FLUX PUMPS AS POWER SUPPLIES IN COMPARISON WITH ALTERNATIVES*

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INTRODUCTION

For a better understanding of the losses associated with energizing a superconducting magnet, a comparison of the relative performance between a flux pump and vapor-cooled input leads supplied by a conventional power source will prove illuminating. Thus, for the same magnet, the flux pump losses for various modes of operation and the losses for vapor-cooled leads optimized for the same operating current will be calculated. Since both calculations are based closely on experimental results, the comparison that is presented for a particular magnet is quite realistic. The inferences and conclusions, however, may not be applicable to all magnet systems since only one type of flux pump is discussed. The loss problem becomes more important with the size of the magnet, and so a scheme for powering large magnets with minimum loss will be proposed. Only partial experimental observation is available on this latter point.

LOSS CALCULATIONS

Flux Pump. The general theory of the losses associated with flux pumps has been presented by various authors.[1-3] It has also been shown how these theories — along with some experimentally determined parameters — can be applied to a particular system to obtain the losses associated with pump switching as a function of the rotation frequency[4] for a rotating magnet, Nb-foil flux pump. In addition to the switching losses, one must also consider the ac losses of the current carrying pump material and the joule losses in the normal shunt. For the small magnet system, which has been previously described[4] (H_{max} = 39 kG at I_{total} = 1480 A), the loss rate (in watts) takes the form

$$\text{Switch loss} = 9 \times 10^{-3}\, \omega + 4.7 \times 10^{-2}\, \omega^2 \quad , \tag{1}$$

$$\text{Ac loss} = 2 \times 10^{-2}\, \omega \quad , \tag{2}$$

$$\text{Shunt loss} = 3.5 \times 10^{-4}\, (dH/dt)^2 \quad . \tag{3}$$

The relationship between dH/dt (G/sec), the rate of increase of the field, and ω (rev/sec), the pump rotation frequency, was experimentally determined. For the mode of operation consistent with the above equations, $\omega = 0.105$ dH/dt rev/sec as shown in

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1. S.L. Wipf, in Proc. Intern. Symposium on Magnet Technology, Stanford, Calif., 1965, p. 615.
2. D. van Houwelingen and J. Volger, in Proc. Intern. Cryogenic Engineering Conference, Tokyo and Kyoto, Japan, 1967, p. 135.
3. H. Voigt, Z. Naturforsch. 219, 510 (1966).
4. M.S. Lubell and S.L. Wipf, in Advances in Cryogenic Engineering (Plenum Press, New York, 1968), Vol. 13, p. 150.

Fig. 1. The total losses in watts [Eqs. (1), (2), and (3)] for different rates of energizing are shown in Fig. 2. As is readily evident, the loss increases rapidly with rotation or dH/dt. This particular pump was operated at a maximum speed of 4 rev/sec, but rotating pumps have been operated at much higher rates[1,5] so larger rates will be considered in the analysis. For the magnet being discussed, a dH/dt = 26.3 G/sec was equivalent to a dI/dt = 1 A/sec.

Vapor-Cooled Leads. A description has recently been given for the design of current leads which are cooled by the helium boil-off gas.[6] The size of the leads and number of woven silver-plated copper conductor tubes (also serving as gas passages) are chosen to minimize the losses at the anticipated maximum operating current.

For a comparison with the system discussed above, a set of vapor-cooled leads which are optimized for 1480 A are needed. Since data for this are not available, a close approximation (described in Fig. 2 of Ref. 6) will be used. The loss rate as a function of current is given for a set of leads (3/4 in. o.d., 80 conductor strands, optimized for 1320 A) up to a maximum current of 1400 A. The loss as a function of current can be obtained in analytic form by fitting the experimental loss data with a quadratic dependence on current. For the leads optimized for high currents, this approximation is quite good. The loss rate in watts for a pair of 1400 A leads is

$$\dot{m} = 1.55 + 6.7 \times 10^{-7}\, I^2 \quad . \tag{4}$$

For the magnet system being considered, the current can be expressed in terms of the rate of energization as

