The Electronic Alignment System at the Fermilab DØ Detector

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1. A Surveyor's Overview of the DO Detector

The DØ detector is a general purpose detector of products from high energy pbar-p collisions in the Tevatron. It is scheduled for first operation in July 1991.

Like most collider detectors, the DØ detector (Fig. 1) is constructed in shells. The Tevatron beam tube, carrying the proton and antiproton beams, passes through the center of the detector. In addition, the beam pipe of the Main Ring passes through all three calorimeters and through the end iron walls. The Main Ring will continue to operate during beam stores to make antiprotons for the next machine fill. Clearly this beam tube poses design problems and potential radiation background problems, which are, however, not the subject of this discussion.

Starting from the collision point, the produced particles encounter the beryllium beam tube at 2.5 cm radius, a vertex chamber out to 12 cm radius, and a drift chamber assembly with embedded transition radiation detectors. In the forward directions tracking is done by drift chambers only. All detectors mentioned so far are mounted within a 90 cm radius Aluminum support tube. As far as alignment of the tracking detectors is concerned, it is this tube that must be placed in a known position.

The aluminum tube rests in the "donut-hole" of the Central Calorimeter (CC). In addition to the CC there are two *End Calorimeters (EC's)*, which have a very small hole, just large enough to accommodate the 5 cm Ø beam pipe. All three calorimeters are of the Uranium/liquid

Argon type and consist internally of an electromagnetic and several hadronic detector shells, all finely segmented.

The CC and both EC's are supported by the *Central Beam,* which is a 1m wide x 1m thick x 9 m long piece of steel, running along the proton beam direction (the z-axis). The Central Beam rests on the *Platform,* which consists of two crossed pairs of box-beams, each 81 cm wide and 137 cm high, made from 3.7 cm thick steel plate. One pair of beams is oriented along the proton beam (z-axis), while the other points in the x-direction, across the proton beam.

The tracking chambers and calorimeters are surrounded on all sides by the *Muon Detection System.* The Muon Detector consists of a shell of magnetized iron and three shells of *Muon Chamber* planes.

The *iron* is divided into four major iron parts. They are the two *Central Iron (CF)* halves and the two *End Iron (EF)* pieces.

The CF halves match to form an open-ended box, with 1 m thick walls when the detector is ready to take data. They ride on rollers atop the transverse pair of platform beams. They are driven apart (by hydraulic cylinders) for access to the central detectors, and closed up for data taking.

The CF "open-ended box" is closed off by the two *End Iron (EF)* pieces. Each End Iron consists of a 1.5 m thick vertical wall of magnetized iron, 9m wide x 9m high, with a 1.5m x 1.5m square opening at the center. The openings contain each a "small" 35 ton toroid as part of the small angle muon system. The small toroids pose no new alignment problems. Each EF rides on rollers on rails supported by the z-oriented pair of the platform beams, and can roll back 1.2 m in order to provide access to the central detectors.

The 164 *Muon Chambers* are arranged in three shells, completely surrounding the proton collision point. Starting from the collision point, the shells are called the A, B and C- layer. The A chambers line the inside of the iron shell, and are supported by the major iron pieces.

Most B and C chambers are mounted on trusses in single or multiple pairs of one B and one C chamber. The trusses are mounted on the top and sides of the CF iron halves and surround the EF's. The bottom B and C chambers roll on rails into slots intricately nested within the platform structure.

A steel framework (off the platform) on the "Sidewalks" of the hall holds up on each side a set of End Muon Chambers (EMC). The location of each EMC frame must be referenced to the detector elements on the platform.

2. The Alignment Problem at DØ

Five features combine to complicate the task of aligning the DØ detector and make it different from the task of aligning other experimental

apparatus:

-- The DØ detector has been designed to be as hermetic as possible. As a consequence, the inner elements can not be seen or surveyed when the detector is in its closed operating configuration

-- The iron components of the detector have been shown to move under the action of magnetic forces when the magnetizing current is switched on. The magnetic closing force takes up previously available slack.

-- Because the detector is so nearly hermetic the major iron pieces must be moved out to allow access for repair, modification, testing etc.. When re-closing, the iron pieces will be in a slightly different position every time they are moved.

-- When the detector platform moves from the assembly hall to the collision hall, it will, to some extent, conform to the shape of the floor, which is not a perfect plane.

-- There will be some settling of the floor, both elastic (short term) and inelastic after it gets loaded with the detector mass. This settling may extend out to the low beta quad locations, which must be referenced to the machine lattice at a distance beyond the range of these settling motions.

3. The Reference System

All elements of the DØ detector must ultimately reference to a common coordinate system which includes the proton beam collision points and directions. The collision points (the “diamond”) lie on a line, approx. 1.4 m long and less than 0.1 mm in diameter.

The transverse position of the collision diamond can be derived from beam position measurements elsewhere in the machine, once the positions of the two sets of final beam lenses (the *Low Beta Quadrupoles)* are known. Thus, the origin and orientation of the detector elements is best expressed in a system defined by the proton beam direction, usually taken to be the line joining the centers of the two sets of Low Beta Quadrupoles, and by the direction of gravity. The center of the line joining the Low Beta Quadrupoles is the origin of the system, the nominal collision point.

The central tracking systems are all supported within the same aluminum cylinder (aligned optically to the low beta quadrupoles), and find their own location by vertex reconstruction from tracks, once data taking starts.

By contrast, the muon detection system is supported independently by the four major iron pieces, by the platform, and by the EMC frames. Yet the muon chambers must be referenced to each other, and to the central tracking system, to an accuracy comparable to the muon drift chamber resolution, which is about 0.3 mm. Thus the muon system poses the greatest challenge of establishing adequate alignment and maintaining it over time.

4. Major Detector Pieces: Locations and Fundamental Deformations

All muon chambers are attached to one of the major detector pieces:

-the platform (inner tracking chambers)

-the central beam

-the two central iron halves

-the two end irons

-the two EMC frames

We take the view that the mounting hardware for individual chambers is stable enough and well surveyed, and need not be monitored. If we know where the major detector pieces are, and if we know their fundamental deformations (where applicable), then we can know where each chamber is.

The **platform** is analyzed here as a sheet that can only warp in the vertical (y) direction. The projected shape is assumed to be invariant. This assumption is justified by the near absence of horizontal deforming forces.

Consequently, the platform *shape* can be monitored by measuring the elevation of a sufficient number of points on the platform.

The elevation at ten selected points (see Fig. 2) chosen to lie directly underneath the iron piece support points, is obtained from a liquid level system, made from interconnected pools with electronic readout.

The platform *position* can be determined from:

-the platform absolute elevation

-the platform position horizontally in x and z relative to the proton beams (via hall monuments)

-the platform rotation (about the y-axis) relative to the proton beams, via hall monuments (bench marks).

This information will be acquired from a set of docking sensors, which measure the gap to surrounding hall monuments.

The location of the **platform docking sensors** (Fig. 2) must be expressed in the system of the low beta quadrupoles, as described above. This alignment refers to

-position along the beam

-horizontal position across the beam (x)

-rotation about the vertical (y) axis

-elevation.

The position along the beam (z) is used for tracking between platform chambers and forward (EMC) chambers. Its value relative to the accelerator is not critical, since the beam interaction zone is long (sigma=0.7 m).

The docking sensors for x determine the platform position in the x-direction (across the beam). They reference the x-position of the low beta quadrupoles. Together with the z-docking sensors they also measure the rotational alignment.

The docking sensors for elevation (y) will also reference the low beta quadrupoles. These x and y references to the low beta quadrupoles may be obtained by a pair of vertical invar rods, one hinged to each quadrupole, and socketed near ground level, which carries each a pair of tilt sensors for angle, and a proximity sensor for height.

The **Central Beam** is welded to the platform; hence its location, rotation, and elevation are known. The central beam location and leveling is very important information since the central calorimeter (with the inner tracking) is fixed on the central beam. In addition the two end calorimeters move along the central beam on precision guided roller assemblies. The calorimeters and central tracker have their centers 4.5 m above the central beam. An 0.1 mrad tilt of the central beam moves the detector centers by 0.45 mm. Therefore this tilt (and the twist of the central beam) is carefully monitored by six tiltmeters distributed along the central beam.

The **Central Iron (CF) halves** will undergo displacement due to opening/closing and also fundamental mode deformation under the action of magnetic forces and warping of the platform. Since the CF's rest on the platform, the CF location is best expressed relative to monuments on the platform. This is done with a system of guidance and docking sensors.

