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RESULTS OF HEATER INDUCED QUENCHES ON A 1-m SSC MODEL DIPOLE*

W. V. Hassenzahl

October 10, 1985

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SSC-MAG-56

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INTRODUCTION

This report describes the results of a series of heater induced quenches on the 1-m long SSC model dipole D-12C-7 constructed at LBL. Test results of the following types are described.

- o Quench propagation velocities - axial
- o Quench propagation velocities - transverse
- o Rate of temperature rise in the conductor

The primary purpose of these tests was to measure quench velocities at a variety of locations and for several currents/fields which can be used to refine the quench predictions for longer magnets. Because of limited data in the low field region of this magnet, it is recommended that it be retested with additional voltage taps.

Experimental Set Up

The SSC model magnet D-12C-7 was instrumented with 3 heaters and a special set of voltage taps. These were all in the "top" half of the coil as it was tested. (We do not anticipate any difference between quenches in the top and bottom halves of the coil.) The positions of the relevant voltage taps and heaters are shown in Fig. 1 and the configuration of voltage taps, data acquisition channels and heaters are described in Table I. The lengths of the regions between voltage taps is indicated for those regions where quench velocities are calculated.

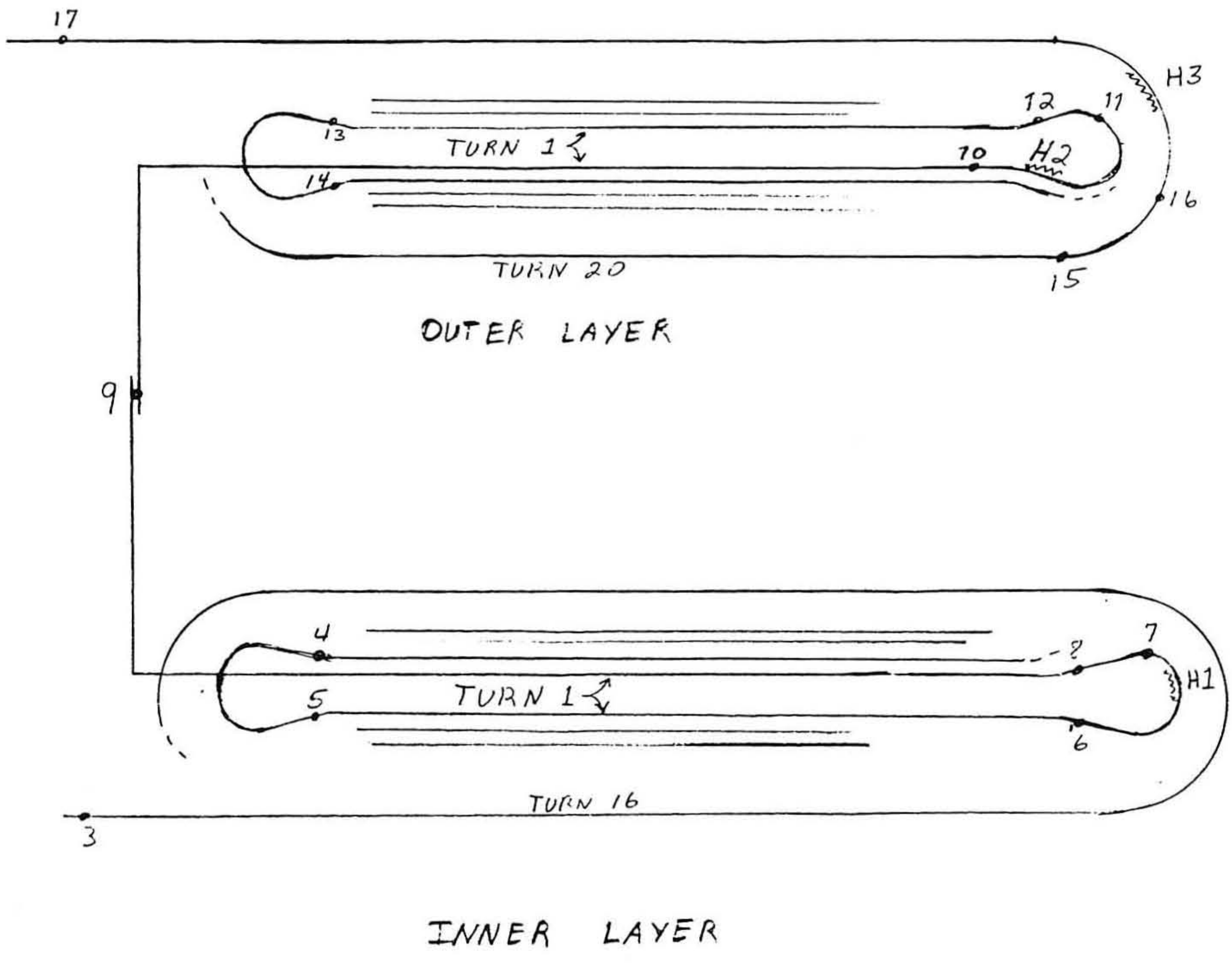


Fig. 1

Voltage Tap and Heater Arrangement for SSC Model Dipole D-12C-7.

TABLE I

Voltage Tap, Channel, and Heater Distribution

Taps	Channel #	Volts, f.s. (V)	Length (cm)	Heater #
T3-T4	6	50	-	-
T4-T5	7	5	24.31	-
T5-T6	8	5	74.78	-
T6-T7	9	5	-	1
T7-T8	10	5	4.85	-
T8-T9	11	5	-	-
T9-T10	12	5	-	-
T10-T11	13	5	-	2
T11-T12	14	5	5.0	-
T12-T13	15	5	74.80	-
T13-T14	16	5	18.92	-
T14-T15	17	50	-	-
T15-T16	18	5	5.0	-
T16-T17	19	5	-	3

The D-12C-7 dipole, which is described elsewhere, has the proposed SSC' Design D conductor and winding cross section. The insulation is the BNL combination of glass and Kapton and is similar to that considered for the final SSC dipole.

Longitudinal Quench Propagation

Some of the quenches induced in the coil were monitored with our high speed data acquisition system. The data file labels, current, and heater number for these quenches are given in Table II.

TABLE II

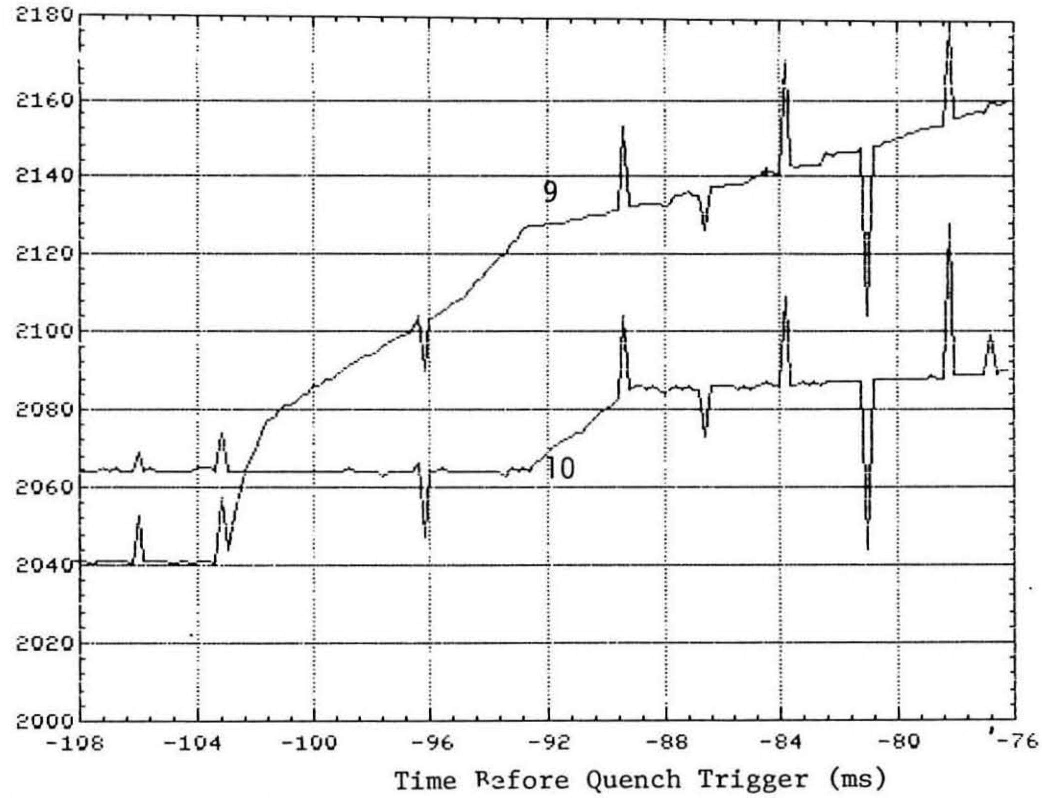
File Names for Data Records of Heater Induced Quenches

File #	Heater #	Current (A)
D12C7010	2	4500
D12C7011	2	6000
D12C7012	3	6000
D12C7013	1	6000
D12C7014	1	4500
D12C7019	3	6500
D12C7020	1	6500
D12C7021	2	6500

Some typical curves of the voltages in these events are shown in Figs. 2a and 2b, which are from File D12C7020. The abscissa on these graphs is the time in milliseconds before the quench trigger energized the energy extraction system. To obtain this data, a delay of about 100 ms was introduced between the quench detection and the extraction trigger. In Fig. 2a the voltage in the region with heater #1, channel 9, begins to rise at -103 ms. The break in this curve at -101 ms shows propagation of the normal region into channel #8, see Fig. 2b, and the one at -93 ms reflects propagation into channel #10. The inflection in channel #10 at -89 ms shows the normal region propagating on into channel #11.

