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The offline lead thickness measurement system for the ATLAS Electromagnetic Barrel Calorimeter

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Abstract

We describe the apparatus that will be used to measure the thickness of the lead plates that are to be used for the production of the absorbers of the ATLAS Electromagnetic Calorimeter. Its performance is analysed, and the coherence between these measurements and the X-ray measurements obtained at the factory is studied, using the data that has been taken in view of the construction of module 0. The results of the measurements that have been done in view of the construction of Module 0 are shown.

[1] deceased

1 Introduction

After the lead plates for the ATLAS Electromagnetic Barrel Calorimeter have been produced, their thickness has been measured a first time using X-ray thickness gauges positioned after the roller. This measurement has allowed a preselection of the parts of each lead roll that would be suitable for ATLAS, and has given us a preview of the characteristics of the lead thickness distribution. However, the distance step between two consecutive measurements is of the order of 10 cm in the z direction (η coordinate), and 15 cm in the radial direction, and since different measurements at different radial positions have been taken using different X-ray gauges, whose relative calibration differences was of the order of 10 μm, it is very hard to infer the profiles of the lead plates, along the r coordinate. Furthermore, after being laminated, the lead undergoes several operations : storing during several hours or days as laminated rolls, cutting, handling and machining. After all these operations, it is suitable to ensure the full traceability of the production process to measure the thickness of the lead plates just before their transformation into absorbers. This measurement is being done using ultrasound control, which is a well-known and mature technology in the industry, used to control the thickness of various materials and also to look for defects, for example during welding operations.

2 Choice of the measurement technology

Several techniques could have been used to measure the thickness of the lead plates. The evaluation and the description of these techniques has been already presented in [1] and it will not be repeated here. Let us simply recall the reasons that have motivated the choice of the ultrasounds for the measurement :

- Its ease of use. The only thing the ultrasound sensor requires to work is to be in close mechanical contact with the piece of material whose thickness is to be measured. In addition, correct operation of the sensor does not require tightly controlled operating environments, as would be the case for purely mechanical methods.
- It needs only access to one face of the plate to be measured, which eases the conception and the construction of the mechanical structure needed to hold and position the sensor on the plate.
- Its insensitivity to small deformations of the surface that do not alter the actual thickness of the plate, like bulges or folding.
- Its relatively low cost, after comparison with other methods.

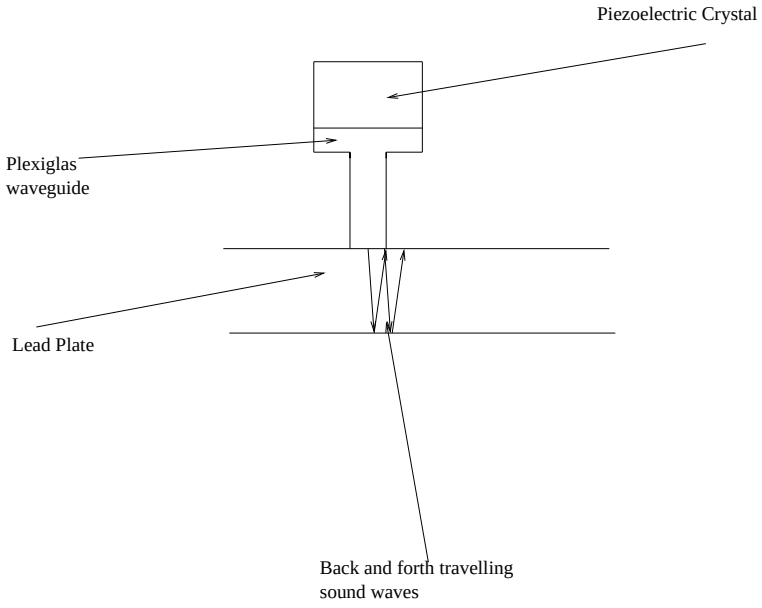

Figure 1: Principle of the measurement of the thickness with an ultrasound sensor.

3 Principle of the measurement

The principle of the measurement is described in figure 1. A piezoelectric crystal is used as receiver and transmitter. This crystal is submitted to a high frequency electrical pulse train, whose frequency is 10 MHz. This causes the crystal to contract and dilate alternatively, giving rise to a mechanical wave train. The typical duration of this wave train is of the order of a few microseconds. The wave train passes through the plexiglas waveguide, whose purpose is to focalise the waves and to bring them to the surface of the lead plate. Once the wavetrain has reached the lead, the waves travel back and forth between the two surfaces of the lead plates. Each time the wavetrain reaches the surface of the lead in contact with the sensor, part of the mechanical energy of the wavetrain is sent back through the waveguide to the piezoelectric crystal where it is detected. Since the time between two consecutive echoes is the time needed for the waves to travel through twice the thickness of the lead plate, this time is related to the lead thickness by the following very simple equation :

$$e = c \times \frac{t}{2} \tag{1}$$

The time is measured by a TDC, and several shots (typically of the order of 25) are averaged to increase the resolution of the measurement.

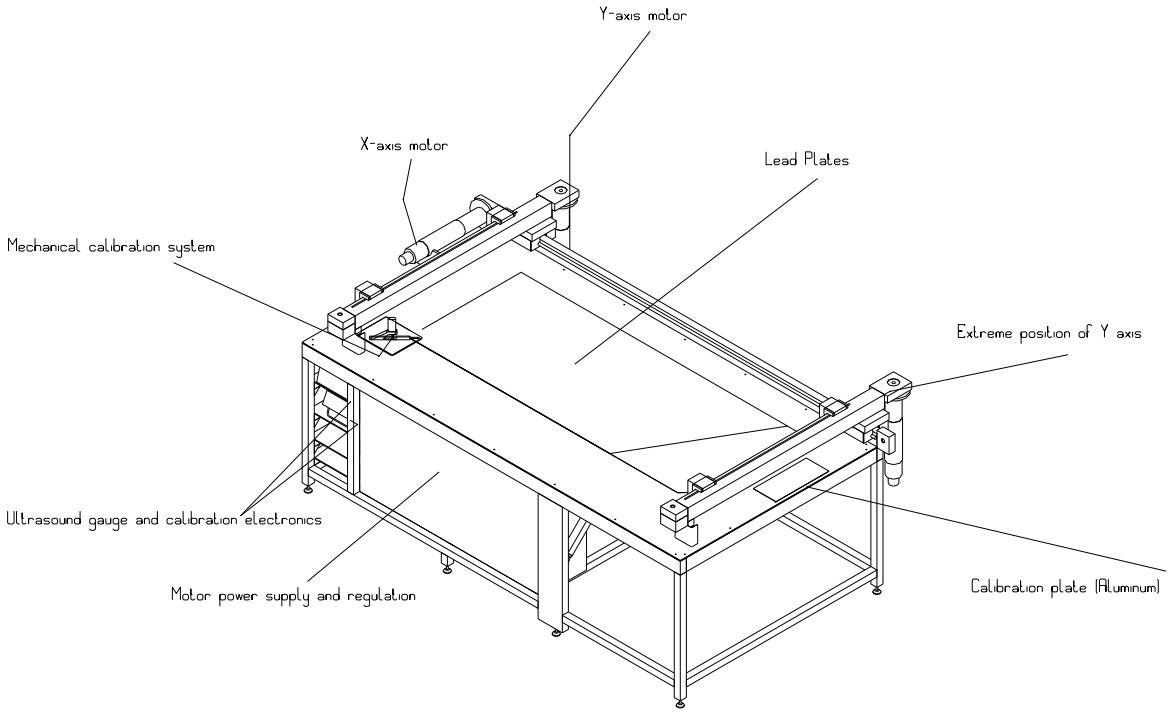

Figure 2: Sketch of the X-Y measurement table that has been used for the measurements of the module 0 lead and that will be used for the production.

4 Overall system description

The ultrasound system has been integrated into an X-Y measurement table, whose shape and disposition have been chosen so as to be able to measure 1.13 mm and 1.53 mm plates with the same setup, although the shapes are different. A general view of the table is shown in figure 2.

The ultrasound device is attached to a measurement head, which is shown in figure 3, and is equipped with the following elements :

- A pneumatic actuator, which is used to push the ultrasound sensor against the lead, maintain it as long as needed for the electronics attached to the sensor to proceed to the measurement, and pull it back once the measurement is finished.

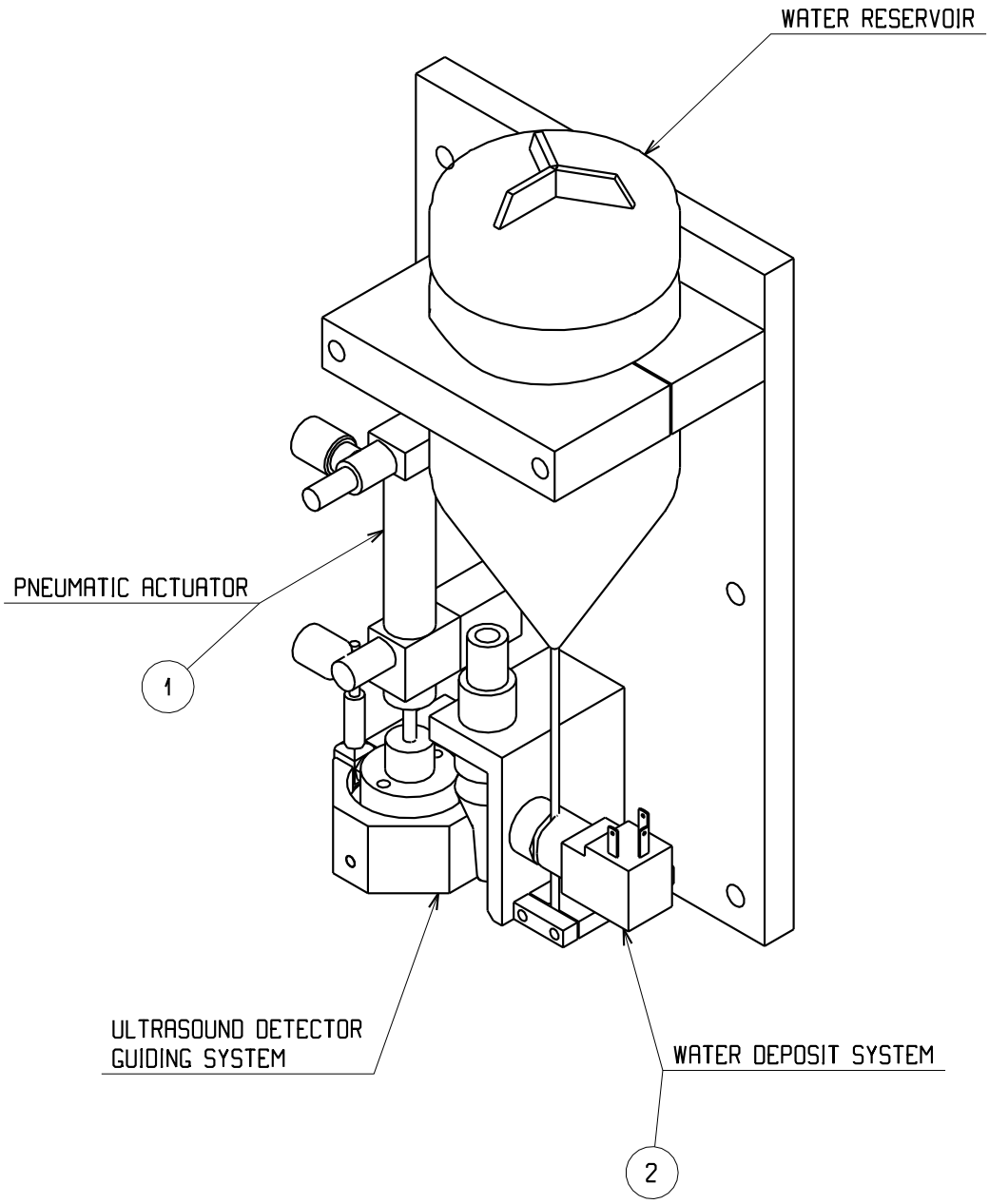

Figure 3: The ultrasound measurement system, with its assembly

- A small water tank, to which is connected a small tube that can be closed or opened electrically. The water is deposited on the lead before the measurement itself, at the place where the measurement has to be done. The purpose of the presence of a drop of water at the place where the sensor comes into contact with the lead is to ensure a good mechanical contact between the lead and the plexiglas of the waveguide. If water were not present, there would be always small cavities filled with air between the lead and the sensor, the mechanical contact being perfect only at the places where the lead is the highest. Since the mechanical impedance of air is almost zero, the waves would be reflected at this interface, instead of passing through the lead, and measurement would be impossible. When water is present, the cavities are filled by the water, whose mechanical impedance is high enough to ensure that enough energy is transmitted into the lead to ensure a correct measurement. Any dense enough liquid would also have been usable (oils) ; we have chosen to use water simply because it does not contain any electronegative chemical that could stay on the lead and be released later in the cryostat, or possibly perturb the glueing of the stainless steel during the absorber production. An other argument in favour of the use of water was of course its low cost.

