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REVIEW OF NEW DEVELOPMENTS IN SUPERCONDUCTING UNDULATOR TECHNOLOGY AT THE APS*

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Abstract

Superconducting undulator technology for storage ring light sources has evolved from proof of principle to the working insertion device level. Both planar and helical magnet topologies using NbTi superconductor have been successfully incorporated into functional devices operating in the Advanced Photon Source (APS) storage ring at liquid helium temperatures using cryocooler-based, zero-boil-off refrigeration systems. Development work on higher field magnets using Nb_3Sn superconductor is ongoing at the APS, as are concepts for FEL-specific magnets and cryostats for future light sources.

BACKGROUND – EXISTING DEVICES

The APS currently operates three SCUs in the storage ring. Two are nominally identical vertical gap planar devices with period length 1.8 cm and overall active length 1.1 m. These devices reside in Sectors 1 and 6. The third is a helically wound, circularly polarizing device located in Sector 7 with period length 3.15 cm and overall active length 1.2 m. Device parameters are listed in Table 1.

Table 1: Parameters for SCUs Installed at APS

Parameter	Value	
	Planar	Helical
Cryostat length [m]	2.06	1.85
Magnetic length [m]	1.1	1.2
Period [mm]	18	31.5
Magnetic gap [mm]	9.5	29 (diameter)
Beam chamber aperture [mm]	7.2	8(V) x 26(H)
Peak field [T]	0.97	0.42 (B_x=B_y)
K value	1.63	1.2 (K_x=K_y)

Additional details regarding the existing devices as well as a fourth planar device developed for LCLS R&D are provided in [1,2]. For details on magnetic performance see [3]. Table 2 lists the operational statistics for planar device SCU18-1 which has operated in Sector 1 of the APS storage ring since May 2015. Device performance has been highly reliable, with overall availability of 99.99%. Figures 1 and 2 show the devices installed in the APS storage ring.

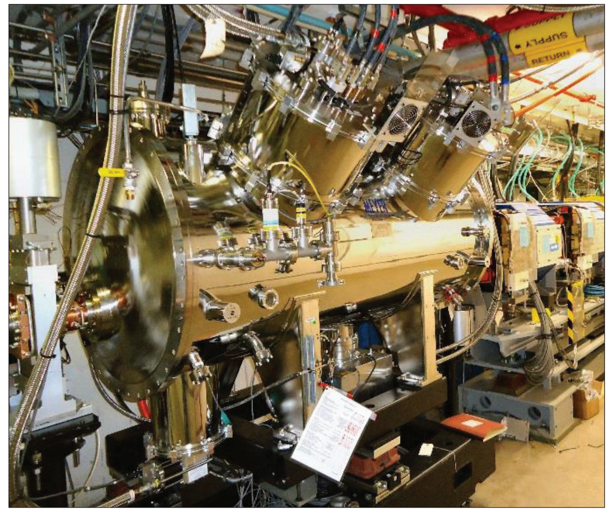

Figure 1: Planar SCU installed in the APS ring, Sector 1.

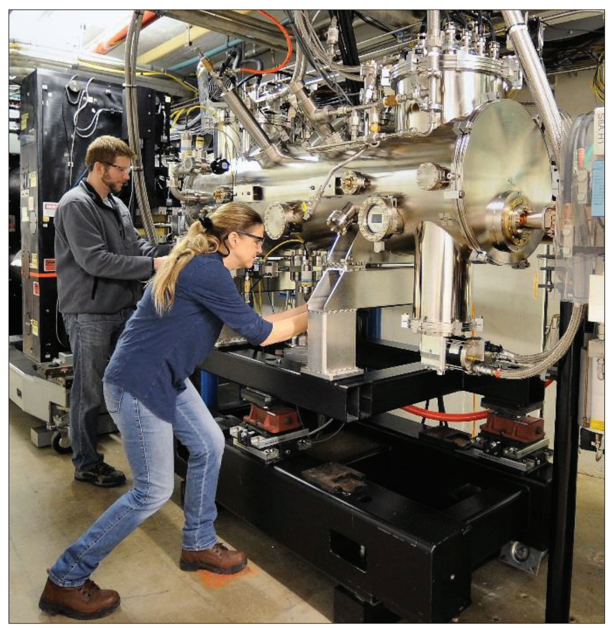

Figure 2: Helical SCU installed in Sector 7.

