ATLAS Internal Note
MUON-NO-174
14 July 1997

X-ray Tomograph Prototype for MDT Quality Control

Status of the X-QC project

J. Berbiers, D. Drakoulakos, V. Falaleev, E. Gschwendtner,
J.-M. Maugain, S. Rangod, F. Rohrbach
E. Sbrissa, Y. Sedykh

1 Introduction

The production of the ATLAS muon tracking detectors, the Monitored Drift Tubes chambers (MDT), is based on the concept of ultimate mechanical precision and the use of X-ray tomography as a Quality Control platform. The development design, construction and tuning of an X-ray tomograph suited for the MDTs, was the aim of the X-QC project.

1.1 Quality control

The MDT project in ATLAS has the size of a very large industrial project aiming at an exceptional quality of the construction in term of accuracy ($\leq 20\ \mu m$), material reliability, delivery and assembly schedule.

The only known engineering way to reach this ambitious goal is to establish quality management and quality systems, inspired by the 9000 ISO standard ([1], [2], [3], [4], [5]), adapted to the ATLAS project from design to final assembly. In particular, taking into account the large size and complexity of the project, the implementation of a Quality Assurance Plan (QAP) [6], [7] is needed to reduce cost and improve quality.

The X-Tomograph quality control platform may be considered as one of the key instrument needed for the MDT QAP.

The production of the Monitored Drift Tubes chambers, is based on the concept of very high mechanical precision and the use of X-ray tomography as a Quality Control platform for the mechanical achieved precision.

The successful completion of the project will depend, in the first place, on the timely construction of the MDTs. After the completion of prototyping, which should occur by the beginning of 1998, each assembly site will construct a so-called 'module zero' of each type of chamber that it will later fabricate in series, in order to certify the assembly process and gain experience for the series production. Those 'module zero' will be measured and qualified at CERN. This feed-back control procedure is a part of the quality insurance plan. Series production of most chambers will take place from 1999 until 2003 and delivery to CERN will have to be organized in order to match smoothly both, the production schedule and the quality control platform availability.

The chambers will be delivered to CERN, equipped with readout boards, which will allow for easy installation of the front-end electronics. For efficiency, it would be possible to join the functional test of drift cells and the mechanical control of the wire positioning of each drift tube using the 'active method' procedure for X-ray scanning (see 2.3).

1.2 X-ray tomography

The choice of X-ray tomography as a quality control tool for MDTs was based on two essential features:

- the ability of X-rays to detect µm size tungsten wires hidden inside the aluminium drift tubes of the muon detector. Due to the fact that the value of the absorption coefficient for X-ray photons is very sensitive to the atomic number of the matter, the large difference in the attenuation coefficient values between tungsten and aluminium materials is used to detect signal wires in the multilayer structure of the MDTs. Sharp absorption spikes are observed either as a shadow seen by a X-ray detector placed under the chamber (passive method) or as a detection peak registered by the muon tube wire itself hit by X-rays (active method).
- the very high intrinsic precision of narrow collimated X-ray beams could allow to reach the range of a few µm accuracy.

The scanning along the multilayer cross section of the chambers is done under different inclination angles of the X-ray beam and provides stereo-measurements. A two-dimensional map of wire positions can be reconstructed. Every chamber is scanned in a few cross sections along the tube length. A full calibration of the muon chambers may be completed, producing a list of all the wire coordinates in 2-dimensions. Using an external fiducial wire installed along the chambers, a 3-d map would finally be constructed.

After the analysis of raw data, the results will be stored in a Data Base providing the full list of the wire position and accuracy.

2 Development work

The X-QC project has already a long story. Let us remind the main steps of the development work and the most important results achieved.

2.1 The pioneer work

The first manual and then automatic X-ray scannings of drift tubes were done in JINR, Dubna during the years 1988-1990 [8].

Nice shadow signals from the W and Cu-Be wires were detected through up to 11 mm of aluminium material. In 1992-1994 this method was discussed during Muon Group meetings. To end of 1994, the joint CERN-JINR team constructed a high precision X-ray scanning prototype (XTOMO-1), with 600 mm scanning length (5 µm accuracy) using a 1 kW power X-ray tube [9].

In 1995, a MDT muon chamber prototype with 2x4 layers of tubes was scanned with a single X-ray beam providing projective measurements with the expected precision [10].

2.2 Measurements with a small prototype

The XTOMO-1 scanner was upgraded in 1995-1996 with two stereo X-ray beams (XTOMO-2) with the following main purposes:

- Realization of the stereo measurements.
- Detailed comparison between 'active' and 'passive' scanning mode.

The measurement of the wire position in two-dimensions, along a cross section of a chamber, was performed by using two separate measurements using two different X-ray beam inclination angles. The selection of the inclination angles Θ, the so called 'scanning angles', was an important issue under consideration [11] for two reasons:

- They define the two-dimensional accuracy of the position of the wires.
- They depend upon the chamber structure characteristics, i.e. the height of the spacer, the symmetry between the two multilayers and the horizontal and vertical wire pitch.

The most suitable scanning angle values were tested, i.e.± 31°, relative to the chamber surface normal incidence.

The XTOMO-2 consists of the following main components:

- A scanning head with two X-ray beams equipped with optical systems defining two fine collimated beams. A lead shielding was provided around the sources for reducing background and for safety considerations.
- An industrial linear stage with a 600 mm travelling distance. The quality of the stage is based on the calibration curves delivered by the constructor for three essential mechanical parameters: the scanning position, the vertical straightness and the angular displacement around the axis perpendicular to the scanning cross section plane (pitch angle). The excellent repeatability (better than 1 μm) of this linear stage was crucial for achieving high reconstruction accuracy.
- A detection system depending on the operating mode. For the passive mode a plastic scintillator covering the scanning area was used. For the active mode the detection system was the whole MDT itself.
- A CAMAC crate with an interface to a PC was used for the data acquisition and for the scanner operation control. Three parameter data were recorded on-line: the scanner position, the number of counts and the counting duration.

The analysis program has been written using the PAW package. For reconstructing the 2-dimensional image of the wires, a calibration procedure using a precise triangle tooling was developed in order to determine the scanning angles within the required accuracy (below 10 μrad).

2.3 Passive method and Active method

Two principles for measuring MDT chamber's wire position were developed.

1. - The 'passive' method which may be seen as the conventional method for many X-ray applications which exploits the significant X-ray absorption contrast between different materials. Therefore, it is based directly on the absorption's difference between the aluminium material of the tubes (tube wall thickness 400 μm) and the tungsten anode wires (50 μm diameter). The output intensity of the X-ray beam was measured by a scintillator. Fig. 1 shows the counting rate of the scintillator as function of the scanning position for a small Nikhef chamber prototype.
2. - The 'active' method. This mode is based on the position dependence efficiency of drift tubes for X-rays. When the X-ray beam hits the wire, photo-electrons, Auger electrons and fluorescence are produced at a much higher rate than in the gas or in the walls. These radiations have a high probability to escape from the surface of the wire and to be detected by direct ionization in the gas. Fig. 2 shows the wire signal from the active tube belonging to the fourth layer of the small Nikhef chamber prototype. It is striking to see the wires of the upper layers inducing a shadow effect which is observed as inverted peaks compared to the tube wire signal itself.

