Design of a Helium-Free Test Cryostat for Superconducting Wires, Cables, and Windings

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***Abstract*— A helium-free test cryostat is being built to support testing of superconducting wires, cables, and windings. Three cryocoolers are mounted on the top hat of an LN_2-shielded open-top cryostat and used to heat-sink thermal intercept shells at 50 K, 20 K, and 4.2 K. Ternary leads are used for supply and return of a 10 kA circuit (for a background-field dipole) and a 20 kA circuit for a test sample. Each lead is a series connection of a N_2 vapor-cooled lead and a Bi-2223 Type G lead. A closed-flow liquid helium loop is used to maintain the Nb_3Sn CIC windings of a 10 T background field dipole at 5 K. The objective of the design is to make it possible to sustain the test environment relying solely on LN_2 and three cryocoolers, without the expense of a helium liquefier or a large inventory of liquid helium.**

***Index Terms*— Ternary leads, cryocoolers, HTS leads, test cryostat, vapor cooled leads**

I. Introduction

The cost of liquid helium (LHe) continues to rise and is a barrier for many smaller labs who wish to test superconducting wires, cables, and magnets. The purpose of this paper is to describe the design of a test cryostat that relies solely on three cryocoolers and liquid nitrogen (LN_2) to cool down and test samples between 4 K and 20 K.

The design is inspired by the test cryostats [1,2] that were developed at NHMFL and are used with their series-connected hybrid magnets. Each of their cryostats utilizes a pair of 20 kA binary leads to supply the magnet's operating current. Their binary leads employ two features to reduce the flow of liquid helium that must be supplied from a closed-circuit refrigerator:

- In the region 300 K → 80 K, current flows through a heat exchanger structured as a 'jelly-roll' of perforated copper sheet. The resistive and conductive heat is transferred away by boiling LN_2 at the lower end of the exchanger and flowing the cold vapor through its upper body before venting the warm vapor into the atmosphere.
- In the region 80 K → 20 K, current flows through a cylindrical array of Bi-2223/Ag/Au tapes. The resistive and conductive heat is transferred to the flow of boil-off vapor from the LHe filling the cold region of the cryostat.

The Ag-Au alloy in the stabilizer of the Type G Bi-2223 tapes [3] has a very low thermal conductivity in the range 20 K → 4 K, so the He boil-off rate that is required to operate each NHMFL binary lead is 17 liters/hr, compared with 60 liters/hr for a conventional vapor-cooled lead of the same capacity.

The TAMU/ATC design utilizes a *ternary* lead, in which the above innovations are employed with two additional modifications:

- The Bi-2223 tape array is heat-sinked at an intermediate location along its length to the 20 K cold head of a single-stage cryocooler, and the cold end of the lead is heat-sinked to the 4 K cold head of a 2-stage cryocooler.
- A normal-state liquid helium (LHe) closed-flow loop is heat-sinked to the test specimen and to the background-field dipole to maintain ~4.5 K temperature.

The test cryostat is shown in Fig 1a. Its major components consist of a vacuum can with an internal LN_2-cooled radiation shield, 4 ternary current leads, an onboard LN_2 supply dewar, one 20 K cryocooler and two 4 K – 50 K cryocoolers, a 10 T CIC background field magnet, and a supercritical He reservoir and flow loop.

With these provisions, the entire cryostat system can be operated without requiring additional LHe, so that both cooldown and operation require only electricity and a modest quantity of LN_2.

II. Ternary leads

Two pairs of ternary current leads are used in the cryostat, one pair rated for 10 kA for use with the CIC winding of a background-field dipole [4] and one pair rated for 20 kA used to drive current in test samples. The design for the 20 kA ternary lead is shown in cross-section in Fig. 1b. The design builds upon that of the binary lead developed by Miller *et al*. [5] and Weijers *et al*. [6].

