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AUTHOR(S): W. V. Hassenzahl, CTR-9

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QUENCHES IN THE SUPERCONDUCTING MAGNET CELLO

by

W. V. Hassenzahl

ABSTRACT

The superconducting magnet CELLO was tested with currents up to 3200 A at Saclay and has been installed at DESY in Hamburg where it will be used for particle physics experiments requiring colliding beams of electrons and positrons. The testing of this unique, large, one-layer solenoid provides an excellent opportunity to evaluate the theory of quench propagation under adiabatic conditions, that is, in a coil in which the conductors are not in direct contact with helium. In an early test of this coil, quenches occurred as a result of a broken conductor in the 6th of 1276 turns. This report describes the quenches that occurred, gives the details of the damaged conductor, and includes an analysis of the quenches. Observed axial quench velocities are compared to the calculated values based on both measurements and calculations of the thermal conductivity of the fabricated coil.

I. INTRODUCTION AND SUMMARY

The superconducting magnet CELLO was tested with currents up to 3200 A at Saclay and has been installed at DESY in Hamburg where it will be used for particle physics experiments requiring colliding beams of electrons and positrons. The testing of this unique, large, one-layer solenoid provides an excellent opportunity to evaluate the theory of quench propagation under adiabatic conditions, that is, in a coil in which the conductors are not in direct contact with helium. In an early test of this coil, quenches occurred as a result of a broken conductor in the 6th of 1276 turns. This report describes the quenches that occurred, gives the details of the damaged conductor, and includes an analysis of the quenches. Observed axial quench velocities are compared to the calculated values based on both measurements and calculations of the thermal conductivity of the fabricated coil. The coil and conductor dimensions and characteristics are given in Table I. The coil and conductor are shown in Fig. 1, and a complete description can be found in Reference 1.

II. QUENCHES IN THE CELLO COIL

A. Theoretical Background

Superconducting coils are known to undergo transitions from the superconducting to the normal state. These transitions or quenches, which may begin at one or more places in the coil, propagate both along and perpendicular to the conductor. In the single-layer CELLO coil there is only one effective direction in which the quench can propagate perpendicular to the conductor.

TABLE I

CELLO COIL AND CONDUCTOR CHARACTERISTICS

Internal diameter	1 656 mm
External diameter	1 705 mm
Length	3 414 mm
Thickness	24.5 mm
Number of turns	1 276
Design current	3 400 A
Guaranteed current	2 800 A
Operating current	3 100 A
Short-sample critical current	~4 000 A
Protection resistance	0.16 Ω
Inductance	1.06 H
Cu to NbTi ratio	1/1
Cu + NbTi section	1.6 x 2.22 mm^2
High-purity Al section	2.24 x 9 mm^2
Residual-resistivity ratio of Al	700
Thermal conductivity of high-purity Al at 4.2 K	≈60 W/cmK

1. Quench Velocity Along a Conductor. The propagation velocity of quenches has been studied extensively.[2-6] The calculation by Broom and Rhoderick[2] gives the velocity of propagation, v_c, as a function of various conductor parameters and of the maximum temperature in the normal region:

$$v_c = \frac{I(\theta_m - 2\theta_c)}{C}\sqrt{\frac{k\rho}{\theta_c\theta_m(\theta_m-\theta_c)}} = \frac{I}{C}\sqrt{\frac{k}{\theta_c}}\,G(\theta) \ , \qquad (1)$$

where C is the specific heat, k is the thermal conductivity, ρ is the resistivity, I is the current, θ_c is the difference between the critical temperature and the operating temperature, and θ_m is the difference between the maximum temperature in the normal region and the operating temperature.

Stekly and Hoag[3] made the approximation that $G(\theta) = 1$, which is valid only after the central temperature of the normal region of a NbTi conductor reaches about 25 or 30 K.[6,7]

The velocities calculated with the actual conductor characteristics and $G(\theta) = 1$ are shown in Fig. 2 for the complete conductor including the aluminum. For comparison, the results of several measurements by Scherer and Turowski[8] are also shown in Fig. 2. The calculated velocities are typically higher than those measured. As the length of the conductor used by Scherer and Turowski is well known, one can calculate the evolution of temperature within the sample and thus the propagation velocity as a function of time. The reduced theoretical values, which agree better with the experiments are marked with an asterisk (*) in Fig. 2. This simple example demonstrates the need for a complete analysis of measurements made on small samples under laboratory conditions before applying the results to the performance of large coils.