Since we know the length of the conductor monitored by channel #10 is 0.050 m, and the time to cross it is 0.003 s, the quench velocity is about ≈ 17 m/s. Using similar results from other channels and quenches, we obtain the data summarized in Tables III, IV, and V.

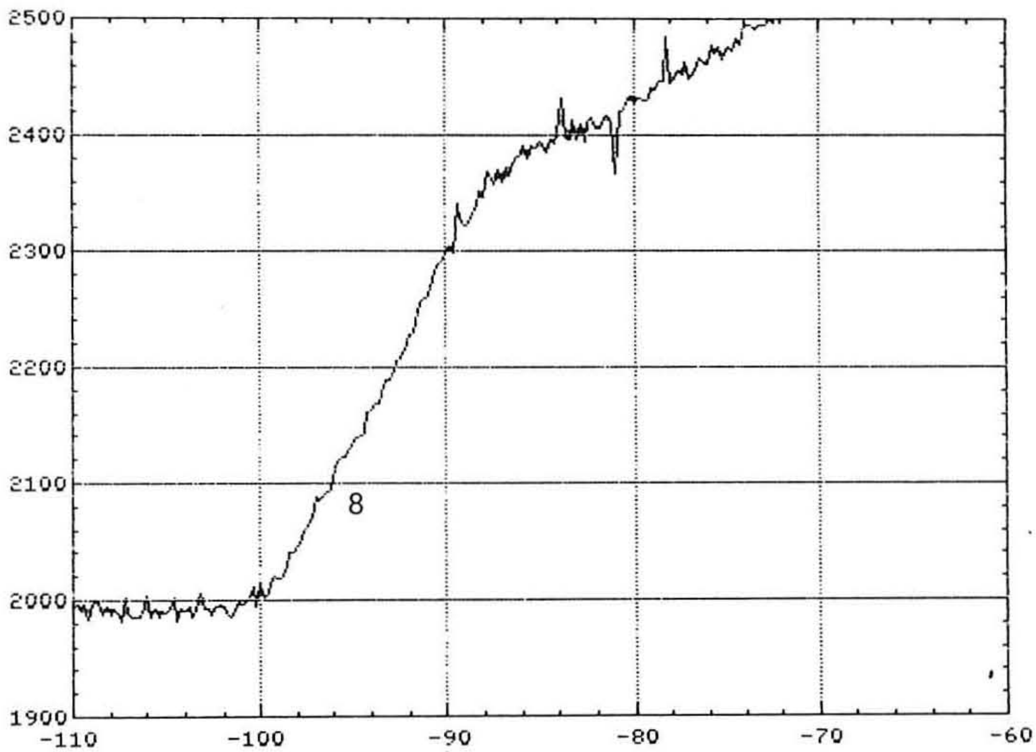
The rise in voltage in channel #10 after -89 ms and in channel #9 after -93 ms is due to Joule heating in the conductor and will be discussed in some detail below. The voltage spikes on the signals are generally thought to be noise in the data channels rather than power supply or magnet induced, though some spikes caused by conductor motion have been seen.



Data file: D12C7020

Fig. 2a

A 6500 A Quench in Layer 1 of SSC Model Magnet D-12C-7.



Data file: D12C7020

Fig. 2b

A 6500 A Quench in Layer 1 of SSC Model Magnet D-12C-7.

TABLE III

Quench propagation velocities in the axial direction for the outer conductor in the second layer - at the end. The magnetic field is small here, but not known exactly. Perhaps 1T.

Current (A)	Channel #	Length (cm)	Δt (ms)	Velocity (m/s)
6000	18	5.0	3.8	13.1
6500	18	5.0	3.6	13.9

TABLE IV

Quench propagation velocities in the axial direction for the inner conductor in the second layer - at the end. The magnetic field is about 5T in the straight section* at peak current of 6.5T and is probably down to about 3+T at the area of the heater.

Current (A)	Channel #	Length (cm)	Δt (ms)	Velocity (m/s)
4500	14	5.0	3.2	15.6
	16	18.9	10.0	18.9
6000	14	5.0	1.7	29.4
	15	74.8	14.4	51.9
	16	18.9	3.3	57.3
6500	14	5.0	1.4	35.7
	15	74.8	11.2	66.8
	16	18.9	3.3	57.3

*Note that the training and short sample quenches in this magnet were in the inner turn of this layer - indicating the conductor is near short sample here.

TABLE V

Quench propagation velocities in the axial direction for the inner conductor in the inner layer. The conductor is near critical current at 6500A.

Current (A)	Channel #	Length (cm)	Δt (ms)	Velocity (m/s)
4500	8	74.78	6.0	12.5
	10	4.85	5.0	9.7
6000	8	74.78	19.2	38.95
	10	4.85	2.2	22.0
6500	8	74.98	13.2	56.6
	10	4.85	3.0	16.2

Temperature Rise During a Quench

By observing the conductor in one of the short regions after the quench front has passed it, we can monitor the temperature development with time. As an example, we plot the data from channel #14 in data file D12C7021, which was for a 6500A quench in layer 2. The quench velocity was 29 m/s. This channel is quite short so we assume the temperature across it is uniform. (There may actually be a gradient, but it should be small as the transition time of the quench across this segment is about 1.7 ms.)

The temperature is estimated by first determining the resistance of the segment from the channel voltage, which is shown in Fig. 3, and the current, which is steady at 6500A. The temperature is then found by comparing the resistance of the segment to a known curve of resistance as temperature. Both the inner (XT21) and outer (XT22) conductors for D-12C-7 have been measured at BNL and the relations between resistance and temperature that they suggest we use (private communication - M. Garber) is given in Fig. 4. The conductor in segment 14 is probably in a field of between 3 to 4T, which lies between the 0 and 5T data from BNL.

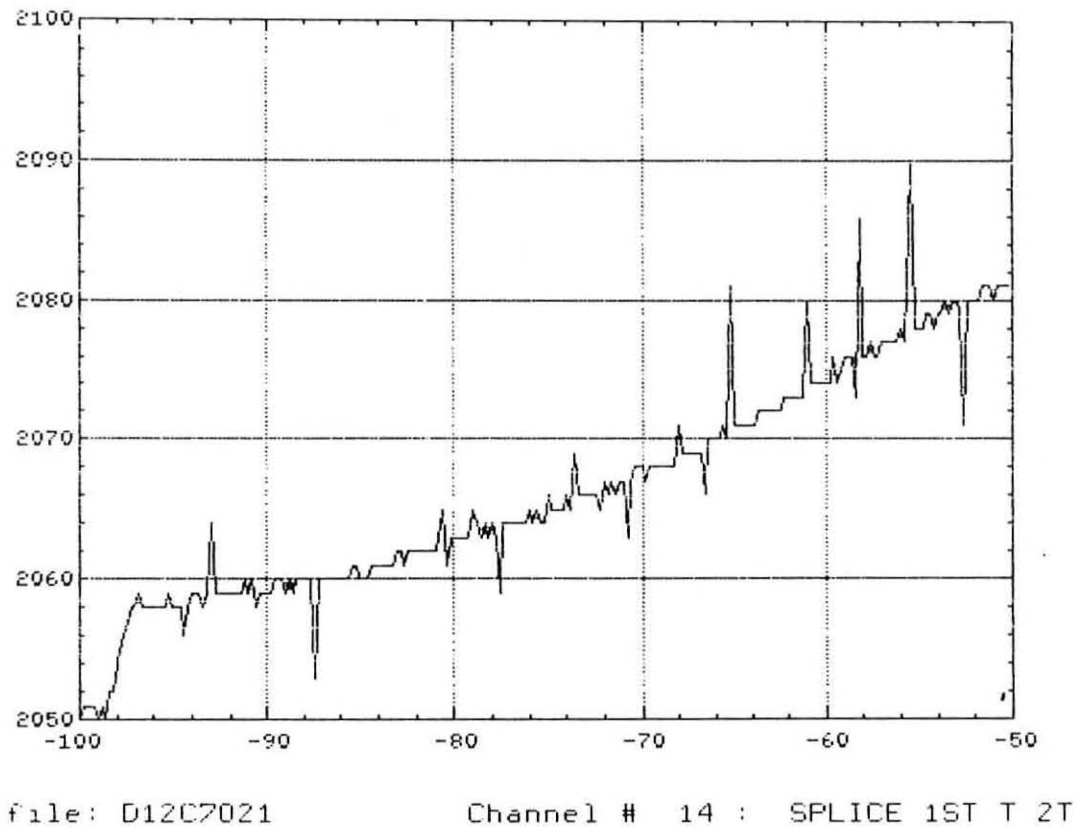


Fig. 3

A 6500 A Quench in Layer 2 of SSC Model Magnet D-12C-7. The Voltage Rise After -97 ms Shows the Temperature Increase of This 5 cm Long Section.

