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Tiltmeters for the Alignment System of the CMS Experiment: Users Handbook

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39 pp. 14 figs. 16 refs.

Abstract:

We present the instructions for the use of the electrolytic tiltmeters installed in the link alignments system of the CMS experimental and give the Data Base to be used as a Handbook during CMS operation.

Inclinómetros para el Sistema de Alineamiento del Experimento CMS: Manual de Usuarios

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39 pp. 14 figs. 16 refs.

Resumen:

Presentamos el modo de empleo de los inclinómetros electrolíticos instalados en el sistema link de alineamiento del experimento CMS y damos la Base de Datos que ha de ser usada como Manual a lo largo de la operación de CMS.

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1. Introduction

The measurement and monitoring of small tilts (in the mrad range) with high precision (of the order of 30-40 μrad) requires the use of very high performance sensors. Electrolytic tiltmeters are very sensitive devices appropriate for a precise angular measurement. They have been used for many years in a large variety of applications in physics, engineering and geology [1-8]. Tiltmeters are one-dimensional sensors that measure the angle, with respect to the gravity, of the elements to which they are attached. They will be called 1D sensors.

Tiltmeters can be mounted in pairs, orthogonally placed, on the same base. This means that in the same mechanical unit there is a tiltmeter, named X-sensor, and another one, named Y-sensor perpendicular to it. This allows the simultaneous measurement of longitudinal and transverse tilts of the piece to which they are attached. They will be called "dual sensors" or 2D sensors.

In addition, a third type of clinometers, called "biaxial sensors", are a single mounting allowing to measure tilts in two coordinates.

These are the three types of tiltmeters used in the Link Alignment System of CMS. Sketches of the 1D, dual and biaxial sensors are shown in Figs. 1 a) to c), respectively.

In the alignment scheme for the CMS experiment [9], the Φ co-ordinate will be monitored using this kind of sensors. They are installed both in the Muon Spectrometer [10] and in the Tracker [11], in order to measure the relative position of the two detectors. Tracker and muon detectors must be aligned with a precision of about 40 μrad in the bending plane, and this requires that angular movements are measured with a precision of about 30 μrad.

Figures 2 a) and b) show a longitudinal and a transverse view of the CMS detector, respectively. The CMS coordinate system, as well as the Φ angle definition, can also be seen in Fig. 2. The Link Alignment System is shown in Fig. 3.

The alignment of the Barrel part of the Muon System is based on several very stable mechanical structures, the MABs (Module for the Alignment of the Barrel) with different optomechanical instruments fixed to them. MABs are attached to the iron yoke barrels in the space between the wheels of the Muon Barrel detector. At YB+2 and YB–2 wheels, the MABs are equipped with a tiltmeter sensor.

1D sensors were chosen for the MABs because only small rotations around the CMS Z-axis are expected. As the MAB structures are 60^o apart in Φ (starting at $\Phi = 15^o$, with Φ positive defined), there are a total of 12 electrolytic clinometers on the MABs.

Fig. 4 shows a sketch of a MAB with the position of the tiltmeter attached to it. The sensor is placed in a X – Y plane in order to register the eventual rotation of the structure in that plane. Rotations will be small variations (μrads) around the nominal Φ value of the particular MAB structure. Those angular variations are precisely the angle we try to monitor.

Since one of the purposes of the CMS Alignment System, in particular of the Link Subsystem, is to measure the relative Φ position of Muon Chambers and Tracker Systems, tiltmeters will also be attached to the rigid endcaps of the Tracker.

The Tracker (as well as the Link Discs) may experience small bends of the end cap walls towards de Z axis in addition to rotations in the X-Y plane. Therefore, 2D sensors will be installed at the tracker Alignment Ring (AR) and Back Disc (BD) and on the Link Disc (LD), at both Z+ and Z–.

A total of 8 dual tiltmeters will be installed on the Tracker, 4 at the Z+ and 4 at the Z– side. At each end, two clinometers will be attached to the AR, and two will be attached to the BD. Nominal Φ positions in both rings are 90^o (top tiltmeters) and 270^o (bottom tiltmeters). Fig. 5 sketches the sensor positions in the AR and BD rings at one of the Tracker ends. At each LD (+ and –) one, and only one, dual sensor will be installed in the top position.

Any dual tiltmeter in AR, BD and LD, will be placed such that the X-sensor will lie in a CMS X-Y plane, in order to monitor tilts around the CMS Z-axis (Φ angle variations), while the Y-sensor will lie in a CMS Y – Z plane, to monitor tilts around the CMS X-axis.

Rotations around the CMS X-axis correspond to bending of the AR, BD and LD rings towards the CMS Z-axis. If we call Θ the angle the AR, BD and LD rings make, by construction, with the CMS Z-axis, the nominal values for Θ will be 0^o for the top sensors and 180^o for the bottom sensors. The Y-sensors in the dual tiltmeters will therefore measure the Θ deviations from their nominal values.

The two output coordinates of the biaxial sensors, mounted on the Transfer Plates (TP), in the ME1/1 zone (see Fig.3), will provide the corresponding Φ and Θ tilts of these structures. There are as many biaxial sensors as 1D MAB sensors: 6 at TP+ and 6 at TP–, corresponding to the six nominal Φ values of the TP at the two CMS sides.

Tiltmeters on the MABs, TPs and ARs will work at ambient temperature (around 17 ^{o}C), while those in the BD will work at about –16 ^{o}C. In both cases the working temperature will undergo variations of a few degrees Celsius. In addition, the sensors will be subject to irradiation (by ionising and non ionising particles) and magnetic fields.

The CMS experiment is expected to be operational during 10 years (1 year run lasts ~ 10^7 s). After that time, tiltmeters on the MABs will have received a total ionisation dose (TID) equivalent to 0.010 kGy and a total neutron fluence (NF) of 5×10^{10} cm^{-2}. In the same period the tracker sensors will have received a TID up to 150 kGy and a NF of 2×10^{14} cm^{-2}. In a previous work we have already checked that the tiltmeters selected for their use in CMS are radiation resistant [12].

The CMS solenoid will generate a magnetic field of 4 T. On the MABs area, where 1D sensors will be placed, we expect fields in the range B = (150 – 350) mT. The field difference, between the two excitation electrodes of the sensor, is expected to be in the range ΔB = (10 – 70) mT. The dual sensors at the Tracker will be exposed to B ~ 4T, expected to be uniform, ΔB ~ 0. Measurements at the laboratory indicate that the sensors are sensitive to magnetic field gradients (ΔB ? 0). These measurements will be described in a separated paper.

This document is organised as follows: the working principle of the tiltmeters is explained in section 2. The instructions for use, including the dependence with temperature, are given in section 3, while section 4 explains how to interpret the change in output voltage of a given tiltmeter. Finally, section 5 provides the complete tiltmeter Data Base and some related information.

2. The working principle

Tiltmeters or tilt sensors measure tilts with respect to the most stable reference: the vertical gravity vector. Tiltmeters are high precision sensors. The sensor operation is based on the principle that an enclosed bubble of gas, suspended in a liquid, will always orient itself perpendicular to the gravity vector. The bubble (see Fig. 6) is located in a liquid filled glass case (the liquid is a conductive fluid: a potassium iodine solution in ethanol, 0.02 N), with three electrodes. The glass case is allocated inside a cement structure, covered by a thin layer of anodised aluminium. When an AC voltage is applied across the two excitation electrodes, the AC output voltage measured at the central pick-up electrode depends on the tilt angle.

We have selected, for the CMS alignment system, tiltmeters commercialised by AGI [15], in particular, the 1D M756-1172 miniature tilt sensors (MTS) for the MAB, and the 2D M756-1150 MTS for the Tracker AR and BD and for the LD. Finally, biaxial 900-H sensors were selected for the TP.

Dimensions and weights of tiltmeters are:

- 1D sensors: (length × width × height) = 50.8 × 15.7 × 15.7 mm^3; weight = 42 g.
- 2D sensors: (length × width × height) = 50.8 × 41.2 × 25.4 mm^3; weight = 142 g.
- Biaxial sensors: (base diameter × height) = 12.7 mm × 16.3 mm; weight = 15 g.

2.1 General specifications

The series 756 mid-range MTS to be used in CMS MABs, ARs and BDs, were requested to have a certain number of basic characteristics, and tiltmeters were constructed and calibrated according to them.

The most important requested parameters are:

- Working range:

A total tilt range of ± 2 degrees (~ ± 35 mrad). Once they are installed in CMS and the 4T solenoid is turned on, motions are not expected to exceed ± 3 mrad during data taking operation. However, the installation of the sensors in the MAB, AR and BD may be subject to inaccuracies and tiltmeters may start their operation relatively far from the horizontal position. Requiring a total range of ± 35 mrad ensures that the sensors will always work in range.

The output voltage of the tiltmeters varies in the range of ± 10 V because of readout constraint. Sensors will saturate beyond these values. The reason for this constraint is the following: the ELMB electronic cards accept voltages in the range ± 2.5 V. Therefore, the tiltmeter output voltage must be divided before it is sent to the ELMB. By setting the output voltage range to ± 10 V, the output voltage can be divided by 4 without any loss of precision.

- Scale factor:

With the above conditions of angular and output voltage ranges, the scale factor will be roughly 3.5 μrad/mV.

- Resolution:

The sensor readout electronics can resolve voltage differences as small as 1 mV. Therefore, the angular resolution will be about 3.5 μrad. This is the minimum measuring error: a systematic always present.

Dual tiltmeters for the LD rings and biaxials for the TPs were bought without any particular requirement and they were calibrated, at room temperature, in our laboratory in restricted angular ranges.

2.2 Calibration of tiltmeters and measurement precision

For small angular motions (as it is our case in CMS), the dependence between the tilt angle and the measured output voltage is essentially linear. The calibration of a tiltmeter consists in finding the relation ship between the output voltage and the tilt angle, that is, the function:

$$\alpha(\mu rad) = S(\mu rad/mV) \times V(mV) + c(\mu rad) \qquad (1)$$

where α is the tilt angle, S is the calibration constant or scale factor, V the sensor output voltage and c an offset value that gives the angle that corresponds to a zero output voltage.

We have evaluated in the past [13, 14] the performance of various electrolytic clinometers available in the market and compared how well their behaviour can be described in terms of eq. (1). In particular, the parameter we have compared is the precision. This tiltmeter characteristic is calculated as the width of the distribution of the residuals of the data with respect to the linear fit. See [13] and [14] for further details.

Some calibrations were done by the vendor at AGI and some others were done at Ciemat. Distinction between places of calibrations will be done in the Data Tables.

