New Folder Name SERVO COILS CALIBRATION

Interoffice Memorandum

# CALIFORNIA INSTITUTE OF TECHNOLOGY

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**To:** All **Date:** May 22, 1991

**From:** Yekta Gürsel **Ext:** 2136 **Mail Code:** 130-33


**Subject: The calibration of the main servo coils in the 40m system**

This memorandum summarizes the design, construction and the calibration of the main servo coils in the 40m interferometer. The design, construction, calibration of these coils were performed by me during the two-week time interval spanning April 20, 1987 to May 6, 1987. After the results of the calibration is discussed with the group members, the coils were installed into the 40m system by me, Mike Zucker and Sheri Smith. The experimental procedure for calibration and the data were recorded in the logbooks and notebooks, but they were never presented in a concise form.

## Design of the Coils

The design rules for the coils were the following:

- The coils should produce sufficient force to move the fused-quartz test masses when used with the Samarium-Cobalt magnets we had in house at the time. The magnets are cylinders with a diameter and a radius of 0.25". Their average weight is 1.75 grams. The magnetic properties of these magnets are shown in Figure 1. These were the strongest magnets one can buy at that time. Today, the strongest magnets (Neodymium-Iron-Boron) have twice the energy density.
- The maximum heat dissipation in the coils should be small enough not to cause damage to the coils or other sensitive apparatus in the vacuum.
- In order not to obstruct the light beams in the interferometer, the diameter of the coil should be as small as possible without causing the magnet to move off the center-line of the coil.
- The coil-former should be designed to allow the coil to be mounted with minimum of extra hardware.
- The coil-former material should be vacuum-compatible.

After some experiments with various coil diameters and wire thicknesses, I chose the coil-former which is shown in Figure 2. Delrin was chosen to be the material for the coil-former. It is not as good as Teflon for vacuum compatibility, but it holds its shape under load and it is very easy to machine. I personally made five coil-formers in the small machine shop on the roof of the West Bridge Building in one afternoon.

The coils were constructed by winding about 200 turns of Number 26 wire-gauge, insulated magnet wire on these coil-formers. We had no coil winding machinery at the time. In order to form tight windings which would stay fixed when the current was applied to the coils, I wound the coils on the same lathe used to manufacture the coil-formers. The slowest speed of this lathe was barely sufficient to guide the wire by hand to form uniform, tight windings. The lathe had no turn counters. Because of this, the coils had to be balanced after the winding operation. The final turn on the coils was tied with a piece of a string to the coil-formers in order to prevent the coils from unwinding. The coils were labeled 1, 2, 3, 4 and X. "X" was the reference coil which was not installed in the vacuum system.

**Balancing of the Coils**

After the winding operation, the coils were crudely balanced using the following method. A small plexiglass tube with a smooth bore is constructed to fit the aperture of the coils. The inner bore of the tube was slightly larger than the diameter of the magnets. The coil, the magnet and the small plexiglass tube is shown in Figure 3. The magnet was placed inside the small tube. The tube was mounted on the coil, and the whole assembly was positioned so that when there is no current flowing through the coil, the magnet was resting on the surface of the table which was carrying the assembly (Figure 4). The current was applied to the coil until the magnet just floated off the surface and it was hanging above the surface in the tube. The position of the magnet relative to the surface and the value of the current was measured. The number of windings in the coils were adjusted so that each coil lifted the magnet to the same height with the same current value when the magnet just floated off the surface.

The coils were then ultrasonically cleaned with Methanol as the solvent. After the cleaning operation, a small amount of cellulose based glue was used to affix the final winding to the rest of the coil, and the string was removed.

**Calibration of the Coils**

It is well-known that the force exerted by a coil with a shape as described above on a small magnet which is concentric with the axis of the coil goes through a maximum as the distance between the coil and the magnet is varied. It is very easy to show that if the coil is formed out of a single circular winding, then the force exerted on a small magnet (dipole) is maximum when the dipole is placed half a radius of the coil away from the center of the coil. If the magnet is placed at this location, then the force on the magnet is independent of the position of the magnet to first order in the displacement of the magnet as measured from the maximum force position.

Since our coils were not single turn coils, the maximum force position for the magnet had to be determined experimentally. The same experiment also calibrated the force produced by the coils as a function of the current flowing through them.

The experiment was performed in the following manner: The Samarium-Cobalt magnet was attached to one end of a small delrin rod as shown in Figure 5. The other end of the delrin rod had a counter-weight made out of thick copper wire to balance the rod. There were two cross-shaped vanes attached to the middle of the rod by stiff, thick wires. The rod-magnet-vane assembly was suspended as a pendulum with two thin strings. Two strings were used to constrain to pendulum to swing along the axis of the rod without any rotation of the rod. The vanes below the rod were dipped in a cup of water to damp the pendulum motion both along the axis of the rod and perpendicular to the rod. The coil was placed on a X-Y stage with micrometers. One of the micrometers was along the axis of the rod, the other was perpendicular to it. The perpendicular micrometer was used to center the rod with respect to the coil. The other micrometer was used to vary the distance between the coil and the magnet. The height of the coil assembly was carefully shimmed so that the rod was pointing along the axis of the coil. A translucent ruler with millimeter divisions was placed along the rod in the plane passing through the axis of the rod and parallel to the table top which is supporting the apparatus (Figure 6).

The whole assembly as described above was built on top of a transparency projector which projected enlarged silhouettes of the magnet and the coil on a screen. The projector was focused so that the divisions on the ruler are clearly visible on the screen. The projector and the experimental assembly was shrouded with cardboard in order to eliminate the motions caused by air currents in the room (Figure 7). The suspension point of the pendulum was on a tower built out of rods and stabilized by guy wires to a heavy base.

Figure 8 shows the typical image on the screen. The large dark circle is the water cup under the rod. The magnet protrudes from the edge of the cup towards the right. Part of the coil is visible in front of the magnet as a part of a dark rectangle.