Table 2: Operating Statistics for SCU18-1

Year	SCU hours operating	Availability %
2015	3059	99.997
2016	4585	99.990
2017	4818	99.984

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NEW MAGNET DESIGNS

Planar Polarizing

The APS continues to explore the feasibility of alternative superconductors for SCU magnets such as Nb_3Sn although this activity is in the very early stages. Recent developments in planar magnet mechanical design have focussed on minimizing phase error via tight machining tolerances, gap control, and overall magnet straightness for magnetic lengths beyond 1.5 m. As part of the APS Upgrade a new planar magnet design based on 1.8 m magnetic length is in development. Target phase error will be 2-3 degrees rms with period length 16.5 mm and target field strength approximately 1.1 T. Several features of the existing 1.1-meter magnets will be retained, including: conductor winding technique, liquid helium cooling strategy, gap separation mechanism, control of magnet straightness, and beam vacuum chamber support with thermal isolation from the 4.2 K magnets. Verifying the extension of these techniques to longer magnetic lengths is a crucial element of our development activity. Figure 3 shows a CAD model of a 1.8-meter planar magnet pair.

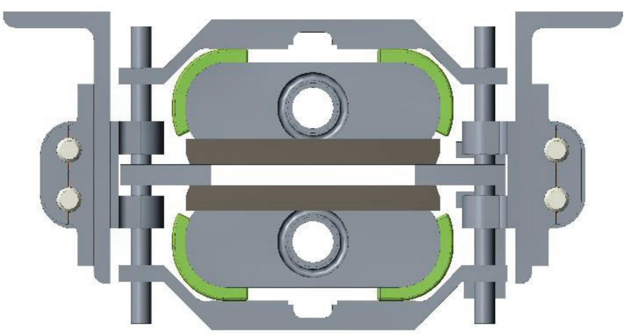

Figure 3: Cross-section of planar magnet pair showing magnet cores with helium cooling passages, pole pieces, gap separator system, and magnet support system. Superconducting wire is not shown.

Circular Polarizing

The helical SCU presently in operation was designed to be compatible with the APS storage ring. Future development of this magnet type will likely focus on free electron laser (FEL) applications where a very small "magnetic gap" is allowed and the subsequent magnetic field is large. These magnets would be installed in a multi-undulator array as opposed to individually as in a storage ring. In that regard their design can be tailored to provide an optimal magnetic length for field tapering. The superconductor in the existing helical SCU is wound continuously into a double-helical "2-lead" rectangular-thread groove machined into the magnet core. Magnet performance is strongly dependent on the machining accuracy of the groove depth and pitch. Future devices may benefit from precision thread grinding, perhaps as a finishing step following the multi-axis CNC milling process. Figure 4 shows a helical magnet core wound with superconducting wire and prepared for epoxy impregnation.

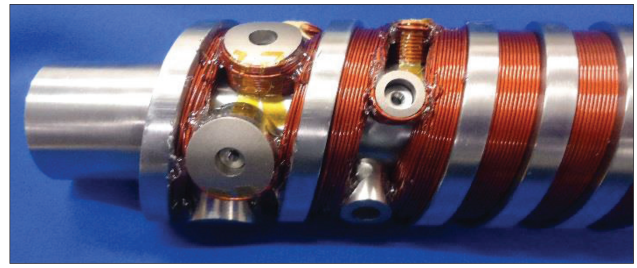

Figure 4: Closeup of the helical SCU wound core showing conductor end turn-around detail.

Universal Polarizing

Development work continues on a universal superconducting undulator capable of arbitrary polarization. At the APS this work takes the acronym SCAPE (Superconducting Arbitrarily Polarizing Emitter) and consists of two orthogonal planar magnet pairs with roughly triangular cross-section, offset longitudinally by ¼-period. The four magnet cores are arranged around an X-shaped beam vacuum chamber. The chamber operates at a higher temperature than the cores and is thermally isolated from them. Two views of the SCAPE geometry are shown in Figs. 5 and 6 while Fig. 7 shows a prototype SCAPE magnet core after winding with NbTi superconductor.

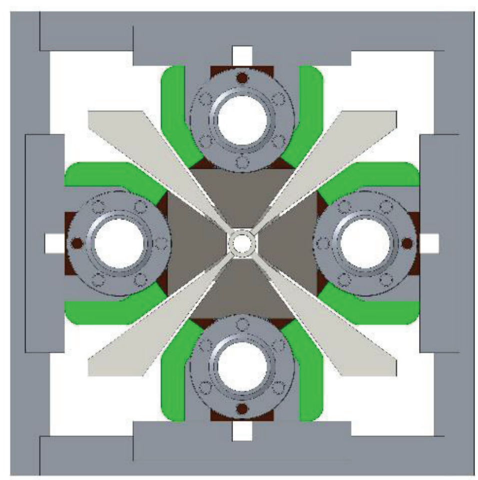

Figure 5: End view of the SCAPE SCU concept.

