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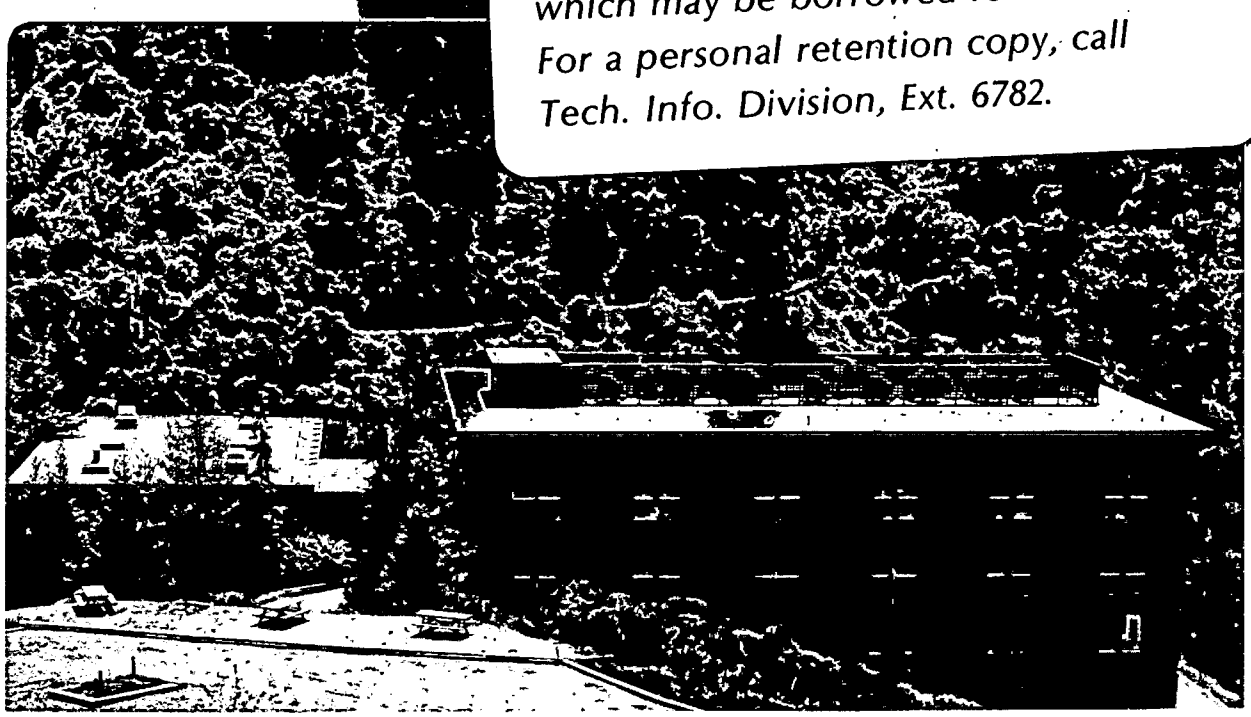

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PULSED MAGNETIC FIELD TESTING OF MULTIFILAMENTARY Nb_3Sn SUPERCONDUCTING WIRE

J. Glazer, D.R. Dietderich and J.W. Morris, Jr.
Dept. of Materials Science and Mineral Eng. and the
Lawrence Berkeley Laboratory,
University of California, Berkeley, CA 94720

INTRODUCTION

Critical current density as a function of applied field, $J_c(H)$, is the key design criterion for many applications of superconducting wire. Some correlations between microstructure and good properties have been made on the basis of both theory and experiment; however, these relationships are not yet well enough defined to obviate the need to test actual samples frequently during the research and design process. The availability of accurate and reliable testing facilities is therefore critical to the development of practical superconductors.

The relationship between the critical current, (J_c), and the applied field, (H), may be determined by fixing either parameter while varying the other. Pulsed field testing employs a fixed current and a rapidly increasing field that eventually exceeds the critical field for that current, while steady field testing uses a fixed field and a slowly increasing current. There is a fundamental difference between pulsed and steady field methods in that the superconductor is near equilibrium during steady field testing, but is far from equilibrium in a pulsed magnetic field. In this sense, steady field testing is superior to pulsed field testing.

