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13. ABSTRACT (Maximum 200 words) A two-year research effort on Navy applications of High-Tc SQUIDS is described. Over the course of the contract, we reviewed materials research and operation of SQUIDS in a small magnetic field. We examined some applications of SQUIDS, including Naval Gradiometers, Biomagnetometers and Scanning SQUID microscopes.			
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High-Tc Superconducting Multilevel Materials and Device Development and Device Physics

Contract N00014-95-C-0056

**PROBLEM TO SOLVE:
DEVELOP NAVY APPLICATIONS OF HIGH-TC SQUIDS**

**OUR PART OF SOLUTION:
UNSHIELDED/MOBILE OPERATION OF SQUIDS**

**Roger Koch IBM Research
Frank Milliken Yorktown Heights, NY
Jim Rozen
Steve Brown
Pieter Woeltgens**

Review materials research

Review operation of SQUIDs in a small magnetic field

Examine some applications of SQUIDs

- 1. Naval Gradiometers**
- 2. Biomagnetometers**
- 3. Scanning SQUID microscopes**

28 June 1999

Final Report Covering December 22, 1994 to December 21, 1996

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Prepared for:

**Office of Naval Research
Department of the Navy
800 North Quincy Street
Arlington, VA 22217**

SQUID APPLICATIONS:

Successful in a "marketplace":

1. Brain biomagnetometer
2. SQUID susceptometer
3. SQUID microscope
4. Scientific applications
5. Rock magnetometer

OPERATE WHILE
SHIELDED AND/OR
STATIONARY

Technically successful:

1. Geophysical sensors (e.g. MT)
2. Radiation receivers

OPERATE WHILE
STATIONARY &
"AWAY FROM IT ALL

Technically still very difficult:

1. Heart biomagnetometers
2. Navy submarine or mine detection
3. Most NDE applications

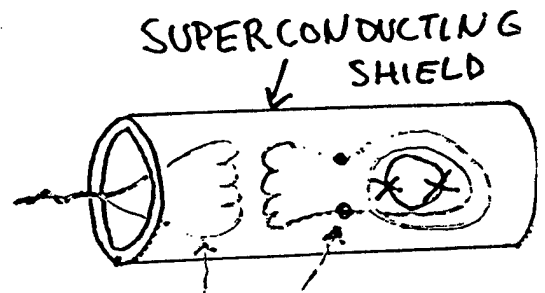
OPERATE WHILE/
AFTER MOVING
AND WHILE
"POORLY" SHIELDED

USING SQUIDS IN UNSHIELDED ENVIROMENTS:

If High-Tc SQUIDS are to become economically viable products (that survive without government funding) we need to learn how to operate them outside of $B=0$, $\Delta B=0$, $\Delta T=0$, and RFI and magnetically shielded enclosures:

- | | |
|-------------------|---|
| $B = B_{EARTH}$ | use narrow lines and/or holes, fluxdams, heaters, laser zappers |
| $\Delta B \neq 0$ | TSG active cancellation, fluxdams, good quality materials |
| $\Delta T \neq 0$ | fluxdams, good quality materials |
| RFI $\neq 0$ | high bandwidth electronics |
| Magnetic noise | magnetic references, gradiometers |

OR DO WHAT IS DONE IN LOW-TC....
superconducting shields and wires

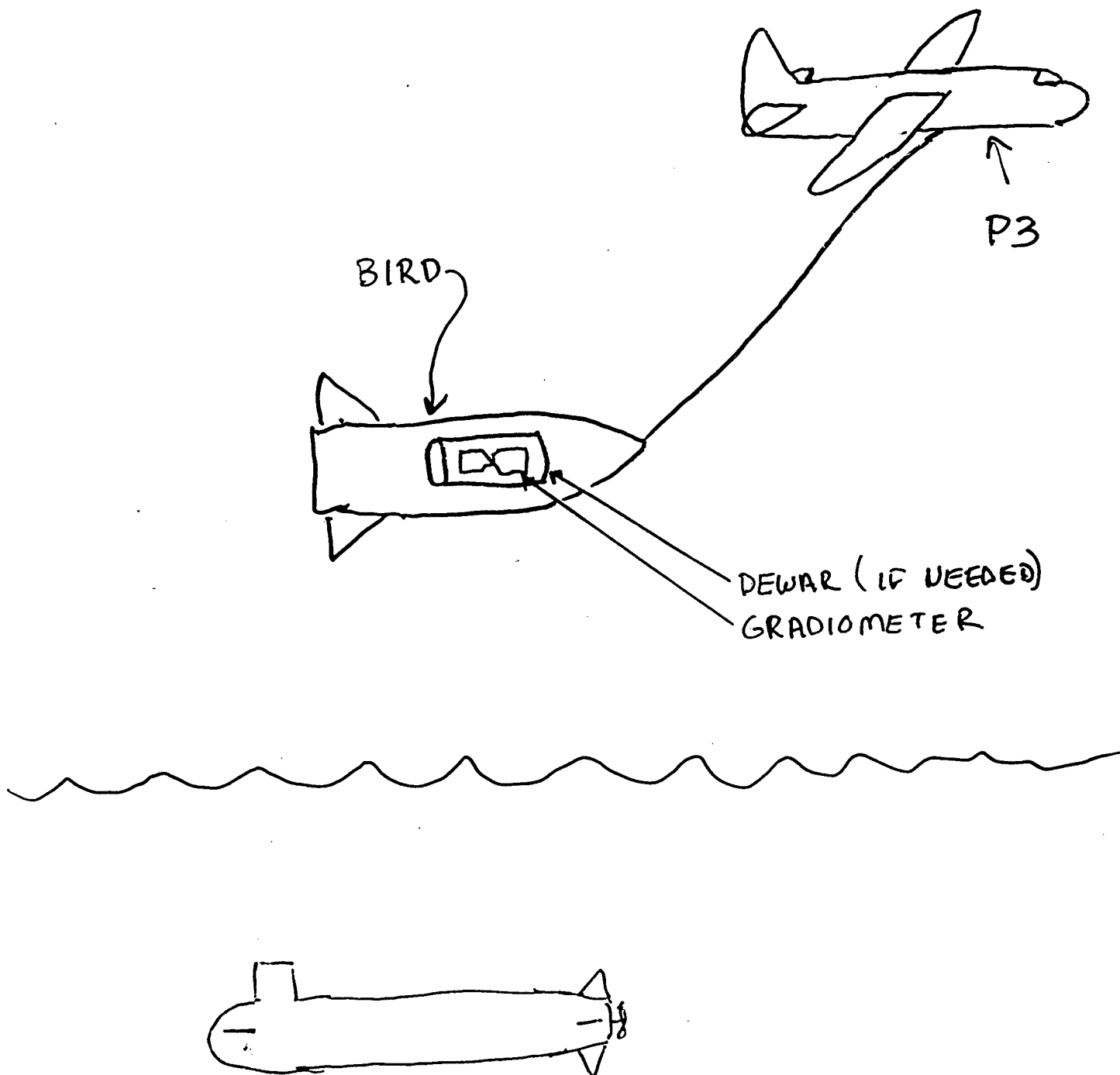


SUPERCONDUCTING WIRE & JOINT

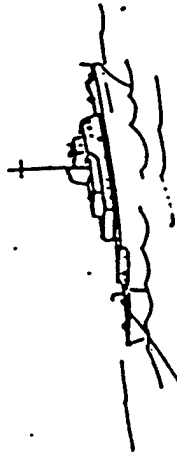
What we really need is the usability and cost of a fluxgate!

FLUXGATE	$\rightarrow 2 \text{ pT}/\sqrt{\text{Hz}}$	@ 1 Hz	-	\$ 1,000
HIGH-Tc SQUID	$200 \text{ fT}/\sqrt{\text{Hz}}$		-	\$ 10,000

SUBMARINE DETECTION

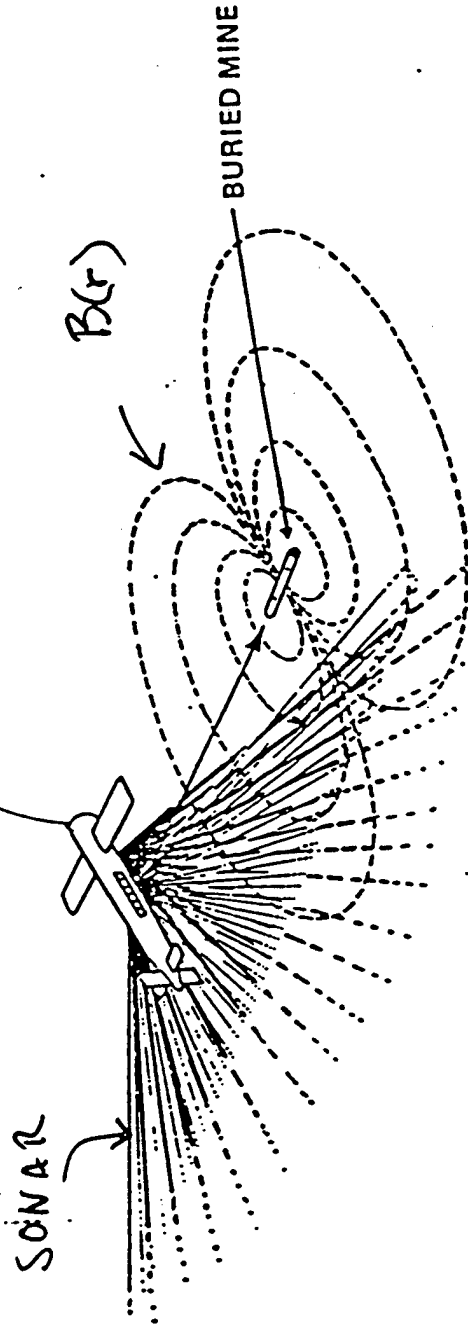


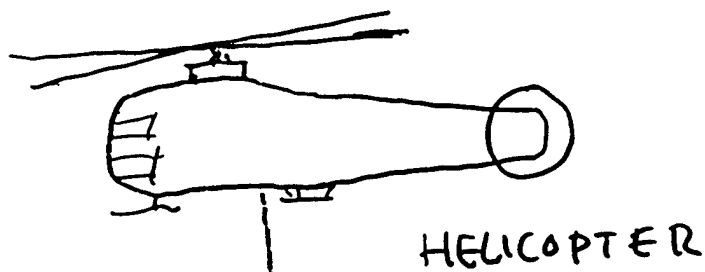
FUTURE MADOM CONCEPT



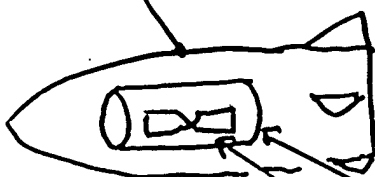
A SENSOR TRIAD WILL PROVIDE:

- HIGH DETECTION PROBABILITY
- LOW FALSE CONTACT RATE





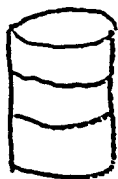
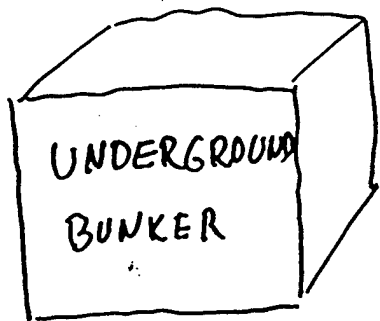
OTHER
MAGNETIC
ANAMOLIES



DEWAR (IF NEEDED
GRADIOMETER

EARTH

LAND
MINES



WASTE
(NUCLEAR &
OTHERWISE)



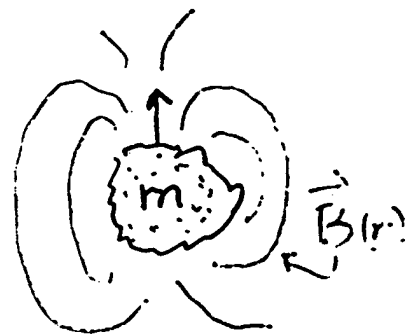
UNEXPLODED
ORDNANCE

WHAT THE USER WANTS TO DO:

FIND MAGNETIC ANOMALIES

M.A.D. \equiv MAGNETIC ANOMALY DETECTION

WHAT TO MEASURE?