The CF deformation, e.g. warp of its 4-point support plane, twist and bending due to magnetic forces, is monitored with a set of 8 bi-axial tiltmeters on each CF half, located near the comers (Fig. 3).

The **End Iron (EF)** will undergo displacement due to opening/closing. Due to its shape and support style and the absence of relevant forces, deformations are expected top be negligible. Nevertheless, 4 bi-axial tiltmeters located near the EF corners (Fig. 4), will monitor each EF.

There are no plans at present to monitor the **EMC frames** electronically; the frames are located near vertical walls of the hall and are readily accessible to conventional optical monitoring.

The location of the **low beta quadrupoles** will be referenced to the accelerator lattice away from the collision hall at a distance of, perhaps, 20 meters. This will be done in elevation only, the most likely motion under settling forces. The sensors will be liquid pools, positioned at each of the component quadrupole lenses, and at a few monument points. This is done mostly for the benefit of accelerator operation.

5. Sensor Types and their Properties

5.1 Sensor Requirements

All sensors will have to operate for periods of a year or more between conventional surveys. Therefore long-term stability is the determining criterion for their usefulness. To detect sensor failure, enough sensors must be deployed to allow cross checks. Sensors should respond to any changes with a time constant of a minute or so. This suppresses sensitivity to brief disturbances while allowing live monitoring during platform motion, experiment closing and magnetic field turn-on.

Three sensor types are used to acquire the necessary information:

-the liquid level system for the platform and tunnel magnets

-the tilt sensor system on the major iron pieces

-proximity sensors to acquire docking data.

5.2 The Liquid Level Sensing System

The platform level sensing system is based on a number of interconnected liquid filled pools, as shown in Fig. 5. The liquid levels in the pools will reach a common height.

The pools communicate with one another via two sets of tubing (clear vinyl or polyethylene), one for the liquid interconnects and another for the air spaces. The system is sealed off from the atmosphere. This is to avoid evaporation of the liquid and to prevent level errors due to small local variations in atmospheric pressure, e.g. due to air currents. A reservoir mounted on a vertical machine slide is available to raise or lower the liquid level in all pools simultaneously. This is used for pool calibration and to extend the measurement range of the system if some pools should bottom out (or top out) due to an excessive tilt of the platform.

The original prototypes used mercury as a liquid, sensed by AC magnetic proximity sensors. The detection method is insensitive to surface contamination and surface waves. The mercury system had a system limit of error of 1 to 2 mils over more than a year. But environmental and safety concerns led us to switch to water or oil as a liquid, with capacitive sensing. We are currently testing a prototype capacitive system[1] for this application. The capacitive proximity sensors are driven by nearby drive modules and have a nearly linear response (Fig. 6). The stability of the test system appears adequate (Fig. 7 and 8), but more tests are needed to understand the residual drifts and to select the best suited liquid.

5.3 The Tilt Sensor System on the Major Iron Pieces

The attitude of the major iron pieces is monitored by gravity referenced tilt meters. We aim to monitor the top location of a 13 m high piece of CF (with chambers) to 0.5 mm, then the tilt meter must exhibit a long term drift of no more than 40 micro radians.

A suitable sensor is commercially available[2], and the drive circuitry[3] has been developed by a group at the California Institute of Technology for geological applications. Dr. Westphal from that group has sent me a set of electronics, and R. Marquardt of the Fermilab AD Controls group has modified the electronics to work with capacitive coupling, rather than transformer coupling, to remove the effects of magnetic fields. The sensors are mounted in pairs on aluminum thermal blocks containing a heater circuit that holds their temperature stable within ± 0.05 Celsius. Fig. 9 shows the design and electronic connection.

We have performed many calibrations and long term drift tests in the laboratory. The sensors have a nearly linear response to tilt angle,

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[1] Made by CAPACITEC, P.O.Box 819, 87 Fitchburg Road, Ayer, MA 01432, USA, Tel. (508) 772-6033

[2] Electrolytic bubble tilt meter, Model 0711-0701-99, Radius 7 inches, made by The Fredericks Co., P.O.Box 67, Huntington Valley, Pennsylvania, 19006

[3] "Expendable bubble tiltmeter for geophysical monitoring", by J. A. Westphal et.al., Rev. Sci; Instrum., Vol. 54, No. 4, April 1983

but require additional terms to reach their full accuracy. Long term drift measurements (Fig. 10) are consistent with a drift range of ± 20 microradians over a one year time for most sensors.

We have also operated four tiltmeter attached to the bottom face of the central beam. The output voltages were sent to a Scanner /DVM/ Macintosh computer. Each tiltmeter had a parallel "P" bubble and a transverse "T" bubble. The "P" bubble measured tilts about a North-south axis, while the "T" bubbles measured tilts about an East-West axis.

Fig, 11 shows the response of the four P and T tiltmeters. When the central iron (CF) was closed, the P sensors were unaffected, while all four P sensors changed by about 70 microradians, presumably due to platform deformation when the load was shifted. When the magnet was energized (Fig. 12), additional tilts were observed in the four T bubbles. This time, however, the tilt was near zero for bubble A and increased roughly linearly with location to bubble D, which showed about a 100 microradian increase. Evidently, the central beam was being twisted, presumably due to the magnetic clamping in the jaws of the CF's. 100 microradians correspond to a 0.05 mm motion at each corner of the central beam. By the way, the pitch of the central beam "screw" is about 42 kilometers.

These observed tilt angles can not be neglected. A detector module 3 m above central beam will suffer displacements of 0.5 mm under the kind of tilts observed above. Once we move the platform, larger deformations can be expected to occur.

5.4 Proximity Sensors for Docking

We sense the distance to iron pieces with AC eddy current detectors[4] that provide a sensing distance of about 1 cm to steel, with linear response. The elctronic circuit is contained in each sensor. The sensor readings are stable to within ± 1 mil/year.

When the muon toroids are excited, their stray magnetic fields can reach up to 100 Gauß The iron used in the proximity sensors begins to saturate at those field levels. It was found experimentally that a 1/8 inch wall iron tube around the sensor reduces the stray field effect below 1 mil equivalent. This tube also protects the sensors mechanically from the harsh environment.

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[4] Proximity sensor made Microswitch division of Honeywell, model 924AB4W-L2P

6. Data Acquisition, Software and Use of Data

6.1 Electronics

Every muon PDT module contains a monitor card with a multiplexed ADC and readout capability to the host computer.

A multiwire cable carries supply voltages to from a nearby PDT module to the tilmeter assembly, and returns the readout voltagesfor digitizing and readout.

6.2 Host Resident Software

The host computer software will combine four types of information to generate absolute detector position data. These are:

1. Data from conventional surveying regarding the shape and relative position of the iron pieces, the “Baseline Survey”

2. Readings from the alignment sensors taken simultaneously with the above mentioned optical survey data

3. Position information of individual detector elements relative to monuments on the iron pieces, obtained by conventional surveying

4. Current alignment sensor data.

The host computer will determine the change in sensor readings that occurred since the last optical survey, and add that change to the Baseline Survey, to determine the current position of the iron pieces.

To get the current position of all the detector elements, their offsets relative to monuments on the iron pieces are added in. The result will be available to analysis programs and live displays.

6.3 On-Line Position Information

The host computer will be able to send numbers and graphs about the current location of the iron pieces to a portable Mactinosh or other computer located close to the experiment. The information aids the installation crew in the correct docking and leveling of the platform when moving into the collision hall.

In addition, any possible sagging of the hall floor will be monitored "live" due to the tie-in of the quad elevations to remote tunnel locations.

When closing major iron pieces, the sensors will indicate proper engagement and, positioning. They will also point out incomplete closure, e.g. due to obstructions. Beam pipe centering information and stress data from beam pipe sensors will be displayed in the same way during closing.

When energizing the magnet coils, any motion of the iron pieces can be monitored and recorded.

7. Status and Conclusions

We are in the process of installing all tiltmeters this summer. Most of the guidance proximity sensors on the platform are installed and need to be checked out.

The liquid level system will have to be modified for oil or water use. Also, long term stability tests are yet to be performed.

We plan to have the whole system installed, calibrated and continuously operating early in 1991.

