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The ATLAS Muon Chamber Assembly Station at NIKHEF

NIKHEF ATLAS MUON GROUP

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Abstract: At NIKHEF (Amsterdam), the largest muon chambers for the outer layer of the barrel ATLAS muon spectrometer have been constructed. At this facility, more than 40000 single drift tubes have been produced and 100 muon chambers have been assembled. We report on the quality assurance of both single drift tube production and chamber assembly. This, together with the presented results obtained in a dedicated cosmic ray test set-up, also part of the facility, demonstrates that the chambers fulfil ATLAS specifications.

1 Introduction

To stand-alone measure muons that emerge with a transverse momentum of 1 TeV/c with an accuracy $\frac{\sigma_{P_T}}{P_T}$=10% is the most stringent requirement for the muon spectrometer of the ATLAS experiment at the LHC. This translates to 50 μm uncertainty on the sagitta measurement in the 2 Tm integrated magnetic field, provided by an air core toroid.

The muon system in the barrel region ($\eta < 1$) is designed such that muon trajectories are measured by three muon chambers, each with at least 2×3 drift tube layers. Earlier tests show that the drift tubes under well-controlled conditions have single hit resolution of about 80 μm (averaged over drift distance). To meet the above requirement we aimed to construct muon chamber with a mechanical precision of 20 μm (RMS). The components serving the internal (in-plane) and inter-chamber alignment have to be precisely positioned and calibrated with a similar precision.

The outer layer of the barrel region covers an area of $1700m^2$ and consists of an equal amount of small and large type chambers. At NIKHEF (Amsterdam, The Netherlands) we constructed 100 large 'Barrel Outer Large' (BOL) chambers. This number includes four spare chambers. Our facility is unique in the sense that we have produced single tubes, assembled the chambers and consequently performed cosmic ray tests before shipping the chambers to CERN.

In this report, we describe the requirements on single tubes and completed chambers, moreover we present the results on the quality assurance operations. Among the tests is the dedicated measurement in the X-ray tomograph at CERN of a limited amount (roughly 10%) of the BOL chambers. Finally, we summarise the muon chamber performance in the cosmic ray set-up at our facility.

2 Drift tube chambers

The BOL muon chambers consists of two separate layers (multi-layers), each with three drift tube layers, mounted on an aluminium support structure (spacer) as shown in figure 1. The spacer connects the multilayers by three 'I' beams, called cross-plates, running orthogonal to the tubes. The crossplates are itself are connected by two beams, that run longitudinal (which are therefore called long-beams). The BOL chambers have a length of 5 m and come in three different widths: 2160 mm (72 tubes), 1680 mm (56 tubes) and 1440 mm (48 tubes).

Physical deformations of the chambers during construction, transport and operation are monitored [1] with the in-plane alignment system consisting of four RASNIK systems (see appendix A) also indicated in figure 1. In addition, 16 temperature sensors provide supplementary information on possible chamber deformations. The inter-chamber alignment consist of RASNIK systems monitoring the position of neighbouring chambers of the same type and RASNIK systems that monitor the projective alignment of the three muon chamber layers. In a test setup at CERN [2] it was demonstrated that an alignment accuracy better than 10 μm (on the change of the relative chamber positions) can be achieved with this system.

A schematic view of a drift tube is shown in figure 2. A drift tube has a diameter of 29.970xxxxxx$\pm$ 0.015 mm and a wall thichness of 400xxxxxxxx μm . The tube is swaged on two precise end-plugs that are manufactured with a precise outer ring of aluminium to position the tube during the assembly in jigs with high precision. The end-plug also connects to the gas system and is closed by a signal cap to connect High Voltage (HV) and Read-Out (RO) electronics boards at the tube's HV and RO ends respectively. The 50 μm gold-plated tungsten wire is tensioned at 285xxx gram and then crimped to the end-plug leading to a gravitational sag of about 405 μm for

[1] For this reason the ATLAS muon chamber are called Monitored Drift Tube (MDT) chambers

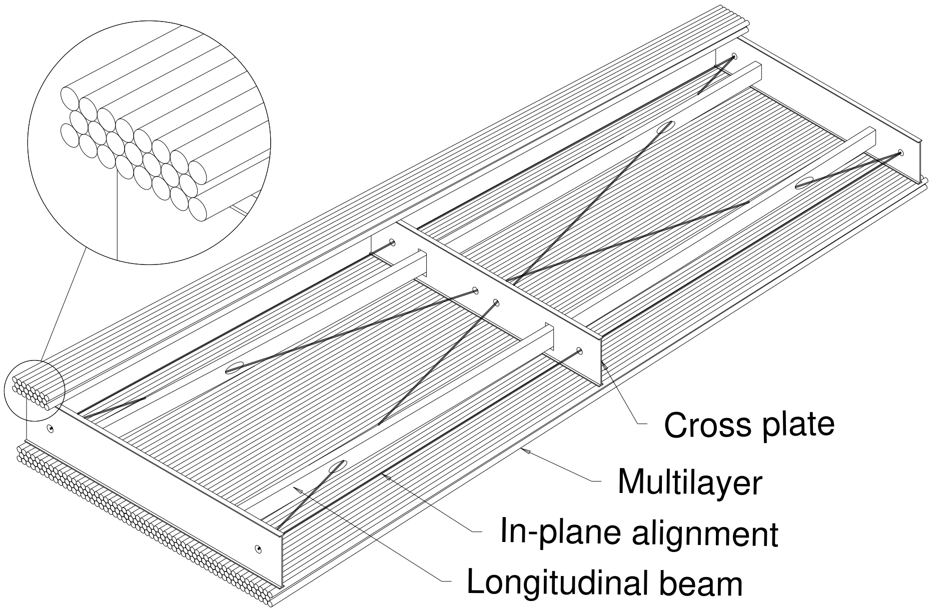

Figure 1: *Schematic view of a muon chamber.*

a horizontally placed tube with a length of 5 m. A locator ('twister') designed to have a small gas flow resistance, accurately centres the wire with respect to its outer ring.

