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Construction of the Full-Scale Prototype of a BOS MDT Chamber

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Abstract

The full-scale prototype of a BOS MDT chamber has been constructed at MPI Munich as a common effort of several ATLAS muon institutes following the specifications in the ATLAS Muon Technical Design Report. The 432 drift tubes in the chamber have been produced at MPI with help from Dubna and NIKHEF and fully tested according to the quality control specifications at LMU Munich. The spacer frame, including the RASNIK in-plane alignment system, was designed and constructed by NIKHEF. The gas distribution system and the Faraday cages were designed and installed by the University of Freiburg. The HV boards were designed and delivered by Boston University; the readout boards are being designed and produced by BNL. The assembly jigging was set up in a temperature controlled clean room at MPI where the glueing of the multilayers took place between 26 January and 16 February 1998 including extensive measurements of the mechanical accuracy. The completed chamber has been scanned in the X-ray tomograph at CERN and is currently being prepared for the test beam at CERN.

Contents

1 Introduction

The full-scale prototype of a BOS MDT chamber has been constructed at MPI Munich as a common effort of several ATLAS muon institutes following the specifications in the ATLAS Muon Technical Design Report (TDR) [1]. The goal was to demonstrate that with the assembly method for series production of barrel chambers as described in the TDR, including the force compensation system for eliminating the cross plate sag, the specified accuracy of 20 μm rms in the relative wire positions can be achieved as well as centering of the wires over the whole length of the tubes within a tolerance of 100 μm.

The BOS chambers are among the largest in the barrel with a tube length of 3800 mm and a width of 2160 mm with 72 tubes per layer and 432 tubes in total. The layout of the prototype chamber with these dimensions is shown in Fig. 1. On the side with the high-voltage connection (HV side), the long beams are connected by a plate to which one of the three bearings for the 3-point support of the chamber is connected (the other two supports are at the opposite ends of the two long beams).

All tubes have been produced at MPI with help from Dubna and NIKHEF and fully tested according to the quality control specifications [1] at LMU Munich. The spacer frame as described in the TDR [1], including the RASNIK in-plane alignment system, was designed and constructed by NIKHEF. The gas distribution system and the Faraday cages were designed and installed by the University of Freiburg. The HV boards were designed and delivered by Boston University; the readout boards are being designed and produced by BNL.

The assembly jigging as described in the TDR [1] was set up in a temperature controlled clean room at MPI where the glueing of the multilayers took place between 26 January and 16 February 1998 including extensive measurements of the mechanical accuracy. The completed chamber has been scanned in the X-ray tomograph at CERN and is currently being prepared for the test beam at CERN.

2 Tube Production and Test

The 3800 mm long tubes have been ordered from ALU-MENZIKEN and cleaned at CERN according to the TDR specifications [1]. In a sample of 100 tubes, the outer diameter at the ends was measured to be (29.975 ± 0.005) mm with a cutoff of the gaussian distribution at 29.970 mm [2]. The tubes have been wired with the MPI glueing method for positioning the wire in the tube center with respect to the tube outer surface where it is placed in identical jigs for for wiring and chamber assembly and in the same azimuthal orientation to be insensitive to tube non-roundness. The wiring method and setup are described in detail in [3].

The endplug compatible with the wiring method and used for the BOS chamber prototype is shown in Fig. 2 and described in the TDR[1]. The tube length including endplugs was adjusted to ± 0.5 mm during the insertion of the endplugs into the tubes.

The tubes were wired at MPI in a dust-free temperature controlled room. The results of the standard quality control tests at LMU Munich are described in [3]. The wire frequency and sag was measured to be equal for all tubes within 1% rms. The wire position has been measured for each individual tube with the X-ray method. The results for the wire coordinates y and z are shown in Figs. 3 and 4 separately for the tubes in the two multilayers of the BOS chamber and for both tube ends (A and B). Side A corresponds to the HV side of the chamber for the multilayer 1 (glued first) and to the readout (RO) side for multilayer 2. The tubes for the first multilayer were produced first.

The standard deviations of gaussian fits to the wire coordinate distributions from the X-ray measurements are $8 - -12$ μm. The tube straightness was significantly worse for the tubes used for the second multilayer. The shift in the average wire position in y by -37 μm on side A of the second-multilayer tubes is due to a displacement in the wiring jig which occured during construction in the clean room. Since it is common for all tubes in the multilayer it was not changed for the rest of the tube production.

3 Assembly Setup

The chamber assembly jig used for the construction of the BOS prototype has been described in detail in the TDR [1]. The setup installed on a granite table of size 2500 mm $\times$ 4200 mm is shown in Fig. 5. The assembly table is set up in a climatized clean room of class 100000. The working temperature of 20° was stabilized to $\pm 0.5°$ in a volume of 2 m height above the surface of the table. A temperature difference of 0.1° has been measured between the top and the bottom of the chamber on the assembly table. Humidity was controlled to be (45 ± 5) %. Clean room clothes and gloves were used during the installation of the jigging and the whole assembly operation.

The tube jig is assembled out of comb modules with 20 tube positions each. 9 comb lines are installed on the granite table at a distance of 500 mm (300 mm for the two comb lines at the tube ends) with 4 comb modules per comb line. The layout is shown in Fig. 6.

The precision comb modules (see Fig. 7) are cut out of hardened FORTAL 7075 aluminum plates with an industrial wire erosion technique. The V-groove design of the comb modules which minimizes sensitivity to tube outer diameter variations is shown in Fig. 8. Fig. 7 illustrates the installation of the comb modules on the granite table. More details are given in the Appendix.

All comb modules have been measured on a 3D measuring machine by placing precise steal cylinders of 30.000 mm diameter in the V-grooves. Results for the z-pitch and the vertical (y) position of the cylinders are shown in the TDR [1]. The average z-pitch of 36 comb modules produced was measured to be (30.0366 ± 0.0008) mm.

The 8 best comb modules with respect to uniform height were selected for the comb lines at the tube ends. Distributions of the residuals from the nominal value of the y-position of a test cylinder in the V-grooves are shown in Figs. 9 and 10 for the two end comb lines. The rms values of the distributions are $3 - 4$ μm.

Table 1: Vertical layer spacing $\Delta y - 26.011$ mm [μm]: comparison of sphere block height and X-ray tomograph measurements (with uncertainty in the global y distance scale due to errors in the angles of the two X-ray sources).

Layers	Tower height		X-ray scan	
	RO	HV	RO	HV
1–2	+35	+35	+46	+55
2–3	+50	+50	+53	+48
4–5	+30	+30	+39	+41
5–6	+55	+55	+59	+44

4 BOS Chamber Assembly

4.1 Insertion of Tubes

During the assembly, the tubes are held down in the V-grooves using vacuum suction pads with 15 mm diameter in the end combs (suction force of about 400 g) and with 8 mm diameter in the intermediate combs. The tubes are held in the end combs 25 mm from the tube ends. Measurements of the relative y-position of wired tubes (height of the top of the tube above the granite table measured measured with a feeler gauge) in the end combs on the HV and the readout side (tube sides A and B, respectively, during glueing of the first multilayer) are shown in Fig. 11. The widths of the residual distributions are $7 - 8$ μm which include the effect of tube outer diameter variations and uncertainties in the correct placement of the tubes in the V-grooves.

The horizontal glue gap between the tubes inserted in the combs was verified by visual inspection with illumination of the tube layer from below. This method was found to be quite efficient for detecting touching neighbouring tubes due to tube non-straightness as well as problems with the suction of the tubes into the combs.

4.2 Vertical Stacking of Tube Layers

For vertical stacking of the tube layers, the spheres mounted at both sides of the cross plates are supported on 6 sphere blocks (towers) which are increased in height for succesive tube layers in a multilayer using precisely machined distance plates (see the TDR [1]). A compressibility in the tower height of approximately 10 μm under the load of the chamber was found during the first tests and confirmed by independent measurements. The reason was identified in the ball bearings which make the sphere supports moveable in x and z (with the exception of one tower at one chamber end fixed in both coordinates and a second tower at the opposite end on the same (reference) side fixed in z). For safety reasons, the height of the distance plates and therefore the vertical spacing between tube layers was increased with foils by $30 - 50$ μm per gap between layers compared to the nominal value of $\Delta y = 26.011$ mm (see details in Table 1). The extra vertical spacing was reproduced by the X-ray tomograph measurements up to a global vertical distance scale uncertainty left in the calibration of the angles of the two stereo X-ray sources (see Table 1).

4.3 Force Compensation for the Cross Plates

The sag of the cross plates under the weight of the spacer and of the glued tubes layers was eliminated by a force compensation system with 4 removable bars inserted through the long beams at the inside of the two outer cross plates and on both sides of the middle cross plate (see the TDR [1] and Fig. 5). The force compensation bars are supported on both ends on the granite table with adjustable screws.

The sag of the cross plates was measured with RASNIK systems installed on the side of each cross plate over its full length. The RASNIK in-plane alignment system and the RASNIK systems on the cross plates were calibrated by placing the spacer on the jigging (sphere towers) and reading the RASNIK measurements in an initial (INI) position and in the inverted (INV) position after rotation around the x axis by 180° (see Figs. 12 and 13). The cross plate sag is the average of the on-cross-plate RASNIK readings if the forces of the long beams on the cross plates are symmetric for both orientations. The calibration measurements were repeated after glueing of each tube layer. The optical monitoring systems were read out continuously during the whole assembly operation.

The long beams were adjusted in the center of the middle cross plate with an accuracy of ± 50 μm by comparing the spacer sag measurements of the longitudinal RASNIK in-plane alignment systems on both sides of the chamber while the spacer was supported vertically on the crane at the support points on the plates connecting the long beam ends. After this adjustment, the readings of the on-cross-plate RASNIK systems in the two vertical positions of the spacer on the crane (V1, V2) were in the middle between the readings in the initial and inverted position on the table as expected for vanishing cross plate sag (see Figs. 12 and 13). The cross plates sags in the initial (INI) and inverted (INV) position are now symmetric (with opposite signs) with respect to the vertical calibration measurements and can be used as references for the force compensation adjustment.

In the two horizontal (H1, H2) positions of the spacer on the crane, the cross plates are slightly curved upwards (see Figs. 12 and 13) due to the additional weight of the spheres which holds them on the sphere support towers even with full force compensation.

After the long beam adjustment and the RASNIK calibration, the RASNIK measurements on the cross plates can be used to adjust the force compensation: The screws of the force compensation bars were turned sequentially in steps until the measured curvature of all three cross plates was minimized. The RASNIK sag measurements before and after force compensation with increasing number of tube layers glued are given in Table 2 and Fig. 14. The relatively large cross plate sag of the 2160 mm wide chamber makes the force compensation necessary to achieve the precision requirements for the wire positions. After force compensation, the sags of the outer cross plates were below 5 μm for the first multilayer glued and at most 10 mum for the second multilayer which is sufficient for the required accuracy. For the middle cross plate which carries more weight and where the positioning requirements for the tube walls are much reduced, the remaining sag was ≤ 7 μm for the first multilayer and ≤ 17 μm for the second multilayer.

The lifting of the spacer during force compensation was monitored with two lasers passing through transparent MPA-ALMY position sensors mounted close to the spheres on the cross plates and on both ends of the granite table as reference (see [1], [4] and Fig. 5). Lifting by $20 - 25$ μm was measured which is consistent with the straightening of the cross plates

Table 2: Sag of the HV, readout (RO) and middle cross plates before and after force compensation with increasing number of tube layers glued (with y-axis pointing upwards). The number of turns of the force adjustment screws need to achieve the compensation are given in the last column (note: after glueing of layer 4 a readjustment of the fixations of the force compensation bars to the long beams was done).

Layers	Cross plate	Initial sag	Compensated	# Turns
0	HV	$-28\ \mu$m	$-\ 2\ \mu$m	5
	MI	$-36\ \mu$m	$+\ 7\ \mu$m	3
	RO	$-29\ \mu$m	$-\ 5\ \mu$m	5
1	HV	$-28\ \mu$m	$0\ \mu$m	6
	MI	$-37\ \mu$m	$+\ 1\ \mu$m	3.5
	RO	$-27\ \mu$m	$+\ 1\ \mu$m	6
2	HV	$-28\ \mu$m	$-\ 1\ \mu$m	6.5
	MI	$-39\ \mu$m	$+\ 2\ \mu$m	4
	RO	$-29\ \mu$m	$-\ 2\ \mu$m	6.5
3	HV	$-38\ \mu$m	$-\ 3\ \mu$m	8
	MI	$-52\ \mu$m	$-16\ \mu$m	4.5
	RO	$-39\ \mu$m	$-11\ \mu$m	8
4	HV	$-47\ \mu$m	$-\ 6\ \mu$m	5
	MI	$-59\ \mu$m	$-17\ \mu$m	3
	RO	$-42\ \mu$m	$-\ 8\ \mu$m	5
5	HV	$-39\ \mu$m	$-\ 5\ \mu$m	5
	MI	$-63\ \mu$m	$-16\ \mu$m	3
	RO	$-40\ \mu$m	$-10\ \mu$m	5

between the sphere supports.

4.4 Glueing of the Tube Layers

Two semiautomatic glue dispensers were used in parallel to deposit well defined glue ropes between and on the tubes inserted in the combs. The glue deposition can be shut off automatically at any position along the tubes. 45 minutes were needed for a full layer of 72 tubes. There are many possibilities to speed up the glue distribution further.

The three glue outlets of each dispenser together with the speed were optimised such that the diameter of the glue ropes is not larger than 0.5 mm. The amount of glue on the tubes was minimised to reduce out-of-plane deflections of the tubes between the cross plates when two tube layers are glued together (see the illustration in Fig. 15). The tube deflections have to be controlled in order to keep the 100 μm tolerance on the centering of the wires in the tubes. The effect is expected to be most pronounced for the glueing of the second to the first tube layer in each multilayer since the force of the first-layer to compress the glue is only $1-2$ g/cm per tube.

Out-of-plane deflections of the tubes have been measured in a glueing test where a second tube layer was put on the first one in the combs with a 50 μm nominal spacer foil in between at the positions of the cross plates along the tubes and with weights replacing the cross plates. Fig. 16 shows the deviations in the tube height from the nominal value for the first layer in the combs and for the second layer glued on top. The measurements were done with a feeler gauge on top of several tubes at the ends of the comb lines where they are accessible. A maximum deviation of 130 μm was observed at the position of the third comb 80 cm from the end which has to be corrected.

To compensate the observed out-of-plane deflections during the assembly of the chamber, weights were put on the tube layers already glued to the spacer above the positions of the third combs 80 cm from the tube ends while a 50 μm thick and 1 cm wide aluminum foil was placed between the tube layers glued together at the same positions (see the illustration in Fig. 15). A gap was left in the glue ropes along the tubes by the glue dispenser at these positions.

Measurements of the tube heights after glueing of the second to the first layer in multilayer 1 (see Fig. 17) and after glueing of the fifth to the fourth layer in multilayer 2 (see Fig. 18). The glued layers are numbered sequentially. The remaining tube deflections are on an acceptible level. Since 50 μm foil is thinner by $30 - 40$ μm than the average vertical glue gap size (compare Table 1), the tubes layers could be pushed together closer at the position of the weights. No significant difference is seen between the measurements on both sides of the chamber: tubes 1–6 where the glue was distributed first and tubes 67-72 which were glued last. One concludes with a foil of thickness equal to the average vertical glue gap size out-of-plane deflections due to the glue can be virtually eliminated.

5 Results of X-ray Tomograph Measurements

The completed BOS chamber has been scanned in the X-ray tomograph at CERN [5]. Three scans, one along each cross plate, have been analysed. A wire pitch in z of 30.0360 mm was measured which coincides exactly with the comb pitch. The average measured wire pitch in y of 26.059 mm (compare Table 1) is still affected by a vertical distance scale error of the tomograph measurements due to uncertainties in the angles of the two stereo X-ray sources. For the same reason, the X-ray measurements are not yet reliable to evaluate the relative position of the two multilayers.

The residuals of the X-ray measured wire positions in y and z with respect to a fixed grid with z- and y-pitch as given above for both multilayers and all three scans are shown in Figs. 19–21. Except for arbitrary offsets in y and z for both multilayers which cannot be determined reliably yet from the X-ray data, no parameter was left free. The sag of the outer cross plates as measured with the on-cross plate RASNIK systems during the X-ray scans and also seen in the X-ray data was corrected. The standard deviations from gaussian fits are well below the required 20 μm in y and z at both chamber ends and even about a factor of $1/\sqrt{2}$ better in the middle as expected from the average of the positions of the wire ends: $\sigma_y(HV) = 17.4$ μm, $\sigma_z(HV) = 17.7$ μm, $\sigma_y(RO) = 16.3$ μm, $\sigma_z(RO) = 14.6$ μm, $\sigma_y(MI) = 12.5$ μm, $\sigma_z(MI) = 13.9$ μm.

