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PULSED MAGNETIC FIELDS AND THE CRITICAL CURRENT DENSITIES OF SUPERCONDUCTING Nb3Sn STRIPS IN THESE FIELDS

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PULSED MAGNETIC FIELDS AND THE CRITICAL CURRENT DENSITIES OF SUPERCONDUCTING \( \text{Nb}_3\text{Sn} \) STRIPS IN THESE FIELDS

Terry Nathaniel Garrett
(M.S. Thesis)

December 1971

AEC Contract No W-7405-eng-48
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PULSED MAGNETIC FIELDS AND THE CRITICAL CURRENT DENSITIES OF SUPERCONDUCTING Nb₃Sn STRIPS IN THESE FIELDS

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ABSTRACT

In this thesis a 70 KJ capacitor bank installation for the generation of pulsed magnetic fields is described. The construction of a helical magnet coil is discussed. The apparatus was used to study the effect of cold work on Nb₃Sn samples prepared by a new technique.

The microstructure of the samples produced by this technique were examined using anodic etching. The microstructure consisted of a network of continuous Nb₃Sn filaments in a matrix of niobium. In a sample that was highly cold worked, the filaments were about one micron in diameter in a niobium matrix. A current density of $7.5 \times 10^4$ amp/cm² at 120 KG was obtained.
I. INTRODUCTION

To the author's knowledge Betterton et al.\(^1\) were the first to conduct pulsed magnetic field and pulsed current studies on superconducting \(\text{Nb}_3\text{Sn}\) wire. This wire was prepared by a method suggested by Kunzler et al.\(^2\) Flippen\(^3\) used the pulsed field method to study the superconducting properties of \(\text{Nb}_3\text{Sn}\) ribbons. These ribbons were prepared by a method suggested by Hanak et al.\(^4\) The aim of these investigators was to determine whether \(\text{Nb}_3\text{Sn}\) produced by different techniques would result in improved superconducting properties as well as a sufficiently ductile material that could be wound into superconducting magnet coils to produce high steady state magnetic fields. Due to technological problems and costs, the magnetic fields above 150 kG\(^5,6\) are necessarily transient in nature. Pulsed magnetic fields produced by an apparatus which most often consists of a capacitor bank and an inductive load (usually an axially constrained helical magnet coil) are used primarily because they are highly efficient in transferring the stored energy into the inductive load (efficiencies up to 90% can be attained in practice\(^5\)). Since \(\text{Nb}_3\text{Sn}\) is a brittle material, special techniques are required to produce it in a useful form. Two approaches have been referred to above. The technique used to prepare \(\text{Nb}_3\text{Sn}\) has also been observed to have a pronounced effect on its superconducting properties.\(^2\)

The object of this investigation was two-fold:

(i) to present a description of a pulsed magnetic field apparatus and
(ii) to study the influence of microstructure on the critical current density of superconducting \(\text{Nb}_3\text{Sn}\) produced by a new technique.\(^7\)
Powders of niobium were roll compacted and sintered. Next the porous niobium compact was infiltrated with molten tin. Then the infiltrated compact was cold worked and subsequently reacted in a molten tin bath. Anodic etching was used to examine the microstructure of these samples. Certain changes in the microstructure have been correlated with the amount of cold work. The critical currents versus magnetic field were determined with the pulsed magnetic field apparatus mentioned above. Correlations have also been observed between the critical currents, applied magnetic field and the microstructure.
II. THE PULSED FIELD APPARATUS

A. The Capacitor Bank

1. Charging and Discharging System

The capacitor bank was designed to operate in an underdamped oscillating region; \(^8,9\) that is \(\gamma < 1\), the damping of which depends on the dimensionless quantity \(\gamma = R^2C/4L\) (Fig. 2). The charging voltage is limited by the electrical insulation in the coil; whereas the value of capacitance is restricted in the upper limit dictated by the fact that design requires \(\gamma < 1\) and the lower limit by the fact that pulses have to be relatively long (oscillation-quarter period of the order of \(10^{-2}\) sec) in order to minimize \(dH/dT\) effects \(^3\) on the critical current measurements.

