Version 1.1.3
28.05.1999

Quality Assurance and Control Reference Document

for ATLAS MDT Chamber Construction

Hubert Kroha
Max-Planck-Institut für Physik, Munich

Guidelines for the implementation of the quality assurance and quality control procedures during the construction of the Monitored Drift Tube (MDT) Chambers for the ATLAS Muon Spectrometer.

(Version prepared for the MDT Production Readiness Review, 16–17 June 1999.)

Contents

1 Introduction–The Quality Assurance Plan

The performance goals of the ATLAS muon spectrometer require unprecedented mechanical precision in the construction of the large number of Monitored Drift Tube chambers (1194) built at many production sites (11) over a period of more than 4 years. At the same time, the reliability the large number of drift tubes (371000) and chambers must be very high.

Measurement of the wire locations in assembled chambers and verification of their accuracy with the X-ray tomograph can only be performed for a fraction of the chambers, approximately 15 %.

The strategy for the distributed, large-scale production of the precision chambers is to guarantee the mechanical precision of drift tubes and assembled chambers by the design of the components and of the assembly method and tooling supplemented by an extensive monitoring program and detailed quality assurance plan for all production sites.

In addition, in a common quality control program of the important parameters for the reliability and performance of individual drift tubes and of assembled chambers are tested. The quality control tests are designed such that they safely detect bad drift tubes and chambers while they can be performed at all production sites and keep up with the production rate. Only small failure rates are acceptable in the production process. The main purpose of the tests is to provide quick feed back for adjustment of the assembly tooling in the case of problems.

Faulty chamber components and drift tubes will be rejected. The failure rate of assembled drift tubes must not exceed the few percent level. Chambers failing the quality control tests have to be repaired (identification of leaks, sputtering of noisy tubes); faulty tubes in a chamber which cannot be recovered will be disconnected. Chambers exceeding the mechanical accuracy requirements can be recovered by measureing the wire locations with the X-ray tomograph. Only in exceptional cases chambers will have tobe rejected.

The quality assurance procedures for MDT chamber construction can be broken down into the following steps:

1. Chamber Components and Materials,
2. Drift Tube Assembly,
3. Drift Tube Test,
4. Chamber Assembly,
5. Chamber Test,
6. Transport and Storage.

The quality assurance procedures for each step are decribed in this document. Quality control of the electronics and data aquisition to be mounted on the chambers during installation in the ATLAS detector will be described in separate documents.

Detailed archiving of the monitoring and test data is necessary in order to monitor and control the production process and to provide complete documentation for the operation of the chambers. The data will be stored in local quality assurance data bases at the production sites and as well as in a central production data base.

The central data base contains the information needed to monitor the production and evaluate the quality of the chambers to be installed and which will be kept for the operation of the muon spectrometer.

In the local data bases all available data from assembly monitoring and quality control should be kept until the completion of all chambers to allow the detection and tracing of problems during chamber production.

In addition, the information about delivery and stock of components and the completion, transport and storage times of drift tubes and chambers is kept in the local and central production data bases at different levels.

The production sites are requested to report all problems occuring during tube and chamber assembly. Production should not continue before the problems are not understood and solved in consultation with the other production sites.

An internal review of each production site will take place before module 0 construction at the site in order to ensure that all procedures and tools follow the specifications.

Before the start of series production, each production site will be qualified based on the data from module 0 construction and test.

This document gives the guidelines and serves as reference for the implementation of the quality assurance procdures and quality control tests at the MDT chamber production sites.

The document and regularly updated versions are available at
ftp://wwwatlas.mppmu.mpg.de/outgoing/qaqc/document.

2 Documentation

Information relevant for quality assurance and control of the MDT chamber construction is contained in the following documents:

1. **Technical Specifications of Chambers and Assembly Tooling:**
    - Technical Design Report for the ATLAS Muon Spectrometer and updates.
    - Drift tube assembly tooling:
      http://atlasinfo.cern.ch/Atlas/GROUPS/MUON/mdt/mdthere/mdt3.html,
      http://lepton.phys.washington.edu/ãtlas/Tube_ Assembly/tube_ assembly.html.
    - MDT chamber design and chamber assembly tooling:
      http://atlasinfo.cern.ch/Atlas/GROUPS/MUON/mdt/mdthere/mdt3.html.
    - On-chamber gas distribution:
      http://hpfrs6.physik.uni-freiburg/˜mohr/scan_ text.html
    - Alignment platforms (barrel and endcap chambers):
      http://atlasinfo.cern.ch/Atlas/GROUPS/MUON/alignment/.
2. **Procurement Documents for Chamber Materials:**
   Tendering documents and contracts with suppliers for the chamber components listed below.
3. **Drift Tube Assembly Manual:**
   Describes all steps of drift tube assembly including QA/QC procedures. The assembly plan will be partially implemented in a Tube Assembly Control Program.

4. **Chamber Assembly Manual:**

   Describes all steps of chamber assembly including QA/QC procedures. The assembly plan will be implemented in a **Chamber Assembly Control Program**.

   The use of the monitoring devices, the handling of the glue and the installation of the gas distribution system are described in more detail in separate manuals.

5. **The Quality Assurance and Quality Control Reference Document (this document):**

   Describes the quality assurance strategy and procedures including guidelines for the quality control tests and instructions for handling, transport and storage of chamber materials, drift tubes and assembled chambers.

These general manuals serve as reference and guidelines for the preparation of the assembly and quality control manuals at each production site and for the implementation of coherent quality assurance procedures.

Other Documents Related to MDT Quality Assurance Procedures:

General

1. ATLAS Collaboration, A. Airapetian et al., *ATLAS Muon Spectrometer Technical Design Report*, CERN/LHCC/97-22, May 1997.
2. F. Linde et al., *MDT Quality Assurance for Module 0 MDT Chambers*, ATLAS Internal Note, ATL-MUON-98-238, May 1998 (replaced by this document).

Specifications and Procurement of Components

1. Technical Specification (Barrel Chambers), *Supply of Aluminum Alloy Extruded Profiles for the ATLAS Muon Spectrometer (Module-Zero Chambers, Barrel)*, for Price Enquiry: DO-98010, October 1998 (NIKHEF).
2. Technical Specification, *Supply of Gold-Plated Tungsten-Rhenium Fine Wire for the ATLAS Muon Spectrometer (Module-Zero Chambers)*, for Price Enquiry: DO-1045107, September 1998 (CERN).
3. Technical Specification, *Supply of Thin-Walled Precision Aluminum Alloy Tubes for the ATLAS Muon Spectrometer (Module-Zero Chambers)*, for Invitation to Tender: IT-2549/EP/ATL, November 1998 (CERN).
4. Technical Specification, *Supply of Endplugs (Endplug Body) for the ATLAS Muon Spectrometer*, for Invitation to Tender: IT-2575/EP/ATL, May 1999 (CERN).
5. Hedgehog boards and mezzanine cards,

   http://ohm.bu.edu/bmc/summer_ pcbs/hedgehog_ spec.html

   (Boston University).

Drift Tube Assembly

1. R. Dumps et al., *A Prototype Wiring Automate for the Twister/Tango Based Endplug of the ATLAS Muon Drift Tubes*, ATLAS Internal Note, ATL-MUON-98-267, January 1999 (CERN).

2. University of Michigan ATLAS group, *Michigan Wiring Table, MDT Tube Assembly Electronics Control and Computer Program*,

   http://ganesh.physics.lsa.umich.edu/~atlas

   (Michigan).

3. H. Kroha and A. Manz, *Laser Welding for the Ground Contact of MDT Tubes*, May 1999,

   draft **Laser Welding Manual**,

   ftp://wwwatlas.mppmu.mpg.de/outgoing/qaqc/laserwelding/laserwelding_ doc.ps (.pdf), laserwelding_ doc.fig2.ps, laserwelding_ doc_ fig3.ps, laserwelding_ doc_ fig4.ps

   (MPI Munich).

Chamber Assembly

1. H. Kroha and S. Schael, *Optical Monitoring System for the MDT Assembly Stations*, ATLAS Internal Note, MUON-NO-156, April 1997 (MPI Munich).

2. G. Kaptsis et al., *Mechanical Design of the BIS Module Zero MDT Chamber*, ATLAS Internal Note, ATL-MUON-98-242, June 1998 (Thessaloniki).

3. G. Ciapetti et al., *A QA/QC System to Monitor the Planarity of the Tube Layers in MDT Chambers Construction*, ATLAS Internal Note, ATL-MUON-98-255, September 1998 (Rome I).

4. V. Bartheld et al., *Construction of the Full-Scale Prototype of a BOS MDT Chamber*, ATLAS Internal Note, ATL-MUON-98-256, October 1998,

   http://wwwatlas.mppmu.mpg.de/mdt.html

   (MPI Munich).

5. V. Bartheld et al., *The Construction and Performance of the BOS 98 MDT Prototype Chamber*, ATLAS Internal Note, May 1999

   (MPI Munich).

6. D. Kalkbrenner, H. Kroha and A. Manz, *Glue Dispenser for MDT Assembly and Glueing Instructions*, January 1999,

   draft **Glueing Manual**,

   ftp://wwwatlas.mppmu.mpg.de/outgoing/qaqc/glueing/glue_ manual.ps

   (MPI Munich).

7. H. Kroha, *BOS Chamber Assembly Quality Assurance Plan*, February 1999,

   ftp://wwwatlas.mppmu.mpg.de/outgoing/qaqc/bos_ assembly_ plan.ps (.pdf)

   (MPI Munich).

8. H. Kroha, *BOS Chamber Assembly and Test Plan*, February 1999,

   ftp://wwwatlas.mppmu.mpg.de/outgoing/qaqc/bos_ assembly_ test.ps (.pdf)

   (MPI Munich).

9. H. Kroha, *BOS Chamber Production and QA/QC Data Base Structure*, February 1999,

   ftp://wwwatlas.mppmu.mpg.de/outgoing/qaqc/bos_ qaqc_ db.ps (.pdf)

   (MPI Munich).

10. Task Owners Chamber Assembly, *Chamber Assembly Manual*, April 1999,
    http://www.lnf.infn.it/~curatolo/BMLmanual.draft/
11. University of Freiburg, On-Chamber Gas System for the Barrel MDT Chambers, March 1999, and **Assembly Description for the MDT On-Chamber Gas Distribution**, May 1999,
    draft **Gas Distribution Installation and QA Manual**,
    at http://hpfrs6.physik.uni-freiburg/~mohr/scan_text.html
    (Freiburg).
12. H. Kroha and A. Ostapchuk, *Optical Monitoring of MDT Chamber Assembly*, April 1999,
    draft **Monitoring Manual**,
    ftp://wwwatlas.mppmu.mpg.de/outgoing/qaqc/monitoring/monitoring.ps (.pdf)
    (MPI Munich).

Drift Tube Test

1. V.T. Braic et al., *Leak Detection System for Mass-Production of Drift Tube Detectors*, ATLAS Internal Note, ATL-MUON-98-225, March 1998,
   http://nuweb.jinr.ru/~dcbp/atlas/QAQC/gasleak/foto.htm
   (Dubna).
2. M. Cambiaghi et al., *An Electromagnetic Micrometer (EMMI) to Measure Wire Location Inside an ATLAS MDT Drift Tube*, ATLAS Internal Note, ATL-MUON-98-259, November 1998 (Pavia, Rome).
3. A. Balla et al., *MDT Wire Tension Measurement Using an Electrostatic Method*, ATLAS Internal Note, ATL-MUON-98-264, November 1998 (Frascati).
4. Pavia and Roma I Atlas Groups, *The Pavia–Roma I MDT QA Facility*,
   ftp://cobra1.pv.infn.it/pub/MDT/mdt_qa.ps.gz
   (Pavia, Rome I).
5. A. Albanese et al., *Quality Assurance and Quality Control for ATLAS Drift Tubes at the Cosenza Production Site*, description of setup and quality control test plan,
   ftp://fermi.cs.infn.it/atlas_qaqc
   (Cosenza).
6. University of Michigan ATLAS group, *Michigan Leak Detector*,
   http://ganesh.physics.lsa.umich.edu/~atlas
   (Michigan).

Chamber Test

1. 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 (CERN).
2. CERN X-Ray Tomograph, http://wwwcn.cern.ch/~xtomo.

3. C. Bacci et al., *Design of a Cosmics Test Site for the Quality Assurance and Quality Control (QAQC) of Full MDT Chambers*, ATLAS Internal Note, ATL-MUON-98-241, June 1998 (Rome III).

4. N. Hessey, A. Staude and T. Trefzger, *Cosmic Ray Test Stand at the LMU Munich*, ATLAS Internal Note, ATL-MUON-98-266, December 1998 (LMU Munich).

5. H. Kroha, *BOS Chamber Assembly and Test Plan*, February 1999,
   ftp://wwwatlas.mppmu.mpg.de/outgoing/qaqc/bos_assembly_test.ps (.pdf)
   (MPI Munich).

3 Chamber Components

The main chamber components and materials to be controlled are:

1. Precision aluminum tubes.
2. Gold-plated W-Rh wire.
3. Precision endplugs and endplug components.
4. Spacer components.
5. Components of the optical alignment system.
6. On-chamber gas distribution system.
7. Faraday cages and patch panels.
8. Glue (several types).
9. Hedgehog boards.
10. Mezzanine cards with readout electronics.
11. Temperature and magnetic field sensors.
12. Protective covers.

Quality and tolerances of the chamber components delivered to the chamber production sites are controlled in four steps:

1. Quality assurance by the supplier
2. Central monitoring of material production including sample tests at an responsible institute.
3. Acceptance tests and visual inspection at the chamber production sites.
4. Specification for packing, transport, storage and handling of the components.

3.1 Aluminum Tubes

The thin-wall aluminum tubes for the drift tubes of the MDT chambers follow tight mechanical tolerances with respect to the outer and inner diameter and the straightness in order to be suitable for the precision assembly of the chambers.

The tubes are cleaned on the inside and outside by the manufacturer according to a cleaning procedure defined in detail which has been approved by the collaboration after ageing tests. The cleaning procedure must not be changed without the agreement of the collaboration and after new ageing test have been performed with the new cleaning procedure.

The mechanical tolerances and the cleanliness of the tubes must be conserved during all further transport, storage and handling of the bare tubes and of the assembled drift tubes (see: Drift Tube Assembly and Storage).

The precision aluminum tubes are procured centrally via CERN.

3.1.1 Quality Control by Supplier

The following quality control tests of the bare tubes are required from the supplier with certification:

1. Chemical and mechanical analysis and ultrasonic test of the tube raw materials.
2. Geometrical tolerances of extruded tubes.
3. Geometrical tolerances of drawn and straightened tubes.
4. Geometrical tolerances, including straightness, of at least 10% of finished tubes of each batch.
5. Visual inspection of inside and outside of at least 10% of finished tubes of each batch, including proper deburring of tube ends.

Each finished tube is identified by a bar code (industrial format 39B) which contains the production run number, a sequential tube identifcation number, tube length and a date and appears also in alphanumeric form. The bar code is written in locations along the tube which will not be attached to the spacer in case additional cleaning is required for glueing.

Quality control documents and data with reference to the tube bar code are provided to the collaboration and are kept in the **Production Data Base** for monitoring of the production.

Detection of small holes on the tube walls by the supplier, e.g. with the eddy current method, is too expensive. Therefore, the walls of all drift tubes have to be tested for gas tightness at the chamber production sites.

3.1.2 Production Monitoring

Production monitoring is done centrally at CERN including the following sample tests per batch of tubes delivered to the chamber production sites:

1. Visual inspection, inside and outside (obvious defects or holes, cleaning, deburring, straightness).
2. Geometrical tolerances with 3D metrology.
3. Chemical and mechanical analysis of the finished tube material.
4. Metallurgical analysis of the finished tubes.
5. Chemical analysis of inner tube surface (monitoring of cleaning procedure).
6. Quality control of cleaning procedure over time with the ageing test stand.

In case of failed tests, the supplier is notified and the affected batches are returned.

During tube assembly at the production sites, each tube is visually inspected at the inside and outside for obvious defects, proper deburring and cleanliness.

3.1.3 Tube Transport and Storage

The aluminum tubes are cleaned on the inside and outside by the manufacturer. Afterwards, the tubes are kept under clean conditions and are not cleaned anymore at the chamber production sites, especially not on the inside.

The tubes are transported and stored under the following conditions:

1. The tubes are always transported in stable wooden boxes like the ones used for delivery by the manufacturer.
2. The individual tubes are kept separated from each other and held such that that they cannot move inside the transport box.
3. The tube ends are closed and protected with soft plastic caps.
4. Inside the transport box and in storage, the tubes are enclosed in air-tight plastic bags containing dehumidifier bags.

   During longer storage periods, the enclosing plastic bags should be filled with inert gas to prevent corrosion.

3.1.4 Quality Control at Production Sites

Quality control tests of the bare tubes at the chamber production sites are summarized in Table 1.

3.2 Wire

The gold-plated tungsten-rhenium sense wire for the drift tubes is procured centrally via CERN.

3.2.1 Quality Control by Supplier

The following quality control tests of the wire are required from the supplier with certification:

1. Measurement of tensile strength at beginning and end of each spool.
2. Test of precentage of gold plating at beginning and end of each spool.
3. Visual and microscopic inspection of gold plating quality for at least first meters of each spool.

Each wire spool is certified and labelled with date, wire length and production run number.

3.2.2 Production Monitoring

Production monitoring is done centrally at CERN including the following sample tests per production run:

1. Measurement of wire diameter.
2. Microscopic inspection of gold plating quality.
3. Inspection of cleanliness.
4. Measurement of tensile strength.
5. Measurement of electrical conductivity.

In case of failed tests, the supplier is notified and the affected batches are returned.

3.2.3 Quality Control at Production Sites

Quality control at the chamber production sites is summarized in Table 1.

