MULTI-POINT WIDE-RANGE PRECISION ALIGNMENT BASED ON A STRETCHED WIRE TECHNIQUE

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SUMMARY

A novel, simple and inexpensive multi-point two-coordinate alignment technique is proposed. The idea was simulated and tested in a laboratory. Over a very wide range (~10 mm) of possible displacements in two directions, this technique is capable to provide a few micron accuracy for one coordinate and an accuracy of a few tens of microns for another one.

1. AN AXIAL ALIGNMENT OPTION FOR THE GEM MUON SYSTEM

A high accuracy muon system is one of the major goals of the GEM Detector design [1]. Muon track bending is measured by three superlayers of muon chambers placed inside of a big solenoid (magnetic field - 0.8 T, solenoid diameter - 20 m and full length - 15+15 m). The systematic error in measuring a muon track sagitta due to chamber misalignment is required not to exceed 25 μm (RMS). Rather than maintain chamber position at this level of accuracy and stability, it would be beneficial to monitor and measure a false sagita due to misalignment and then use it in calculating a true muon track bending. It has been shown [2,3] that a projective alignment in combination with an interpolation method allows one to take out error contributions due to many kinds of chamber misplacements and distortions (shifts, rotations, expansion or contraction and torque) over a very wide range (around ±3 mm and ±5 mrad), assuming that alignment monitors provide an accuracy of 25 μm. Detailed discussion of the interpolation method and a wide-range precision alignment technique are presented in these proceedings (Ref.'s [4] and [5] correspondingly).

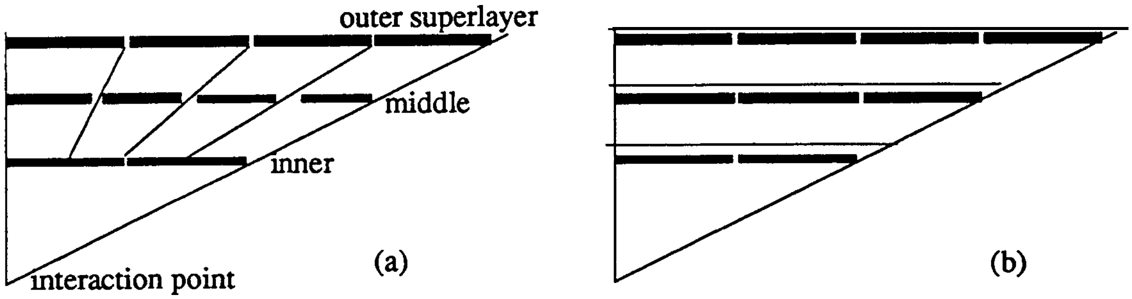

Fig. 1. Alignment Options: pure projective alignment (a), axial+projective alignment (b).

The maximum muon chamber length is such that it takes four chambers to cover the barrel region (from 90° to 30° in θ) in the outer superlayer (fig.1a). The need for projective paths (with significant clearance of 5 cm for lenses) in the middle superlayer results in significant coverage losses. Keeping in mind that one of the gold-plated Higgs-meson signatures is its four-muon decay, one can imagine how important the desire to have the coverage as full as possible. It was realized that these coverage losses can be avoided by replacing the projective alignment in the inner barrel volume by an adequate axial alignment (fig. 1 b). The benefits from an axial+projective alignment are as follows: improving coverage by ~4%, saving number of chambers and electronics in the middle superlayer, the possibility of measuring and monitoring chamber droop and bend. The word “adequate” in this context means that the axial alignment should provide a position monitoring of 8 or more reference points on surface of up to 4 chambers placed along a 15 m long muon half barrel. The required accuracy is better than ~10 μm in one direction (bending) and better than ~200 μm for the another one (radial). The range of possible displacements should around ±3 mm.

2. A STRETCHED WIRE WITH MINI-STRIP READOUT

A stretched wire with capacitive readout [6] is a well-known technique (fig.2) for position determination. Though appearing as a very simple, it turns out to be rather expensive when a wide range is required together with a high accuracy, say, 10 μm over 10 mm range. The reason for the complexity in this case is a necessity to keep all systematic errors very small. When an accurate coordinate comes from a measurement of a single value of ΔC, one has to calibrate electronics and mechanics with a 10^{-3} accuracy, measure ΔC with the same accuracy and control everything which can influence the measurements at this level.

