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Measurements on Pulsed Superconducting Magnets

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Abstract

Several experiments with superconducting multifilament NbTi wires have been done to measure ac losses, degradation effects and reachable $\dot{H}$, in order to find a suitable conductor for an ac-dipole. Solenoids were built with NbTi multicore wires having the following parameters: composite diameter 0.04 cm ... 0.1 cm, Cu and Cu/CuNi (3-component) matrix, twist rate between 0.5 and 2 turns/cm, filament diameter 13 μm ... 48 μm. The solenoids typically had an inner diameter of 2.5 cm, an outer diameter of 8.5 cm and a length of 5.5 cm, yielding a central field between 40 kG and 72 kG. The solenoids were not potted and reached 85 % ... 90 % of short sample critical current. For the chosen cooling conditions a maximum $\dot{H}$ was reached of 95 kG/s with a field amplitude of 52 kG. The measured ac losses agree with theoretically predicted ones. Significant additional self field losses, as computed by M.N. WILSON et al.[1], could not be confirmed quantitatively.

Zusammenfassung

Supraleitende Multifilament-NbTi-Drähte wurden auf Wechselstromverhalten, Degradationseffekte und erreichbares $\dot{H}$ untersucht, um einen geeigneten Leiter für pulsbare Dipolmagnete zu finden. Die zum Bau von Testspulen verwendeten Drähte hatten folgende Parameter: Außendurchmesser 0.04 ... 0.1 cm, Cu- und Cu/CuNi-(3-Komponenten-)Matrix, Twist mit Ganghöhen zwischen 6 und 25 mm, Filamentdurchmesser 13 μm... 48 μm. Die Solenoide hatten folgende typische Abmessungen: Innendurchmesser 2.5 cm, Außendurchmesser 8.5 cm und Länge 5.5 cm. Die damit erreichten Felder lagen zwischen 40 und 72 kG. Die Spulen wurden nicht vergossen und zeigten eine Degradation von 10 ... 15%. Bei den gegebenen Kühlbedingungen wurde ein maximales $\dot{H}$ von 95 kG/s mit einer Feldamplitude von 52 kG erreicht. Die gemessenen Wechselstromverluste stimmen mit den theoretisch vorhergesagten überein. Erhebliche zusätzliche "Self-Field"-Verluste, wie sie von M.N. WILSON et al.[1] berechnet worden sind, wurden quantitativ nicht bestätigt.

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Introduction

In order to check the possibilities of the application of filamentary superconducting wires to synchrotron magnets, solenoids have been tested wound from available conductors.

2. Measuring Method

The losses were measured using a calorimetric method. The magnets were fixed in a Plexiglass cylinder, whose bottom has holes in order to allow liquid helium to enter the cylinder. The copper current leads (with Nb_3 Sn-strips at its ends) were connected outside the cylinder to both ends of the solenoid. The evaporating helium gas from the magnet flows through a tube into a gas flow meter. Taking into account the residual gas flow rate for zero current, the accuracy of the measuring equipment was checked using a carbon resistor and determined to 2 - 3 %.

All the measurements were carried out with positive triangular current wave forms. The magnets were energized by a 36 kW power supply, designed for dc operation, controlled by a function generator to give the desired wave form.

The tested wires are specified in table 1.

3. AC Losses

3.1 Copper composites:

SPURWAY et al.[1] derived a formula for loss computation in coils

$$W \left[\mathrm{WATTS}\right] \approx \frac{V \cdot d \cdot J_o \cdot H_o}{2 \cdot 10^8} \left\{ \ln \left(\frac{H_M + H_o}{H_1 + H_o} \right) \right\}_{\text{average over coil}} \qquad (1)$$

where H_1 (Gauss) is a lower limit for the field (typically 1 kG), H_M the maximum local field in the windings, H_o and J_o (A/cm^2) constants, V (cm^3) the volume of superconductor, and d (cm) the filament diameter. For equ. (1) the $J_c(H)$-curve is supposed to be a hyperbolic function. As we have found linear and exponential dependences, too, the loss formula is written as

$$W \left[\mathrm{WATT}\right] \simeq \frac{V \cdot d}{2 \cdot 10^8} : \left\{ \int_{H_1}^{H_M} J_c(H)\, dH \right\}_{\text{average}} \qquad (2)$$

