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HYSTERESIS LOSS TEST OF SUPERCONDUCTING WIRES

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In order to determine the refrigeration load of a superconducting accelerator, hysteresis loss and ac loss tests of superconducting wires are being conducted. The ac loss includes hysteresis as well as eddy current losses. However, since hysteresis causes the major portion of the loss at slower cycle times, it is being investigated separately. Total ac loss is measured using a fast pulsed solenoid and will be reported in a different publication.

1. Setup for Hysteresis Loss Measurement

The hysteresis loss is measured using the same solenoid magnet as is used for short-sample tests . This magnet can be cycled at rates between 0.05 and 2.0 kG/sec. The physical setup is described in detail elsewhere[2]. Two identical search coils are placed 5.0 cm apart at the center of the solenoid. These are connected to individual potentiometers, bucking against each other, and the output from the potentiometers is adjusted to zero when the magnet is excited without a sample.

When a sample is present there is an output signal proportional to the difference of flux within the two pick-up coils. This signal is integrated and fed to the Y axis of an X-Y recorder. The current in the magnet is monitored and connected to the X-axis of the recorder. The area inside the loop gives the hysteresis loss W_H where $W_H = \oint HdB$ and B is in teslas, H in amp/m and W_H in joules/m^3.[3]

II. Samples and Their Orientations

The geometry of a sample, search coils and the solenoid is shown in Figure 1. The search coils are wound on G-10 tubings, which have an outer diameter of .83 inch. The coils themselves have an outer diameter of .93 inch and a height of 1.0 inch. A sample is put into a hole in a cartridge, which is screwed onto a G-10 rod. The size of the hole is .63 inches in diameter and 2 inches deep.

Usually a wire sample is cut into 2-inch long pieces and put into a cartridge. Thus, the magnetic field direction is along the length of the superconducting wire. This is the normal orientation, is used in most cases, and is called "wire ∥ ".

To investigate the field orientation effect, a flat cable of superconducting wires is cut into small pieces less than the diameter of the cartridge hole. In the second orientation, the pieces are placed one by one on top of each other, with the wide face of the wire perpendicular to the field direction. This orientation is called "wide surface perpendicular" or "W⊥" in short.

In the third orientation, a flat sample cable is cut into small rectangular pieces. They are also placed in the cartridge one by one, with the narrow face of the wire perpendicular to the field direction. This orientation is called "narrow surface perpendicular" or "n⊥" in short.

In the first orientation, the superconducting filament length is on the order of 2 inches, though twisted. In the second and third ones, it is on the order of a half inch, roughly perpendicular to the field. Having many very short

pieces makes the end effect more complicated to correct in the perpendicular directions.

III. Measurement Data

Seven-strand IGC wire, and solid, 13-strand, 17-strand and 23-strand MCA wire were measured with the sample parallel to the field. Hysteresis losses were measured for cycles from 0 kG to 45 kG (which corresponds to 1000 GeV for the proposed Energy Doubler) and from 9 kG (injection at 200 GeV) to 45 kG. Wires were also tested to intermediate maximum fields, including several below 9 kG.

The MCA 17- and 23-strand wires were tested more extensively than the others. These wires were also measured from 18 kG (injection at 400 GeV) to 45 kG. Both soldered and unsoldered wires were tested and their results compared. The two orientations with the wire perpendicular to the field were investigated. Some attempt was made to determine end effect; i.e., the decrease in apparent hysteresis loss due to finite sample length W(measured) = W(wire) - E(end effect).

All of the wires with orientation parallel to the field had self-consistent results. Table I gives pertinent data and shows that the hysteresis losses W_H are proportional to the critical current density at zero field J_o, filament diameter d, and cross sectional areas of wires in agreement with theory. $W_H \propto dJ_oS$.

Theoretical calculations of hysteresis loss were made, and their results along with the actual measured values are presented in Table II. These measured data are taken in the normal orientation, but corrections are not applied.

When tested for cycle rate dependence, samples oriented parallel to the field had losses which were independent of the cycle rate in the range .1 to 2 kG/sec.

Figures 2-7 show energy loss per cycle in terms of Joules per meter of wire and Joules per cm^3 of superconductor for various wires.

Some of the data are shown on a log-log scale in Figure 8. All of them show a bending point at their respective penetration fields. Their measured and calculated penetration fields are shown in Table I. Above these, the loss is roughly linear and below them, it is cubic when there is no residual magnetization. When we measure at low fields after being excited to a higher field, we observed a quadratic relation instead of a cubic one.

IV. MCA 17-Strand Wire

The hysteresis losses in the parallel orientation of soldered and unsoldered 17-strand wire were very similar, as shown in Figure 5. The losses for the unsoldered wire are consistently higher by .02 Joules/meter of wire/cycle for the 0 to 45 kG cycle and half of that for the 9 to 45 kG cycle. This small discrepancy could easily be due to the different preparations the two cables had undergone.

Only soldered 17-strand wire was tested in the perpendicular orientations. The two orientations gave very similar results at H=.5 kG/sec, but these results were somewhat differnt than those obtained when the wire was parallel to the field. This is shown in Figure 6. This difference is probably due to the different effective radii of the superconducting filaments. Also due to the configuration of the testing apparatus, it was necessary to use rather short pieces of the wire, when measuring perpendicular to the field.

With the wide face of the wire perpendicular to the field, there was a definite cycle-rate dependence. As the rate is increased by a factor of ten from .2 kG/sec to 2 kG/sec, the hysteresis loss approximately doubled. This behavior was not exhibited when the narrow face of the wire was perpendicular to the field.