3.3 Endplugs

The endplugs for the drift tubes consist of the following components:

1. Injection moulded insulator made of Noryl GFN3 which contains 30% glass fiber and is machined to be concentric and coaxial with the aluminum ring reference surface.
2. Precisely machined metal inserts in the plastic body:
   (a) Aluminum ground ring with precise reference surface for drift tube tube positioning on assembly combs and precise front face for accurate endplug insertion.
   (b) Central brass insert holding the wire locator in a precisely concentric and coaxial hole with respect to the reference surface.
3. Precise wire locator, machined separately and held in the concentric hole of the brass insert with an injection moulded Noryl clip.
4. Copper wire crimp tube inserted in central brass piece.
5. Brass sealing cap with signal pin to be screwed onto the brass insert.
6. Injection moulded Noryl gas connector sealed with two O-rings between the front face of the plastic body and the signal cap.
7. Brass ground pin in contact with the aluminum ring through a threaded hole and a nut with lock washer.
8. O-ring for gas seal of the plastic endplug body in the aluminum tube.

The endplugs and their components are not individually labelled for cost reasons. Endplugs of different production batches are kept in separate boxes at each production site and are not mixed during tube assembly to help tracing of problems.

The endplug components are procured centrally via CERN. At least parts of the endplugs have to be assembled at the chamber production sites.

3.3.1 Quality Control by Supplier

The following quality control tests of the endplugs and their components are required from the suppliers with certification for a fraction of at least 2% of the endplugs:

1. Visual inspection of the injection moulded piece: smooth surfaces without air bubbles or cracks, especially in the O-ring grooves.
2. Inspection of the bulk of the injection moulded piece by cutting longitudinally through the center: no enclosed bubbles larger than 0.2 mm in diameter, no cracks.
3. Metal inserts must not detach under specified force.
4. Visual inspection of machined endplug components:

   Proper cleaning and deburring, smooth surfaces, no sharp edges, no metal chips, no scratches, no air bubbles or cracks in plastic piece.
5. Test of fitting of components.
6. Verification of all mechanical tolerances of endplug and wire locator with 3D metrology.

3.3.2 Production Monitoring

The production is monitored by responsible institutes which centrally perform the following sample tests per production batch:

1. Visual inspection of all parts: Proper cleaning and deburring; smooth surfaces, no sharp edges, no metal chips, no scratches, no air bubbles or cracks in the plastic parts.
2. Test of fitting of all components.
3. Verification of all mechanical tolerances of endplug and wire locator with 3D metrology.
4. Inspection of the bulk of the injection moulded piece by cutting the endplug longituinally through the center: no enclosed air bubbles, no cracks.
5. High voltage test of a fraction of endplugs per production batch assembled in drift tubes filled with dry nitrogen: leakage currents below 2 nA up to a voltage of 5 kV.
6. Measurement of the shape and diameter of the wire locating hole and of the concentricity with respect to the endplug reference surface with a CCD camera.

In case of failed tests, the supplier is notified and the affected batches are returned.

3.3.3 Quality Control at the Production Sites

Quality control tests at the chamber production sites are summarized in Table 1.

During assembly of the endplugs at the production sites and during preparation for tube assembly, all endplug components, including wire locator and crimp tube, are visually inspected for obvious defects (no sharp edges, proper deburring, no metal chips, no scratches, no air bubbles or cracks in the plastic parts).

All O-rings are inspected for obvious defects during assembly on the endplug. The O-rings must not be exposed to light during storage or assembled on the endplugs to prevent ageing.

The endplug components are cleaned in an ultrasonic cleaning bath using only pure ethanol. Other cleaning fluids are not allowed.

3.4 Spacer Components

The extruded aluminum spacer profiles are procured centrally via a responsible institute which monitors the production. Machining of the profiles to reach the final mechanical tolerances is the responsibility of each production site.

The mechanical tolerances of the extruded and cut profiles are verified by the supplier and the responsible institute for each batch delivered.

The mechanical tolerances of the machined spacer components are verified for each chamber at the chamber production sites. The glue gaps between cross plates and tubes layers are verified during spacer assembly (see the **Chamber Assembly Manual**). The functioning of the sag compensation system is tested after assembly on the spacer.

3.5 Optical Alignment System Components

The components of the ATLAS optical alignment monitoring systems installed on the chambers during assembly are:

1. Components of RASNIK monitors (LED with mask, custom-fabricated lens and CCD with infrared filter with housings) for the in-plane alignment system.
2. Mounting platforms for components of the projective alignment monitors.
3. Mounting platforms for the axial/praxial alignment monitors.

The components are procured centrally from industry by responsible institutes which monitor the production and perform sample tests of the optical quality of the lenses (focal length within ±3 mm of the nominal value and mismatch between optical and geometrical center < 1 mm) and of the electrical functionality of light sources and CCDs.

The focal length of the RASNIK lens is specific for each monitor and engraved on the lens holder. It is specified to be within ±3 mm of the nominal value (1/4 of the distance between mask and CCD). This tolerance corresponds to a maximum forseen longitudinal range of adjustment of ±12 mm of the light source with mask with respect to the lens. This can be verified on a special RASNIK test stand at the chamber production sites prior to the assembly of the spacer. Otherwise the lens is rejected.

As part of the chamber assembly procedure, each in-plane alignment monitor is adjusted and fully tested on the spacer (sharp and analysable image of the center of the mask with sufficient brightness) before permanent fixation with glue (see the **Assembly Control Plan** in the **Appendix**).

The RASNIK components on the spacer must not move after the first zero-reading; otherwise the in-plane alignment system has to be zeroed again on a granite table. In order to detect and trace potential errors of the in-plane alignment system, it is recommended to cover the fixation points of the in-plane alignment components on the spacer with special paint used in air craft industry which indicates by colour change if a component has moved.

Correct relative orientation of the RASNIK mask and CCD is important for the analysis software and ensured with labelling by the supplier.

The use of the RASNIK systems is described in **RASNIK Manuals** by the responsible institutes.

3.6 On-Chamber Gas Distribution System

The components of the on-chamber gas system are centrally procured by a responsible institute which monitors the production and the quality control by the suppliers.

The gas manifolds are preassembled at the chamber production sites and tested for gas tightness and flow rate per tube (see Table 3). After mounting on the chamber, the gas system is leak tested together with the whole chamber (see Tables 4 and 5).

Assembly and test of the on-chamber gas system is described in the **On-Chamber Gas System Manual** by the responsible institute.

3.7 Faraday Cages and Patch Panels

The fabrication and quality control of the Faraday cages and patch panels for readout electronics and optical, temperature and B-field monitors are the responsibility of each institute.

3.8 Glue

All glue types used for chamber assembly are epoxy resin based two-component glues. They have been selected because they provide sufficient strength in contact with aluminum and handling and curing time are suitable for chamber series production. In dedicated tests and during chamber prototype construction, the shrinkage of the selected glues was found to be small enough to prevent significant chamber deformations. Epoxy resin based glues are known to be radiation tolerant far beyond the radiation levels in the ATLAS muon spectrometer.

Only glue from one supplier, Ciba Geigy, will be used at all production sites. The selected glue types are all widely used standard products of the supplier with well known properties and reliability and have been exclusively used for the construction of all prototype MDT chambers.

The quality of the glue is guaranteed by the supplier. Glue storage and handling follow strictly the recommendations by the glue supplier. Storage time and conditions of the glue is monitored at the chamber production sites.

Details of the glue types and the glueing procedures are given in the chapter **Chamber Assembly**.

3.9 Hedgehog Boards

The hedgehog boards are delivered to the chamber production sites fully tested and certified. They are either delivered clean in sealed packages or they have to be cleaned in an ultrasonic cleaning bath at the chamber production site before installation. After unpacking or cleaning, the boards are handled only with gloves.

All boards are visually inspected for obvious defects upon delivery. Correct positioning of the electrical contact holes is verified on a template in order to avoid forces on the endplugs when the boards are installed.

Installation of the boards and high voltage test on the chamber takes place in the chamber test stands at the production sites. The boards stay on the chamber.

3.10 Mezzanine Cards

The mezzanine cards with the readout electronics are delivered to the chamber production sites fully tested and certified. The boards are visually inspected for obvious defects upon delivery. Mounting of the cards on the chamber and high voltage and functionality test will take place either in the local chamber test stand or in the central storage area at CERN as soon as the cards have been delivered.

3.11 Temperature and B-Field Sensors

The temperature and B-field sensors, including cables, are procured and fabricated centrally by responsible institutes and are sample tested by them. The function of each sensor is tested at the chamber production site before the installation on the chamber.

3.12 Protective Covers

The material for the protective covers for installation in the detector will be procured centrally. Cutting to size and installation on the chambers is done at the chamber production sites.

4 Drift Tube Fabrication

4.1 Drift Tube Assembly

Operation of the large number of drift tubes in the ATLAS muon spectrometer requires very high reliability with respect to wire tension, gas thightness and high voltage stability. At the same time, the sense wires have to be centered in the precision aluminum tubes with high accurcay: with ±10 μm rms relative to the endplug reference surfaces in the y and z coordinates of the azimutally oriented tubes and with a tolerance of ±100 μm with respect to the inner tube wall envelope. The wire tension has to stay inside tight tolerances in order to predict the wire sag with high accuracy.

During series production, typically 50–100 drift tubes per day have to be assembled and tested at each production site. Because of the large number of tubes, rejection of only few percent of the assembled drift tubes can be afforded after the quality control tests.

The drift tube assembly procedures are designed to guarantee the high precision and reliability of the drift tubes:

1. The drift tubes are assembled in a temperature controlled clean room of class 50000.
2. The room temperature is controlled to be 20 ± 1°C. This allows to set the tube length and the wire tension of the assembled tubes with sufficient accuracy.
3. Automatic or semi-automatic wiring stations are used.

   Manual handling of the wire is minimized.
4. Colinearity of the endplug and tube axes, the relative azimutal orientation of the two endplugs of a drift tube and the drift tube length (defined as the distance between the aluminum front faces of the endplugs) at a given temperature are mechanically determined by the assembly tooling.
5. Critical parameters of the drift tube assembly process are controlled by computer.
6. The wire is over-tensioned for a defined time interval in order to minimize wire creeping.

The **Drift Tube Assembly Manual** contains detailed instructions for handling and assembly of the drift tubes. The main drift tube assembly steps are implemented in a **Drift Tube Assembly Control Program**.

In particular, the following procedures are applied to maintain the quality of the drift tubes:

1. The tubes are stored in the temperature controlled wiring room before assembly to adapt to the temperature.
2. Each individual tube is identified by its bar code which is read into the data base directly with a bar code scanner just before wiring.
3. The tube wiring room is cleaned regularly.

4. During work in the tube wiring room, hair and shoe protection, coats and gloves certified for clean rooms are used. Before entering the clean room, clothes are changed in a separate chamber.

5. Before assembly, the endplugs are cleaned in an ultrasonic cleaning bath. Only pure ethanol is allowed for cleaning of Noryl plugs.

6. The bare tubes, the endplugs, the wire and the assembled tubes are visually inspected before, during and after the wiring procedure (see Tables 1–3). They are only handled with gloves certified for clean rooms.

7. The sense wire is inserted into the tubes directly from the spool without additional cleaning and risk of contamination.

8. It is recommended to orient the tubes such during tube wiring that the bar codes are accessible when the tubes are inserted into the chamber assembly jig.

4.2 Drift Tube Ground Contact

A reliable ground contact between aluminum tube and the aluminum ground ring of the endplug which is long-term stable is ensured by laser spot welding at the tube ends with at least three spots per endplug. Detailed instructions for the laser welding process are given in the **Laser Welding Manual for Drift Tube Ground Contact**.

The quality of the laser welds is verified by the following procedures:

1. Visual inspection for each tube during (all welds) and after (random sample of tubes) laser welding: welds at correct place, no deformations on the endplug reference surface, visible quality in agreement with reference welds.

   In case of problems, the laser and setup are adjusted and the welding is redone.

2. Inspection of randomly selected welded drift tubes under a microscope: no obvious cracks in the welding spots.

   In case of problems, the laser and setup are adjusted and the welding on the affected tubes is redone.

3. At the start of production, a sample of welds from each production site is evaluated metallurgically by cutting and inspection under the microscope.

4.3 Drift Tube Transport and Storage

The assembled drift tubes are transported and stored under the following conditions:

1. The tubes are always transported in stable wooden boxes like the ones used for delivery of bare tubes by the manufacturer.

2. The individual tubes are kept separated from each other and held such that that they cannot move inside the transport box.

3. The tube ends and endplugs are covered and protected with soft plastic caps like the ones used for the transport of bare tubes.

4. Inside the transport box and in storage, the tubes are enclosed in air-tight plastic bags containing dehumidifier bags.

5. After assembly and test, the drift tubes are always kept gas sealed until the gas distribution system is installed on the chamber.

   It is recommended to store and transport the drift tubes filled with inert gas in order to prevent corrosion.

6. During transport, only temperature variations in the range 0 – 50°C are allowed.

   (This means that the wire tension can increase temporarily by up to 45 g (1.5 g/°C) above the nominal tension of 350 g at 20°C, i.e. by 13%.)

7. During storage, the temperature has to stay within the range 10 – 30°C.

5 Drift Tube Test

Successful operation of the large number of drift tubes in the ATLAS experiment requires, in addition to the high mechanical accuracy in the wire location, very high reliability of the tubes with respect to high voltage stability, gas tightness and minimized risk of ageing.

Quality control tests of the drift tubes are a major part of the chamber construction. They must ensure the reliability of the drift tubes over their long lifetime. At the same time the tests are designed such that they can be performed routinely and in reproducible manner and fast enough to keep up with the speed of the tube production at a rate of 50-100 tubes per day at each production site. Automatized tubes test stands operated under computer control are in preparation (see Figure 2).

The following quality control tests are performed for each assembled drift tube at the tube production sites:

1. Visual inspection.
2. Wire tension (oscillation frequency) measurement.
3. Wire location measurement.
4. Gas pressure and leak test of the whole drift tube.
5. HV stability test:
   (a) Leakage current measurement.
   (b) Cosmic count rate measurement (optional).

The mechanical tolerances are tested for a random sample of drift tubes per day.

The ground contact resistance between tube and the aluminum ground ring of the endplug is measured for a random sample of drift tubes after production and monitored over time for selected drift tubes before assembly and in an assembled chamber.

If drift tube and chamber production sites do not coincide, instructions for packing and transport of the assembled drift tubes have to be observed.

The following tests are recommended to be performed at the accepting site for a random sample of the delivered drift tubes:

1. Visual inspection (defects on endplugs or tubes).

2. Leak test of endplugs.
3. Ground contact resistance (as Table 3).

The wire tension (oscillation frequency) is measured at the chamber production sites for each drift tube before assembly in the chamber.

During all tests, individual drift tubes are identified by their bar code with a bar code scanner.

The drift tube quality control tests performed at all production sites are summarized in Tables 2 and 3. The test procedures are explained in the following. Table 4 gives an overview of the drift tube quality control equipment planned to be used at the production sites.

5.1 Wire Tension Measurement

The gravitational sag of the wires has to be controlled within a tolerance of ± 10 μm in order to predict the wire position between the tube ends with sufficient accuracy. The wire sag s between the wire locators is related to the wire tension T by $s = g\pi\rho d^2 L^2/(32\ T)$ where g is the gravitational acceleration.

Measurement of the ground mode wire oscillation frequency ν allows to determine the tension T of the wire with density ρ, diameter d and length L according to the relation $T = \pi\rho d^2 L^2 \nu^2$ and, using the above relations, directly the wire sag $s = g/(32\ \nu^2)$ independent of geometrical and material parameters of the wire.

The wire tension is required to stay within a tolerance of $\pm 5\%$ of the nominal value of 350 g at the nominal temperature of $20 \pm 1°$C (the wire ground mode frequency therefore has to stay within $\pm 2.5\%$ of the nominal value). During wire tensioning and tension measurement, the tube temperature has to be controlled and measured with this accuracy. The wire tension is measured immediately after drift tube assembly to give feed-back to the tube assembly and tested again after at least two weeks before installation in the chamber in order to minimize the risk of wire creep or slippage.

The measurements of the wire oscillation frequency and of the corresponding temperature are stored in the central data base for the accepted tubes installed in the chamber. All measurements including history are kept in the local data bases for reference and tracing of problems.

The instruments used for wire oscillation frequency measurement at the production sites are summarized in Table 4. An example with a commercial tension meter is shown in Figure 1.

5.2 Wire Location Measurement

Measurements of the wire locations at the tube ends in the two transverse coordinates are performed with two methods (see Table 4).

1. X-ray measurement:

   For the wire position measurement, the tube ends are held in a jig in the same way and in the same azimutal orientation as later in the chamber assembly jig. Reference wires with known distances are embedded in the V-block holding the endplug. With two X-ray sources illuminating the tube under a stereo angle close to the endplug, shadows of the sense and the reference wires are projected onto two X-ray CCDs (see Figures 3 and 4). Using the reference wire grid, the y and z positions of the sense wire can be reconstructed with respect to the endplug reference surface (on which it is supported on the jig) with a resolution of 2 μm. The measurement determines the wire position as in the chamber independent of the roundness of the endplug reference surface. A second measurement after rotating the tube around its axis by 180° determines the wire location for both orientations of drift tubes in the chambers and tests if the wire is held correctly by the wire locator.

The layout of a wire location measurement station for series production is shown in Figure 6.

The straightness of bare and assembled drift tubes including coaxiality of the endplugs with respect to the tube (see Tables 1 and 2) can be tested on the same jig (tubes interferences and wire displacements).

2. Electromagnetic pickup measurement:

   Signals of an alternating current circulating through the sense wire is picked up by two coils on opposite sides of the tube (see Figure 5). The difference in the signal amplitudes allows to determine the wire displacement from the center in the plane of the coils with a resolution of 2 μm. By rotating the tube on the support points on the endplug reference surface, the wire displacement from the center of the reference surface in both transverse coordinates can be determined.

The measurement setups are regularly aligned and recalibrated with a calibration tube. Tubes are accepted if the measured wire locations at both ends are within ± 25 μm of the centers of the endplug reference surfaces in the y and the z coordinates (defined by the endplug orientation). The tolerance corresponds to 2.5 times the required rms of 10 μm of the wire location in individual drift tubes.

The wire location measurements should be performed for azimutally oriented tubes, for example by means of the tube clocking piece installed on one endplug which is used during chamber assembly and which seals the tube after tube quality control until installation of the gas system on the chamber. In this way, the wire locations can be determined in a common coordinate system, for instance the ATLAS coordinate system. This helps for the tracing of problems and allows to make contact with the X-ray tomograph measurements and to improve their reliability. It is therfore particularly important for chambers with mechanical problems which need to be recovered by X-ray tomograph measurement.