1000+
SYSTEMS IN
USE TODAY

$|B|$

{ EASY TO MEASURE
HARD TO INTERPRET

NONE
IN USE
TODAY

$\vec{B} = [B_x, B_y, B_z]$

{ IMPOSSIBLE TO
MEASURE ON A
MOVING PLATFORM

20 YEARS
OF
RESEARCH

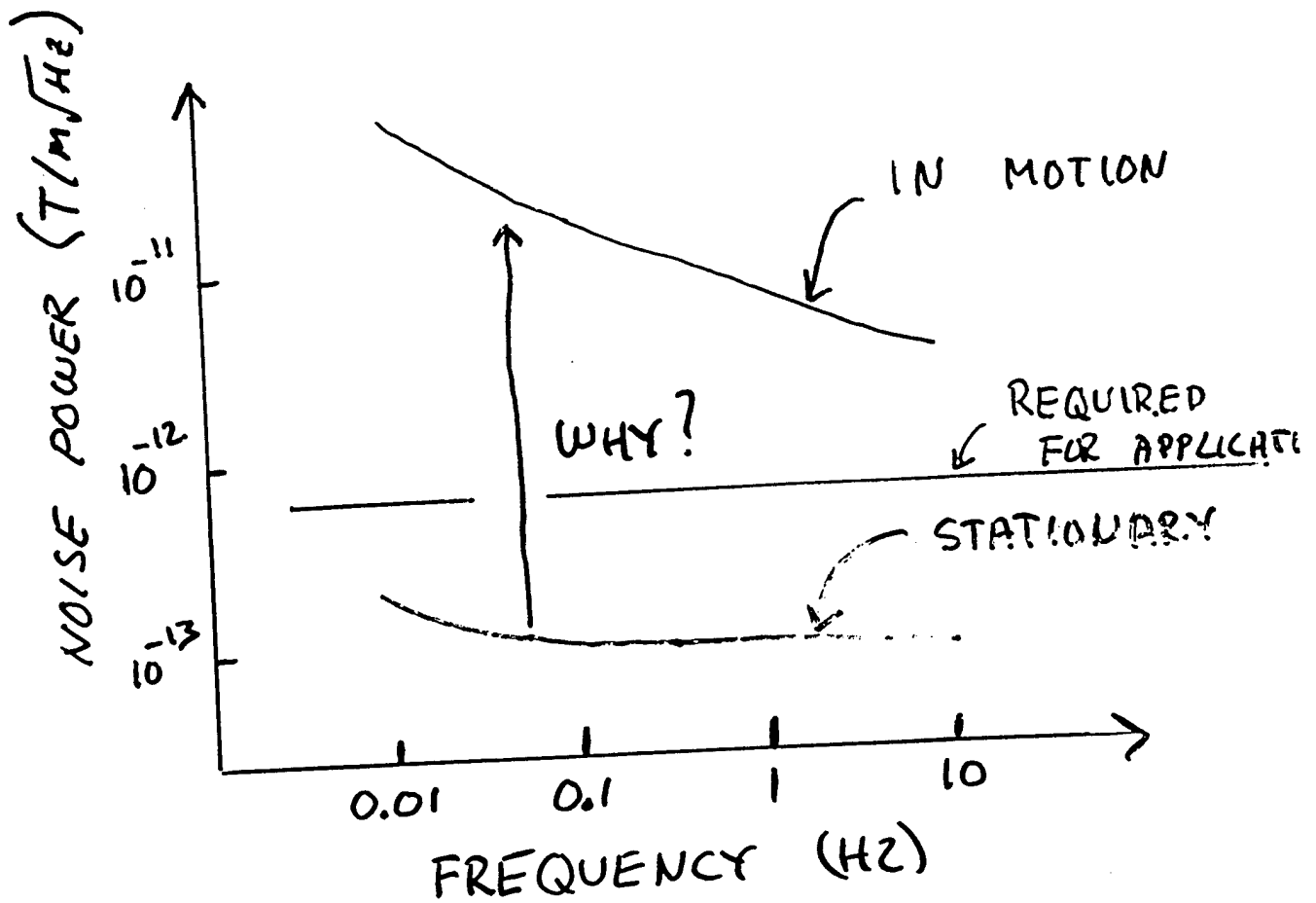
$\frac{d\vec{B}}{d\vec{r}}$

$\begin{bmatrix} \frac{dB_x}{dx} & \frac{dB_y}{dx} & \frac{dB_z}{dx} \\ \frac{dB_x}{dy} & \frac{dB_y}{dy} & \frac{dB_z}{dy} \\ \frac{dB_x}{dz} & \frac{dB_y}{dz} & \frac{dB_z}{dz} \end{bmatrix}$

{ HARD TO
MEASURE

{ EASY TO
INTERPRET

MOTION INDUCED NOISE



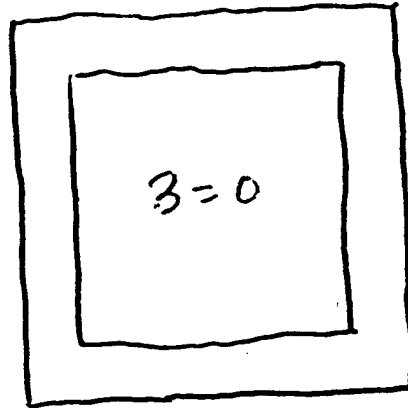
WHY THE INCREASE IN NOISE
WHEN IN MOTION?

BIG PROBLEM FACING
THE APPLICATION

LOW FREQUENCY NOISE (γ_f) IN A MAGNETIC FIELD:

ZERO FIELD-COOLED

IN ZERO FIELD

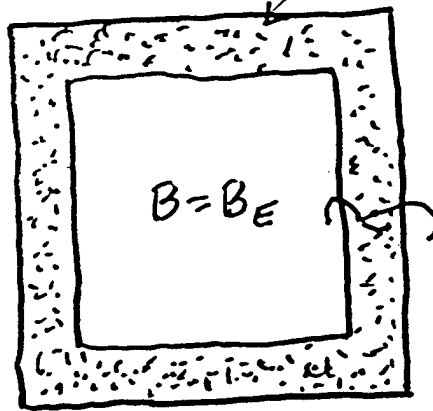


NO TRAPPED FLUX \Rightarrow

NO EXTRA γ_f NOISE

FIELD-COOLED

IN SAME FIELD



TRAPPED FLUX

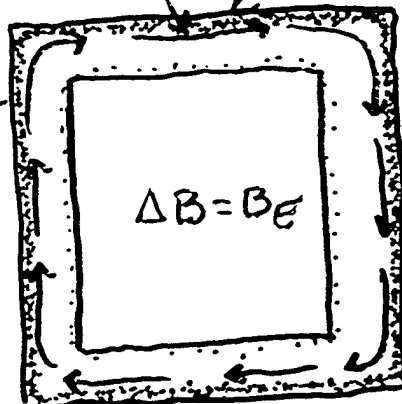
UNIFORMLY TRAP FLUX \Rightarrow

A LITTLE EXTRA γ_f NOISE (20-100%)

LARGE CURRENT (500 mA)

ZERO FIELD-COOLED

IN A FIELD

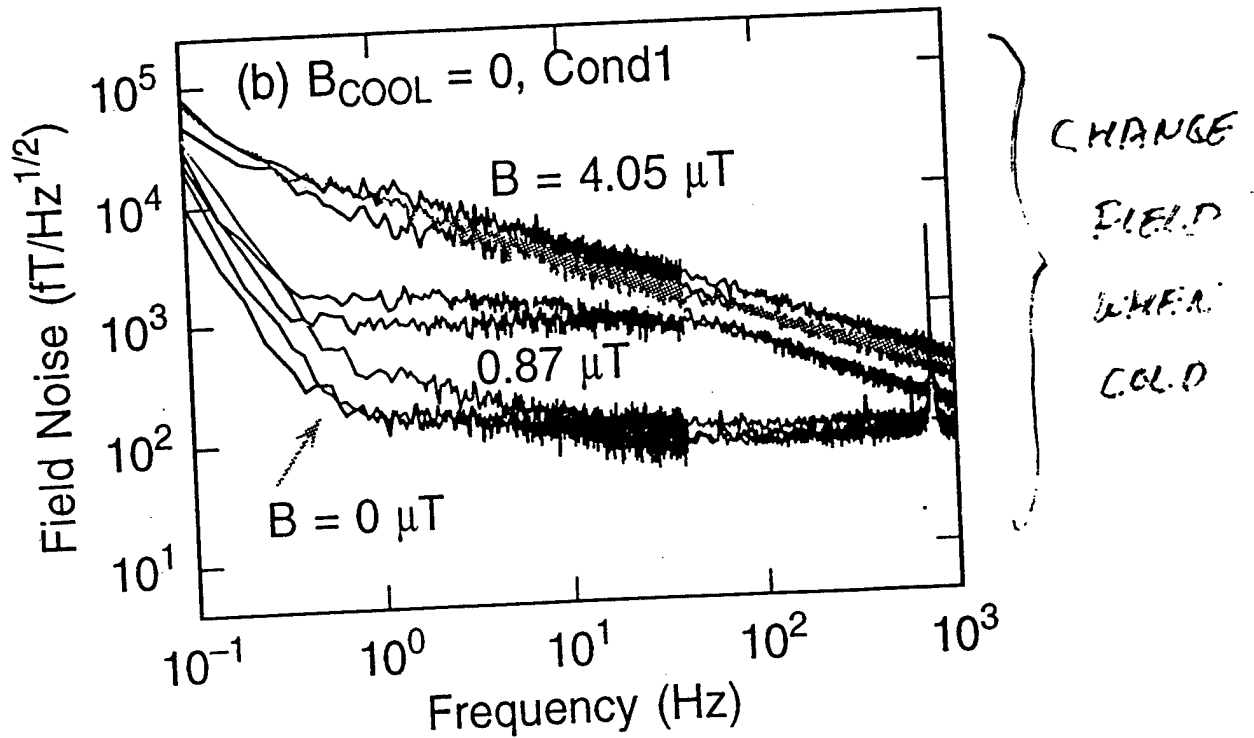
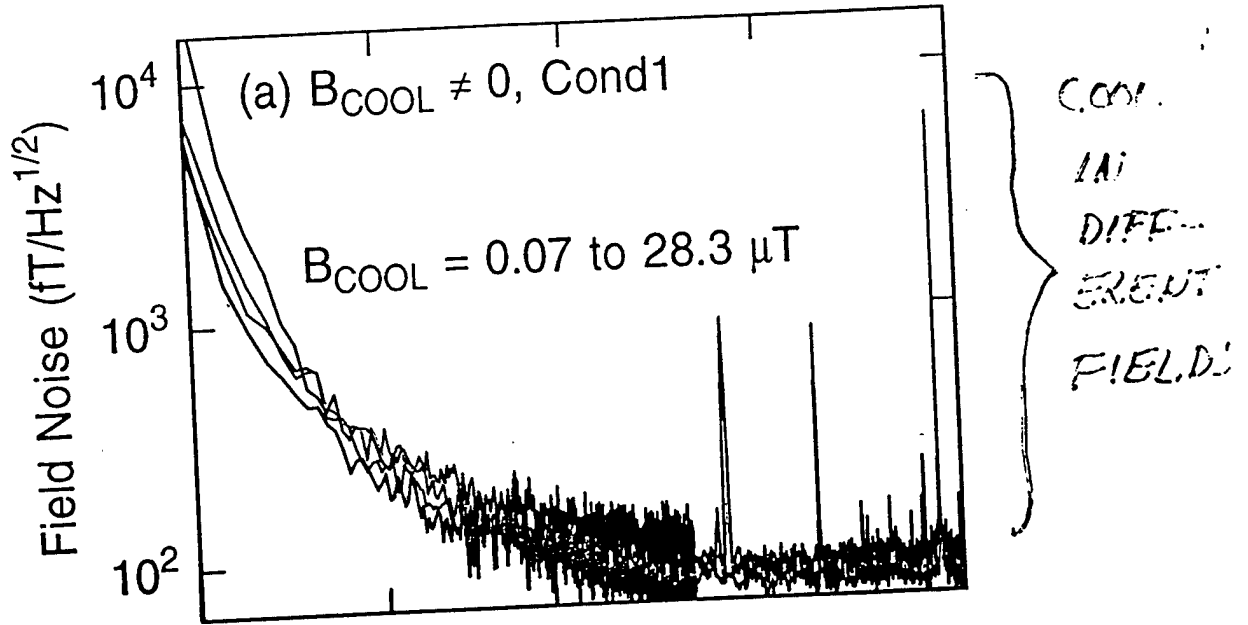