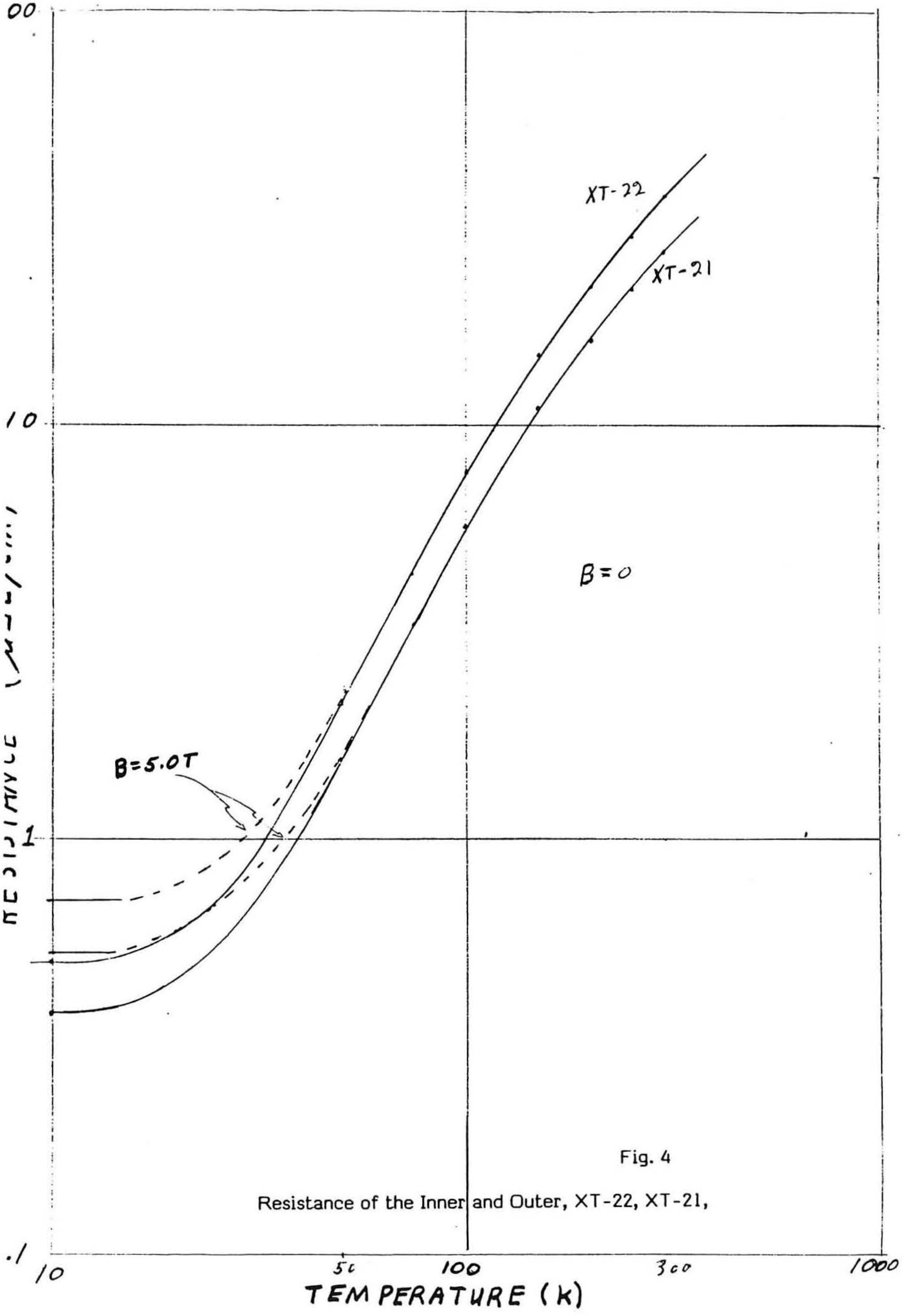


Fig. 4

Resistance of the Inner and Outer, XT-22, XT-21, The estimates of voltage, temperature, etc., vs. time are given in Table VI, and finally the development of the temperature as a function of time is given in Fig. 5. Note again that the current has remained steady during this time so it should be possible to compare this curve to a prediction of a quench in an SSC magnet of arbitrary length.

The temperature rise during 1.7 ms is about 3K at the beginning of the quench and less than 2K later. This sets a maximum for the termperature difference across the segment so the assumption of a constant temperature gave reasonable results and the error in the curve due to a temperature gradient can only be about 1K.

The development of quench velocity with central quench temperature is given by:

$$V_q = \frac{I}{C}\sqrt{\frac{k\rho}{\theta_c}}\left[\frac{(\theta_m - 2\theta_c)}{(\theta_m\ (\theta_m - \theta_c))^{1/2}}\right]$$

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

The term in [ ] is usually dropped in the analysis, because it approaches 1.0 as the central quench temperature approaches 20K. This term predicts, from first principles, an accelerating quench front. The peak velocity is reached in 10 to 15 ms for the quench described in Table VI and Figs. 3 and 5. A somewhat longer time is required for lower temperature quenches.