3 Coordinate systems

When the chamber is located on the granite table in the 'upward' position the local chamber coordinates are defined such that the y coordinate points to the sky, the x coordinate runs along the tubes in the horizontal plane. The z coordinate, the precision coordinate, runs perpendicular to the tubes. The x, y and z axis constitute a left-handed coordinate system. The global coordinate system in our cleanroom is then defined by a south-north and west-east direction that runs in the x

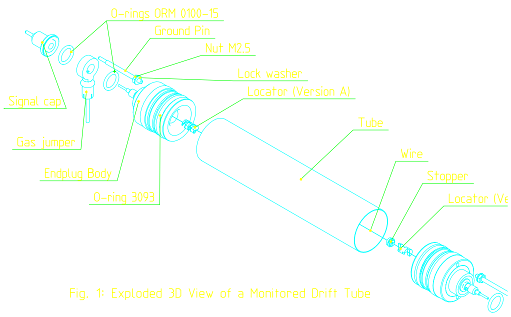

Figure 2: *Schematic view of a drift tube. Several components are indicated.*

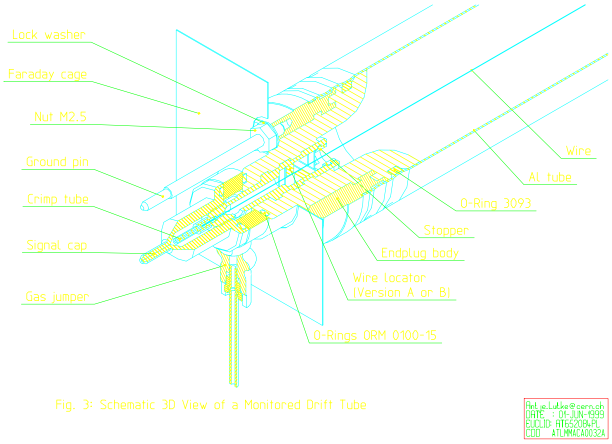

Figure 3: *Picture of an end-plug.*

and z direction respectively. In the 'upward' position, the Read-out (RO) and High-Voltage (HV) side of the chamber coincides with the south and north respectively. In addition, for engineering purposes, we defined the west side of the setup as the 'reference-side'. The reference side always coincides with the smallest z coordinate of the chamber.

4 requirements and impositions

The mechanical precision of 20 μm RMS is implemented as follows. Any transverse cross section of any chamber can be represented by a single wire grid. The individual wires of a particular chamber are mapped on this grid with residuals distributed within 20 μm RMS. Therefore, we aimed to set-up an assembly stand based on a granite table with precision mechanics, such as jigs to hold the drift tubes, machined with a precision of 10 μm or better. The precision of individual drift tubes has to be of the same order, which imposes the accurate machining of the end-plugs (which determine the position of the wire). Furthermore, to guarantee this precision over the full length of the chamber, the wires need to be tensioned within 285+-15gram with corresponding gravitational sag of 406+-22um.

The requirement on the co-centricity of the wire due to non-straightness of the drift tube (anode-cathode distance) is a second order effect and set at 100 μm RMS. The gravitational sag of a horizontally mounted chamber can be as large as 2 mm. In this case the tubes sag by 2 mm, while the wires maintain their nominal gravitational sag mentioned above. This requirement imposes us to equip each chamber with a system to adjust the sag of the tubes to follow that of the wires depending on its final orientation in the ATLAS experiment.

In order to achieve long term stable operation in the ATLAS experiment the dark current of individual drift tubes shall not exceed 10nA at 3300V at 3bar absolute pressure with an Ar/CO_2 (93%/7%) gas mixture (gas gain 2×10^4). The leak rate under these conditions must be less than 10^{-8} bl/s.

5 Drift tube production

The 40 thousand drift tubes were produced in the temperature-controlled cleanroom parallel to the assembly of the chambers, using a semi-automated wiring machine. On the picture shown in figure 4, taken at the north side (as we defined it), several components are indicated.

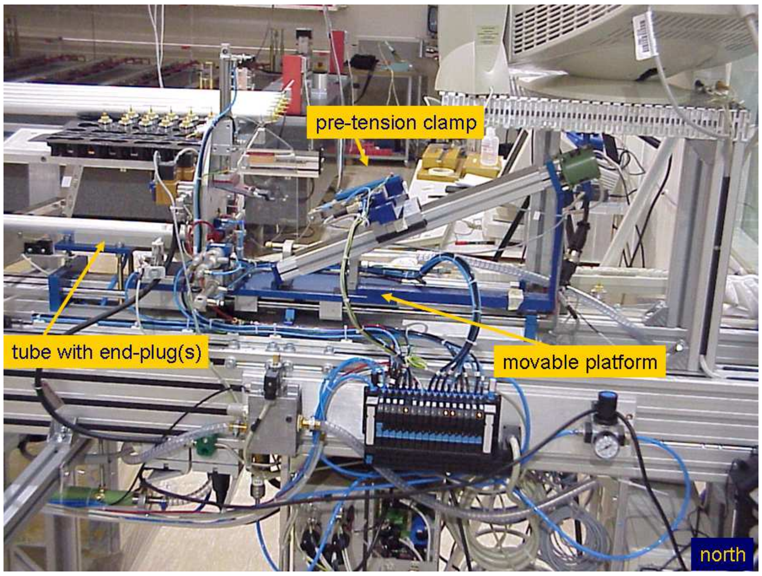

Figure 4: *Picture of the wire machine taken at the north side. Indicated are the movable platform in the final position and the clamp to pre-tension the wire. Also indicated is the tube with has fixed end-plugs in this stage.*

The machine is loaded by an aluminium tube and two complete endplugs. The wire is transported from its supply by means of airflow through the 'south' end-plug toward the 'north' end of the tube. At the north end the wire is literally sucked through the end-plug and fetched by a wire clamp. Now, movable platforms at both sides bring the end-plugs to their final positions in the tube. The two end-plugs are fixed by tube swager using air pressure. At the south end, the wire is fixed at the left end-plug by crimping it and the tube is in the state as shown in the picture. The clamp at the other side moves away to pre-tension the wire by 400xxxxx gram before releasing it slowly to its final tension of 280xxxxx gram. Crimping the wire at the north end-plug finalises the drift-tube.

The wire tension, length and position was measured immediately after production for every tenth tube to assure proper operation of the wiring machine.

The tension is derived from the measurement of the fundamental harmonic resonance. This measurement is als used in [**?**] and it is based on the induced response to a sinusoidal current while the tube is partially immersed in a magnetic field.

The wire position with respect to the outer ring of the end-plug was measured using an eletromagnetic method (see [5]). the method uses the response of two coils sensing the field of an sinusoidal current that is driven through the wire. One set of coils is used at each end of the tube and by rotating the tube by 90 degrees two projections (called y and z) for each end are obtained.

Figure 5a shows a scatter plot of these projections. The radial deviation is better than 10 μm (RMS) as appropriate. In these tests, we found only eleven tubes with a deviation larger than 25 μm in one of these projections, which we stored for further (destructive) studies.

