Large-Scale Production of the Precision Drift Tube Chambers for the ATLAS Muon Spectrometer*

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Abstract— **The muon spectrometer of the ATLAS detector at the large hadron collider (LHC) will contain about 1200 high-precision drift chambers with a position resolution of 40 μm covering an active area of 5500 m^2. The chambers consist of three or four layers of pressurized drift tubes on either side of a space frame which carries an optical monitoring system for measuring deformations (Monitored Drift Tube chambers, MDT). We report about the serial production of the MDT chambers which are to be installed at the outer circumference of the barrel part of the muon spectrometer. With 432 drift tubes of 3.8 m length and a width of 2.16 m these chambers are among the largest in the ATLAS muon spectrometer. The signal wire positions in 5 of these chambers have been measured with an X-ray scanning device at CERN. A wire positioning accuracy of better than 10 μm (rms) has been reached which exceeds the requirement of 20 μm (rms). The performance of one of the chambers equipped with a prototype version of the final readout electronics for ATLAS has been tested in a muon beam at CERN.**

Keywords— **ATLAS detector, drift tubes, drift chambers, muon spectrometer.**

I. Introduction

The ATLAS muon spectrometer [1] consists of three layers of precision drift detectors, the Monitored Drift Tube (MDT) chambers, in a toroidal magnetic field generated by the worlds largest superconducting air-core magnet system. It has been designed to provide stand-alone a muon momentum resolution of $\Delta p_T/p_T = 2-10\%$ for transverse momenta between 6 GeV and 1 TeV over a pseudo-rapidity range of $|\eta| \leq 2.7$. The MDT chambers therefore have to provide a track position resolution of 40 μm covering an active area of 5500 m^2.

The MDT chambers (see Fig. 1) consist of three or four layers of aluminum drift tubes of 29.970 ± 0.015 mm diameter and 400 ± 30 μm wall thickness on either side of a space frame. The space frame (see Fig. 12) consists of three cross plates supported by two long beams close to the points of minimum deflection. The space frame carries an optical alignment system [1] which monitors the planarity of the chamber and is used to adjust the gravitational sag of the tube layers to the sag of the sense wires prior to installation in ATLAS.

The drift tubes are operated with an Ar:CO_2 (93:7) gas mixture at a pressure of 3 bar in order to provide an average single-tube resolution of better than 80 μm at a gas gain of 2×10^4. The low gas gain is used as a precaution against ageing of the drift tubes under the high radiation conditions at the large hadron collider (LHC). The sense wires of the drift tubes have to be positioned within a chamber with an accuracy of 20 μm (rms) in order to achieve the required chamber resolution.

1200 MDT chambers containing 400000 drift tubes of varying lengths between 0.9 and 6.2 m have to be built for the ATLAS muon spectrometer at world-wide 13 production sites. The Max-Planck-Institut (MPI) is leading in the construction of the large MDT chambers for the barrel part of the spectrometer. In Munich, 88 chambers of the type BOS (for "Barrel Outer Small") have to be constructed until summer 2004 for the outermost layer of the barrel muon spectrometer comprising 23% of its active area. A BOS MDT chamber consists of 432 drift tubes of 3.8 m length in two triple layers and has a width of 2.16 m.

The construction of the MDT chambers consists of two major steps, the fabrication of the drift tubes with an anode wire positioning accuracy of 10 μm (rms) in the tube center and the assembly of the tubes in the chamber. Extensive quality control tests are performed for each individual drift tube and for all completed chambers in to order to ensure the reliable operation of the unprecedentedly large number of drift tubes and precision chambers over the whole operating time of the experiment at the LHC. Further details of the design of the MDT chambers are described in [1]–[4].

II. Drift Tube Design and Production

In order to position the sense wires at the tube ends with the required accuracy, an endplug with precisely machined

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reference surfaces has been developed (see Fig. 2). The wire is located in a spiral hole in the brass central pin which is concentric with an outer aluminum reference ring. The wire is crimped in a soft copper tubelet fixed in the central pin. The insulating plastic body of the endplug (Noryl with 30% glass fiber) separating central pin and reference ring is injection moulded in a carefully optimized process in order to minimize stresses and to prevent the development of cracks during operation. All gas seals are with O-rings.

TABLE I

DRIFT TUBE QUALITY CONTROL TESTS FOR BOS MDT CHAMBERS

Measurement	Requirement (absolute)	Achieved (rms)	Rejection rate
Wire pos. w.r.t. endplug center (in y and z coord.)	0 ± 25 μm	< 7 μm (rms)	0.1%
Wire frequency at 20° C	39.9 ± 0.8 Hz	39.8 ± 0.25 Hz (rms)	0.1%
Wire tension	350 ± 15 g	348 ± 5 g (rms)	
Wire sag	195 ± 8 μm	194 ± 3 μm (rms)	
Wire relaxation after 2 months	< 1 Hz		0.01%
Argon gas leak rate at 3 bar	$\leq 10^{-8}$ bar $\cdot l/s$		0.1%
Dark current at 3400 V	≤ 2 nA/m		0.6%
Cosmic count rate at 3080 V		39 ± 8 Hz (rms)	
Assembled tube length	3773.3 ± 0.2 mm	3773.3 ± 0.07 mm (rms)	0.01%

The drift tubes for the BOS chambers are assembled at the Joint Institute for Nuclear Research in Dubna in a common facility of MPI and JINR where also the drift tubes for the MDT chambers built in Dubna are produced (see Fig. 3). The endplug design with the spiral hole for wire location allows for the use of an automated assembly station developed by CERN, INFN Frascati and NIKHEF. It is operated in a climatized clean room of class 10000 with temperature and relative humidity stabilized to $20 \pm 0.5°$ C and $45 \pm 10\%$, respectively. The sense wire is fed through the tubes and the endplugs with clean air flow avoiding any manual contact with the wire. The facility allows for the production of more than 100 drift tubes per day which is necessary for the chamber construction at MPI and JINR. Between September 2000 and December 2001, 35% of the 36000 BOS drift tubes have been fabricated and tested. Until October 2002, the number has increased to 65%.

Reliable long-term ground contact between the aluminum tube and the aluminum reference ring of the endplug is provided by a dedicated laser spot welding procedure developed at MPI employing aluminum wire as filler material and an optimized laser pulse shape (see Figs. 8,9,10).

Each drift tube has to pass stringent quality control tests before they are transported to Munich which are summarized in Table I. The results of the most important measurements, namely of the wire positions at the tube ends, the wire tension, the argon gas leak rate and the dark current, are shown in Figs. 4–7 for about 30% of the drift tube production for the BOS chambers. A tube rejection rate of less than 1% has been reached after the production of the first 1000 drift tubes. In addition, about 1% of the tubes

TABLE II

RESULTS OF THE X-RAY MEASUREMENT OF 6 BOS MDT CHAMBERS AT $20 \pm 0.2°$ C (SEE TEXT): PARAMETERS OF THE FITTED WIRE GRID AND RMS OF THE RESIDUAL DISTRIBUTIONS IN MICROMETERS. THE CHAMBERS ARE NUMBERED ACCORDING TO THE SEQUENCE OF CONSTRUCTION. THE NOMINAL PARAMETER VALUES ARE: y-PITCH $= 26.034$ MM, z-PITCH $= 30.0357$ MM, SEPARATION BETWEEN WIRE TRIPLE LAYERS $\Delta y = 346.899$ MM AND $\Delta z = 0$.

Param. [μm]	BOS-0	BOS-4	BOS-5	BOS-9	BOS-18	BOS-30
Glue type	DP 460	DP 490	Araldit 2014	Araldit 2014	Araldit 2014	Araldit 2014
High-voltage end						
y-pitch	26038	26037	26031	26029	26039	26032
z-pitch	30035.6	30035.5	30035.9	30035.5	30035.3	30035.5
Δy	346877	346897	346892	346921	346898	346904
RMS_y	14.8	17.7	10.8	12.5	13.8	10.8
RMS_z	16.1	16.6	8.8	13.9	11.6	10.9
RMS_{tot}	15.5	17.2	9.8	13.2	12.7	10.9
Readout end						
y-pitch	26041	26035	26034	26030	26044	26034
z-pitch	30035.7	30035.7	30035.7	30035.8	30035.7	30035.5
Δy	346852	346904	346902	346912	346917	346898
RMS_y	16.0	13.9	11.4	11.6	20.4	10.9
RMS_z	15.3	17.6	10.3	12.5	12.9	9.1
RMS_{tot}	15.7	15.8	10.8	12.0	16.7	10.0
Average of both ends						
RMS_y	15.4	15.8	11.1	10.6	17.1	10.9
RMS_z	15.7	17.1	9.6	11.4	12.3	10.0
RMS_{tot}	15.6	16.5	10.3	11.0	14.7	10.5

is lost due to damage during transport and handling.