The chief limitation on the steady field testing of superconductors is the limited availability and great operating costs of high field magnets. As a result, until the last fifteen or twenty years almost all testing was done in pulsed magnetic fields of a few milliseconds duration. A number of investigators were concerned about dynamic effects that might affect the relevance of the data to steady field applications. But, while there was general agreement that critical currents are degraded in pulsed fields, the

causes were not clearly determined. With the construction of the Francis Bitter National Magnet Laboratory, steady field magnets of 15-20 T became readily available and pulsed field testing was relegated to experiments that required even higher magnetic fields. As a consequence, the study of the relationship between pulsed field and steady field testing was largely abandoned. The disadvantage in this nearly complete transition is that while large steady field testing facilities will probably always be few in number and expensive to operate, pulsed field testing facilities are suitable for decentralized testing. It would thus be desirable if pulsed field testing could be used with confidence as a complement to steady field testing. However, there has been little interest in doing the comparative work necessary to make this possible.

The present work was undertaken to investigate the reliability of pulsed magnet data. The principal objective was not to find a replacement for steady field testing at fields below 20 T but rather to determine the feasibility of using pulsed magnet data for screening prior to steady field testing. Consequently, the goal was to determine whether pulsed magnet data were accurate in a qualitative sense and, if possible, to identify the likely magnitude and direction of any differences from the steady field data.

EXPERIMENTAL PROCEDURE

Samples

The samples used in this work were 133-filament bronze-processed Nb_3Sn wires manufactured in our laboratory. The manufacturing process is described elsewhere [1]. A typical cross-section is shown in Fig. 1. The pulsed-field samples were made by bending a 4.5 cm length of annealed wire into a u-shape with straight portions of about 1.5 cm. This shape was required so that the sample would be both narrow enough to fit into the small bore of the magnet and long enough for good current transfer. Steady field samples were straight pieces of wire 3 cm in length. Both types of samples were heat-treated in evacuated tubes backfilled with argon. Samples of various compositions and heat treatments were tested. The data shown in Fig. 2 are for wires of composition 6.7Sn + 0.2Mg (a/o) reacted at 700°C for 4 and 8 days respectively.

Testing Technique

All steady field critical current measurements were made using a four-point probe technique in a 15.2 T magnet at the Francis Bitter National Magnet Laboratory. The critical current characteristic was measured for transverse fields between 8 and 15 T. The reported value of the critical current is that which produced a 1.0 microvolt potential between voltage taps 5 mm apart.

Pulsed field testing was done using the apparatus shown in Fig. 3, which is capable of producing fields of 20 T. Both the current and the field are triggered by the same pulser unit. It was found desirable to trigger the current first, so that the current was steady throughout the duration of the field. The sample current is fixed prior to each pulse by adjusting a potentiometer. The magnet pulse is produced by discharging the capacitor bank. The voltage to which this capacitor bank is charged controls the peak field. The rise time of the pulse is about 8 msec. The sample probe utilizes the 4-point testing method. It is also equipped with an auxiliary coil on the reverse side that may be used with a differential mode oscilloscope to null out induced voltages in the resistive matrix of the sample which may obscure the superconducting to normal transition. This apparatus has been more fully described elsewhere [2,3].

The sample current, magnetic field and sample voltage are all displayed on a multi-trace oscilloscope as in Fig. 4. The critical magnetic field was defined to be the field at the time the sample went from superconducting to normal. To limit the possible effect of dH/dt on the critical current, the current and field were adjusted so that the superconducing to normal transition occurred as close as possible to the peak field. The values of dH/dt ranged from 10^3 T/sec initially to zero at the peak. Samples were tested over the range of 8 to 15 T. Two to three samples of each type were tested so that averaged results could be compared with the steady field data.

The probes used for both types of testing were designed to minimize strain effects that might distort the data. Strains arise from two major sources, thermal contraction differences between the probe and specimen and Lorentz forces on the sample [4]. An effort was made to minimize these sources of error. The sample holders were constructed of fiberglass-epoxy (G-10), which has a similar coefficient of thermal contraction to bronze. They were both designed to provide a firm support to the sample. The polarity of the currents was chosen so that the Lorentz force pressed the samples against the probes.

RESULTS

The critical current characteristics Ic(H) determined under both steady and pulsed fields were compared for a large number of samples. Representative data are shown in Fig. 4. At high fields, i.e., above 11 or 12 T the data from both methods is almost identical. The pulsed field data is reproducible to within about 10 percent, which may be accounted for by sample to sample variations. Above 12 T the averaged pulsed field and steady field data generally agree to within 15 percent or less. As the applied field decreases, the agreement deteriorates. At lower fields, the steady

field current is almost always higher than the pulsed field critical current. However, only the absolute current-carrying capability of the samples is distorted by the pulsed field; their relative capability is not.