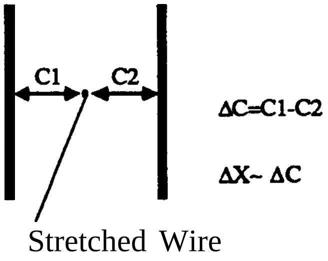

Fig.2. A stretched wire with a capacitive readout.

The GEM muon tracking detectors are multi-wire cathode strip chambers, fast invented by G. Charpak in 1979 [7]. The principal of operation is as follows: an avalanche created by a track generates an induced charge on a cathode surface, “whose” centroid indicates the position of an avalanche and, as a consequence, the position of a track (fig.3).

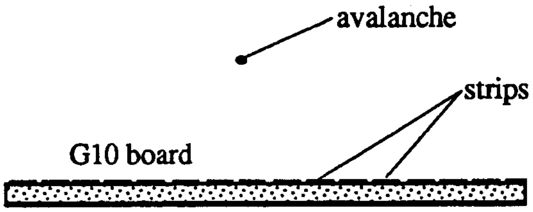

Fig.3. An avalanche over a cathode plane creates an induced charge on that surface. With a help of strips one can find a centroid of the distribution.

Now if one, as in fig.3, would imagine a stretched wire in a place of avalanche (compare to fig.2), the idea of mini-strip readout becomes apparent. If the wire were pulsed, one could pick up charges induced on the strips and the centroid of the distribution would give a transverse ("horizontal") wire position with respect to the strip board, while the width of distribution would provide information on the distance between the wire and the board ("vertical" coordinate). The word "mini" is added to stress that these strips are supposed to be narrow, e.g., 1 mm wide (compare to a 5-10 mm readout pitch for chamber strips). An isometric picture is shown in fig.4.

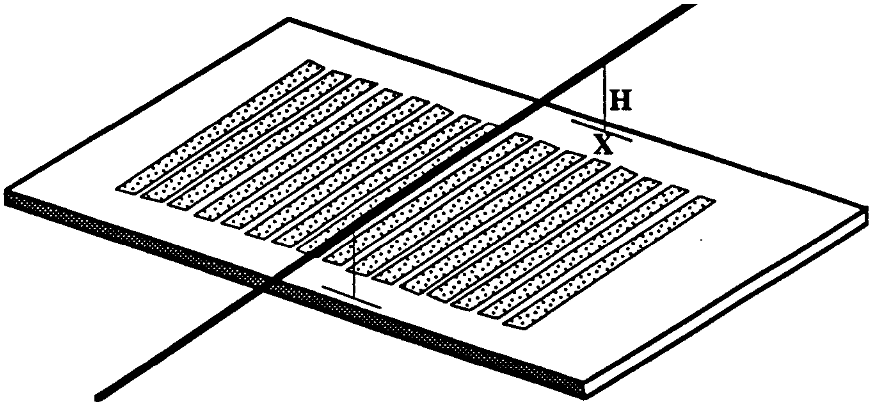

Fig.4. Isometric picture of a wire stretched over a board with mini-strips. For this particular orientation: X - "horizontal" displacement, H - "vertical" displacement.

It is important to note that the shape of the distribution is determined by electrostatics and therefore well-determined:

$$\rho(x) \sim \frac{1}{H\ln(2H/r)\quad 1+(x/H)^2}, \tag{1}$$

where p(x) - density of the induced charge along coordinate x, H - distance between the wire and the board.

First of all, this method of strip readout provides measurements of two coordinates simultaneously. Second, one expects that the calibration accuracy is probably relaxed very much since an elementary readout element is narrow (e.g., 1 mm wide) so that 10 time worse calibration error, i.e. $\sim 10^{-2}$, is equivalent to the same 10 **μm.** The fact that the distribution covers several strips should help to reduce this error even further.

One more advantage arises from a particular chamber type chosen for the muon system. The alignment mini-strips can in principle be etched on the same board and at the same time as the cathode strips. The advantage is obvious: no additional specific alignment devices, no transfer points between a chamber and these devices. The entire alignment system finally consists of a stretched wire and some simple electronics.

It should be mentioned that any stochastic noise in the alignment system is not a problem, as simple repetition of the measurement permits its elimination. It is the systematic errors, such as calibration errors and accumulation of errors in transfer points, that limits the accuracy.