On Figure 1, one can see the scanning profile of a 4-layer chamber. We can clearly see the four wires as deep absorption peaks from top to bottom layer in the passive mode and as a large signal above the tube background in the active method. It is interesting to note that the 3 wires above the active layer are clearly seen as absorption peaks by the active tube.

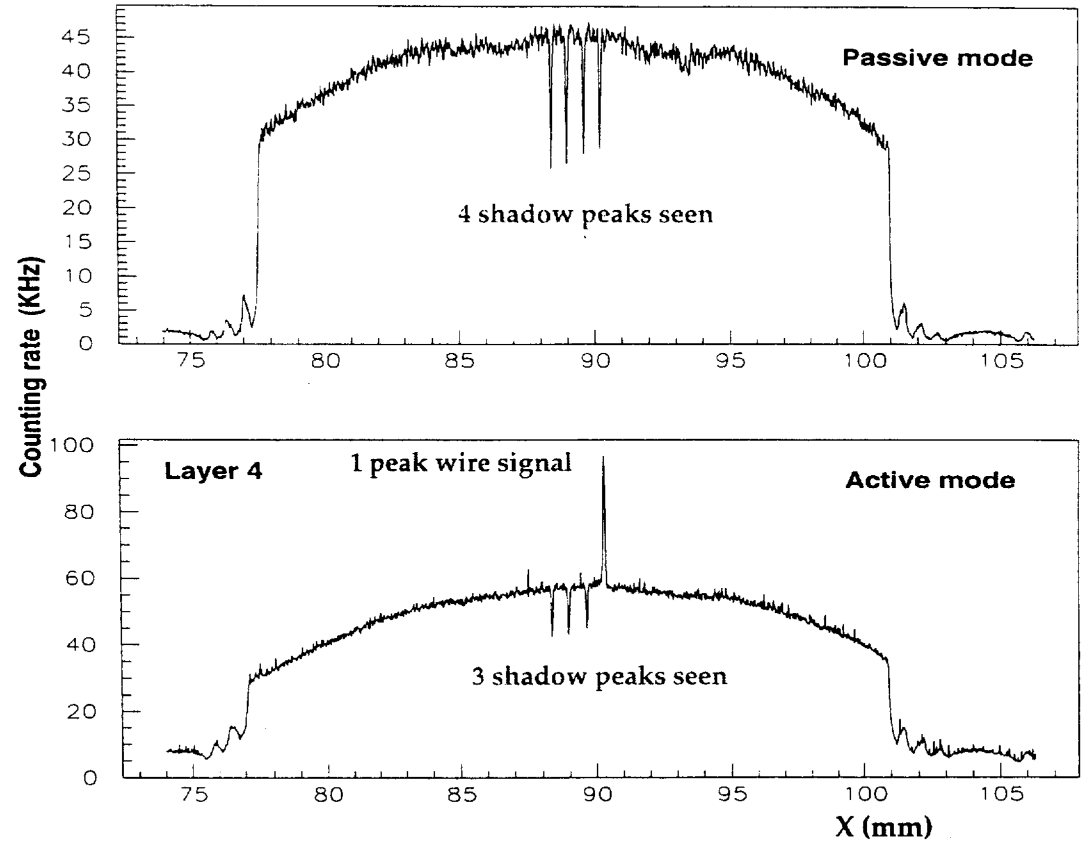


Figure 1 **Passive shadowgram** and **active signal** from a tube in the 4th layer when scanning the small four-layer Nikhef chamber prototype.

2.0.1 Data analysis and results

As a main result, XTOMO-2 demonstrated the two dimension measuring power accuracy of both methods (passive and active): a 6 µm r.m.s. accuracy was obtained [11] when measuring a small Nikhef chamber prototype (4 x 8 tubes). It showed the importance of corrections based on the availability of reproducible calibration plots for the small linear stage [12].

3 The Large X-Ray Tomograph

3.1 The challenge

Driven by the encouraging results obtained during the early stage of this project, the decision to build at CERN a large X-Tomograph using a similar approach was taken early 96 in view of measuring full size prototypes of muon chambers which were expected to be delivered before end 1996. This was a difficult challenge, mainly for two reasons:

- Scaling from 600 mm to 2200 mm without reducing final accuracy,
- Tight schedule within resources constraints,
- Novelty of the technological approach.

The main challenge was to provide in time a safe measurement on a chamber prototype designed for 20 μm accuracy using an X-ray tomograph prototype aiming at maximum accuracy but built within stringent constraints.

3.2 Design considerations

Based on the previous experience, the concept design of the Large X-Ray Tomograph for MDT was elaborated:

- Combination of two features:
    1. A 3 m Linear Stage, covering the full width of real chambers, equipped with two stereo-beams,
    2. A single X-ray beam installed on a rotary stage allowing the use of different scanning angles required for special measurements, in particular the centering of the wires and the positioning of reference Fiducial wires.
- Very high precision survey tools to monitor the main parameters controlling the X-ray beam position in space during the scanning.

During the design and construction phase of the tomograph, collaboration and constructive discussions were organized with the X-ray TRT team using a rotary stage for the calibration of the straws in the TRT wheels.

3.3 Prototype specifications

The main specifications for the Large X-Tomograph were as follows:

1. The prototype should run end 1996.
2. The accuracy must reach a value below 10 μm in X[1] and Z (see Appendix B) over the full cross section of the measured chambers in order to fit the expected accuracy of the chamber construction (20 μm r.m.s.) in view of a full, safe and secure quality control.
3. The prototype should accommodate for the size of the biggest chambers (2200 mm in z, 600 mm in y and 6 m in x, see Appendix B).
4. The prototype should provide automatic measurements on all chamber cross sections.
5. Without taking into account time overheads and chamber installation and thermal stabilization, the prototype should make possible the measurements of chambers at a rate of one chamber per day.
6. The time overheads for installation, alignment and temperature stabilization should not exceed one day per chamber.

The long term goal of the X-QC project is to prepare a platform for measuring all MDTs if this would be technically possible within the constraints.

3.4 Design and construction of the first Large X-Tomograph Prototype

Due to limited resources and time constraints, industrial solutions were chosen where and when ever possible. Figure 2 shows the Large X-Tomograph prototype designed and built at CERN during 1996. Due to the necessity of a very stable environment, the tomograph was installed in a clean room on the ground floor of building 188 (one of the most stable ground floor at CERN) equipped with temperature control ($T \leq \pm 1\,^{\circ}C$).