  It should be noted that the position of the water outlet is such that the drop of water is deposited not for the current measurement point, but for the next one. This allows to minimize the number of displacements of the head.

- An outlet for compressed air, used to clean the lead surface before measurement, blowing out the impurities that could cause bad contact between the lead and the sensor. It was found during the measurements that this cleaning was actually not really needed, and it was no longer done, to save some time on the measurements.

The whole system is controlled by a program running under LabView, which instructs the head to move at given positions, takes care step by step of the sequence of operations to be done, checks the results, recovers as much as possible from error conditions (either by retrying the measurement, or by stopping and warning the user) and makes sure the hardware status is in agreement with the software status.

To give an example, the program continuously checks sensors to make sure the ultrasound sensor is actually in the position it is believed to be. This is essential to avoid movements of the head to be done will it is being pushed on the lead, which would cause deep scratches on the lead and also possibly damage the measuring head.

The typical measurement cycle for one measurement point was as follows :

1. Push the sensor onto the lead, wait for the measurement to be ready.
2. Acquire the measurement.
3. Pull the head back.
4. Check the measurement is valid. It may happen indeed that the measurement is invalid. If the quality of the detection of the reflected wave train is low, the ultrasound devices sends a flag indicating that the measurement is not usable. This quality is directly evaluated by the electronics of the measuring device, who checks the intensity of the reflected wave train. Typically, low quality of the reflected wave train can arise from the presence of scratches on the lead surface.
5. If the measurement is not valid, remove the sensor from the lead, go back to (1), up to three times. If the measurement has been tried three times with no success, give up, flag this point as definitely bad in the logfile and move to the next point to be measured, after removing the sensor from the lead. If the measurement is valid, remove the sensor from the lead and continue the cycle at (6).
6. Move to the next point.
7. Repeat from the start.

In addition to bad measurements that are directly flagged by the ultrasound system and handled in the way that has just been described, it may also happen that the measurement is considered as valid by the ultrasound system, but with a reading that is not stable to better than about 10 microns. At the beginning of the measurements of the plates for module 0, each point was measured three times, i.e. the cycle we described above was repeated three times for all the measurement points. This was done to help detecting unstable measurement, since unstable measurements could be detected by looking at the r.m.s. of three successive measurements taken at the same point. However, due to the need to speed up the measurement process, and given the fact that such bad points were rare (of the order of a few percent), it was rapidly decided to make only one measurement per point. The wrong measurements were then flagged by looking for measurements that were more than 20 microns away from the mean of their closest neighbours, since there are no significant variations of the lead thickness over small distance scales like the ones separating two closest neighbours (a few cm). Unstable measurements are removed from further analysis and not used to compute the r and η profiles of each plate. They are not used either in the pairing process.

The intrinsic resolution of the apparatus has been checked by comparing two measurements of the same plate taken at different time. The distribution of this difference is shown figure 4. One can see that intrinsically, the

resolution of the apparatus is good. More detailed studies of the resolution, done while still developing the system, can be found in [1].

In addition to the measurement system, the table is equipped with a pneumatic marking system, which is used at the end of the measurement to stamp a unique number on each plate. This number allows the plate to be identified visually during the storing and during the transformation into an absorber.

5 Calibration

5.1 Principle

Since the thickness of the lead plate is not measured directly, but has to be computed from a propagation time measurement, one has to know the velocity of the sound waves through the material to be measured. In other words, one has to calibrate the measurement system. This can be done by comparing the measurement provided by the ultrasound device with a purely mechanical measurement giving the actual thickness of the lead. We have implemented such a device on the X-Y measurement table (see figure 2). The calibration device itself is depicted more closely in figure 5.

It consists of a fork holding two mechanical sensors. The fork is moved by a pneumatic actuator, so that both mechanical sensors may come into contact with the lead. The mechanical sensors are then pushed onto the lead, and the measurement is read out. The accuracy of this device has been checked by substituting standard iron slabs of accurately known thickness to the lead. This allows to check that the measurement is linear and that the scale (i.e., one mm measured by this system is actually one mm long) is correct. As can be seen from figure 6, the results are indeed very good : the linearity is very good, as can be seen from the fit. In addition to that, by doing the measurement several times on the same slab, and comparing the results, it can be estimated that the resolution of the system is below one micron for one measurement. However, one should be aware that this resolution of one micron has been measured with cleaned standard slabs, whose surface is rectified. On lead whose surface is not cleaned and is very soft, such a reproducibility would certainly not be attained, and the result we gave above only ascertain that our mechanical calibration system is working perfectly well.

In addition to the mechanical calibration system, to be able to follow possible drifts of the ultrasound system, we equipped the table with so-called "calibration plates". These are made of aluminum. At first, it was decided to make them out of lead of the same composition as the lead to be used for

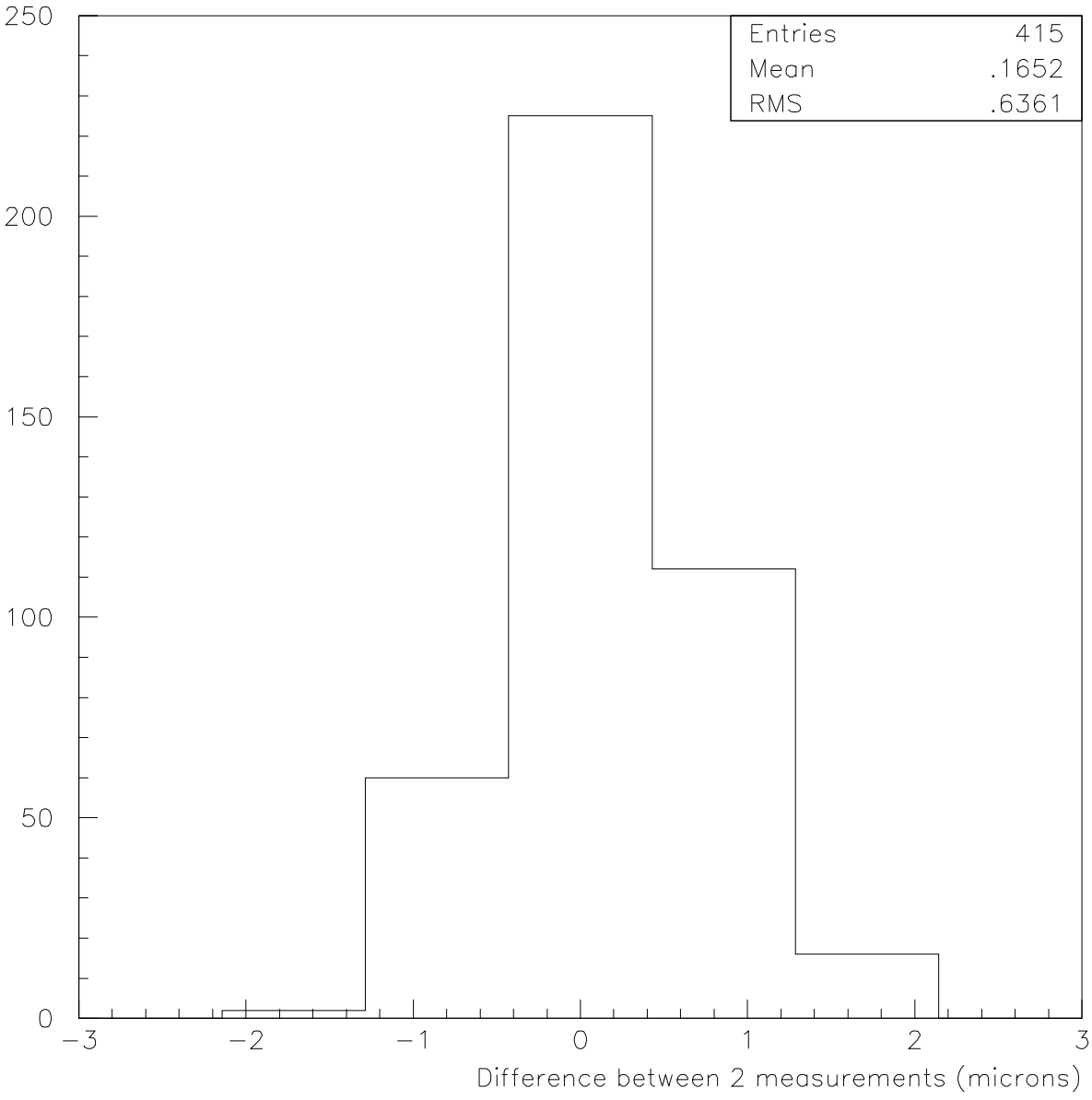

Figure 4: Difference of two measurements taken on the same plate, on the same point. This allows to study the intrinsic resolution of the apparatus

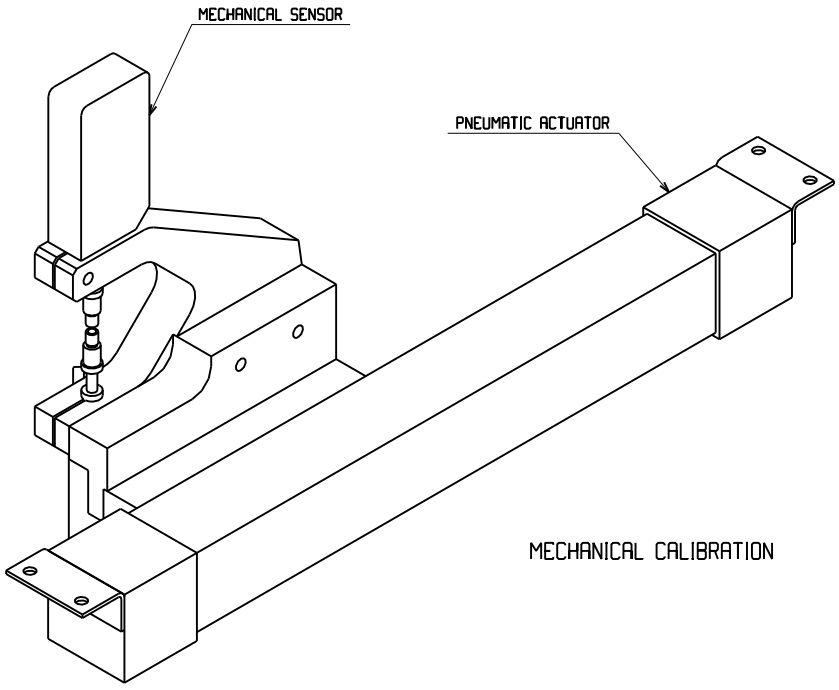

Figure 5: Sketch of the mechanical calibration system.

the calorimeter. However, lead is very soft, and during testing, it was found that calibration plates made of lead would wear out rapidly enough that they would have needed to be changed every twenty of thirty plates, which would have complicated significantly the following of long-term variations of the apparatus. To overcome this problem, two aluminum plates were used, whose thickness was chosen so that the time the ultrasound device measures between two consecutive reflections is about the same as for the lead of 1.13 mm and for the 1.53 mm lead, so as to mimic the thickness of 1.13 and 1.53 mm lead plates.

5.2 Study of the calibration data

We have studied the stability of the ultrasound sensor as a function of time. This study has first been done separately for the 1.13 and 1.53 thick plates. Figure 7 shows first the correlation between the mechanical measurement and the ultrasound measurement. The correlation is obvious, and looks qualitatively quite nice. However, looking at the distribution of the difference between the mechanical and ultrasound measurement (figure 8), it appears that the r.m.s. of this distribution is significantly different for the 1.13 and 1.53 plates. In fact, this discrepancy is already visible in figure 7, simply from the shapes of the cloud of dots : In the case of the 1.13 plates, the cloud looks narrower than for the 1.53 plates. The r.m.s. values given on figure 8, combined with the intrisic resolution of the apparatus (figure 4), mean that if we use the data as it is, we would be able to see very small structures within one plate, since the ability to distinguish very small structures within one single plate is given by the intrinsic resolution, but we would be unable to tell to better than 5 to 7 microns what the average thickness of the plate is. Since we expected somewhat better results, we have investigated to try to understand where the high r.m.s. of figure 8 come from.