The wire positions in the y (vertical) and z (horizontal) coordinate perpendicular to the tube axis are measured with respect to the center of the aluminum reference ring of the endplugs with a stereo X-ray method of 2 μm (rms) intrinsic accuracy. A wire positioning accuracy at the endplugs of 7 μm (rms) has been achieved in serial production taking into account also misalignment between the tube and endplug axes. For the measurement, the endplugs are placed on combs with their reference rings in the same way as during chamber assembly (see below).

The wire oscillation frequency is a measure of the wire tension which determines the gravitational sag of the wire. It is measured immediately after the assembly of the drift tube and approximately two months later after the transport from Dubna to Munich and just before assembly in a chamber. A significant but reproducible relaxation of the wire tension by on average 2% is observed after the wires have been overtensioned to 475 g for 15 s during drift tubes assembly.

The gas leak rate of a complete drift tube filled with argon and a 10% admixture of helium at 2 bar overpressure is measured inside an evacuated container using a helium leak detector and renormalizing the leak rate to argon gas. The high voltage stability of the drift tubes is tested with the nominal gas mixture at 3 bar and 3400 V, i.e. at 8 times higher gas gain than nominal. In addition, the cosmic ray count rate of each 3.8 m long tube is measured at the nominal operating parameters.

III. Chamber Serial Production

The BOS MDT chambers are assembled at MPI in a climatized clean room of class 100000 with temperature and relative humidity stabilized to $20 \pm 0.5°$ C and $45 \pm 10\%$, respectively (see Fig. 1). For the assembly in the chambers, the drift tubes for each layer are positioned on precision aluminum combs installed on a flat granite table (see Fig. 11). The correct positioning of the endplugs on the end combs is verified for each layer by measuring the heights of the endplug reference rings above the granite table to be within ± 20 μm of the nominal value for each endplug and below 10 μm (rms) for the whole layer. The surface planarity of the table and the alignment of the combs are monitored by means of optical sensors and electronic tilt meters.

The tube layers are glued successively to the space frame which is positioned on the table with respect to the combs with an accuracy of ± 5 μm in vertical and horizontal direction provided by 6 precision reference towers located at the ends of the three cross plates (see Fig. 12). The effect of the shrinkage of the glue in the 0.5 mm wide gap between the cross plates and the first tube layer on either side of the space frame which moves each of the two layers by approximately 20 μm (see below) is taken into account in the tower heights in order to maintain equal distances between the tube layers.

The glue needed between the tube layers is distributed on the tubes positioned on the combs using an custom designed automated glue dispenser (see Figs. 13,14,15). The amount of glue and the glue locations on the tubes are controlled very accurately (see Fig. 15). The glue dispenser uses premixed glue and reaches a moving speed along the tubes of 0.25 m/s. The glue distribution on a layer of 72 tubes can be completed within 30 minutes well before the glue starts setting.

The correct positioning of the chamber on the table and deviations of the space frame as well as of the tube layers from planarity are monitored with optical sensors during the whole assembly process. The assembly procedure and the monitoring data including their storage in a data base and the online reconstruction of the chamber geometry are managed with the help of an assembly control program which is operated by technicians.

For the glueing of a tube layer, the space frame is supported on the table at the ends of the three cross plates (see Fig. 12). The gravitational sag of the two outer cross plates in this position, monitored by optical sensors, increases from about 50 μm for the bare space frame to about 80 μm after 5 tube layers have been glued [3]. In order to prevent built-in deformations of the tube layers, the cross plate sag is fully compensated within a few micron during glue curing using computer controlled pneumatic actuators. The 8 actuators support the cross plates via the long beams by means of 4 bars inserted through holes in the long beams close to the cross plates (see Fig. 12). Further details of the MDT chamber assembly procedure can be found in [1]–[4].

Between December 2000 and December 2001, 18 of the 88 chambers have been assembled. Until October 2002, 50% of the chambers have been constructed. The chamber production rate is limited by the glue curing time in the clean room of a least 12 hours overnight. A routine assembly rate of 8 working days per chamber has been reached in the second half of 2001. In the first half of 2002, the chambers have been assembled at a rate of 7 working days per chamber. One additional working day could be saved by setting up an additional precise assembly table for the space frame outside of the clean room. At the time of publication, the maximum production speed of 6 working days per chamber has been reached which corresponds to the 6 glueing steps for the 6 tube layers.

After the glueing of the tube layers, the gas distribution system for the individual drift tubes, readout electronics boards and Faraday cages have to be mounted (see Fig. 16). The performance of each chamber will be tested in a dedicated cosmic ray stand at the Ludwig-Maximilians University in Munich which consists of a tower of three chambers. Until the installation in the ATLAS detector, the completed and tested chambers are stored in universal transport and storage frames in a dedicated storage hall (see Fig. 17).

IV. Chamber Accuracy

The accuracy of the MDT chambers is monitored by measuring the wire coordinates with an X-ray scanning device at CERN [5],[6]. Five out of 44 BOS chambers already built and the preseries chamber BOS-0 have been X-rayed so far. From a fit of an ideal wire grid to the measured wire coordinates at each chamber end (high-voltage and readout end), the main geometrical parameters of the chamber are determined: the wire pitches in the coordinates perpedicular (y) and parallel (z) to the tube layers, the separations Δy between the two triple layers and the widths of the residual distributions RMS_y and RMS_z (see Table II). RMS_{tot} is the average wire positioning accuracy from the fit in both coordinates.

The wire positioning accuracy of all measured chambers is better than 15 μm (rms) exceeding the requirement of 20 μm (rms). The geometrical parameters of the chambers are well reproducible. The y separation between the wire triple layers Δy is sensitive to the shrinkage of the glue between the cross plates and the tube layers. The Δy shrinkage effect decreases from approximately 2×35 μm for the DP 460 glue (used for the BOS-0 chamber only) to about 2×20 μm for DP 490 glue and for Araldit 2014 glue which was used starting from the BOS-5 chamber. The shrinkage effect for the latter glue is taken into account in the nominal y separation between the two triple layers.

The X-ray scan results for the BOS-5 chamber (see Fig. 18) and the BOS-30 chamber show that a wire positioning accuracy of 10 μm (rms) can be achieved in serial production even for the widest MDT chambers which are the most difficult ones to build because of the large gravitational sag of the cross plates which has to be compensated during assembly. Fig. 19 shows the residuals of the y coordinates of the wires with respect to the fitted grid for the 6 layers of the BOS-5 chamber and the gravitational deformations which would have been built into the chamber without cross plate sag compensation (the dashed lines indicate where the adjacent tube layers would have touched each other during glueing).

V. Acknowledgements

We are indebted to the X-ray tomograph group at CERN for the careful and accurate measurement of our chambers.

