A TWO DIMENSIONAL DIGITAL CCD OPTICAL POSITION SENSOR FOR RELATIVE ALIGNMENT MONITORING

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In the Compact Muon Solenoid Detector (CMS) for the Large Hadron Collider (LHC), the Endcap Muon System needs relative position monitoring of detector elements to trigger and match other muon/tracking chambers. We plan straight line monitors (SLMs) across layers of Endcap Muon Chambers (Figure 1.) and across the CMS barrel for linking to the Central tracker/barrel muon chambers (Figure 2.)

We have been testing ATLAS detector (LHC) -Max Planck Institute transparent silicon 20 mm^2 photodiode detectors (glass substrates) with 64 X, Y strip current out electrodes, on board electronics and ADC conversion with 128 word Digital Readout in 16 sensor strings into VME. [1, 2]. These detectors are our technical design report baseline detectors using beamsplitting of the laser or first sensor signal saturation.

We have demonstrated in tests of 6m in line groups(SLMs) of these MPI detectors (using simple fixed optics laser diode modules (LDMs)) the following results: [3, 4, 5]

Short term resolutions of 2 -10 μm and Long term resolutions (many days) of 10-25 μm (after corrections for laser beam motions-pointing and thermal effects) and a 15 mm beam motion (dynamic) range and comparable resolution results with optically split opposing LDM beams.

However, with simple 670 nm LDMs and the first sensor near ADC saturation, we can only transmit through seven detectors and have good signal-background spectra peak fits.There is substrate refraction and X, Y variation, back reflection/scattering of the laser beam from the faces of the detector, variation in AR coating (signal response), and sensitivity to beam abberations. Upstream detectors influence downstream detectors and degrade their resolution. Prototypes have been expensive.

We need a larger beam motion (dynamic) range as the motion of CMS endcap return iron in the 4 Tesla solenoid field can be 14-25 mm depending on the mechanical connection of iron pieces and preloading.

We want in line detectors with minimum interactions, making independent beam sampling, and having a larger dynamic range, of standard technology with well defined costs.

Jean Christophe Gayde (CERN Geodesy Group) proposed a window frame CCD detector using crossed laser beams for X, Y beam position measurements (FAST) and performed some initial tests of such a device (with CEIMAT) but could not continue a program of development. [6]

We decided to develop a comparable device with ON BOARD electronics to provide serial digital readout of CCD arrays (1, 2, 4) to study background light filtering, dark current, vibration effects, laser beam position resolution - Short and Long term, linearity, spectrum signal processing, window boundary effects, and crossed laser beam requirements. [7] The device (COPS) consists of four linear CCD arrays around a square opening on a printed circuit board with serial readout . A crosshair laser (known directions in space) beam is detected by the four linear arrays to determine two X, Y positions at the detector. This allows redundancy or a measurement of torsion.

For these tests we used a crosshair laser diode module (SNF-501H-6705-10-5 Lasiris; Quebec, Canada) with a 5 degree fanout angle and approximately uniform line intensity which proved adequate over our 6m test range. In long range tests, we will use a laser diode module/beamsplitter/cylindrical lens setup to produce a Gaussian line intensity for large signal to noise in detectors far from the source. This COPS sensor is the front end electronics of our planned digital readout detector. The CCD sensors are SONY ILX503A =2048 14μm x 14μm pixel devices, 22 pin DIP, for a 28.67mm range. Each CCD has a signal amplifier, double correlated sample circuitry, and differential amplifier to make a single ended signal. Timing signals are made by a string of one shots. Each CCD is multiplexed into a 16 bit ADC with calibration inputs and the board includes control and interface circuits to a byte wide interface board in a dedicated PC. The PC control board signals the shift of charge (from CCD sensitive area) to the transfer shift register, initiates double correlated sampling of charge simultaneously, multiplexing, ADC conversion, and two byte readout by PC I/O bus.

The ATLAS MPI sensors confirmed that the crosshair beam profile did not change shape as a function of distance (to ~5.3m) due to air currents, temperature gradients, or fluctuations in the laser source. These measurements indicated that the beam profile could be fitted by a Gaussian distribution.

