FLUX PUMP WORK AT LOS ALAMOS*

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Flux pump work at Los Alamos has a long but somewhat sporadic history. I started thinking about what we now call flux pumps in October, 1961, when for both mechanical and electrical reasons, I had some coils made from large cross-section Kunzler wire and ribbon, and somehow could not get the courage to push 1000 A into a liquid helium cryostat. I think we all feel differently now and an additional heat load of 2 to 4 W is of small consequence in the big engineered coils to be used in most high or medium energy physics experiments.

However, there is a regime of medium sized coils with field energies below 50 or 100 kJ where relatively high flux pump inefficiencies may be tolerated. Specifically, these are situations where a pumping loss of 10 to 30 liters of liquid helium can be of the same magnitude as the cool-down losses. This then has to be weighted against a steady loss of 2 to 4 liters/hour for the duration of the experiment. Unfortunately, even this comparison is not necessarily clear-cut because you also have to consider disconnectable or extendable leads, i.e., variable loss leads in conjunction with a thermally, magnetically, or automatically operated persistent switch. So what I am really saying is that we have a complex systems analysis problem involving questions of operational stability, simplicity, and reliability that are hard to evaluate. Hence there is still need for new concepts and for novel implementations of the old ideas to suggest alternatives for the systems designer. That is essentially the objective of our present, part-time flux pump effort. We are trying a number of approaches, but cannot as yet quote definite numbers for flux pump efficiencies or for power levels.

As I mentioned, some of our first flux pumps (Fig. 1) were built with rigid, heat treated, large diameter Kunzler Nb_3Sn wire.[1] We minimized joints and made persistent contacts through NbSn powder-filled capsules. In 1963 we actually pumped one of these coils, which was potted in indium, well into the Kim-Anderson flux creep region (at 10 kG and 800 A). Our switches (Fig. 2) were just copper capsules with gas inlet and outlet tubes covering a previously flattened section of the conductor. There were several things wrong with this approach:

1) The switches were short. Hence, their "off" or "resistive" state resistances were small. This lengthened the time for flux transfer and, hence, limited the repetition rate of the pumps.

2) Our switching process was highly irreversible. We really just had triggered instabilities, as indicated by the fact that the switches worked best at 1000 A.

3) We had to use a fairly complicated electronic timer to synchronize power supply reversal, the programming of the primary current, and the timing of the switches.

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1. H.L. Laquer, Cryogenics 3, 27 (1963).

Our second flux pump[2] tried to avoid these shortcomings by making the switches automatic. It arose out of some discussions about the nature of persistent currents in superfluid helium and the magnitude of the critical superfluid velocities, a phenomenon which is quite analogous to the onset of electrical resistance in a superconductor. Hammel[3] was interested in determining critical velocities from the persistent circulation possible in a parallel superfluid circuit (Fig. 3). Since soldering is quicker than glass-blowing, and since field or flux measurements are easier than the observation of superfluid circulation, Hammel asked me to assemble the equivalent superconducting circuit which consists of a small and large inductance in parallel, either in a ring circuit (Fig. 4) or as separate entities (Fig. 5).

The performance of this superconducting equivalent turned out completely as one might predict. At a fixed applied voltage, current will divide inversely as the inductances, until the smaller (L_2) reaches its critical or limiting value and it takes the entire applied voltage (E) just to maintain a constant limiting current through L_2; hence the power dissipated in L_2 and in the liquid helium bath is EI_2. The field in the larger coil will continue to build up and, as long as the voltage is maintained, all the additional current will flow into L_1. Reduction of the applied voltage will make L_2 immediately superconductive again, trapping all flux. When the external current reaches zero, a field will have been trapped in L_1 and the current in L_2 will have been reversed. The process can be repeated with external current leads or with a low temperature condenser until L_1 reaches its critical current. We can reduce fields by simply reversing polarities and we have a hysteresis loop (Fig. 6). The hysteresis figure suggests an optimum critical current in the switching inductance just equal to the desired maximum current in L_1.

One also wants these slightly contradictory properties in L_2: minimal inductance, maximum "normal" or perhaps "flux flow" resistance, and stable (non flux jump) switching. Also, it is evident that there may be some advantages in varying or controlling the critical current in L_2 by magnetic or thermal biasing.

A device of the type just described is clearly not a flux pump since it requires the introduction of at least $2I_{1\,max}$ into the cryostat. A flux pump needs a changing or moving magnetic field at a low temperature, such as a step-down transformer. I always felt that an iron core was desirable for energetic reasons. However, Dick Britton last week showed me a very cleverly designed pump without any iron in it. There are some real advantages in not having to worry about fringe fields saturating the iron.