### The data

The experimental arrangement is shown schematically in Figure 9. The parameters of the experiment are:

- The length of the pendulum = $l = 865 \pm 1$ mm.
- The weight of the rod-magnet-vane assembly = $m$ = $7.18 \pm 0.02$ gm. The lift produced by water on the vanes is found to be less than the error on the mass measurement.
- The displacement of the magnet from its rest position = $x$
- The distance between the end of the magnet facing the coil and the edge of the coil = $y$
- The current through the coil = $I$
- The acceleration of gravity = $g$

Here are the experimental data:

| Coil 1, $I = 7$ mA | |
|---|---|
| x (in mm, ± 0.1 mm) | y (in mm, ± 0.1 mm) |
| 6.8 | -3.3 |
| 7.1 | -2.9 |
| 7.4 | -2.5 |
| 7.1 | -1.5 |
| 6.8 | -0.5 |
| 6.3 | 0.7 |
| 5.5 | 2.1 |
| 4.5 | 3.8 |
| 3.7 | 5.3 |
| 3.0 | 6.6 |

| Coil 1, $I = 5$ mA | |
|---|---|
| x (in mm, ± 0.1 mm) | y (in mm, ± 0.1 mm) |
| 2.1 | 7.5 |
| 2.3 | 6.6 |
| 2.6 | 5.6 |
| 3.0 | 4.5 |
| 3.6 | 3.2 |
| 4.0 | 2.0 |
| 4.3 | 1.0 |
| 4.5 | 0.1 |
| 4.8 | -0.9 |
| 5.0 | -1.8 |
| 4.8 | -2.3 |
| 4.6 | -2.8 |
| 4.4 | -3.2 |

| Coil 2, $I = 7$ mA | |
|---|---|
| x (in mm, ± 0.1 mm) | y (in mm, ± 0.1 mm) |
| 7.4 | -3.5 |
| 7.7 | -2.9 |
| 7.9 | -2.4 |
| 7.7 | -1.6 |
| 7.2 | -0.4 |
| 6.6 | 0.8 |
| 6.0 | 2.2 |
| 5.5 | 3.3 |
| 4.5 | 5.0 |
| 4.1 | 6.1 |

| Coil 3, $I = 7$ mA | |
|---|---|
| x (in mm, ± 0.1 mm) | y (in mm, ± 0.1 mm) |
| 7.5 | -3.3 |
| 7.6 | -2.1 |
| 7.8 | -1.6 |
| 7.6 | -0.8 |
| 7.3 | 0.1 |
| 7.0 | 1.1 |
| 6.2 | 2.5 |
| 5.2 | 4.2 |
| 4.7 | 5.4 |
| 4.0 | 6.7 |
| 3.3 | 8.0 |

| Coil 4, $I = 7$ mA | |
|---|---|
| x (in mm, ± 0.1 mm) | y (in mm, ± 0.1 mm) |
| 7.0 | -3.1 |
| 7.2 | -2.6 |
| 7.5 | -2.3 |
| 7.5 | -1.6 |
| 7.2 | -0.5 |
| 7.0 | 0.4 |
| 6.6 | 1.4 |
| 5.9 | 2.8 |
| 5.2 | 4.1 |
| 4.6 | 5.4 |
| 3.9 | 6.8 |
| 3.1 | 8.2 |
| 2.7 | 9.2 |

The Figures 10, 11, 12, 13, 14 show the data presented above in the form of plots. From the data above, I conclude that the maximum of the force occurs for a magnet-coil separation of $y = -2.0 \pm 0.4$ mm. The deflection $x$ of the pendulum from its rest position at maximum force for a current $I = 7$ mA is $x = 7.7 \pm 0.2$ mm. For a computation of the 40m calibration voltages, please see 40m Logbook 9, page 29 Yellow.

Fig 1

## REMCO 18

Magnets of rare earth-cobalt yield the highest magnetic energy product of any commercially available material. REMCO 18 is a samarium cobalt alloy manufactured to obtain a typical maximum energy product of 18 x $10^6$ G·Oe.

REMCO 18 exhibits the highest resistance to demagnetization of any magnet marketed. Temperature stability can be provided to 300°C. Rare earth-cobalt magnets provide maximum magnetic field from a minimum volume of magnetic material. This allows the size and weight of the magnetic circuit to be minimized. Varying magnetic properties can be obtained by alloying cobalt with rare earths such as samarium and praseodymium.

REMCO 18 magnets are ideal for traveling wave tubes, microwave circulators and isolators, gyroscopes, generators, motors, electronic watches, magnetic latching devices, instrumentation, magnetic suspension systems, accelerometers, magnetic drives and loudspeakers.