The gas tightness and dark current of all produced tubes was measured in a set-up (in the clean-room) specially designed for this purpose (see appendix **??**). This set-up consists of 80 vacumized large tubes (diameter 6xxxx cm) loaded with the drift tubes under test. The drifttubes are filled with 4 bar 1%/99% helium/argon mixture and the wire is set at 3300 V. The leakrate (for Ar/CO_2 at 3 bar) and dark current measurement is shown in figure 6 and 7 respectively. The results indicate that the majority of the tubes is well within specifications. However, the long tail of the leakrate distribution (not shown) leads to a failure rate of about 1%, making the leakrate the

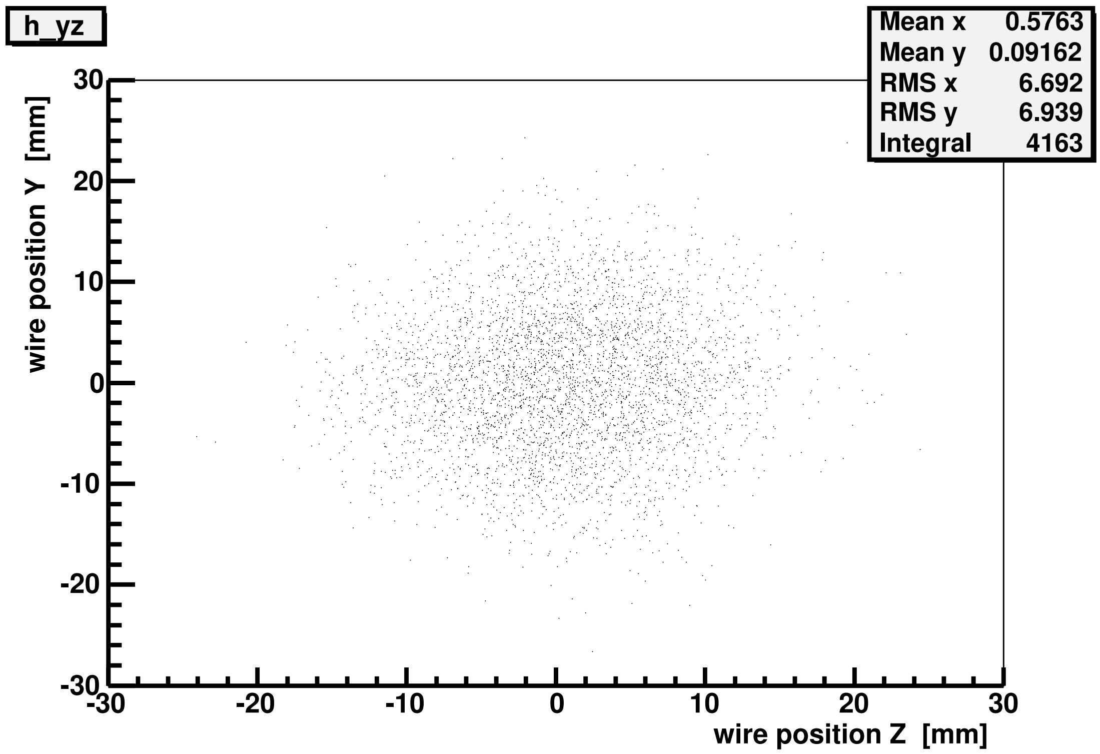

Figure 5: *Scatterplot of the y and z deviation of the wire position measured on a sub-sample of produced drift tubes.*

dominant rejection source.

After ageing of at least one month and just prior to using the tubes in the actual chamber assembly, all the tubes were subjected to a second wire tension test. Like the frist measurement, the tension is also derived from the measured resonance frequency, but without the requirement that the tube is immersed in an magnetic field. The electrostatic force due to a supplied sinusoidal HV leads to mechanical wire oscillations. The changing capacity of the tube is measured in an LC circuit, leading to a resonance curve. the method is described in [4]. For our wire with length 4940 mm a weight per unit length of 38.70 mg/m, a resonance frequency of 27.2 ± 0.5 Hz corresponds to 285 ± 15 gram tension. Only 21 tubes failed and the results for tubes that passed are shown in figure 8. As mentioned above, for 10% of the tubes a 'fresh' measurement of the wire tension is available, allowing to study 'slippage' that may occur over time. We expect that if any slippage occurs, it occurs dominantly in the in the ageing period and possibly during handling of the tubes. // No evidence for wire slippage was found. The change in resonance frequency exhibits an assymetric shape as shown in figure **??**. This suggest a comfortably small wire slippage for a fraction of the tubes.

In total, we have produced about 40000 drift tubes. Our stringent criteria led to a rejection rate of 2.5%. The 100 BOL chambers (96 ATLAS chambers and 4 spares) we produced, contain 38448xxxxxxx tubes that fullfil our requirements.

6 Chamber production

The gluing of six layers of 72 tubes onto a structure with dimensions 5m $\times$ 2m , with a precision of 20 μm is a delicate procedure. Depending on the actual layer to be glued, mistakes are costly in time and material. We constructed an accurate assembly station and adopted a robust procedure

