DEVELOPMENT STATUS OF A SUPERCONDUCTING UNDULATOR FOR THE ADVANCED PHOTON SOURCE (APS)*

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Abstract

A number of prototype magnetic structures for a superconducting undulator have been successfully built and tested. The field quality of a test undulator was measured in a vertical dewar; the rms phase error was 7.1° at the maximum design current with no phase shimming applied. The Advanced Photon Source (APS) specification for overall trajectory was met using the end compensation coils. The design of a cryostat to hold the undulator for installation in the APS storage ring is nearing completion, and a cryogenic measurement facility to measure the magnetic field of the completed undulator is under development. Several Hall probes have been calibrated at cryogenic temperatures.

INTRODUCTION

A frequent request of Advanced Photon Source (APS) users is for more photons with some specific photon characteristic. In order to satisfy one such request, for photons in the 20-25 keV range, the possibility of building a short-period superconducting undulator (SCU) has been under investigation. After many test prototypes using both NbTi and Nb_3Sn conductor, NbTi was chosen, at least for the first undulator. While the higher critical current of Nb_3Sn is appealing, and short test undulator sections were successfully built by several institutions [1-3], it was decided not to tackle the additional challenges presented by Nb_3Sn just yet.

As has been reported previously [4], a period length of 1.6 cm was chosen. A beam-stay-clear of 7 mm vertically and +/- 18 mm horizontally is required if the maximum single-bunch beam current is to remain largely unaffected by the presence of the SCU. Allowing space for a beam chamber results in a magnetic gap of 9.5 mm; this period length gives a good margin for the operating current while achieving the desired photon energy tuning range.

PRODUCTION AND MAGNETIC MEASUREMENT OF CORES

After successful tests of 10-pole prototypes of the magnetic structure [5], 42-pole prototypes were fabricated, wound, and potted in epoxy. They were tested in a vertical dewar and, after a few training quenches (5 for one prototype, less than 20 for another) reached a maximum current that was, as expected, well above the current needed for the required tuning range.

As was discussed in Ref. 5, a magnetic structure is assembled from individual iron poles and a central core with slots for the poles. The central core can be made from Al or iron. The field on the beam axis that results from a given current is higher for the iron core, but an Al core offers the possibility of better thermal conductivity. A pair of prototype magnet coils with an Al core was assembled and tested, and a pair of Fe-core coils was assembled and tested. Both performed satisfactorily. Figure 1 shows a pair of 42-pole coils assembled relative to one another as they will be in an undulator, ready to be inserted into a vertical dewar. For these tests, instead of having a beam vacuum chamber between the two coils, a tube was inserted to serve as a guide to a cryogenic Hall probe so that measurements of the field on the beam axis could be made.

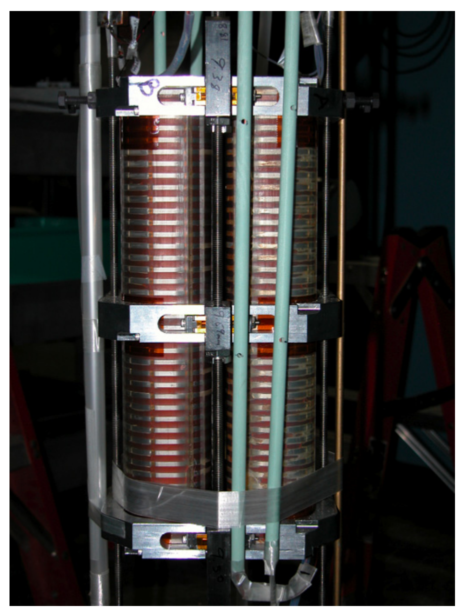

Figure 1: Two 42-pole magnet cores, assembled into a prototype magnetic structure, ready for liquid He immersion testing in a vertical dewar.

The measurements were made using a cryogenic Hall probe obtained from Arepoc [6]. The probe was calibrated using NMR probes in the APS calibration magnet, with the Hall probe itself mounted in a custom-made cryostat designed to place and properly orient the cold Hall probe

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in the gap of the calibration magnet. This setup allows calibration to be done as a function of temperature. We were concerned about the reproducibility of the calibration between successive cool-downs and discussed the issue with Arepoc, so Arepoc cycled the temperature of one of their probes many times and found the calibration to be reproducible. We confirmed that the calibration reproduced after repeated thermal cycling.