Figures:

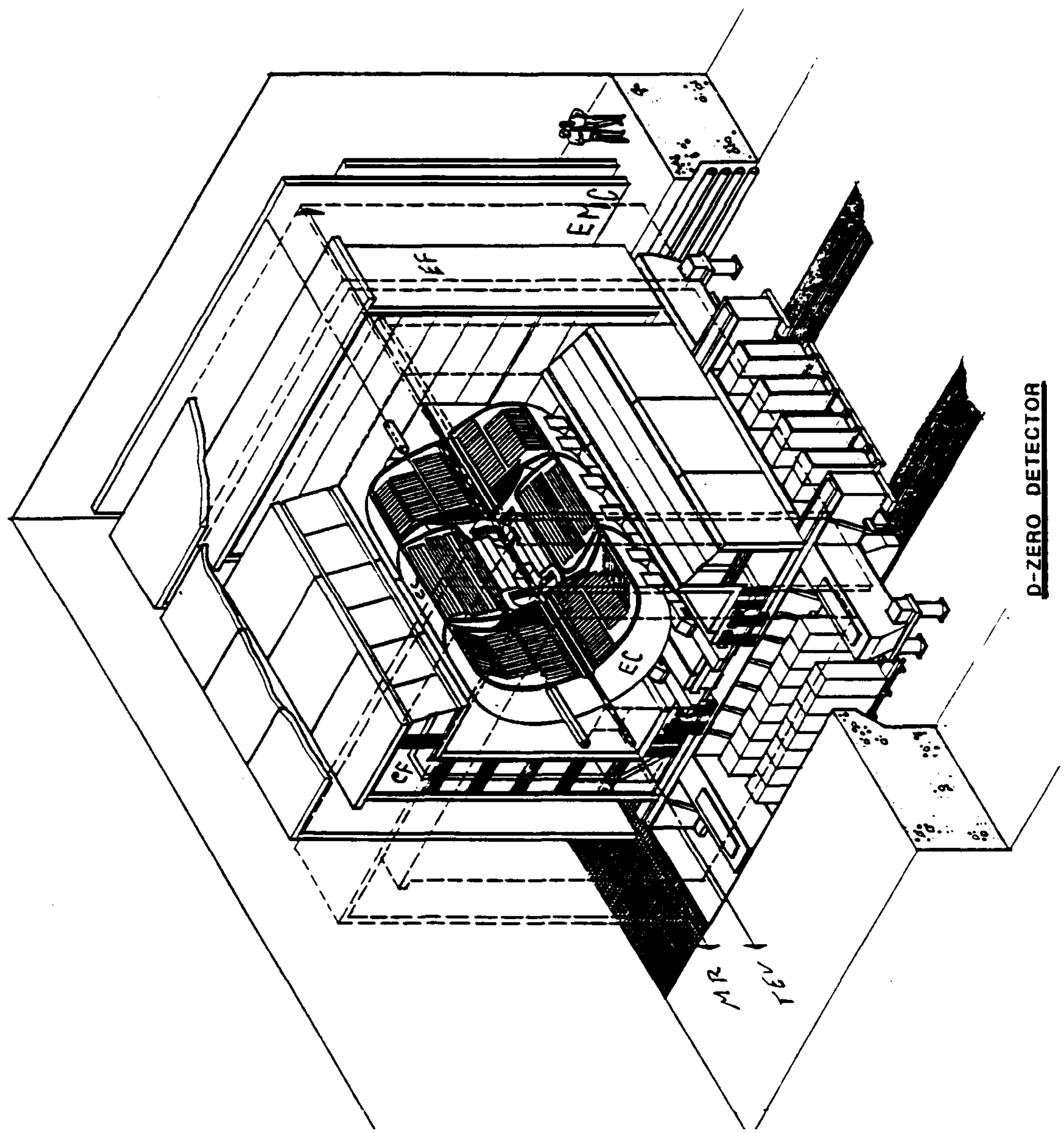


Fig. 1 Cut-away View of the DØ Detector

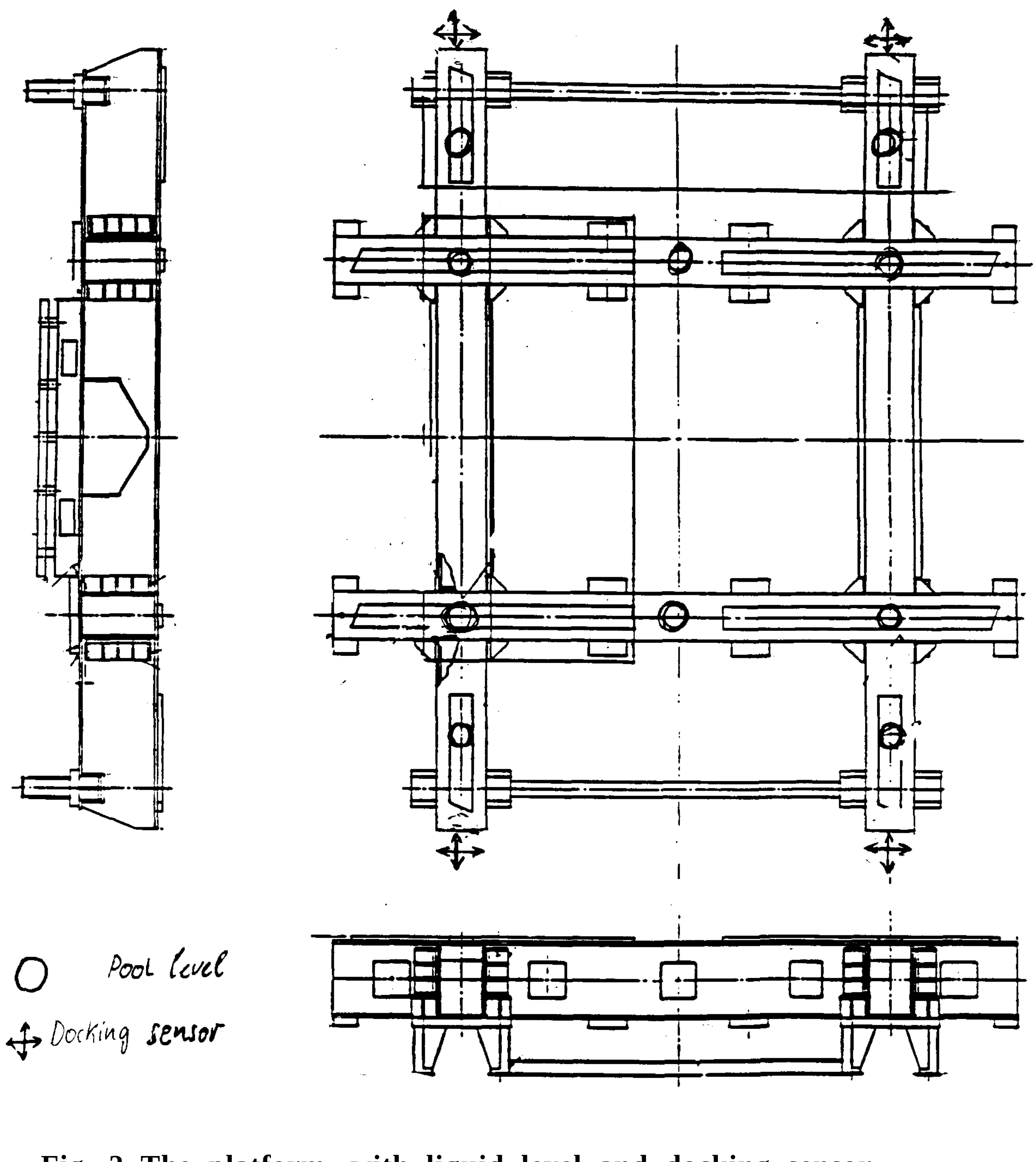


Fig. 2 The platform, with liquid level and docking sensor locations

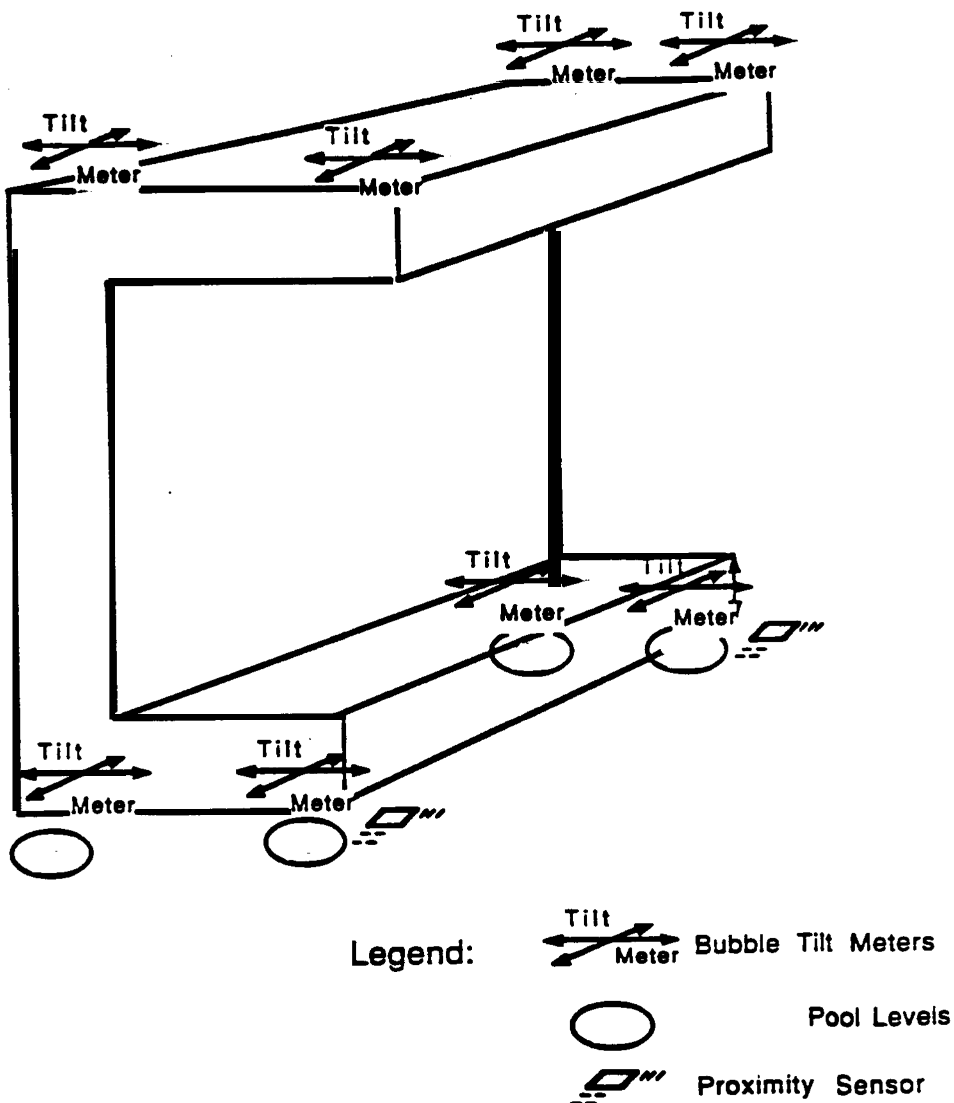