We implemented the following beam position fits: measure and subtract laser off background from the laser on data, do a constant “threshold” of 300 ADC counts (zero negatives), do a center of gravity (mean). We also did a Guassian fit to the difference spectrum in early testing. The results of testing are:

(1) CCD optical filter development. The linear arrays saturate with background light and must be covered with a film absorber to detect the desired signal. To minimize refraction, distortion, beam broadening effects and to provide a stable (radiation, aging) low cost filter we tried evaporated nickel (Ni), Ni-Cr (90-10%), and sputtered gold (Au) coatings on the CCD windows as well as applied plastic films.The metal films can have the right absorption (900-1000 A^o), but they are not uniform (variation). They had pinholes; which results in spiky peaks and background and affects measured linearity, with a standard deviation of21-24 μm for Gaussian fits, and 45 μm for a simple mean fit (Figure 3). The long term resolution was (7-14 μm) (Figure 4).

So we tested 3M vinyl adhesive tapes. Tape color is strongly correlated with ambient light opacity. One tape (brown) allowed normal background illumination and laser light sensitivity. The signal, background, and difference spectra are shown in Figures 5, 6,and 7. Long term stability of the tape(temperature, radiation) has to be established. The following tests were done at a 4m distance from the laser diode module:

(2) Linearity measurements. COPS was mounted on a X-Y micrometer stage. Ten measurements at each point (for simple mean fit) gave an RMS under 3 μm. The deviation from linearity (500 μm steps) had an RMS of 5 μm, motions in 100 μm steps had a RMS close to 3 μm. [8]. See Figure 8.

(3) Measurement of torsion around the laser beam. The spacing between two parallel CCD arrays (XX or YY) is 52mm, so we could expect 1/10 mrad angular resolution in using the two measurements to define a torsion angle. Initial simple tests (with a coarse screw adjustment) gave an angular resolution better than 0.2 mrad. See Figure 9.

(4) We tested the effect of moving an upstream PC board (window) to cut the laser beam reaching the CCDs on COPS detector 2m downstream. The downstream CCD observed beam position did not shift (due to light scattering/refraction), only the profile was cut.

(5) Observed background dark current. Our exposure was set at 5-10msec. With up to 0.10 sec exposure, the dark voltage was a linear function $V = kN_{pix} + T_{exp}$; the integrated background was small wrt laser beam peak.

Given these results, we proceeded to develop the digital signal processor readout version with simple means fit.

DSP Readout detector:

The concept is to have an easy to use, simple, LOW power hardware system with flexible software, phone cable connection (two wires as a bi-directional differential data line (RS485), one supply voltage, ground), run by a system Controller (+slave VME interface), again with flexible software.

DSP/COPS Board Hardware Description:

Physical Size approx. 75 X 250 mm
Processor: Analog Devices ADSP2103 running at 10MHz
ROM: 32Kx8 writable flash EPROM divided into 8- 2Kx8 Boot pages and one 14Kx8 constants storage area (2Kx8 is unused)
RAM: 32Kx16 SRAM divided into 4 overlaid 8Kx16 pages
CCDS: Sony P/N ILX503 2048 pixel (14 μm), linear CCDs
ADC: [12bit 10uS conversion time], serial data path
DAC: [12 bit DAC for offset adjustment]
Temperature Sensor: Dallas Semiconductor [0.5 deg. C resolution] readback with serial data path.
Communication: [serial] RS-485 transceivers. Max baud rate: 1.2 Mbaud on std telephone connectors.
Power requirements: +12v @ < 300 mW. On board DC-DC converters (inductive regulators except in high B field - linear, charge pumps) for +9v CCD supply, +5v analog supply, +3.3v digital supply

DSP Software: The analysis code in ADSP-2100 Assembler language is complete. It will be loaded into the boards in assembly and will be booted after power up by the system controller.

Initialization : The detector boards are queried for self assignment (establishment) of unique addresses [N] = (0-14).

Send Processed Data: [S] + [P] +[70]   Take Data and Process:

Subaddress 15,   [70] ASCII   is used to broadcast commands to all boards simultaneously.