For calibrations at Ciemat, the experimental setup consisted of a 460 ± 0.1 mm long arm tripod which can be moved by one of its ends in steps of 0.5 μm (equivalent to about 1 μrad). A sketch of this structure with the axis definition can be seen in Fig. 7. The sensor to be calibrated is placed on top of the longest arm. The sensor is screwed on a platform which is the interface between the tripod and the sensor (see Fig. 8). The knob "A" tilts the tripod around the Y axis. The Z displacement of the knob is measured by a Heidenhain length gauge [16] with a resolution of 0.5 μm. Tripod, platform and sensor are placed on a stable optical table as shown in Fig. 8.

The platform is first adjusted to the horizontal (20 μrad precision level) by moving the tripod knobs. This situation is taken as a reference and the Heidenhain is set to zero height. The platform is then moved up and down (equivalent to a rotation around the Y axis in Fig. 7) and the output voltage of the tiltmeter and the length measured by the Heidenhain are recorded. This operation allows the simultaneous measurement of the output voltage variation of the sensor and the tilted angle (ratio between the Heidenhain output and the length of the longest arm of the tripod), with respect to the reference. With this set-up the tilted angle varies in the range ±23 mrad (output voltage range of about ±7 V).

As an illustration we show in Fig. 9 a), the tilted angle versus the output voltage, for one of the 1D sensors. Data points are fitted to the function:

$$\alpha(\mu rad) = (3.5270 \pm 0.0012)\ (\mu rad/mV) \times V(mV) + (20.47 \pm 4.58)\ (\mu rad)$$

The distribution of the residuals, Fig. 9 b), has a width (the precision, or error, in the angular reconstruction) of 20.1 μrad.

Notice that eq. (1) only allows to measure angular changes, within the measured precision, but does not represent the real angle the tiltmeter makes with the gravity vector.

3. Tiltmeters in operation conditions: dependence on the temperature

The angle the gas bubble makes with the gravity vector (the true angle the tiltmeter base makes with the horizontal), can be calculated through the following expression, which includes the dependence of the measured output voltage with temperature:

$$\alpha\ (\mu\text{rad}) = P(V) \times [1 + K_s\,(T - T_{cal})] - B(T) \qquad (2)$$

where,

$$P(V) = S \times V$$

and

$$B(T) = K_z \times T + B_o$$

with:

V = tiltmeter output voltage in mV

T = temperature (in ^{o}C) when reading the voltage

T_{cal} = calibration temperature (in ^{o}C)

K_s = constant giving the scale factor change with the temperature (in $^{o}C^{-1}$)

S = calibration constant or scale factor

K_z = slope of the zero bias as a function of the temperature (in μrad/^{o}C)

B_o = zero bias constant (in μrad)

3.1 The first term in the a (mrad) equation

The first term in eq. (2) is the product of two factors. The first one, P(V) = S × V, corresponds to a linear equation in V.

For the calibrations done at AGI, the constructor provides a table of tilt angle (μrad) vs. output voltage (mV) obtained by varying the tilt angle from + 35 mrad (10 V of output voltage) to – 35 mrad (– 10 V of output voltage) in steps of 1 mrad. The data is taken at a given constant temperature, T_{cal}. The data received from the producer is then analysed by us.

As an illustration Fig. 10 a) shows, for one of the MAB tilt sensors, the tilt angle (μrad) versus the output voltage (mV), together with the result from a linear fit to the function:

$$\alpha(\mu\text{rad}) = (3.4828 \pm 0.0008)\ (\mu\text{rad/mV}) \times V(\text{mV}) + (-2.27 \pm 3.91)\ (\mu\text{rad})$$

The residuals distribution (Fig. 10 b)) shows an rms of 35.8 μrad.

The second factor in the first term of eq. (2), $[1 + K_s (T - T_{cal})]$, takes into account the change of the scale factor with temperature. To measure the value of K_s, the constructor calibrates the sensor at four temperatures around the T_{cal} value, using a linear expression for the moved angle as a function of the output voltage. At each value of T, a value of the calibration constant S, is calculated and a linear fit of S, as a function of T, is then performed. The change of the scale factor with the temperature is defined as:

$$K_s = \left[\left(S(T_{max}) - S(T_{min})\right)/S(T_{min})\right]/(T_{max} - T_{min})$$

For the sensor used for illustration, the calculated value is $K_s = 0.577 \times 10^{-3}\ {}^{o}C^{-1}$.

In a tiltmeter at rest, there are two main reasons why the output voltage may change with the temperature. From one side, the liquid expands or shrinks giving rise to a change in the volume of the bubble and thus modifying the area the liquid covers in each of the two excitation electrodes and, hence, the output voltage. On the other hand, the electrical characteristics of the liquid, specially the conductivity, may also change with temperature, inducing changes in the output voltage. However, the changes are so small that, in most of the cases, they can be ignored.

3.2 The second term in the a (mrad) equation

The second term of Eq. (2), $B(T) = K_z \times T + B_o$, represents the angle the tiltmeter base makes with the horizontal when the readout voltage is zero and it is related with the so-called temperature coefficient of Zero Shift, K_z.

The fact that the output voltage from one tiltmeter is zero does not mean that the tilt base is perpendicular to the gravity vector. If a tiltmeter is placed on a flat surface, one would get an output voltage V1. If the tiltmeter is rotated 180^o, a voltage V2 will be read. A tiltmeter is in level position (fully horizontal) when the output voltage read out is $V = (V1 + V2)/2$, the average bias voltage. This value, multiplied by the scale factor, gives the offset angle to be subtracted to get the actual angle the tilt sensor makes with the horizontal.

This offset depends also on the temperature: the glass case may move slightly due to dilatation or contraction of the cement in which it is inserted. The temperature coefficient of the zero shifts is calculated by recording the output B_i (voltage transformed to angle) on a smooth granite surface at 1 minute intervals at four temperatures around T_{cal}, rotating the granite surface 180^o, and repeating the process. The bias is calculated based on the average output values $< B_i > = ½\ (B_i + B^{rot}{}_i)$ at the different temperatures. With the four pairs of values ($< B_i >$, T_i), a linear fit of the form $B(T) = K_z \times T + B_o$ is done to calculate K_z and B_o.

For the sensor used as illustration, the measured values are: $K_z = -0.287$ μrad/^{o}C and $B_o = 21.7$ μrad. Assuming an ambient temperature of 20 ^{o}C, the angle the tiltmeter makes with the horizontal (zero shift angle) when the output voltage is zero, would be $B(20^oC) = 16.0$ μrad.

4. How to interpret a change in the output voltage

The CMS coordinate system definitions for the X, Y, Z axis, together with the azimuthal (Φ) and polar (Θ) angles are shown in Fig. 11.

The X-axis points horizontally to the LHC circumference centre. The Y-axis points upwards. The Z-axis completes the right handed coordinate system: $\mathbf{Z} = \mathbf{X} \times \mathbf{Y}$. Direction of the positive Z axis coincides with the sense of the solenoid magnetic field. The angle Φ (in the X–Y plane) is positive defined and runs from 0^o to 360^o. The angle Θ (in a Y–Z plane) runs from 0^o to $\pm 180^o$.

Tiltmeters arrive from the producer with their two excitation electrodes already assigned as positive and negative (indicating direction of increasing/decreasing output voltage). Labels are drawn by the constructor in one of the front sides. An observer looking at the labelled (front) side of a tiltmeter would see the marks as in Fig. 12 a). If the same observer looks at the tiltmeter from the back side, no mark is seen, but the relative position of the excitation electrodes, with respect to the observer, would obviously look as shown in Fig. 12 b).

When a tiltmeter in position **[+ -]** is rotated anticlockwise around an axis perpendicular to that face, the readout voltage will move to positive values, increasing up to the saturation voltage (10 V) for a tilt of 35 mrad. If the rotation is clockwise, the readout voltage will move to negative values, decreasing down to the saturation voltage (–10 V) for a tilt of –35 mrad.

If the tiltmeter is in position as in Fig. 12 b), **[- +]**, readout voltages will behave the opposite way: an anticlockwise rotation will induce negative values for V and a clockwise rotation will give rise to positive values of V.

4.1 The MABs tiltmeters

All the tiltmeters in the MABs are 1D sensors located in a X–Y plane, either at positive or negative values of the Z-coordinate.

For an observer sitting outside CMS at the Z+ axis, the 1D tiltmeters located on the Z+ MABs, are placed in position **[+ -]**.

Let V_o be the output voltage at a given position. A positive increase in the output voltage translates into a tilt, $\Delta\alpha = \alpha(V) - \alpha(V_o)$, in the direction of **positive Φ**. A decrease in the output voltage means a tilt in the direction of **negative Φ** by an amount equal to $\Delta\alpha$.

For tiltmeters placed at the Z– MABs, the same observer will see a configuration **[- +]**. In that case, if the output voltage V increases, the tilt is in the direction of **negative Φ** and if the output voltage V decreases the tilt goes in the direction of **positive Φ**.

4. 2 The Tracker and Link Disc tiltmeters

All 2D units in the Tracker and Link Discs (wherever they are located on the AR or on the BD or on the LD) have the X-sensor in a X–Y plane, at several Z values (positive or negative), to measure Φ variations. The Y-sensor in the unit lies in a Y-Z plane, to measure Θ variations, at a positive or negative value of the CMS X-coordinate.

For an observer sitting outside CMS, on the Z+ axis, the X-sensor of the tiltmeters placed on the AR+, BD+ and LD+ rings, will have the electrodes in position **[- +]**, while X-sensors on the

AR–, DB– and LD– will look as **[+ -]**, and the translation of the voltage variations into a tilt (either in the positive or negative Φ direction) follows the rules explained in *4.1*.

The Y-sensors of the 2D Tracker tiltmeters monitor bends, ΔΘ, of the AR, BD and LD rings towards the Z axis, in the Y–Z CMS plane, which means they measure the angle between the rings and the positive CMS Z-coordinate.

For an observer placed at the X+ axis, outside CMS, the relative position of the electrodes of the Y-sensor of the units located at the positive Z end of the Tracker (AR+, BD+) and the one at LD+, will be **[- +]**. Therefore, if the output voltage V of the sensors decreases, the tilt goes in the direction of positive CMS Z-axis by an amount $\Delta\Theta = \alpha(V) - \alpha(V_o)$. If the output voltage increases, the tilt is in the direction of the negative CMS Z-axis.

For the same observer, the relative position of the electrodes of the Y-axis sensors of the units located at the negative Z end of the Tracker (AR–, BD–) and the one at LD– will be **[+ -]**, and the interpretation of the changes in voltage of the up and bottom Y axis sensors is the opposite to the one given above for the sensors at Z+.

