CRYOSTAT DESIGN FOR AN FEL SCU DEMONSTRATOR

C1Po2D-07

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ABSTRACT

A design for a 4.2 K cryostat to support superconducting undulator (SCU) magnets is being developed as part of an SCU free electron laser (FEL) technology demonstrator. An array of several cryostats will be installed as an afterburner at the end of the existing hard x-ray beam line of the LCLS-II facility at the SLAC National Accelerator Laboratory (SLAC).

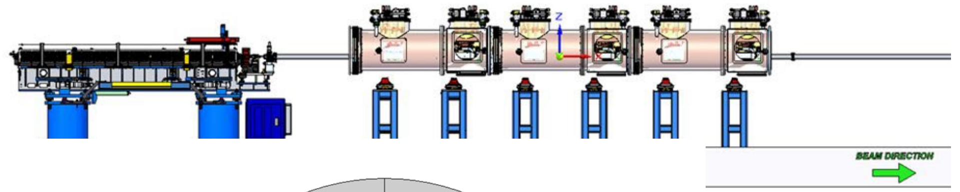
Cryostat requirements include high operational availability, precision positioning and measurement capability to support beam-based alignment, high undulator magnet packing fraction, operational transparency to the electron beam, and compatibility with the existing LCLS hardware and space constraints. A cryocooler-based refrigeration system is appropriate given the scale and operational profile of the demonstration.

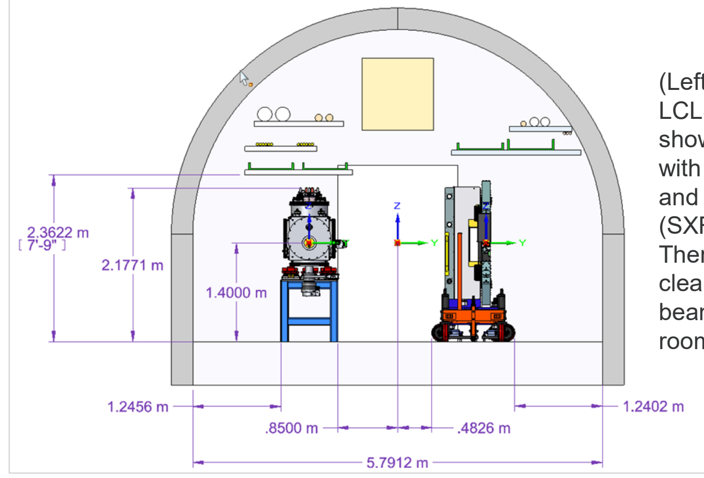
The design is being developed as part of a collaboration between SLAC and Argonne National Laboratory (ANL) and draws on ANL's experience with SCUs at the Advanced Photon Source.

MOTIVATION

X-ray FELs (XFELs) capable of high-intensity, high-repetition-rate operation are recognized as key tools to address pressing scientific challenges. An earlier collaboration among SLAC, ANL, and Lawrence Berkeley National Laboratory (LBNL) [1] delivered promising results with FEL-specific SCU magnet technology and demonstrated that SCUs can offer performance advantages compared to permanent magnet undulator technology. The present SLAC/ANL collaboration continues to develop and extend existing SCU technology for FELs [2] by installing up to three 1.5-meter SCU cryostat segments as an afterburner at the end of the existing hard x-ray (HXR) undulator beamline at SLAC's LCLS-II facility.

The goal of the current effort is to demonstrate the key technologies required for SCU FEL operation in an operating FEL facility. Chief among these technologies is precision positioning and alignment of the beamline elements to the electron beam. A dedicated alignment test stand is under construction to validate this capability in parallel with the cryostat design effort. For demonstration purposes, the cryostat design can take advantage of existing storage-ring light source SCUs to shorten the cryostat design and construction timeline as well as reduce performance uncertainty and risk. It is recognized that production cryomodules for an operational FEL SCU array may follow a more purpose-built configuration and implement a cooling strategy better suited to a large array of cryomodules, such as a central helium refrigerator and associated distribution system. The figures below illustrate a concept for a three-segment FEL SCU installed at the end of the Hard X-ray Undulator (HXR) line at the SLAC LCLS-II facility.