Fig. 3 Tiltmeters and Liquid Level Sensors on the Central Iron

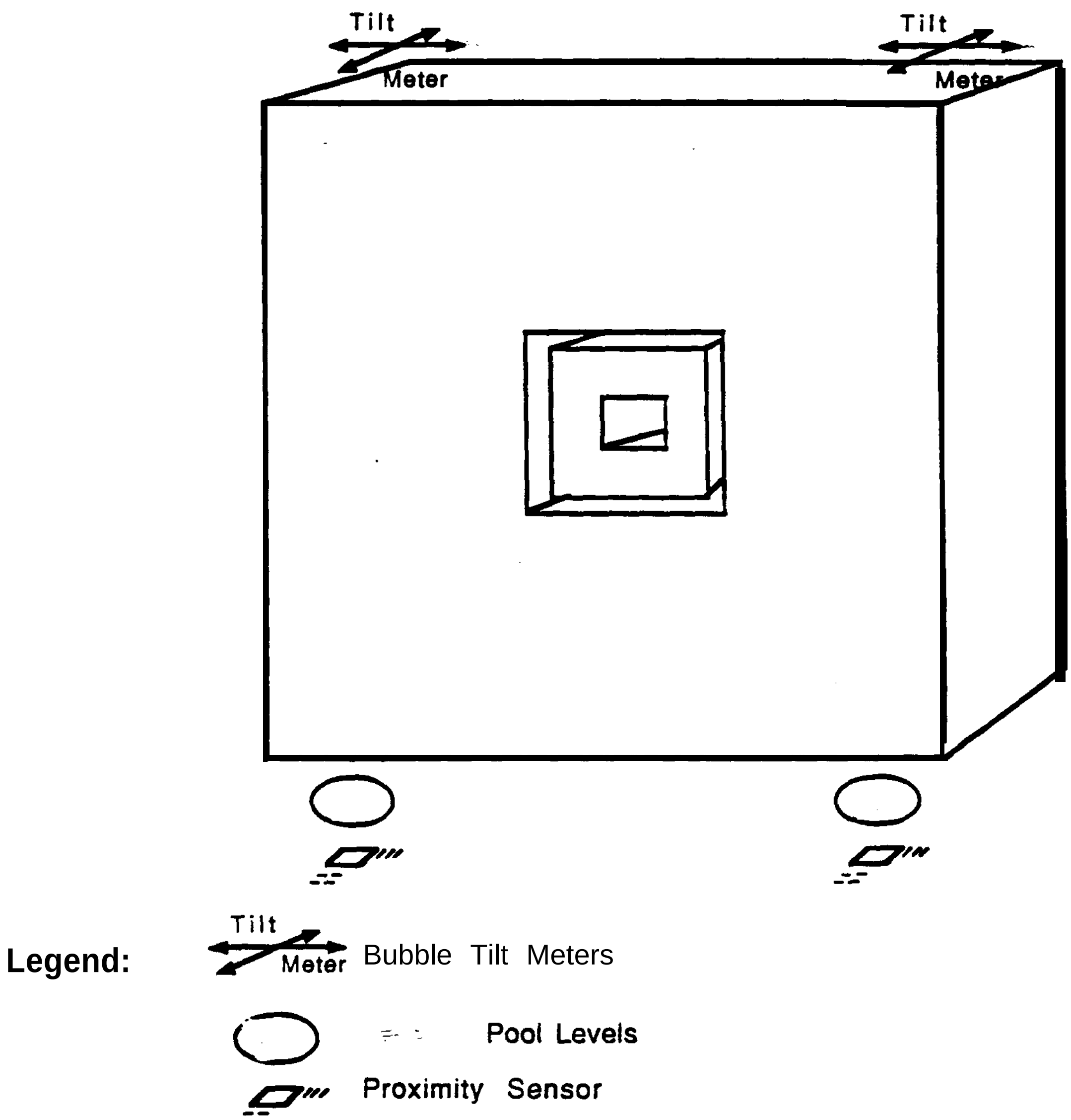


Fig. 4 Tiltmeters and Liquid Level Sensors on the End Iron

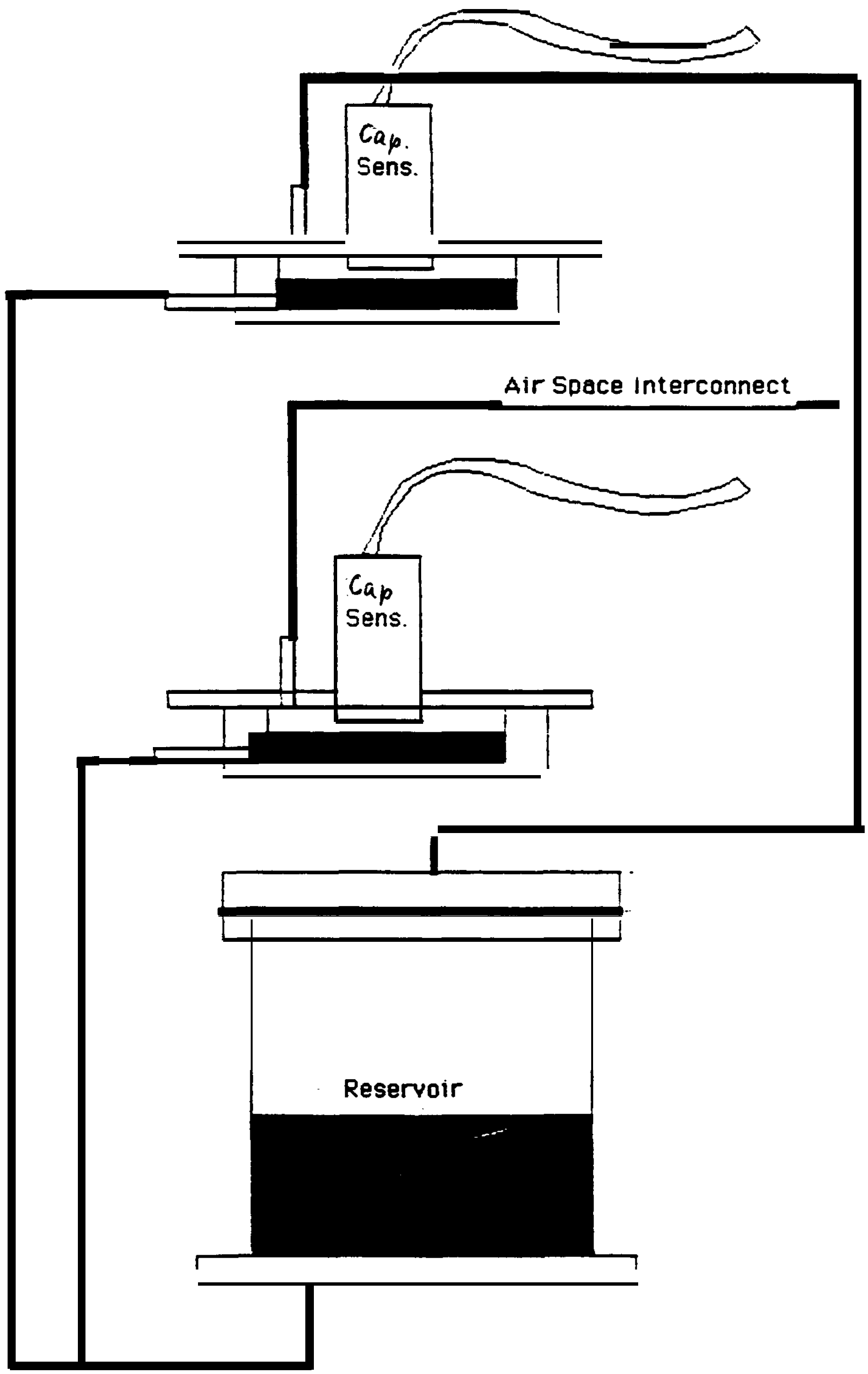