Normal Algorithm of processing signal

* DSP receives command to read the signal and find center of gravity of the signal
* COPS measures signal spectra
* DSP performs calibration of the signal - if calibration values are previously measured (PC command)
* DSP subtracts background - if background was previously measured (MB command)
* DSP performs a simple mean calculation (center of gravity) = (one number/2bytes each CCD chip)
* DSPs send word count (2 bytes), address/status (2 bytes), and 4 numbers (8 bytes) each in token sequence to the Controller. End of transmission is established by summed word count /(time-out).

Special commands/responses: Commands(2 bytes) can also be sent to specific board addresses (1 byte).

MB: [M]+[B]+[N] measure background spectrum. Without MB, the program takes background =0

PC: [P]+[C]+[N] perform internal optical gain calculation (difference of pixel charge and nearby pixels in flood illumination) -check against calibration

SG: [S]+[G]+[N] send gain values for the four CCDs.

SR: [S]+[R]+[N] send Raw Data + means - allows external data processing and fitting to check

Using a DSP software simulator, the program code has been tested on data buffers taken from the first test COPS board and demonstrated to yield the same fits as derived with the PC analysis.

Boards are under construction; calibration, linearity measurements, long term stability tests will be done at Northeastern University to meet the March 98 CMS milestone. Controller development will proceed at Fermilab. Detector cost: $33.5 (bd) +$164.5(parts) +$66(CCD)+ $35 (assy) = $299 US

Long SLMs can dictate the use of multiple window sizes and a minimum distance between detectors (window-pixel distance). Different windows can be achieved by sliding CCD pairs (XY). Alternately, by using a 2 CCD board for single X, Y measurements that is open on two sides, half detectors can be interleaved.

Calibration:

(1) Using reference pin holes in the PC board to mount into a “standard” fixture, X, Y calibration of CCD detectors (location, twist, pitch) will be done with illuminated precision pinhole/slit masks

(2) Uniform illumination will check dark current levels and for “hot/pixels” -more photoresponsive pixels, dead pixels, and to provide pixel gain (size/shape) corrections - flat fielding.

The corresponding accelerator uses could be:

The relative alignment of quadrupole strings

Straight line monitor concatenation of groups of linear accelerator elements and limited arcs of dipoles.

References

[1] Transparent Silicon Strip Sensors for the Optical Alignment of Particle Detector Systems, W. Blum, H. Kroha, P. Widmann, Max Planck Institute for Physics/MPI-PhE/95-13

[2] A Novel Laser Alignment System for Tracking Detectors using Transparent Silicon Strip Sensors, W. Blum, H. Kroha, P. Widmann, Max Planck Institute for Physics/MPI-PhE/95-05

[3] CMS Endcap Muon System Evaluation of MAX PLANCK INSTITUTE Transparent Amorphous Silicon- X, Y Strip Readout Optical Beam Position Sensors; David P. Eartly, Robert H. Lee, Adam Bujak, Denis O. Prokofiev, CMS IN 1997-005.

[4] CMS Endcap Muon System Tests of Max Planck Institute Transparent Amorphous Silicon X, Y Strip Optical Beam Position Sensors in Two Way Split Laser Diode Module Beams; David P. Eartly, Robert H. Lee, CMS IN 1997-020.

[5] CMS Endcap Muon Position Monitoring System - Linking, Rasnik, and CSC Layer Straight Line Monitor Long Term Tests; David P. Eartly, Robert H. Lee, CMS Note (to be published).

[6] FAST system concept and tests at CERN :Jean Christophe Gayde (CERN) and R. Molinero (CEIMAT); see CMS Alignment Meeting proceedings of March 7, 1995

[7] COPS Position Monitoring System for the CMS Endcap Muon Detector; D. P. Eartly, T. F. Droege, E. Hahn, R. H. Lee, D. O. Prokofiev, J. Moromisato, E.vonGoeler, CMS Note 1996/021.