The present installation (Fig. 1) is a capacitor bank (Fig. 2) of 110,000 \(\mu F\) with a maximum operating voltage of 1.1 kV. The capacitor bank actually consists of 10 smaller capacitor banks (Fig. 3) which are connected in parallel. The small capacitor banks are made up of 20 modules connected in parallel and each module consists of four 2,200 \(\mu F\) capacitors connected in series. This arrangement was chosen because it allows the capacitance to be varied in steps of 11,000 \(\mu F\) from 11,000 \(\mu F\) for one small capacitor bank to 110,000 \(\mu F\) for the entire capacitor bank.

The capacitors (Fig. 3) are divided into 40 groups of 20 elements and each group is charged through a resistance of 100 \(\Omega\). Typical charging times ranged from a few seconds to several minutes depending on the charging current and the voltage to which the capacitor bank is charged. The discharge system (Fig. 3) consists of a unit of ten ignitrons connected in parallel triggered by thyratrons. The capacitor bank is discharged through a helical magnet coil of 540 \(\mu H\). This discharge
produces a high intensity current pulse. The rise time (approximate time between the zero point and the quarter sinewave point) of the pulse is about 8 milliseconds and the rated peak value of the current is 11 kA.

2. **Auxiliary Circuits**

In order to increase the lifetime of the capacitors and to minimize heating of the magnet, it is important to prevent high negative voltage back-swing; also because the ratings of ignitrons are not sufficient to be sure that they can withstand this high negative voltage at the end of the pulse, it is necessary to remove this remaining energy. This is done by connecting a diode, correctly orientated, in parallel with the magnet coil. After the current pulse reaches its peak, it begins to decrease. This changes the electrical polarity of the magnet coil and causes it to act momentarily as a source which tends to oppose any change in the current. The voltage developed by this source is sufficient to turn on the diode and the voltage back-swing is clamped to approximately 0.7 volts. This is commonly called a free wheeling diode damping system. The damping system, current, and voltage waveforms are shown in Fig. 4.

The sequence of steps that leads to firing the ignitrons will be described. At the control panel, a relay is closed, which gives a positive voltage pulse on the grid of a thyatron in the trigger amplifier chassis (Fig. 5). After the pulse has been amplified, it is fed to the grid of a more powerful thyatron in the capacitor bank pulser chassis (Fig. 5) where it is amplified again. This pulse is now powerful enough to fire an igniton and hence is fed into the ignitor of an ignitron.
3. Problems

The main difficulties encountered with this capacitor bank were (1) lack of synchronization of the 10 ignitrons and (2) the capacitors of ten smaller capacitor banks charged to different voltages. These problems are discussed in Appendix A.

B. Description of the Helical Magnet Coils

1. Construction of the Coils

The requirements imposed on the magnet coil were: (1) the coils had to have an inside diameter of about 19 mm and a length of about 125 mm to provide space for the finger of a glass cryostat and the measurement apparatus (probe, sample) in the homogeneous region of the field; (2) the inductance of the magnet coil had to be approximately 540 μH to obtain pulses with rise times of the order of 10⁻² sec; (3) the field at 11 kA should be approximately 350 kG.

The coils were made from fully work-hardened high conductivity copper sheets. The coil construction that was originally designed to be used in this investigation will be discussed later. For now the coil construction that was finally adopted will be discussed; the present coil is a variation of the Bitter type coil.

The magnet coil is a conductor-insulator double helix (Fig. 6) composed of 240 flat copper plates and 239 capton insulator disks. The flat plates were split and overlapped to make contact over a small sector; the plates were separated by split insulating disks which had been passed through the split in the copper plates to form the desired amount of overlap and a certain amount of interference between the copper plates. The copper plates for the coils were photo etched¹² six at a time from
a 10 mil thick rectangular sheet of copper. The capton insulating disks were made as follows: (1) squares 4 3/4 by 4 3/4 inches were cut from a roll of 1 mil thick capton; (2) these squares were placed in an aluminum drum which was mounted on a lathe and turned to the final diameter destroying the aluminum drum in the process. (3) A hole was drilled through the stack of disks and finally each disk was split prior to placing it between copper plates. These insulating disks had a smaller inside diameter but a larger outside diameter than the copper plates to prevent arcing between copper plates when the assembly was clamped together.

