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RESULTS FROM HEATER-INDUCED QUENCHES of a 4.5 m TWO-IN-ONE SUPERCONDUCTING R&D DIPOLE FOR THE SSC*

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Abstract

Quench studies were performed using a 4.5 m long SSC R&D dipole to determine the temperature rise during a quench by measuring the resistance of the conductor cable in the immediate vicinity of the quench. The 2-in-1 magnet was wound with improved "high homogeneity" NbTi conductor in a 2-layer cosine Θ coil configuration of 3.2 cm inner diameter with each layer powered separately to simulate graded conductor. Twelve pairs of voltage taps were installed at various locations in the coils around one bore of the magnet. "Spot" heaters were placed between the voltage taps of 8 of these pairs to initiate magnet quenches. The resistance of the conductor was obtained from observations of the current and voltage during a magnet quench. The temperature of the conductor was then determined by comparing its resistance to an R vs T curve measured independently for the conductor. The quantity $\int I^2 dt$ is presented as a function of current and location, and the maximum conductor temperature is shown as a function of $\int I^2 dt$ and location. Measured longitudinal and azimuthal quench propagation velocities are also presented.

Introduction

This paper reports on tests conducted with the third of a series of four 2-in-1, 4.5 m long superconducting dipoles built to specifications similar to those for SSC Reference Design A. This magnet, which is described in detail elsewhere in these proceedings[1], was wound with improved "high homogeneity" NbTi conductor in a 2-layer cosine Θ coil configuration of 3.2 cm inner diameter. To simulate graded conductor each layer was powered separately with the current in the outer layer always set 35% higher than the current in the inner layer as the currents were varied during these tests. The temperature of the liquid helium bath in which the magnet was suspended was also decreased from 4.5° to 2.4°K

third turn on the left and right sides of both the inner and outer coils next to the heaters positioned on the straight sections of the coils. These pairs of taps, which are designated in Fig. 1 by the numbers 5 and 6 on each coil, were used to determine the azimuthal quench velocity. The leads from each pair of voltage taps were carefully twisted to minimize any induced voltage in the voltage tap signal due to a change in magnetic field.

Table I. Conductor Parameters for the SSC R&D Dipole

Multifilamentary Wire	
Superconductor	Nb 46.5 wt % Ti High Homogeneity Alloy
Diameter	.0681 mm
Filament Diameter	19 microns
No. of Filaments	528
Cu to SC Ratio	1.3 to 1
Cabled Conductor	
Width (bare)	7.823 mm
Mean Thickness (bare)	1.257 mm
Keystone Angle	2.8°
No. of Wires	23
Filling Factor	88%
Insulation Thickness	
Kapton	0.0508 mm
Fiberglass-epoxy	0.0762 mm

Experimental Results

Since one of the objectives of the tests was to measure the highest temperature to which the conductor could be raised before the magnet was damaged, the first heater quenches were made at a constant bath temperature of 4.4°K at different values of magnet current to determine the current, Im, at which $\int I^2 dt$ was maximum. This procedure was repeated for each heater and the curves for two of the heaters in and location. Measured longitudinal and azimuthal quench propagation velocities are also presented.

Introduction

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Experimental Arrangement

The parameters of the conductor with which the magnet was wound are given in Table I. Eight heaters were installed in different locations in the inner and outer coils around one bore of the magnet, 4 in the inner coil and 4 in the outer coil. Each heater consisted of a 0.0635 mm thick strip of stainless steel with an overall length of 30.5 mm and width of 7.62 mm with the width reduced to 2.54 mm over the 17.8 mm long center section of the heater. By varying the voltage from 5.0 to 7.5 V, about 1 to 2 j of energy could be delivered to the heater in approximately 60 millisec. The heaters were wrapped with one layer of 0.0508 mm thick Kapton and positioned against the inner surface of the insulated mid-plane turns of the inner and outer coils in the locations shown in Fig. 1. At each heater position a pair of voltage taps, separated nominally by 12.7 cm, was connected to the conductor with the heater located centrally between the taps. Four additional pairs of similar voltage taps were installed on the

*Work performed under the auspices of the U.S. Department of Energy.

