Fermi National Accelerator Laboratory

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A Magnetically Coupled Quench Detector for Superconducting Magnets

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1.0 ABSTRACT

This note describes a low voltage signal detector that is useful for detecting quenches or excessive lead voltages at superconducting magnets. It can also be used for other applications where it is needed to detect low level signals present on high voltage installations. The application of isolated operational amplifiers is often not practical for high voltage applications because of their limited input voltage rating, common mode rejection and sensitivity.

The described detector can withstand 7.5 kV input to ground voltage. It has a typical common mode rejection of -150 dB at 60 Hz and an input sensitivity better than 1 mV.

The magnetically coupled quench detector assembly is very sensitive to extremely small (order of 1 μAmp) current changes in the sense windings. The detector assembly can therefore also be referred to as a micro current detector.

2.0 APPLICATION OF THE MAGNETICALLY COUPLED QUENCH DETECTOR

The transition of a superconducting magnet winding conductor from the superconducting state to the normal state is called a quench. A quench detector that compares the voltage drop across different parts of a magnet coil can be used to start a dump (Fig. 1). Opening the dump switch minimizes the amount of energy dissipation in the magnet windings. A quench starts at some location in the coil winding and then propagates at a relatively low speed. During a quench a voltage drop develops across the increasing resistance of the quenched portion of the coil winding. At the same time the resistance of the rest of the conductor remains zero while the induced voltage will try to keep the current constant. A typical requirement is to detect quench voltages or lead voltage drops as low as 50 mV. The potential difference between the monitored point and ground can be several kilovolt during a dump. Isolated operational amplifiers (ISO-OP AMPS) are commonly used for quench detectors. These amplifiers are mostly rated to withstand up to 2500 V and some may require cascade connections for higher voltages. Common mode rejection is mostly in the order of -100 dB or less. Operational amplifiers are sensitive to radiation damage and therefore may need to be located away from the load they monitor. This complicates electrical safety and requires higher voltage rated monitoring cables, which makes the installation more cumbersome and expensive. A quench detector using magnetic coupling exceeds the noise and voltage withstand ratings of ISO-OP AMPS. The detector core assembly is not easily damaged by radiation and can be mounted close to the load being monitored. All high voltages remain in the load area, so that electrical safety is not compromised.

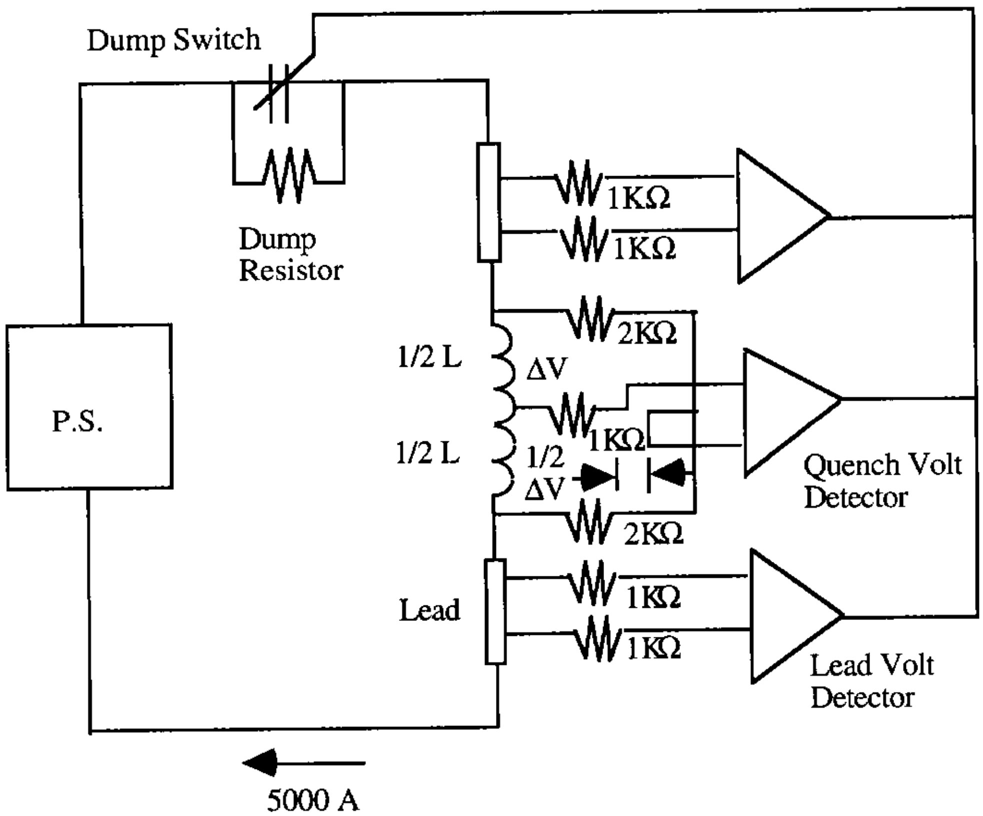


Figure 1: Typical Application of a Quench/Lead Voltage Detector

3.0 GENERAL DESCRIPTION OF THE MAGNETICALLY COUPLED DETECTOR

The magnetically coupled quench detector consists of two parts, a core assembly mounted inside a magnetic shield and an electronics card.

A simplified schematic of the magnetically coupled detector is shown in Fig. 2. The core assembly consists of two toroidal magnetic cores with two identical excitation windings, W1 and W2, wound on each core. There are also additional other windings installed at the cores. The excitation windings are connected in parallel to a 7 kHz excitation voltage source. The excitation voltage waveform may be sinusoidal, or rectangular, or triangular.

A triangular waveshape of 7 kHz, 6 V peak at 40 mA was chosen for the excitation voltage because it is easy to generate. The triangular waveshape provides a constant slope to the excitation voltage and yields a wide saturation current peak for the cores. This type of signal is relatively easy to process. Triangular waves cause less ringing on long cable runs compared to squarewaves.

The excitation winding currents create opposite directed magnetic fluxes in the cores. $R_{balance}$ (Fig. 3) is adjusted to equalize the flux magnitude in both cores. A sense winding W3 is wound around both cores. A current flowing through sense winding W3 boosts the excitation flux in one core and opposes it in the other. Accordingly, the core excitation aided by the boosting sense winding current saturates at a lower excitation current value than the core with the opposing sense current.