VI. References

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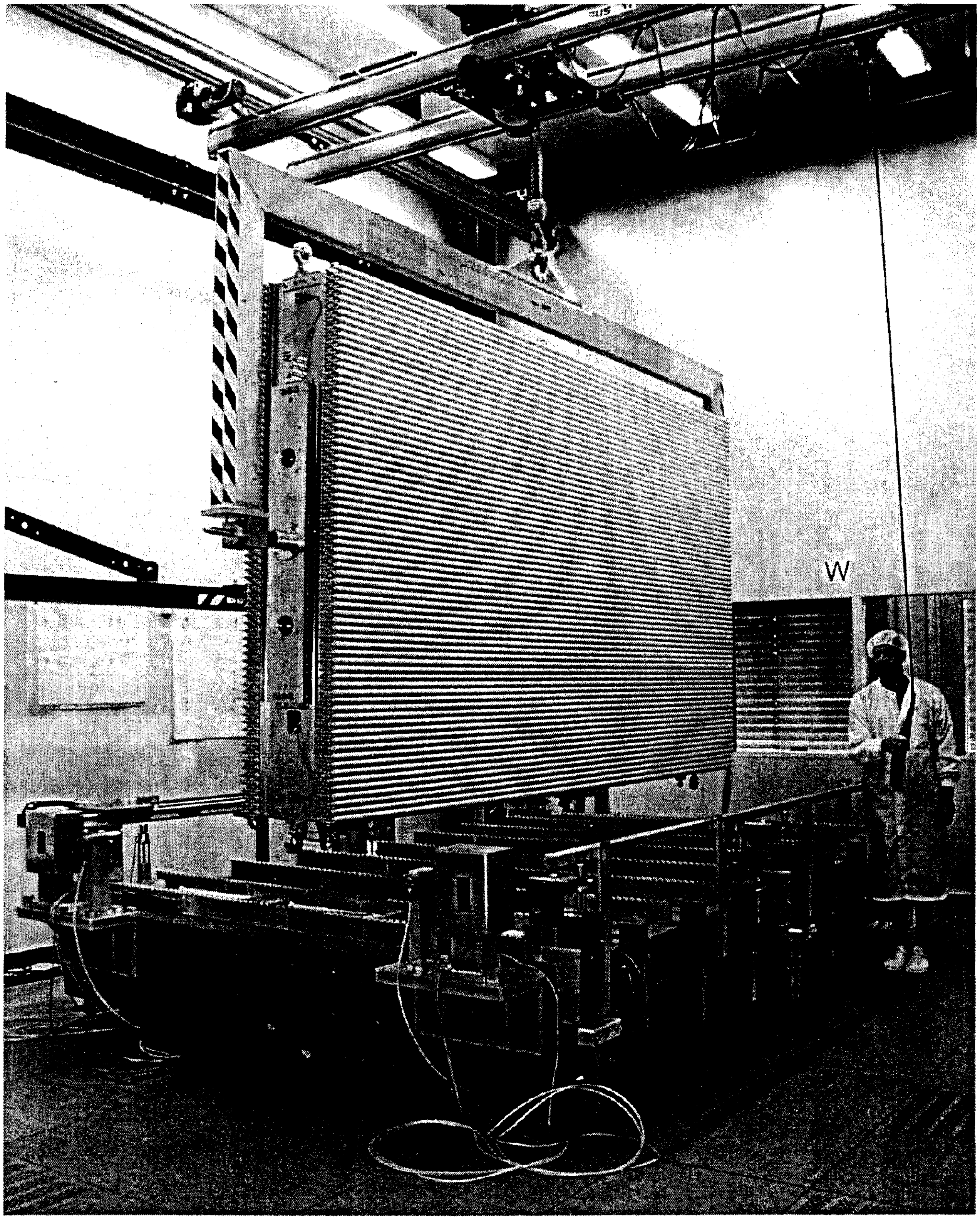


Fig. 1. MDT chamber assembly facility with the first completed BOS chamber for ATLAS in a temperature and humidity controlled clean room at MPI (see text).

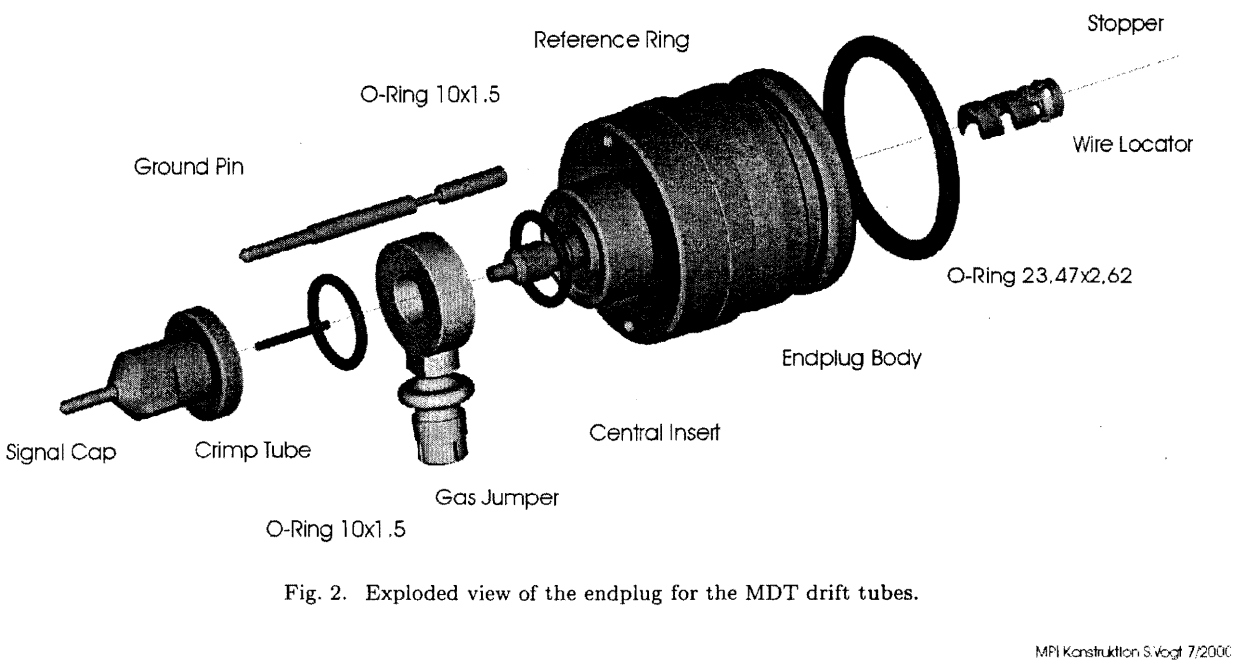


Fig. 2. Exploded view of the endplug for the MDT drift tubes.

