DEVELOPMENT OF LASER INTERFEROMETER GRAVITY-WAVE DETECTORS, AND RELATED INVESTIGATIONS IN EXPERIMENTAL GRAVITY AND GRAVITATIONAL RADIATION

(R. W. P. DREVER)

(PAC 6 JAN 1997)

LIGO-G970018-00-R

TWO MAIN AREAS OUTLINED IN PROPOSAL

1) Extending Low Frequency Performance

- Coupled isolation systems
    - Coupled in position and tilt.
    - Use of magnetic levitation. ← LARGELY PASSIVE

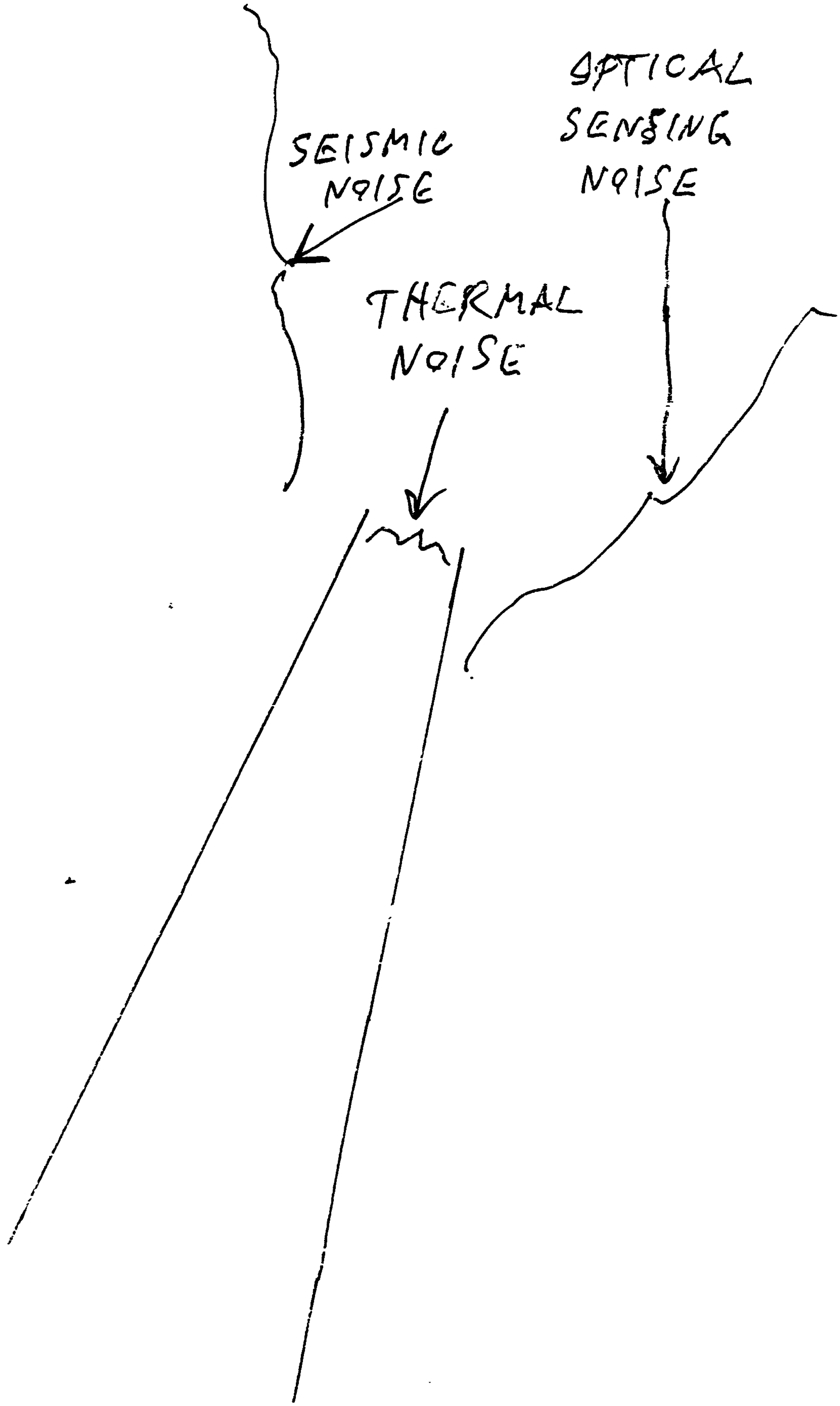
2) Extending High Frequency Performance

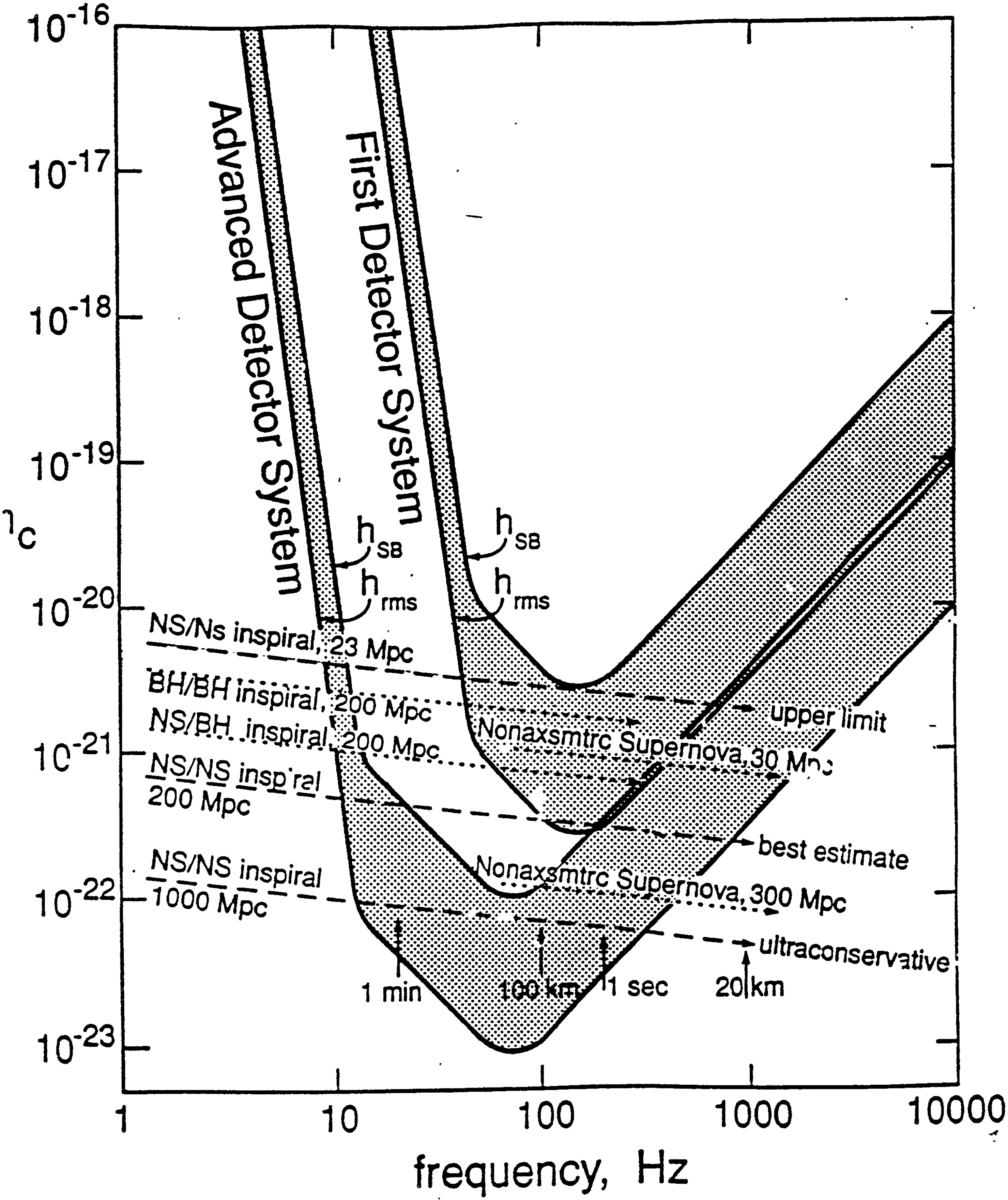
Use of diffractive optics – can allow higher light power –> reduce shot noise

- Reduces internal test mass thermal noise.

We concentrate on (1) initially, since in our situation this seems likely to give important results earlier.

THE MAIN SOURCES OF NOISE
WHICH LIMIT SENSITIVITY.





10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
h_c
Advanced Detector System
First Detector System
h_{SB}
h_{rms}
h_{SB}
h_{rms}
NS/Ns inspiral, 23 Mpc
BH/BH inspiral, 200 Mpc
NS/BH inspiral, 200 Mpc
NS/NS inspiral
200 Mpc
NS/NS inspiral
1000 Mpc
upper limit
Nonaxsmtrc Supernova, 30 Mpc
best estimate
Nonaxsmtrc Supernova, 300 Mpc
ultraconservative
1 min
100 km
1 sec
20 km
1
10
100
1000
10000
frequency, Hz

T4

PAC2

STANDARD SEISMIC ISOLATION – SPRING-MASS STAGES OF LOWEST CONVENIENT RESONANT FREQUENCY

ADVANTAGES of Using Magnetic Fields Instead of Metal or Rubber "Springs":

a) Avoid high-frequency paths through springs, etc.

b) Low resonant frequency obtainable in passive systems.

(Servo is only a stabilizer.)

c) Relatively simple – essentially passive.

d) Easy damping by eddy currents.

e) High vacuum compatible.

OBVIOUS DISADVANTAGES

a) Superconductors require reduced temp – inconvenient.

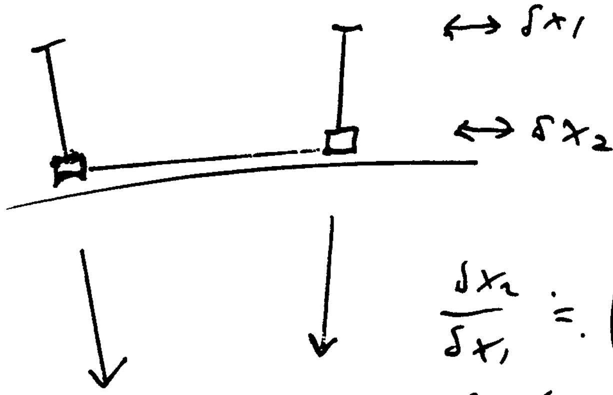
Plan to avoid them.

b) Permanent magnets unstable alone (Earnshaw's theorem).

- But can make stable by servo sytem

c) Must avoid response to outside field noise.

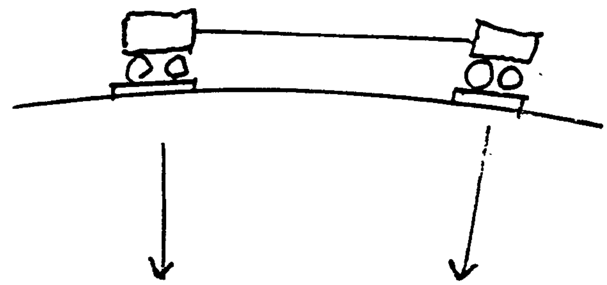
PENDULUM



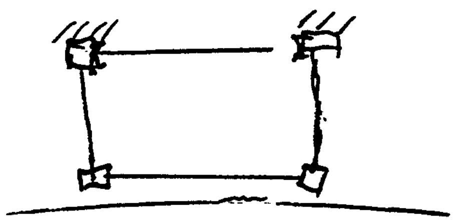
$$\frac{\delta x_2}{\delta x_1} \doteq \left(\frac{f_0}{f}\right)^2$$

for $f >> f_0$.

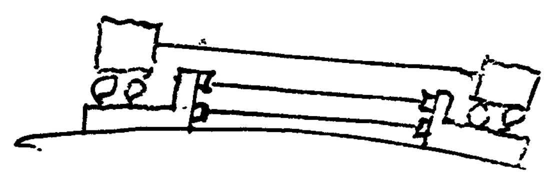
LONG-PERIOD WEIGHTLESS, FRICTIONLESS WHEELS



MONITOR SUSPENSION POINTS



MONITOR RELATIVE TILTS



ALMOST ANY PASSIVE LONG-PERIOD SUSPENSION IS EQUIVALENT TO THIS.

(INCLUDES GATE-TYPE SUSPENSION, X-PENDULUM, MAGNETIC SYSTEMS TO BE DESCRIBED)

MAGNETIC SUSPENSIONS PROPOSED CAN GIVE PRACTICAL WAY TO IMPLEMENT THIS.

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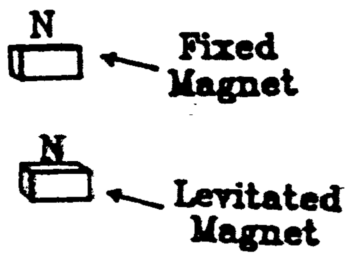
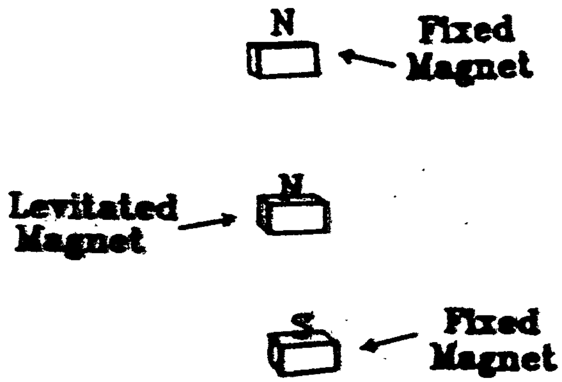
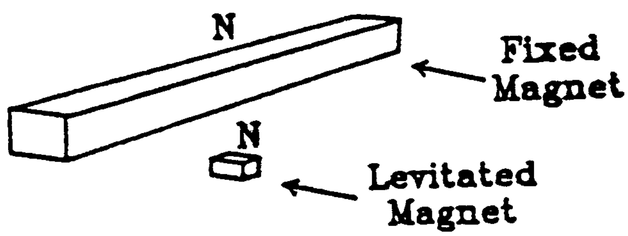
SOME MAGNET ARRANGEMENTS PROPOSED



(A) SIMPLE



(B) LONGER PERIODS THAN (A).
TRANSLATION-ROTATION COUPLING CAN GIVE INSTABILITY.



(C) INHERENT LONG PERIODS IN ONE DIRECTION.

ONE STAGE FOR A SEISMIC ISOLATION SYSTEM.

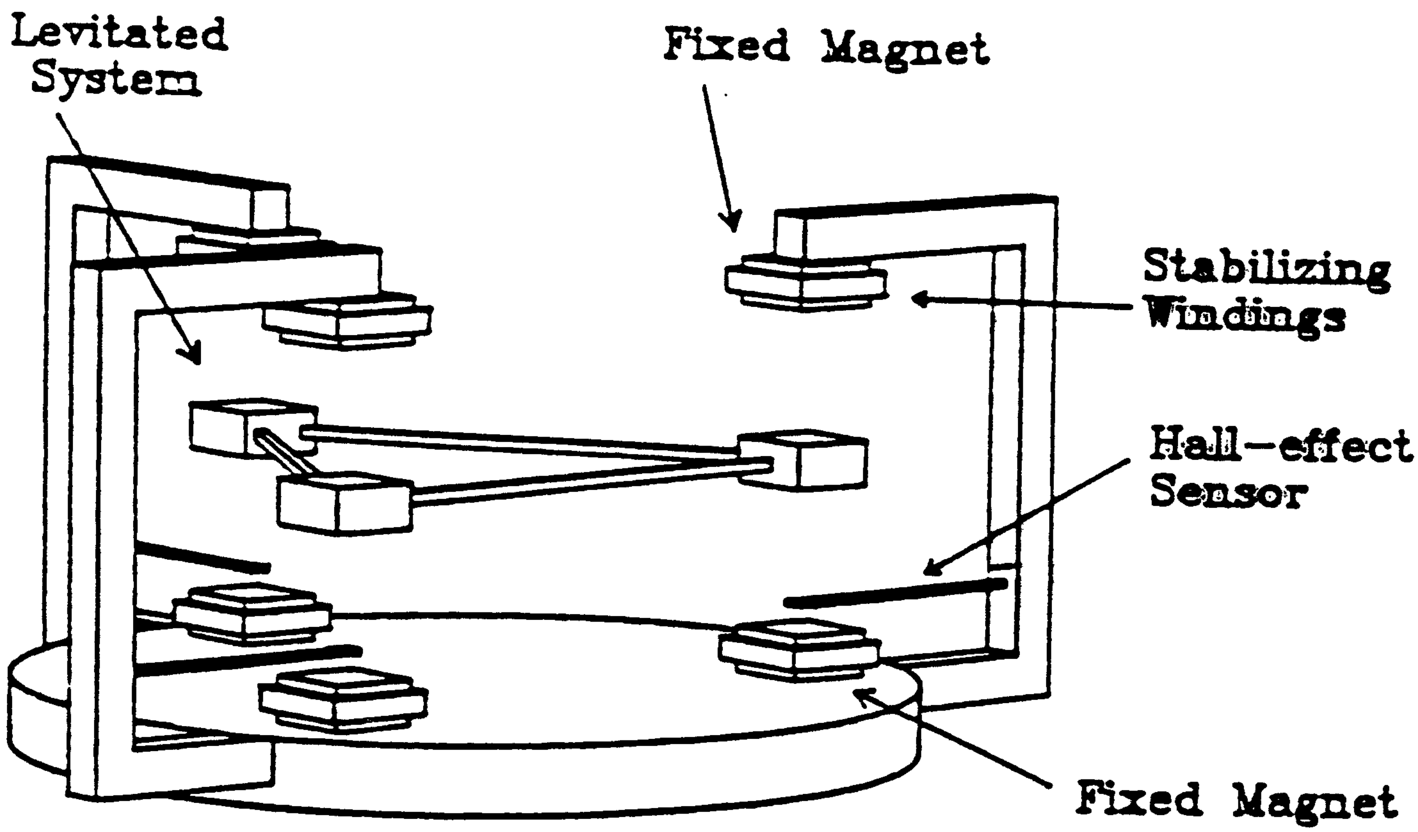


Fig. 8.