6 Conclusions

With the construction of the BOS prototype chamber it has been demonstrated that with the assembly method described in the Technical Design Report for the barrel chambers the required wire positioning accuracy can be safely achieved. It has been shown that the cross plate sag compensation scheme works and that out-of-plane deflections of the tubes between the cross plates can be controlled in a straight-forward way.

Pictures and two short videos of the BOS tube wiring and test and of the BOS chamber assembly are available at http://pcatlas4.mppmu.mpg.de.

References

[1] *ATLAS Muon Spectrometer Technical Design Report*, A. Airapetian et al., CERN/LHCC/97-22, May 1997.

[2] T.Ferbel and A. Manz, ATLAS Internal Note, MUON-NO-99, 1995; A. Manz, ATLAS Internal Note, MUON-NO-167, 1997.

[3] U. Bratzler et al., *MPI Endplug and Wiring Technique*, ATLAS Internal Note, MUON-NO-xxx, May 1998 (see ftp://pck19.mppmu.mpg.de/Atlas-read/MDT/ENDPLUG/DOCUMENTATION).

[4] H. Kroha and S. Schael, *Optical Monitoring System for the MDT Assembly Stations*, ATLAS Internal Note, MUON-NO-156, April 1997.

[5] D. Drakoulakos et al., *The High-Precision X-ray Tomograph for Quality Control of the ATLAS MDT Muon Spectrometer*, CERN-OPEN-97-023, July 1997.

Appendix: Design and Fabrication of the Assembly Jigs

6.1 Parameters and Fabrication of the Comb Modules

The wire erosion technique for the fabrication of precision combs uses a bath with 680 mm maximal length. The combs of the tube jig are assembled out of shorter modules. The width of the BOS chambers of 2160 mm is the largest chamber width with 72 tube per layer. The comb lines in this case are assembled with the maximum number of 4 modules for 20 tubes each.

The wire erosion process proceeds in several computer controlled cutting steps. The process has been optimized in collaboration with the company. A set of precise pin holes of 10 mm diameter is eroded in the first cutting step. The pin holes allow to reproduce the position of the piece in the erosion machine. Typically five cuts are used to reach the specified precision (see below). Before the last cut the module is measured on a certified machine. Systematic deviations of the pitch as function of the tube position are compensated in the last cut.
The following parameters of a comb module (see Fig. A1 and A2) have been chosen:

- The shape of the V-groove is formed by two circles of 16 mm radius with shifted centers.
- The opening angle of the V-groove is optimised to be 90 degrees. The optimisation includes minimum deformation of the tubes and minimum effect of tube diameter variations and of comb errors.
- The pitch of the comb modules was defined to be 30.035 mm. Systematic deviations in the fabrication process are specified to be less than 5 μm over the module length, with rms errors less than 2 μm.
- The comb module width of 25 mm is determined from considerations of minimum deformations of the tubes under typical forces vs. cost aspects.
- The height of a comb module is 94 mm. Two support feet make contact to the granite table. The sag of individual modules is negligible. The height gives sufficient space e.g. for vacuum lines.
- The vacuum suction cups are flexible silicon rubber pads (NIKHEF type) which will be imbedded directly into the V-grooves (see Fig. A3).

6.2 Assembly of the Tube Jig

Each comb module has reference surfaces for the assembly and adjustment in the z direction. Two precision calibers define the distance between modules and keep the pitch correct (see Fig. A3). Even with the slight overconstraint, the module position will be kept within tolerances. A screw in the neutral line holds two adjacent modules together. Shimming is possible but probably not necessary.

The granite table ordered for MPI Munich has a second precisely polished surface at the side. The side and top surfaces of the table form a precise reference system. The combs assembled out of 4 modules are aligned along the side surface. The comb is fixed to the side surface in only one point allowing for thermal expansion of the comb. Alternatively an additional precise granite bar can be used to replace the precise side surface.

On the granite table there is a pattern of screw holes. They are used to install for each comb an aluminum fixation bar (see Figs. A4 and A5). A second bar connected to the first one is used to press down the comb with an adjustable force. A set of screws allows to adjust each comb module perpendicular to the side surface (Fig. A7). The fixations in x and y are such that the long comb line can thermally expand without stresses in the z direction. All the tooling is arranged on one side of the comb line, the other one is accessible for measurment of positions and angles.

The vacuum is distributed independently for each comb module (see Fig. A6) such that the vacuum can be switched selectively for subsets of tubes.

Hardened aluminum (7075 FORTAL STS with hardness of 140 Brinell) was chosen for the fabrication of the combs. It was thermally treated to take out stresses.

To test abrasion of the combs by inserting tubes, a tube was put 1000 times into a V-groove of a comb module made of less hard aluminum from a previous comb production which has a width of 12 mm. The tube was turned each time by 90 degrees under a load of 380 g. The change in the vertical y position due to possible material abrasion was measured at every tenth trial. Fig. A8 shows the change in y over 1000 trials (100 measurements) which is acceptable.

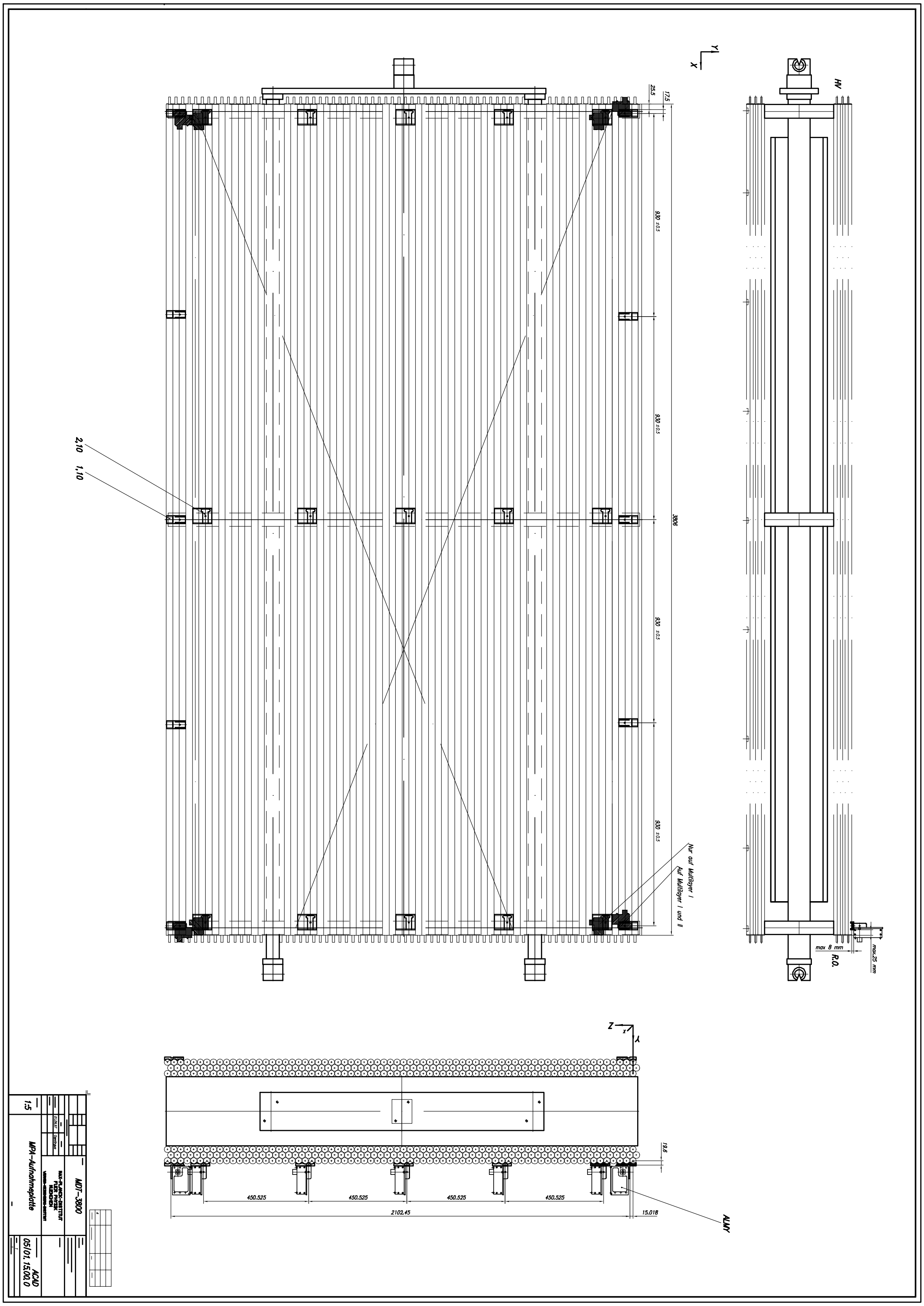

Figure 1: Dimensions of the BOS prototype chamber. The locations of mounting plates for alignment sensors (MPA-ALMY sensors) are indicated.

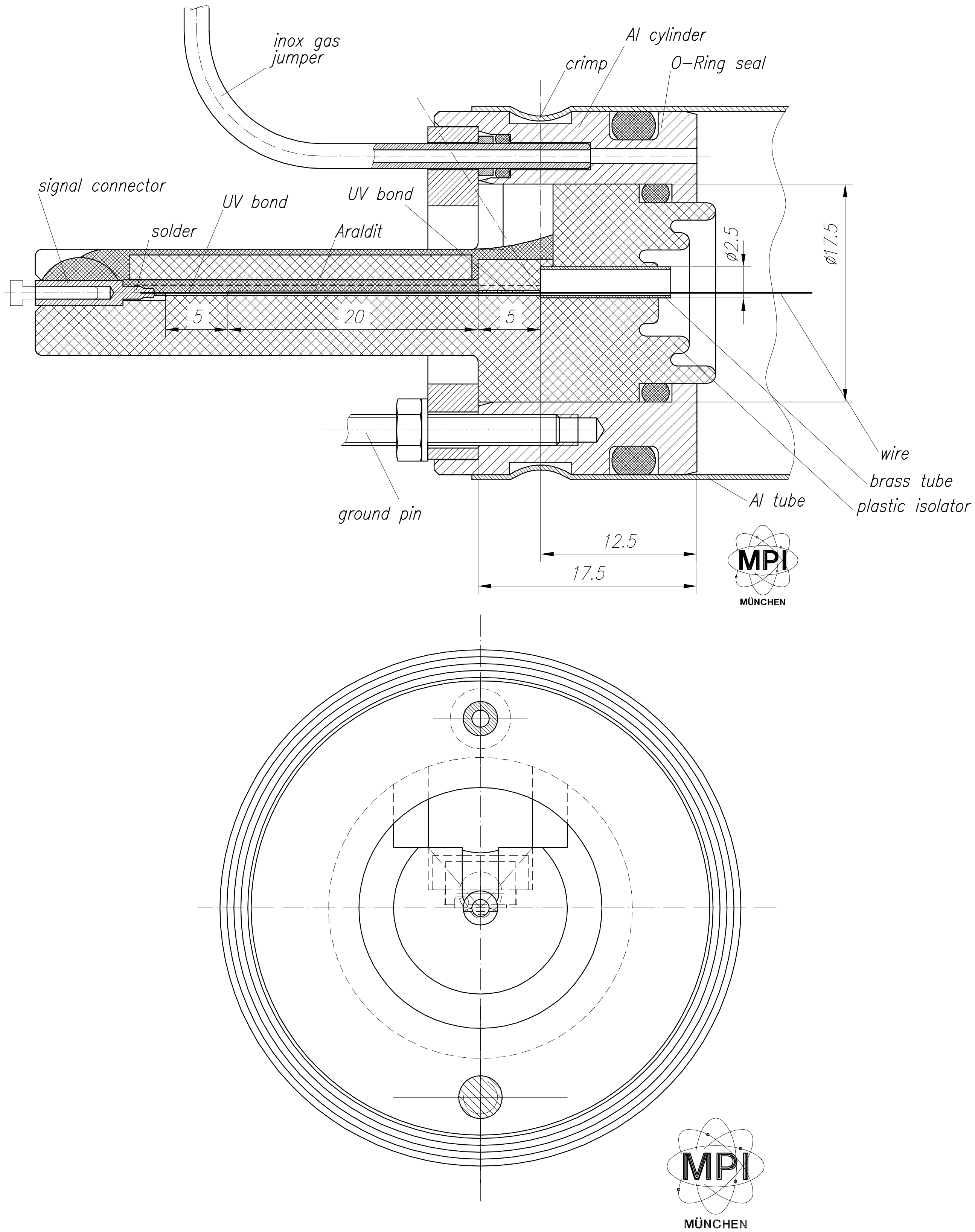

Figure 2: Endplug for the tubes of the BOS prototype chamber.

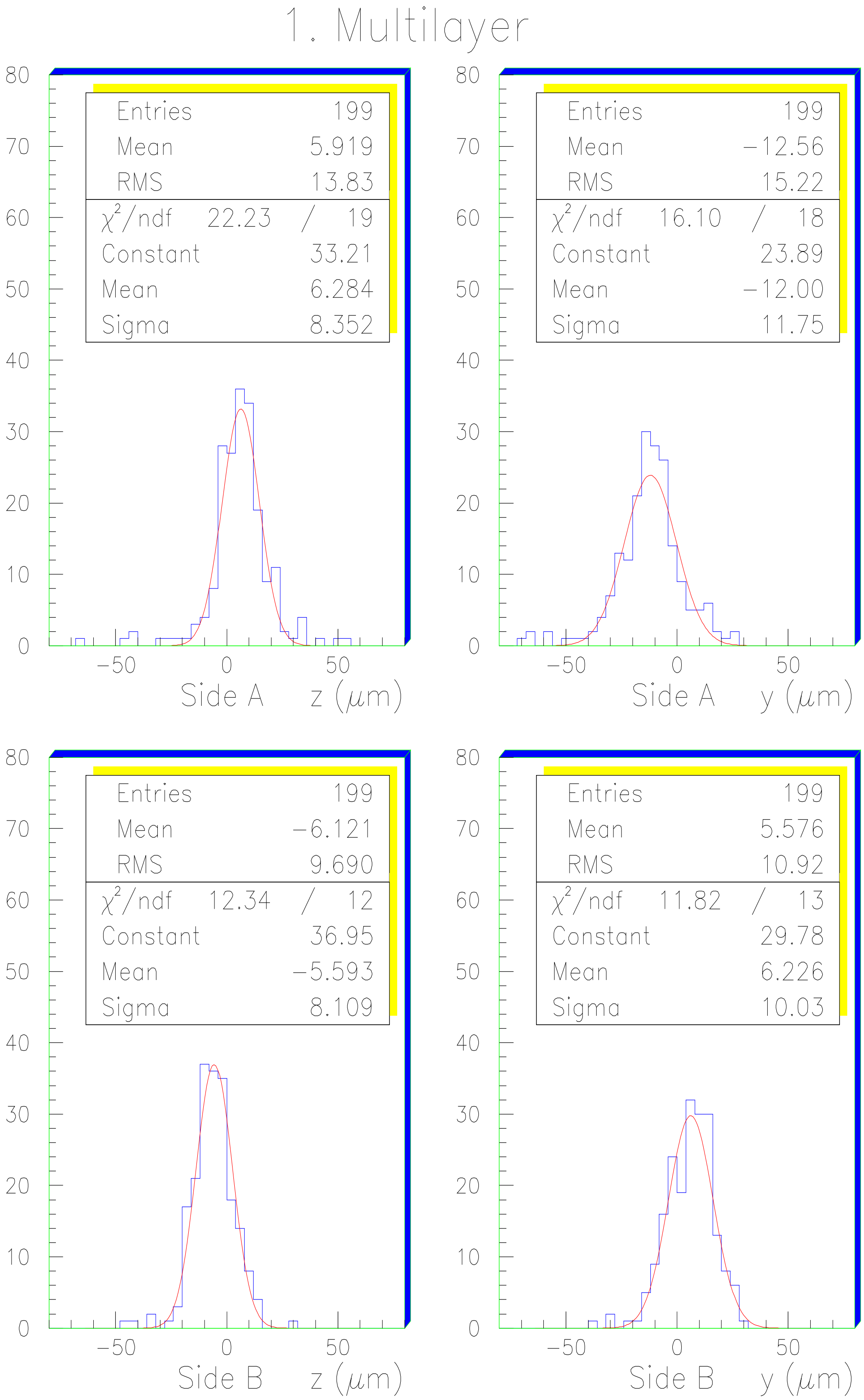

Figure 3: Wire coordinates y and z measured with the X-ray method for side A and B of the tubes in the first multilayer.