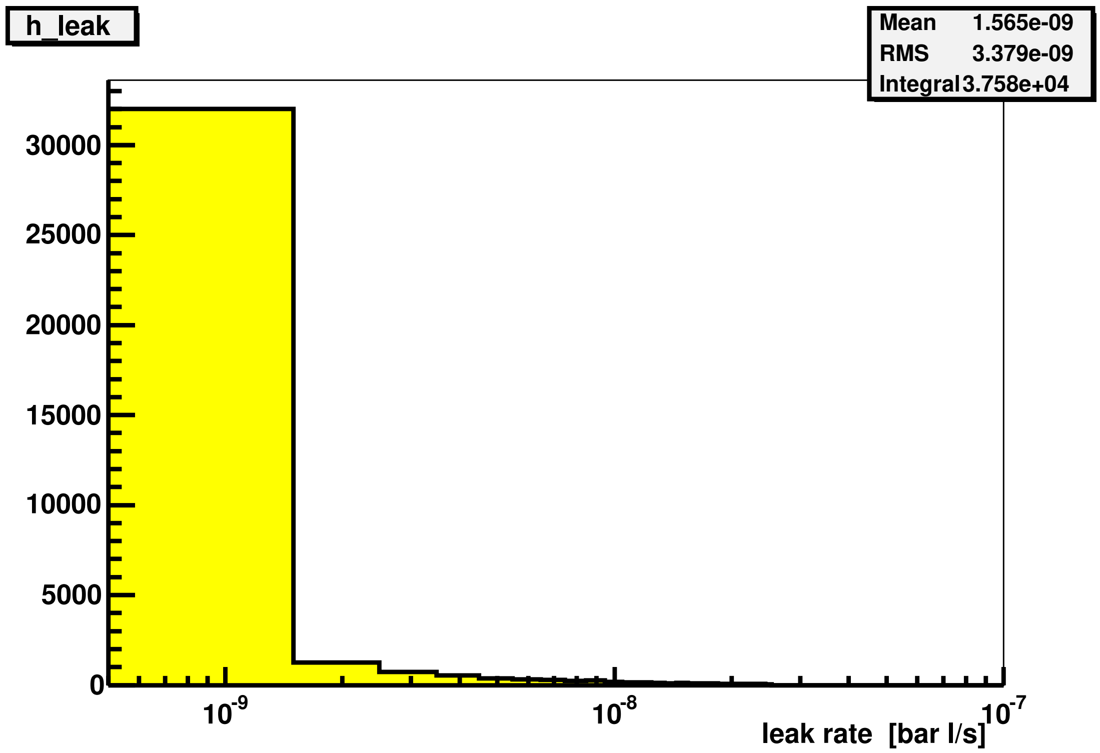

Figure 6: *Leakrate of all used tubes in b l/s*

to assemble the muon chambers with high precision.

6.1 Assembly station

Figure 10 shows the granite table equipped with precision mechanics. The end-plugs are hold by the outer jigs, which are constructed and positioned with a tolerance of 20 μm . The stacking towers have the same accuracy and have adaptable heights to absorb the thickness of the vertical pitch of the tube layers. The central stacking position is shifted by half the horizontal pitch as appropriate. The jigs are fixed at the west side, the reference side, and can expand freely to absorb temperature variations. These components, combined with a stable and uniform temperature (typical variation < 0.5°C over one day) allow to assemble chambers within the 20 μm RMS precision requirement.

During assembly, extensions with precise spheres (diameter 6cmxxxx) are mounted on the cross-plates as can be seen in figure 11. The stacking towers at the reference side support the spheres with so-called sphere-holders that can move freely in the x direction to absorb temperature variations. At the east side, the non-reference side, the sphere-holders can move freely in the horizontal plane. The sphere-holders are designed such that their height during possible horizontal movements is maintained with an accuracy better than a few microns.

When the spacer (with or without already fixed tube layers) is supported by the stacking towers the gravitational of the cross plates is considerably, of the order of 50 μm . To reduce this sag considerably to typically 10 μm the unfinished chamber is carried by an additional system. One of the the eight pneumatic cylinders constituting this system is also visible in figure 11.

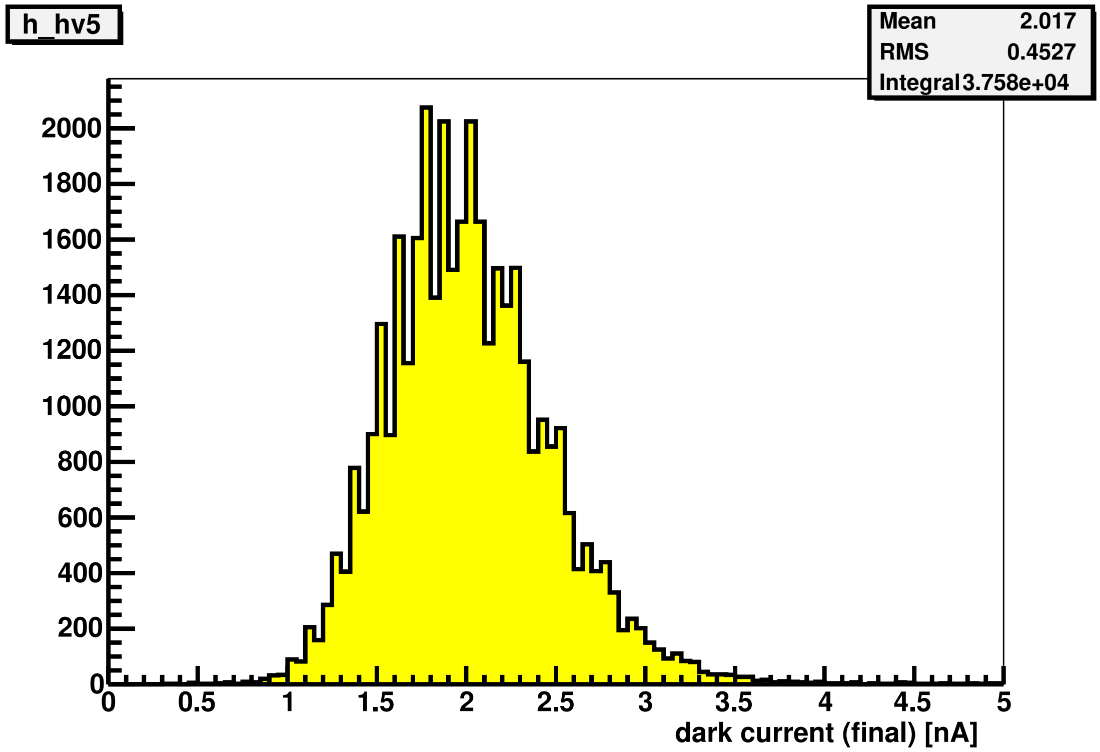

Figure 7: *a: Dark current in nA of all used tubes.*

6.2 Chamber assembly

The assembly procedure starts with the assembly of the bare spacer, with a 'loose' accuracy of typically 500 μm . Then, the tubes are attached, layer by layer, using glue.

As already mentioned the quality control during chamber assembly start with re-measuring the wire tension of the tubes to be glued in the particular sequence. After this test, the tubes are positioned in the jigs and the horizontal position of the end-plugs, both at the RO and HV side, is measured using laser beam running parallel to the end-plugs [6]. For this test, a reference rod is placed between two adjacent tubes which partially blocks the laser beam measured by an optical sensor. Deviations in the response respresent a measure of deviations in tube heigts. Note that by measuring between adjacent tubes, the results of this test are somewhat ambiguous case neighbouring tubes are both badly poistioned. In addition, the test is sensitive to tube heights (y) as well as to the distance (z) between tube pairs and the radii of the corresponding end-plugs. On the other hand, a badly positioned tube shows up twice and is tagged easily. In practice, only a few tubes needed to get re-positioned. In some rare cases, we had to replace the complete tube due to, as it turned out, bad swaging of the end-plug. Bad swaging occurred for a particular batch of tubes where the end-plug was not well inserted in the aluminium tube. We aimed at tube height deviations below 20 μm and investigated all tube pairs with responses above 10 μm were inspected by the operators.

The result of these measurements as shown in figure 12, indicate that the tubes are well positioned.