SMALL TEST SYSTEM :-

PAYLOAD 1 Kg

NATURAL PERIODS ;- HORIZONTAL 2 — 4 SEC.

VERTICAL 0.5 SEC.

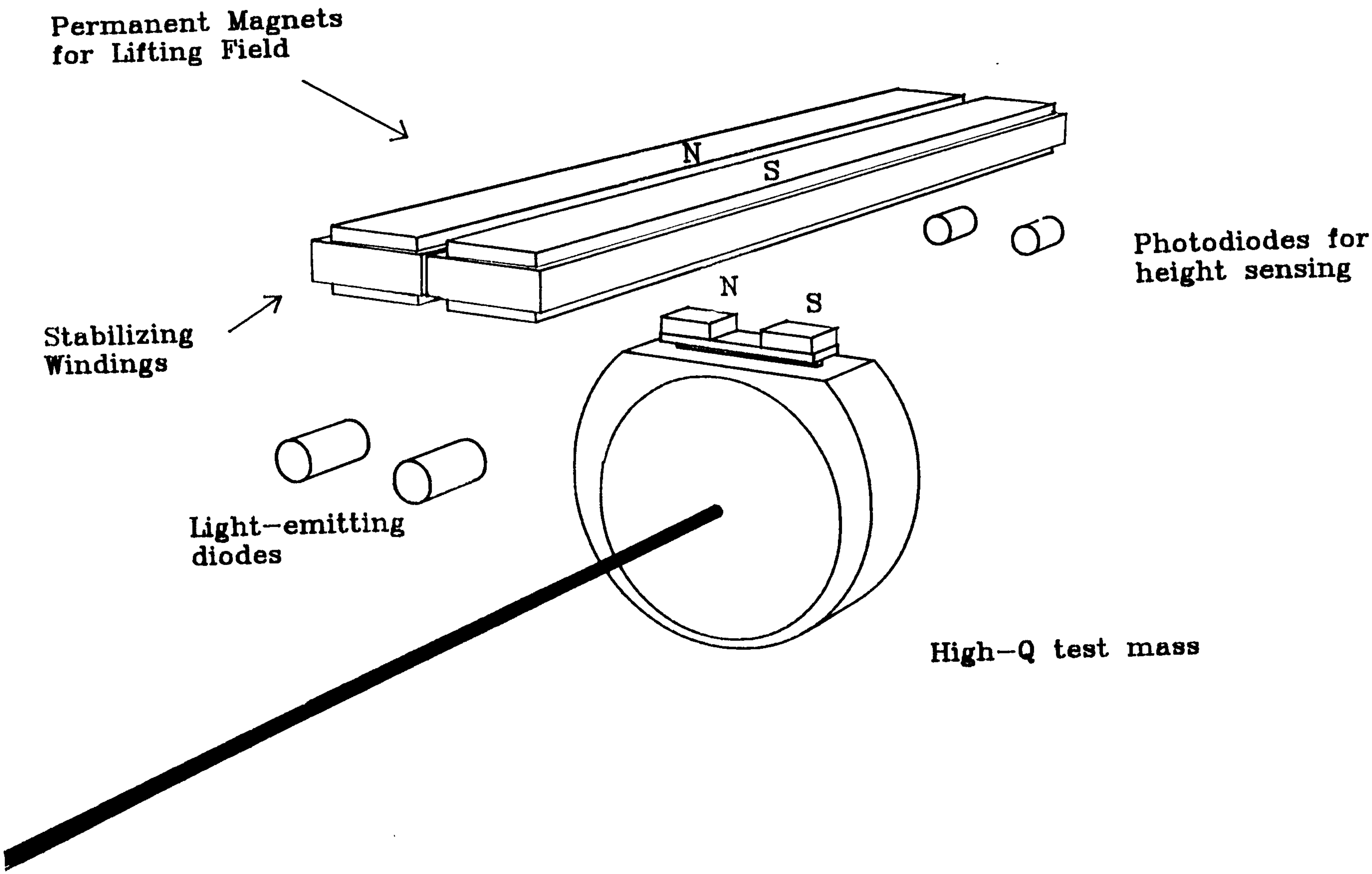
(CAN BE MADE LONGER BY TRIMMING FIELDS AND SERVO RESPONSE)

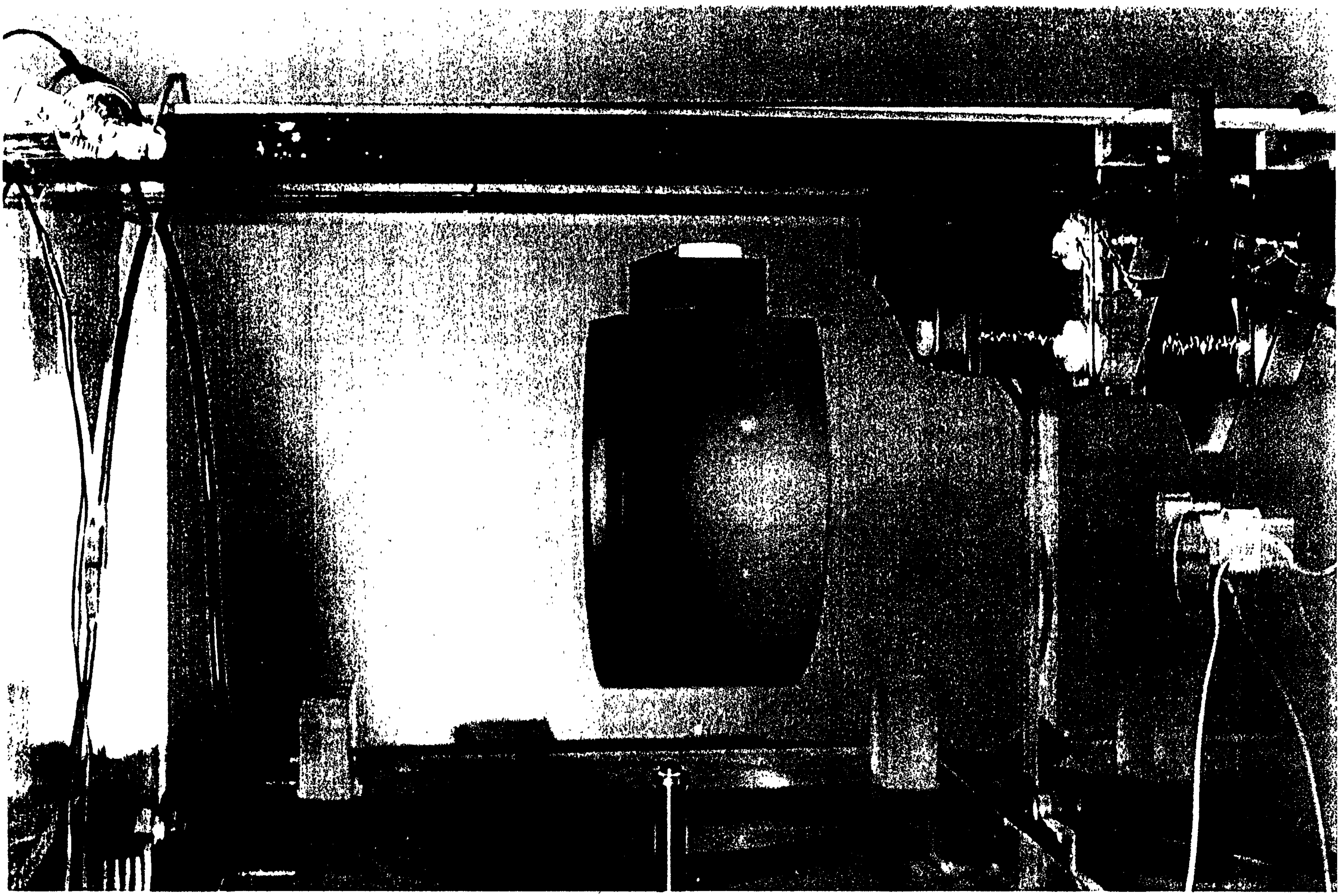
BUILT AND TESTED BY S. AUGST.

PAGE

Magnetically Levitated Test Mass

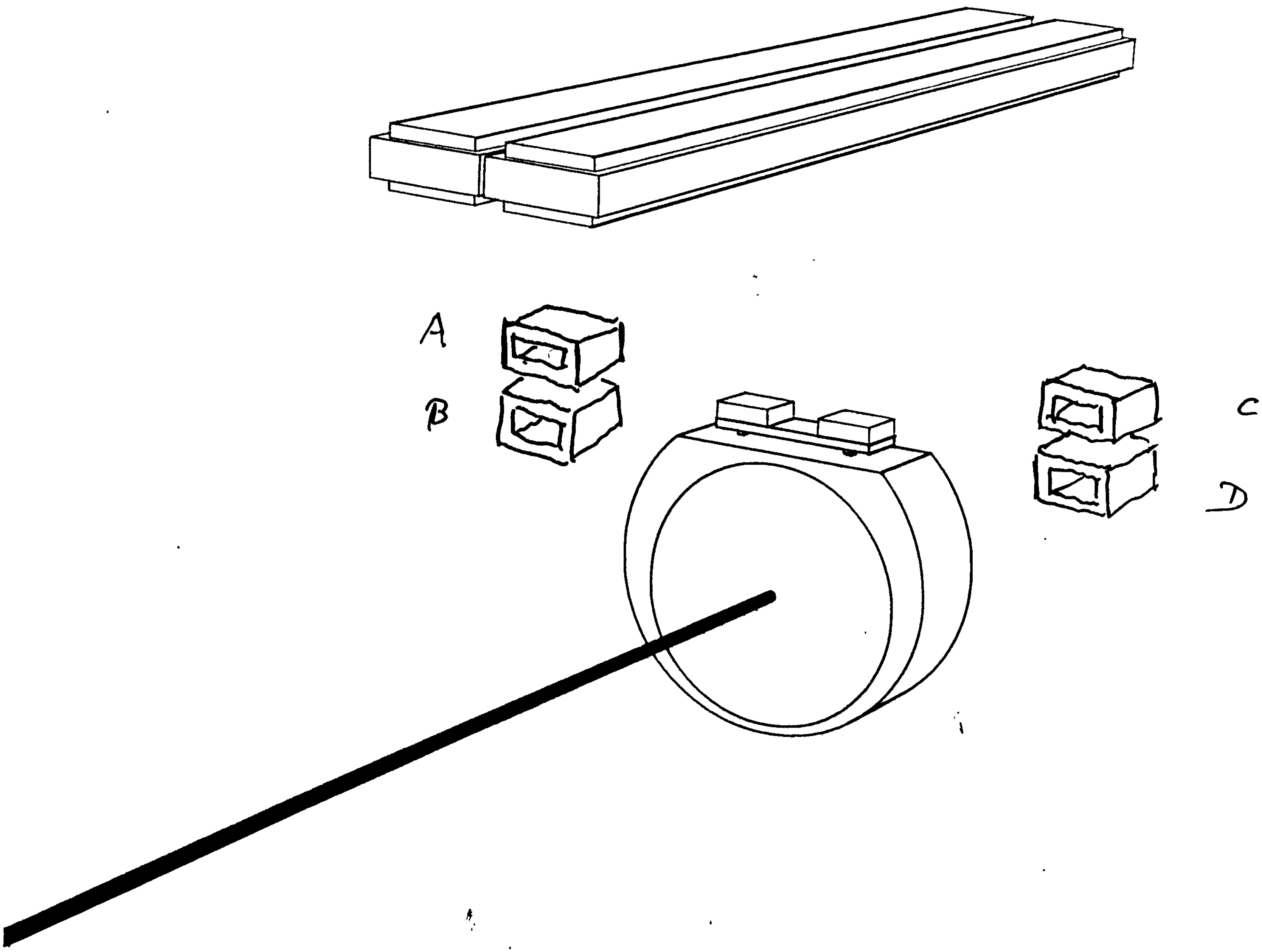
"QUADRUPOLE" VERSION – 2 MAGNETS ON MASS



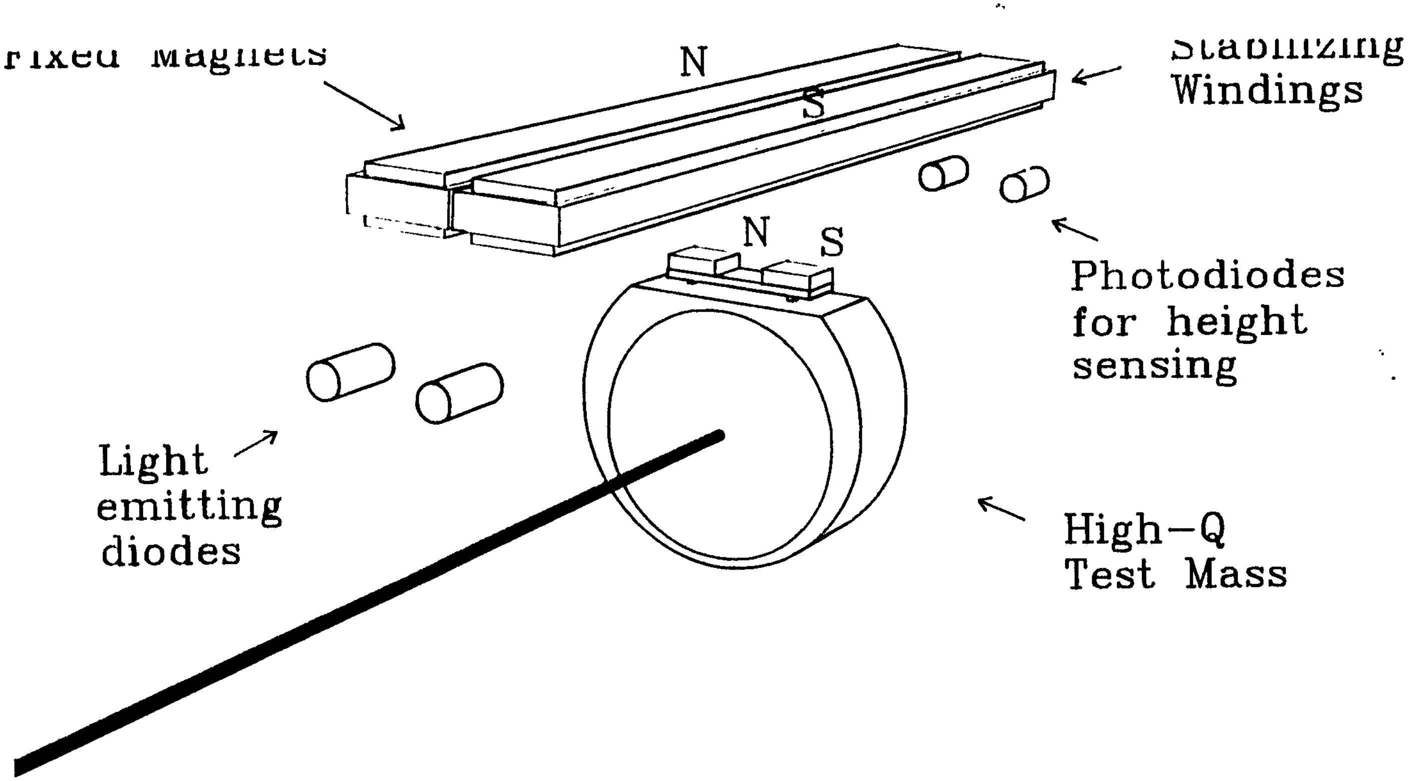


~ PAc 8

TEST MASS LEVITATION SYSTEM :— FINE CONTROL OF MIRROR ROTATION, TILT, AND LONGITUDINAL POSITION, BY AUXILIARY COILS A, B, C, D.



