E951 High-Power Pulsed Cooling

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Background

Brookhaven National Laboratory Experiment E951 requires a periodic, short flattop, maximum 15 Tesla field over a 1-m long 15 cm warm bore[1]. A cryogenically cooled, pulsed solenoid magnet (PSM) most efficiently provides that field over the required volume[2]. Realization of this magnet and the power supply system[3] to drive it requires that the magnet is cooled to reduce the copper conductor's resistance and thus the power consumed and the refrigeration required per pulse. Optimization of the 15 T pulsing[4] concludes that the magnet be must be cooled to 27 K before the pulse and from 71 K to 27K thereafter in 30 minutes for the next pulse. This note addresses methods to extract the 13.5MJ-delivered/PSM pulse.

Task Definition

At the intended repetition rate the 15 T pulse dynamic energy deposition[5] results in a 27 kW peak and 7.5 kW average cooling system power load. The sum of the steady state background loads is ca. 700 W. PSM heat is extracted at temperature by circulating cooled gaseous helium (GHe). The GHe cooling system circulator flow work, pump inefficiency and conductive heat loads[6] add ca. 1 kW to the background steady state average conductive and radiation loses.

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1 H.G. Kirk, *Overview of E951 Pulsed Solenoid Proposal* (Feb. 9, 2002) http://pubweb.bnl.gov/users/kirk/www/e951/iit_feb_02/pulsed_solenoid.pdf

2 R.J. Weggel, *A Three Stage Cryogenic Pulse Magnet Program for the BNL Targetry Experiment* (Feb. 9, 2002), http://www.hep.princeton.edu/~mcdonald/mumu/target/weggel/chicago_020902.pdf

3 I. Marneris, *E951 Power Supply to Pulse a 14.5-T Solenoid Magnet* (Feb. 9, 2002), http://www.hep.princeton.edu/~mcdonald/mumu/target/marneris/e951_power_supply_km2.pdf

4 R.J. Weggel, *A Three Stage Cryogenic Pulse Magnet Program for the BNL Targetry Experiment* (Feb. 9, 2002), http://www.hep.princeton.edu/~mcdonald/mumu/target/weggel/E951Juan2.pdf

5 Exclusive of all steady state background losses: circulator, cryostat, transport, storage dewar, etc.

6 An estimated minimum value. Replace with the optimized design estimates of Jeff Shull/Bob Linden of Barber-Nichols when available.

Refrigerator or Cryogen Cooling

The 9.2 kW average operating load must sustain peaks to 27 kW and turn down to ca. 1.7 kW standby load. A helium refrigerator to provide 20 kW at 80 K has recently been purchased[7] for $1.2 million. Scaling linearly by the power and temperature, a budgetary cost estimate for a 10 kW at 20K refrigerator is (10/20)*(80/20)*$1.2 million = $2.4 million[8], exclusive of installation, housing, power consumption, etc.

Cryogen consumption (use of the liquid's heat of vaporization and release of the vapor to the atmosphere) cooling must, for normal boiling point temperature reasons, be chosen from the first five entries in Table 1. (Nitrogen has been added as a point of comparison.)

Fluid	MW	TNBP	rho $_L$	rho $_V$	rho $_G$	^2H_V	V_V/V_L	V_G/V_L	VI
Units		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	0.1780	20.3	7.4	701	117.0
H_2	2.016	20.3	70.8	1.34	0.0899	446.0	52.8	788	8.9
D_2	4.028	23.6	161.0	2.3	0.1790	305.0	70.0	899	5.6
T_2	6.032	25.0	257.0	3.14	0.2690	231.0	81.8	955	4.6
Ne	20.180	27.1	1207.0	9.58	0.9000	85.8	126.0	1341	2.6
N_2	28.010	77.3	808.0	4.62	1.2500	199.0	175.0	646	1.4

Table 1. List of cryogens with a NBP below 30 K and liquid nitrogen for reference. Subscript G values taken at 0˚C. The Vaporization Index (VI) = ((300-T_{NBP})*(1/(rhoL*ΔHV))*E+3).

