A New Superconducting Undulator Cryostat for the APS Upgrade

E Anliker¹, J Fuerst², Q Hasse¹, Y Ivanyushenkov¹, M Kasa¹, and Y Shiroyanagi¹

¹ Advanced Photon Source, Argonne National Laboratory, Lemont, IL 60439, USA
² SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Email: fuerst@slac.stanford.edu

Abstract. The Advanced Photon Source (APS) is in the midst of a major facility upgrade including both a new electron storage ring (SR) and many new insertion devices (IDs) providing x-ray photon beams to a new suite of experimental end stations. Included among the new IDs are four 4.8-meter superconducting undulator (SCU) cryostats, each containing two 1.8-meter planar undulator magnets operating at 4.2 K in either a phase shifted or canted configuration. We describe a new, compact cryocooler-based cryostat design which supports the magnets and associated subsystems and also fits the space constraints of the SR ID straight sections. The design is an evolution of earlier single-magnet 2-meter cryostats, retaining some subsystem commonality while incorporating lessons learned and several features unique to the challenge of supporting two independently operable undulator magnets in a single device.

1. Introduction
The Advanced Photon Source (APS) located at Argonne National Laboratory (ANL) is currently undergoing an upgrade consisting of a new storage ring and new insertion devices. Among these new IDs is a new 4.8-meter long superconducting undulator (SCU) being designed and assembled at ANL. This SCU is being developed as a first article item and will be the first of multiple SCUs to be constructed for the APS Upgrade (APSU). The design of this SCU cryostat is an evolution upon previous SCU cryostats developed by ANL [1]. Unlike previous 2 meter long SCUs, the new undulator will occupy the entire space provided in a straight section of the new storage ring. Using experience obtained by building prior devices, the design will aim to preserve some previous subsystem commonality while integrating new features that are needed so that the device can operate as two independent undulators or as a single photon source. The cryostat will be a cryocooler based design providing refrigeration at 4.2 K for the undulator magnets and helium reservoir, 14-17 K for the beam chamber, and about 40 K for the thermal shield.

2. Design Overview
The design is an evolution of the second generation cryostats developed by ANL to support a helical superconducting undulator (HSCU) currently in use at the APS [1]. Figure 1 shows three major cryostat subsystems (vacuum vessel, thermal shield, and liquid helium reservoir). For the HSCU cryostat these
systems were successfully fabricated in industry as a build-to-spec procurement and a similar strategy will be followed for the APSU SCU. The 508 mm diameter vacuum vessel is constructed of stainless steel similar to the HSCU although the length is 4.8 meters compared to 2 meters for the HSCU. A further major design change includes the addition of full-diameter cube crosses at the center and ends of the vessel to provide improved access to internal components during assembly as well as mounting points for the cryocoolers and instrumentation.

The thermal shield is constructed from 3.2 mm copper sheet. The shield consists of a main cylinder, two smaller turret cylinders, and multiple cover plates for access ports. Access ports are located at each corresponding port on the vacuum vessel. The shield is wrapped in 40 layers of multi-layer insulation (MLI).

The liquid helium reservoir is fabricated as a rolled partial cylinder of explosion-bonded Copper 102/SST 316L sheet welded to a 19.05 mm stainless steel base plate. The assembled weldment functions as a rigid strong back to support the magnets and beam chamber. The reservoir is conduction cooled via copper foil thermal links connecting the outer copper layer of the reservoir shell to the 4 K cryocooler cold heads. The reservoir is ASME code stamped and includes Conflat (CF) flanges to allow connection of helium fill/vent lines, pressure relief line, liquid level probes, and magnet piping. The CF flanges are either welded in place or machined directly into the reservoir. Several machined copper blocks are soldered to the reservoir exterior to serve as points of attachment for the cryocooler thermal links and also as heat sinks for instrumentation, current leads, and other systems.