If we look at the difference between the mechanical measurement and the ultrasound measurement as a function of plate number, we get the very striking pattern of figure 9. Distinguishing 1.13 and 1.53 plates gives us the plots of figure 10. We have investigated with great detail the logbooks and tried to correlate events noted in the logbook with some of the sudden changes, either in drift direction or in absolute value itself that can be seen on figure 9, for example at plate 50, 160, 200. First, we have found, not very surprisingly, that no change is associated with the changes from 1.13 lead to 1.53 lead. Since such a change does not induce any modification in the measuring head, there is no reason that it could change the measuring device's behaviour. We have found that the change in behaviour at plate 50 is associated to significant maintenance operations and to the correction of a defect : after plate 50, the position at which the mechanical measurement

and the ultrasound measurement are adjusted to be the same within 2 or 3 mm, whereas before they were distant by almost 1 cm. Clearly, this has improved the correlation between both measurements, as one can conclude from the fact that the differences fluctuate less immediately after plate 50, as can be seen on figure 9. The changes at plates 160 and 200 are also associated to maintenance or cleaning operations of the ultrasound system. However, several other cleanings did not induce visible changes on the plot of fig 9. To explain the slow drift, several causes are possible :

- A wear out of the plexiglas waveguide. This had to be changed once, because we found that its extremity, initially flat, after being pushed approximately 10^5 times onto the lead with a force of about 20 N, had visibly started to be a portion of sphere. This change in the shape of the waveguide may change slightly the shape of the wavefront that is sent through the lead, and hence modify slightly and slowly the measurement.
- A slow drift in the mechanical positioning of the sensor onto the lead.

5.3 Compensation of drifts and sudden changes

The drifts and the sudden changes we have investigated in the previous section can be monitored using the aluminum calibration plates we described in the previous section. Figure 11 shows the correlation between the difference of the ultrasound measurement and the mechanical measurement taken at the common measurement point, as a function of the measurement taken on the aluminum calibration plates. The correlation is clearly visible. This means that the drifts observed in figure 9 are indeed drifts of the ultrasound apparatus. However, these drifts and jumps, as we have shown in the previous section, occur on very large time scales (of the order of one month or more), and the apparatus can be considered as stable for periods as long as several days. As a consequence, the drifts can be easily corrected in the data without downgrading the resolution of the measurement, by simply compensating plate by plate the offset between the mechanical measurement and the ultrasound measurement, using the mechanical measurement as a reference measurement. It will be shown later that this correction is efficient, by comparing the X-ray measurements with the ultrasounds. For the first 50 plates, where the mechanical calibration was not very good, we have determined their absolute mean thickness by using the radiography, using the following procedure :

- First, we established the correlation between the X-ray average thickness measurements and the ultrasound measurements, after correction as described above. This will be shown in the next sections.

- Next we used this correlation to compute the average thicknesses of the 50 first plates to be measured.

6 Results

6.1 Comparison X-rays / ultrasounds

The first thing we did with the ultrasound data was to cross-check it with the X-ray measurements. This exercise is important for the production of the whole calorimeter, because doing it successfully means that as soon as the lead will have been produced, and measured by the X-rays at the factory, we will be able to tell quite precisely what the thickness of a given plate is, and use this information to help the pairing of the plates that will be done in order to reduce the lead inhomogeneities of the calorimeter. The main difficulty to do the comparison between the X-ray and ultrasound measurement is to determine precisely on which place of the plate the X-ray data has been taken. For a precise description of the X-ray measurement system and its characteristics, we refer to [2]. The association between X-ray measurements and ultrasound measurement has been done by using the X-ray measurement numbers printed in black on the lead. Figure 12 shows the correlation we get for various rolls, between the average thickness, plate by plate, computed from the X-ray measurements and from the ultrasound measurements. One can see that the correlation is qualitatively good. We have used this correlation to check wether the procedure we have descrived in the previous section to correct for the drifts of the ultrasound device actually worked. To check that point, we have plotted in figure 13 and 14, roll by roll, the average thickness deduced from the X-ray minus the average thickness deduced from ultrasounds as a function of plate number. For comparison, we have also done the same for the difference between the mechanical measurement point and the ultrasound reading taken at the same point, before the correction is applied. Rolls 5 (19 plates) and 6 (10 plates) are not plotted, due to low statistics and also to the fact that the plates belonging to them are quite scattered in time. If the correction works, one expects the plot of the difference between X-rays and ultrasounds as a function of plate number to be flat, since the X-ray measurement has no reason to drift significantly during the time it takes to measure one roll (a few minutes). However, the average difference between X-rays and ultrasounds has of course no reason to be exactly zero, due to the fact that for module 0, the X-ray system and the ultrasound apparatus have not been intercalibrated. For the serie production, this intercalibration will be done. In fact, one can notice that for the 1.13 mm lead, the X-rays are overestimating the true thickness by 10 microns, and by 30 microns for the 1.53 mm. In constrast to that, the differ-

ence between mechanical and ultrasound measurement on one same point, before correctiom, has no reason to be flat, due to the already mentioned drifts. One clearly notices that the corrections we do correct the effects of the drifts. To be more quantitative about that, we have plotted in figure 15 the distributions of the differences between the X-ray and ultrasound measurements, after and before correction, for the 1.13 and 1.53 plates. If we remind the study of the intrinsic resolution done in section 4, we know that we are able to see small thickness details of the order of the micron within one given plate, and to tell its mean thickness with a resolution of 3 microns for the 1.13 plates, and of 4.7 microns for the 1.53 plates.

From that, we can also ascertain that already after the X-ray measurement, we will have information available on the individual plate average thickness that will allow us to reasonably prepare the plate pairing procedure for the series.

6.1.1 Temperature effects

Temperature may change the Young modulus of the material being measured, and hence the sound velocity, leading to a change in the measured value. We have looked for such effects, by keeping track of the temperature at which the measurement was done. Although the expected effect is quite small (amounting to a few microns for a 10° C variation), we have chosen to monitor it, because the measurement has to be done in a non-airconditioned area, where the temperature difference between summer and winter can be higher than 10° C. To look for temperature effects, the best would have been to look always at the same piece of lead, measuring it several times in different temperature conditions. In practice, some plates were measured two or three times at different times, but this does not provide enough temperature points to give evidence of a temperature effect. What we have done to look for a temperature effect, is to use the X-rays measurement as a reference, and to study the difference between the X-rays measurement and the ultrasound measurement, as a function of the temperature. For the lead plates, this corresponds to figure 16. One clearly sees some effect for the 1.53 lead plates, but for the 1.13 plates, it is far from obvious. We have also looked wether the aluminum calibration plates that we used are sensitive to temperature effects. To do that, we have plotted the value of the thickness measured on the aluminum reference plates as a function of temperature, after correcting the reference plate thickness measurement as if it were a normal lead plate measurement. In this case, the effect is much more obvious than for the lead, and it amounts to almost 2 microns per degree Kelvin. This is shown in figure 17.

6.2 Detailed thickness maps

For each individual plate, we have established detailed thickness maps similar to the ones showed in figures 18 and 19. From these detailed thickness maps, we can evaluate the "flatness" of each plate by taking the r.m.s. of all the measurements that have been done on this plate. One can see on figure 18 and 19 that it is possible to see very small details, of a height of the order of a few microns. Not surprisingly, the structures we can see on the plates are organised in lines that are parallel to the rolls that have been used during the laminating.

6.3 Thickness distributions

Figure 20 shows the average thickness of the plates as a function of their number, for several chunks of plates consecutive on each roll. As one can see, the thicknesses are far from being randomly distributed. This means that building the calorimeter using the plates in the same order as they are delivered will produce a calorimeter with regions significantly thicker than other regions, thus increasing the constant term. Using the information our measurement system provides, we will pair and choose consecutive plates in such a way that this problem will be largely reduced.

Figure 21 gives the thickness average distribution, all rolls combined, for the 1.13 and 1.53 plates. For the 1.53 mm plates, this distribution looks reasonable, with a roughly gaussian shape. For the 1.13 mm plates, however, the distributions has two peaks. We have looked where this shape comes from, by superimposing the individual average thickness distributions for each roll. This is done in figure 22. It can be seen that the two peaks come from roll 2 clearly having two populations, and roll 1 and roll 3 contributing one to the first population, the other to the second population. For the series, such a distribution is rather unlikely, simply due to the much higher statistics (about 32 times higher), which will naturally tend to smooth out such effects to a gaussian.

Figure 23 gives the r.m.s. roll by roll. One can notice that the distribution of the sigmas look very similar from one roll to another one, however, some rolls turn out to have slightly lower sigmas than other ones. The explanation of this is that the rolls where the average of the r.m.s. of the measurements over one plate is especially high are also rolls where significantly large thickness oscillations took place during the laminating, as can be seen on figure 25 and 26 : rolls 3 and 5, who have the highest average r.m.s, also have the highest oscillation amplitude.

Figure 27 gives a longitudinal profile along several plates, corresponding to consecutive parts of the original lead roll. The projection direction is

orthogonal to the rotation axis of the roll. The profile shown here is typical in the sense that it gives an idea of the thickness evolution that can be encountered along one given roll ; one can note that there is no really flat region in the roll. The amplitude of the smallest periodic oscillations that can be seen is of the order of 20 microns. The periodicity of these oscillations corresponds to roughly one plate (i.e. 35 measurements every 5 cm). This is very likely to be a mere coincidence, due to the fact that the diameter of the rolls of the roller is about 50 cm, and so correspond to a length of 160 cm, not far from the total length of the final lead plates.

Figure 28 and 29 give the transversal profiles of the lead plates, roll by roll. The projection axis is parallel to the rotation axis of the roll. The reason to show the profiles roll by roll is that it is likely that once the roller is started, the axes of the laminating rolls stay locked in the position they have when the laminating starts. However, this position may change from roll to roll. It was obviously expected that the inhomogeneities that would be found in this projection would be much smaller than the ones in the other direction. Indeed, the deviations from flatness in this direction are quite small, not greater than 5 microns in general. It seems that if the rolls are not flat in this projection, there is some tendancy for the laminating rolls to get inclined systematically in the same direction, with the thickest lead being produced always at the same coordinate. Fortunately, this position corresponds to the highest radius of the calorimeter. These profiles could not be obtained by the radiography measurements, due to the fact that the errors coming from the intercalibration of the gauges were of the same order of magnitude than the effect that is measured here.

7 Conclusion

We have studied in detail the correlation between the measurement we have very early in the production process, i.e. the X-ray measurement, done at the lead factory, and the measurement done before the absorber production is done, i.e. the ultrasound measurement. Both measurements are understood for the module 0 and yield complementary information. The X-rays allow us to have very rapidly an idea of the distribution of the average thicknesses that is useful to prepare the sorting and the pairing of the lead plates. The ultrasound system allows to prepare very detailed maps of each plate, that can be used for the pairing.

We have studied in great detail the calibration procedure of our ultrasound system and feel that it is now understood. Some undesirable effects have been found (possible temperature effects, risk of drifts of the measurements over time) ans studied. Due to the significant redundancy of the

various calibration systems that are present in the measurement system, we have shown how to track and correct possible variations in the calibration of the measurement system.