For the module 0 chambers, the wire locations in all tubes will be measured. During series production, the measurement of only a fraction of the tubes produced per day is required to test the quality of the precision endplugs and the tube assembly tooling. The results for accepted tubes installed in the chambers are stored in the central data base; all measurements including history are kept in the local data bases for reference and tracing of problems.

5.3 Gas Pressure and Leak Test

Each complete drift tube (including endplugs and tube wall) has to pass a gas pressure test at 1.5 times the nominal overpressure of 2 bar for safety reasons. Afterwards the tubes are visually inspected and tested for gas leaks.

A tight limit of $1 \cdot 10^{-8}$ bar l/s is required for the gas leak rate of each individual drift tube in the MDT chambers at the nominal operating pressure of 3 bar in order to prevent back diffusion and gas contamination. The direct detection of holes in the tube walls by the manufacturer, e.g. with the eddy current method, proved to be too expensive. Therefore the whole drift tube including endplugs and tube walls has to be leak tested.

For this purpose, the drift tubes are fully enclosed in a container. The drift tubes in the container are filled with an Ar:CO_2 gas mixture with helium admixture up to 3 bar overpressure to perform the required pressure test. Subsequently, the argon or helium leak rate into the evacuated container is measured at the nominal overpressure of 2 bar with a mass spectrometer of helium leak detector (see Figures 7 and 8).

For the many different tube lengths in the endcap chambers an alternative method is also used. The leakage of the whole tube is measured in evacuated fixtures at the tube ends (endplugs) and with a fixture moved along the tube using a helium leak detector (see Figure 9).

A drift tube is accepted if its individual leak rate at 2 bar overpressure is demonstrated to be below $1 \cdot 10^{-8}$ bar l/s. The test results for accepted tubes installed in the chambers are stored in the central data base; all measurements including history are kept in the local data bases for reference and tracing of problems.

The gas leak test is the most time consuming part of the drift tube quality control. Automated leak test stands are prepared which measure the daily tube production over night under computer control (see Figure 2 and Table 4). A large number of tubes is either tested simultaneously in multi-tube containers or sequentially in many single-tube containers (see Figure 8). In the automated test stands, the leak test is integrated with automatic wire tension measurement and leakage current measurement for the high voltage stability test.

5.4 High Voltage Stability Test

The high voltage stability of the drift tubes is tested with Ar:CO_2 (93:7) at 3 bar because this is the baseline gas mixture and particularly sensitive to imperfections of inner tube wall and wire.

Tests have shown that the leakage currents of good drift tubes with this gas mixture at 3 bar are typically 70 pA/m at the nominal operating point at 3080 V ($2 \cdot 10^4$ gas gain) and 120 pA/m and 520 pA/m at 3190 V ($4 \cdot 10^4$ gas gain) and 3400 V ($16 \cdot 10^4$ gas gain), respectively. These currents are close to the expectation from the cosmic count rate.

A common high voltage stability test is defined as measurement of the drift tube leakage current at 3400 V with a sensitivity of 1 nA which the existing commercial HV systems provide. The high voltage is ramped up slowly, typically in steps of 100 V. The tube current at each step is limited to be less than 2 nA/m (measured after settling time). The duration of the high voltage test at 3400 V is limited to 10 minutes.

Drift tubes are accepted if the tube leakage current at 3400 V is below 2 nA per meter tube length. The test results for accepted drift tubes installed in the chambers are stored in the central data base; all measurements including history are kept in the local data bases for reference and tracing of problems.

Optionally, the following additional high voltage tests will be performed at a number of production sites for all or a fraction of the drift tubes (see Table 4):

1. Monitoring of the leakage current over night at the nominal operating point at 3080 V.
2. Measurement of the leakage current with increased sensitivity with pA-meters.
3. Measurement of the cosmic count rate at 3190 V (2× the nominal gas gain).
4. Monitoring of the cosmic count rate over night at the nominal operating point at 3080 V.
5. Measurement of the signal rate and shape with a radioactive source.

The test results are recorded in the local data bases.

To improve the comparibility of the cosmic count rate measurements at different sites, readout electronics using the BNL preamplifier and shaper is prepared at BNL for a common test.

In the automated drift tubes test stands, wire tension, leak rate and leakage current measurements are integrated (see Figure 8).

Table 1: Quality control tests of drift tube materials at the chamber production sites

Test	Acceptance criteria	Reaction if failed	Data base	Comment
Aluminum tube				
Visual inspection of inside and outside	no obvious defects or holes, proper cleaning, deburring, straightness, bar code, packing	reject tube, notify supplier	central	1: sample test/box 2: every tube before wiring
Outer diameter envelope, from 8 points on circumference	$29970 \pm 15\ \mu$m	reject box	central	sample test/box
Wall thickness, at 8 points on circumference	$400 \pm 30\ \mu$m	reject box	central	sample test/box
Length L	$L \pm 0.5$ mm ($L \leq 4$ m) $L \pm 0.7$ mm ($L > 4$ m)	reject box	central	sample test/box
Straightness	insertion into jig without difficulties	reject tube, notify supplier	central	sample test/box
Wire				
Visual inspection	no defects of gold-plating, proper cleaning, no kinks	reject spool	central	1: first meters and every 400 m per spool under microscope, 2: inspection during wiring
Endplug				
Visual inspection	proper cleaning and no obvious defects of plastic, O-rings, wire locator, Al reference surface, crimp tube	reject endplug, notify supplier	central	1: sample test/batch 2: each endplug before wiring
Outer diameter envelope, from 8 points on circumference (**optional**)	$30010 \pm 10\ \mu$m	reject batch	central	sample test/batch
Wire locator outer diamter	within tolerance	reject batch	central	sample test/batch

Table 2: Quality control tests of drift tubes at the chamber production sites

Test	**Acceptance criteria**	**Reaction if failed**	**Data base**	**Comment**
Drift tube				
Visual inspection	no obvious damage of tube or endplug, no visible defects of tube and wire crimp, tube correctly sealed	reject drift tube, adjust wiring station	local	each tube after wiring, before chamber assembly
Aluminum tube outer diameter envelope in endplug region	less than 30.020 mm	reject drift tube, adjust tube crimping setup	local	sample test/day, shortly after wiring
Aluminum tube outer diameter envelope at tube end	less than 30.010 mm	reject or repair tube, adjust tube crimping or laser welding setup	local	sample test/day, after laser welding
Length L	Nominal length ± 0.25 mm at 20 ± 1°C	reject drift tube, adjust wiring station	local	1: sample test/day 2: each tube on chamber assembly jig
Relative azimutal orientation of endplugs	± 10 mrad	reject drift tube, adjust wiring station	local	1: sample test/day 2: each tube on chamber assembly jig
Straightness	insertion into jig without difficulties	reject drift tube	local	1: sample test/day 2: each drift tube during chamber assembly
Tube ground contact resistance (for 5 mA current)	less than 100 mΩ per endplug	repeat laser welding	local	1: sample test/day 2: monitoring of selected tubes over time

Table 3: Quality control tests for all drift tubes at the chamber production sites

Test	Acceptance criteria	Reaction if failed	Data base	Comment
Drift tube				
Room temperature	$20 \pm 2°$C	adjust	local	during tube tests
Relative humidity (**optional**)			local	monitoring
Temperature of tube	$20 \pm 1°$C	adjust temperature or tension	local	during tube assembly
Temperature of tube	known within $\pm 1°$C	repeat measurement	central	during wire tension measurement
Wire tension (from oscillation frequency meas.)	within $\pm 5\%$ of the nominal value at $20 \pm 1°$C	reject drift tube	central	1: shortly after tube wiring 2: after min. two weeks, before assembly
Wire location at the tube ends	within ± 25 μm of the center of the endplug ref. surface in y and z	reject drift tube, inspect endplugs and wiring station	central	sample test on day of wiring, tube held as in assembly jig, incl. test of coaxiality of endplugs, measurements at 0 and 180°
Gas pressure test at 3 bar overpressure	no obvious leaks	reject drift tube, inspect endplugs, adjust wiring station	local	
Gas leak rate at 2 bar overpressure	less than 10^{-8} bar l/s	reject drift tube, inspect endplugs, adjust wiring station	central	after pressure test
HV stability test: leakage current	less than 2 nA/m	reject drift tube, inspect endplugs, tubes, wire	central	with $Ar:CO_2$ (93:7) at 3 bar and 3400 V
HV stability test: cosmic count rate (**optional**)	within $\pm 3\sigma$ of nominal value	reject drift tube, inspect endplugs, tube, wire	central	with $Ar:CO_2$ (93:7) at 3 bar and 3190 V

Table 4: Drift tube test equipment at the production sites

Site	Wire tension (osz. frequency)	Wire position	Leak rate (whole tube)	HV test (leakage current)	HV test (cosmic rate)
Freiburg	Excitation in B-field	Brandeis X-ray system	As Frascati	HV system with pA-meter	Yes
LMU/MPI (accept. test)	CAEN SY502 meter, excitation in B-field	Brandeis X-ray system, MPI jig	Pressure rise in evacuated volume at endplug (8 tubes sim.)	HV system with 1 nA sensitivity	BNL preamp., shaper
NTU Athens	CAEN SY502 meter, excitation in B-field	Electromagnetic, as Pavia, Rome	As Frascati or Pavia	Keithley current meter with 1 nA sensitivity	
Univ. Athens	as NTU Athens (after module 0)				
Thessaloniki (accept. test)	excitation in B-field			CAEN SY127 (40 channels), 1 nA sensitivity HV system	
Frascati	Electrostatic excit., multi-channel system, integration with leak test	Electromagnetic micrometer, as Pavia, Rome	Helium leak detector, 60 single-tube containers	CAEN SY546 (96 channel) 1 nA sensitivity HV system, integration with leak test	Yes
Cosenza	CAEN SY502 meter, excitation in B-field integration with leak test	Electromagnetic micrometer, as Pavia, Rome	As Pavia, automatic control system	CAEN SY546 (96 channel) 1 nA sensitivity HV system, integration with leak test	
Pavia	As Rome	Electromagnetic micrometer	Argon mass spectrometer, 10 single-tube containers (commercial system)	HV system (10 channels) with pA-meter, integration with leak test	
Rome	Excitation in B-field, multi-channel	Electromagnetic micrometer	As Frascati or Pavia,	As Pavia	
NIKHEF	Mechanical excitation, piezo-electric measurement	Electromagnetic, as Pavia/Rome	As Frascati	Multi-channel HV system, integration with leak test	Yes
Dubna (also for MPI)	Excitation in B-field, meter custom design	Brandeis X-ray system, MPI jig	Helium mass spectrometer, multi/single-tube containers	CAEN SY546 (96 channel) 1 nA sensitivity HV system	BNL preamp., shaper
Protvino	Excitation in B-field, meter custom design	Brandeis X-ray system	Mass spectrometer		
Boston	Excitation in B-field, meter custom design	Brandeis X-ray system	Mass spectrometer, multi-tube container	Multi-channel HV system, integration with leak test	Yes
Michigan	As Seattle	Electromagnetic micrometer, as Pavia, Rome	Helium leak tester, evacuated volume at end-plug and moving along tube	Multi-channel HV system	
Seattle	Excitation in B-field, meter custom design	Electromagnetic, as Pavia/Rome	As Michigan	As Michigan	

6 Chamber Assembly

6.1 Assembly Setup

6.1.1 Assembly Room

The MDT chambers are assembled in a climatized room in clean environment. The following requirements are important to control the mechanical precision and stability of the chamber construction:

1. The temperature in the assembly room is controlled such that that it is stable and uniform within 20 ± 0.5°C above the surface of the assembly table and within 20 ± 1°C in the rest of the assembly room.
2. Temperature differences between the outer cross plates and the end combs (measured with the temperature probes on the spacer and temperature sensors on the combs) should be below 0.5°C during the glueing process in order to avoid unwanted wire offsets between adjacent layers.
3. The relative humidity in the assembly room is controlled to be $50 \pm 10\%$ to ensure proper curing of the glue.
4. The assembly room is cleaned regularly.
5. During work in the assembly room, hair and shoe protection, coats and gloves certified for clean rooms are used. Before entering the clean room, clothes are changed in a separate chamber.

Emergency power is needed in order to restore the climatization quickly after a power failure during glue curing. The vacuum underpressure must not fall below the tolerance before power is restored.

6.1.2 Granite Table

A granite table surface with absolute flatness of at least 20 μm serves as reference for the setup of the assembly jigging. To guarantee the flatness of the granite table and therefore the alignment of the assembly jigging over the whole time period of chamber production, it is recommended to follow the following procedures:

1. The table is kinematically supported on 3 feet as specified by the manufacturer and on a stable concrete floor.
2. The planarity of the table has to be measured after setting it up in the climatized room and before installation of the assembly jigging.

   The measurement is best done by professionals using tilt meters.

   If necessary, the required planarity has to be recovered by polishing the surface after installation and measurement of the table in the assembly room.
3. It is recommended to inspect the feet of the table regularly (every week). The load of the table must be only on the 3 kinematical supports; additional feet installed for security reasons must always be free of load (indicated by a loose nut). If this should not be the case, the feet have to be adjusted (best by professionals); chamber assembly can continue only after at least 2 days to allow for relaxation of the table to its original shape.

4. No installations on the table which are firmly connected to the floor.
5. Load on the table must not exceed the design value as specified by the manufacturer.
6. The surface of the granite may have to be cleaned before installation of the jigging. Cleaning should be done only with special fluid and cloth recommended by the manufacturer of the table.
7. The granite table must be kept under constant and uniform environmental conditions which are monitored continuously after setup and measurement as specified by the manufacturers. This includes:
    (a) Constant and uniform illumination (even with tube layer on combs).
    (b) Constant relative humidity, typically $50 \pm 10\%$.
    (c) Constant and uniform temperature within ±0.5°C long-term (monitored with temperature probes on the granite).
    (d) Temperature gradient between top and bottom of the table below 0.2°C (monitored with temperature probes on the granite).
8. The planarity of the granite table surface (where accessible) and the alignment of the jigging have to be measured regularly (initially every 3 months). Tilt meters are recommended for this purpose.

6.1.3 Assembly Tooling

The components of the assembly jigging are measured before or after the installation on the granite table:

1. z-distances and y-coordinates of cylinders in the V-grooves of the combs (on a 3D coordinate measureing machine).
2. Height of the sphere towers with the different interfaces (on a 3D coordinate measureing machine).
3. y, z and angular alignment of the comb lines installed on the assembly table (with optical or mechanical gauges).
4. y-coordinates of the V-grooves of the end comb lines installed on the assembly table (using a feeler gauge) to make sure the combs have not been deformed by mounting them.

The alignment of the comb lines is measured in regular time intervals (typically 3 months which corresponds to the construction of about 6 chambers). The data are stored in the local production data bases for reference and tracing of errors.

The assembly jigging is visually inspected regularly and cleaned when necessary.

The following labelling of the assembly jigging is proposed:

1. Mark readout and high voltage side on assembly table.
2. Mark chamber coordinate system on granite table.
3. Mark sequential numbers of tube insertion on both end combs.
4. Mark reference side on assembly table.

5. Mark sphere support towers with numbers.
6. Mark tower with fixed sphere position.
7. Mark tower interfaces including correspondence to towers.
8. Mark identifiers of force compensation supports on granite table, corresponding with DB.
9. Mark location of transfer blocks for alignment platform positioning on combs.
10. Mark chamber identifier (ATLAS numbering scheme) on RO and HV cross plate outer surfaces and on protective covers.

During the 12 hour curing time of the glue for the assembly of a tube layer, the vacuum suction force of the tubes in the combs has to be continuously active and must not be lost in case of a power failure. Otherwise the accuracy of the tube layer cannot be guaranteed and the layer may have to be discarded. The vacuum underpressure is continuously monitored. Emergency power should be available. The reaction time depends on how long the vacuum system can maintain the underpressure with pump off.

6.2 Preparation of Chamber Components

Before entering the assembly room, all chamber components go through a final quality control procedure. The quality of the components is verified by consulting the quality control documentation by the suppliers and the information in the production data base (see the **Assembly Control Plan** in the **Appendix**).

All components, except for the drift tubes which are stored dust-free conditions, are carefully cleaned, the cleaning is verified and the components are properly labelled. All components are stored in the temperature controlled assembly room at least 12 hours before assembly in order to adapt to the temperature of 20°C.

The following labelling of components is proposed:

1. Mark readout and high-voltage side cross plates.
2. Mark orientation to top multilayer on all cross plates and long beams.
3. Mark identifiers of the in-plane alignment, cross plate sag and sphere monitors on the spacer corresponding with DB.
4. Mark locations of mask, lens and CCD of permanent and temporary RASNIK monitors on cross plates and long beams.

6.3 Qualification of Personell

The assembly of a chamber is carried out by 3 operators as described in the **Chamber Assembly Manual**.

Operator 3 coordinates the work in the assembly room and the preparation of materials, ensures that all assembly and quality control steps are performed correctly according to the **Assembly Control Plan** and operates the monitoring devices for assembly control with the help of the **Assembly Control Program**. He also operates the crane during assembly.

The operator team starts its work only after detailed instructions and training on all assembly and quality assurance procedures.

The **Production Manager** (physicist or engineer) supervises the whole chamber assembly process and makes sure that the quality assurance instructions are correctly followed. He evaluates the monitoring data and has to be consulted when alarms occur. Critical steps have to be approved by him as defined in the **Assembly Control Plan**. He is also responsible that the operators are correctly instructed and trained.

6.4 The Chamber Assembly Process

All steps of the MDT chamber construction procedures are described in detail in the **Chamber Assembly Manual** of each production site and, in addition, in associated manuals for specific components and procedures (**Assembly Monitoring Manual**, **Gas System Installation Manual**, **Glueing Manual**).

The detailed work and quality assurance plan for chamber assembly is described in the local **Assembly Control Plan** which to a large extent will be implemented in software, the **Assembly Control Program**, to control the process with the help of a computer which also aquires and analyzes the monitoring data.