Fig. 5 Schematic of as Liquid Level System

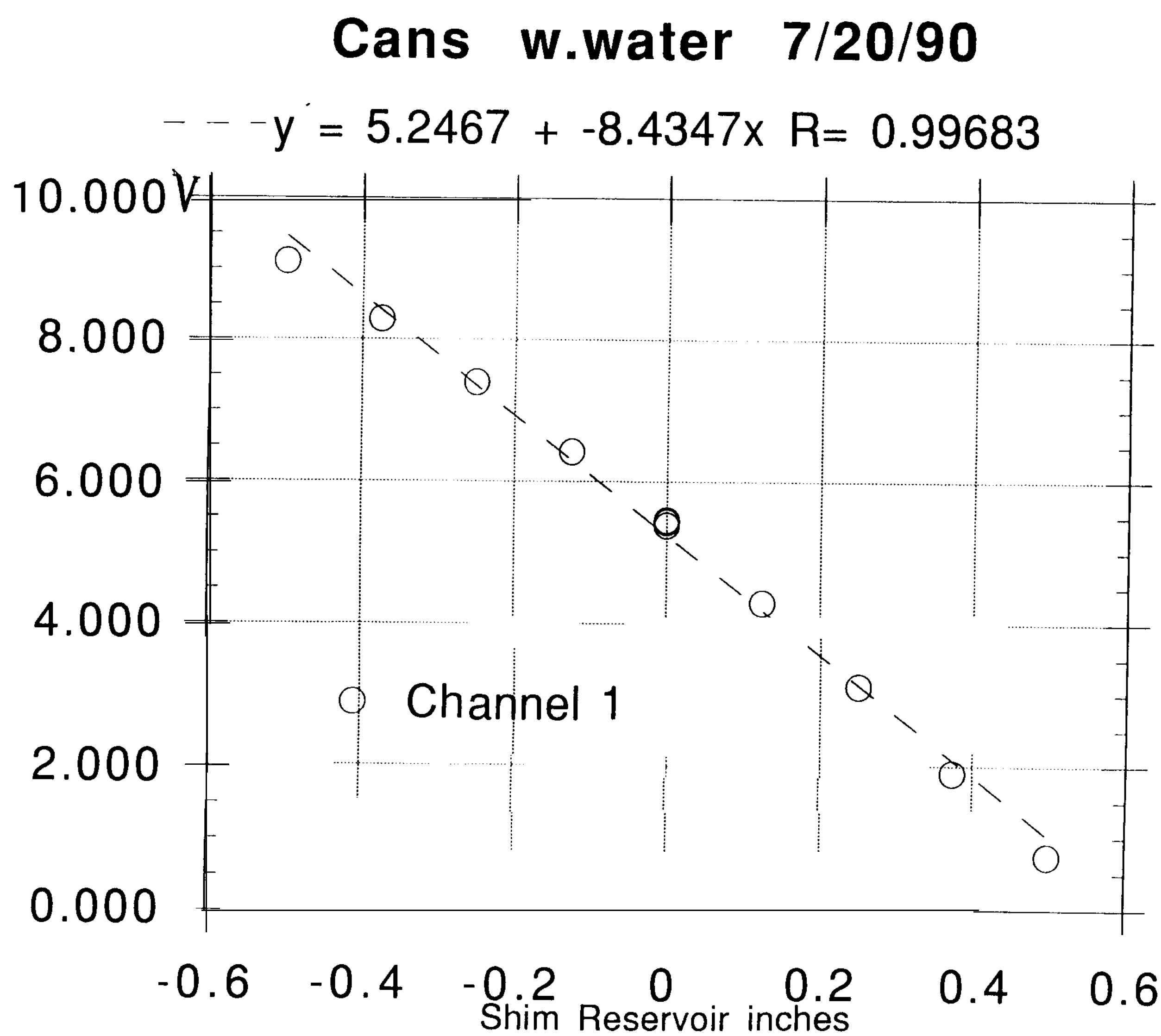


Fig. 6 Response Function of a Capacitive Sensor above Water

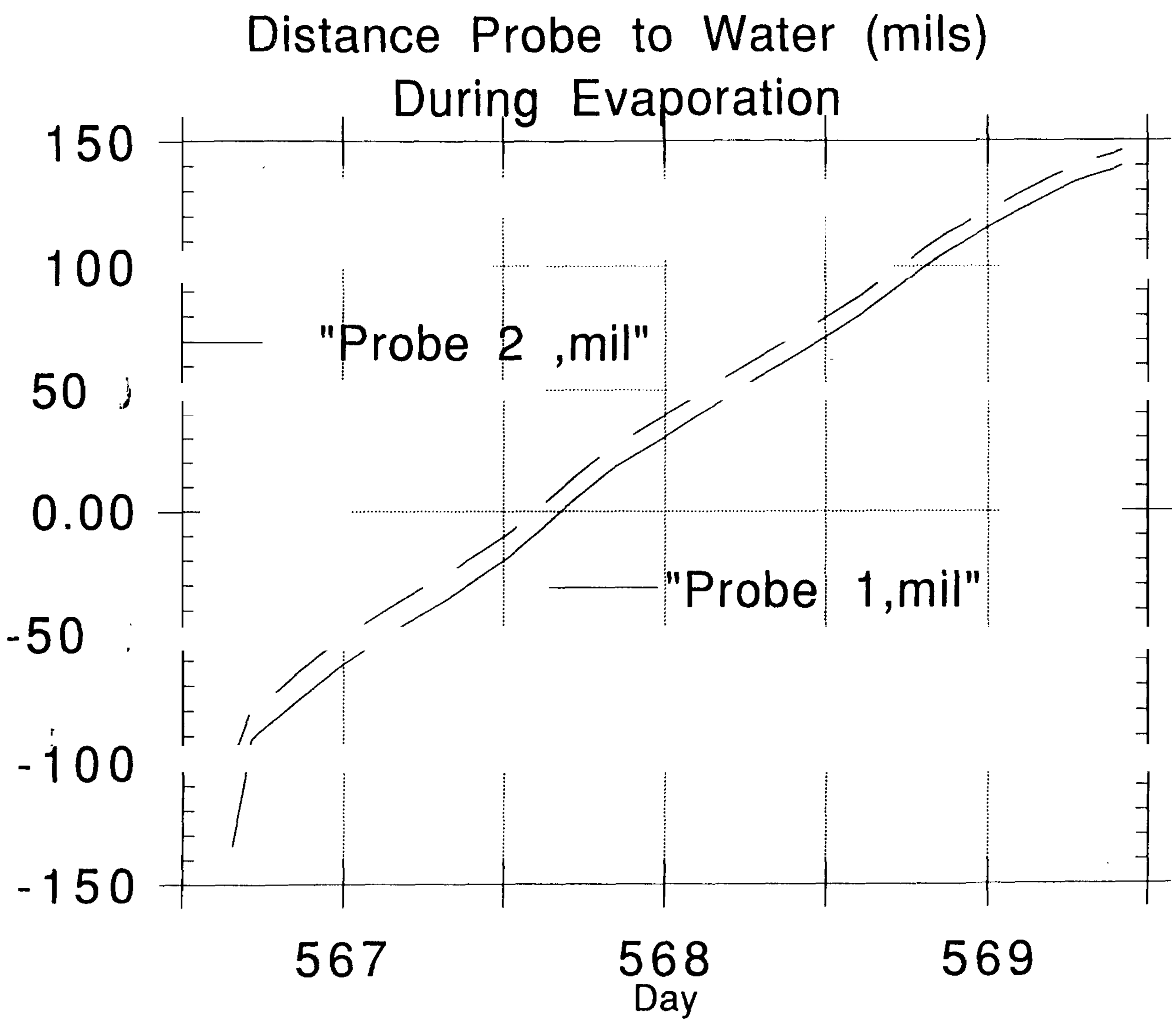


Fig. 7 Readback from two Interconnected Water Pools