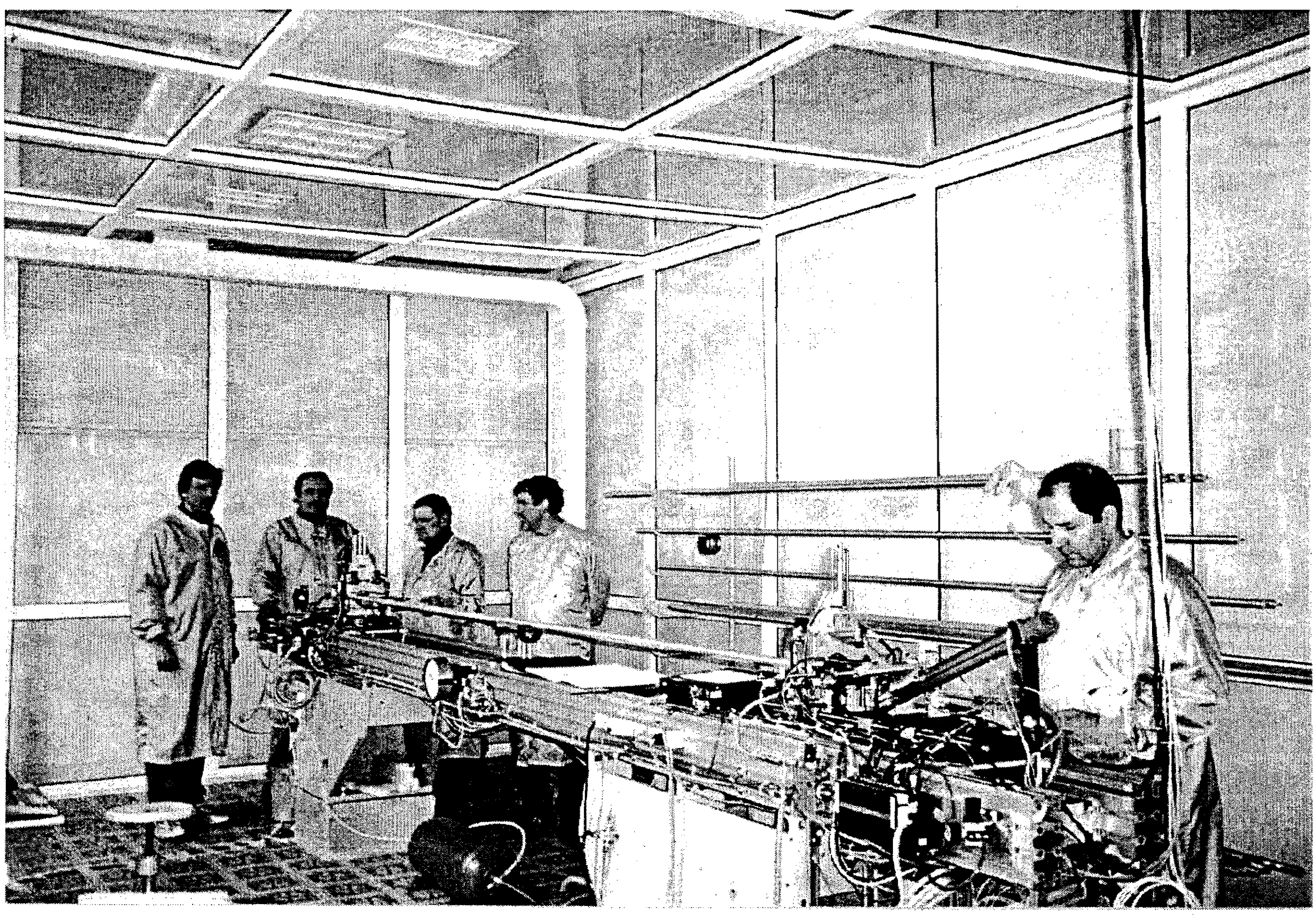


Fig. 3. The joint JINR-MPI drift tube assembly facility in a temperature controlled clean room at JINR (see text).

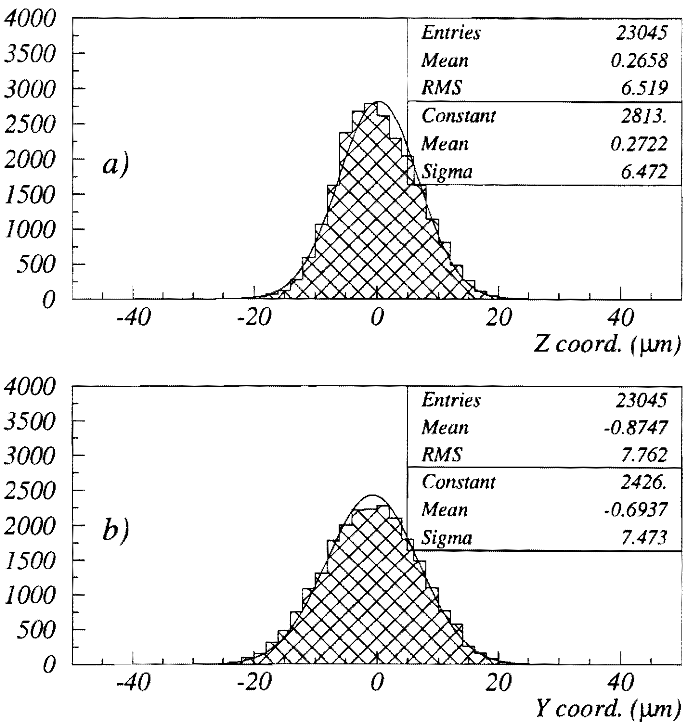


Fig. 4. X-ray measurements of the concentricity of the sense wires with respect to the outer diameter of the endplugs in individual drift tubes for about 65% of the BOS drift tube production. (a) The z coordinate of the wire parallel to the tube layers and perpendicular to the tubes. (b) The y coordinate of the wire perpendicular to the tube layers.

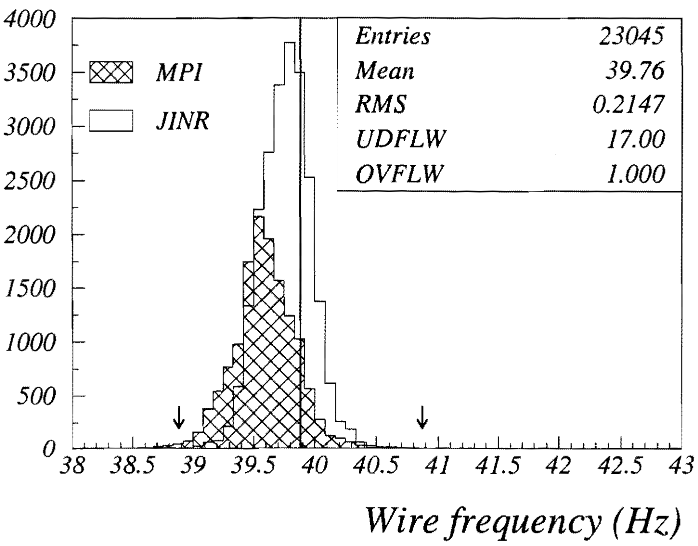


Fig. 5. Measurements of the wire oscillation frequency immediately after the drift tube assembly (JINR) and, approximately two months later, just before assembly of the tubes in a chamber (MPI) after 65% of the BOS drift tube production and 50% of the chamber construction. The nominal value is indicated by the vertical line and the accepted range by arrows.

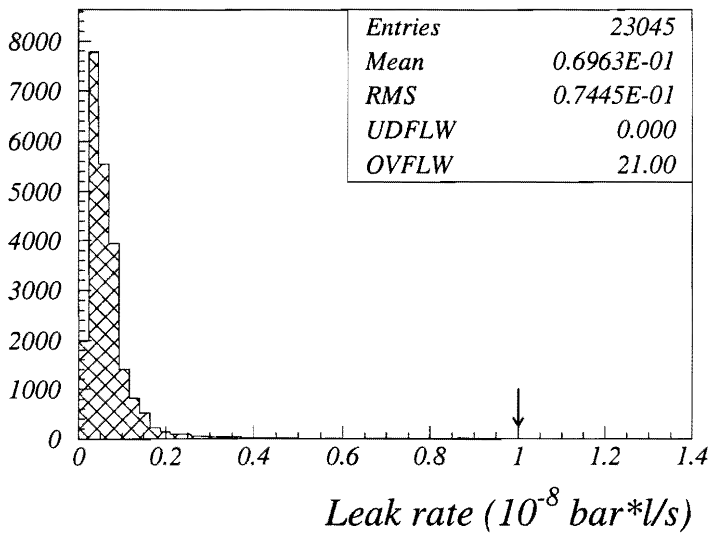


Fig. 6. Measurements of the argon leak rate of individual BOS drift tubes at 2 bar overpressure for 65% of the tube production. The allowed leak rate limit is indicated by an arrow.

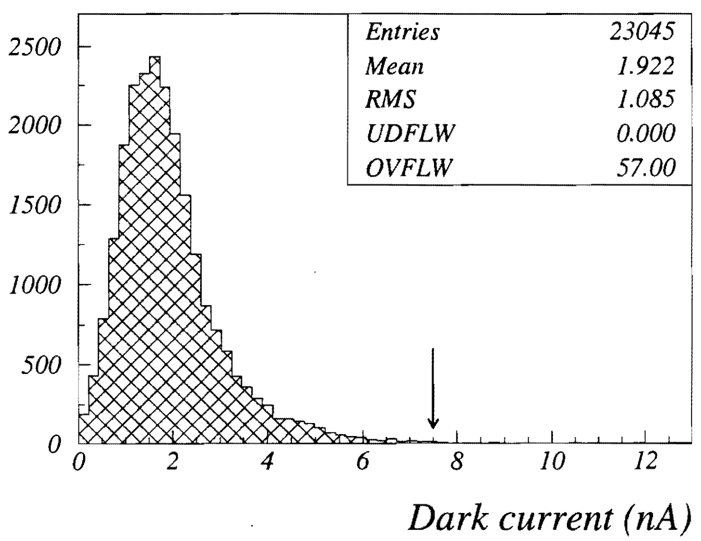


Fig. 7. Measurements of the dark current of individual BOS drift tubes for the nominal gas mixture and a voltage of 3400 V after 65% of the tube production. The allowed dark current limit is indicated by an arrow.

