**Thermal Analysis of Superconducting Undulator Cryomodules**

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**Abstract**

A cryocooler-cooled superconducting undulator (SCU) has been operating in the Advanced Photon Source (APS) storage ring since January of 2013. Based on lessons learned from the construction and operation of SCU1, a second superconducting undulator (SCU) has been built and cold tested stand-alone. An excess cooling capacity measurement and static heat load analysis show a large improvement of cryogenic performance of SCU1 compared with SCU3. ANSYS-based thermal analysis of these cryomodules incorporating all of the cooling circuits was completed. Comparisons between measured and calculated temperatures at the three operating conditions of the cryomodule (static, beam heat only, beam heat and magnet current) will be presented.

**1. Background**

**415D**

- The magnetic structure and the beam chamber are cooled *independently*
- Outer Shield: the warm end of magnet leads, the beam chamber and the outer shield are cooled by the 1st stage of four cryocoolers
- Inner Shield: the beam chamber and the inner shield is cooled by two bottom cryocoolers (RDK-408S)
- Magnet Circuit: the magnet and LHe tank is cooled by two top cryocoolers (RDK-415D)

**408S**

- LHe Tank
- Magnet
- Beam Chamber

**2. Numerical Analysis**

**Load Map of 415D**

- 2nd Stage Cooling Power[W]
- 2nd Stage Temperature (K)

- Top of the magnet lead and the end of the beam chamber is @300K
- The temperature dependent cooling power based on the load maps were applied on the eight cold head surfaces
- Additional Heat inputs (Kevlar, Instrumentations etc)

**3. SCU0 Analysis and Measurement**

**SCU0 Analysis and Measurement**

**Summary of Heat Load of SCU0**

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>HTS Main</td>
<td>0.218</td>
<td>0.218</td>
<td>0.280</td>
</tr>
<tr>
<td>HTS Connection</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
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<tr>
<td>Kevlar support</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
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<tr>
<td>He shield</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Inner Shield</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
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<tr>
<td>Outer Shield</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Magnet (trim heater on)</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>Magnet (trim heater off)</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
</tbody>
</table>

**Heat Load**

- Measured trim heater power is subtracted from applied cooling power to yield total static heat load.

**4. SCU1 Analysis and Measurement**

**Summary of Magnetic Circuit heat load for SCU1 (Mode 1)**

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>HTS Main</td>
<td>0.212</td>
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<td>0.212</td>
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<tr>
<td>HTS Connection</td>
<td>0.064</td>
<td>0.064</td>
<td>0.064</td>
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<tr>
<td>Kevlar</td>
<td>0.032</td>
<td>0.032</td>
<td>0.032</td>
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<tr>
<td>Beam chamber support</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
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<tr>
<td>Dewar Neck</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
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<tr>
<td>Total static heat load</td>
<td>0.44</td>
<td>0.44*</td>
<td>0.49*</td>
</tr>
</tbody>
</table>

**Heat Source**

- *measured trim heater power is subtracted from applied cooling power to yield total static heat load.

**5. Future Optimized Cryomodule Designs**

- Use four 415D’s and eliminate the inner thermal shield. In this model, the electron beam chamber is thermally intercepted by the first stages of the cryocoolers along with the single thermal shield.
- Higher beam chamber temperature (about 35 K compared to 12 K) and larger conduction heat leak between the chamber and the magnet circuit.
- However, the 4K cooling power is doubled, which more than offsets the added load.

**Comparison of model results for an optimized design with SCU1 design**

**Number of cryocoolers**

- SCU1: 2
- SCU0: 4

**Cooling power [W]**

- SCU1: 0.54
- SCU0: 1.9

**Heat Load [W]**

- SCU1: 0.67
- SCU0: 1.22

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