INJECTED TRAPPED FLUX

CIRCULATING CURRENT LOWER TRAPPING BARR & FLUX RUSHE IN. \Rightarrow

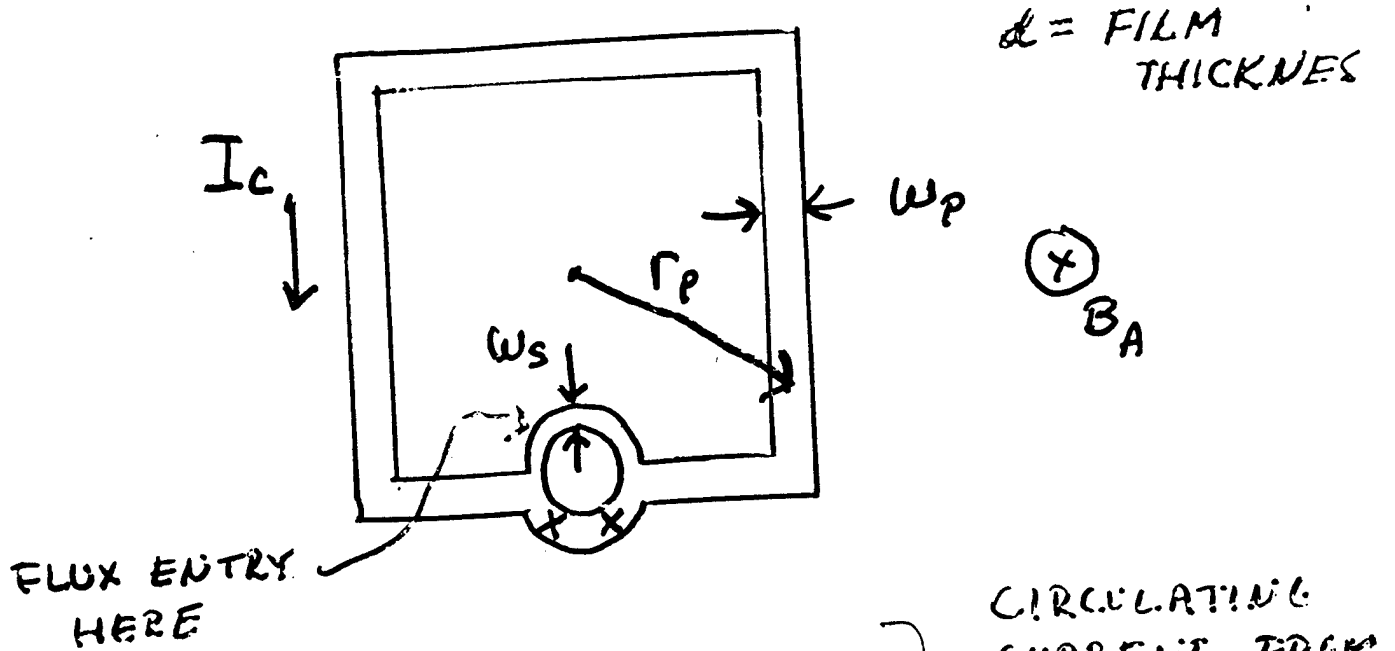
A LOT OF γ_f N

CONDUCTUS IMAG MAGNETOMETER



$B_T \approx 1 \mu T$

SOURCE OF NOISE WITHOUT FLUXDAM



$$I_c \approx 4 B_A r_p / \pi \mu_0 \quad \left. \begin{array}{l} \text{CIRCULATING} \\ \text{CURRENT FROM} \\ \text{B}_A \end{array} \right\}$$

$$I_T \approx (J_c d w_s) \left[2.5 \left(\frac{\bar{I}_0 / w_s^2}{10^6 J_c d} \right)^{1/4} \right] \quad \left. \begin{array}{l} \text{MAX } I_c \\ \text{BEFORE} \\ \text{FLUX} \\ \text{ENTRY} \end{array} \right\}$$

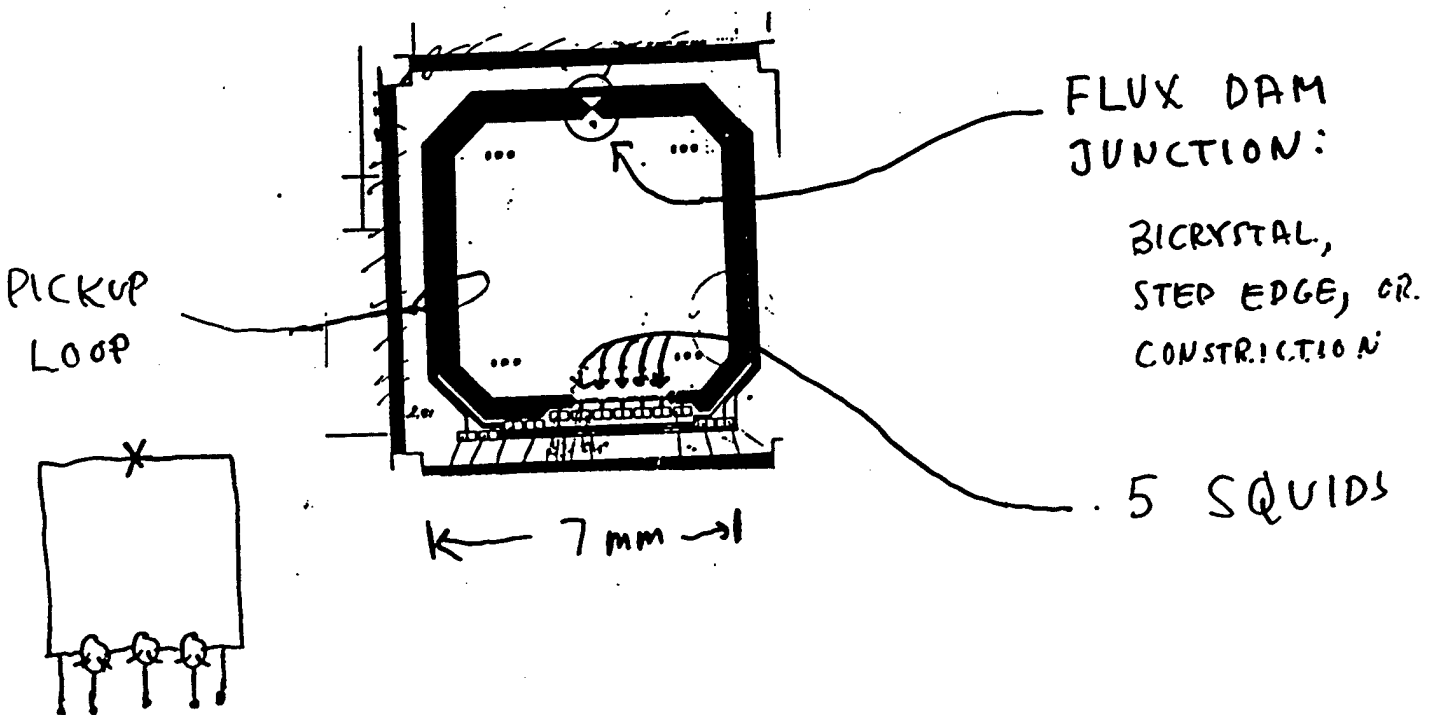
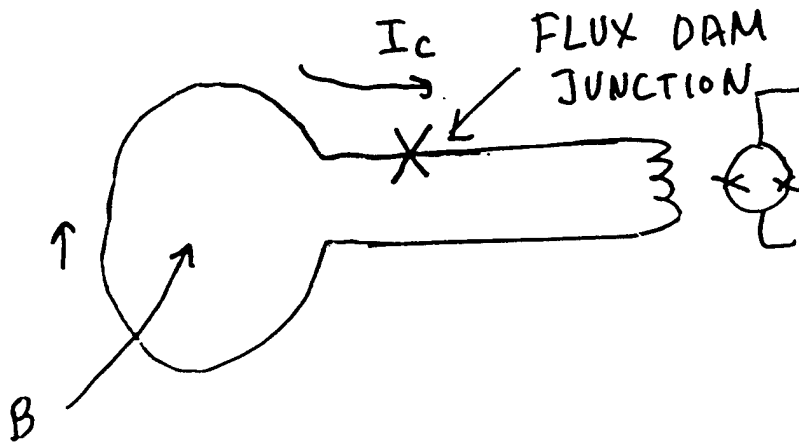
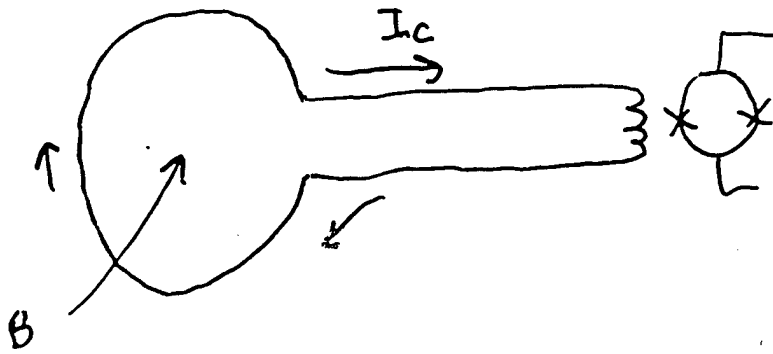
$$I_T \approx \sqrt{w_s^2}$$