A. Vapor cooled lead section

The upper section of each lead is cooled by boiling LN_2 and flowing the boil-off vapor through a perforated heat exchanger. Table I summarizes the main design parameters. For the 20 kA lead, a sheet of perforated C122 copper is wrapped around a 2.5 cm dia. SS-304 tube 18 times to create a "jelly-roll" vapor heat exchanger (VHX). Fig. 1c shows the first two layers of perforated Cu. No metal is removed while perforating the sheet, and the small crowns protrude in the gaps between layers to produce turbulent flow of vapor as it passes up the exchanger. A sample rolling of the first few layers of this perforated copper is shown in Fig. 1c. The number of turns in the jelly-roll was determined using the conventional criterion $IL/A = 3\ MA/m$ [7], where $L =$

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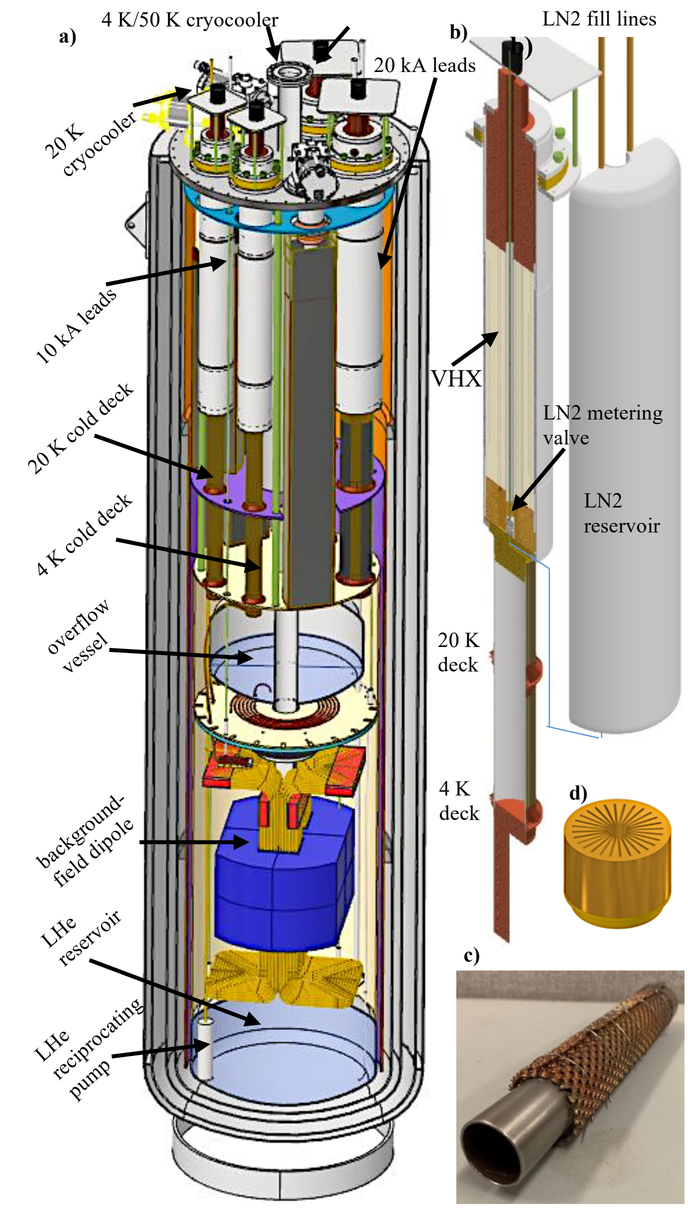

Fig. 1. Cutaway views of **a)** the test cryostat and **b)** one 20 kA ternary current lead; **c)** a sample rolling of the first two layers of the Cu jelly-roll for the VHX; d) detail view of the LN2 manifold at the bottom of the VHX..