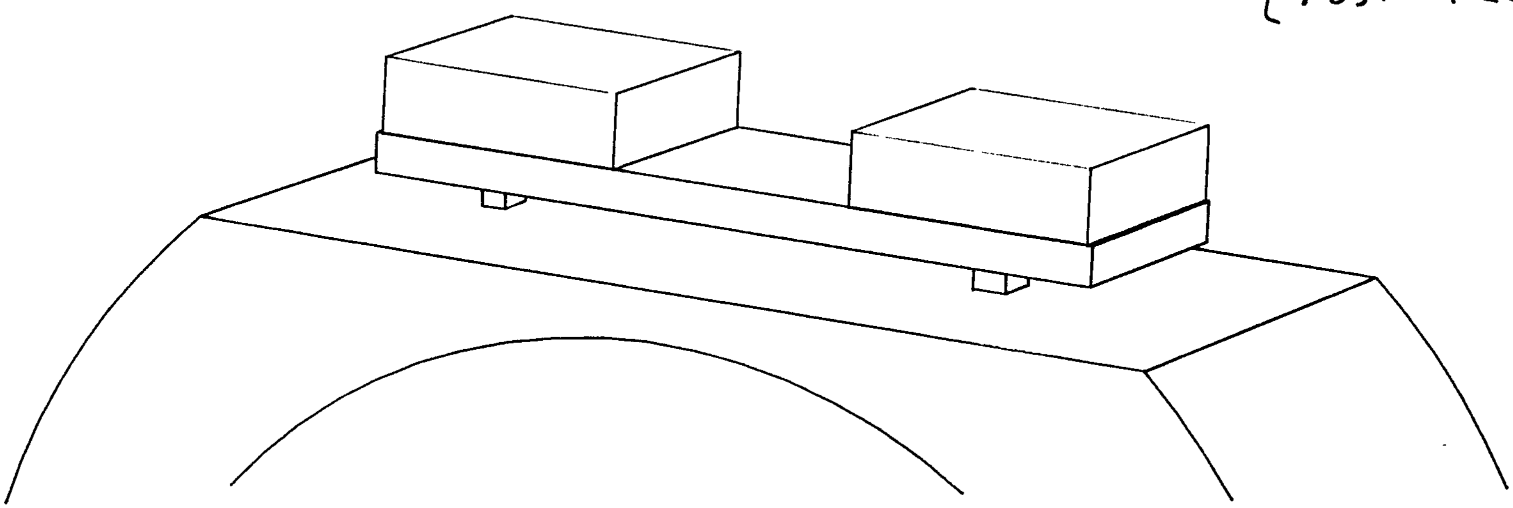
PAC 9



PAC 10

Enlarged view of top of Test Mass

(POST FLEXURE VERSION)



(15)

EXPERIMENTAL FINDINGS

with 1-magnet and 2-magnet versions test mass systems

1) Natural period depends on non-uniformity of support magnet(s).

   Typical period   8 seconds –> 12 seconds

   with simple trim   –> 20 seconds

2) Relaxation Time (Horizontal mode)

   Typical in range 8 to 18 hours

   (under investigation – preliminary only)

   Typically longer with insulating magnets on mass (ceramic) than conducting (rare-earth) (by factor <2).

3) Stabilizing Power   << 1 mw

   Typical ~50 microwatts

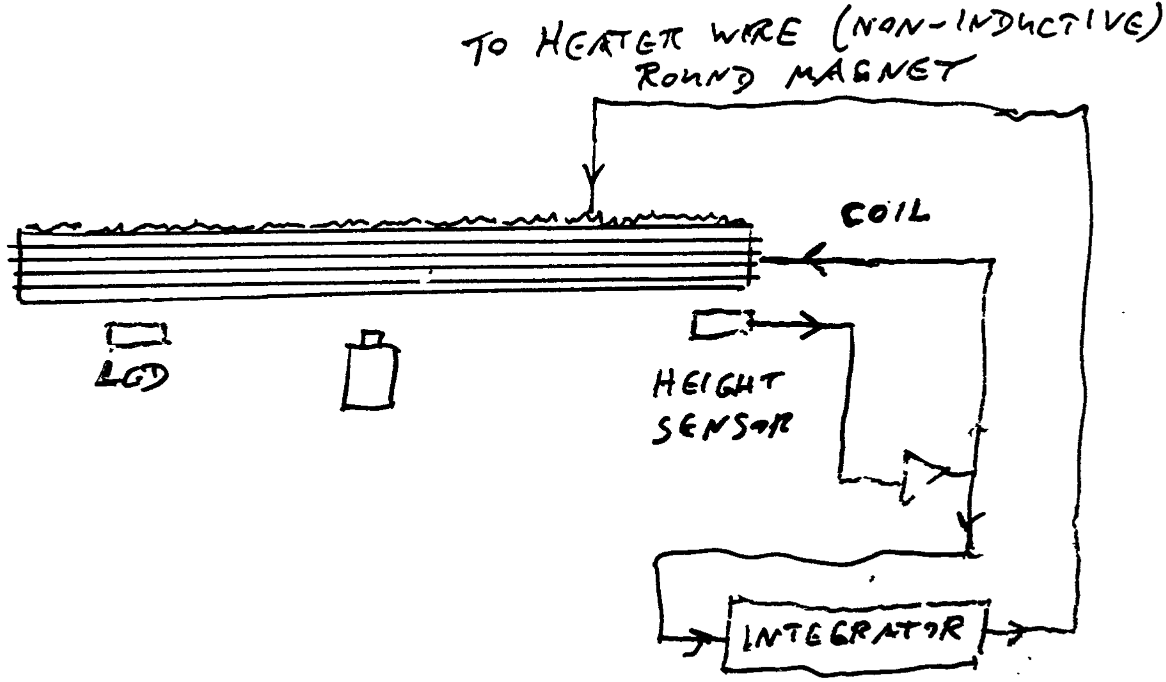
4) Permanent magnets have temp coefficient.

   Equilibrium height function of room temperature.

   Now using servo to control field via temperature.

5) Thermal Noise Plans

CONTROL OF MAGNETIC FIELD
VIA MAGNET TEMPERATURE.

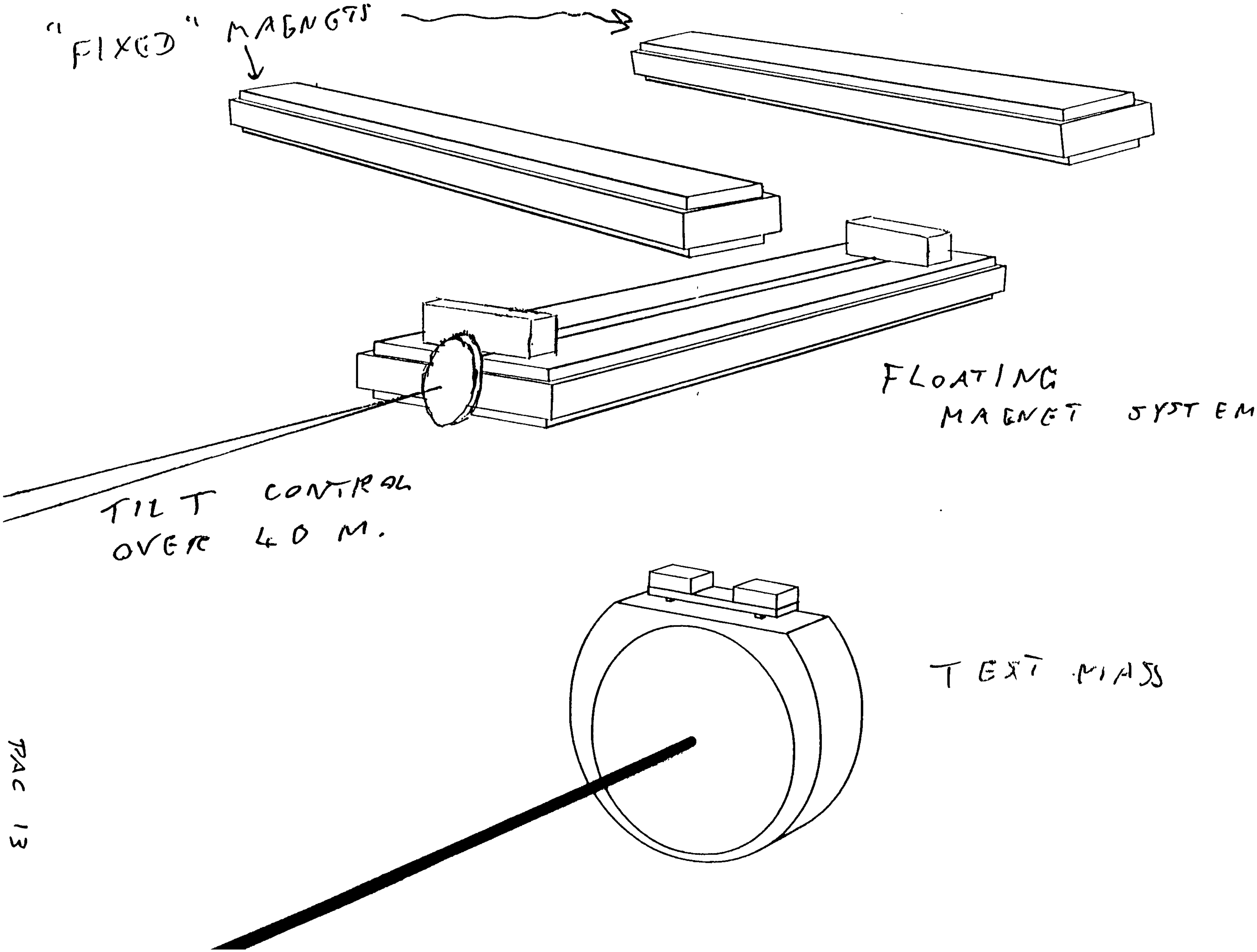


(INTEGRATE COIL VOLTAGE OVER MINUTES → TO DRIVE MEAN VALUE TO ZERO)