![Figure 1. (From right to left) The vacuum vessel, thermal shield, and liquid helium tank that make up the APSU SCU cryostat.](image)

**2.1. Layout (Internal)**

The design of the new SCU will encompass two separate planar undulator magnets in either an inline or canted configuration. This is accomplished by independently supporting two magnet pairs off of the liquid helium reservoir. The liquid helium reservoir will also include support points to suspend the beam chamber between the magnets. Once assembled, these components make up the cold mass of the SCU. The cold mass will be vertically supported at the ends at four points with the option for two additional supports located in the center cube of the cryostat. These supports will be suspended from the outer vacuum vessel on adjustable tensioners that are used for alignment and to compensate for any unexpected movement or misalignment during cool down. A cutaway model showing the different components inside of the cryostat can be seen in Figure 2.

The magnets are cooled via liquid helium through two parallel internal channels per magnet. Each magnet pair is supported in three locations, one of which being an anchor point that allows for a controlled contraction when the magnets are cooled to operating temperature. These supports allow for
adjustment in the vertical and axial directions. The magnet design is an evolution of past planar magnet designs [5] and has specific new elements due to their increased length (1.9 meters) and tight tolerances. The magnetic gap is defined by gap spacers held in place by the clamping mechanism that holds the magnets together. The beam chamber is notched periodically along the outer edges to provide space for the gap spacers. The cold mass also includes the horizontal and vertical corrector magnets that are located in sets at the ends and in the middle of the SCU.

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Figure 2. A cut away model showing the interior of the APSU SCU showing the thermal shield and cold mass installed inside of the vacuum vessel.

The aluminum beam chamber is supported off brackets connected to the bottom of the helium reservoir and thermally isolated from the reservoir with Torlon™ standoffs. The beam chamber measures 4.8-meters in length including the stainless steel end transitions which terminate in 4.5-inch CF flanges which mate to storage ring vacuum system [3]. The aluminum chamber is cooled via a distributed copper bus connected to a dedicated “20 K” cryocooler.

The SCU has four turrets that act as mounting points for the cryocoolers and instrumentation needed for operation. Two main end turrets house two 4 K cryocoolers each along with the main and corrector magnet leads. The 4 K stages are connected to the helium reservoir by copper foil links while the first stages connect to a plate that distributes cooling power to current leads and to the thermal shield via braided copper links. The upper center turret supports a fifth 4 K cooler which is thermally linked to the helium reservoir and the shield. The “20 K” cooler is located on the lower turret.

2.2. Assembly and Installation
Because of its weight and length, the installation of the cold mass poses many challenges. A reliable and repeatable system for assembling the cold mass into the vacuum vessel has been developed. The installation method involves statically supporting the cold mass using extension beams and leveling tables. The vacuum vessel/thermal shield is rolled over the cold mass along a guide rail system. The complete installation plan for the cold mass can be seen in Figure 3. Analyses were completed to validate the support beam design with respect to the stresses created by the weight of the cold mass. Peak stress and deflection of less than 172 MPa and 125 mm are expected in the support beam. Leveling tables will account for this deflection as well as enable elevation adjustment when the vacuum vessel is wheeled over the cold mass.
Existing APS SCUs are installed in the SR on a multi-function rolling/stationary base [1]. The APSU SCU will use fixed pedestal supports. This allows greater access during maintenance periods and installation, as well as reducing vibration. A temporary rolling base is bolted to the pedestal supports throughout the entire assembly and installation of the SCU into the SR. The temporary rolling base must also support lift points to permit fork lift transport of entire SCU and maintain a sufficiently narrow profile to fit the minimum 1.1-meter aisle width of the SR tunnel. A plan for SCU installation was developed in a skeleton model of the SR tunnel created using the CREO Parametric 3D CAD application. Figure 4 shows a section of the skeleton model and the SCU installation path. A tipping analysis was performed that determined it would take about 5960 Newtons of force in the worst case scenario to tip the SCU and it would require a velocity of 1.65 meters per second to create a tripping moment and cause the SCU to tip over.