2. <u>Quench Velocity Perpendicular to a Conductor</u>. A quench propagates not only along but also perpendicular to a conductor. The perpendicular velocity depends strongly on the transverse thermal conductivity $k_\perp$. Wilson[9] shows that $v_\perp = v_c\sqrt{k_\perp/k_c}$. The question is: what is the magnitude of $k_\perp$? Of course, one can calculate $k_\perp$ and hope that the result is acceptable. We are reasonably confident in this calculation for a coil such as CELLO, but not for coils with round or cabled conductors nor for those cooled directly by helium.

Table II gives the value of the axial thermal conductivity, k_{axial}, calculated from the known thermal conductivities of epoxy fiber-glass and aluminum at 4.2 K. The thermal conductivities of copper and NbTi are also given in Table II, even though they contribute little to k_{axial} because they are very small relative to that of aluminum.

The average thermal conductivity for a layered structure can be calculated from the equation

$$\frac{\ell_{total}}{k_{av}} = \frac{\ell_1}{k_1} + \frac{\ell_2}{k_2} + \frac{\ell_3}{k_3} + \ldots + R_{12} + R_{23} + \ldots \quad , \qquad (2)$$

TABLE II

THERMAL CONDUCTIVITY OF MATERIALS IN THE CELLO COIL AT 4 K

Material or Configuration	Thermal Conductivity (W/cmK)
Pure aluminum[a]	≈ 60
Structural aluminum[a]	≈ 0.06
Copper[b,c]	~ 0.05
Superconductor[c]	1×10^{-3}
Epoxy fiber-glass insulation[c]	1.3×10^{-3}
Conductor insulation[a]	1.0×10^{-3}
As wound axial conductivity	1.1×10^{-2}

[a] Measured value.
[b] Calculated value.
[c] Literature value.

where ℓ_i is the length of a section of material, k_i is the thermal conductivity of that section, and R_{ij} is the contact resistance between materials. For CELLO, we can use the values in Table II and the contact resistance $R \approx 5\ \mathrm{cm}^2\ \mathrm{K/W}$ (Ref. 10) to calculate

$$k_{axial} \simeq 2.518 \left\{ \frac{2.24}{60} + \frac{0.278}{1.3 \times 10^{-3}} + 2 \times 5 \right\}^{-1} \approx 0.011\ \mathrm{W/cmK}\ .$$

To determine if this calculation was correct for the CELLO coil, we assembled a sample of 10 insulated conductors in a block that simulated the actual coil. Table II gives the measured thermal conductivity of this sample.

We believe the difference between the measured and calculated values of k_{axial}, a factor of 10, is quite large because the test sample was not under compression; consequently the calculated value is closer to the characteristic of the assembled coil. One possible reason for this difference is the very poor cohesion between the epoxy and the thin layer of solder that forms the conductor surface.

3. Quench Volume. The quench volume in two- and three-dimensional coils, V_2 and V_3 respectively, can be characterized by

$$V_2 = 2 v_c t v_x t h = 2 v_c^{\,2} t^2 h \sqrt{\frac{k_x}{k_c}}\ , \quad \text{and} \tag{3}$$

$$V_3 = \frac{4}{3} v_c t v_x t v_y t = \frac{4}{3} v_c^{\,3} t^3 \sqrt{\frac{k_x\ k_y}{k_c\ k_c}}\ , \tag{4}$$

where t is the time, k_x and k_y are the thermal conductivities in the x and y directions, v_x and v_y are the velocities in the x and y directions, and h is the thickness of a two-dimensional coil.[11]

These equations are vaild only until the quench reaches a boundary of the coil. In CELLO, for example, if an entire turn is normal before the quench reaches one end of the coil, the quench front will then propagate only along the axis of the coil, and its speed will be $v_x = v_c \sqrt{k_x/k_c}$, that is, about 1/100 as fast as in the conductor. Here the normal volume increases linearly with time $\frac{dV}{dt} \propto v_c \sqrt{k_x/k_c}$, until one end of the coil is reached.