At first, for simplification, we took for the average the integration from zero or H_1 to $\bar{H}_M = \frac{1}{2} H_{max}$ (H_{max} is the maximum field of the coil). The results showed a good agreement with the linear parts of the W(ν)-curves. For example the measured losses of coils no. 20, 1, and 32 are shown in fig. 1,2, and 3 respectively . Nevertheless, a computer calculation, taking into account the spatial variation of the field, resulted in smaller losses than measured (or computed from equ.(2)). But if we add the losses from transverse currents in the matrix, computed by program, too, a good agreement with the measurements can be observed in those cases, where no significant self field losses should be expected. M.N. WILSON et al.[1] noted a formula for the ratio of self field losses Q_s to filament losses Q_f

$$\frac{Q_s}{Q_f} \simeq \frac{0.2 \cdot \lambda \cdot J_c \cdot a^2}{\bar{H}_M \cdot d} \tag{3}$$

where a is the composite radius, λ a space factor equal to the ratio of (filament area)/(composite area over filaments), and d the filament diameter.

Coil no.3 should show the biggest self field effect: $Q_s/Q_f \simeq 0.6$. Coil 3 is geometrically equal to coil 1 and the wires are the same except for composite and filament diameters. Therefore the losses of coil 3 should be twice the losses of coil 1 in the linear part of the W(ν)-curves not taking into account the self field losses. But the experiments (fig.4) give a factor of 2.5. That could be a hint for self field losses existing beside the transverse current losses, but they will be smaller by at least a factor of 3 than predicted by equ. (3).

The region, where the additional losses resulting from insufficient twisting become significant, can be calculated from

$$\dot{H}_c = \frac{\pi^2}{8} \frac{2 \cdot 10^8 \cdot J_c \cdot \lambda^{1/2} \cdot d \cdot \varrho}{l^2} \cdot \frac{w}{w+d} \tag{4}$$

(c.f. WILSON and WALTERS[1]), where 2l is half the twist pitch, ϱ the resistivity of the matrix, and w the width of matrix between filaments. For average values of H, J_c, and ρ (measured values[2]) the critical region should be near 0.03 Hz and 0.14 Hz for coils no. 20 and 2 respectively, in agreement with the experimental results.

Looking only at the twist pitches for wire no. 32 and 1 (6 and 8 mm pitch) one could expect a similar non-linear $W = W(\nu)$ - curve for coil 32 as for no. 1.

Fig.3 shows the measured values. There is no departure from linearity up to a $\dot{H}_{rise}$ of about 70 kG/sec. (at this field sweep limitations of the available power supply give current wave forms as indicated at the top of fig.3).

This linearity is due to the fact of the high critical current density in the superconductor ($2.5 \cdot 10^5$ A/cm^2 at 50 kG) and the three times larger filament diameter. Together with the shorter twist length the result according to equ.(4) is a $\dot{H}_c$ of 15 times the value for wire no.1.

3.2 Three-composite-matrix-wires

For example the results for two wires (No.7 and 9) are discussed.

Coil no.7 had an inner and outer diameter of 2 cm and 8.6 and a length of 11 cm; while coil 9 had the dimensions of 2.4 cm, 8.5cm and 5.3 cm respectively.

The observed losses are shown in fig.5. It is to be seen, that the loss/cycle for wire no.7 is about four times the loss of coil 9, although the filament diameter is only doubled. But normalizing, to unit superconductor colume (120 cm^3 for coil no.7 and 51 cm^3 for no.9) and to unit superconductor critical current density ($1.4 \cdot 10^5$ A/cm^2 and $2.1 \cdot 10^5$ A/cm^2) shows that the loss/cycle is doubled for a twice larger filament diameter. Significant self-field losses could not be confirmed quantitatively.