4.3 Important note

The user should be warned that, at least for now, it will be not possible to use Eq. (2) to know the angle a tiltmeter makes with the gravity vector: the amplifier oscillations which appeared after sensors installation in Z+ forced us to introduce changes in the Signal Conditioning cards supplied by AGI. This fact makes it rather insecure to use Eq. (2) before further in-depth studies are performed.

Therefore, once a tiltmeter is installed in its CMS location, and for the time being, the initial conditions (Φ or Θ angles) will be taken from the survey (photogrametry) measurements. Let us take an example.

Tiltmeter T1 (T5237/SC5247) is placed (as sketched in Fig. 4) on the Z– MAB having a nominal position of Φ = 15 arc. deg.

Let us assume that the survey measurements give, for this MAB, an angle of:

$$\Phi_{15} = 15 \text{ arc. deg.} + XX \text{ mrad} + YY \ \mu\text{rad}$$

and that the output voltage read at T1 is, at the moment of its installation on the MAB, $V = V_{initial}$ (V). In that case, we will make the following correspondence: $V_{initial}$ (V) ⇔ Φ_{15} (µrad).

In any further output voltage readout V_t, made at time t, an eventual change with respect to the initial value, $\Delta V = V_{initial} - V_t$, accounts for a change in the inclination that amounts to: $\Delta\Phi$ (µrad) = ΔV (mV) × S (µrad/mV), where S is the tiltmeter calibration constant and, therefore the actual position of the MAB at time t will be: $\Phi_{15,t} = \Phi_{15} + \Delta\Phi$.

It is clear that, although the error in ΔΦ will typically be of the order of 30 µrad, the error in $\Phi_{15,t}$ will be affected by the survey errors that are much larger.

5. The CMS tiltmeters Data Base

The parameters appearing in Eq. (2), together with the precision (the error in the reconstructed tilt), resulting from the linear fit to the calibration data, and the foreseen location for a particular unit (sensor/signal conditioning card), defines the full characterization of a tiltmeter.

5.1 Tiltmeters in the MABs: Data Base

The tiltmeters to be placed in the MABs are, as already said, 1D sensors. Each sensor is associated with its own electronics Signal Conditioning (SC) card and MUST be connected at the indicated CONTACT on the SC card.

Every sensor has to occupy a definite location in the CMS MABs, characterized by the Z side and the nominal Φ angle of the MAB. Two tiltmeters in the same CMS-MABs quarter share the same SC card connected to their specifics contacts.

The list of the tiltmeters to be used on the MABs is the following:

Short Label	Sensor serial number Model: 756-1172	Electronic serial number Model: 83162 SC	CONTACT	Location: Z side and Φ(MAB)
T1	5237	5247	P2	Z– 15^o
T2	5238	5247	P1	Z– 75^o
T3	5239	5248	P2	Z+ 195^o
T4	5240	5248	P1	Z+ 255^o
T5	5241	5249	P2	Z+ 15^o
T6	5242	5249	P1	Z+ 75^o
T7	5243	5250	P2	Z– 195^o
T8	5244	5250	P1	Z– 255^o
T9	5245	5251	P2	Z+ 135^o
T10	5246	5251	P1	Spare sensor
T11	5511	5513	P2	Spare sensor
T12	5512	5513	P1	Z+ 315^o
T13	5514	5516	P2	Z– 135^o
T14	5515	5516	P1	Spare sensor
T15	5517	5519	P2	Z– 315^o
T16	5518	5519	P1	Spare sensor

In the Table that follows, and for each tiltmeter, the provided information is:

First column: short label.

Second column: side of Z.
.
Third column: nominal Φ angle of its MAB.

Fourth column: tiltmeter and signal conditioning card serial numbers.

Fifth column: indication of the appropriate connector (P1 or P2) in the electronics card, voltage range used for calibration and place where the calibration data was taken.

Sixth column: fitted calibration coefficient.

Seventh column: calibration temperature.

Eighth column: precision, or measurement error, in the reconstructed angle. When the tiltmeters output voltage is outside the voltage calibration range, the error in the reconstructed angle should be increased by a 50%.

Ninth column: constant giving the dependence of the calibration constants with temperature (K_s) and constants which allow calculation of the zero bias angle at the measuring temperature (K_z and B_o).

Notice that the only quantity we can measure is the angle variation, calculated in the simple form:

$$\Delta(\text{angle in } \mu\text{rad}) = (V_{measured}(\text{mV}) - V_{initial}(\text{mV})) \times S\ (\mu\text{rad/mV})$$

Label	**Side**	F_{MAB} (degrees)	**Serial numbs.**	**Connector** **Cal. range** (V) **Cal. place**	**S** (μrad/mV)	$\mathbf{T_{cal}}$ (° C)	**Precis.** (μrad)	$\mathbf{K_s}$ (° C^{-1}) $\mathbf{K_z}$ (μrad/° C) $\mathbf{B_0}$ (μrad)
T1	–Z	15	T5237/ SC5247	P2 ±7.0 V Ciemat	3.4641	23.4	10.8	0.00006037 2.4874 –216.37
T2	–Z	75	T5238/ SC5247	P1 ±7.0 V Ciemat	3.5935	23.4	10.6	–0.00028314 -.28206 –136.41
T3	+Z	195	T5239/ SC5248	P2 ±9.0 V AGI	3.4693	24.3	42.4	–0.00041732 6.6549 –277.91
T4	+Z	255	T5240/ SC5248	P1 ±9.0 V AGI	3.4708	24.3	41.7	–0.00039629 2.8617 –140.86
T5	+Z	15	T5241/ SC5249	P2 ±9.0 V AGI	3.4939	23.8	37.4	–0.00034974 3.1921 –262.00
T6	+Z	75	T5242/ SC5249	P1 ±9.0 V AGI	3.4828	23.8	35.8	–0.00057653 –.28714 21.702

Label	**Side**	F_{MAB} (degrees)	**Serial numbs.**	**Connector Cal. range** (V) **Cal. place**	**S** (μrad/mV)	T_{cal} (° C)	**Precis.** (μrad)	K_s (° C^{-1}) K_z (μrad/° C) B_0 (μrad)
T7	–Z	195	T5243/ SC5250	P2 ±7.0 V Ciemat	3.5254	21.8	12.0	–0.000413444 –0.89062 –14.434
T8	–Z	255	T5244/ SC5250	P1 ±7.0 V Ciemat	3.5270	21.8	12.0	0.00016210 –1.4034 –114.39
T9	+Z	135	T5245/ SC5251	P2 ±9.0 V AGI	3.4883	26.3	37.7	–0.00027368 –3.3050 83.584
T10	+Z	135	T5246/ SC5251 (spare for T5245)	P1 ±9.0 V AGI	3.4867	26.3	43.5	–0.00003566 0.71116 –192.01
T11	+Z	315	T5511/ SC5513 (spare for T5512)	P2 ±9.0 V AGI	3.4510	22.2	44.5	–0.000027792 –0.78823 99.239
T12	+Z	315	T5512/ SC5513	P1 ±9.0 V AGI	3.4603	22.5	32.8	0.000268808 0.62149 –231.99

Label	**Side**	Φ_{MAB} (degrees)	**Serial numbs.**	**Connector** **Cal. range** (V) **Cal. place**	**S** (µrad/mV)	$\mathbf{T_{cal}}$ (° C)	**Precis.** (µrad)	$\mathbf{K_s}$ (° C^{-1}) $\mathbf{K_z}$ (µrad/° C) $\mathbf{B_0}$ (µrad)
T13	–Z	135	T5514/ SC5516	P2 ±7.0 V Ciemat	3.5060	24.3	17.6	0.00020091 1.2694 –197.91
T14	–Z	135	T5515/ SC5516 (spare for 5514)	P1 ±9.0 V AGI	3.4950	22.4	42.4	–0.000018822 3.7530 –1945.5
T15	–Z	315	T5517/ SC5519	P2 ±7.0 V Ciemat	3.4815	23.5	25.1	0.000452055 1.0037962 –192.09
T16	–Z	315	T5518/ SC5519 (spare for 5517)	P1 ±9.0 V AGI	3.4799	22.0	45.5	0.000452055 3.2181758 –1927.1

5.2 Tiltmeters in the Tracker: Data Base

All the tiltmeters in the Tracker are 2D sensors. Every tiltmeter is associated to its own electronics Signal Conditioning card. The X-sensor in the tiltmeter MUST be connected to the P2 contact in the SC card, and the Y-sensor in the tiltmeter MUST be connected to the P1 contact in the SC card.

The 2D sensor/SC card serial numbers and the place it should occupy in the CMS Tracker is the following:

Sensor serial number Model 756-1150	Electronics serial number Model 83162 SC	Calibration at T < 0 ^{o}C	Location in the Tracker end-caps
5848	5849	no	AR + bottom
5850	5851	no	AR + top
5852	5853	yes	BD + top
5854	5855	yes	BD + bottom
5858	5859	no	AR – bottom
5860	5861	no	AR – top
5862	5863	yes	BD – bottom
5856	5857	yes	BD – top

Tiltmeters calibrated at temperatures below 0 ^{o}C, were also calibrated at ambient temperature.

In the Table that follows, and for each tiltmeter, the provided information is:

First column: tiltmeter serial number, axis (X or Y) and signal conditioning card serial number.
Second column: indication of the appropriate connector (P1 or P2) in the electronics card, voltage range used for calibration and place where the calibration data was taken.
Third column: fitted calibration coefficient.
Fourth column: calibration temperature. Tiltmeters calibrated below 0 ^{o}C are flagged with a double asterisk (**).
Fifth column: precision or measurement error in the reconstructed angle. When the tiltmeters output voltage is outside the voltage calibration range, the error in the reconstructed angle should be increased by a 50%.
Sixth column: constant giving the dependence of the calibration constants with temperature (K_S) and constants which allow calculation of the zero bias angles at the measuring temperature (K_z and B_0).