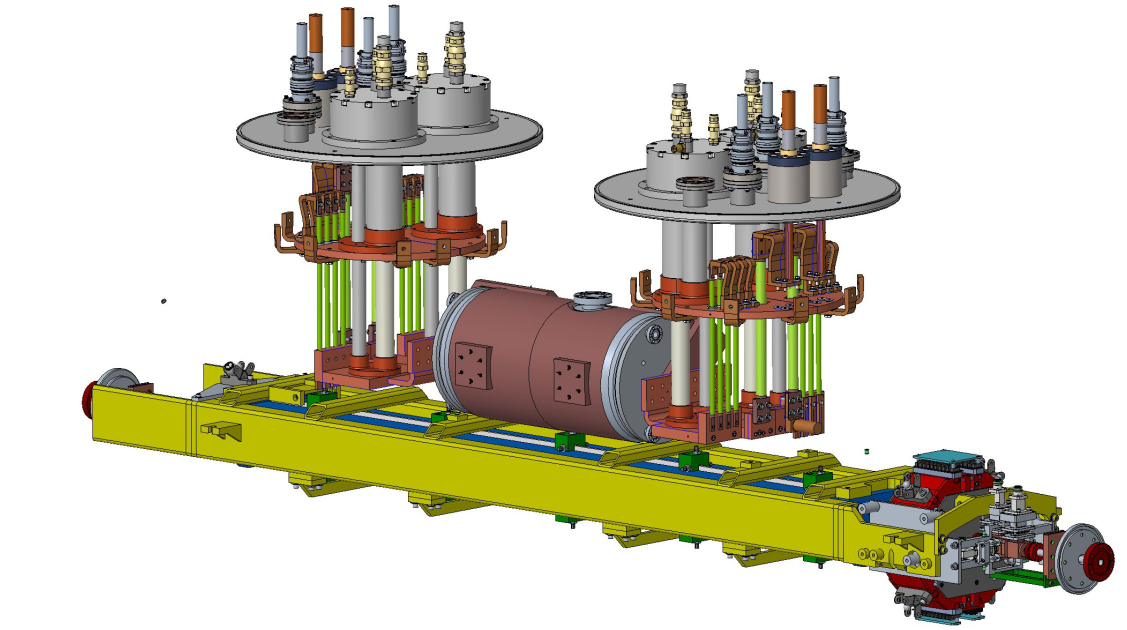




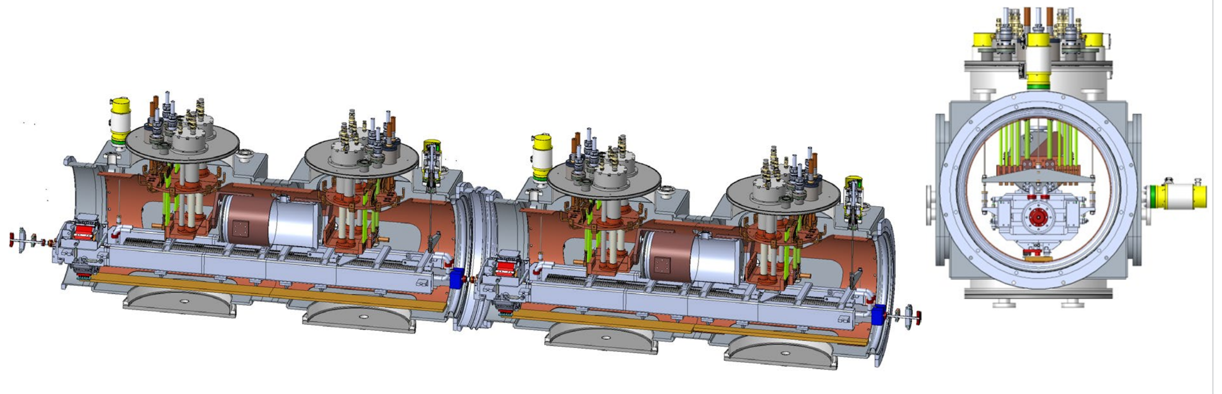
(Left): Cross-section of the LCLS-II undulator hall showing the HXR undulator with SCU array on the left and the Soft X-ray Undulator (SXR) array on the right. There is adequate access clearance for both undulator beam lines, as well as head room for the cable trays.