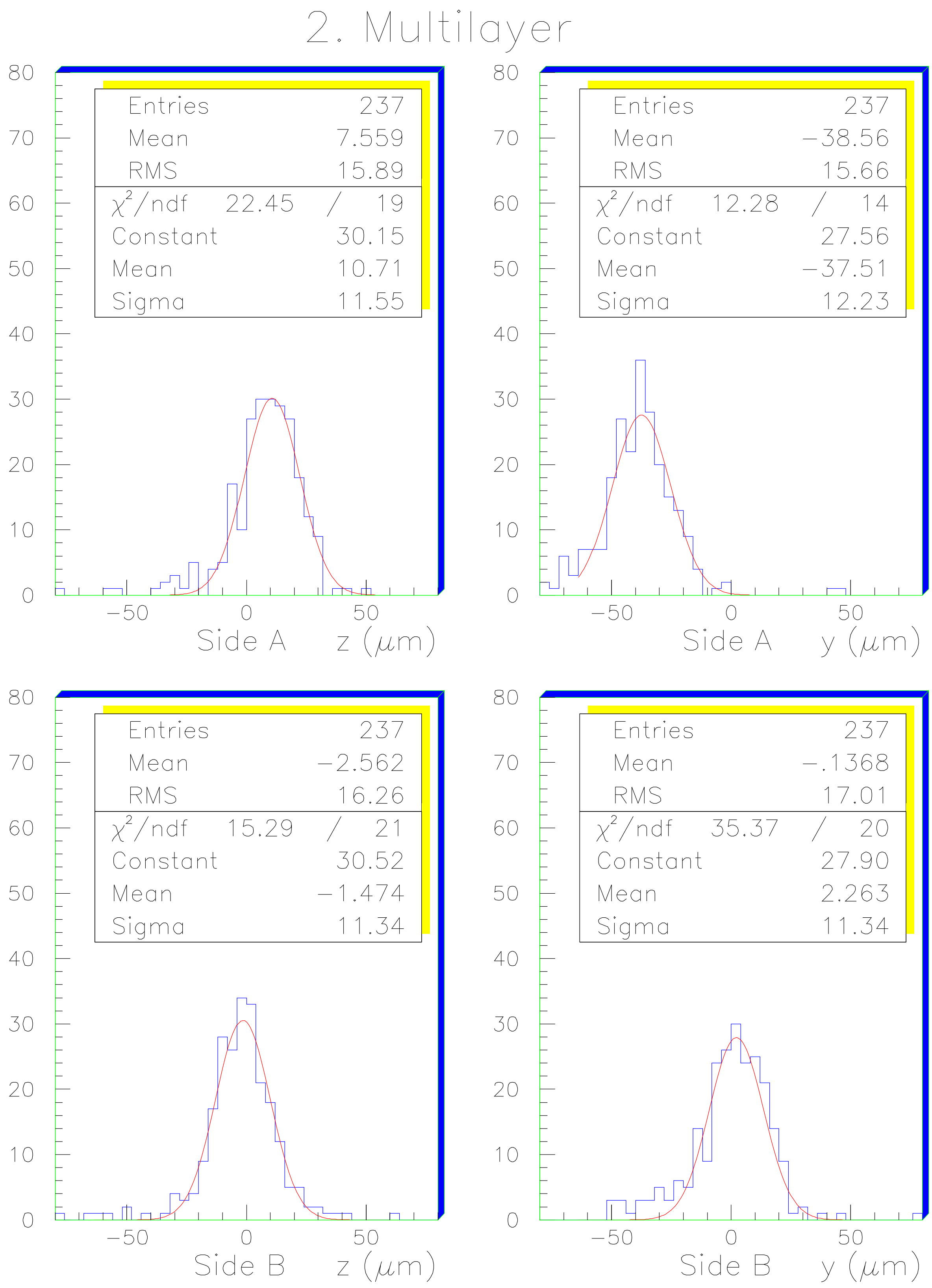

Figure 4: Wire coordinates y and z measured with the X-ray method for side A and B of the tubes in the second multilayer.

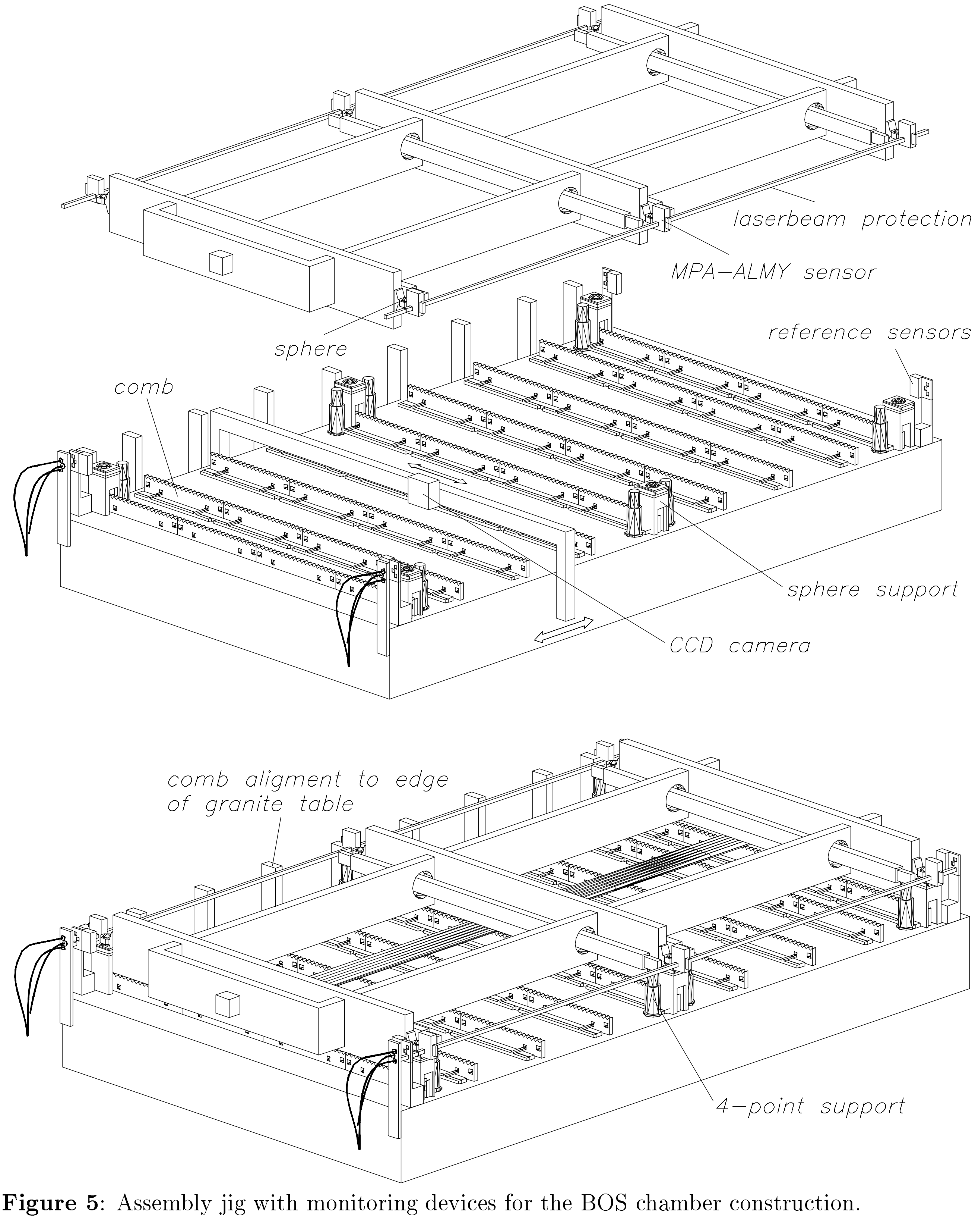

Figure 5: Assembly jig with monitoring devices for the BOS chamber construction.

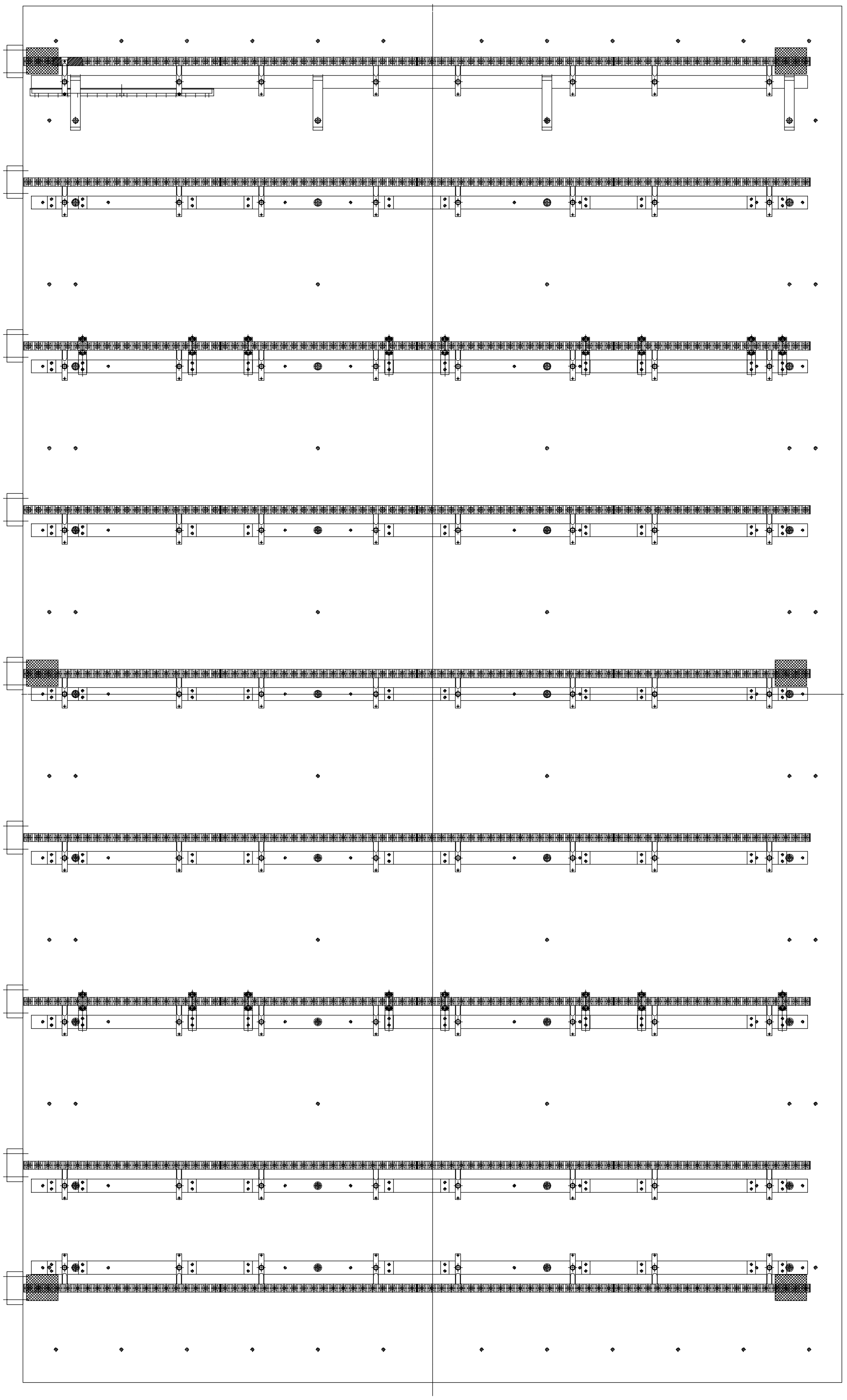

Figure 6: Layout of the comb lines on the granite table.

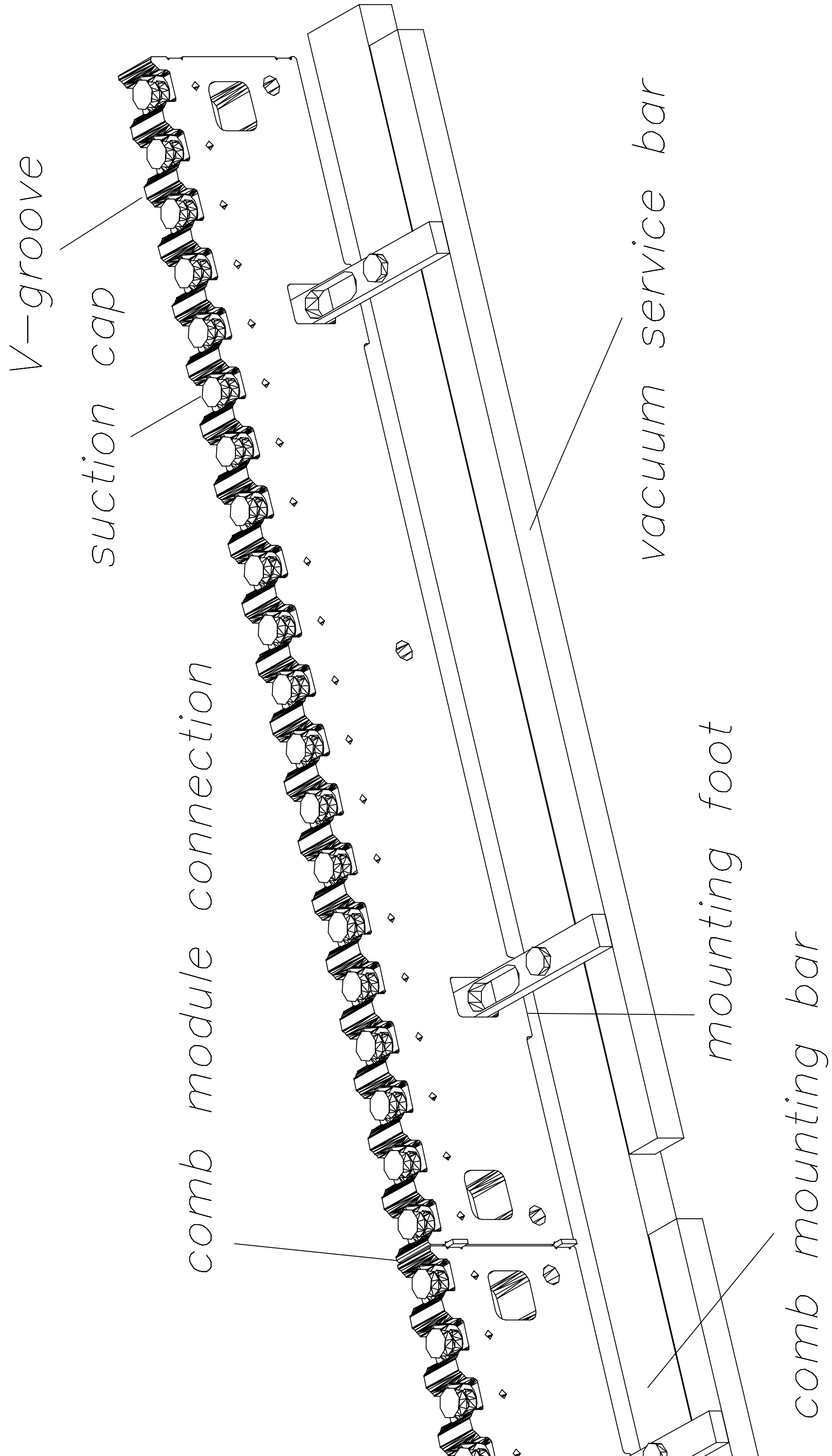

Figure 7: 3D picture of a comb module for the tube jig.