Notice that the only quantity we can measure is the angle variation, calculated in the simple form:

$$\Delta(\text{angle in } \mu\text{rad}) = (V_{measured}(\text{mV}) - V_{initial}(\text{mV})) \times S\ (\mu\text{rad/mV})$$

Serial numbers	**Connector Cal. Range** (V) **Cal. place**	**S** (μrad/mV)	$\mathbf{T_{cal}}$ (° C)	**Precis.** (μrad)	$\mathbf{K_s}$ (° C^{-1}) $\mathbf{K_z}$ (μrad/° C) $\mathbf{B_0}$ (μrad)
5848X/ SC5849	P2 ±9.0 V AGI	3.5102	16.9	37.0	0.000350073 −.43650 −352.89
5848Y/ SC5849	P1 ±9.0 V AGI	3.4787	17.1	40.0	0.000116822 −1.8561 −327.51
5850X/ SC5851	P2 ±9.0 V AGI	3.4754	17.3	29.5	0.000589126 2.8070 1321.3
5850Y/ SC5851	P1 ±9.0 V AGI	3.4865	17.1	27.3	0.000228926 −6.2553 −435.96
5852X/ SC5853	P2 ±9.0 V AGI	3.4760	17.0	30.6	0.000251498 −1.9723 102.46
5852Y/ SC5853	P1 ±9.0 V AGI	3.4834	17.1	37.5	0.000276846 −6.0461 −1021.37

Serial numbers	**Connector Cal. Range** (V) **Cal. place**	**S** (μrad/mV)	$\mathbf{T_{cal}}$ (° C)	**Precis.** (μrad)	$\mathbf{K_s}$ (° C^{-1}) $\mathbf{K_z}$ (μrad/° C) $\mathbf{B_0}$ (μrad)
5852X/ SC5853	P2 ±9.0 V AGI	3.4556	−21.3 **	37.5	0.000156003 −11.935 57.577
5852Y/ SC5853	P1 ±9.0 V AGI	3.4623	−22.1 **	39.8	0.000238718 −8.4762 −1049.6
5854X/ SC5855	P2 ±9.0 V AGI	3.4810	17.0	29.8	0.000354115 0.8056 −343.01
5854Y/ SC5855	P1 ±9.0 V AGI	3.4727	17.1	31.3	0.000146085 −1.7582 −1300.33
5854X/ SC5855	P2 ±9.0 V AGI	3.4558	−21.8 **	38.4	0.000194402 −5.7264 −414.04
5854Y/ SC5855	P1 ±9.0 V AGI	3.4527	−22.3 **	41.5	0.000310529 −14.183 −1326.8

Serial numbers	**Connector Cal. Range** (V) **Cal. place**	**S** (µrad/mV)	$\mathbf{T_{cal}}$ (° C)	**Precis.** (µrad)	$\mathbf{K_s}$ (° C^{-1}) $\mathbf{K_z}$ (µrad/° C) $\mathbf{B_0}$ (µrad)
5856X/ SC5857	P2 ±8.0 V AGI	3.4836	17.1	32.7	0.000097398 7.4071 −777.06
5856Y/ SC5857	P1 ±8.0 V AGI	3.4912	17.1	21.2	0.000495313 -2.0319 −172.56
5856X/ SC5857	P2 ±8.0 V AGI	3.4647	−21.5**	38.9	0.000283231 −4.5089 −768.11
5856Y/ SC5857	P1 ±8.0 V AGI	3.4638	−21.9**	23.2	0.000358674 −15.704 −188.76
5858X/ SC5859	P2 ±7.0 V Ciemat	3.5015	18.2	14.8	0.000176466 1.8615 658.88
5858Y/ SC5859	P1 ±7.0 V Ciemat	3.4883	20.4	12.2	0.000371890 −4.5629 −893.63

Serial numbers	**Connector Cal. Range** (V) **Cal. place**	**S** (μrad/mV)	$\mathbf{T_{cal}}$ (° C)	**Precis.** (μrad)	$\mathbf{K_s}$ (° C^{-1}) $\mathbf{K_z}$ (μrad/° C) $\mathbf{B_0}$ (μrad)
5860X/ SC5861	P2 ±7.0 V Ciemat	3.4950	20.6	27.6	0.000439809 11.3663 −1434.26
5860Y/ SC5861	P1 ±7.0 V Ciemat	3.5106	20.6	19.9	0.000381154 6.1256 −1115.05
5862X/ SC5863	P2 ±8.0 V AGI	3.4898	17.2	41.4	0.000323004 −1.5304 459.38
5862Y/ SC5863	P1 ±9.5 V AGI	3.4846	17.1	36.3	0.000137298 −2.1254 −1778.19
5862X/ SC5863	P2 ±8.0 V AGI	3.4611	−21.8**	39.1	0.000335218 8.8677 478.72
5862Y/ SC5863	P1 ±8.0 V AGI	3.4602	−21.6**	24.5	0.000510225 −3.0492 −1805.74

5.3 Tiltmeters in the Link Discs: Data Base

One dual tiltmeter is placed, in the top position, in each of the Link Discs. Calibrations were done in our laboratory at ambient temperature and in a restricted working range.

Sensor serial number Model 756-1150	Electronics serial number Model 83162 SC
6268 6270	6269 6271

Notice that the only quantity we can measure is the angle variation, calculated in the simple form:

$$\Delta(\text{angle in } \mu\text{rad}) = (V_{measured}(\text{mV}) - V_{initial}(\text{mV})) \times S\ (\mu\text{rad/mV})$$

The measured calibration parameters are:

Serial Numbers	**Connector at the SC**	**Location**	**S** (μrad/mV)	**Cal. Range** (V)	**Precision when in range** (μrad)	**Precision when out of range** (μrad)
6268X SC6269	P2	LD – top	3.50670	± 4.0 V	16	24
6268Y SC6269	P1	LD – top	3.51270	± 4.0 V	30	45
6270X SC6271	P2	LD + top	3.50020	± 6.0 V	28	42
6270Y SC6271	P1	LD + top	3.49475	± 6.0 V	36	54

5.4 Tiltmeters in the Transfer Plates: Data Base

Tiltmeters on the TPs are biaxial 900-H sensors. They measure tilts in Φ and Θ, as a dual sensor does, but all the four excitation electrodes as well as the pick-up one are placed in the same volume and the gas bubble is common for both coordinates (see Figs. 13 and 14).

The sensors are integrated on their own signal conditioning card as shown in Fig. 13. In addition, a home made electronic card is added to the SC (see Fig. 14) in order to take data in differential mode, instead of single ended (the mode provided by the constructor). This allows increasing by a factor two the original resolution of the biaxial clinometers and, in addition, canceling eventual noises.

5.4.1 Important notes related with the 900-H sensors

1.- Interpretation of the readout voltages:

900-H at TP+:

The output wires come out towards the Interaction Point (IP)

The Y coordinate of the sensor monitors tilts in Φ. If ΔV(Y) > 0 ➔ ΔΦ > 0, the TP rotates in the sense of positive values of Φ (see Fig. 11).

The X coordinate of the sensor monitors tilts in Θ. If ΔV(X) > 0 ➔ ΔΘ < 0, the TP gets inclined towards Z –, towards the IP (see Fig. 11).

900-H at TP–:

They are placed as mirror images of those at Z+, and their output wires also come out towards the IP.

The Y coordinate of the sensor monitors tilts in Φ. If ΔV(Y) > 0 ➔ ΔΦ < 0, the TP rotates in the sense of negative values of Φ (see Fig. 11).

The X coordinate of the sensor monitors tilts in Θ. If ΔV(X) > 0 ➔ ΔΘ > 0, the TP gets inclined towards Z+, towards the IP (see Fig. 11).

2.- The precisions given in the table below are only valid for a working range of ± 600 mV. Outside this range the precisions should be increased by a 50%.

3.- The only quantity we can measure is the angle (the tilt), which is calculated in the simple form:

$$\Delta(\text{angle in } \mu\text{rad}) = (V_{measured}(\text{mV}) - V_{initial}(\text{mV})) \times S\ (\mu\text{rad/mV})$$

4.- The calibration range was ± 600 mV, equivalent to ± 22 mrad.

5.- The output voltage goes to the ELMB cards without any division. The ± 2.5 V ELMB working range should allow resolving tenths of mV.

What follows is the complete list of the available 900-H sensors and their characteristics. The positions appearing in the table may have changed due to mechanical requirements during installation.

Serial number/ co-ordinate	**Location**	**S** (μrad/mV)	**Precision** (μrad)
N8315/X	Z + 15^o	35.825	62
N8315/Y	Z + 15^o	36.825	46
N8314/X	Z + 75^o	37.552	53
N8314/Y	Z + 75^o	38.146	68
N8213/X	Z + 135^o	37.405	41
N8213/Y	Z + 135^o	37.684	91
N8323/X	Z + 195^o	40.581	49
N8323/Y	Z + 195^o	40.451	46
N8325/X	Z + 255^o	37.343	57
N8325/Y	Z + 255^o	38.766	31
N8771/X	Z + 315^o	39.584	26
N8771/Y	Z + 315^o	39.057	39
N8322/X	Z + spare	36.462	26
N8322/Y	Z + spare	36.463	32
N8316/X	Z – 15^o	38.278	20
N8316/Y	Z – 15^o	39.243	33
N8770/X	Z – 75^o	38.867	15
N8770/Y	Z – 75^o	38.943	28
N8178/X	Z – 135^o	37.664	69
N8178/Y	Z – 135^o	37.855	59
N8324/X	Z – 195^o	37.596	59
N8324/Y	Z – 195^o	37.427	50
N8768/X	Z – 255^o	38.365	45
N8768/Y	Z – 255^o	39.119	28
N8769/X	Z – 315^o	39.742	59
N8769/Y	Z – 315^o	39.692	32
N8179/X	Z – spare	38.903	29
N8179/Y	Z – spare	38.730	28

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[15] Applied Geomechanics Incorporated. 1336 Brommer Street, Santa Cruz, CA 95062 USA.

The models in this document belong to the 756- Series Mid-range and 755-Series High-Gain Miniature Tilt Sensors.

[16] Heidenhain Digital Length Gauge Systems, http://www.heidenhain.com.

Figure Captions

Fig. 1: Schematic drawings of the various tiltmeters used in the Link Alignment System of CMS, as they appear in the Applied Geomechanics Incorporated Web site:

a) 1D M756-1172 MTS for MAB,

b) 2D M756-1150 MTS for AR and BD rings of the Tracker and

c) for Link Disc ring, 900-H biaxial for TP.

Fig. 2: CMS views and coordinates system definition:

a) Longitudinal view,

b) Transverse view.

Fig. 3: Sketch of the Link Alignment System.

Fig. 4: Sketch of a MAB structure giving the position of the attached tiltmeter and notice about the angle we try to monitor (Φ). CMS axis coordinates system is also shown.

Fig. 5: Sketch of the AR and BD rings at one of the Tracker ends, giving the positions of the top dual tiltmeters attached to them and notice about the Φ and Θ angles to be monitored. CMS axis coordinates system is also shown.

Fig. 6: Schematic structure of a tiltmeter.

Fig. 7: 3D view of the tripod used in the tests.

Fig. 8: Lateral view of the optical table, tripod, tiltmeter and Heidenhain set-up. The Heidenhain is supported by a heavy holder, to ensure it does not move when the tripod tilts.

Fig. 9: Result of the calibration of one of the tiltmeters at Ciemat (see text):

a) Angle moved as a function of the output voltage, fitted to a linear function in V,

b) Distribution of the residuals from the fit.