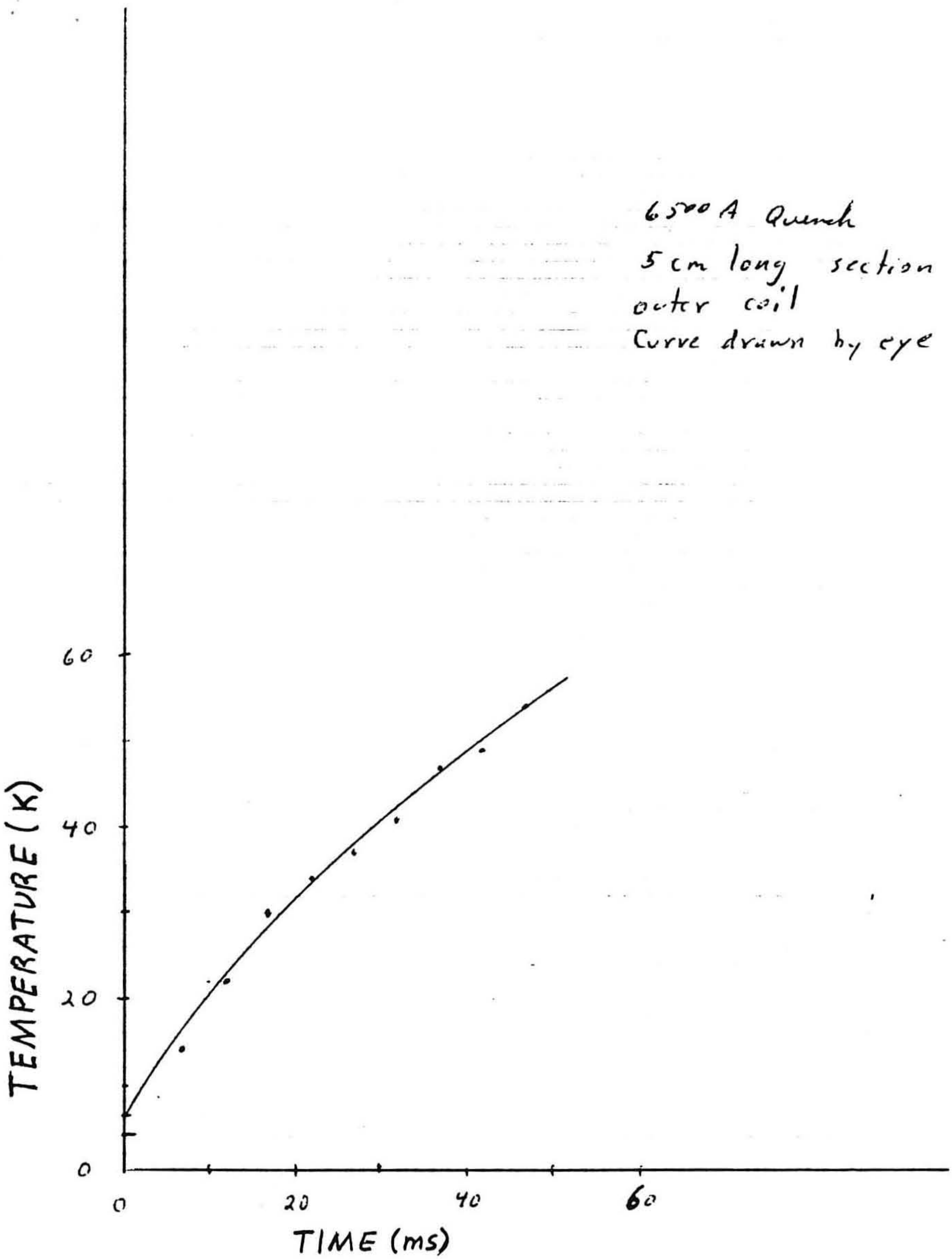


Fig. 5

Temperature Development in Section 14 of Model SSC Dipole D-12C-7
During a 6500 A Heater Induced Quench.

TABLE VI

Determination of quench temperature in 5 cm long channel #14, file D12C7021; a 6500A heater induced quench. Note that the resistance is constant up to about 15 to 20K so the early temperature induction is ambiguous.

Time (ms)	a to d (#)	a to d (Δ#)	Voltage (mV)	T (k)	Δt (ms)
-97	59.5	8.0	19.5	6.0	0
-95	58.5	8.0	19.5		2
-90	59.0	8.5	20.7	14.0	7
-85	60.0	9.5	23.2	22.0	12
-80	63.0	12.5	30.5	30.0	17
-75	65.0	14.5	35.4	34.0	22
-70	67.0	16.5	40.3	37.0	27
-65	70.0	19.5	47.6	41.0	32
-60	75.0	24.5	59.8	47.0	37
-55	77.0	26.5	65.0	49.0	42
-50	81.0	30.5	74.5	54.0	47

Transverse Quench Propagation

Because of the placement of voltage taps, there is little definitive data on turn-to-turn quench propagation. However, for some quenches in the outer layers, the inner turns were observed to go normal. This is shown in Fig. 6, which includes records for channels #14 and #18. Assuming this is due to transverse propagation, the time is 80 ms and the distance is 20 turns, giving a turn-to-turn propagation of about 4 ms/turn.

This result is questionable because it is possible to induce quenches in the conductor by rapidly ramping the magnet. The current in the magnet has dropped by 250A at -30 ms corresponding to a dI/dt of 7000A/s at the time the quench reaches the inner layer. It is debatable whether the current change at this time is great enough to cause a quench, and the transition time is consistent with the recent BNL measurements.

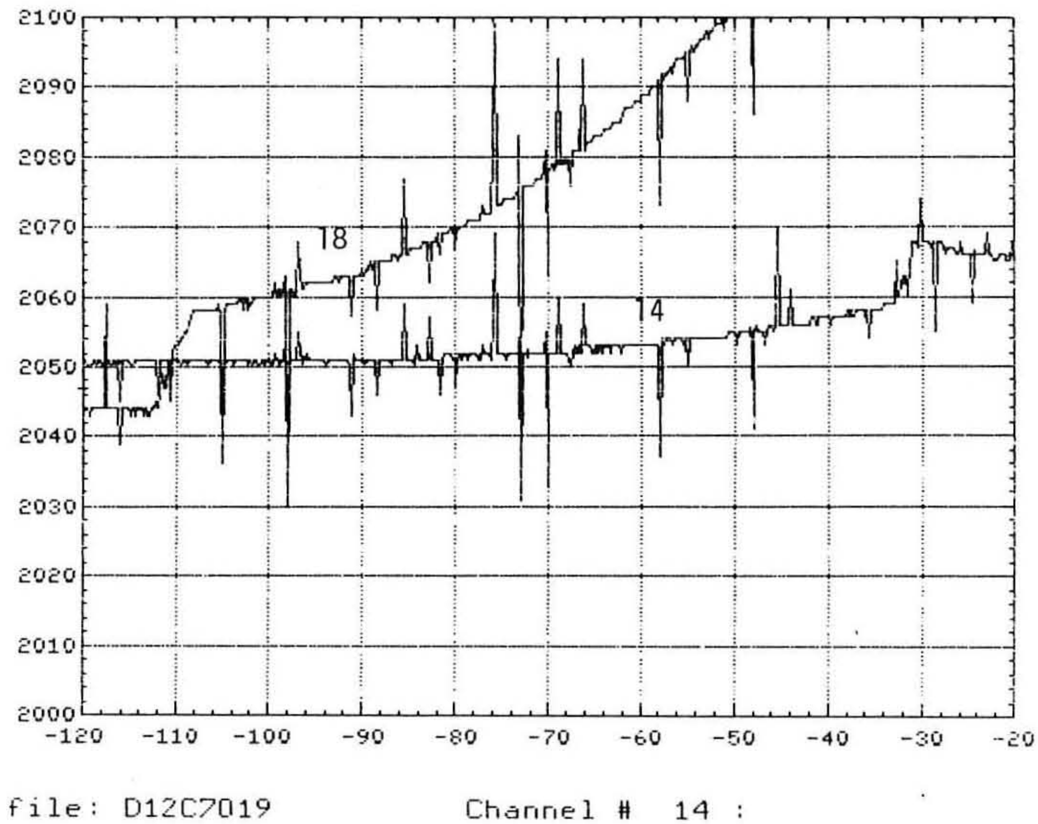


Fig. 6

Possible Transverse Propagation of a Quench in SSC Model Dipole D-12C-7 from the Outer Turn, Channel #18, to the Inner Turn, Channel #14.

A set of figures are given at the end of the report for the reader's use to study the quenches. The time axes are all labeled and can be clearly understood. The y or voltage axis are the direct digital output of the a-to-d converter. They may be converted to volts by reading the scale voltage for the channel in Table I and observing that the scale voltage will produce 2048 counts, + or -, relative to the "zero" at 2048. Thus, +50V on channel 6 will produce 4096 and -50V will produce Ø.

Conclusions/Direction for Future Work

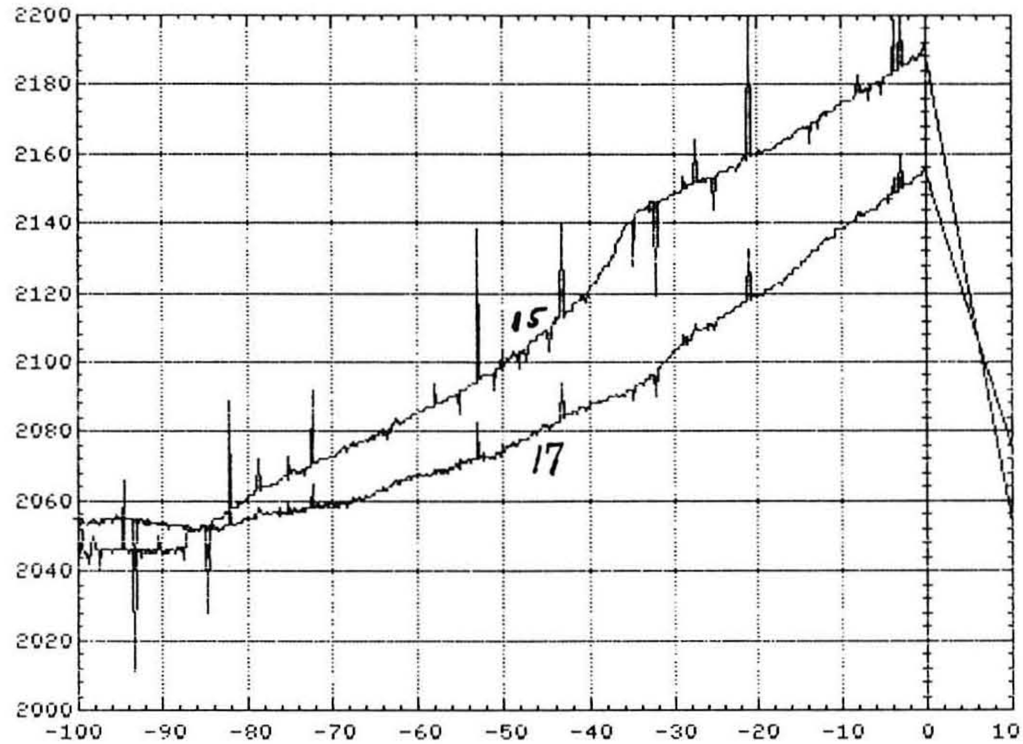
Based on previous analyses of quenches in dipoles of the SSC Design D type, it appears that if the quench velocities are as high as observed here, the magnets will be safe with single or at most double diode protection. To assure safety in all conditions, however, it is necessary to assess some "worst case" scenarios. There appear to be three quench initation regions that may lead to hot quenches. These are

1. The outer turns of layer 2 at the magnet ends where the field is low.
2. The superconductor that is a connection between magnets and/or between a magnet and the associated shorting diode.
3. The pole turn of layer 1, due to the wedge between turns 3 and 4.