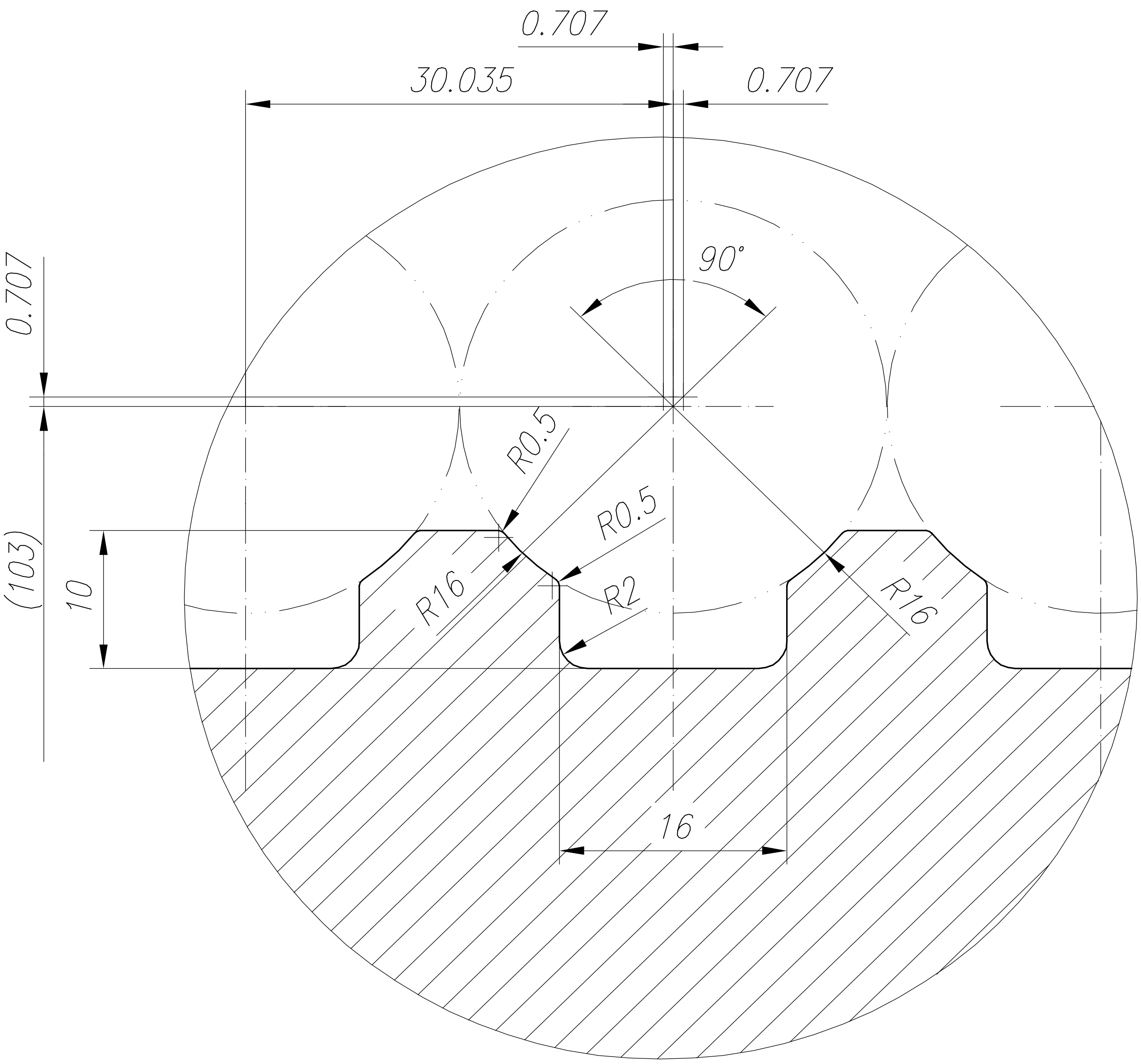

Figure 8: Design of the V-grooves of the comb modules.

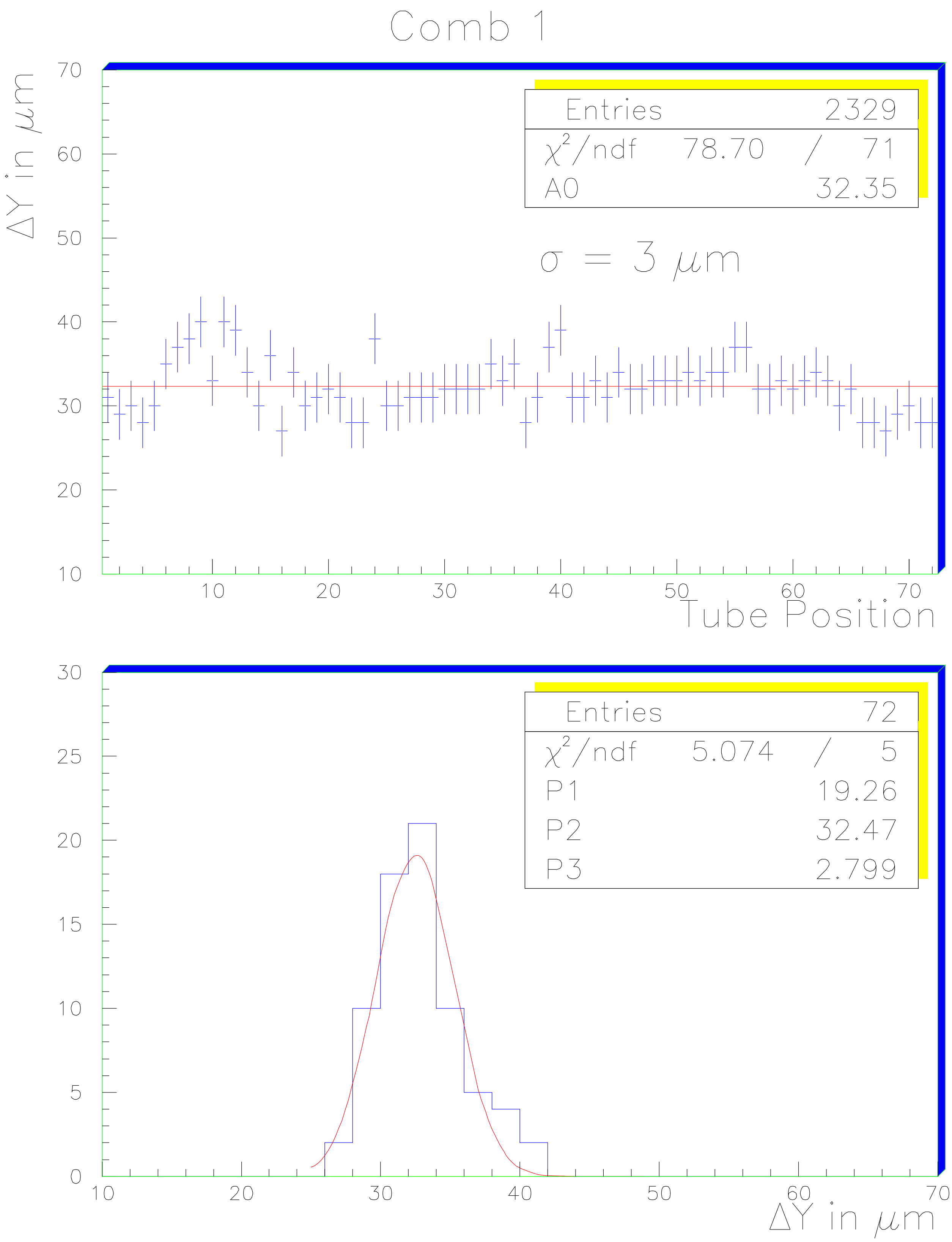

Figure 9: Measurement of the relative heights (y-coordinates) of the 72 V-grooves of one end comb (comb no. 1) with a precise test cylinder.

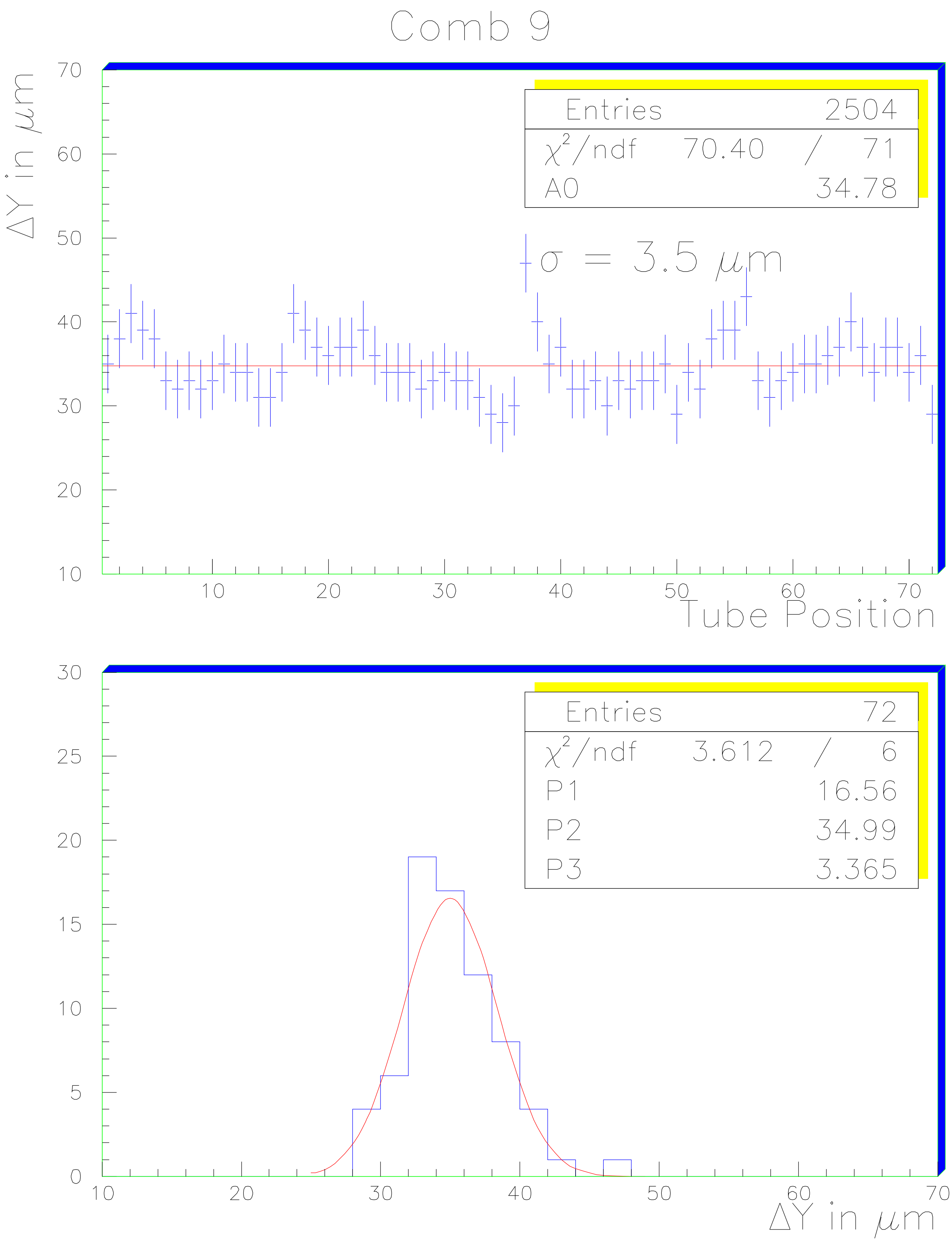

Figure 10: Measurement of the relative heights (y-coordinates) of the 72 V-grooves of the second end comb (comb no. 1) with a precise test cylinder.

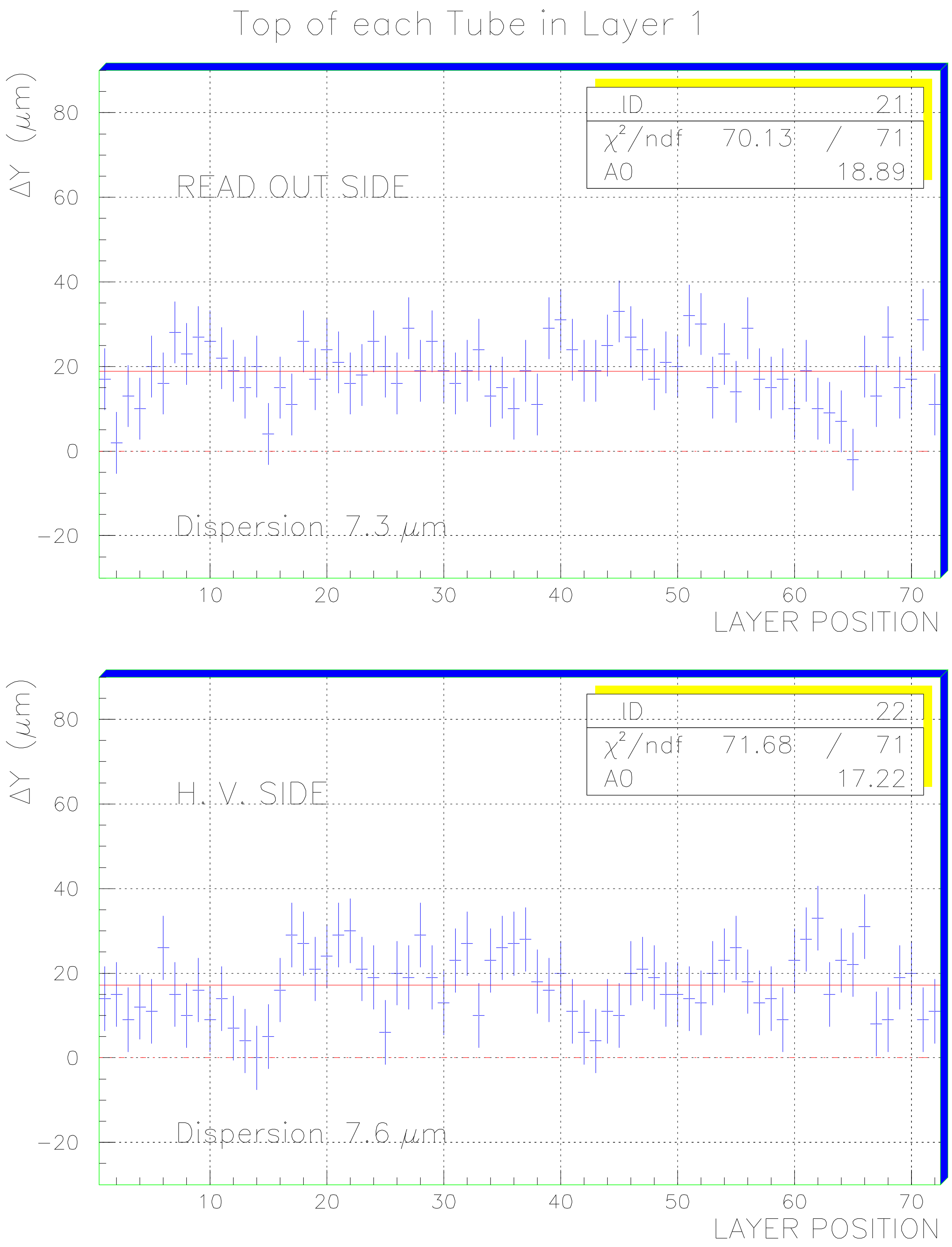

Figure 11: Measurement of the relative heights (y-coordinates) of 72 wired tubes in the two end combs on the HV side (comb no. 1) and on the readout side (comb no. 9).

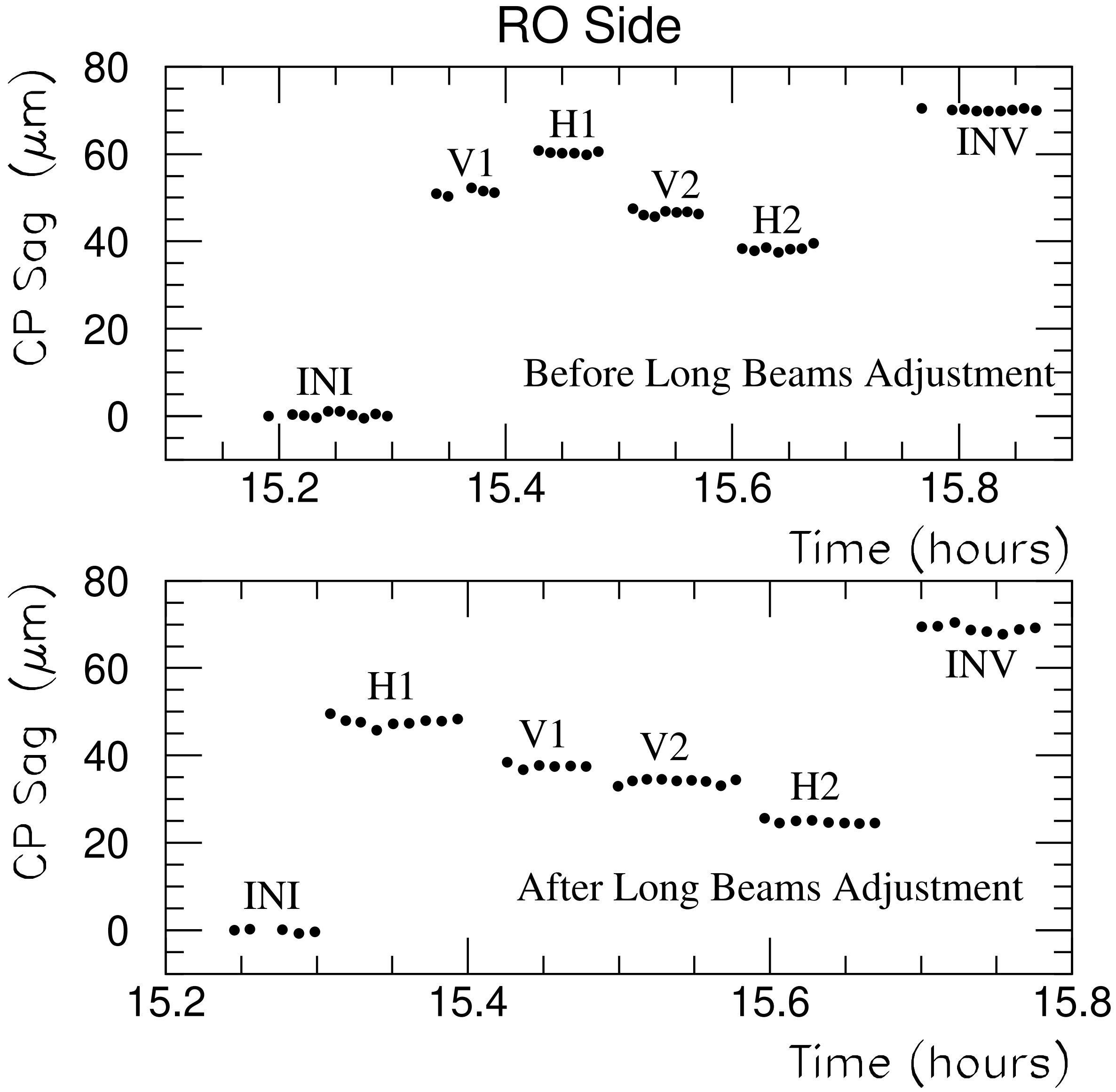

Figure 12: Readings of the RASNIK system on the readout (RO) side cross plate before and after long-beam adjustment (see text) for two positions of the spacer on the sphere supports, initial (INI) and inverted (INV) around the x axis, and for 4 positions of the spacer on the crane in the two vertical (V1, V2) and the two horizontal (H1, H2) orientations. After the long-beam adjustment the cross plate sag is symmetric for the initial and inverted with respect to the vertical (no sag) positions and can be determined as the average between the INI and INV readings.

