A cryostat for a 6 T conduction-cooled, no-insulation multi-pancake HTS solenoid

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Abstract. There is a growing requirement for high-field (>20 T) magnets capable of continuous operation, driven by the needs of both fundamental research and technological advance, particularly in application to an eventual pilot plant for magnetic confinement fusion. Even with HTS windings, such magnets will still require cryogenic cooling, and liquid helium (LHe) immersion, the typical solution to this problem, adds significantly to the operating expenses of such facilities. This reality makes cryogen-free cooling systems a necessity in future high-field magnet systems. The Princeton Plasma Physics Laboratory (PPPL) is exploring conduction-cooling systems of HTS pancake solenoids for a scanning tunneling microscopy (STM) facility at Princeton University, and potentially also for the central solenoid of the Fusion Nuclear Science Facility (FNSF). To these ends, PPPL is designing a cryostat to evaluate the thermal stability of a 5-6 T, 30 double-pancake (DP) REBCO insert coil of 40 mm ID / 70 mm OD, and smaller prototypes, operated in self-field with conduction cooling provided by a 2-stage GM cryocooler. The current design is expected to achieve 1st and 2nd stage temperatures of 44 K and 4-10 K, respectively, with the resistivity of DP-DP solder joints being the principal source of uncertainty in 2nd stage temperature predictions.

1. Introduction
Magnets capable of generating 20-30 T and operating in background fields of similar strength will be required for pure and applied research in several disciplines, including particle physics [1], electron microscopy [2] and magnetic confinement fusion. For context, the ITER tokamak, intended to be the first reactor to achieve net energy generation through controlled fusion, will generate 5.3 T toroidal fields on plasma major radius, but will experience peak axial fields of 12.8-13.5 T on its central solenoid with operating currents up to 46 kA [3]. By comparison, future HTS-based fusion experiments such as SPARC and the Fusion Nuclear Science Facility (FNSF) are being designed for fields of 12.2 T and 9.0 T at plasma center, respectively [4, 5]. The power generated in magnetic confinement fusion is proportional to $B^4$, and so an eventual fusion pilot plant (PPP) may be expected to operate at even higher peak fields and currents, with commensurately smaller stability margins even when using HTS windings.

REBCO and BSCCO have enabled hybrid-magnets capable of up to 32 T at steady-state [6] and an all-REBCO magnet capable of 26 T [7], however to-date such magnets have similarly used LHe immersion.
for thermal management. Similarly, both the LTS-based ITER and the HTS-based experimental reactors that will follow it all utilize forced convection cooling with liquid helium (LHe). Cooling with LHe imposes significant practical constraints on the operation of such magnets due to the rising cost of helium and its unpredictable supply [8].

Cryogen-free cooling, in which coils are cooled entirely through conductive thermal links to one or more cryocoolers, offers an economical alternative to LHe immersion, substituting the cost and reliability of electricity to operate cryocoolers for the cost of a helium reservoir and its attendant risk of shortages. Conduction-cooled SC magnets have been implemented since the 1990’s in applications ranging from materials processing [9] to particle accelerators [10] to magnetic energy storage devices [11]. While there have been proofs-of-concept of > 20 T conduction-cooled magnets [12], so far conduction-cooling has been restricted primarily to < 10 T magnets, with lower fields on the windings. In the absence of an LHe thermal buffer, ensuring dynamic stability of the windings becomes an even greater design challenge at near-critical fields and current densities. However the economic and pragmatic advantages of cryogen-free cooling compared with LHe cooling make it compelling for > 20 T SC magnet engineering.

2. Scope of Current Work

The Princeton Plasma Physics Laboratory (PPPL) is exploring conduction-cooled HTS magnet systems in application to a scanning tunneling microscope [2] and a general user facility for Princeton University, and is studying the feasibility of conduction-cooling for the central solenoid modules of FNSF. The ultimate goal of the current project is a 40 mm ID / 70 mm OD, 30 double-pancake (DP) REBCO insert solenoid for the Princeton user facility. The insert will need to achieve 5-6 T self-fields and operate stably in a 25 T background with cryogen-free cooling. Dimensions and other critical parameters of the insert and the REBCO conductor are given in table 1a and 1b, respectively.