Another possibility is that at some time t_1 the quench reaches one end of the coil before a complete turn is normal. If this occurs, the volume is

$$V = v_c{}^2 t^2 \sqrt{\frac{k_x}{k_c}} + v_c{}^2 t . t_1 \sqrt{\frac{k_x}{k_c}} \quad , \quad t > t_1 \quad , \qquad (5)$$

until the quench completely encircles the coil.

B. Quenches in the CELLO Coil

Figure 3 shows the resistive voltages observed across the CELLO coil. These voltages indicated that the quenches started near one end of the coil. Of the three regions apparent in this figure, the first two appear to be quadratic, but the third is almost linear. These three regions are characterized in Table III.

TABLE III

VOLTAGES OBSERVED ACROSS THE CELLO COIL DURING A QUENCH

Quench Region	End Time[a] (s)	Change in Voltage (V)	Change in Resistance (Ω)	Voltage/Time Characteristic
1	0.035	0.9	4.9×10^{-4}	Quadratic
2	0.105	0.85	4.4×10^{-4}	Quadratic
3	1.1	2.75	1.5×10^{-3}	Linear

[a] Because the voltage changes very slowly at the beginning of a quench it is difficult to estimate exactly when it starts. Thus, the times may be low by as much as 0.007 s.

The linear slope during Region 3, after t = 0.2 s, indicates that the quench is propagating in only one direction. The very low values of axial thermal conductivity in the coil and the slow increase in resistance indicate that this propagation is along the axis of the coil. As the quench was known to start near one end of the coil, the velocity can be calculated by assuming the quench front is moving axially along the coil in one direction. The velocity is given by

$$v = \frac{\Delta R}{\Delta t} \quad \frac{sA}{2\pi\rho r} \approx 0.34 \text{ m/s} \qquad (6)$$

where ΔR is the change in resistivity during the time Δt, s is the axial length of a turn, A is the area of the aluminum, ρ is the resistivity of the aluminum at 4 K, and r is the radius of the coil.

The slope during Region 3 appears to deviate a bit from linearity in the last 0.3 s. This fact indicates that the maximum temperature is probably less than about 20 K, which is consistent with direct temperature measurements taken during the test and with computations made using the program QUENCH.

From the calculated axial velocity of 0.34 m/s, the quench should have traveled about 1.2 cm or 5 turns during the first 0.035 s, Region 1. The fact that the quench actually started in the sixth turn, as discussed later, supports this calculation and gives an axial velocity of about 0.40 m/s. Thus, at the end of ~0.035 s, the quench has reached one end of the coil.

For Region 2, the quench propagates along the axis of the coil in only one direction and continues propagating along the conductor, circumferentially around the coil. Finally, after 0.105 s, the quench had completely encircled the coil, traveling 2.64 m, to give quench velocity of 24 m/s along the conductor. This value, which is plotted in Fig. 2, is considerably higher than either the calculated value or the value measured by Scherer and Turowski. As discussed above, the time at which the quench begins is not well defined, but a change of 0.007 s will not reduce the velocity significantly. On the other hand, for the quench to meet itself on the opposite side of the coil it must transfer to the adjacent turns and then propagate along them. Thus the quench that begins in the broken section actually travels more than halfway around the coil before meeting itself in the fifth and seventh turns. Correcting for this effect would give a slightly higher velocity. The error bar on the point at 1900 A in Fig. 2 indicates these two effects. During subsequent tests of the CELLO coil a quench was initiated at 2550 A. It took 0.07 to 0.08 s for the quench to circle the coil, giving a propagation velocity of 33 to 38 m/s, which is also plotted in Fig. 2.

If the above sequence were reversed, that is, if the quench had encircled the coil after 0.035 s, then, instead of being quadratic, the voltage characteristic in Region 2 would be linear.

There remains a slight discrepancy between the axial quench velocity determined from the slope of the voltage in section 3 and the velocity found simply from the duration of the first region and the known position of the origin of the quench. This difference may be due to one or a combination of several factors.

1. The temperatures of the adjacent turns were elevated by Joule heating in the broken section before the quench began. This effect would reduce the heat required to achieve a given propagation velocity. Equivalently, θ_m and θ_c of Eq. 1 would be reduced and v_c would be higher.

2. The actual duration of Region 1 could have been 0.042 s, because the voltage increases slowly at the beginning of a quench.