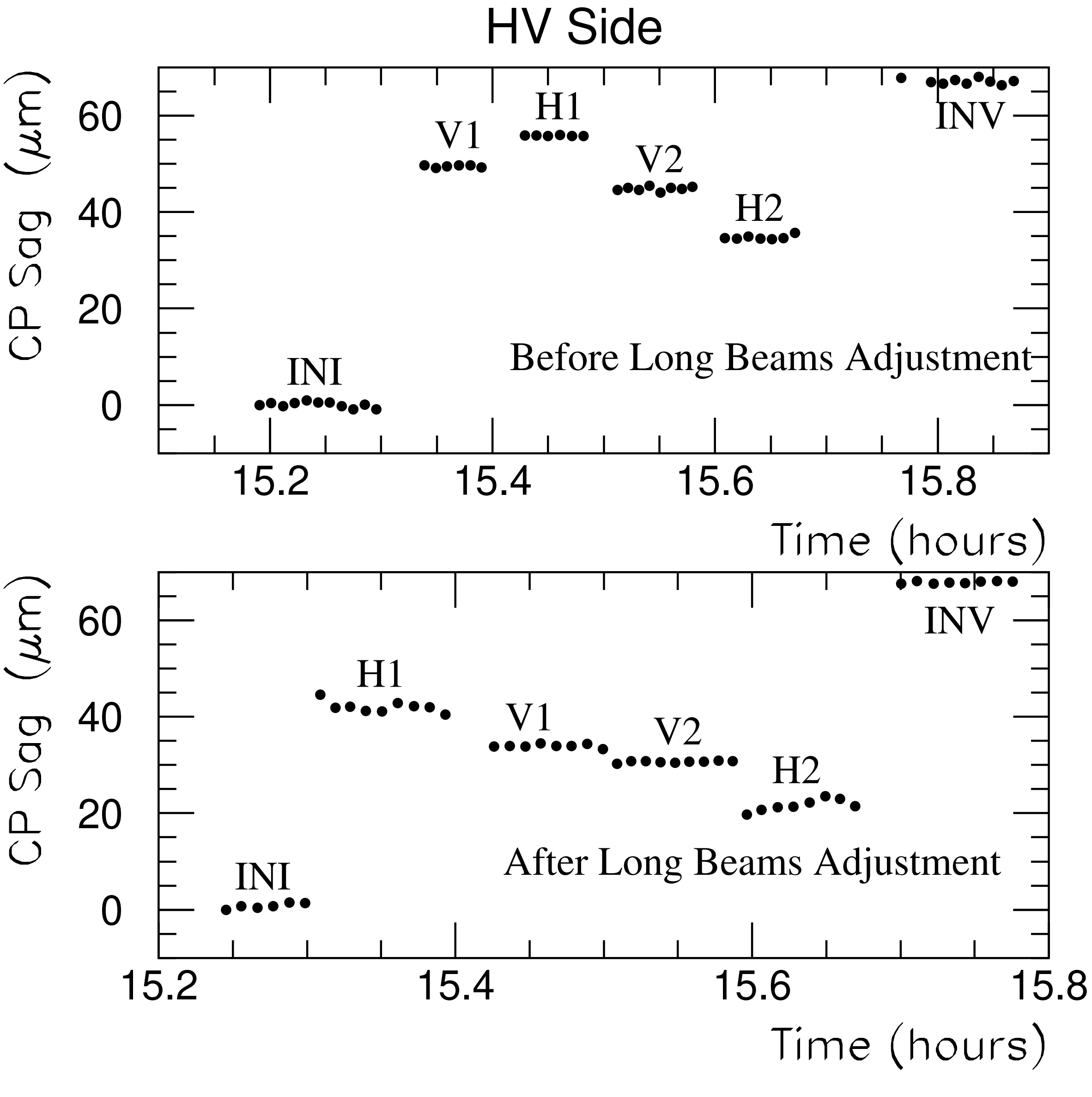

Figure 13: Same as Fig. 12 for the HV side cross plate.

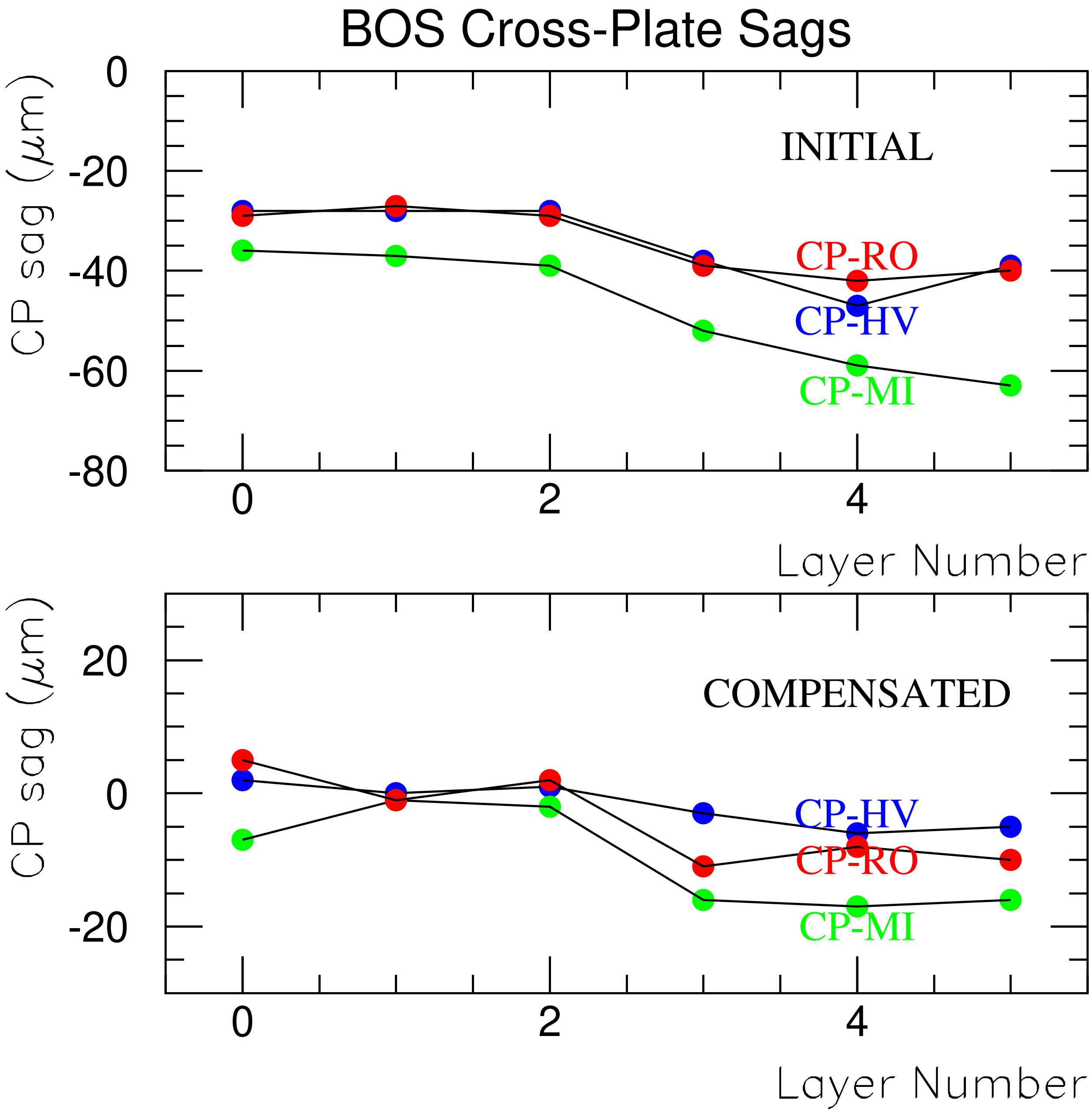

Figure 14: Sag of the three cross plates at the HV and readout (RO) ends and and in the middle of the chamber before and after sag compensation as measured with the on-cross plate RASNIK systems.

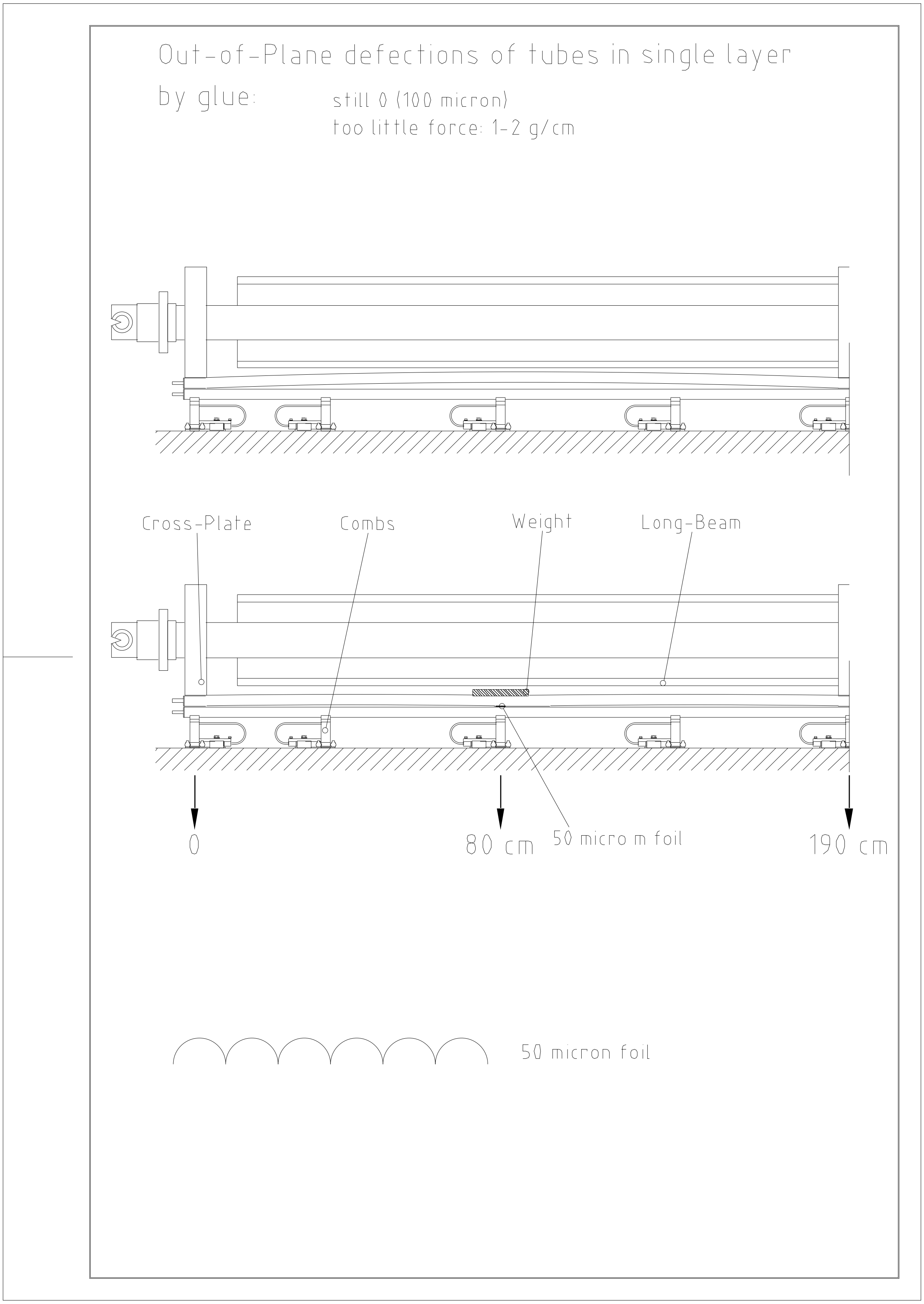

Figure 15: Illustration of out-of-plane deflections of tubes due to the glue and their control by using spacer foils and weights when two tube layers are glued together.

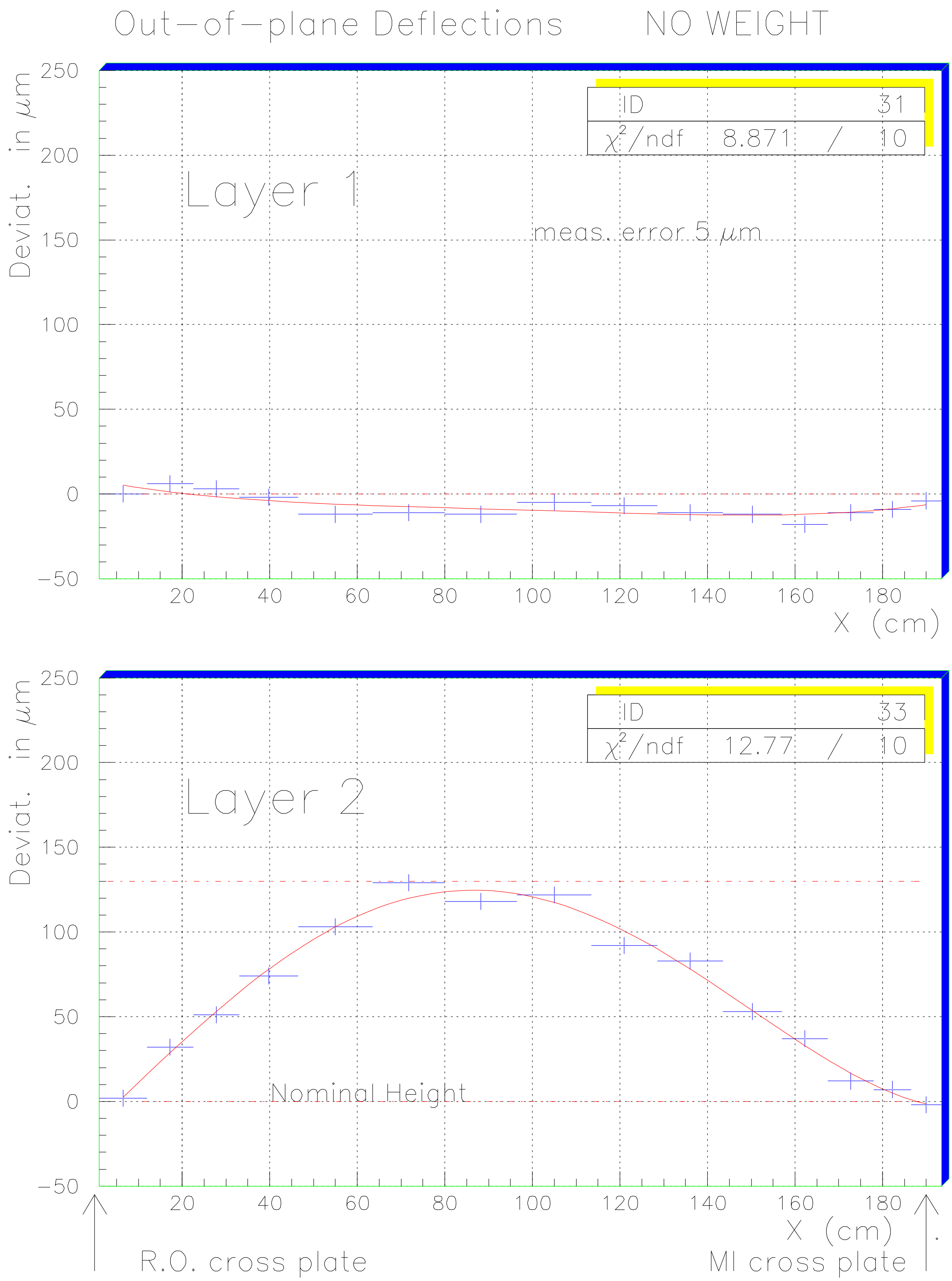

Figure 16: Out-of-plane deflection from nominal height in the top tube layer due to the glue in comparision with the measurement of the tube height along the tube in the bottom layer in the combs.