$$I = 137\,(dH/dt)\; t_h \quad , \tag{5}$$

where dH/dt is given in G/sec and t_h is the time in hours necessary to reach the maximum current. Since the flux pump losses depend only on the rate of excitation while the vapor-cooled leads depend on the current level in addition to an appreciable zero current heat leak, the only way to compare them is to calculate the total loss in liters of helium for various energizing rates and times. For the vapor-cooled leads, the total loss in liters of helium is obtained by substituting Eq. (5) into Eq. (4) and integrating. The loss in liters of helium is

$$\text{Loss} = (2.07 + b\, t_h^2)\; t_h \quad , \tag{6}$$

where $b = 5.6 \times 10^{-3}\,(dH/dt)^2$ and the latent heat of helium is 2.7×10^3 J/liter (hence 3/4 W dissipates 1 liter/h).

Comparison of Losses. In comparing the losses between a flux pump and vapor-cooled leads on the same system, we are assuming that the Dewar losses are the same and that the losses introduced by the magnet support structure are identical, and not significantly dependent on the helium level. We are also assuming that the flux pump can be attached to the existing structure without introducing any significant heat leak and also that the vapor-cooled leads do not require any additional supports.

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5. K.R. Efferson, Rev. Sci. Instr. 38, 1776 (1967).

6. For an up-to-date discussion of the Buchhold flux pump, see R.L. Rhodenizer, these Proceedings, p. 654.

Figure 3 shows the losses as a function of time for various rates of energizing for a flux pump and a set of vapor-cooled leads. The losses due to the flux pump cease as soon as the maximum operating current is reached — thus, with the system in persistent mode, there are no operating losses at maximum field. On the other hand, while the losses for the vapor-cooled leads are small if the system is energized rapidly, the operating losses at maximum field are large and continue, of course, until the magnet is de-energized. We are comparing here only the energizing and operating losses, but in practice one must also consider the losses on decreasing the field. Even in the special case considered here, the essential features are evident; the mode of operation (steady state or ramp) and the rate of energizing determine which system of powering a magnet leads to minimum loss. Except for the fastest rates, the vapor-cooled leads have much larger losses. Even for the fastest rate considered, 10^3 G/sec, however, the total losses of the vapor-cooled leads surpass the flux pump losses after four hours of operation.

In common practice most magnet systems are operated at a preset field for a long interval. In these cases, the flux pumps available at present are much more efficient than the vapor-cooled leads for small magnet systems. The flux pump considered in this discussion has an efficiency of approximately 50%, so that the comparison would be even more striking had we used the Buchhold-type of flux pumps,[6] which have efficiencies approaching 95%.

POWERING LARGE MAGNETS

The rotating magnet flux pumps are unsuitable for powering large magnets because of their low efficiencies. Buchhold-type pumps have been built with output powers of 50 W, but even these would only be adequate for magnets with stored energies below, say, about 0.5 MJ. It seems most likely, therefore, that in the near future only vapor-cooled leads will be used for energizing large magnet systems. To reduce the over-all losses, we suggest the following operating scheme as being possible for large magnets: (1) Use vapor-cooled leads to energize the magnet. (2) After maximum current is reached, the system can be placed in persistent mode with a superconducting short. The normal state resistance of the switch should be hundreds of ohms so as not to interfere with the charging. (3) At this point to further reduce the heat leak into the system, the current contact at the top of the vapor-cooled leads (after the current is reduced to zero) can be opened. In this manner the system's only thermal contact to room temperature is through thin-walled stainless steel. The thin-walled stainless-steel tubes of ohms or tens of ohms resistance connected in parallel provide both an exit vent for the helium vapor and also serve the important function of an external short for protection should it be necessary to discharge the magnet rapidly because of a quench, loss of coolant, failure of switch, etc. (4) For very large systems operated in persistent mode, it may be necessary to also employ a flux coil detection system which can be used to remotely control a relay activated motor to quickly reconnect the vapor-cooled leads. With this refinement the stainless-steel tubes only have to carry the load current during discharge for the short time necessary to reactivate the main current leads.

