Effect of Fast-Pulsed Magnetic Fields on Single-Layer Superconducting Coils

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Institut für Plasmaphysik GmbH und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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Abstract

Pulsed fields (rise time ≈ 7 μsec, $dH/dt = 10^7$ to 10^9 Oe/sec) were applied to small single-layer coils (Nb-25 % Zr, Nb-48 % Ti) short-circuited by a low-resistance shunt, with transport current I_s and superposed background field. Within the experimental error, I_s and the current I_p induced in the sample by a pulse just large enough to cause field penetration add up to the statically determined critical current I_c of the sample.

This paper describes preliminary experimental work with the ultimate aim of determining the behavior of superconducting coils and materials in fast-pulsed magnetic fields.[1] Steady magnetic fields (possibly generated by superconducting coils) with superposed fast-pulsed fields are used, for instance, in certain plasma machine configurations.

The samples tested are single-layer coils made of non-copper-plated, insulated Nb-25 % Zr (Nb-48 % Ti) wire of diameter d = 0.25 mm (coil length l = 20 mm, coil diameter D = 14 mm, number of turns $N \approx 70$, inductance $L \approx 35\ \mu H$) The sample coils are short-circuited in the Dewar with a low-resistance shunt ($< 10\ \mu\Omega$, as determined from current decay measurements)and have therefore a time constant τ = L/R greater than 3 sec.

The transverse (i.e. along the coil axis) pulsed field superposed on the sample is produced by discharging a capacitor bank into a pulsed coil around the helium Dewar containing the sample. The pulsed field consists of a burst of sinusoidal signals (damped periodic function, frequency ≈ 35 kHz). The first half-cycle of the signal has an amplitude varying from 50 to 10,000 Oe, $dH/dt = 10^7$ to 10^9 Oe/sec, and a rise time $\approx 7\ \mu$sec (much smaller than the time constant of the coil). A transverse steady magnetic field (0 to 25 kOe) is generated by a water-cooled magnet enclosing the pulsed coil and sample.

Figure 1a presents pulsed measurements made for a Nb-25 % Zr sample, H (stationary background field) and H_p (pulsed field) being in opposite directions during the first half-cycle of H_p. Each pulsed measurement is made in the following stages:

a) The background field H is superposed on the non-superconducting sample (e.g. 8 kOe, path OA in Fig. 1a). The observed effect (negligible at fields higher than about 25 - 30 kOe or transport current I_s close to the critical current I_c) of the magnetization currents (induced in the sample if superconducting during this stage) on the transport currents will be described elsewhere in a more detailed account of this work.

b) A direct transport current I_s is fed into the superconducting sample coil, thus producing an axial self-field H_s in the center of the sample coil, which adds to H (e.g. 20 A, path AB). Path AB forms the angle α with the y axis (tg α = H_s/I_s = k N/l is given by the geometry of the sample coil).

c) A pulsed field H_p is superposed (e.g. 2 kOe, path BC). The first half-cycle of the signal H_p is displayed on the first channel of a dual beam oscilloscope. The signal is given by a pick-up coil concentric and external to the sample. A second pick-up coil, concentric and internal to the sample, is shielded from H_p by the superconducting sample up to the penetration threshold value H_p'. At the instant H_p' is reached the field penetrates the sample (which reverts to normality) and induces a sharp voltage signal in the internal pick-up coil. This is displayed on the second channel of the oscilloscope. H_p' is evaluated and the corresponding point N of normalization is plotted on the line BC. Segment BN corresponds to the value H_p' (e.g. 1.3 kOe) and segment MN to the induced pulsed current I_p (e.g. 40 A), which flows in the same direction as the transport current I_s and therefore adds to it (BN/MN = tgα).

Figure 1b presents the complementary set of pulsed measurements to Fig. 1a. Here H and H_p have the same direction during the first half-cycle of H_p (H and H_s having the same direction); I_s and I_p in the sample thus have opposite directions, and they subtract. It is observed that H_p reaches higher values before penetration than in the measurements in Fig. 1a. (During the second half-cycle of H_p, I_p and I_s have the same direction, and H_p, if it has not penetrated during the first half-cycle but is sufficiently high, penetrates at the same values observed in Fig. 1a.) Oscilloscope observation was limited to the first and second half-cycles of H_p since field penetration occurs only in the first or second half-cycle.