| Parameter          | Quantity       | Parameter          | Quantity       |
|-------------------|----------------|-------------------|----------------|
| (a)               | (b)            |                   |                |
| Parameter         | Quantity       | Parameter         | Quantity       |
| Parameter         | Quantity       |                   |                |
| Number of pancakes| 60             | Conductor         | REBCO tape     |
| Turns / pancake   | 150            | Width             | 4 mm           |
| Operating Current | 180 A          | Thickness         | 0.1 mm         |
| Winding Pack Engineering | 357 A/mm² | Superconductor     | 1 µm           |
| Current Density   |                | nominal thickness |                |
| Expected Field on- Axis | 6.62 T | Substrate / thickness | Hastelloy / 50 µm |
|                   |                | Stabilizer / thickness | Copper / 40 µm (surround-copper-stabilized) |

A small cryostat is being designed to evaluate the peak field, V-I characteristics, charging times and thermal stability of the 30 DP insert coil and intermediate prototypes in self-field with conduction-cooling. No-insulation (NI) [13] and partially-insulated (PI) [14] pancake designs, along with semi-continuous winding methods to reduce the number of solder joints, will also be studied through tests of 2-3 DP prototypes to assess how these features may improve thermal stability.
3. Cryostat Design

3.1. Summary
The current design concept for the test cryostat is presented along with critical dimensions in figures 1 and 2. The cryostat will consist of two thermal stages installed in a stainless steel vacuum can of 330 mm ID and 760 mm internal height. Cooling power will be provided by a lid-mounted Sumitomo RDK-305D GM cryocooler, capable of nominal heat lifts of 20 W at 40 K from the 1\textsuperscript{st} stage coldhead and 0.4 W at 4.2 K from the 2\textsuperscript{nd} stage coldhead. Three conflat-flanged ports will provide feed-throughs for the vacuum pump line and instrumentation leads, with a separate port for a hall probe that will align with the central axis of the solenoid being tested. The cryostat and vacuum system will need to maintain high vacuums of at least $10^{-5}$ torr. An additional two conflat-flanged ports will provide junctions for the normal current leads.

![Figure 1. CAD model of the 30 DP insert coil test cryostat with significant features annotated](image1)

![Figure 2. Critical Dimensions of the test cryostat design concept](image2)

The 1\textsuperscript{st} stage will consist of an Al 1100-O cylindrical radiation shield and thermal intercept flange wrapped in MLI and bolted to the cryocooler 1\textsuperscript{st} stage coldhead. The latter will provide a heat sink for structural supports and a pair of normal current leads, as well as junctions composed of braided copper cable links between these normal leads and a pair of HTS leads. AlN interposer plates will be used for electrical isolation between these junctions and the thermal intercept flange. The 1\textsuperscript{st} stage will be supported from the lid of the cryostat by the cryocooler and a pair of 6.35 mm diameter stainless steel threaded rods, where the combined mass of the 1\textsuperscript{st} and 2\textsuperscript{nd} stages is anticipated to be 25 kg.
The 2nd stage will consist of the magnet assembly and an array of copper foil thermal straps and busbars linking the magnet assembly to the 2nd stage coldhead. The magnet assembly will be supported at its bottom endplate by four G10 rods hanging from the thermal intercept flange, with end support for these rods provided by threaded G10 bushings. AlN plate will again be used at the interfaces between the solenoid and the top and bottom endplates for electrical isolation of the magnet from the cooling system.

3.2. Thermal Design

Stage temperatures at thermal equilibrium were calculated to ensure the as-designed 2nd stage operates under the critical surface of the REBCO windings. Steady-state heat loads were developed assuming 1st and 2nd stage nominal temperatures of $T_1 = 40 \text{ K}$ and $T_2 = 4 \text{ K}$, respectively, and treating the vacuum can inner surface as isothermal with the ambient environment at $T_{\text{amb}} = 300 \text{ K}$. A cryostat vacuum of $10^{-5}$ torr was assumed for gas conduction and MLI calculations. The current leads are expected to contribute the bulk of the 1st and 2nd stage heat loads, and related calculations are described in section 4. Resultant heat loads were used to interpolate cryocooler coldhead temperatures from load curves provided by Sumitomo [15]. Based on this analysis the present cryostat design is predicted to achieve actual coldhead temperatures of $T_{1,\text{actual}} \approx 44 \text{ K}$ and $T_{2,\text{actual}} \approx 4 - 10 \text{ K}$, where the 2nd stage temperature will depend heavily on joule heating loads and hence solder joint quality. Table 2 summarizes these results.