The ideal persistent switch,[2,7] of course, is a small flux pump to overcome any decay due to resistive contacts and joints, etc. Although this over-all scheme has not to our knowledge been employed, we have used vapor-cooled leads on a test system and

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7. Private communication with S.L. Wipf; H. Brechna at SLAC and P.F. Smith at Rutherford are both contemplating use of a flux pump as a persistent switch and field trimmer.

the anticipated saving in refrigeration requirements was realized when the external electrical and thermal contact was broken (Fig. 4). Figure 4 shows a schematic of this system and the measured losses are also indicated. With the contacts in the open position, the helium vapor exits through thin-walled stainless-steel tubes. Note that the leads are switched in a vacuum chamber and thus, no frosting occurs to prevent a low resistance contact from being re-established. Even without the use of a persistent switch, detachable contacts to vapor-cooled leads aid in keeping the heat input to the system at a minimum between use and save in over-all refrigeration requirements.

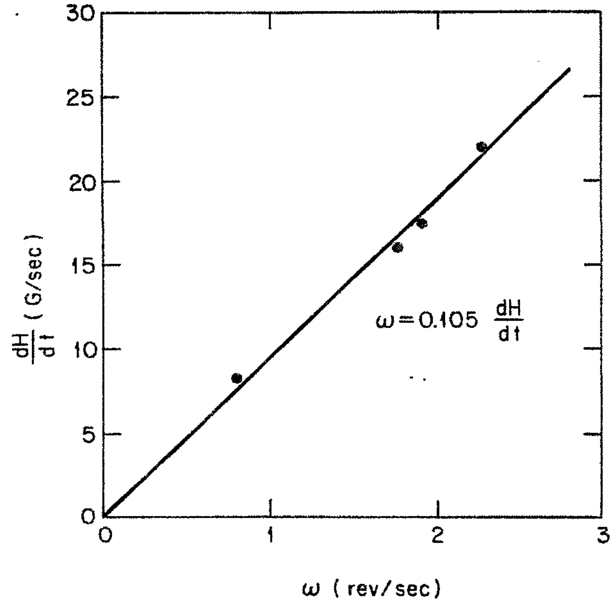

Fig. 1. Rate of field increase vs flux pump rotation from data of Ref. 4.

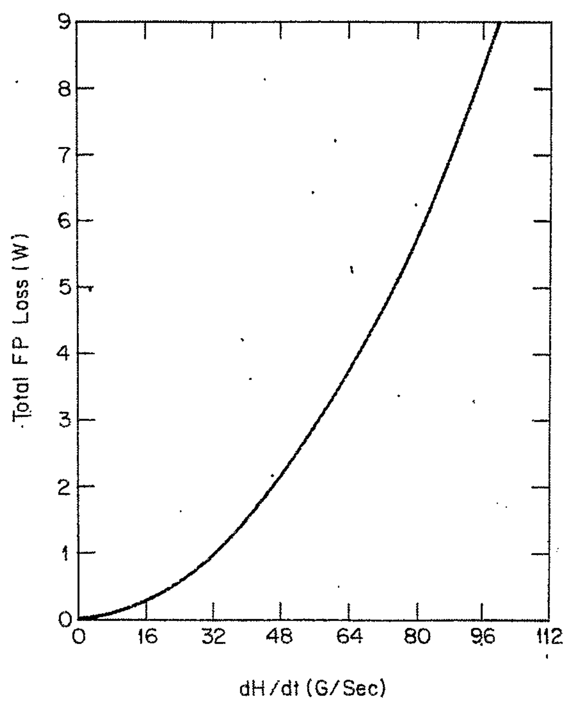

Fig. 2. Flux pump loss rate [Eqs. (1)-(3)] vs rate of field increase.