4. Final Remarks

According to different cooling conditions a variation in reachable maximum $\dot{H}$ and critical current I_c is expected. For coil no.7 with only one 0.1 cm thick cooling channel in the middle of the windings the maximum $\dot{H}$ was limited to about 20 kG/s. An improvement of the cooling conditions to 3 channels distributed nearer to the inner windings results in an increase of the $\dot{H}$ up to 90 kG/s and 95 kG/s with a field amplitude of 52 kG for coils no.9 and 32, respectively. For the latter coils no additional decrease of the critical current was measured with rising frequency (besides the 10 %... 15 % degradation observed for dc operation). Wire no.32 shows the highest current density of the tested wires, i.e. $2.5 \cdot 10^5$ A/cm^2 in the superconductor at 50 kG or $5.3 \cdot 10^4$ A/cm^2 over the windings (filling factor $\approx$ 0.6). Based on the tested wires, a rough estimation shows that for an economical ac dipole further improvements are necessary, e.g. higher twist rate and/or higher current density for wire no.1 or a decrease in filament diameter for wire no.32.

References

1) LEWIN, J.D., P.F. SMITH, A. H. SPURWAY, C.R. WALTERS, and M.N. WILSON, Rutherford Lab., RPP/A73

2) FESSLER, N., G. HARTWIG, K.P. JÜNGST, and G. KRAFFT, Gesellsch. f. Kernforschung, Externer Bericht Nr. 3/69/23

Table 1

Coil + Wire Reference No.		Matrix	Twist "pitch" (mm) (approx.)	composite diameter (cm)	Ratio matrix/s-c	No. of filaments	Filament diameter (μm)
20	*)	Cu	25	0.05	1.35:1	61	42
3	**)	Cu	5	0.1	3:1	361	26
1	**)	Cu	8	0.05	3:1	361	13
32	***)	Cu	6	0.04	1.4:1	61	35
9	**)	Cu, CuNi	6	0.05	2.7:1	119	24
7	**)	Cu, CuNi	13	0.1	2.7:1	119	48