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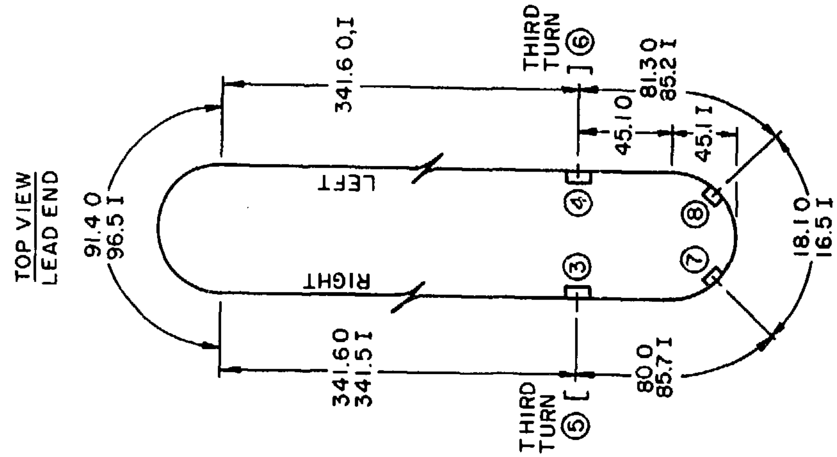
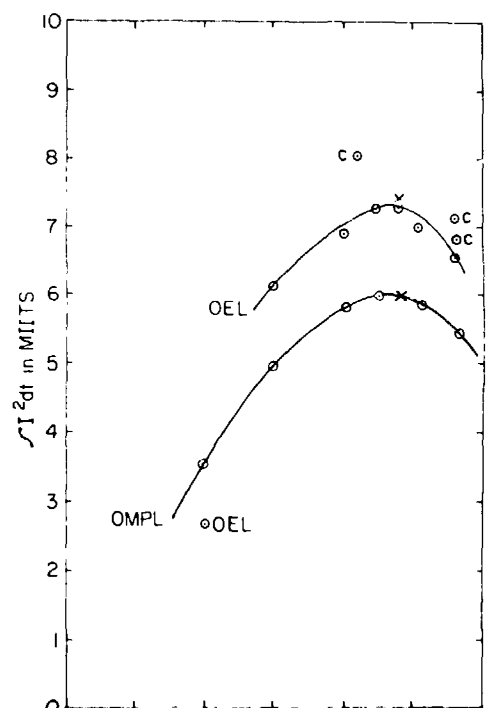
The temperature rise of the conductor cable during a heater-induced quench was measured by monitoring the magnet current and the voltage across the 12.7 cm section of cable where the heater was fired. The resistance of this length of cable was calculated from which the average temperature over the 12.7 cm length between voltage taps could be determined by using the R vs T calibration curve. A correction to obtain the "hot spot" temperature was made by calculating an incremental ΔR following the procedure of Ganetis and Stevens.[2] From the trace of the voltage across the section of cable where the heater was fired as a function of time and knowledge of the magnet current the slope $d(\int I^2 dt)/dR$ may be obtained. The trace in Fig. 3 shows that when the heater is fired the voltage and thus the resistance increase rapidly as the quench propagates away from the heater toward the voltage taps as both ρ and ℓ are increasing in the relationship, $R = \rho\ell/A$. The slope changes when the normal quench fronts reach the voltage taps since ℓ is now constant between the taps and R is a function only of ρ. From such traces, for each heater quench the time from the beginning of the quench to the time when the entire 12.7 cm length is resistive can be measured. Half this time multiplied by I^2 gives $\Delta\int I^2 dt$, the difference in $\int I^2 dt$ between the hot spot and the length of 6.35 cm which, to first approximation, is the position corresponding to T_{ave}. R is then corrected by adding ΔR where $\Delta R = \Delta\int I^2 dt / d(\int I^2 dt)/dR$ and with this addition the hot spot temperature is found. The corrections for these tests varied from less than 1°K to 15°K.