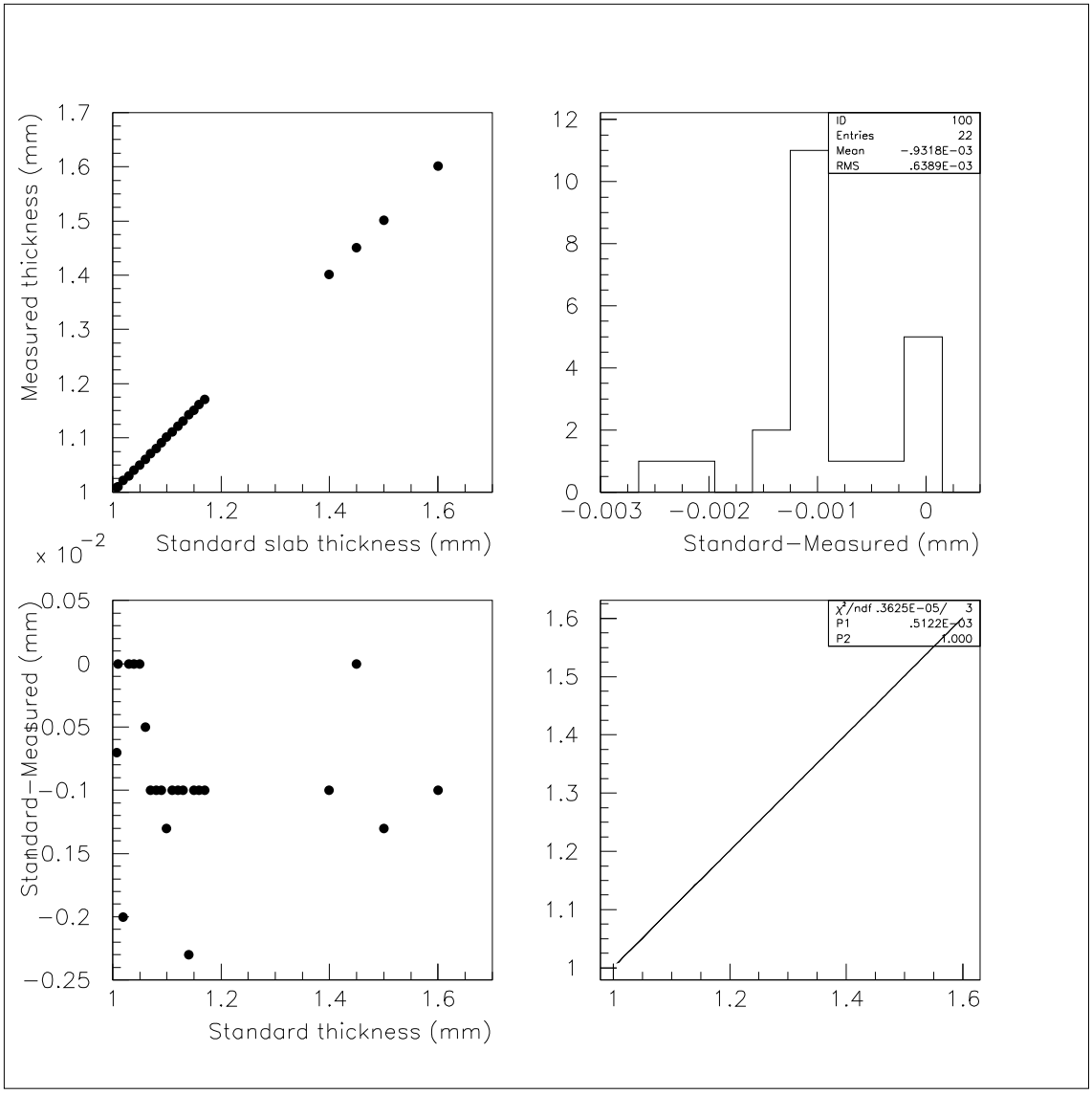

Figure 6: Check of the mechanical calibration with standard slabs. Upper left, correlation between true thickness of the slabs and the thickness measured by the mechanical calibration system. Upper right, distribution of the differences between slab thickness and mecahnically measured thickness. Lower left, difference between slab thickness and mechanically measured thickness and as a function of slab thickness. Lower right, fit of the upper left plot to a straight line.

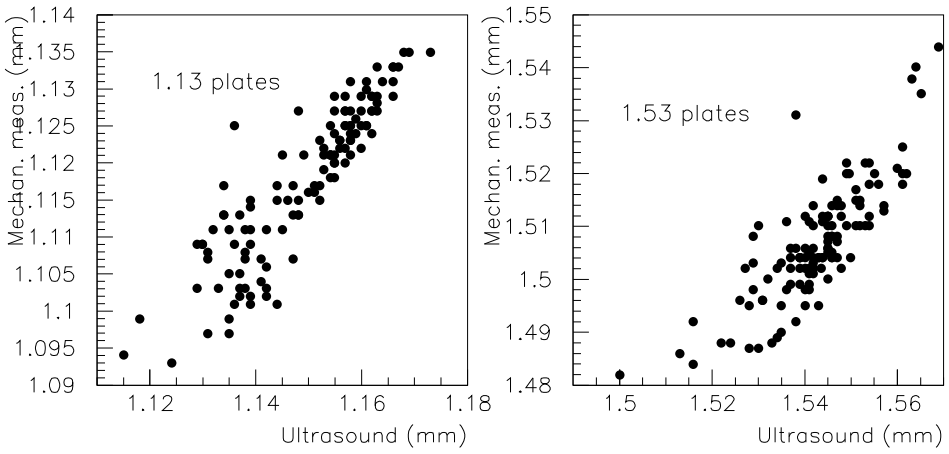

Figure 7: Correlation between ultrasound and mechanical measurement at the common measurement point.

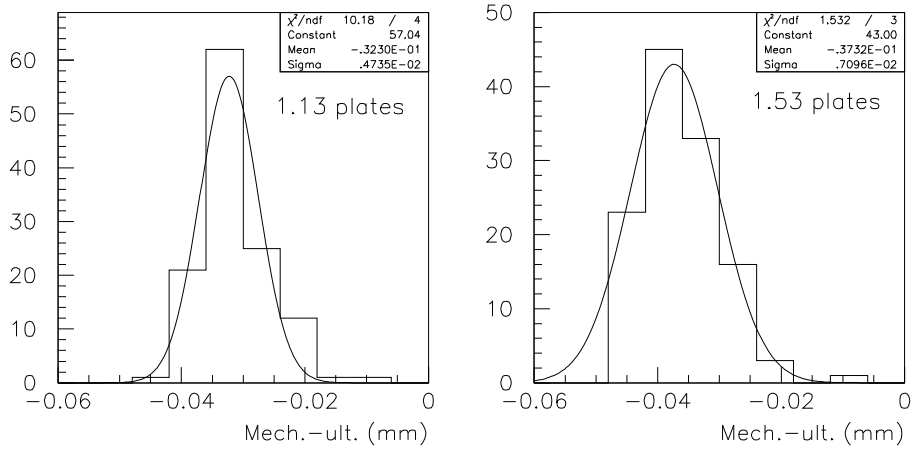

Figure 8: Difference between ultrasound and mechanical measurement at the common measurement point for 1.13 and 1.53 plates.

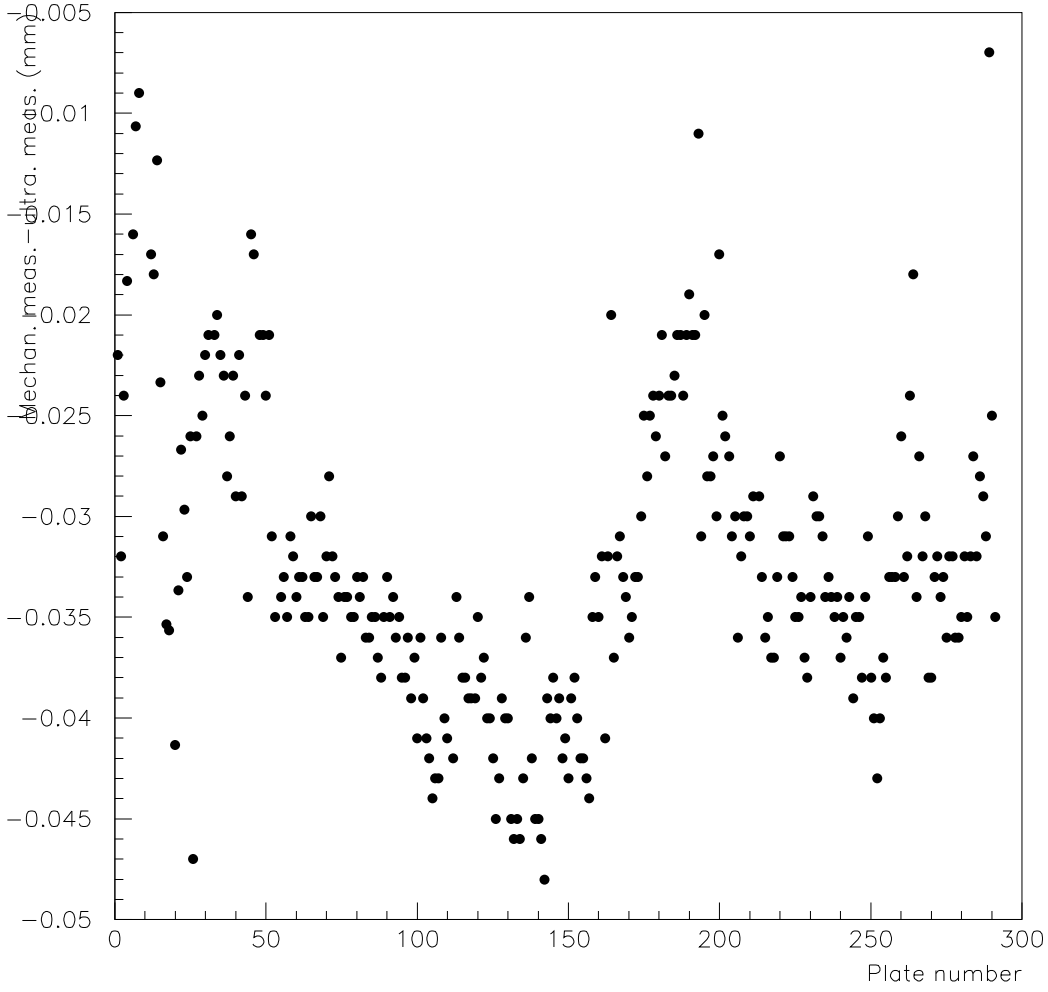

Figure 9: Difference between the mechanical measurement and the ultrasound measurement at the common measurement point, as a function of plate number.

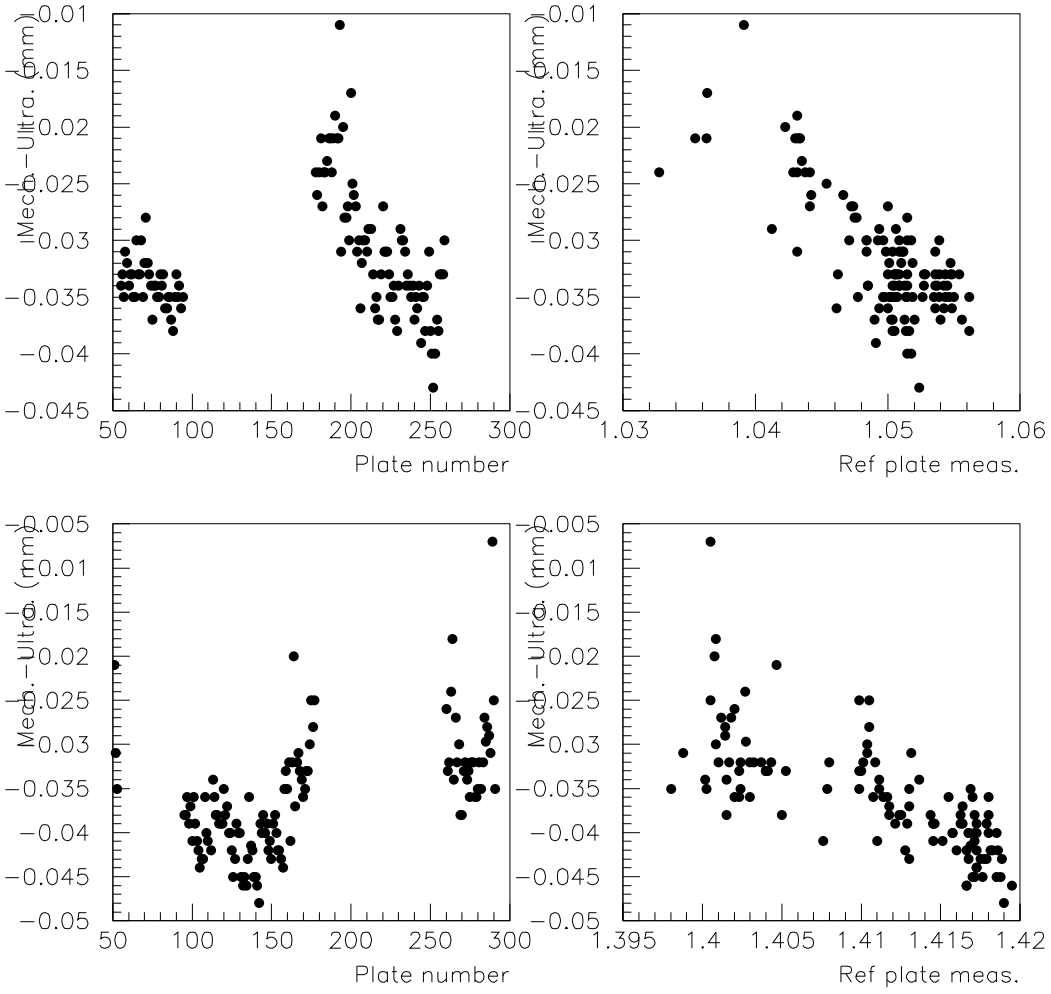

Figure 10: Upper left : Difference between mechanical and ultrasound measurements at the reference point, 1.13 mm plates, as a function of plate number. Lower left : same for 1.53 mm plates. Upper right : Difference of mechanical and ultrasound measurement at the common measurement point as a function of the reference aluminum plate measurement, 1.13 plates. Lower right : Same for 1.53 plates. The rightmost plots show a clear correlation, implying that the ultrasound apparatus has drifted.