[8] Study of Position Resolution with COPS; J. Moromisato, E. vonGoeler, S.Reucroft, D. P.Eartly (to be published)

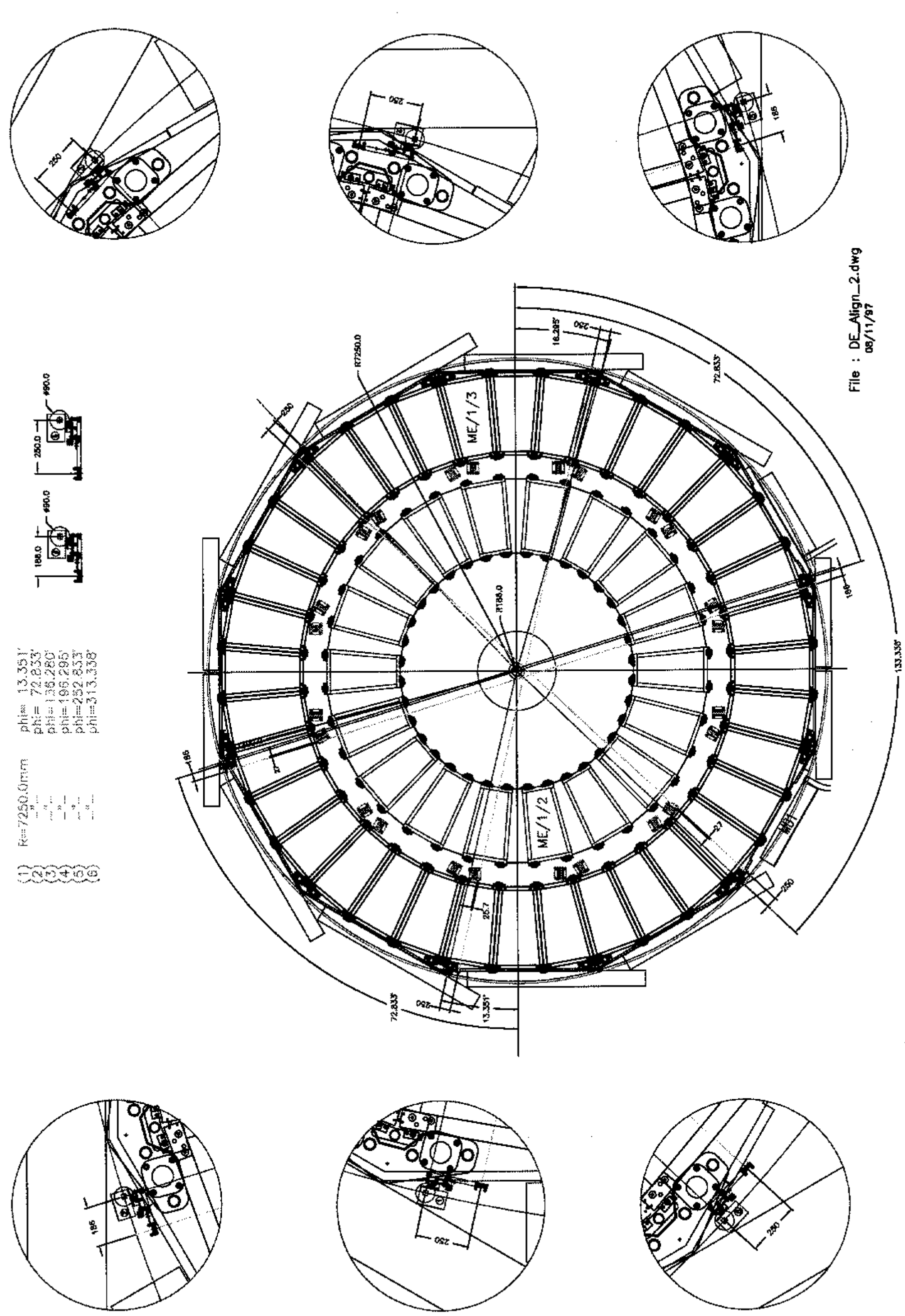

Figure 1. CMS Endcap Muon Straight Line Monitors across the ME1 layer of chamb