The curves in Fig. 4 show the temperature rise of the section of conductor where a heater quench was initiated as a function of $\int I^2 dt$ for locations OMPL and OEL. The curves for the inner coil, IMPL and IEL, not shown, followed closely the curve for OMPL to a maximum of 345°K for IEL and 280°K for IMPL. As mentioned above, the current in the outer coil (curves OMPL and OEL) was 35% greater than that in the inner coil. It was apparent from Fig. 2 that larger values of $\int I^2 dt$ for a given current could be obtained during a heater quench by firing the heater (OEL) near the end of the outer coil. This heater was then used in the final series of heater quenches at reduced liquid He bath temperatures in an attempt to damage the magnet coil. After each heater quench in this series the magnet current was increased until a quench occurred to ascertain if there had been any deterioration in the magnet performance. For the last heater quench which caused no damage, $\int I^2 dt$ = 8.72 MIITS and T ≈ 920°K. For the next and last heater quench which damaged the magnet, $\int I^2 dt$ = 9.04 MIITS and T reached an estimated 1170°K. The He



Key:
Coil Dimensions in cm: O-Outer, I-Inner
Heater + Voltage Taps: 3,4,7,8. Taps only: 5,6
Mid Plane Right: OMPR-Outer, IMPR-Inner Coil
Mid Plane Left: OMPL-Outer, IMPL-Inner Coil
End Right: OER-Outer, IER-Inner Coil
End Left: OEL-Outer, IEL-Inner Coil

Figure 1. Location of heaters and voltage taps on the magnet coils.



initiated as a function of $\int I^2 dt$ for locations OMPL and OEL. The curves for the inner coil, IMPL and IEL, not shown, followed closely the curve for OMPL to a maximum of 345°K for IEL and 280°K for IMPL. As mentioned above, the current in the outer coil (curves OMPL and OEL) was 35% greater than that in the inner coil. It was apparent from Fig. 2 that larger values of $\int I^2 dt$ for a given current could be obtained during a heater quench by firing the heater (OEL) near the end of the outer coil. This heater was then used in the final series of heater quenches at reduced liquid He bath temperatures in an attempt to damage the magnet coil. After each heater quench in this series the magnet current was increased until a quench occurred to ascertain if there had been any deterioration in the magnet performance. For the last heater quench which caused no damage, $\int I^2 dt$ = 8.72 MIITS and T ≈ 920°K. For the next and last heater quench which damaged the magnet, $\int I^2 dt$ = 9.04 MIITS and T reached an estimated 1170°K. The He bath temperature for these last quenches was 2.4°K.

Measurements were also made of longitudinal and azimuthal quench velocities by measuring the distance between pairs of voltage taps and recording the time when a voltage signal would appear at the several pairs of taps after a heater quench had been initiated at a particular location. The longitudinal quench velocities as a function of current are shown for the outer coil in Fig. 5 (OMPL) and Fig. 6 (OEL), for the inner coil in Fig. 7 (IMPL) and Fig. 8 (IEL), and the azimuthal quench velocities for both the outer and inner coils in Fig. 9. The numbers next to the curves in each of the figures are the locations between which the velocities were measured (see Fig. 1). The quench velocities given by these curves were measured in a He bath at 4.5°K. Additional data, not shown here, indicate a dependence of the quench velocities on temperature for the same magnet current.

References

1. P. Dahl et al., "Performance of Four 4.5 m Two-in-One Superconducting R & D Dipoles for the SSC", these proceedings.
2. G. Ganetis and A. Stevens, "Results of Quench Protection Experiment on DM1-031," SSC Technical Note No. 12, Brookhaven National Laboratory.

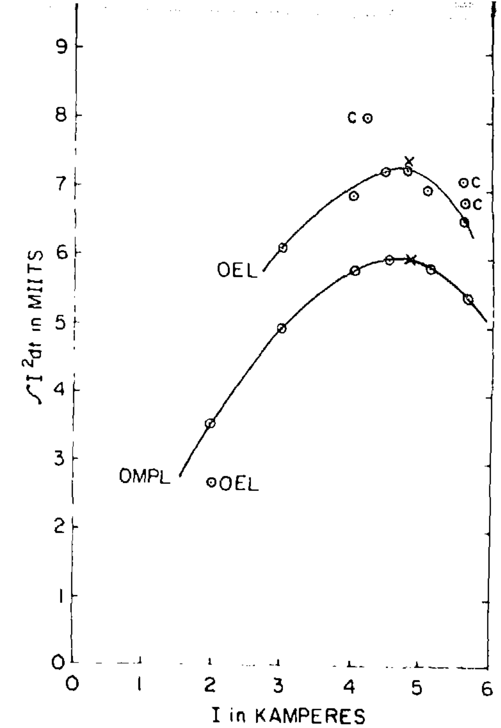


Figure 2. $\int I^2 dt$ vs I for Outer Coil at 4.4°K.