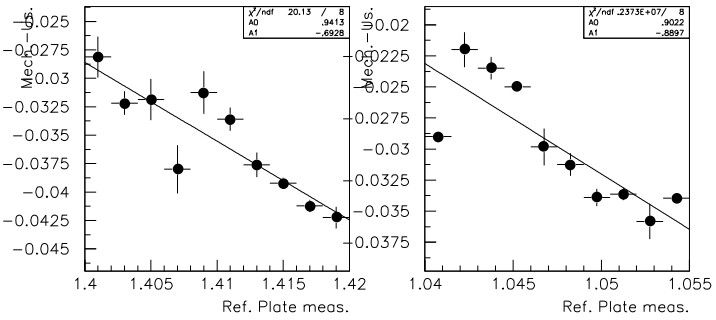

Figure 11: Correlation between the difference of the ultrasound measurement and the mechanical measurement at the common measurement point, as a function of the ultrasound measurement on the aluminum reference plates. This plot is basically the same as the two plot of the right of the previous figure, presented in a different way to better show the correlation. Left is 1.53 plates, right is 1.13 plates.

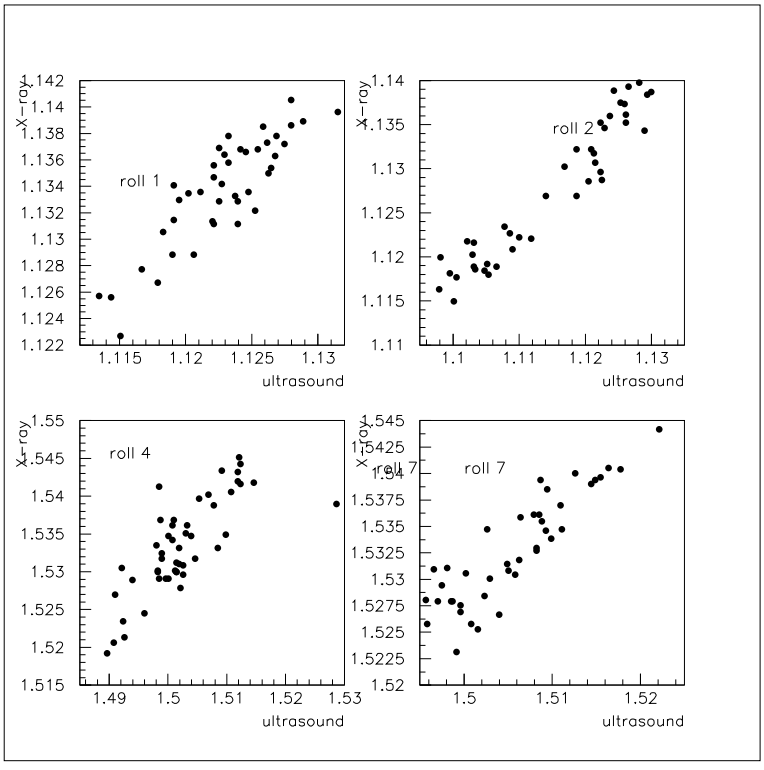

Figure 12: Correlation between X-ray and ultrasound measurements of the mean thickness of plates. Upper plots are for some 1.13 rolls, lower plots for 1.53 rolls.

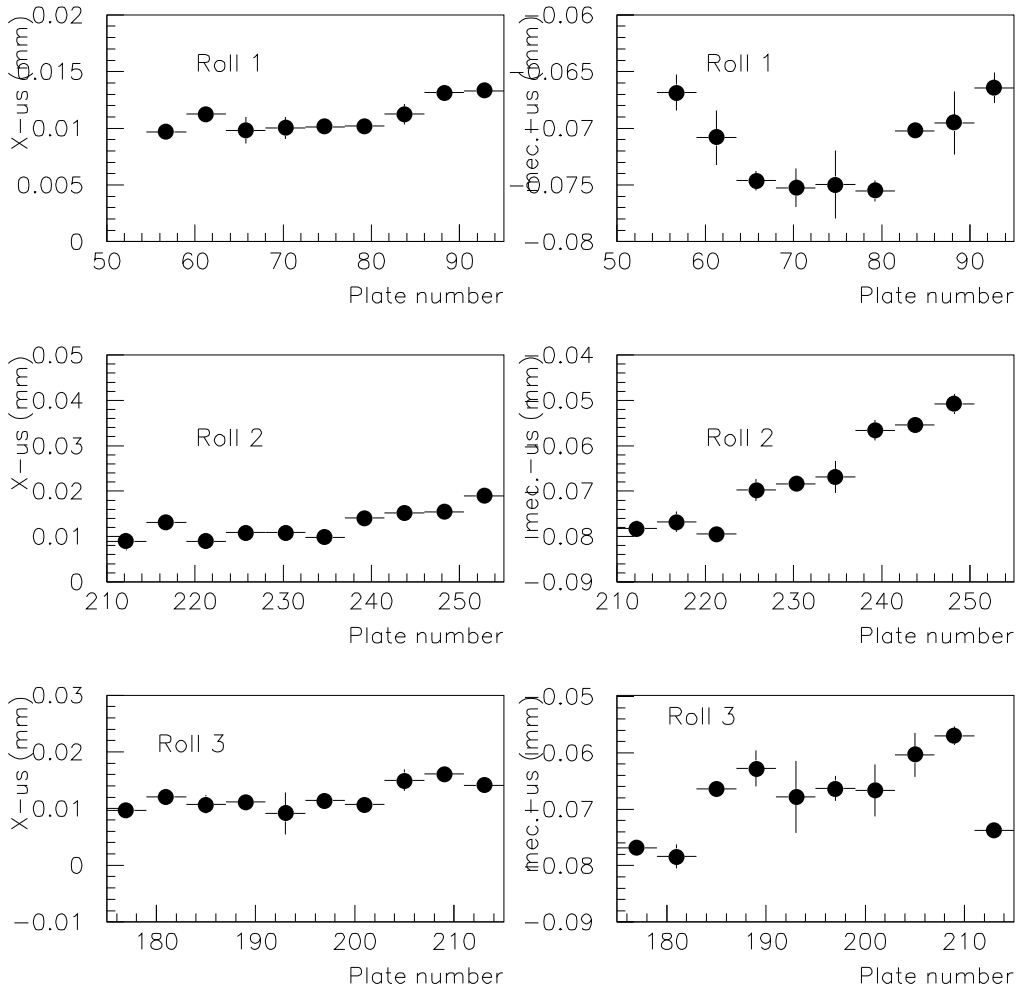

Figure 13: Difference between the X-ray and ultrasound measurement of the mean thickness of the plates, as a function of the plate number, roll by roll, for the 1.13 plates. In the leftmost plots, the ultrasound thickness that has been used has been corrected for the drifts, whereas it has not been corrected in the rightmost plots. The vertical scales are the same on the left and on the right.

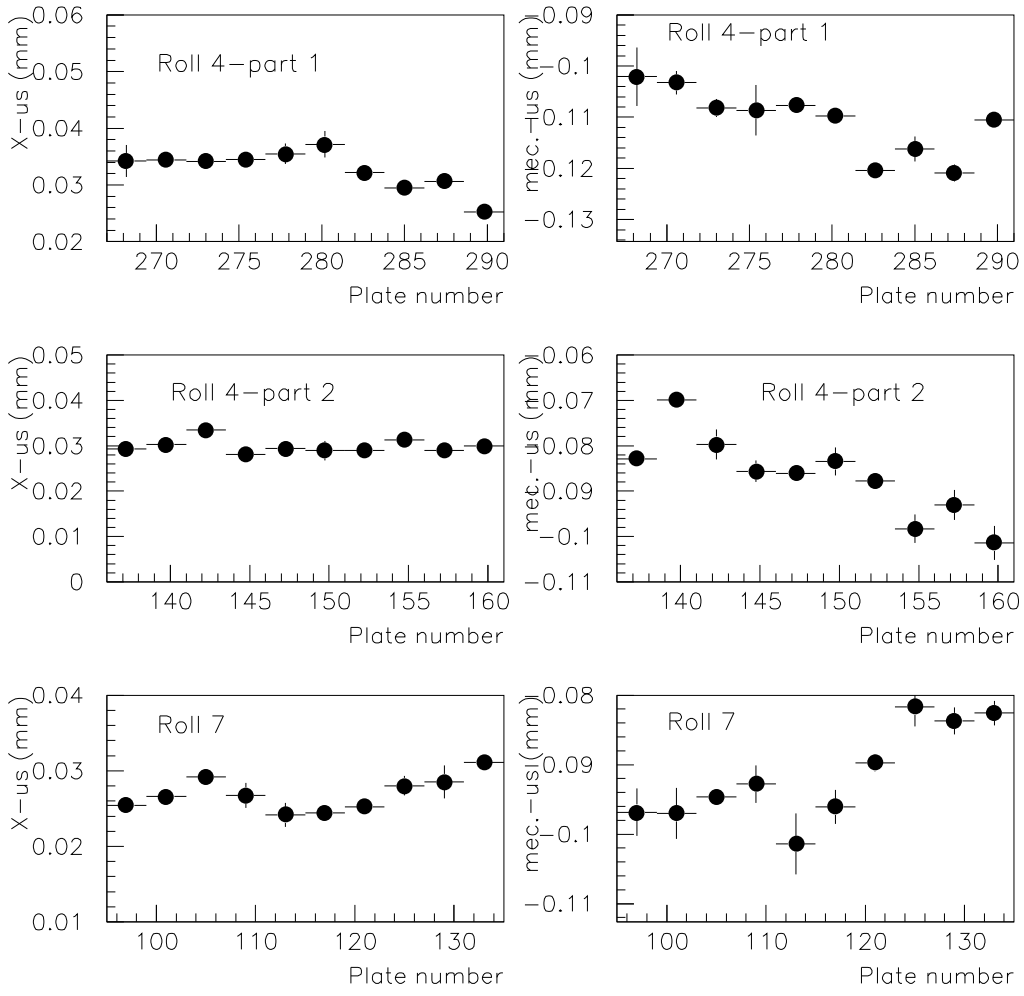

Figure 14: Difference between the X-ray and ultrasound measurement of the mean thickness of the plates, as a function of the plate number, roll by roll, for the 1.53 plates. In the leftmost plots, the ultrasound thickness that has been used has been corrected for the drifts, whereas it has not been corrected in the rightmost plots. The vertical scales are the same on the left and on the right.

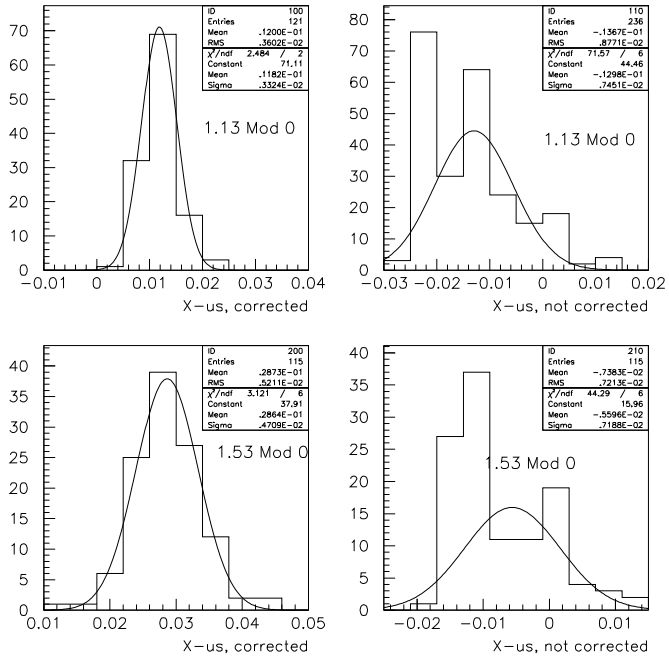

Figure 15: Distribution of the differences between X-ray and ultrasound measurements of the average thickness, for all plates. Upper left, 1.13 plates, using ultrasound measurements, corrected for the drifts. Lower left, 1.53 plates, using ultrasound measurements, corrected for the drifts. Upper right, 1.13 plates, ultrasound measurements not corrected. Lower right, 1.53 plates, ultrasound measurements not corrected.