3. MONTE CARLO SIMULATION

To verify the idea, a simple Monte Carlo simulation was performed.

The first issue to be checked was a requirement on a calibration accuracy. Thirty one 1 mm wide and 5 cm long strips were assumed to be calibrated with 0.5% accuracy (an RMS error in calibration slopes). Accuracy in reconstruction of “horizontal” (most accurate) and “vertical” coordinate is presented in fig.5. One can see that the 10 μm goal for the “horizontal” coordinate has been achieved over 10 mm range of wire displacements in both direction. Not surprisingly, the “vertical” coordinate, being determined from the distribution width, turned out to be less accurate, but many times better than the 200 μm goal.

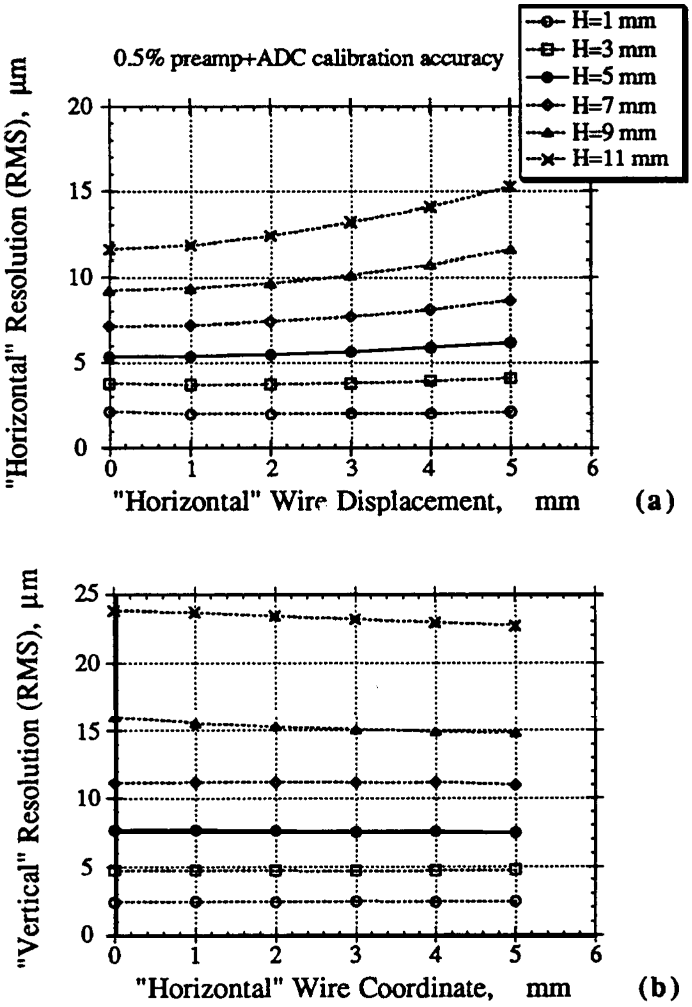

Fig.5. The accuracy (RMS) in measuring the precision “horizontal” coordinate (a) and “vertical” coordinate (b).

Second, we checked if the strips need to be aligned with respect to the wire. If the wire is tilted in only one direction, either vertically or horizontally, it widens the distribution. This should not shift the distribution center. However, a wire tilt in both directions would result in skewing the distribution shape so that one may get a bias in the fit. Therefore, a simultaneous wire inclination in two directions, representing the worst case, was simulated. A sensitivity turned out to be very low (fig.6). Keeping in mind the 10 μm goal, one can see that aligning with an ~1° accuracy is absolutely acceptable.

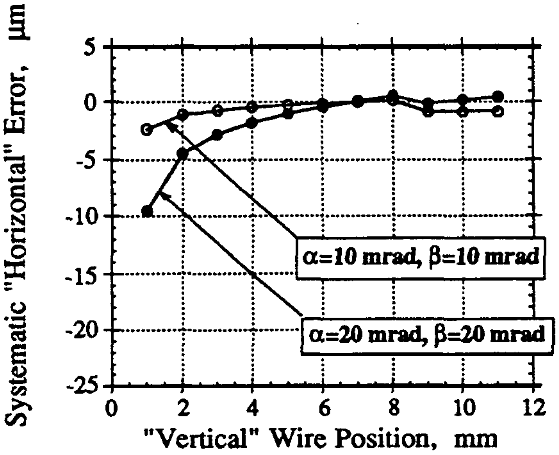

Fig.6. A systematic error in measuring the precision coordinate vs. double tilt of the wire (i.e. tilt is assumed in two directions)

Third, we checked if there is any prospect of cross-talk between neighboring channels. Again, cross-talk will make the distribution look a little wider and will not shift its center. As expected, even 5% strip-to-strip cross-talks did not degrade the transverse resolution more than by 1 µm, while the change in the distribution width resulted in only 5-10 µm systematic error in a "vertical" coordinate H.