3. The resistance of the aluminum used to calculate the velocity may be too great.

The third item deserves extra attention because an unrepresentative sample may have been used to measure the 4 K resistivity, which was found to be about 4.5 to 5 x nΩ-cm. This value may be high by as much as a factor of two due to excessive handling of the sample. The dV/dt during the quench gives dR/dt, which, in quench section 3, is proportional to the product ρv. There is thus an ambiguity and neither ρ nor v can be found directly from Region 3. However, as the velocity, 34 cm/s, is in error by at most 20%, the measured resistance can be off by at most 20%, neglecting magnetoresistance,[12,13] which is quite small in aluminum at fields below 1 T.

The voltage of Region 1 corresponds to almost 40 turns normal, even though it is certain that only 12 turns have portions that are normal and that the total normal length must be between 10 and 12 m. This difference is very puzzling. There is, however, a long delay between the time when the current transfers from the superconductor into the copper and when most of it has transferred to the aluminum. This process of current transfer is described by the well known diffusion equation

$$\frac{d^2J}{dx^2} = \frac{1}{D}\frac{dJ}{dt} \quad , \qquad (7)$$

which gives an exponential solution for the penetration of current into a conducting slab. The characteristic time constant, τ_m, is given by

$$\tau_m = \frac{16L^2}{10^9 \pi\rho} \quad ,$$

where L is the thickness of a slab conductor in cm and ρ is its resistance in Ω cm. The current penetrates 1 mm of aluminum having ρ = 5 nΩ cm in about 0.011 s. But 1 s is required for current to fully penetrate a 9-mm-thick aluminum slab.

Though the diffusion of current into the aluminum conductor CELLO is more complicated than a simple exponential function, the program QUENCH was modified to give an exponential characteristic for the resistivity of the high-purity aluminum.

The diffusion time τ_m and the aluminum resistance were varied in the program. One of the closest approximations to the observed quench voltage is given in Fig. 4 along with an expanded version of the observed curve of Fig. 3.

III. REPAIR OF THE CELLO COIL

During these tests of CELLO a resistive section was observed at all currents. The voltage between turn 1059 and the end of the coil corresponds to a resistance of $2\,\mu\Omega$ or to a normal region about 12-cm long.

It was originally believed that this normal region was probably produced by overheating the conductor during the fabrication process when the copper superconductor composite was being soldered to the aluminum stabilizer. But it was possible that the conductor was broken so the coil was x-rayed. In CELLO, because there is only a thin layer of material that is relatively opaque to x-rays, ≈1.6 mm of copper superconductor composite, it is possible to detect a mechanical defect in the composite with this technique. Figure 5, a magnified copy of the original x-ray, shows a bad section of conductor, found in the sixth turn from one end of the coil. The broken conductor contained an inclusion of NbTi with a high oxide content.

Inspection of the broken region clearly indicated that the break occurred before the epoxy in the coil was cured as there was some penetration of epoxy into the space between the composite and the aluminum near the break. Certainly the conductor was not broken before the soldering operation when the composite and the superconductor were joined. The last seven turns of the coil were removed and the void filled with an aluminum spacer and epoxy.

IV. FINAL TEST OF THE CELLO COIL AND CONCLUSIONS

During the final test of CELLO a heater produced quenches at 2550 A and there were unprovoked quenches at 3200 A. We used the resistance of a section of conductor glued to the outside of the coil to monitor these quenches and to determine the final temperature after a quench. A temperature of 60 K was reached in less than 20 s after a 3200 A quench, indicating good thermal contact between all coil components. That the current is limited to 3200 A probably is due to a defect in the conductor similar to that which caused the break. This explanation is supported by the fact that the composite was ordered in a single length, ≈7000 m, but broke several times during fabrication, probably because of other inclusions.

The analysis of this rather complex quench lends support to the use of existing theories to calculate quench propagation velocities and to predict the behavior of coils subjected to quenches.