Fig. 10: Result of the calibration of one of the tiltmeters at AGI (see text):

a) Angle moved as a function of the output voltage, fitted to a linear function in V,

b) Distribution of the residuals from the fit.

Fig. 11: CMS definitions for X, Y, Z, Φ and Θ coordinates.

Fig. 12: The two possible orientations of a tilt sensor in a given plane:

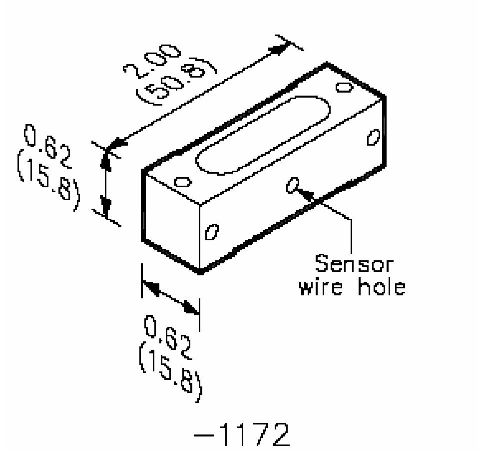
a) position **[**+ - **]**

b) position **[**- +**]**

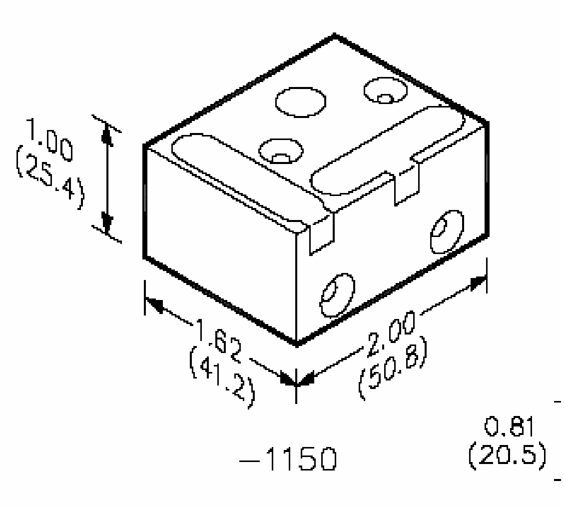
Fig. 13: Sketch and size of one 900-H series biaxial tiltmeter for the Transfer Plates.

Fig. 14: Picture of two 900-H sensors on the calibration setup. On the left, unit for TP on the CMS Z– side. On the right, unit for TP on the CMS Z+ side. The cards allowing the differential mode operation can be seen on top of the 900-H clinometers.

a)


2.00
(50.8)
0.62
(15.8)
Sensor
wire hole
0.62
(15.8)
–1172

b)


1.00
(25.4)
1.62
(41.2)
2.00
(50.8)
–1150
0.81
(20.5)

c)

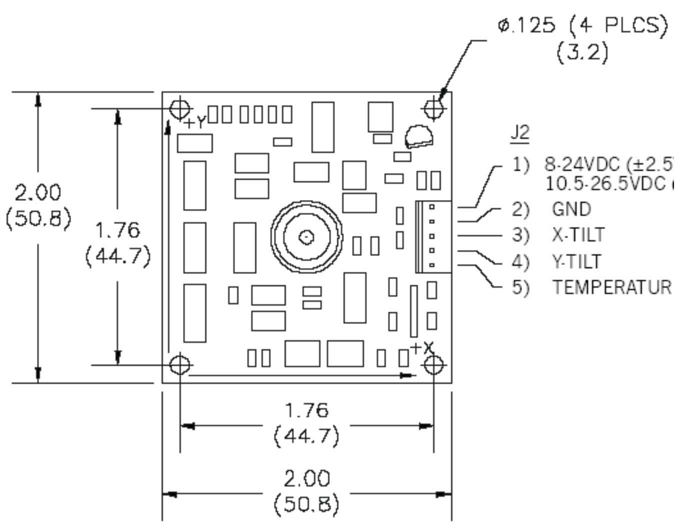
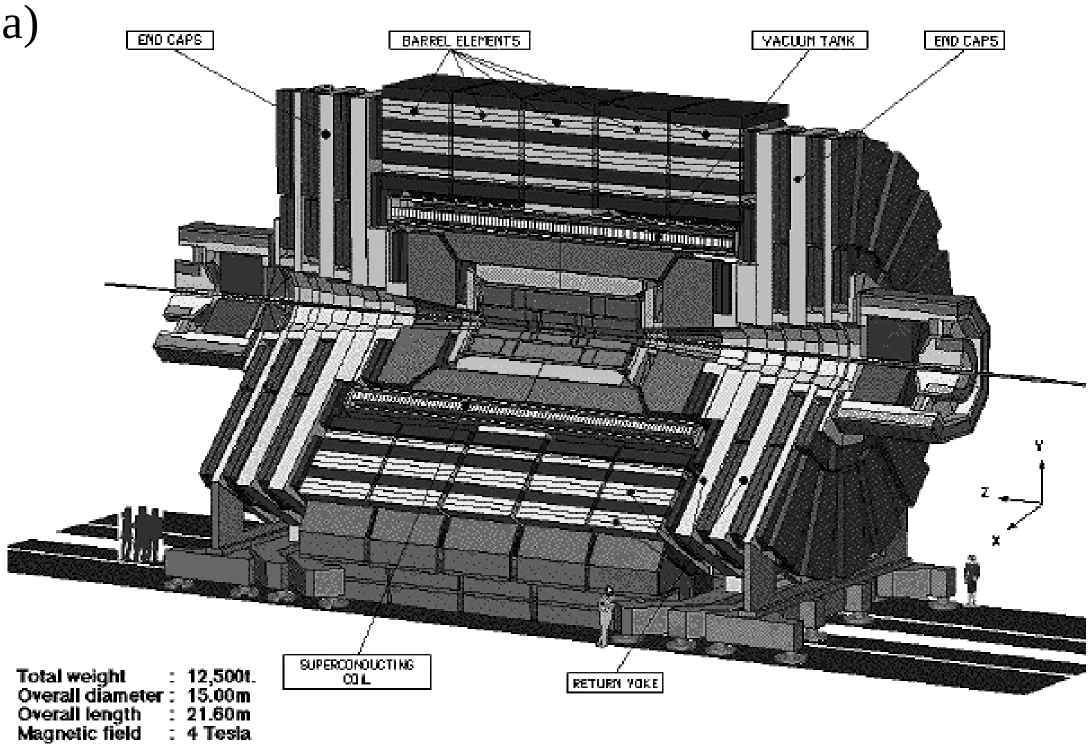

ϕ.125 (4 PLCS)
(3.2)
2.00
(50.8)
1.76
(44.7)
+Y
+X
J2
1) 8-24VDC (±2.5
10.5-26.5VDC
2) GND
3) X-TILT
4) Y-TILT
5) TEMPERATUR
1.76
(44.7)
2.00
(50.8)

Fig. 1

a)


END CAPS
BARREL ELEMENTS
VACUUM TANK
END CAPS
Y
Z
X
SUPERCONDUCTING COIL
RETURN YOKE
Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

b)

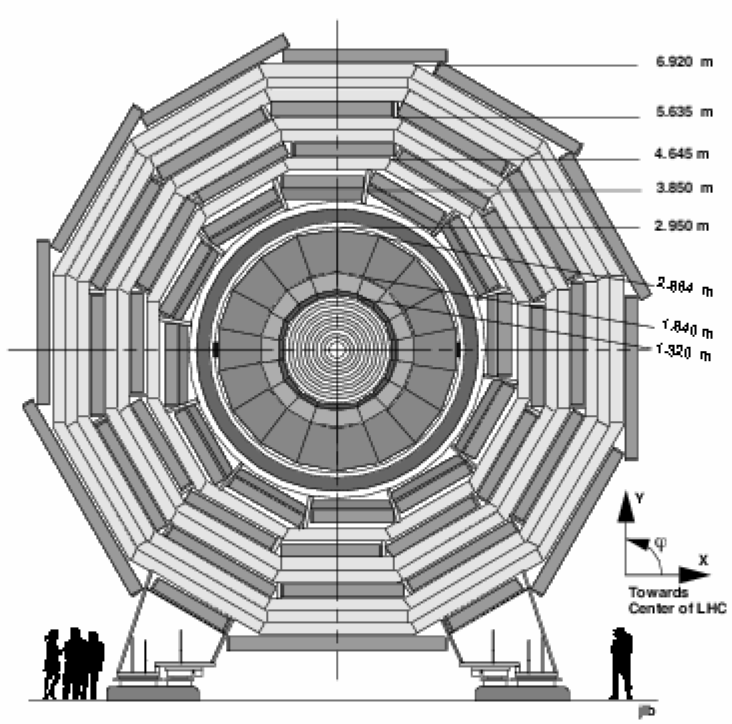
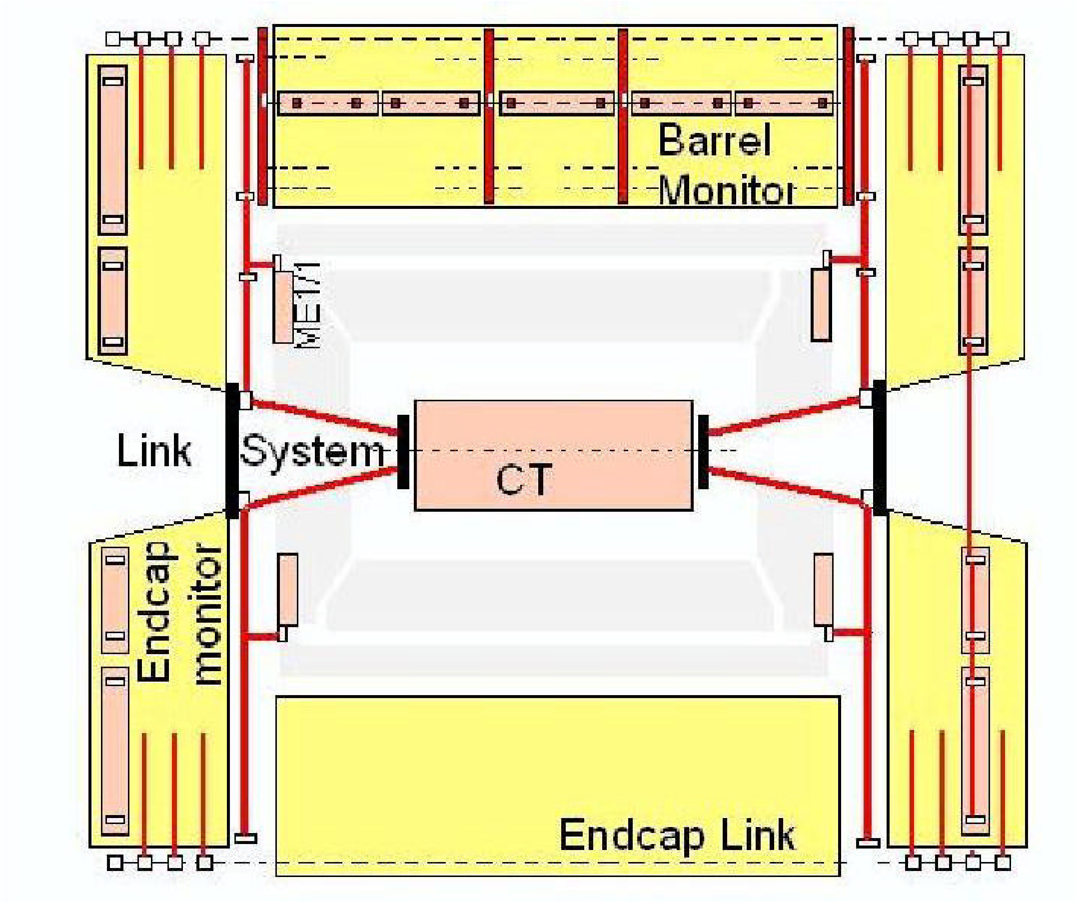