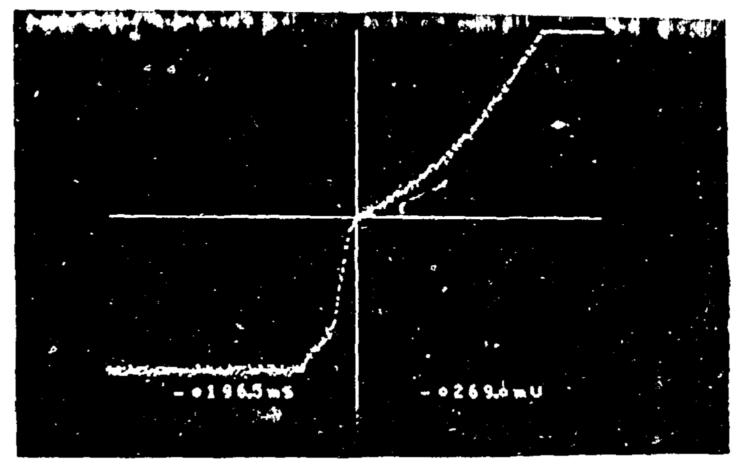


Figure 3. Voltage vs Time across a 12.7 cm section of conductor cable where a heater quench was initiated.

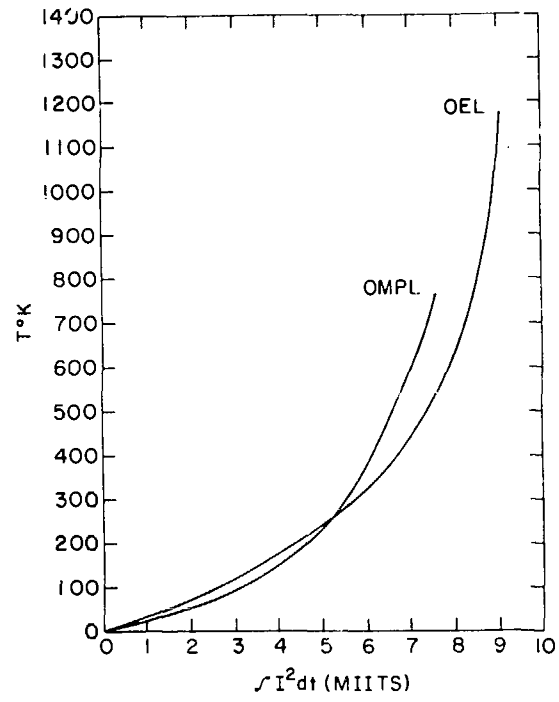
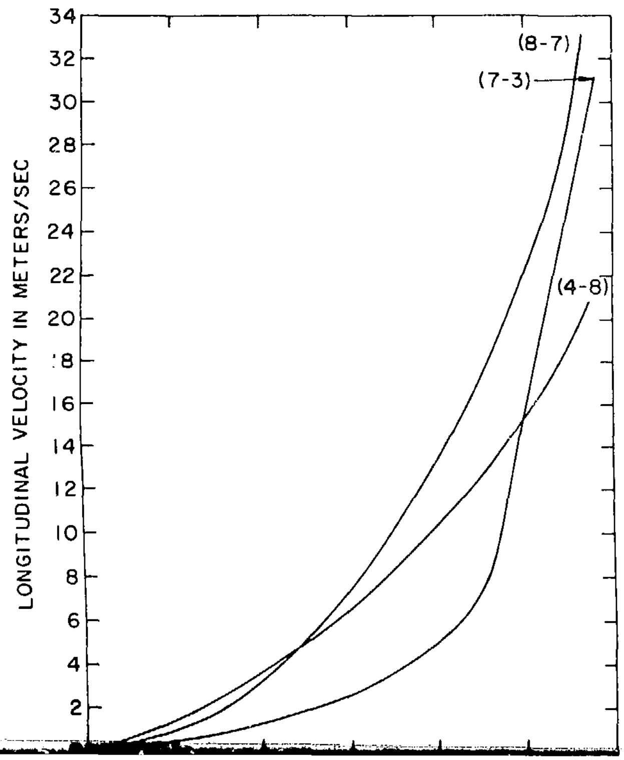


Figure 4. T vs $\int I^2 dt$ for OMPL and OEL.