The coil was rigidly constrained axially by clamping the helix with six Al-Si-Cu alloy bolts between two massive NEMA G-10 fiberglas end-plates. The bolts holding the end-plates were torqued to about 23 ft-lbs. This resulted in a helix that was internally connected by a series of pressure contacts. The end-plates contained a small 1 mil thick copper disk connected to a copper bolt which provides on the one hand for an interference fit between the ends of the helix and the end-plates and on the other hand for bracket and cable connections to the entire magnet coil assembly.

The various components are shown in Fig. 7 and the assembled coil is shown in Fig. 8 with the current leads attached. The coil was immersed in a bath of liquid nitrogen when being pulsed; this had several advantages.

(1) The measured electrical conductivity for copper at 77°K is about 7 times higher than at room temperature\textsuperscript{13} and there is a general improvement in all mechanical properties with decreasing temperature.\textsuperscript{14,15}

(2) After a pulse of a given maximum field, not only was the final temperature\textsuperscript{16} lower when the system had been previously cooled, but the temperature variation, ΔT, was about 10% smaller. Although the
mechanical effects caused the most serious problems in pulsed operation, the consequences of thermal limitations cannot be neglected either. The insulation may be damaged, the hardened coils may be annealed and even worse, as Foner and Fisher have observed, melting of the inside surface of air cooled helices may occur.

(3) The joule energy, which corresponds to practically all the energy stored in the capacitor bank (20 kJ for a 180 kG max. field), is dissipated much quicker by liquid nitrogen than by air and permits a greater repetition rate. Waiting 3 minutes between successive discharges for maximum fields not exceeding 200 kG proved to be adequate.

(4) Another convenience was the differential expansion between the Al-Si-Cu alloy bolts, the fiberglas end-plates and the copper helix, which increased the clamping forces at low temperature.

2. Stresses in the Coil

The magnet current flowed in a manner that tended to minimize the coil inductance and hence was driven to the inside surface of the coil; whereas the conducting material tended to move in the opposite sense and tended to maximize the coil inductance. The forces exerted when a pulse occurred were thus of two kinds: The radial explosion forces which affected particularly the inner wall of the helix, and axial compression forces. Although the initial axial stress increased the pressure on the insulator, it was necessary in order to avoid any rebound of the coil due to its own axial forces at the moment of discharge. The design of the coil discussed in the previous section has several advantages when the radial and axial forces occur.
The magnet current flowed mostly near the inner radius of the much larger and sturdier strips which make up the body of the helix. The forces on the periphery of the helix were reduced approximately in the ratio of inside to outside diameters from the maximum value (which is near the inside wall).\textsuperscript{5,8} Secondly the helical coils could be compressed axially with forces that are comparable to the magnetic forces. Lastly the use of split plate permits nonviolent slippage, instead of rupture, when the magnetic field pulse exceeds the holding capacity of the coil;\textsuperscript{5} it is well known that destructively high voltages may be produced by interrupting the current of an electromagnet.

3. Problems

The original coil construction was also a variation of the Bitter type coil. The main difference between this coil construction and the previously described one was that the tabs of the copper plates were soldered together and insulating disks were not split but instead inserted directly between these plates. These soldering joints proved to be the source of trouble in this construction. The construction of the coil and the problems encountered are discussed in Appendix B.
III. THEORY AND EXPERIMENT

A. Theory of $J_c$ vs $H$

When a transport current is present in a type II superconductor, it disturbs the equilibrium of the system in two ways: The first is caused by an increase in the free energy due to the kinetic energy of the transport current; the second occurs due to the interaction between the current and quantized flux lines, the Lorentz force. When the current flows perpendicular (transverse) to the magnetic field, as it does in usual sample orientation, the Lorentz force becomes the important factor. If the current density is denoted by $J$ and the magnetic field strength by $H$, Kim, et al. had shown that the current density is limited by the Lorentz force parameters.

$$\alpha_c = J \times H < \alpha_c$$

where $\alpha_c$ is a measure of the number and pinning strength of defects per unit volume. When the Lorentz force is greater than the pinning force, motion of the flux lines occurs creating an effective resistance. Figure 9 shows $J_{c_S}$ vs $H$ curves for different degrees of flux pinning. Two curves are normally reported; (1) that corresponding to the onset of resistance ($J_{c_n}$) and (2) that corresponding to normal state resistance ($J_{c_S}$).