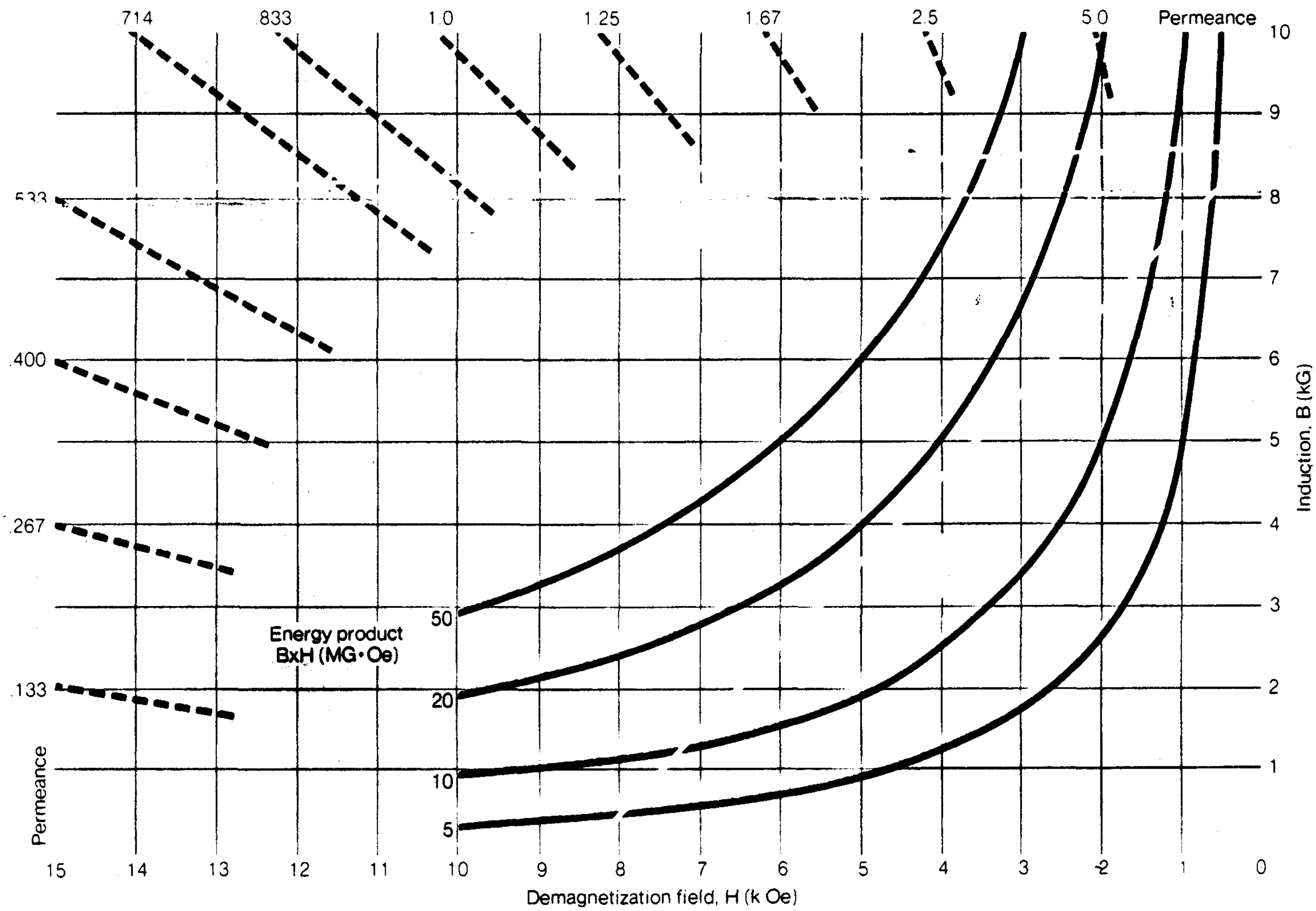
REMCO 18 magnets can help improve your product. Tell us your requirements. We'll respond fast with quotations on rare earth-magnets for your specific application. Prototype or production quantities are produced accurately to your specifications and are delivered promptly at a competitive price.

### Typical Magnetic properties

| | |
|---|---|
| Residual induction, $B_r$ | 8500 G |
| Coercive force, $H_c$ | 8300 Oe |
| Intrinsic coercive force, $H_{ci}$ | >20000 Oe |
| Energy product, $(B_dH_d)$ max. | 18 x $10^6$ G·Oe |
| Reversible temperature coefficient, to 250°C | −0.04%/°C |
| Reversible permeability | 1.0-1.1 |
| Curie temperature | 700°C |

### Physical properties

| | |
|---|---|
| Density | 8.2 g/cm³ |
| Hardness | 50 $R_c$ |
| Electrical resistivity | 60 ±2 micro ohm cm |
| Coefficient of Electrical Resistivity, 20°C to 300°C | .175 micro ohm cm/°C |

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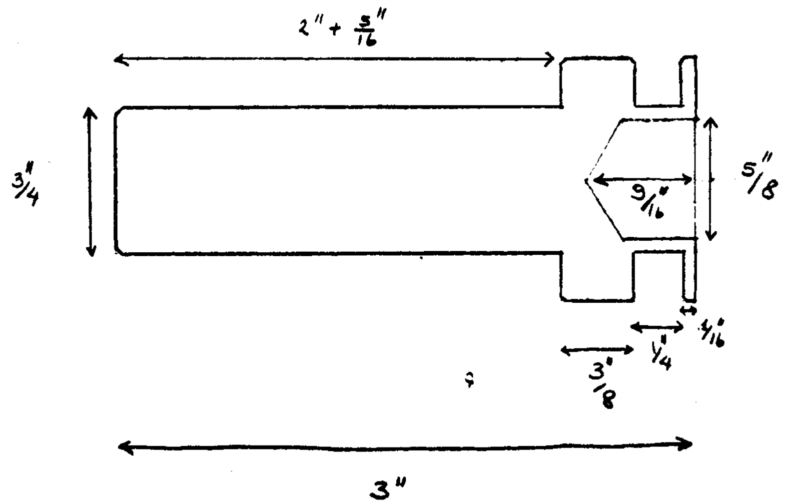
April 29, 1987
Yobta

# The Coil Former

Material: DELRIN

Quantity: 5




Average Coil radius = 0.5"