6.920 m
5.635 m
4.645 m
3.850 m
2.950 m
2.864 m
1.840 m
1.320 m
Y
φ
X
Towards
Center of LHC

Fig. 2



Barrel
Monitor
ME1/1
Link
System
CT
Endcap
monitor
Endcap Link

Fig. 3

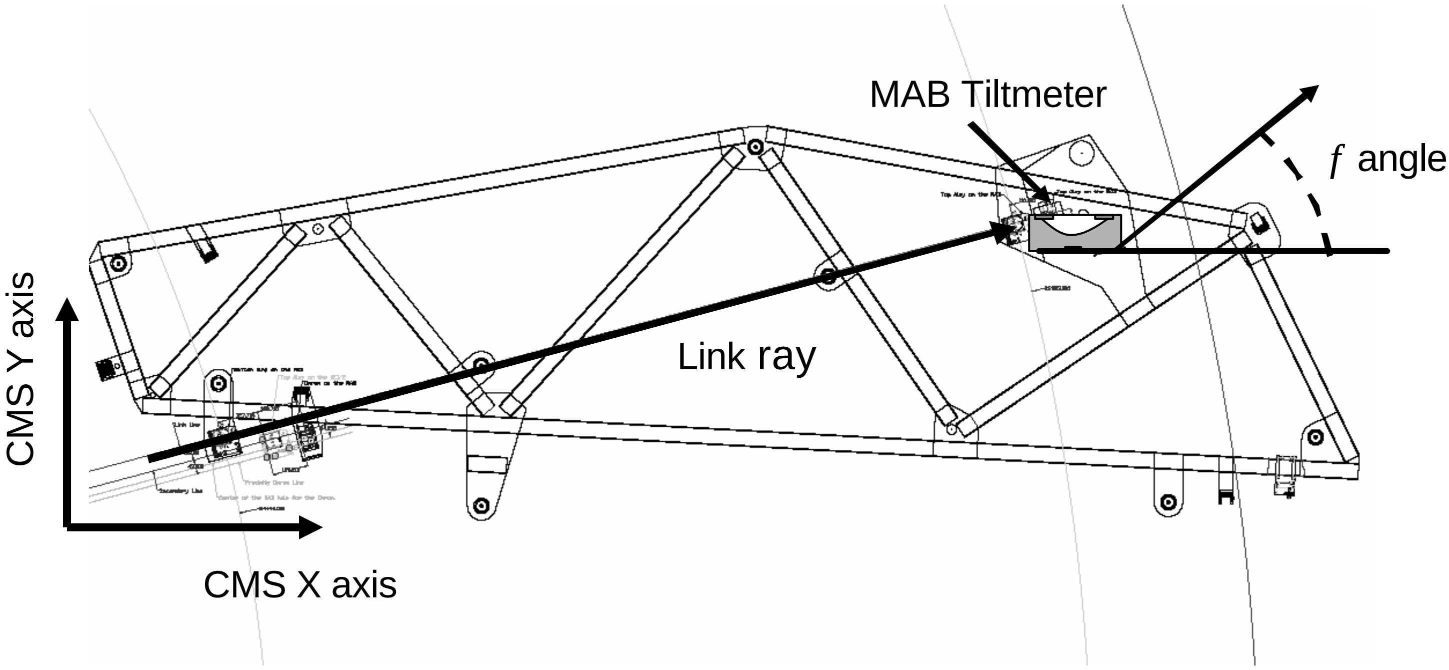


Fig. 4

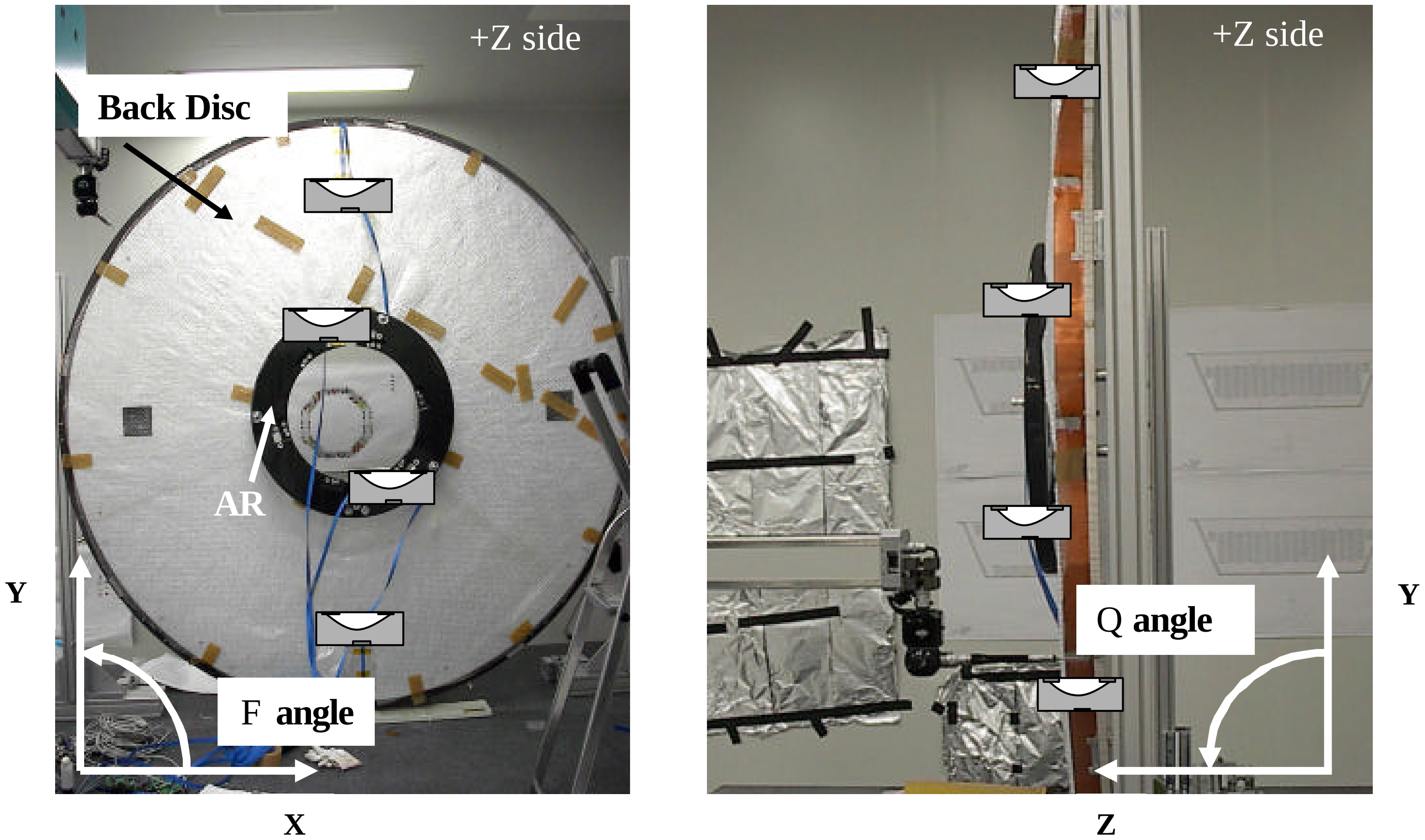


Fig. 5

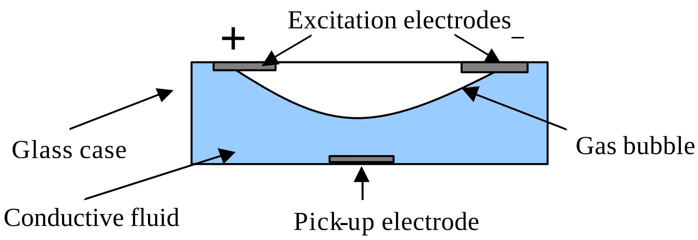

Excitation electrodes
+
−
Glass case
Gas bubble
Conductive fluid
Pick-up electrode