This project was done in close collaboration and with the full support of the ECP/EOS group. At this early stage, the basic design concept for the construction of the first proto-

---

[1] In this note, the X-tomograph system of coordinates (X, Y, Z) is always used, except when clearly stated.

type could not follow all the specifications previously quoted, but only the main criterions could be considered (points 1. to 3. above).

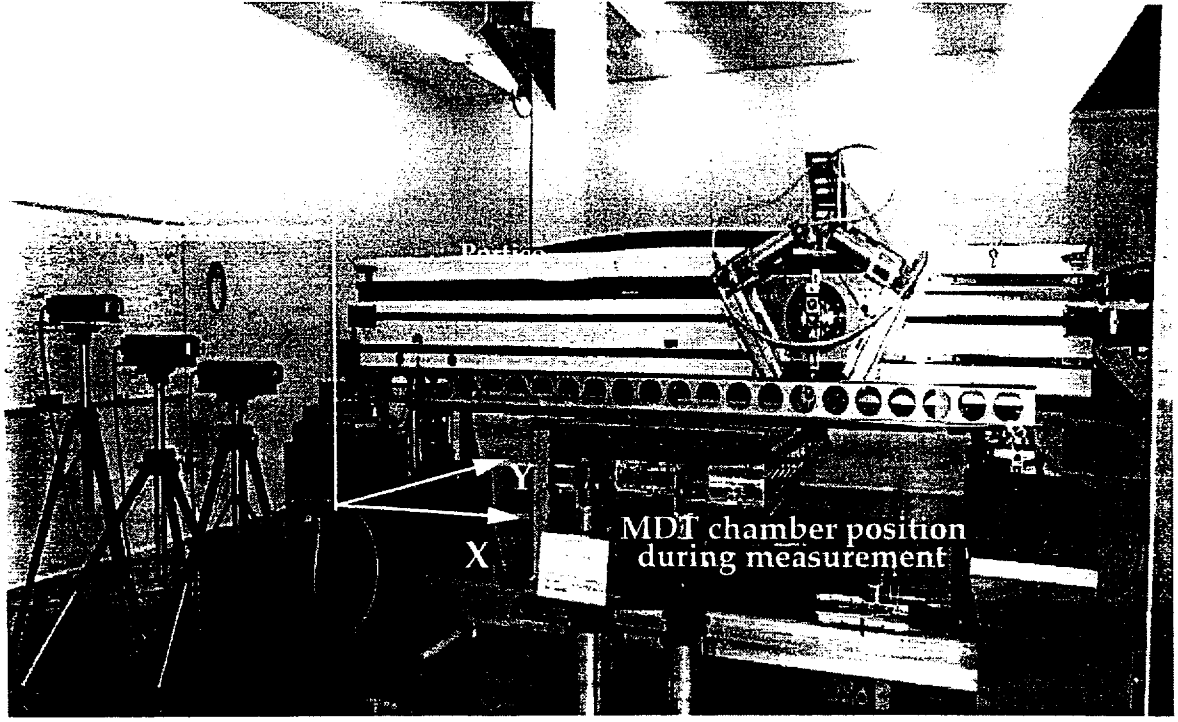


Figure 2 The X-Ray Tomograph prototype. The natural reference system for the tomograph is indicated (see Appendix B).

The best mechanics, compatible with a reasonable cost, was not fulfilling our tight schedule and constraints. In order to overcome this problem, we have chosen to build a linear stage with a reasonable mechanical precision of 20 μm and to monitor in space the movement of the X-ray beam fixed on the rolling cart. This was achieved by using the best but standard principle of interferometer on-line control used in the industrial high precision tooling machines [13]. Industrial interferometers based on a two frequency laser measurement system allow a monitoring at very high precision for all parameters (one μm linear, one μrad angular measurements) with a resolution below 0.1 μm.

The prototype which was built in 1996 consists of:

1. A fixed 3500 mm iron portico equipped with a precise motorized cart rolling along the X axis of the tomograph (across the tubes, the z axis of the MDT chambers, Appendix B).
2. The rolling cart is equipped with two collimated X-ray beams at ≈ ± 30° in respect to the Z axis. The 60° stereo angle has been chosen on the basis of our previous experience and fits perfectly the tubes corridor provided the spacers between the multilayers are correctly chosen. The X-ray beams have a cross section of about 30 μm x 8 mm and a divergence of about 60 μrad. The longer axis is aligned to the wires to be measured.
3. A computer control system for the X displacement which provides steps as low as 10 μm.
4. A set of three interferometers which monitor the main parameters of the scanner movement: the linear X value, the pitch angle (rotation around the Y axis), and the vertical straightness (deviation in the vertical plane from the X axis). The yaw (rotation around the Z axis) and the horizontal straightness are not monitored as they only have a second order effect in the corrections. At this early stage, the interferometers

were on free loan, both for testing the interferometer control concept and for shortening the time delays in order to cope with the chamber prototype schedule.

5. A tilt-meter for measuring the roll angle (rotation around the X axis). Unfortunately, this requires a 5s stop of the movement before each data recording. This is why the roll angle is measured only every 2 mm during the scanning.
6. A calibration ruler split into two parts and placed above the chamber to be measured. It consists of two precisely (1 μm r.m.s.) optically measured pattern of wires mounted on a fibre carbon support. This ruler provides two layers of reference wires giving two very precise peaks which appear in the shadow pattern every 30 mm. This calibration ruler is used for checking the stability and reliability of the X-tomograph and to provide a calibrated grid frame for the two dimension stereo reconstruction.
7. A manual rolling cart for supporting and aligning the chamber to be measured. It moves the chamber under the portico, along the Y axis, over 12 m in view of accommodating the longest BOL MDT chambers (see Appendix A). It can only position the chamber under the portico with a reduced accuracy of a mm in Y (x for MDT).
8. Two moving X ray detectors which are enslaved to the X-ray cart. The scintillators, optimized for the X-ray beam energy spectrum, are accompanying the beams in order to record the two stereo shadowgrams.
9. A full control of the tomograph movement, data acquisition and slow control based on the use of the LabView package working on PC (a detailed description of the operation and operating software can be found in [14]).
10. Two Phillips X-ray high voltage power supplies (60 kV, 20 mA, on free loan, old technology without remote control nor monitoring). The two cables for feeding the X-ray tubes move in synchronism with the scanner in order to insure a perfect stability of the X-ray rolling cart.

The large X-Tomograph prototype, now referenced as DiMiTriX, was operational November 11, 1996.

4 Muon chamber prototypes measurements

The four prototypes recently delivered by the Institutes to CERN have been measured during the first campaign of measurements (November 96 to March 97):

1. Roma-Pavia-Seattle BIL prototype,
2. Frascati-Cosenza BML prototype,
3. Protvino BIL prototype,
4. Munich MPI BMS prototype.

