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Analysis of the MDT chamber assembly

Layered Approach Proponents

Athens - Boston - Cosenza - Dubna - Frascati - Freiburg - MPI - Nikhef - Protvino - Thessaloniki

Contents

1 Introduction

The challenging mechanical precision required in the assembly of the MDT chambers (20 μm rms on the wire position at the ends of the tubes and in the position of the central wire-locator, 100 μm tolerance on the tube wall - wire relative position in the other points) has stimulated an active design and R&D work by MDT groups of the ATLAS Collaboration. A number of groups, working in close collaboration, are converging on a design, which is being finalised. Some work has still to be done and the final design will be verified with the construction of two prototypes at MPI and Frascati this year.
In this note our present understanding of the MDT assembly is discussed.
The *layered* method, here advocated, has been developed by the common work of the groups involved, following the first design presented [1] by the Frascati group and the successive improvements by a joint design work of the Frascati, Protvino, and Nikhef groups [2]. The main issues will be analysed and the relative advantages or disadvantages of the *layered* and *multilayer* methods will be examined.

2 The jig of the *layered* assembly method

The concept of the method has been discussed in [1] and [2].
The jig we are now considering is shown in fig. 1. Some details are shown in fig. 2.
The jig is made of a series of precision combs on a granite table, aligned at one side. The combs are made with the technique of the wire electro-erosion, which can achieve very high precision. They are modularly built by pieces 600 mm long, precisely joined together by means of reference precision positions provided on them. The shape of the groove is made of two circles with shifted centres. The thickness of the combs is 25 mm. The distance between combs is 50 cm. Vacuum suckers are inserted in the centre of the grooves.
The positioning of each cross-plate is determined by locating two spheres, rigidly attached to the cross-plate during the assembly, in precision support blocks. The support blocks are layed on the granite table by a C-shaped support, so that they can be slided along the combs, in order to adapt the jig to the construction of chambers of different width.
The vertical and horizontal displacement of the spacer, needed in the various steps of the construction, is achieved with the use of calibrated steel rods inserted below the blocks.
The sag of the cross-plate is controlled through the system shown in fig. 3, by supporting the weight of the chamber below the long beams with bars, supported at their ends on pneumatic pistons [3].

3 Tube positioning

To achieve the highest precision in the positioning of the tubes, the jig and the assembly procedure has been designed so that the position of each tube can be controlled individually, following the proposal, originally made by the Nikhef group, and then adopted by other