V. MCA 23-Strand Wire

For both soldered and unsoldered 23-strand wire, the hysteresis loss was measured with the wire in the three previously mentioned positions. The shape of the curves for the three orientations were very similar to those for the 17-strand wire, as shown in Figure 7.

The losses for soldered and unsoldered wire tested parallel to the field were very close.

In both perpendicular orientations, the soldered wire exhibited cycle rate dependence at low cycle rate. This dependence was not significant below H=1 kG/sec, when the narrow face of the wire was perpendicular to the field. However, when the wide face of the wire was perpendicular to the field there was a 15% increase in loss at H=.25 kG/sec, indicating that ac losses have become significant at slow ramp rates. The unsoldered wire had no difference in hysteresis loss for ramp rates up to H=2 kG/sec for both perpendicular orientations. This increased loss is due to interstrand eddy current loss by soldering the strands.

VI. End Effect

Since the length of the test sample was relatively short, it was necessary to correct for end effect. One-inch and two-inch samples were tested. It is expected that one-inch samples would show somewhat more effect, which is borne out by the lower losses in the wire of the one-inch sample. Very simplistically, in analogy with the standard bar magnet, one could assume that the end effect for the two-inch sample is just half of that for the one-inch sample. This would result in corrections to the measured hysteresis losses of two-inch samples of 25% to 30% for samples in the parallel orientation and 15% to 20% for samples in the perpendicular orientations.

However, the pick-up coil has a length of one inch, so the smaller sample just fills it, whereas the larger sample sticks out a half inch on each side. With this in mind the end effect of the larger sample is expected to be somewhat less than half of that on the smaller sample. Assuming it to be a quarter, then the corrections are: 8% to 10% for parallel orientation, and 5% to 6% for perpendicular orientations for the two inch sample.

There is an interference effect between the two search coils, which is expected to be less than a few per cent.

These corrections are not applied to the data in Tables and Figures.

REFERENCES:

1. M.E. Price and R. Yamada, IEEE Trans. Nucl. Sci. NS-22, 1190 (1975)

2. R. Yamada, M.E. Price and H. Ishimoto
Submitted to 1975 Cryogenic Engineering Conference, Queen's University, Kingston, Ontario, Canada, July 1975 and TM 598 (1975)

3. C.P. Bean, Rev. Mod. Phys. 47, 31 (1964)

4. D.B. Thomas and M.N. Wilson, Rutherford Laboratory, Preprint RPP/A93, 1972

5. B.P. Strauss, Private Communication

TABLE I

Wire	Filament Diameter (μ)	Area of Superconductor (cm^2)	At 45 kG J_c (KA/cm^3)	At 45 kG Joules/Meter of Wire	At 45 kG Joules/cm^3 of Superconductor	Penetration Field (k oe) Calculated*	Penetration Field (k oe) Measured
IGC 7 75x150							
0-1000GEV	12.3	.0173	235	.283	.175	1.0	1.3
200-1000GEV				.184	.115		
MCA solid 50x150							
0-1000	29	.0156	140	.370	.233	1.4	4
200-1000				.232	.150		
MCA 13 75x250							
0-1000	11.7	.0322	190	.512	.158	0.77	1.35
200-1000				.320	.100		
MCA 17 50x250 unsoldered ∥							
0-1000	7.9	.0192	200	.218	.112	0.55	1.2
200-1000				.149	.076		
MCA 17 50x250 soldered ∥							
0-1000	7.9	.0192	200	.202	.105		
200-1000				.140	.072		
400-1000				.089	.046		
MCA 17 50x250 soldered n⊥							
0-1000	7.9	.0192	200	.170	.088		
200-1000				.102	.054		
400-1000				.068	.035		
MCA 17 50x250 soldered w⊥							
0-1000	7.9	.0192	200	.165	.086		
200-1000				.103	.054		
400-1000				.066	.034		
MCA 23 50x300 soldered ∥							
0-1000	7.9	.0260	200	.274	.105	0.55	1.15
200-1000				.186	.073		
400-1000				.126	.048		

* $H_p = \frac{1}{2} d\, J_o$ (Mks), $J_c = J_o B_o/(B+B_o)$, B_o = 1T assumed

TABLE II Hysteresis Loss Data from 0 to 45 kG

	Measured*		Relation**		Relation***	
	Joules/m of wire	Joules/cm^3 of Superconductor	Joules/m of wire	Joules/cm^3 of Superconductor	Joules/m of wire	Joules/cm^3 of Superconductor
IGC 7	.29	.17	.20	.11	.30	.17
MCA solid	.37	.24	.22	.14	.34	.22
MCA 13	.51	.16	.29	.09	.44	.14
MCA 17	.20	.11	.12	.06	.19	.10
MCA 23	.28	.11	.17	.06	.25	.10