4. EXPERIMENTAL RESULTS

To check how accurately the proposed readout scheme works, we ordered several G10 boards with 30 strips (1.016 mm pitch, 5 cm long) etched on them. The etching was performed at a regular firm. We added an etched pad on the other side of a board directly underneath of strips. This allowed a simple calibration by pulsing this pad and picking up signals from strips. By using an optical microscope, the boards were scanned across strips.

The accuracy of our optical microscope (which is based on a precision glass scale with a minimum readout step of 2.5 µm) was not sufficient to let us measure the inaccuracy of the etching. The RMS of strip center deviations turned out to be ~1.5 µm or less (fig.7) which is consistent with an accuracy of measurements. The strip width deviated from the specified one: strips were over-etched by ~30 µm. Yet an absolute strip width is not important at all. Its uniformity could be important if the calibration were done in a different way. However, with the calibration technique we used even strip width non-uniformity is not crucial since it is automatically calibrated. Nevertheless, it should be said that the strips were over-etched very uniformly so that measured width variations again were around 1.0-1.5 µm. The strip edges were not perfect either, but small edge jigging, which did not typically exceed 10-15 µm, is not important: it is the average strip width that matters.

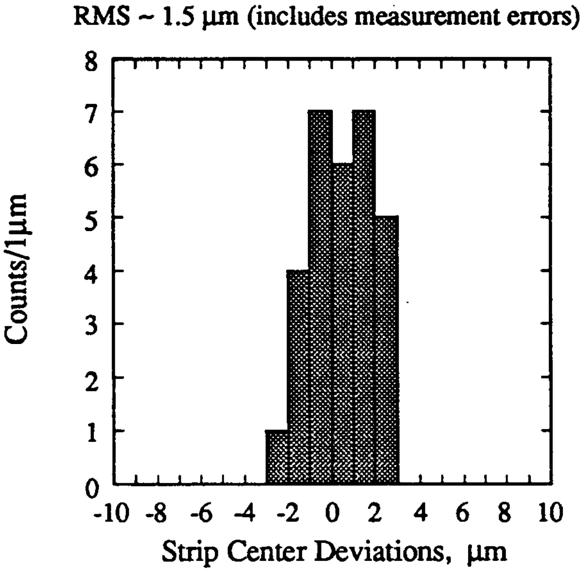

Fig.7. Residuals of strip centers as measured by an optical microscope. RMS~1.5 µm is consistent with an accuracy of measurements.

A 1 m long, gold-plated tungsten wire (100 µm in diameter) was stretched over one of the strip boards. The strip board was placed on a precision stage movable with micrometers (2 µm minimum division) over wide range (2.5 cm) in all three directions. 11 strips were equipped with current sensitive preamps (Ru~50 kΩ; Rin~100 Ω) and the amplified current was integrated with a LeCroy 2249W ADC. With a 500 ns integration gate, the equivalent noise charge was quite high (~30,000 e), but, as it was mentioned above, any stochastic noise is not a problem.

The wire was placed parallel to strips with an accuracy of the eye without any special precision aligning. Signal fed to the wire had a step-function shape with an amplitude which was varied from 2 to 13 V depending on a distance between the wire and strip board so that the maximum pick-up charge on a strip was always around 0.7 pC (after amplification it corresponded to about 1500-1800th ADC channels).

There was no attempt to make an extremely careful calibration. We just fed pulses of different amplitudes onto the underneath pad and did a relative calibration of strip channels. This does not permit an accurate calibration. For instance, synchronous saturation of preamps or synchronous non-linearity in ADC channels would not be taken into account (or would be taken into account incorrectly) in such a channel-to-channel relative calibration.