The values of I_s and the threshold values of I_p (corresponding to the field H_p') as obtained in Fig. 1a are added and plotted in Fig. 2 as a function of H. Similarly, the I_s and I_p values from Fig. 1b are algebraically added (I_p is now opposite to I_s), and the absolute values are plotted in Fig. 2. Seven sets of points are obtained which depict an equal number of dynamic characteristics corresponding to different preset values of I_s. These curves coincide within the experimental error indicated in Fig. 2. For clarity only one curve (dashed) is drawn. The curves also coincide with the static characteristic ($I_p = 0$) obtained on quenching the sample by gradually increasing I_s. (The points corresponding to this curve are also plotted in Fig. 1.) The short sample H_c-I_c characteristic (Westinghouse) is also shown (solid curve). Similar results were also obtained for Nb-48 % Ti samples.

The experimental data show and suggest the following:

(1) There is a direct relationship between the static H_c-I_c characteristic of a superconducting layer (material) and the pulsed-field characteristics. This relationship could be extended to a multilayer coil and to each layer of a multilayer coil (assuming L/R coil $> \tau_p$ (pulse rise time)) on which a pulsed field is superposed if allowance is made

for the different environmental and geometric conditions (absence of magnetization currents is still supposed).

(2) I_s and I_p add up to the critical value I_c. This can be explained by means of a current distribution according to the critical state model of Bean and Kim. A skin effect was observed in preliminary tests on copper-clad single-layer samples, most of the induced pulsed current being carried by the copper sheath.

(3) Owing to the geometry (ratio D/d) of the sample, the current I_ℓ locally induced by the pulsed field in the wire is negligible relative to I_p and will not prevent the total current $I_s + I_p$ from approaching the critical value I_c.

Considering the almost ideal heat transfer conditions of our sample (single layer), it appears that the thermal dissipation due to the currents induced locally by the pulsed field does not initiate the transition of the sample, at least not until $I_s + I_p$ reaches values close to the critical value I_c (i.e. not until thermal dissipation and flux creep occur when the sample is in the critical state).[2]

(4) Flippen reports degradation of the critical field H_c to 25 % of its static value in a wire short sample when the rise time of the superposed pulsed (longitudinal) field decreases from 10^4 to 10 μsec (at low transport current).[3] Supposing that the above degradation is caused by induced currents with radial distribution in the wire sample (longitudinal pulsed field), the lack of degradation in our case (transverse pulsed field), where I_p flows in the axial direction, could be ascribed to the different metallurgical structure of the wire material in the axial and

radial directions, these differences being due to the manufacturing process. As already mentioned, however, owing to the geometry of our sample the pulsed fields required to induce a critical transport current I_p in it (at $I_s = 0$) are well below (one to two orders of magnitude) the degraded critical field measured by Flippen as a function of the pulse rise time (Flippen's dH/dt = 10^9 to 10^{11} Oe/sec).

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REFERENCES

1. A.P. Martinelli. "Behaviour and Application of Hard Superconductors in Fast-Pulsed Fields". Paper presented at the Fifth Symposium on Fusion Technology, Oxford, England (2nd - 5th July, 1968).

2. Y. Iwasa and D.B. Montgomery, Appl.Phys.Letters 7, 231 (1965)

3. R.B. Flippen, Phys.Rev. 137, 6A, A 1822 (1965).

FIGURE CAPTIONS

Fig. 1a and 1b	Set of pulsed measurements for a non-copper-clad Nb-25 % Zr sample (Westinghouse). The diagrams are explained in detail in the text. In Fig. 1a H and H_p have opposite direction (I_s and I_p have the same direction). In Fig. 1b H and H_p have the same direction (I_s and I_p have opposite direction).
Fig. 2	Sum of transport current I_s and threshold values of induced pulsed current I_p in the sample vs. preset background field H, at different values of transport current I_s.