$$B_T \approx \mu T$$

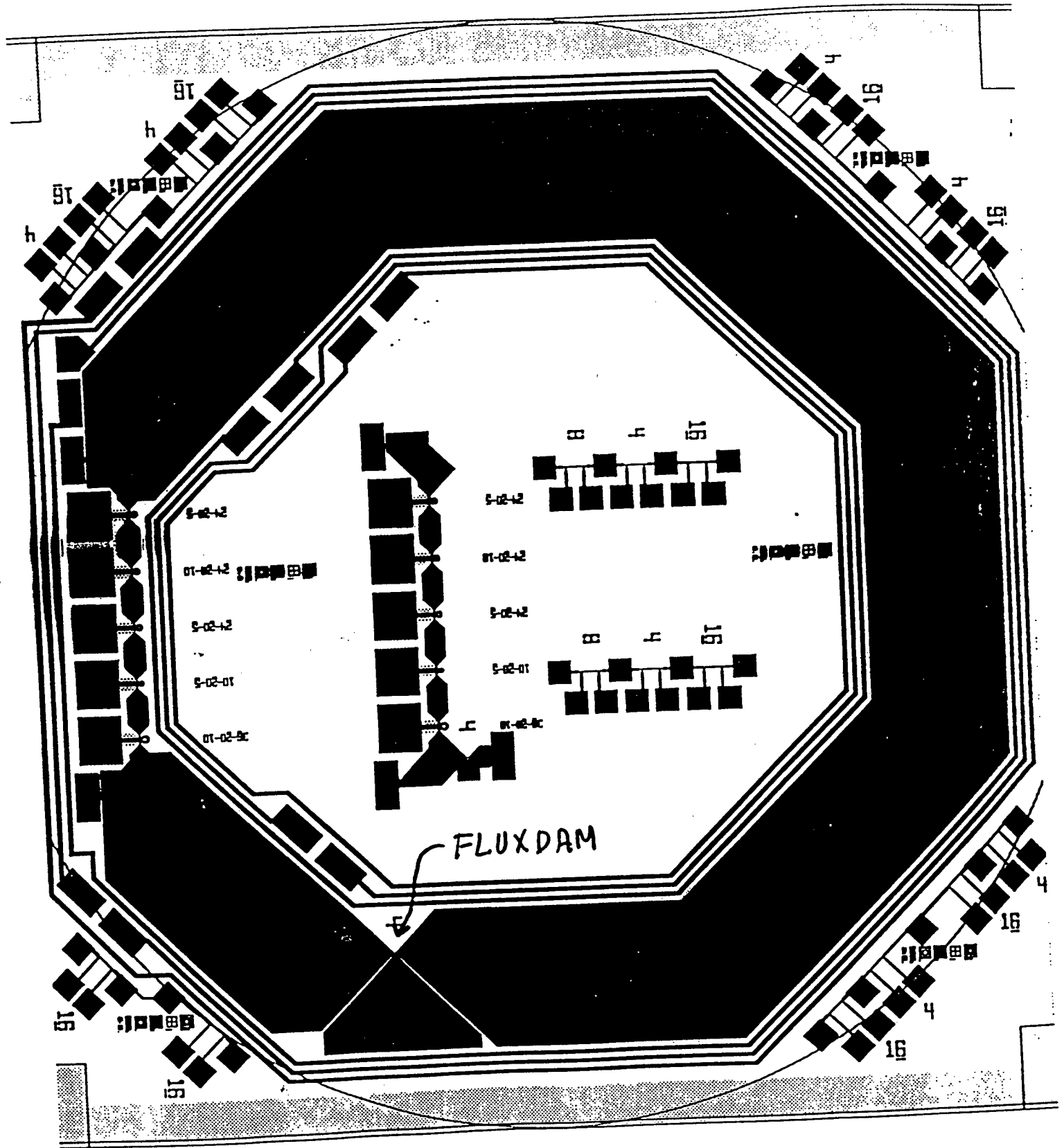
DESIGN
RULE

IF $I_0^{F.D.} < I_T$ AVOIDS THIS PROBLEM

HOW TO AVOID PERSISTENT CIRCULATING CURRENTS

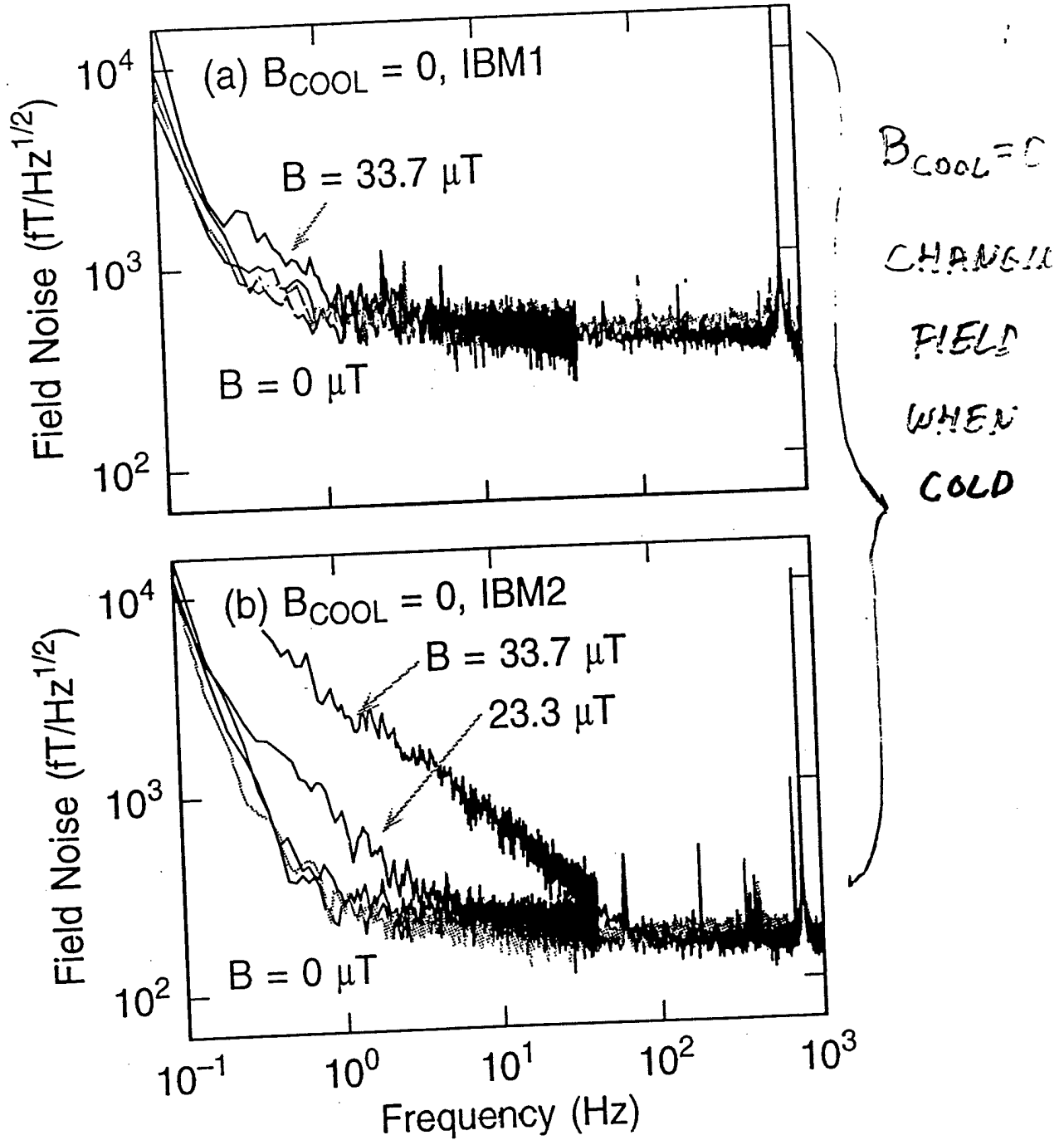


STEP EDGE 1x1 CM MAGNETOMETER



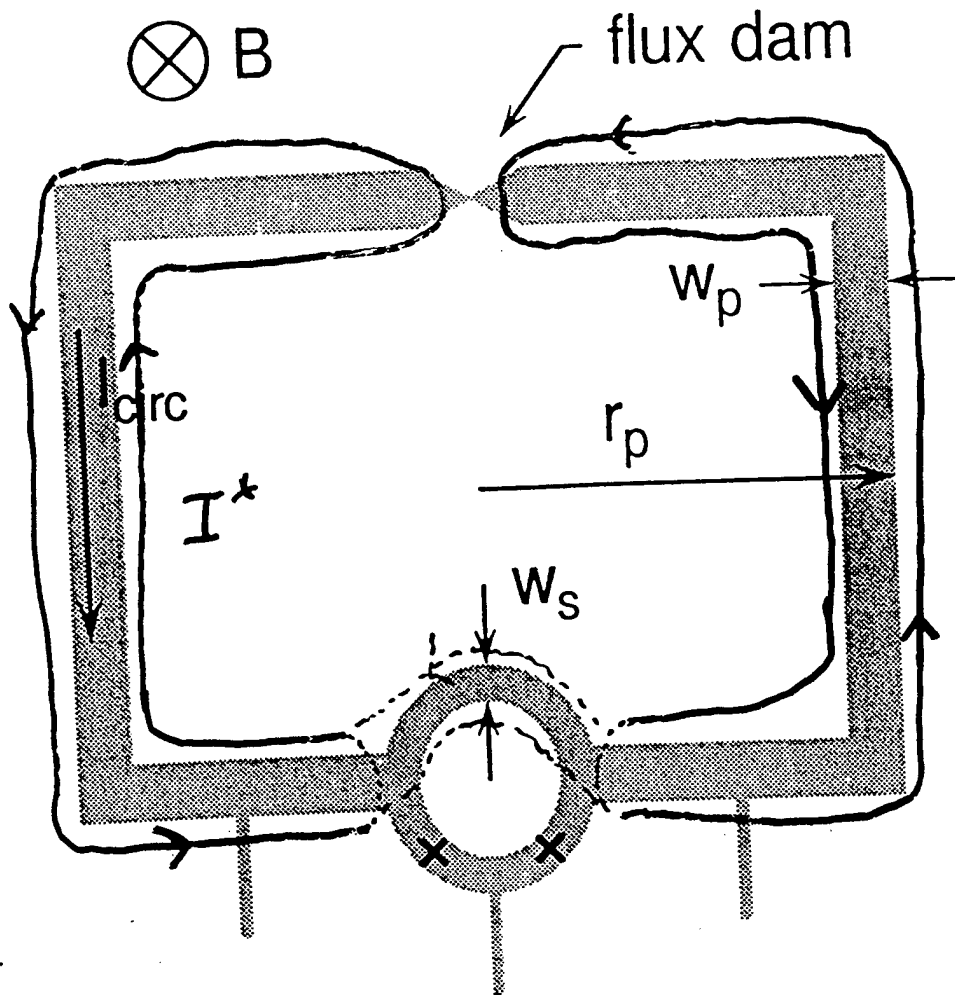
IBM SQUIDS WITH FLUX DAMS:

1 x 1 cm D.C. MAGNETOMETERS



NOISE FROM CURRENTS
AROUND THE PICKUP LOOP FILMS:

$$I_{\text{circ}} \leq I_0^{\text{F.D.}}$$



$$I_T < I_0^{\text{F.D.}}$$

DESIGN RI

$$I^* = 4Bw_p / 4\mu_0$$

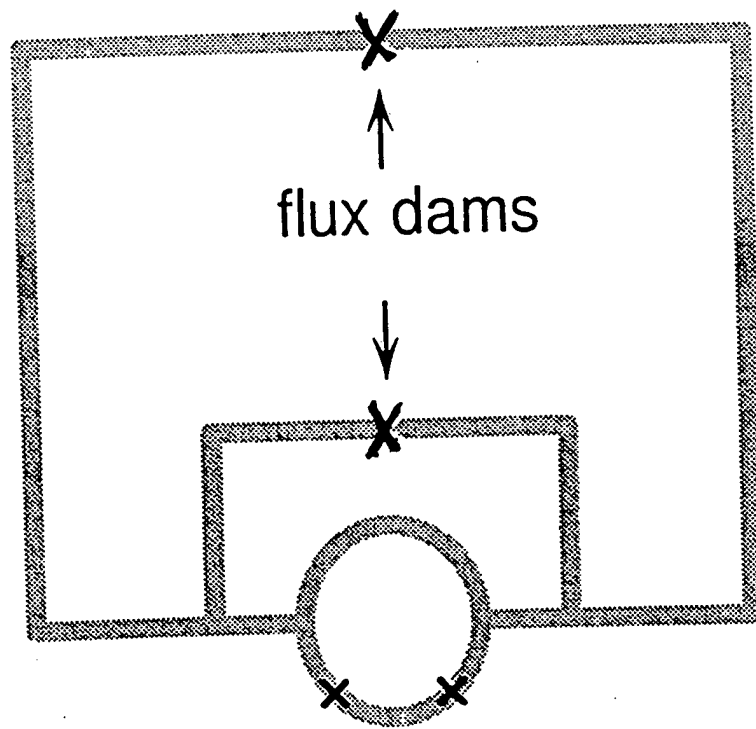
$$I_T^* \approx (J_c d w_p) \left[2.5 \left(\frac{J_0 / w_p^2}{10^6 J_c d} \right)^{1/4} \right]$$

$$B_T^* \approx 27 \mu\text{T}$$

SOLUTIONS TO I^* NOISE:

1) ω_p SMALL $\Rightarrow L_p$ BIG \Rightarrow POOR RESPONSE

2) ADD A SECOND LOOP:



"DUAL FLUXDAMS"

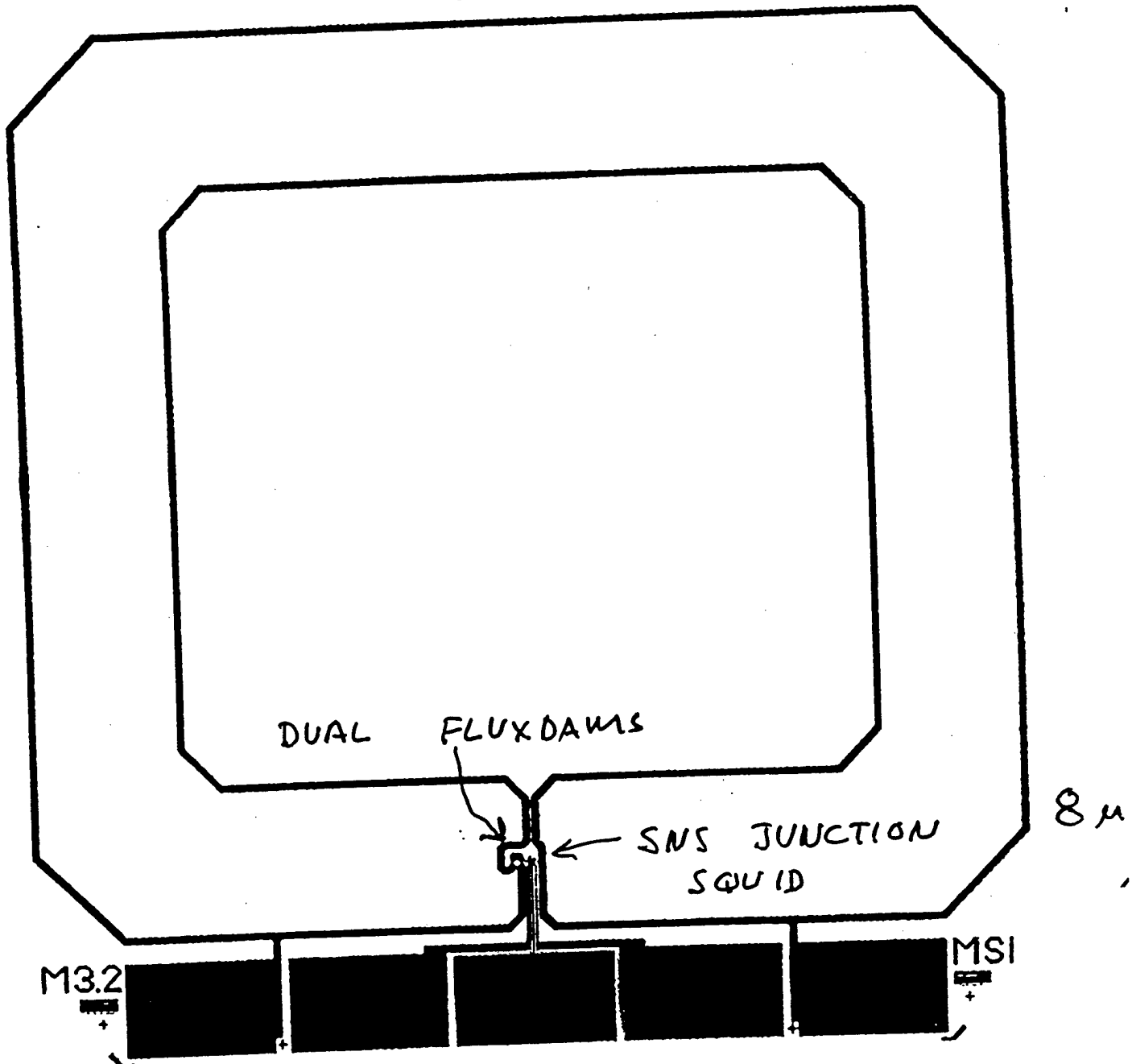
MAKE ω_p SMALL SO THAT:

$$I_{\text{FROM EARTH FIELD}}^* \ll I_T^*$$

TWO FLUXDAM SQUID MAGNETOMETER

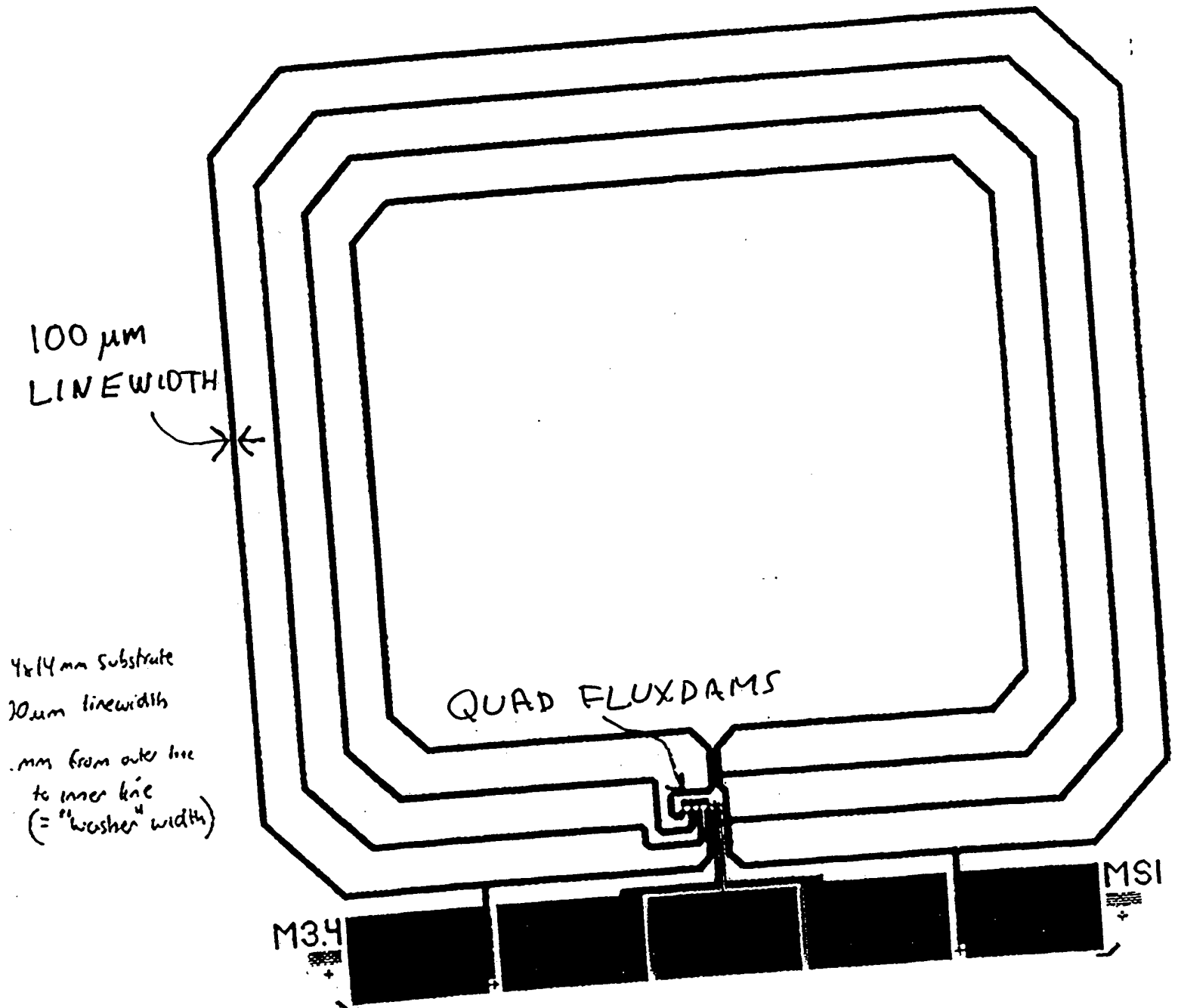
14x14 mm substrate
2 flux dams
100 um line width
2mm "washer" width

Lo: A10, SUBSTRATE
#30 / SQ

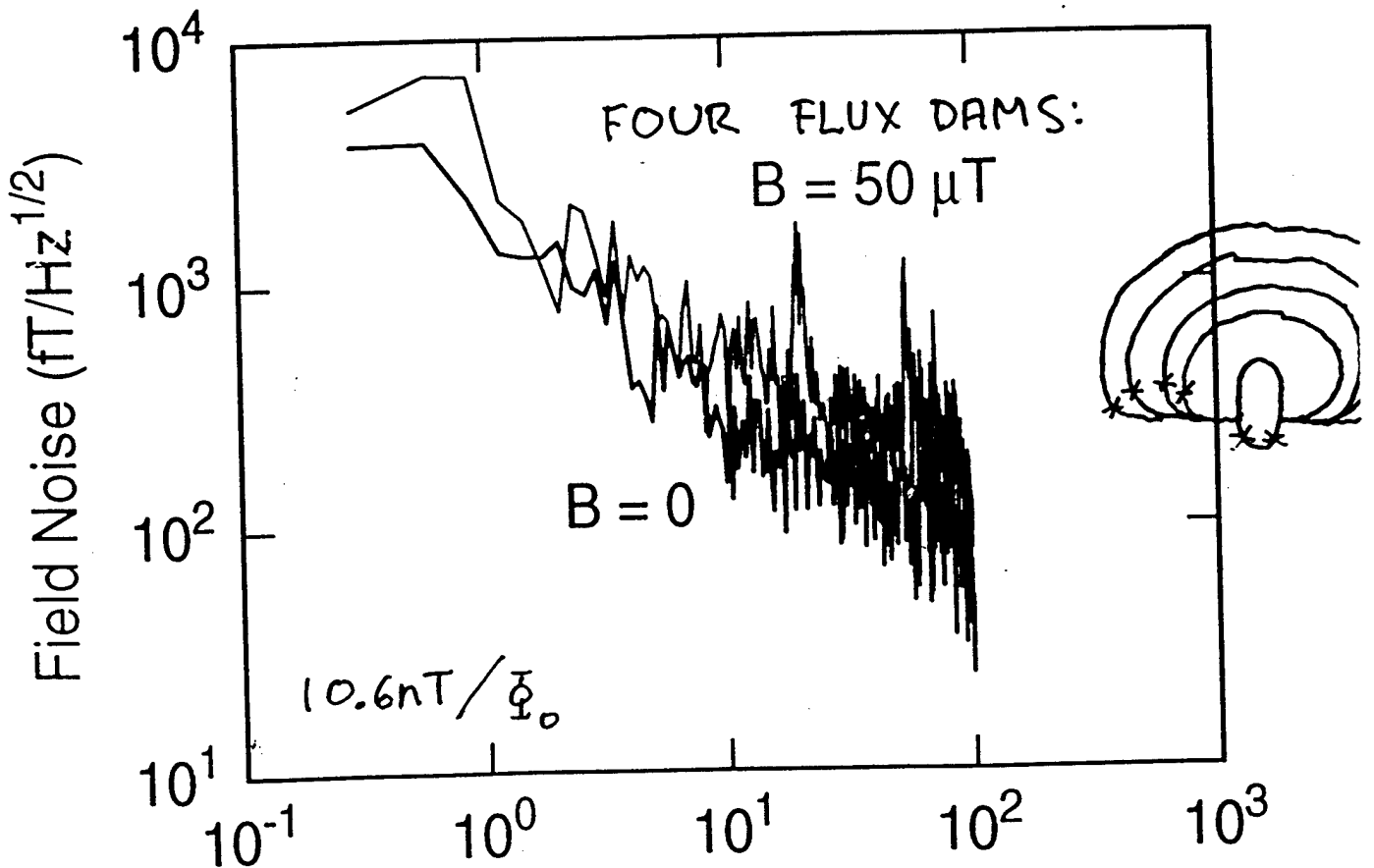
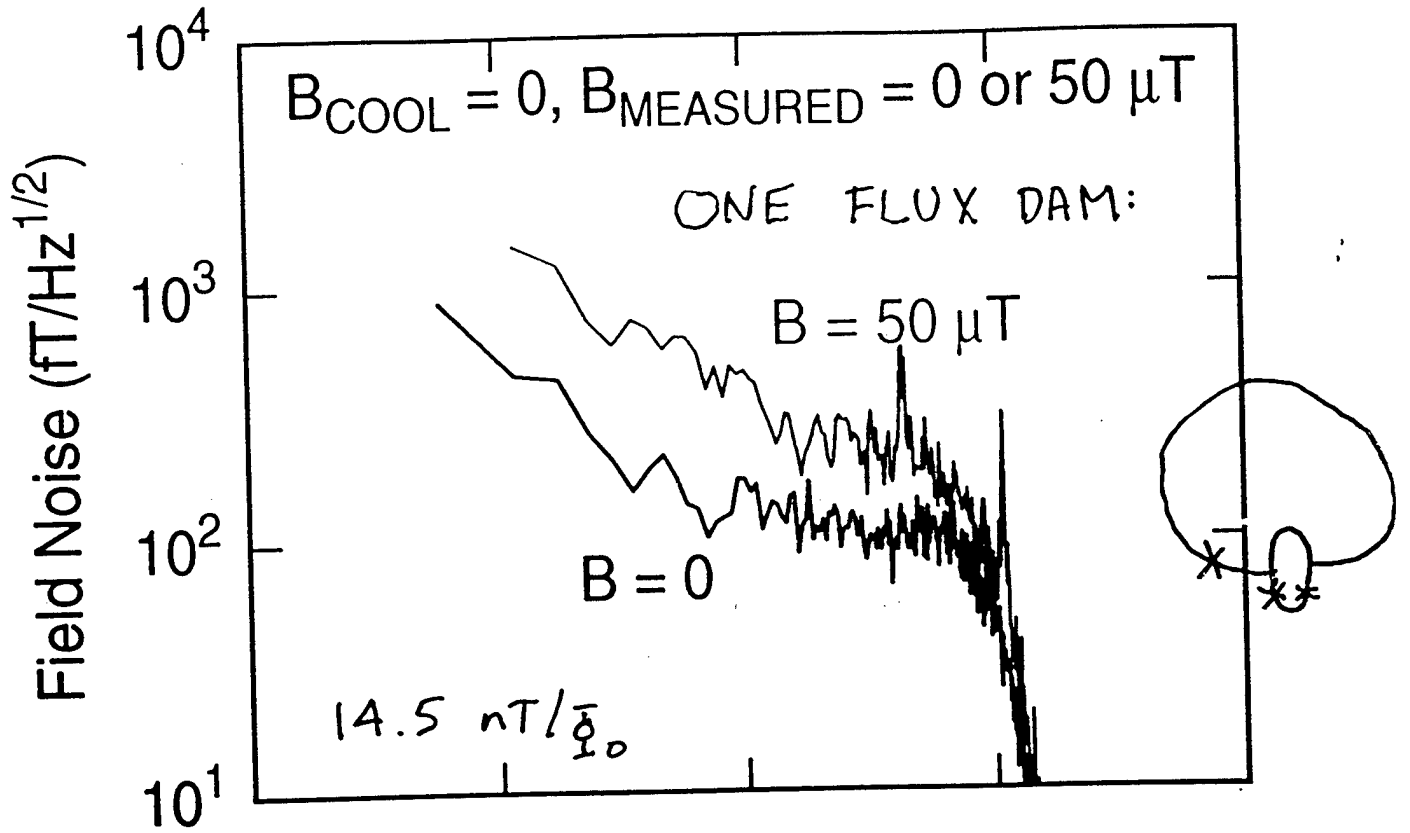


FABRICATED BY MAGNESENSORS (SAN DIEGO)
FOR IBM
WITH DAN LATHROP (QM)

FOUR FLUXDAM SQUID MAGNETOMETER



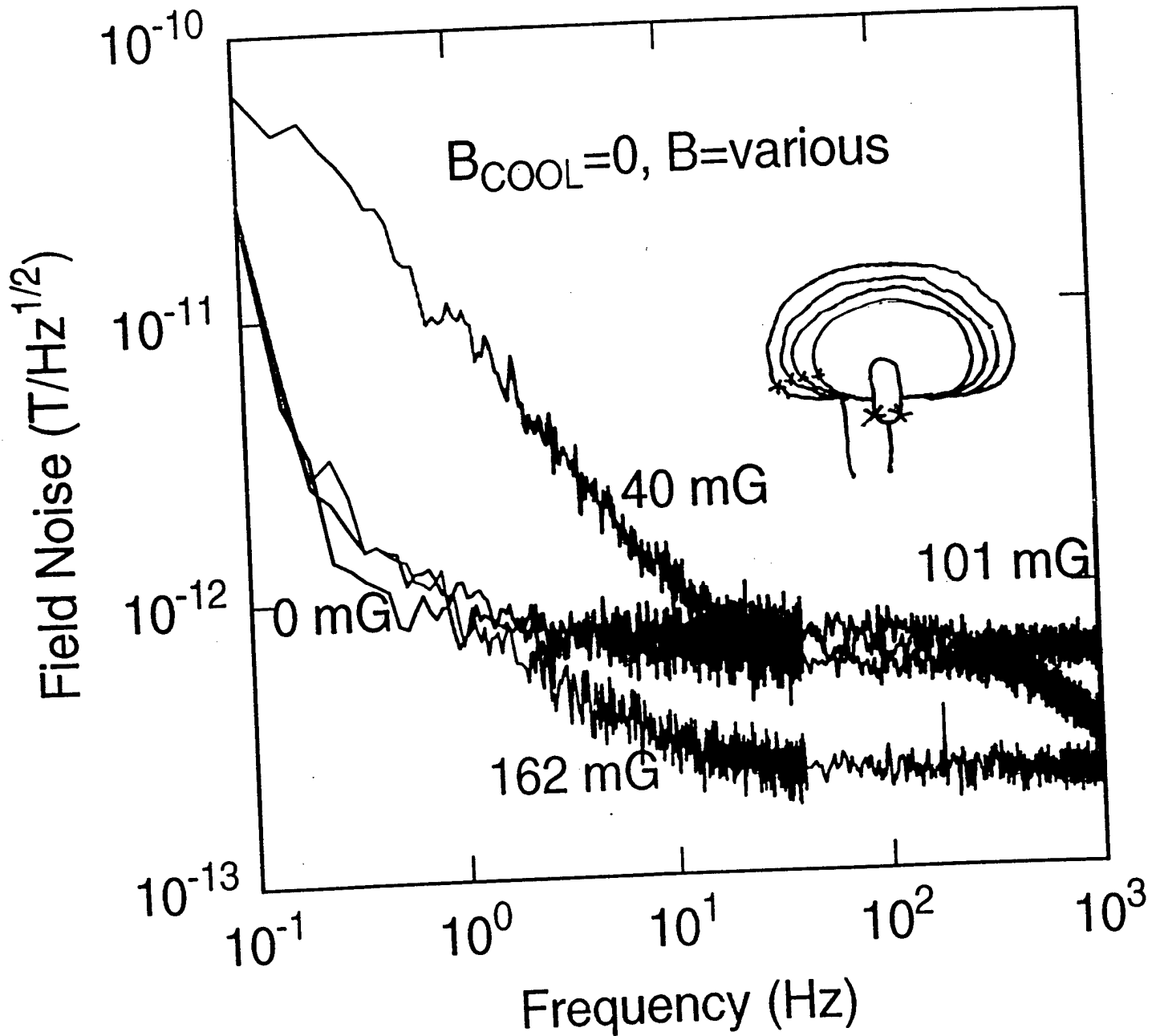
FABRICATED BY MAGNESENSORS (SAN DIEGO)
FOR IBM
WITH DAN LATHROP (QM)