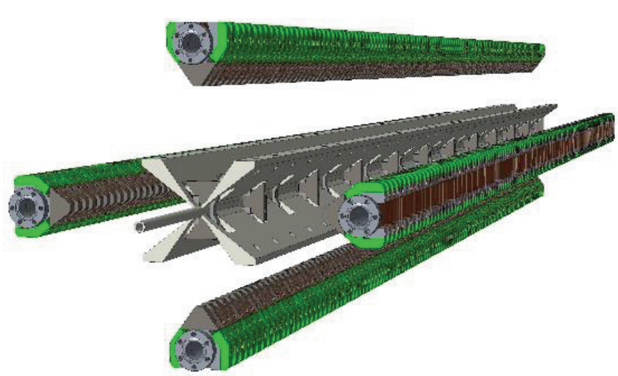

Figure 6: Exploded view of the SCAPE magnet/vacuum chamber concept.

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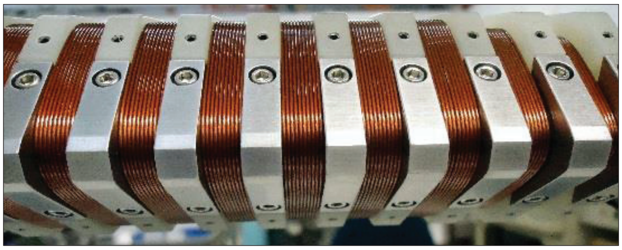

Figure 7: (top) Close-up view of a prototype SCAPE core after winding with superconducting wire.

This magnet technology has application for both storage ring and FEL light sources, providing planar horizontal through circular to planar vertical (as well as intermediate elliptical) polarizations. As in the storage ring-based planar devices, the SCAPE vacuum chamber can operate at elevated temperature relative to the magnets in order to intercept both electron- and photon-based heating and maintain a reasonable 4.2 K heat load to the magnets.

Correctors

Existing SCUs use both internally wound and externally mounted magnets to perform first and second integral correction. Future multi-magnet SCUs will require either dipole chicanes for phase shifting or (for storage ring applications with multiple straight section end stations) canting magnets between the undulator magnets. These devices may be superconducting or cryogenically cooled/normal conducting depending on magnet current requirements and installation complexity. Figure 8 shows a closeup of the helical SCU dipole correctors.

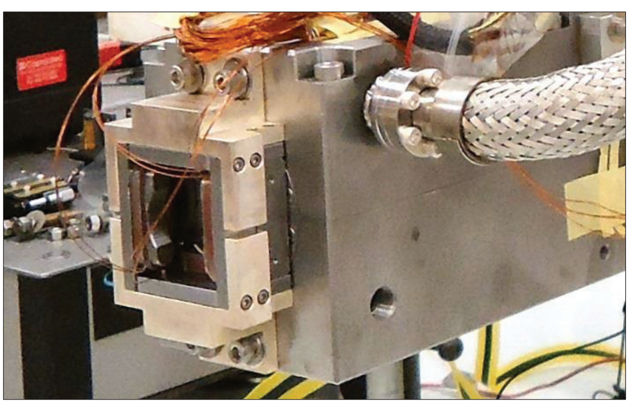

Figure 8: Conduction-cooled helical SCU superconducting horizontal and vertical dipole correction package mounted to the end of the main magnet.

NEW CRYOSTAT DESIGNS

Storage Ring-Specific

Cooling Systems The existing APS SCU cryostat design descends from liquid helium-based, cryocooler-cooled insertion devices developed at the Budker Institute for Nuclear Physics (BINP), Novosibirsk [4]. The relatively sparse and isolated nature of today's storage-ring-based SCU installations argues in favour of individually cooled units (in contrast to a central helium refrigeration plant plus cryogenic distribution system) in terms of capital cost. Careful management of cryogenic heat leak permits use of a reasonable number of 1.5 W, 4.2 K cryocoolers while maintaining zero-boil-off operation. Future plans include pursuit of alternative cryocooler technologies such as a new 2-W class of 4.2 K pulse-tube cryocoolers. Cryogen-free designs present an attractive option by eliminating liquid helium and the associated pressure system and cryogenic leak issues. Regardless of architecture, the cooling system must provide some capacity overhead to allow for recovery from magnet quench within a reasonable interval. During routine operation the excess capacity is dissipated with a regulated heater. The heater power level provides an excellent diagnostic with respect to the overall health of the system.