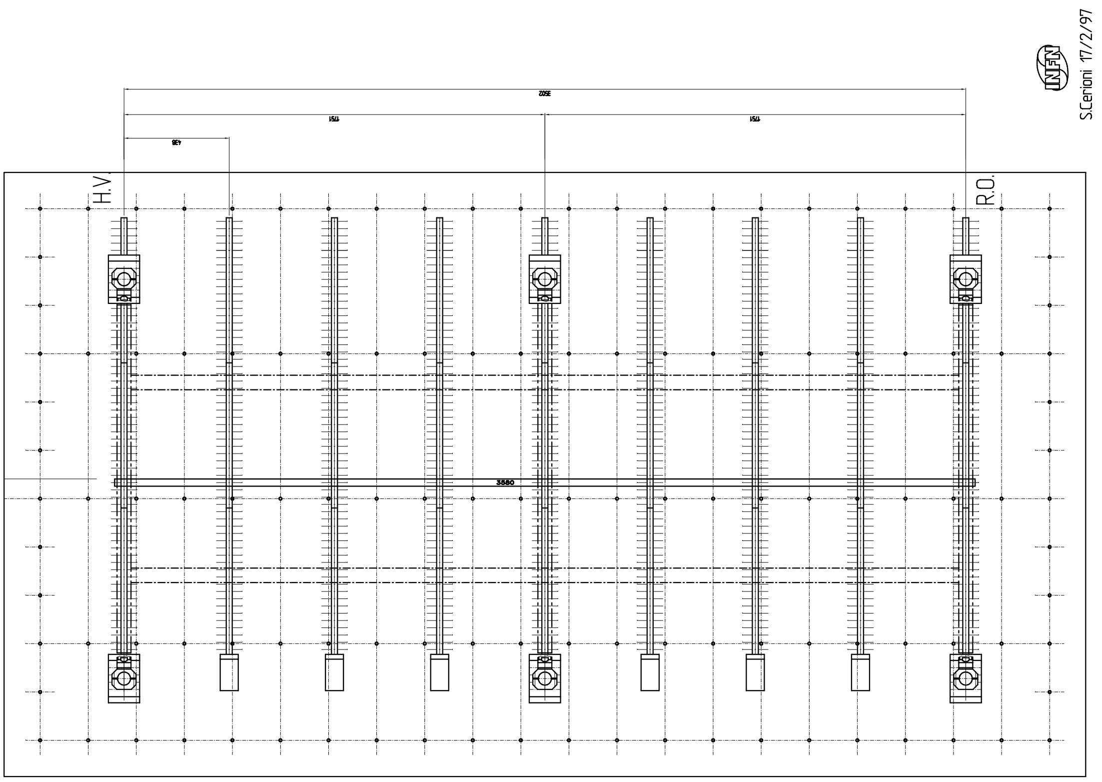

Figure 1: The MDT assembly jig

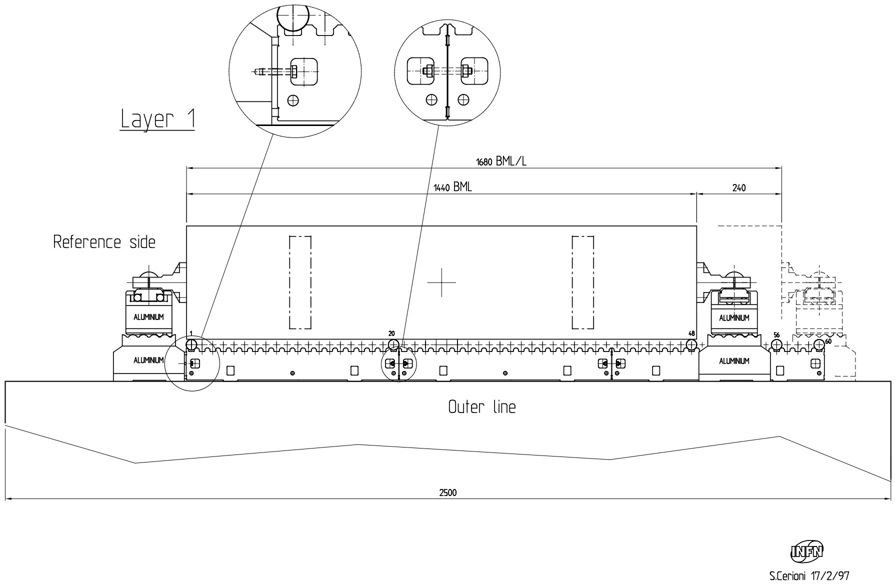

Figure 2: Details of the MDT assembly jig

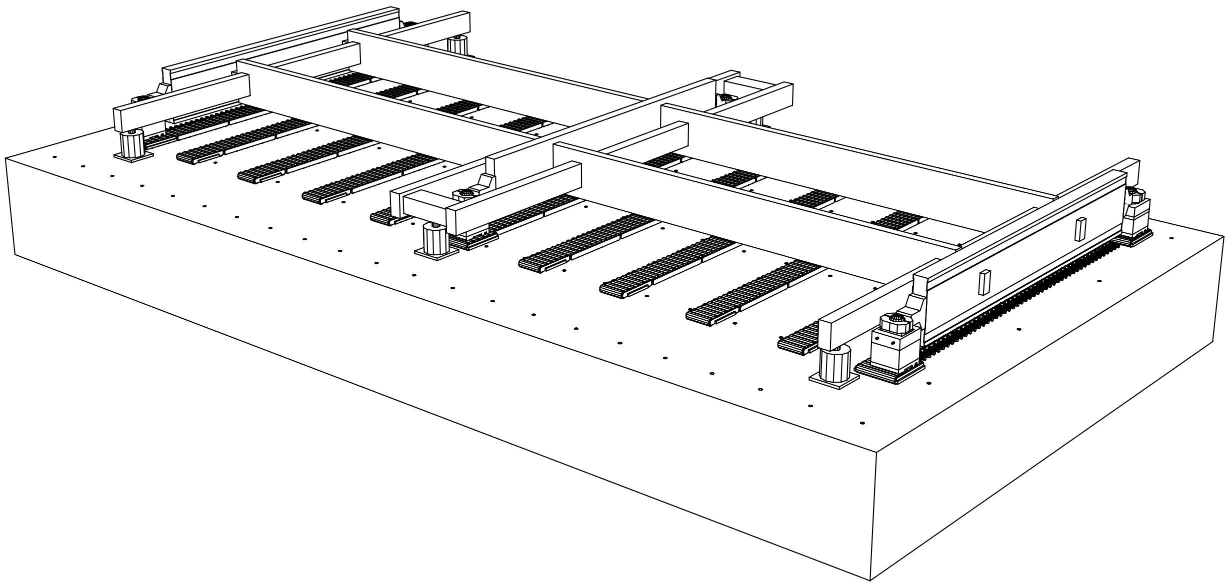

Figure 3: Sag control system

groups (Boston, Frascati, MPI, Protvino).
Given that a jig is needed to position the tubes - as commonly accepted by all the MDT groups - we do not see reasons to limit the jig performance by positioning only a fraction of the tubes and not every one of them.
In the *multilayer* close packing method [4], a full multilayer (3 or 4 layers) is packed between bottom and top combs. This introduces a different level of precision in the different layers. The first layer is positioned directly in the bottom comb, as in the case of the *layered* method. Provided the same combs are used and the same vacuum suction, there is no difference in principle between the two methods. (In the following paragraphs the comb design and the vacuum suction system will be discussed, since a different aptitude has been followed on those issues by the proponents of the two methods).
The last layer is positioned through top combs. If vacuum suction from the top were used, and if the top combs had the same precision of the bottom combs, again there would be no difference in the tube positioning precision between the two methods.
However, vacuum suction is not used.
Therefore tubes of smaller diameter, due to the tolerances on the tube parameters, will not touch the groove in the top comb, and will not be fully controlled in their position by the top comb.