An additional common winding W4 has also been added to the core assembly. This winding can, in the future, be used for a DC offset source or as a feedback winding.

DC offset injects a constant magnetic field in both cores, which shifts the zero point. A comparator window can be set up to accept this zero point shift as normal. This assures the system integrity and readiness. If something is wrong with the quench detector electronics or hookup, it will trip or not allow a magnet startup.

Winding W4 can also be used as a feedback winding to provide an answer current to the sense current, and maintain the cores in a state of virtual zero flux. This should reduce the amplitude of the residual inbalance voltage seen on the sense winding. Common feedback could possibly improve the frequency response of the core assembly. Common feedback is not needed for this application.

Several sense windings can be added to the current detector core assembly. The sense windings can be interconnected or isolated from each other. Additional sense windings make it possible to add or subtract signals from different sources to each other.

4.0 DESCRIPTION OF THE DETECTOR ELECTRONICS

The excitation current from each core develops an ac voltage across sense resistors R_{sense1} and R_{sense2} , located at the input to the detector circuit, shown in Fig. 3. This ac voltage is processed by a constant input impedance, split phase, full wave active rectifier circuit (IC1,IC2).

That is, the positive going signal across R_{sense1} is inverted and summed with the negative going signal of R_{sense2}, which occurs 180 degrees later. This produces a negative pulsating dc voltage that is filtered by capacitor C1. Capacitor C1 acts as a peak hold circuit with a short charging time (~ 10 μsec) and a long discharge time (~ 500 μsec). Likewise, the negative going signal on R_{sense1} is inverted and summed with the positive going signal across R_{sense2}. This signal is similarly processed to produce a positive pulsating dc voltage at C2.

The two dc signals on C1 and C2 are summed in a half bridge which is connected to a two pole low pass filter (IC3). The analog output voltage of this filter is proportional to the current in the sense winding W3 of Fig. 2. The analog voltage is routed to a window comparator and an output voltage buffer. The window comparator will only trip from a persistent input signal, which lasts at least 20 msec. Sporadic input noise spikes will not cause trips.

The two dc voltages on C1 and C2 are also processed by an automatic gain control (AGC) circuit. The purpose of the AGC is to keep the sum of the absolute peak values of the two excitation currents constant. This helps to linearize the output signal of IC3 and reduces the overall noise at the output. For AGC the negative voltage at C1 is inverted and summed with the positive voltage at C2. This sum voltage is compared to a negative reference voltage in an error amplifier. The error amplifier provides a control voltage to the voltage controlled oscillator IC7 and causes minor changes in IC7's output frequency. IC7 in turn drives IC8, a flip-flop which produces a square wave input to IC9. IC9 is the integrator that generates the triangular excitation voltage. The output voltage of IC9 can thus be changed by frequency variations of IC7. This causes changes in the excitation current value of the core assembly.

A detailed schematic of the electronics card used is shown in Fig. 4.

5.0 DESIGN CHOICES AND COMMENTS

Magnetics Inc. tape wound core #80608-1/2D-MA was chosen for the transducer core assembly. Both ferrite and tape wound type toroidal cores were tried. The tape wound cores provided better signal to noise ratio than the ferrite cores for use in the current transducer core assembly. Tape wound cores also produced a larger signal response.

The excitation current is chosen to drive both cores to about 1.25 Oersteds, which is well into saturation, (Fig. 5). Operating in this region of the B-H curve eliminates remnant field effects caused by the previous excitation history of the cores.

The two core design was chosen for several reasons as described below.

Two cores reduce the effects of external magnetic fields on the core assembly. The core assembly is however still very sensitive to magnetic stray fields in the order of several Gauss and must therefore be mounted in a magnetically shielded enclosure for reliable operation.

Two cores also provide a differential signal source to the electronics which reduces induced electrical noise or common mode voltage disturbances from long cable runs.

Two cores provide a signal source for full wave rectification allowing wider bandwidth and lower ripple levels in the output signal.

The net induced voltage produced in the sense winding by the opposing excitation of both cores is reduced.

The effects of core differences are reduced by adjusting the differential signal to zero in the absence of sense winding current.

Cable capacitance can add sufficient capacitive currents to the signal currents to cause a reduction in the system gain. This occurs with long cable runs between the core assembly and the electronics card. Approximately 25% gain reduction was observed with a 1000 ft. cable. A working upper limit of cable length is probably 2 to 3 thousand feet unless cable capacitance can be reduced or future electronics incorporates a compensation circuit. The capacitive cable current increases the base noise level and makes it difficult to detect the desired signal. The change in system gain can easily be adjusted for in the present electronics card.

There is both an amplitude change and a time displacement of the current peak through the excitation winding when the cores are excited by current through the sense winding. The measured peak to peak amplitude change of the excitation current is 4 μA with a sense winding excitation of 100 μAturns. The measured time displacement of the current peak is 2 nanoseconds for 100 μAturns sense winding excitation (Fig. 6A). The amplitude change of the excitation current yields the largest and easiest signal to process. Amplitude change is therefore chosen for sense current detection.

A magnetic and electrostatic shield surrounds the core assembly (Fig. 8). The magnetic shield provides protection to transverse stray magnetic fields of about 600 Gauss and axial stray fields of about 100 Gauss. Shielding is important when the core assembly is mounted in the stray field of a magnet. The magnetic shield also provides mechanical protection for the core assembly.

6.0 CONSTRUCTION NOTES

The construction details and sequence of the core assembly process can be seen in Fig. 7. The schematic and wiring diagram is shown in Fig. 2.

The excitation winding is wound single layer and spaced as evenly as possible. At this point it is Glyptal dipped and air dryed to secure the winding to prevent any motion, which can result in electrical noise on the output signal.

The effects of capacitive currents flowing through the electrostatic shields can induce a magnetic flux in the cores and cause poorer common mode rejection.

The first detector head assemblies used foil shields wrapped in a non-inductive manner. All testing was done with this type of shielding. A spray on high conductivity graphite coating (Manufacturer, G.C. Electronics #10-4807) was tried later on. This coating is easier to apply than wrapped shields and creates a more uniform product as far as electrical characteristics are concerned. Initial testing of graphite shielded core assembly showed an improvement in common mode rejection and no changes in performance. Spray on shields are therefore preferred.