Item 1 and to a certain extent 2 can be studied in 1-m model magnets. The relevant data could be obtained on D-12C-7, for example, if it is to be retested in HEII. Item 3 may not be able to be tested unambiguously in a 1-m model because the relative axial and transverse velocities may allow turn-to-turn propagation at the ends of the magnet to produce a normal region at the center of the 4th turn before the quench propagates across the wedge.

Further work will also be required to give exact results on the turn-to-turn propagation times. Though the data indicates they are about 4 to 7 ms per turn at high fields, this should be confirmed with some more direct measurements. These data could also be obtained on D-12C-7 if it is retested and if some voltage taps are moved.

REFERENCE DATA FILES



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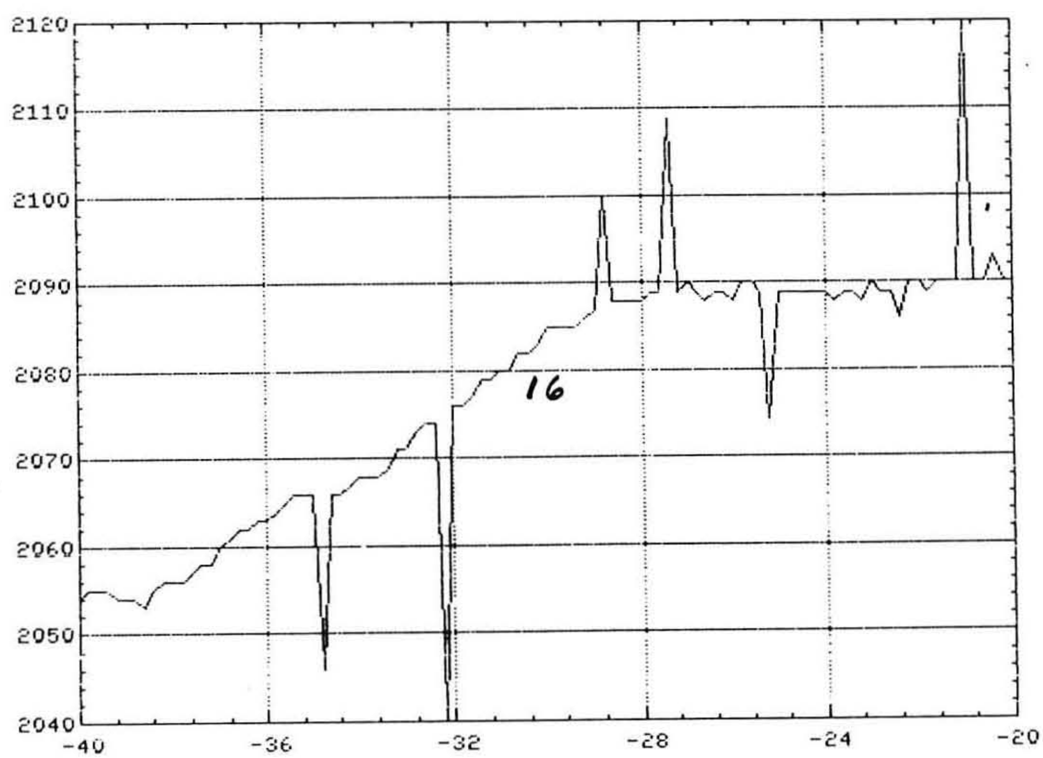

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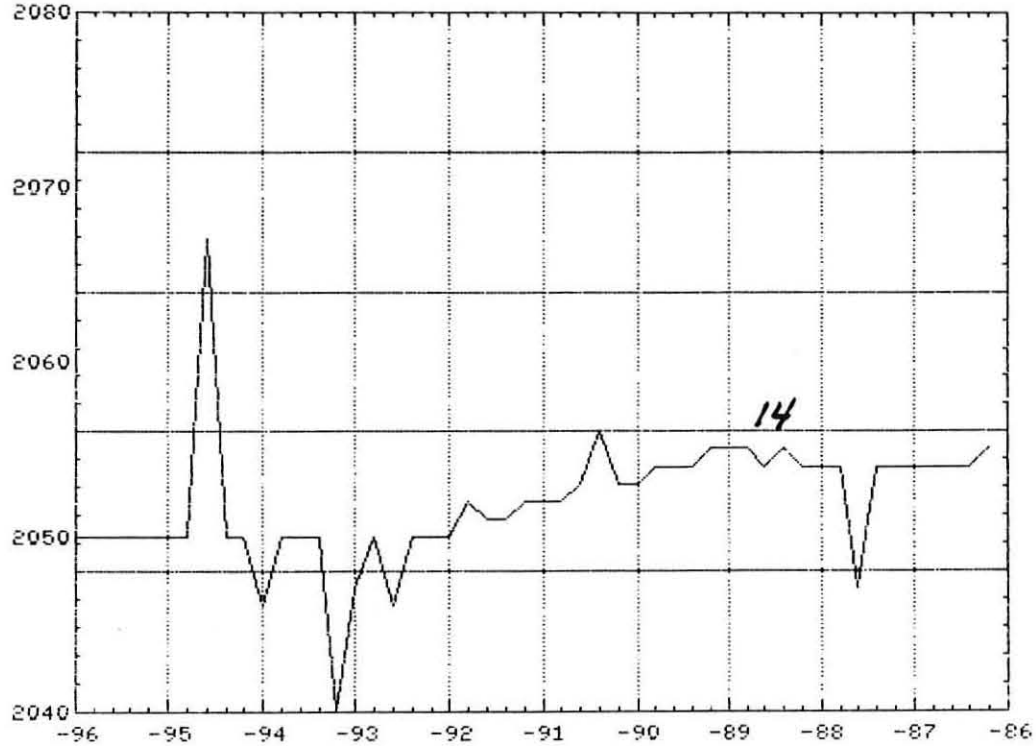

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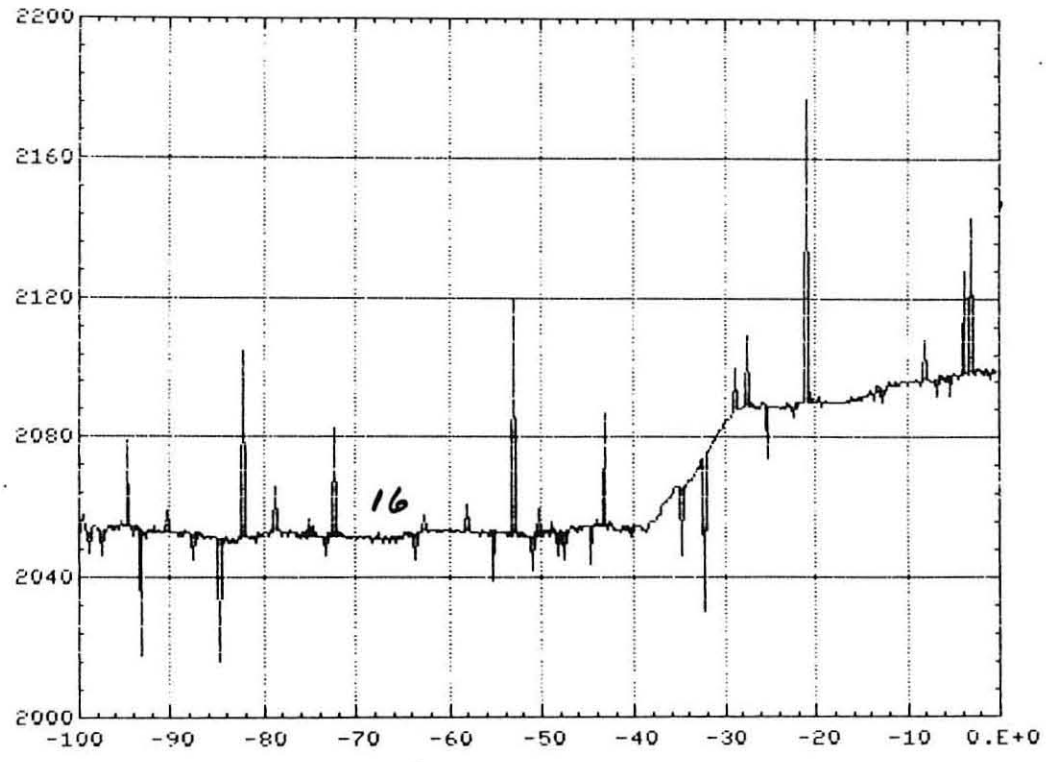

