

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 calorimeters.

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Abstract

In October 1996, the thickness of the lead plates corresponding to the whole production (about 5 tons) for modules 0 of the barrel and the end-cap e.m. calorimeters has been measured at the factory, using X-ray radiography. Data were recorded and processed both on-line and off-line, using the same algorithms than foreseen for the full production. A detailed study of the thickness variations that have been observed are reported in this paper. It allows to ensure the thickness variations to be kept within 1% already at the factory. This work on Modules 0 is pioneer in checking how well the lead thickness can be handled by the manufacturer and for planning the full production. It ensures that the lead delivered by the factory will have thickness variations matching the ATLAS physics requirements.

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1 Introduction

This note is organized in the following way : First we recall rapidly which thickness variations can be tolerated from a physics point of view. Next we describe the production process, and the control procedures that have been used for module 0. We will next describe the measurements done for the module 0 and comment them, showing where improvements can be done for the whole production, from the measurement point of view, and from the production point of view.

2 Motivations

It is well known that correct physics performance of the Electromagnetic Calorimeter requires a constant term as low as possible, less than 0.7% being considered as adequate, with a contribution coming from the mechanics below 0.3% . The most important contribution to the constant term is lead thickness variations from absorber to absorber and from point to point within one absorber. These lead thickness variations induce local changes in the thickness of the calorimeter in terms of radiation lengths, changes in the absorber over liquid argon ratio and hence changes in the calorimeter response. These changes are known from measurements [1] : it has been measured that an increase of 10 μm in the lead thickness for 1.8 mm plates induces locally a decrease of 0.4% in the response of the calorimeter. The goal for the lead thickness production and control procedures is to keep the average thickness variation from absorber to absorber below 10 μm , and if it is possible, to do of course better.

3 Lead Production Process

3.1 Lead laminating apparatus

The lead plates for the Barrel and End-Caps are produced in Germany, by the company ROHR+STOLBERG GmbH. The lead first is in the form of blocks of approximate dimensions 2 m long by 1.20 m width and 10 cm thick. About 80 tons of lead represent one foundry batch, with constant chemical composition (nominally 99.5% lead). This means that it is possible to have the whole barrel lead have the same chemical composition, and the same will be true for both End-Caps. The lead blocks are put on the roller, which is sketched figure 1. The thickness of the block is decreased in several passes (typically 4). During the two first passes, the lead thickness decreases very rapidly, going from 100 mm to 3-4 mm. As soon as the lead thickness is below

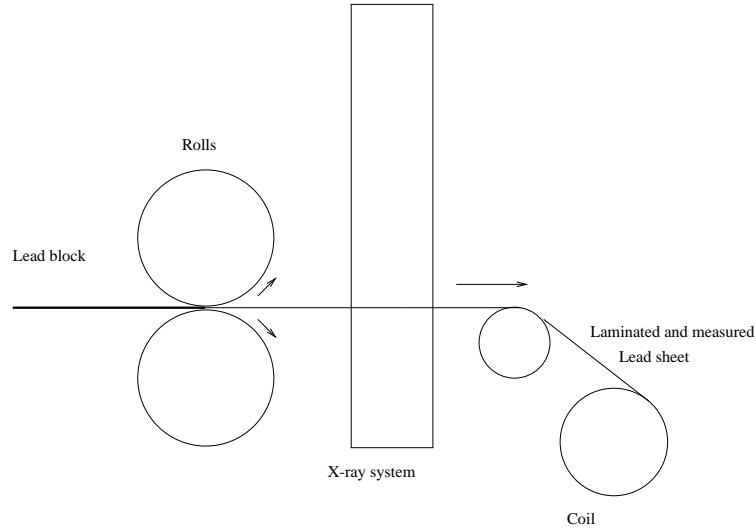


Figure 1: Sketch of the roller and X-ray measurement system

3 to 4 mm, the lead block is so long that it has to be wound (see figure 1). The two last passes bring the lead from 3-4 mm to the final thickness. Since the lead is very ductile, any thickness inhomogeneities that may be created during one pass are very easily removed during the next one. As a consequence, it is only the last pass that is likely to produce inhomogeneities in the delivered lead and that has to be controlled and monitored with high precision. After having been laminated, the lead sheets, wound on cylindrical pieces made of steel (called “coils”) may be stored some time as such, before being cut out in rectangular pieces by an electrical saw and put into boxes of an approximate weight of 1 ton, before precision cutting and transformation into absorbers.