2 EFFECTS:-

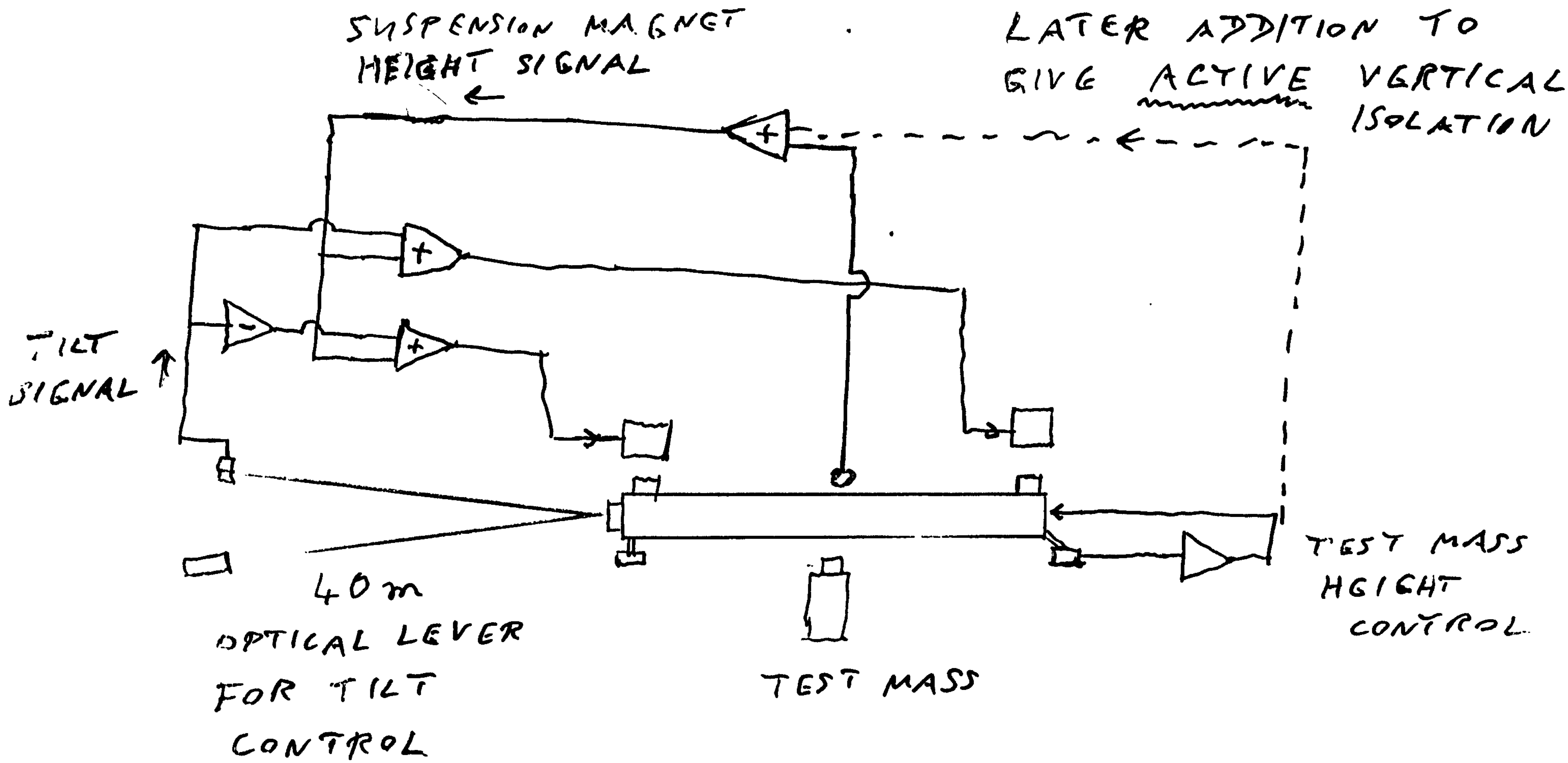
① KEEPS COIL POWER << 1 mW

② KEEPS HEIGHT OF TEST MASS CONSTANT INDEPENDANT OF AMBIENT TEMPERATURE

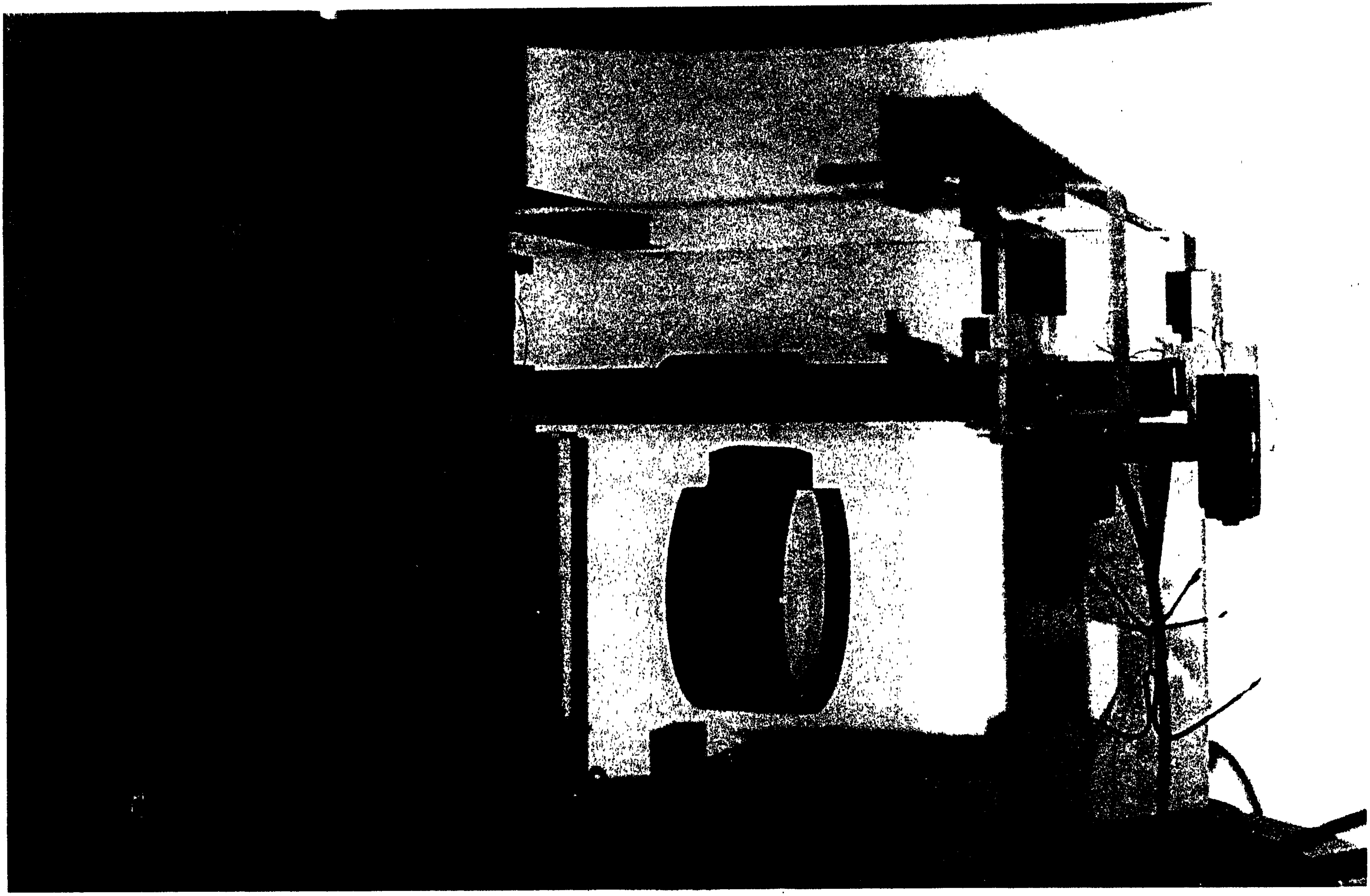

"FIXED" MAGNETS
FLOATING MAGNET SYSTEM
TILT CONTROL OVER 40 M.
TEST MASS

PAC 13

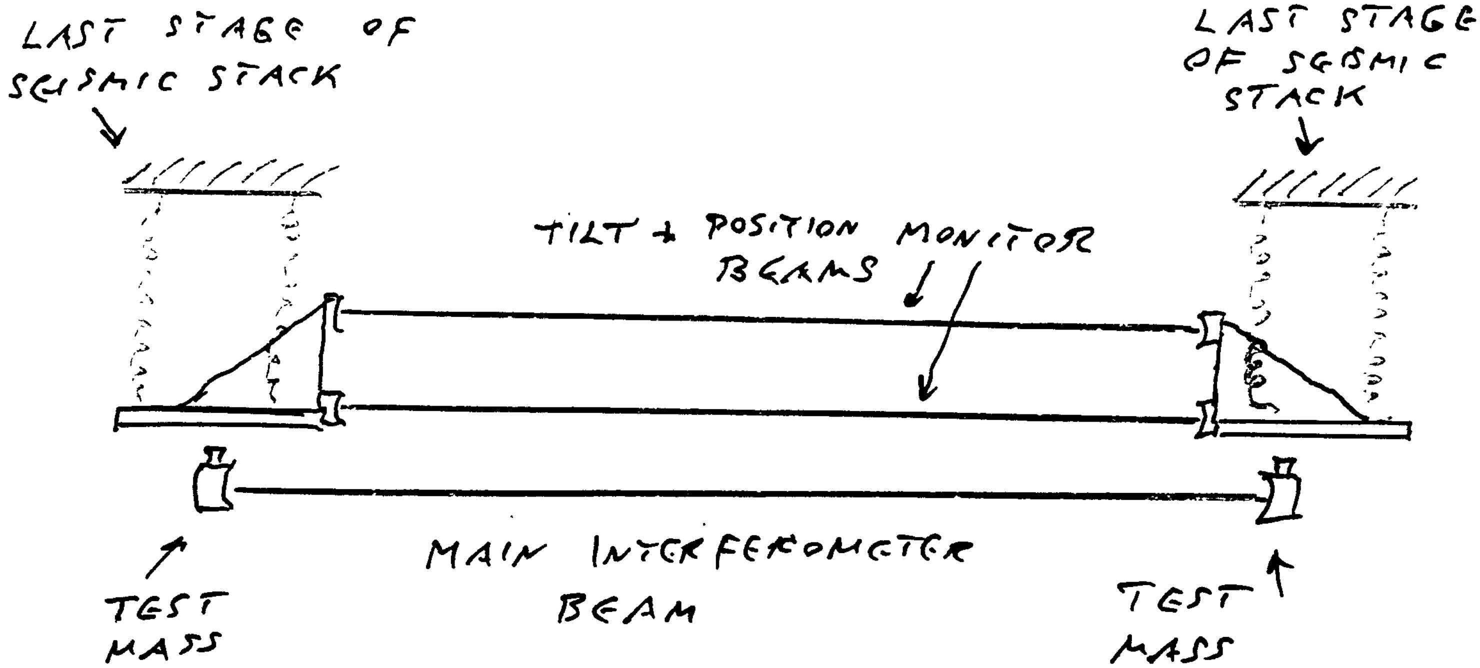
SUSPENSION SYSTEM LEVITATED FROM ISOLATION STAGE



(UNDER CONSTRUCTION NOW.)



PAC 15.



TILT-COUPLED SUSPENSIONS — MAGNETIC LEVITATION EXAMPLE.

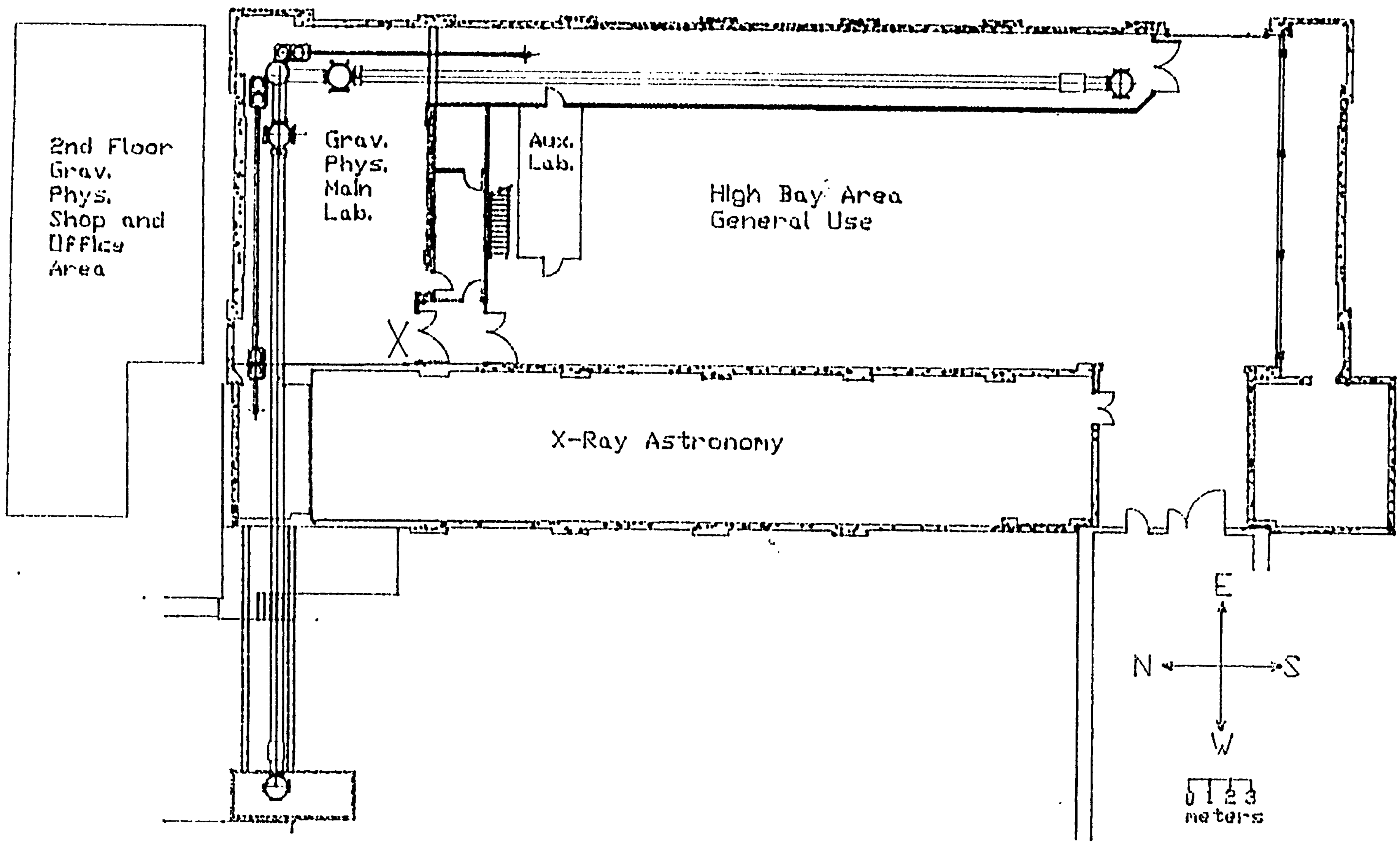


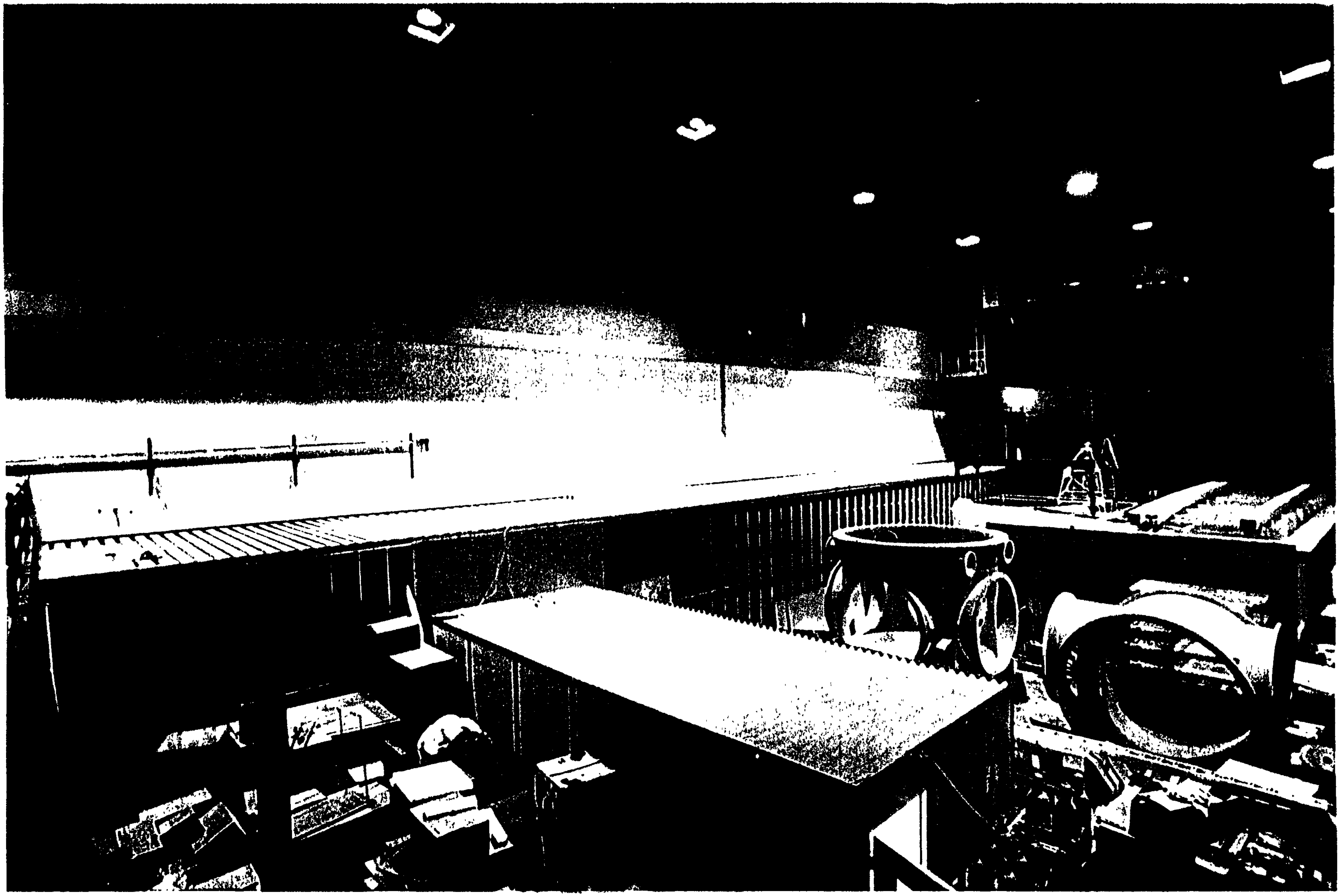
Fig. 16. Simplified layout of new laboratories and facilities planned for this project.

PAC 17

T20

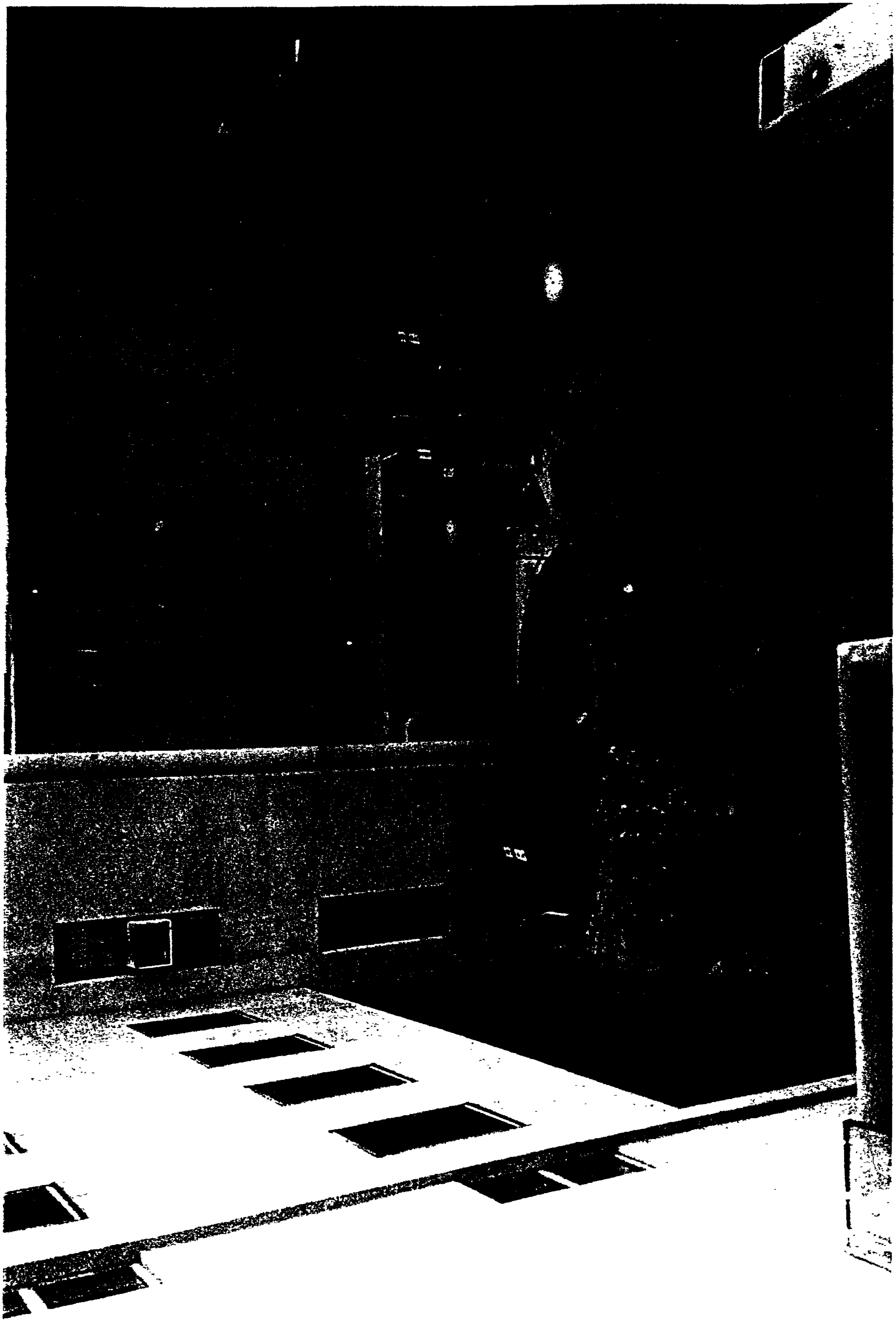
PAC 18

(20)



PAC 19

PAC 19



PAC 20

INITIAL EXPERIMENTAL PLAN

Low Frequency Interferometers

1. Assemble and begin testing levitated test mass suspension — dummy masses.
2. Extend to 2 levitated stages.
3. Duplicate, make first differential measurements with simple interferometer (low frequencies).
4. Build up 2-arm system to improve sensitivity of tests.
5. Extend interferometer to multi-bounce system to allow higher frequency tests.
6. Develop high-performance system for sensitive noise studies.

When practicable (~ Step 4), set upper limit to gravity gradient background.

Diffractive Optics Interferometer

- Fit in when system is good enough (~ Step 5).

OVERALL AIM:

To explore and develop wider-range interferometers as rapidly as build up of personnel and equipment allows.

Eventually expected to lead to significant advances in gravity-wave research.

Diffractive-Coupled Interferometers

- proposed new technique aimed at improved power-handling capability and thermal noise.