The thermophysical parameters/unit cost based cryogen consumption refrigeration quality, Q, for the candidates is:

$$Q\ (kJ/\$US) = (\Delta H_v)*(rho_L)*(1/(1E3\ l/m^3))*(l/\$US),$$

That is, a kilo-joule of heat of vaporization/$US at T_{NBP}.

[7] This is the cost of the CERN ATLAS refrigerator.
[8] And a ca. 1 year minimum fabrication delay.

Fluid	T_{NBP}	^2H_v	rho_L	Cost	Q
Units	K	kJ/kg	kg/m^3	$US/l	kJ/$US
He	4.2	20.3	124.9	2.00	1.27
H_2	20.3	446	70.8	0.53	59.76
D_2	23.6	305	161	*100.00*	0.49
T_2	25	321	257	*1000.00*	0.08
Ne	27.1	85.8	1207	*10.00*	10.36
N_2	77.3	199	808	0.07	2,297.03

Table 2. Cryogens with a NBP below 30 K and liquid nitrogen, and their NBP refrigeration/cost quality Q value. Italicized costs are best estimates

Ne and N_2 can be eliminated on the basis of T_{NBP} for a 27K secondary load. Deuterium (D_2), Tritium (T_2) and Ne can be eliminated on the basis of their availability or, equivalently, cost as reflected in their low Q values. Only Helium and Hydrogen remain T_{NBP} contenders.

The estimated cost to operate a 10 kW average load[9] with consumed LH_2 for eight hours is:

$$H_2 \text{ Cooling Cost} = (10/59.76)*3600*8 = \boxed{\$4,829.28} \text{ per 8 hrs}$$

The corresponding eight hour He cost would be:

$$\begin{aligned} \text{He Cooling Cost}^{10} &= (59.76/1.27)*(H_2 \text{ Cooling Cost}) \\ &= 47.06*(\$4,829.28) \\ &= \boxed{\$227,242.00} \text{ per 8 hrs.} \end{aligned}$$

The economic reason to choose liquid hydrogen over helium cryogen cooling is clear. (See foot note 9 as well.)

If the experiment is operated for 3 months of one 8 hour shift/day, i.e., 90*8 hrs = 720 hrs, the cost to provide a 10 kW@20K refrigerator/liquefier in capital and power costs are:

$$\text{R/L Cost} = 720*[(\$2.4E+6/720) + (600*0.75)*(\$0.05)],$$

[9] Assumes there is no rate-dependent load non-linearity.
[10] If 5-20K sensible heat utilized, could be (20/95)*$227k = $47.8k.

$$= 720*[\$3,333 + \$22.50]$$
$$= \boxed{\$2.416 \text{ million}}$$

Which compares to the liquid hydrogen 10KW@ 20K consumption 720 hour cost of:

LH2 Cost = 720*(10/59.76)*3600 = $\boxed{\$0.434 \text{ million}}$

Unless there is a subsequent R/L use that can afford the ca. $2 million residual cost, the experiment is most economically performed and through LH_2 consumption.

Conclusion

Liquid Hydrogen is flammable and must be handled with care. Some additional cost for making a proper LH2 installation could have been provided above. The estimated direct cost to modify those items (mostly electrical) hydrogen area items and install a hydrogen gas monitor system is $20k. At that level of additional cost none of the above conclusions change.

The system design will be reviewed by the BNL safety organization and committees to assure that the PSM cryogenics satisfy all of the relevant safety rules. Once the design review is complete, operating procedures are detailed and safety reviewed and BNL personnel trained in the use of the equipment the hard piped, vacuum jacketed, automatically hydrogen leak monitored/interlocked, the system can be safely operated in the BNL E951 experimental area.

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