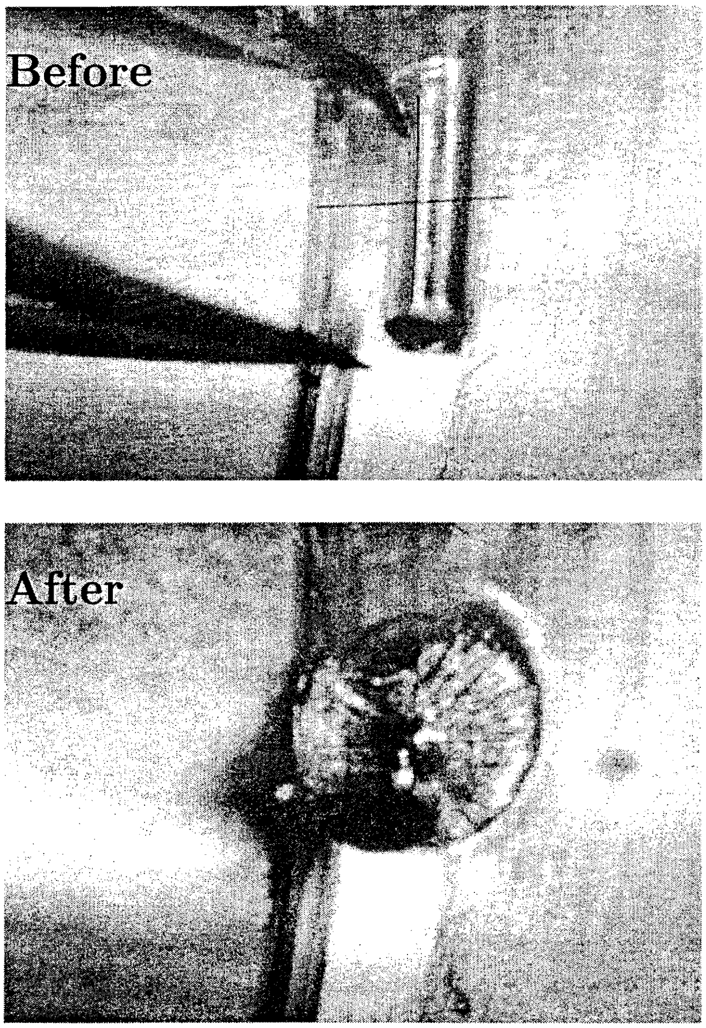


Fig. 8. Laser welding of the ground contact of the MDT drift tubes monitored by a video camera. Before the laser shot, the filler wire is visible in the endplug crimp groove at the tube end (right). After the shot, the filler material is melted providing a solid metallic connection between tube and endplug reference ring (left).

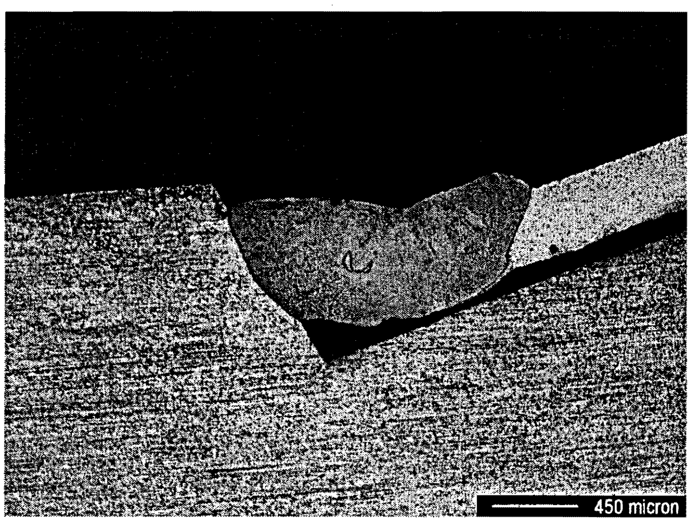


Fig. 9. Microscope picture of a cut through a laser welded metallic joint between the aluminum tube and the reference ring of the endplug using aluminum wire as filler material.

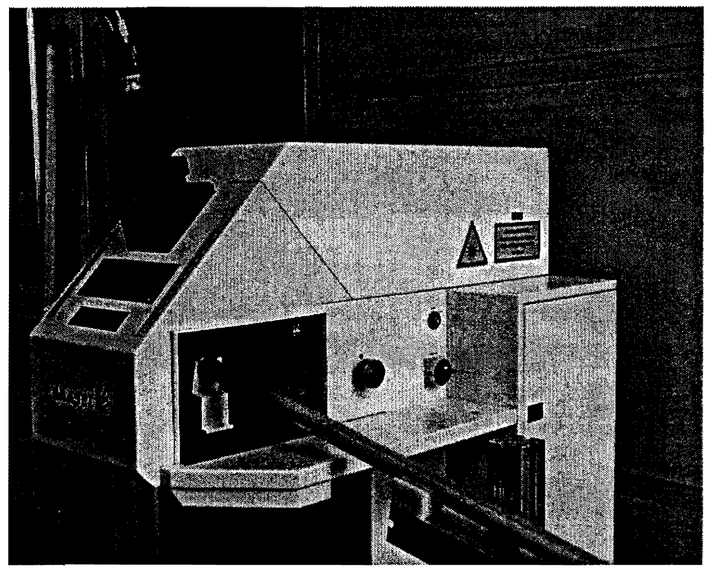


Fig. 10. The laser welding station with the drift tube support.

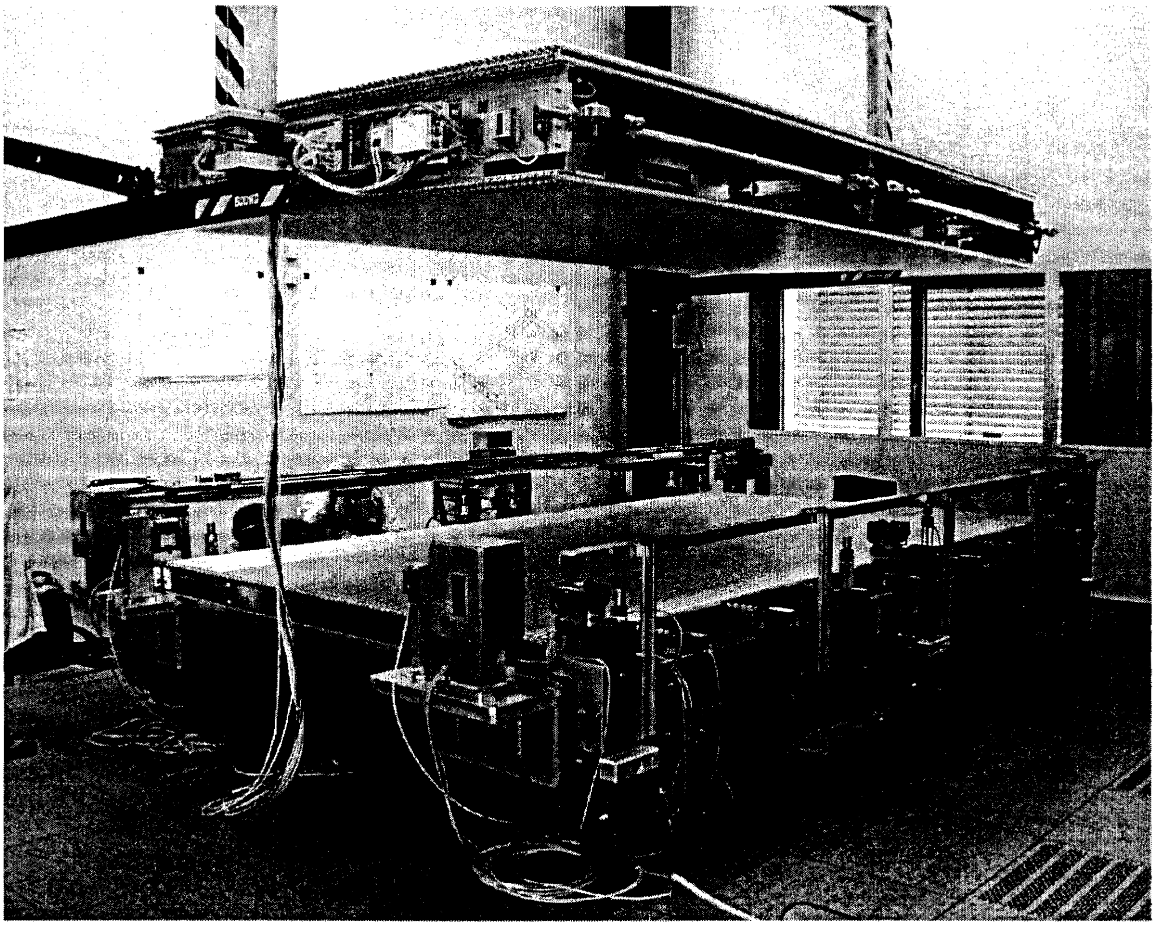


Fig. 11. The assembly of a BOS MDT chamber. The first three tube layers are already glued to the space frame on the crane while the tubes of the fourth layer are waiting for glueing on the precision combs on the granite table.