DISCUSSION

The most important result of these experiments is that the pulse field data is qualitatively similar to that obtained by steady field methods. Significant differences in sample quality may be easily identified. This alone justifies using pulsed field testing to direct research efforts and to identify promising material for steady field testing.

Any quantitative comparison of our pulsed field and steady field results is only approximately valid. The inherent problem is that these wires may vary considerably along their cross-section (as do many commercial wires). As a result, while each method produces data consistently for a given wire sample, there is considerable scatter between different samples that received the same heat treatment. Since the different probe designs meant that the single sample could not be tested by both methods, this sample to sample variation could not be eliminated from the test results.

Despite this problem, it is possible to make some general comments about the differences between pulsed and steady field data. At intermediate and high fields the data are comparable, but at fields below 10 T the test results diverge significantly. The good agreement at high fields may be more surprising than the spread at low fields since there are a number of experimental differences between the testing techniques that are known to affect critical current. The different sample geometries and the coarser criterion used to determine the superconducting transition in pulsed field testing are obvious dissimilarities that may affect the results [4]. On a more subtle level, pulsed field testing introduces dynamic effects (dH/dt and possibly dI/dt) which are not present under steady field conditions.

During the 1960's, a number of investigators studied the intrinsic differences between pulsed and steady field magnets. The concensus that emerged was that pulsed field data is generally lower than steady field data, and that smaller values of dH/dt are preferable to large ones [5,6,7]. Several theories were advanced to explain these results. For samples in which the superconductor is clad with a resistive matrix, eddy current heating and a consequent lowering of the critical current due to higher local temperatures was considered to be a factor [5,6]. Flippen also noted shielding of magnetic flux could contribute to higher currents in pulsed field tests. Induced currents due to the changing magnetic field might be expected to translate the entire critical current characteristic

downward, with the greatest shift being at high fields where dH/dt is largest [8]. A further complication is that microstructural parameters that differ from sample to sample may determine how important each of these effects is for any given current and field. Since critical current in type II superconductors such as Nb_3Sn is known to have different microstructural dependences at high and low fields, it is perhaps not surprising that the relationship between steady and pulsed field data should have a breakpoint at intermediate fields.

CONCLUSIONS

This work confirms that, at a minimum, pulsed field magnets may be used to obtain preliminary qualitative results about superconducting samples. Although the quantitative critical current data is not as reliable as that obtained under steady fields, at high fields there is good agreement between the data. Because of the many factors that may play a role, explanation of the degraded critical currents found under pulsed fields at lower applied fields is difficult. Given the current state of theory, much further investigation would be needed to clarify the precise causes of this effect and its generality to other superconductors. Nonetheless, it is apparent that pulsed field magnets may be effectively used to direct the design process, thus allowing steady field testing facilities to be reserved for testing the more promising materials.