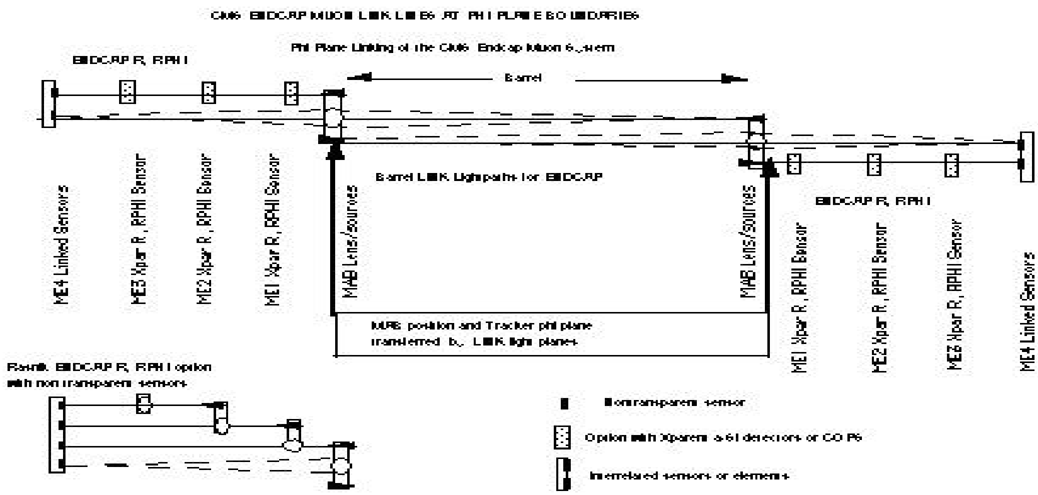

Figure 2. Endcap Link Straight Line Monitors (12) across CMS with sensors

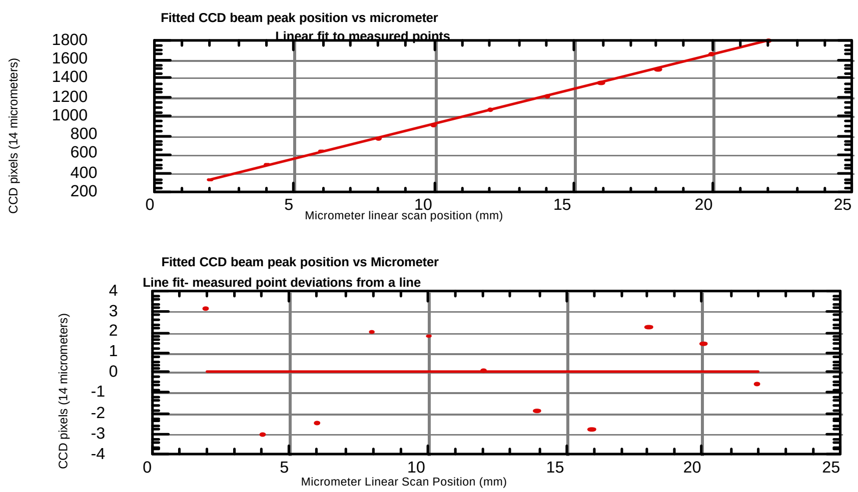

Figure 3. Linearity of measured CCD signal position in mechanical scan