Fig.8 shows charges as read out from strips for different distances H (height) between the wire and the strip board. We did not make any measurements at H>7 mm. The reason is obvious: even at H~7 mm the width of the distribution is considerably wider than the band of 11 strips. Fig.9 demonstrates another feature: as was mentioned above, the charge distribution on a strip plane is determined by electrostatics and nothing else. Indeed, one can see a remarkable agreement of data and theoretical shape.

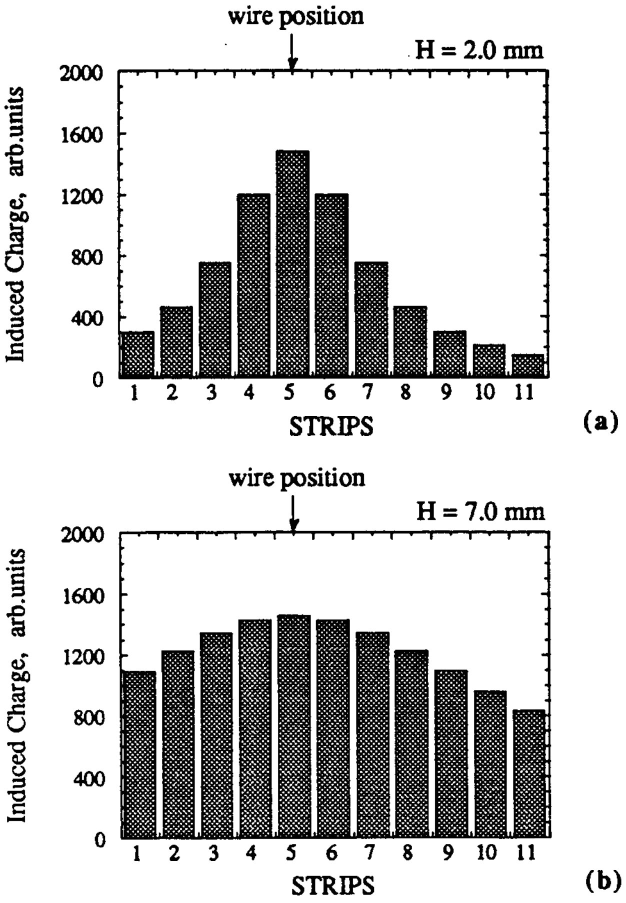

Fig.8. Induced charges on mini-strips for different distances between the wire and the board (H).

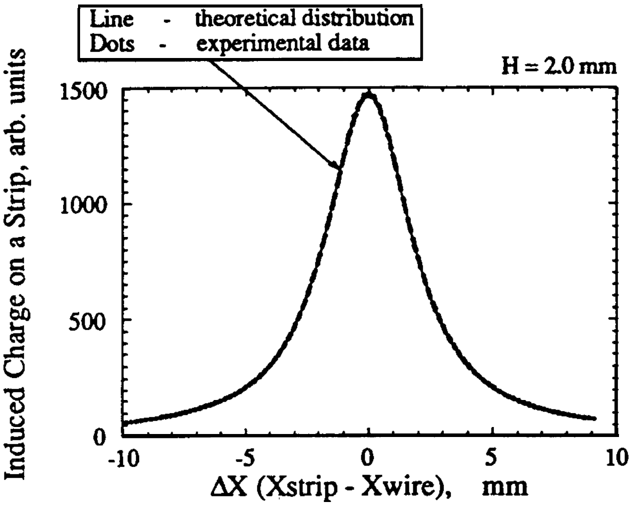

Fig.9. Charge on a strip vs. distance between strip center and the wire coordinate (dots -data, line - analytical calculation)

At each given wire-to-board distance (H) we moved the board across the wire with steps either 100 µm or 200 µm. At each step we accumulated around 10000 measurements (1 s of taking data with a pulse frequency set at 10 kHz) so that there was no worry about noise whatsoever. Average charges from strips were used for fitting. An example of the relationship of a measured coordinate and an actual one is given in fig.10. It should be emphasized that a slope was constrained to be exactly 1.000. Deviations from this one-parameter linear fit for different heights H are presented in fig. 11. One can see some systematic structure in the residuals which probably reflects inaccuracy of the calibration. The RMS of residuals is calculated for a 8 mm wide range. A summary of these RMS's is shown in fig.12.