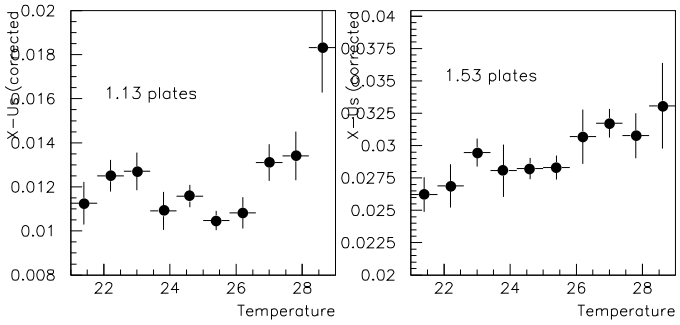

Figure 16: Temperature effect on the measurement : Difference between the X-ray and ultrasound mean thickness measurements, as a function of the temperature of the room in which the measurement has been done. This difference is not centered at zero, due to the fact that the X-ray and ultrasound calibration is not the same.

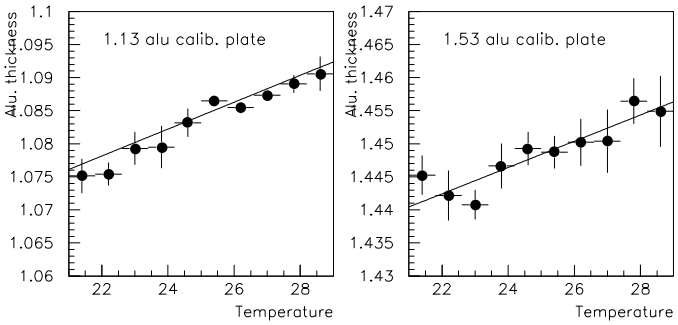

Figure 17: Evidence of temperature effect on the thickness of the aluminum reference plates.

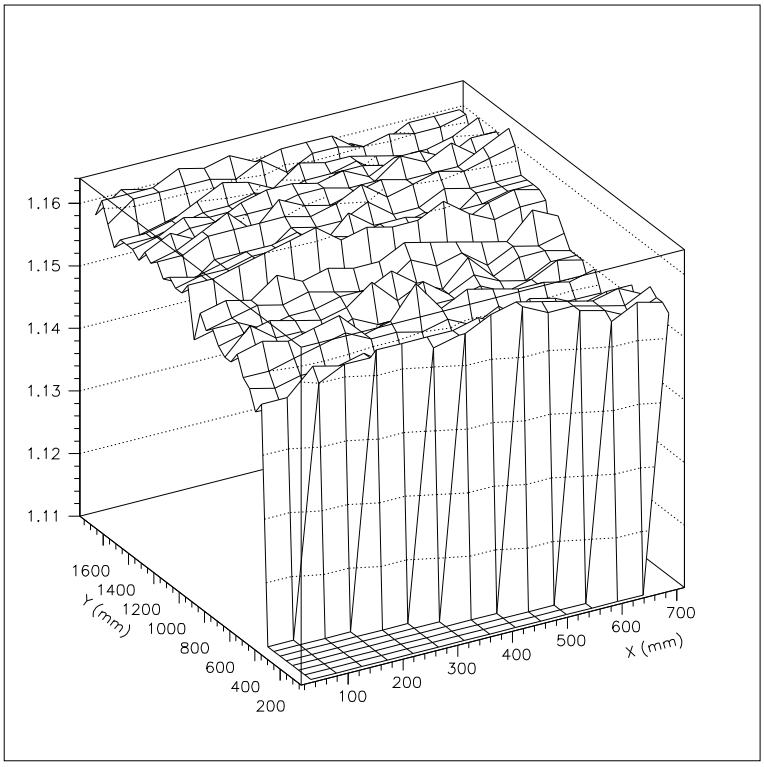

Figure 18: Detailed map of a 1.13 plate, from ultrasound measurements

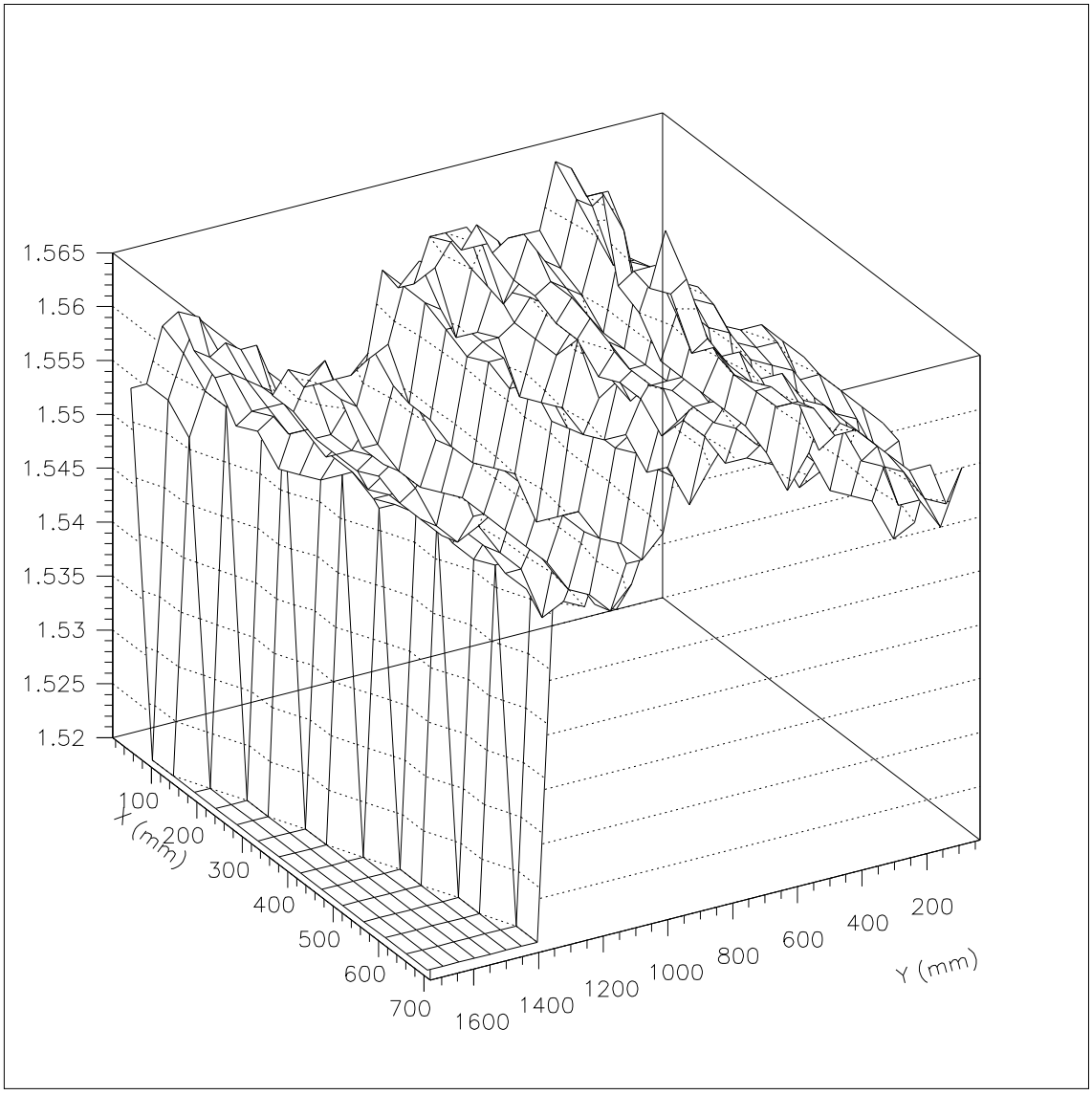

Figure 19: Detailed map of a 1.53 plate, for ultrasound measurements

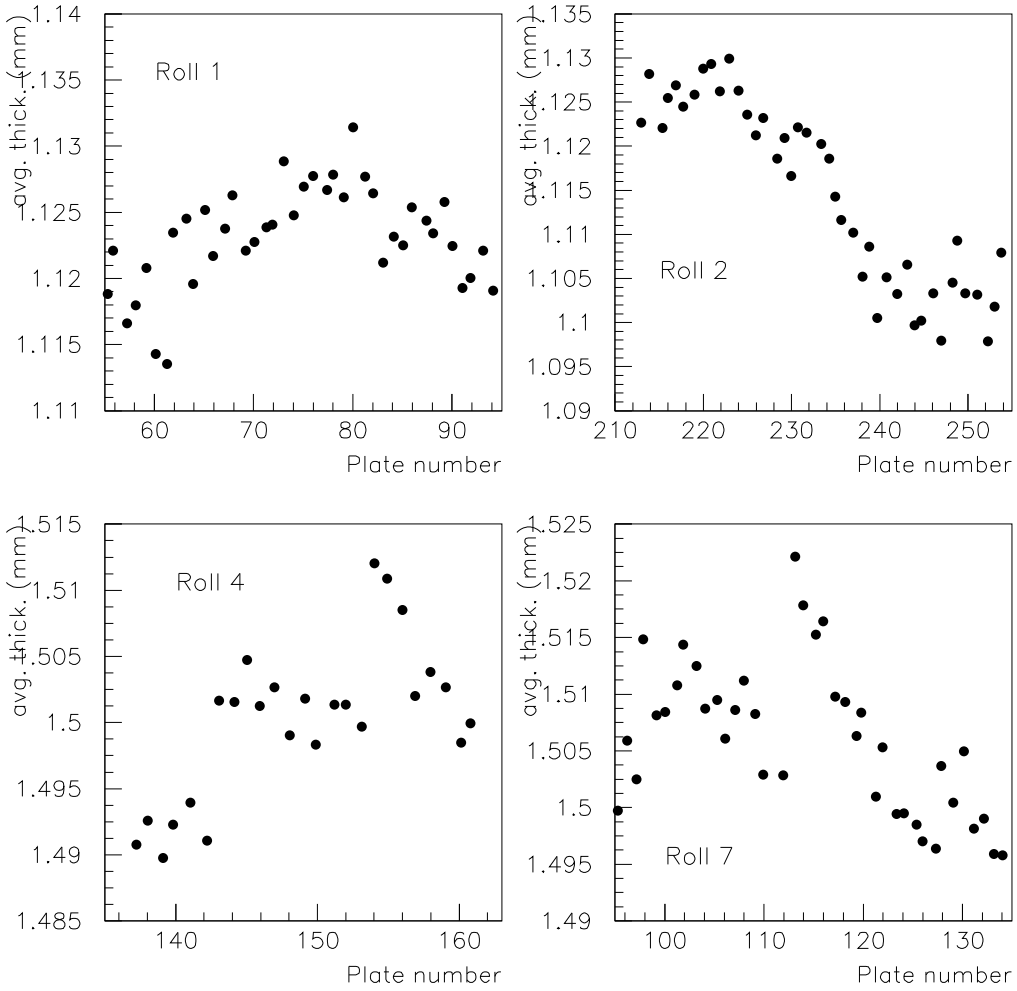

Figure 20: Mean thickness of the plates as a function of plate number, for a few rolls.

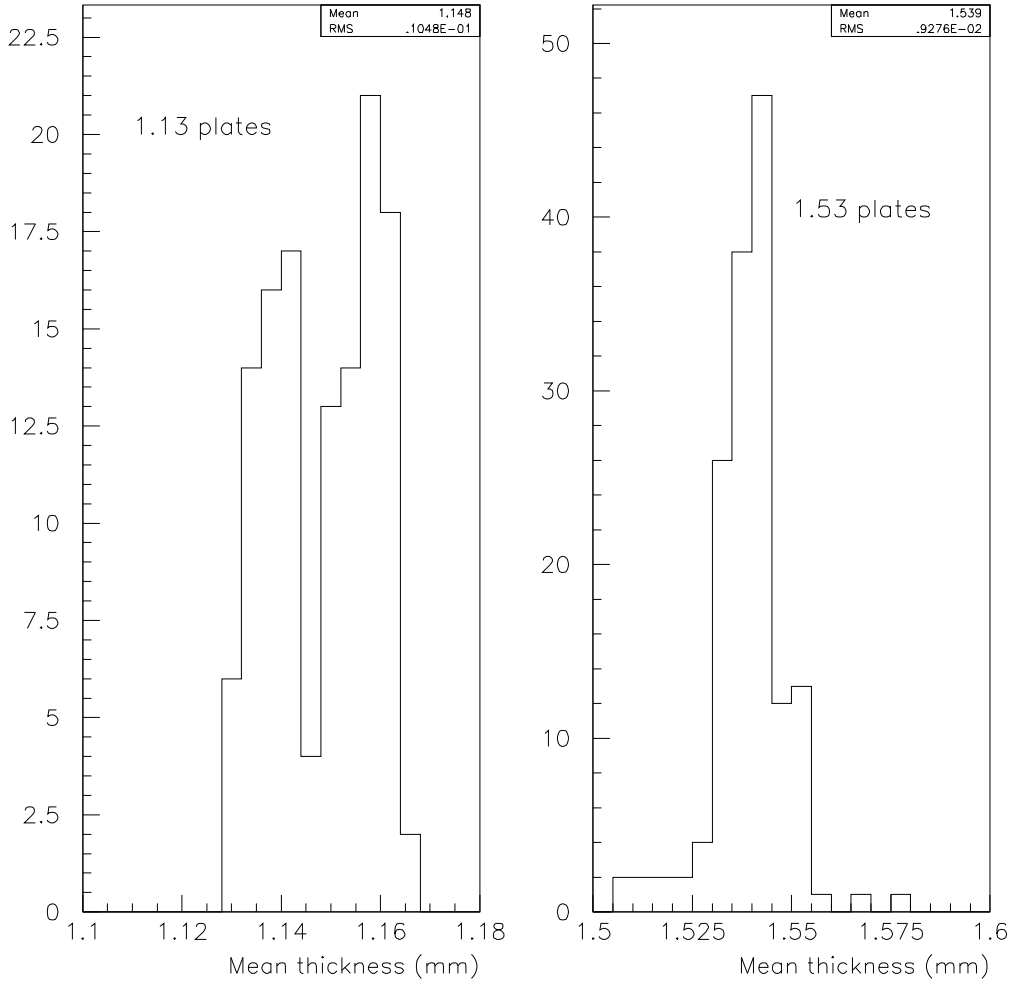

Figure 21: Distribution of the average thicknesses of the measured plates for the module 0.

