Use of He Gas Cooled by Liquid Hydrogen with a 15-T Pulsed Copper Solenoid Magnet

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The power required to energize a copper magnet is minimized by operation at the lowest possible temperature. However, the resistance of copper drops very little at temperatures lower than 30 K, which defines a desirable temperature for economic operation of high-field/high-current magnets. Liquid hydrogen (at 1 bar) is therefore a natural candidate as the coolant for high-power copper magnets. Issues of safety make it prudent that the copper conductors (which could generate sparks during magnet failures) not be directly cooled by liquid hydrogen. Hence, a favorable scheme is that the magnet be cooled by flow of helium gas at ~ 30 K, with this gas cooled in an external heat exchanger with a liquid-helium bath. A design based on this scheme was developed (although not implemented) for the 15-T pulsed solenoid used in the so-called MERIT experiment at the CERN Laboratory (Switzerland).

INTRODUCTION

The motivation to cool any magnet cryogenically, DC or pulsed, superconducting or not, is to improve the electrical conductivity of its conductor. The application described in this paper involved a 15-T pulsed, copper solenoid magnet [1,2] requiring a peak current of 7500 A. The room-temperature resistance of the magnet was 1.25 Ω, such that a peak power of 70 MW would have been required to energize the magnet at this temperature. To be able to operate with an available power supply of only a few MW capability, we cooled the magnet.

Figure 1 (left) shows that the resistivity of high-purity copper declines greatly from room temperature down to 30 K. The incentive to operate at cryogenic temperatures is great indeed. Cooling to 80 K (with liquid nitrogen at atmospheric pressure) improves the electrical conductivity by a factor of nearly seven. Cooling to 66 K (with liquid nitrogen subcooled to nearly its freezing point of 64 K) gives a ratio of about ten. Cooling to 30 K (with liquid hydrogen as the heat sink, for example) can achieve a ratio of about 30.

There is very little motivation to cool copper conductor still further; one has entered a regime of diminishing returns. Figure 1 (right) illustrates two of the reasons for this. One is that electrical resistivity improves rather little. This is true even for copper that is exceedingly pure, unless it is so completely annealed as to be too weak for a very high field magnet. The other reason is that, if the copper is uncooled, with only its heat capacity to limit its temperature rise, it will heat up very rapidly, because its heat capacity plummets, approximately as T^3, below ~30 K. The heating rate, proportional to ρ/c_p, is three times worse at 20 K than at 30 K.