Actual Size. 1:1

Fig 2

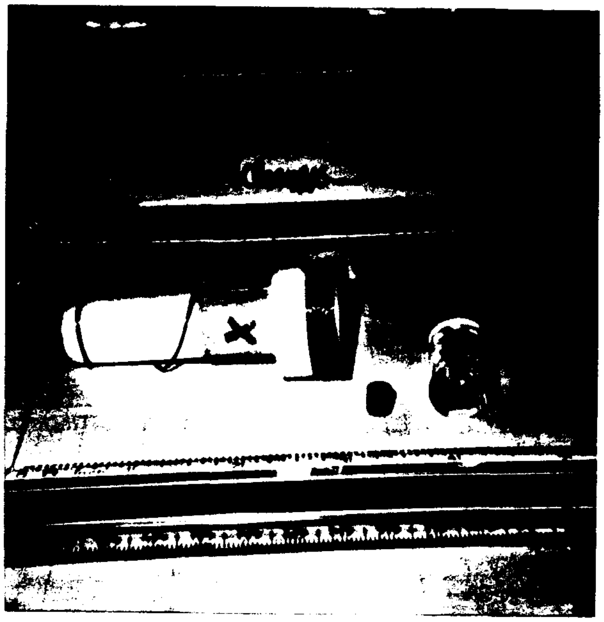


Figure 3

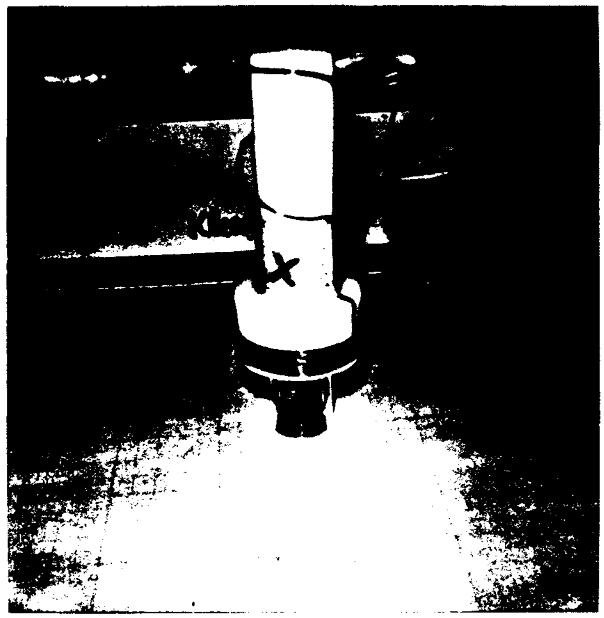


Figure 4