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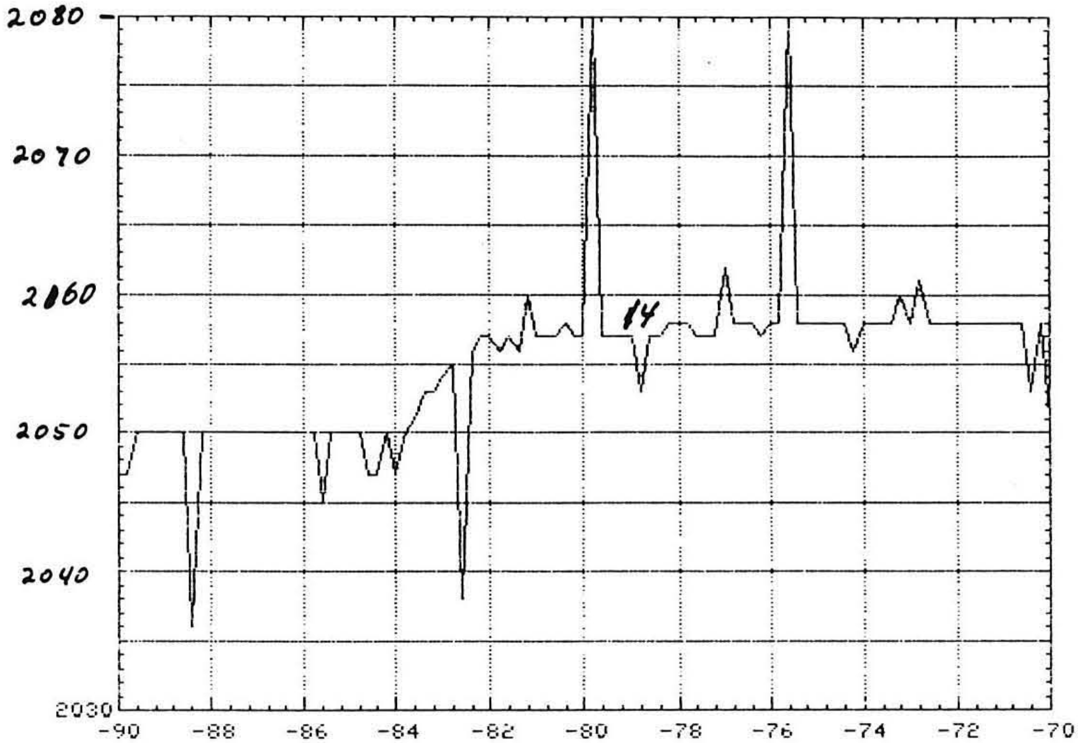

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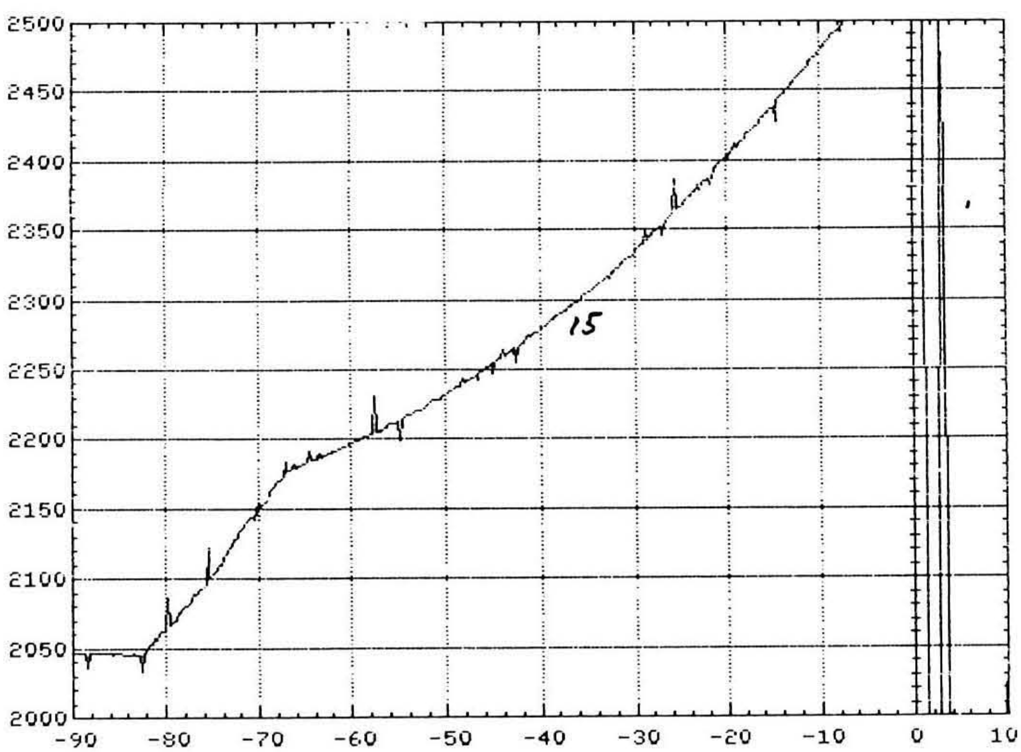

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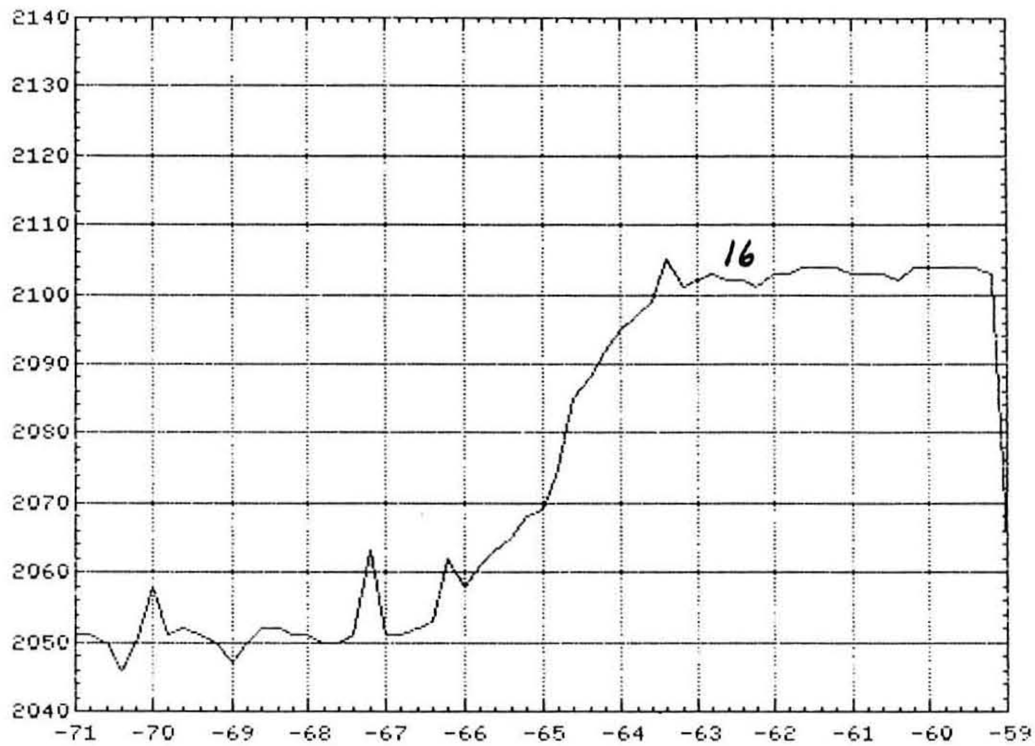