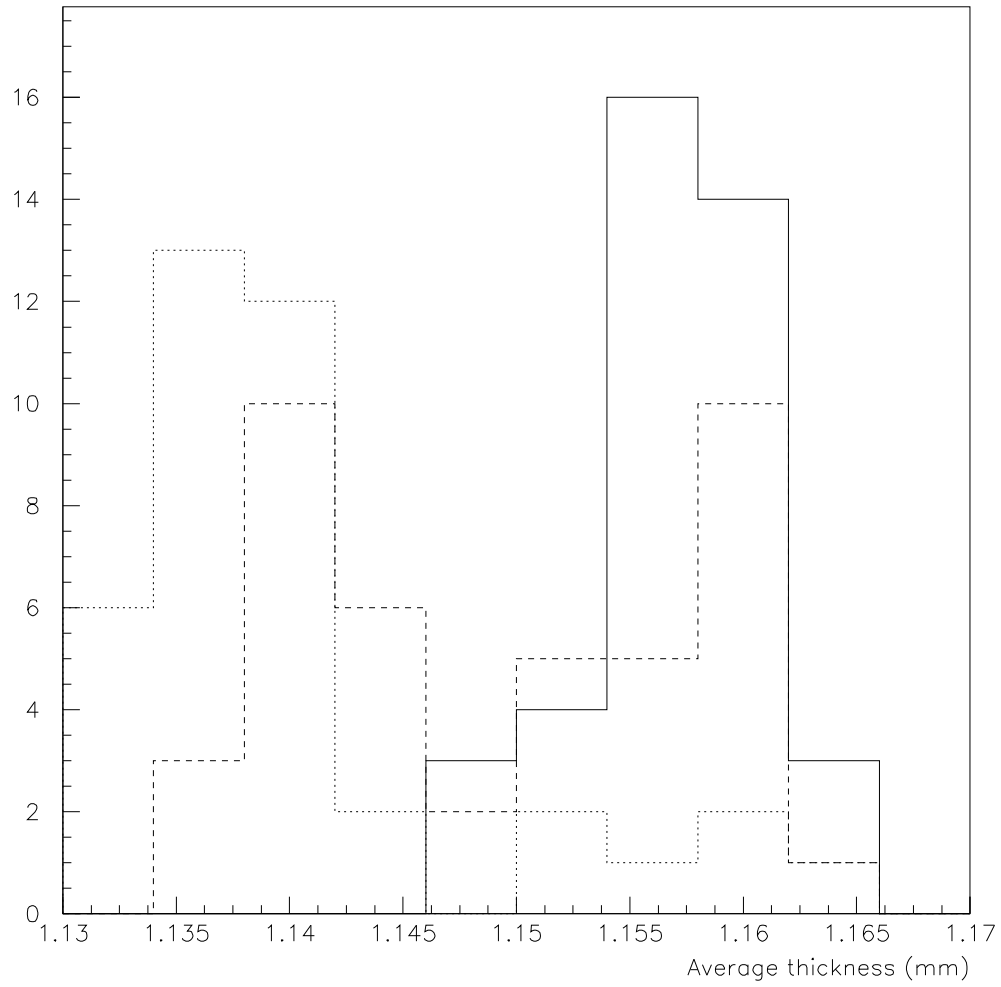

Figure 22: Mean thickness distribution, roll by roll, for the 1.13 plates. Solid histogram : roll 1. Dashed histogram : roll 2. Dotted histogram : roll 3

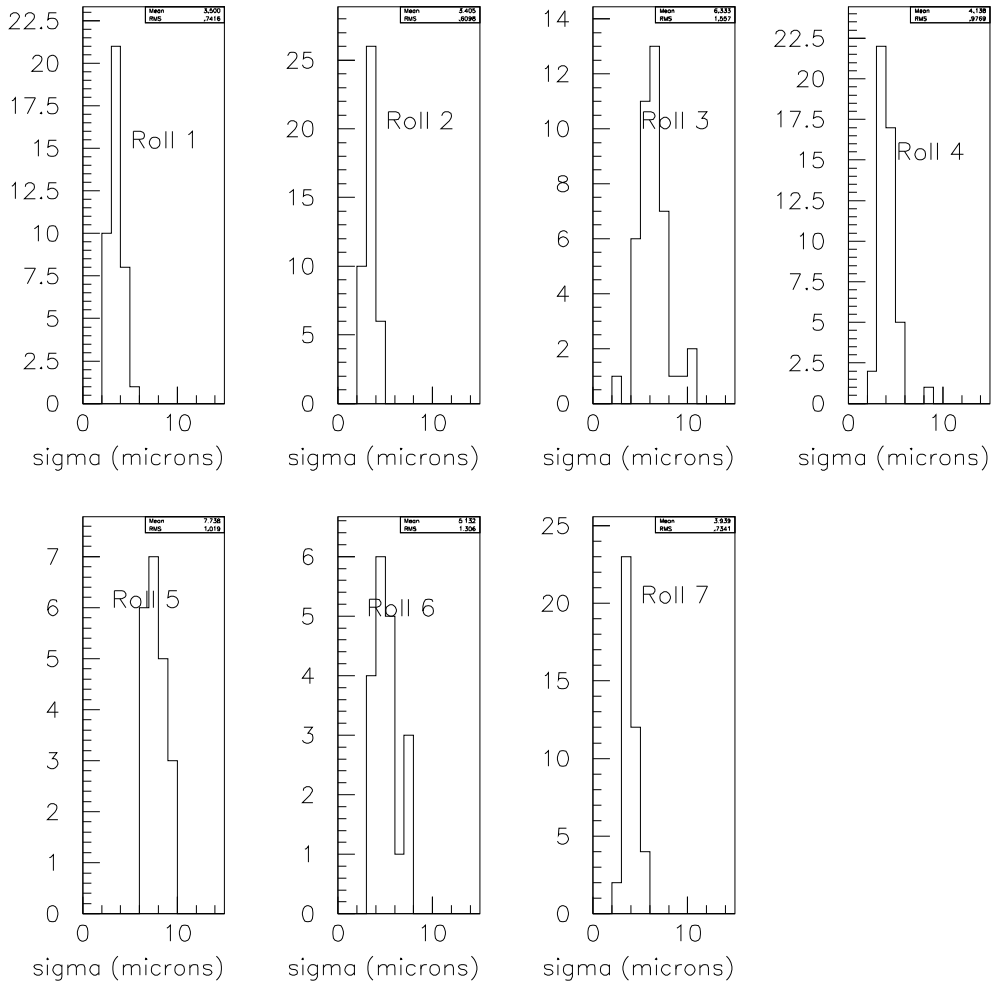

Figure 23: Distributions, roll by roll, of the r.m.s. of the measurements on each plates.

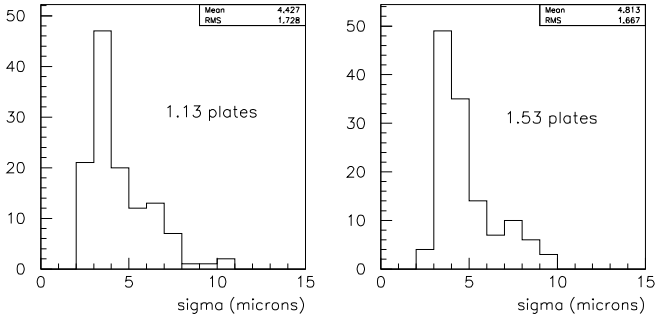

Figure 24: Distribution of the r.m.s. of the measurements on each plate, by plate type.

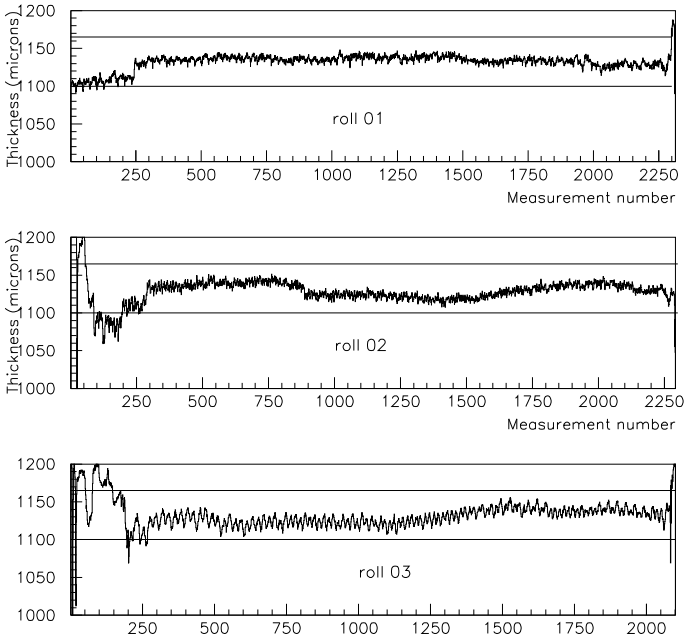

Figure 25: X-ray thickness profiles for the three 1.13 mm rolls.

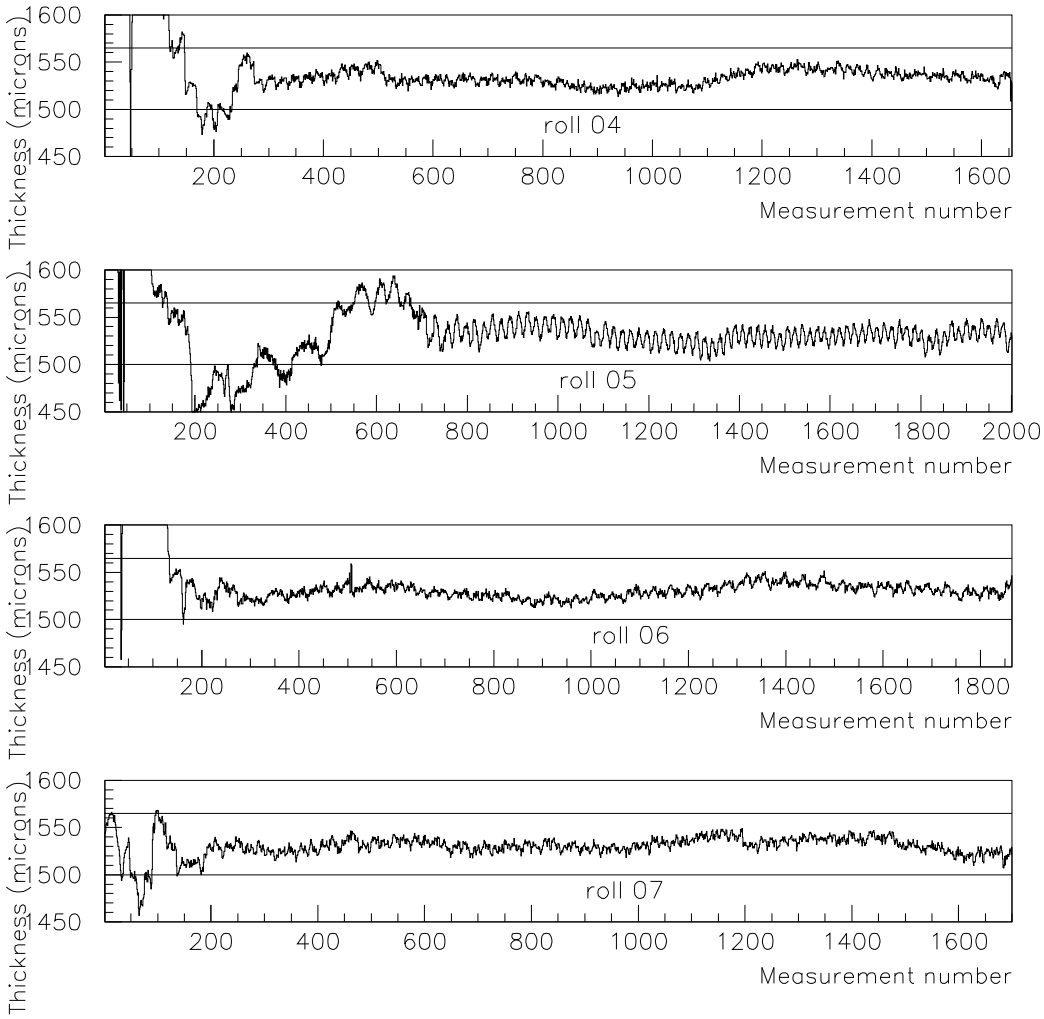

Figure 26: X-ray thickness profiles for the three 1.13 mm rolls.