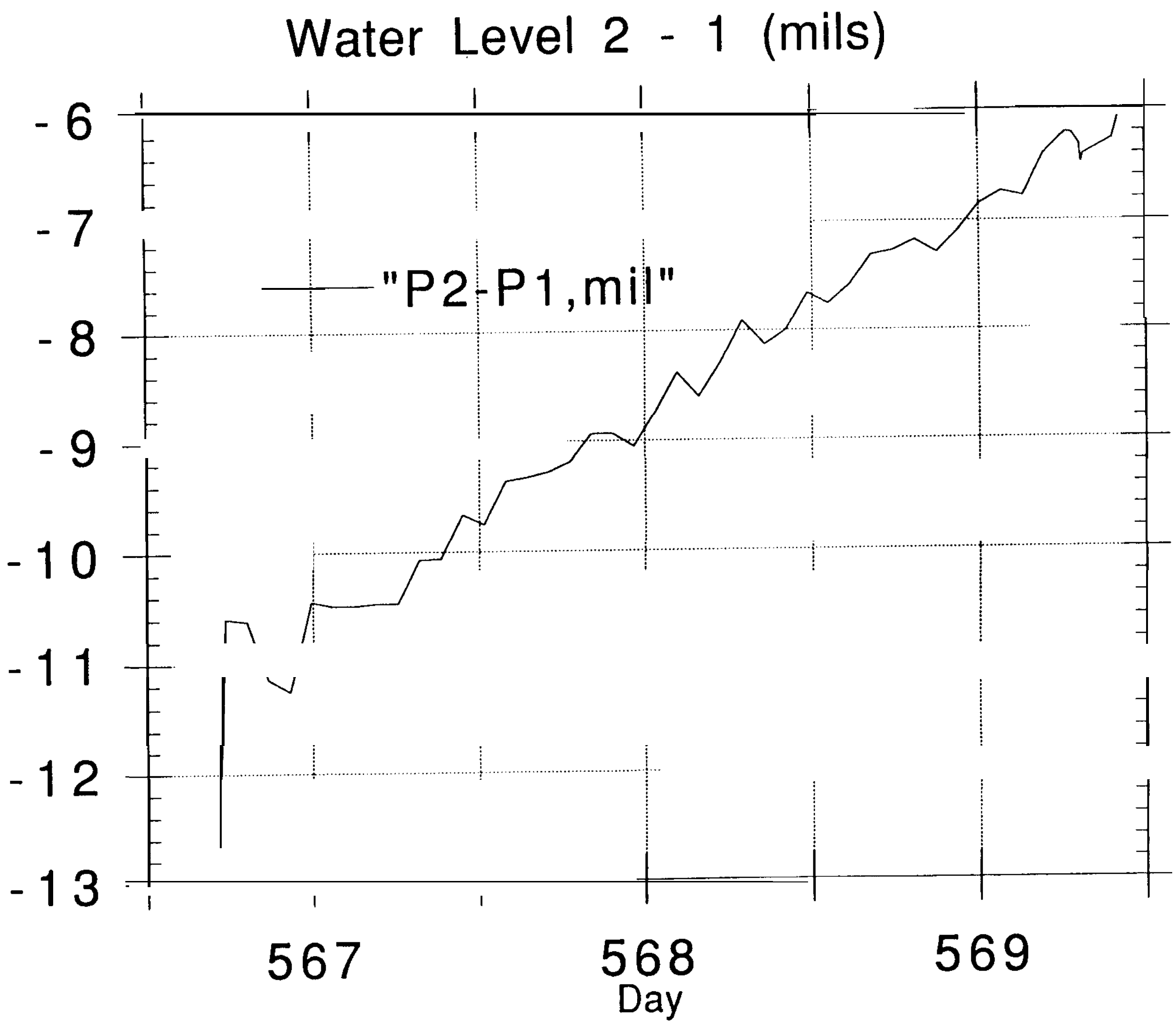


Fig. 8 Level Difference Readback rom two Water Pools

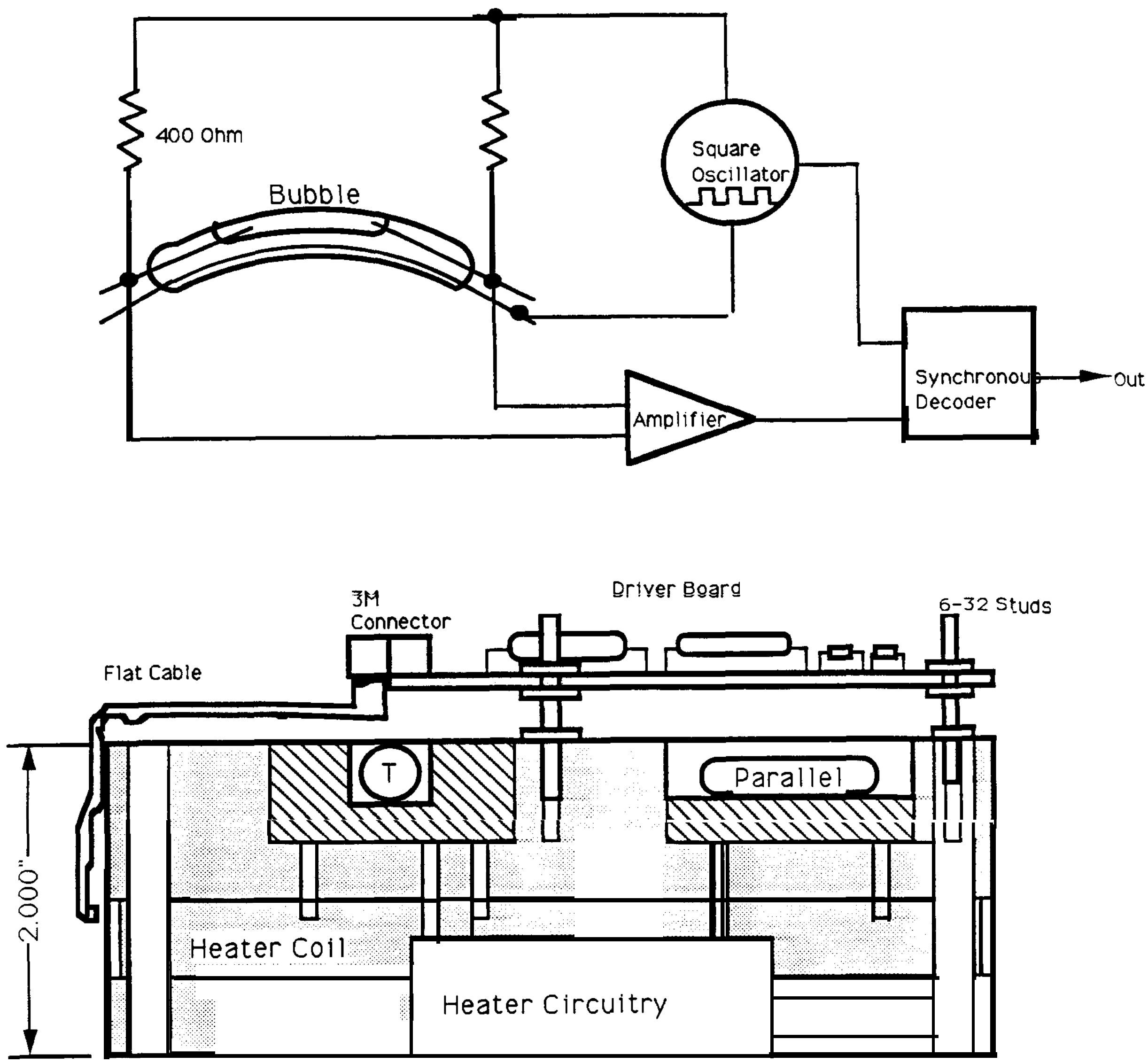


Fig. 9 Tiltmeter Block and Schematic

Readback from Two Tiltmeters on a Common Support Over a 38 Day Period.