CRYOSTAT

The basic design for the cryostat draws from existing SCUs at ANL [3, 4]. Beamline elements of the cryostat include the SCU magnet with co-wound superconducting field correction coils, a superconducting phase shifter, a normal-conducting quadrupole (quad) magnet to provide periodic focusing of the electron beam, and a rf beam position monitor (BPM) with sub-micron resolution. The SCU magnets and associated components are mounted and aligned to a rigid frame. The quad and BPM reside on a subframe which permits independent alignment of these two components due to their tighter alignment tolerance requirements. The frame, associated beamline elements and ancillary components are referred to as the cold mass. The figure below shows the cold mass including the liquid helium (LHe) reservoir as well as the cryocooler and current lead assemblies.



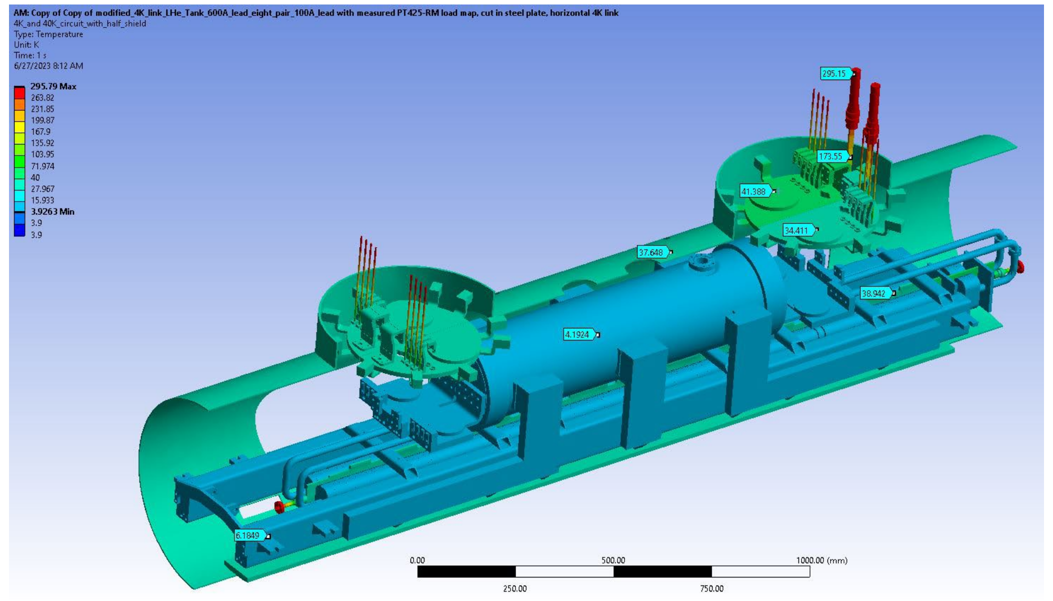
Refrigeration for the 4.2 K magnet and 40 K thermal shield is provided by multiple parallel cryocoolers. This cooling strategy is suitable for the small scale and temporary nature of the present technology demonstration. For a full-scale undulator array with many tens of meters of active length, a cooling system comprised of a central cryoplant with distribution system is envisioned. The demonstrator cryostat segments are equipped with a LHe reservoir as part of the cold mass for operational flexibility. High-temperature superconductor (HTS) current leads bridge the low-temperature superconducting (LTS) magnets from 4.2 K to 40 K. Normal-conducting copper bus extends from the 40 K shield to room temperature (RT).