6.4.1 Monitoring of Chamber Assembly

Monitoring and control of all critical parameters of the assembly process is essential to guarantee the quality and precision of the chambers, in particular since only a fraction of the chambers can be measured completely and with sufficient accuracy after construction. The monitoring and test data taken during assembly are kept in the local production data base for reference and tracing of problems.

The following parameters are measured and monitored during chamber assembly (see Tables 5 and 6):

1. Climatization of the assembly room (temperature and relative humidity).
2. Temperature of the cross plates (with the temperature probes to be installed on the spacer) and of the end combs.
3. Vacuum underpressure for tube suction in the combs.
4. Identification of each drift tube and its location in the chamber via the bar code using a bar code scanner. This includes automatic verification that the tube has been accepted by the quality control tests.
5. Uniform tube length and azimutal orientation of endplugs (by visual inspection).
6. Horizontal glue gap between tubes in combs (by visual inspection with illumination from underneath) to verify the tube straightness (relevant for the 100 μm tolerance on the wire concentricity with respect to the tube wall).
7. Height (in y coordinate) of endplug reference surface on the combs to verify proper fitting and suction of tubes in the combs.

   Measurement devices used are: feeler gauges, tilt meters or laser monitors (see Figure 10).
8. Uniform glue distribution with glue dispenser (visual inspection) and glue curing time.
9. Stability of the in-plane alignment monitor readings and of the planarity of the assembly jigging using the in-plane alignment system (RASNIK monitors).

10. Precision of the vertical stacking of tube layers in the y and z coordinates using proximity RASNIK monitors (sphere monitors) with large masks mounted close to the spheres at the 4 ends of the two outer cross plates and the in-plane alignment system for the middle cross plate.
11. Measurement of angluar deviations $\Delta\theta_x$, $\Delta\theta_y$ and $\Delta\theta_z$ (around the x-, y- and z-axes) of the axial/praxial and the projective alignment platforms from alignment with the axes of the chamber coordinate frame.

    The measurements are performed with an optical angle measuring device developed at Brandeis University (BCAM) and adapted for this purpose by Saclay (for relative alignment of platforms), and with feeler gauges and tilt meters after installation of the platforms and after assembly of each further tube layer.
12. Monitoring of the forces (measured with strain gauges) applied to the long beams by the automatic force compensation system which is used for the BM and BO chambers to compensate the gravitational sag of the cross plates when supported on the sphere towers during assembly.
13. Monitoring of the gravitational sag of the two outer cross plates during assembly and test of the chambers using RASNIK monitors temporarily installed on the cross plates between the long beams (recommended for the BM and BO chambers initially).
14. Regular verification of the planarity of the granite table and the alignment of the jigging (combs and sphere towers); see section **Assembly Tooling**.

The **Assembly Control Program** automatically generates alarms if any of the monitored parameters is outside the tolerances. Resulting actions are:

- Immediate corrections for the chamber currently under construction (see the **Assembly Control Plan** in the **Appendix**).
- The monitoring data are stored in the local production data base as reference for tracing of errors.
- If the deviations cannot be completely eliminated:

  The problem is reported and the data are recorded in the central data base; the chamber is flagged for measurement in the X-ray tomograph.

More details on assembly quality control and monitoring procedures are given in the **Monitoring Manual** and the **Assembly Control Plan** in the **Appendix**.

6.4.2 Calibration of the Optical Monitors

The optical monitoring devices require careful calibration (see the **Monitoring Manual**):

1. The angular orientation around the x-axis of the masks of the in-plane alignment RASNIK monitors relative to the surface of the assembly table has to be measured with an accuracy of 10 mrad for the barrel chambers. This allows to measure the gravitational sag (y displacement of the middle cross plate) of even the longest barrel chambers with an accuracy of 5 μm after compensation of the wire sag of up to 350 μm relative to the zero-readings of the in-plane monitors on the assembly jigging.

   The calibration can be done after assembly of the spacer by moving the middle cross plate supported on the sphere towers in z direction parallel to the surface of the granite table by about 1 mm and measuring the change in the y and z readings of the in-plane monitors.

The resolution in the angle measurement between mask and CCD around the x-axis by the RASNIK image analysis software is much better than 10 mrad and does not contribute to the error.

The calibration data have to be stored in the central data base.

2. The zero-readings of the in-plane alignment RASNIK monitors on the flat granite table are needed as reference for the measurement of deformations of the chamber during assembly, test (in the cosmic ray test stand and the X-ray tomograph) and operation in the ATLAS detector.

   Readings of the in-plane monitors are taken as part of the chamber construction procedure after each glueing step, for assembly of the spacer and of the tube layers (see the **Appendix**). The readings have to be stable within ±10 μm during the assembly of the chamber. The average or a selection of the readings is taken as zero-reading for the future operation of the chamber.

   The zero-readings of the in-plane alignment monitors and their readings after each glueing step are stored in the central data base.

3. The zero-readings of the RASNIK cross plate sag monitors are needed as reference for the measurement of the sag of the cross plates during assembly and test (in the cosmic ray test stand and the X-ray tomograph).

   The zero-readings are taken with the cross plates suspended at one end from a crane such that there is no deformation. They can be verified by measuring the cross plate sag in the initial and inverted orientation of the spacer on the jigging after adjustment of the long beams on the middle cross plate (see the **Appendix**).

   The zero-readings of the cross plate sag monitors are stored in the local production data base.

4. The angular orientation around the x-axis of the masks of the RASNIK sphere monitors relative to the surface of the granite table has to be measured and regularly recalibrated with an accuracy of 50 μrad. This accuracy is needed in order to measure the y and z positions of the spheres (where the masks are mounted) with a precision of 5 μm over the measurement range of 52 mm for 3-layer chambers and 78 mm for 4-layer chambers. (The same is true for the reference sensors on the granite table for a laser sphere monitoring system with transparent MPA-ALMY sensors.)

   The calibration measurement can be done with a tilt meter on the granite table and and on the housing of the large mask in which it has been accurately aligned with respect to an external reference surface. Optical measurement of the mask orientation with a pendulum in front of it using a tilt meter to measure the orientation of the granite table has also been proposed.

   The angle measurement between mask and CCD around the x-axis by the RASNIK image analysis software has to be at least as accurate as the calibration in order not to increase significantly the y and z measurement error of the sphere monitors. Optimized RASNIK analysis programs have shown 30 μrad angular resolution.

   Once the angular orientation of the sphere monitor CCD has been precisely measured in this way with respect to the surface of the assembly table on which it is permanently mounted, the mask orientation on the sphere holders mounted on the next chamber can be measured the same way without calibration. Nevertheless, regular recalibration is necessary in order to be sure that the CCD holder has not moved.

   The calibration data are stored in the local production data base.

6.4.3 Glueing Procedures

The following glue types are used for chamber assembly:

1. For spacer assembly, glueing of tube layers to the spacer and mounting of gas distribution bars:

   Ciba Geigy Araldite 2014 (AW 139/ XB 5323) with high viscosity to fill the large glue gaps with shrinkage $< 1\%$, setting (usage) time of 40 minutes, curing time of 3.5 (5) hours to achieve minimum shear strength of 1 (10) N/mm^2 at 23°C on aluminum and a shelve time of 3 years at $18 - 25$°C.

   As alternative with higher peeling strength, 3M Scotch-Weld DP 460 is under consideration which otherwise has similar properties as Araldite 2014 with about 1.5% shrinkage.

   The glue is applied with a manual glue dispenser with static mixer. It will be cured for 12 hours during chamber assembly.

2. For glueing of tubes on tubes:

   Ciba Geigy Araldite 2011 (AW 106/ HV 953U) with viscosity of $40-45$ Pa after mixing at 23°C, setting (handling) time of 105 minutes in glue container and 90 minutes exposed to air, curing time of 7 (10) hours to achieve minimum shear strength of 1 (10) N/mm^2 at 23°C on aluminum and a shelve time of 3 years at $18 - 25$°C.

   The glue is applied in premixed form on a complete tube layer inserted in the assembly combs using an automatic glue dispenser with a speed of typically 20-30 minutes for a layer depending on chamber size which leaves enough reserve in case of problems. Up to 90 minutes glue handling time can be accepted with the proper control of out-of-plane deflections of tubes in the assembly process.

   Good control of the amount and location of the glue distributed on the tube layer by design of the glue dispenser is important to minimize glue shrinkage and out-of-plane deflections of tubes which can affect the mechanical accuracy of the chambers.

   The glue will be cured for 12 hours during chamber assembly. Handling of the premixed glue and the automatic glue dispensers is described in the **Glueing Manual**.

3. For glueing of alignment platforms, Faraday cage mouting bars, in-plane alignment monitor components, temperature and B-field sensors:

   Ciba Geigy Araldite 2012 (AW 2104/ HW 2934) with viscosity as Araldite 2011, setting (usage) time of 5 minutes, curing time of 20 (105) minutes to achieve minimum shear strength of 1 (10) N/mm^2 at 23°C on aluminum and a shelve time of 3 years at $18 - 25$°C.

All surfaces glued must be cleaned with alcohol and dried before glueing according to the glue handling specifications. This includes the components of the spacer, the gas system, Faraday cages, on-chamber monitors and alignment platforms.

The tubes are stored and transported in air-tight bags at all times after cleaning by the manufacturor. The bags are only opened and packed inside the clean rooms for tube assembly and test and for chamber assembly at the production sites. The tubes are handled with plastic gloves only in order to avoid contamination. If nevertheless tubes get contaminated by dust or grease etc., they have to be carefully cleaned with ethanol without destroying the bar code and bending the tubes.

Details about the glueing processes during chamber assembly and the associated quality assurance are described in the **Chamber Assembly Manual** and the **Glueing Manual**.

For each glueing step, an aluminum test piece is glued simultaneously from the same glue mixture as used for the chamber assembly to evaluate independently the proper curing of the glue. The glue on the chamber is inspected after the nominal curing time. If the glue should not cure as required even after an extended time period, the tube layer or even the whole chamber have to be discarded depending on the assembly step.

6.4.4 Assembly Control Plan

The **Assembly Control Plan** contains detailed instructions for quality assurance and quality control during the construction of a MDT chamber.

An example for the construction of BOS MDT chambers is given in the **Appendix**. The plan is intended as guideline for the preparation of the local QA/QC plan and for the implementation of the QA/QC procedures in an **Assembly Control Program**.

6.4.5 Assembly Control Program

Following the specifications in the **Assembly Control Plan**, the **Assembly Control Program** allows to verify all major assembly steps, acquires and analyzes the data of the monitoring devices, stores the data in the local production data base and issues alarms if parameters are out of tolerances. In most cases the control program will be based on the LABVIEW package.

The schematical layout of an **Assembly Control Program** is shown in Figure 11. Figure 12 shows an example of a graphical user interface for the control program.

7 Chamber Test

The following quality control tests are performed for each chamber at the production sites immediately after assembly to provide fast feed back (see Tables 7 and 8):

1. Tests of chamber mechanics on the kinematical supports:
   (a) Measurement of the gravitational sag of the chamber before and after sag compensation with the in-plane alignment monitors.
   (b) Measurement of the gravitational deformation of the cross plates with the cross plate sag monitors (recommended for BM and BO chambers).
2. Gas pressure and leak test of the whole chamber.
3. High voltage stability test with mounted electronics.
   (a) Leakage current measurement.
   (b) Cosmic count rate measurement (optional).
4. Evaluation of performance in cosmic ray test stand.

The following tests are performed for each chamber after transport to CERN and during chamber storage (see Table 9):

1. Acceptance test at CERN: visual inspection.
2. Acceptance test at CERN: gas leak test.
3. Monitoring of gas pressure in sealed chambers over storage time.
4. If final readout electronics installed during storage: high voltage stability test and operation test of electronics.

The following tests are performed for selected chambers after transport to CERN and during chamber storage (see Table 10):

1. Measurement of wire coordinates with the CERN X-ray tomograph.
2. Monitoring of wire tension in one chamber per production site over storage time.
3. Monitoring of drift tube ground contact in one chamber per production site over storage time.

Details of the chamber quality control tests are described in the following. Examples of the test sequence are given in the sections **Chamber Test Program at the Production Sites** and **Chamber Test Program at CERN**.

7.1 Gas Pressure and Leak Test

Immediately after assembly, the chambers with in-chamber gas distribution system have to be pressure tested at an overpressure of 3 bar which is 1.5 times the nominal overpressure of 2 bar used during chamber operation.

After the pressure test, the complete chamber is tested for gas leaks at the nominal overpressure of 2 bar with an inert gas. For the same reasons as explained for the single-tube leak test, the leak rate of a complete chamber including the gas distribution system has to be below $2 \cdot 10^{-8}$ bar l/s per tube.

The leak rate is determined by monitoring the pressure drop and together with the temperature difference between the chamber and a gas tight reference volume (see Figures 13 and 14). With the sensitivities of differential manometers ($\Delta p/p = 10^{-4} - 10^{-5}$) and calibrated temperature sensors (0.1°C) distributed on the chamber (permanent or temporary ones) and on the reference volume, the test takes several days in order to be able to detect a pressure drop in the chamber corresponding to the required leak rate limit.

The duration of the test is limited by the accuracy of the temperature monitoring. The reference volume should be close to the chamber and thermally coupled to it to minimize temperature differences. The temperature of the chamber should be uniform. Performing the test in a temperature controlled room helps to accelerate it.

The same leak test is performed as acceptance test after delivery of the chamber to CERN. During the whole storage time, the chambers stay filled with the baseline gas at 3 bar and the gas pressure is monitored with cheap manometers together with the temperature.

Contact addresses for differential manometers for the test are: JINR Dubna (see Figure 14) and Brandeis University.

All test results including history are recorded in the local production data base for reference and tracing of problems. The leak rate limit and faulty tube identifiers are stored in the central data base.

7.2 High Voltage Stability Test

After installation of the high voltage and readout boards at the production sites, a high voltage stability test is performed with the baseline gas at 3 bar. The leakage current per channel should be below 2 nA/m +5 nA at 8 times the nominal gas gain. For Ar:CO_2 (93:7) gas mixture, this corresponds to a test high voltage of 3400 V. The high voltage is ramped up carefully as for the single-tube high voltage test where the current per channel is limited to be below 2 nA/m +5 nA.

Optionally, the cosmic count rate per tube at the nominal operating point is measured and recorded in the local data base.

The high voltage stability test is repeated after installation of the final readout electronics which for a large fraction of the chambers has to take place in the storage area after the chamber test at the production sites. For these chambers, also a minimum operation test of the final electronics has to be performed which is practical with the setup in the storage area (e.g. without external cosmic trigger). It includes test of all electronics interconnections with pulser, verification of signals from all tubes, measurement of noise level, random rate and uniformity of response.

All test results including history are recorded in the local production data base for reference and tracing of problems. The results of the high voltage stability test, including faulty tube identifiers, are recorded in the central data base.

7.3 Cosmic Ray Test Stand

The performance of each chamber is evaluated in a cosmic ray test stand at the production site with the baseline gas at the nominal operating point. One or several chambers simultaneously are tested in a tower with trigger chambers (see Figure 15). The chambers are installed with their kinematical supports on rails as in the ATLAS detector. The in-plane alignment system, cross plate sag monitors if existing and the temperature sensors on the chamber should be continuously active.

Chambers are accepted after all channels have shown the expected performance stable over a period of 1–2 weeks. The measurements are stored in the local data base. Examples of parameters to be monitored are: drift tube efficiency, noise level, random rate, maximum drift time, resolution as a function of x, local wire displacements and uniformity of all channels.

Faulty drift tubes discovered during the operation of the chamber are recorded in the central data base.

7.4 Wire Location Measurement in Cosmic Ray Teststands

Several cosmic ray test stands in preparation for the barrel chambers (see Figure 15) allow to test 3 or more chambers simultaneously in horizontal orientation. By selecting high-momentum particles with a lead absorber and using the two outer chambers with precisely known wire locations (e.g. from X-ray tomograph measurement) as reference for the reconstruction of tracks of cosmic rays in the tower, the wire locations in the tested chamber in the middle can be reconstructed. Useful information about the wire positioning accuracy and possible systematic shifts can be obtained already after a data taking time of typically 10 hours. Second coordinate measurement of the tracks with accurcay of typically 1 cm is needed.

The 3 chambers are aligned with respect to each other with tracks. Rotations between the MDT chambers and between MDT and second coordinate chambers around the vertical y axis must be limited by construction of the rail support system of the chambers in the same way as in the ATLAS muon spectrometer. The tolerances for the rotation angles depend linearly on the second coordinate resolution; for a second coordinate resolution of 1 cm, the rotation angles θ_y must be smaller than 1 mrad in order not to deteriorate significantly the first-coordinate resolution.

During the measuring time, the relative chamber alignment has to be stable and is monitored with optical sensors.

Simulations show that after half a day of data taking, the wire locations in the horizontal z coordinate can be measured with an accuracy of $10 - 50$ μm depending on the setup. The measurement accuracy is limited by systematics from autocalibration and alignment stability. Tests will be performed with the Barrel DATCHA test stand at CERN.

For measurement of the wire y coordinates, the acceptance for cosmic tracks in a horizontal tower is limited; a reconstruction accuracy of typically $50 - 100$ μm is expected under the above conditions.

The average y-pitch and the separation between multilayers can be measured with considerably higher precision. The statistics can be improved by rotating the tested chamber around the x-axis. More detailed studies are in progress.

For the endcap chambers, the feasibility of measuring wire locations in a configuration where the test chamber is oriented vertically, with wires horizontal as at $\phi = 0$ in the ATLAS detector, will be investigated.

The wire coordinate measurements and the measurement errors of the tested chamber are recorded in the local and central data bases.

7.5 Wire Tension Measurement

During the storage time, in one chamber per production site the wire tension (oscillation frequency) is monitored for a large fraction of the drift tubes to obtain information about the long-term behaviour.

Devices for practical wire oscillation frequency measurement in complete chambers have been developed at JINR Dubna (excitation in a magnetic field) and at LNF Frascati (electrostatic excitation).

7.6 The CERN X-Ray Tomograph

The X-ray tomograph at CERN (see Figure 16) scans a whole chamber horizontally with two X-ray sources under a stereo angle of 30° to measure the wire positions in a global coordinate system in the $y - z$ plane. The shadows of the wires in all layers are reconstructed on the X-ray detector images.