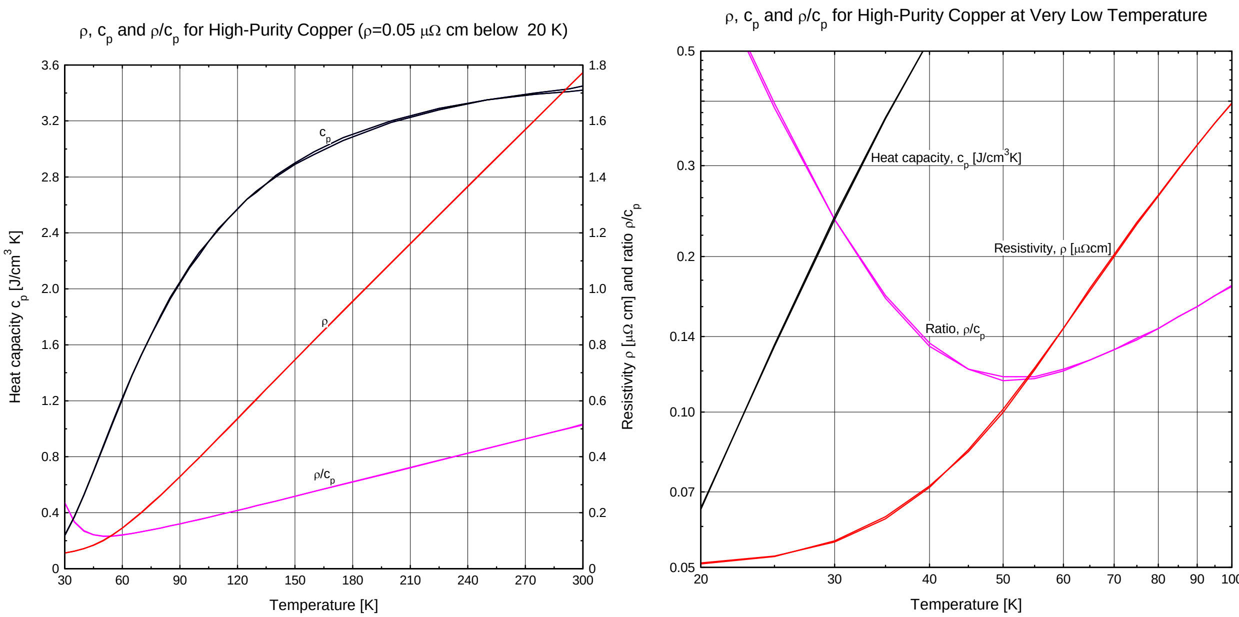

Fig. 1. Left: Electrical resistivity ρ, heat capacity c_p, and ratio ρ/c_p between room temperature and 30 K, for copper with a residual resistivity of 0.05 μΩ cm below ~20 K. Right: Low-temperature electrical resistivity ρ, heat capacity c_p, and ratio ρ/c_p for copper with a residual resistivity of 0.05 μΩ cm below 20 K.

THE COOLING CONCEPT

Although the magnet was eventually operated at 80 K with an 8 MW power supply [3], we also designed a system [4,5] to cool the pulsed solenoid magnet (PSM) to 30 K (at which a 4 MW power supply would have sufficed) by helium gas that circulated through an external heat exchanger (HE) filled with liquid hydrogen (LH_2) from a storage Dewar, with the exhaust hydrogen gas vented to the atmosphere, as illustrated in Fig. 2. This concept is based on a magnet built in 1946 [6] that was directly cooled by liquid hydrogen, following a suggestion by Cockcroft in 1928 that magnet coils be cooled by liquid air [7]. See also [8,9].

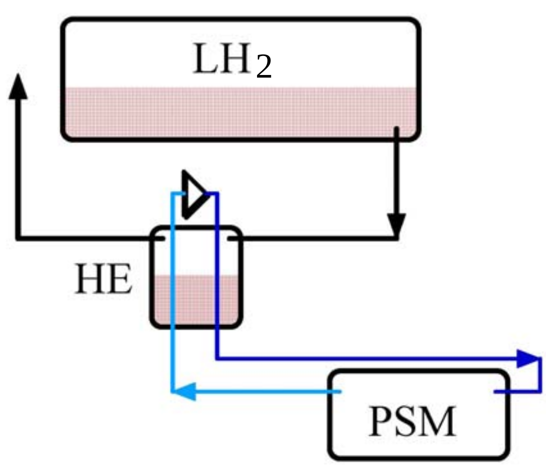

Fig. 2. Concept of the scheme to cool a pulsed solenoid magnet (PSM) by helium gas that is in turn cooled by liquid hydrogen (LH_2) in a heat exchanger (HE).

CHOICE OF CRYOGENS

Having chosen an operating temperature of 30 K for the magnet, possible cryogens for the circulating gas and liquid coolant were helium, hydrogen and neon. As magnets have been known to catch fire due to internal shorting, hydrogen was not considered for the circulating gas. Since helium and neon gas have the same capacity per volume at a given temperature (such that both are gases), there was no advantage to using the more expensive neon, and helium was chosen as the circulating gas.[1] The choice of liquid hydrogen for use in the heat exchanger was made on the basis of a calculation [11], based on parameters given in Tables 1 and 2.