Angles are in Microradians

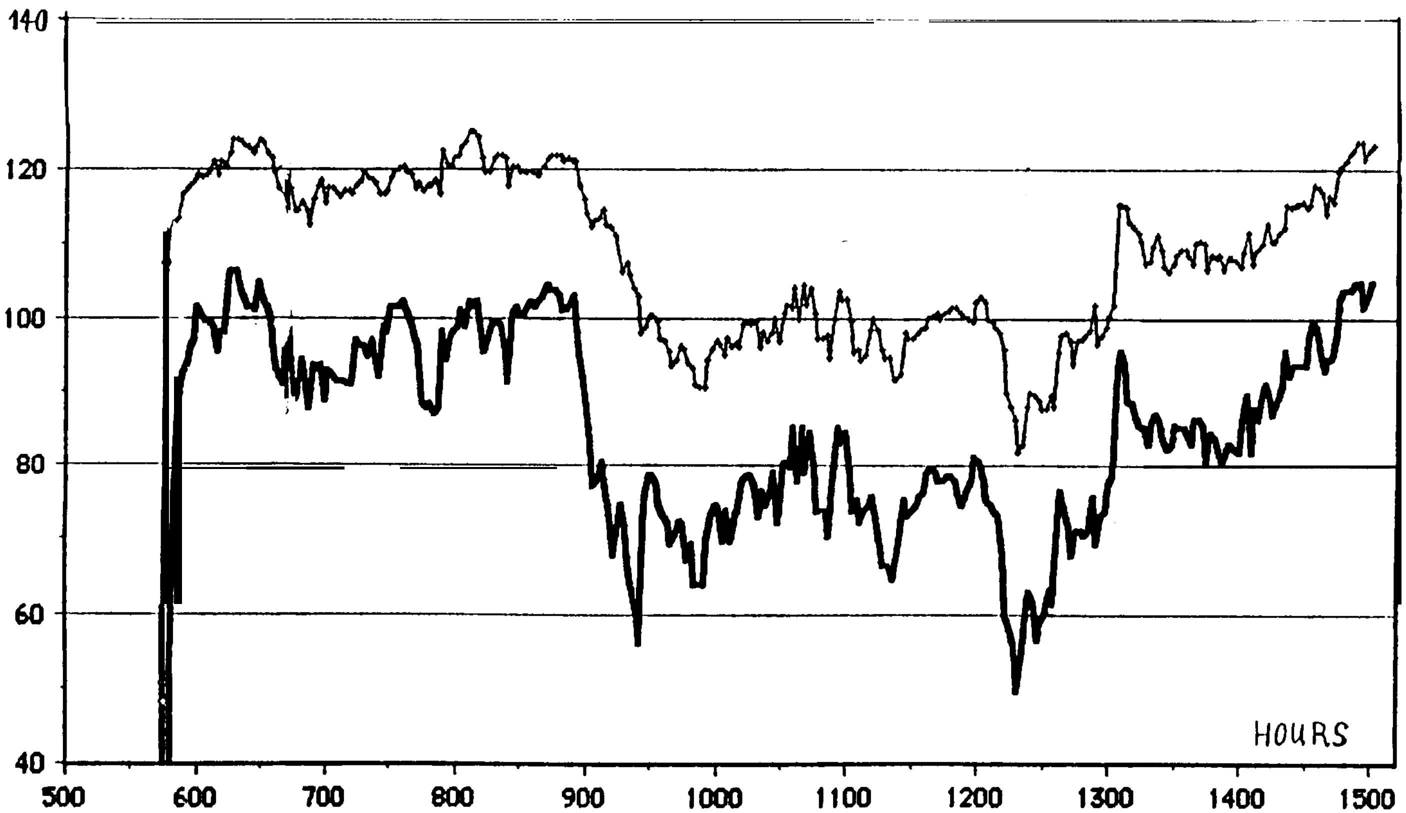
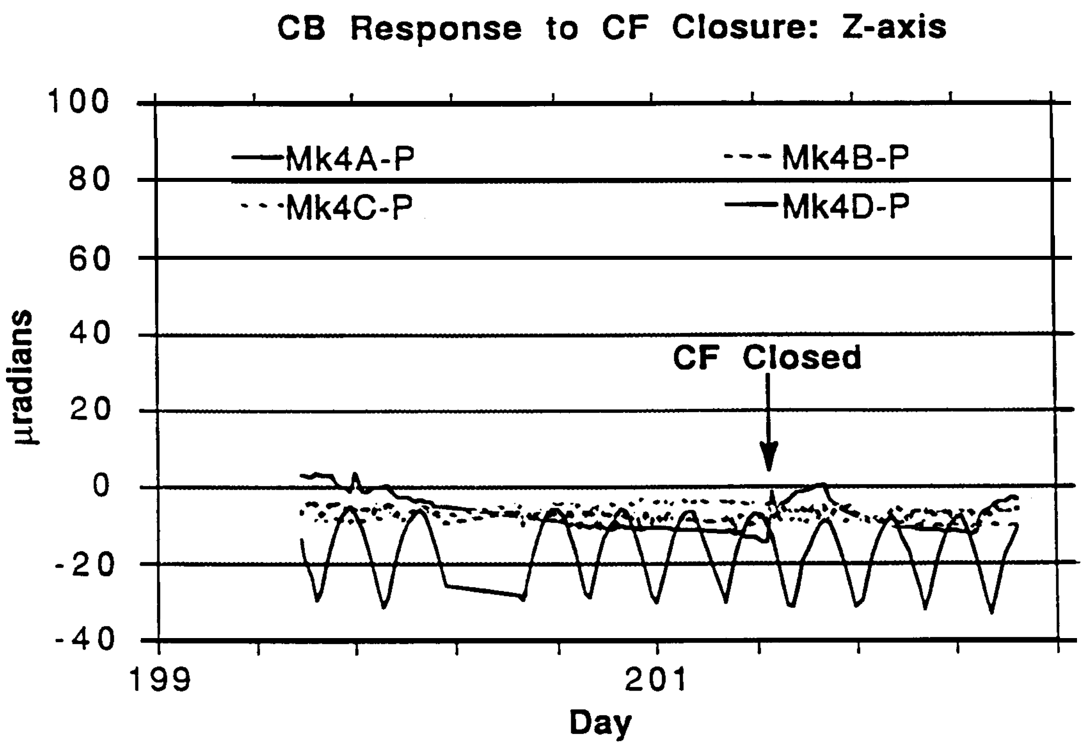


