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DEVELOPMENT OF A CRYOGEN FREE MgB2 HIGH TEMPERATURE SUPERCONDUCTING UNDULATOR

O. Chimalpopoca[†], R. Agustsson, Y. C. Chen, A. Schillaci, RadiaBeam, Santa Monica, USA

Abstract

RadiaBeam is designing and manufacturing a 15-mm period, 1.15 T field superconducting undulator. Realizing these parameters require a small gap, on the order of 5 mm. This small gap imparts a thermal management challenge due to heating from resistive walls, wakefields, upstream dipoles, and particle losses which is challenging to overcome with NbTi or NbSn3 wires without the use of liquid helium. Further, to reduce operating costs and reliance on liquid helium infrastructure, this undulator is designed to run off cryocoolers. In order to provide sufficient thermal overhead for cryocooling capacities, we will utilize Magnesium Diboride (MgB2), a metallic superconductor with a transition temperature at around 39 K. Thermo-mechanical engineering design studies and production plans of our prototype will be presented.

INTRODUCTION

Superconducting undulators (SCU) are rapidly emerging as very attractive insertion device technologies for synchrotron light sources and X-ray free-electron-lasers (FELs) [1-3]. The superconducting undulators outperform permanent magnet undulators in terms of undulator peak field [4] in most practical geometries. The performance of SCUs critically depends on the superconducting material/wire. The most explored superconducting magnet material to date is NbTi, but there are also considerable efforts to develop Nb3Sn wire [3, 5] that would allow ~ 20-30% further improvement and could further extend the SCU technology range towards shorter period undulators.

However, the development of SCUs that can stably operate at shorter periods and higher peak fields require designs with smaller vacuum gaps. These smaller gaps devices can be subjected to higher heat loads due to increased sensitivity to resistive wall impedances, beam losses, geometric impedance contributions and synchrotron radiation heating. If the operating temperature of SCU could be increased to 10-15 K range, a simpler cryogenic system with much larger cooling capacity could be utilized to mitigate the beam induced heat effects; however, this requires the use of different types of the superconducting wire.

In response to this need for higher operating temperature SCU requirements, RadiaBeam is developing MgB2 - based SCUs, an idea proposed by Dr. Toshi Tanabe [6]. MgB2 is a metallic superconductor with a transition temperature of around 39 K, significantly higher than NbTi or Nb3Sn. The higher anticipated operating temperatures have allowed for the use of a two staged pulse tube cryocooler. Fig. 1 shows the design of the 0.3m long prototype MgB2 SCU that RadiaBeam is developing.

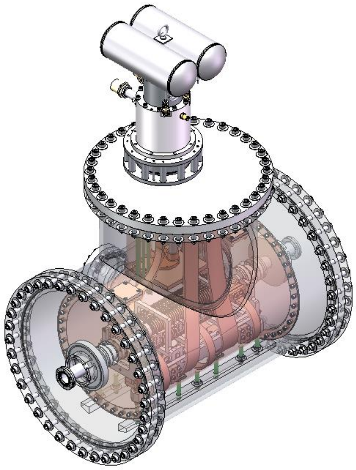

Figure 1: Advanced engineering design of the MgB2 wire based undulator assembly.

THERMO-MECHANICAL DESIGN

As previously mentioned, RadiaBeam's 0.3m long prototype MgB2 SCU is cooled using a two staged pulse tube cryocooler. More specifically, the Cryomech PT420's two stage system will be used to keep the SCU bellow critical temperature.

The two cooling stages of the cryocooler have been split to reduce the thermal load on the SCU. The first stage of the cryocooler is responsible for the cooling of the radiation shield, ultra high vacuum (UHV) chamber, and SCU strongback. The goal is to reduce the radiative heat load the SCU coils will see from the surrounding components during operation by keeping them relatively cold. Shown in Fig. 2 is the resulting temperature of the first stage cooled components.

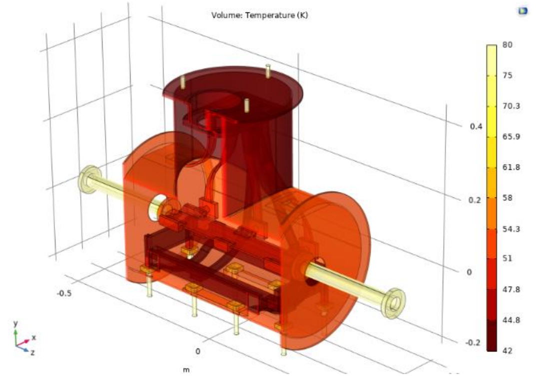

Figure 2: Temperature map for the first stage assembly.