Basic Concept: Couple light into and out of cavities and interferometer arms by diffraction grating pattern on mirrors of tes masses or beamsplitters

- to divide wavefront by diffraction instead of transmission

Possible Advantages: No need to pass light through test masses or beamsplitters, so -

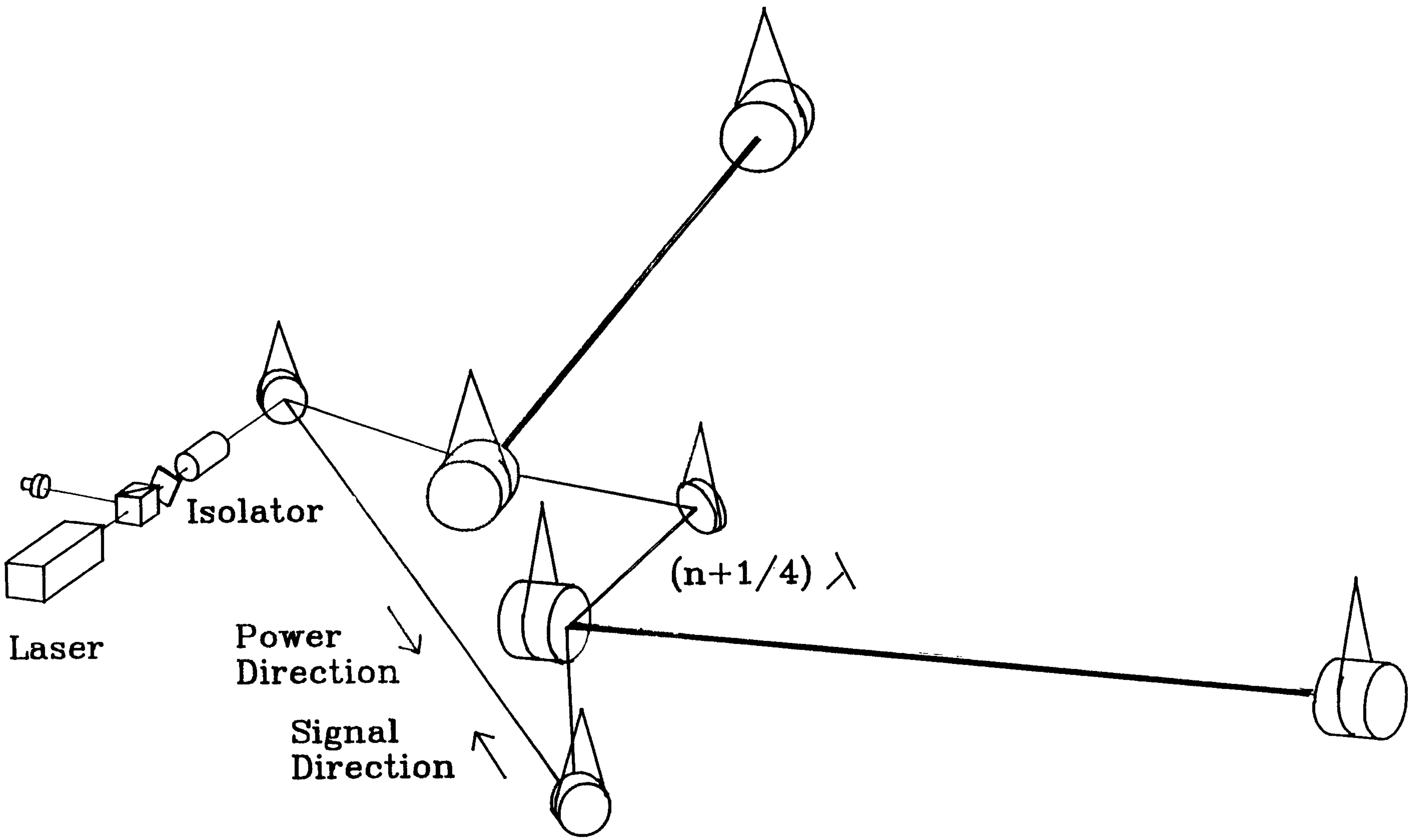
1. Can select materials for high Q, and if needed good thermal conductivity / expansion properties
   - without any transparancy constraint

2. Thermal lensing eliminated, leaving thermal expansion as the only thermal effect - so higher light power is practicable

3. Power dissipation reduced, as transmission losses eliminated
   - reduces thermal distortions further

4. Reduction in power dissipation makes cryogenic test masses more practicable
   - improving possibility of getting higher Q than at room temperature, and possibility of further reduction in thermal noise.

PAC 23 (SKIPPED)



(Diagram shows main beams only)

DIFFRT1
5/8/?4 RD

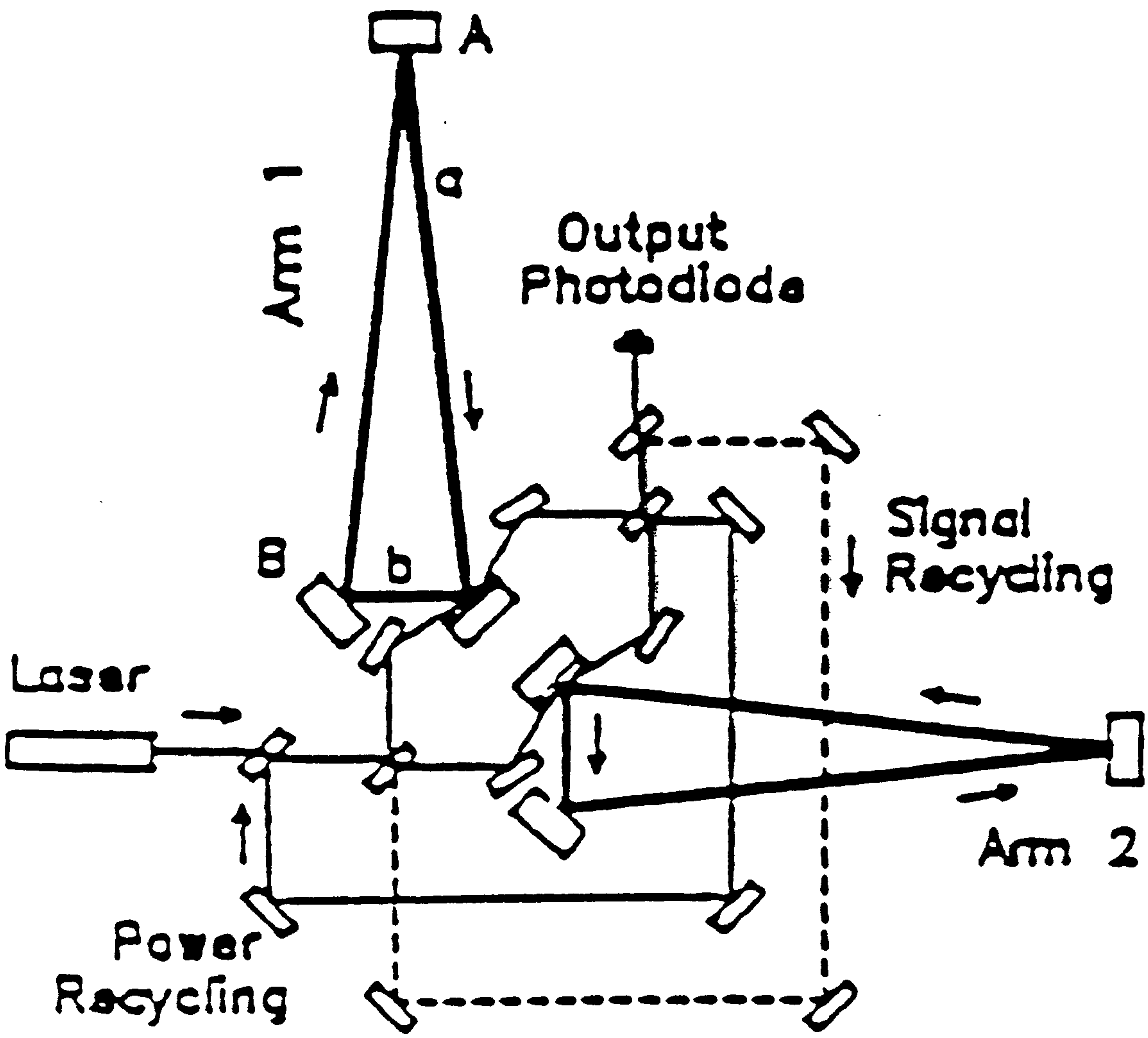


Fig. 13.

PAC 25 (SKIPPED)

DEVELOPMENT OF LASER INTERFEROMETER GRAVITY-WAVE DETECTORS,

AND

RELATED INVESTIGATIONS IN EXPERIMENTAL GRAVITY AND GRAVITATIONAL RADIATION.

(SAME TITLE AS 1980 GRANT
- CONTINUING THE WORK)

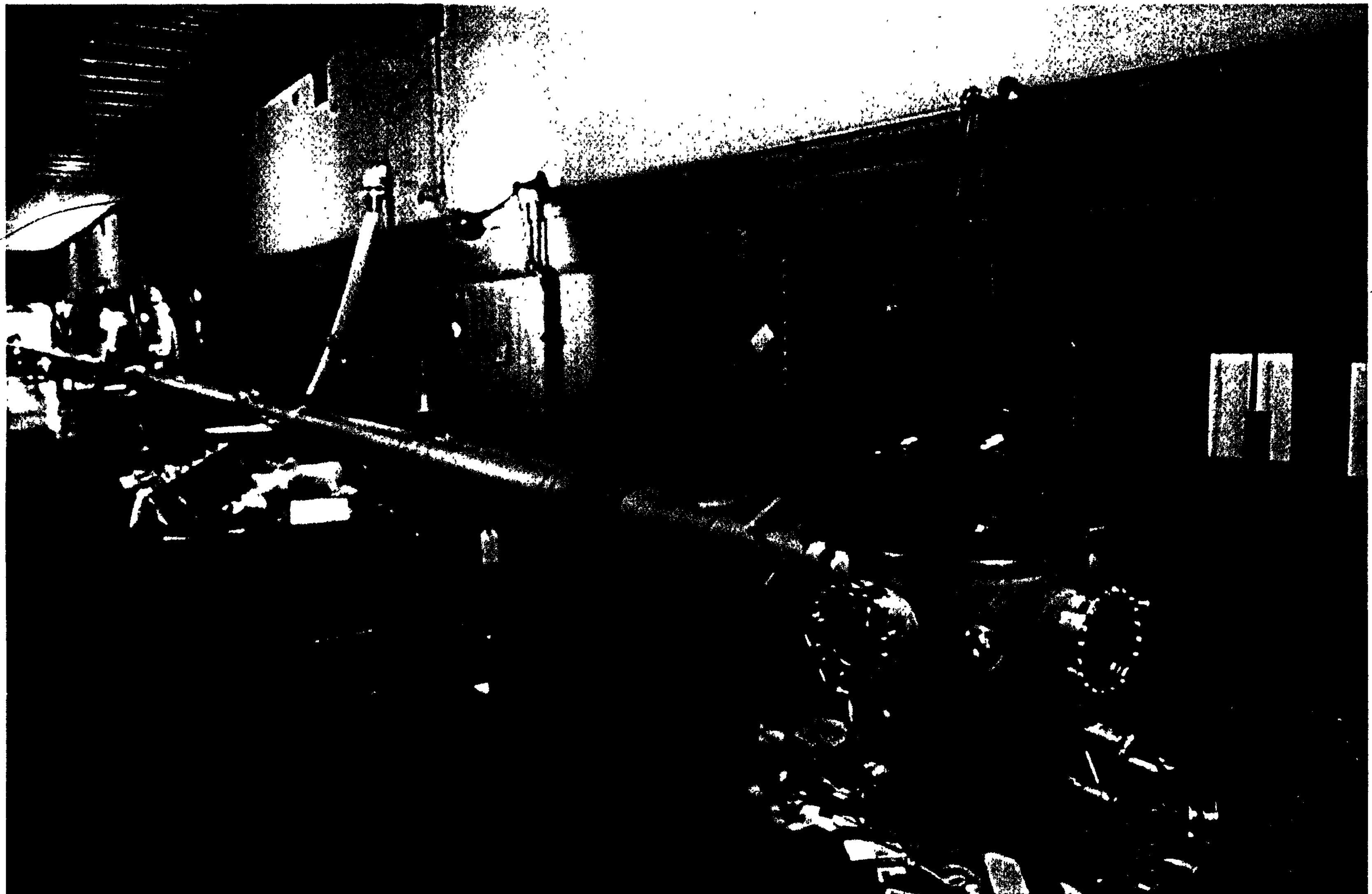
[CALTECH - WITH SOME (LIMITED) CALTECH FUNDING]

RON DREVER - P.I.
STEVE AUGST
STEVE VASS - PART-TIME TECHNICIAN

1ST OF NEW 3-YEAR GRANTS ENDING —
THIS PROPOSAL IS FOR NEXT 3-YEAR CONTINUATION

AIM - EXPLORING, TESTING NEW CONCEPTS FOR DETECTORS - TO ENHANCE LIGO POSSIBILITIES.

SETTING UP FLEXIBLE 40M TEST INTERFEROMETER - USING PARTS FROM ORIGINAL ONE OF 1980'S - IN SPECIALLY-MODIFIED LAB.



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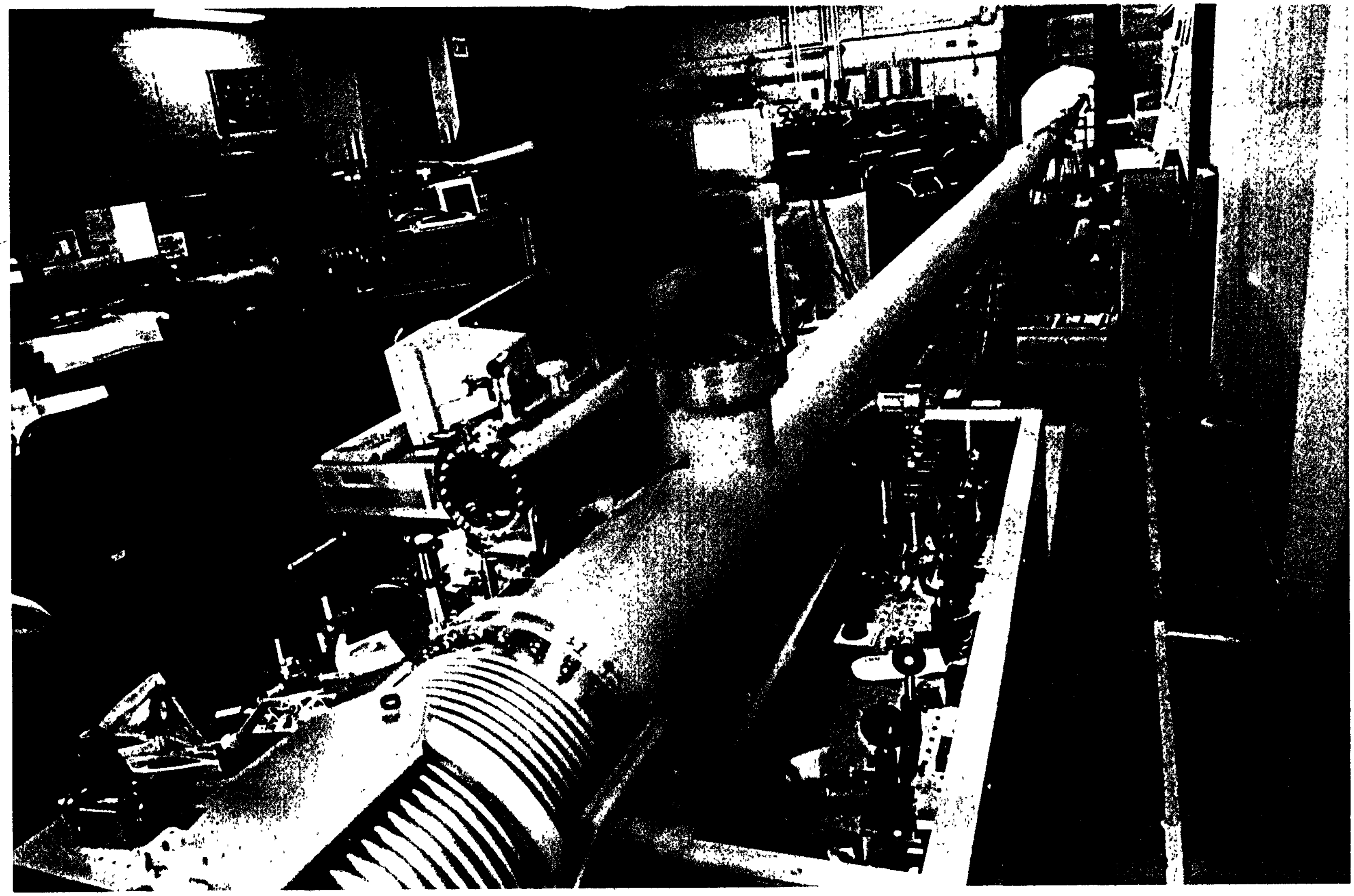
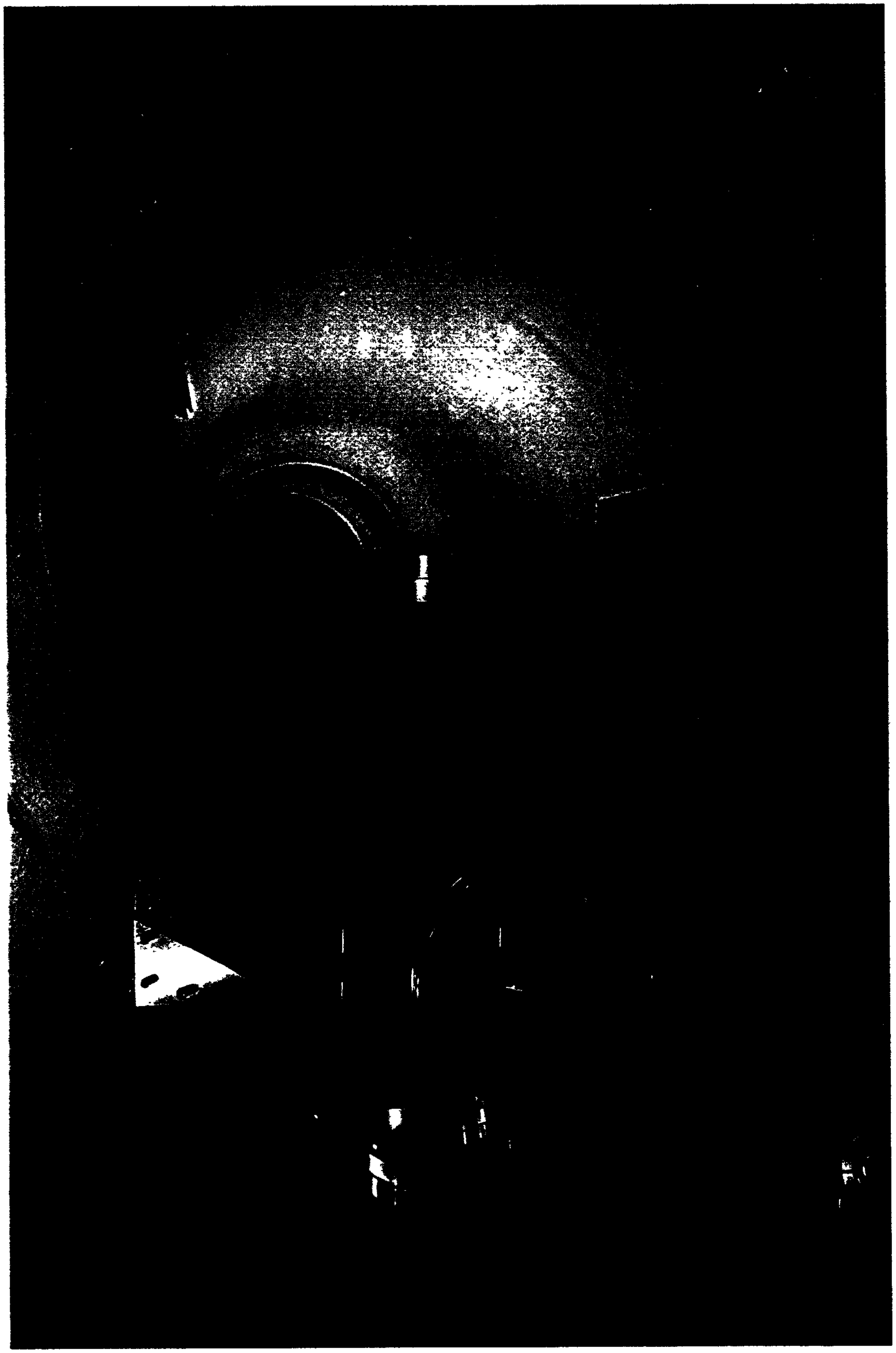