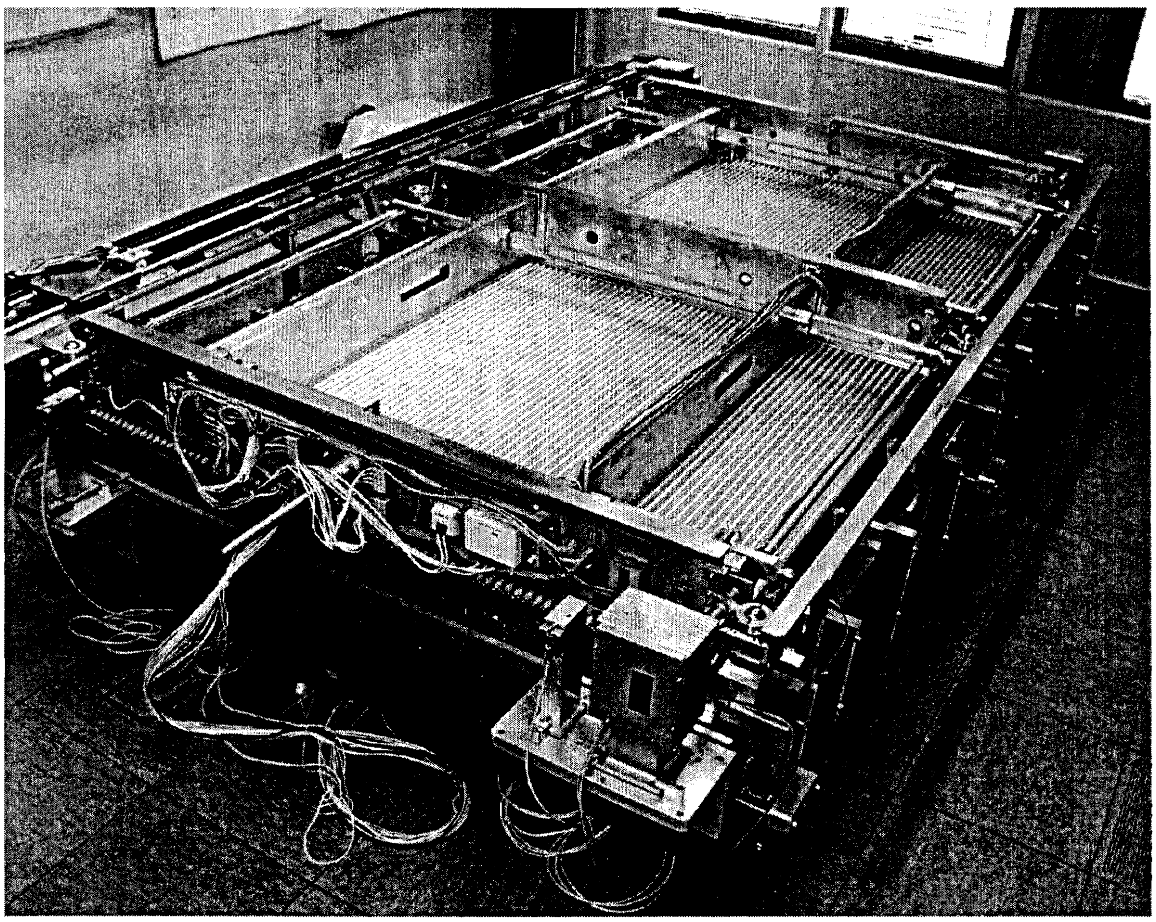


Fig. 12. The aluminum space frame, consisting of three cross plates connected by two long beams, positioned on the assembly table during glueing of the first tube layer of a chamber. The four bars of the cross plate sag compensation system are inserted through holes in the long beams near the cross plates and are supported at each end by computer controlled pneumatic actuators.

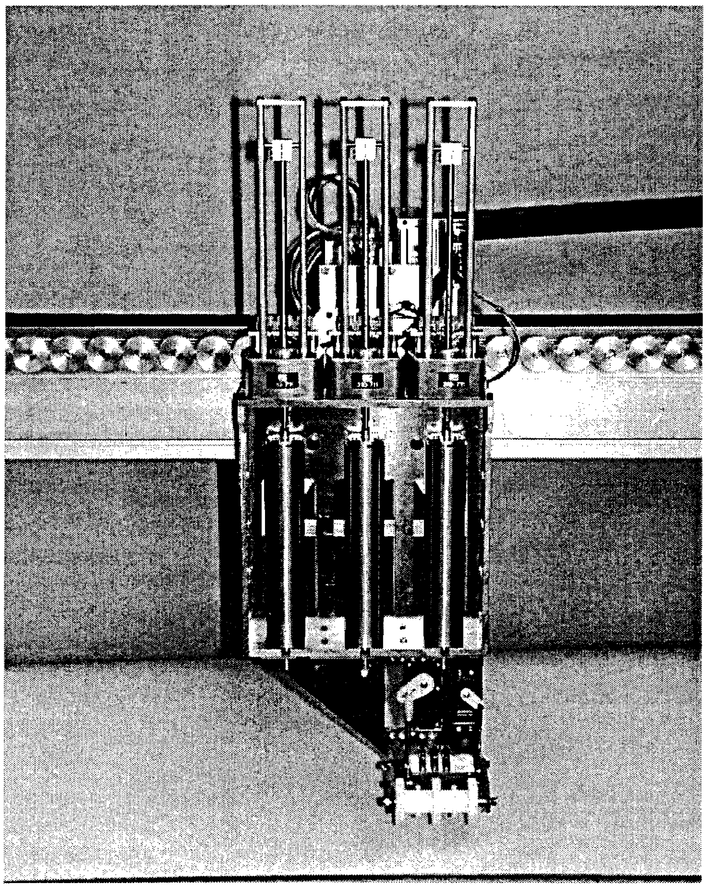


Fig. 13. Glue dispenser unit with three parallel outlets mounted on the transverse stepping bar.

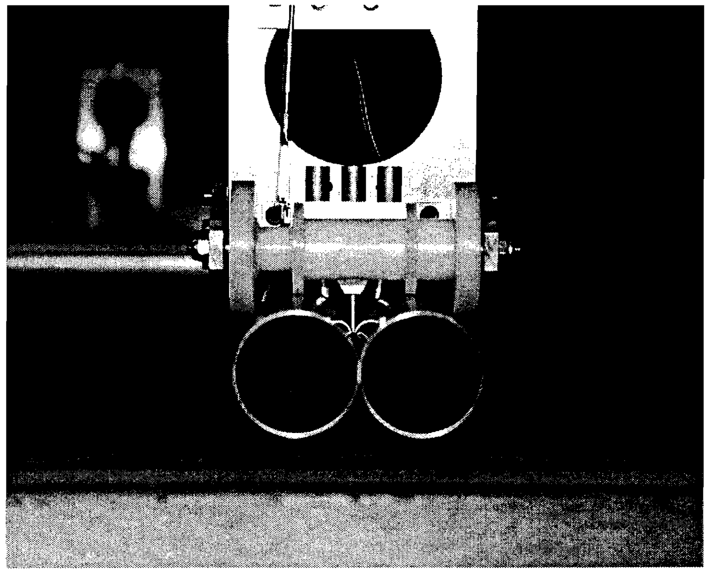


Fig. 15. Alignment of the three glue nozzles of a glue dispenser unit with respect to the drift tubes. The amount of glue distributed is determined by the size and shape of the glue outlet, the distance between tube and nozzle and the moving speed of the glue dispenser.