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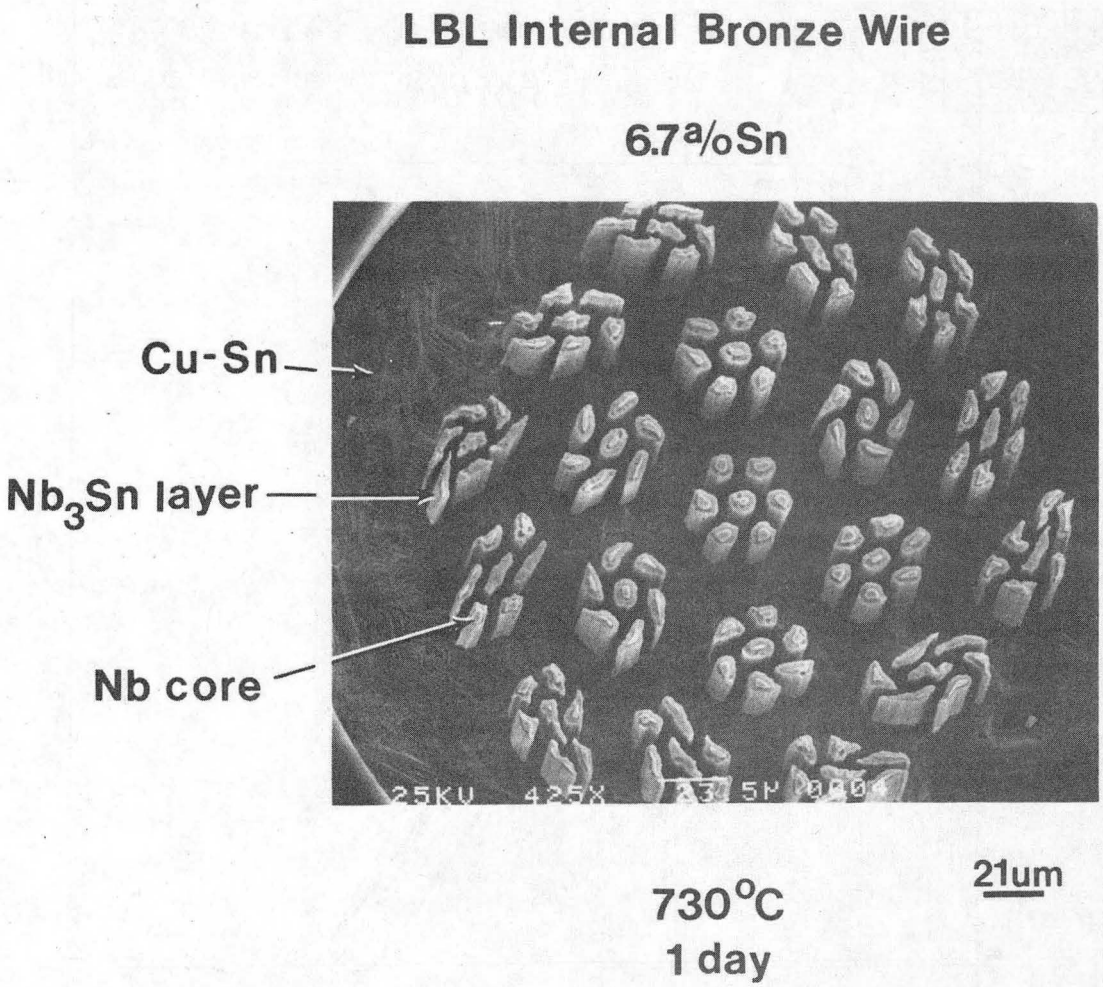

Fig. 1. Cross-section of a 133-filament Nb_3Sn wire. The bronze matrix has been etched away to reveal the Nb_3Sn filaments and the residual Nb cores.