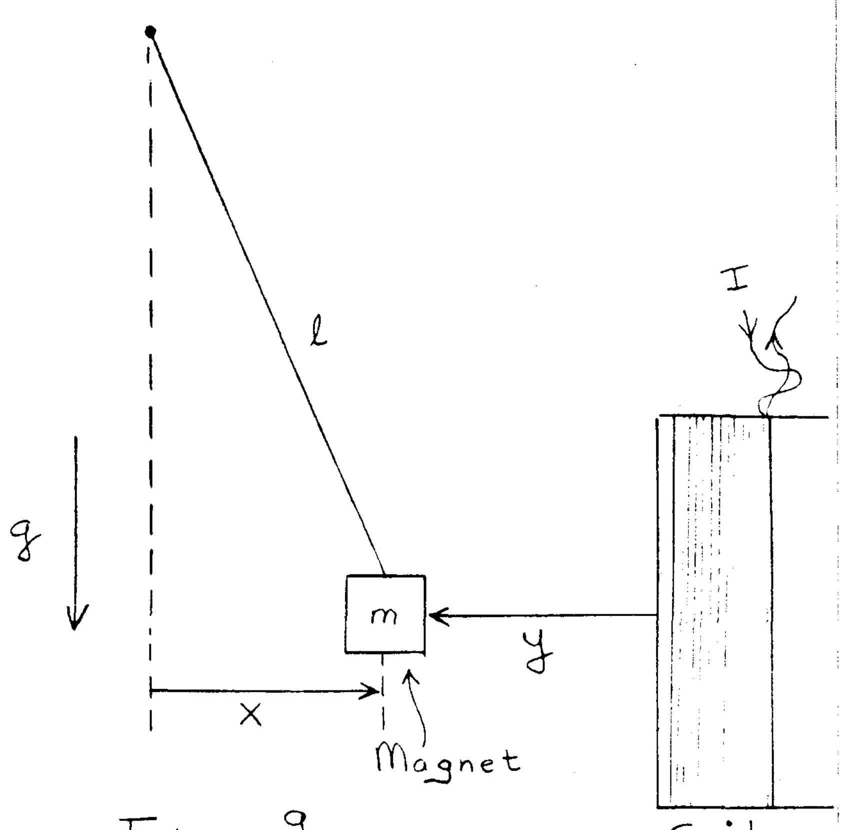



Fig. 9

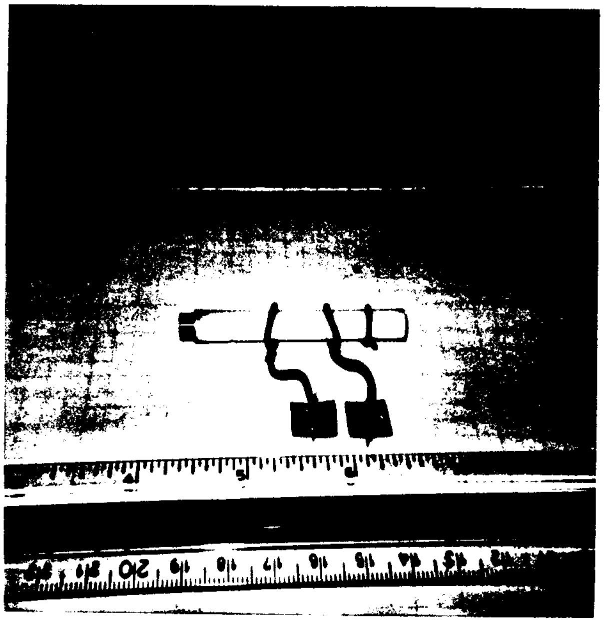


Fig 5

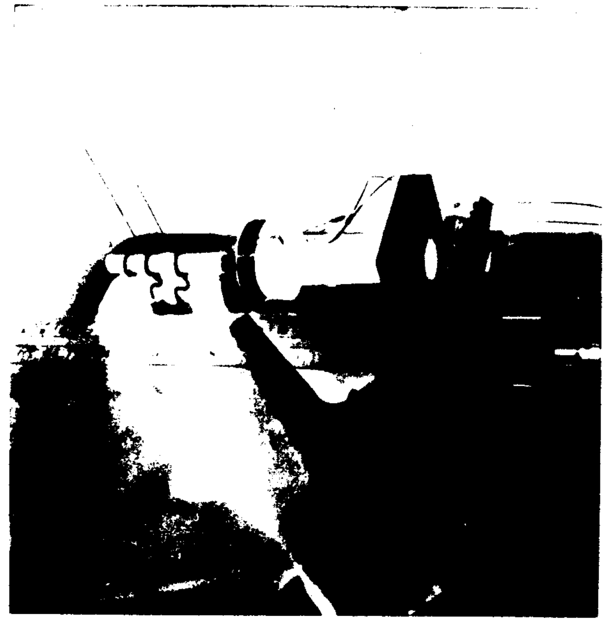