*) Manuf. by Imperial Metal Industries, Kynoch, Great Britain

**) Manuf. by Airco, Murray Hill, USA

***) Manuf. by VAC, Vacuumschmelze GmbH, Hanau, Germany

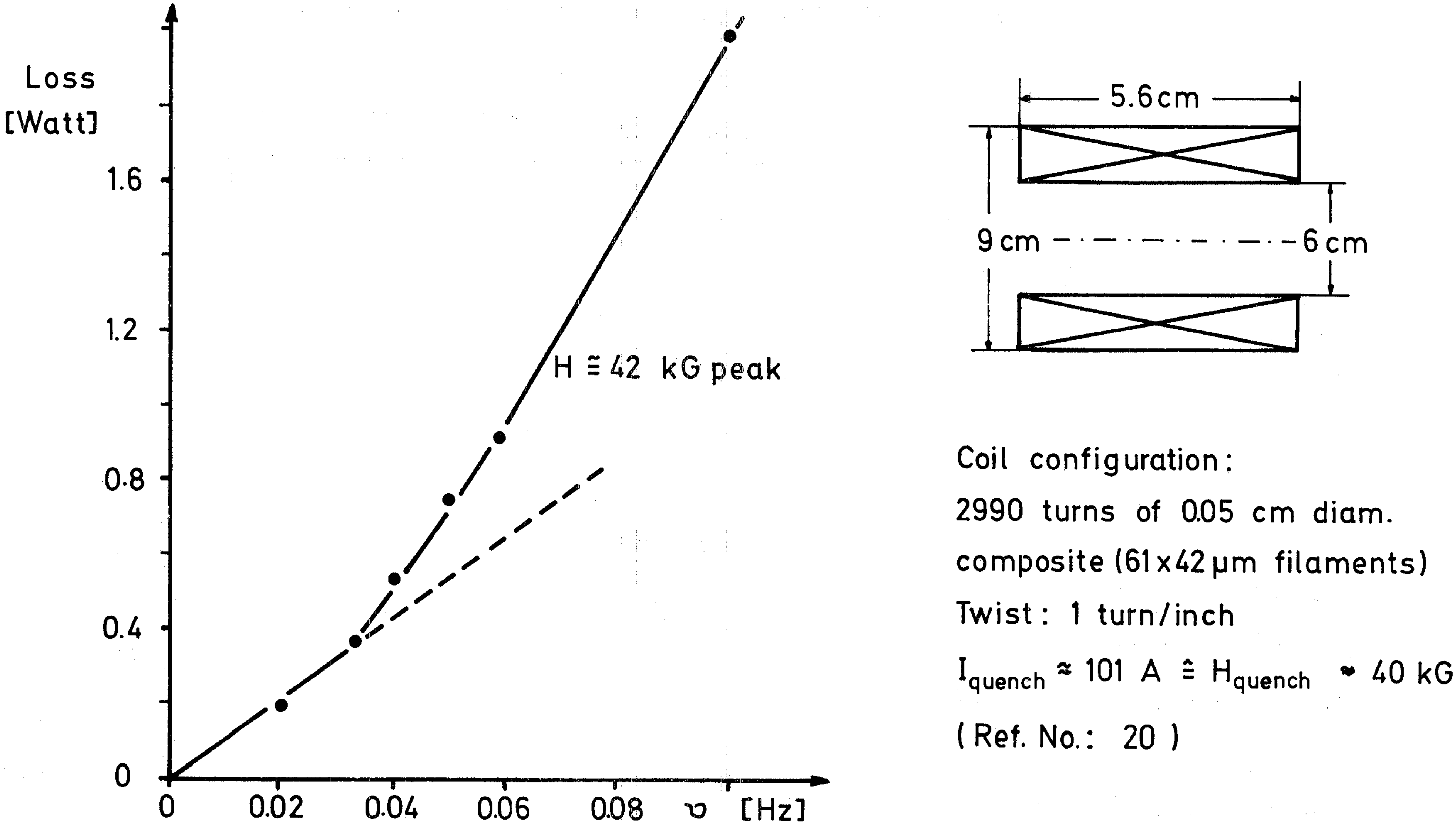
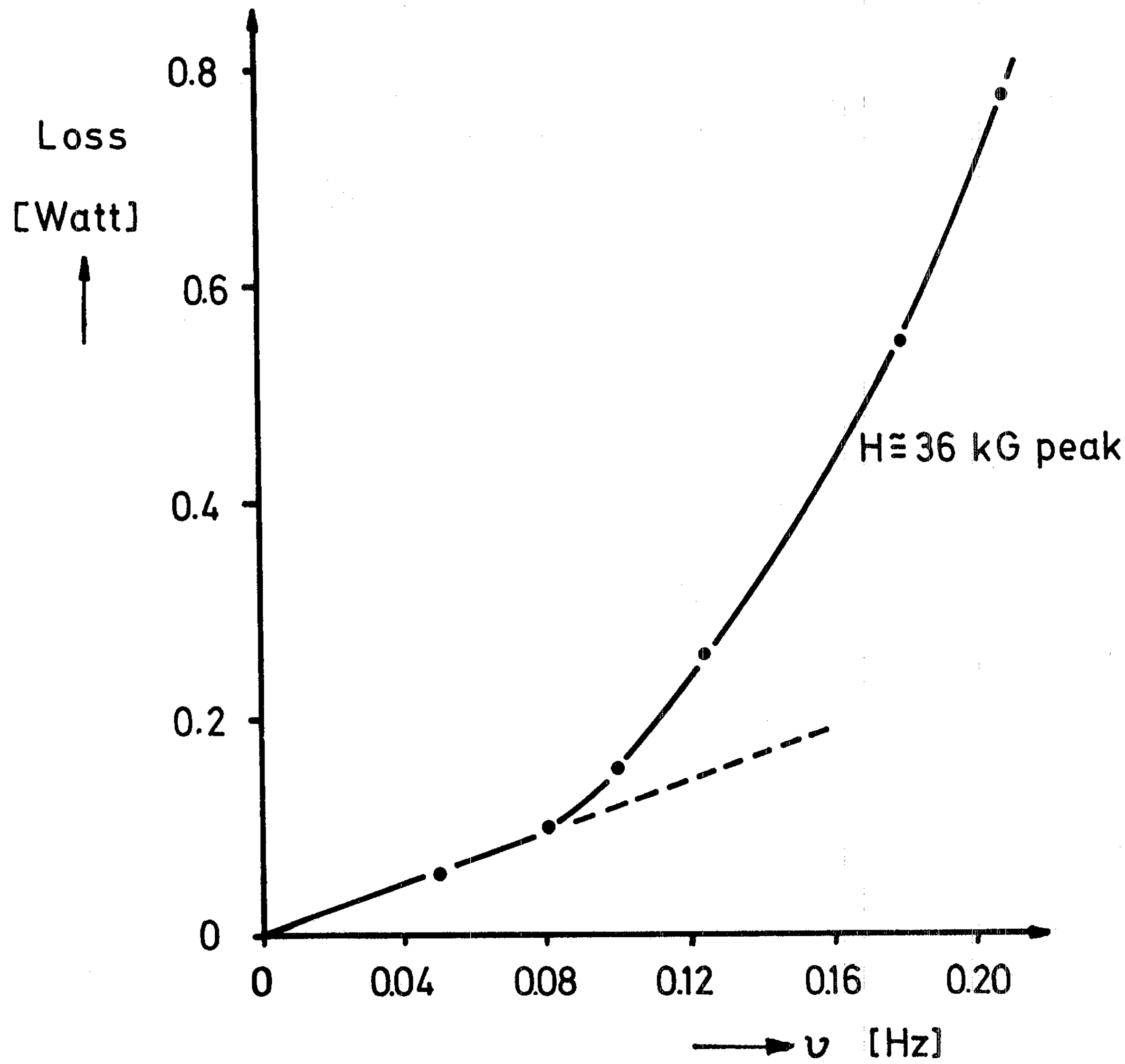
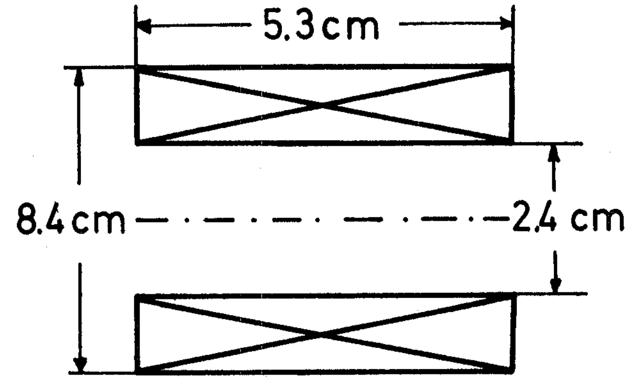