*Corrections mentioned in text are not applied to measured data

**Reference 4 $W_H = \frac{4d\ J_o B_o}{3\pi} \ln\left[\frac{B+B_o}{B_o}\right]$

***Reference 5 $W_H = \frac{4}{3} B_{max} J_c d_{sc} A_{sc}$

Fig. 1

HYSTERESIS LOSS APPARATUS

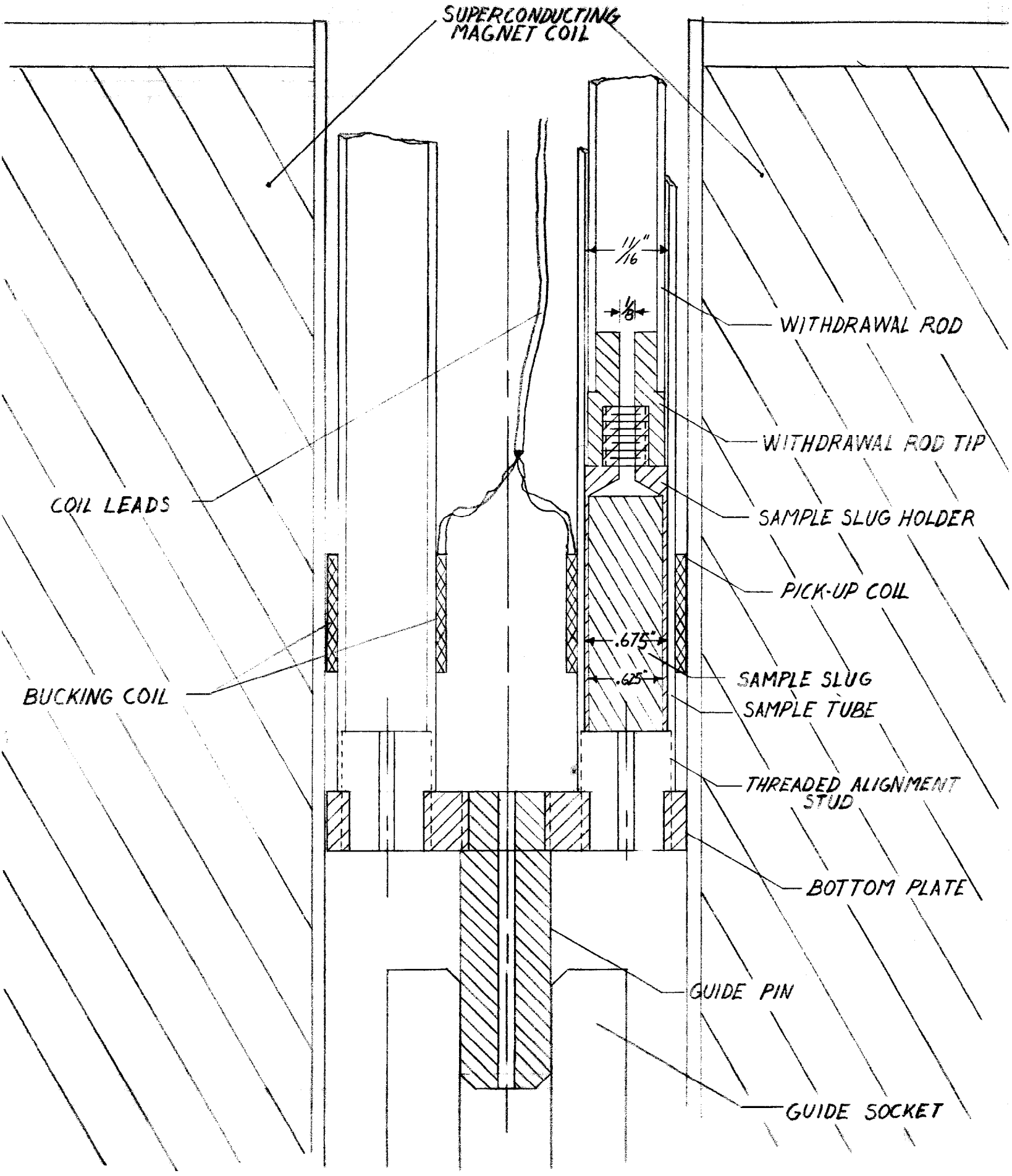