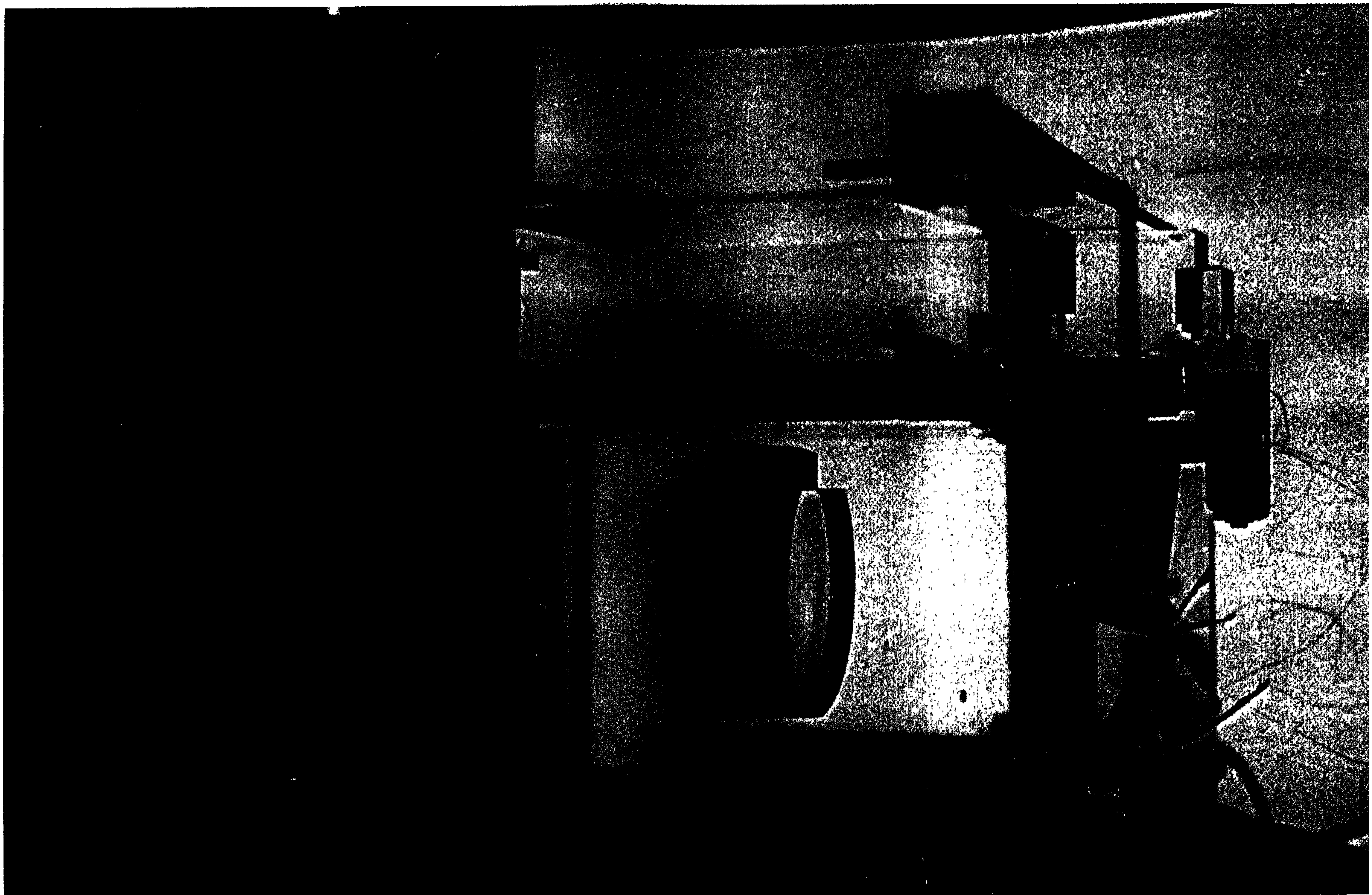
MAIN INITIAL AIM — EXTEND OPERATION TO LOWER FREQUENCIES

FIRST EXPERIMENTS DETERMINED PARTLY BY LIMITED MANPOWER AND NEED TO GRADUALLY BUILD UP FACILITIES —

BEGAN WITH MAGNETIC LEVITATION,

WHILE BUILDING INTERFEROMETER ENCLOSURES ETC. AT SAME TIME.

COUPLING SUSPENSION SYSTEMS A KEY CONCEPT....



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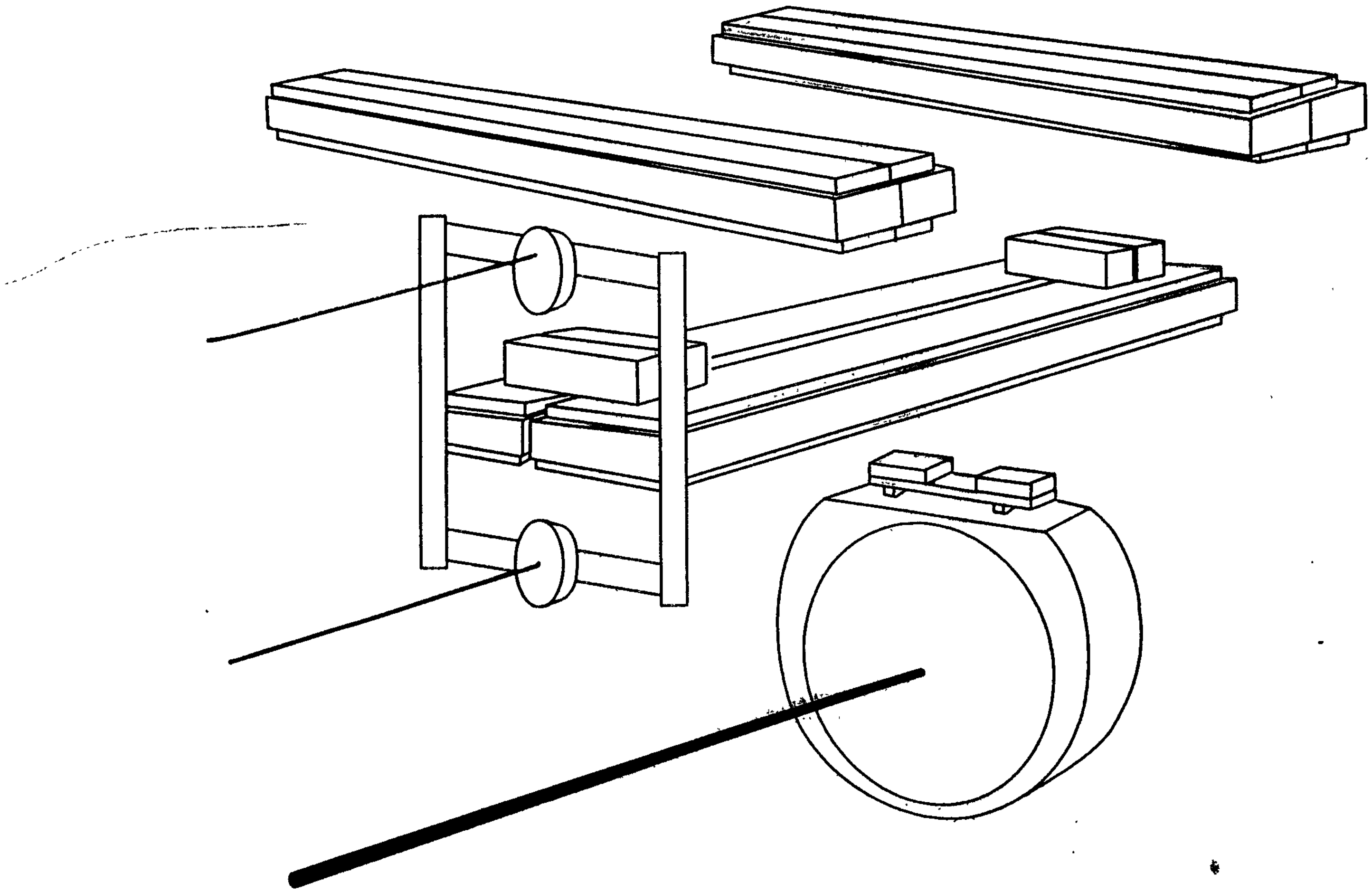

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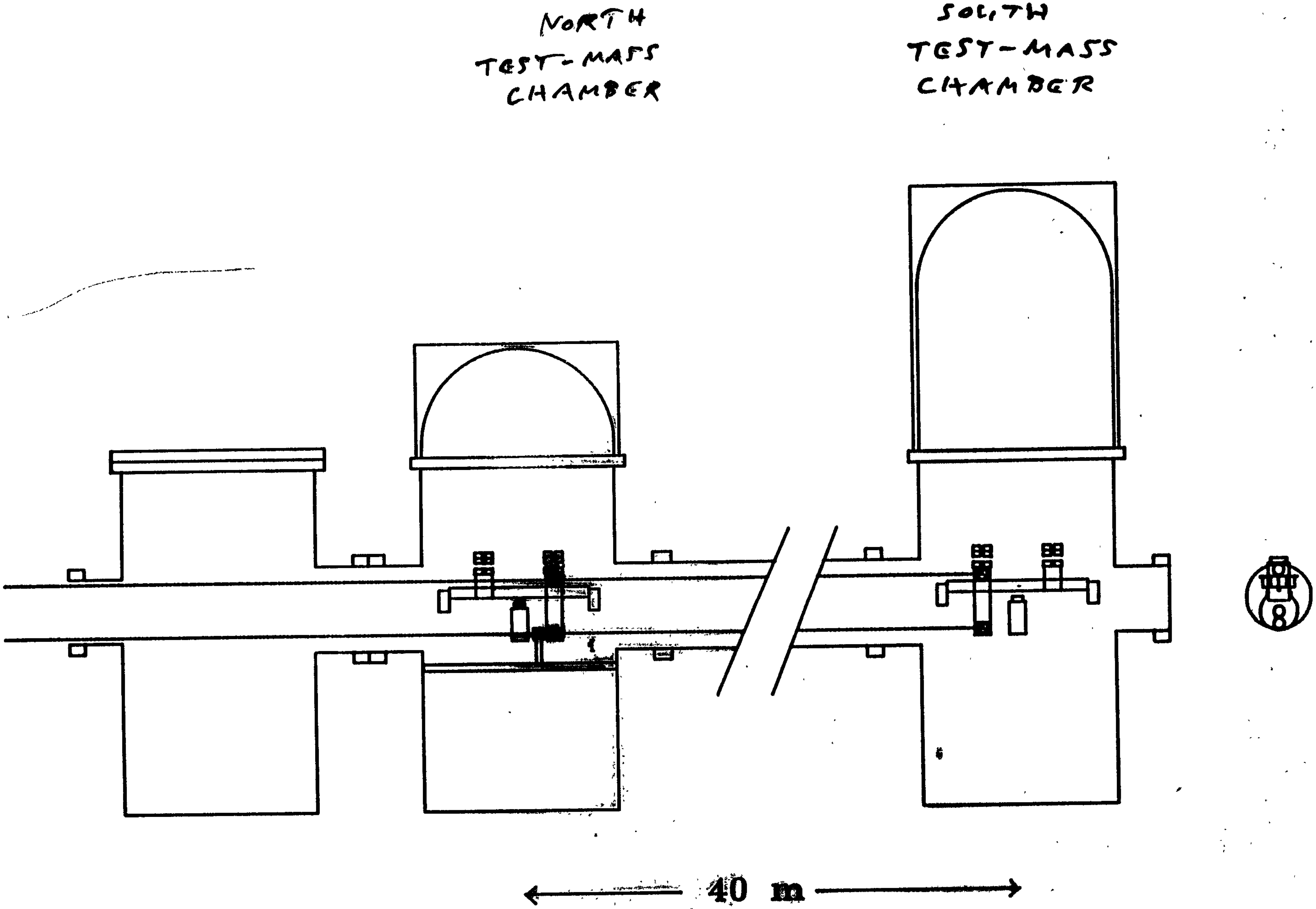


RD 3/98
AV17

(8)

(H11)

PRESENT SITUATION – MAGNETIC LEVITATION

WORKS TECHNICALLY – BUT INTERFEROMETER BUILDING NOT FAR ENOUGH TO KNOW IF USEFULL YET

(HAVE REQUESTED TRANSFER OF PARTS OF OLD 40 m AS IT IS REBUILT – WOULD HELP A LOT)

SEARCH FOR HIGH-Q MATERIALS WHICH CAN BE LEVITATED [SIDE EXPT]

NEW FINDING

TGG
GGG } BOTH HIGH Q WHEN LEVITATED

NEW LAST WEEK – GGG $Q \sim 10^7$
IMPROVED BY POLISH

SOME PROMISING APPLICATIONS

(SMALL QUIET TEST MASSES)

→ (REPLACE CONTROL MAGNETS ON NORMAL TEST MASSES (LIGO II)?
– ALLOWS H.F. AC OPERATION)

AVOID EFFECTS OF OUTSIDE SLOW FIELDS (EARLIER TALK)

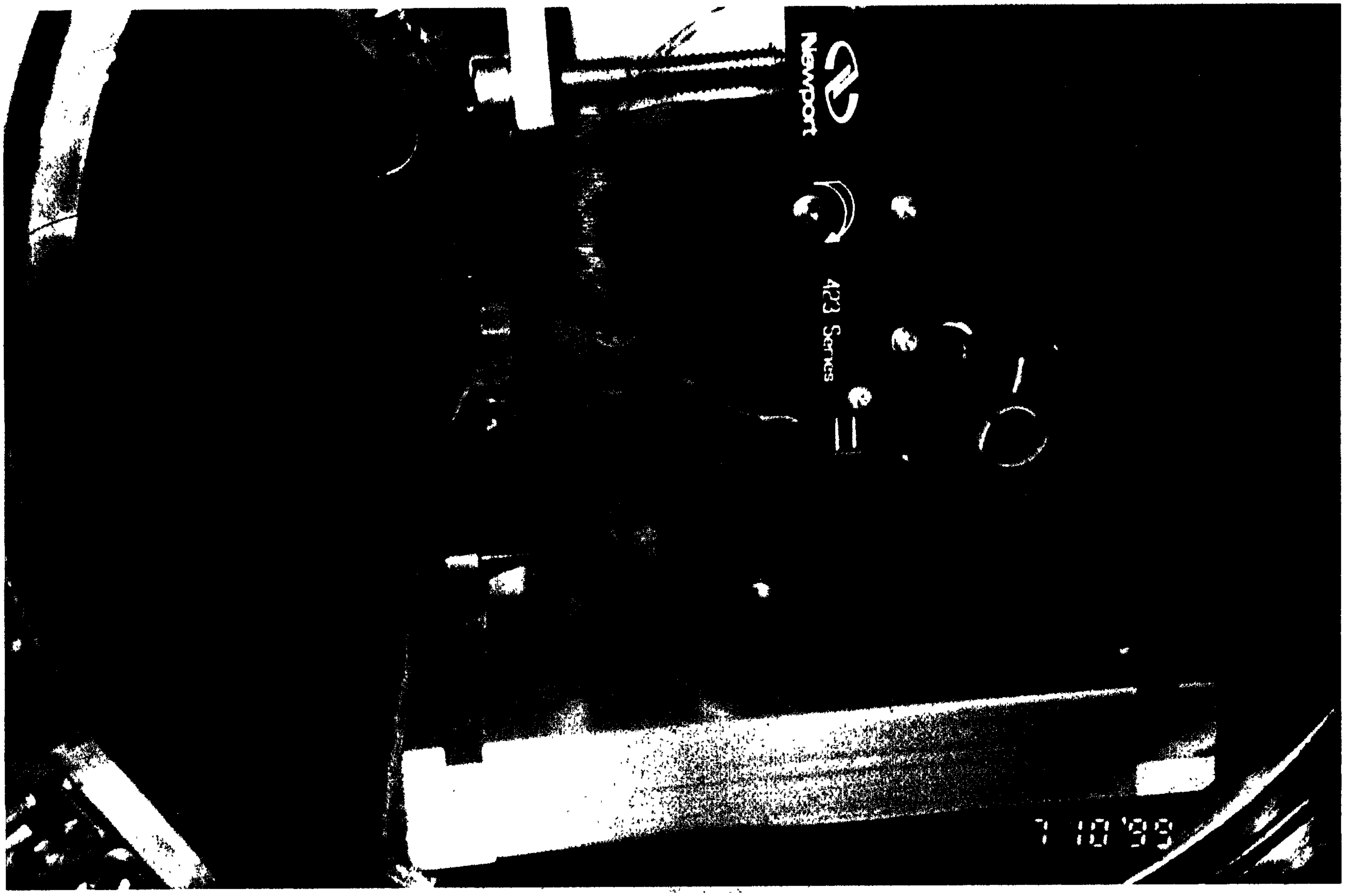
Experimental Q values for magnetically levitated crystals.

