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EXPERIMENTAL SUPERCONDUCTING TRANSFORMER FOR CURRENT STEP-UP†

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For certain applications one would like to use relatively few turns of a high current conductor to make superconducting magnets. High current conductors introduce the problem of large heat leaks, and also the problem of a high current power supply. These problems would be simplified if one could make a suitable current step-up transformer. A design equation for such a transformer is presented. An experimental test was performed on a transformer made of superconducting solenoids which we had on hand. It had a primary current of 79.2 A, and supplied 670 A to a small load solenoid. The transformer was operated in two modes. In the first, the primary current was held constant for 24 hours. The magnetic field in the load solenoid was monitored and the rate of decay in field could be measured. In the second mode, the primary current was regulated to maintain constant field in the load solenoid. The time constant of the secondary circuit was 1.4×10^6 seconds. Such a system could be operated for a number of weeks without recycling.

For applications where the conductors of a superconducting magnet must be accurately wound in place by hand, it is advantageous to use relatively few turns of a large conductor. Large conductor, on the other hand, means large heat leaks and cumbersome, expensive power supplies. These problems would be simplified if one could make a suitable, superconducting, current step-up transformer to go in the cryostat with the magnet.

We shall first discuss the parameters that influence the design of such a superconducting transformer. An equivalent circuit is shown in Fig. 1, in which secondary resistance is neglected. From this circuit we find the ratio of secondary current to primary current to be

$$\frac{i_S}{i_P} = K\frac{N_P}{N_S}\frac{1}{1+(L_L/L_S)}, \qquad \text{where } K = \frac{M}{\surd(L_P/L_S)}$$

is the coefficient of coupling between primary and secondary.

It is interesting that the current step-up ratio is dependent not only on the turns ratio and the coefficient of coupling, but also on the ratio of load inductance to secondary inductance. If one were willing to make the secondary inductance identical to the load magnet inductance, the L_L/L_S would equal one and the inductance factor would be one-half. For a practical transformer, however, it would seem necessary for L_L/L_S to be at least ten. Then in order to have a current step-up ratio of ten, the factor $K(N_P/N_S)$ must be 100.

Although it is easy to get a large turns ratio, considerable care must be used to keep the coefficient of coupling near unity. We have a short computer program to investigate the coefficient of coupling between interwound layers on a solenoid, but we do not yet have a final design. It seems possible to make this kind of transformer with a $K > 0.9$. It should be noted that the size of the primary wire is determined by the current step-up ratio, and not by the usual turns ratio. Once a practical design for a given current step-up ratio is fixed, the transformer size can be scaled to the inductance of the load magnet.

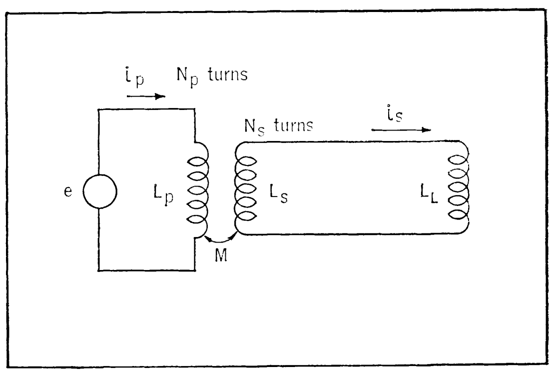

FIG. 1. Step-up transformer circuit.

To demonstrate to ourselves that this simple concept was valid, we constructed a simple step-up transformer from the three superconducting

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solenoids shown in Fig. 2. The large solenoid has 11 550 turns and can carry a current of 134 A. The two small solenoids are very similar to each other with 219 and 238 turns of 1500 A conductor. The two small solenoids were connected in series and mounted one above the other, so that the lower coil was inside the large solenoid and the upper coil was about ten inches above the large

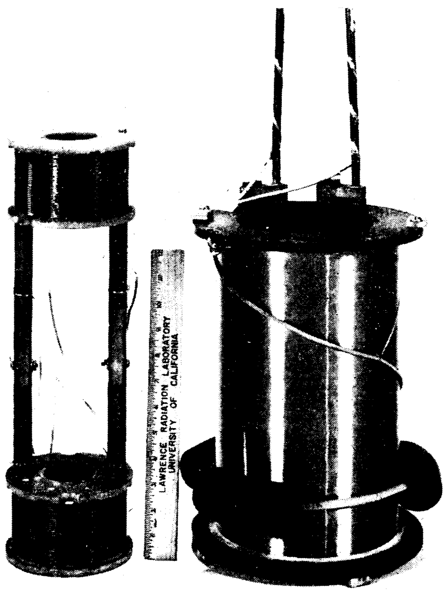

FIG. 2. Experimental transformer components.

solenoid. Bismuth magnetoresistive probes were placed in the center of each of the small coils. From the relative cross sections of the solenoids we estimated that the coefficient of coupling between primary and secondary was about $\frac{1}{3}$. Since the load coil and the secondary coil have nearly the same inductance, the current step-up ratio can be calculated:

$$\frac{i_S}{i_p} = \frac{1}{3} \times \frac{11\,550}{219} \times \frac{1}{1+1} = 8.7.$$

The experiment consisted of two parts. In the first part, the transformer primary was connected to a power supply and the current gradually increased to 79.2 A and held constant for 24 hours. The bismuth probe signal in the load solenoid is proportional to current in the secondary circuit, and it was observed that the secondary current was proportional to the primary current. From the load lines of the solenoids and the field in the center of the secondary solenoid, we were able to determine that the primary current was 659 A. Thus, the step-up ratio was

$$\frac{i_S}{i_p} = \frac{659}{79.2} = 8.3.$$

The secondary current would continue at 659 A indefinitely if there were no resistance in the secondary circuit. However, there were two solder joints where the leads of the solenoids were connected in series. The time constant of the secondary should be $T = (L_L + L_S)/R$, where R = total resistance in the secondary circuit.

The inductances of the two small solenoids were about 3 mH. The field in the load solenoid decayed from 25 kG to 23 kG in 24 hours indicating a time constant of about 10^6 seconds. Thus, the total resistance of the joints was about 5×10^{-9} ohms.

In the second part of the experiment, the power supply was reconnected to regulate on the bismuth probe signal. The primary current was increased until the field was 18.2 kG in the load magnet. This required 57.7 A in the primary. After 730 minutes the primary current had increased to 59.8 A to make up for the loss in the secondary circuit, while keeping the field in the load magnet constant.

The experiment confirmed that it is possible to build a superconducting transformer to step-up current, and that it may be a practical method of powering certain superconducting magnets. In a practical example, the inductance of the load magnet would be many times the 3 mH of our solenoid, while the total number of resistive joints need not increase very much. Then a time constant of 10^7 seconds or longer for the secondary circuit might be possible. In our experiment we could have powered the load magnet for as long as five days without recycling, so a larger system might be powered for a month or longer with such a device.

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