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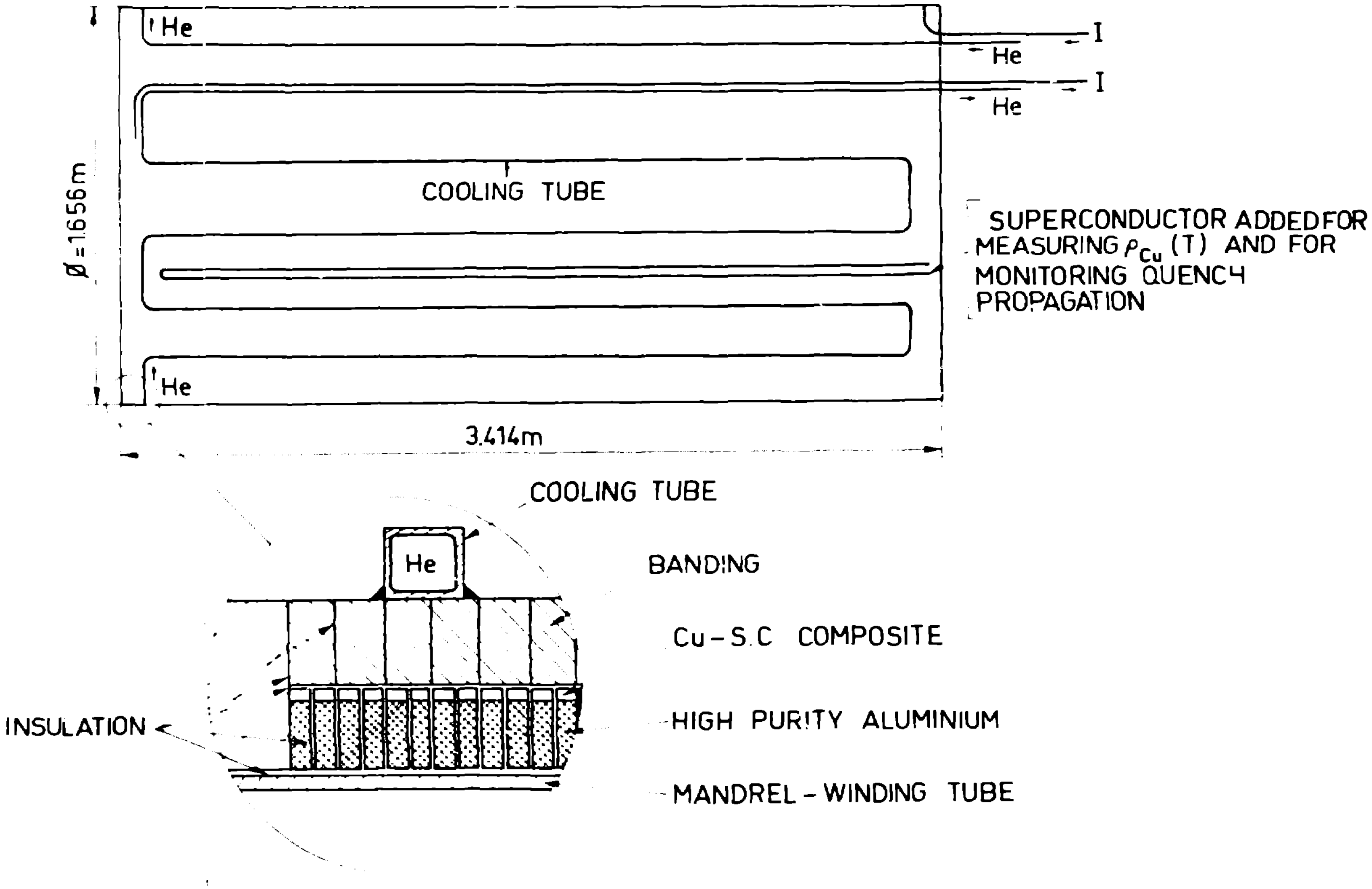
Fig. 1 Layout and detailed cross section of the superconducting magnet CELLO.