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†chimalpopoca@radiabeam.com

The analysis considered:

- The expected first stage flange temperature given the cooling capacity of the cryocooler.
- A radiative heat load from the surrounding room temperature vacuum vessel.
- Expected resistive wall heating from the UHV Chamber.
- Conductive heating paths from the 300K supports

The resulting radiative shielding temperature is expected to be about 45k-55k. The UHV chamber and the strong back support structure are both expected to reach temperatures of about 60K.

Stage 2 of the cryocooler is responsible for the cooling of the SCU coils. The results from the stage 1 multiphysics simulation shown in Fig. 2 were used to provide the ex-pected radiative heat load from the surrounding cooled components onto the SCU coil surfaces. Shown in Fig. 3 are the resulting temperatures of the second stage cooled components.

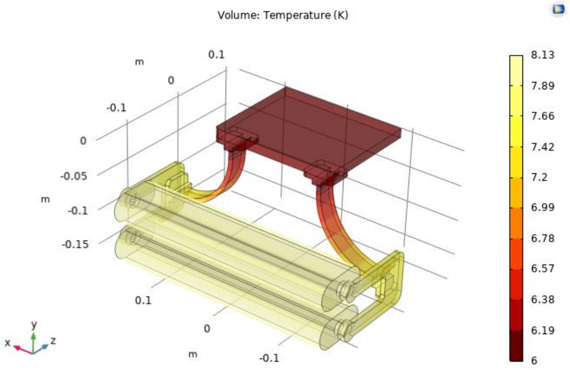

Figure 3: Temperature map of the second stage assembly.

The analysis considered:

- The expected second stage flange temperature given the cooling capacity of the cryocooler.
- The radiative heat load from the components fist stage cooled components.
- The conductive heat loads expected from tie in points to the strong back support structure.

As a result, the predicted steady-state temperature for the MgB2 superconductive magnet is around 8 K which makes us confident about the expected performances of the SCU.

UNDULATOR PRODUCTION PLAN

Production of the primary undulator assembly can be split into two parts: the production of the UHV chamber; the production of the SCU coils.

The UHV chamber that will be used to transport the beam through the magnet will need to fit within the 5mm magnetic gap of the SCU coils. The UHV chamber has been designed to be assembled through a series of brazing and welding operations. The UHV chamber can be seen in Fig. 4. Pump down of the chamber to 1E-9 Torr is expected to happen through pumps placed along the beamline outside of the room temperature cryostat vessel.

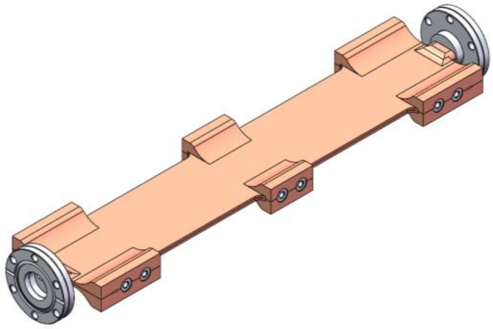

Figure 4: Fully assembled UHV chamber.

To ensure that the deflection experienced by the chamber walls is small enough to not affect the beam, static simulations of the chamber were conducted. The chamber internal volume was pressurized to 1E-9 Torr. The external profile of the chamber was pressurized to atmospheric pressure to capture the expected installation conditions. Under these load conditions, we noted that the deflection was negligible as can be seen in Fig. 5. Ongoing studies are being con-ducted to ensure thermal strains do not have yielding ef-fects on the copper structure.

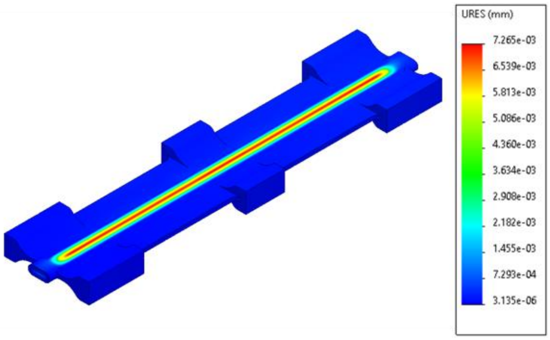

Figure 5: UHV Chamber expected deflection.

The production of the SCU coils begins with the SCU core shown in Fig. 6.