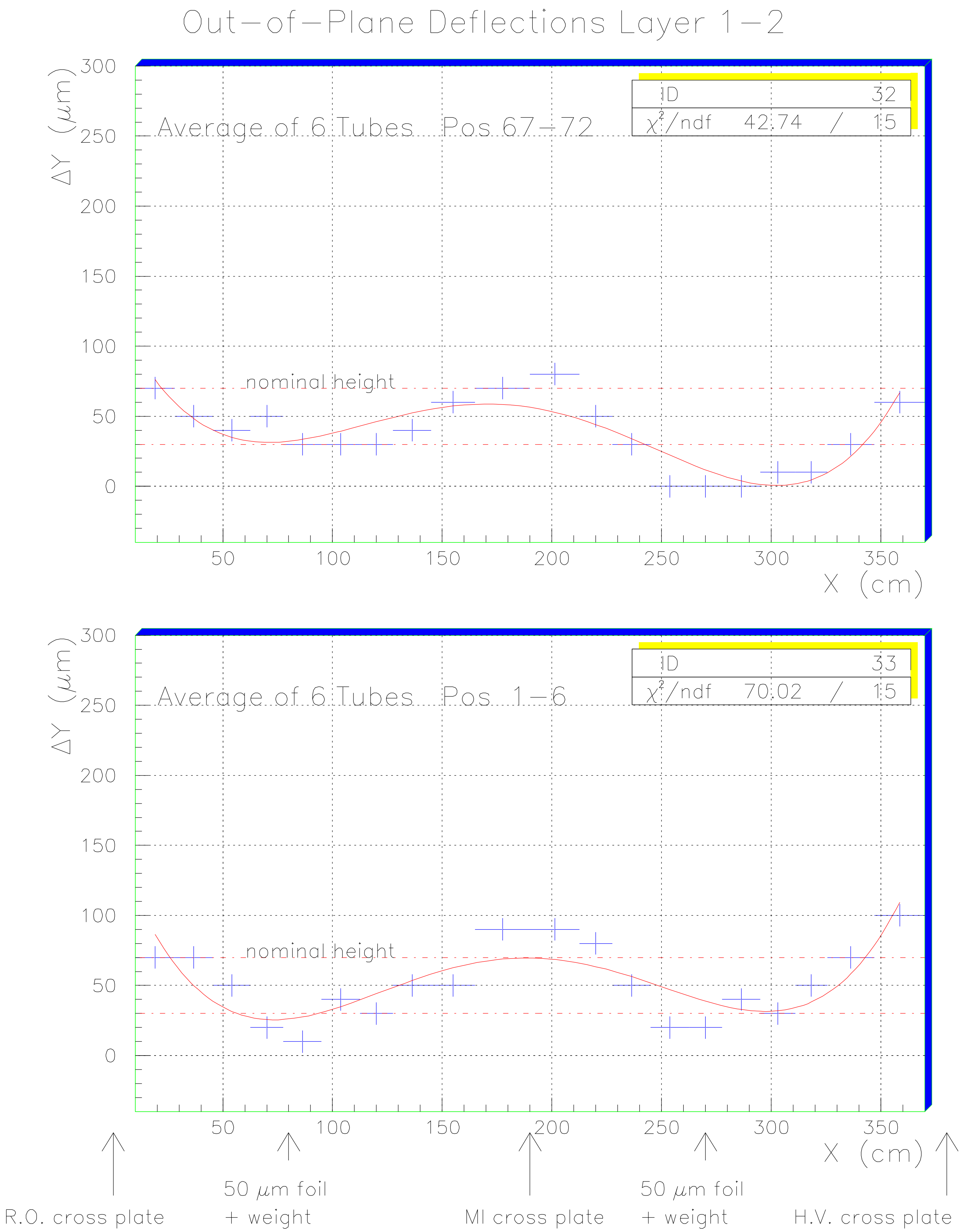

Figure 17: Out-of-plane deflections in layer 1 (multilayer 1) suppressed with weight and spacer foil during glueing of layer 2.

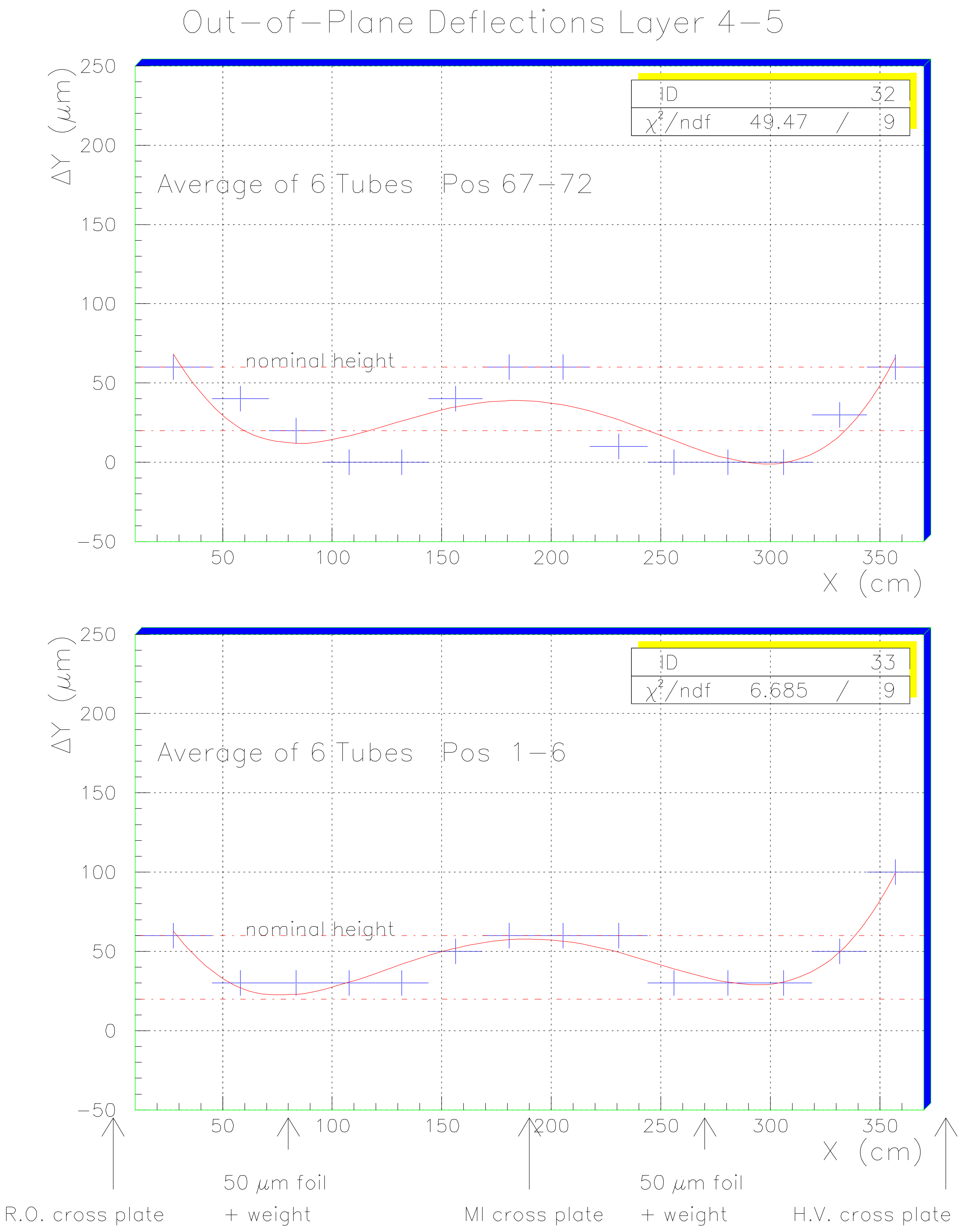

Figure 18: Out-of-plane deflections in layer 4 (multilayer 2) suppressed with weight and spacer foil during glueing of layer 5.

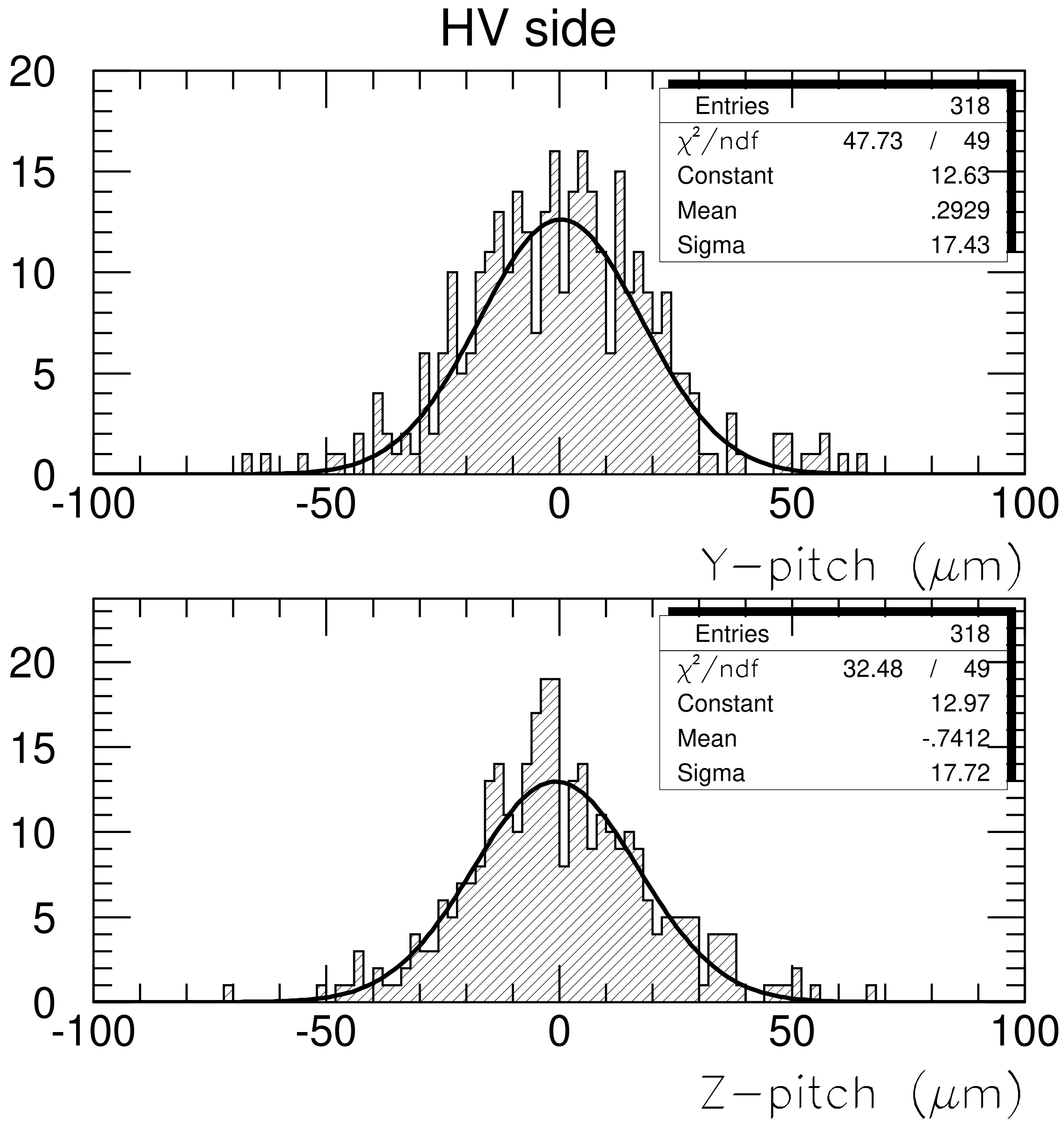

Figure 19: Distributions of the residuals of X-ray tomograph measured wire positions in y and z relative to a fixed grid (see text) for the scan on the HV side.

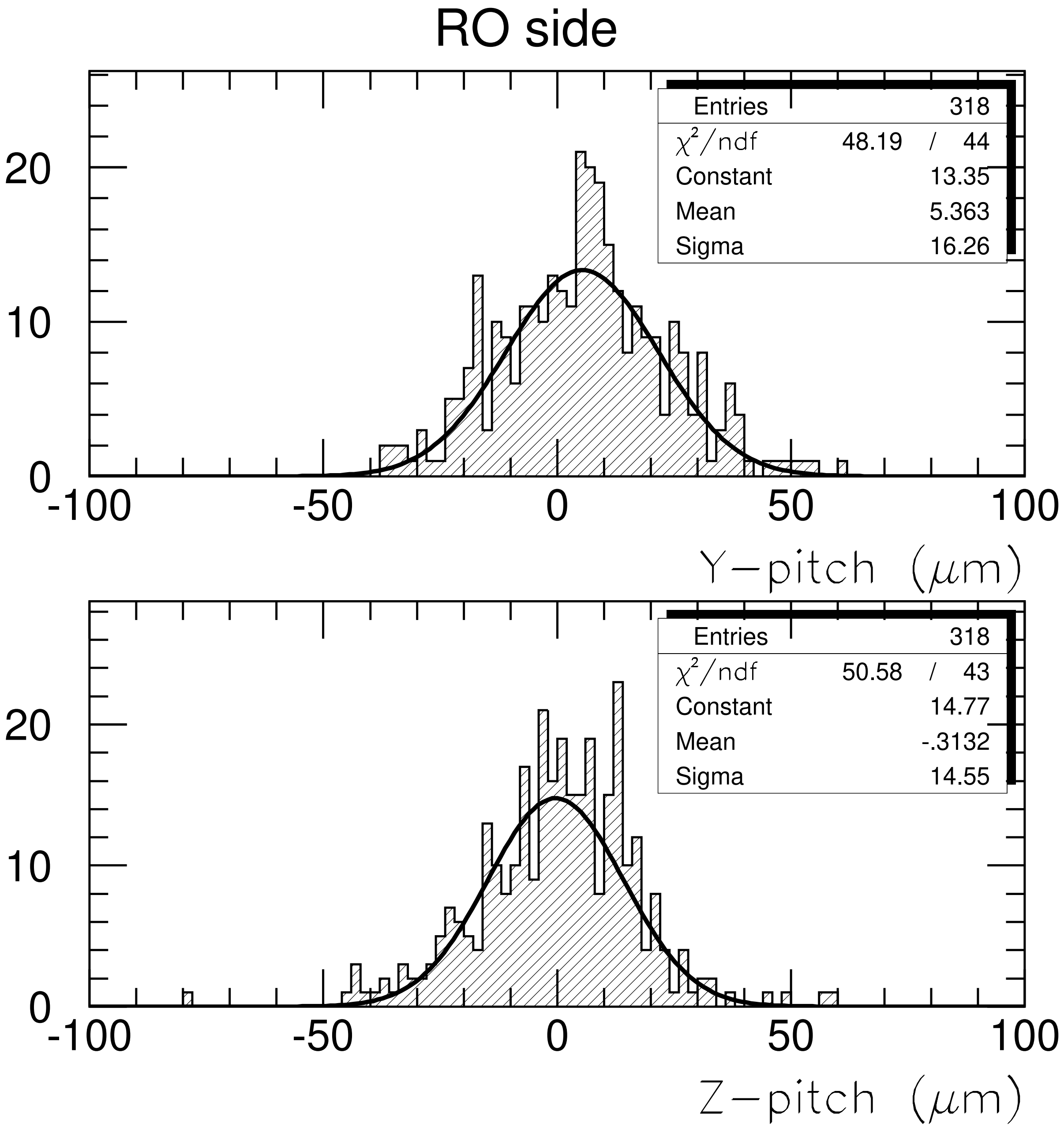

Figure 20: Distributions of the residuals of X-ray tomograph measured wire positions in y and z relative to a fixed grid (see text) for the scan on the readout side.