Fig 6

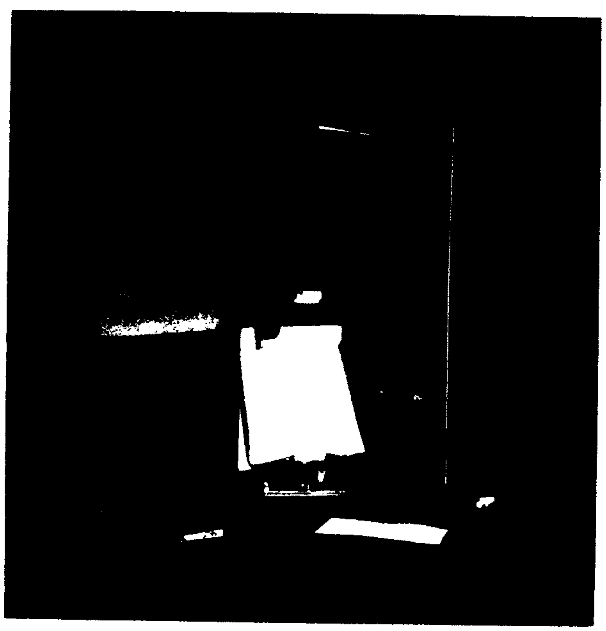


Fig 7

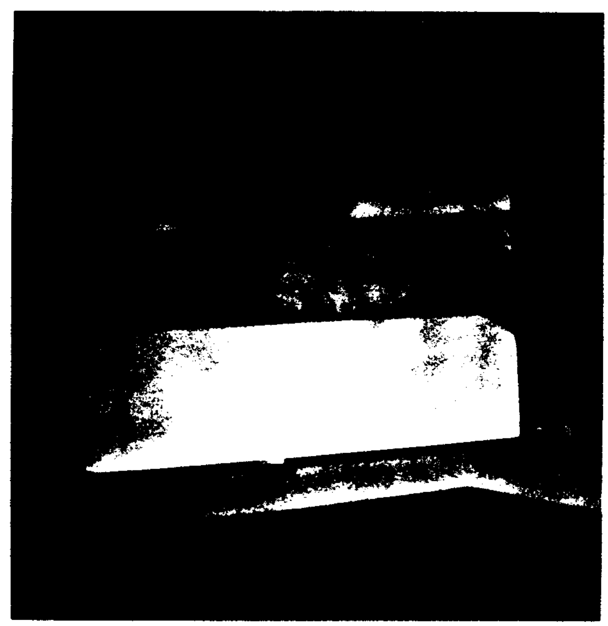


Fig 8