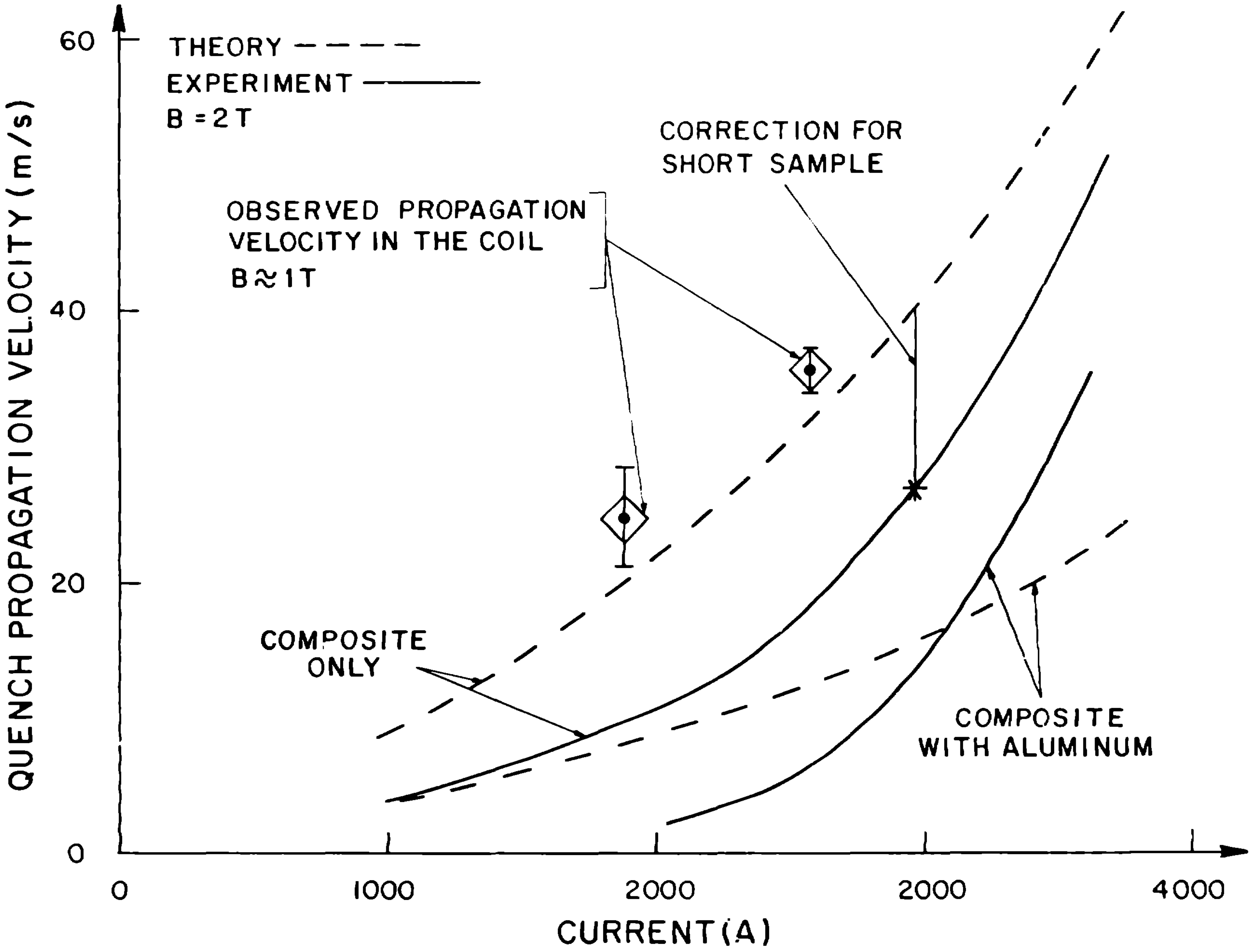
Fig. 2 Quench-propagation velocities for the CELLO superconductor-copper composite and the complete conductor with high-purity aluminum. Both theoretical and experimental values are shown.