From this description, one can identify several possible sources of lead thickness variations :

- Variations in the roller setup : the speed of the rolls and the intensity of the traction exerted by the coil ($\simeq 1$ MN) on the lead sheet influence the final thickness. The speed that has been used to laminate the lead for modules 0 is approximately 20 m per minute. This speed is about three times lower than what is used to laminate “usual” lead, and has been chosen to give less inhomogeneities, according to the manufacturer.
- Non-uniformities in the roll shapes. If the rolls are not perfectly cylindrical, one expects this to translate into periodical thickness variations.

It should be noted that all these sources of non-uniformities can be detected by the online measurements. The following ones, since they appear only after the measurement, can only be controlled by the offline measurements.

- Problems with the coils (scratches, holes...). These defects may be “printed” into the lead sheets.
- During storage of the coils, the lead is of course under stress from gravitational sagging.

3.2 Lead Measurement System

3.2.1 General description

A picture of the lead online thickness measurement system is shown in figure 2. This system is based on X-ray radiography. The X-ray source, located at the top of the apparatus, delivers X-ray radiation with tunable intensity and energy (typically of the order of 120 keV). The X-ray beam passes through the lead, where part of it gets absorbed, the rest being detected by seven compact detectors made each of a NaI scintillator, a 3/4 inch photomultiplier, a small high voltage generator and a discriminator. This detection system has been developed by DAMRI (CEA-SACLAY). The detectors are all put in a line perpendicular to the lead sheet movement, spaced by about 15 cm. The logical pulses are read out by a computer, counted and converted to absorption coefficients and thicknesses. The results are displayed on the fly in graphical form. This allows almost immediate feedback (a few seconds) to be applied by the workers on the roller setup, if needed. The results (counting rates, thicknesses, absorption coefficients) are stored on a file for later analysis.

In addition to the measurement, the computer controls also the marking and the rejecting of the lead. One of the important purposes of the online lead measurement being to reject “bad” lead, whose thickness is so much away from the nominal value that it would in any case not be transformed into absorbers, as soon as the thickness measured by any of the seven detectors is out of the tolerance interval, a very visible green paint line is drawn on the lead, to indicate that this lead has to be cut out at the factory and not shipped to ATLAS. This allows ATLAS to get lead which is already of good quality and eases the subsequent work of choosing the lead plates during the absorber construction process. The system has been designed, built and assembled by LPNHE-Paris, the DAMRI contributing the X-ray source, the detectors and the data acquisition system.

The tolerance intervals were set up as follows :

- For the 1.13 mm lead (barrel $0.8 < \eta < 1.4$) : accepted from 1.100 to 1.165 mm.
- For the 1.53 mm lead (barrel $0.0 < \eta < 0.8$) : accepted from 1.500 to 1.565 mm.