Each chamber was measured at least in 4 cross sections along the tube length. In order to start more investigations, different scans were done with tubes under pressure (CO2, 3 Bar), high voltage on the wires and using different X-ray energies. Full analysis of all data is under way. Preliminary results have been obtained in the one and two dimension analysis for the four prototypes.

Concerning the measuring time duration, the efficiency improved from one good scan per week (November 96) to approximately one good scan per day (January 97). Most of the lost time was due to power supply breakdowns and chamber installation handling difficulties. At present, the minimum time duration for one scan of a 2m chamber cross section is about 12 hours (with one point measured every 20 μm scan along X).

The absorption spectra of the two X-Ray beams is provided as the plot of counting rate versus the X position given by the linear interferometer. A typical shadowgram can be seen in Figures 3 and & 4.

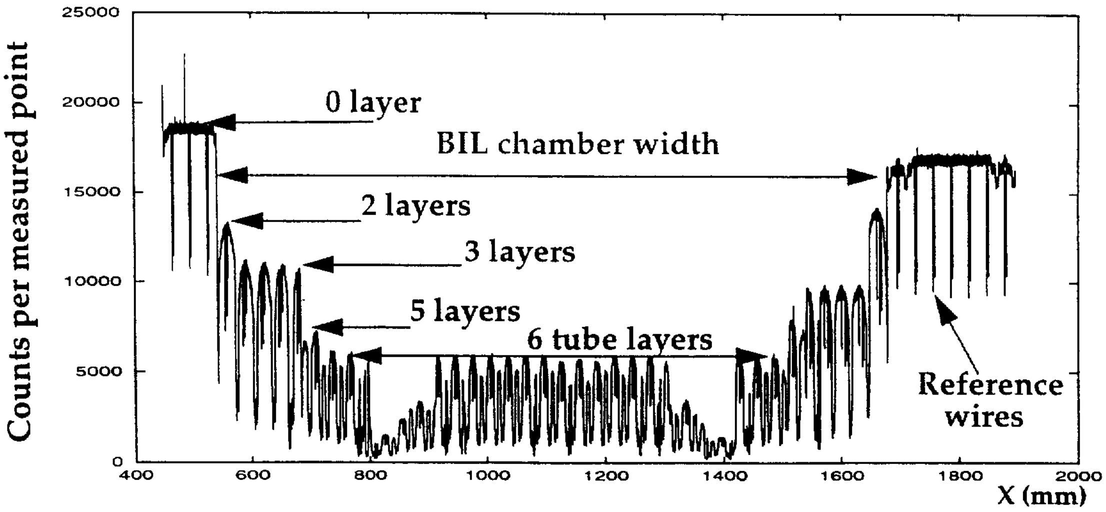


Figure 3 Shadowgram of the BIL-I prototype chamber. The regions of increased absorption between 800 mm and 1000 mm, or 1300 mm and 1500 mm are due to the chamber Al frame. The absorption of the layers is seen and the number of counts per measured point remains large enough for a good statistical significance even for the deepest layer. Scanning parameters: average speed per measured point including data taking overhead: 48 µm per second. Total scan: 1450 mm, 8:26 hours, one data point every 20 µm X displacement, 40 ms per point for counts.

Each scan delivers a file of about 12 MBytes of raw data which consists of a list of interferometers parameter values and counts registered over 40 ms at each 20 µm steps. Storage and back-up protection of the raw data are under study (development of high compression algorithms).

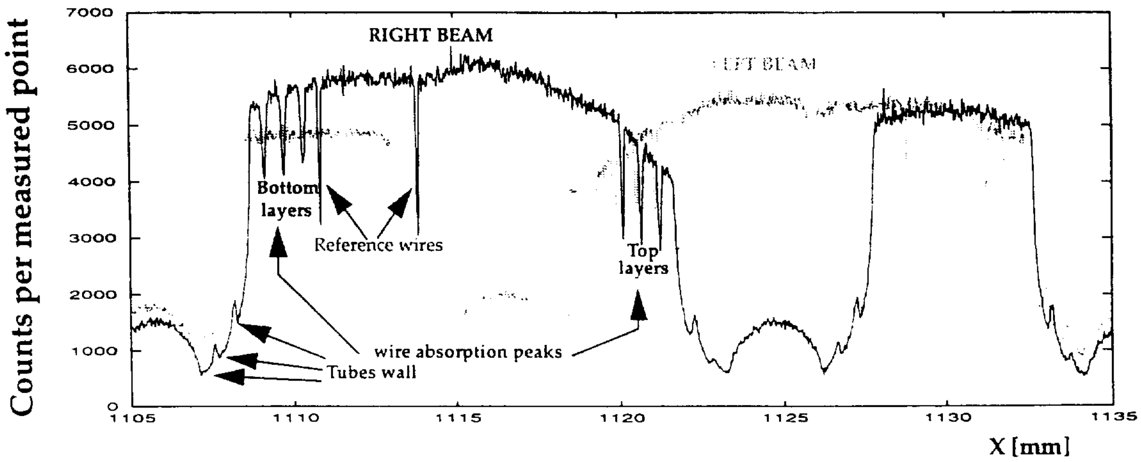


Figure 4 The zoom displays the absorption peaks due to the chamber and reference wires, as well as the increased absorption in the region where the X-ray beam is aligned with several consecutive tube walls. Tube wall signals can be seen, but partially masked by the shadow of upper walls.

4.1 One dimension analysis and results

The 1-D analysis consists of:

- The pattern recognition of the left and right X-ray projective shadowgrams. This is achieved by comparing the absorption peak pattern to the expected one (obtained by simulation).
- After identifying the peaks in each absorption spectrum, one fits the following Gaussian + first order polynomial function:

$$f(X) = p_0 + p_1 X + c_1 \exp[-(X - pos)^2/2\sigma^2]$$

  - where:
  - X is the coordinate measured by the linear interferometer,
  - pos is the X wire position,
  - p_0, p_1, c_1, pos and σ are free parameters.
  - f(X) was fitted to a $\pm(100 \div 200)\,\mu m$ region around each peak ($(20 \div 30)$ points per profile).

Table 1 shows the results obtained for the four prototypes.

Each layer is fitted to a grid function $(\mathrm{LayerShift} + i \times \mathrm{LayerPitch})$ in order to find the best estimate of the layer parameters and their r.m.s. This is only valid locally in X, as no more correction due to the other scanner parameters are possible in the one dimension analysis.

Although the plane of the chamber is usually tilted around the Y axis in respect to the X, Y plane of the tomograph, the mean values of the fitted pitches obtained from the two beams can be averaged in order to get a very good approximation of the actual average distance between wires (the error induced by this approximation is only ≈ 0.3 μm for a tilt below 5 mrad).