Alignment Systems Alignment requires precision in both position adjustment and measurement. Development efforts include precise (<10 micron) external adjustment capability for the magnet cold mass with respect to the cryostat when the system is at 4.2 K along with sub-5-micron laser displacement-based position measurement capability [5]. These requirements are particularly important for multi-undulator-magnet cryostats where magnet-to-magnet alignment at the 5-micron level is desirable. Multi-magnet alignment to a common rigid cold mass support is the baseline choice for the APS Upgrade SCU cryostat (see Figure 9) although independent magnet supports with external precision adjustment capability are a potential alternative.

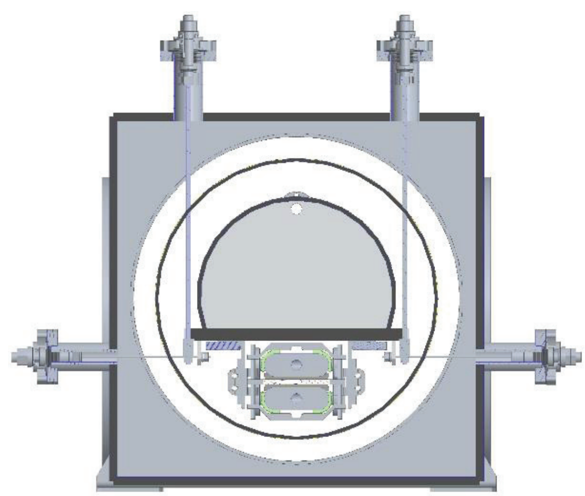

Figure 9: End view of a magnet support and alignment concept for the APS Upgrade SCU cryostat. Externally adjustable low-heat-leak supports provide precise positional control.

Beam Vacuum Chambers SCU magnets must be screened effectively from substantial beam and/or x-ray-induced heating in a storage ring application. An independently cooled beam vacuum chamber provides an adequate screen for planar SCUs. However the helical SCU at the APS is vulnerable to x-ray heating caused by the bending-magnet (BM) beam line immediately upstream. This potentially fatal heat source was mitigated

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by sophisticated beam orbit correction to steer the BM x-ray fan away from the helical SCU magnet. The vulnerability arises due to the helical magnet core design which completely envelopes the beam vacuum chamber. For the planar geometry, there is no magnet exposure along the horizontal plane of the electron beam orbit (see Figure 3).

FEL-Specific

Cooling Systems An FEL SCU array, perhaps of order 100 m length, lends itself to the use of a centralized cryoplant coupled to a cryogenic distribution system (compared to a very large number of cryocoolers). The 4.2 K heat load per meter is likely around one watt if thermal design discipline similar to the storage-ring-specific cryostat is maintained. However given the available cooling power of even a small liquid helium refrigerator, it is possible to loosen the heat load budget as a means to simplify cryostat design. A small commercial refrigerator is shown in Fig. 10.

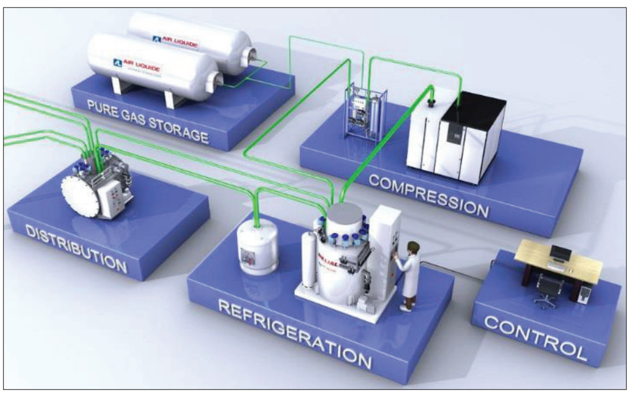

Figure 10: A small helium refrigerator system (from the Air Liquide website).

Alignment Systems FEL requirements push the state of the art and may involve active, beam-based component alignment. Individual control of undulator magnets, focusing quadrupoles and phase shifters may be required. Room-temperature remote adjustment of cold mass supports via cryostat insulating vacuum feed-throughs may be sufficient. Piezo actuators can be located outside of or internal to the insulating vacuum and may find an application for short-distance, fast position adjustment. In the longer term, fiber-optic interferometer-based systems may provide improved precision and multi-channel capability for real-time magnet location measurement as part of an active positioning system

Beam Vacuum Chambers A 4.2 K beam vacuum chamber becomes feasible, in part due to the lower expected beam-induced heating relative to a storage ring but also due to the refrigeration capacity inherent in a centralized helium refrigerator. This could enable smaller magnetic gaps and larger magnetic fields for a given magnet operating current.