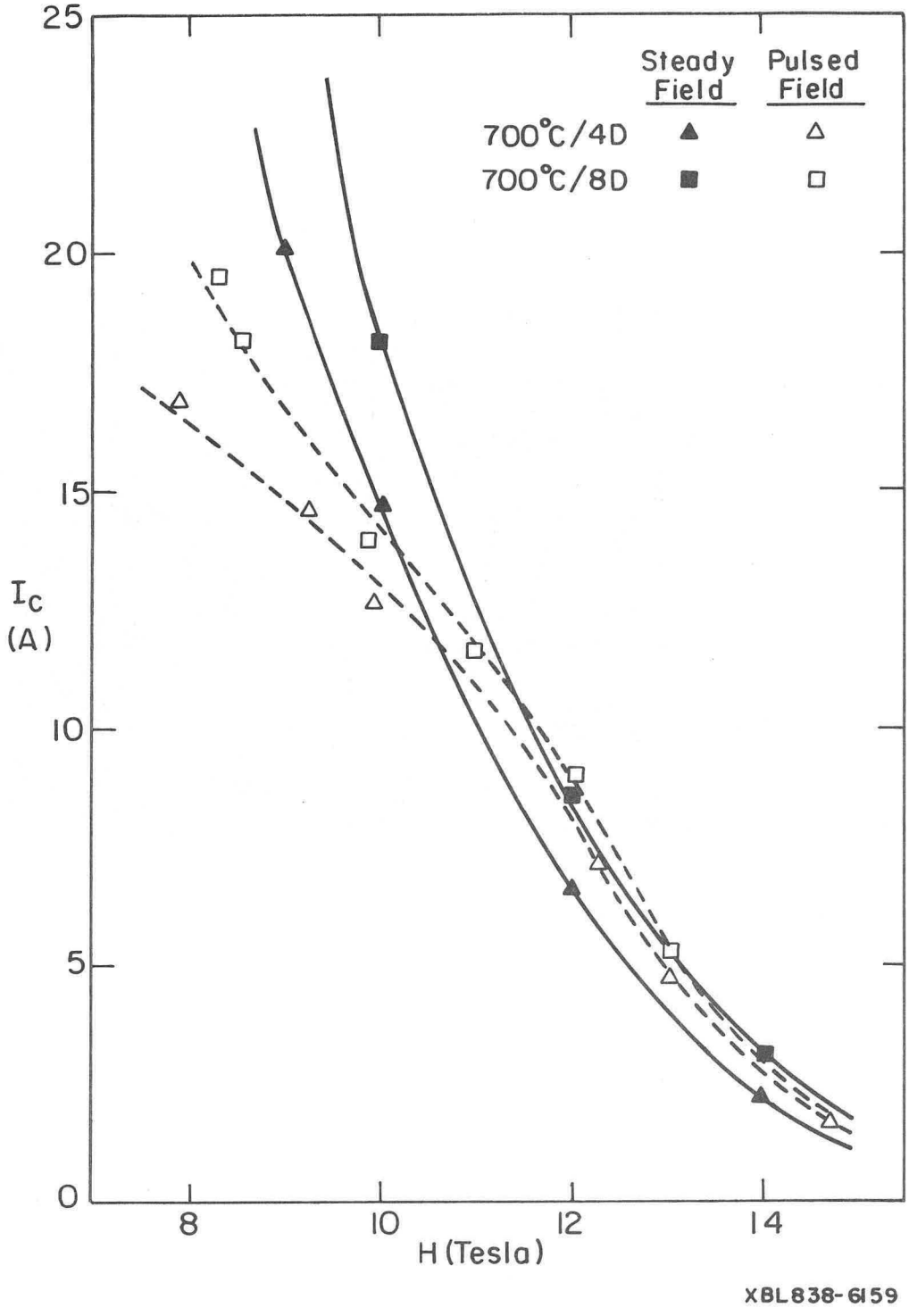

Fig. 2. Comparison of critical current characteristics Ic(H) determined by pulsed field (dashed line) and stead field (solid line) testing.

