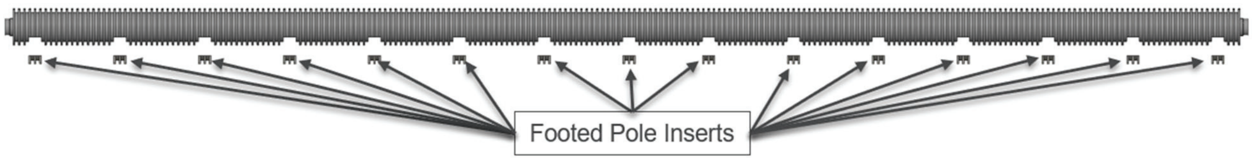

Figure 3: 1.9 m long magnet showing footed pole inserts and corresponding cutouts in the magnet core.

The inserts were machined to match the curvature of the grooves in the magnet core. The magnet core has corresponding pockets machined out to incorporate the inserts. The full-length magnet and insert locations can be seen in Fig. 3.

MANUFACTURING CHALLENGES

While the design was aimed at creating a more universal and straightforward approach for manufacturing, it did not eliminate all the challenges that come with fabricating magnets of this length to the level of precision required. Prior to fabrication, the initial design was finalized after consulting with reputable vendors and incorporating the inner cooling channels that run the entire length of the magnet; constructing the majority of the magnet out of a single piece of stock and with achievable tolerances for the grooves. The magnets operate at cryogenic temperatures in an insulating vacuum environment resulting in little to no accessibility for shims. The groove dimensions are thus critical dimensions that define the period of the magnet and require tight width and depth tolerances as small as ± 0.02 mm.

The magnets for the APS-U SCUs vary in length from 1.3 m to1.9 m. The 1.9 m long magnets proved to be especially challenging for many manufacturers due to the difficulty holding the required tolerances of the grooves over that length. This limited the number of available vendors capable of producing the 1.9 m magnets whereas the fabrication of shorter magnets would be achievable by a wider range of manufacturers.

The inserts that were machined to fit in the corresponding cutouts on the bottom of the magnet also had to be machined to match the radius of the magnet core so that there was a seamless joint in each groove. A closer view of this joint can be seen in Fig. 4.

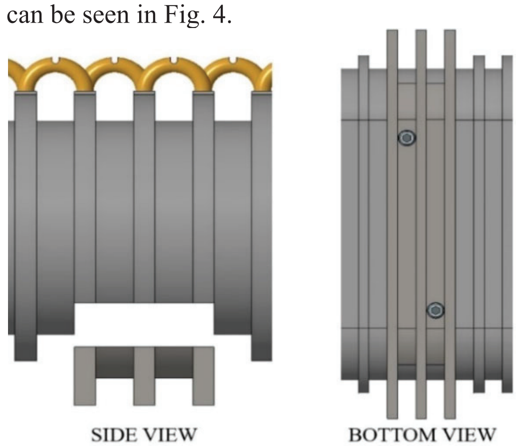

Figure 4: Side and bottom view of the footed pole insert and its 4-40 fasteners.

DATA AND PERFORMANCE

The magnets are required to pass a thorough measurement and inspection process completed by the vendor that consisted of measuring multiple points in every groove. This information was then tabulated into a report and required the approval by the technical representative before delivery. The points allow for the creation of virtual maps that could be used to determine the flatness of the pole face and the groove dimensions. The grooves are also verified with ceramic gauge blocks to ensure there is adequate space all around the core for the conductor winding. The measurements taken showed that there were inconsistencies in the flatness along the bottom pole surface of the assembled magnet located at each of the footed pole locations. The measurements that show this inconsistency are shown in Fig. 5.

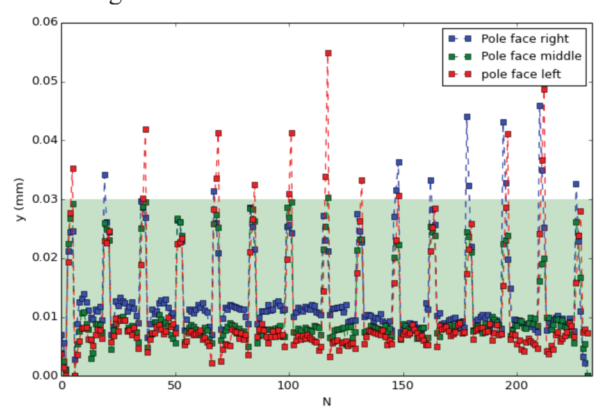

Figure 5: Plot of the pole face flatness along the bottom of the magnet core (number of measurements on X-axis) showing spikes out of the tolerance zone (green).

As shown in Fig. 5, the differences between poles largely fall within the required tolerances on the magnet yielding a minor impact on the periodicity of the magnet. However, the difference in pole height was a representation of the mismatch of the interfaces between the footed pole inserts and their cutouts in the magnet core.