Now the problem of putting a transformer on the circuit of Fig. 5 lies in (a) avoiding losing on the back swing what was gained on the forward swing, and (b) getting the flux into the (single turn) secondary if it is a superconducting circuit. The solution which we originally applied to these problems was (1) putting a small resistance R_o into the secondary circuit, and (2) applying an asymmetric primary current so that R_o can limit the secondary current during the back swing to a value insufficient to switch L_2 (Fig. 7).* It is also apparent that a dc field bias

*The equipment necessary for these experiments is now readily available commercially. We use a Hewlett-Packard 3300 A Function Generator with a 3304 A Sweep-Offset plug-in. Presently, the transformer primary is driven from an HP 6824 A ± 50 V ± 1 A Power Supply/Amplifier, but the new Kepco BOP 36-5M ± 36 V ± 5A Bipolar Operational Power Supply should allow higher primary currents.

2. H.L. Laquer, K.J. Carroll, and E.F. Hammel, Phys. Letters 21, 397 (1966); in Pure and Applied Cryogenics (Pergamon Press, 1966), Vol. 6, p. 539.

3. P. Sikora, E.F. Hammel, and W.E. Keller, Physica 32, 1693 (1966); see also Proc. 10th Intern. Conf. Low Temperature Physics, Moscow, 1966, Vol. 2B, p. 347.

on L_2 should make it switch more easily for one current direction than for the other direction. This, of course, would eliminate the need for an asymmetric primary current and we have done some preliminary experiments along this line. These experiments quickly pointed out the obvious fact that one needs a rather carefully calculated winding profile in order to make the bias field most effective in producing the maximum "normal state" resistance.

Our main effort in the last few months, however, has been on the switch proper. There are again conflicting requirements in that one wants a steep and stable rise in the E-I curves to minimize switch losses. We have reported on solder switches that could be used up to 200 A and niobium switches stable at 600 A.[4] However, what one really would like is a 1000 A switch which can be readily soldered into the circuit. It may be possible to obtain copper-clad niobium wire or ribbon, but lacking this kind of material we did what should make the wire manufacturers shudder. We took some 750 A at 20 kG, 0.050 in. diameter multistrand NbTi conductor and heat treated it for two hours at 700°C. The resulting material had a critical current of about 400 A at 2.6 kG so that it would switch itself in a coil with 5.2 turns/cm. Hence, we obviously need a less severe heat treatment.

Once the bias switches are working, we can consider replacing R_o with another biased automatic switch. At this point, then, we have probably six wires leading to the flux pump so that it is no longer a simple device and we will have to ask ourselves again:

1) Are the resistances of our inductive switches on one hand and their losses on the other still competitive with externally controlled noninductive switches?
2) Are flux pumps themselves competitive with high current leads?

The answer to the first question lies, I believe, in a more complete understanding of partial stability, and the answer to the second question may well limit flux pumps to field energies below 100 kJ.

There is, of course, still another unexplored possibility, namely the use of truly automatic, passive, semiconductor rectifiers at liquid helium temperatures. This is again a materials problem. Commercial 5 A silicon rectifiers can be operated at 50 A in liquid nitrogen, but 4°K operation will require III-V or IV-VI semiconductors such as gallium-arsenide and lead-telluride. As a further speculation one might even consider a niobium-niobium oxide structure which would avoid one of the normal to superconducting metal contacts.

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4. H.L. Laquer, J. Appl. Phys. 39, 2639 (1968).

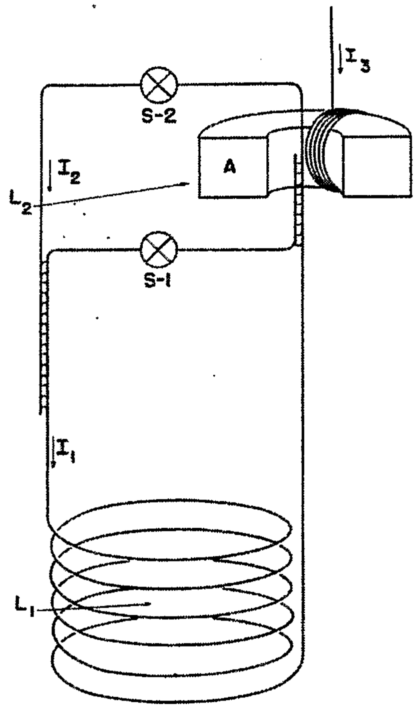

Fig. 1. Electrical flux pump with externally timed switches.

