Development of a superconducting undulator for the APS

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Abstract. As the western hemisphere’s premier x-ray synchrotron radiation source, the Advanced Photon Source (APS) continues to advance the state of the art in insertion device technology in order to maintain record high brightness, especially in the hard x-ray wavelength region. Due to the unique bunch pattern used for normal APS operations and its ultimate capabilities, the APS has chosen superconducting technology for its future hard x-ray undulator sources. In the last several years, the APS in collaboration with the Budker Institute of Nuclear Physics has been developing the technology for planar, small-period superconducting undulators (SCUs). These developments include the design and construction of several prototypes and the construction of the necessary mechanical, vacuum, and cryogenic infrastructure at the APS site. Several prototypes of the SCU magnetic structure have been built and tested. The first SCU is assembled and will be installed in the APS storage ring at the end of 2012. Expected SCU performance in terms of x-ray brightness should noticeably exceed that of existing APS undulators. Immediately after commissioning, the SCU will be used at APS Sector 6 as the radiation source for high-energy x-ray studies.

1. Introduction
Superconducting technology has successfully been employed in building both wiggler and undulator insertion devices for synchrotron light sources [1, 2]. Superconducting undulators can potentially outperform permanent magnet or hybrid devices in terms of peak magnetic field at small period length (near 15 mm), thereby resulting in higher photon fluxes at higher energies.

The Magnetic Devices Group of the Advanced Photon Source together with staff from Budker Institute, Novosibirsk, are working on the first full-scale superconducting undulator, SCU0. This device employs a 42-pole magnetic structure developed at the APS during the feasibility study. It will then be replaced with a 1.14-m-long magnet in the second undulator, SCU1.

The parameters of the SCU0 and SCU1 are listed in table 1.
Table 1. SCU0 and SCU1 parameters.

|                      | SCU0       | SCU1       |
|----------------------|------------|------------|
| Electron energy      | 7.0 GeV    | 7.0 GeV    |
| 1st harmonic photon energy | 20-25 keV  | 20-25 keV  |
| Period length        | 16 mm      | 16 mm      |
| Magnetic gap         | 9.5 mm     | 9.5 mm     |
| Magnetic length      | 0.33 m     | 1.14 m     |
| Cryostat length      | 2.063 m    | 2.063 m    |

2. Undulator design and fabrication

2.1 Cryostat design
The design of the SCU0 cryostat is based on the concept developed at Budker Institute for building superconducting wigglers [3]. The main components include a cold mass, two radiation shields, and a vacuum vessel. A general view of the undulator cryomodule is shown in figure 1, while the internal structure is shown in figure 2. A superconducting magnetic assembly together with a liquid helium tank (LHe) and LHe piping comprise a cold mass that is kept at 4 K. A stainless steel frame holds both the magnet and the LHe tank and is supported inside the vacuum vessel by Kevlar strings.

2.2 Magnet
The undulator magnetic field is created by a pair of identical magnets separated by a gap where a beam vacuum chamber is accommodated. Each magnet, or jaw, contains a set of racetrack-type superconducting coils separated by magnetic poles, with current flowing in opposite directions in adjacent coils. A round 0.75-mm NbTi wire is wound into precisely machined rectangular grooves between the poles. A special winding scheme was developed that allowed continuous winding of the structures.

Each magnetic jaw contains a main coil and two correction coils that are wound on the top of the main coil in the last two end grooves. The correction coils are separately powered and are used for tuning the magnetic field integrals. The operating current for the main coil ranges from 200 A to 500 A to produce the 0.4–0.64 T field on axis required to produce 25- to 20-keV photons in the first harmonic.

Figure 1. Drawing of the cryomodule for the superconducting undulator.

Figure 2. Cutaway view of the inside of the cryostat.
Several magnet prototypes were built and tested in a LHe bath cryostat in order to verify the magnetic design and the manufacturing technique. Field errors as small as 2 degrees rms were achieved without applying any magnetic shimming—a standard technique used for tuning the magnetic performance of conventional undulators. Such a remarkable field quality was possible due to a precise winding onto the magnetic structure that was machined and assembled with the precision of less than 20 μm.

Finally, the magnetic structure for the SCU0 was fabricated and tested before installation into the cryomodule.

2.3 Cooling system
The cooling system design is based on a concept of thermal insulation of the beam vacuum chamber from the superconducting magnet. In such a scheme the heat generated by the electron beam is prevented from reaching the superconducting coils and is intercepted by the two lower cryocoolers shown in figure 3. These cryocoolers hold the beam chamber at approximately 20 K and are also used for cooling two radiation shields to 20 K and 60 K.

![Figure 3. Cooling system structure.](image1.png)

The superconducting coils are cooled by liquid helium that flows through the channels in the magnetic cores. The helium circulation is a gravity-driven in a thermosyphon loop comprised of a LHe tank, magnet cores, and LHe piping. Assembled cold mass is shown in figure 4.

![Figure 4. Assembled cold mass.](image2.png)

2.4 Cryomodule assembly
The components of the SCU0 cryomodule were manufactured by several companies according to the detailed design developed at the APS. The cryomodule was then assembled at the APS. Figures 5 and 6 show the cryomodule during the different stages of the assembly.

![Figure 5. Partially assembled cryomodule.](image3.png)

![Figure 6. Fully assembled cryomodule.](image4.png)
3. Cold test
After the assembly was completed, the device did pass a cold test. The system demonstrated a stable performance in accordance with the design specifications. The magnet quenched at the current that was about 30% higher than the maximum operating current of 500 A. The magnetic field was then measured with a specially developed horizontal measurement system [3]. The measured field profile and the first and the second integrals are shown in figures 7, 8 and 9. The phase errors value of about 1° is well below the specifications requirement.

![Figure 7. Measured on-axis $B_y$ field.](image1)

![Figure 8. Measured first field integral.](image2)

![Figure 9. Measured second field integral.](image3)

4. Conclusions
The superconducting undulator is built and tested at the APS with the goal to install the device into the APS storage ring at the end of 2012.

5. References
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