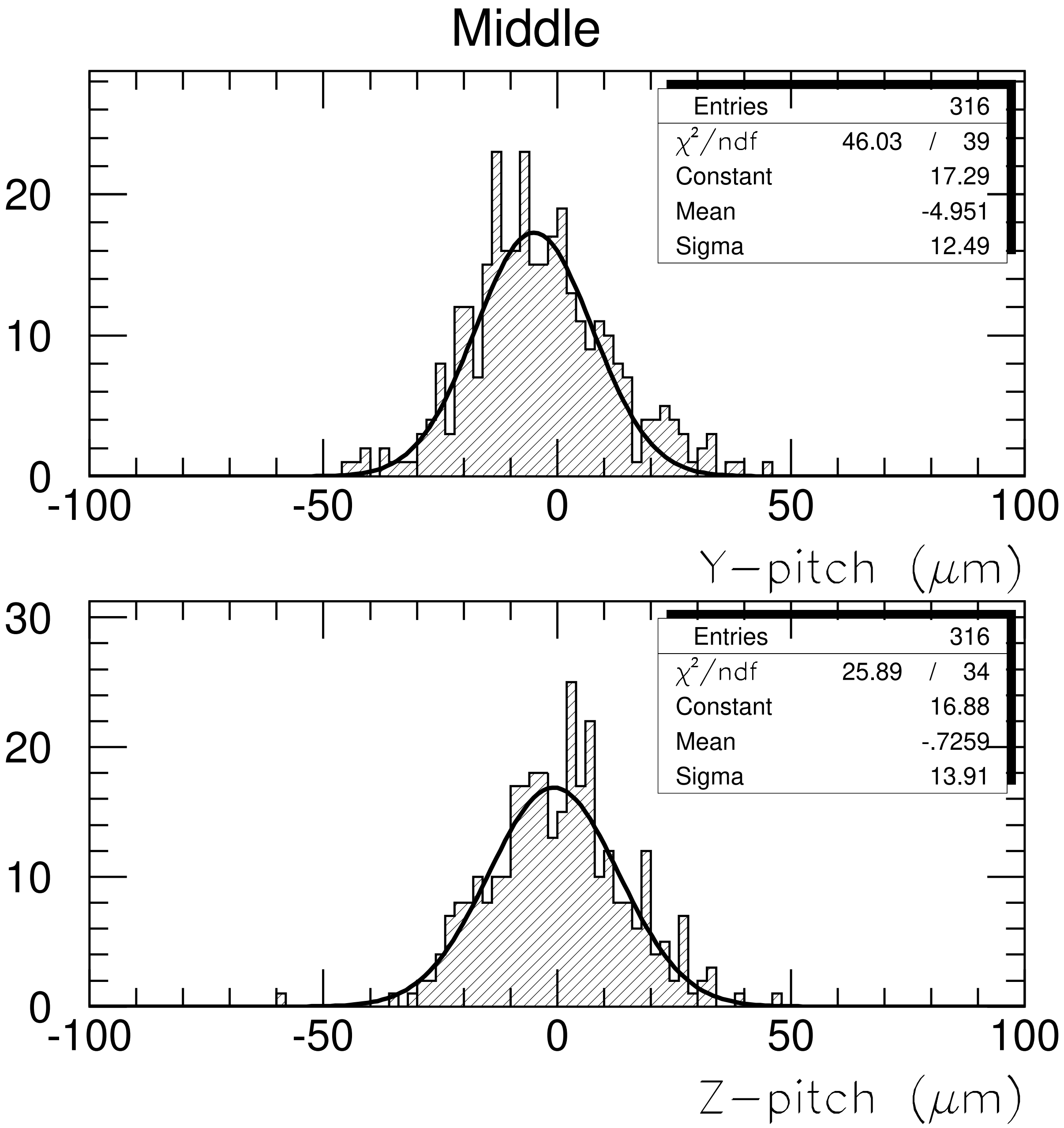

Figure 21: Distributions of the residuals of X-ray tomograph measured wire positions in y and z relative to a fixed grid (see text) for the scan along the middle cross plate.

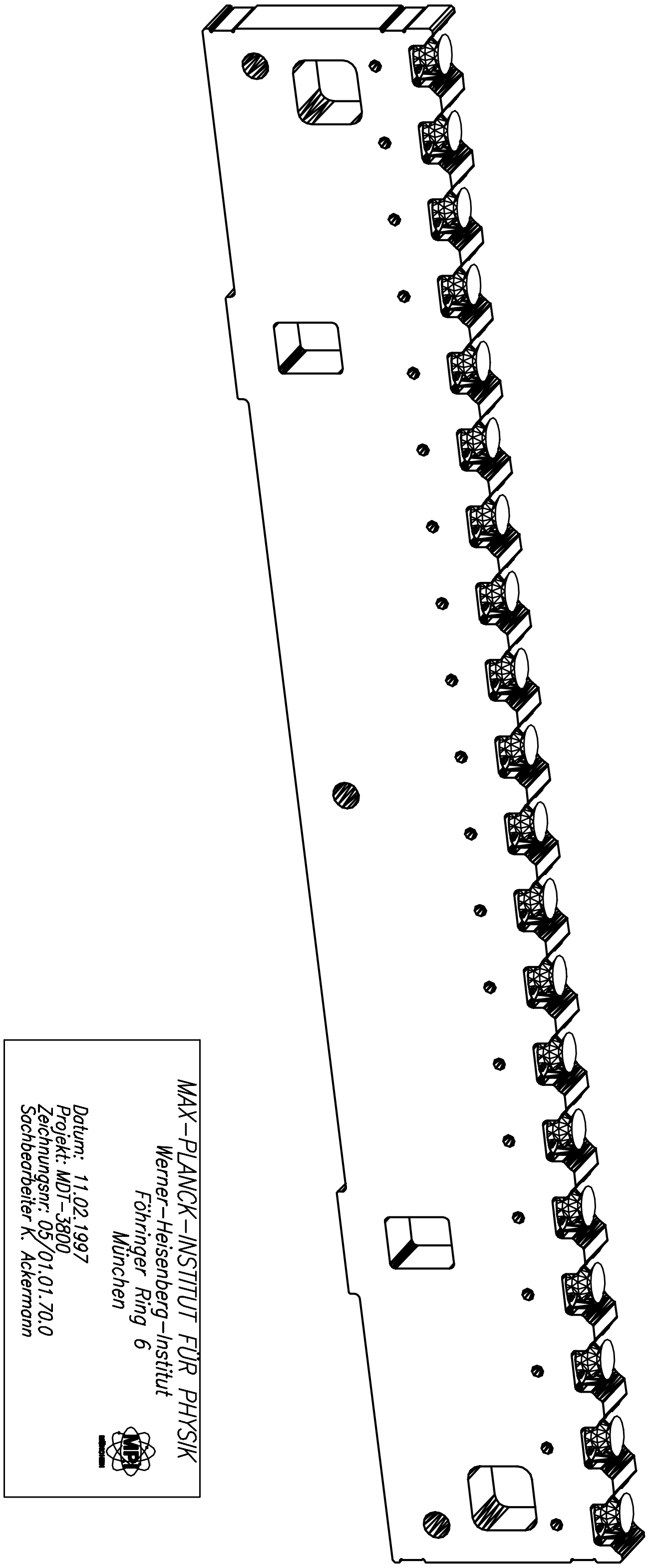

Figure A1: 3D drawing of a comb module.

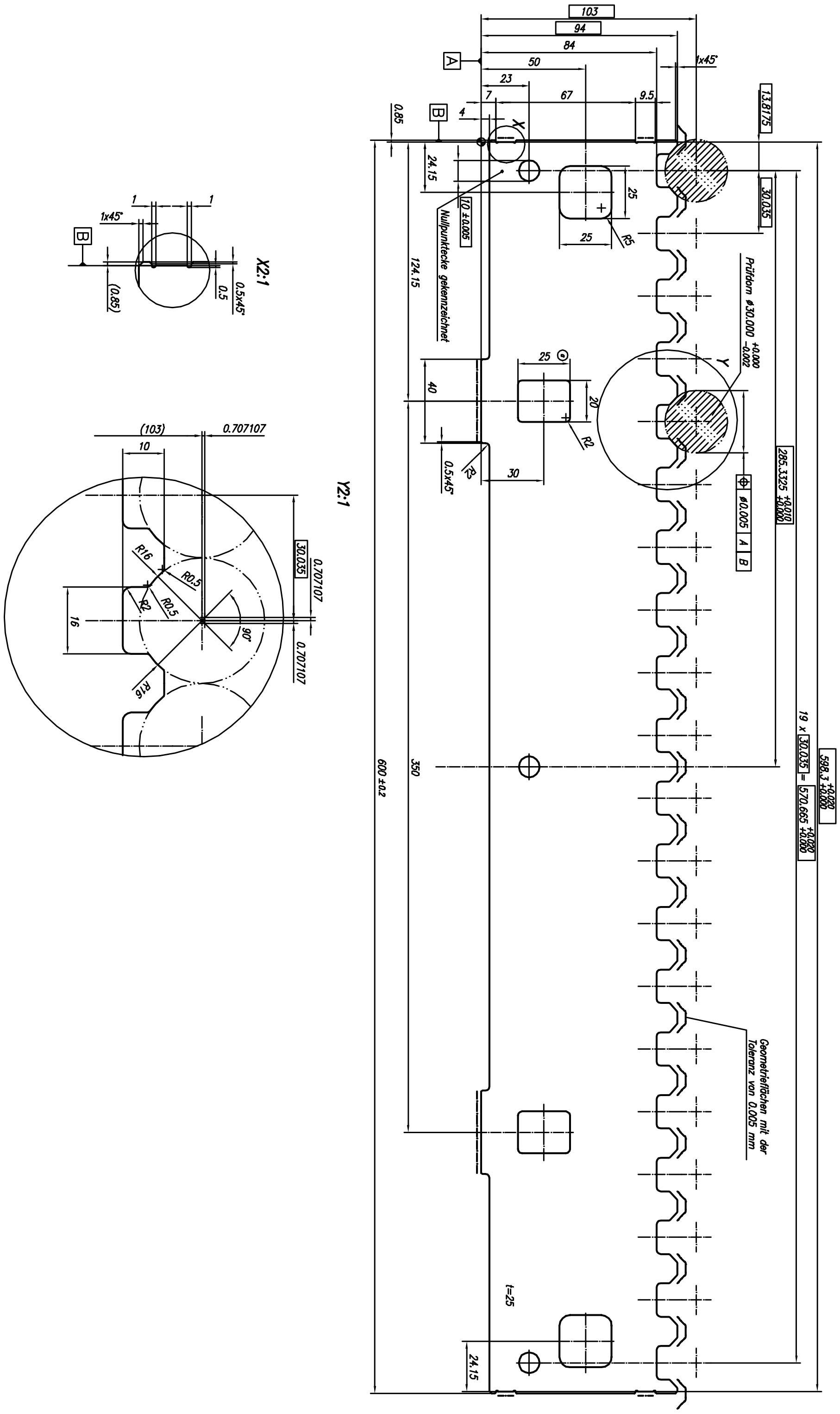

Figure A2: Production drawing for the wire erosion of a comb module.

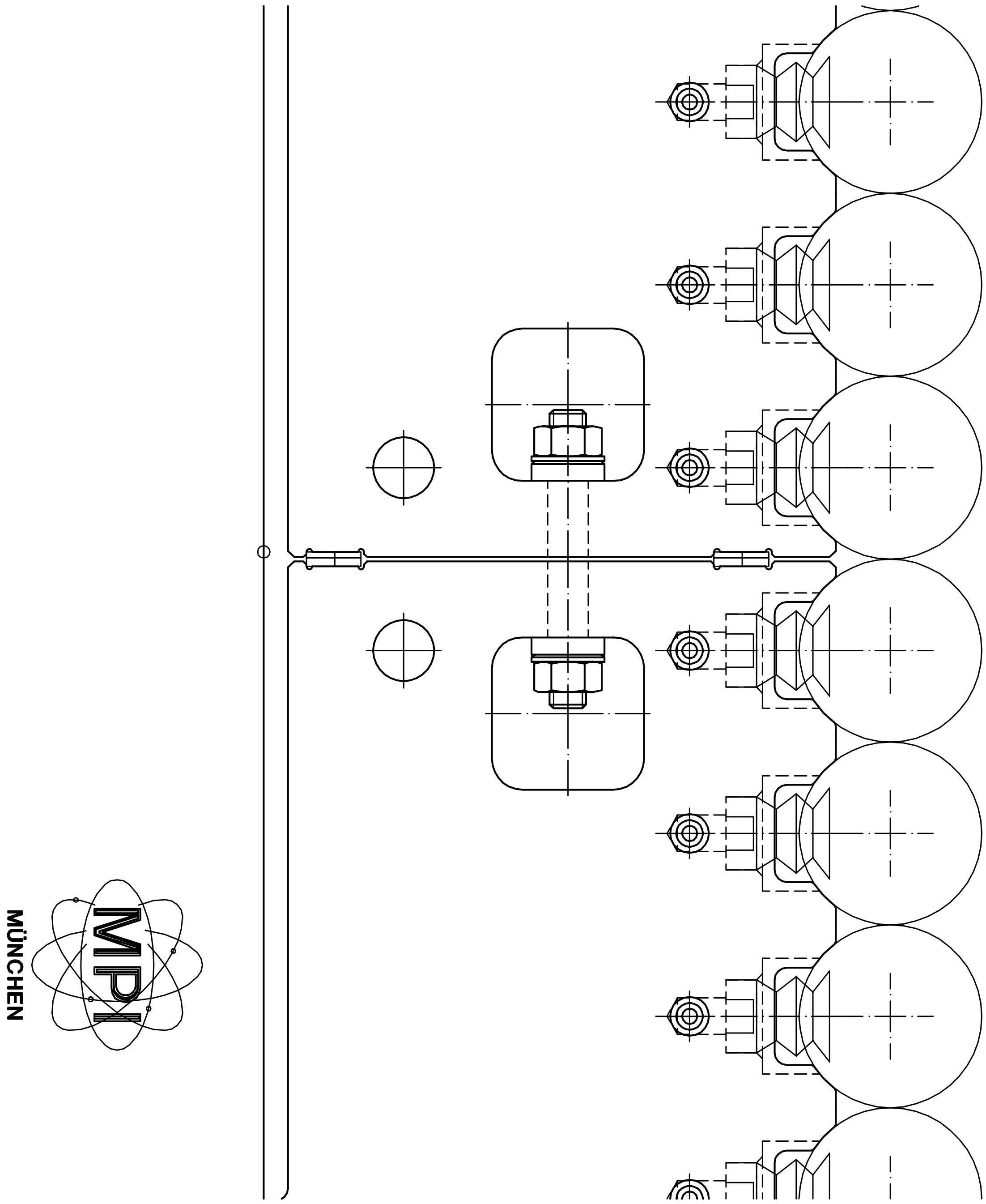

Figure A3: Interconnection between two adjacent comb modules.