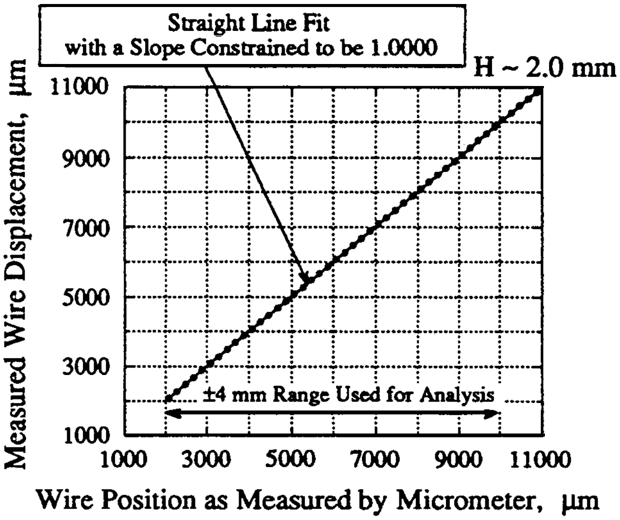

Fig. 10. Measured coordinate (given by fit) vs. actual coordinate (micrometer reading).

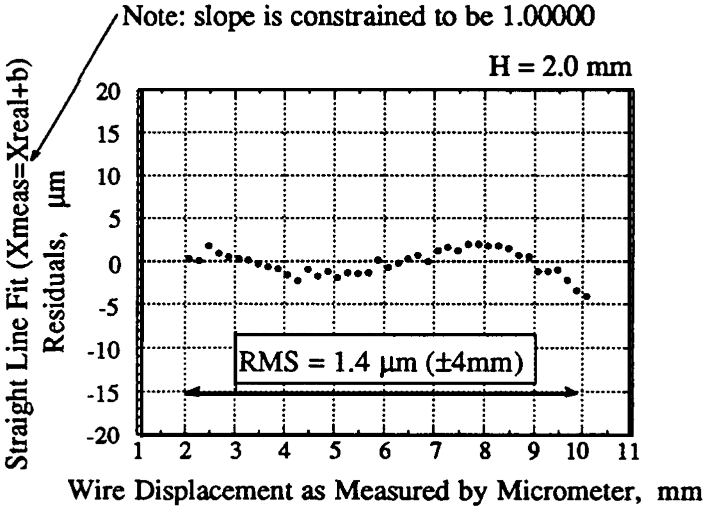

Fig. 11. Straight-line residuals corresponding to fit in fig. 11. The RMS is calculated for 8 mm range.

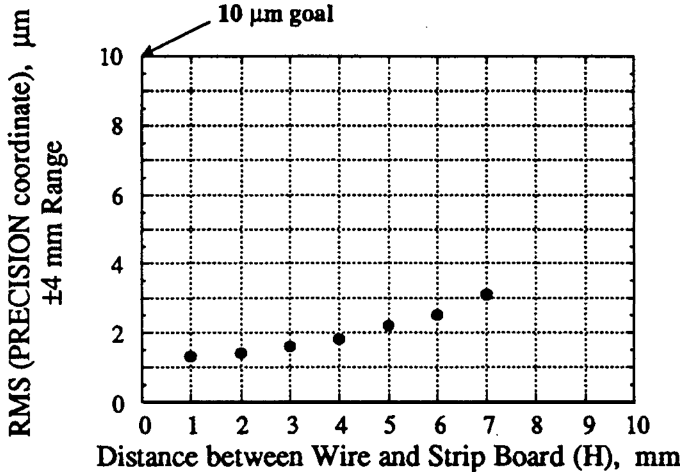

Fig. 12. The RMS of residuals over 8 mm range for different distances between the wire and the board (H).