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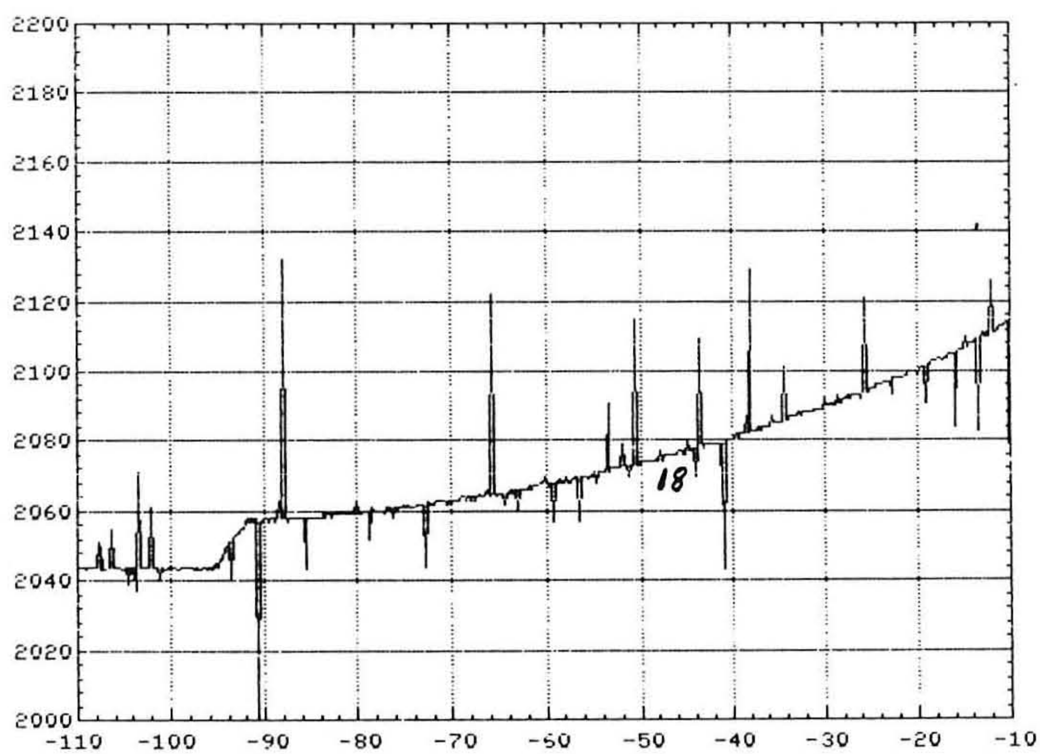

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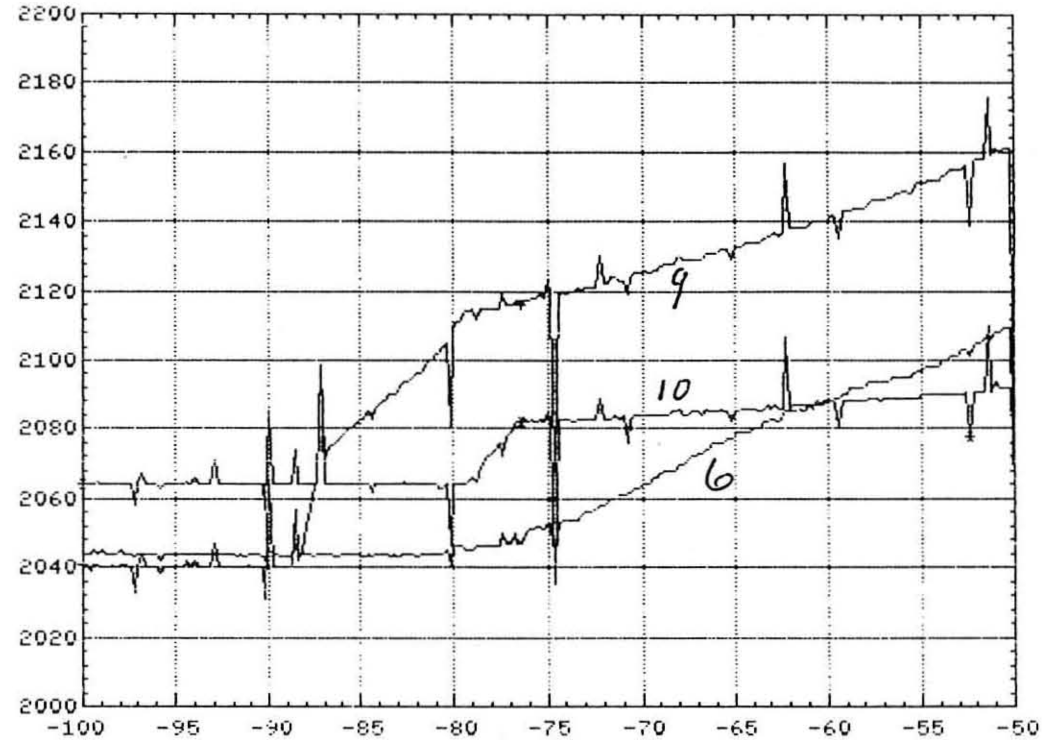

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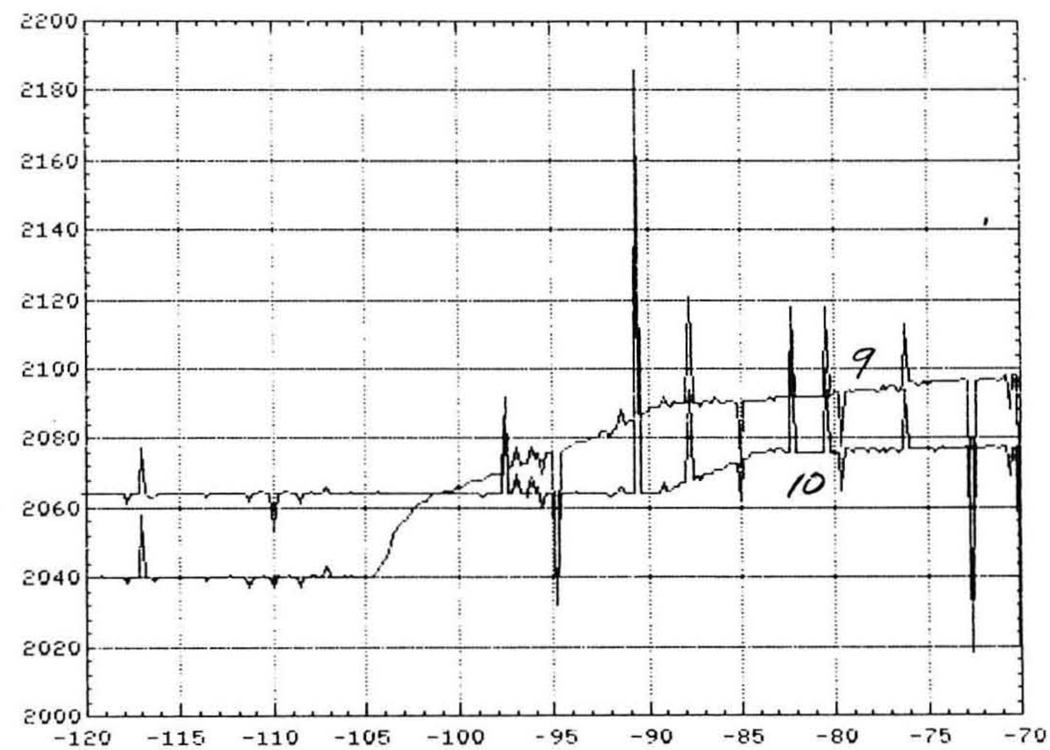

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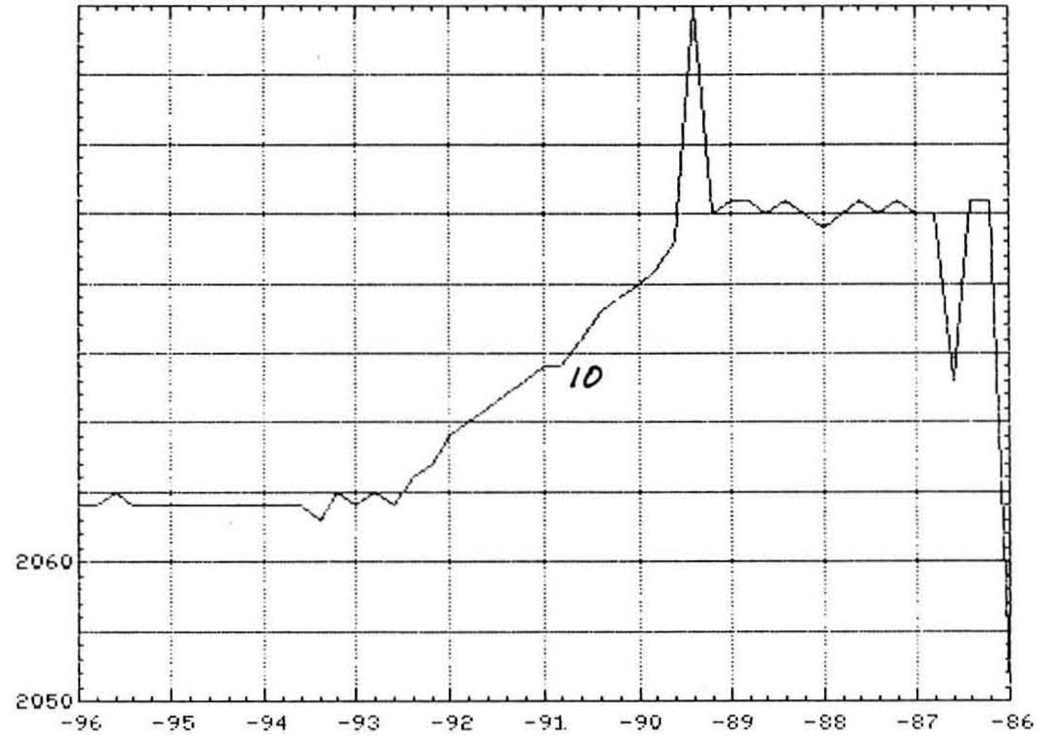