Furthermore, as we will discuss later, top combs are more difficult to be manufactured and positioned in the jig.
The intermediate layers are only controlled by the neighbouring tubes. Therefore the tube tolerances in the diameter and the straightness will affect the precision of the positioning. This effect will be enhanced, in the case of the chambers with 4 layers, which is the solution adopted for the inner station chambers and is still in consideration for the chambers of the

middle station. The effect will be further enhanced in the case of the end-cap chambers, where tubes must be held in a curved shape to match the sag of the wire.
In conclusion the *multilayer* method only partially makes use of the jig to position the tubes and it relies heavily on the tube precision.
The *layered* method makes use of the jigging to position each tube and is less dependent on the tube tolerances.
It has also been pointed out [5] that if the MPI gluing method to localise the wire is adopted, the *layered* method provides a wire positioning completely independent of tube characteristics.

4 Sag of cross-plates

This issue has been exhaustively addressed in another paper [3].
As shown in [3], for the barrel chambers the proposed method provides a support equivalent to the support of the chambers in the detector, and then, by chamber design, the sag is limited.
For the end-cap chambers, a solution has been proposed [3], which by optimising the position of the long beams in the design of the spacer, reduces by a factor 250 the maximum sag with respect to the end-support, and this should be adequate to allow a precision assembly.