Fluid	MW	T_{NBP}	ρ_L	ρ_V	ρ_G	ΔH_V	V_V/V_L	V_G/V_L	VI
		K	kg/m^3	kg/m^3	kg/m^3	kJ/kg			K*cm^3/J
He	4.003	4.2	124.9	16.9	0.178	20.3	7.4	701	117
H_2	2.016	20.3	70.8	1.34	0.0899	446	52.8	788	8.9
Ne	20.18	27.1	1207	9.58	0.9	85.8	126	1341	2.6
N_2	28.01	77.3	808	4.62	1.25	199	175	646	1.4

Table 1. Viable cryogens with a normal boiling point (NBP) below 30 K, and liquid nitrogen for reference. Subscripts L and V refer to liquid and vapor at T_{NBP}, while subscript G refers to values taken at 0˚C. The Vaporization Index (VI) = $10^3 \cdot (300-T_{NBP}) / (\rho_L \cdot \Delta H_V)$, where ρ is density and ΔH_V is the heat of vaporization.

A quality factor Q for the refrigeration of the circulating gas via liquid cryogen consumption (boiling in the heat exchanger) was defined as

$$Q\ (\text{kJ/\$US}) = \Delta H_V \cdot \rho_L \cdot (1\ \text{m}^3/1000\ \text{liter}) \cdot (\text{liter/\$US}).$$

That is, Q is a kiloJoule of heat-of-vaporization/$US at T_{NBP}. Relevant Q values are given in Table 2.

Fluid	T_{NBP}	ΔH_V	ρ_L	Cost	Q
	K	kJ/kg	kg/m^3	$US/liter	kJ/$US
He	4.2	20.3	124.9	3.00	0.85
H_2	20.3	446.0	70.8	0.53	59.58
Ne	27.1	85.8	1207.0	173.00	0.60
N_2	77.3	199.0	808.0	0.07	2297.03

Table 2. Viable cryogens with NBP below 30 K and liquid nitrogen, and their quality value Q, based on refrigeration/cost at T_{NBP}. The costs are representative of the year 2002 when this study was made.

An operational cycle of the system involved a few-second-long pulse of the 15-T magnet during which about 18 MJ = 18,000 kJ of energy was generated, followed by a 30-minute cooldown during which this energy was transferred to the boiling liquid in the heat exchanger. The estimated cost for one cooling cycle (pulse) with LH_2, LHe and LNe is

$$LH_2\ \text{Cooling Cost} = 18{,}000 / Q = \$300\ \text{per pulse},$$

$$\text{LHe Cooling Cost} = (60/0.85) \cdot (LH_2\ \text{Cooling Cost}) = \$21{,}000\ \text{per pulse}.$$

$$\text{LNe Cooling Cost} = (60/0.60) \cdot (LH_2\ \text{Cooling Cost}) = \$30{,}000\ \text{per pulse}.$$

Clearly, liquid hydrogen is much more economical than either helium or neon on a per pulse basis.

[1] This contrasts with recent proposals to cool high-temperature superconducting magnets directly with liquid hydrogen [9].

A full PI diagram for this system was developed, as shown in Fig. 3.