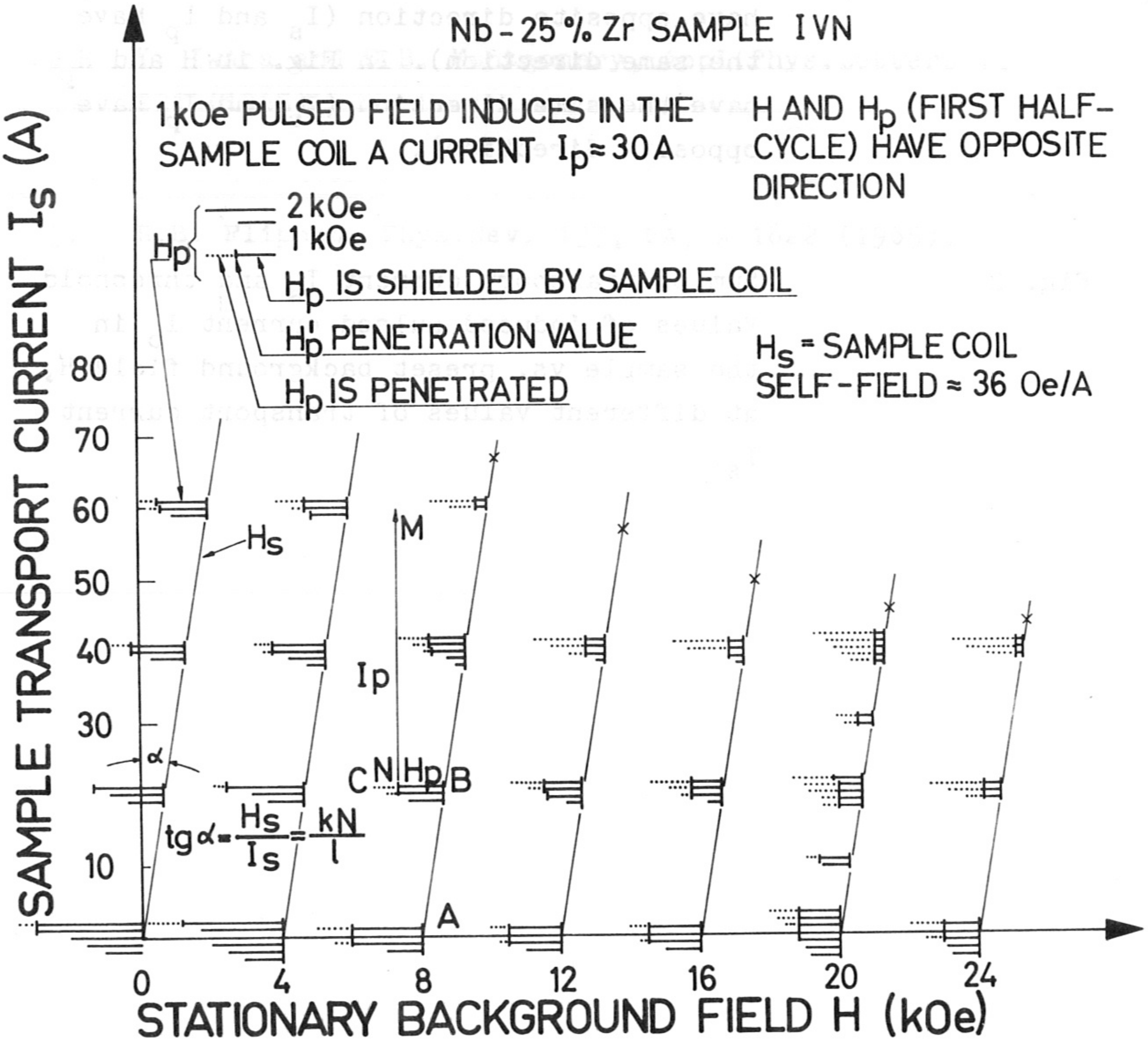
Nb - 25 % Zr SAMPLE IVN
1 kOe PULSED FIELD INDUCES IN THE SAMPLE COIL A CURRENT $I_p \approx 30$ A
H AND H_p (FIRST HALF-CYCLE) HAVE OPPOSITE DIRECTION
H_p
2 kOe
1 kOe
H_p IS SHIELDED BY SAMPLE COIL
H_p' PENETRATION VALUE
H_p IS PENETRATED
H_s = SAMPLE COIL SELF-FIELD ≈ 36 Oe/A
H_s
M
I_p
C
N
H_p
B
A
α
$\mathrm{tg}\,\alpha = \frac{H_s}{I_s} = \frac{kN}{l}$
SAMPLE TRANSPORT CURRENT I_s (A)
10
30
40
50
60
70
80
0
4
8
12
16
20
24
STATIONARY BACKGROUND FIELD H (kOe)