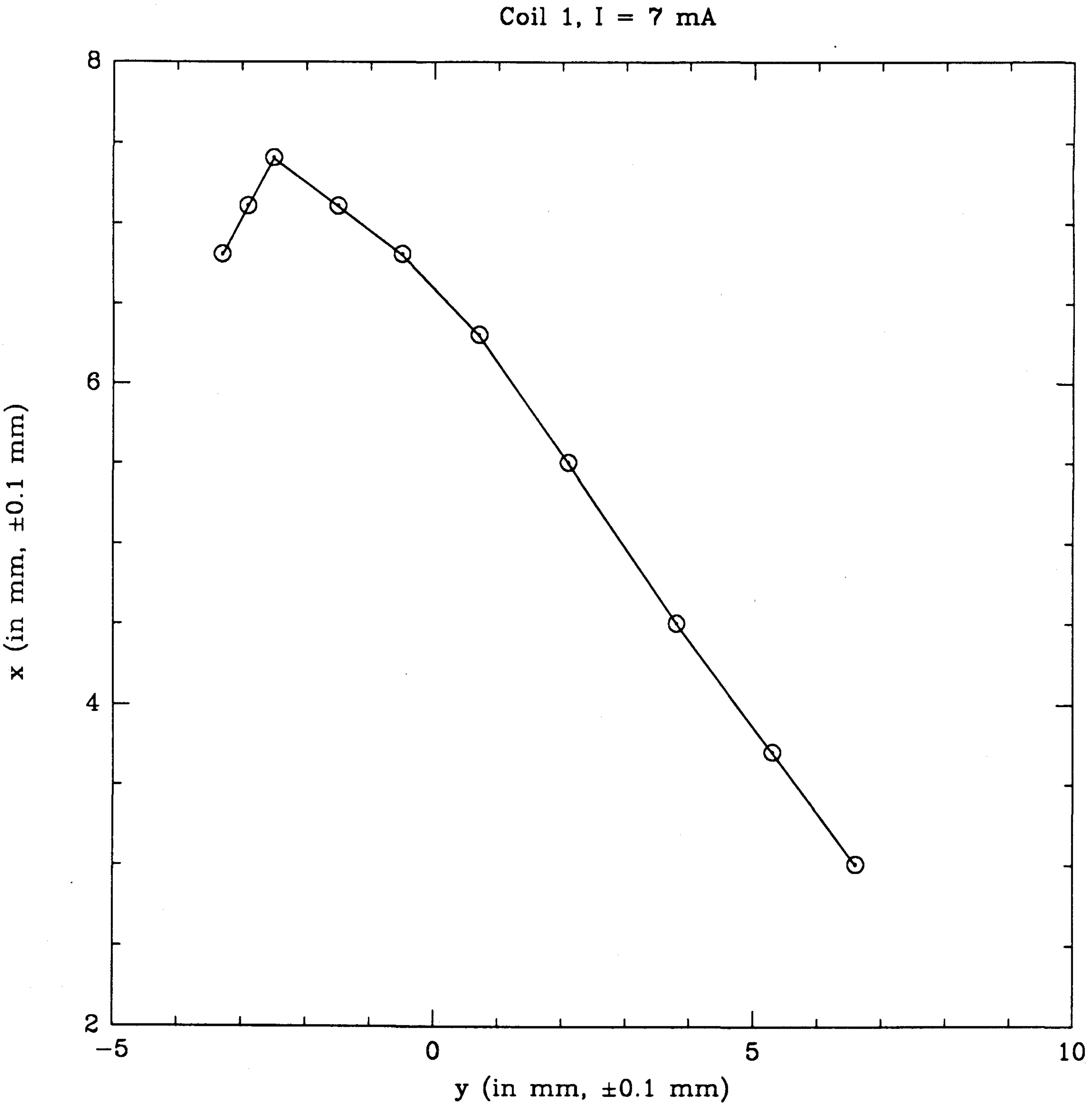



Fig 10

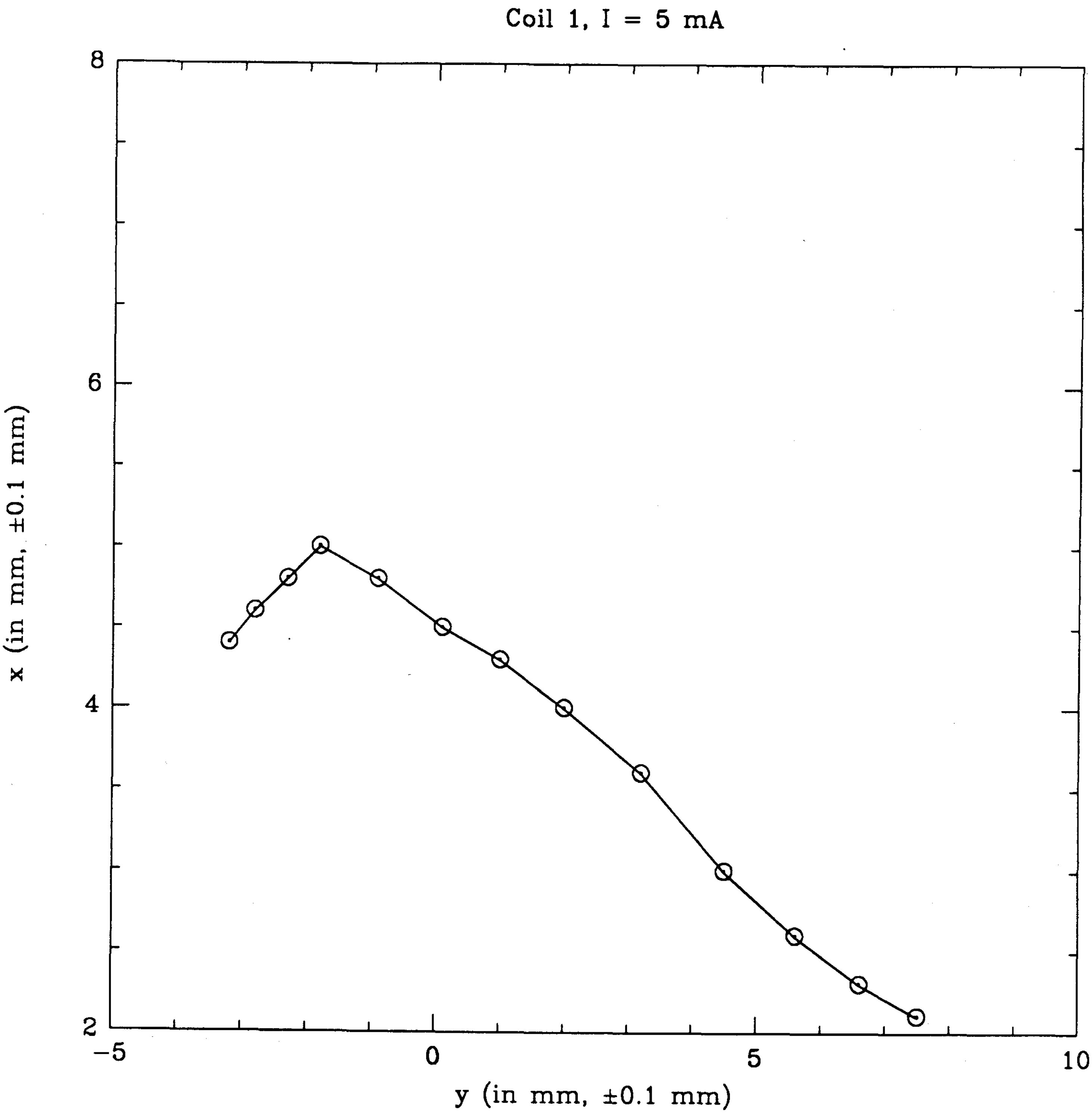



Fig 11

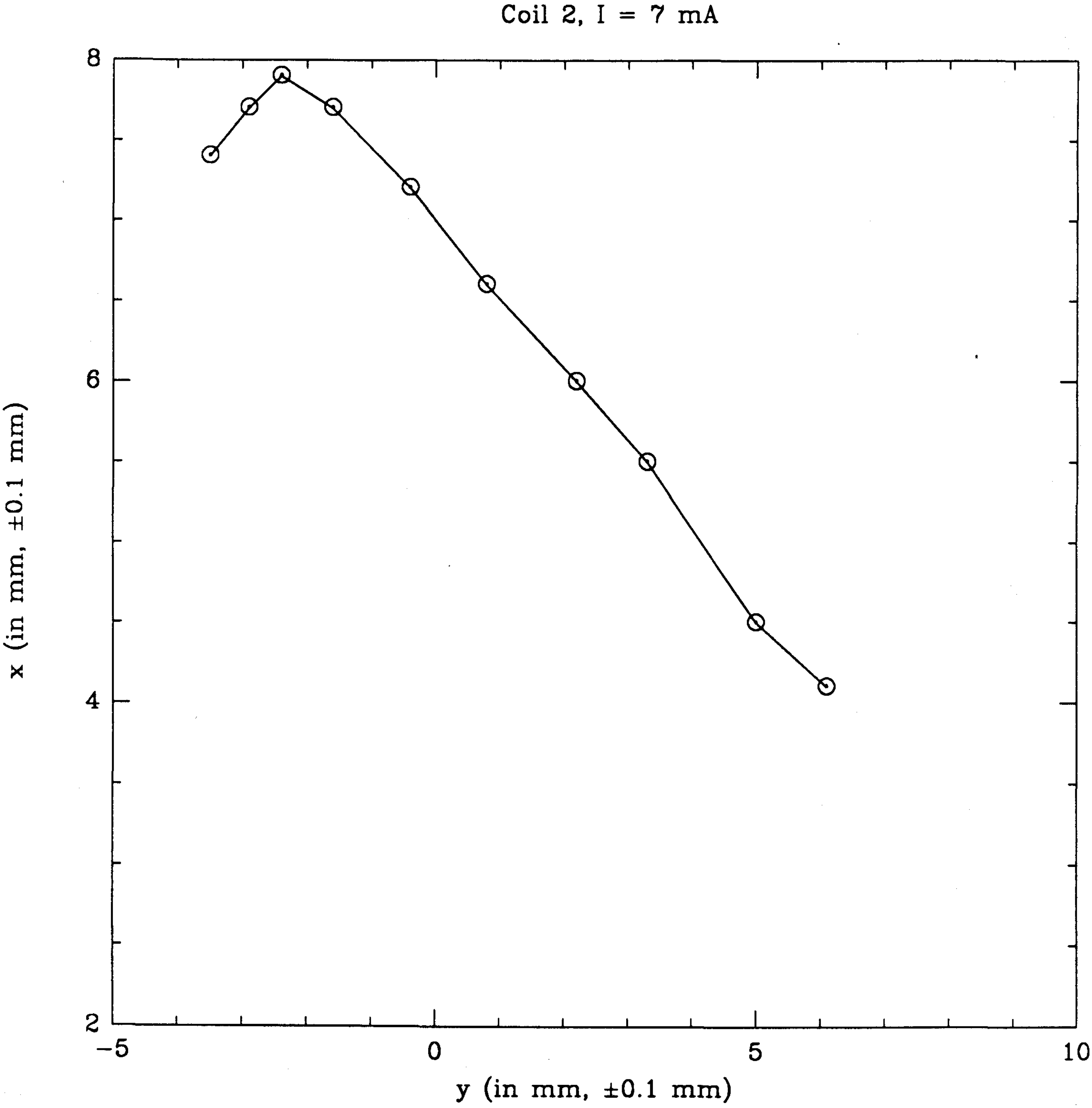