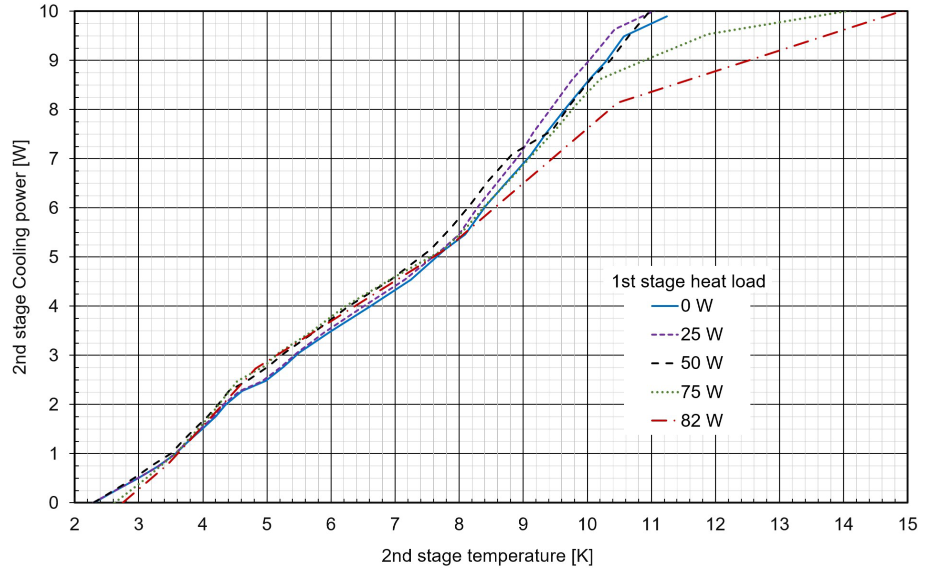
Cryostat segments share a common insulating vacuum space to maximize the packing factor (active magnetic length vs. installed length). A full-scale SCU array with common insulating vacuum would leverage the presence of "installed spare" segments to maintain FEL operation with some level of in-situ SCU failures. Segments could be configured as individual insulating vacuum spaces by adding end caps with beam line spools and isolation valves between segments. This topology would permit warmup and removal of individual SCU segments. However, a full-scale SCU array built in this manner and using a cryoplant for cooling would require an external cryogenic distribution system (CDS) resulting in a reduced packing factor.

THERMAL PERFORMANCE

Thermal management techniques are similar to those used on previous SCUs. Numerical simulation models have been developed using ANSYS to predict temperature profiles and determine the level of heat input required to maintain 4.2 K operation given the amount of installed cooling power. Data collected over years of SCU operation at ANL have confirmed the accuracy of this simulation technique. The figure below shows preliminary simulation results for one FEL SCU segment.