A concern, shared by many considering SCUs, is achieving the quality in the on-axis field that is required for strong high harmonics in the photon spectrum. A poor rms phase error may not impact the first harmonic strongly, but negatively affects higher harmonics, more so the higher the harmonic. The phase errors measured for both of the assemblies, while leaving some room for improvement, were reassuringly small. Figure 2 shows the magnetic field profiles measured for the Fe-core assembly, at 200 and 500 A, the (approximate) currents needed for 25- and 20-keV photons, respectively. The rms phase errors at these two currents were 3.3° and 7.1°, respectively, despite an error in the epoxy potting process that resulted in a deformed pole at one end. When the measurement was repeated with the Al-core assembly (and no potting error), the rms phase errors were 3.0 and 5.0 degrees. As a result, no field shimming is planned for the first complete 42-pole undulator.

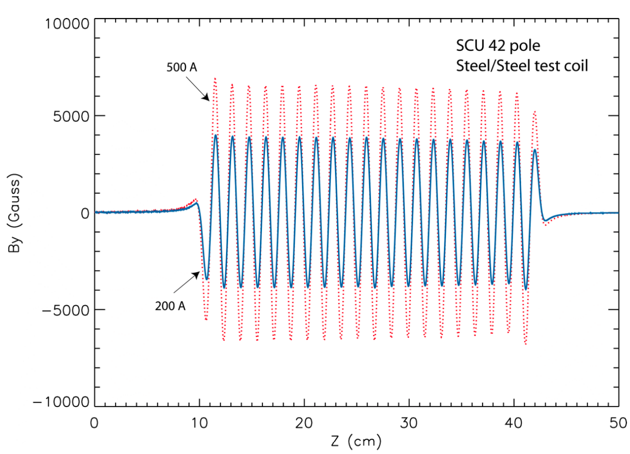

Figure 2: Measured magnetic field profiles for the assembled magnetic structure, at the currents needed for 20- and 25-keV photon production.

There will be end-field correction, however. A smooth entrance and exit of the beam into the undulator requires a systematic reduction in the field strength under the last two poles at each undulator end. The end field is achieved by reducing the number of windings in the last two grooves [5]. The ideal number of turns in those grooves for an optimum end field configuration is not an integer, however, so some end-field correction is needed. With fewer main coil turns in the last groove, there is space for a separate correction coil as well. These separate coils have been included in the winding pack and can be powered separately to provide the correction needed.

CRYOSTAT

With the production of the magnetic cores well underway, it was time to focus on the design of the cooling system and cryostat to hold the magnetic jaws and keep them cold. This task is benefiting tremendously from collaboration with the coauthors from the Budker Institute. The design is based on the Budker Institute design for superconducting wigglers that were built for a number of institutions worldwide.

The desire was for a cryosystem that would not need frequent liquid He refills, so the use of cryocoolers was preferred. However, the system needs to stay cold for some time even if, say, the power were to be lost. The solution is to incorporate a liquid He tank in the cryostat and to use a thermal siphon system to flow the He through channels in the center of the magnetic cores. A cryocooler-powered recondenser in the He tank reliquifies evaporated He, making it a closed system. In the most recent wiggler systems by Budker, the He loss is minuscule, and the devices can operate for a period of months to a year between He refills.

Estimates of the various contributions to the heat load due to the stored beam are shown in Table 1. This heat is deposited into the beam chamber. In order to prevent this heat from reaching the superconductor, the chamber will be thermally isolated from the superconducting coils, and separately cooled by the two cryocoolers mounted to the bottom of the cryostat, shown in Fig. 3. These cryocoolers will hold the beam chamber at approximately 20 K and will also cool the 20 K and 60 K radiation shields.

Table 1: Beam-Related Heat Loads

Heat source	**Heat load on 2-m-long beam chamber**
Image current	2.44 W (at 100 mA) 4.88 W (at 200 mA) [7]
Synchrotron radiation from upstream magnets	~0.1 W (for wide chamber) [7] (40 W for narrow chamber)
Electron cloud	2 W [7]
Wakefield heating in the beam chamber transition	0.093 W [7]
Injection losses	40 W (injection accident) 2 W (non-top-up mode) 0.1 W (normal top-up mode) [8]
Max heat load	~45 W (injection accident) ~6.6 W (non-top-up mode)

Two additional cryocoolers will be mounted to the top of the cryostat. One will cool the current leads, the other will cool the recondenser, and both will cool a 60 K radiation shield. A listing of the heat loads and the temperatures at which the heat loads will occur is shown in Table 2, along with the total cryocooler cooling capacity of the four cryocoolers. A cut-away view of the assembled cryostat is shown in Fig. 3.