After position of the tubes glue (Araldytexxxxx) is dispensed by means of an automated gluing machine. For the first (and later second layer), glue is dispensed only in between adjacent tubes. The relevant side of the cross-plates is supplied with a sufficient amount of glue (3Mxxxxxx) and the spacer is lowered onto the tube layer. To check the correct positioning of the spacer we used RASNIK systems that monitor the cross-plate extensions at the four stacking towers at

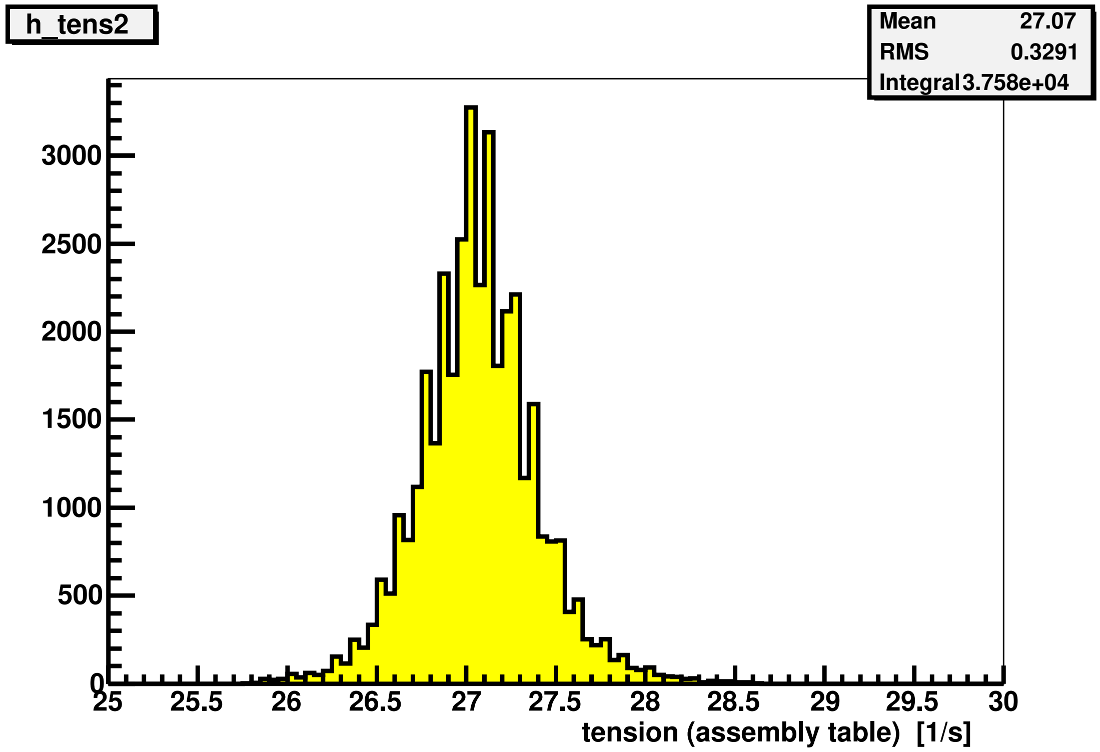

Figure 8: *Measurement of the wire tension of all tubes just before chamber assembly.*

the corners of the assembly table. In addition, we used a temporary RASNIK system on both the HV and RO crossplate to monitor their sag. Together with the 'standard' in-plane alignment components of the spacer, these RASNIK systems provided crucial position information with an precision of 10 μm , which may be regarded as remarkably accurate for such large structure.

PLOTRASNIK, Graziano

After glue curing for at least 12 hours the spacer with the first tube layer is rotated upside down, effectively over its x axis, thus respecting the reference side. The second tube layer is prepared the similar procedure as for the first layer is followed. Now both sides of the spacer have a tube layer attached to it. To glue the third layer, the spacer is lifted and the stacking tower height is adapted to attach the third tube layer. On the tubes of the third layer and onward, two additional glue ropes (Araldytexxxxx) are dispensed to connect adjacent tube layers. To glue the fourth layer, the spacer with its three tube layers is rotated back to its original orientation, limiting the (un)balance of the spacer and tube layers and thus avoids possible effects of asymmetrical weight distribution. After gluing the fifth layer the chamber is turned once more to finish it by attaching the sixth layer.

About every 25-th chamber several checks concerning the accurate positioning of the mechanics were performed. Notably, the distances between the corner stacking towers and the corresponding jig at the RO and HV reference side was measured with an auxiliary device. When these distance deviate, the chamber obtains an unwanted stereo angle build in. Our checks demonstrated that such stereo angle is smaller than 4 μrad over the full period of the production.

7 Results of X-ray scans

About 10% of all chambers undergo a mechnical precision check in X-ray tomograph [**?**] at CERN. The tomograph consists of a unit with two stereo X-ray beams that runs over the chamber

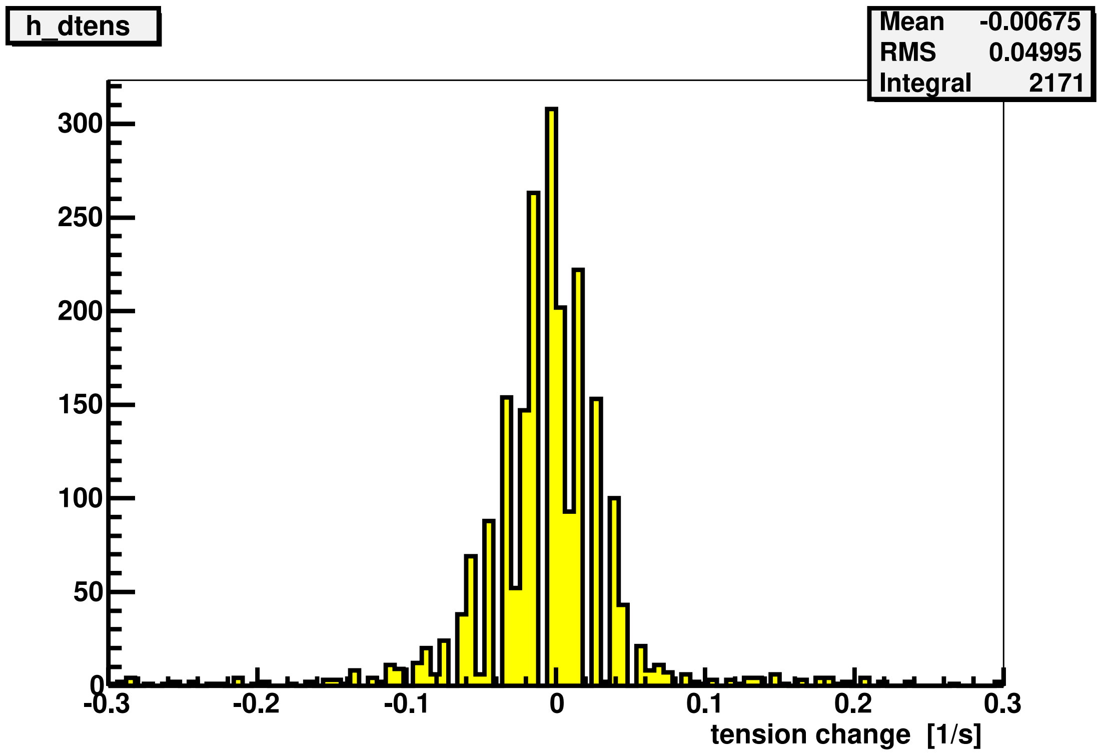

Figure 9: *Measurement of the change in wire tension between production of the tube and chamber assembly.*