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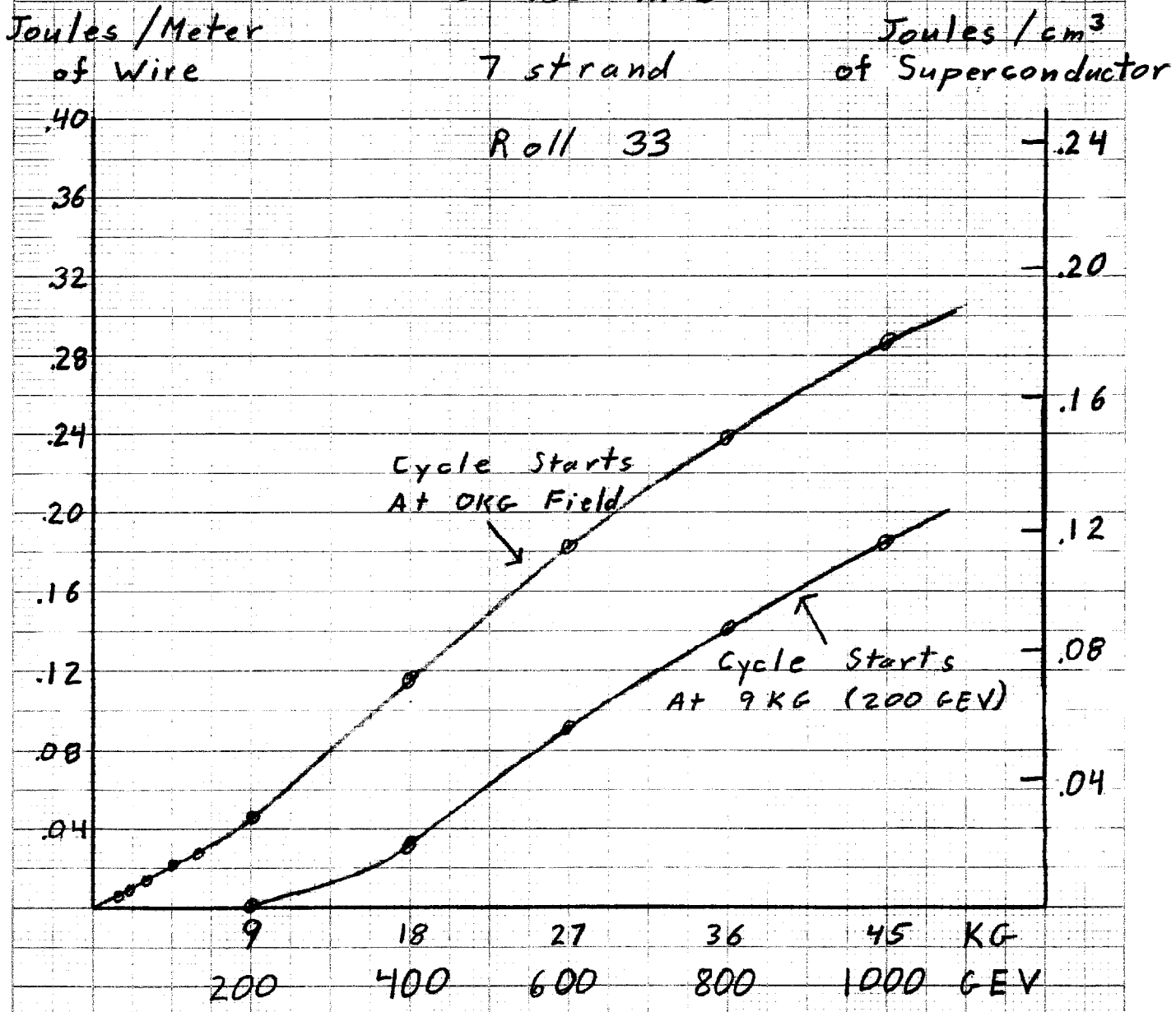
Fig. 2

IGC Wire

75 x 150 mils



Field of Magnet in KG
and
Corresponding GEV for Purposed Doubler

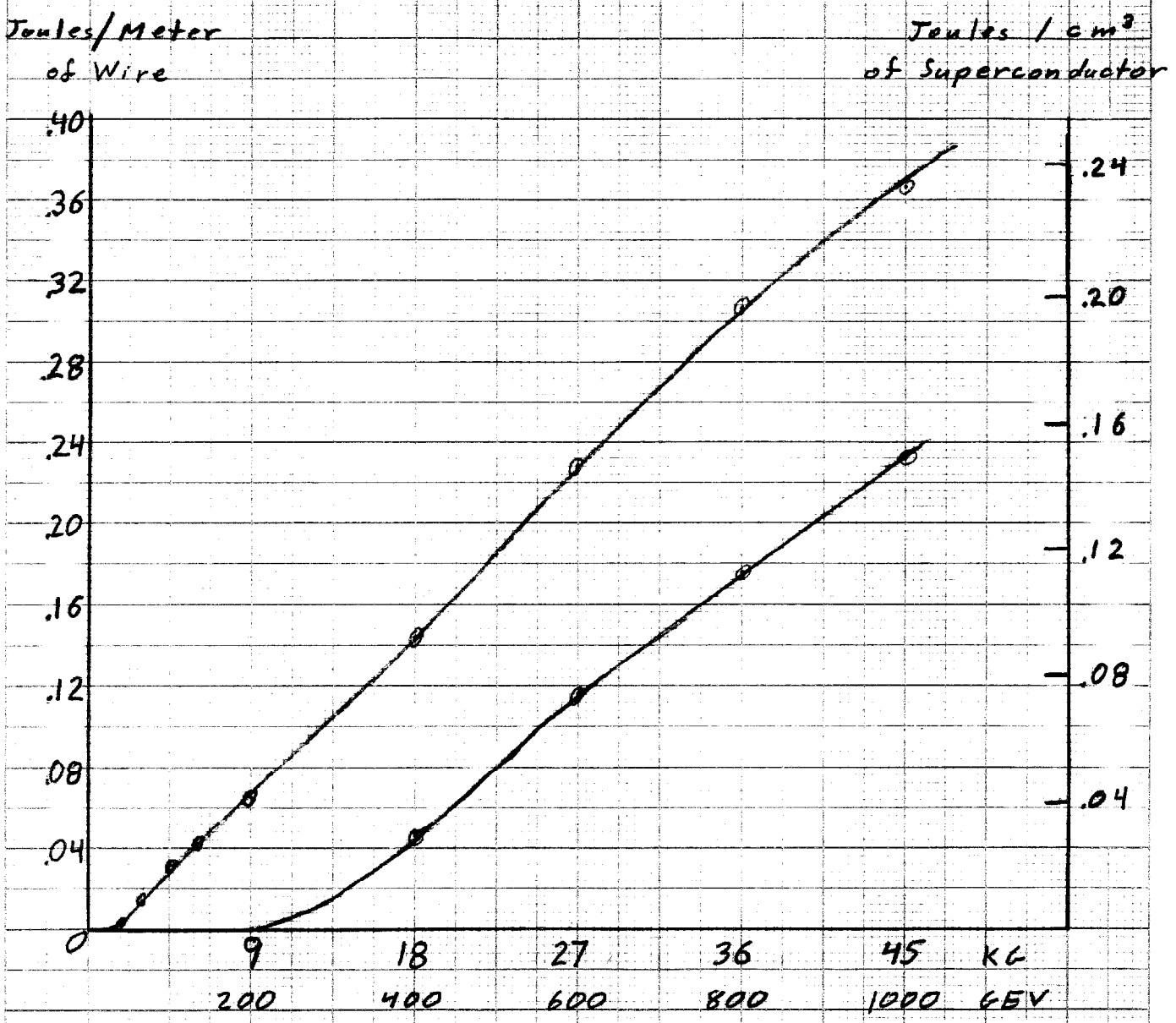
No. of Filaments = 15,246 Diameter = 12.3 μ
Cross Sectional Area of Superconductor = .01734 cm²