ONE WIDE PICKUP
 LOOP $\Rightarrow 7 \text{ nT}/\bar{\Phi}_0$

Frequency (Hz)

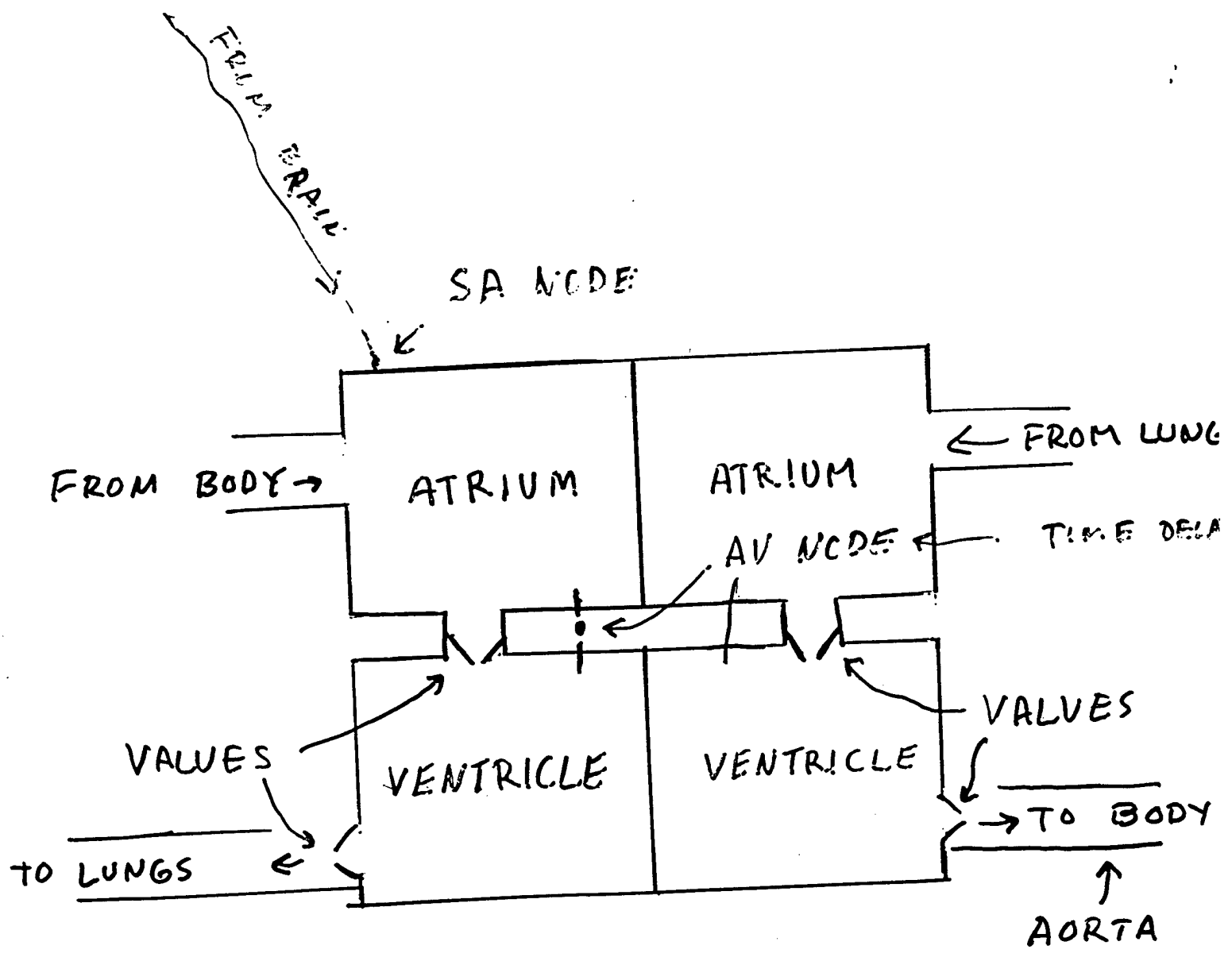
ANOTHER FOUR FLUX DAM SQUID:

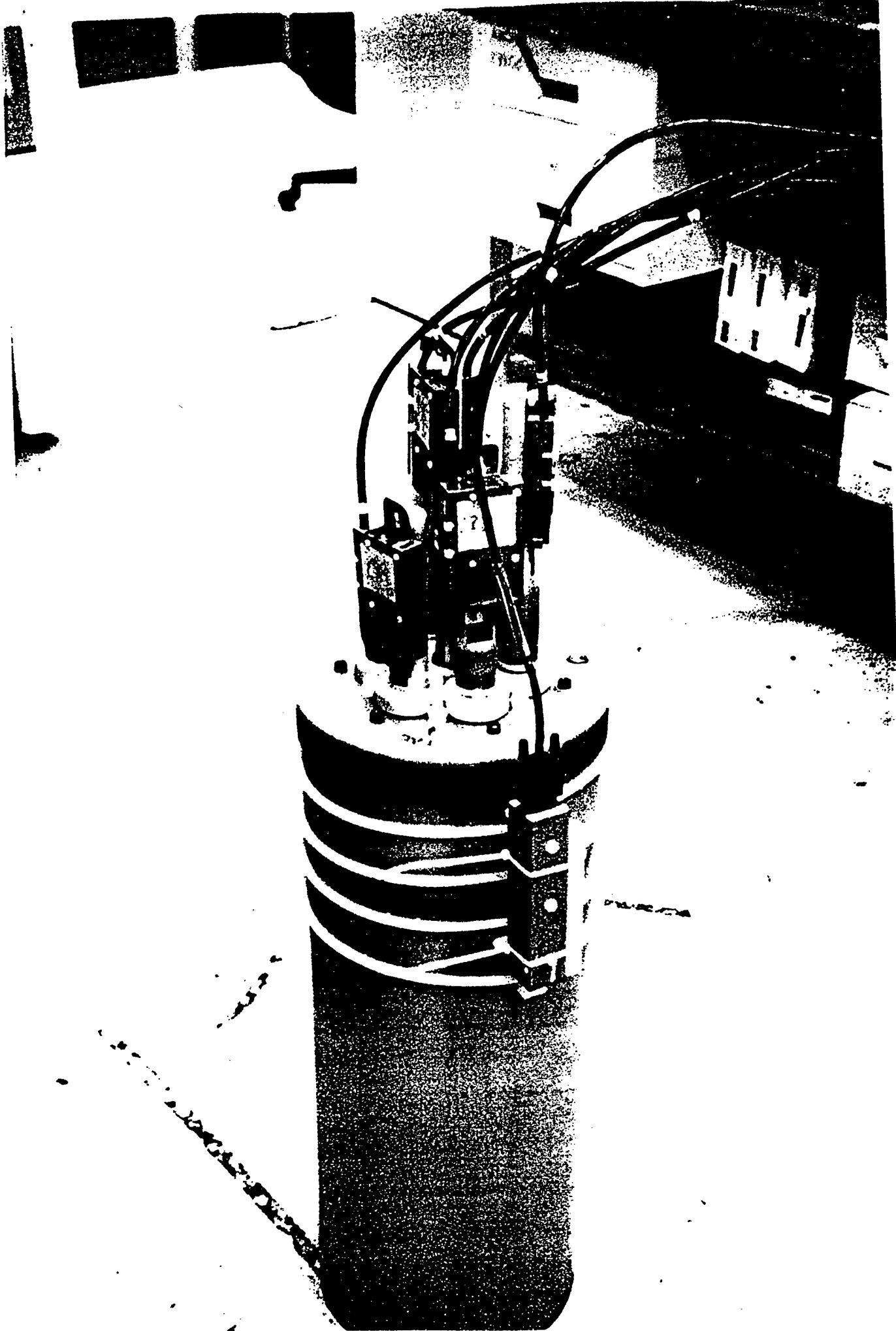


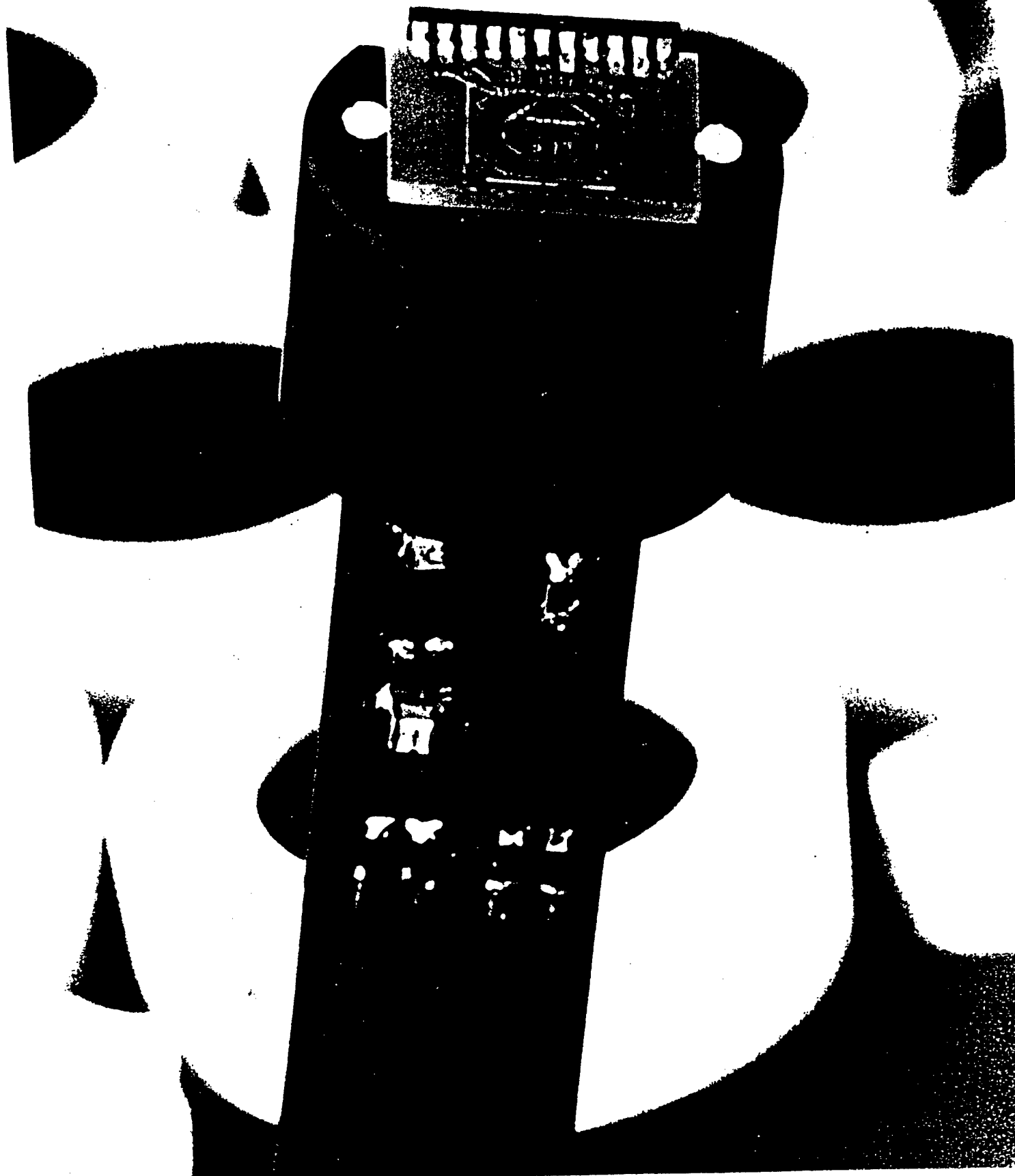
OPERATING WITHOUT BIAS REVERSING

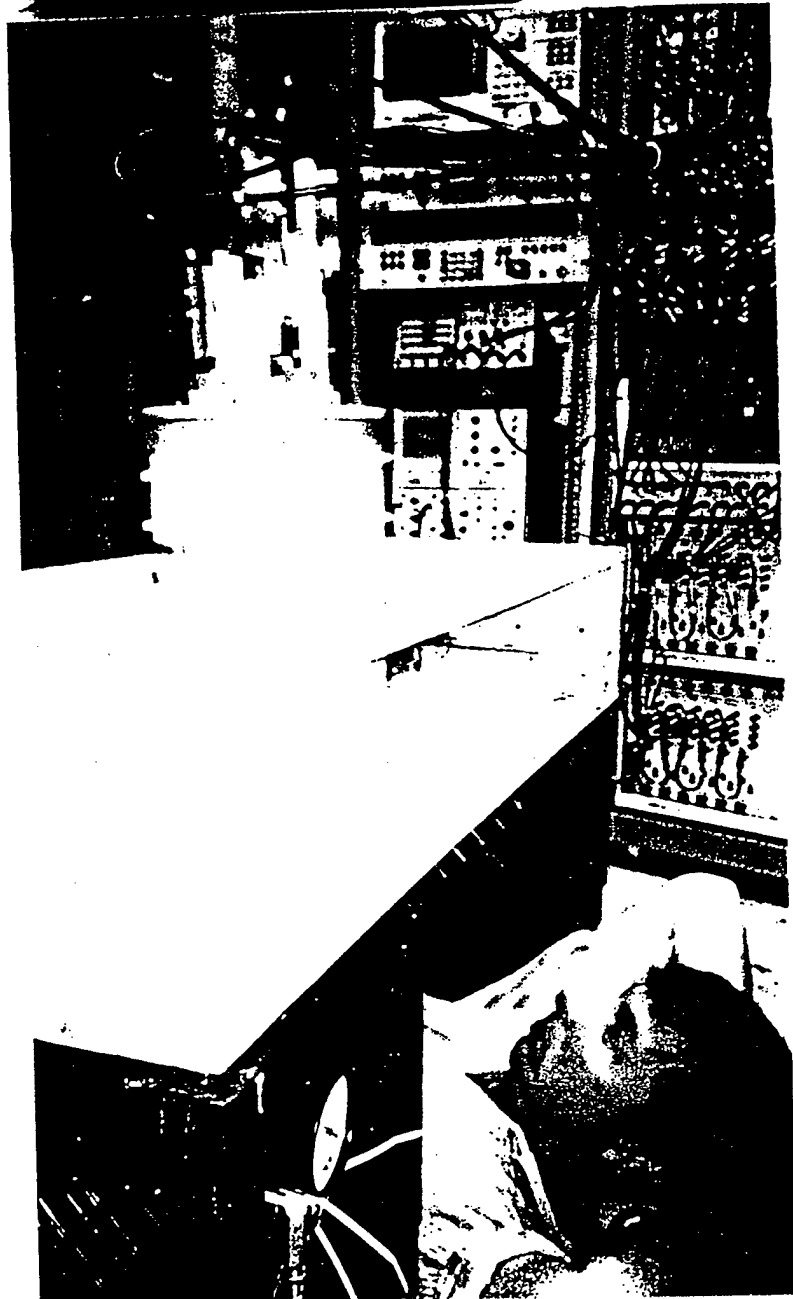
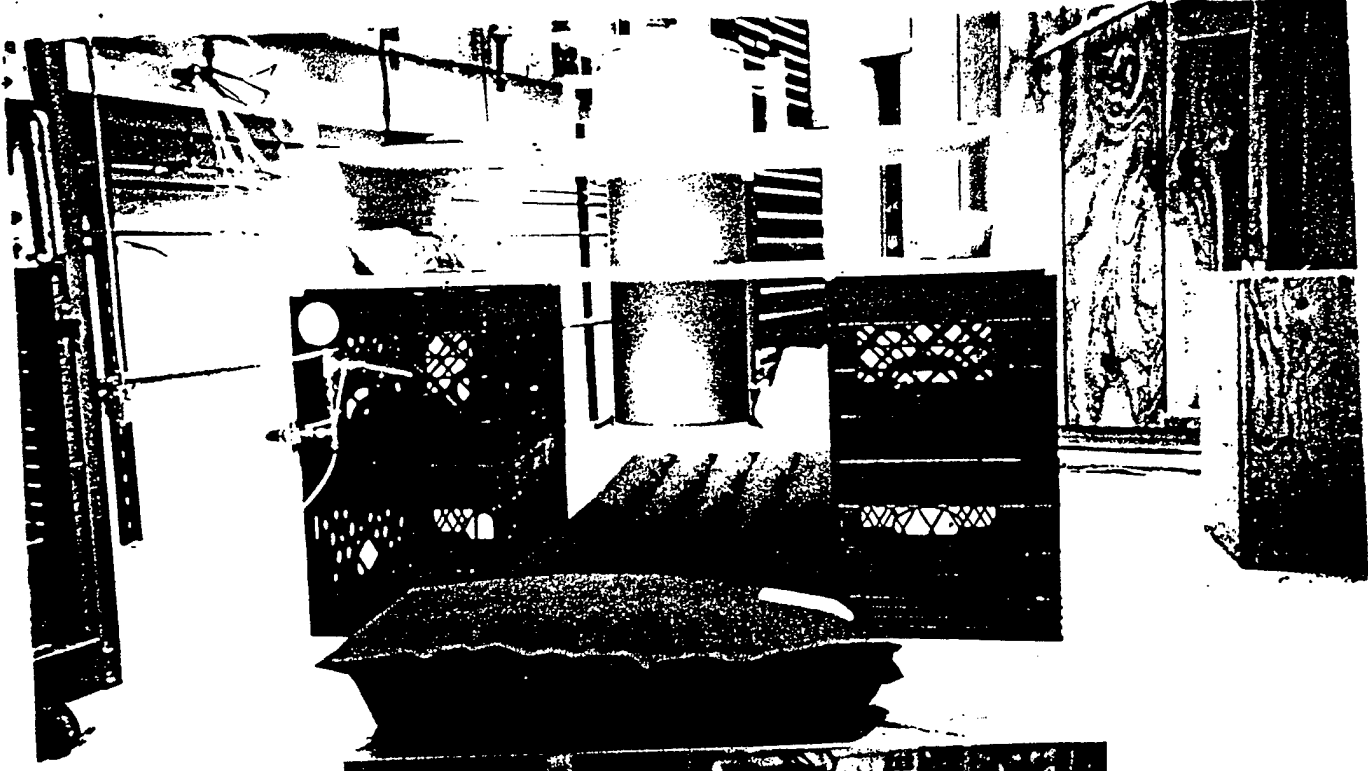
BIOMAGNETISM