0.5 m is the width of the jelly-roll, $I = 20\ kA$ is the lead current, and $A = 17\ cm^2$ is the cross-section area of the copper in the jelly-roll. The jelly-roll is housed in a 15 cm dia. SS-304 shell to form a hermetic VHX assembly. LN_2 is injected into the bottom of each VHX through a metering valve (Fig. 1b), and warm vapor is vented from the top to an exhaust manifold. The metering valve is adjusted to maintain an approximately constant temperature of the exiting warm vapor at $T_V \sim 250\ K$. In this way the temperature distribution of the VHX can be sustained in an optimum manner for both static operation ($I = 0$) and full-load operation ($I = 20\ kA$).

Soldered to the bottom of each VHX is a Cu cylinder with a starburst of thin EDM-cut slits in it (Fig 1d). The LN_2 flow from the metering valve is distributed through the slits to uniformly feed all layers of the VHX, providing direct contact within the slits between the copper and the LN_2. The heat from thermal conduction and ohmic resistance is thus removed by the

TABLE 1
DIMENSION DIFFERENCES BETWEEN 10 KA AND 20 KA TERNARY LEADS

Parameter	10 kA Lead	20 kA Lead
Optimum L/A (1/m)	303	152
Active length (m)	0.51	0.51
Active CS area (cm^2)	17	33
Foil length (m)	4	8
Turns	18	21
VCL OD (cm)	11	15
Reservoir wetted perimeter (m)	1.84	2.91
Reservoir LN_2 volume (L)	0.35	0.52
Tape stacks	32	60
HTS OD (cm)	5	10

combined heat of vaporization of the liquid and the enthalpy change in warming the vapor, and the bottom of the VHX is sustained at ~80 K. With the 20 kA-rated leads running at operating current, the total heat to be removed from each lead is ~1 kW. The mass flow rate of LN_2 through the system needs to be ~2.7 g/s per lead. With no current, only 490 W is coming into the system, corresponding to a LN_2 flow of ~1.3 g/s per lead. These results, and those for the 10 kA lead, are shown in Table 2.

The heat balance equation for the resistive portion of the ternary lead is given by:

$$\frac{d}{dx}\left[k_{Cu}(T)A_{cs}\frac{dT}{dx}\right]+\frac{\rho_{Cu}(T)I^2}{A_{cs}} = \dot{m}_{N_2}C_{P,N_2}(T)\frac{dT}{dx} \quad (1)$$

which solves to

$$\frac{A}{L}\int kdT + \frac{I^2L}{A\Delta T}\int \rho dT = \dot{m}\Delta h - \dot{Q} \quad (2)$$

where $\dot{Q}$ is the heat generated by the LN_2 reservoir and Δh is the enthalpy change of the nitrogen [5,8]. Subscripts and function arguments have been removed from Eq (2) for conciseness. The heat-balance calculations for the 10 kA and 20 kA VCLs are summarized in Table 2. The results of Eq (1) and Eq (2) were verified in the COMSOL simulation, as seen in Fig 4 and Fig 5, and Section VI of this paper.

TABLE 2
CALCULATED HEATING AND FLOW VALUES FOR 10 KA AND 20 KA LEADS

Parameter	10 kA Lead, I=10 kA	10 kA Lead, I=0 kA	20 kA Lead, I=20 kA	20 kA Lead, I=0 kA
Q conducted down VCL (W)	235	235	488	488
Q generated by resistive lead (W)	277	0	534	0
Q removed by N_2 gas (W)	244	112	489	235
Q removed by LN_2 evaporation (W)	268	123	537	258
N2 flow rate (g/s)	1.340	0.614	2.674	1.277
Heat load on 20 K deck (W)	3.10	3.10	5.85	5.85
Heat load on 4 K deck (W)	0.591	0.324	0.877	0.610
Current per tape (A)	62.5	0	66.6	0

B. HTS Leads

The 20 kA HTS lead is composed of 60 stacks of 5 Sumitomo Bi-2223 Type G superconducting tapes soldered into machined grooves around a copper-electroplated, 6 mm thick SS-304 tube. The tape stacks are soldered together using Sn96.5Ag3.5 solder, and the stacks are soldered into the grooves with Sn63Pb37 solder. With 20 kA flowing through the lead, each tape carries a current load of 67 A, ~half of its I_c at 80 K [9].