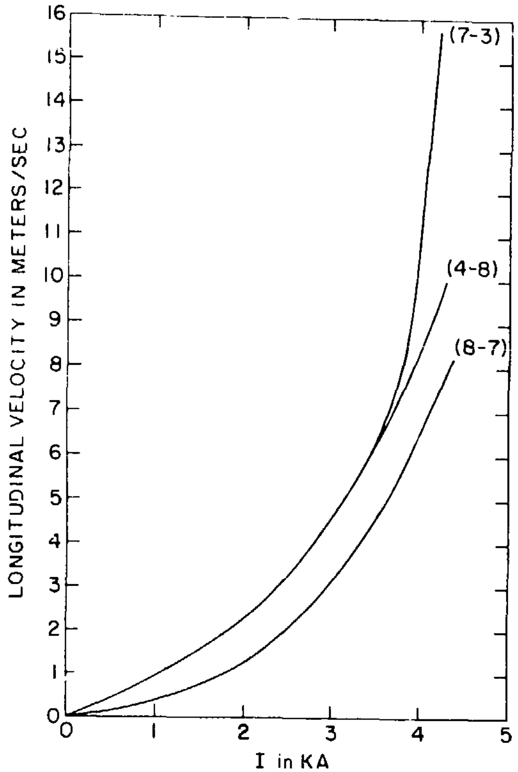
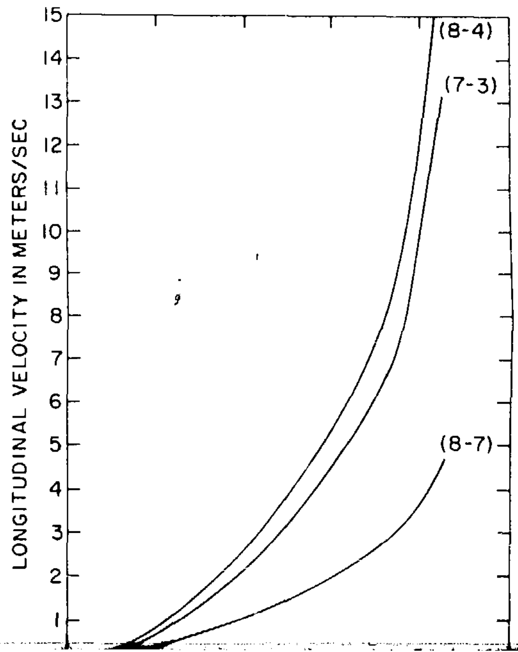


Figure 7. IMPL: Longitudinal Quench Velocity vs I at 4.5°K.



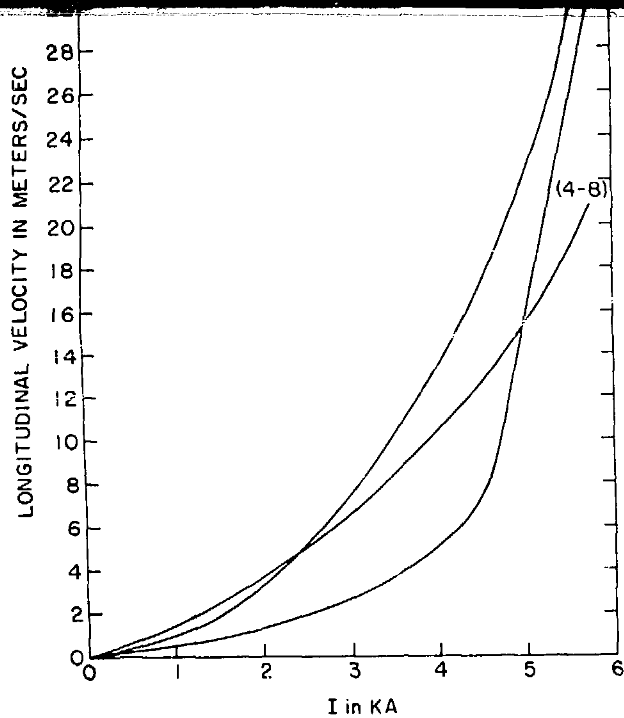


Figure 5. OMPL: Longitudinal Quench Velocity vs I at 4.5°K.