Fig. 1: AC-losses vs frequency for twisted copper composite





Coil configuration:

5650 turns of 0.05 cm diam.

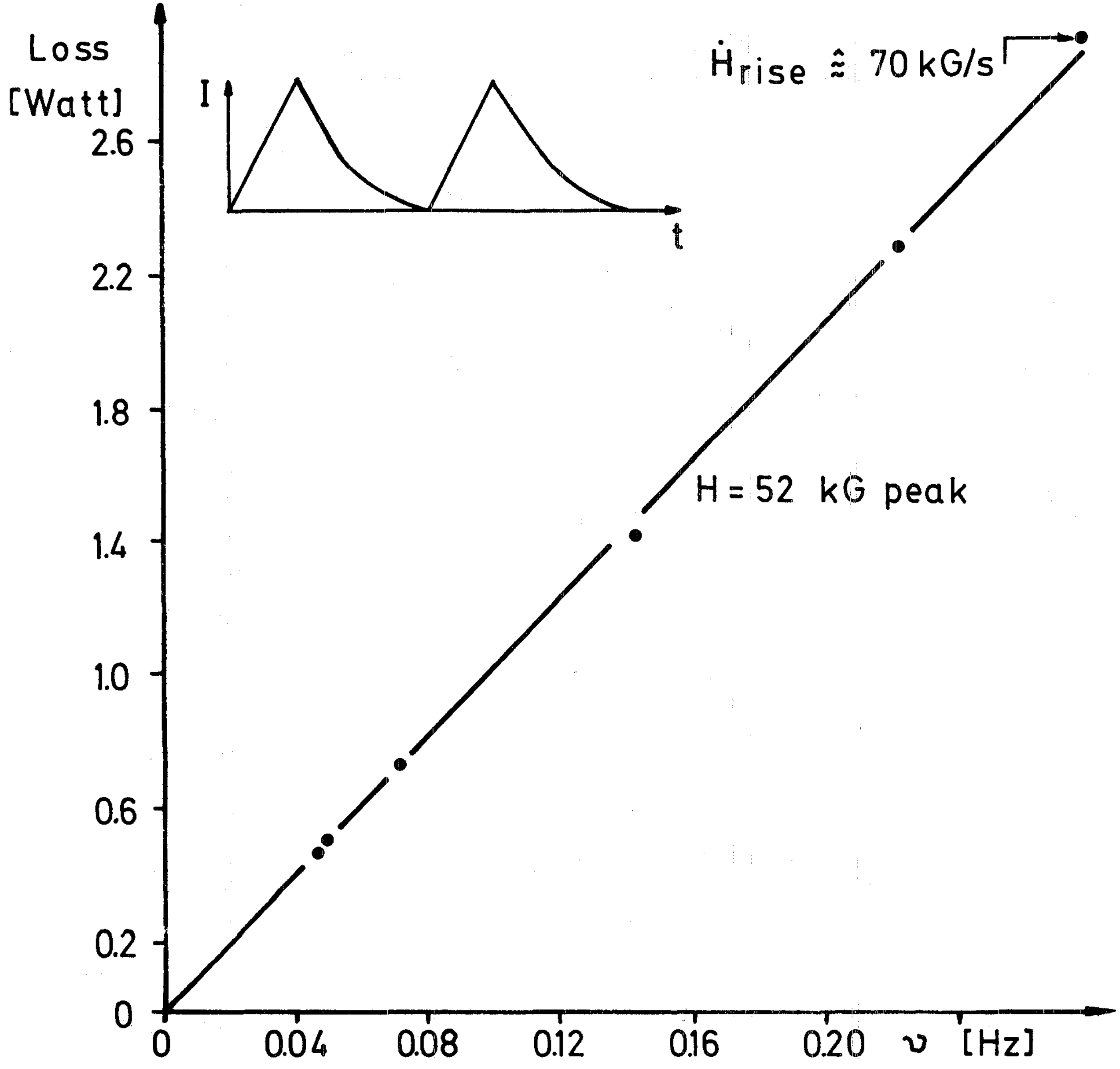
composite (361 x 13 μm filaments)

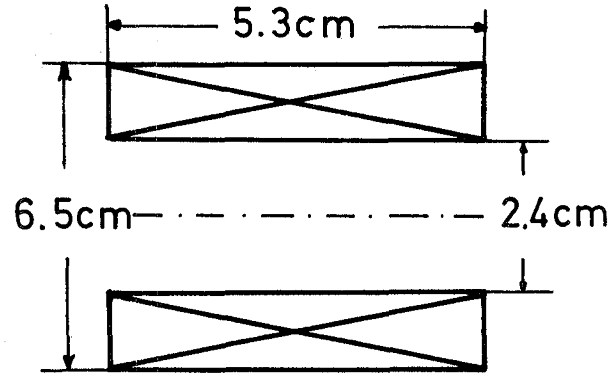
Twist : 3 turns/inch

$I_{quench} = 52$ A $\hat{=}$ $H_{quench} = 50$ kG

(Ref. No. 1)

Fig: 2: AC-losses vs. frequency for twisted copper composite





Coil configuration:

6125 turns of 0.04 cm diam. composite (61x35 μm filaments)

