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CRYOGENIC TESTING AND INITIAL PERFORMANCE OF A HELICAL SUPERCONDUCTING UNDULATOR AT THE APS*

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Abstract

A helical superconducting undulator (HSCU) has been installed and is presently operational at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL). We describe the final assembly and cryogenic test program which led to successful operation, representing the culmination of a two-year development effort. Details of the cryostat and cryogenic system design are presented along with as-installed performance data and a comparison with design expectations.

INTRODUCTION

The HSCU is an insertion device producing circularly polarized x-ray radiation at the APS. A period length of 31.5 mm gives 38.5 oscillation periods over the 1.21-meter magnetic length of the device [1].

The magnet operates at a temperature of 4.2 K, producing a field of 0.41 T. Refrigeration is provided by four Sumitomo RDK-415D cryo-coolers. The system operates in zero-boil-off mode, with about 0.4 W of excess 4.2 K cooling power dissipated by an electric heater. The cryocooler first stages refrigerate both the thermal radiation shield and the electron beam vacuum chamber. Figure 1 shows the device installed in the 7-ID location of the APS storage ring (SR).

Figure 1: HSCU installed in the APS storage ring.

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CRYOGENIC TEST PROGRAM

The HSCU cryostat components [2] were fabricated in parallel with the magnet and beam vacuum chamber development program. Major cryostat subsystems include the cold mass (including magnet, beam vacuum chamber and liquid helium reservoir), cryocooler/current lead turret assemblies, thermal radiation shield, and insulating vacuum vessel. Figure 2 shows a cross-section of the HSCU while Figures 3 and 4 show some key subsystem assemblies.

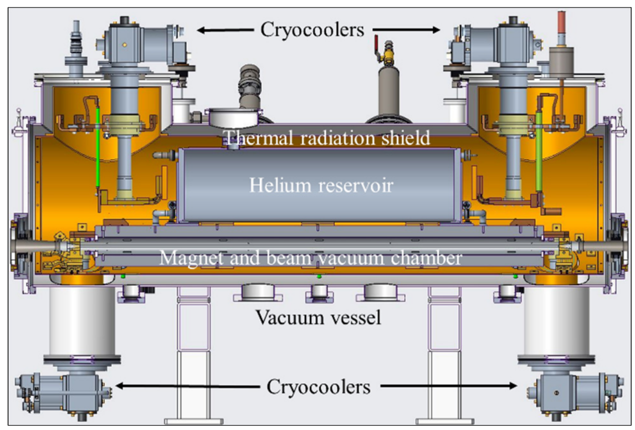

Figure 2: HSCU cross-section.

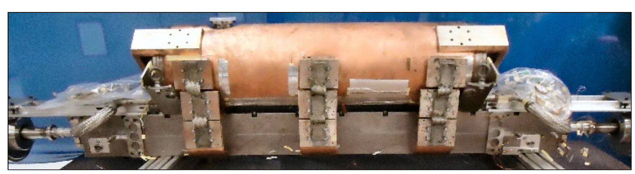

Figure 3: HSCU cold mass assembly including magnet, beam vacuum chamber, and liquid helium reservoir.

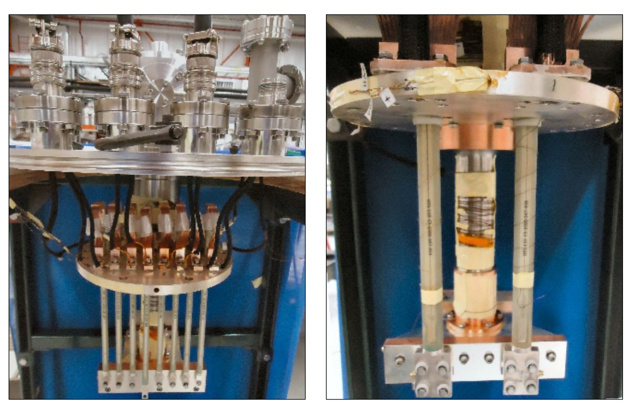

Figure 4: Cryocooler/corrector current lead package (left); cryocooler/main current lead package showing high-temperature superconductor (HTS) leads (right).