B. Sample Preparation

A comprehensive treatment of the details of this new technique for preparing $\text{Nb}_3\text{Sn}$ has been given in a M. S. thesis by P. Babu. A brief outline only is given here.

Niobium powders of -270 mesh were poured into the hopper of a roll mill which roll compacted these powders into porous strips. Each strip
was attached to a holder and separately placed in the furnace and sintered at 2225°C for 3 minutes under a vacuum of $2 \times 10^{-5}$ mm of Hg. Next, molten tin, through capillary action, was infiltrated into this porous compact by immersing a portion of the sintered strip into a molten tin bath at 650°C for 1-1/2 minutes under the same vacuum. The end result of these steps is a niobium-tin compact. A strip of this compact about 2 inches long was cold worked by 75% and then divided into three equal parts. One of the two remaining parts was cold worked by 85% and the other by 95%. These unreacted samples were attached to a holder and separately reacted in a tin bath at 950°C for 2 minutes in the presence of a helium atmosphere inside the furnace. For samples that were originally 17 mils thick, 4.2, 2.6, and 1.0 mil thicknesses correspond respectively to 75, 85, and 95% cold work.

Table I presents a summary of the heat treatment and amount of cold work given to the samples. The sample cold worked by 75% will be referred to as sample 1 and those cold worked by 85 and 95% will be referred to as samples 2 and 3 respectively. These reacted samples were cut to the desired cross section for J vs H measurements and the remainder was reserved for metallography.

C. Microstructure

Anodic etching was used to examine the microstructure of the samples. Metallographic samples were prepared for anodization by mounting in Koldmount and abrading with silicon carbide paper down to 600 grit. The final polishing was a chemical-mechanical polish in a slurry composed of 4 gm of alumina, 7 ml of hydrogen peroxide, 10 ml of 10% NaOH solution, and 75 ml of distilled water. These samples were anodized with Pickelsimer's solution at 27 volts for 6 minutes.
D. \( J_{cs} \) vs H Measurements

Measurements were made using pulsed magnetic fields up to 180 kG produced by the apparatus and coil previously discussed. A schematic of the arrangement of equipment is shown in Fig. 10. Samples 1 and 2 were cut to a cross section of 400 square mils and 325 mils long on a micrometer feed shear machine. Sample 3 was not wide enough to give the desired cross section and was cut to a cross section of 154 square mils by 325 mils long. The samples were placed on a four wire (tightly twisted pair of current leads and a tightly twisted pair of voltage leads) probe and oriented so \( J \perp H \). The four wire probe was equipped with an auxiliary coil in parallel with a \( 1 \mathrm{~kW} \) potentiometer. The samples were soldered with rosin core solder to the current contacts. The voltage contacts separated approximately by 170 mils were held against the sample by pressure but were also soldered to the sample at the contact points. These samples soldered very easily because they had a tin coating as a result of being reacted in the tin bath. To facilitate cooling the magnet coil was immersed in a Dewar of liquid nitrogen. A glass helium cryostat with a special finger that rested inside the bore of the magnet coil was also immersed in the liquid nitrogen and rested on a support. After liquid helium had been transferred into the glass cryostat the four wire probe and sample were gradually lowered into the liquid helium until the tip of the probe entered the finger of the helium cryostat.

By adjusting controlled time delays, a rectangular current pulse was started prior to the magnetic field pulse and stopped at the peak of the field pulse as shown in Fig. 11; this was done to reduce sample
heating. A Type 555 Tetronic dual-beam oscilloscope was used in these measurements. Type G and D amplifiers were used to record the field and voltage drop across the sample respectively. The Type D amplifier is a differential amplifier. The twisted pair from the auxiliary coil and the voltage contacts were respectively connected to the "A" and "B" inputs channels of this amplifier. With no sample current (transport current) the potentiometer, which is connected to the auxiliary coil, was adjusted until the induced voltage on the voltage leads signal caused by field pulse was made as small as possible.