The X-ray tomograph has been tested with recent MDT prototype chambers. The results of a typical X-ray scan of the BOS prototype chamber (along the readout side) are shown in Figure 17: distributions of the residuals of the measured wire positions with respect to a fitted ideal grid including correction for the observed gravitational deformation of the readout-side cross plate due to external moments (sag by -17 μm for this scan). The fitted parameters y- and z-pitch and y-separation between multilayers agree well within the measurement errors with the expectation from the construction of the assembly jigging. From repeated scans at the same position and for the same orientation of the chamber in the tomograph one estimates the measuring accuracy of the X-ray tomograph to be about 5 μm rms in z and 10 μm rms in y direction. This is sufficient to verify the accuracy of the MDT chambers.

The CERN X-ray tomograph provides a scan capacity of typically one chamber per week including the chamber setup time. This allows to measure a fraction of about 15% of all chambers built. Initially, approximately the same fraction will be measured for each production site.

The purpose of the X-ray tomograph measurements of MDT chambers is to

- qualify production sites with the scan results of the module 0 chambers,
- verify the mechanical accuracy of the chambers on the basis of a sample test,
- provide feed back to the production sites about systematic deviations from the mechanical specifications,
- measure the coordinates of all wires in chambers flagged for the X-ray tomograph because of problems discovered during assembly or transport.

After measurement in the X-ray tomograph, the wire coordinates of a chamber are known with higher accuracy than specified for the chamber construction. The fraction of scanned chambers therefore will be used in the ATLAS detector even if outside the mechanical tolerances. Only in exceptional cases chambers will have to be discarded because of large distortions detected by the X-ray measurements. Chambers with cutouts in the multilayers require special attention in the X-ray tomograph measurement schedule.

The barrel chambers are installed in the tomograph with their kinematical supports and on rails as in the ATLAS detector. External moments deforming the chamber must be avoided. The endcap chambers have to be mounted in a special support frame for the horizontal scan. The temperature in the X-ray tomograph room is controlled to be 20±0.5°C as on the assembly table. The temperature of the chamber is monitored during the measurememts with an accuracy of 0.1°C. Each scan is performed twice in order to test the reproducibility of the measurement and to verify bad wire positions.

The measurements are performed for 3 bar gas pressure in the chamber; for module 0 chambers also at 1 bar to determine the effect of the pressure on the positioning of the alignment platforms.

Repeating the scan at the same x-position after inverting the chamber around the x-axis helps to disentangle gravitational deformations of the cross plates on the supports from wire displacements caused during chamber construction. This will be done for the characterization of the module 0 chambers. Additional information about cross plate deformations during the X-ray scans is provided by cross plate sag monitors. The mechanical stability of the cross plates and the effect on the wire positioning accuracy after the chamber assembly should get special attention in the X-ray tomograph measurements of all types of module 0 chambers.

The X-ray tomograph measurements provide the following information:

1. y and z coordinates of all wires at the tube ends (in active scan mode) at known temperature including extra scans at the x-position of cutouts.

   This allows to recover chambers outside the mechnical tolerances.

2. y and z coordinates of wires embedded in special gauge blocks mounted on the alignment platforms to verify their positioning accuracy.

3. Parameters extracted from the wire coordinate measurements on readout and high-voltage side for evaluation of the quality of the chamber and of the construction procedure:

   (a) Average z pitch.
   (b) z-pitch for each layer.
   (c) Average y-pitch.
   (d) y-distance between adjacent layers.
   (e) y-distance between multilayers.
   (f) z-shift between adjacent layers.
   (g) z-shift between multilayers.
   (h) Global deformations of the chamber in the $y - z$ plane (fit vs. cross plate monitor measurements).
   (i) Systematic deformations of individual layers in the $y - z$ plane (fit vs. cross plate monitor measurements).
   (j) Rms of the residual distributions of the measured wire coordinates with respect to the nominal wire grid in y and z.
   (k) Rms of the residual distributions of the measured wire coordinates with respect to the nominal wire grid in y and z, separate for each layer.
   (l) Deviations of residuals from Gaussian distribution; number of wires outside $\pm 3\sigma$.

The X-ray tomograph data, wire coordinates, analyzed mechanical parameters and the temperature of the chamber for the different scans, are stored in the central data base.

Table 5: Quality control tests during chamber assembly.

Test	**Acceptance criteria**	**Reaction if failed**	**Data base**	**Comment**
Environment				
Room temperature	$20 \pm 1 \circ$C	adjust	local	before glueing
Relative humidity	50 ± 10 %	adjust	local	before glueing
Atmospheric pressure (**optional**)			local	monitoring
Temperature of outer cross plates	20 ± 0.5°C	adjust	local	uniform, before glueing
Temperature of end combs	20 ± 0.5°C	adjust	local	uniform, before glueing
Temperature difference outer cross plates–end combs	< 0.5°C	adjust	local	during glueing
Spacer assembly				
Glue gaps between tube layer on combs and cross plates	$200 - 1000\ \mu$m	adjust	local	both orientations of cross plates around z-axis
On-chamber gas system				
Leak rate	less than 10^{-6} bar l/s	repair or replace	local	for preassembled gas manifolds
Flow rate/tube	equal within 10%	repair or replace		for preassembled gas manifolds

Table 6: Quality control tests during chamber assembly (cont.)

Test	Acceptance criteria	Reaction if failed	Data base	Comment
Assembly of tube layers				
Vacuum suction underpressure	at nominal value	adjust	local	tube positioning on combs during glueing
Horizontal gaps between tubes	not more than two adjacent tube walls touching, no adjacent endplugs touching	relocate drift tubes	local	before glueing
Height of endplug reference surfaces on jig	within ±20 μm of nominal value in y	relocate drift tubes	local	before glueing
Stability of in-plane monitor readings (image displacement)	within ±10 μm of nominal value in y and z	adjust	central	after each glueing step (definition of zero of in-plane monitors), after correction for middle
Sphere locations	within ±10 μm of nominal value in y and z	adjust	local	before each glueing step, with sphere and in-plane monitors
Outer cross plate sags on the assembly table (**optional**)	zero within ±10 μm	adjust	local	before glueing of a layer, measured with temporary cross plate sag monitors
Middle cross plate sag on the assembly table (**optional**)	zero within ±20 μm	adjust	local	before glueing of a layer, measured with in-plane monitors plus outer cross plate sag correction
Alignment Platforms				
Angular alignment of axial/praxial platforms	within ±60 μrad, ±200 μrad, ±80 μrad around x-, y-, z-axes with chamber coord. axes, orthog. ±100 μrad× cross plate length	store data	central	after each glueing step (initially); tolerances include accuracy of reconstruction of thermal and gravitational deformations with the in-plane system
Angular alignment of projective platforms	within ±200 μrad, ±80 μrad, ±80 μrad around x-, y-, z-axes with chamber coordinate axes	store data	central	tolerances include accurcay of reconstruction of thermal and gravitational deformations with the in-plane system

Table 7: Quality control tests of all assembled chambers at the production sites

Test	Acceptance criteria	Reaction if failed	Data base	Comment
Mechanical Tests				
Sag of chamber on kinematical supports before sag compensation		store data	central	y readings of in-plane monitors
Sag of chamber on kinematical supports after sag compensation	within $\pm 20\ \mu$m of nominal wire sag	adjust sag compensation until within tolerance, store data	central	y readings of in-plane monitors
Deformation of cross plates on kinematical supports (**recommended for BM, BO**)	$< 20\ \mu$m	store data	central	with temporary cross plate sag monitors and FEA model
Rel. angular alignment of alignment platforms on kinematical supports after sag compensation, with 1 and 3 bar pressure	see Table 6	store data	local	tolerances include accuracy of reconstruction of thermal and gravitational deformations with the in-plane system (measurements as during assembly)

Table 8: Quality control tests of all assembled chambers at the production sites (cont.)

Test	**Acceptance criteria**	**Reaction if failed**	**Data base**	**Comment**
Operation Tests				
Gas pressure test at 3 bar overpressure	test done, no obvious leaks	repair gas manifold, repair/disconnect faulty tubes, store ID	central	
Gas leak rate at 2 bar overpressure	less than 2×10^{-8} bar l/s per tube	repair gas manifold, repair/disconnect faulty tubes, store ID	central	after pressure test
HV stability: leakage current	less than 2 nA/m +5 nA per channel	replace electronics boards; identify, sputter/disconnect faulty drift tubes, store ID	central	with installed electronics boards, baseline gas at 3 bar and nominal and 8× nominal gas gain
HV stability: cosmic count rate (**optional**)	within $\pm 3\sigma$ of nominal value	identify noisy channels, store ID	local	with installed electronics boards, baseline gas at 3 bar and nominal gas gain
Operation in cosmic ray test stand	evaluation of performance: noise level, efficiency, random rate, max. drift time, resolution vs. x, uniformity, local wire displacement, stable performance of all channels over 1–2 weeks	make chamber operational, store ID of faulty tubes	local	with test electronics, baseline gas at 3 bar and nominal gas gain
Wire location measurement with cosmic rays (**optional**)	no systematic deviations from expected wire grid	store wire location data incl. meas. errors, adjust assembly tooling	central	track reconstruction in cosmic ray tower

Table 9: Quality control tests of all assembled chambers after transport to CERN and during storage

Test	**Acceptance criteria**	**Reaction on failure**	**Data base**	**Comment**
Visual inspection	no visible damage	perform possible repairs, mark chamber for X-ray tomograph and full leak test		acceptance test after transport to CERN
Gas leak rate at 3 bar	less than 2×10^{-8} bar l/s per tube	repair gas manifold, repair/disconnect faulty tubes, store ID	central	1: full leak test for one chamber per transport to CERN (acceptance test) or if visible damage of chamber 2: monitoring of pressure (at known temperature) over storage time
HV stability: leakage current	less than 2 nA/m +5 nA per channel	replace electronics boards; identify, disconnect faulty tubes, store ID	central	after mounting of final electronics, with baseline gas at 3 bar and nominal and 2× nominal gas gain
Operating test	evaluation of performance: pulser test (correct connections), signals from all channels, noise level, random rate, uniformity	replace electronics, make chamber operational	local	after mounting of final electronics, with baseline gas at 3 bar and nominal operating conditions

Table 10: Quality control tests of selected chambers from each production site after transport to CERN and during storage

Test	**Acceptance criteria**	**Reaction on failure**	**Data base**	**Comment**
Wire location measurement with X-ray tomograph (incl. location of wire on the alignm. platforms)	±20 μm rms in y and z with respect to the expected wire grid	store wire location data and chamber ID, adjust assembly tooling in case of deviations, measure chambers since problem first detected	central	1: sample test/production site 2: for chambers with expected mechanical problems
Wire tension (from oscillation frequency meas.)	within ±5% of the nominal tension value at given temperature	store data, notify production sites, measure other chambers	central	for one chamber/production site at regular intervals over storage time (temperature meas. to ±1°C)
Tube ground contact resistance (for 5 mA current)	less than 100 mΩ per endplug	store data, notify production sites, measure other chambers	central	for one chamber/production site at regular intervals over storage time

7.7 Chamber Test Program at the Production Sites

1 Install chamber in leak, high voltage and cosmic ray test stand with kinematic supports as in ATLAS.

2 Chamber pressure test.

  2.1 Connect gas supplies.

  Fill chamber with Argon or N_2 to 4 bar pressure.

  Identify and repair obvious leaks, disconnect faulty tubes. Store ID of faulty/repaired tubes in data base (central). ⟶ DB

  If no obvious leaks, reduce gas pressure to 3 bar.

3 Chamber leak test.

  3.1 Monitor changes of gas pressure and temperature difference of the chamber with respect to a reference volume with a differential manometer in intervals of 12 hours over several (2-10) days depending on sensitivity of the temperature and pressure measurements.

  3.2 Calculate leak rate limit from temperature-corrected pressure drop in the chamber.

  Stop when required leak rate limit is reached.

  If required leak rate limit is not reached after the time period expected from the measuring sensitivity: identify and repair leaks, disconnect faulty tubes. Repeat leak test from 3.1.

  After successful leak test: store leak rate limit in data base (central). ⟶ DB

4 After start of leak test with no obvious leaks detected: Install hedgehog boards (already tested individually).

Boards are installed properly cleaned using gloves.

5 Install mezzanine cards with test electronics; connect to DAQ system.

7 Store all optical monitor and temperature sensor readings in data base (local). ⟶ DB

Store longitudinal in-plane monitor y-readings (gravitational sags of the chamber) before sag adjustment in data base (central). ⟶ DB

8 Compensate sags of the chamber with the sag compensation systems of the two long beams.

9 Store all optical monitor and temperature sensor readings in data base (local). ⟶ DB

Store longitudinal in-plane monitor y-readings (gravitational sags of the chamber) after sag adjustment in data base (central). ⟶ DB

Read all optical monitors and temperature sensors on the chamber continuously during chamber tests.

10 Measure relative angular alignment of alignment platforms with optical angle monitors as during assembly at 1 and 3 bar gas pressure.

11 High voltage stability and operating test with installed readout electronics.

  11.1 Fill chamber with baseline gas to 3 bar.

  Operate chamber at baseline operating point within tolerances.

  11.2 Document gas composition and electronics settings in data base (local). ⟶ DB

  11.3 Monitor temperature, gas pressure, high voltage and chamber currents at each step.

11.4 Turn on high voltage: start at 1 kV below operating voltage, ramp up in 100 V steps until voltage corresponding to a gas gain of $16 \cdot 10^4$ is reached.

At each step, limit chamber currents to stay below 5 nA/tube.

If high voltage cannot be raised with this current limit: identify faulty channels.

If caused by electronics: replace boards.

If caused by drift tubes: disconnect tubes.

Record disconnected tube IDs in data base (central). ⟶ DB

11.5 At the nominal operating voltage: identify channels with cosmic count rate outside $\pm 3\sigma$ of nominal value.

Record noisy channel IDs in data base (central). ⟶ DB

11.6 Sputter faulty tubes due to leakage current.

Record sputtered tube IDs in data base (central). ⟶ DB

11.7 Repeat HV test from 10.4.

Record faulty tube IDs in data base (central). ⟶ DB

Store chamber currents and cosmic count rates at operating voltage and at voltage corresponding to a gas gain of 10^5 in data base with temperature, gas pressure and high voltage values (local). ⟶ DB

12 Operation of chamber in cosmic ray test stand at baseline operating point for at least one week.

12.1 Monitor temperature, high voltage, gas pressure, chamber currents, count rates and optical monitor readings continuously.

12.2 Evaluation of chamber performance.

Sensitive parameters among others: noise level, tube efficiency, random rate, minimum and maximum drift time, local wire displacements, position resolution as function of x, uniformity.

Store in data base (local). ⟶ DB

Make chamber operational.

12.3 Optional: Reconstruction of global wire locations with reconstruction of cosmic ray tracks in tower of three chambers. ⟶ DB

13 Store optical monitor and temperature sensor readings on the chamber at the end of the chamber tests. ⟶ DB

14 Keep chamber filled and sealed with baseline gas at 3 bar during all future transport and storage.

Monitor temperature and gas pressure of the chamber.

7.8 Chamber Test Program at CERN

1 Acceptance test of chamber after arrival in the storage area at CERN:

1.1 Chambers are installed on their kinematical supports during storage.

1.2 Store optical monitor, temperature sensor and gas pressure readings on the chamber (after first arrival and after every future transport). ⟶ DB

1.3 Visual inspection of each chamber for visible damage; flag chambers for X-ray tomograph measurement and full leak test.

1.4 Leak test at 3 bar (as at the production sites) of one chamber per transport (acceptance test) or if incidences during transport or visible damage.

Store leak rate limit in data base (central). ⟶ DB

2 Wire location measurement with the X-ray tomograph at CERN:

- routinely for selected chambers as soon as possible after arrival of a transport to provide feedback to the production sites,
- for chambers with problems discovered during construction,
- for chambers with visible damage after transport.

2.1 Install chamber in the X-ray tomograph on the kinematical supports and rails as in the ATLAS detector.

Compensate chamber gravitational sag as specified for horizontal chambers.

2.1.1 Handling and transport of chambers at CERN only with supervisor nominated by production site present.

2.1.2 Transport of chamber in special transport frame provided by production site.
Handling of chamber with tooling provided by production sites.

2.2 Monitor optical monitor and temperature sensor readings on the chamber during measurements in the X-ray tomograph. ⟶ DB

2.3 X-ray scans: close to each end of the chamber (including wires on alignment platforms) and at the ends of cut outs.

Repeat each scan to check reproducibility.

Store reconstructed wire coordinates (y and z at x-position of scan) for each scan in data base with temperature and optical monitor readings (central). ⟶ DB

3 Monitor gas pressure (with temperature) of the chamber during storage time.

Store data in data base (local). ⟶ DB

4 High-voltage and operating test after installation of final readout electronics (already tested individually):

4.1 Document electronics settings in data base. ⟶ DB

4.2 Monitor temperature, gas pressure, high voltage and chamber currents at each step.

4.3 Turn on high voltage: start at 1 kV below operating voltage, ramp up in 100 V steps until voltage corresponding to a gas gain of $1.6 \cdot 10^5$ is reached.

At each step: limit current to stay below 5 nA/channel.

If high voltage cannot be raised with this current limit: identify faulty channels.

If caused by electronics: replace boards.

If caused by drift tubes: disconnect tubes if voltage cannot be raised to nominal value.

Record faulty tube IDs in data base (central). ⟶ DB

4.4 Store chamber currents at operating voltage and at voltage corresponding to a gas gain of $1.6 \cdot 10^5$ in data base with temperature, gas pressure and high voltage values (local). ⟶ DB

4.5 Operating test of final electronics setup:

Pulser test of connections, signals in all channels, random rate, evaluation of noise level and uniformity.

Store in data base (local). ⟶ DB

Make chamber operational.

5 Store optical monitor and temperature sensor readings on the chamber before transport to ATLAS cavern for detector installation (central). ⟶ DB

8 Chamber Transport and Storage

Chambers are transported and stored in the following condition:

1. The chambers are transported and stored with Faraday cages (protection of the endplugs) and protective covers (protection of the tubes) installed.
2. The chambers are transported and stored suspended on their kinematical supports in a special frame inside a closed container.
3. After test at the production sites, the chambers are kept filled with the baseline gas at 3 bar during all further transport and storage.
4. The chambers are enclosed in an air-tight plastic bag containing dehumidifier bags.
5. The temperature of the chambers is monitored during transport and storage.