During the potting process the magnets undergo a bakeout process where they are heated to 80 ºC for 24 hours, then cured at 135 ºC for 1.5 hours. Once potted the magnets are trained and tested in a liquid helium bath at an operating temperature of 4.2 K. The temperature differential was sufficient for the conductor to expand and contract enough that the protective layer around the conductor was penetrated or rubbed off at specific interfaces where the footed poles are attached to the magnet core. This created shorts to the magnet core which in turn created local hot spots where the conductor would burn up during coil training. The interface location where problems occurred, and

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a cutout of the conductor damage can be seen in Figs. 6 and 7, respectively.

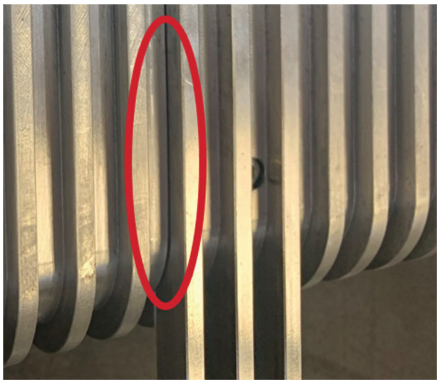

Figure 6: Interface where footed pole meets the magnet core where the conductor could potentially get pinched.

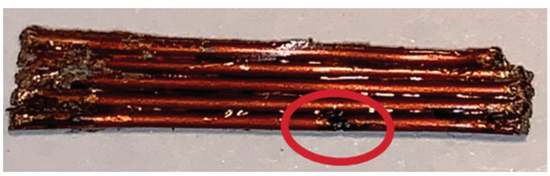

Figure 7: Conductor removed from a magnet after it had shorted to the core and caused a magnet failure. Red circle highlights the hot spot where the conductor burned.

FINAL DESIGN

Given that the interface between the footed pole inserts and magnet core exist in multiple locations along the length of each magnet, there was the possibility for failure on additional magnets on the remaining SCUs to be built. The design was modified to completely remove the footed poles. The magnet outer profile was changed to include a taper to the bottom pole surface to replace the footed poles and machining the entire magnet core out of a single piece of steel as shown in Fig. 8. The change was influenced by the single piece magnet cores manufactured for the Helical Superconducting Undulator (HSCU) built at Argonne in 2017 [3]. This would eliminate any interfaces where the conductor could potentially be damaged. The final design would retain the winding groove dimensions, turn around pins, helium channels, and tapered grooves on the top of the magnet, while removing the footed poles from the design, thus eliminating the interfaces that were causing the shorts to the magnet to occur. The final design also includes a new feature of channels machined down the sides of the magnet core to allow for epoxy to better flow through the magnet during the potting process. The final design also allows the magnet to maintain the same magnetic performance as the initial design and allows for the use of all the same components surrounding the magnet structure inside of the cryostat creating uniformity between all the magnets. The surrounding components are shown in Fig. 9.

As a result of removing the footed poles from the design, the potting molds for the magnets needed to be redesigned to fit the new magnet profile. The footed poles were an integral part of the potting mold, as they were used to fasten the magnet onto a flat plate, ensuring a clean surface on the bottom of the magnet. A new method consisting of pressing the magnet down from the top was developed to retain the smooth surface on the bottom pole face.

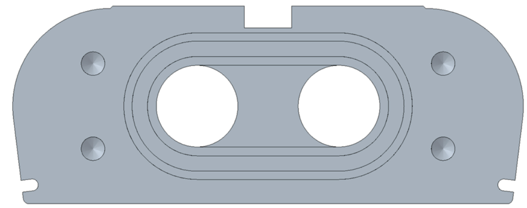

Figure 8: New single piece magnet design with tapered profile to be used on all future APS-U SCUs.

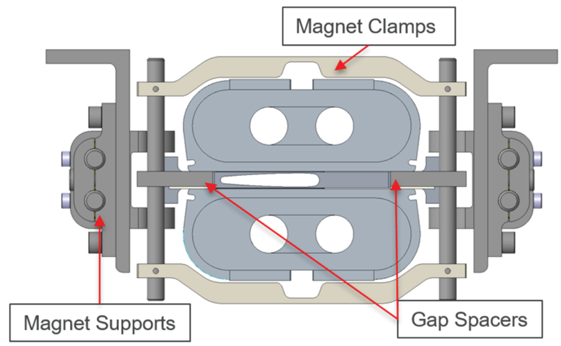

Figure 9: New single piece magnet design and corresponding components being reused inside of the SCU cryostat.

CONCLUSION

Following an extensive design, assembly, and testing process, the latest evolution of the superconducting magnet cores for the APS-U have been approved and are currently being manufactured with an anticipated arrival date of late 2021. After delivery, the magnets will be wound, potted, and tested before being installed into the new SCUs currently being assembled at the APS.

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