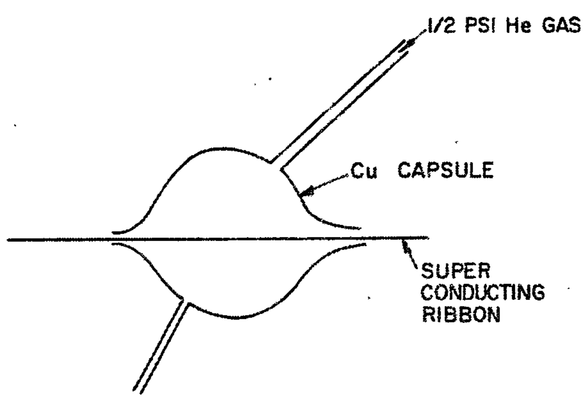

Fig. 2. Switch using warm helium gas.

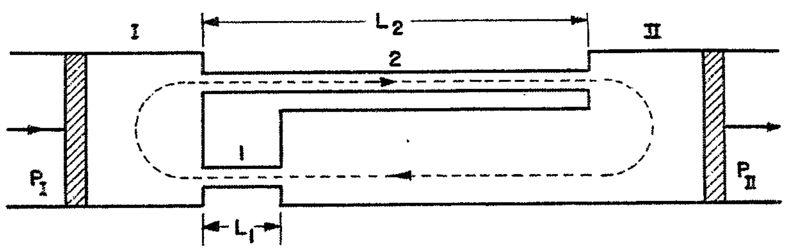

Fig. 3. Superfluid circuit with persistent circulation of He II.

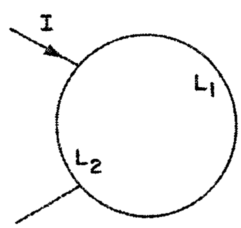

Fig. 4. Simple ring circuit with self-switching properties.

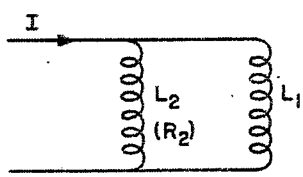

Fig. 5. Parallel inductance circuit, with L_2 acting as an automatic switch.

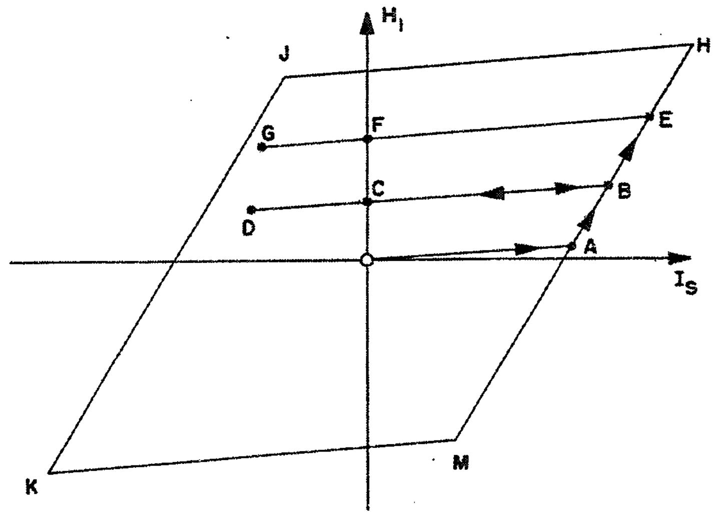

Fig. 6. Complete hysteresis pattern of circuit in Fig. 5. Field H_1 in coil L_1 as a function of externally applied current I_S.

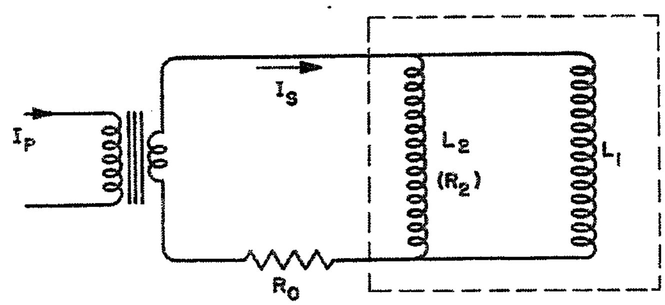

Fig. 7. Automatic flux pump with limiting resistor R_o.