The precision of the tomograph, for the determination of the projected position of a wire along the X axis, has been established by minimizing the distance between the measured position and the calibrated values found for the reference wires of the calibration ruler. The result gives an accuracy of 13 μm. The results have been calculated without taking into account individual features of chambers (different lengths of tubes in one chamber, technological shifts between layers etc.) which may significantly change the values. It is necessary to take care about it comparing the results for different chambers.

Quite a few interesting comments and conclusions are made:

- for the Roma-Padova BIL prototype, all scans and all layers give an average pitch of 30 mm + 7.3 μm with a standard deviation 0.5 μm: this result agrees with the nominal design parameter (8μm). The r.m.s. of the pitch is within the 20 μm r.m.s. construction design requirements for up and down layers in all cross sections. However, for the intermediate layers of the multilayers, the r.m.s. is worse.
- for the Frascati BML prototype, the r.m.s. of the pitch in the central cross section is quite good (below 20 μm) but bigger than 20 μm (up to 40 μm for some layers) at both chamber ends.

It is striking and encouraging to point out that those results have already been of a great interest for the prototype chamber constructors and will help in the final decision for the technological and assembly issues and choices. Detailed results for every measured prototype can be found in [16].

As previously pointed out, the average rate of measurements over the first campaign was very slow compared to the final goal (at present, the scanning time itself is ≈ 6 hours per meter). More precisely, at present the situation is as follows for the duration of the measurements:

- One week per chamber,
- One day per cross section,
- Two days handling & installation for exchanging chambers,
- A lot of time lost for reparations (≈ 29 days).

The major losses in efficiency were due to the use of unreliable old HV power supplies.

		BIL-I		BML		BIL-R		BMS	
		Beam 1	**Beam 2**	**Beam 1**	**Beam 2**	**Beam 1**	**Beam 2**	**Beam 1**	**Beam 2**
Nominal Pitch		8		45		100		100	
Multilayer 2	**Layer 4**	-	-	-	-	-	-	103.3	
								(18.1)	(28.6)
	Layer 3	7.7		47.05		100.0		101.8	
		(15.4)	(17.6)	(17.0)	(16.7)	(37.0)	(28.0)	(30.9)	(26.1)
	Layer 2	6.9		46.9		99.95		100.95	
		(22.5)	(25.4)	(17.8)	(13.4)	(23.1)	(25.9)	(24.7)	(19.3)
	Layer 1	6.55		47.15		99.65		99.05	
		(19.3)	(16.5)	(14.1)	(13.1)	(26.3)	(19.0)	(17.7)	(19.9)
Multilayer 1	**Layer 4**	-	-	-	-	-	-	99.85	
								(25.5)	(23.2)
	Layer 3	7.0		47.0		99.85		99.85	
		(16.3)	(21.1)	(25.2)	(24.4)	(10.2)	(16.7)	(25.8)	(20.6)
	Layer 2	7.85		46.55		99.25		95.9	
		(14.7)	(17.6)	(22.8)	(22.5)	(15.7)	(18.5)	(23.4)	(25.6)
	Layer 1	7.6		46.75		99.15		92.7	
		(16.1)	(15.0)	(23.9)	(26.5)	(13.8)	(15.5)	(20.7)	(25.3)

Table 1 Results of the pitch value from 1D analysis for the four chamber prototypes measured: BIL-I, the BIL prototype from Roma-Padova-Seattle, BML from Frascati, BIL-R from Protvino and BMS from MPI-Munich. The numbers are in µm (pitch values = 30 000 + table numbers), they are the average results of the two X-ray beams scans; the r.m.s. values are shown in parenthesis. For the BMS chamber, the results are taken from a single module of the chamber multilayer (The BMS prototype was made of four different modules per multilayer)

4.2 Two dimension analysis and results

A program, known as 'scana', has been developed and written for the two dimension analysis of the raw data produced by the two X-ray beams of the tomograph. It should be, as a final goal, fully automatic, delivering the results shortly after the measurements. The organization of the 'scana' program, written in C++, for the 2D analysis consists of four main parts:

1. Automatic pattern recognition of peaks and layers, and matching of tube wires and calibration wires for the two beams. Calculation of peaks position similar to 1D.
2. Determination of geometrical parameters of the scanner using the precise calibration rulers and the interferometers measurements. It needs to fit 24 global parameters. Value of the global parameters are obtained by making minimum the mean square distance in the cross section plane between the actual position of all calibration wires and the reconstructed position of each X-ray beam.
3. Chamber wire position analysis which provides the X, Z position of all detected wires. Calculation of the displacement of the wires in respect to an ideal template fit with five parameters fixing the position of the chamber in space. Determination of some integral parameters in view of studying the possibility to establish integral chamber quality factors.

4. Graphics presentation of results, Web publishing and saving. Listings of all analyzed data, giving the position of all detected wires together with preliminary analysis of the results. All tables and drawings are provided on the Web [17].

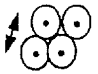
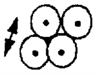
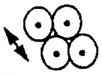
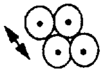
Multi		 Δy $\Delta z = z_{measured} - 30000$				**Interlayer distances - 30000 (Sigma)**							
		Δz distance & (sigma)		**sigma Δy**									
layer		**BIL-I**	**BIL-R**	**BIL-I**	**BIL-R**	**BIL-I**	**BIL-R**	**BIL-I**	**BIL-R**	**BIL-I**	**BIL-R**	**BIL-I**	**BIL-R**
2	3	7.3 (19.7)	95.1 (24.7)	18.6	53.3	-0.7 (19.6)	111.6 (39.7)			-2.8 (18.3)	100.1 (18.0)		
	2	10.4 (26.8)	99.6 (13.2)	22.6	39.1			8.5 (17.9)	137.6 (23.8)			-13.3 (18.4)	126.6 (28.3)
	1	7.0 (18.2)	98.6 (14.8)	22.6	31.0								
1	3	7.8 (22.0)	96.0 (15.1)	23.7	25.6	6.6 (24.5)	123.0 (17.2)			-8.7 (18.6)	111.5 (14.5)		
	2	8.3 (21.2)	97.7 (14.6)	22.4	20.3			-0.7 (19.0)	154.7 (26.3)			-4.2 (20.0)	119.7 (29.8)
	1	7.7 (13.7)	99.2 (15.6)	24.4	36.0								

Table 2 Results of the pitch value from 2D analysis for the two different BIL chamber prototypes measured (BIL-I: Roma-Pavia-Seattle chamber prototype, BIL-R: Protvino chamber prototype). The numbers are in μm.