in the z direction at a fixed x position. Scintillator counters measure the 'shadow-pattern' of the wires and tube-walls. A dedicated analysis of such pattern results in a wire position map with an accuracy of typical 5 μm . The chamber is considered certified as the distribution of the residuals with respect to the nominal wire map has an RMS below 20 μm . Table 1 lists the RMS values of the residual distribution for the scanned BOL chambers. The numbers indicate that these chamber are assembled according to the specifications.

	RMS z μm	RMS y μm	RMS combined
BOL 2	1000	0000	0
BOL 3	1000	0000	0

Table 1: *The table list for each scanned BOL chamber the residuals of the wire coordiantes obtained in the X-ray tomograph. The numbers of the BOL chambers refer to their serial production number.*

In figure. 13 we compare the layer Z-pitch deviations obtained by the X-ray tomograph with those derived from the RASNIK monitoring at the time the layers were glued. The RASNIK deviations are shifted to set their average deviation to zero as appropriate for this comparison. The distribution of the differences of the two measurements has an RMS of 6 μm , indicating that the quality control during the assembly is well understood.

8 Chamber completion

After the mechnical completion of the chambers, we started with installing the gas system, read-out electronics [ref] and HV system [ref].

The on chamber gas system consists of two gas manifolds for each multilayer. Tubes of the

Figure 10: *Picture taken in the cleanroom, illustrating the last step of the chamber assembly. The jigs on the granite table hold the final tube layer. The chamber, which consistst at this point of the spacer with 3 layers on top and 2 layers at the bottom is lowered on the last tube layer. Also visible are the stacking towers, sag compensation towers and RASNIK towers that control the positioning of the spacer. (xxxxxxxxxx indicate this in pixture? xxxxxxxx)*

same layer are grouped in series of three (tripplets) to reduce the number of gas connections to the manifold. Only the first and last tube in the tripplet connects to the manifold at the RO side and HV side respectively. After installing the gas system, the chamber is filled to 3 bar and its pressure (corrected for temprature effects) is monitored for at least 24xxxxhours to assure the gas tightness of the added components.

8.1 Broken wires

After the completion of the first chambers we detected a number of broken wires in several chambers. Despite many dedicated studies, the cause of this problem has not been recovered. However, we observed that broken wires seem to occur only in chambers that have 'seen' high gas flows (xxxbar/l). Moreover, this problem is restricted to the first (or last) tube of a triplet connecting to the gas manifold. To avoid such high flows we put mechnical flow restrictors in the on chamber gas outlet tubing. In total we have xxxx chambers with broken wires. Usually, the number of broken wires is limited to 1xxxxx, except for one chamber, BOLxxxx, whch has the 24xxxx broken wires. We repair the broken wires, using a procedure that uses the existing o-ring and thus not requires any glue. This comes not for free. The accuracy of the wire position is estimated to a few 100 μm . In principle, the wire position of such wires can be obtained later in the ATLAS experiment with a procedure that uses tracks xxxxxxxxxxxxxxxxmore?.

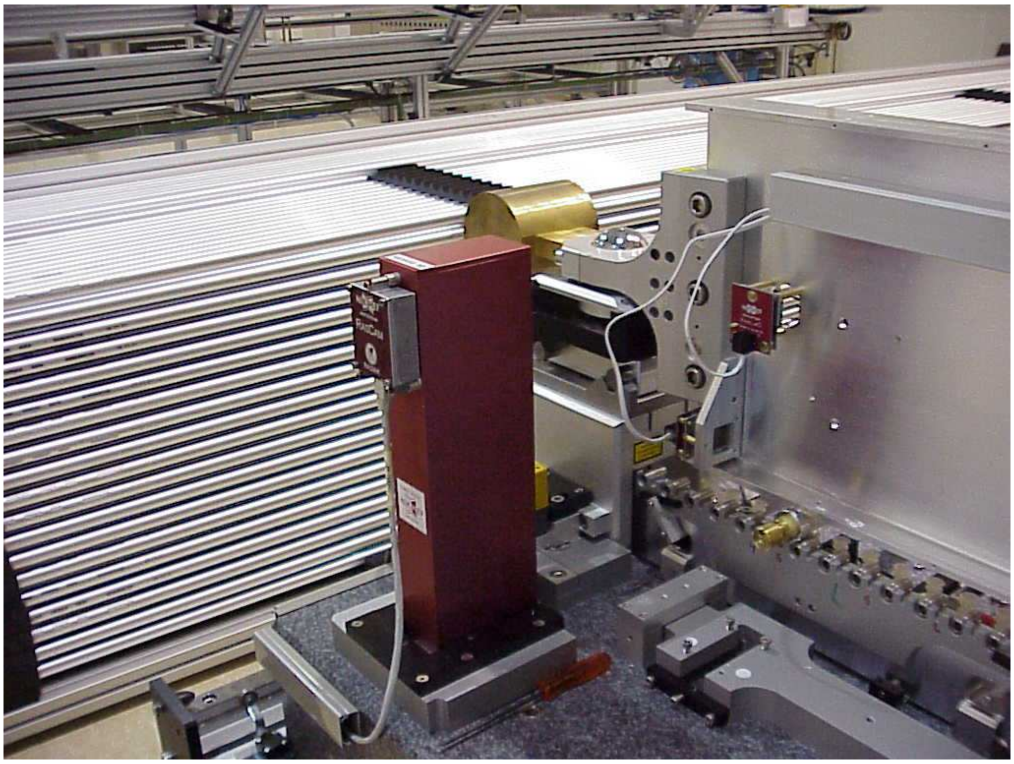

Figure 11: *The picture shows the stacking tower supporting the extension of the spacer. The position of the spacer is monitored the alignment system. xxxxxxxxxindicate in the piture?xxxxxxxx*

9 Cosmic ray test stand

The cosmic ray test facility at NIKHEF accomodates five BOL chambers and has a fixed trigger system as shown in figure 14. The trigger units (also visible in the figure) consist of two layers of scintillators, separated by 50cm thick iron block to filter out the low energetic muons (i.c. muon with energies smaller below 0.7 GeV). Since the summer of 2004 till the autum of 2005 we routinely tested BOL chambers; usually we exhanged three chamber middle chamber and kept the outer chamber in place to have a stable reference.