The sense winding stray capacitance from either end of the sense winding to the high potential shield should be equally distributed for best common mode rejection. This is accomplished by winding it with a "skip turn" technique. That is, one half of the sense winding turns are wound completely around the cores with a one wire diameter space in between the turns. Then the second half of the turns are wound inside the space of the first turns.

The turn count of the excitation windings of the production cores is checked against a "standard" core with a known turn count. Every production core is adjusted to have the same number of excitation turns. This minimizes the induced inbalance voltage in the sense winding and reduces ripple and noise on the output of the electronics card. The installed number of excitation turns on production cores is checked with a constant voltage excitation and compared to the "standard" core.

A second test is performed to match the production cores in sets of two for magnetic characteristics to 5% or better. Constant current excitation at their nominal operating point is used for this matching test.

Nine identical core assemblies, using Magnetic, Inc. cores #80608-1/2D-MA, were made to obtain a representative data sample. The cores were wound with 100 turns for the excitation windings and 100 turns for the sense winding. All core assemblies were tested with the same electronics card and instrumentation.

7.0 TEST RESULTS

The first test performed on the core assemblies was a hipot test between the high potential shield and the second earth shield. 7.5 kVDC was placed on these shields for one minute. The core assemblies had a leakage current of 24 nanoAmps or less at 7.5 kVDC after one minute. Cores with spray on shields had leakage currents of 2 nanoAmps or less.

The linearity of the ratio between the input sense current and the output voltage signal was tested by changing the sense current from 0 to 5 mA. The sense current source impedance was varied across a range from 50 Ohm to 10 kOhm. The linearity of the output signal at the electronics card was equal to or better than ± 1% for a sense current range of 10 uA to 2 mA for the entire source impedance range. This test was done for all nine core assemblies.

The gain variation between the nine different core assemblies was about 12% This amount of gain difference can easily be adjusted out in the electronics.

During development tests it became obvious that the transfer function of the core assembly depended on the current source impedance, the current sense resistors in the electronics (termination impedance), and the turns ratio between the sense winding and the excitation windings.

The transfer function of the core assembly is the ratio of the source current in the sense winding and difference in the peak to peak voltage developed across the sense resistor. It was found that the relationship between the source impedance, the sense resistor, and turns ratio follows the empirical equation 1, shown below. The value of the transfer function is a relative number and is only used to observe the effects of changing one or more of the variables in Eq. 1.

$$\text{Transfer function} = K \bullet \frac{aR_{source}}{R_{source} + a^2 R_{sense}} \qquad a = \frac{\text{number of sense winding turns}}{\text{number of excitation winding turns}} \qquad (1)$$

K = coupling coefficient

It is apparent that making R_{sense} smaller or R_{source} larger improves the transfer function. However, reducing R_{sense} to half value also reduces the voltage developed across R_{sense} in half. Likewise doubling R_{source} reduces the input voltage sensitivity in half.

It was decided to use 50 Ohm for R_{sense} because it provides a workable signal level and this value matches the impedance of the cable used between the core assembly and the electronics.

The effect of the turns ratio between the sense and the excitation windings was also studied and follows Eq. 1. This ratio affects the reflected impedance of the current sense resistors.

The core assembly was built with a=1, R_{sense} = 50 Ohm and R_{source} as large as possible. R_{source} was chosen to be 2 kOhm when used for quench detection or lead voltage detection. Choosing 2 kOhm for R_{source} yields a scaling factor of 1 mV input equal 1 mV output at R_{sense} and a noise level of 0.5 mV. High values of R_{source} make it possible to reduce the wattage rating of the bridge resistors (Fig. 1) used for superconducting magnet quench detection. The wattage ratings of these resistors are a concern because the entire dump voltage is developed across them.

A 2 kV peak 60 Hz voltage source was used to generate a voltage for common mode tests. The measured common mode rejection varied for different core assemblies. This is probably due to minor construction variations. The poorest CMR observed was -147 dB. More than 50% of the core assemblies had a CMR of -150 dB or better.

The effect of a dc magnetic stray field at the core assembly was studied in a uniform magnetic field. Stray fields cause an output voltage shift, which depends on the field magnitude and direction. Both axial and transverse stray fields through the core assembly cause output shifts which look like an "apparent input signal".

Each core assembly is therefore protected by a shield as shown in Fig. 8. The shielded core assembly produces a worst case "apparent input signal" of ±4 mV at 100 Gauss axial field.

This error can be reduced by aligning the core assembly axis perpendicular to the stray field direction or by installing additional magnetic shielding. The ratio between the "apparent input signal" and various values of the magnetic stray field is not linear.

7.0 MAGNETICALLY COUPLED QUENCH DETECTOR PERFORMANCE DATA

- Maximum comon mode voltage input to output: ± 5000 Vpeak
- Common mode rejection @ 2 kVpeak 60 Hz AC: -150 dB typ.
- Leakage current input to output @ 7.5 kVDC: 0.1 uA max.
- Input capacitance to ground: 60 pF typ.
- Recommended source impedance: 100 Ohm or greater
- Maximum permissible stray field at core assembly: 600 Gauss transverse, 100 Gauss axial
- Output voltage with R_{source} = 1 kOhm, R_{sense} = 50 Ohm

  Gain set to minimum, Output scale factor: 1.5 V/1mA input
  Gain set to maximum, Output scale factor : 10 V/1mA input
  Stray field disturbance: ± 1 mV apparent input at 600 Gauss transverse
  ± 4 mV apparent input 100 Gauss axial

- Output voltage span : ± 10 V
- Input to output trip response delay: 20 msec
- Output ripple at minimum gain: I_{sense} = 0.0 mA 250 µV peak (0.1 Hz to 30 kHz)
  I_{sense} = 6.6 mA 1 mV peak (0.1 Hz to 30 kHz)

- Frequency response of core assembly and electronics:
  (limited by two pole filter)

  Bandwidth: DC to 100 Hz: -1dB
  250 Hz: -6 dB
  500 Hz: -12 dB

- Temperature coefficient of electronics card output with scale factor at 2V/1mA, range 20°C to 40°C: 200 µV/°C
- Distance of core assembly to electronics: 1000 ft typ.
- Interconnecting cable between core assembly and electronics: Belden #9773 or equiv. Shielded, 3 pair, AWG #18

FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	AD/EES			

SUBJECT	NAME	
MICRO CURRENT TRANSDUCER HEAD CONNECTIONS AND CABLEING	W. JASKIERNY	
	DATE: 14SEP93	REVISION DATE:

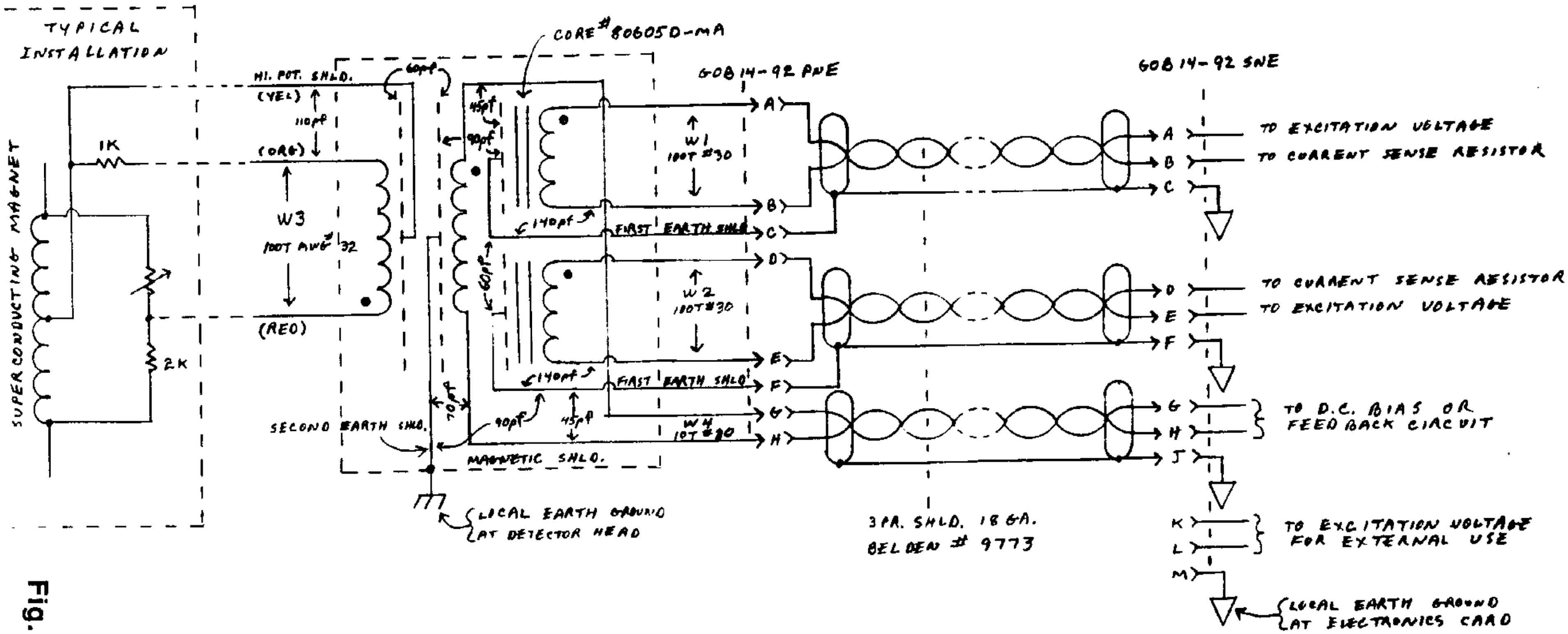


Fig. 2

FERMILAB
ENGINEERING NOTE

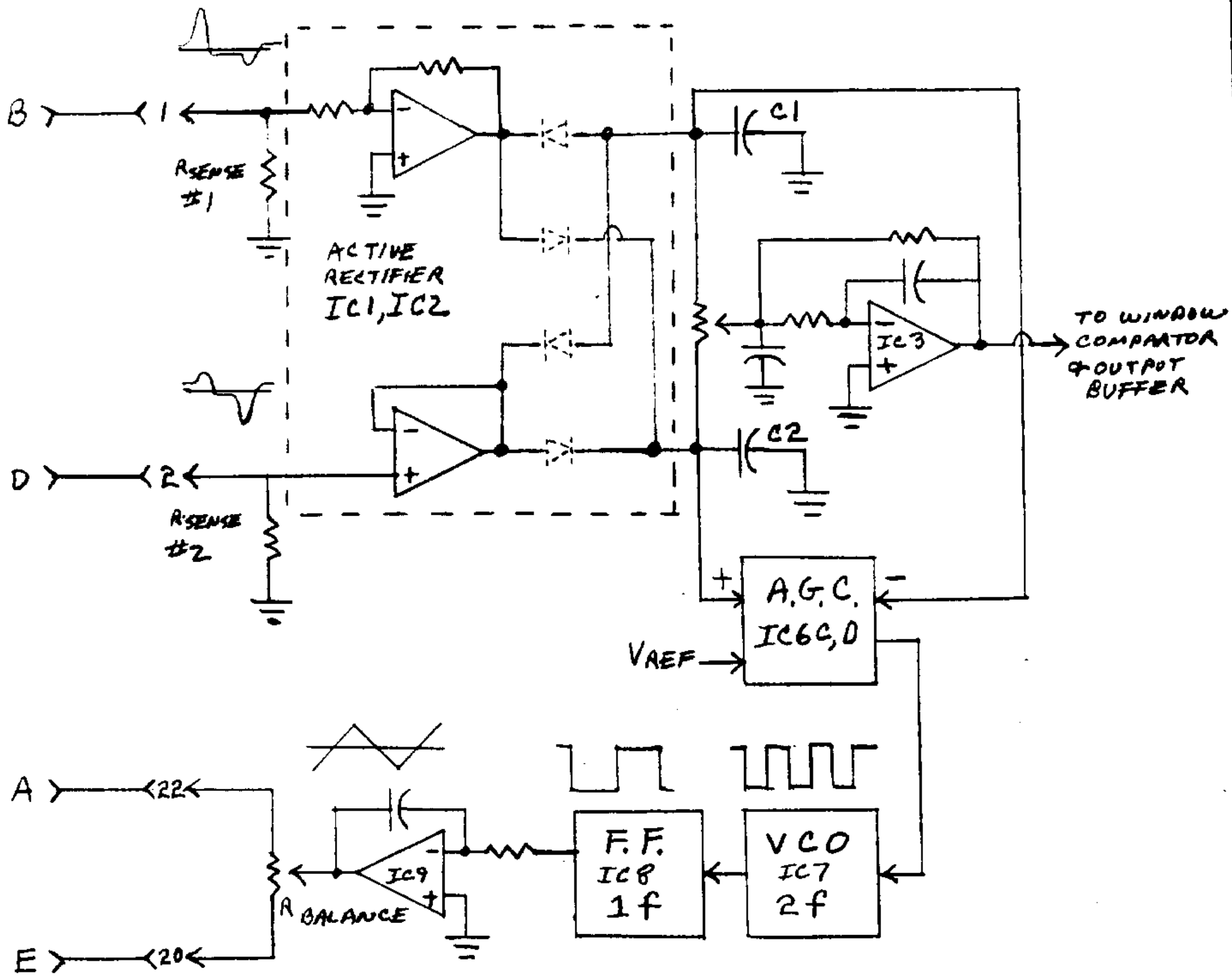
SECTION	PROJECT	SERIAL-CATEGORY	PAGE
RD/EES			

SUBJECT: MICRO CURRENT TRANSDUCER
FUNCTIONAL DIAGRAM OF DETECTOR ELECTRONICS

NAME: W. JASKIERNY

DATE: 16 SEP 93