![Figure 3. Assembly of the cold mass into the vacuum vessel/thermal shield. A) Cold mass with support beams bolted to helium reservoir supported from leveling tables. B) Vacuum vessel/thermal shield on rolling transport base is moved over long support beam. C) A third leveling table is added to the end of the long support beam and the middle table is removed. D) Vacuum vessel/thermal shield is rolled along track into position around cold mass. E) Middle table is re-introduced and the table at the beam end is removed. Cold mass supports are installed. F) Cold mass weight is transferred from tables to cold mass supports. Beams are removed.](image)

![Figure 4. Skeleton model showing installation path of the SCU into the storage ring.](image)

### 2.3. Integration (Skeleton Modeling)

A new top down modeling and integration approach has been implemented for designs going into the new SR. This modeling method consists of creating skeleton models that drive the dimensions and constraints of the actual models. The skeleton models start as space claims, then progress into more detail depending on the application. This allows groups working on different subsystems to pull information from the skeleton model and maintain live links between interfaces preserving overall system integration. Smaller details can be neglected in the skeleton models but interface points are
critical. The skeleton also provides a lightweight, top-level, easily manipulated model of the overall SR. As seen in Figure 4, a high level skeleton assembly model contains all necessary integration references for all subsystems including magnet arrays, front ends, insertion devices, and the tunnel itself. A closer view of the skeleton model of the SCU can be seen in Figure 5.

Specific to the APSU SCU, the skeleton model drives the dimensions and positions of the cryostat, supports, magnets, beam chamber, and other subsystems. It also constrains SCU width and length to preserve interfaces with the upstream and downstream SR vacuum system and also prevents interference with other neighboring components. This “top-down” modeling method preserves space-claim envelopes for individual subsystems which are only at the conceptual design level. Once the models progress to final design, an integration model including all subsystem detail is created. This integration model is shown in Figure 6.

3. Mechanical Analysis

Mechanical analyses of the vacuum vessel and helium reservoir were performed using an ANSYS Structural numerical model. Reservoir analyses provided initial design parameters consistent with a maximum allowable working pressure (MAWP) of 45 psi differential (30 psig plus full external vacuum). Final design and supporting ASME Section VIII analysis together with a code stamp will be provided by the vessel fabricator. The vacuum vessel analyses also provided initial design parameters and are to be validated by the vessel fabricator as part of their final design. An integrated model of the cold mass and removable shipping supports was also created to validate the design against shipping and transport loads. Figures 7, 8, 9 and 10 show analysis examples. These examples simulate stresses seen when transporting the cryostat and helium tank. The peak stresses were concentrated where the lifting lugs attach to the vacuum vessel and on the lifting eye itself (Figure 8 & 9). This was an expected result as the lifting lug is welded to the vacuum vessel and would want to be pulled away when under load.
While this peak stress is located in an expected area, the value of 101.6 MPa is a result of a meshing artifact that simulates the joint as a sharp corner. Once welded, that corner will disappear and a lower stress value would result.

The peak stresses on the shipping supports seen in Figure 7 are located at the fixed point on the support rod. These support rods are loaded axially with the weight of the cold mass. All of the stresses calculated are still well below the yield stress of 215 MPa for Stainless Steel. The displacement shown in Figure 10 simulates the cold mass under installed loading conditions. This displacement can be accommodated for by adjusting the vertical supports that suspend the cold mass in the cryostat or by aligning the equipment under the helium tank and allowing the helium tank to deflect naturally. Thermal analysis of the system was also performed under operating conditions. The details of the thermal analysis performed are given in [4]. Loads are calculated using an ANSYS numerical model which has been benchmarked against existing SCUs in operation at the APS.

Figures 7, 8: (left) numerical simulation of transverse 3-g load during shipping showing peak stress of 64.5 MPa; (right) numerical simulation of lift lug under full cryostat weight showing peak stress of 101.6 MPa.