The primary heat source in the HTS leads is the heat being conducted down from the LN_2 reservoir - 5.9 W for a single 20 kA lead. Most of this heat is removed at the 20 K deck by the single-stage cryocooler.

An important detail of the lead design is limiting the heat load to the 4 K cold deck so that the modest 4 W capacity of the two cryocoolers can handle it. The stabilizing matrix for Sumitomo G-type Bi-2223 tape is an Ag-Au alloy that has a remarkably low thermal conductivity in the range 4 K - 20 K, as shown in Fig. 2. An electrically isolated heat intercept collar is clamped to the HTS barrel, 10 cm below the 80 K end and 40 cm above the 4 K end. The clamp is heat-sinked to the 20 K cold deck with sapphire washers. The cold end of the HTS lead is similarly clamped to the 4 K deck. The total heat load on the 4 K deck from each 20 kA lead at operating temperature and current is 0.9 W. The 10 kA HTS lead follows a similar design, but is approximately half-size.

Combining these results, the total heat load on the 20 K deck (and the single-stage cryocooler) from a system with two 10 kA ternary leads and two 20 kA ternary leads is 17.9 W, and the total heat load on the 4 K is 2.9 W. Both loads can be supported within the capacity of the two cryocoolers.

III. Cryocoolers

Three Sumitomo cryocoolers are used to provide the primary cooling power to the cryostat. One single-stage cryocooler (RDK-500B [10]) cools the 20 K cold deck to remove heat from an intercept collar on each HTS lead. The cryocooler is also attached to an Alzak-coated reflective shield that encloses all elements that operate at <20 K. The rated cooling power of this cryocooler is 45 W at 20 K.

Two two-stage cryocoolers (RDE-418D4 [10]) are used to cool a 50 K cold deck and a 4 K cold deck. A two-stage cryocooler creates an intermediate temperature at its first stage, then has its coldest point on another stage below that. The 50 K deck is heat-sinked to an Alzak-coated intermediate-temp reflective shield. A pair of smaller shields surround copper buses that connect the second stage of the cryocoolers to the 4 K deck. The 4 K stage of each cryocooler is also heat-sinked to a third Alzak-coated thermal radiation shield that surrounds all cryostat components operating at LHe temperatures. The rated cooling power of the first stage of each cryocooler is 50 W at 50 K, and the second stage of each cryocooler is 2.0 W at 4 K.

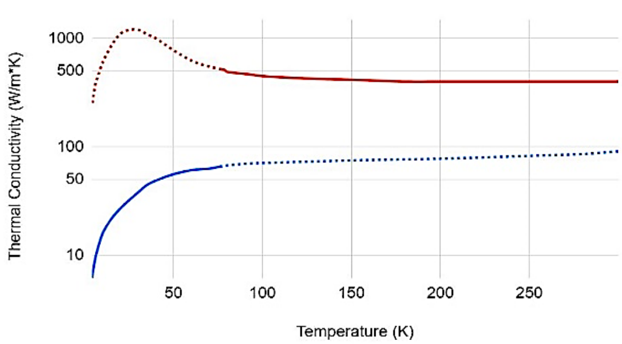

Fig. 2. Temperature dependence of thermal conductivity of copper and of the Ag/Au alloy used for the stabilizer matrix of Bi-2223 Type G tapes.

A. LN_2 System for the VHX

A 34 liter LN_2 storage dewar is suspended within the test cryostat as shown in Fig. 1. The liquid level within this dewar is monitored using a chain of RuO_2 resistors (a smaller version of which is described below) and is refilled from an external supply. The largest portion of cooling power for both the high-current leads during operation, and the entire system during cooldown, comes from an LN_2 flow system. From the bottom of the large dewar come four transport lines which pass through electrical breaks before attaching at the base of the LN_2 reservoirs of each VHX. With a light pressure difference from the supply dewar to the lead bases, the flow rate of the incoming LN_2 at each reservoir is approximately 300 g/s.