REVISION DATE:

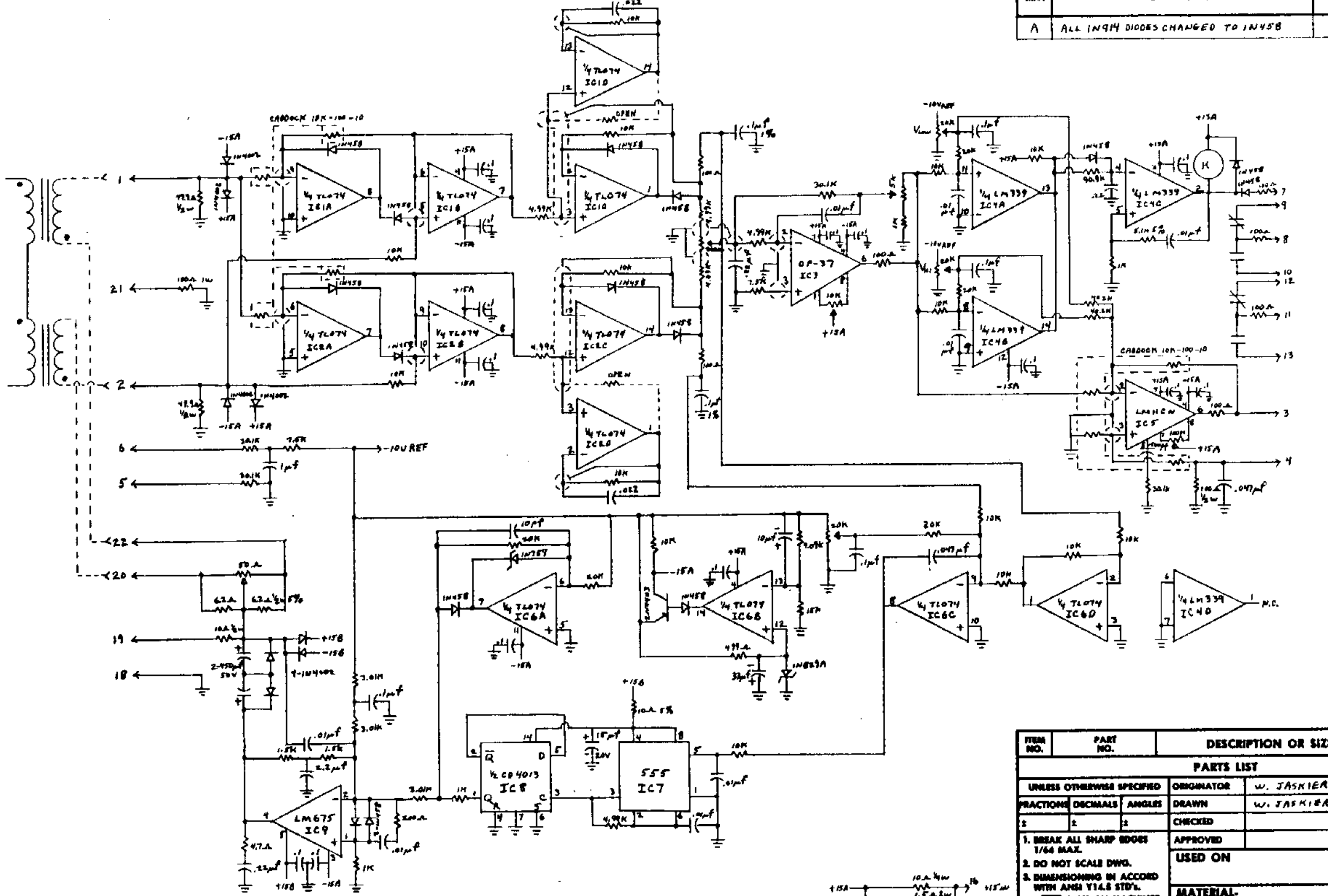


$f_{OUT} \cong 7\ kHz$

Fig. 3

559924

REV.	DESCRIPTION	DRAWN / APPD.	DATE
A	ALL 1N914 DIODES CHANGED TO 1N458	MCJ	8 DEC 93



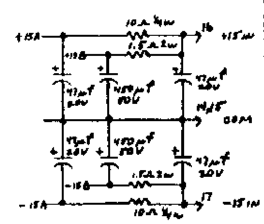


Fig. 4

ITEM NO.	PART NO.	DESCRIPTION OR SIZE	QTY. REQ.