5 Gap between tubes

The gap between tubes is designed to avoid contacts between neighbouring tubes to interfere with precise positioning of the tubes by the jig.
The nominal tolerance on the tube diameter, $30.000^{+0.}_{-0.030}$ mm requires at least an average gap of 15 μm. This would correspond to 0 gap for tubes with diameter at the upper side of the tolerance interval.
Any variation with respect to the nominal tolerance, for some tubes or for some successive productions, any local imperfection either during the manufacturing or in the handling of the tubes during the cleaning, wiring, testing, transporting operations, any extraneous particle attached to the tubes, would cause contact between neighbouring tubes.
On the basis of this concern, it has been thought that increasing the gap by additional 35 μm would make the assembly procedure safer against the effects considered above.
Therefore the proposed average gap between tubes is $15\ \mu m\ +\ 35\ \mu m\ = 50\ \mu$m.

6 Design of bottom combs

The comb design is shown in fig. 4.

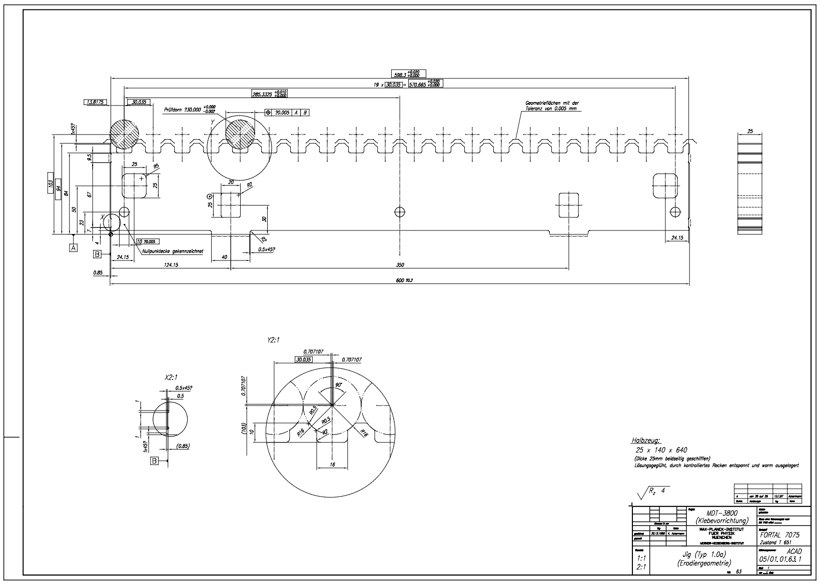

Figure 4: Comb design

6.1 Fabrication technique

The combs need to have a very high level of mechanical precision. Over the lengths needed (up to 2,16 m) that is not easy to achieve.
Various methods are being investigated and the final choice will be based on the actual measurements of the combs produced.
A very promising solution is the one illustrated in the drawing in fig. 4 (on which, in particular, the MPI group is working).
Since the bottom combs are positioned on the flat surface of the granite table, one can easily make them modular. For length up to about 600 mm, a very precise technique is available, namely the wire electro-erosion.
Samples produced by a German firm for the MPI group have shown a few microns precision rms on the pitch.
Work is going on to improve the level of control of the systematics.
The new production samples, ordered by MPI, will tell us if the achieved precision comply with our requirements.

6.2 Shape of the grooves

To define the position of the tubes in a controlled way, independently of the tube diameter fluctuations and without producing deformation of the tube, the groove in the combs must locate the tube through two lines of contact.
The simplest way to achieve this is to use a V-shaped groove, or two cylindrical rods. Both solutions have been used in the jigs built so far by various groups, with excellent results.

A study has been made to optimise the location of the tube and to reduce possible deformations. It has turned out that an optimal value of the angle of the V is 90^0.
The proposal by the Nikhef group to use a shape made of two circles with shifted centres will further reduce possible deformation effects, when the tube is sucked against the locating surfaces.
This shape has been considered optimal.
The positioning by a single circle shaped groove, as made with the boring technique, has the drawback of depending on the tube diameter fluctuations. Tubes with diameter larger than the groove diameter cannot be housed, while tubes with smaller diameter can move inside the groove.
The circular groove can be apt to position very precise rods. This possibility is being considered, among others, to build precision combs. It will not, however, be discussed here.

6.3 Thickness of the combs

Various comb thicknesses have been implemented in the jigs built so far, from 1 cm to 10 cm. An optimised value, which reduces tube deformations and dependence on comb misalignment, has been considered to be 25 mm.