Twist: 4 turns/inch

I_{quench} = 65 A $\hat{=}$ H_{quench} = 72 kG

(Ref. No.: 32)

Fig. 3: AC-losses vs. frequency for copper composite

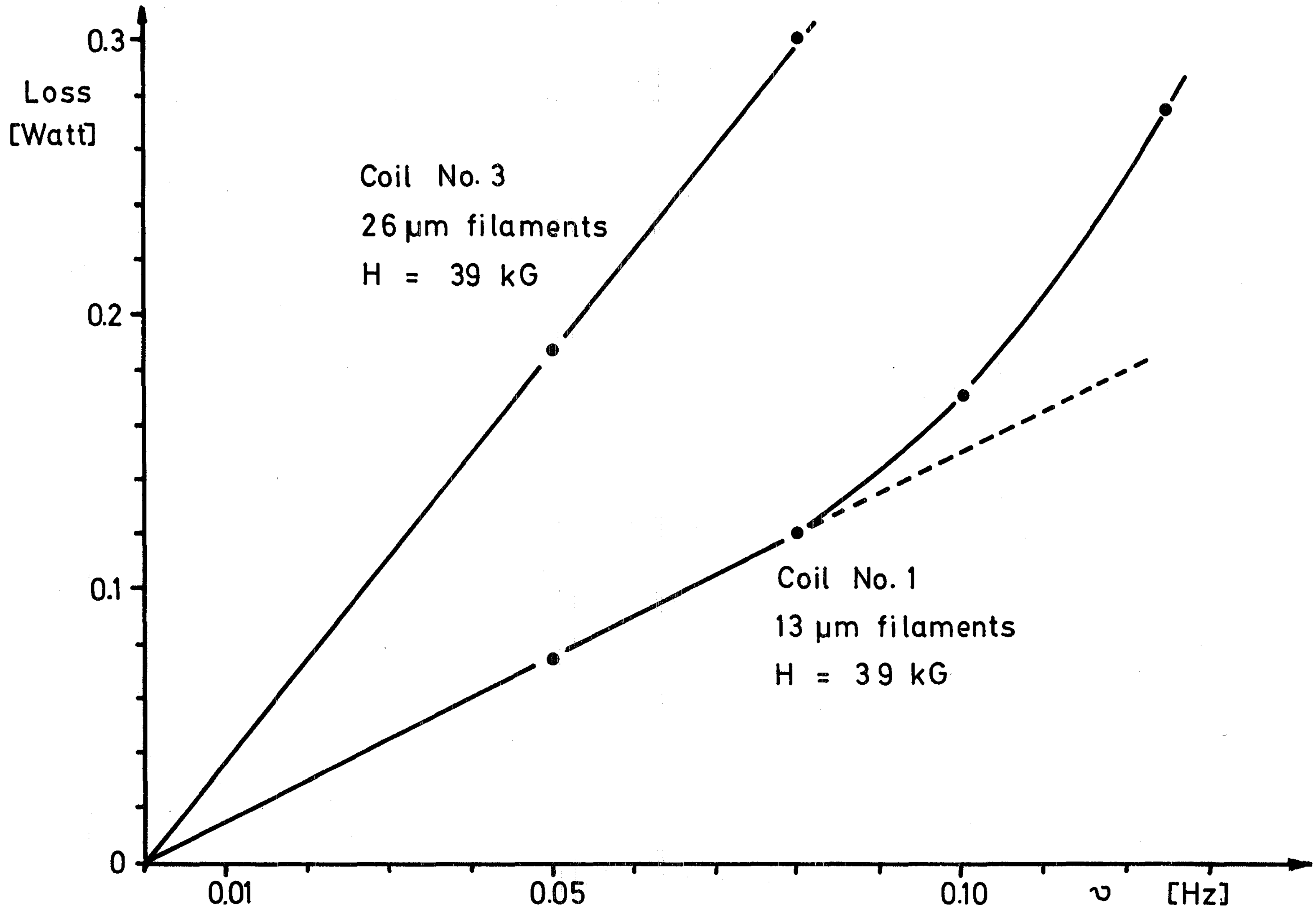


Fig. 4: Variation of ac-losses with filament diameter for twisted copper composites