While the magnetic field pulse and the signal voltage from the sample were being displayed on the dual-beam oscilloscope, a photograph of the screen was simultaneously taken with high speed polaroid film. The voltages on the voltage leads were recorded with and without sample current and the difference between these waveforms was taken to be the voltage drop across the sample. The $J_{cs}$ vs $H$ curve was obtained by plotting the field which produces the first measurable voltage versus the current density. The $J_{cn}$ vs $H$ curve was obtained by plotting the field at which the voltage drop across the sample ceased to increase or was increasing slowly (because sample heating increases its resistance) versus the current density. The largest single error in these measurements was due to the width of the oscilloscope trace, and total error was estimated as ±3%.
IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Microstructure

After the samples were anodized Nb$_3$Sn appeared as a dark blue or violet color, niobium appeared as a pale blue color and tin appeared as a white color. Summary of the phases observed in the samples are shown in Table I. The microstructure of the samples consisted of a network of continuous filaments of Nb$_3$Sn and unreacted tin in a matrix of niobium.

The thickness of the filaments decreased as the percent cold work given the samples increased, as shown in Table II. The amount and distribution of Nb$_3$Sn, as well as the amount of unreacted tin, depended on the amount of cold work given the samples as shown in Table II and Figs. 12, 13, and 14. The amount of unreacted tin in the samples was observed to decrease as the percent cold work increase. This was due primarily to two factors: (1) Increasing amounts of tin were squeezed out of the compact as the amount of cold work was increased. (2) The diffusion distance was reduced with increasing amounts of cold work so that a larger fraction of tin could react in a given time.

B. $J_c$ vs $H$ Measurements

The $J_c$ vs $H$ results for samples 1, 2, and 3 are shown respectively in Figs. 15, 16 and 17. Sample 3 was observed to have the highest critical current densities. The fact that the $J_{c_s}$ and $J_{c_n}$ curves of sample was displaced by only a small amount from the $J_{c_s}$ and $J_{c_n}$ curve of sample 2 suggests that the critical current properties of these samples were rather insensitive to samples cold worked in the range 75 to 85%.
The total critical current density of the samples described above were as good as those reported by Montgomery, et al.\textsuperscript{20} and better than those reported by Otto.\textsuperscript{21} The current densities reported by Montgomery, et al. were \(3 - 6.5 \times 10^4\) amp/cm\(^2\) at 120 kG and those reported by Otto were \(0.8 - 4 \times 10^3\) amp/cm\(^2\) at 120 kG. The samples reported in this work have current densities of \(1 - 5 \times 10^4\) amp/cm\(^2\) at 120 kG.

The position of the \(J_c\) point (chosen in this work as 2\% of full scale resistance) was observed to be very sensitive to \(dH/dt\); i.e., \(J_c\) increases as \(dH/dt\) decreases. Flippen\textsuperscript{3} found that the resistive transition of \(\text{Nb}_3\text{Sn}\) was lowered to 75 kG at low current densities for \(dH/dt\) of \(5 \times 10^{10}\) G/sec whereas in a steady field at similar current densities the resistive transition occurred at 200 kG. Similar findings have been reported by Hart, et al.\textsuperscript{22}; these investigators also found that \(J_c\) was less sensitive to \(dH/dt\) when it is less than \(1.6 \times 10^7\) G/sec. The rise time of the magnetic coil in this experiment was about 8 msec and for a maximum field of 200 kG a \(dH/dt\) of approximately \(2.5 \times 10^7\) G/sec occurs.

To check the agreement between pulsed field and steady field data and to check \(dH/dt\) effect, sample 1 was tested in the steady field of a superconducting magnet; samples 2 and 3 were not tested in these fields. The results are shown in Fig. 15. As expected the pulsed field data for \(J_{c_n}\) is in good agreement with the steady field data. The transition where \(J_{c_n}\) was determined occurred close to the peak of the field pulse, that is, where \(dH/dt\) was small. The data for \(J_{c_s}\) were much lower than the steady field data. Therefore, in this investigation the rise time of the magnetic field was thought to be responsible for the low \(J_{c_s}\).
V. SUMMARY AND CONCLUSIONS

A description of the pulsed magnetic field apparatus which consists of a 70 kJ capacitor bank and a helical magnetic coil has been presented. This apparatus was used to determine the effect of cold work on the critical current density of Nb₃Sn produced by a new technique.