Figure 6: MgB2 undulator magnet half. Magnet core consists of a copper conductive cooling rod, 1006 carbon steel magnet core, vanadium permendur yokes (colored in blue for clarity), and the main coil

The main conduction path for cooling the coils is through the copper core. Due to the large temperature changes that the SCU halves will see during cool down, it

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is important to ensure that good thermal contact is preserved. We are planning to metallurgically bond the copper conductive cooling rod to the 1006 carbon steel magnet using a silver based brazing alloys. The bonded magnet core is then mounted onto the coil winder to begin winding process. To avoid splicing the conductor, the coils is wound continuously. Fig. 7 shows the resulting 0.3m long coil.

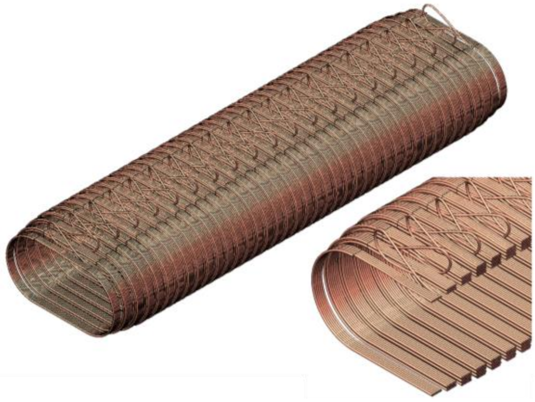

Figure 7: MgB2 super conducting undulator coil.

As MgB2 is produced through a ‘wind and react’ process, after the coil is wound, it is heat treated. At this stage, the conductor is brittle and must be encapsulated in epoxy to protect it from damage during installation. Encapsulation also provides a thermal path for coil cooling. The encapsulated coils are then installed onto the welded strongback frame. The fully assembled undulator can be seen in Fig. 8.

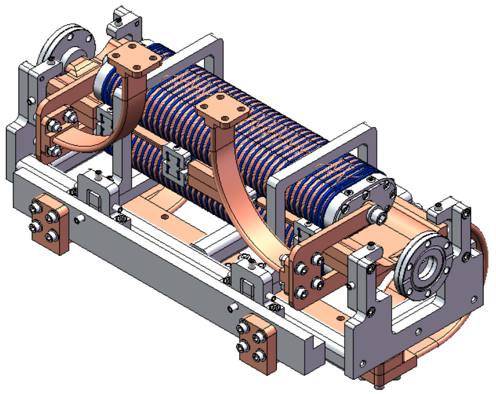

Figure 8: Fully assembled undulator assembly.

PROCESS DEVELOPMENT

As mentioned above, the brittleness of the MgB2 material require specific process sequencing in order to be suitable for fabricating superconductive magnets. RadiaBeam is executing tests on the wind-&-react process through prototype coils manufactured with different winding tension and temperature reacting cycles to validate the resulting electrical properties in a cryogenic test bed picture in Fig. 9. In parallel, we are validating inter subcoil transition geometries and the effectiveness of the conducting cooling rod previously mentioned.

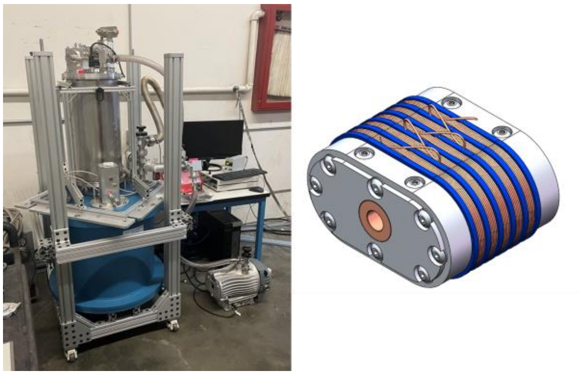

Figure 9: Cryogenic test bed shown on the top. Shortened version of the undulator coil shown on the bottom.

CONCLUSION

The development of SCUs that can stably operate at shorter periods and higher peak fields require designs with smaller vacuum gaps. This results in the need for higher temperature SCUs. In response to this need for higher operating temperature superconducting materials compatible with SCU requirements, RadiaBeam is developing MgB2 -based SCUs. This new SCU allows for the use of two staged pulse tube cryocoolers, significantly reducing the capital costs and complexity of cooling needs. RadiaBeam is in the process of testing coil geometries and winding processes to produce a 0.3m long SCU, with the objective of expanding the design to 2.0m in the future.

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