Array Segmentation Cryogenic distribution may be external (for example CEBAF at JLab [6]) or internal (LCLS-II [7] and European X-FEL [8]) depending on overall cooling power, capital cost, and maintenance strategy (individually removable cryostats compared to a full-system warm-up for cryostat removal). Figures 11 and 12 illustrate the minimal-segmentation concept where the distribution system resides internal to the cryostat.

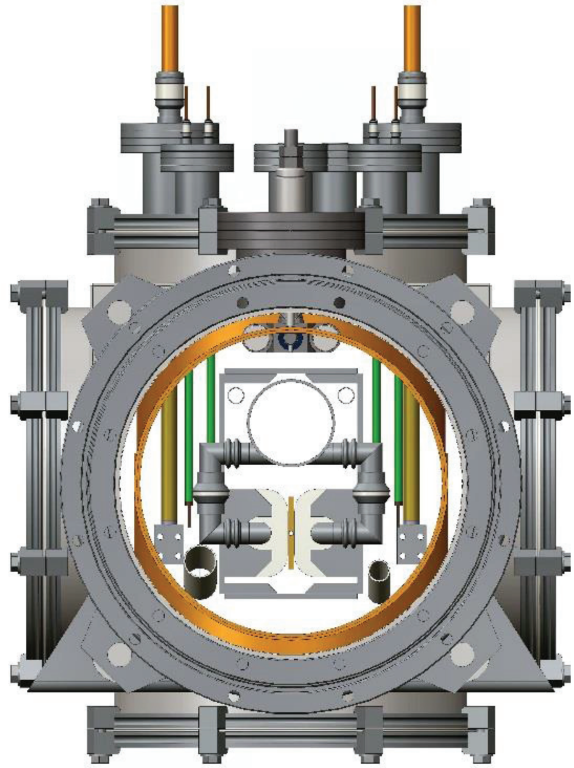

Figure 11: End-section view of a minimally-segmented SCU cryostat showing horizontal-gap planar magnets packaged with internal helium cryogenic distribution.

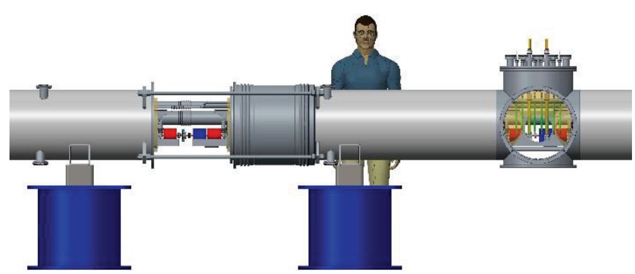

Figure 12: Concept representation of multiple cryostats connected in a minimally-segmented FEL array. The inter-cryostat vacuum vessel spool is shown in the retracted (assembly) position.

Multi-line FEL Cryostats An SCU cryostat represents a space-efficient means of packaging an undulator magnet. As such, it is possible to design a single cryostat capable of housing multiple undulator lines in parallel. Figure 13 shows a cryostat concept containing four parallel helical SCU magnet arrays in parallel, each with an independent beam vacuum chamber. This represents a packing capability which is likely unachievable using permanent magnet undulator technology.

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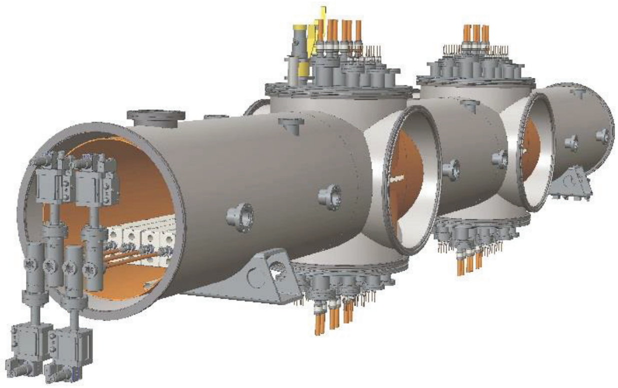

Figure 13: FEL helical SCU concept containing four independently powered SCU arrays in a common cryostat.

CONCLUSION

The APS is working to develop the next generation of superconducting undulator (SCU) technology for future storage ring and FEL light sources. At present there are three SCUs operating in the APS storage ring (two planar, one circular polarizing). Development is underway for a new generation of SCUs for the APS Upgrade. SCU technology is well-suited to FEL applications and development work on FEL-specific devices is ongoing.

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