   Temperature gradients on the chamber must not exceed 10°C during transport and storage to prevent mechanical deformations.
6. During transport, only temperature variations in the range 0 – 50°C are allowed.

   (This means that the wire tension can increase temporarily by up to 45 g (1.5 g/°C) compared to the nominal tension of 350 g at 20°C, i.e. by 13%. The supports in the transport frame have to be able to cope with length variations of the chambers of up to 0.5 cm.)
7. During storage, the temperature has to stay within the range 10 – 30°C.
8. Shocks are limited during transport and are monitored during transports to CERN.

8.1 Local Chamber Storage and Transport to CERN

1 Dismount test electronics (mezzanine cards only).

2 Install chamber in local storage and transport frame.

3 Store all optical monitor and temperature sensor readings after installation in transport frame. ⟶ DB

4 Chamber stays filled with baseline gas at 3 bar during transport and storage.

5 Enclose chamber air-tight in plastic bag.

6 Monitor temperature and humidity in storage room. Protect chambers from temperature gradients.

7 Monitor gas pressure during storage with cheap manometer on the chamber. ⟶ DB

8 Store optical monitor, temperature sensor and gas pressure readings before transport to CERN. ⟶ DB

9 Transport, load, unload chambers according to handling instructions (only with certified supervisor present).

Monitor temperature on the chamber and record shocks during transport.

8.2 Chamber Transport and Storage at CERN

1 Transport chamber to storage area at CERN. Load, unload chamber according to handling instructions (only with certified supervisor present).

Transport in transport frame.

2 Store chamber in transport frame.

Store all optical monitor and temperature sensor readings immediately after installation of chamber in storage area. ⟶ DB

3 Enclose chamber air-tight in plastic bag during storage and transport.

4 Leak test of the chamber with the baseline gas at 3 bar immediately after installation in the storage area (as 10.8).

5 Monitor temperature and humidity in storage room. Protect chambers from temperature gradients.

6 Monitor gas pressure during storage with the cheap manometer on the chamber.

⟶ DB

7 After arrival of final electronics boards: install on stored chambers and connect to DAQ.

8 High-voltage and operating test with installed electronics boards (as 10.9).

9 Store all optical monitor and temperature sensor readings before transport to ATLAS cavern for detector installation. ⟶ DB

9 Monitoring of Chamber Production

The quality control data for chamber materials, drift tube production and chamber construction will be stored in the production data base in order to monitor the production and identify the source of problems at each production site and for the whole collaboration. It is important to keep track of the history and time relations of the quality control and monitoring measurements performed during chamber construction. Each individual tube is identified by a bar code which is read directly into the data base with a bar code scanner everytime the tube is handled in the construction process.

9.1 Central Production Data Base

Data relevant for the global monitoring of the chamber production and for the later operation of the chambers are kept in the central production data base. Each production site is required to report the necessary data as soon as they are available. The data base will be implemented using the Microsoft ACCESS package, a relational data base for Windows, and will be maintained by the Rome MDT group. The content and structure of the central data base as far as quality control information is concerned are described in Table 11. An ACCESS data base template and instructions for the implementation are available at

http://mulflx.roma1.infn.it/atlas/rmwork.

In the ACCESS data base structure, each object is associated with a table. The following objects have been defined for the central MDT production data base: 'Tube', 'Layer', 'Multilayer', 'Spacer' and 'Chamber' tables. The rows of the table correspond to the different data entries related to the object ('items') and the columns ('fields') contain the data associated with each item. Relationships between different tables are defined via a common field ('primary key') in the linked tables.

9.2 Local Production Data Base

The history of the quality control tests and the full monitoring data (see the **Assembly Control Plan** in the **Appendix**) have to be kept in the local production data bases of the production sites. These data are essential for reference and tracing of problems. It is recommended to keep as much information as possible. The suggested minimum content with a possible ACCESS structure of the local data base is described in Table 12. A template for implementation in ACCESS is available at

http://mulflx.roma1.infn.it/atlas/rmwork.

The **Assembly Control Program** communicates directly with the local ACCESS data base.

Table 11: Contents and structure of the central production data base (includes only drift tubes accepted after the drift tube quality control tests)

CENTRAL DATA BASE

DRIFT TUBE Table

No.	**Data field**	**Format**	**Description**
1	Tube identifier	Number	Bar code: unique number, prod. date and batch no., length; **Link** to TUBE Table
2	Layer identifier	Number	**Link** to LAYER Table
3	Tube no. in layer	Number	
4	Date/time, start tube assembly	Date/time	
5	Tube assembly site	Text	
6	Endplug identifier	Number	Supplier, production batch no.
7	Wire identifier	Number	Supplier, production batch no.
8	Tube temperature, wiring [°C]	Number	Average during tube assembly
9	Date/time, start tube QC 1	Date/time	Shortly after tube assembly
10	Tube QC 1 site	Text	
11	Wire frequency 1 [Hz]	Number	
12	Tube temperature, QC 1 [°C]	Number	During wire frequency measurement 1
13	Wire y displacement, side A [μm]	Number	From center of the endplug reference surface
14	Wire z displacement, side A [μm]	Number	
15	Wire y displacement, side B [μm]	Number	
16	Wire z displacement, side B [μm]	Number	
17	Wire y displacement, side A (180°) [μm]	Number	After inversion of tube by 180° with respect to initial orientation as on assembly combs (for X-ray method)
18	Wire z displacement, side A (180°) [μm]	Number	
19	Wire y displacement, side B (180°) [μm]	Number	
20	Wire z displacement, side B (180°) [μm]	Number	
21	Gas leak rate [10^8 bar l/s]	Number	
22	Leakage current [nA]	Number	HV stability test
23	Cosmic count rate [Hz]	Number	HV stability test **(optional)**
24	Date/time, start tube QC 2	Date/time	Wire frequency measurement 2
25	Tube QC 2 site	Text	Wire frequency measurement 2
26	Wire frequency 2 [Hz]	Number	After 2 months, before chamber assembly
27	Tube temperature, QC 2 [°C]	Number	During wire frequency measurement 2
28	Disconnected tube code (leak)	Number	After chamber leak test
29	Disconnected tube code (high voltage)	Number	After chamber HV test

Table 11: Contents and structure of the central production data base (cont.)

LAYER Table

No.	Data field	Format	Comment
1	Layer identifier	Number	Unique number
2	Multilayer identifier	Number	**Link** to MULTILAYER Table
3	Date/time layer assembly	Date/time	Layer assembly completed
4	Relative Humidity [%]	Number	Average during glue curing
5	Temperature comb HV side [°C]	Number	Average during glue curing
6	Temperature comb RO side [°C]	Number	Average during glue curing
7	In-plane monitor 1, y reading [mm]	Number	Before glueing (lens displacement)
8	In-plane monitor 1, z reading [mm]	Number	Before glueing (lens displacement)
9	In-plane monitor 1, magnification	Number	Before glueing
10	In-plane monitor 1, angle θ_x [mrad]	Number	Before glueing
11–14	In-plane monitor 2, 4 readings	Number	After glue curing
15–18	In-plane monitor 3, 4 readings	Number	After glue curing
19–22	In-plane monitor 4, 4 readings	Number	After glue curing

MULTILAYER Table

No.	Data field	Format	Comment
1	Multilayer identifier	Number	Unique number
2	Chamber identifier	Number	**Link** to CHAMBER Table

SPACER Table

No.	Data field	Format	Comment
1	Chamber identifier	Number	**Link** to CHAMBER Table
2	Date/time spacer assembly	Date/time	Spacer assembly completed
3	In-plane monitor 1, y reading [mm]	Number	After glue curing for spacer assembly
4	In-plane monitor 1, z reading [mm]	Number	
5	In-plane monitor 1, magnification	Number	
6	In-plane monitor 1, angle θ_x [mrad]	Number	
7–10	In-plane monitor 2, 4 readings	Number	After glue curing
11–14	In-plane monitor 3, 4 readings	Number	After glue curing
15–18	In-plane monitor 4, 4 readings	Number	After glue curing

Table 11: Contents and structure of the central production data base (cont.)

CHAMBER Table

No.	**Data field**	**Format**	**Comment**
1	Chamber identifier	Number	Unique number (TDR naming scheme)
2	Date/time, end chamber assembly	Date/time	Chamber completed
3	Chamber production site	Text	
4	In-plane monitor 1, mask angle θ_x [mrad]	Number	RASNIK calibration: angular orientation of the mask with respect to the granite table
5	In-plane monitor 2, mask angle θ_x [mrad]	Number	
6	In-plane monitor 3, mask angle θ_x [mrad]	Number	
7	In-plane monitor 4, mask angle θ_x [mrad]	Number	
8	In-plane monitor 1 zero, y reading [mm]	Number	RASNIK zero readings (lens displacement): taken during assembly as reference for chamber operation
9	In-plane monitor 1 zero, z reading [mm]	Number	
10	In-plane monitor 1 zero, magnification	Number	
11	In-plane monitor 1 zero, angle θ_x [mrad]	Number	
12–15	In-plane monitor 2 zero, 4 readings	Number	RASNIK zero readings
16–19	In-plane monitor 3 zero, 4 readings	Number	RASNIK zero readings
20–23	In-plane monitor 4 zero, 4 readings	Number	RASNIK zero readings
24–41	Angles $\theta_{x,y,z}$ [mrad] of alignment platforms with respect to assembly table	Number	For axial/praxial and projective platforms
42	Chamber test site	Text	
43–58	In-plane monitor readings, before sag comp.	Number	On kinematical supports
59–74	In-plane monitor readings, after sag comp.	Number	On kinematical supports
75	Date/time chamber leak test	Date/time	Leak test completed
76	Chamber gas leak rate [10^8 bar l/s]	Number	At production site
77	Date/time chamber leak test, CERN	Date/time	Leak test completed
78	Chamber gas leak rate [10^8 bar l/s], CERN	Number	Acceptance test at CERN
79	Date/time HV test	Date/time	Test completed at prod. site
80	Date/time HV test, CERN	Date/time	Test completed at CERN

Table 12: Contents and structure of the local production data base (min. recommendation)

LOCAL DATA BASE

DRIFT TUBE Table

No.	Data field	Format	Description
1	Tube identifier	Number	Bar code: unique number, prod. date and batch no., length; **Link** to TUBE Table
2	Layer identifier	Number	**Link** to LAYER Table
3	Tube no. in layer	Number	
4	Date/time, start tube assembly	Date/time	**Link** to WIRING SETUP Table
5	Date/time, end tube assembly	Date/time	
6	Tube assembly site	Text	
7	Operator team, wiring	Text	
8	Room temperature, wiring [°C]	Number	Average during tube assembly
9	Relative humidity, wiring [%]	Number	Average during tube assembly
10	Tube temperature, wiring [°C]	Number	Average during tube assembly
11	Endplug identifier	Number	Supplier, production batch no.
12	Wire identifier	Number	Supplier, production batch no.
13	Tube rejection code, wiring	Number	
14	Date/time, start tube QC 1	Date/time	Shortly after tube assembly; **Link** to TUBE QC SETUP Table
15	Date/time, end tube QC 1	Date/time	
16	Tube QC 1 site	Text	
17	Operator team, QC 1	Text	
18	Room temperature, QC 1 [°C]	Number	Average during tube assembly
19	Relative humidity, QC 1 [%]	Number	Average during tube assembly
20	Wire frequency 1 [Hz]	Number	
21	Tube temperature, QC 1 [°C]	Number	During wire frequency measurement 1
22	Wire y displacement, side A [μm]	Number	From center of the endplug reference surface
23	Wire z displacement, side A [μm]	Number	
24	Wire y displacement, side B [μm]	Number	
25	Wire z displacement, side B [μm]	Number	
26	Wire y displacement, side A (180°) [μm]	Number	After inversion of tube by 180° with respect to initial orientation as on assembly combs (for X-ray method)
27	Wire z displacement, side A (180°) [μm]	Number	
28	Wire y displacement, side B (180°) [μm]	Number	
29	Wire z displacement, side B (180°) [μm]	Number	
30	Gas leak rate [10^8 bar l/s]	Number	
31	Leakage current [nA]	Number	HV stability test
32	Cosmic count rate [Hz]	Number	HV stability test **(optional)**
33	Date/time, start QC 2	Date/time	Wire frequency measurement 2
34	Tube QC 2 site	Text	Wire frequency measurement 2
35	Wire frequency 2 [Hz]	Number	After 2 months, before chamber assembly
36	Tube temperature, QC 2 [°C]	Number	During wire frequency measurement 2
37	Disconnected tube code (leak)	Number	After chamber leak test
38	Disconnected tube code (high voltage)	Number	After chamber HV test

Table 12: Contents and structure of the local production data base (cont.)

LAYER Table			
No.	**Data field**	**Format**	**Comment**
1	Layer identifier	Number	Unique number
2	Multilayer identifier	Number	**Link** to MULTILAYER Table
3	Date/time, start layer assembly	Date/time	
4	Date/time, start glue distribution	Date/time	
5	Date/time, end glue distribution	Date/time	
6	Date/time, start layer glueing	Date/time	
7	Date/time, end layer glueing	Date/time	
8	Operator team, assembly	Text	
9	Room temperature [°C]	Number	Average during glue curing
10	Relative Humidity [%]	Number	
11	Temperature comb HV side [°C]	Number	
12	Temperature comb RO side [°C]	Number	
13	Temperature cross plate HV side [°C]	Number	
14	Temperature cross plate RO side [°C]	Number	
15	Vacuum underpressure [bar], minimum	Number	During glue curing
16	Vacuum underpressure [bar], maximum	Number	During glue curing
17–24	Force measurements 1–8 [kg]	Number	At start glueing
25	In-plane monitor 1, y coord. [mm]	Number	At start glueing (lens displacement)
26	In-plane monitor 1, z coord. [mm]	Number	At start glueing (lens displacement)
27	In-plane monitor 1, magnification	Number	At start glueing
28	In-plane monitor 1, angle θ_x [mrad]	Number	At start glueing
29–32	In-plane monitor 2, 4 readings	Number	At start glueing
33–36	In-plane monitor 3, 4 readings	Number	At start glueing
37–40	In-plane monitor 4, 4 readings	Number	At start glueing
41	Cross plate monitor (HV), y coord. [mm]	Number	At start glueing (lens displacement)
42	Cross plate monitor (HV), z coord. [mm]	Number	
43	Cross plate monitor (RO), y coord. [mm]	Number	
44	Cross plate monitor (RO), z coord. [mm]	Number	
45–52	Sphere monitor 1–4, y, z coord. [mm]	Number	At start glueing (mask displacement)
53–56	In-plane monitor 1, 4 readings	Number	After glue curing (lens displacement)
57–60	In-plane monitor 2, 4 readings	Number	
61–64	In-plane monitor 3, 4 readings	Number	
65–68	In-plane monitor 4, 4 readings	Number	
69–72	Cross plate monitor (RO-, HV-side), y and z readings [mm]	Number	
73–80	Sphere monitor 1–4, y, z coord. [mm]	Number	After glue curing (mask displacement)

Table 12: Contents and structure of the local production data base (cont.)

MULTILAYER Table			
No.	**Data field**	**Format**	**Comment**
1	Multilayer identifier	Number	Unique number
2	Chamber identifier	Number	**Link** to CHAMBER Table

SPACER Table			
No.	**Data field**	**Format**	**Comment**
1	Chamber identifier	Number	**Link** to CHAMBER Table
2	Date/time, start spacer assembly	Date/time	
3	Date/time, end spacer assembly	Date/time	Spacer completed
4	Operator team, spacer	Text	
5	In-plane monitor 1, y reading [mm]	Number	After glue curing for spacer assembly
6	In-plane monitor 1, z reading [mm]	Number	
7	In-plane monitor 1, magnification	Number	
8	In-plane monitor 1, angle θ_x [mrad]	Number	
9–12	In-plane monitor 2, 4 readings	Number	After glue curing
13–16	In-plane monitor 3, 4 readings	Number	After glue curing
17–20	In-plane monitor 4, 4 readings	Number	After glue curing

Table 12: Contents and structure of the local production data base (cont.)

CHAMBER Table

No.	Data field	Format	Comment
1	Chamber identifier	Number	Unique number (TDR naming scheme)
2	Date/time, start chamber assembly	Date/time	**Link** to ASSEMBLY SETUP Table
3	Date/time, end chamber assembly	Date/time	Chamber completed
4	Chamber production site	Text	
5–6	Cross plate monitor (HV) zero, y, z reading	Number	RASNIK zero readings (lens displacement)
7–8	Cross plate monitor (RO) zero, y, z reading	Number	
9	In-plane monitor 1, mask angle θ_x [mrad]	Number	RASNIK calibration: angular orientation of the mask with respect to the granite table
10	In-plane monitor 2, mask angle θ_x [mrad]	Number	
11	In-plane monitor 3, mask angle θ_x [mrad]	Number	
12	In-plane monitor 4, mask angle θ_x [mrad]	Number	
13	In-plane monitor 1 zero, y reading [mm]	Number	RASNIK zero readings (lens displacement): taken during assembly as reference for chamber operation
14	In-plane monitor 1 zero, z reading [mm]	Number	
15	In-plane monitor 1 zero, magnification	Number	
16	In-plane monitor 1 zero, angle θ_x [mrad]	Number	
17–20	In-plane monitor 2 zero, 4 readings	Number	RASNIK zero readings
21–24	In-plane monitor 3 zero, 4 readings	Number	RASNIK zero readings
25–28	In-plane monitor 4 zero, 4 readings	Number	RASNIK zero readings
29–46	Angles $\theta_{x,y,z}$ [mrad] of alignment platforms with respect to assembly table	Number	For axial/praxial and projective platforms
47	Chamber test site	Text	
48	Operator team, chamber test	Text	
49–64	In-plane monitor readings, before sag comp.	Number	On kinematical supports
65–80	In-plane monitor readings, after sag comp.	Number	On kinematical supports
81	Date/time chamber leak test	Date/time	Leak test completed
82	Chamber gas leak rate [10^8 bar l/s]	Number	At production site
83	Date/time chamber leak test, CERN	Date/time	Leak test completed
84	Chamber gas leak rate [10^8 bar l/s], CERN	Number	Acceptance test at CERN
85	Date/time HV test	Date/time	Test completed at prod. site
86	Date/time HV test, CERN	Date/time	Test completed at CERN
87	Date/time, start cosmic ray test	Date/time	
88	Date/time, end cosmic ray test	Date/time	

Table 12: Contents and structure of the local production data base (cont.)