Fig. 1a

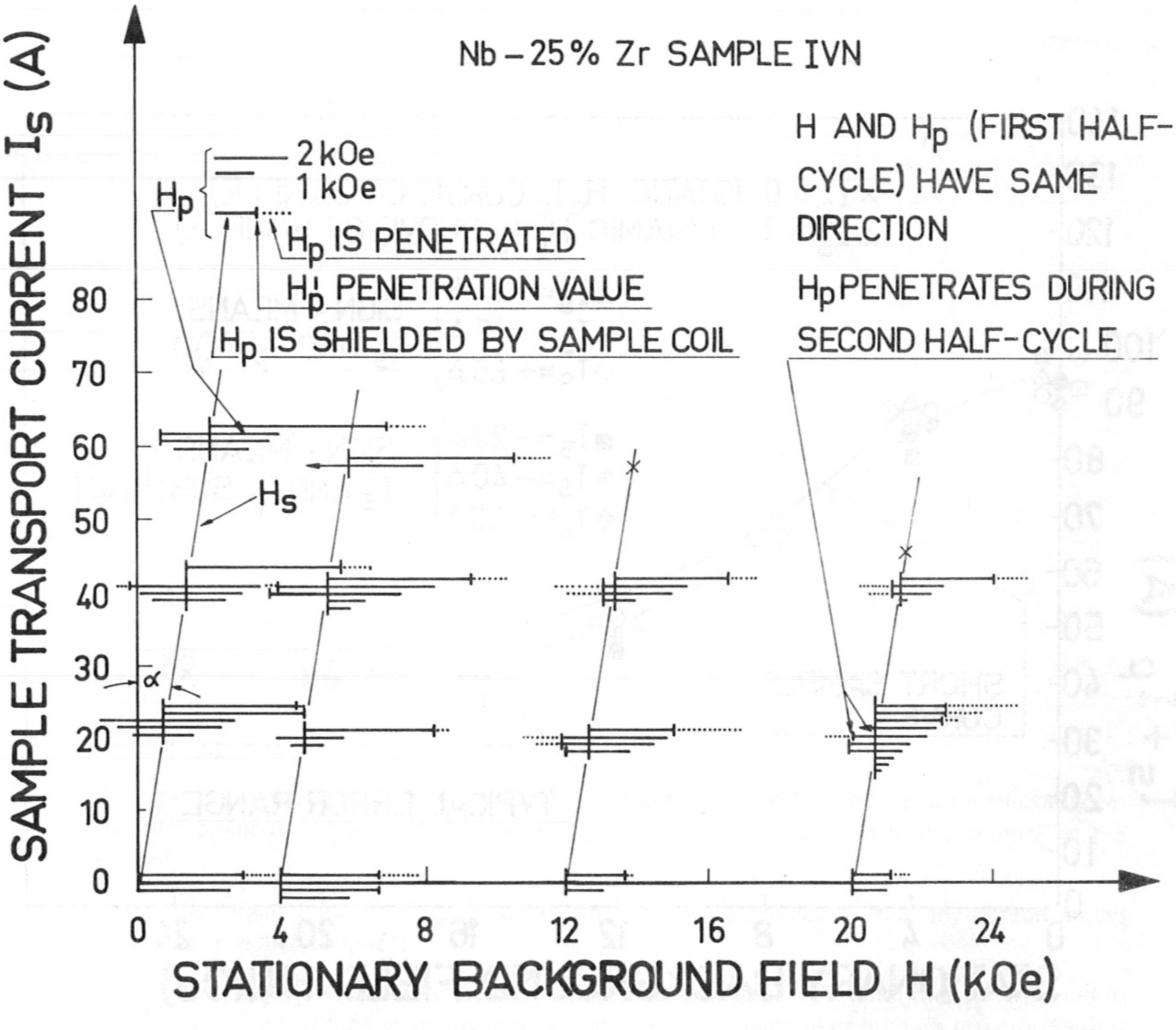
Nb – 25% Zr SAMPLE IVN
SAMPLE TRANSPORT CURRENT I_S (A)
STATIONARY BACKGROUND FIELD H (kOe)
0
10
20
30
40
50
60
70
80
4
8
12
16
20
24
H_p
2 kOe
1 kOe
H_p IS PENETRATED
H_p' PENETRATION VALUE
H_p IS SHIELDED BY SAMPLE COIL
H AND H_p (FIRST HALF-CYCLE) HAVE SAME DIRECTION
H_p PENETRATES DURING SECOND HALF-CYCLE
H_S
α