Fig 12

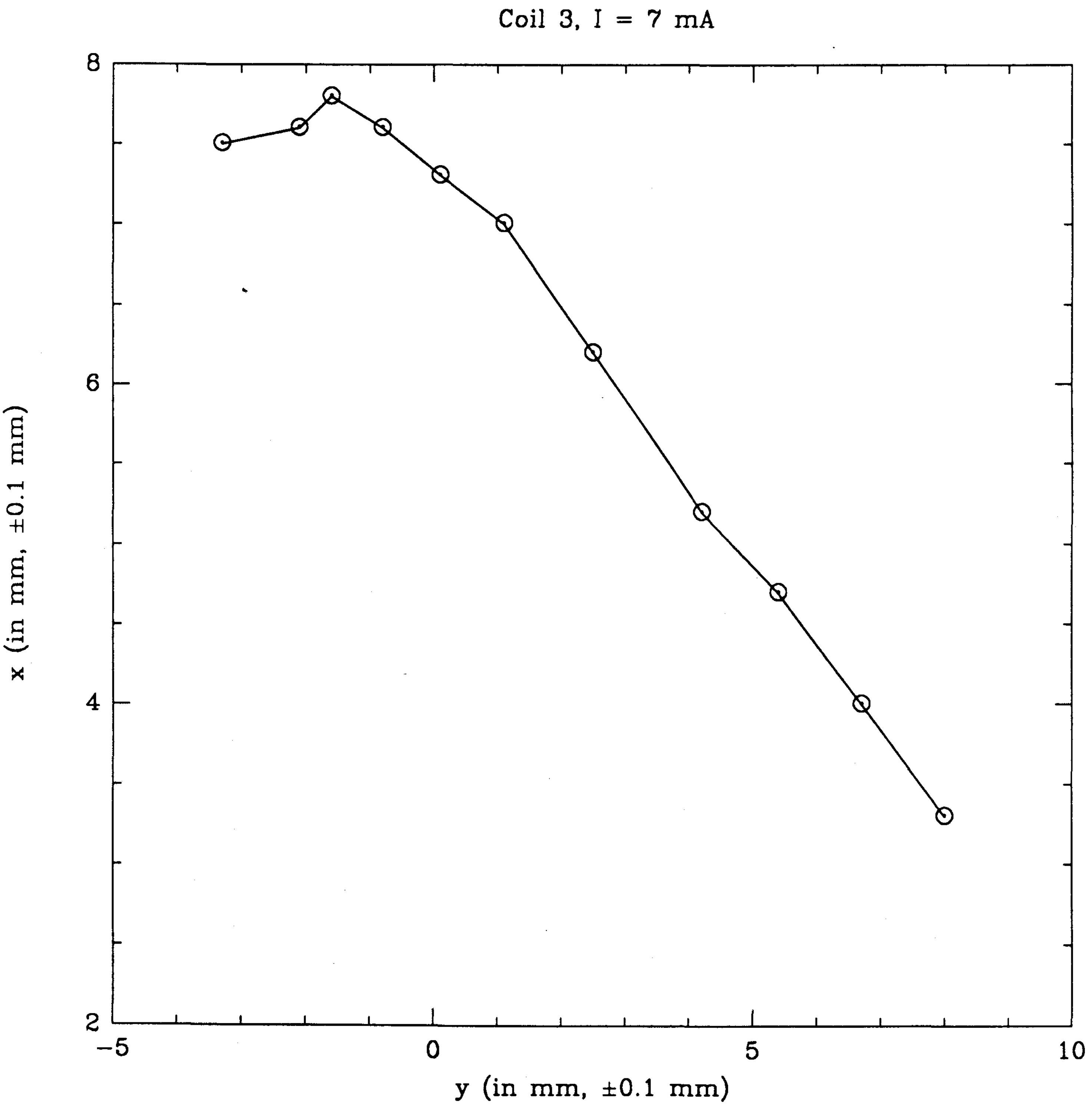



Fig 13

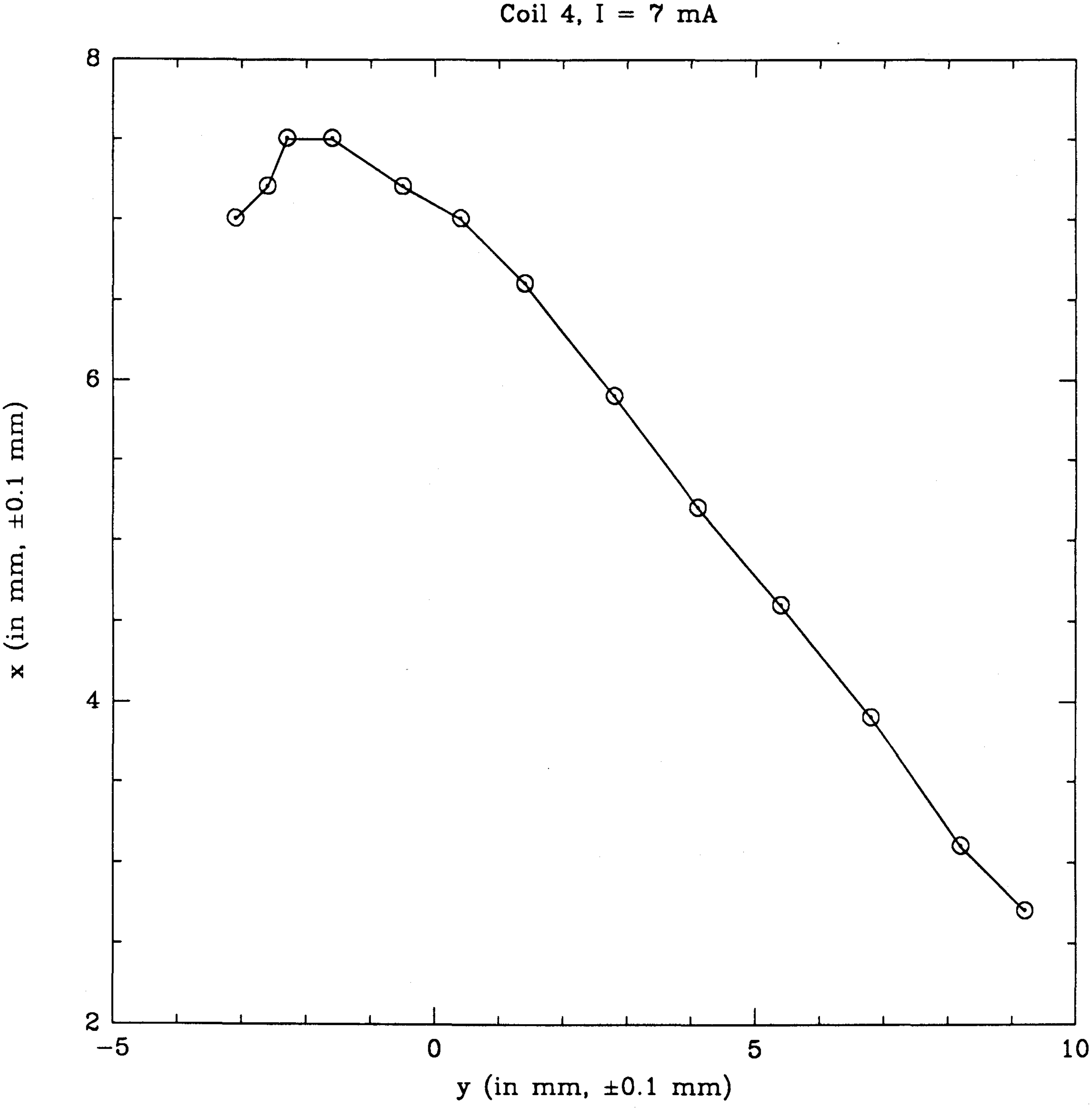



Fig 14