The microstructure of the samples produced by this technique consisted of a network of continuous Nb₃Sn filaments in a matrix of niobium. As the amount of cold work increased, the thickness of the filaments decreased and for highly cold worked samples the critical current density was increased. Filaments about one micron in thickness, in a niobium matrix, with a current density of $7.5 \times 10^4$ amp/cm² at 120 kG were obtained; whereas the total current density was $5 \times 10^4$ amp/cm² at 120 kG.
ACKNOWLEDGMENTS

It is a pleasure to acknowledge the advice and encouragement of Victor I. Zackay, Earl R. Parker, and Milton R. Pickus throughout the course of this investigation. The author also wishes to thank Chet Pike, Ed Hartwig and John Holthuis for their invaluable technical assistance and Bill Harris for many helpful discussions.

This research was performed under the auspices of the U. S. Atomic Energy Commission through the Inorganic Materials Research Division of Lawrence Berkeley Laboratory.
APPENDIX A

The main difficulties encountered with the capacitor bank were caused by lack of synchronization of the 10 ignitrons. The set nearest the coil tended to suppress the anode voltage on the sets farther away so that some of the small capacitor banks discharged and others did not. Another problem occurred when the capacitor bank was energized after being idle for a week or so; when the capacitor bank was energized and set to charge to a specified voltage the small capacitor banks charged to different voltages, some of which were too low others too high.

The first problem was solved by removing all but one of the ten ignitrons and wiring the circuit so that this one ignitron would fire the entire capacitor bank (all ten small capacitor banks) simultaneously. The pulse used to ignite the ignitron was increased from 0.1 μsec to 10 μsec and the power of the pulse was increased from about 0.1 joules to 2 joules. A simplified schematic of the modified capacitor bank is shown in Fig. A1. The second problem was due to leakage capacitance (difference in resistance around a capacitive circuit) and was solved by allowing the capacitor dielectric to form, that is, the capacitor bank was set to charge to a specified voltage and left at that setting for 3 or 4 hours.
APPENDIX B

The construction of the original magnet coil is shown in Fig. Bl. The magnet coil is made up by alternately stacking flat copper plates and capton insulator disks. The tabs of the copper plates which extend beyond the capton insulator were soldered together to form a connected helical magnet coil. The tabs proved to be the weak point in this type of construction. The cross section of the tabs through which the current had to flow was approximately 0.32 cm by 2.2 cm. A current of approximately 5600 amps must flow through the magnet coil to generate a field of 180 kG. This implies the current density of the tab must be at least $7.94 \times 10^3 \text{ amp/cm}^2$. From this observation and a simple calculation of the temperature rise of the tab, it was concluded that the solder connecting the copper tabs together may soften or even melt as a result of this current density thus causing the coil to fail. Magnet coils constructed as described above have been observed by the author to fail on three occasions after a number of pulses which suggests that the solder joints may be weakened by each current pulse.
REFERENCES

11. Private communications with C. Pike and E. Hartwig.
Table I. Summary of heat treatment and phases in samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temperature °C</th>
<th>Time Min.</th>
<th>Cold Work %</th>
<th>Phase* ( \text{Nb}_3\text{Sn} )</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>950</td>
<td>2</td>
<td>75</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>950</td>
<td>2</td>
<td>85</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>950</td>
<td>2</td>
<td>95</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

*Phases observed based only on anodic etching.

Table II. Comparison of \% \( \text{Nb}_3\text{Sn} \) and filament thickness to \% cold work.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cold Work %</th>
<th>( \text{Nb}_3\text{Sn} ) in Cross Section* %</th>
<th>Range in Thickness of Filaments (( \mu ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75</td>
<td>27</td>
<td>1.4 - 3</td>
</tr>
<tr>
<td>2</td>
<td>85</td>
<td>36</td>
<td>1.2 - 2.5</td>
</tr>
<tr>
<td>3</td>
<td>95</td>
<td>66</td>
<td>0.7 - 1.5</td>
</tr>
</tbody>
</table>

*This is a longitudinal cross section.
FIGURE CAPTIONS

Fig. 1. Ten smaller capacitor banks which make up the larger capacitor bank. The pulsed magnet is in foreground. The entire bank is approximately 20 feet long by 2 feet wide by 10 feet high.