**Table 2.** Heat loads and predicted stage temperatures for (a) the 1st Stage and (b) the 2nd Stage

| Source                                    | Power   | Source                                    | Power   |
|-------------------------------------------|---------|-------------------------------------------|---------|
| Normal Leads (ohmic and parasitic heat leak) | 15.6 W  | Solder Joints (ohmic heating)             | 0.9 – 1.9 W |
| Radiation                                 | 0.5 - 1.0 W | Gas Conduction                           | 0.01 W         |
| Gas Conduction                            | 0.3 W   | Parasitic leak (structural supports)      | 0.016 W        |
| Parasitic leak (structural supports)      | 1.4 W   | Parascopic leak (HTS current leads)       | 0.13 W         |
| Heat leak to 2nd Stage                    | -0.16 W | TOTAL                                     | 0.35 – 2.0 W |
| TOTAL                                     | 17.6 - 18.1 W | Predicted Stage Temperature               | 4.0 – 10 K     |

3.2.1. 1st Stage. Parasitic conduction through the threaded rods to the thermal intercept flange is predicted to add 1.4 W of heat, based on the shape factor of the rods and the integrated thermal conductivity of 304 stainless steel from 40 K to 300 K, obtained from NIST’s cryogenic material properties database [16].

$$ Q_{\text{supports,1st}} = \frac{A_c}{L} \int_{T_1}^{T_{\text{amb}}} k_{SS} dT $$

The radiative heat load was calculated for a range of MLI options using equation (2), using effective MLI thickness-direction conductivities $k_{eff}$ from [17], and assuming 60 layers of MLI. It was also assumed that the vacuum can inner surface is isothermal with ambient. Temperature gradients in the radiation shield were also neglected at this stage of analysis.
\[ Q_{\text{rad,1st}} = \frac{k_{\text{eff}} A_{s,1}}{N_{\text{layers}} t_{\text{MLI}}} (T_{\text{amb}} - T_1) \]  

Here, \( N_{\text{layers}} \) is the number of MLI layers, \( t_{\text{MLI}} \) is the combined thickness of one reflective and one spacer layer, \( A_{s,1} \) is the total surface area of the radiation shield, and a view factor of unity is assumed.

Gas conduction in the 1\textsuperscript{st} stage was calculated using equation (3) from [17], and assuming accommodation coefficients \( \alpha_{\text{amb}} \) and \( \alpha_1 \) of 1.0 for both warm and cold surfaces for a conservative estimate. A specific heat ratio \( \gamma = 1.4 \) and gas constant \( R = 287 \text{ J/kg} \cdot \text{K} \) for air, and a pressure gauge temperature \( T_{\text{meas}} = T_{\text{amb}} \) were assumed for all gas conduction calculations.

\[ Q_{\text{gas,1st}} = F_a A_{s,1} \left( \frac{R}{\gamma - 1} \right)^{1/2} \left( T_{\text{amb}} - T_1 \right) \left( F_a = \frac{1}{\alpha_1} + A_{s,1} \frac{1}{\alpha_{\text{amb}}} \left( \frac{1}{\alpha_{\text{amb}}} - 1 \right) \right) \]  

3.2.2 2\textsuperscript{nd} Stage. Gas conduction and conductive heat leaks through the G10 supports were estimated using the same methods as were used for the 1\textsuperscript{st} stage analysis. For the case of joule heating in the joints of the 30 DP insert coil, it is assumed that each DP will be linked electrically to adjacent DP’s by bridge joints composed of 5 cm long, 10-12 mm wide REBCO tape. To account for variability in DP-DP joint quality and resistivity, as observed in previous REBCO solenoids [7, 18], joule heating was estimated using a range of 0.2 – 2.0 \( \mu \Omega \cdot \text{cm}^2 \) for the solder joint contact resistivity. Radiative heat loads on the magnet were calculated by implementation of equation (4).

\[ Q_{\text{rad,2nd}} = \sigma (T_1^4 - T_2^4) \left[ \frac{1}{A_{s,1} \epsilon_1} + \frac{1}{A_{s,2,\text{mag}}} + \frac{1 - \epsilon_2,\text{mag}}{A_{s,2,\text{mag}}} + \frac{2}{A_{s,1} \epsilon_1} + \frac{1}{A_{s,2,\text{end}}} + \frac{1 - \epsilon_2,\text{end}}{A_{s,2,\text{end}}} \right] \]  

Here, the first the first term in brackets represents radiation to the solenoid and the second term represents radiation to the end-plates.