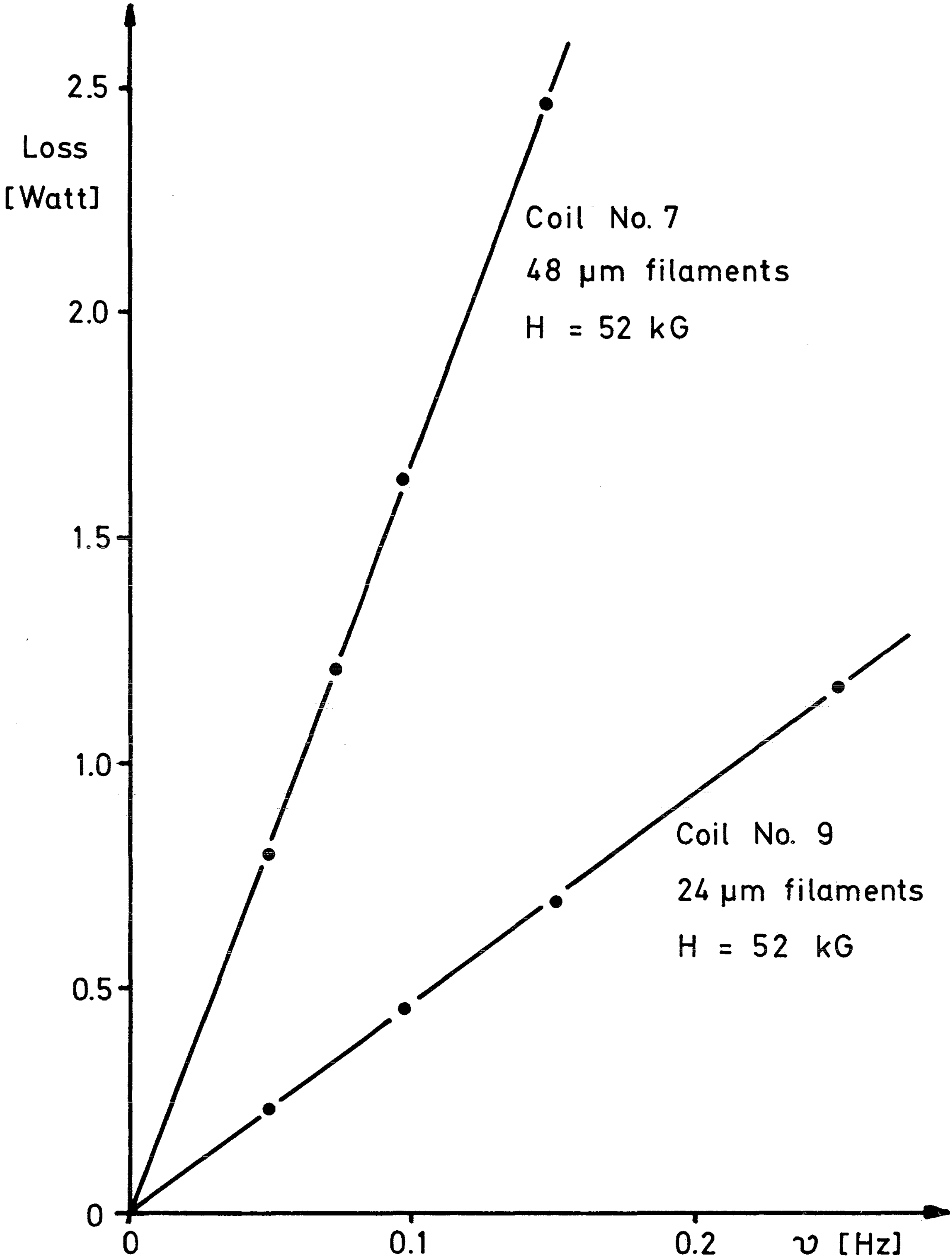


Fig. 5: Variation of ac-losses with filament diameter for twisted Cu/CuNi composites