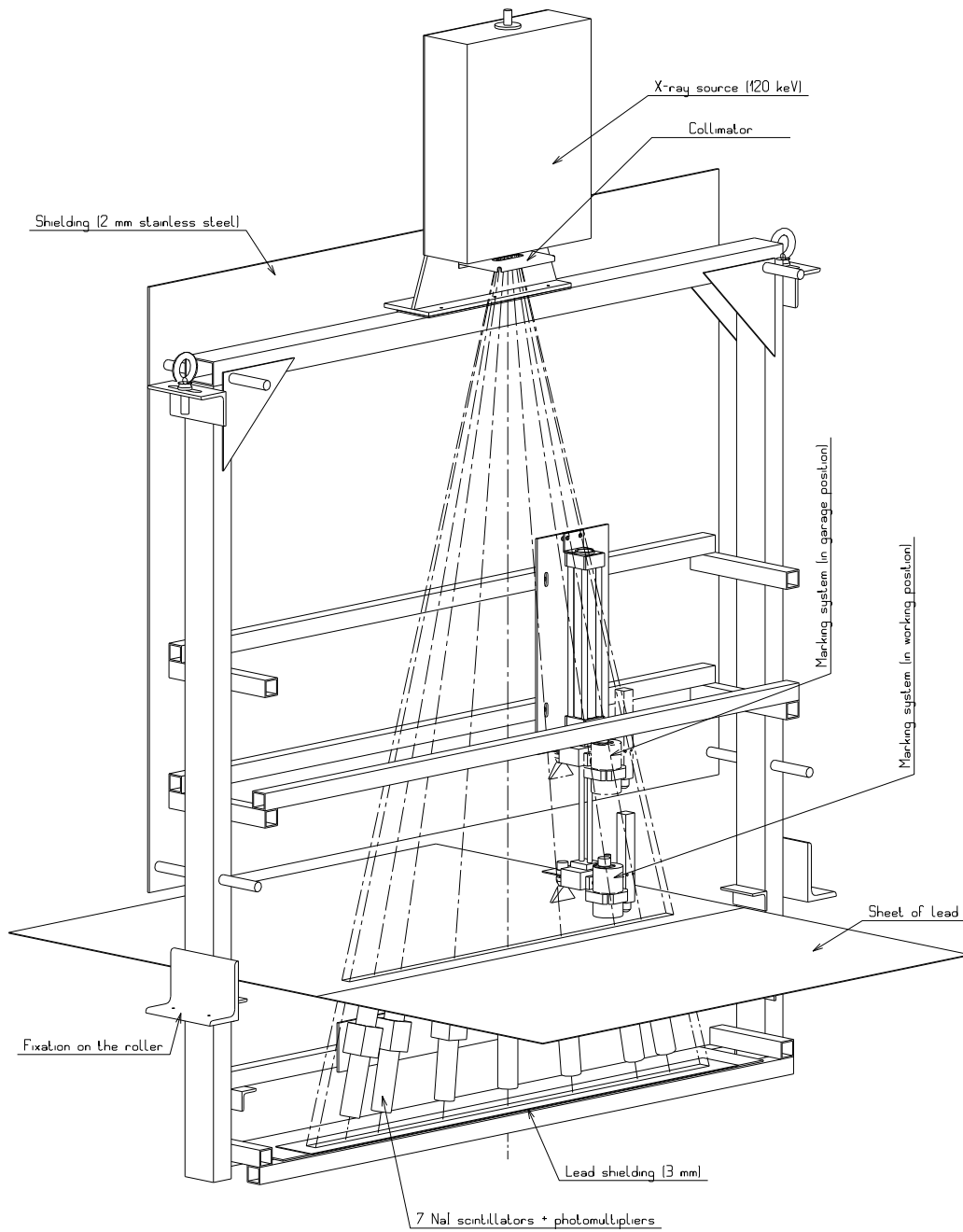


Figure 2: Detailed view of the X-ray measurement system

- For the 1.70 mm lead (end-cap outer wheel) : accepted from 1.670 to 1.735 mm.
- For the 2.20 mm lead (end-cap inner wheel) : accepted from 2.170 to 2.235 mm.

The radiation is collimated into a sharp cone by lead collimators, to avoid sending X-ray photons much out of the acceptance of the detectors : photons out of the detector acceptance may encounter Compton scattering in the iron shielding enclosing the whole system and perturbate the measurement if they are scattered back to the detectors. Furthermore, such out of acceptance photons must also be avoided for obvious radiation protection reasons. Measurements have shown that the radiation dose was below 1 mrem/hour outside of the shielding, and compliance of the whole system with German safety regulations and laws has been ensured.

3.2.2 Calibration

Since we want to perform a measurement at the percent level, being able to convert absorption coefficients into thicknesses must be done with this level of precision. Furthermore, once this correspondence has been established, one has to check from time to time that it has not changed. Many factors may influence the intensity of the X-ray beam and its spectral characteristics. One of the most important factors is the temperature : the X-ray source dissipates a significant amount of thermal power. It is powered by a 120 kV high voltage power supply of typical intensity 200 μ A. This represents a dissipated power of 24 W, the most of it being directly converted into thermal energy at the X-ray tube anticathode, and the thermal dilatation of the elements of the tube may change the characteristics of the beam. To keep this effect under control, the X-ray system has been left permanently under power to let it reach thermal equilibrium, the X-ray beam being interrupted by a thick slab of lead placed on the tube output slit. From time to time, it has been checked if there were significant variations of the calibration parameters as a function of time.

In principle, calibrating an X-ray thickness measurement system is very simple : one needs only to use the very simple law :

$$I = I_0 \log \frac{e}{e_0} \quad (1)$$

where I is the measured intensity, I_0 the X-ray intensity coming out of the tube, e the thickness of the measured plate and e_0 the absorption length. Several phenomena complicate somewhat this simple law : Equation 1 is valid if the X-ray radiation is monochromatic. This is never perfectly true

in practice with X-ray tubes, where the emitted energy is concentrated into several emission peaks superimposed to a continuum. Since the absorption coefficient has a very strong dependency upon the incoming photon energy, the energy spectrum of the photons emerging from a piece of given lead thickness is itself a function of this thickness. This means that one has to use in practice a different set of (I_0, ϵ_0) values for the different thicknesses to measure.

To keep the drifting of the X-ray source and of the photomultipliers as much as possible under control, the value of I_0 was checked as often as possible² (before almost every roll, so that each measurements of I_0 was taken roughly every half our).