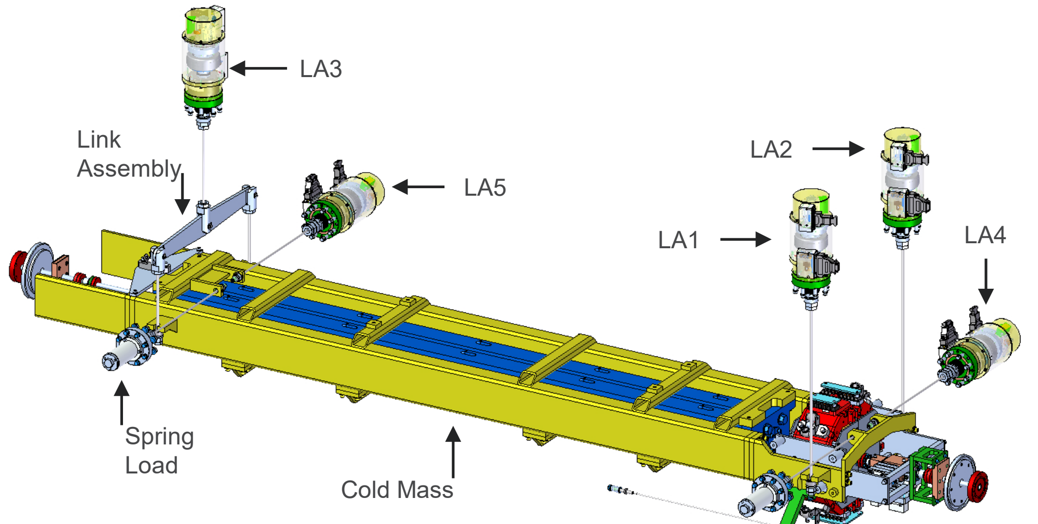
Refrigeration for each cryostat segment is provided by Cryomech PT-425 RM cryocoolers. The remote motor design of these units reduces vibration at the cryostat while still providing in excess of 2 W of 4.2 K refrigeration per unit. The cryostat is designed for up to four cryocoolers per segment although two are anticipated based on demonstrated cooling power and thermal simulations. The figure below shows the performance data collected on a PT-425 RM cryocooler from its minimum attainable second stage temperature (zero applied load) up to 10 K for various constant first stage heat loads [5].



The cooling system design follows that of earlier ANL SCUs which use cryocoolers to refrigerate a LHe reservoir which is connected by piping to cooling channels extending through the SCU magnet cores. Heat dissipated in the magnets generates helium vapor which travels to the reservoir and is recondensed at the reservoir walls by the action of the cryocoolers. The desired operating temperature is regulated using a trim heater to maintain a reservoir operating pressure of one bar by adding heat sufficient to match the total cooling power of the cryocoolers. The heater power level serves as a system diagnostic.

ALIGNMENT AND PRECISION POSITIONING SYSTEMS

FEL operation requires micron-level alignment of the quadrupole focusing elements to the electron beam. This is accomplished by applying a beam-based alignment strategy. Beam position monitors (BPMs) adjacent to each quadrupole will provide a beam offset signal to a positioning system to adjust the vertical and transverse positions of the quadrupole to center the device on the beam with sub-micron accuracy.



The positioning system is designed to move the entire cold mass assembly inside the cryostat, leaving the vacuum vessel, thermal shield, and cryocooler assemblies fixed in position. Five linear actuators are mounted to the exterior of the cryostat and act in tension to shift the cold mass. Three actuators (LA1-3) are mounted on the top of the cryostat to provide vertical as well as roll and pitch adjustment. Two more (LA4-5) are mounted on the side of the cryostat for transverse and yaw adjustment. The side positioners act against spring loads located on the opposite side of the cryostat. The arrangement is shown in the figure above. Each actuator is capable of supporting a 2 kN load and consists of a servomotor driving a satellite roller screw with a positional resolution of 250 nm. Actuator range is 5 mm, providing coarse as well as precision positioning and must park the load and remain fixed with locational accuracy and repeatability of +/- 250 nm. When parked, the motor is deenergized and the position is locked via a failsafe compact servomotor brake which must be energized to release. The roller screw assembly is supported by a preloaded crossed roller bearing. A 17-bit rotary encoder with a resolution of 3.8 nm/bit is backed up by a linear encoder with 50 nm resolution. Limit and power cutoff switches protect the actuator against overrun.

The precision alignment capability will be demonstrated early in the project by building a test stand [2] that mimics the SCU cryostat, cold mass, and alignment system. The test stand will follow a phased approach to demonstrate cold mass positioning first in air, then evacuated, and finally with the cold mass at operational temperature. Alignment targets on the cold mass will confirm positional accuracy with in-vacuum laser interferometers mounted to the inside of the vacuum chamber. The test stand may also support additional measurement studies of the beamline elements to minimize cryostat design risk.

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