Fig. 3 Aug 8

MCA Wire

50×150 mils *

solid



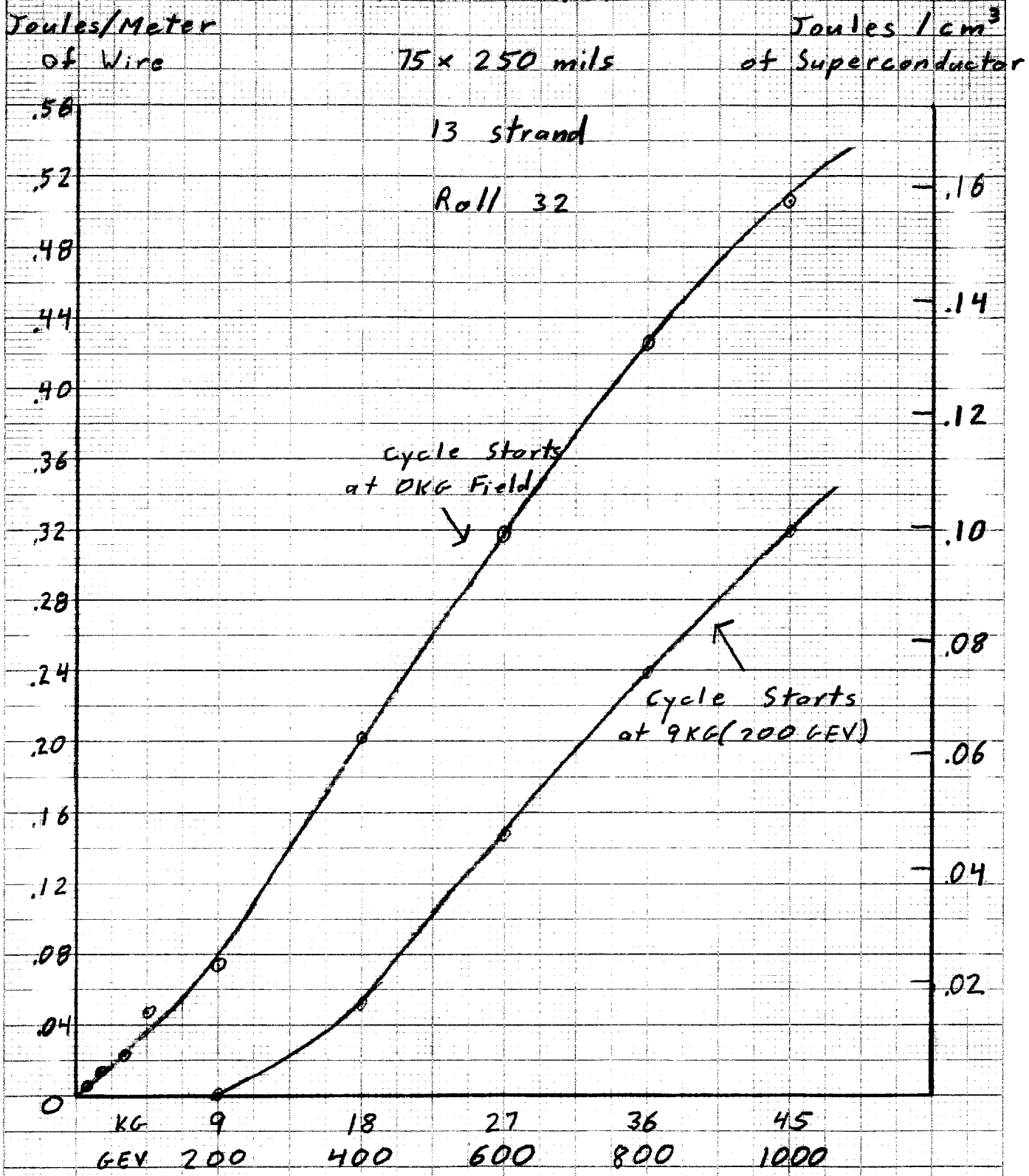
Field of Magnet in KG
and
Corresponding GEV for Purposed Doubler

No of Filaments = 2300 Diameter = 29 μ
Cross Sectional of Superconductor = .0156 cm²
*Extrapolated from data for 75×150 mil wire.