Figures 9, 10: (left) Numerical simulation of the vacuum vessel under 1 bar external pressure and under lift; (right) numerical simulation of cold mass displacement under gravity and internal pressure when suspended from the low-heat-leak support system showing maximum displacement of 300 micron.
4. Expected Operational Performance

From a cryogenic standpoint, cooldown and steady-state full-current operation of the undulator magnets is expected to resemble that of existing 1.2-meter devices currently in operation at the APS. The increase in installed cooling power relative to existing devices not only provides suitable operating margin but also enables system cooldown from room temperature on a similar timescale (about four days). During magnet power-up, ramp rates will be chosen to avoid excessive hysteresis and eddy-current heating which could induce a quench. At 450 A flattop some additional heat load associated with current leads is expected but will be well within the available cooling margin as shown in the thermal analyses. Simultaneous operation of both undulator magnets is expected to be the default condition, either as a single photon source (using an intermediate phase shifter magnet) or as two independent sources (using an intermediate canting magnet). Since each magnet pair is independently powered, individual operation of either magnet is also possible. It is uncertain whether a quench event in one magnet will induce quench in the other. The undulator magnet pairs are electrically isolated but are both tied to a common LHe reservoir – the resultant pressure and temperature transients caused by a quench of one magnet may induce quench in the other.

Figure 11: Quench response of SCU 18-2 in operation at the APS. At quench onset, magnet temperature and system pressure spike rapidly indicating non-equilibrium conditions in the LHe circuit. Recovery time back to 760 torr operating pressure for this SCU takes several hours. Additional cooling power in the APSU SCU design achieves the required goal of <1 hour recovery time.

The system is designed for zero-boil-off operation such that even during a magnet quench the pressure does not exceed the helium reservoir relief pressure. A simple Excel spreadsheet using helium thermophysical property data via the NIST REFPROP add-in [2] together with the SOLVER calculates the final pressure, temperature, and liquid fraction of the reservoir-magnet system given starting
conditions (pressure, system volume, and liquid fraction) and the input energy associated with a quench event. For the purposes of the analysis we assume both magnets are energized and that both magnets quench simultaneously, releasing 15 kJ of energy (7.5 kJ per magnet at full current). The LHe reservoir volume totals 170 L and the initial liquid fraction impacts the final pressures reached due to the quench. The analysis calculates an initial non-equilibrium peak system pressure by allowing the liquid phase to deviate from the saturated condition. A second “equilibrium” pressure is calculated assuming saturated conditions are maintained. Quench data on SCUs in operation confirm this behavior (see Figure 11). The data indicates an initial spike in magnet temperature and system pressure (non-equilibrium conditions) followed by a return to saturated conditions for both the liquid and vapor phases and subsequent linear reduction in pressure as the quench energy is extracted. For the APSU cryostat operating at 760 torr with 70 L of LHe and a reservoir volume of 170 L, a 15 kJ quench event produces peak and equilibrium pressures of 1109 and 928 torr, respectively.

Quenches are almost always induced by unintended loss of the electron beam. Quench recovery should be rapid enough to enable re-powering the SCU magnets before the electron beam has been restored. It typically takes over an hour to diagnose the cause of beam loss and re-establish circulating beam, so a quench recovery time under one hour is acceptable. If the SCUs used Sumitomo RDK-415D cryocoolers, it would take 63 minutes for the available 3.99 W of 4.2 K cooling power to extract 15 kJ of quench energy. At a cooling power of 5.61 W (using Sumitomo RDE-418D4 cryocoolers), the recovery time is 44 minutes, making the latter coolers the preferred choice for these SCUs.

5. Discussion
The design of a new superconducting undulator for the APS is near completion. The main components of the cryostat (vacuum vessel, thermal shield, and liquid helium reservoir) are already in fabrication and the remaining components are following close behind. The design is integrated with all the required systems in the APSU SR and resides within the APSU skeleton and global assembly models. Analyses were performed which demonstrate that the design is suitable for fabrication/operation and meets the project design requirements. The cryostat provides a versatile platform capable of supporting different undulator magnet concepts and operating parameters. Off-line testing and operational performance data will be compared to simulations as done with previous SCUs.

6. References

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