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THE USE OF CALORIMETRY IN SUPERFLUID HE II TO MEASURE LOSSES IN SUPERCONDUCTING MAGNETS*

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DISCLAIMER

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THE USE OF CALORIMETRY IN SUPERFLUID HE II TO MEASURE LOSSES IN SUPERCONDUCTING MAGNETS

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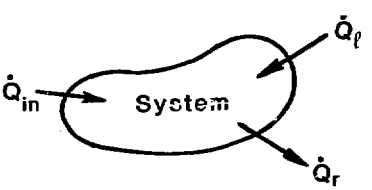
A method using calorimetry to measure magnet losses in pressurized Helium II is described. The isothermal nature of He II is used in measuring the overall heat capacity of the system and the net refrigeration power. During the measurements, the refrigeration power is held fixed, and the system (400 liters) temperature is near 1.92 K. The calorimetric measurement was calibrated against known power inputs between 1 and 20 W. This technique can even measure heat loads higher than the available refrigeration. Results of loss measurement on two dipole magnets are reported.

INTRODUCTION

Superconducting magnets are lossy when they operate under AC conditions. Magnet losses have been measured in the past using sophisticated electronic devices [1]. Calorimetry has the advantage of measuring the loss by monitoring the cryogenic system alone. Stratification in subcooled He I restricts calorimetry to the equilibrium vapor pressure where the rate of vaporization is measured to determine the losses [2]. The isothermal behavior of superfluid He II and the absence of vapor when it is used at 1 atmosphere reduces the energy loss calculations to a straightforward energy balance.

ANALYSIS

The thermodynamic system sketched below, which is maintained at a constant pressure, has a fixed volume and can only undergo heat interaction with external reservoirs. The enthalpy change of the system is $dH = TdS + VdP$. Since $dP = 0$ the total energy balance is written as in Eq. (1), where m = system mass, c = specific heat per unit mass, $\dot{Q}_{in}$ = input heat flux, $\dot{Q}_\ell$ = leak heat flux, $\dot{Q}_r$ = refrigeration heat flux and t = time.



$$\Delta H = m \int_{T_i}^{T_f} c_p(T)\, dT = \int_0^t \left(\dot{Q}_{in} + \dot{Q}_\ell - \dot{Q}_r\right) dt \qquad (1)$$

We can define the total heat capacity as:

$$m\bar{c}_p(T_f - T_i) = \rho V \int_{T_i}^{T_f} c_p(T)\, dT$$

where ρ = density and V = system volume. The total heat capacity $m\,\bar{c}_p$ is fixed for a given T and small ΔT. If we insist that all heat interactions are in steady state, then the heat leak $\dot{Q}_\ell$ and refrigeration power $\dot{Q}_r$ are both fixed. Equation (1) is rewritten using the substitution $M = mc_p$.

$$M\frac{\Delta T}{\Delta t} + \dot{Q}_{nr} = \dot{Q}_{in} \tag{2}$$

where $\Delta T = T_f - T_i$, and $\dot{Q}_{nr} = \dot{Q}_r - \dot{Q}_\ell$ the net refrigeration power.

For a heat input $\dot{Q}_{in1}$, this will result in a constant temperature rate $(\Delta T/\Delta t)_1$. If we would have decided on a different value for the heat input $\dot{Q}_{in2}$ the result would have been $(\Delta T/\Delta t)_2$. The relation between $\dot{Q}_{in}$ and $(\Delta T/\Delta t)$ is functional as long as M and $\dot{Q}_{nr}$ remain constant. This can be expressed as

$$\begin{pmatrix} \left(\frac{\Delta T}{\Delta t}\right)_1 & 1 \\ \left(\frac{\Delta T}{\Delta t}\right)_2 & 1 \end{pmatrix} \begin{pmatrix} M \\ \dot{Q}_{nr} \end{pmatrix} = \begin{pmatrix} \dot{Q}_{in1} \\ \dot{Q}_{in2} \end{pmatrix} \tag{3}$$

If $(\Delta T/\Delta t)_j$ and $\dot{Q}_{inj}$ are known ($j = 1,2$), the equation can be solved for M and $\dot{Q}_{nr}$. Once these values become available, for every given $\Delta T/\Delta t$, its corresponding $\dot{Q}_{in}$ can be calculated using Eq. (2) .

A superfluid He II system at 1 atm meets the assumptions made for the thermodynamic system described above. It is isothermal over its volume during heat interaction (narrow channels are excluded). Transformation to vapor or He I is avoided as long as the heat flux density is below a limiting value and a constant one atmosphere pressure can be maintained with accuracy without net mass exchange.