Fig. 4

Aug 8

MCA Wire



Field of Magnet in KG
and Corresponding GEV for Purposed Doubler

No of Filaments = 29,900 Diameter = 11.7 μ
Cross Sectional Area of Superconductor = .0322 cm²

Aug 12

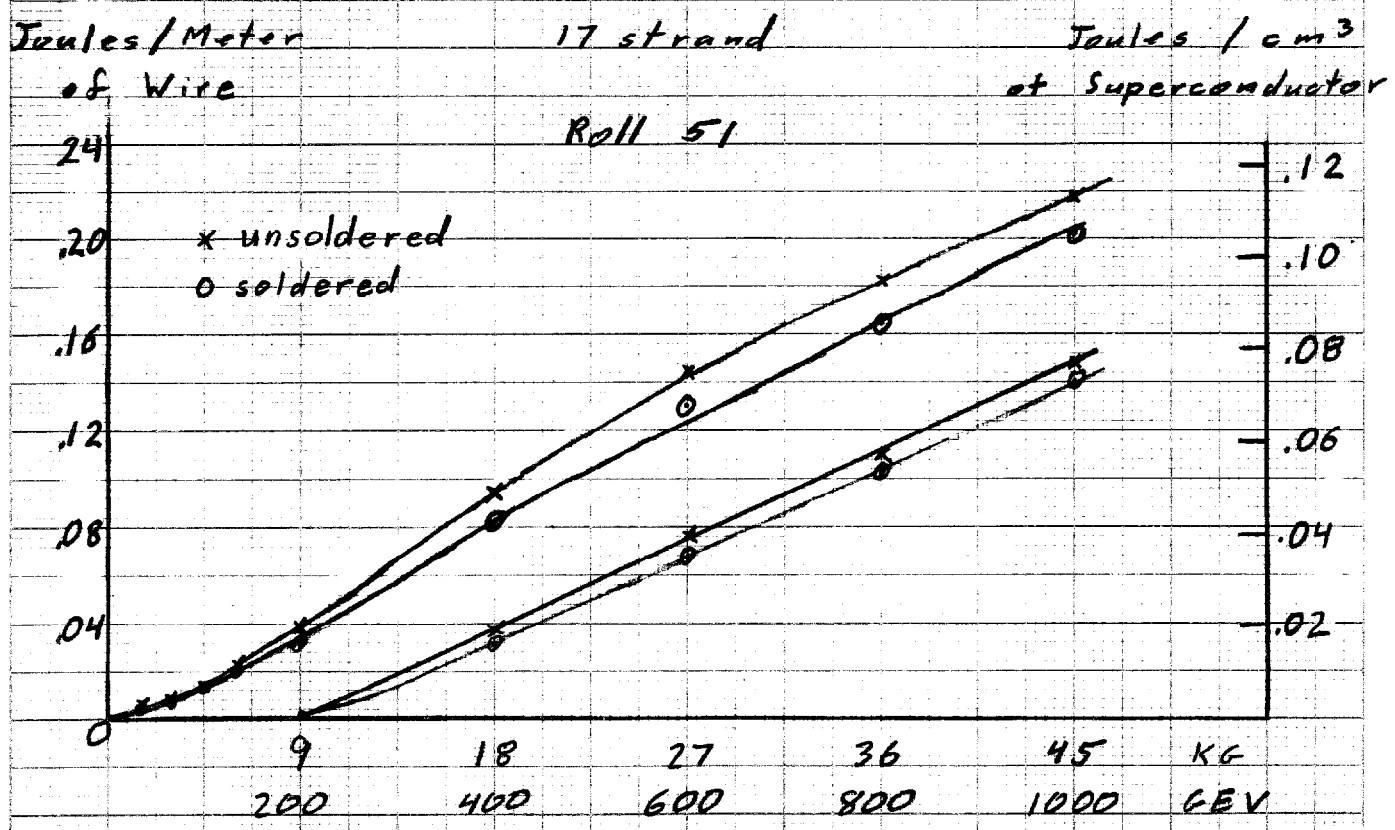
Fig. 5

MCA Wire

50 x 250 mils

17 strand

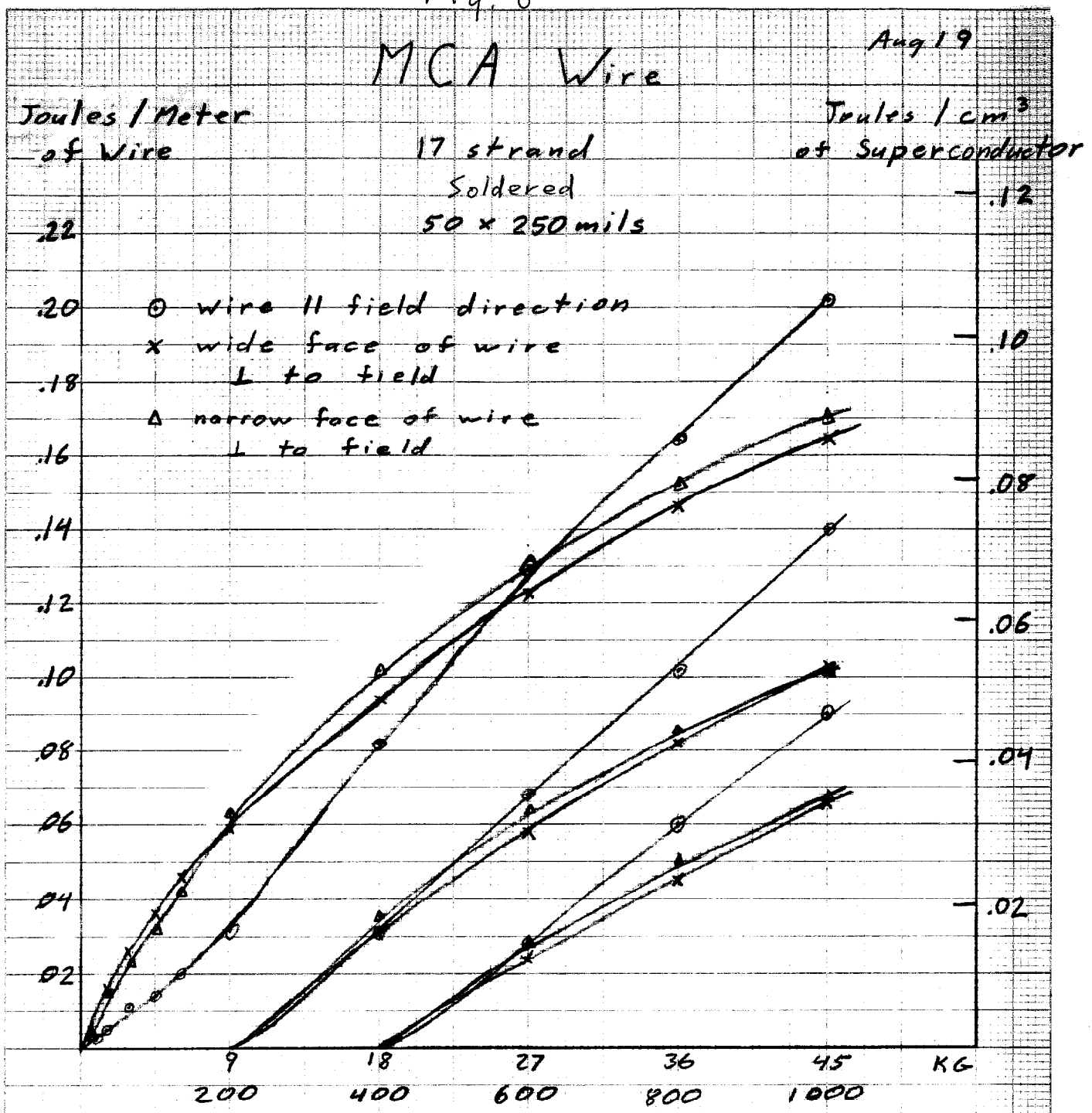
Roll 51



Field of Magnet in KG
and
Corresponding GEV for Purposed Doubler

Number of Filaments = 39100 Diameter = 7.9 μ
Cross Sectional Area of Superconductor = .0192 cm²