4. Electrical Design

For the electrical connection between the 1\textsuperscript{st} and 2\textsuperscript{nd} stages, temperatures are expected to be sufficiently low to permit use of HTS leads, and a set of 250 A CryoSaver\textsuperscript{TM} Bi-2223 current leads made by GMW Associates will be used. The junction linking the HTS leads to the solenoid terminals must be designed so that the peak c-axis and ab-plane magnetic fields on the leads do not exceed the conductor’s critical values. Using simulated field distributions, it was determined that locating the HTS lead junctions 100 mm away radially from the solenoid’s magnetic axis could reduce \( B_1 \) and \( B_\perp \) on the HTS leads to 140 mT and 10 mT, respectively, within vendor-advised limits for a warm end temperature under 50K [19]. These leads are expected to introduce 130 mW of parasitic heat leak to the magnet [20]. Figure 3 presents the radial component of the simulated magnetic field around the 30 DP insert coil and a schematic of the approach to designing the location of the HTS leads relative to the solenoid.
Figure 3. (a) Radial component of magnetic flux density for the 30 DP insert coil from FEA, and (b) schematic description of the method used to design the location of the HTS current lead junctions to the solenoid. From trigonometry and estimates of the radial field distribution around the solenoid, the normal component of the predicted magnet field on the HTS windings can be inferred.

Normal conductor current leads will be required for the link between the power supply at ambient temperature and the HTS leads. Their design is driven by the need to minimize heat loads on the coldmasses by optimizing the balance between conductive heat leaks and joule heating as a function of shape factor. A finite difference model was developed to solve the 1D heat equation for the case of joule heating with temperature-dependent thermal and electrical conductivity for a range of conductor lengths and cross-sections. This model converged to the results of the analytical model for optimal current leads in the limit of no radiative heat exchange [21]:

$$l \left( \frac{L}{A} \right)_{opt} = \frac{1}{\sqrt{2}} \int_{T_1}^{T_{amb}} \frac{k(T)}{\int_{T_1}^{T_{amb}} k(t) \rho(t) \, dt}^{1/2} \, dT \approx \int_{T_1}^{T_{amb}} \frac{k(T)}{k_{wrf} [T_{amb}^2 - T^2]^{1/2}} \, dT$$  \hspace{1cm} (5)

where $L_{wrf}$ is the Lorenz number from the Wiedemann-Franz Law, and a nominal value of $2.45 \times 10^{-8} \, W\Omega/K^2$ is used. 2 AWG copper wire is currently being considered for the leads to ensure a minimum stiffness, and for this wire gage and operating current it was determined that the optimal lead length is approximately 750 mm with a resultant joule heating load of 15.6 W for a current lead pair, as shown in figure 4. To accommodate this length above the radiation shield, an undulating lead design is proposed, with the leads supported from the lid by U-bolts of G10 or other dielectric material, as shown in figure 5.
5. Summary

PPPL is pursuing a program of conduction-cooled HTS magnets capable of generating and/or operating as insert coils in fields of 20-30 T, with an immediate goal of building a 6 T REBCO insert coil for an eventual 30 T user facility at Princeton University. A cryocooler-based cryostat is being designed to study prototypes and ultimately test the peak field and thermal stability of the insert coil itself in self-field. The current design is anticipated to achieve 1st and 2nd stage temperatures of 44 K and 4 - 10 K, respectively. Achieving base temperatures in the 2nd stage will depend heavily on developing a scalable, repeatable DP-DP joint-making capability. Future work will include constructing 2-3 DP prototypes with different no-insulation winding methods and thermal link designs and testing them in this facility.

6. References

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