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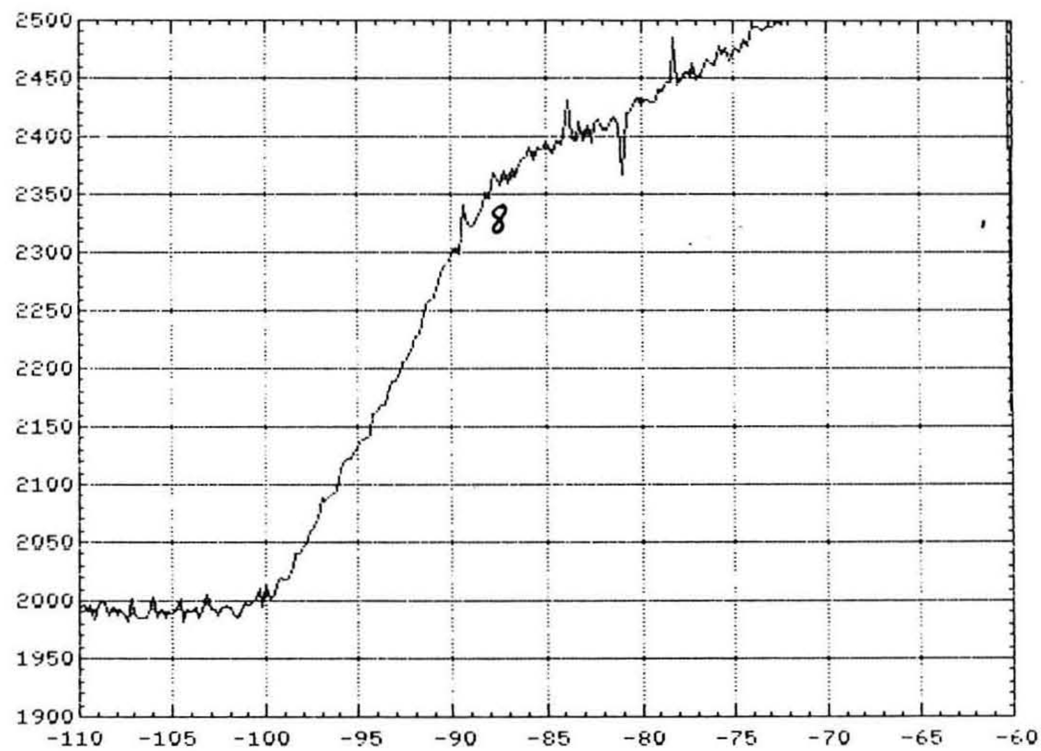

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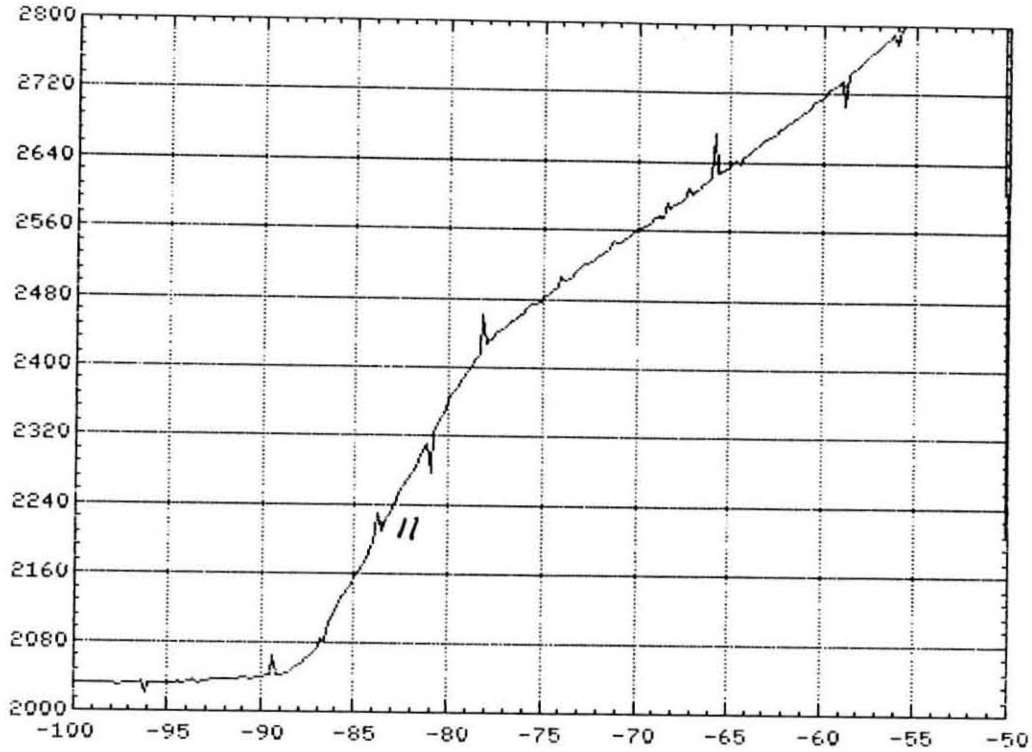

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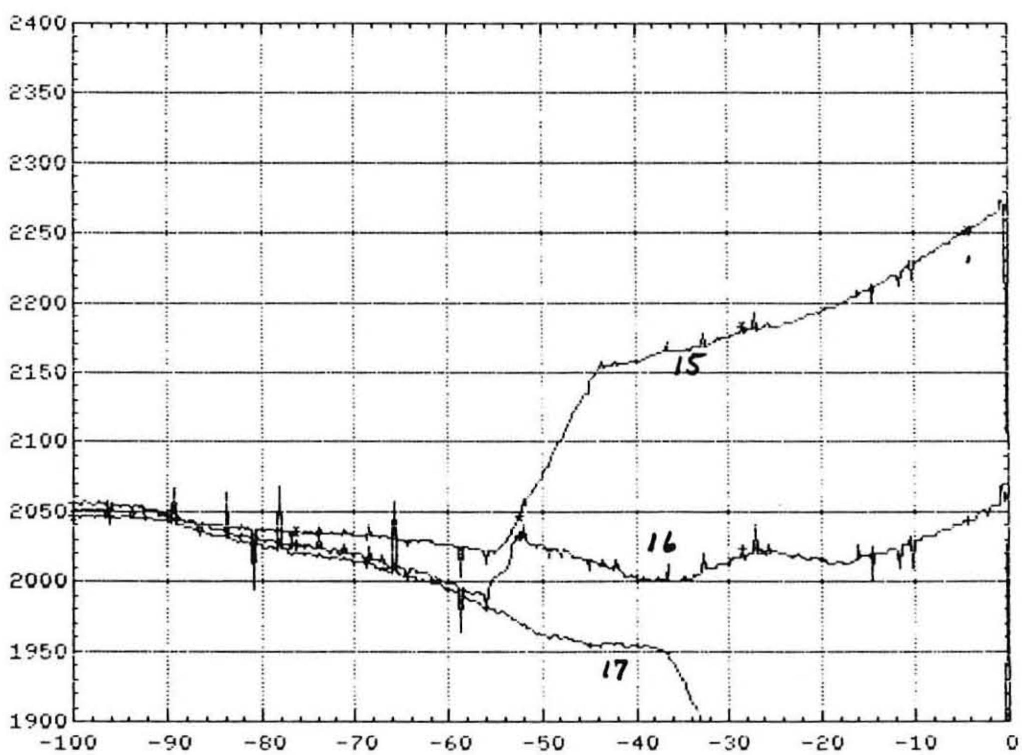

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