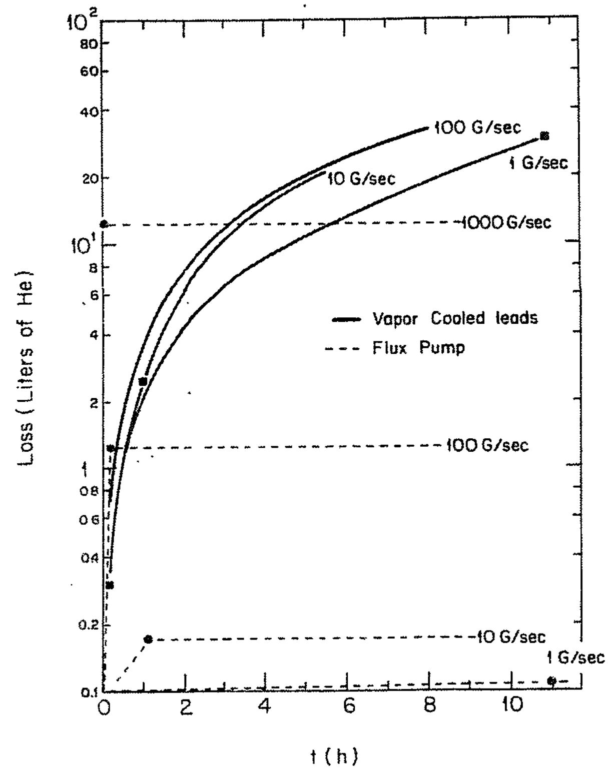

Fig. 3. Comparison between flux pump and vapor-cooled leads of loss vs time for different rates of energizing. The symbols indicate the time at which the maximum operating current was reached. For the vapor-cooled leads, faster rates ($dH/dt \geq 10^3$ G/sec) are undistinguishable from the 100 G/sec curve after approximately 3 hours.

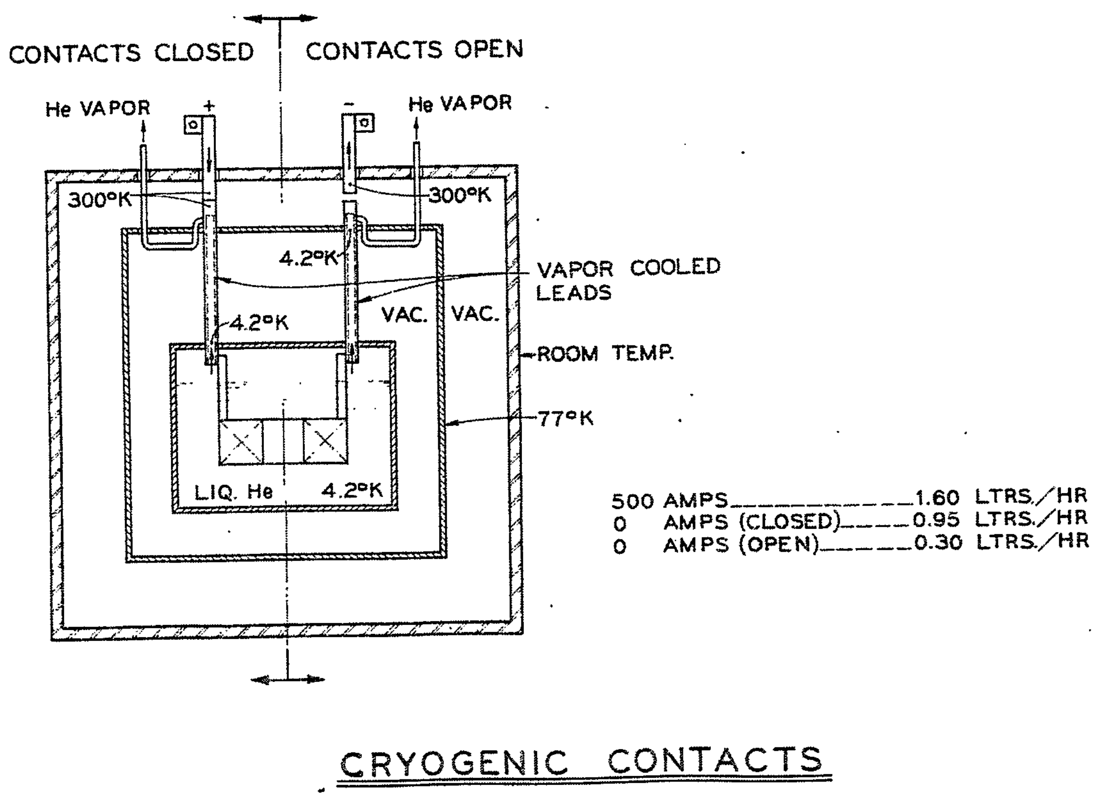

Fig. 4. Measured heat leak through vapor-cooled leads compared with the leads being opened. With the contacts in the open position, the helium vapor passes out through thin-walled stainless-steel tubes.