Fig. 10 Response of two Tiltmeters during a 38 Day Run



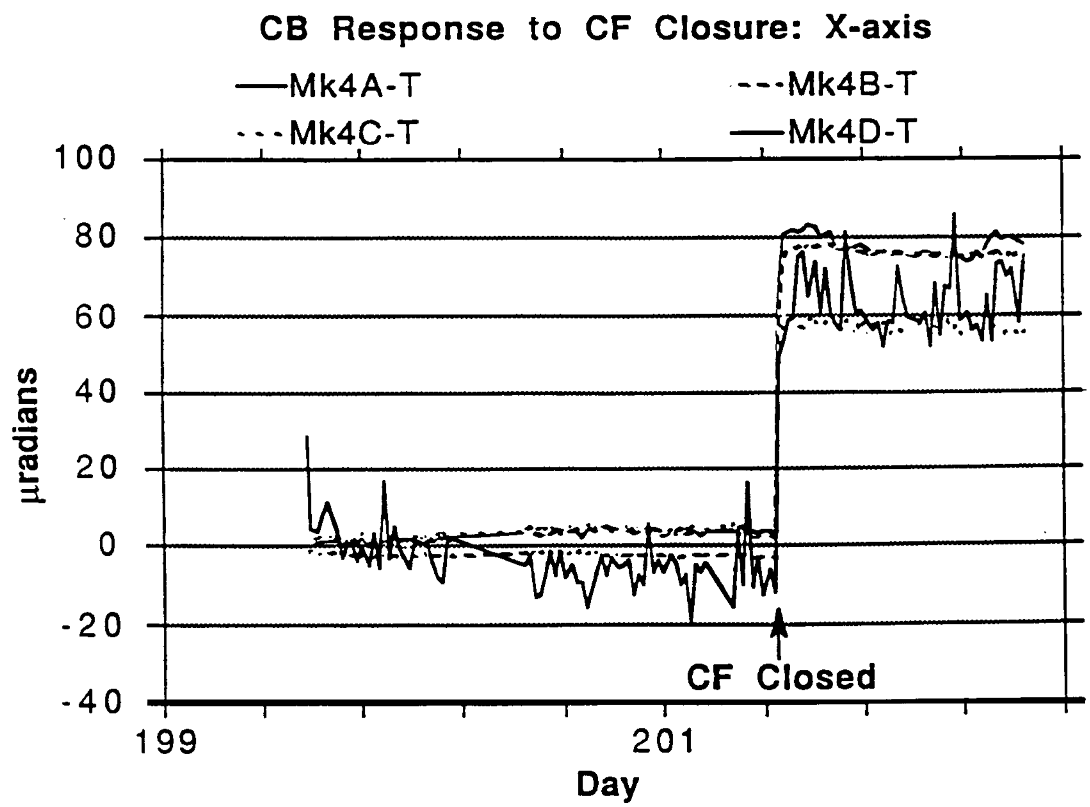
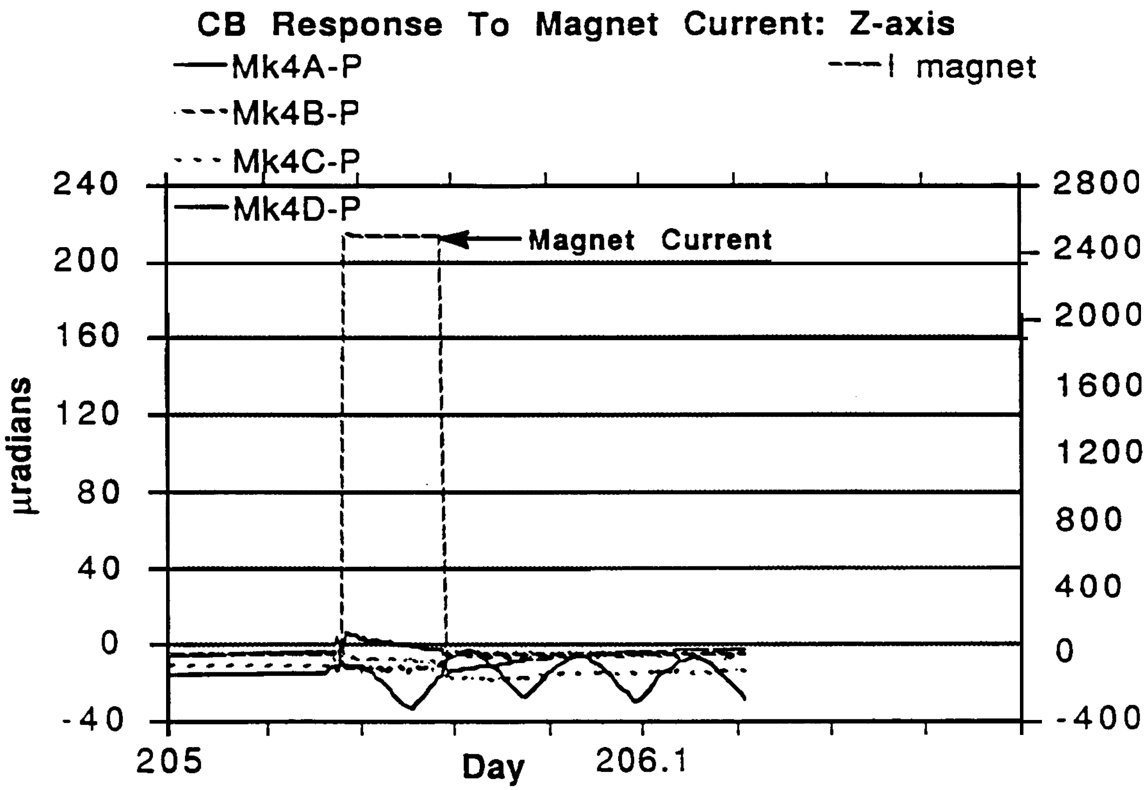


Fig. 11 Response of the P and T Sensors on the Central Beam during Central Iron Closure



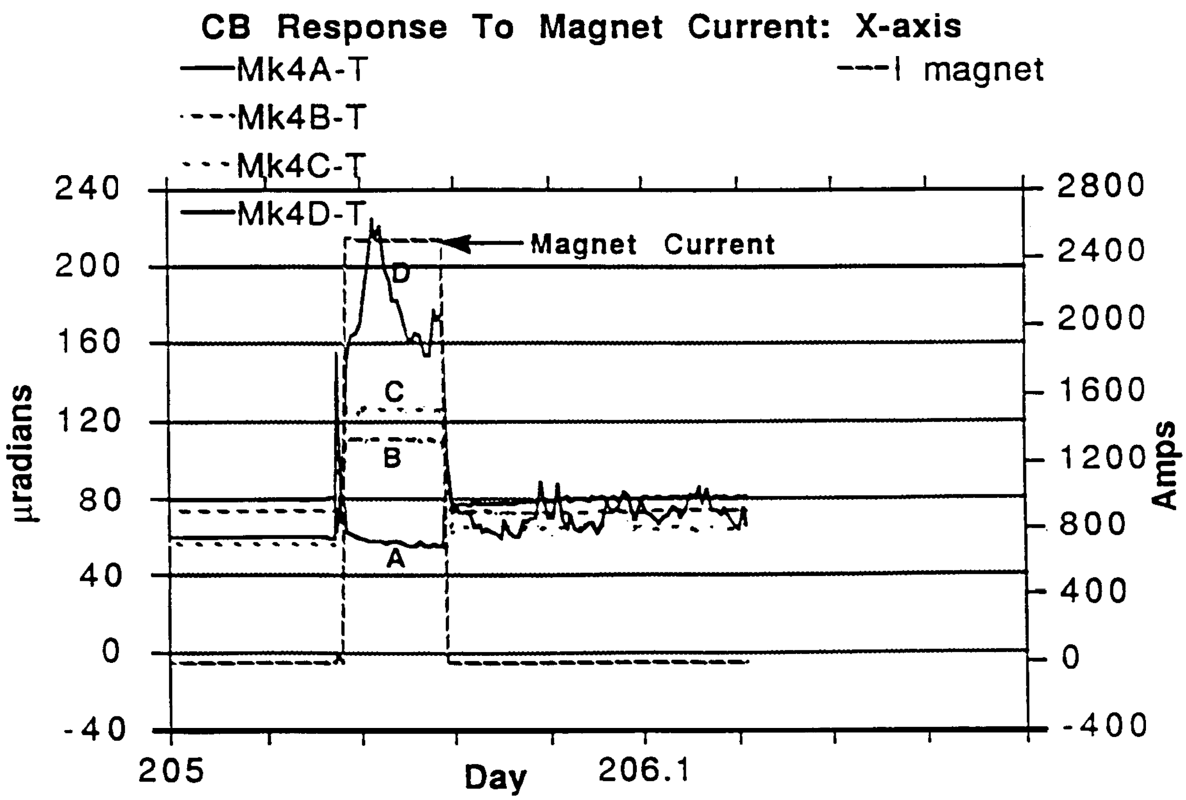


Fig. 12 Response of the P and T Sensors on the Central Beam during Magnet Excitation