6.4 Height of the combs

Being the bottom combs supported on the granite table, there is no special requirement on their stiffness and consequently on their height.
The height is determined from practical considerations, to have some room available for the accessory equipments.
A height of 100 mm has been retained.

6.5 Distance between combs

Taking into account the straightness of the tubes, an interval of about 50 cm between combs is considered reasonable.

7 Vacuum suction

From the experience up to now, the vacuum suction has appeared to be a necessary tool. A force has to be applied to position the tubes on the combs and straighten them. The diameter of the suckers and the under pressure can be adjusted, as needed. The systems used up to now have worked well.

In particular, the experience of the Nikhef group has been excellent. Therefore the components used in their system will be adopted.
The line of the suckers will be placed in the centre of the combs, and each line will be connected independently to the vacuum pump.
The vacuum suction will be activated on each line at a time, in sequence.
In comparison, we should consider that for combs with no vacuum suction, the positioning in the grooves is demanded to the force exerted by neighbouring tubes. In that case, no adjustment of any parameter is possible and the question can be raised if this force has the right value and the right direction (taking into account the non - straightness of the tubes) to correctly position the tubes.

8 Top combs

Top combs are not used in the *layered* assembly method; however,since they are used in the *multilayer* assembly method, some comments on top comb features are reported in the following.
Top combs are different from bottom combs concerning their positioning in the jigging. In fact, top combs can be supported on the table in two points only, at their ends, outside the width of the layers of the tubes, while bottom combs are supported in more points. This implies that, to build top combs, a modular arrangement, as presently foreseen for the bottom combs, cannot be adopted: top combs need to be made in one piece over the full lenght. As a consequence, the required precision can only be achieved if the machining can provide such a precision over the full lenght. That has not yet been proven to be feasible for all the MDT chamber lenghts (up to 2.16 m).
In the case in which the required machining precision were achieved, to maintain it a further requirement has to be complied, namely that the sag of the comb due to the gravity does not affect the precision.
In order to limit the sag in the case of the top combs, they have to be high enough to guarantee the necessary stiffness; therefore, for wide chambers, top combs need to be quite heavy, and their handling - to remove them or put them in position - during the assembly, can be difficult and delicate, since damages to the precise surfaces, caused by unappropriate handling, have to be avoided.
The considerations reported above are supported by the direct experience[6] that top combs are more difficult than the bottom ones to be built with the necessary precision and to be handled during the assembly operation.

9 Controlling the spacer positioning

During the operation of gluing the tubes to the spacer, the spacer position must be controlled with precision, in any method.
In the *layered* method, the control is obtained by carefully defining the parameters to be

controlled:

- one point

- one line

- one angle around this line.

The fixed point is provided by locating one sphere attached to the spacer in a fixed location on the support block.
The line is fixed by locating the sphere, attached the other end of the spacer on the same side (reference side), in a location fixed transversally and in height, but free to move longitudinally.
The angle around this line is fixed by locating the other 4 spheres in locations fixed only in height and free to move in a plane.
Other methods of controlling the spacer positioning by fixing more parameters than needed can have uncontrollable results and cannot be easily analysed.
Furthermore the use of precision spheres is optimal to guarantee the precision positioning after the rotation of the chamber.
The displacements in the horizontal and vertical direction are controlled by means of precision steel rods.
The hardware realized by the Frascati group has been checked by measuring on a 3-D machine all the steps required for the assembly. A better than 10 μm precision was shown[2].
The operation of the various steps (moving the chamber in position, rotating it) has also shown from the experience with the Frascati BML construction to be very smooth and easy.

10 Glue distribution

The glue is distributed on the layer on the jig, once the correct positioning has been checked. Since the surface, on which the glue has to be distributed is exposed, the glue distribution operation is easy and fast, and can be visually inspected.
The glue distributor used in the Frascati BML construction has worked well, however there is the possibility of using any kind of distributor. The time required to distribute the glue was typically 20 min - 30 min. With further automatization, it can be reduced to 10 min.
A completely different scenario is offered by the gluing operation in the *multilayer* method. Here glue has to be put in the interstices between tubes, along the whole length of the tubes. The operation is slow and cannot be checked. For distributing the glue a special device is needed, which has a long thin pipe filled of glue and this may be the source of troubles for the smoothness of the operation.