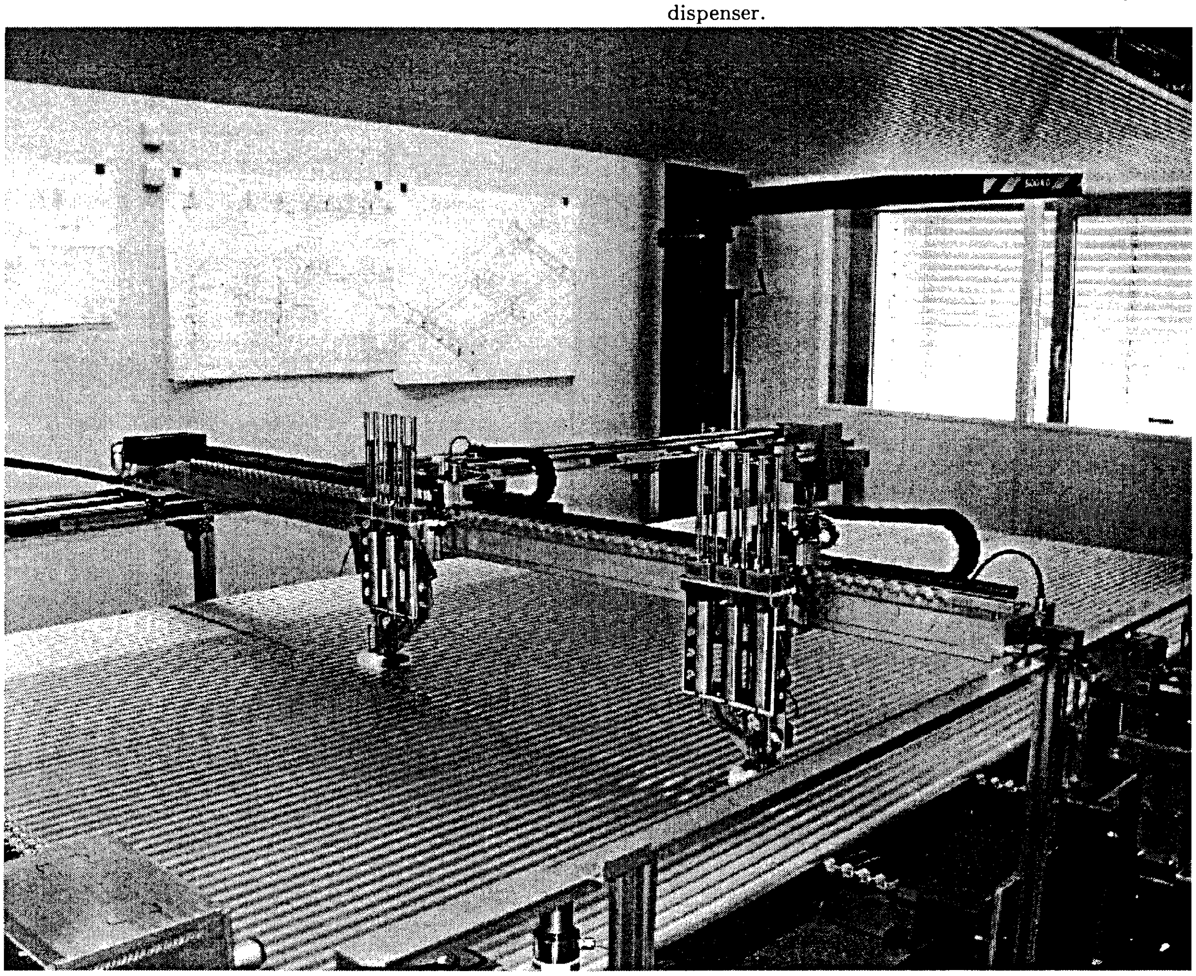


Fig. 14. Distribution of the glue on a tube layer on the assembly table with the automated glue dispenser consisting of two units which are moving parallel and stepping transverse to the tubes.

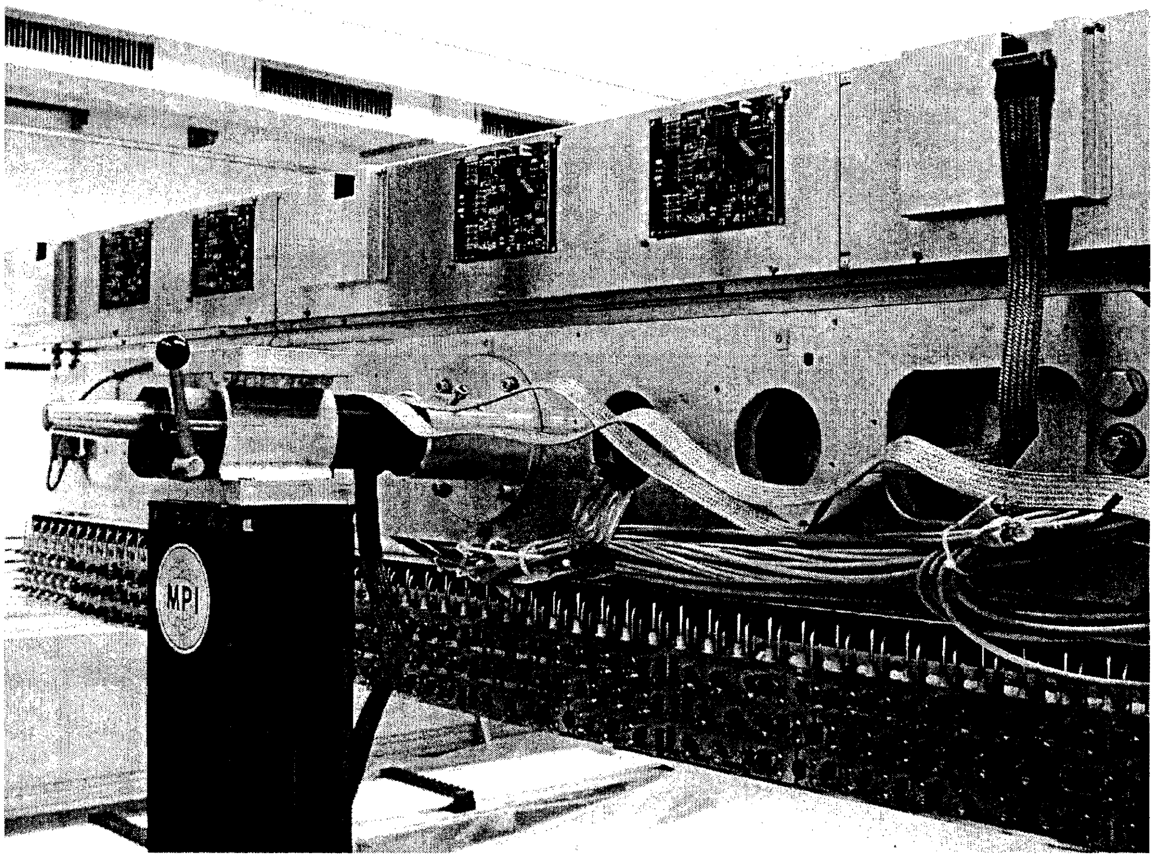


Fig. 16. MDT chamber with gas connections to the individual drift tubes, readout electronics boards and Faraday cage.