PARTS LIST

UNLESS OTHERWISE SPECIFIED			ORIGINATOR	W. JASKIERNY	18 JAN 93
FRACTIONS	DECIMALS	ANGLES	DRAWN	W. JASKIERNY	21 JUN 93
±	±	±	CHECKED		
			APPROVED		

1. BREAK ALL SHARP EDGES 1/64 MAX.
2. DO NOT SCALE DWG.
3. DIMENSIONING IN ACCORD WITH ANSI Y14.5 STD'S.

MAX. ALL MACHINED SURFACES

USED ON

MATERIAL-

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

Micro Current Transducer for Superconducting Quench Detection Electronics Schematic

SCALE	FILMED	DRAWING NUMBER	REV.
		2789-EC-173210	A

BRUNING-40-107

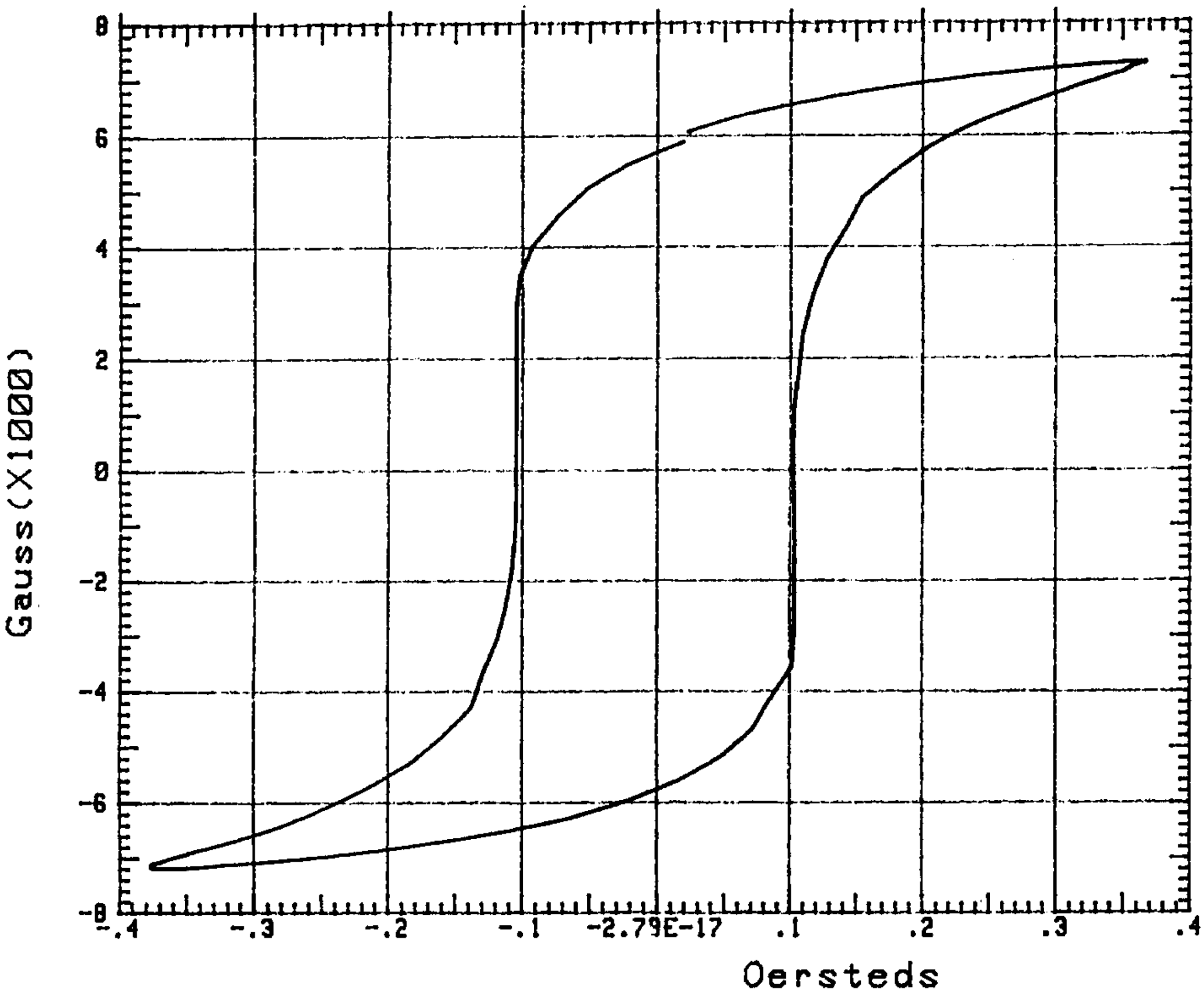
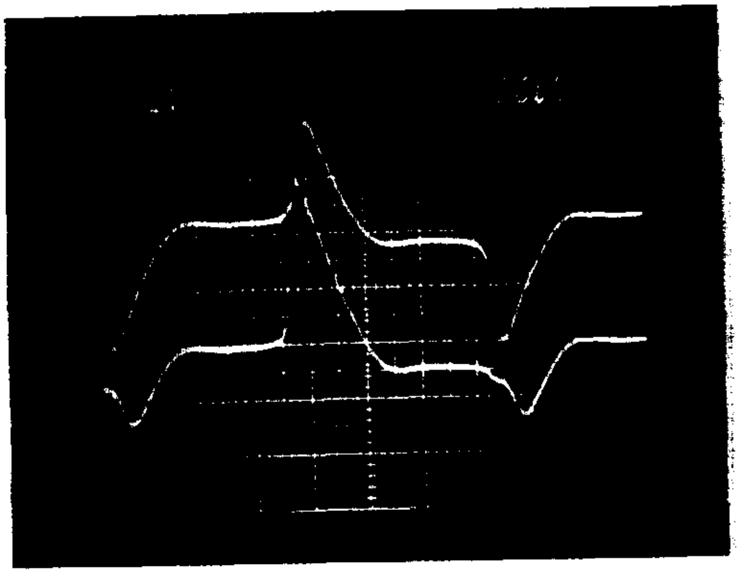


Fig. 5

Hysteresis Loop for 1/2 mil Square Permalloy 80 @ 7 kHZ

VOLTAGE DEVELOPED ACROSS 50 OHM Rsense



Top trace:

Zero Amp Sense Current

Bottom trace:

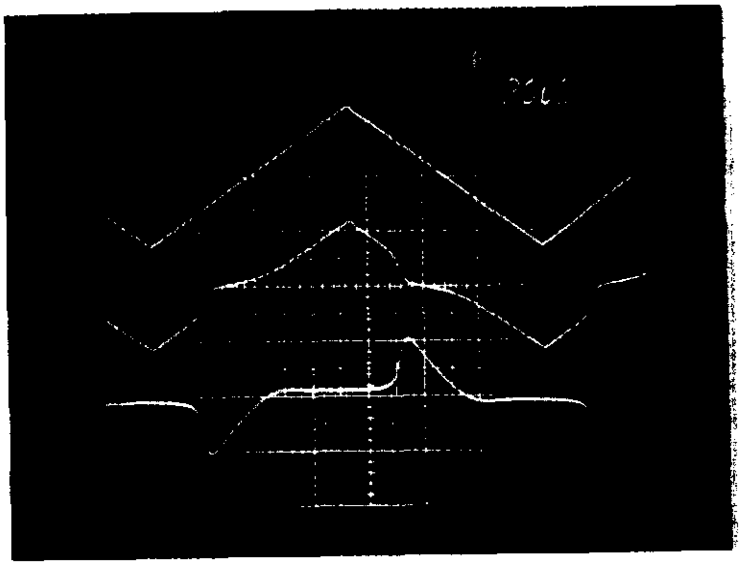
5 mA Sense current

1V / cm

20 usec / cm

Fig. 6A

PHASE RELATIONSHIP



Top trace

Excitation voltage

5 V / cm

Middle trace

Voltage across excitation winding

5 V / cm

Bottom trace

Voltage across 50 Ohm Rsense

2 V / cm

Fig. 6B

20 usec / cm

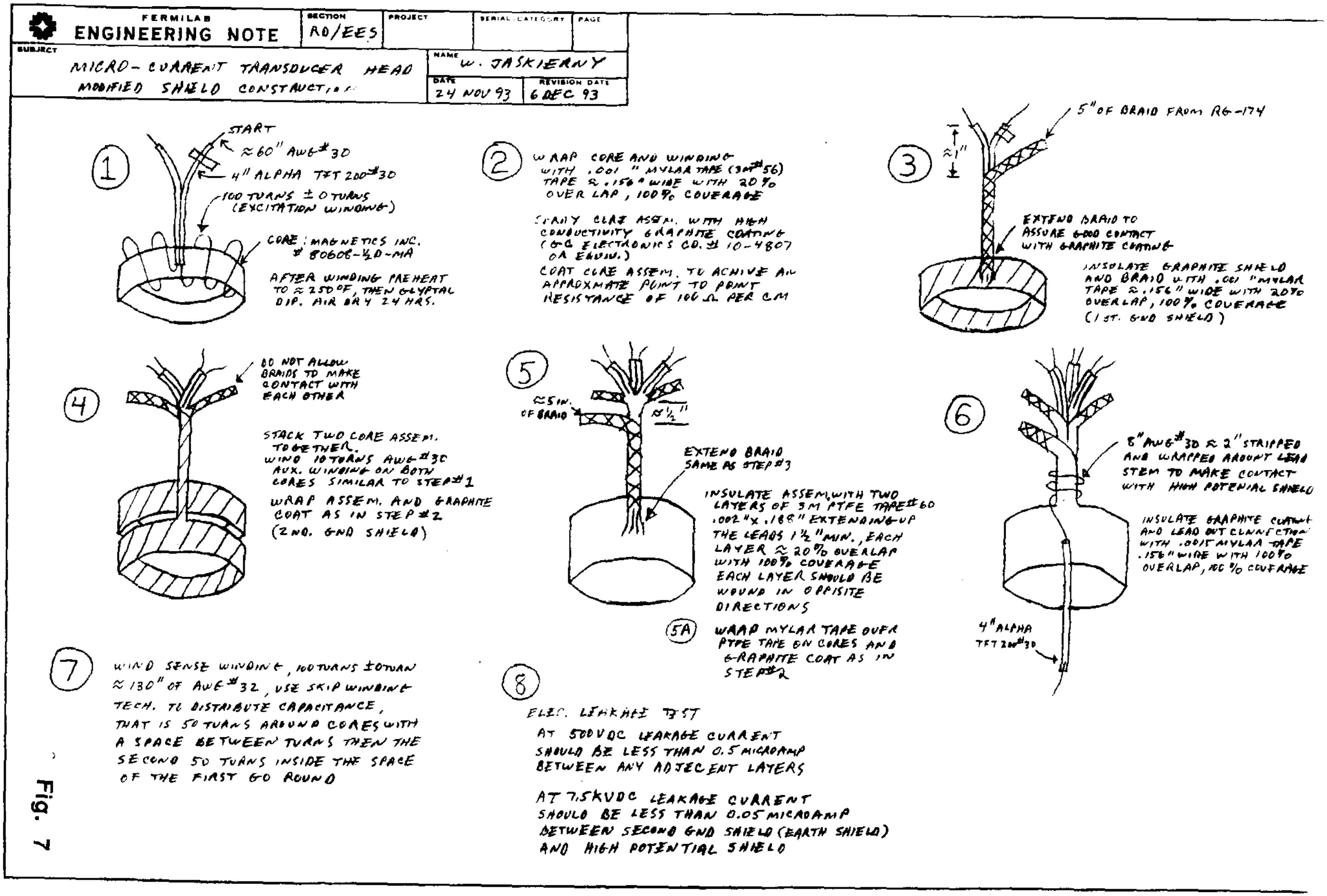

FERMILAB ENGINEERING NOTE
SECTION RD/EES
PROJECT
SERIAL-CATEGORY
PAGE
SUBJECT
MICRO-CURRENT TRANSDUCER HEAD
MODIFIED SHIELD CONSTRUCTION
NAME W. JASKIERNY
DATE 24 NOV 93
REVISION DATE 6 DEC 93
1
START
≈ 60" AWG #30
4" ALPHA TFT 200 #30
100 TURNS ± 0 TURNS (EXCITATION WINDING)
CORE: MAGNETICS INC. # 80606-½D-MA
AFTER WINDING PREHEAT TO ≈ 250°F, THEN GLYPTAL DIP. AIR DRY 24 HRS.
2
WRAP CORE AND WINDING WITH .001" MYLAR TAPE (3M #56) TAPE ≈ .156" WIDE WITH 20% OVER LAP, 100% COVERAGE
SPRAY CLAZ ASSEM. WITH HIGH CONDUCTIVITY GRAPHITE COATING (G-C ELECTRONICS CO. # 10-4807 OR EQUIV.)
COAT CORE ASSEM. TO ACHIVE AN APPROXMATE POINT TO POINT RESISTANCE OF 100 Ω PER CM
3
≈1"
5" OF BRAID FROM RG-174
EXTEND BRAID TO ASSURE GOOD CONTACT WITH GRAPHITE COATING
INSULATE GRAPHITE SHIELD AND BRAID WITH .001" MYLAR TAPE ≈ .156" WIDE WITH 20% OVERLAP, 100% COVERAGE (1ST. GND SHIELD)
4
DO NOT ALLOW BRAIDS TO MAKE CONTACT WITH EACH OTHER