11 Tube positioning in between the cross-plates

For the layer on the jig the position of the tubes is determined by the combs, at a small interval from each other over the full length.
For the tubes glued to the spacer, the position is determined by being glued along three segments to the cross-plates. In correspondence of the cross-plates the tubes are precisely positioned, and this is where the stringent 20 μm rms specification applies.
Concerns have been raised about the position of the tubes over the length in between the cross-plates.
In particular there has been concern for the sag of the tubes, due to gravity, and ,on the other hand, it has also been suggested that the tubes, due to internal stresses, might acquire an upward curved shape[7].
These problems are relevant mostly for the first layer glued to the spacer.
They will become less important with two or more layers glued, since the stiffness increases.
It has to be reminded, at this point, that the accuracy required in between the cross-plates has to meet a tolerance of 100 μm.
The tube tolerance ($+0 \div -30\mu$m), while inadequate for the precision positioning by contact between tubes, is now more than adequate with respect to a 100 μm tolerance.
Therefore there is a conceptually simple and solid way out to any possible trouble with the positioning of the tubes in between the cross-plates.
It is enough just to locate the tubes against the precise layer on the jig by forcing in some points the tubes in contact with the tubes of the layer on the jig. The tubes on the spacer are accessible and can be easily loaded, if necessary, with some weight.
Being the average gap between tubes in the point of closest approach 50 μm, that means an error of positioning on the vertical axis of $50\mu\mathrm{m}\frac{\sqrt{3}}{2} = 43$ μm, in the points where the contact between tubes has been made. The positioning in the horizontal coordinate is still precisely guaranteed. The value of 43 μm is within the tolerance.
The MPI group has experimented a method to insert thin strips in between tubes, to keep a constant spacing between them. If necessary it can be adopted. In such a case, the error on the positioning of the wire with respect to the tube wall would be reduced to values close to zero.
Another possibility to achieve a reduction of the error, without the use of spacing strips, is to proceed with a further optimization of the vertical spacing between tubes, so that the relative displacement of the tube wall with respect to the wire is kept within the desired limit.
In a similar way another concern, which has been raised, namely that the glue on the layer on the jigging could push and displace, in between the cross-plates, the tubes glued to the spacer, can be addressed.
The relevance of this effect has to be checked experimentally.
However, if it has to be dealt with, it is enough to apply some weight on the tubes to push the glue aside and then remove the weight.
The issue of positioning the tubes in between cross-plates has to be addresses by further calculations and, more important, experimentation.

However this issue does not represent a problem of principle and simple solutions can be worked out, according to the needs.
The location in some points of the tubes (glued to the spacer) by other tubes (laying on the jigging) is an easier task than the location of tubes by neighbouring tubes, in the *multilayer* assembly method, for the following reasons:

1. a 100 μm tolerance must be achieved and it is not required to meet the 20μm rms specification
2. only one coordinate (the vertical) is concerned, while the other coordinate (horizontal) is guaranteed to be precise
3. the tubes are positioned against a fixed precise layer on the jigging, to the positioning of which they have not to concur.
4. the tubes are held in precise position in the points where they are glued to the cross-plates and their straightness is guaranteed.

None of these conditions is true in the case of the *multilayer* assembly method.

12 Quality control during assembly

The assembly procedure is quite "open". Therefore quality control checks can be easily implemented, to control the correct positioning of the tubes in the jig, the correct positioning of the spheres on the blocks, the sag of the cross-plate, the quality of glue distribution. Suitable methods and hardware have been designed and will be adopted [8].
In the case of the *multilayer* assembly method, the construction procedure seems incompatible with the quality control on tube positioning and on the glue distribution.
In addition, the quality control of the top comb position seems more complex than the control on the spheres, since not only position but also angles have to be controlled in that case.