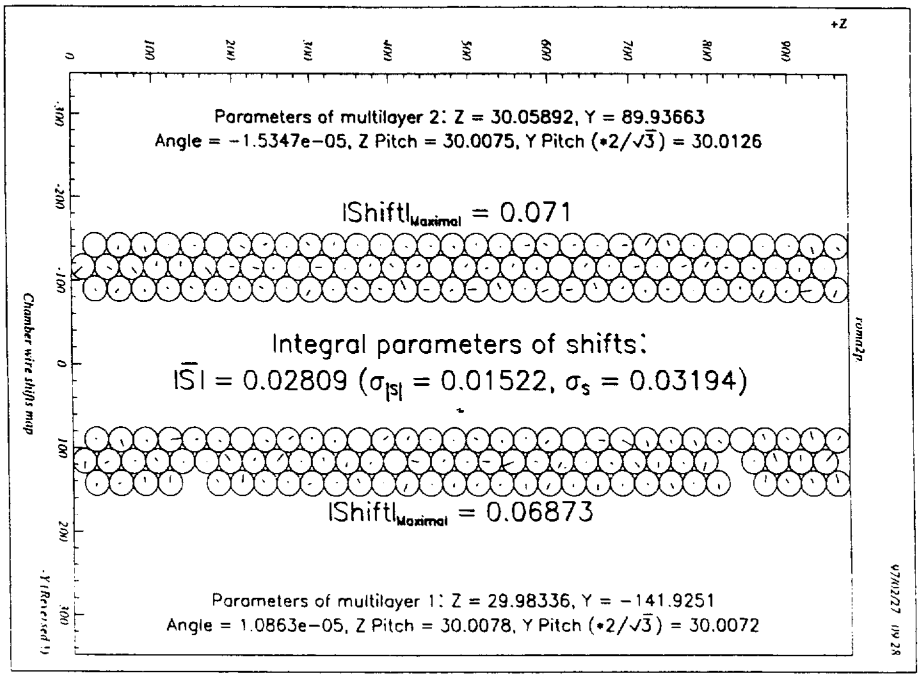


Figure 5 Reconstructed wire displacement in mm in the BIL-I prototype. The lines inside the tubes represent both, the absolute value of the displacement and its direction. Global parameters are calculated: average of absolute shift ($|\bar{S}|$) and r.m.s. value, r.m.s. of the r.m.s. value of the shift projections and maximum absolute shift value of the two multilayers.

As a consequence of the use of all possible corrections made possible thanks to the interferometers control, the analysis gives interesting, good and coherent results: the residuals are around 6 μms for the calibration ruler. Consequently, the positioning accuracy over the whole domain of the measurements in X and Z is below or equal to 10 μm.

At present, the program has been producing preliminary results for the four prototype chambers. In Table 2 we show the results for the BIL chamber prototypes. Detailed results concerning the four prototypes measured are reported in reference [18].

The results for each individual shift wire position for a complete chamber cross section are well represented in a graphics way. In Figures 5 a typical example of a shift map (BIL prototype) is shown.

As could be expected from the better accuracy obtained in the 2-D analysis, the dispersion (r.m.s.) of the wire pitch (in X) per layer give better results than those obtained in the 1-D analysis. The preliminary results also confirm the validity of the one dimension analysis for the determination of the pitch value. In the 2-D analysis of the four chamber prototypes, the pitch r.m.s. values are $(11 \div 28)$ μm in X and $(16 \div 53)$ μm in Z (some within other out from the design construction value of 20 μm).

However, at the early stage, some results looked strange to the chamber constructors: a large shift in the Z position of wires was found for the tubes of multilayers lying at or close to the edges of a chamber prototype. A thorough investigation about possible systematics, eventually generated by the calibration procedure, is under detailed study in order to disentangle this discrepancy. The first conclusion looks to be systematics in the optical measurement of the calibration ruler. Those systematics (up to ≈10 μm) are extrapolated from the top to the bottom layer inducing in the bottom one errors ten times bigger. In view of full systematics control, a new calibration ruler will be done and installed at the bottom just facing the scintillators: this should eliminate possible systematics in Z and solve the question.

Needless to say that during the first measurement campaign, we have learned a lot about the tomograph which allow us to proceed to the second phase of the prototype development towards a full X-tomograph quality control robot needed for future.

5 X-Ray Tomograph prototype upgrading

As already pointed out, our present tomograph was built as a prototype and we could not fulfil all the specifications. In particular there is:

- no robotization along Y (long time delays for chamber alignment),
- no connection between cross sections (no sagging measurement),
- no flexibility in scanning angles (lost of wires and no centering),
- no scanning time constraint (at present 12 hours per scan).

The main purpose of the first prototype was to be able to measure, according to the schedule, a few MDT chamber prototypes. The priority was put on the accuracy of the measurements and their reliability.

We consider that we reached this milestone as we have a fair understanding that our present tomograph is able to provide the required accuracy (10 μm) in the positioning of the wires. We have been able to measure four different kind of chambers and to learn how to realize the required precision with DiMiTriX. We must underline that a breakthrough was obtained by exploiting the full power of the interferometers accuracy in controlling the two X-ray beam position in real time during the scanning.

The main second objective however, has not been reached: the scanning duration should be short enough to measure a chamber in one day. This implies that we have to improve our present speed by about one order of magnitude.

We have also learned that we loose a lot of time in the installation of the chamber on the tomograph. There are many reasons (organization, transport, handling, etc...) but the main delay was due to the difficulty of the alignment procedure: as we have fixed angles scanning, the wire pattern (tubes, fiducials and calibration ruler) as seen in the shadowgram must be adjusted in order to get a good peak detection in all layers for both X-ray beams at the same time. The only way to adjust the pattern is move in two directions X & Z (z & y for MDT) and tilt the chamber itself until all peaks are clearly visible and separated from the background of the tube walls. The relative position 'Tomograph to Chamber' had to be tuned manually for each cross section.

Apart from the very slow present data acquisition (400 ms per measured point), the major factor limiting the time efficiency was due to many breakdowns experienced with the old X-Ray tubes power supplies which were available.

We also have seen that we cannot measure the centering of the wires in the tubes with good precision and redundancy using the present two fixed angle scanning system. We also loose quite a few wires when they are in the shadow of the chamber cross plates. This could be at least solved by implementing the X-ray tubes on rotators.

At present, the next 97 upgrade consists of the ten following points, focused towards solving all the previously described problems:

1. Installation of final interferometers with fast VME data acquisition. This will allow a drastic improvement in the data acquisition rate: we may be able to measure on fly at 0. 5 mm per second.
2. Construction and installation of new calibration rulers for improving systematics correction and our confidence in the results.
3. Upgrading of the rolling mechanics which should improve the correction procedure.
4. Upgrading of the X-ray beam optics (motorized collimator) for safety and better source alignment.
5. Computer control displacement of the chambers in the Y direction (optimization of the total measurement duration for one chamber).
6. Computer control system for the displacement of the chambers in the X and Z in order to align the chamber in respect to the tomograph for each scanning cross section.
7. Implementation of a rotating X-ray beam for the measurement of the wire centering and the detection of fiducial wires and hidden tubes.
8. Heightening of the portico in order to let the biggest chambers (BOL) rolling under the scanner and to accommodate the down calibration ruler.
9. Installation of a small crane for loading and unloading chambers on the tomograph.
10. Preparation of the environment (gas and data acquisition) for running the active scanning method.