STACK TWO CORE ASSEM. TOGETHER.
WIND 10 TURNS AWG #30 AUX. WINDING ON BOTH CORES SIMILAR TO STEP #1
WRAP ASSEM. AND GRAPHITE COAT AS IN STEP #2 (2ND. GND SHIELD)
5
≈ 5 IN. OF BRAID
≈ ½"
EXTEND BRAID SAME AS STEP #3
INSULATE ASSEM. WITH TWO LAYERS OF 3M PTFE TAPE #60 .002" x .188" EXTENDING UP THE LEADS 1½" MIN., EACH LAYER ≈ 20% OVERLAP WITH 100% COVERAGE EACH LAYER SHOULD BE WOUND IN OPPISITE DIRECTIONS
5A
WRAP MYLAR TAPE OVER PTFE TAPE ON CORES AND GRAPHITE COAT AS IN STEP #2
6
8" AWG #30 ≈ 2" STRIPPED AND WRAPPED AROUNT LEAD STEM TO MAKE CONTACT WITH HIGH POTENIAL SHIELD
INSULATE GRAPHITE COATING AND LEAD OUT CONNECTION WITH .001" MYLAR TAPE .156" WIDE WITH 100% OVERLAP, 100% COVERAGE
4" ALPHA TFT 200 #30
7
WIND SENSE WINDING, 100 TURNS ± 0 TURN ≈ 130" OF AWG #32, USE SKIP WINDING TECH. TO DISTRIBUTE CAPACITANCE, THAT IS 50 TURNS AROUND CORES WITH A SPACE BETWEEN TURNS THEN THE SECOND 50 TURNS INSIDE THE SPACE OF THE FIRST GO ROUND
8
ELEC. LEAKAGE TEST
AT 500VDC LEAKAGE CURRENT SHOULD BE LESS THAN 0.5 MICROAMP BETWEEN ANY ADJECENT LAYERS
AT 7.5KVDC LEAKAGE CURRENT SHOULD BE LESS THAN 0.05 MICROAMP BETWEEN SECOND GND SHIELD (EARTH SHIELD) AND HIGH POTENTIAL SHIELD

Fig. 7

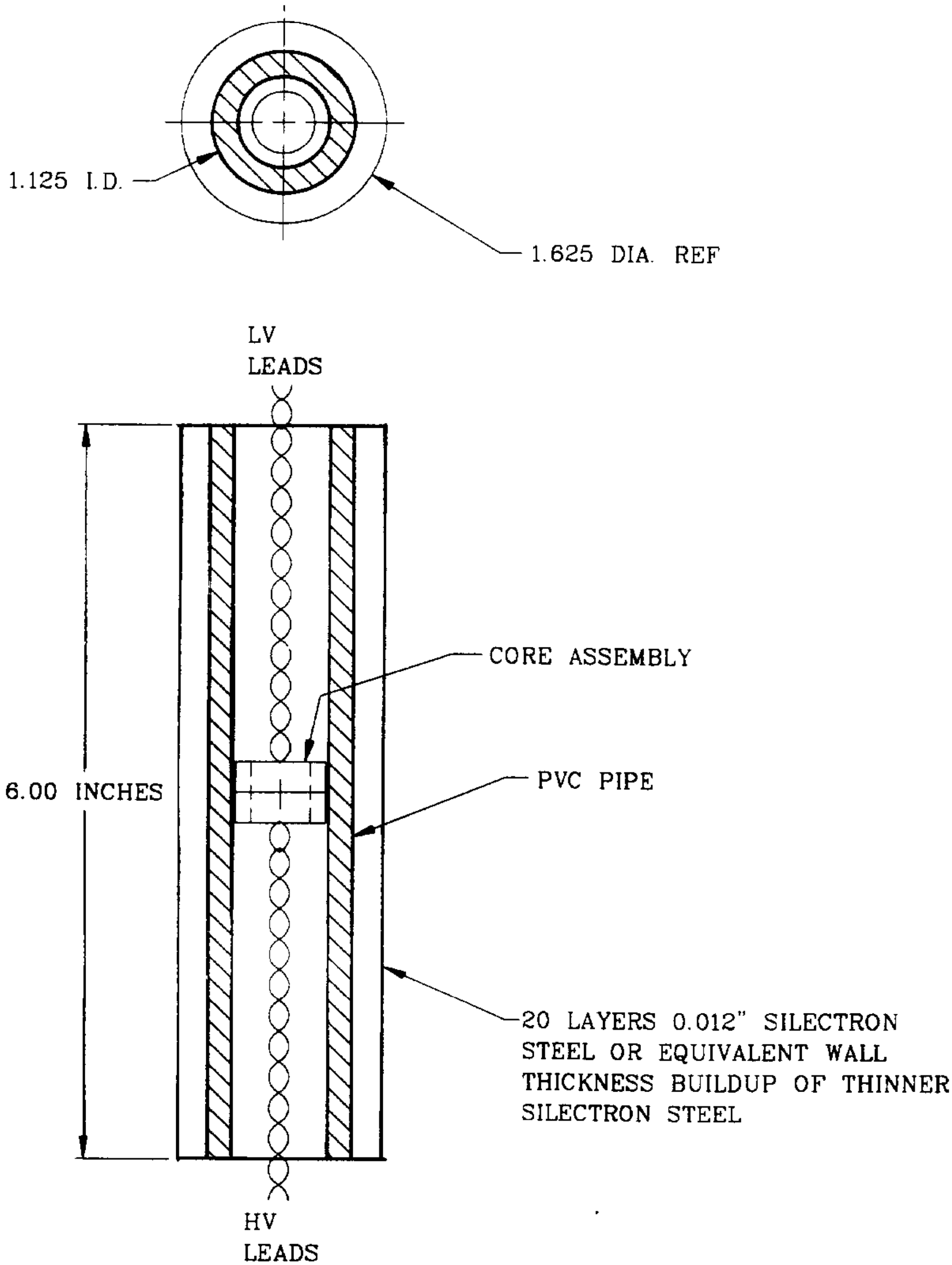


FIG. 8
MAGNETIC SHIELD FOR CORE ASSY