Fig. 6

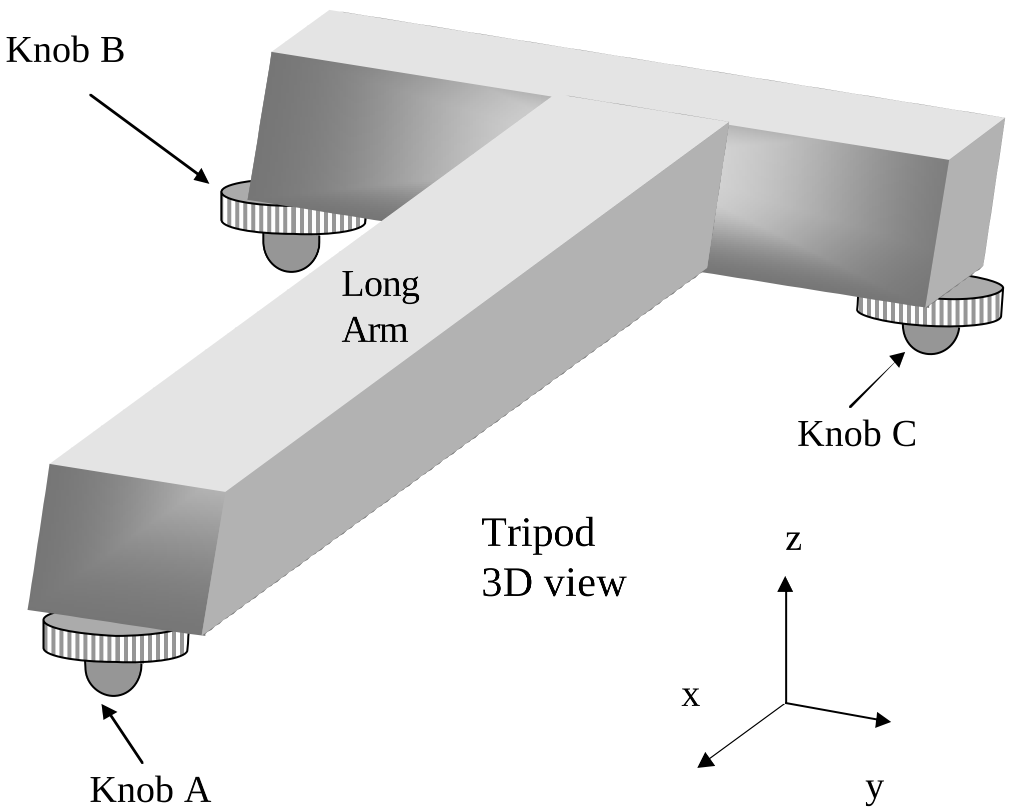


Fig. 7

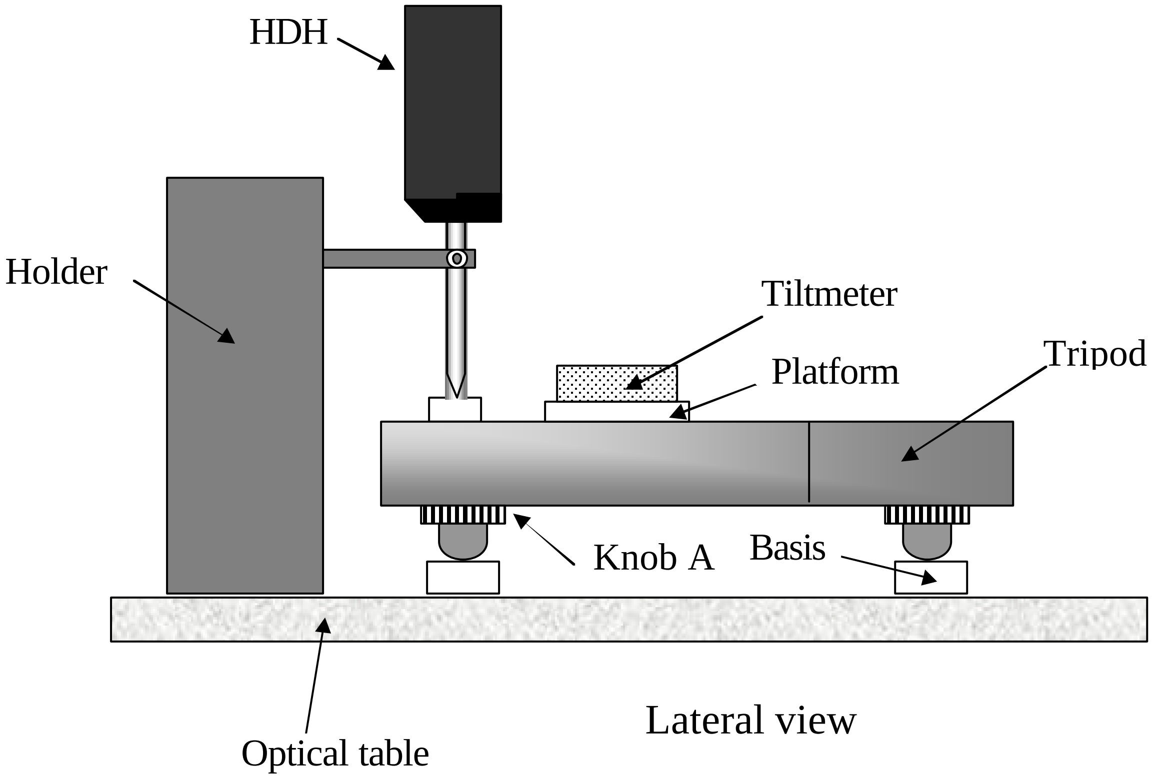
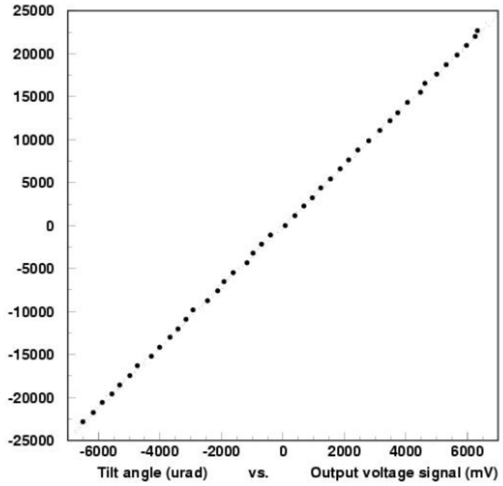

HDH
Holder
Tiltmeter
Platform
Tripod
Knob A
Basis
Optical table
Lateral view

Fig. 8

a)


25000
20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-6000 -4000 -2000 0 2000 4000 6000
Tilt angle (urad) vs. Output voltage signal (mV)

b)

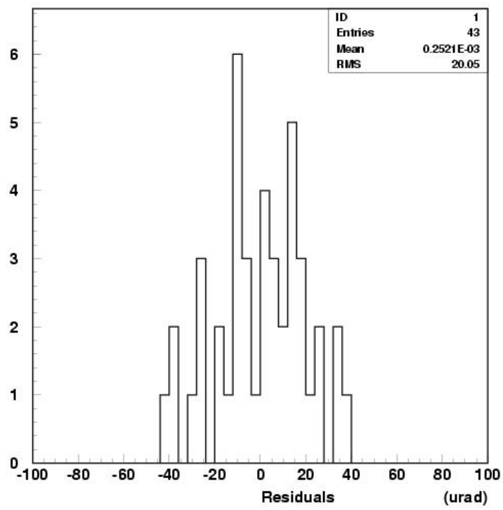
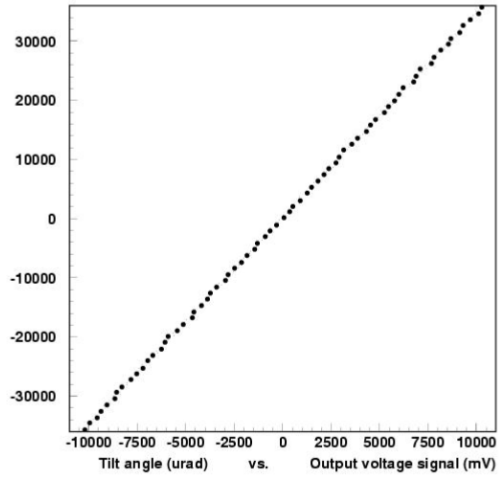

ID 1
Entries 43
Mean 0.2521E-03
RMS 20.05
0 1 2 3 4 5 6
-100 -80 -60 -40 -20 0 20 40 60 80 100
Residuals (urad)

Fig. 9

a)


30000
20000
10000
0
-10000
-20000
-30000
-10000 -7500 -5000 -2500 0 2500 5000 7500 10000
Tilt angle (urad) vs. Output voltage signal (mV)

b)

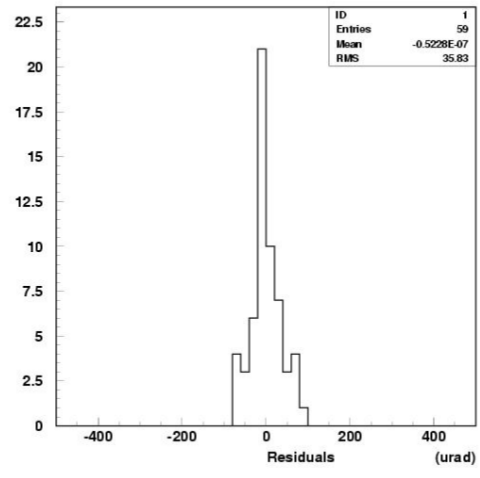

ID 1
Entries 59
Mean -0.5228E-07
RMS 35.83
22.5
20
17.5
15
12.5
10
7.5
5
2.5
0
-400 -200 0 200 400
Residuals (urad)

Fig 10

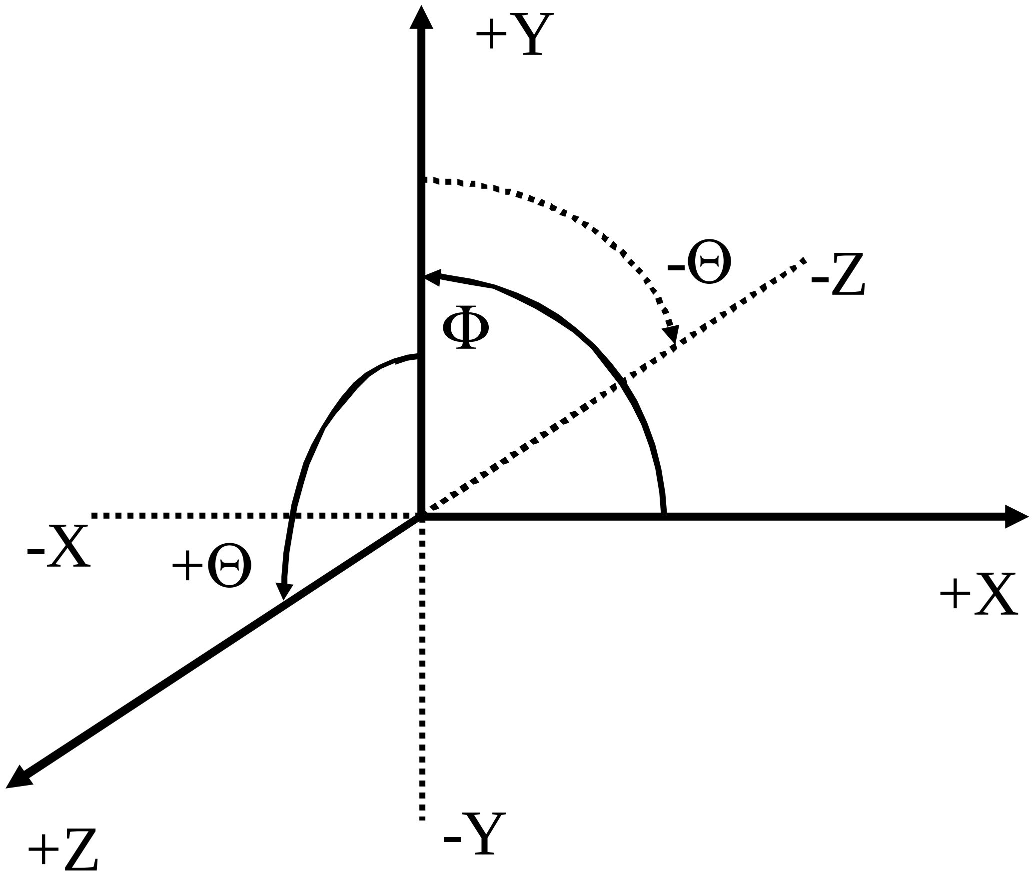
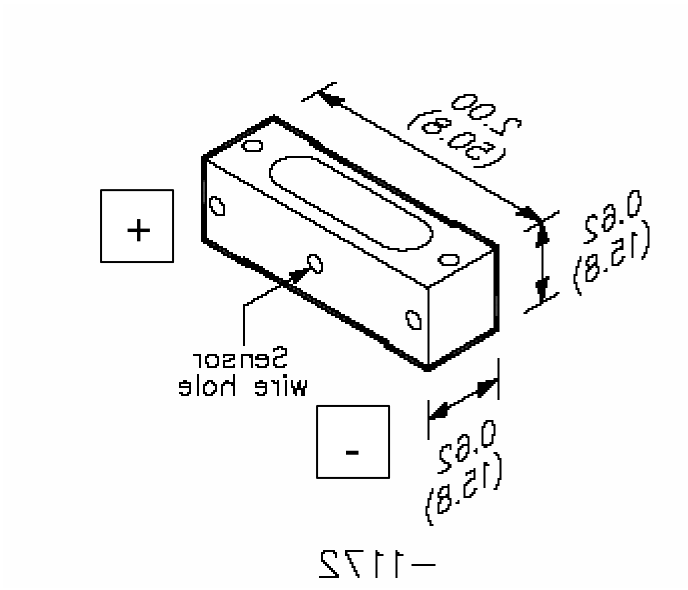