Due to the precision with which the measurement had to be done, we needed to have lead with very well known thickness. Such kind of lead is used for industrial radiography, and were used in our case for calibration purposes. The thickness of these lead sheets has been checked using the same ultrasound gauge as the one that will be used for the offline measurement, because this kind of gauge allows a very easy and fast check of the uniformity of a lead plate. In addition, it has been checked that the thickness provided by this gauge was consistent with the thickness one could deduce from the dimensions and weight of the measured plates, using the standard density of pure lead.

In the future, we plan to try the same kind of procedure. However, we will improve the procedure by using pieces of lead cut out of lead sheets from the lead production for module 0. These pieces will be carefully controlled and their thickness uniformity will be checked. The reason to use lead from module 0 is that lead sheets intended for industrial radiography are very small (typically 10 cm \times 10 cm at best), so that the calibration coefficients determination may be perturbed by diffused X-rays that are stopped or at least strongly attenuated by a full width lead sheet. Using a full width lead sheet would yield a situation much closer to real operation, with lead of exactly the right composition, and hence a more reliable determination of the calibration coefficients. Some serious indication for the existence of diffused X-rays has been inferred from the fact that the calibration constants showed some sensibility to the exact position of the calibration sheets : changing slightly the position of the calibration³ sheet above a given detector cannot change the amount of “direct” transmitted radiation, but only of diffused

²The value of ϵ_0 could not be monitored during lead production, because it would have needed placing carefully several lead sheets of known thickness in the X-ray beam and take several calibration runs. It was felt that this operation would be too long and too dangerous, since someone would have to get very close to parts of the roller that were already in movement to prepare the processing of the next roll.

³A position change of a few cm of the calibration lead sheet could typically induce a change of the order of 1% in the calibration coefficients

radiation.

4 Analysed data

The thickness data is stored as ASCII files, each file representing the measurements taken over one roll. Each file recapitulates the conditions under which the data has been taken (roll number, date, time, minimum and maximum value of the tolerance interval, nominal thickness, counting time). The calibration data used to compute the thicknesses are also stored. For each measurement, the measurement number and the raw counting rates are stored with the corresponding thickness values. In addition, a boolean indicator tells whether the piece of lead corresponding to each measurement is within the tolerances or not. With all these informations, it is possible :

- To know how the thicknesses have been derived from the raw counting rates.
- If needed, to reanalyze the data using a slightly different calibration.
- To know what part of the lead has been accepted (within tolerance) or rejected (out of tolerance, green painting projected on the lead)
- To establish a correspondance between the numbers printed in black on the lead and the thickness measurements (using the measurement numbers ; a printing has been done on the lead every N^4 measurements, starting with the first one). This correspondance will be especially useful to crosscheck the results of the offline measurements using ultrasounds.

4.1 Semi-quantitative evaluation of calibration errors

Since the seven measurements done on one line are done by different detectors, it is likely that there will be miscalibration between the different gauges. From the way the lead has been rolled, one expects only small thickness variations in a direction parallel to the roll axis i.e. between the different photomultipliers. Thickness variations along this axis should arise mainly from misalignment of the rolls, leading to a regular increase or decrease of thickness going from one extremity of the axis to the other one. Another possible thickness variation along the roll axis is the so-called “crowning”

⁴The value of N can be chosen at will. The values that were actually used were $N = 10$ for the 1.13 and 1.53, and part of the 1.7 mm lead, $N = 5$ for the rest of the lead.

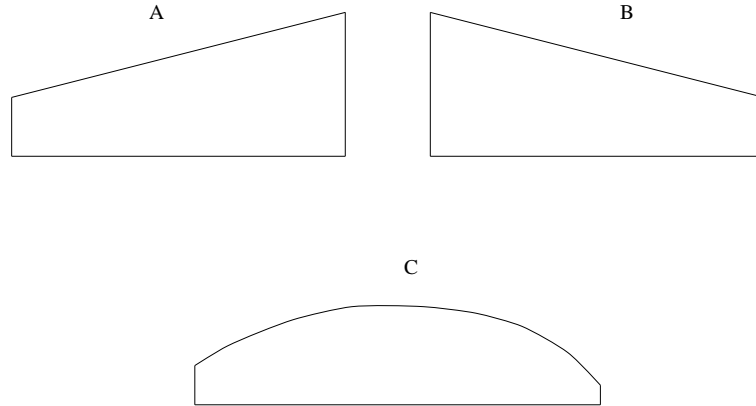


Figure 3: Transverse (i.e. parallel to the axis of the rolls) shapes expected in the case of different imperfections of the roller setup. In cases A and B one would have roll misalignment, in C one would have crowning

effect⁵, due to an incorrect pressure exerted on the rolls, and whose shape is quite characteristic (see figure 3). Any more complicated shape is a serious hint of miscalibration problems.