WIRING SETUP Table			
No.	**Data field**	**Format**	**Comment**
1	Date/time, start tube assembly	Date/time	
2	Tube crimping HV [V] /pressure [bar]	Number	
3	Wire crimping pressure [bar]	Number	
4	Wire pretension value [g]	Number	
5	Wire pretension time [s]	Number	
6	Wire tension value [g]	Number	

TUBE QC SETUP Table			
No.	**Data field**	**Format**	**Comment**
1	Date/time, start tube QC 1	Date/time	

ASSEMBLY SETUP Table			
No.	**Data field**	**Format**	**Comment**
1	Date/time, start chamber assembly	Date/time	
2	Nominal vacuum underpressure [bar]	Number	
3-50	Force 1–8 [kg] for force compensation, (layer 1–6)	Number	Calculated settings as fct. of tube layer glued
51–54	Angle θ_x of mask sphere monitor 1–4	Number	Calibration rel. to table

CHAMBER PARAMETERS Table			
No.	**Data field**	**Format**	**Comment**
1	Chamber identifier	Number	**Link** to CHAMBER Table
2	Tube length [mm]	Number	
3	Number tubes/layer	Number	

Appendix:

Assembly Control Plan for BOS MDT Chambers

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page 1 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
1	**Preparation of Chamber Components**					
	Quality Control of Chamber Components at Production Site					
1.1	Certification of drift tubes	QA/QC Manual	Check test results, visual inspection	Accept/reject tubes, DB entry with bar code	QA/QC Manual	Production Manager
1.2	Certification of spacer parts	QA/QC Manual	Check QC docs. of firm, dimensions, visual inspection	Accept/reject parts	Spacer spec. doc.	Production Manager
1.3	Certification of RASNIK elements for in-plane alignm.	QA/QC Manual	Check QC docs. of firm, test readout, visual inspection	Accept/reject components	RASNIK spec. doc.	Production Manager
1.4	Certification of T and B-field sensors	QA/QC Manual	Check QC docs. of firm, test readout, visual inspection	Accept/reject components	Sensor spec. doc.	Production Manager
1.5	Certification of glue supplies	QA/QC Manual	Check storage time and conditions	Accept/reject glue	Glue supplier specs.	Production Manager
1.6	Certification of Faraday cage parts, patch panel, protective covers	QA/QC Manual	Check QC docs. of firm, dimensions, visual inspection	Accept/replace parts		Production Manager
1.7	Certification of alignment platforms	QA/QC Manual	Check QC docs. of firm, visual inspection	Accept/replace parts	Alignm. specs.	Production Manager
1.8	Certification of gas manifolds, gas distribution bars, connections	QA/QC Manual	Check QC docs. of firms, dimensions, visual inspection	Accept/reject parts	Gas Syst. Manual	Production Manager
1.9	**Store all chamber and jigging components in the assembly room**	Assembly Manual	Store all components at least 12 hours before assembly, clean all components before storage in clean room	Adapt to the assembly room temp.	QA/QC Manual	Operator 3
	Preassembly of Chamber Components in Assembly Room					
1.10	Install and adjust sag compensation system on long beams	Assembly Manual	Test functionality		Assembly Manual	Operator 3
1.11	Mount sphere holders with spheres and sphere monitors on the cross plates	Assembly Manual	Stable fixation, measure position in y	Sphere pos. in y within tolerances (for glue gap)	Assembly Manual	Operator 3

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page** **2 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
1.12			Mark on cross plates and long beams location and orientation		Assembly Manual	Production Manager
1.13			Mark on all RASNIK elements identifier and orientation	Correct corresponendce with readout	Monitoring Manual	Production Manager
1.14	Mount temp. RASNIK monitors on HV and RO cross plates	Assembly Manual	Stable mounting as marked, position adjustment, working readout	Sharp, analyzable images of mask center	Monitoring Manual	Production Manager
1.15	Install in-plane RASNIK monitors comp. on cross plates	Assembly Manual	Stable mounting as marked, position adjustment, working readout		Monitoring Manual	Production Manager
1.16	Install patch panel on spacer	Assembly Manual				Production Manager
1.17	Assemble gas manifolds and distr. bars on their jigs	Gas Syst. Manual	Leak test of the assembled systems, test of gas flows	Accept/repair	Gas Syst. Manual	Production Manager

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page** **3 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
2	**Spacer Assembly and Installation of Optical Monitors**					
	Assembly of the Spacer					
2.1	**Start chamber assembly monitoring and control program**	Assembly Manual	Enter date, time, production manager in charge, operator team	Control program returns param. of chamber	Monitoring Manual	Production Manager
2.2	**Mount interfaces no. 1 on sphere support towers**	Assembly Manual	Interfaces correspond to towers as labelled	Optimum equal tower height	Assembly Manual	Operator 3
2.3	**Zero-readings of cross plate sag monitors**	Assembly Manual	Watch stability of monitor readings. Define zero reference.	Store in **DB** (average of last 5 readings)	Monitoring Manual	Production Manager
2.4			Measure glue gap betw. tubes and the cross plates positioned on the corresponding sphere towers in both orientations around the z-axis using rods inserted in the combs	Accept/reject cross plate, **DB** entry	Assembly Manual	Production Manager
2.5	Position middle cross plate on middle towers with square brackets	Assembly Manual	Positioning as marked on the cross plate and within tolerances (DB). Check positioning of in-plane monitor lenses.		Assembly Manual	Operator 3
2.6	Insert long beams through holes in middle cross plate, support them temp.	Assembly Manual	Positioning as marked on the long beams and within tolerances (DB)		Assembly Manual	Operator 3
2.7	Position outer cross plates on towers with square brackets with long beams inserted	Assembly Manual	Positioning as marked on the cross plate and within tolerances (DB). Check that HV- and RO-side correct.		Assembly Manual	Operator 3
2.8	Adjust distances between pairs of cross plates	Assembly Manual	Nominal values and tolerances (±1 mm) from DB		Assembly Manual	Production Manager
2.9	Adjust distances at the extremities of the outer cross plates	Assembly Manual	Nominal values and tolerances (±0.5 mm) from DB		Assembly Manual	Production Manager
2.10			Test sphere monitors: correct positioning and readout	Sharp, analyzable images of the masks	Monitoring Manual	Production Manager
2.11	**Install temperature sensors on the spacer at the specified pos., fix permanently with Ciba Geigy Araldite 2012**	Assembly Manual	Test readout. Glue curing for at least 1.5 hours. Used also for temperature monitoring during assembly.	Replace faulty sensors or cables.	Monitoring Manual	Production Manager

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page** **4 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
2.12			Start continuous reading of all optical temperature and environmental monitors	Store online in histograms, autom. warnings if parameters out of range	Monitoring Manual	Production Manager
2.13	Insert bars of force compensation system through holes in long beams	Assembly Manual	Stable attachment to long beams		Assembly Manual	Operator 3
2.14	**Compensate sag of long beams with automatic force compensation system**	Assembly Manual	Watch convergence to predefined pneumatic pressure and force values	Store pressure, force and temp. meas. in **DB** after convergence	Monitoring Manual	Production Manager
2.15			Verify correct alignment of sphere monitors, adjust if necessary	Sharp analyzable images of mask center	Monitoring Manual	Production Manager
2.16	Glue and bolt long beams to cross plates (glue: Ciba Geigy Araldite 2014)	Assembly Manual	Prepare glue test sample for monitoring of glue curing		QA/QC Manual	Operator 3
	Preparation of Optical Monitoring Systems					
2.17			Connect in-plane monitors, adjust position and test	Sharp, analyzable images of mask center	Monitoring Manual	Production Manager
2.18	Glue elements of in-plane monitors in place (glue: Araldite 2012)	Assembly Manual	Long-term fixation of in-plane monitors. Curing of glue for minimum 1.5 hours. Paint screws and nuts.	No touching and movements of RASNIK elements after zero-readings	QA/QC Manual	Operator 3
2.19			Calibration of angular orientations of masks of in-plane monitors with respect to granite table by moving middle cross plate on the towers in z. Remove pistons of force compensation.	Better than 10 mrad angle calib. accuracy. Store in **DB**.	Assembly Manual	Production Manager
2.20	Regular calibration of sphere monitors: angular orientation of CCDs with respect to granite table	Assembly Manual	Repeat for every 4^{th} chamber (automatic reminder), identify cause of warning	Store in **DB**, warning if change	Monitoring Manual	Production Manager
2.21			Zero readings of sphere monitors (reference for assembly)	Store in **DB** with date/ time	Monitoring Manual	Production Manager

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page** **5 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
	Curing of Glue					
2.22	Start of glue curing		Check all monitor readings (optical, temperature, force comp., environmental)	Store in **DB** with date and time	QA/QC Manual	Production Manager
2.22.1	Curing of glue for minimum 12 hours	Assembly Manual	Automatic warnings if param. out of range, automatic fast recovery procedure in case of power failure	Climatization, force comp., monitoring and control cont. active	Assembly Manual	
2.22.2			In case of warnings or power failure: check all monitor readings immediately	Store in **DB** after recovery, correct deviations immediately	Assembly Manual	
2.22.3	End of glue curing		Visual inspection of spacer. Inspection of glue on the spacer. Evaluation of proper glue curing with test sample (shear strength).	If glue not properly cured: remove spacer, disassemble. Start new assembly at 1.1.	QA/QC Manual	
2.22.4			Check summary of monitor readings over night, automatic warnings if out of range Check all monitor readings.	Store in **DB**, with date/ time. Identify cause of warnings and resolve.	Monitoring Manual	
	Preparations for Zero-Readings of In-Plane Monitors					
2.23	Dismount square brackets from spacer and assembly table	Assembly Manual				Operator 3
2.24	Turn off force compensation system	Assembly Manual				Operator 3
2.25	Dismount temp. sag monitors and bars of force comp. system from long beams	Assembly Manual				Operator 3
2.26	Install plates for crane support at ends of long beams, mount crane bearings	Assembly Manual				Operator 3
2.27	Lift spacer and lower again in initial orientation, dismount crane bearings	Assembly Manual	Correct placement of spheres on towers	Avoid damage to chamber and jigging	Monitoring Manual	Operator 3
2.28			Check all monitor readings	Store in **DB** as input for zero readings of in-plane monitors	Monitoring Manual	Production Manager

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page 6 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
2.29	Mount crane bearings, lift spacer	Assembly Manual	Correct handling of crane	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
2.30	Rotate spacer by 180° around x and y axes	Assembly Manual				Operator 3
2.31	Lower spacer on towers in inverted orientation, dismount crane bearings	Assembly Manual	Correct handling of crane and positioning of spheres on towers	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
2.32			Check all monitor readings, automatic warnings if out of range, check sags of cross plates	Store in **DB**, correct positioning of spheres on towers	Monitoring Manual	Production Manager
2.33			Check autom. equal height of towers with in-plane and sphere monitors, compare with previous chambers	Correct deviations larger than $\pm 10\ \mu$m	Monitoring Manual	Production Manager
2.34			Check all monitor readings	Store in **DB** as input for zero-readings of in-plane monitors	Monitoring Manual	Production Manager
2.35	Preliminary zero-readings of in-plane monitors	Assembly Manual	Zero defined as average of readings in initial (2.28) and inverted (2.34) orientation	Store in **DB** with date and time	Monitoring Manual	Production Manager
	Fine-adjustment of Long Beams on Middle Cross Plate					
2.36	Mount crane bearings, lift spacer, rotate into vertical position	Assembly Manual	Correct handling of crane	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
2.37	**Fine-adjustment of long beams on the middle cross plate with sag compensation system**	Assembly Manual	Monitor deviations of longitudinal in-plane systems from zero: adjust to less than $\pm 10\ \mu$m	Minimum internal stresses of spacer	Monitoring Manual	Production Manager
2.38	Lower spacer on towers in initial orientation, dismount crane bearings	Assembly Manual	Correct handling of crane and positioning of spheres on towers	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
2.39			Measure sags of cross plates with cross plate monitors and in-plane system	Store all monitor readings in **DB**	Monitoring Manual	Production Manager
2.40	Mount crane bearings, lift spacer, rotate by 180° around x and y axes	Assembly Manual	Correct handling of crane	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
2.41	Lower spacer on towers in inverted orientation, dismount crane bearings	Assembly Manual	Correct handling of crane and positioning of spheres on towers	Avoid damage to chamber and jigging	Assembly Manual	Operator 3

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page 7 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
	Zero-Readings of In-Plane Monitors (Reference for Assembly)					
2.42			Measure sags of cross plates with cross plate monitors and in-plane system. Check that sags of cross plates in initial and inverted orientation are equal within ±5 μm	Store all monitor readings in **DB**. Warning if out of range: repeat adjustm. from step 2.36	Monitoring Manual	Production Manager
2.43	Mount crane bearings, lift spacer, rotate by 180° around x and y axes	Assembly Manual	Correct handling of crane	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
2.44	Lower spacer on towers in initial orientation	Assembly Manual	Correct handling of crane and positioning of spheres on towers. Afterwards: check all monitor readings.	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
2.45			Check all monitor readings	Store in **DB** as input for zero-readings of in-plane monitors	Monitoring Manual	Production Manager
2.46	Zero-readings of in-plane monitors (reference for assembly)	Assembly Manual	Zero defined as average of readings in initial (2.45) and inverted (2.42) orientation	Store in **DB** with date and time	Monitoring Manual	Production Manager
	Install Force-Compensation System					
2.47	**Insert bars of force compensation system through holes in long beams**	Assembly Manual	Stable attachment to long beams		Assembly Manual	Operator 3
2.48	Lift spacer	Assembly Manual	Correct handling of crane	Avoid damage to chamber and jigging	Assembly Manual	Operator 3

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page 8 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
3	**Assembly of Tube Layer 1 (Multilayer A, Outer Multilayer)**					
	Adjustment of Cross plate Sag Compensation					
3.1	Lower spacer on towers in initial orientation, dismount crane bearings, place defined weights on spheres	Assembly Manual	Correct handling of crane and positioning of spheres on towers	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
3.2			Check all monitor readings, automatic warnings if out of range, check sags of cross plates	Store in **DB**, correct pos. positioning of spheres on towers	Monitoring Manual	Production Manager
3.3			Check autom. equal height of towers with in-plane and sphere monitors, compare with previous chambers	Store in **DB**, correct deviations larger than ±10 μm	Monitoring Manual	Production Manager
3.4	**Compensate sag of cross plates with automatic force compensation system for 0 tube layers**	Assembly Manual	Watch convergence to predefined pneumatic pressure and force values	Store pressure, force and temp. meas. in **DB** after convergence	Monitoring Manual	Production Manager
3.4.1	**Verify compensation with cross plate sag monitors**	Assembly Manual	Cross plate monitor readings at zero within ±5 μm, in-plane monitor readings at zero, no lifting of spheres seen by sphere monitors, autom. warnings if monitors out of range	Store all mon. readings in **DB**, adjust force compensation if necessary	Monitoring Manual	
3.5	Remove weights, mount crane bearings, lift spacer	Assembly Manual	Correct handling of crane	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
	Insertion of Drift Tubes into Combs					
3.6	**Insert drift tubes in combs in predefined sequence one by one with vacuum off**	Assembly Manual	Use plastic gloves for all tube handling	Reliable bonding of the glue	QA/QC Manual	Operator 3
3.6.1	Take tube out of storage in assembly room, one operator at each end, read tube bar code	Assembly Manual	Check if visible damage of tube or endplugs	If o.k.: **DB** link to chamber. If damage: discard tube, **DB** entry	QA/QC Manual	
3.6.2	During tube insertion in combs		Check if dust or defects on combs	Clean or repair when necessary	QA/QC Manual	
3.6.3	Insert tube in combs holding it at both ends, position defined by clocking plate		Check if vacuum suction pads are damaged	Replace damaged suction pads	QA/QC Manual	

Production site:		Date:	Chamber type:	Chamber No.:		Page 9 of 17
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
	Control of Tube Placement on the Combs					
3.7	**Switch on vacuum suction in combs in defined sequence after tube insertion**	Assembly Manual	Detect vacuum leaks by noise, check manometer reading (automatic warning if out of range)	Repair leaks, reinsert tubes, adjust under , pressure, store reading in **DB**	Assembly Manual	Operator 3
3.7.1			Check that assembled tube length is within tolerances	Replace tube outside tol., **DB** entry	QA/QC Manual	
3.7.2			Visual inspection if tube walls are touching end combs	Replace tube if touching, **DB** entry	QA/QC Manual	
3.7.3			Check gap between adjacent endplugs on combs (visual inspection or with video camera)	Relocate one of the tubes if endplugs touching, **DB** entry	QA/QC Manual	
3.7.4			Visual inspection of gaps between endplug reference surfaces and end combs with illumination from behind	Reinsert vs. discard tube if gap, **DB** entry	QA/QC Manual	
3.7.5			Check gaps between adjacent tubes with illumination from below (visual inspection or with video camera)	Relocate tubes if more than 2 adjacent tubes touching, **DB** entry	QA/QC Manual	
3.7.6			Measure rel. heights of endplug reference surfaces on combs with laser or mechanical gauge: autom. warning if out of range	Reinsert vs. discard faulty tubes, check if dust or damage, store in **DB**	QA/QC Manual	
3.7.7			Automatic warning if vacuum under pressure out of range. If vacuum off: automatic restart within 10 s.	**DB** entry. Identify leak, adjust vacuum. If vacuum off: perform checks from step 3.7.1.	QA/QC Manual	
	Glue Distribution on Tube Layer					
3.8			Mark location of glue ropes for glueing to spacer on tube layer		Assembly Manual	Operator 3
3.9	**Glue distribution in gap between tubes with automatic glue dispenser**	Assembly manual, sect. x.x	Uniform glue distribution with controlled size, location and start/end of glue ropes ensured by settings of glue dispenser, stop glue ropes before tube crimp	Minimum amounts of glue to min. deform. due to shrinkage, no glue on jigging	Glueing Manual	Production Manager
3.9.1	Setup glue dispenser	Glueing manual	Check settings and positioning		Glueing Manual	
3.9.2	Premix glue (Ciba Geigy Araldite 2011), fill in glue dispenser reservoirs	Glueing manual	Check glue type, quality, storage time and conditions. Ensure immediate use.	Replace glue if bad. Store start time, temperature in **DB**	Glueing Manual	