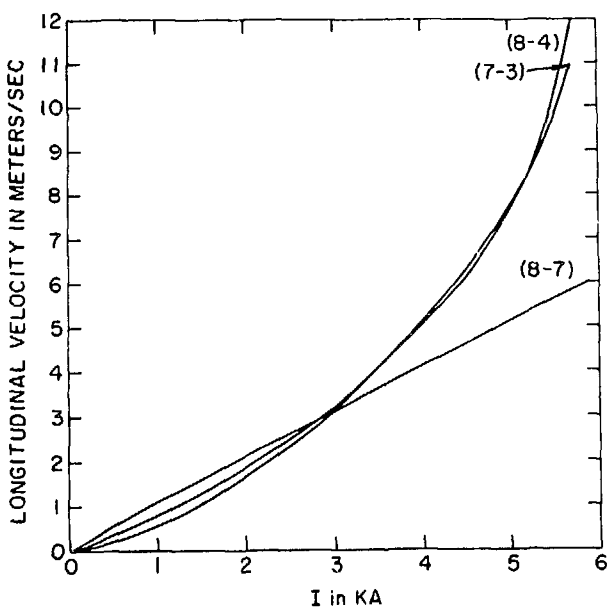


Figure 6. OEL: Longitudinal Quench Velocity vs I at 4.5°K.

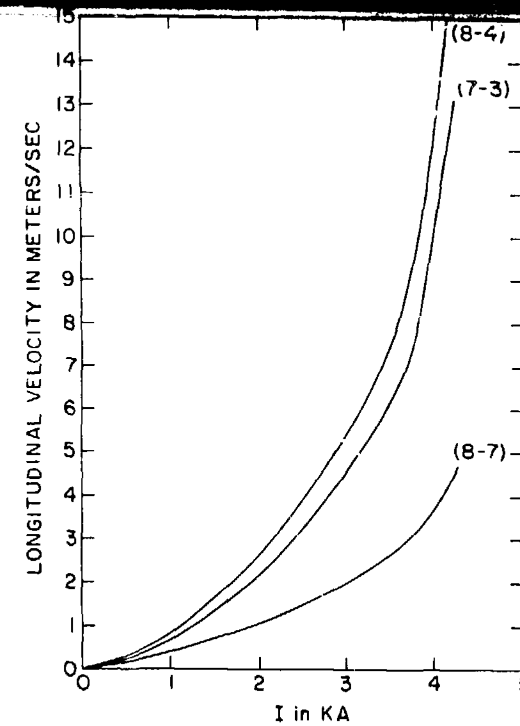


Figure 8. IEL: Longitudinal Quench Velocity vs I at 4.5°K.

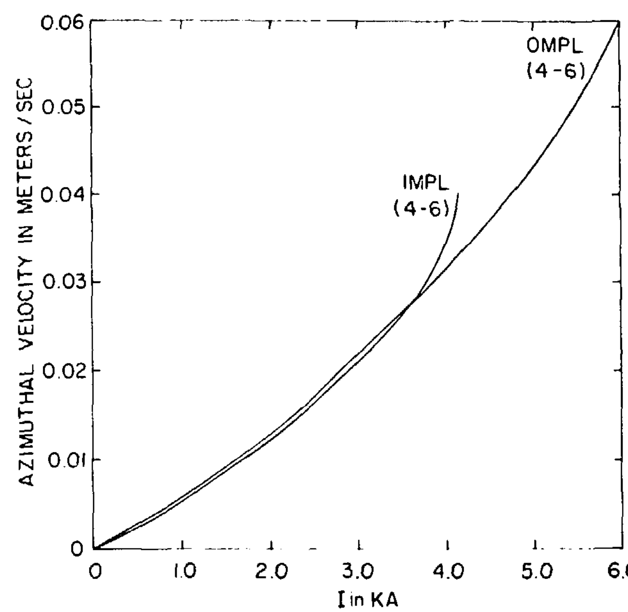


Figure 9. IMPL and OMPL: Azimuthal Quench Velocity vs I at 4.5°K.