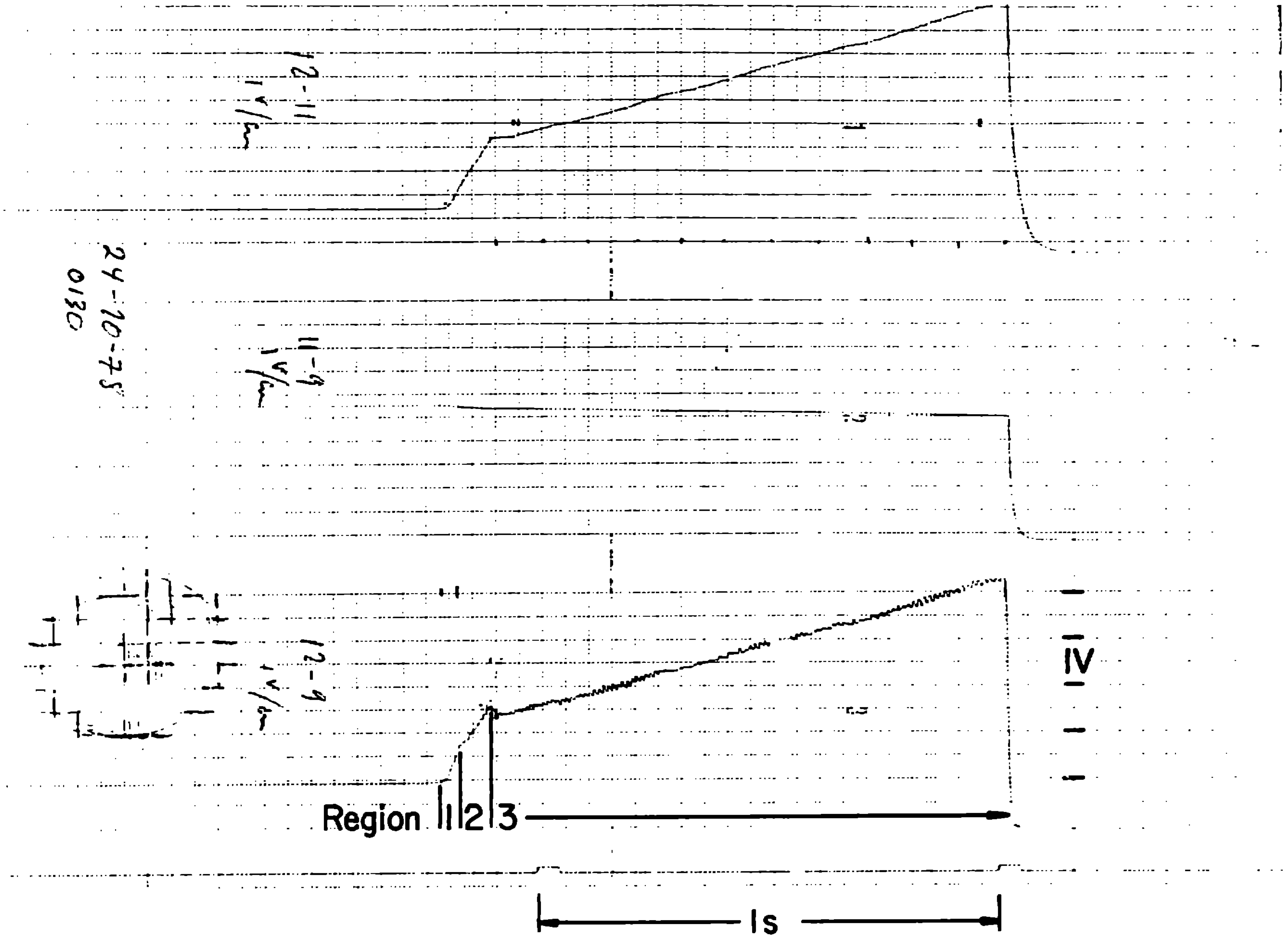
Fig. 3 Voltages observed across the CELLO coil during a quench at 1900 A.

Fig. 4 A comparison of observed and calculated voltages across the CELLO coil during a quench originating in the broken conductor, six turns from one end of the coil. The measured resistances of the high-purity aluminum and copper are used. The only variable is the diffusion time for current into the high purity aluminum.

Fig. 5 Enlargement of the in situ x-ray of the damaged section of the CELLO conductor. There is a gap of about 2 mm between the broken conductor ends.


He
I
He
I
He
COOLING TUBE
Ø=1.656m
SUPERCONDUCTOR ADDED FOR MEASURING ρ_{Cu} (T) AND FOR MONITORING QUENCH PROPAGATION
He
3.414m
COOLING TUBE
He
BANDING
Cu-S.C COMPOSITE
INSULATION
HIGH PURITY ALUMINIUM
MANDREL-WINDING TUBE


THEORY
EXPERIMENT
B = 2 T
CORRECTION FOR SHORT SAMPLE
OBSERVED PROPAGATION VELOCITY IN THE COIL B ≈ 1 T
COMPOSITE ONLY
COMPOSITE WITH ALUMINUM
QUENCH PROPAGATION VELOCITY (m/s)
CURRENT (A)
0
20
40
60
0
1000
2000
2000
4000