EXPERIMENT AND RESULTS

An early version of the cryostat and refrigeration system used for these tests was described in Ref. [4]. Over a year ago parts of the system were changed to accommodate horizontal rather than vertical magnets. Calorimetric measurements were carried out using both systems. The current version shown in Fig. 1 consists of three chambers and is designed to produce superfluid He II at 1 atm pressure on a continuous basis. The upper chamber stores He I and is continuously being filled. It is a heat intercept to all instrumentation wires and magnet leads and a source of He I for the He II refrigeration system. Underneath is the second chamber to which the He I chamber is connected through a narrow channel. This is the refrigeration chamber where the He II heat exchanger is located. During operation He I at 1 atm is drawn from the top chamber, cooled through a counterflow heat exchanger and expanded through a controllable Joule Thomson (J T) valve. Leaving the heat exchanger at low pressure the vapor is drawn back through the counterflow heat exchanger out of the cryostat. Connected to the He II refrigeration chamber is the 1.45-m long and 0.56-m diam. horizontal cryostat, which holds the magnet. Nineteen thermometers (carbon glass) are distributed throughout the system; however, only 4 sensors were used during these tests due to the isothermal behavior of superfluid. The sensors are connected to a data-acquisition system based on a H.P. 9845B computer. The calorimetry procedure was programmed into the computer, which controlled the temperature measurements with minimum operator interaction. The temperature range between 1.91 K and 1.94 K was chosen for the test. This was proven to be adequate since a lower temperature would have increased the heat leak and reduced refrigeration power and a higher temperature would have increased the temperature dependence of the specific heat . The refrigeration power was set at a reasonable rate (this was estimated) using a feedback control J T valve which

maintained a pressure near ~ 6 torr in the heat exchanger. This setting was constant throughout the run.

To calibrate the cryostat, the temperature was lowered to T_i and an auxiliary heater was turned on. Maintaining a constant heat input, the temperature versus time response of the superfluid was monitored by the computer every 30 seconds. Depending on the rate of heat input, this part lasted 5 to 10 minutes, during which the temperature change of each sensor was plotted against time on the desktop screen (Fig. 2). A least square fit of the data was used to compute $\Delta T/\Delta t$. The process was repeated for a different heat input and Eq. (3) solved for the total heat capacity M and net refrigeration power $\dot{Q}_{nr}$. For a liquid volume of 400 liters typical values are $M = 228(kJ/K)$ and $\dot{Q}_{nr} = 12.8(W)$.

To check the accuracy of the procedure a number of different known heat inputs were imposed and their values compared (Fig. 3). The agreement between measured and calculated values is within ± 0.2(W) all the way down to 1 watt. In one case the calibration procedure was repeated after 5 hours and the variation in the net refrigeration power was less than 5%.

The magnet loss during cycling is not constant, however, it can be averaged over the cycle time

$$\dot{Q}_{in} = \frac{1}{\tau} \int_0^{\tau} \dot{Q}_{in}(t)\, dt = \text{constant}$$

Seven magnets have been studied using this technique. The cyclic loss for two of these magnets are given in Fig. 4. (See also C. Taylor this conference.) The losses of epoxy-free magnet D8A, which has iron rings, correlates with epoxy impregnated UNK and Fermi dipoles [5]. Dipole D7D, which is epoxy-free and has aluminum structural (alloy 7075) rings, is much more lossy.

ACKNOWLEDGEMENTS

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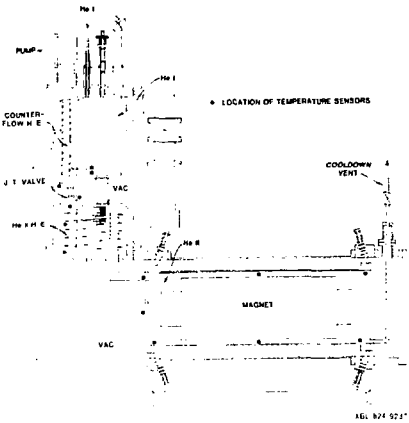

Fig. 1. He II cryostat and refrigeration.

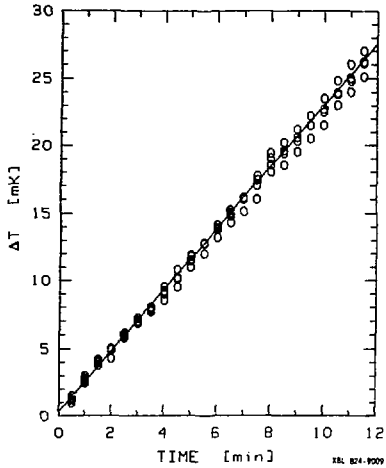

Fig. 2. He II temperature response during heat input.

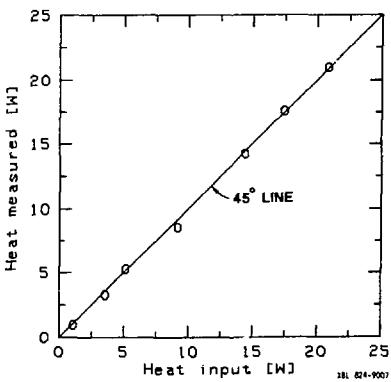

Fig. 3. Comparison between known heat inputs and the one measured using calorimetry.

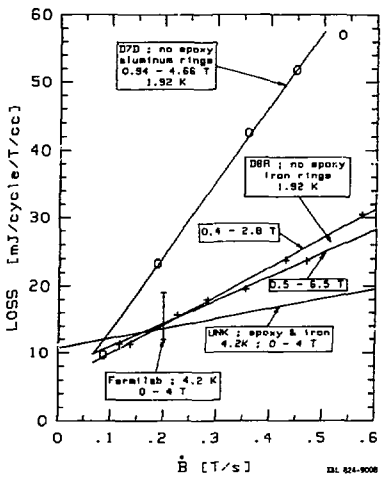

Fig. 4. Magnet loss during cycling per unit volume of superconductor cable.