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Off-line Performance

Heat loads to the magnet and the thermal shield vary according to operating conditions in the APS SR while the available cooling power is a constant 2.2 W at 4.2 K. Static conduction and radiation dominate the 4.2 K heat load while dynamic effects due to energizing the magnet and circulating e-beam through the vacuum chamber constitute the remainder. Table 1 lists the operating conditions and the corresponding 4.2 K heat loads.

Table 1: HSCU 4.2 K heat loads

Heat Source	**Heat Load [W]**	**Excess Cooling Power [W]**
Static alone	1.55	0.65
Static + 100 mA e-beam	1.72	0.48
Static + 450 A magnet current	1.62	0.58
Static + e-beam + magnet	1.79	0.41

Initial cryostat commissioning took place without the magnet and beam chamber while fabrication of these components proceeded. This allowed for early identification and correction of multiple static heat load and cooling system anomalies including gaps in thermal shielding, excessive conduction through the cold mass supports, and lower than expected thermal conductance between the cryocoolers and the 4.2 K load.

Final assembly began when the magnet/beam vacuum chamber assembly became available. Device commissioning proceeded with magnet training, field mapping [1] and quench studies. The magnet stores 3.5 kJ of energy at 450 A. Quench response is passive, resulting in a rise in both magnet temperature and helium reservoir pressure (see Figure 5). Rate of recovery is determined by the available excess cooling power, taking 1.5 hours to return to nominal operating conditions.

The heat flux to the beam chamber due to circulating 100 mA e-beam exceeds 20 W. This load is cooled by thermally linking the shield to the ends of the vacuum chamber where they emerge from the magnet bore. Since only the ends are cooled, the chamber adopts a parabolic temperature profile under uniformly distributed e-beam heating. There remains a small residual conduction load to the magnet (shown in Table 1) through the chamber support pins. The temperature profile and resulting 4.2 K conduction load was measured by energizing heaters imbedded in the vacuum chamber. Figure 6 shows the resulting temperature profile in the beam vacuum chamber for several heat loads.

INSTALLED PERFORMANCE

The device was installed in the downstream half of the Sector 7-ID straight section during the Dec2017/Jan2018 maintenance period. Figure 7 shows the subsequent cool-down, after which the 30 L helium reservoir was filled to 50% by volume via liquid helium transfer.

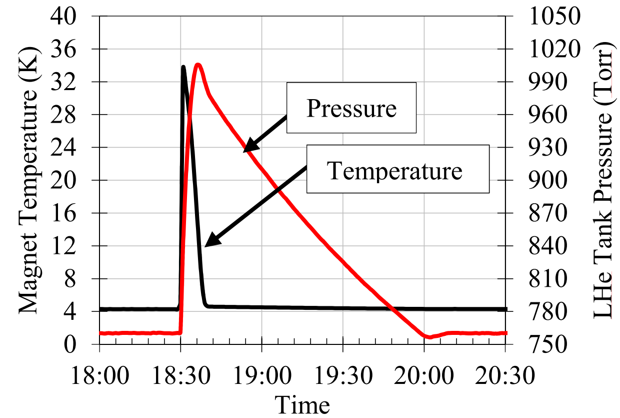

Figure 5: HSCU quench recovery. Magnet temperature spikes comparatively quickly while reservoir pressure decreases gradually over 1.5 hour.

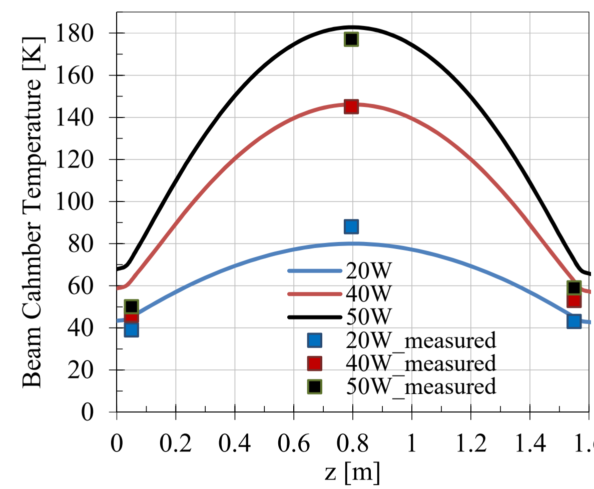

Figure 6: Beam vacuum chamber temperature along chamber length for three different heat dissipation levels. Solid curves are calculation, points are measured data.