13 Barrel versus end-cap chambers

The method described here has been applied in the construction of barrel chamber prototypes, since most of the proponent groups have construction responsibilities for the barrel chambers; it is, however, suitable and proposed for the construction of all MDT chambers. In this paragraph some comments on barrel vs end-cap chamber construction are presented and discussed.
There are 3 main differences between end-cap chambers and barrel chambers:

1. stiffness of the cross-plate,

2. curvature of the tubes,
3. trapezoidal shape.

13.1 Stiffness of cross-plates

Since the end-cap chambers are mounted vertically in the apparatus, the design of the spacer (cross-plates and long-beams) has to be made in a different way than for the barrel chambers.
For the end-cap chambers, less stiffness of the cross-plates is required than in the case of the barrel chambers, and the long beams are not required to be connected to the cross-plates in the *Bessel* points. It has been shown [3] and has been re-discussed in paragraph 4 of this note, that by optimising the position of the long beams (which is not allowed in the barrel chamber case), one can compensate by a factor $\cong 5$ for the lower stiffness of the cross-plates in the end-cap chambers.
This factor together with the factor 48, for the *Bessel* support, produces an overall factor 252 of reduction of the sag for end-cap in the assembly configurations, with respect to a naive support at the ends. Calculations have been made [9] relatively to the case of a support at the two ends. Even if the sag values, in that case, appear to be very large (up to 620 μm), they are not so large, that by a reduction of a factor 252, they cannot be brought back to negligible values.
Therefore the difference between barrel and end-cap chambers regarding the stiffness just requires a different (and, mostly important, differently optimised) design of the spacer.
The same assembly procedure, discussed here, can be applied to the barrel and end-cap chamber construction.

13.2 Curvature of the tubes

The tubes of the end-cap chambers must have a built-in curvature, in order to follow the sag of the wires.
The optimal arrangement of the combs has been studied by the Seattle group [10]. The combs must be appropriately shifted and tilted. This can be done in either method of assembly, the *layered* one proposed in this note, or the *multilayer* method proposed by the Pavia-Roma-Seattle groups.
In the method presented here the layer on the jig is held in position with the right curvature by the jig through vacuum suction. When it is glued to the spacer, the tubes will correctly keep their curved shapes.
The control of the position of the layer on the jigging and the layer(s) in the spacer will occur in the same way as for the straight tubes of the barrel chambers.
Therefore the curvature of the tubes does not introduce any differentiation in the use of the *layered* method for the barrel or the end-cap chambers, since the method is able to deal with straight or curved tubes in the same way.
That is not the case for the *multilayer* approach. All the difficulties of the tube positioning

with that method, discussed in paragraph 3 will be enhanced by the necessity of giving the tubes the curved shape.
The behaviour of the tubes of the intermediate layers not located directly by the combs, raises concern. With which precision will they follow the required curved shape, given that they tend to follow their natural shape? How will this reflect on their ability to correctly push the first and last layer, so that they assume the correct position in the jigging?
Since the method is not designed as a sequence of single steps, which clearly define the positioning of the tubes, it is difficult to analyse the possible outcomes.
The evaluation, by X-ray measurements, of a prototype of end-cap chamber, built with the *multilayer* method, would be very instructive.
Another concern exists about the stability of the shape of the multilayer, once glued and taken out of the jigging.
While in the *layered* method the stability of the shape is guaranteed by the spacer, in the *multilayer* method case the question can be raised if the multilayer, not glued to the spacer, can hold the internal stress and not deviate, because of the stresses, from the shape enforced.
Early experience with tube stacks produced along the multilayer scheme, indeed showed a spring back effect. This was dealt with by so-called shear strips for the Pavia/Rome chamber.
The necessity to build-in a curvature in the tubes, is a peculiarity of the end-cap chambers which is dealt with in a natural way by the *layered* assembly method while the handling of it with the *multilayer* assembly method is more difficult and the achievable precision can be strongly affected.