TGG (60/40 polish on all surfaces) $Q = 6.0 \times 10^6$ at 222.84 kHz

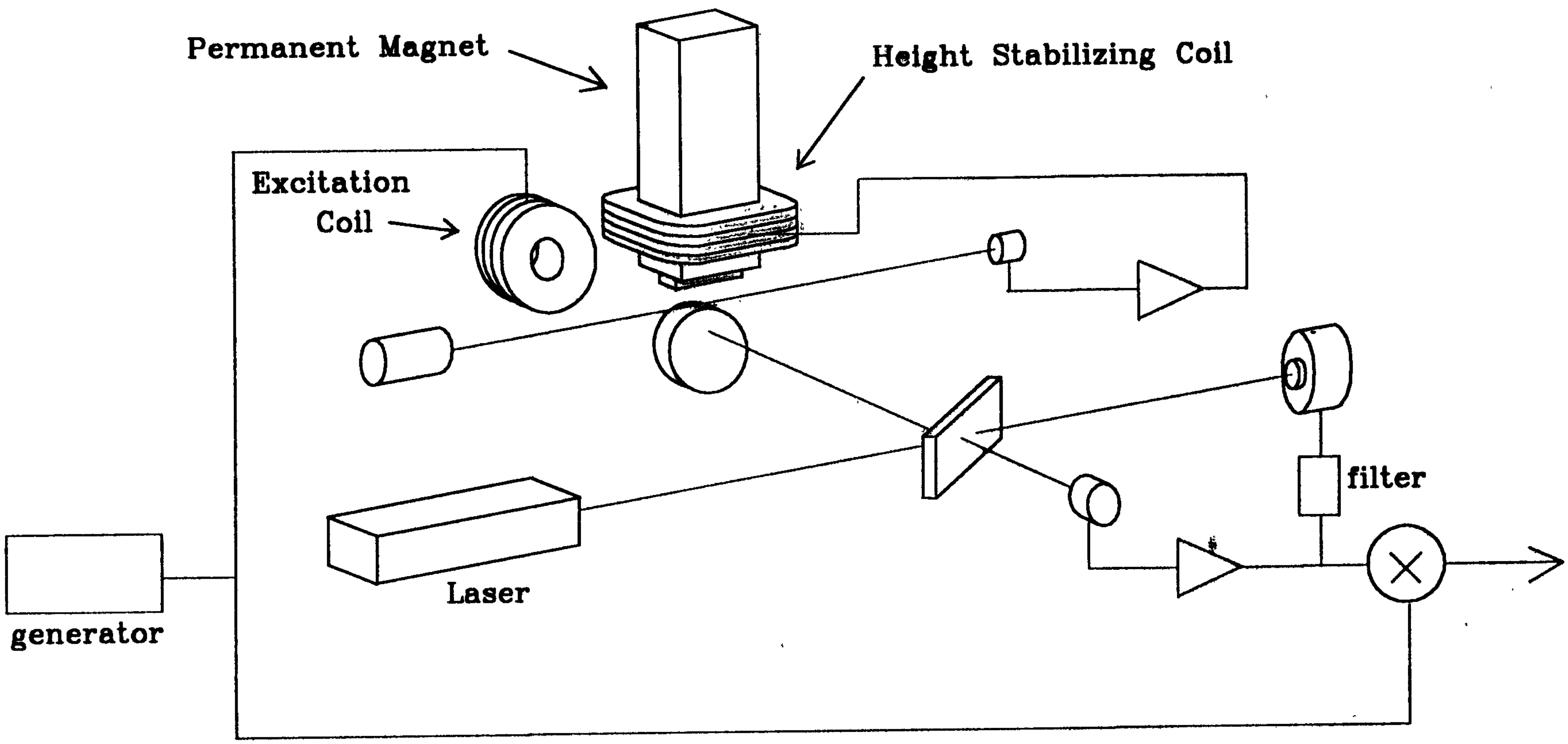
GGG (unpolished circumference) $Q = 6.7 \times 10^5$ at 221.50 kHz

NEW (LAST WEEK) → (60/40 polish on all surfaces) $Q = 9.7 \times 10^6$ at 222.46 kHz

TGG and GGG cylinders: 15 mm diameter x 8 mm long.


Newport
423 Series
7 10 '99

Experimental setup, simplified for clarity



ANOTHER POSSIBILITY FOR A LOW-FREQUENCY INTERFEROMETER

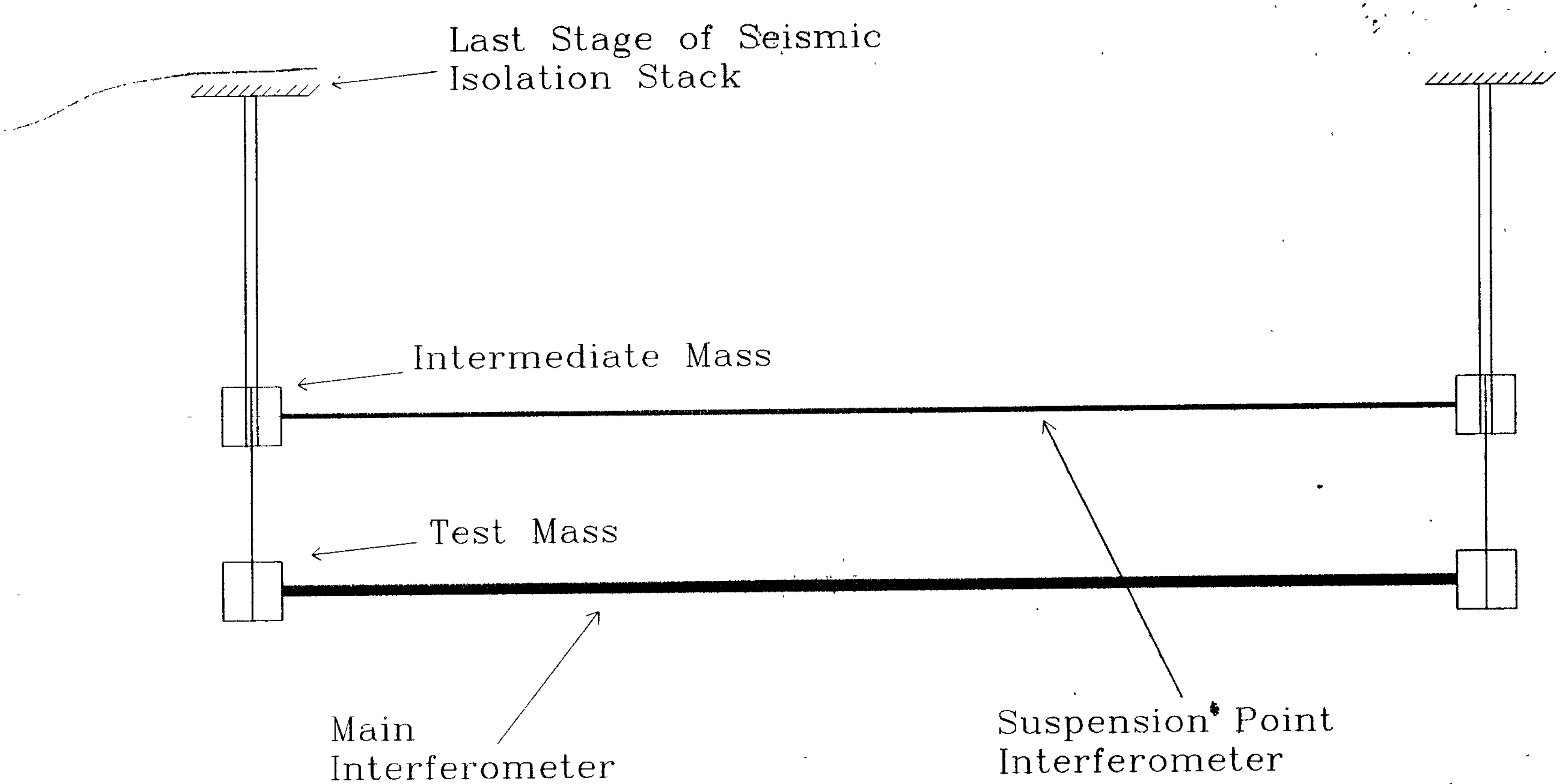
WIRE OF FIBER SUSPENSIONS — COUPLED BY A SUSPENSION-POINT INTERFEROMETER.

CAN OPERATE DOWN TO MILLIHERTZ (OR LOWER) — WITH FORCE FEEDBACK TO REMOVE THE PENDULUM RESONANCE.

AN OLD IDEA — BUT NOW SEE IT AS KEY PART OF NEW CONCEPTS TO EXTEND SEISMIC ISOLATION — AND OPENING NEW AREAS FOR LIGO.

THE FIRST OF A NEW FAMILY OF POSSIBLE FREQUENCY-INDEPENDENT SEISMIC ISOLATION TECHNIQUES .....!

Suspension Point Interferometer.



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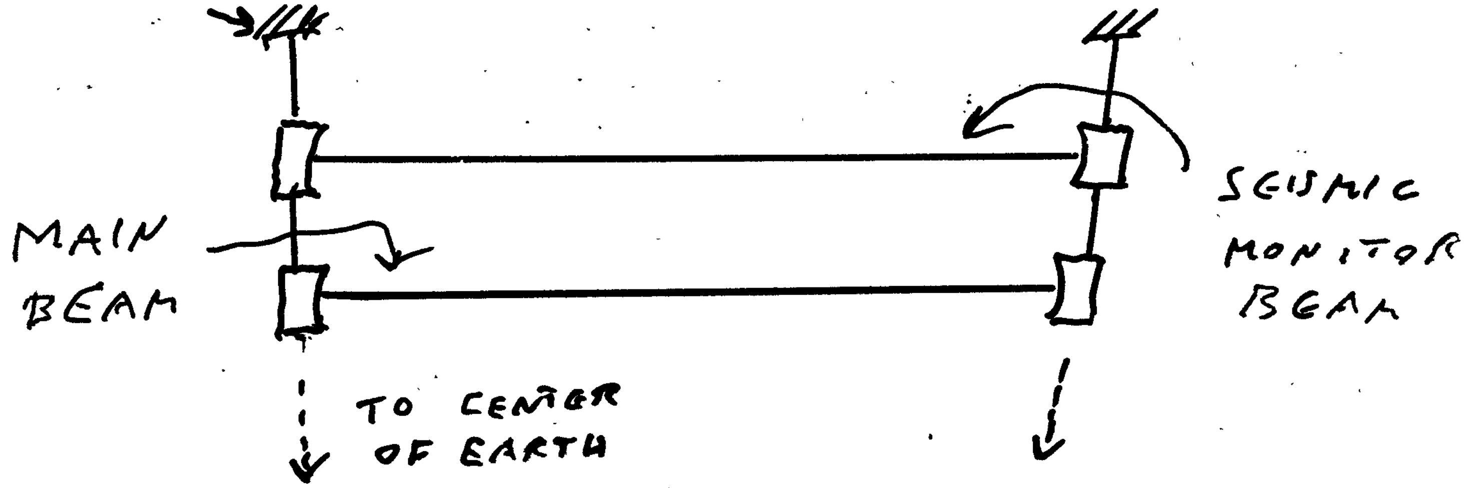
MODIFIED DOUBLE PENDULUM



CLOSED-LOOP OPERATION – LOCK UPPER BEAM TO FIXED LENGTH BY FEEDBACK FORCES

OR OPEN-LOOP RECORD UPPER SIGNAL AND CORRECT FOR EFFECT ON LOWER MASSES.

FREQUENCY RANGE: > 10 HZ – SEISMIC NOISE REDUCED $(\sim \frac{1}{100}\ ?)$

NO LOSS OF SENSITIVITY FOR GRAVITATIONAL WAVES

$\ll$ 1 HZ → DOWN

GRAVITY GRADIENT MEASUREMENT (TO THERMAL NOISE LIMIT)

GEOPHYSICS APPLICATIONS ?

MOTION OF EARTH CORE .... ?

MEASUREMENT OF PROMPT EARTHQUAKE SIGNALS (– NEW) (GEOPHYSICIST SUGGESTION)