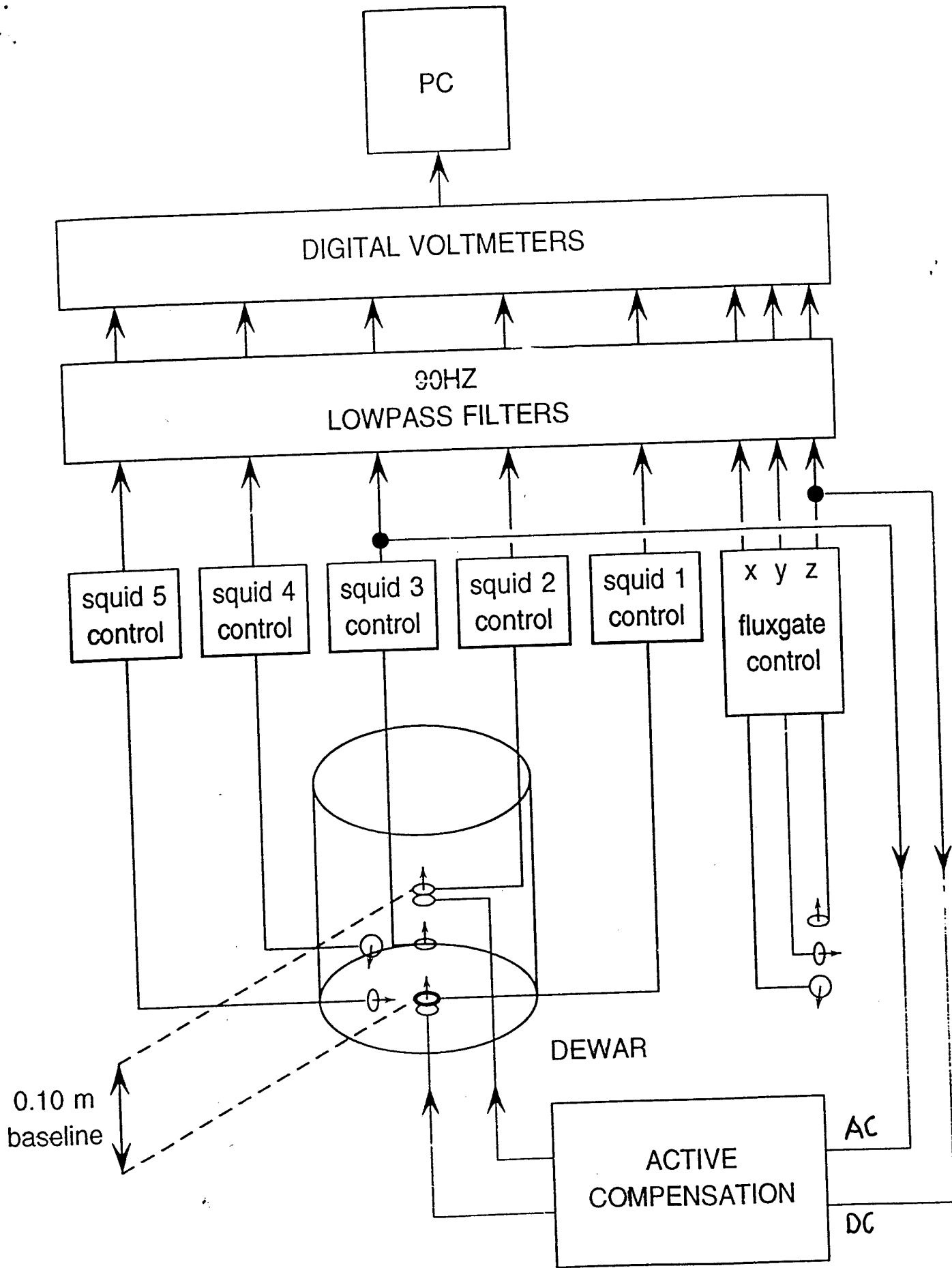
THE HEART AS A PUMP



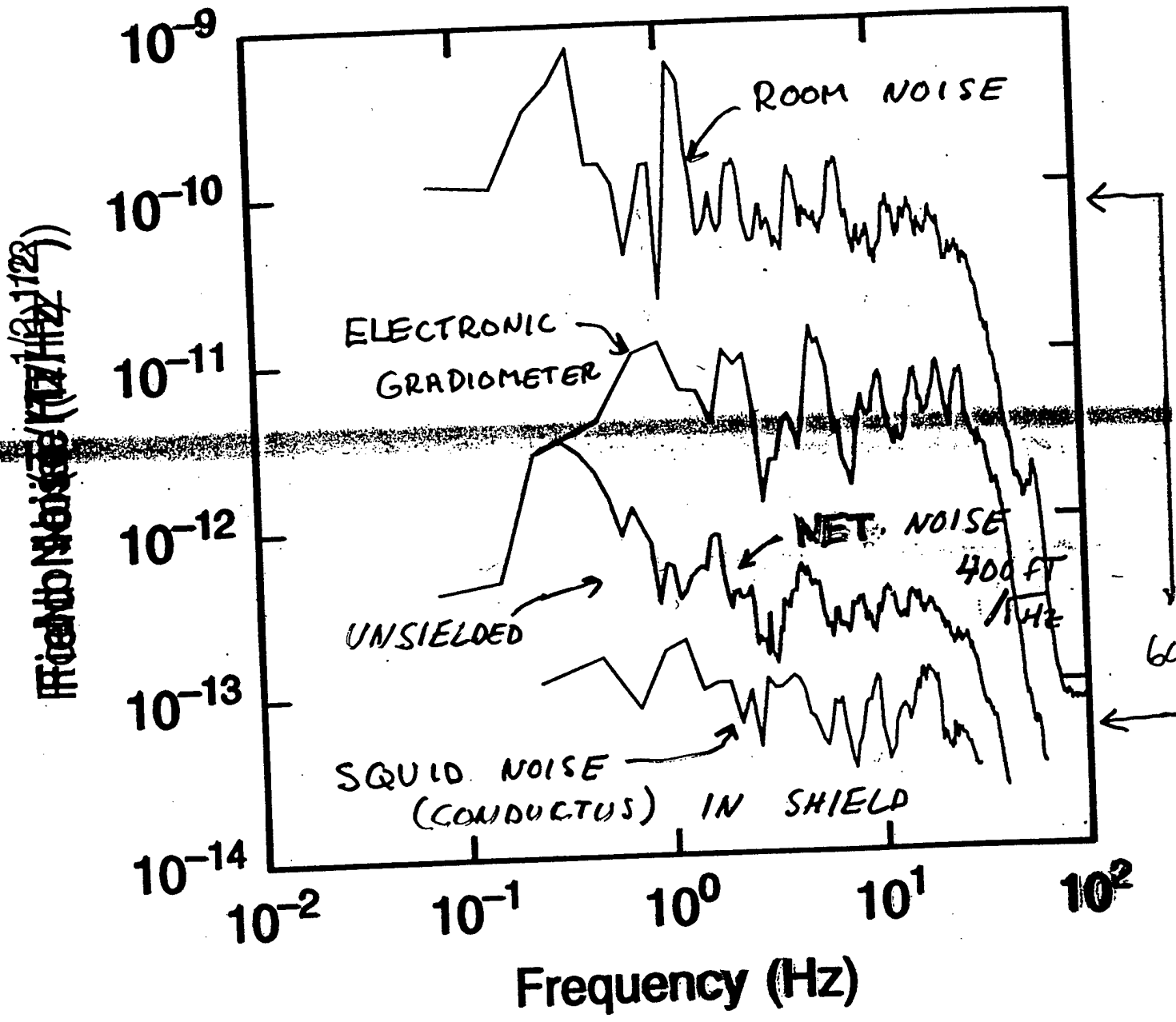


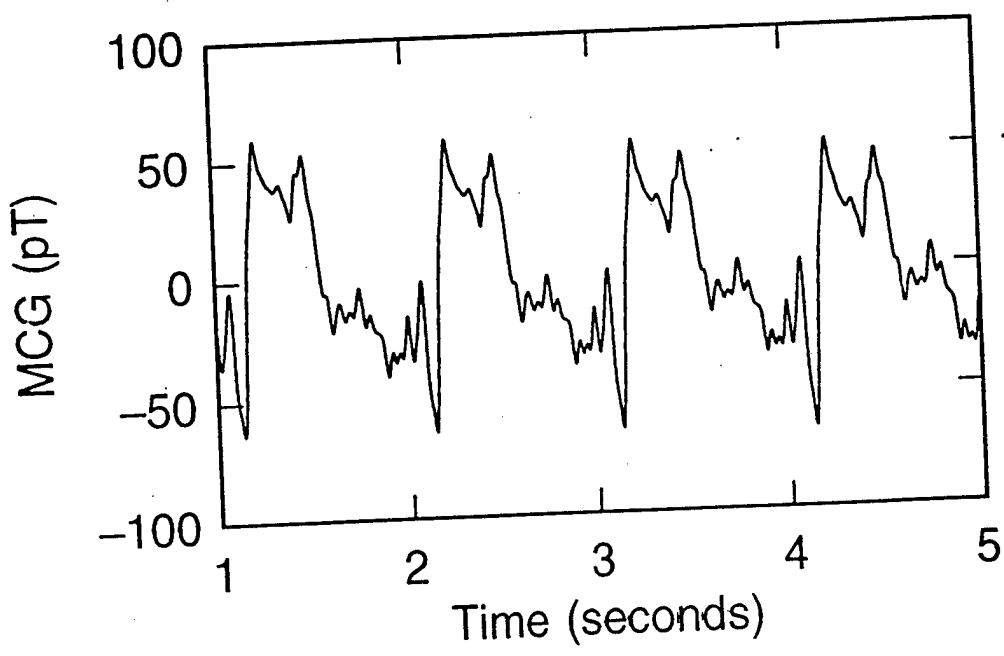






UNSHIELDED BIDMAGNETOMETER:





} TOTALLY UNSHELL

ECONOMIC ISSUES IN SQUIDERY:

Making (just) SQUIDs is a money losing operation today.

- Compare: Conductus (SQUIDs) with Billingsley Magnetics (fluxgates)
- SQUIDs are very high tech and hard to make
- SQUIDs are a "part"
- Most SQUID markets are too small to support the research that is needed to develop the SQUID part of the solution. (-> government money)
- Need cheaper SQUID technology

Making systems that use SQUIDs can make money.

- Look at Quantum Design, biomag companies, and IBM
- The SQUID is a key part but a minor cost item in most systems.
- Cost to enter a new market is far more than that of the SQUID sensors
- Risk is very high since products are new and different.
- There are just a few cases of market pull, usually its technology push.

SQUIDs (and superconductivity) have far more intellectual (and snob) appeal than other types of magnetic sensors, i.e. Fluxgates.

WHAT COULD CHANGE ALL THIS DOOM AND GLOOM?

(small scale) High-Tc needs to become a part of some major research and/or commercialization area (as defined by Dow Jones):

Electronics, computers, communications, and information

Aerospace and transportation

Biophysics, biochemistry, medical, and drug-related

Energy exploration, production, and distribution

Food

Entertainment

Investment, etc.

Defense

How to find a part in the mainstream?

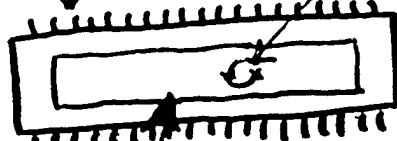
1. Invent a room temperature superconductor.
2. Pretend we did:

Work toward the goal of a micromachined silicon-chip-based refrigerator for high-Tc low-power applications. A small DIP with only electrical power inputs that can cool a high-Tc chip to 77K.

" SILICON MICROMACHINED REFRIGERATOR "

PLUG IN REPLACEMENT
FOR A ROOM-TEMPERATURE
PART

POWER IN:
~ 1 WATT



HIGH-T_c SUPERCONDUCTOR
OR FILTER
OR A/D CONVERTER
OR ...

COMPLETE SILICON-BASED
CLOSED-CYCLE 77°K
COOLER.

PRODUCTION
COST IS
LINKED TO
SILICON

RADIATION LOAD 77° ← 300°K 1x1 cm
~ 0.1 WATTS

CONDUCTION LOAD ~ 0.2 WATTS

Y. TAVRIN & M. SIEGEL

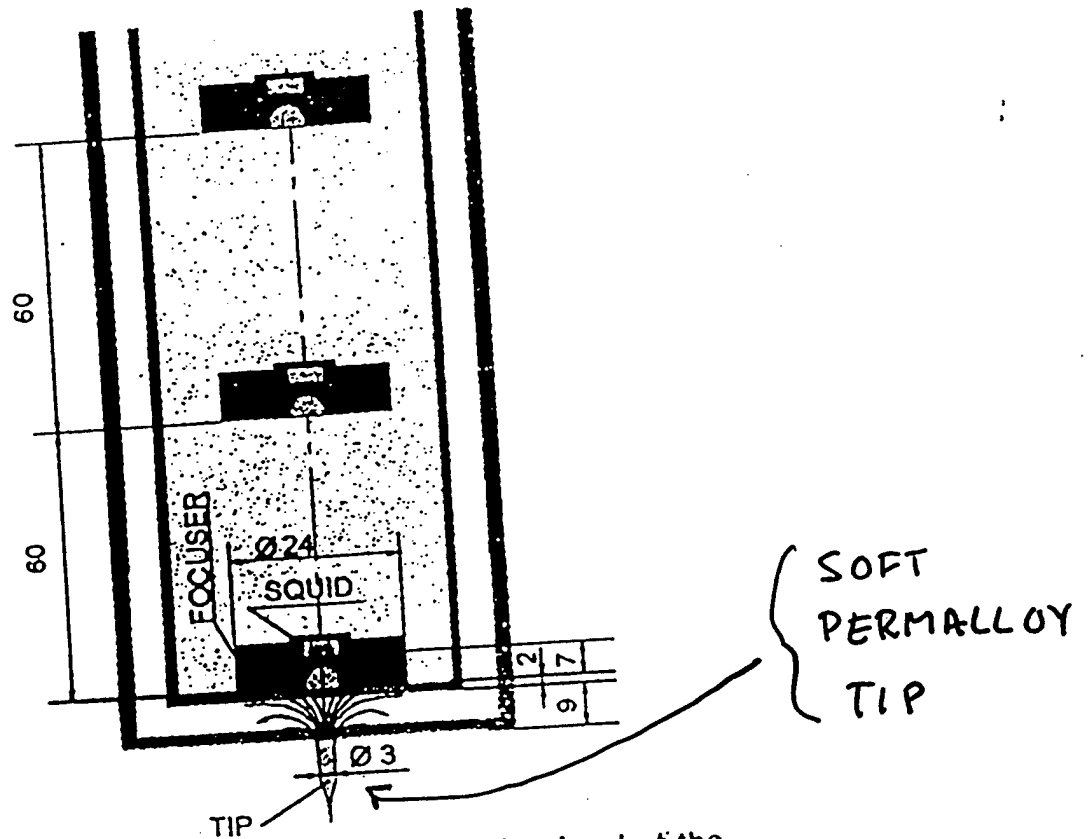
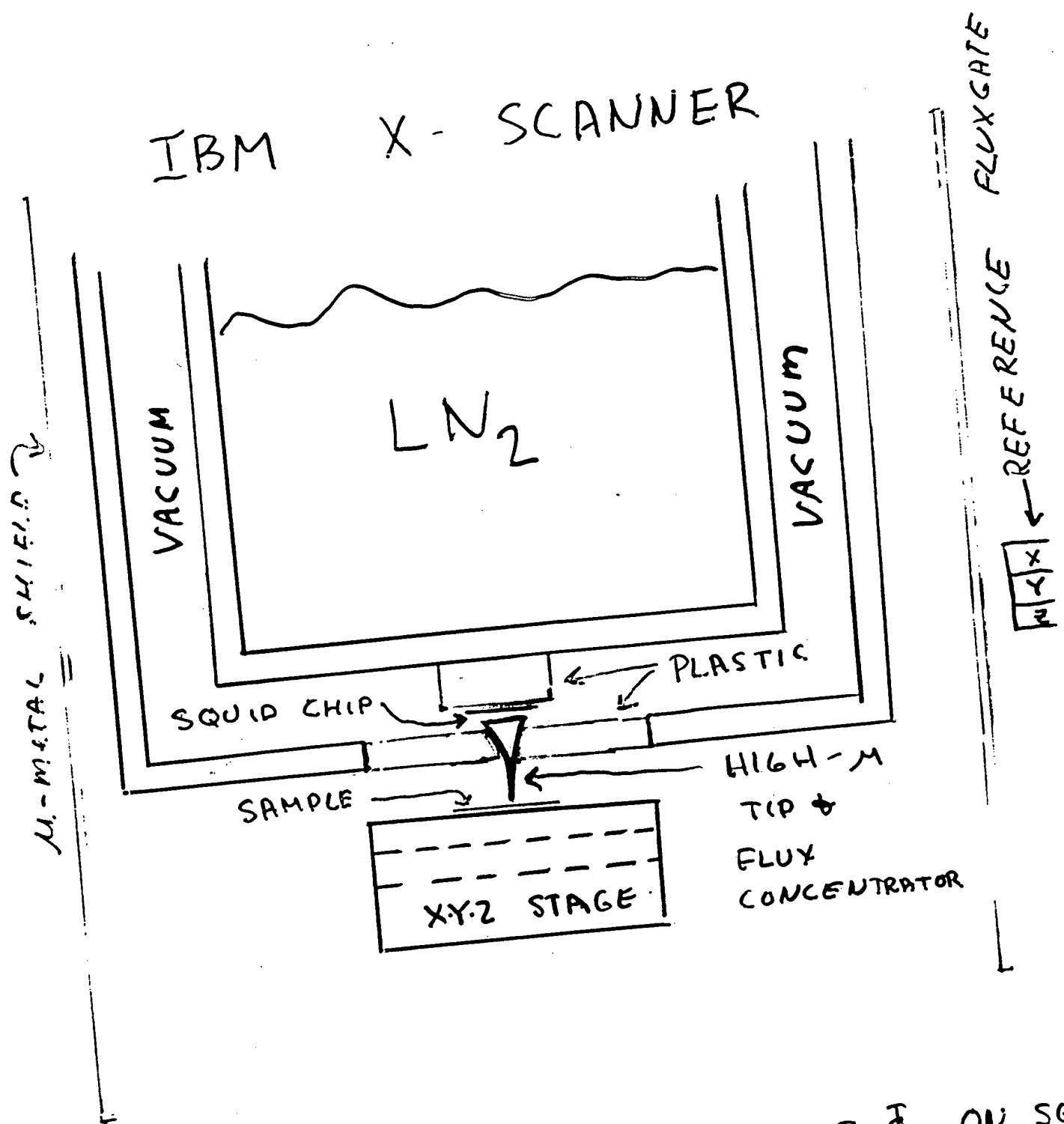


Fig. 1. Schematic view of the measuring head of the HTS SQUID microscope showing a cut of the cryostat containing the three SQUID sensors with flux focusers forming a second order gradiometer.

HTS SQUID · MICROSCOPE
WITH A FERROMAGNETIC FLUX FOCUSER.

IBM X-SCANNER



1 GAUSS ON SAMPLE \Rightarrow $0.002 \cdot I_0$ ON SQ

SPATIAL RESOLUTION:

EXISTING	$\sim 5 \mu m$	} TIP SIZE & SHAPE
POSSIBLE	$\sim 0.1 \mu m$	