13.3 Trapezoidal shape

The end-cap chambers have a trapezoidal shape.
Since during the assembly the chambers are rotated up-side by keeping the same side as reference side, there is no incompatibility with the assembly scheme.
The main effect of the trapezoidal shape is that the load of the tubes is not uniformly distributed. This implies slight different calculations in the design of the load supporting system, with no major conceptual differences expected.
The trapezoidal shape is not expected to make a significant difference for the application of the assembly method.

14 Chambers with limited spacer height

Some of the chambers in the present layout have a limited space left for the spacer, and the height of the spacer is limited to very small values (for example, see the BIS chamber with 2x4 layers).
The collaboration is addressing this issue and solutions have to be worked-out.
If more room can be allowed, those chambers will be treated as the other chambers.

A solution, however, is workable with the assembly method proposed, even in the case of no room available.
In such a case, the spacer could be completely removed and the chamber could be made with the two multilayers in contact. The chamber will then consist of one single multilayer with a number of layers equal to the sum of the numbers of layers of the two multilayers. The *layered* method, dealing with the assembly layer by layer, provides the same required precision even for a 8 layer multilayer.
This is only reported as an example of the flexibility of the *layered* method, however all the engineering aspects of the chamber design should be taken properly into consideration, before a new design of those chambers can be made.

15 Meeting special needs in chamber design

In the previous paragraphs it has been pointed out how special needs in the chamber design can arise (curved shape of tubes, no spacer between multilayers).
Other examples can be made.
If, in particular, a chamber with no spacer is considered, a problem with ghosts may arise in the pattern recognition [11].
This problem can be solved if a shift between layers is introduced.
Beside the use for pattern recognition, a shift of layers has been suggested to implement a technique of autocalibration with reduced systematic errors [12].
The assembly method proposed can deal in a simple and natural way with those requirements. In particular, the Frascati BML has been made with the intermediate layer of one multilayer shifted by 80 μm with respect to the centre of the two neighbouring layers. This will allow testing experimentally the autocalibration method, studied up to now with simulation [12], in this configuration.
Due to the flexibility of the assembly method proposed, the issue of special designs to improve the detector performance can be addressed in a careful study of optimisation of the detector. The method will allow to implement, if necessary, any of those features.
In the case of the *multilayer* assembly method, single multilayers with large number of layers and shifted layers cannot be realized, and it is not clear how well the curved shape needed for the end-cap chamber can be handled.

16 Experience with the prototypes built

So far a large number of full scale prototypes (plus a smaller prototype in '95) have been built with a *layered* method by Frascati, MPI, Nikhef, and Protvino.
In particular the Frascati BML and the Protvino BIL have followed an assembly procedure very close to the one described here. The experience in the construction of those chambers has been very positive.
In particular, during the assembly of the BML in Frascati many 'observers' from ATLAS-

Muon groups (from construction sites) visited Frascati and could personally experience the sequence of operations that went smooth and fast.
The large body of expertise acquired by all the groups has been put together in a common design effort to finalise the assembly.
The progress made in the understanding of the assembly and the design of the jig is presented in this note.
Recently the preliminary results of the X-ray scanning at CERN of the Frascati BML and Protvino BIL have become available, confirming that the assembly method proposed can achieve a precision below specification uniformly for all layers and in large size chambers.

17 Time and man-power

The assembly can be performed by two persons. The time required for each layer is < 2-3 hours.
After that, the glue has to be let to cure.
The construction of one layer/day allows for the production of one chamber in < 2 weeks. This is perfectly in line with the production schedule foreseen for each production centre, as far as we know.
Should the need arise for a faster production, two layers per day can be made: this was done in the assembly of the 80 cm x 50 cm MDT prototype built by Cosenza-Frascati in 1995.

18 Conclusions

The assembly method and the jig design presented is the result of the common work of the groups involved, and represents the conclusion of an intense activity of design, construction, and test.
The main features are summarized in this note, and, where of interest, a comparison has been made with the features of the *multilayer* assembly method.
Our conclusion is that the jig proposed is simpler and easier to be operated and to be controlled, and that it allows to achieve a better precision in the construction of all MDT chambers.

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