Table 2: Heat Loads (all in W)

Heat source	Heat load @ 4 K	Heat load @ 20 K	Heat load @ 60 K
Beam		10	
Radiation	0.0116	1.21	4.2
Conduction through:			
beam chamber bellows			1.4
beam chamber supports	0.08		
He vent bellows	0.006	0.07	0.9
He fill pipe	0.012		
cold mass support	0.005		
radiation shield supports		1.2	5.6
Current leads:			
Total, current off	0		44
Correction coil leads only, 100 A	0.12		22
Main coil leads only, 500 A	0.45		52
Total at I=500 A	0.685	12.5	86.1
Cooling capacity	3	40	224

CONCLUSION

The detailed drawings of the cryostat are being completed and fabrication will begin in the coming months. The intent is to install the device in early 2012, after extensive testing.

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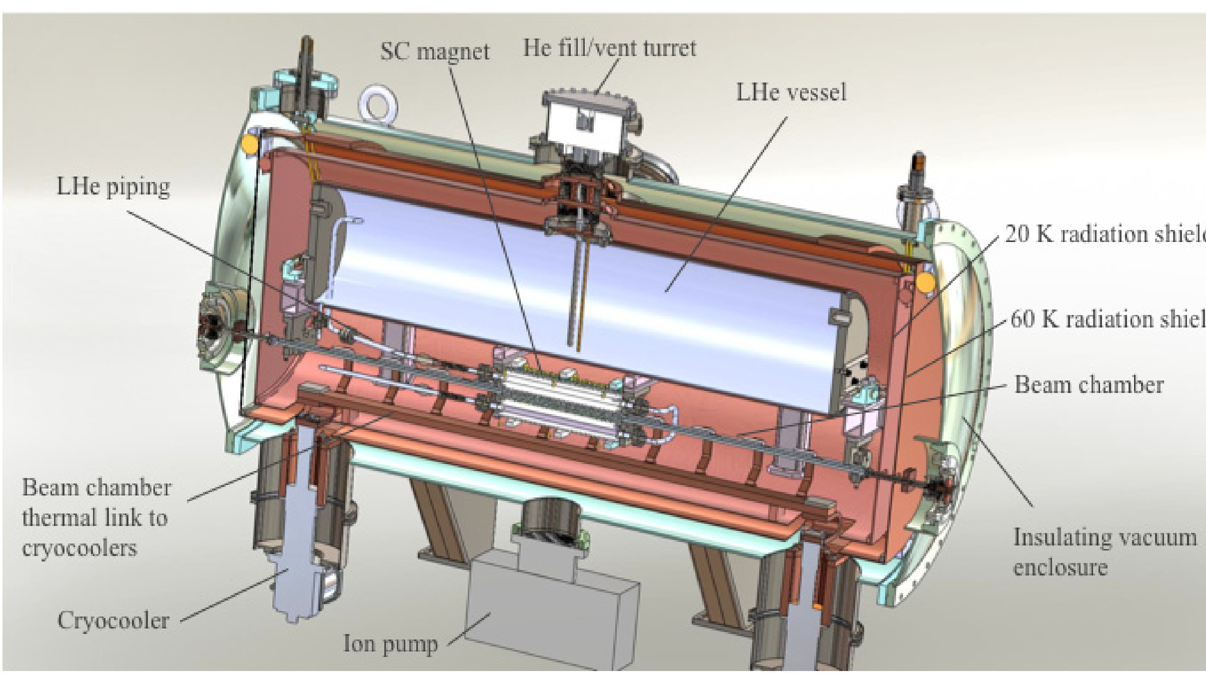

Figure 3: Cutaway view of the inside of the cryostat. It is designed to hold a 1.1-m-long SCU, but is shown holding the initial 42-pole-long magnetic structure. Two cryocoolers will be mounted to the bottom of the cryostat. Two additional cryocoolers will be mounted near the top of the cryostat but are not shown in this view. The same cryostat design will also be used for the second undulator, which will have a 1.1-m magnetic length.