The main purpose of the test stand is to verify the electronic read-out of each chamber under ATLAS gas (Ar/CO_2= 93%/7% at 3 bar) and HV (3300V) conditions. Usually, the chamber under test became operational without any intervention. Figure 15 show a typical difftime distribution for a single wire. The t_0 and t_{max} for each individual wire is extracted from its drifttime distributions. Large deviations are a good indicator for problems. We often observed a pattern related to groups of three drift tubes constituting a gas-tripplet. After an extended period of flushing (xxxxxxx liter) these structures disappear. One, and only one, severe problem remains, which are the broken wires observed in some chambers as mentioned above. xxxxxxxxxx

Further analysis of the data uses software being developped for ATLAS and involves driftdistance versus drifttime calibration with corresponding track fits to drift circles in individual chambers. The distribution of the residuals for a representative wire is shown in figure 16. The efficiency for single hits is 9xxxx% and the resolution is xxxxxx μm as expected for the current conditions.

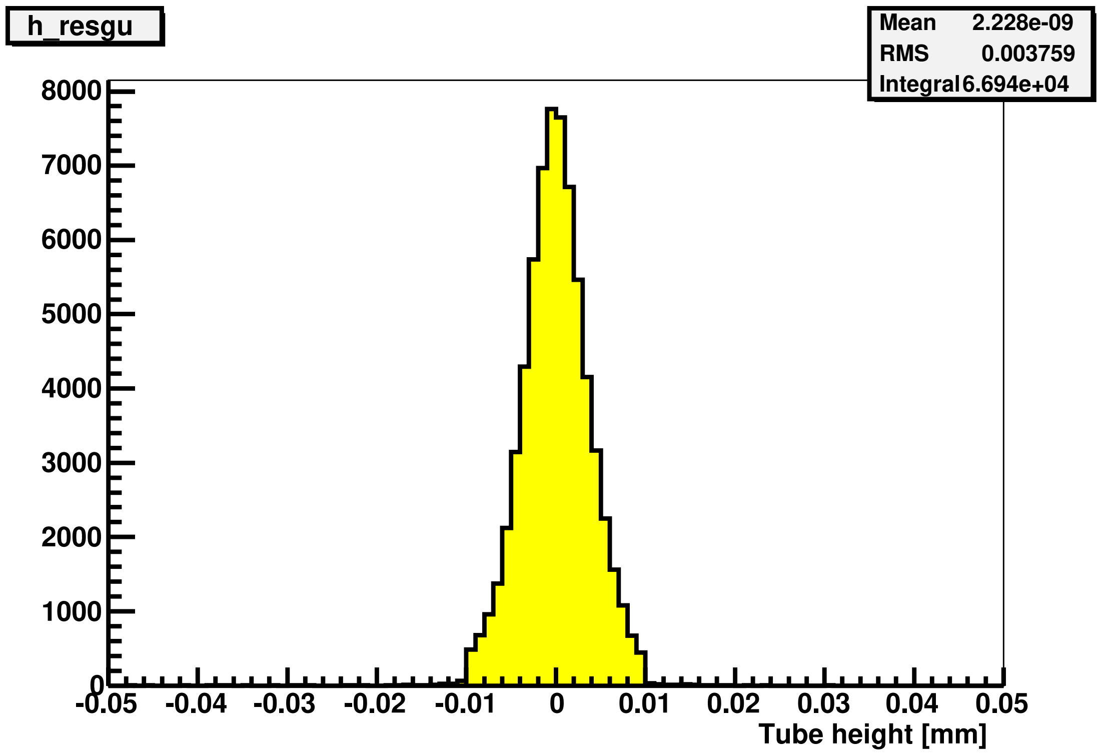

Figure 12: *Tube positions during assembly.*

10 Conclusions

chambers are within specs. Broken wires..????

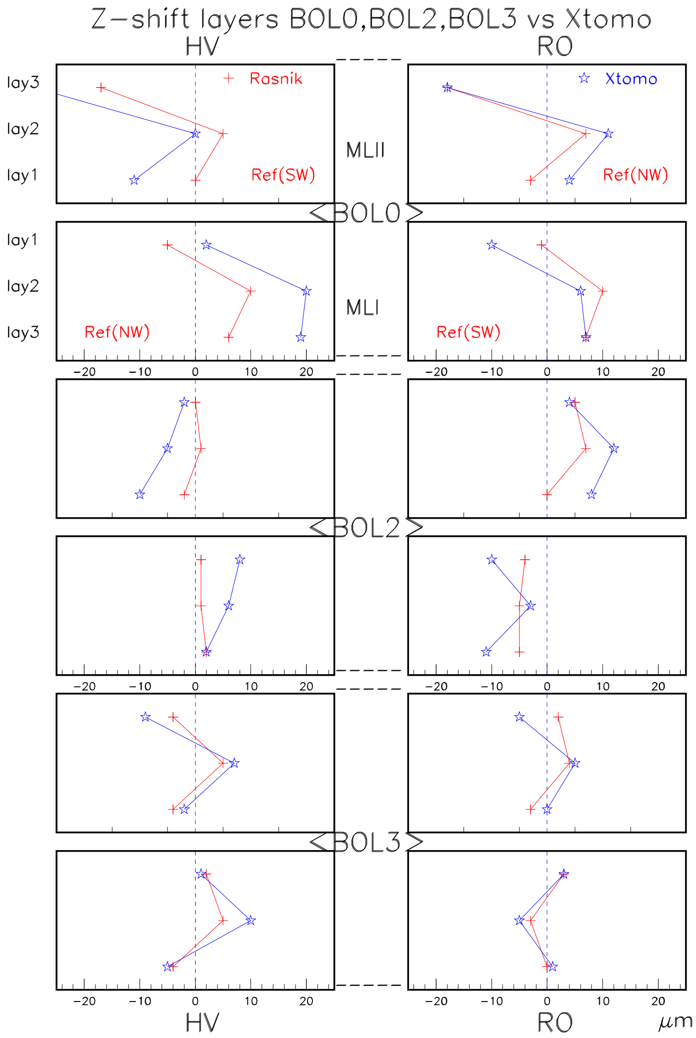

Figure 13: *Comparison of results from the tomograph scans for chambers BOL0, BOL2 and BOL3 with RASAS data taken during glueing of the layers of these chambers. For each chamber a set of 4 plots show the deviations from the nominal Z layer pitch for the 3 layers within each multilayer (MLI and MLII) at the HV and RO side respectively. xxxxxxxxxxxxxxxxxxxkeep it? Then, renew itxxxxxxxxxxxxxxxxxx*