We also wish to improve the reliability of the X-ray sources (new power supplies). A large part of those improvements should be ready during summer 97. The instrument will be able to reliably verify the mechanical accuracy of the two next prototype chambers (BOS and BML) at the end of the year. The full upgrading is expected by mid 1998. It should be ready for controlling the production of the first chambers (modules Zero) delivered by the collaborating institutes.

6 Long term logistics

The main goal of the 1997 program is to deliver for next year a set of recommendations for the final X-QC platform. After the full upgrading in 1998, we will be ready to measure all chambers arriving at CERN. We must be ready to start massive non stop measurements by the end of 1998 when the massive delivery of MDTs is expected to start.

6.1 Scenario for a '1200 muon chambers X-Quality Control' platform

After the upgrading, the time estimate foreseen for the complete measurement of one MDT chamber (typically 4 scans) including all overheads due to handling, installation and alignment is about two days. As a consequence, based on standard working time, a fully robotised X-tomograph should have a capacity of measuring only 100 chambers a year (including tomograph maintenance).

In the second half of 1998, a massive measuring campaign will be performed to validate the assembly methods for the series production. The first chambers from every production site will be carefully evaluated.

However, we have to decide a long term mechanical quality control strategy before the end of 1997. This will leave just enough time to proceed accordingly and build, organize and prepare the reception site. We have to take into account all the facts concerning the scheduling:

- First industrial delivery is expected for middle 98.
- Last chamber will arrive at CERN end 2003. There may be some time left during the assembly period in 2004.
- The industrial fabrication will be spread over many sites (≈ 10), in different countries with different expertise and constraints.
- We will have to be ready to rescan some chambers at regular intervals, in order to study the long-term stability of wire positions. Indeed, it is essential to prove the stability of the chambers after their control (storing, ageing, creeping, transport, temperature constraints recovery, handling, etc...).

Therefore, different possible scenarios — yet to be discussed among the Collaboration — exist, according to the behaviour of the management:

- Realism:
  1. Measurement of all chambers at CERN. This will make necessary the construction of two fully robotised X-tomographs and the use of the prototype for special control and as a spare platform in case of emergency (hard scheduling).
  2. Measurement of chambers at the production site before delivery to CERN. With this strategical approach, only a part of chambers should be controlled at CERN before assembly during the storage period (5 years!). Based on the experience and know-how at CERN, CERN could help the Institutes producing the chambers for the construction and installation of the necessary on-sites X-ray quality control platforms.
- Optimism:

  Reduced quality control might be decided at CERN provided the first bunch of industrial chambers are well inside specifications. In that case, only a fair fraction of chambers would be measured.
- Pessimism:

  It may be found that keeping the chamber quality within the 20 μm precision is an impossible specification and not realistic task for massive chamber production. In that case X-ray measurement will become an essential step for mass production technology as it would then be possible to qualify all chambers by high precision measurements of the real position for all sensitive elements. All calibration data would then be the identity card of each chamber and used for corrections during the analysis.

It is important to stress that the decision should be taken early enough, not waiting for the first deliveries which may then show that all chambers should be measured but leaving people without solution! We may already say that a single X-ray tomograph will not be enough to run all those tasks whichever the chosen scenario would be.

6.2 Resources requirements

As pointed out, scenario 1, implies to build two tomographs. Provided the decision be taken end 1997, this should be possible within the time left in 1998 and 1999. Taken into account the present support, the staff needed should be smoothly increased to about 10 people full time. Detailed budget studies are not yet done. An estimate of 1000 kCHF looks reasonable. A large space (20 x 55 m^2 including a 14 x 35 m^2 clean room) should be granted by CERN for this work.

Scenario 2. would not imply new constructions after the termination of the present development program, as only some minor new improvements should be expected. The technological transfer to the Institutes should be done by CERN. Only a small increase in the present space and manpower should be enough provided the continuity of the know-how is insured.

Optimistic and pessimistic scenarios are not discussed in term of resources as they seem at present unrealistic.

The structure and responsibilities of the MDT quality control should be well defined and strengthen. It will be the ATLAS management responsibility to define, document its policy and objectives for, and commitment to, quality.

Acknowledgments

We would like to thank L. Vertogradov for the excellent pioneer work on the X-ray tomography for the MDT chambers. We are grateful to the members of the ECP/EOS group participating in this X-QC project, for their efficient work all along the project and to the EST/MF & SU groups for the precise survey of the tomograph. In particular, we thank C. Boudineau for his competence and enthusiasm in the preparation and installation of the interferometers and in the precise optical calibration of the reference rulers.

Finally, we address our thanks to the managements of the ATLAS Collaboration and of the Muon Spectrometer System for their advice and continuous support.

Appendixes

A Muon chamber naming

The chambers have a label according to their position within the muon ATLAS spectrometer. The detail code convention can be found in [15].The key labels used in this note are as follows:

- B for Barrel, E for end cap, F for forward chambers,
- I for inner, M for medium, O for outer chambers
- S for small, L for large chambers.

For example, a BMS chamber is a small barrel chamber installed in the intermediate station between the inner and outer stations.

B Systems of coordinate

The system of coordinates for the X-ray tomograph and for the MDTs are not identical for practical reasons. In this paper, we exclusively use the natural system of coordinates of the X-ray tomograph (see Figures 2 & 7),

- X coordinate in the horizontal plane, the scanning direction parallel to the portico,
- Y coordinate in the horizontal plane, perpendicular to the scanning direction,
- Z the vertical coordinate.

MDT uses another system of coordinates:

- x (along the tubes),
- y (normal to chamber plane),
- z (across the tubes).
- Consequently the correspondence between X-tomograph (X, Y, Z) and MDT (x, y, z) is as follows:
  - X ↔ z, Y ↔x, Z ↔ y

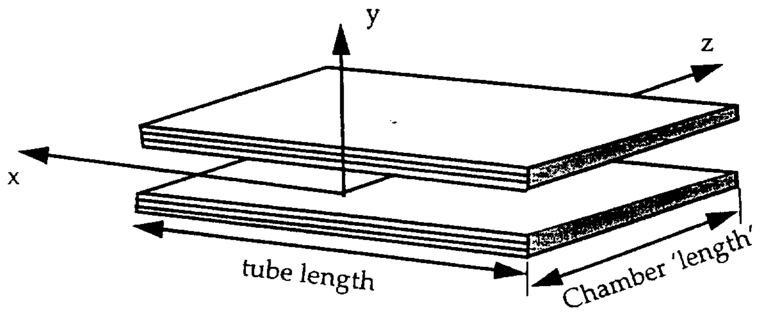


Figure 6 The local system of coordinates (x, y, z) of the MDT chambers.