Fig. 11

a)


+
-
2.00
(50.8)
0.62
(15.8)
0.62
(15.8)
Sensor
wire hole
-1172

b)

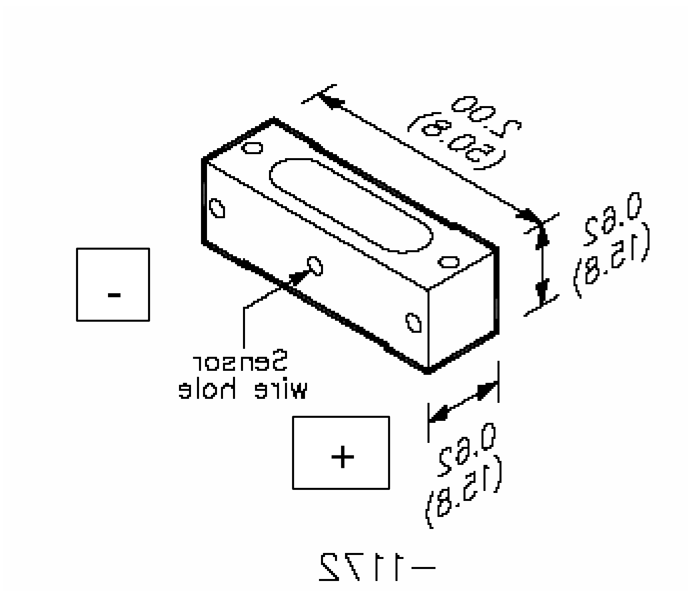
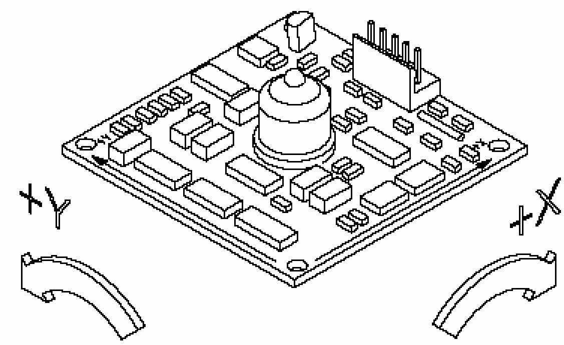

-
+
2.00
(50.8)
0.62
(15.8)
0.62
(15.8)
Sensor
wire hole
-1172

Fig. 12


+Y
+X

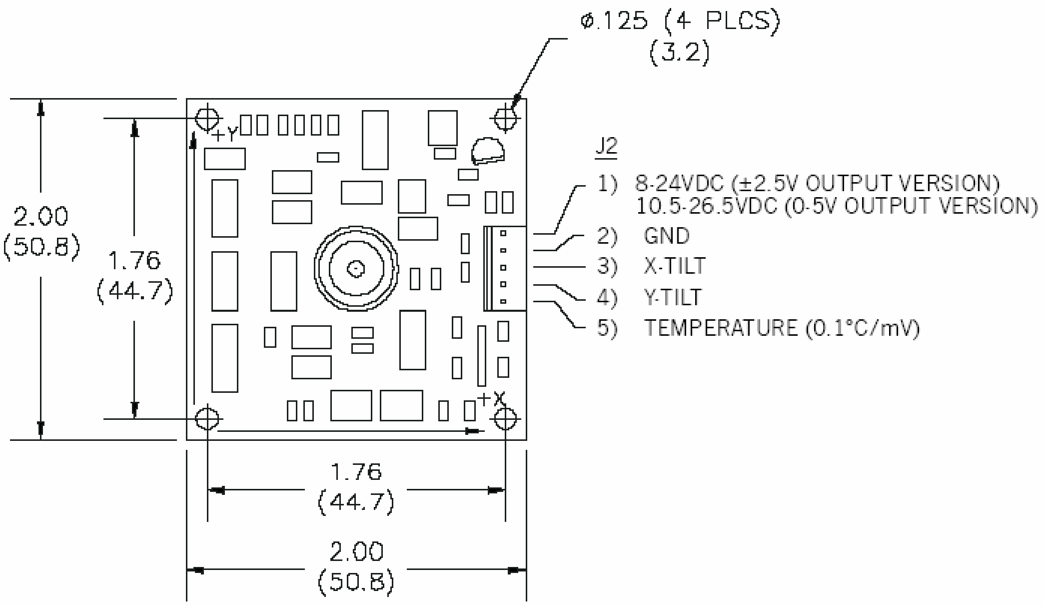

ø.125 (4 PLCS)
(3.2)
2.00
(50.8)
1.76
(44.7)
+Y
+X
J2
1) 8-24VDC (±2.5V OUTPUT VERSION)
10.5-26.5VDC (0-5V OUTPUT VERSION)
2) GND
3) X-TILT
4) Y-TILT
5) TEMPERATURE (0.1°C/mV)
1.76
(44.7)
2.00
(50.8)

Fig. 13

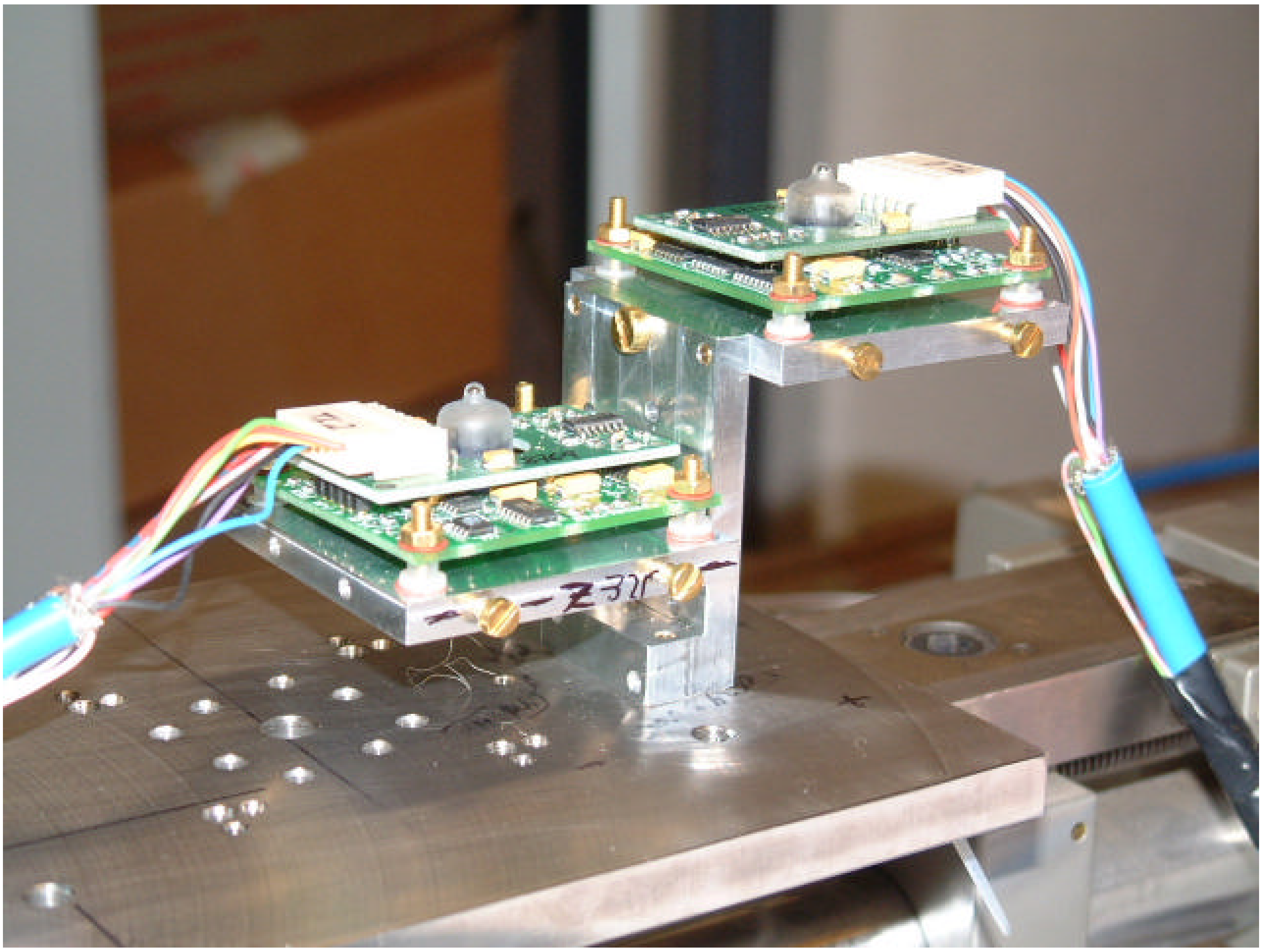


Fig. 14