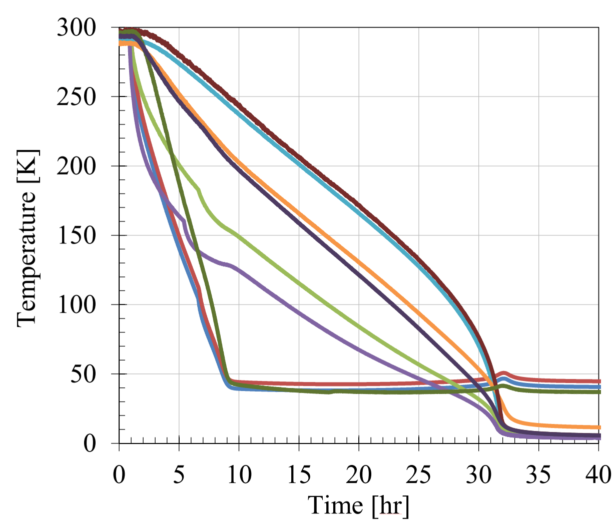

Figure 7: HSCU temperatures vs. time during cool-down. Thermal shield and beam vacuum chamber equilibrate rapidly compared to the 4 K elements due to the corresponding masses and available shield/4 K cooling powers.

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Initial checkouts before e-beam restoration included magnet re-training up to 110% of the nominal 450 A operating current and verification of extended stable operation at 450 A. Once the SR tunnel was secured, machine studies began by gradually increasing e-beam current with the HSCU unpowered. During the studies, magnet temperatures approaching 7 K were observed. These temperatures correlated with e-beam current and suggested the presence of an unexpected, e-beam-related 4.2 K heat source. Figure 8 shows the correlation.

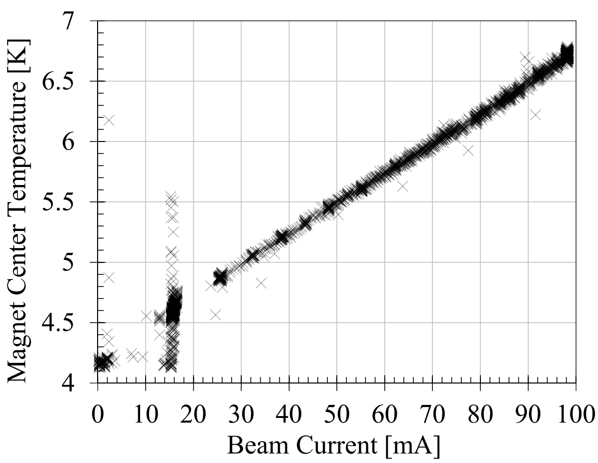

Figure 8: Magnet temperature plotted against circulating e-beam current during initial machine start-up.

The APS Accelerator Operations and Physics (AOP) Group identified the heat source to be hard x-rays generated by the dipole bending magnet (BM) at the 7-BM location immediately upstream of 7-ID and scattered in the wall of the beam vacuum chamber. This had been flagged as a potential issue during device development and installation planning. The solution involved an e-beam orbit correction through the BM. This orbit bump shifted the hard x-rays away from the vacuum chamber aperture, greatly reducing the heat load. This issue is described in detail in [3].

Excess refrigeration capacity is measured directly by the power dissipated in a heater which regulates the helium reservoir pressure to 1 bar. Without this heat load the system cools below 4.2 K until the actual heat load matches the available cooling power in accordance with the cryocooler performance load map. During normal operation, average heater power is constant as long as the heat load and the cooling power are constant.

CONCLUSION

A helical superconducting undulator has been installed and is successfully operating as an insertion device in the APS storage ring. The primary cryogenic components of the device were assembled and incrementally tested off-line to sort out issues before proceeding to final device assembly with the magnet and beam vacuum chamber. Off-line magnet power tests and magnetic measurements confirmed expected performance. Installation was straightforward although commissioning with circulating e-beam revealed an unexpected heat source. The problem was solved with an e-beam orbit correction. A heater supplements the total heat load to match the available cooling power at 4.2 K and serves as a sensitive indicator of system performance.

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