SCHEMATIC OF PULSE MAGNET

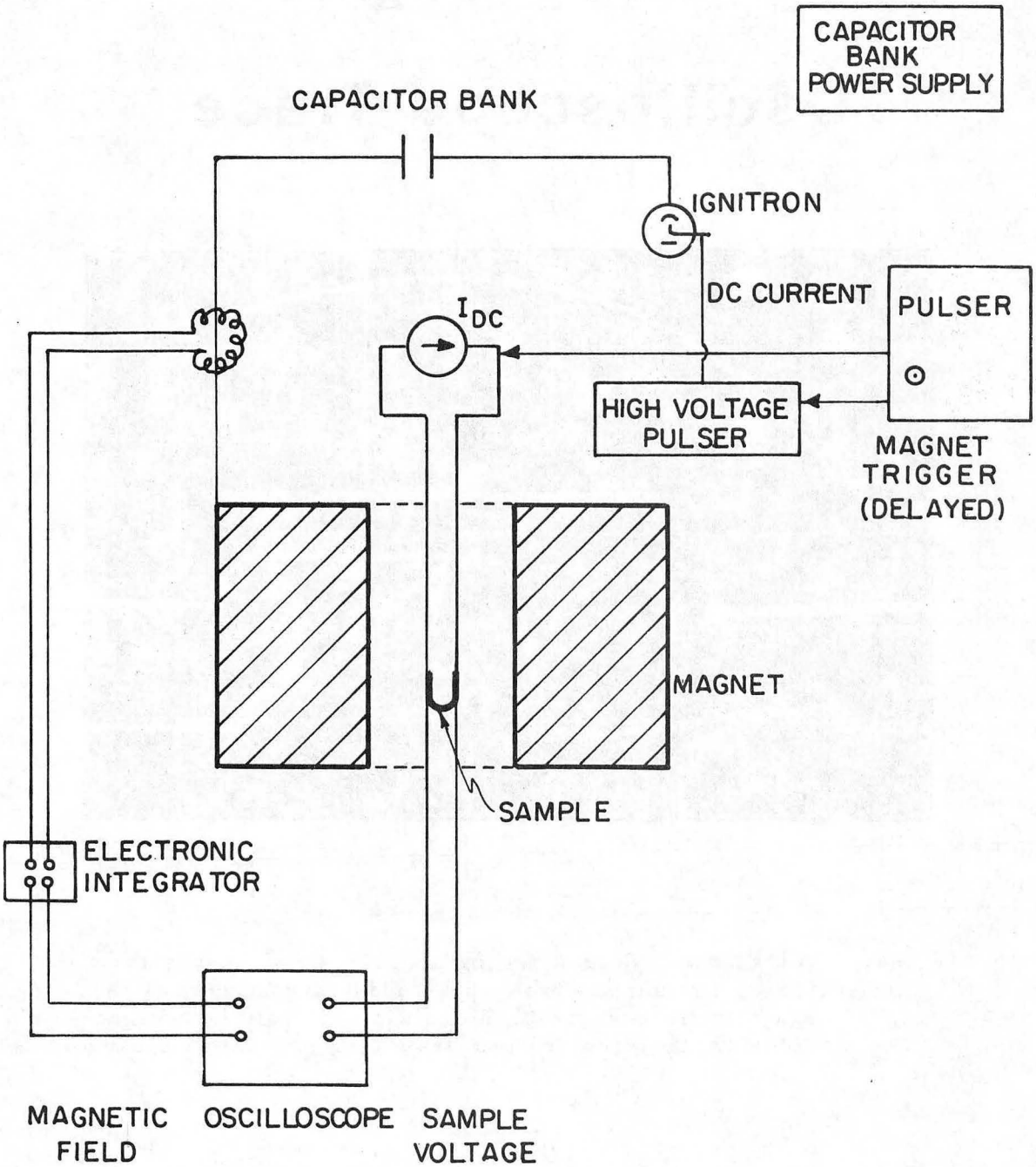

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Fig. 3. Schematic of pulsed magnet apparatus.

Pulse Magnet

Oscilloscope Trace

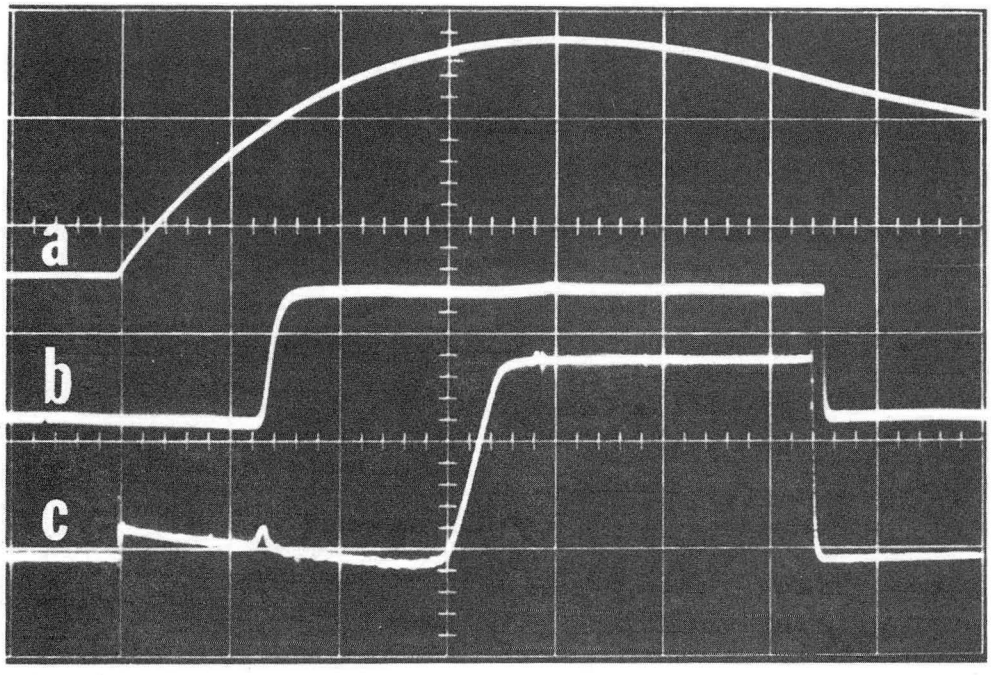

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Fig. 4. Typical oscilloscope photograph illustrating the transition of the sample from superconducting to normal (a) magnetic field-scale 5 T division (b) sample current-scale=10A/division (c) sample voltage-scale=5 mv/division.

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