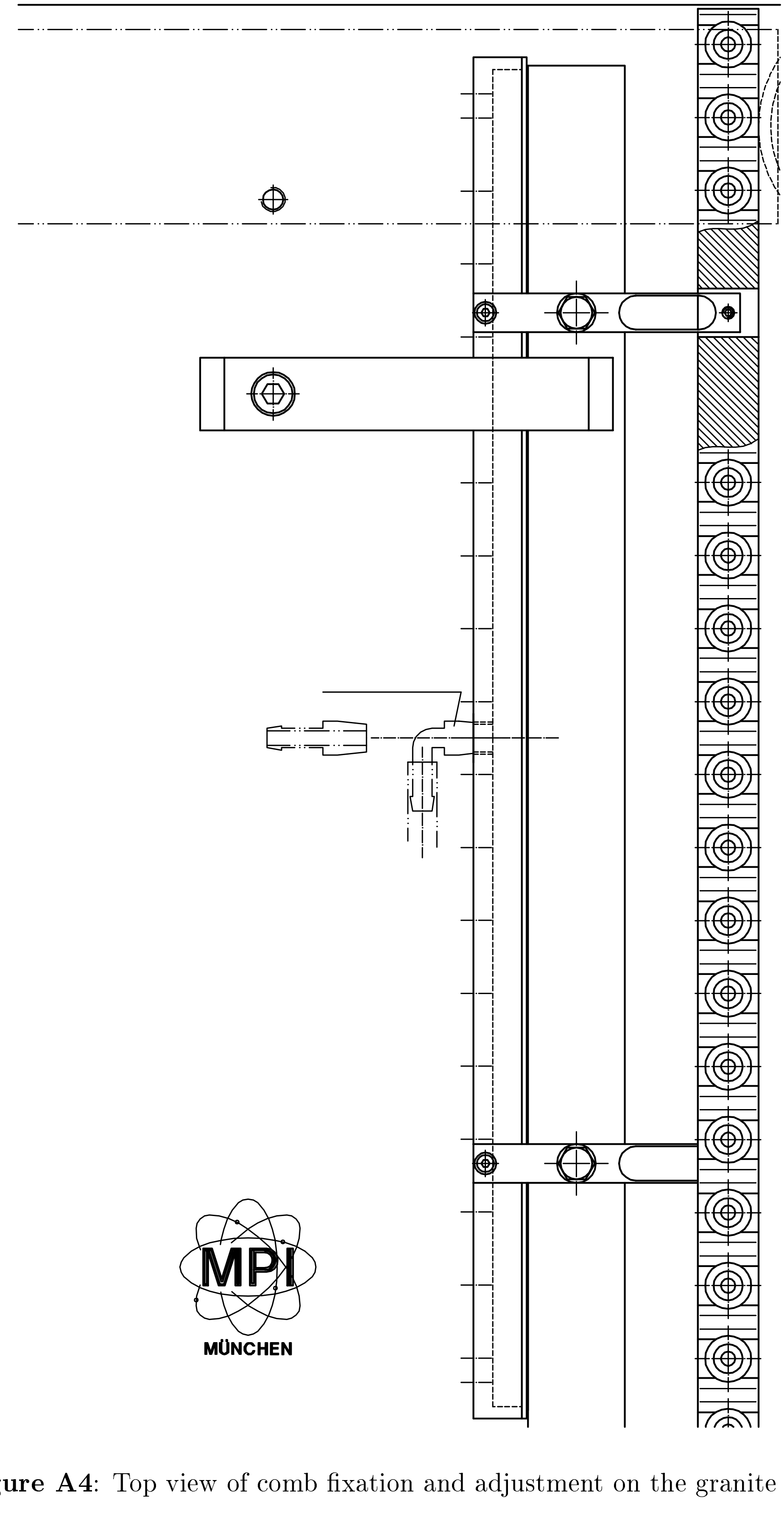

Figure A4: Top view of comb fixation and adjustment on the granite table.

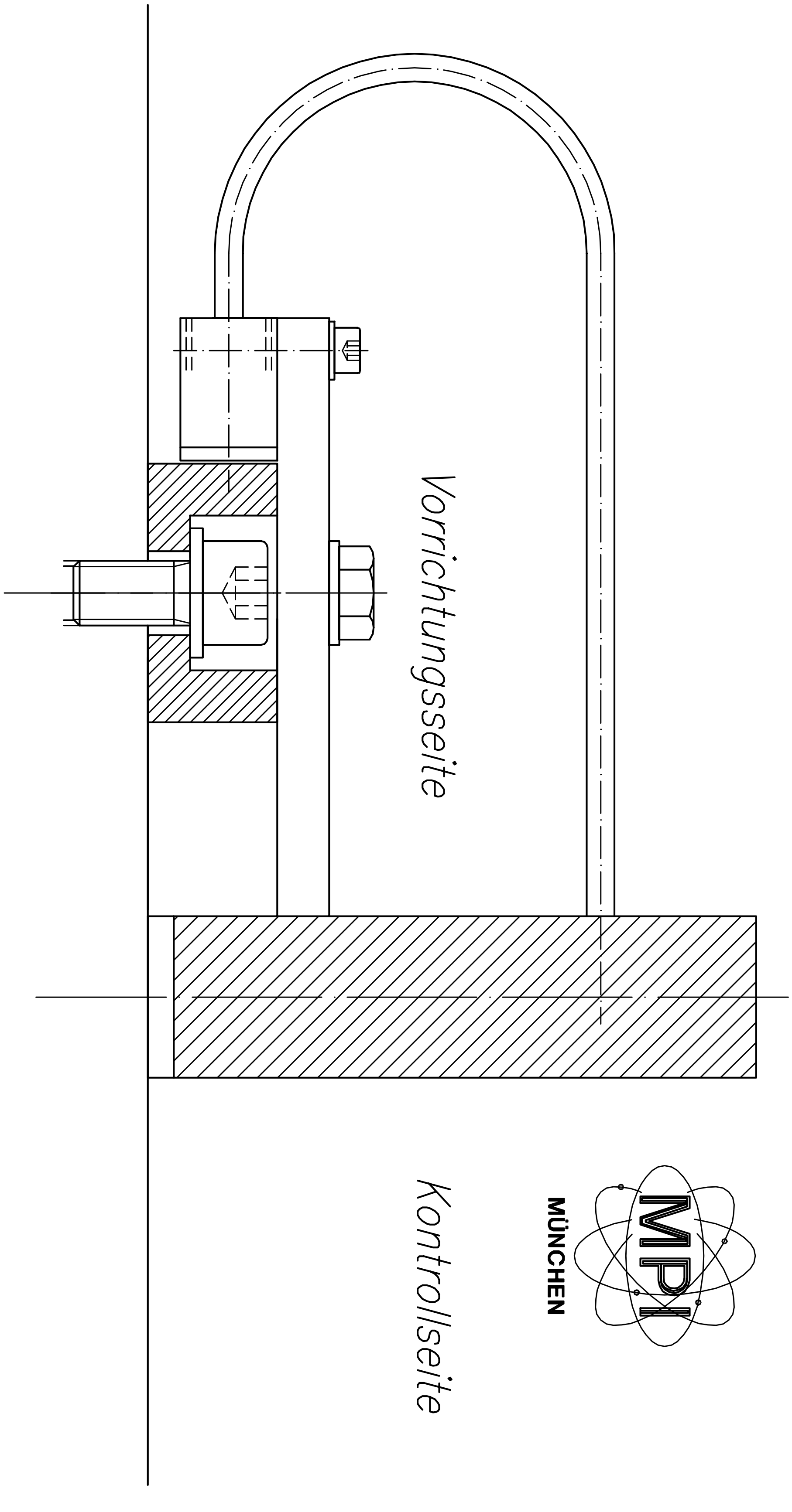

Figure A5: Fixation of combs on the granite table.

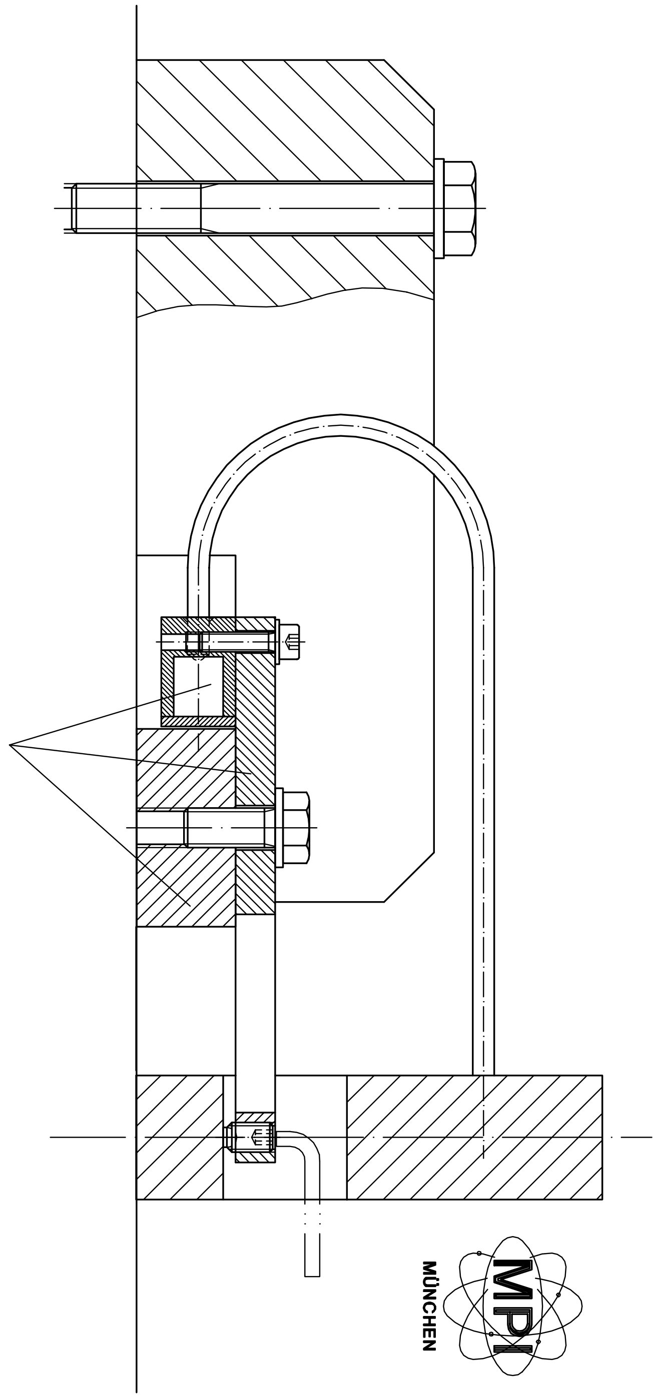

Figure A6: Fixation of combs to the granite table and vacuum distribution.

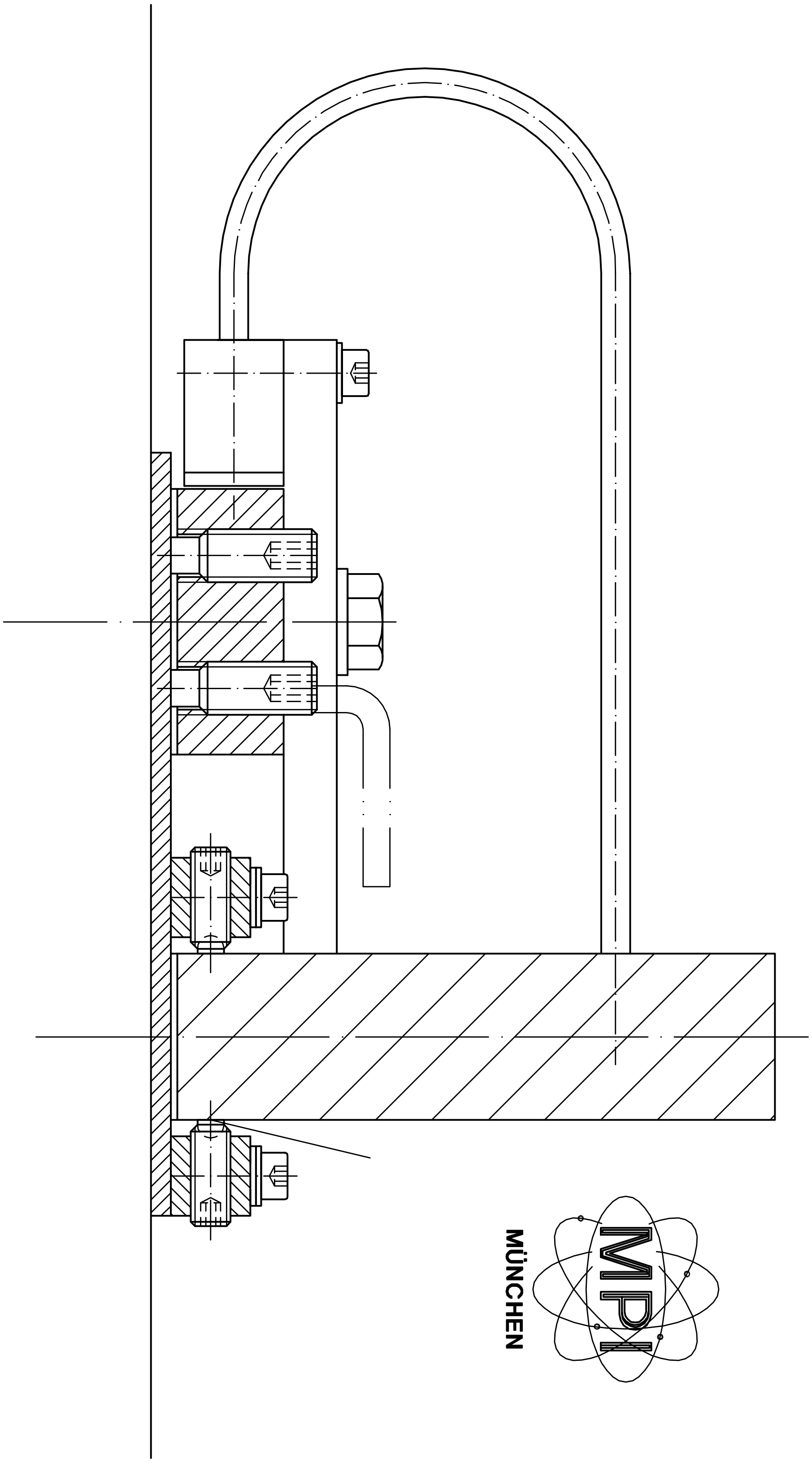

Figure A7: Adjustment of combs in x.

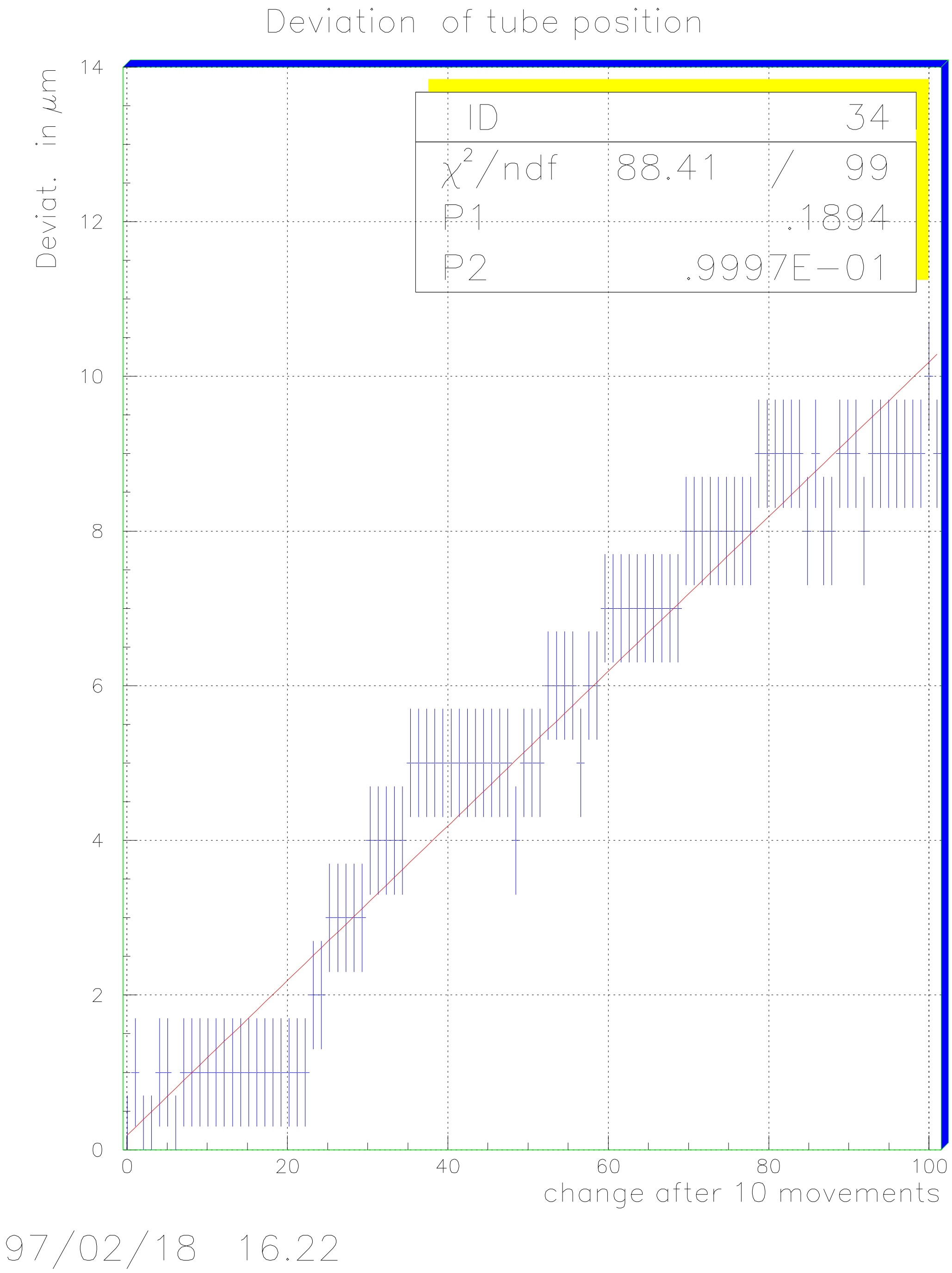

Figure A8: Change in y position over 1000 trials (100 measurements) of inserting a tube in a V-groove of a comb module.