EXPERIMENTAL TEST DESIGN FOR EARLY 40 M INTERFEROMETER

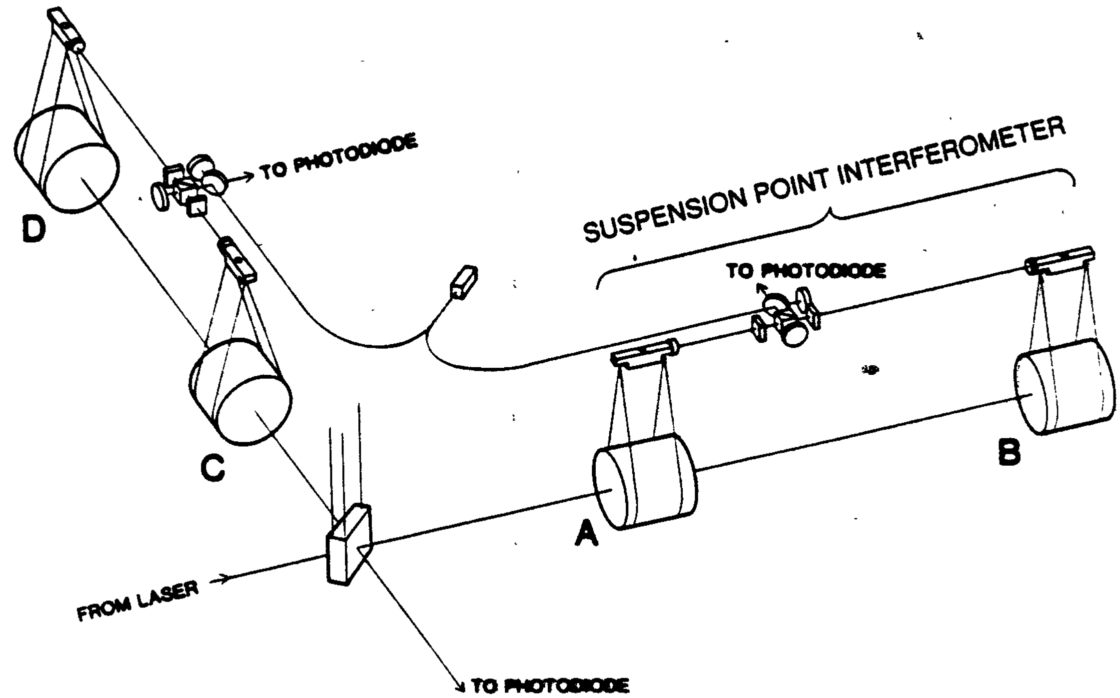
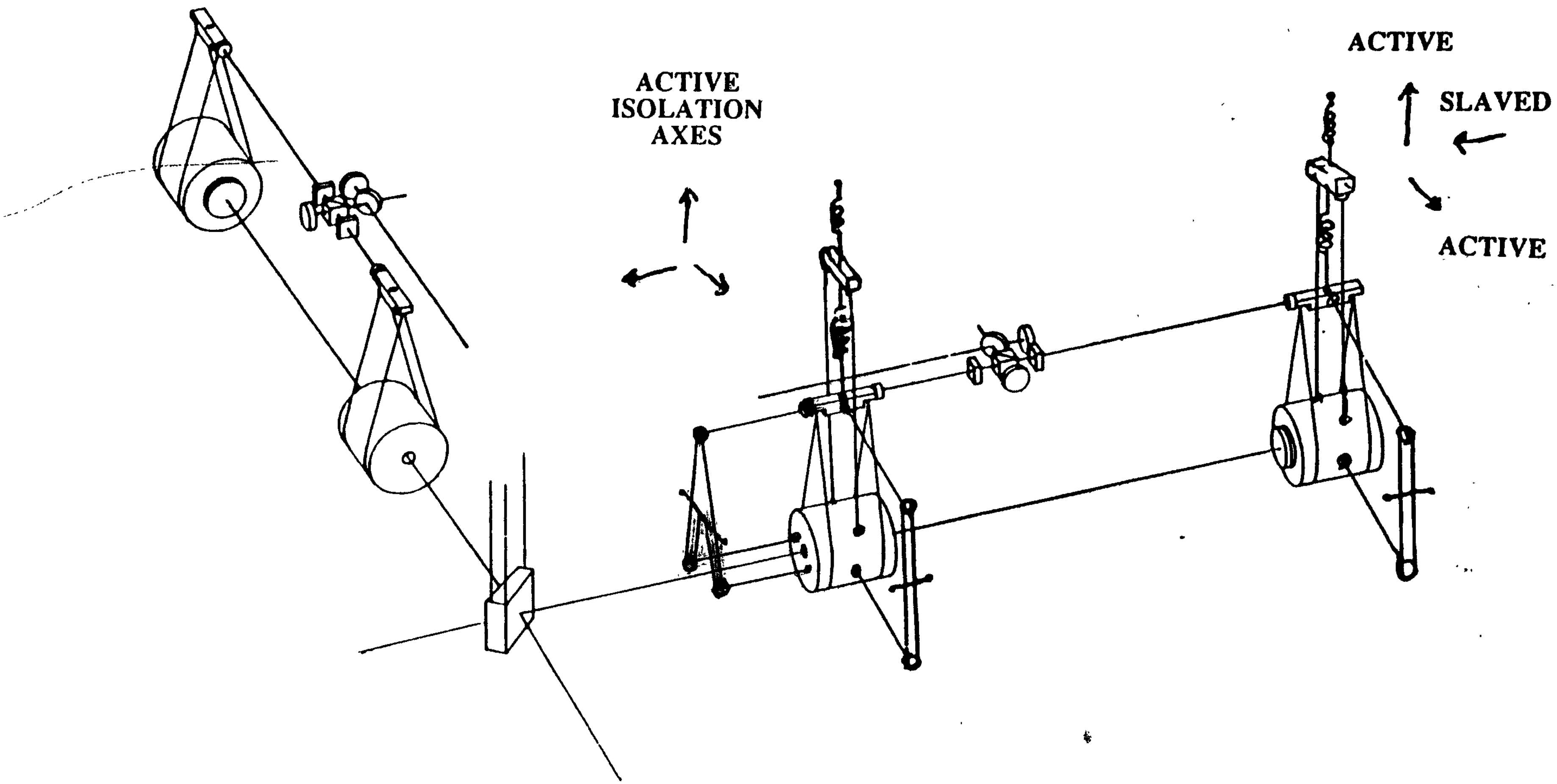


Figure C–6 Schematic representation of a suspension-point interferometer. A stabilized low-power laser excites two unequal-arm Michelson interferometers—one for each Fabry-Perot cavity. Each interferometer senses changes in the separation of the suspension points for the test masses in the associated cavity. The suspended test masses and beam splitter of the main interferometer are shown for context.

(FROM DECEMBER 1987 NSF PROPOSAL)

FIGURE 5. Upgrade 2 - Use of an active antiseismic guard system to supplement the slaved seismic isolation system of the Base Model.

(REDUCING 2ND ORDER EFFECTS)



48A
RWPD

Note: This sketch only illustrates the principle, and the way the various degrees of freedom are controlled in one arm by a combination of the slave and the guard systems. The other arm is arranged in the same way, but is not drawn in here, for simplicity.

(17)

FROM SEPTEMBER 1987 DESIGN FOR A LIGO INTERFEROMETER (LIGO T870001-00-R)

EXPECTED LIMITS TO LIGO OPERATION
(DOWN TO 0.1 HZ).

NOTE: BEST PREVIOUS GRAVITY GRADIOMETER
$\sim$ → 10^{-2} EOTVOS $/\sqrt{Hz}$

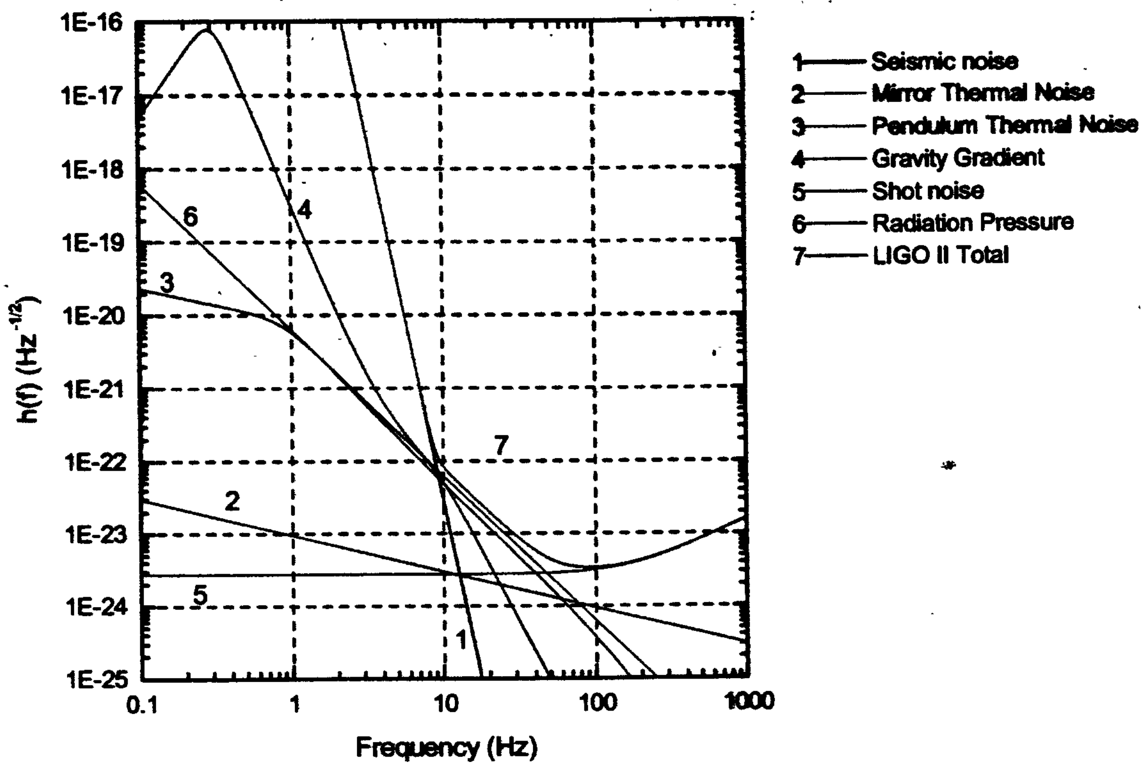


Fig. 4a Predicted contributions to the LIGO II noise spectrum plotted as strain (h).

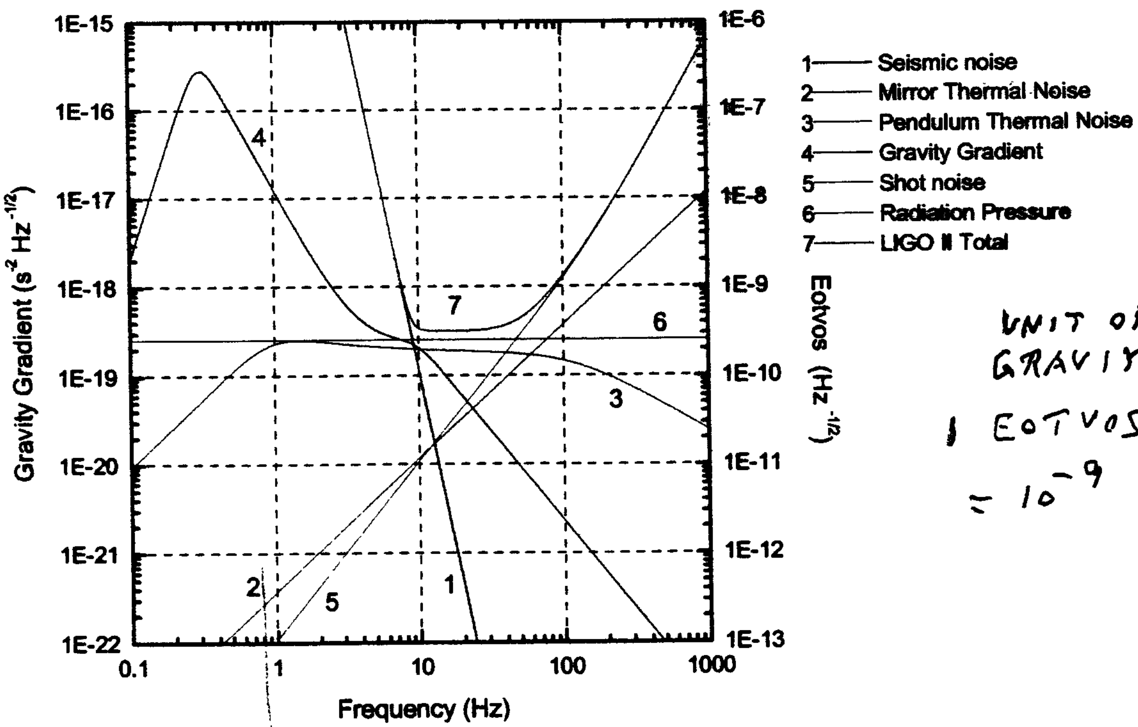


Fig. 5a Predicted contributions to the LIGO II noise spectrum plotted as gravity gradient.

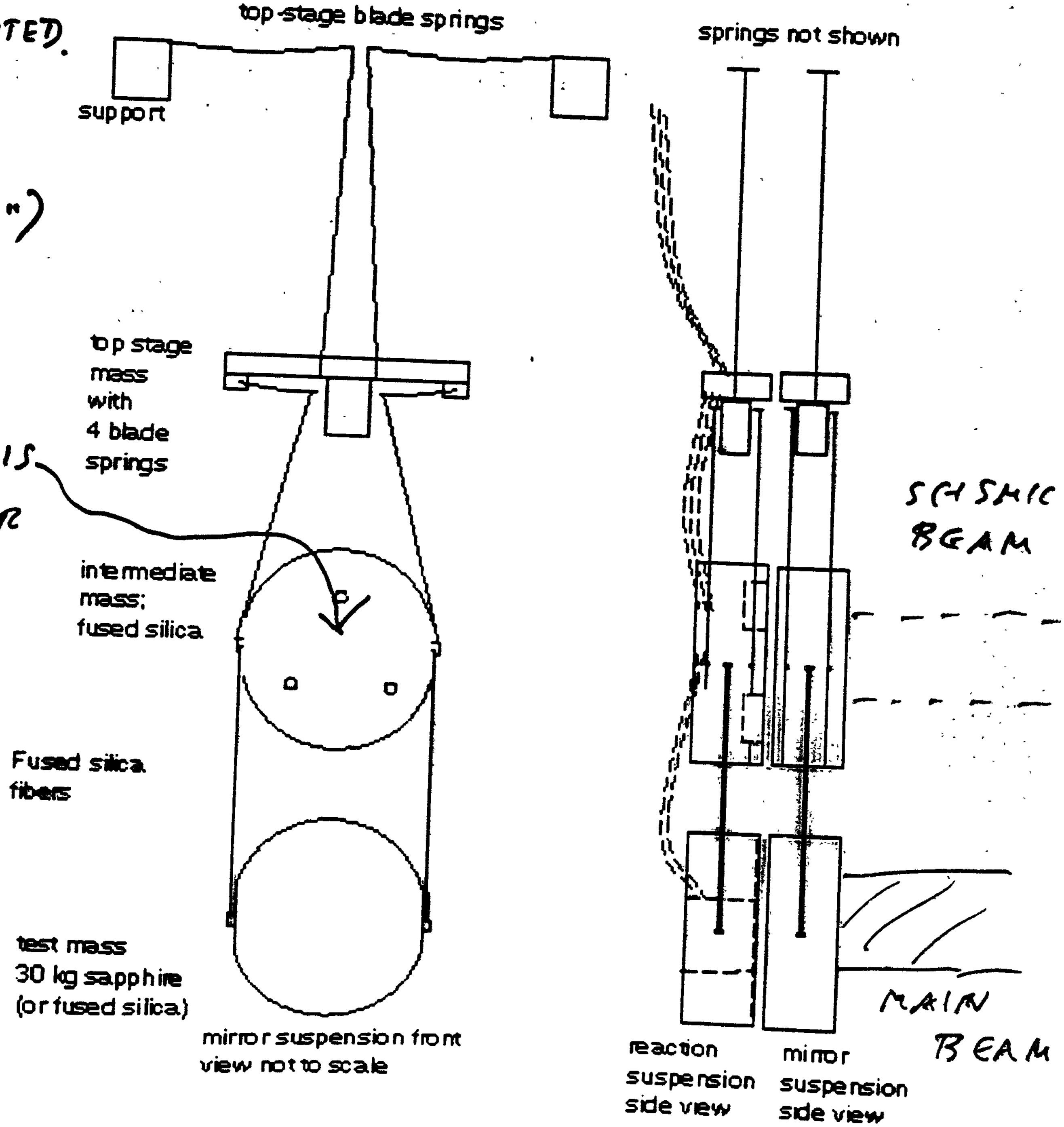
UNIT OF GRAVITY GRADIENT
1 EOTVOS
$= 10^{-9}$ (SECOND)$^{-2}$

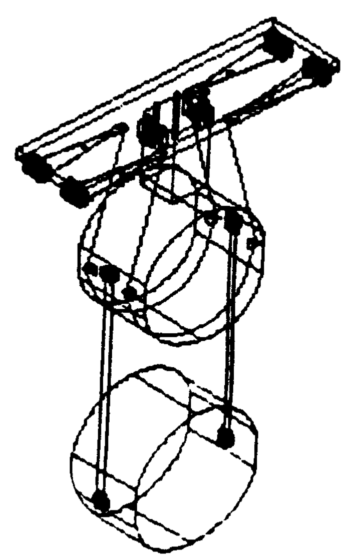
(18)

LIGO II: A CURRENT LSC SUSPENSION DESIGN COULD BE EASILY ADAPTED.

("TRIPLE PENDULUM SUSPENSION")

MAKE THIS A MIRROR FOR SEISMIC BEAM





PLAN TO TEST SOME OF THIS IN TEST INTERFEROMETG.

- MEASURE GRAVITY GRADIENT BACKGROND
TO CHECK ESTIMATES OF LIMITS
(AT NIGHTTIME - WHEN LITTLE TRAFFIC)

- RUN TO LOOK FOR ANY SIGNALS FROM LOCAL EARTHQUAKES

- FIND WHAT THE REAL PROBLEMS ARE

KEY PROBLEM ~ CURRENTLY ONLY 1 FULL-TIME PERSON FUNDED.

WHAT IS PROPOSED :~

	NOW	YEAR 1	2	3
SENIOR	x	x	x	x
POST DOC	0	2*	2*	2*
S. ENGINEER	1	1	1	1
TECHNICIAN	1/4	1/4	1/4	2/4
R A	0	1	1	1
ELECT. ENGINEER	0	1	1	1
GRAD. STUDENT	0	2	2	3
UNDERGRADS	0	2	2	2

* 1/6 TO POST DOC COLLABORATING IN GEOPHYSICS DEPT.

OVERALL SUMMARY.

THIS WORK CAN HELP LIGO GREATLY IN FUTURE

① ALLOW GRAVITY-WAVE SEARCHES DOWN
TO FREQUENCIES PREVIOUSLY IMPOSSIBLE

② MAKE APPLICATIONS IN GEOPHYSICS
PRACTICABLE AT SAME TIME

NEEDS NEW TECHNIQUES – AND HAVE
A RANGE OF IDEAS AND POSSIBILITIES
HERE. (AND MAY HAVE OTHER USES..)
IMPORTANT TO TEST + DEVELOP BEFORE PROPOSING FOR LIGO

BUT. PRESENT GROUP TOO SMALL
FOR FAST ENOUGH PROGRESS.
(MOST EQUIPMENT HAS TO BE BUILT)

SUGGEST. PROVIDING FUNDING FOR
MORE PRACTICABLE GROUP COULD
REAP GREAT BENEFITS FOR
FUTURE LIGO'S.
(AS WELL AS OTHER AREAS
IN GRAVITATIONAL PHYSICS)