In Section II-A, the required flow rates to maintain thermal equilibrium within the VHXs are calculated, all of which fall

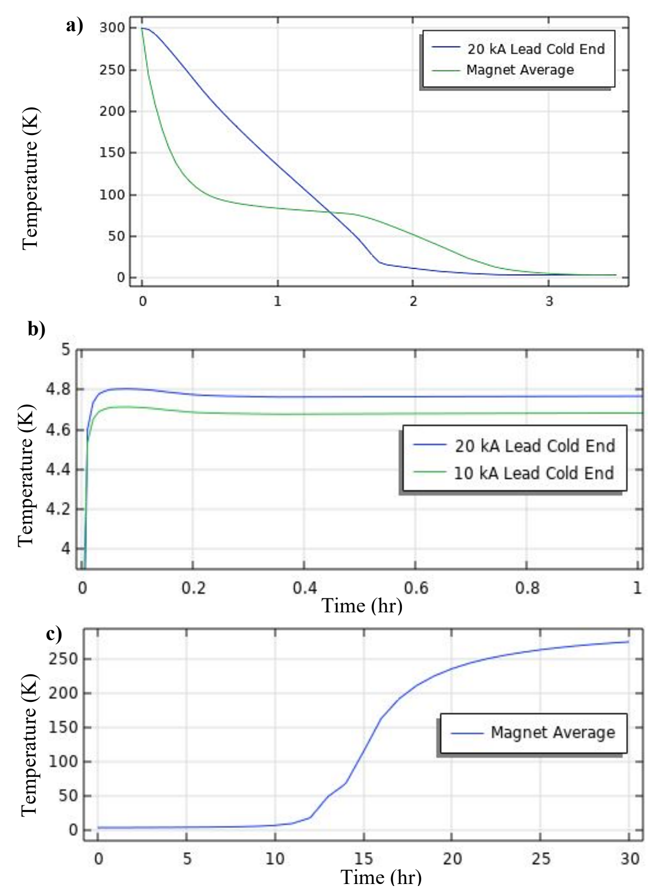

Fig. 3. Temperature *vs* time plots at various operating modes. a) System cooldown from 300 K to operating temps; b) current lead end temps during current ramping and operation; c) magnet temperature during warm-up.

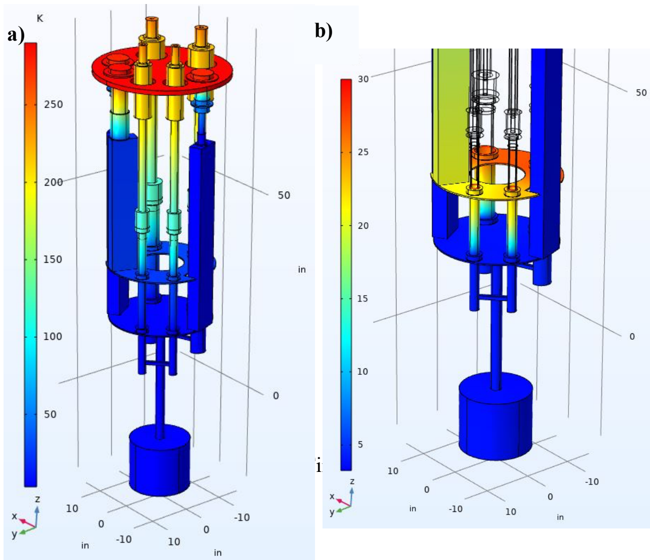

Fig. 4. Temperature profiles of a reduced model of the cryostat at the end of two stages of operation: **a)** after cooldown, with no currents active; **b)** full rated currents in all 4 leads, equilibrium after one hour (data range has been restricted for better visualization).

within the range 0.5 g/s to 3.0 g/s. The incoming flow to each lead is controlled using a metering needle valve. Each valve is adjusted so that the N_2 vapor exiting the warm end of the VHX has a temperature near 280 K.