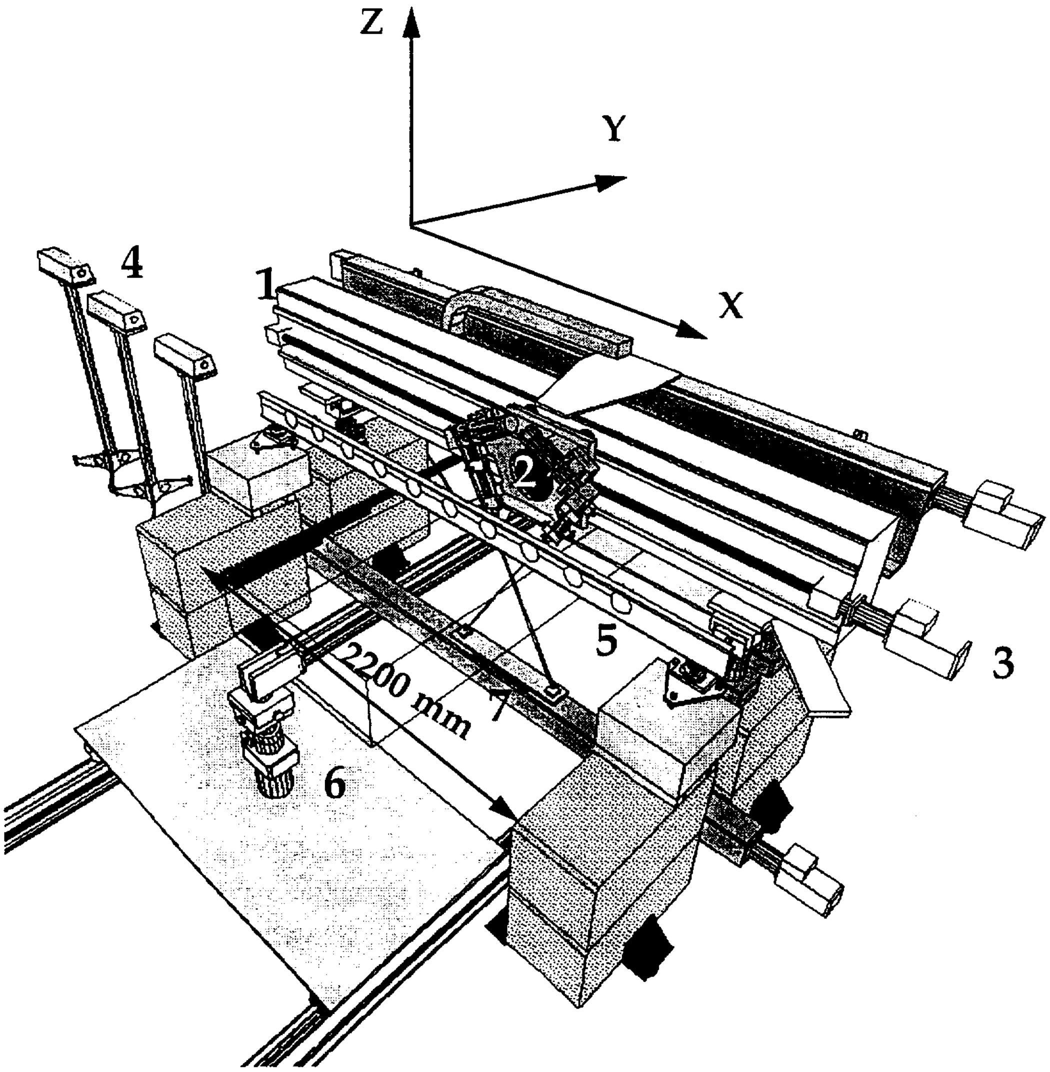


Figure 7 Sketch of the large X-ray tomograph prototype defining the local system of coordinates (X, Y, Z). It also shows the main components of the tomograph: 1) the portico, 2) the rolling cart with the two X-ray sources, 3) the 3-motor driving system for the scanning, 4) the lasers for the three interferometers, 5) the reference rulers, 6) The chamber rolling cart, 7) the two scintillators

References

[1] ISO 9000, Quality management and quality assurance standards, International Organization for Standardization, First edition, 1987-03-15

[2] ISO 9001, Quality systems-Model for quality assurance in design/development, production, installation and servicing, International Organization for Standardization, 1987-03-15

[3] ISO 9002, Quality systems-Model for quality insurance in production and installation, International Organization for Standardization, 1987-03-15

[4] ISO 9003, Quality systems-Model for quality assurance in final inspection and test, International Organization for Standardization, 1987-03-15

[5] ISO 9004, Quality management and quality system International Organization for Standardization, 1987-03-15

[6] Engineering data management-A tool for technical coordination, G. Bachy et al., CERN MT/95-07 (DI)

[7] ATLAS Project, Introduction to the ATLAS quality assurance plan, G. Bachy, Note ATL-CER-QA-001, 22 April 1996,

[8] L. Vertogradov, High precision wire positions measuring in the drift tube package by X-ray scanner (X tomography), ATLAS Internal Note, MUON-041, 11 May 1994

[9] D. Alexeev et al., XTOMO, A prototype of the X-Ray tomograph for high precision measurements of the MDT muon chambers, ATLAS Internal Note, MUON-142, 24 March, 1997

[10] D.G. Drakoulakos et al., XTOMO, one dimensional X-ray scanning of 8-layer MDT prototype using the passive mode, ATLAS Internal Note, MUON-151, 17 April, 1997

[11] D.G. Drakoulakos et al., XTOMO2, Stereo measurements of the MDT muon chambers using a high precision X-ray tomograph, ATLAS Internal Note, MUON-155, April, 1997

[12] D. G. Drakoulakos, Thesis, to be published May 1997

[13] J. H. Klinger et al, A thermally stabilized, two frequency laser measurement system for industrial use, Hewlett-Packard Company, SPIE Vol. 416, Applications of Optical Metrology - Techniques and Instruments II, 1983

[14] F. Lejal et al., On-line conception of the X-tomograph, see the Web at address: http://wwwcn.cern.ch/~lejal/LINKS/internalNote.ps

[15] ATLAS muon spectrometer technical design report, CERN/LHCC/97-22, ATLAS TDR 10, 31 May 1997.

[16] E. Gschwendtner,X-ray tomograph for high precision particle detectors, Diploma thesis, to be published summer 1997

[17] X-Tomo page on the Web: http://wwwcn.cern.ch/~sedykh/X-tomo/

[18] Y. Sedykh et al., Stereo measurements of large full scale MDT prototypes, to be issued summer 1997 as CERN-ATLAS-MUON-NOTE-NO-175