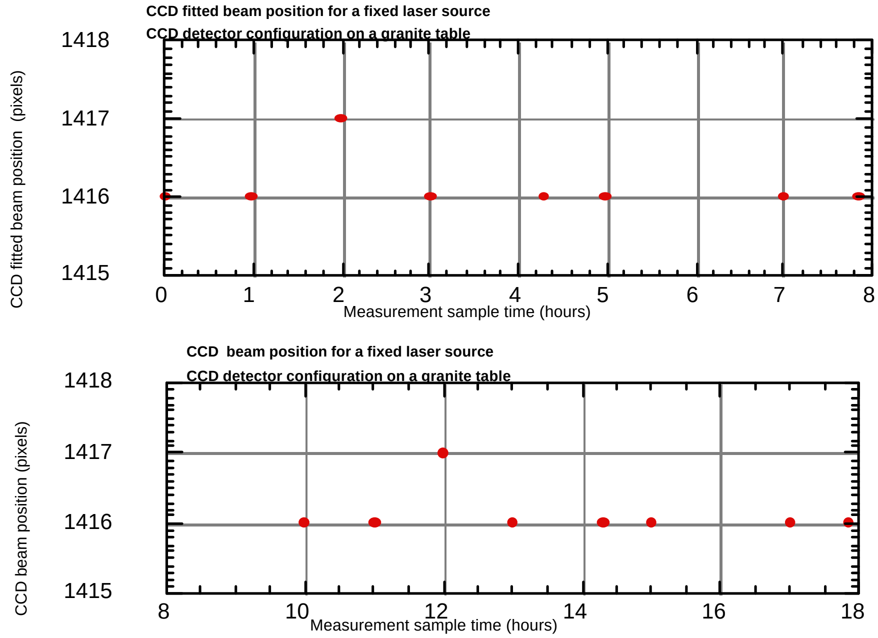

Figure 4. Long term Resolution of CCD signal position for a fixed laser beam

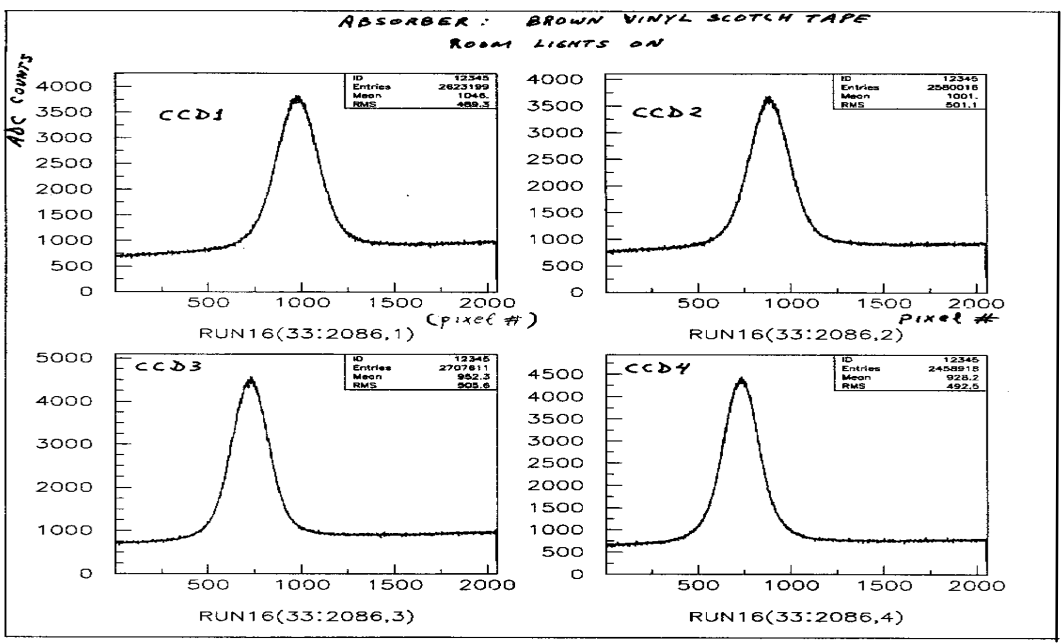

Figure 5. Brown Vinyl mask Laser Signal spectrum in normal background lighting