The liquid level in the small LN_2 reservoirs is monitored using a pulsed-current ladder of RuO_2 resistors along its inner wall [11]. The fill valve from an external supply dewar is controlled to maintain a constant level in the internal dewar.

IV. Closed-Loop LHe Flow Circuit

The test cryostat incorporates a 10 T background-field dipole, shown in Fig. 6. Its winding is driven by the pair of 10 kA HTS leads. It contains a clear bore of 7.5 cm diameter to accommodate testing of cable and winding specimens. Indeed the motivation for developing the helium-free cryostat is to enable testing of the REBCO insert [12] and the Nb_3Sn CIC outsert windings [13] of an 18 T hybrid dipole that is being developed by this group.

The cable-in-conduit (CIC) winding utilizes Nb_3Sn wires and must operate at ~5 K, and thus requires a dedicated flow circuit to transfer heat to the 4 K cold deck of the 2-phase cryocoolers. A closed-flow LHe circuit has been designed to provide cooling to the CIC winding of the 10 T background field dipole and the test specimen. A similar strategy was employed by Schuter, using supercritical He, for a small SMES winding [14]. For the present purpose, LHe is used to accommodate rapid recovery from a quench of either the dipole or the test specimen, and also provides safe provision for a loss-of-coolant accident (LOCA).

The circuit is shown in Fig 3. It contains a 90 liter LHe reservoir and a 60 liter overflow vessel. Two parallel flow circuits are provided, in each of which a small reciprocating pump drives flow. One flow is driven from the reservoir through the CIC winding (8 liter inventory) into the overflow reservoir. The other flow is driven as a recirculating flow from the overflow

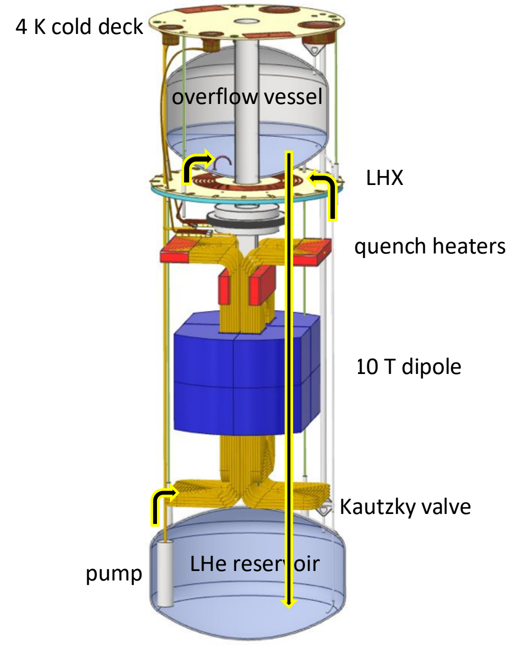

Fig. 5. Diagram of the closed-flow LHe circuit. LHe is pumped through a closed-loop circuit by a reciprocating pump (bottom left) from the reservoir through the CIC winding of the dipole; exits into the overflow vessel. Heat is transferred to the 4 K cold deck of the cryocooler, and LHe is returned by gravity from the overflow vessel to the reservoir.

reservoir through the test specimen and back to the overflow vessel. In each circuit the cryogen flows through a liquid heat exchanger (LHX) pancake winding which is heat-sinked to the 4 K cold deck and to the bottom of the overflow vessel.

The primary LHe reservoir is filled after all other systems in the cryostat are at operating temperature, and sufficient LHe is added to fill the CIC winding and fill ~10 liters of liquid inventory in the overflow vessel..

During operation, the centrifugal pumps gently circulate the LHe through the circuits. The closed-circuit flows remove heat from the CIC winding and the test specimen and transfer it to the 4 K deck of the cryocoolers.

V. Simulation of Operating Modes

COMSOL was used to simulate the three primary modes of the test cryostat. Fig. 3 shows the simulated temperature vs. time for the several locations in the cryostat during the three primary modes: a) cooldown and filling of the LHe reservoir; b) operation with maximum rated currents in all leads; c) warm-up back to room temperature.