Fig. 1b

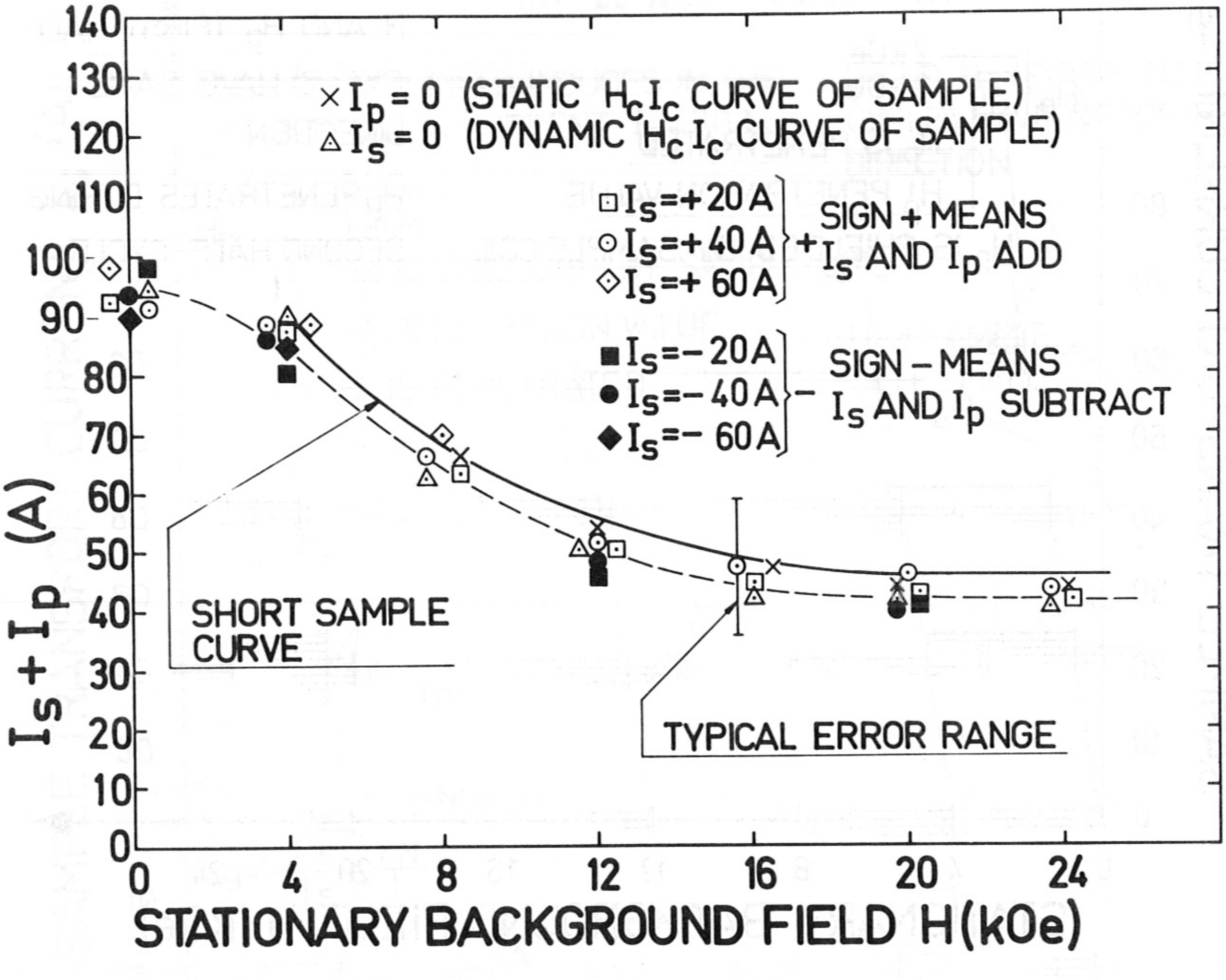
× $I_p = 0$ (STATIC $H_c I_c$ CURVE OF SAMPLE)
△ $I_s = 0$ (DYNAMIC $H_c I_c$ CURVE OF SAMPLE)
□ I_s=+20 A
⊙ I_s=+40 A
◇ I_s=+60 A
+ SIGN + MEANS I_s AND I_p ADD
■ I_s=−20 A
● I_s=−40 A
◆ I_s=−60 A
− SIGN − MEANS I_s AND I_p SUBTRACT
SHORT SAMPLE CURVE
TYPICAL ERROR RANGE
$I_s + I_p$ (A)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
0
4
8
12
16
20
24
STATIONARY BACKGROUND FIELD H(kOe)

Fig. 2