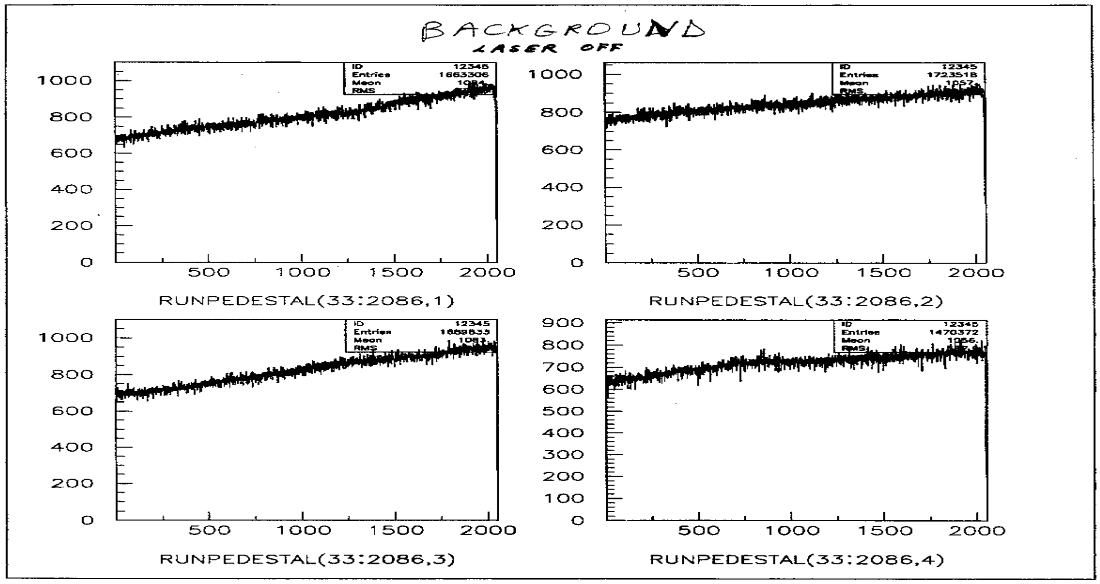

Figure 6. Brown Vinyl mask Laser Background spectra in the four CCDS

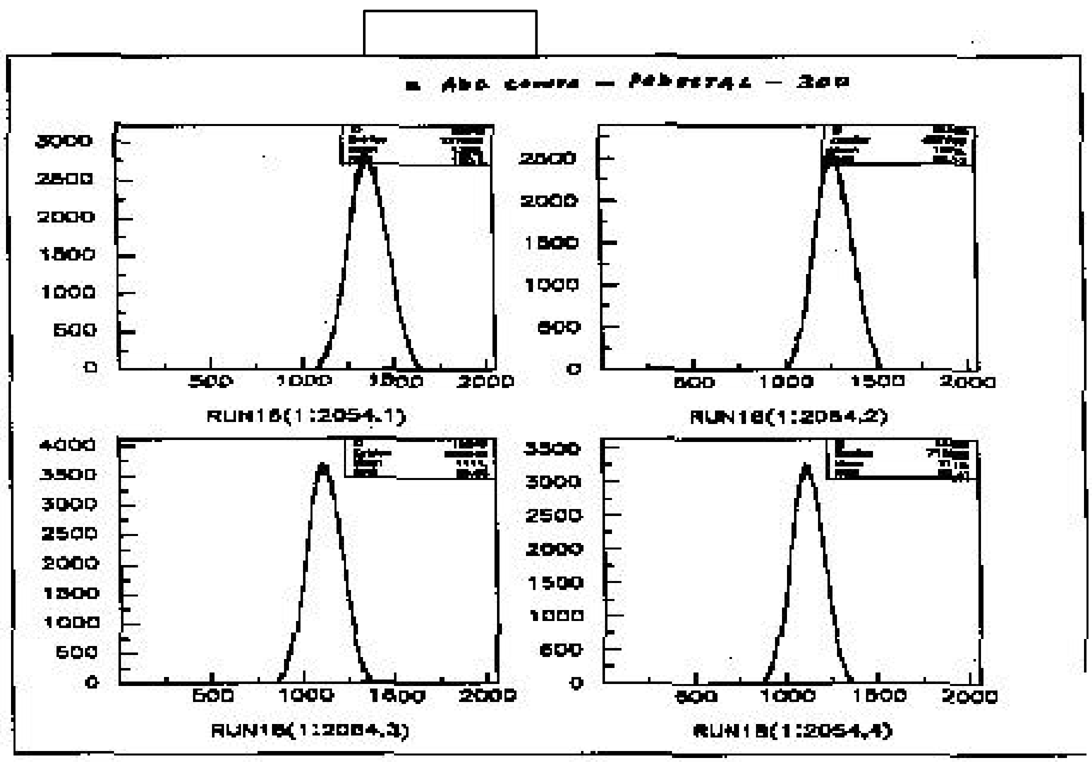

Figure 7. Brown Vinyl Mask Laser signal -background spectrum - 300 ADC counts