Fig. 4 shows the temperature profiles of the inner workings of the cryostat after the system is cold, and during operation with design currents flowing through all leads and a 1 W heat load on the 4 K deck from the LHe circuit.

The test cryostat cools to operating temperatures in approximately 3.5 days, and consumes ~90 L of LN_2. While operating with rated currents, it consumes about ~36 L/h of LN_2. The entire system warms back up to room temperature in 1.5 days.

Table 3 compares characteristics of conventional He vapor-cooled leads, with the binary N_2-cooled leads of NHMFL, and

TABLE 3
COMPARISON OF LHE CONSUMPTION FOR 20 KA LEAD DESIGNS

	Cu vapor-cooled lead	NHMFL binary lead	TAMU ternary lead (calculated)	
Heat load at 4 K	44	13	3	W
LHe consumption	2.1	0.6	0	g/s

the ternary leads being developed by TAMU and ATC presented here. The lack of consumption of LHe in the TAMU/ATC design is a significant performance benefit that may prove important for affordable high-current testing at smaller labs in the future.

VI. FAILURE MODES: DIPOLE QUENCH AND LOCA

During a quench in the dipole winding, its 600 kJ magnetic field energy is transformed into heat. If the heat were taken entirely by increasing the temperature of the CIC winding (not accounting for the slower conduction of heat to the steel flux return), the winding temperature would rise to ~100 K. Quench propagation in a Nb_3Sn CIC cable is slow, and the location where a quench initiated could be heated to a dangerously high local temperature. For this reason a network of resistive quench heaters is installed on one flared-end of the winding that drives a short segment of all turns to their normal state within ~20 ms of a quench being detected. Then the entire winding should heat to ~100 K and then gradually equilibrate with the flux return to a final temperature of ~30 K.

This quench scenario will produce boiling in the ~8 liter inventory of LHe in the winding. The reciprocating pump serves as a one-way valve to prevent reflux of the boiling He to the reservoir, so it is purged rapidly into the overflow vessel. Only a modest fraction of the 600 kJ heat is transferred to the boiling He before it is purged, so only that fraction is transformed into cold vapor. Most of the He inventory remains as liquid, the LHe flow is restored, and the heat in the dipole is removed by the cryocoolers in ~12 hr.

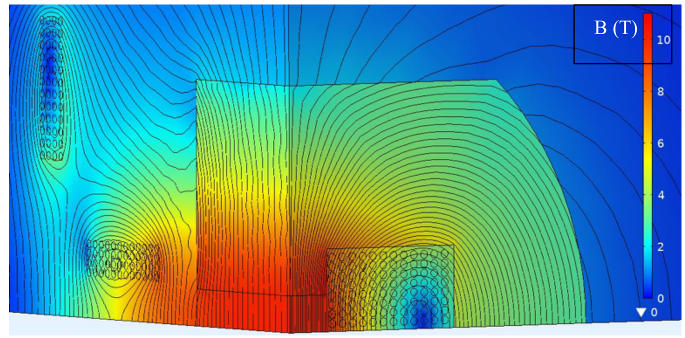

Fig. 6. Cutaway view of magnetic field distribution in one octant of the 10 T CIC background-field dipole.

A Kautzky relief valve [15] is located in the lid of the overflow vessel, and provides high-conductance flow out of the top flange into an exhaust chimney, so that the quench event cannot produce a dangerous pressure surge in the circuits. In the event of a LOCA, the entire LHe inventory of the reservoir and the overflow vessel will purge rapidly to prevent any dangerous conditions.

VII. CONCLUSION

A design has been proposed for a test cryostat that relies upon ternary HTS leads and includes a supercritical helium flow circuit for a background field dipole. The cryostat operates with no consumption of liquid helium. Cooling is provided by a modest consumption of LN_2 and three cryocoolers, so operation costs are mitigated.

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