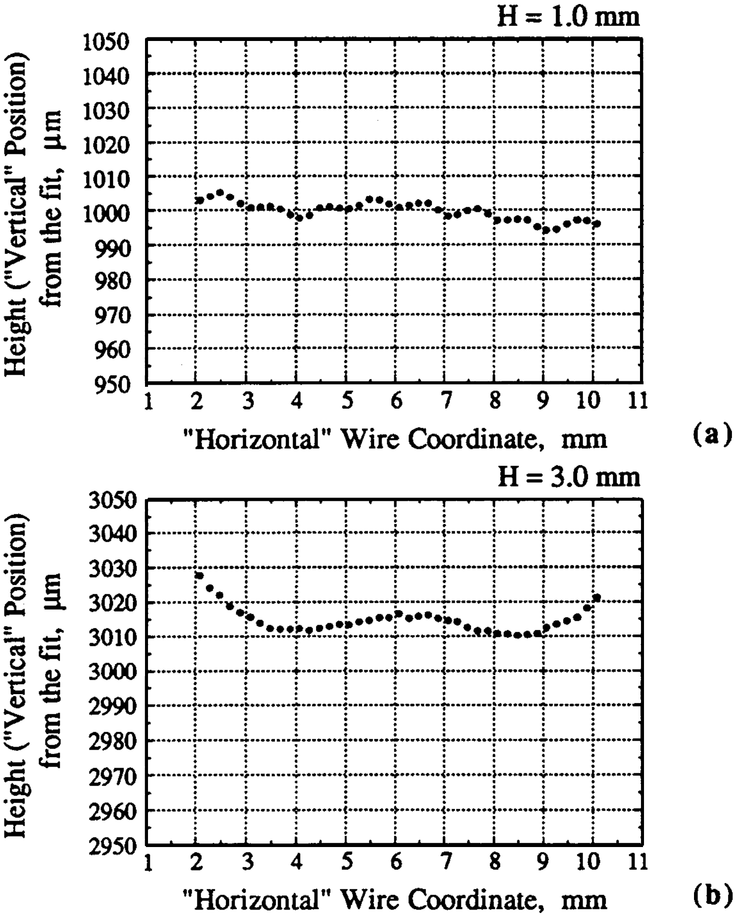

Fig. 13. The distance between the wire and the board (H) as given by fit vs. transverse (“horizontal”) coordinate: H=1.000 mm (a) and H=3.000 mm (b).

Fig.13(a,b) shows how accurately we could reconstruct the height. One can see that when distribution width becomes comparable to a band of strips, a noticeable systematic error appears: the overall measured height tends to be larger than the actual one and, also, one can see that measured height now depends on a transverse coordinate. Fig.14 shows a summary: averaged measured height vs. an actual one. Error bars indicate RMS of residuals within a constant height (it is a reflection of systematic structure as seen in fig. 13).

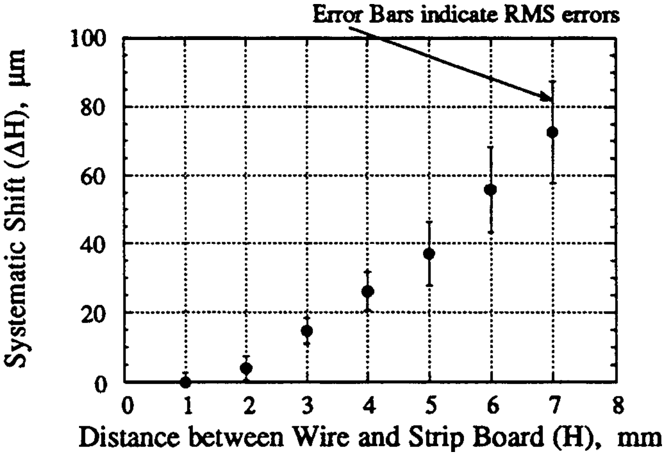

Fig.14. The systematic shift and RMS of residuals in determination of height (calculated for 8 mm range) vs. height, or distances between the wire and the board (H).

5. DISCUSSION

An accuracy of 1-3 μm (RMS) over a ~8 mm range has been demonstrated. An accuracy in simultaneous measurement of an other coordinate was well below 100 μm and is expected to improve considerably with increasing number of strips.

One can see that the first measurements, though being made with a smaller number of strips (11 instead of 30), showed that this alignment technique would meet the GEM spec.'s on an axial alignment accuracy ($\delta X<10\,\mu m$ and $\delta H<200\,\mu m$ over ±3 mm ranges). The method is very reliable and simple, the cost per monitor is estimated [8,9] to be around $50 or less when multiplexed readout is used.

Another important issue is wire droop. For muon chambers at 3 and 9 o'clock orientations the wire droop is a direct contribution to the measurement of a precision coordinate. To minimize this droop, one can use silicon carbide wires [10] which are as strong as tungsten and about 10 times lighter. These wires can be gold-plated to a very good conductivity. A 15 m long silicon carbide wire will droop by 300 μm, which means that monitoring the wire tension to an 1% accuracy (which is simple) will allow one to predict this sag with a 3 μm uncertainty.

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