Fig. 6

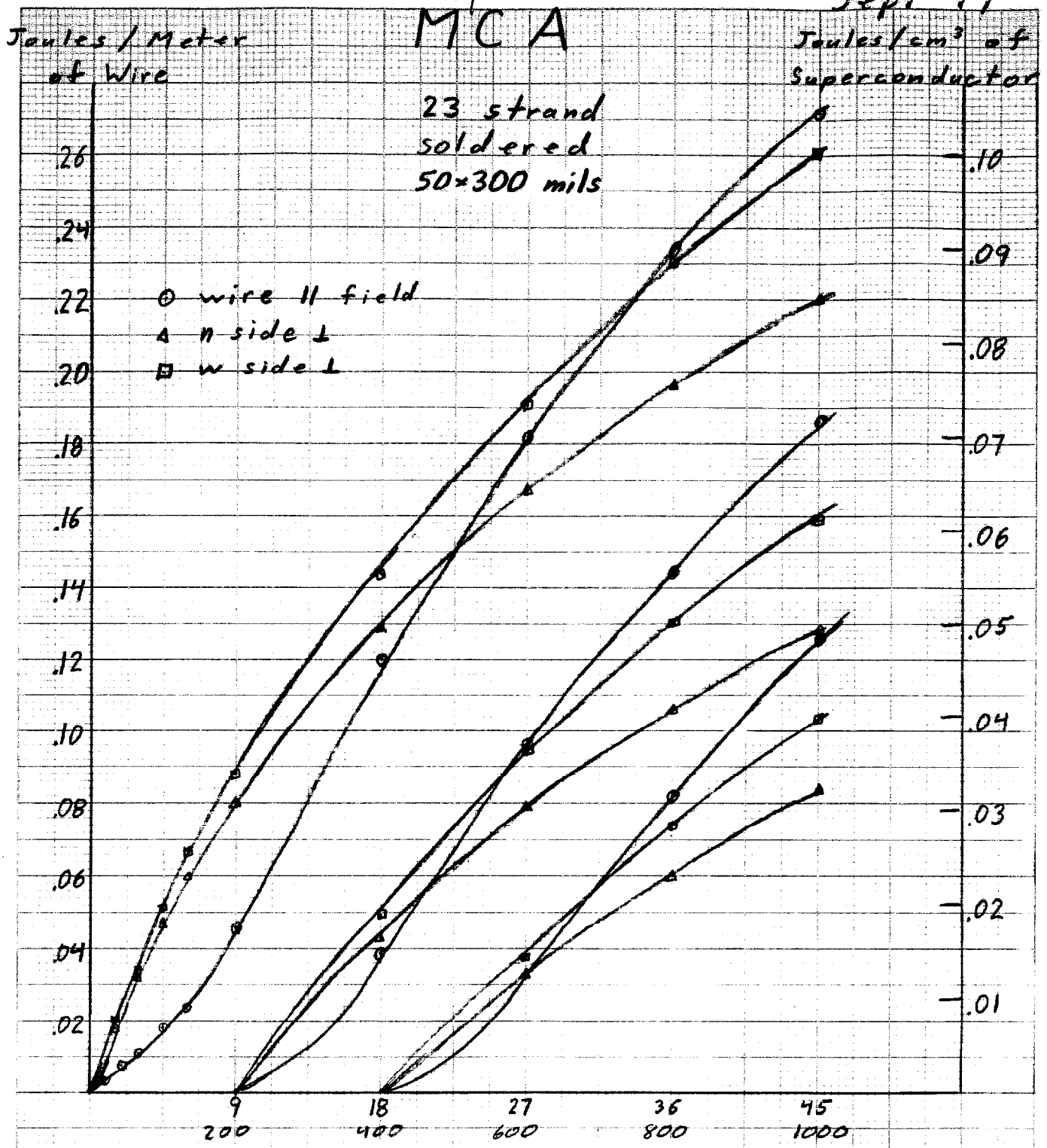


Field of Magnet in KG
and
Corresponding GEV for Doubler

Number of Filaments = 39100 Diameter of Filament = 7.9μ
Cross Sectional Area of Superconductor = .0192 cm²

$\dot{H} \sim .5$ KG/sec

MCA