Figure 14: *Picture of the cosmic ray stand. xxxxxxxxxxxxxfind nicer or photoshop.xxxxxxx*

Figure 15: *Drift time distribution xxxxxxxxxxxxxget it, if we want itxxxxxxxxxxxxxxxxx*

Figure 16: *Residual. xxxxxxxxxxxxxget plot if we want it.xxxxxxxxxxxxxxxx*

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A Alignment system RASNIK

RASNIK is the acronym for Red ALignment System NIK(HEF). The 'red' refers to the color of the LEDs used in the very first version invented at NIKHEF. The system consists of a coded mask that is (partially) projected by a lense on a camera as shown in figure 17. The basic binary blocks have dimenesions of 100 μm $\times$ 100 μm and form a chessboard like pattern as can be seen in figure 18. An additional code on each nineth row and column, also visible in the figure, allows to reconstruct the coarse alignment. This set-up measures relative transverse movements (X,Y) with respect to the optical axis, the relative rotation (α) over the optical axis of the mask and the camera and the ratio of the distance of the lense-camera and lense-mask (the $scale$). The resolution depends on several parameters, such as the quality of the lense. Especially for large distances between mask and camera, temperature gradients in the air affect the light path deteriorating the resolution. However, for a setup of 1 m long (in total), a precision of 1 μm on transverse movement, 50 μrad on the rotation and 10^{-4} on the scale is achieved. is measured with a resolution of 50 μrad and the scale to 10^-4.

The alignment of the ATLAS muon system is completely based on the RASNIK principle as can be read in detail in **??**.

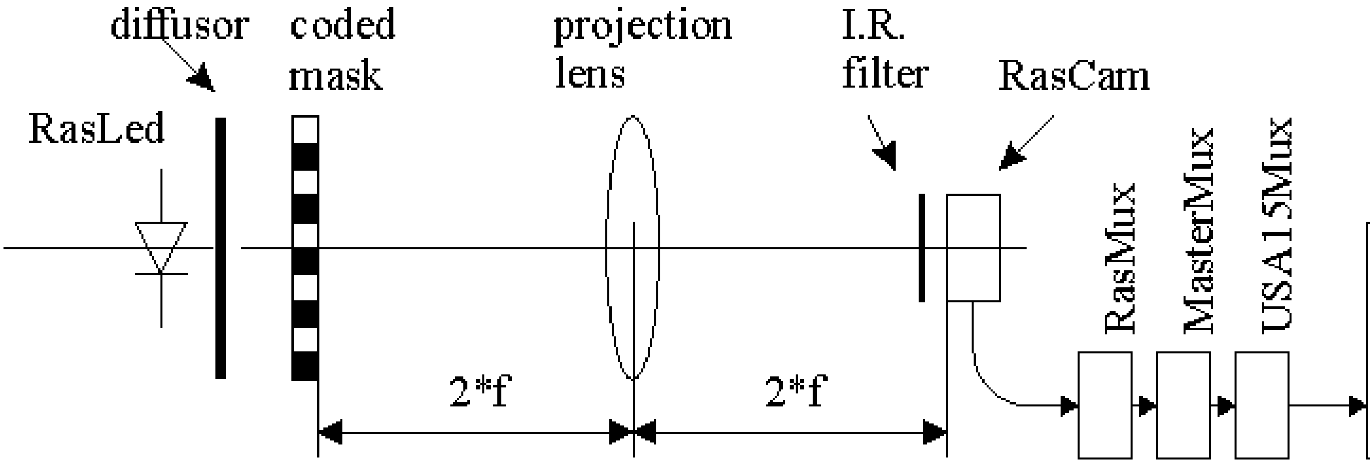

Figure 17: *The principle of RASNIK.*

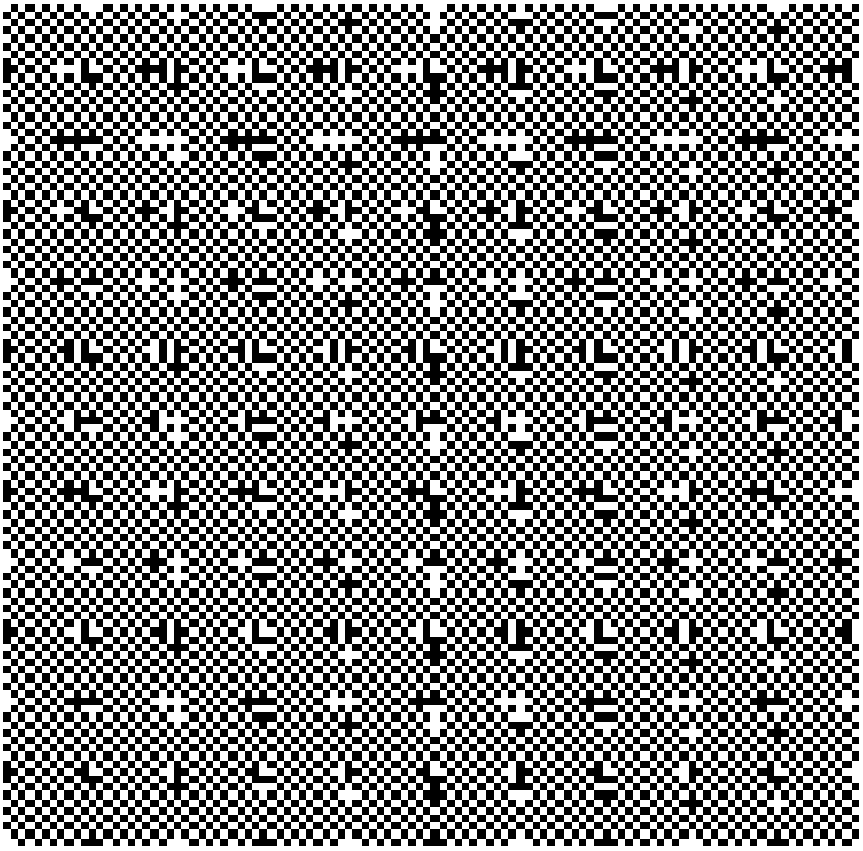

Figure 18: *The coded mask.*