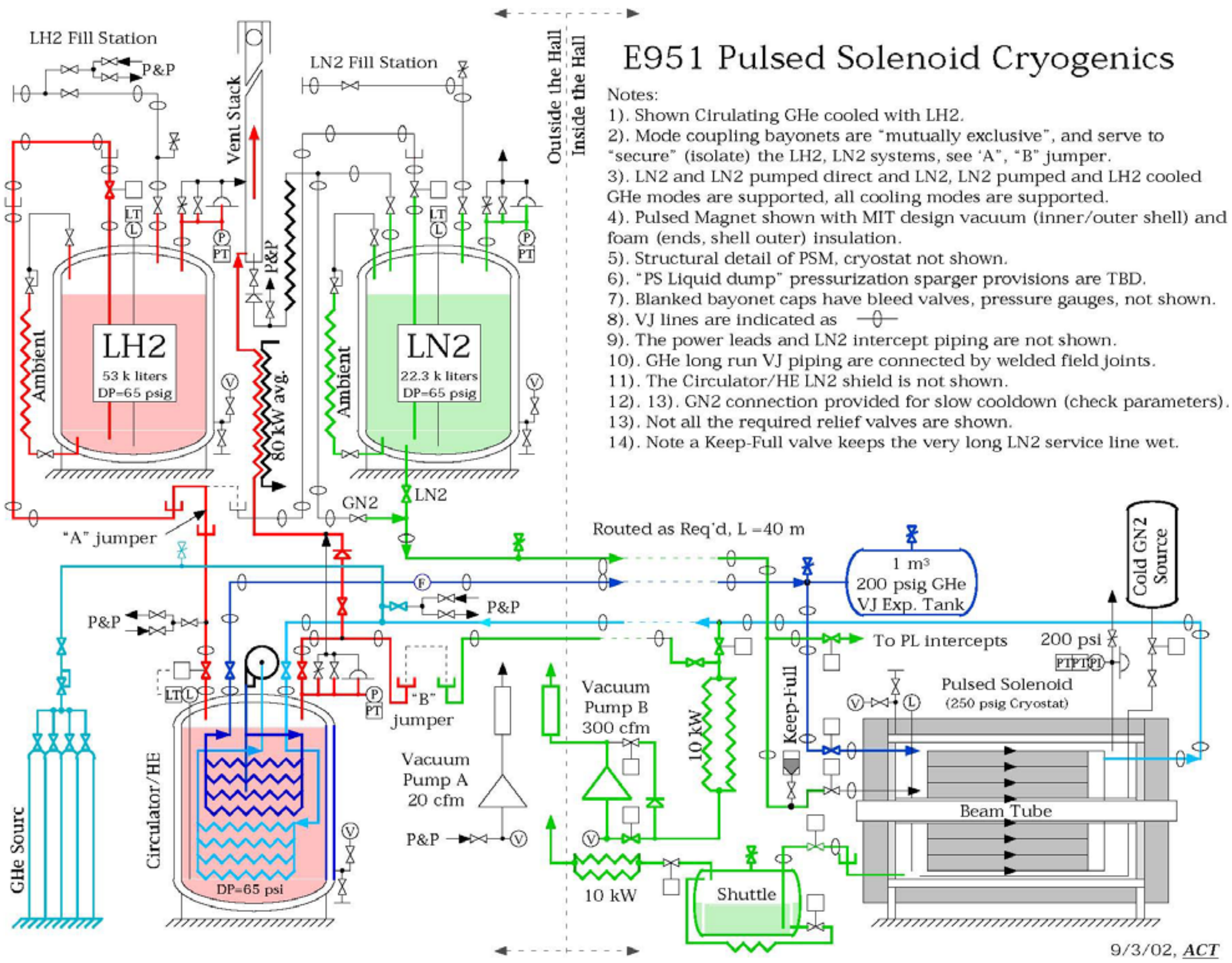

Fig. 3. Piping and Instrument diagram for the proposed cryogenic system to operate a 15-T pulsed, copper solenoid magnet at 30 K.

A surplus heat exchanger (from the never-completed Superconducting SuperCollider) of an appropriate size was identified (Fig. 4). The heat exchanger was to be equipped with s semi-hermetic centrifugal pump operating at about 1.5 bar, circulating He gas at a rate of about 100 l/s, which would have generated about 1 kW of heat (in addition to the 10 kW load of the He gas heated by the magnet). A 20,000-l Dewar was foreseen for the liquid hydrogen.

Fig. 4. The SSC-surplus heat exchanger for possible use in the proposed cryogenic system.

Discussions with the Laboratory Safety Committee as to the use of liquid hydrogen had begun, but when an 8 MW power supply became available that would permit operation of the magnet at 15 T at 80 K, cooled by liquid nitrogen [12], we implemented that option [13].

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