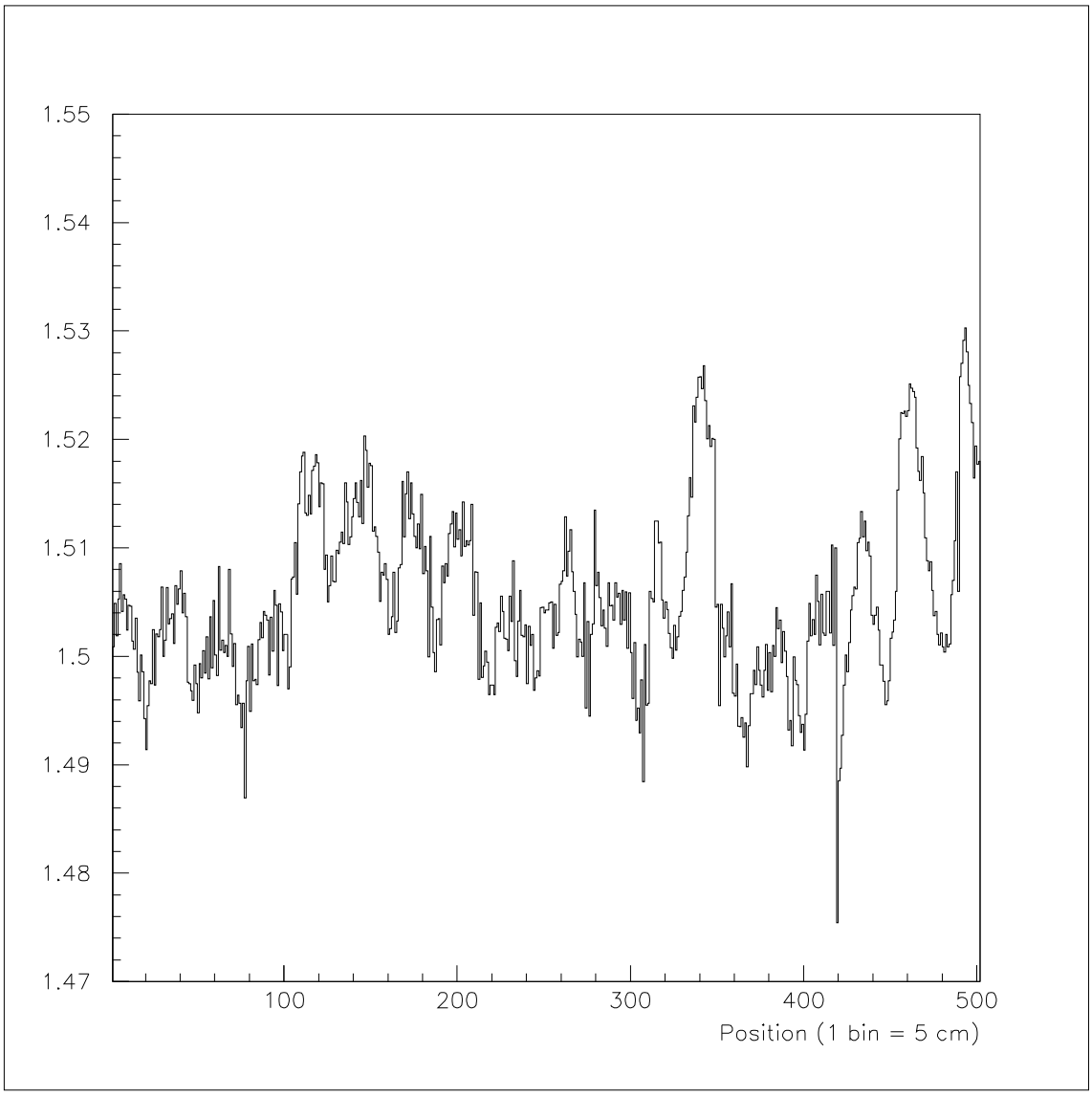

Figure 27: Profile of part of a 1.53 roll, in the direction orthogonal to the roller axis, corresponding to the z direction on the plates. This profile has been obtained by chaining the measurements coming from several consecutive plates on the roll.

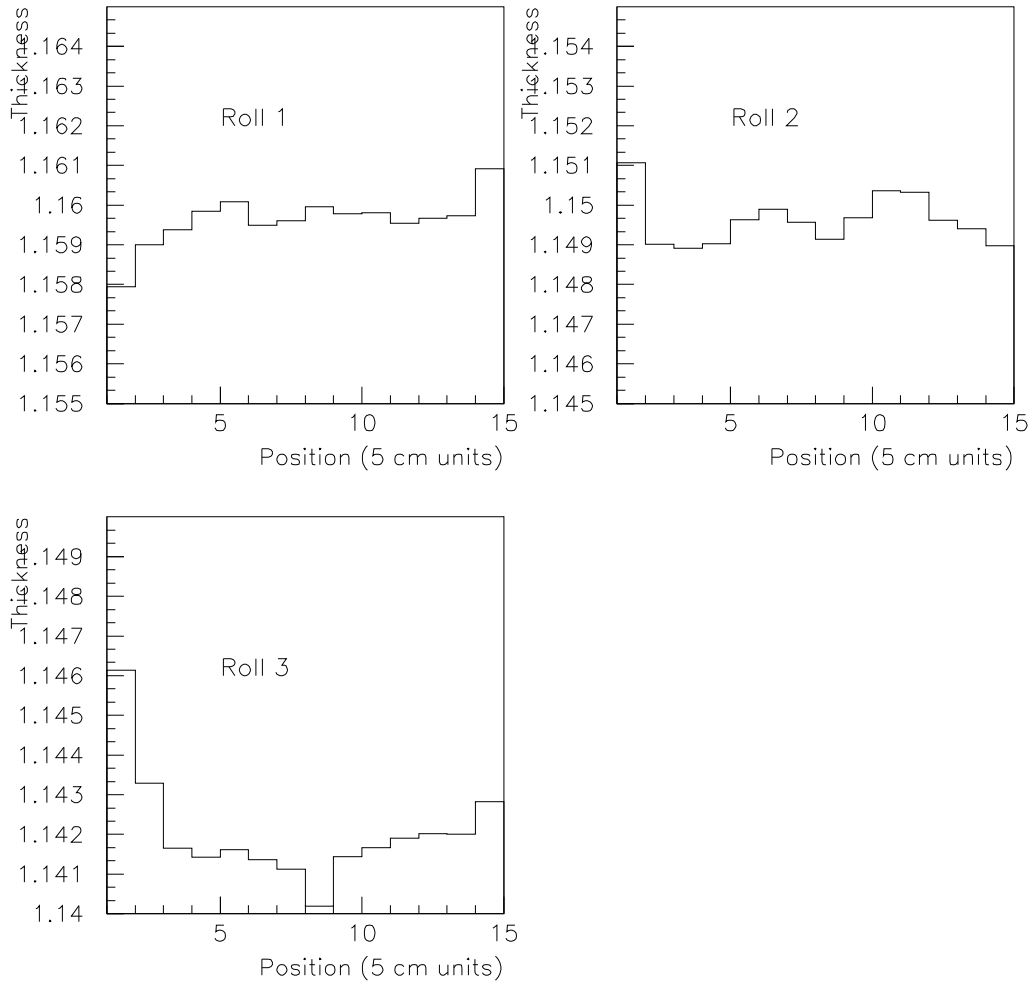

Figure 28: Profiles of each roll for the 1.13 mm plates, in the direction parallel to the roller axis, corresponding to the r direction on the plates.

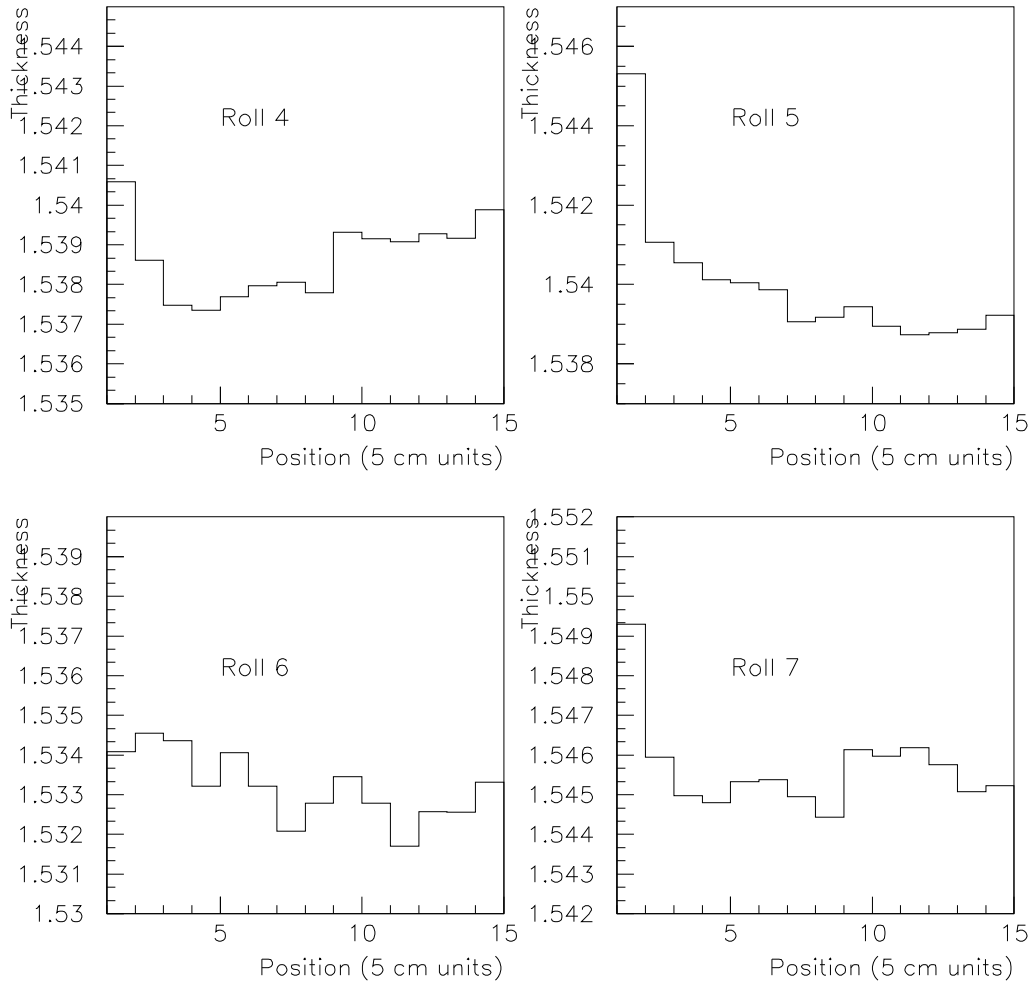

Figure 29: Profiles of each roll for the 1.53 mm plates, in the direction parallel to the roller axis, corresponding to the r direction on the plates.

References

[1] B. Canton et al, Measurement and control of the ATLAS Electromagnetic Calorimeter Lead Plates, ATL-LARG-94-009.

[2] B. Canton et al, Analysis and Results of the measurements of the plate thickness, done at the factory, during the production of the lead for the module 0 of the Barrel and End-Cap ATLAS electromagnetic, ATLAS-LARG-97-076.