Fig. 2. Basic circuit and numerical values and $\gamma = R^2 C/4L$.

Fig. 3. Simplified schematic diagram of apparatus.

Fig. 4(a). Free wheeling diode damping circuit.

Fig. 4(b). Current and voltage waveforms of coil.

Fig. 5. Circuit for firing two ignitrons.

Fig. 6. Construction of helical magnet coil.

Fig. 7. Assembled magnet coil and components. 1 - copper plates; 2 - capton insulators; 3 - Al-Si-Cu bolts; 4 - NEMA G-10 end plate.

Fig. 8. View of the mounted pulsed magnet.

Fig. 9. Typical $J_c$ vs. H curves for (a) high pinning strength, (b) moderate pinning strength, and (c) low pinning strength.

Fig. 10. Schematic of pulsed field equipment for measurements.

Fig. 11(a). Typical oscilloscope record. The upper waveform is the magnetic field pulse inverted; the rectangular waveform is the current pulse; the lower waveform is the voltage drop across the sample.

Fig. 11(b). Typical oscilloscope record. The upper waveform is the magnetic field pulse inverted; the current pulse is not shown; the lower waveform is the voltage drop across the sample.

Fig. 12(a). Sample 1. Anodized. 440x.
Fig. 12(b). Sample 1. Anodized. 680x. 1 - Nb 2 - Nb$_3$Sn 3 - Sn
Fig. 13(a). Sample 2. Anodized. 440x.
Fig. 13(b). Sample 2. Anodized. 680x. 1 - Nb 2 - Nb$_3$Sn 3 - Sn
Fig. 14(a). Sample 3. Anodized. 440x.
Fig. 14(b). Sample 3. Anodized. 680x. 1 - Nb 2 - Nb$_3$Sn 3 - Sn
Fig. 15. $J_c$ vs. $H$ curves for sample 1.
Fig. 16. $J_c$ vs. $H$ curves for sample 2.
Fig. 17. $J_c$ vs. $H$ curves for sample 3.
Fig. A1. Simplified schematic diagram of apparatus.
Fig. B1. Original magnet coil construction.
Fig. 1

Capacitor Bank
$1.1 \times 10^5 \mu F$
$V_{max} = 1.1 kV$

\[ R = 65 \, m \Omega \]
\[ L = 540 \, \mu H \]

$I_{max} = 11 kA$

Fig. 2
10 Small Capacitor Banks

Component Connection
Same As Preceding Bank

Component Connection
Same As Preceding Bank

Fig. 3
Fig. 4a

Fig. 4b

Fig. 5
Section through magnet coil

Fig. 6
Fig. 9
Fig. 10

**Diagram Description**:

- **Magnet Coil**
- **Ignitron**
- **Capacitor Bank**
- **Rogowski Belt**
- **Sample**
- **Integrator**
- **Dual-Beam Oscilloscope**

The diagram shows a circuit with the following labeled components:

- A magnet coil labeled as Magnet Coil.
- An Ignitron labeled as Ignitron.
- A capacitor bank labeled as Capacitor Bank.
- A rogowski belt labeled as Rogowski Belt.
- A sample labeled as Sample.
- An integrator labeled as Integrator.
- A dual-beam oscilloscope labeled as Dual-Beam Oscilloscope.

The diagram illustrates the connection and interaction of these components within the circuit.
Fig. 12(a)

Fig. 12(b)
Fig. 13(a)

Fig. 13(b)

XBB 7112-6038
Fig. 13(a)

Fig. 13(b)
Current density of Nb₃Sn only (steady field) + Current density of Nb₃Sn only ⊙ Total current density

Fig. 15
Fig. 16.

- Current density of Nb$_3$Sn only
- Total current density
Fig. 17

Current density of Nb Sn only
Total current density
Fig. Bl

Kapton Insulators

Copper Plates
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