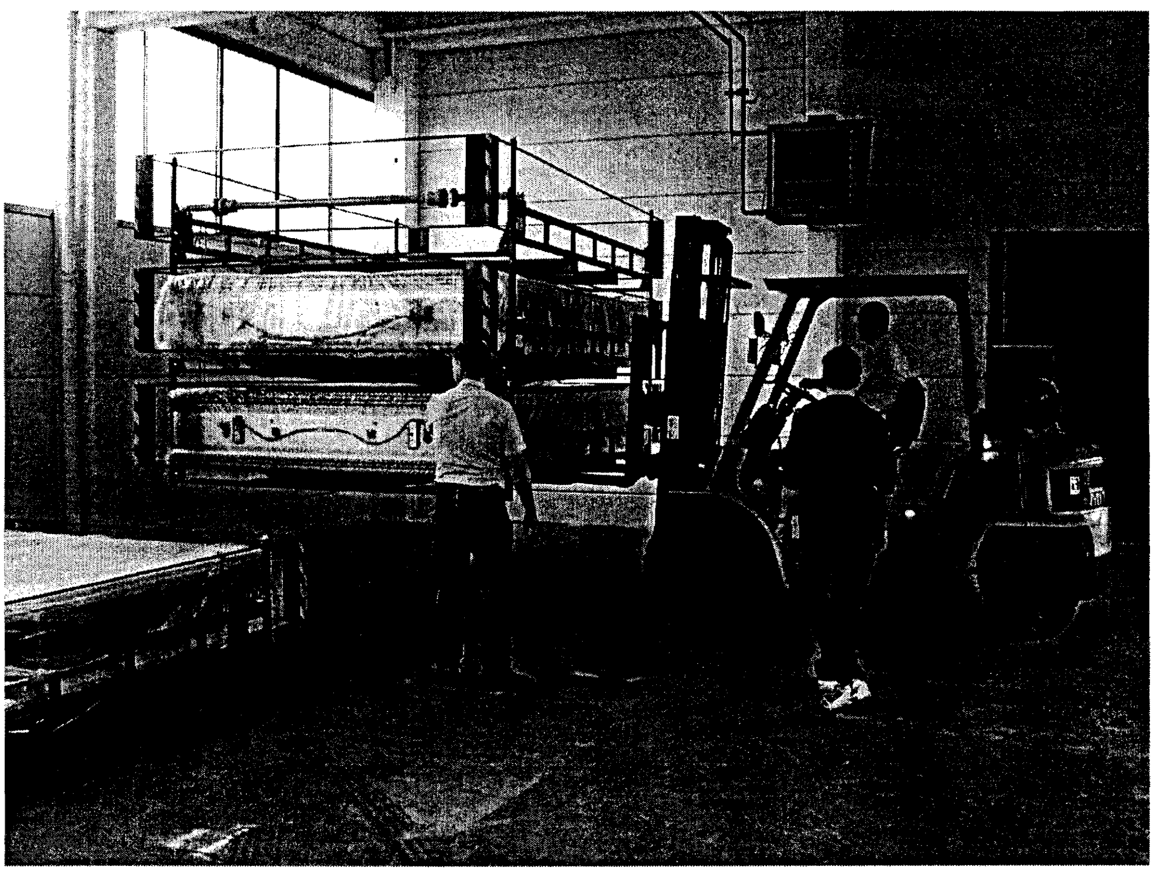
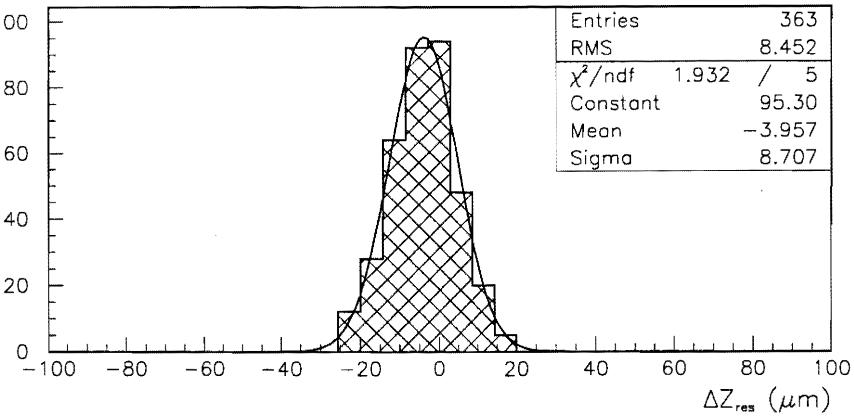


Fig. 17. Storage of the BOS MDT chambers in their transport frames in a dedicated hall.



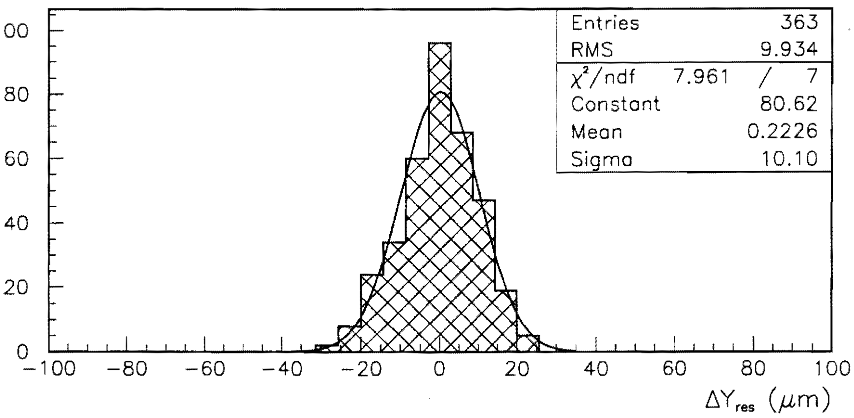


Fig. 18. Distributions of the residuals of the measured wire positions with respect to the fitted grid at the high-voltage end of the BOS-5 chamber. Top: In the z coordinate parallel to the tube layers and perpendicular to the tubes. Bottom: In the y coordinate perpendicular to the tube layers.

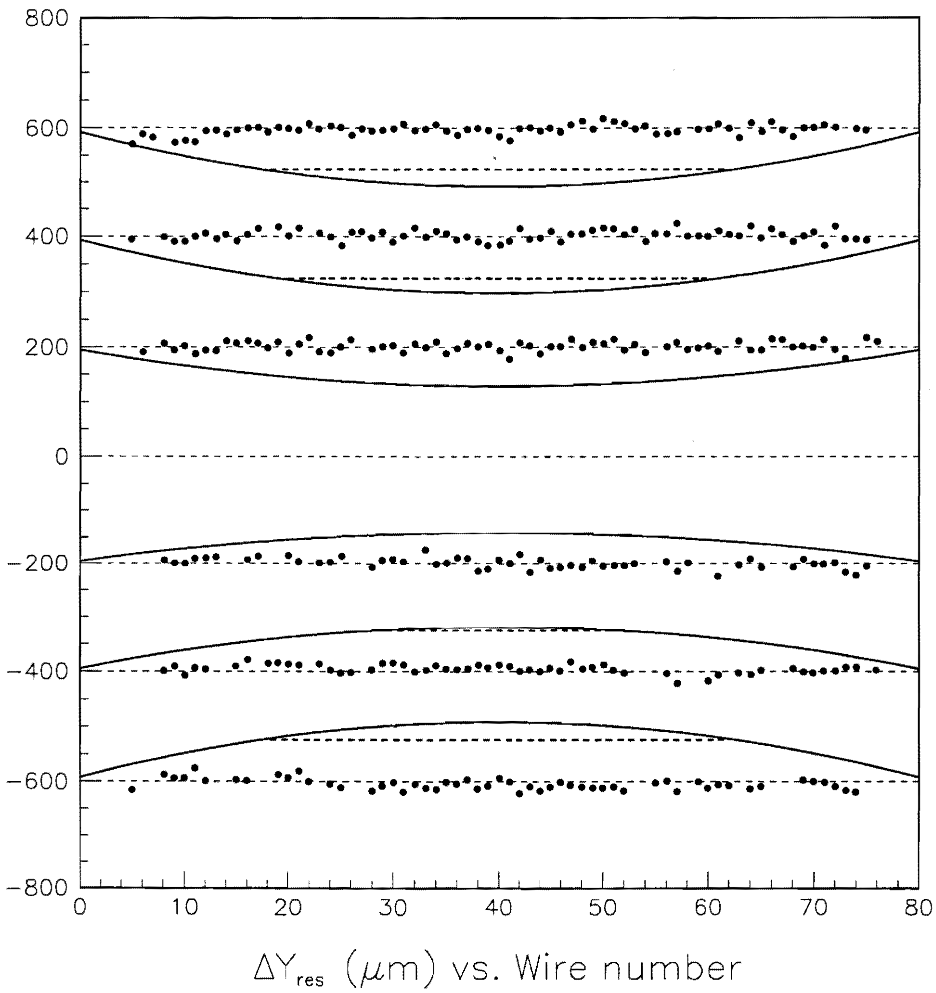


Fig. 19. Residuals $\Delta y_{\rm res}$ of the measured y coordinates of the wires in the 6 tube layers (distances between layers are compressed) with respect to the fitted wire grid at the high-voltage end of the BOS-5 chamber. The gravitational deformations which would have been built into the chamber without compensation are indicated (see text).