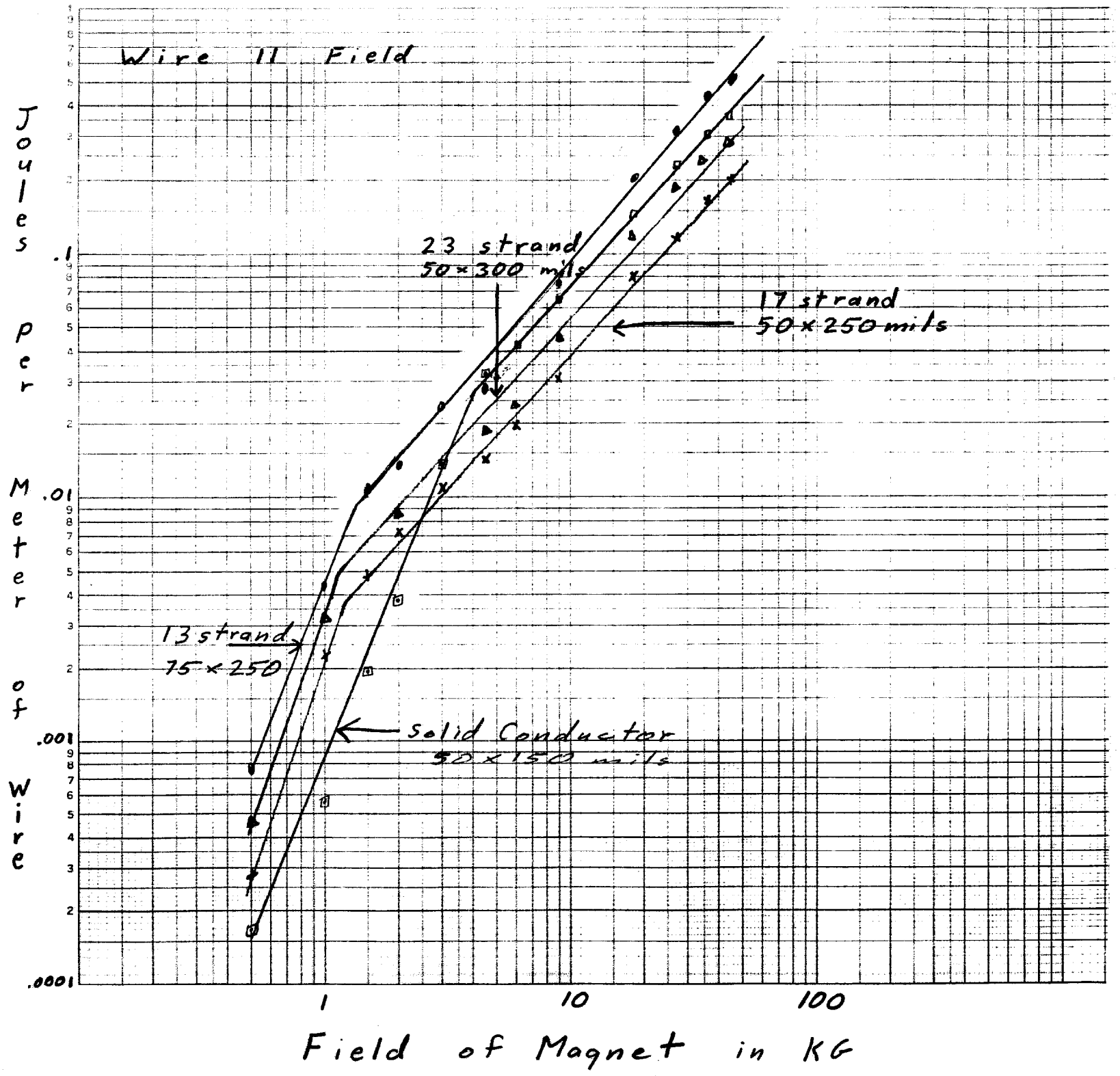


Number of Filaments = 52,900 Diameter of Filaments = 7.9μ
Cross Sectional Area of Superconductor = .0260 cm²

$\dot{H} \sim .5$ KG/sec
* Correction on data of Sept 4

Fig. 8

MCA Wire



$\dot{H} \sim .5$ KG/sec