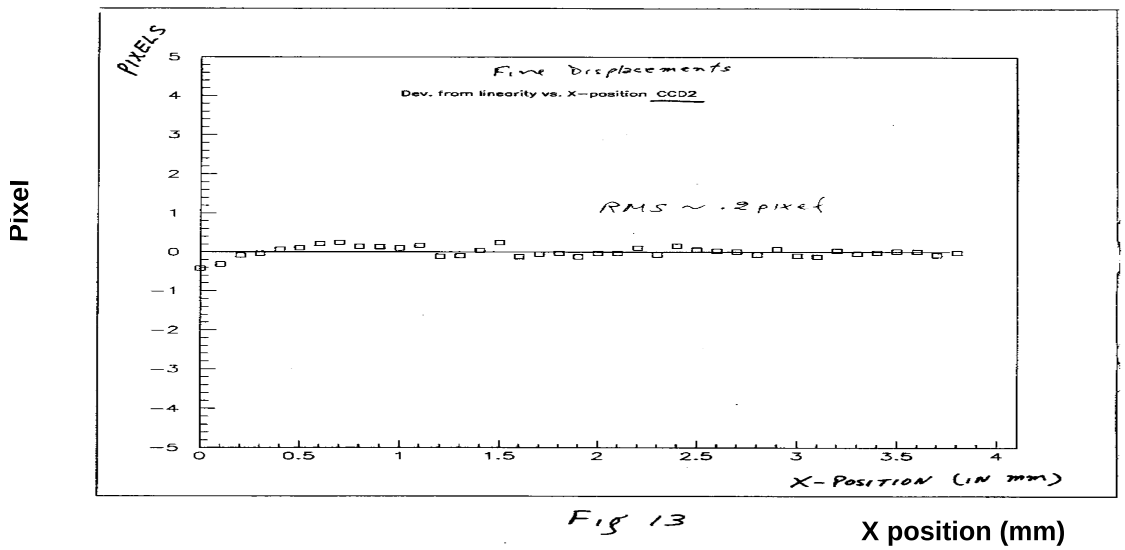

Figure 8. Deviation from linearity of CCD signal position in mechanical scan

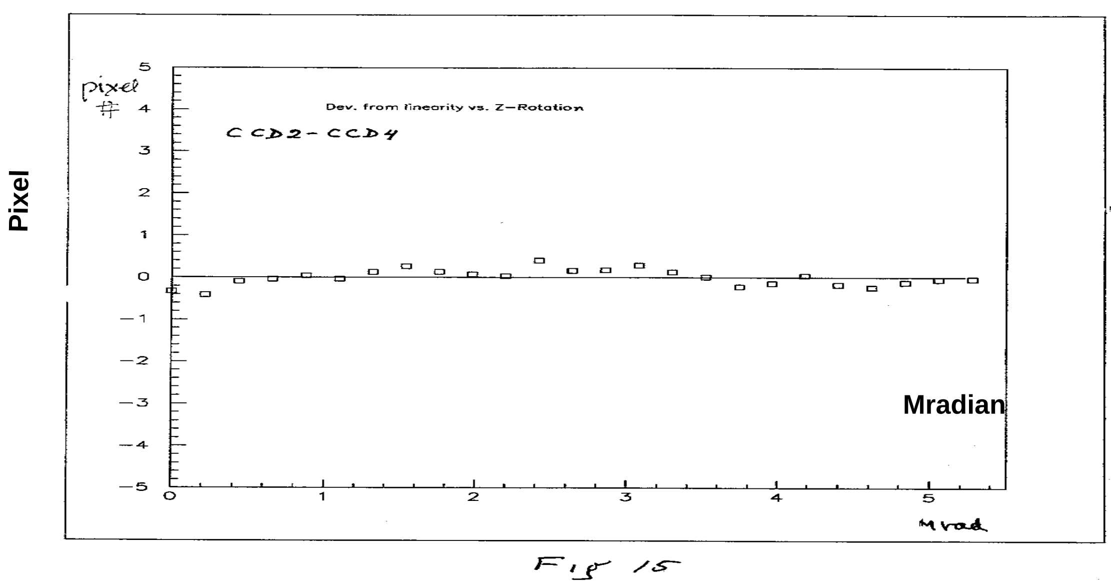

Figure 9. Deviation of CCD2-CCD4 from linearity in rotation of COPS in the beam