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page 10 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
3.9.3	Start automatic glue distribution	Glueing manual	Check quality of glue distribution continuously, (visual inspection or with video camera). Glue dispenser runs only in presence of operator. Stop after first glue line for inspection.	Repairs with manual glue disp. (keep ready in assembly room).	Glueing manual	Production manager
3.9.4	Glue distribution: stop glue lines 2mm before crimp region at tube ends	Glueing manual	Automatic warning 10 min. before nominal glueing time (30 s per tube) and at maximum glue handling time (90 min.)	Replace glue after max. glue handling time exceeded, **DB** entry	Glueing manual	
3.9.5	End of glue distribution: dismount glue dispenser, clean in cleaning bath	Glueing manual		Store time, temperature in **DB**	Glueing manual	
	Glueing of Tube Layer to Spacer					
3.10	Distribute glue ropes (Ciba Geigy Araldite 2014) on top of tubes at marked pos. of cross plates with manual glue dispenser	Assembly Manual	Maximum glue handling time: 90 min.	Replace glue after max. glue handling time exceeded	Glueing Manual	Operator 3
3.11	Lower spacer on towers in initial orientation, dismount crane bearings, place defined weights on spheres	Assembly Manual	Correct handling of crane and positioning of spheres on towers. Force comp. acts instantaneously.	Avoid damage to chamber and jigging	Assembly Manual	Production Manager
3.11.1			Check all monitor readings (environmental, temperature, optical, vacuum, force comp.), automatic warnings if out of range	Store in **DB**. Identify problem, lift spacer carefully and adjust, cont. at 3.11.	Monitoring Manual, Assembly Manual	
	Curing of Glue					
3.12	Start of glue curing			Store date/time in **DB**	QA/QC Manual	Production Manager
3.12.1	Curing of glue for minimum 12 hours	Assembly Manual	Automatic warnings if param. out of range, automatic fast recovery procedure in case of power failure (within 10 min., vacuum: 10 s)	Vacuum, force comp., climatization, monitoring and control cont. active	Assembly Manual	
3.12.2			In case of warnings or power failure: check all monitor readings immediately. If vacuum failure: do checks 3.7.	Store in **DB** after recovery, correct deviations immediately	Assembly Manual	

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page 11 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
3.12.3	End of glue curing		Visual inspection of chamber. Inspection of glue on the spacer. Evaluation of proper glue curing with test sample (shear strength).	If glue not properly cured even after extended curing time: remove chamber and discard. Start with new assembly at 1.1.	QA/QC Manual	Production Manager
3.12.4			Check summary of monitor readings over night, automatic warnings if out of range. Check all monitor readings.	Store in **DB**, with date/ time. Identify cause of warnings and resolve.	Monitoring Manual	
3.12.5			Check if gaps between endplug reference surfaces and combs with illumination from behind (glue shrinkage effects)	Entry in **DB**	Monitoring Manual	
3.12.6	Turn off vacuum	Assembly Manual				
3.12.7	Remove weights, mount crane bearings, lift spacer, then disable force compensation	Assembly Manual	Correct handling of crane	Avoid damage to chamber and jigging	Assembly Manual	

Production site:	Date:	Chamber type:	Chamber No.:	Page 12 of 17

	Assembly step	Applied document	QA/QC step	QA/QC result	Applied document	Approval by
4	**Assembly of Tube Layer 2 (Multilayer B) and Axial/Praxial Alignment Platforms**					
	Adjustment of Cross plate Sag Compensation					
4.1	Lower spacer on towers in inverted orientation, dismount crane bearings, place defined weights on spheres	Assembly Manual	Correct handling of crane and positioning of spheres	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
	Steps 4.2–4.9 as Steps 3.2–3.9					
	Mounting of Axial/Praxial Alignment Platforms					
4.10	**Position axial/ praxial alignment platforms with templates on top of tube layer 2.** **Adjust distances between platforms in tube direction with aluminum rulers.**	Assembly Manual	Ensure correct placement of the platforms on the templates and of the templates on the endplug reference surfaces and		Assembly Manual	Production Manager
4.10.1	Fix platforms to tube layer with fast-curing glue (Ciba Geigy Araldite 2012)	Assembly Manual	Observe glue-handling specifications. Use specified amount of glue. Monitor temperature sensors on the granite table during glue curing. table during glue curing.	Store start time of glue curing and temperature, environment. monitor readings in **DB**	Glue supplier specs., Monitoring Manual	
4.10.2	Dismount templates and aluminum rulers after curing of glue	Assembly Manual	Minimum glue curing time: 1 hour. Inspection of cured glue (shear strength).	Store end time of glue curing in **DB**	Glue supplier specs., QA/QC Manual	
4.10.3			Measure coplanarity of platforms with the granite table surface	Store data in **DB**	Assembly Manual	
	Glueing of Tube Layer to Spacer					
4.11	Distribute glue ropes (Ciba Geigy Araldite 2014) on top of tubes at marked pos. of cross plates with manual glue dispenser	Assembly Manual	Maximum glue handling time: 90 min.	Replace glue after max. glue handling time exceeded	Glueing Manual	Operator 3
4.12	Lower spacer on towers in inverted orientation, dismount crane bearings, place defined weights on spheres	Assembly Manual	Correct handling of crane and positioning of spheres on towers. Force comp. acts instantaneously.	Avoid damage to chamber and jigging	Assembly Manual	Production Manager
4.12.1			Check all monitor readings (environmental, temperature, optical, vacuum, force comp.), automatic warnings if out of range	Store in **DB**. Id. problem, lift spacer carefully and adjust, cont. at 4.12.	Monitoring Manual, Assembly Manual	
4.13	**Curing of Glue (as 3.12)**					

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page 13 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
5	**Assembly of Tube Layer 3 (Multilayer B)**					
5.1	**Increase tower height by one step: mount interfaces no. 2 on sphere towers**	Assembly Manual	Interfaces correspond to towers as labelled	Optimum equal tower height	Assembly Manual	Operator 3
	Adjustment of Cross plate Sag Compensation					
5.2	Lower spacer on towers in inverted orientation, dismount crane bearings, place defined weights on spheres	Assembly Manual	Correct handling of crane and positioning of spheres	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
	Steps 5.3–5.8 as Steps 3.2–3.7					
	Attachment of Spacer Foil to Tube Layer					
5.9			Mark location of spacer foil on tube layer		Assembly Manual	Operator 3
5.10	**Attach self-glueing Al spacer foil (15 mm wide, 60 μm thick) to tube layer at pos. of combs halfway betw. adjacent cross plates**	Assembly Manual	Visual inspection of foil on tubes: flat and fully attached	Replace faulty pieces of foil	Assembly Manual	Operator 3
	Glue Distribution on Tube Layer					
5.11	**Glue distribution in gap between tubes and on top of tubes with automatic glue dispenser**	Assembly Manual	Uniform glue distribution with controlled size, location and start/end of glue ropes ensured by settings of glue dispenser	Minimum amounts of glue to min. deform. due to shrinkage	Glueing Manual	Production Manager
	Steps 5.11.1–5.11.5 as Steps 3.9.1–3.9.5					
	Glueing of Tube Layer to Spacer					
5.12	Lower spacer on towers in inverted orientation, dismount crane bearings, place defined weights on spheres	Assembly Manual	Correct handling of crane and positioning of spheres on towers. Force comp. acts instantaneously.	Avoid damage to chamber and jigging	Assembly Manual	Production Manager
5.12.1			Check all monitor readings (environmental, temperature, optical, vacuum, force comp.), automatic warnings if out of range	Store in **DB**. Identify problem, lift spacer carefully and adjust, cont. at 5.12.	Monitoring Manual, Assembly Manual	
5.12.2	**Place weights (steal bars: 20 mm wide, 6 mm thick) on top of multilayer at the pos. of the spacer foil**	Assembly Manual	Weights wrapped with plastic tape to avoid damage of tubes. Defined procedure independent of glue distr. and setting times	Avoid tube deflections by glue	Assembly Manual	

Production site:	**Date:**	**Chamber type:**	**Chamber No.:**	**Page** **14 of 17**

	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
5.13			Check coplanarity of axial/praxial alignment platforms with granite table surface	Correct for out-of-plane deflections of layer 2 if necessary. Store data in **DB**.	Assembly Manual	Production Manager
5.14	**Curing of Glue (as 3.12)**					

	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
6	**Assembly of Tube Layer 4 (Multilayer A)**					
	Adjustment of Cross plate Sag Compensation					
6.1	Lower spacer on towers in initial orientation, dismount crane bearings, place defined weights on spheres	Assembly Manual	Correct handling of crane and positioning of spheres	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
	Steps 6.2–6.12 as Steps 5.3–5.12 and 5.14					

	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
7	**Assembly of Tube Layer 5 (Multilayer B)**					
7.1	**Increase tower height by one step: mount interfaces no. 3 on sphere towers**	Assembly Manual	Interfaces correspond to towers as labelled	Optimum equal tower height	Assembly Manual	Operator 3
	Steps 7.2–7.14 as Steps 5.2–5.14					

	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
8	**Assembly of Tube Layer 6 (Multilayer A)**					
8.1	**Increase tower height by one step: mount interfaces no. 4 on sphere towers**	Assembly Manual	Interfaces correspond to towers as labelled	Optimum equal tower height	Assembly Manual	Operator 3
	Adjustment of Cross plate Sag Compensation					
8.2	Lower spacer on towers in inverted orientation, dismount crane bearings, place defined weights on spheres	Assembly Manual	Correct handling of crane and positioning of spheres	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
	Steps 8.3–8.5 as Steps 3.2–3.4					

Production site:	Date:	Chamber type:	Chamber No.:	Page 15 of 17

	Assembly step	Applied document	QA/QC step	QA/QC result	Applied document	Approval by
	Preparations for Glueing of Tube Layer 6					
8.7	Remove weights, mount crane bearings, lift spacer	Assembly Manual	Correct handling of crane	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
8.8	**Mount interfaces no. 3 on sphere towers**	Assembly Manual	Interfaces correspond to towers as labelled	Optimum equal tower height	Assembly Manual	Operator 3
	Adjustment of Cross plate Sag Compensation					
8.9	Lower spacer on towers in initial orientation, dismount crane bearings, place defined weights on spheres	Assembly Manual	Correct handling of crane and positioning of spheres	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
	Steps 8.10–8.18 as Steps 5.3–5.11					
	Glueing of Tube Layer to Spacer					
8.19	Lower spacer on towers in inverted orientation, dismount crane bearings, place defined weights on spheres	Assembly Manual	Correct handling of crane and positioning of spheres on towers. Force comp. acts instantaneously.	Avoid damage to chamber and jigging	Assembly Manual	Production Manager
8.19.1			Check all monitor readings (environmental, temperature, optical, vacuum, force comp.), automatic warnings if out of range	Store in **DB**. Identify problem, lift spacer carefully and adjust, cont. at 8.19.	Monitoring Manual, Assembly Manual	
8.19.2	**Place weights (steal bars: 20 mm wide, 6 mm thick) on top of multilayer at the pos. of the spacer foil**	Assembly Manual	Weights wrapped with plastic tape to avoid damage of tubes. Defined procedure independent of glue distr. and setting times	Avoid tube deflections by glue	Assembly Manual	
8.20	**Curing of Glue (as 3.12)**					
8.21	**Store zero-readings of in-plane alignment system (reference for operation of chamber)**	Assembly Manual	Average of in-plane monitor readings with force compensation during construction. Check stability of monitor readings over construction period.	Store in **DB** with date/ time	Monitoring Manual	Production Manager

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page 16 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
9	**Installation of the Gas System and Completion of the Chamber**					
	Preparations for Installation of the Gas System					
9.1	**Increase tower height by one step: mount interfaces no. 4 on sphere towers**	Assembly Manual	Interfaces correspond to towers as labelled	Optimum equal tower height	Assembly Manual	Operator 3
9.2	Lower spacer on towers in initial orientation, dismount crane bearings	Assembly Manual	Correct handling of crane and positioning of spheres on towers	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
9.2.1			Check all monitor readings, automatic warnings if out of range, check sags of cross plates	Store in **DB**, correct pos. positioning of spheres on towers	Monitoring Manual	Production Manager
	Installation of the Gas System					
9.3	**Dismount tube clocking and sealing plates from endplugs**	Assembly Manual				Operator 3
9.4	**Install gas manifolds and distribution bars on the multi-layers**	Assembly Manual	Avoid forces on the tube ends		Assembly Manual	Production Manager
9.4.1	Bolt and glue gas distribution bars to cross plates (with Ciba Geigy Araldite 2014)	Assembly Manual				
9.4.2	Glue Faraday cage mounting bars to multilayers with fast-curing glue (Ciba Geigy Araldite 2012)	Assembly Manual	Observe glue-handling specifications		Glue supplier specs.	
9.4.3	Curing of glue for minimum 5 hours	Assembly Manual	Temperature and environmental monitoring active, automatic warnings if out of range	Identify cause of warnings and resolve	Glue supplier specs.	
9.4.4			Inspection of cured glue (shear strength)	Repair if necessary.	QA/QC Manual	
	Preliminary Test of Gas System					
9.5			Pressure test with Argon or N_2 at 4 bar and preliminary leak test	Repair obvious defects and leaks	QA/QC Manual	Production Manager
9.5.1			If several leaks found: continue with step 9.11, identify and repair leaks in a dedicated place		QA/QC Manual	

Production site:		**Date:**	**Chamber type:**	**Chamber No.:**		**Page 17 of 17**
	Assembly step	**Applied document**	**QA/QC step**	**QA/QC result**	**Applied document**	**Approval by**
	Completion of Chamber and Preparation for Transport					
9.6	Mount Faraday cages	Assembly Manual	Protect tube ends during transport and storage		QA/QC Manual	Operator 3
9.7	Mount bearings for crane support, lift spacer	Assembly Manual	Correct handling of crane	Avoid damage to chamber and jigging	Assembly Manual	Operator 3
9.8	Dismount sphere holders from cross plates	Assembly Manual				Operator 3
9.9			Read in-plane and cross plate monitors in initial and inverted orientation of chamber on the crane	Store all monitor readings in **DB**	Monitoring Manual	Production Manager
9.10			Cross plate sag monitors stay installed until end of wire position measurements in cosmic ray test stand and/or X-ray tomograph		QA/QC Manual	Operator 3
9.11	Install kinematic supports	Assembly Manual				Operator 3
9.12	Install chamber in local transport and storage frame	Assembly Manual				Production Manager
9.13	Install temperature sensors on tube multilayers, fix with fast-curing glue (Ciba Geigy Araldite 2012), connect to patch panel	Assembly Manual	Mount in specified locations. Observe glue-handling specifications, glue curing for at least 1.5 hours. Test readout.	Replace faulty sensors or cables		Operator 3
9.14	Install B-field sensors on tube multilayers, fix with fast-curing glue (Ciba Geigy Araldite 2012), connect to patch panel	Assembly Manual	Mount in specified locations. Observe glue-handling specifications, glue curing for at least 1.5 hours. Test readout.	Replace faulty sensors or cables	Assembly Manual. Glue supplier specs.	Operator 3
9.15	Install protective covers on the multilayers	Assembly Manual	Protect chamber during transport and storage			Operator 3
9.16			Mark identifier (ATLAS numbering scheme) and date on the chamber		QA/QC Manual	Production Manager
9.17	Transport chamber to test stand		Observe transport instructions	Avoid damage to chamber	QA/QC Manual	Production Manager

Figures

Figure 1:

Setup for wire tension measurement in drift tubes with a commercial tension meter using the oscillation frequency excited in a magnetic field (Cosenza).

Figure 2:

Graphical user interface for a drift tube test control program (Cosenza).

Figure 3:

Principle of the stereo X-ray measurement of wire positions in drift tubes with respect to reference wires in the jigging (Brandeis University).

Figure 4:

Endplug holder with X-ray CCD for wire position measurement with X-rays (Brandeis University, LMU Munich).

Figure 5:

Principle of the electromagnetic wire position measurement in drift tubes with two pick-up coils. The tube is rotated by 90° to measure both transverse coordinates (Pavia, Rome).

Figure 6:

Quality control test stand for wire position measurements in drift tubes in series production (here for the stereo X-ray method). The tube is held during the measurement in the same way as in the combs for chamber assembly (MPI Munich, LMU Munich, Dubna).

Figure 7:

Drift tube gas leak test stand with single- and multi-tube containers. The leakage of helium from the drift tubes into the evacuated containers is measured with a mass spectrometer (Dubna).

Figure 8:

Integrated drift tube leak and high voltage test stand with up to 60 single-tube containers. The tubes are tested sequentially with a mass spectrometer under computer control (Frascati).

Figure 9:

Drift tube gas leak test stand with fixtures at the endplugs as well as sliding along the tube which allow to measure helium leakage through endplugs or tube walls into evacuated volumes with a mass spectrometer (system developed for endcap chambers with many different tube lengths; Michigan).

Figure 10:

Control of tube placement on the end combs during chamber assembly with a laser system (Rome).

Figure 11:

Schematical layout of the chamber assembly control software (MPI Munich).

Figure 12:

Graphical user interface for a chamber assembly control program with display of monitoring data (Thessaloniki).

Figure 13:

Gas leak test stand for complete MDT chambers with differential manometer and reference volume (Dubna).

Figure 14:

Differential manometer with reference volume for chamber leak test stands (Dubna).

Figure 15:

Cosmic ray test stand for the operation test of chambers at the production sites. Several chambers can be tested simultaneously. With a tower of three chambers, wire positions can be reconstructed (LMU Munich).

Figure 16:

X-ray tomograph setup at CERN.

Figure 17:

Distributions of the residuals in y and z of the wire locations measured in a typical X-ray tomograph scan of the BOS prototype chamber (readout side) with respect to an ideal wire grid.