12-11
1 V/cm
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12-9
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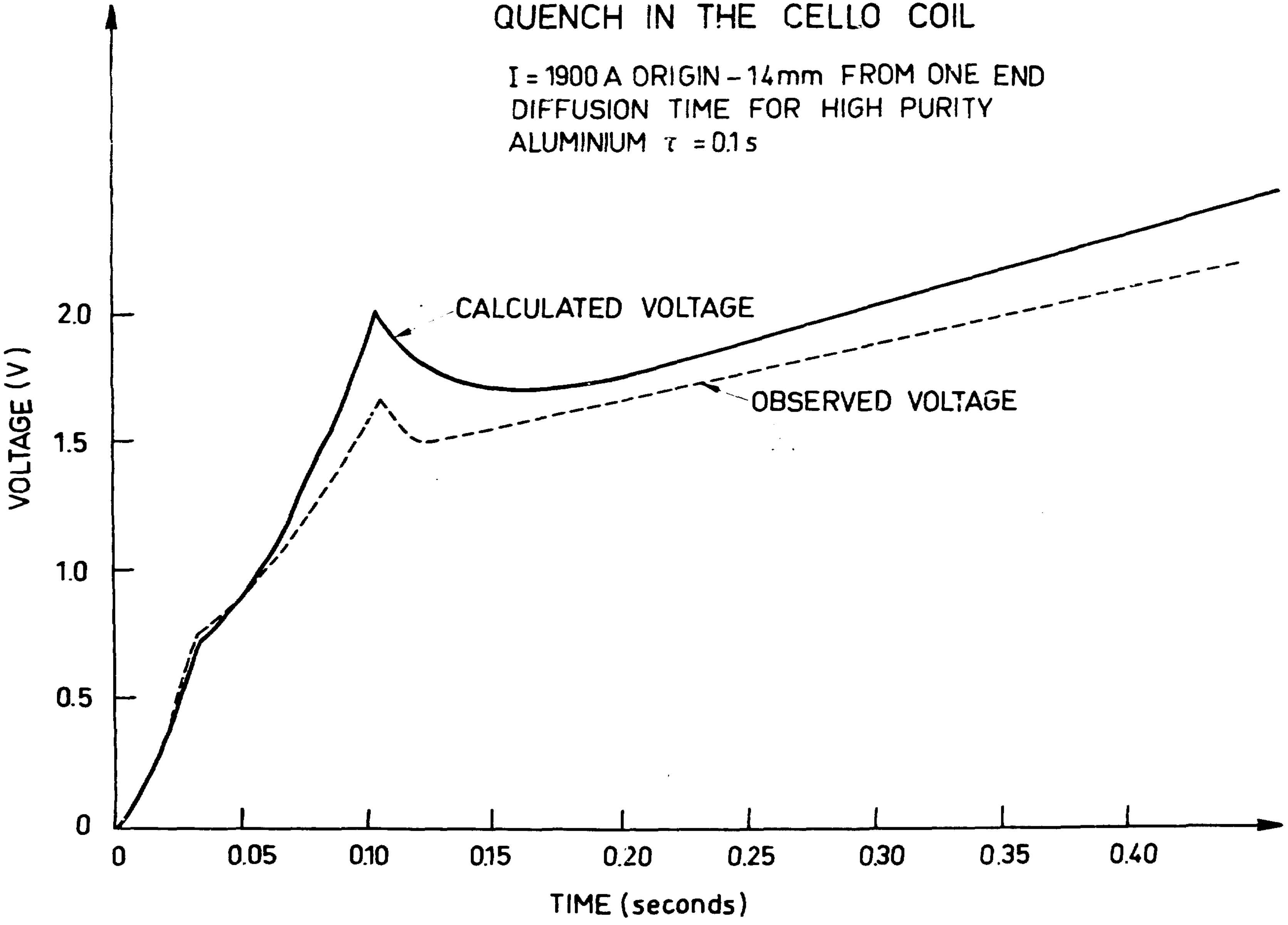
QUENCH IN THE CELLO COIL
I = 1900 A ORIGIN - 14mm FROM ONE END
DIFFUSION TIME FOR HIGH PURITY
ALUMINIUM τ = 0.1 s
CALCULATED VOLTAGE
OBSERVED VOLTAGE
VOLTAGE (V)
2.0
1.5
1.0
0.5
0
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
TIME (seconds)