Since the lead used for the mechanical “maquette” of the barrel came from the same manufacturer and from the same roller, it is possible to use the ultrasound results obtained at that time to evaluate the lead uniformity parallel to the rolling axis. The plots obtained for the lead of the “maquette” are given figure 4 and 5. One sees that the transverse shape is basically flat at the level of a few microns, so there is no reason to expect a much different shape for the lead of module 0.

Figures 7 and 8 show the average thicknesses taken along lines orthogonal to the rolling axis for the various thicknesses of lead that have been used. In these plots, all the data for each gauge has been used. One clearly sees that there are indeed miscalibration problems. This is an inherent problem of this measurement technique, where all the detectors are independant. Assuming a perfectly flat theoretical profile parallel to the rolling axis, the miscalibration can be evaluated by looking at the r.m.s. of the distribution of the average thicknesses in figure 7, and to the difference between the gauges given the highest and the lowest bin in figure 7 and 8, assuming the lead profile is actually flat. This yields to the numbers of Table 1. It can be seen that there is some miscalibration. Typically, the r.m.s. of the distributions of the average thicknesses of figures 7 and 8 are of the order of 5 microns, but the difference between the gauge giving the highest and the gauge giving

⁵The rolls are never perfect cylinders, but are given a cigar-shaped profile, computed in such a way that the pressure exerted by the lead being laminated deforms the profile to give it exactly the shape of a perfect cylinder. If the pressure is too high or too low, the cigar-shape will not be compensated and crowning will occur.

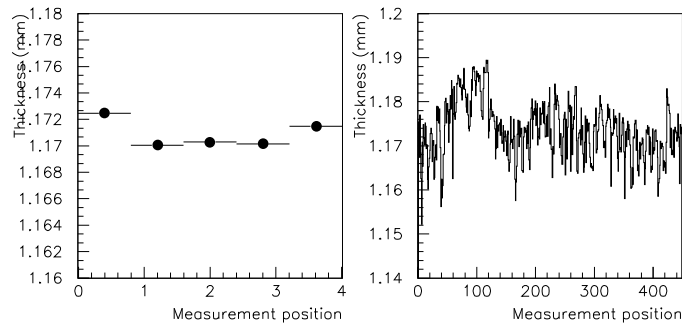


Figure 4: Profiles of the roll used for the 1.2 mm lead plates for the maquette in 1994, obtained with ultrasound measurements. (Left plot is the transverse profile, parallel to the roll axis, right plot is the longitudinal profile) . Notice the similarity of the right plot with plots 15 to 18

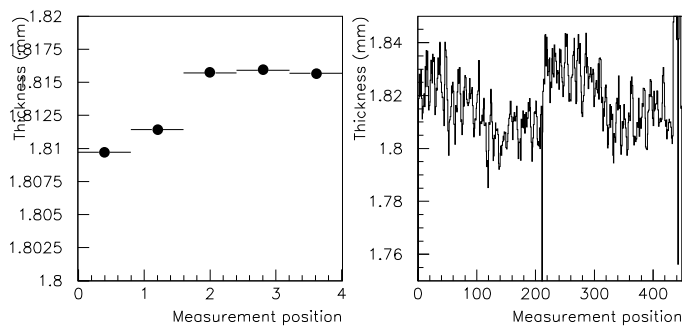


Figure 5: Profiles of the roll used for the 1.8 mm lead plates for the maquette in 1994, obtained with ultrasound measurements. (Left plot is the transverse profile, parallel to the roll axis, right plot is the longitudinal profile). Notice the similarity of the right plot with plots 15 to 18

Thickness (mm)	gauge dispersion (r.m.s.) (in μm)	gauge dispersion (max-min) (in μm)
1.13	4.3	13
1.53	5.4	18
1.7	7.1	24

Table 1: table1

the lowest result is of the order of 15 microns. This makes transverse profile measurements completely unreliable. In the case of the 2.2 mm thick plates, the results are not given because there was an enormous offset (by 200 microns) of one of the gauges clearly due to some mistake at the calibration stage. There is some hope to improve these results by using wide lead sheets taken from the lead production for module 0, as explained in section 3.2.2.

As a conclusion to this study of the calibration, the best way to use the data is to average over all seven gauges (since the transverse profiles are meaningless, due to the gauge intercalibration problems) to gain on the statistical error on the longitudinal profiles.

It is interesting to see whether the X-ray source and the photomultipliers are drifting or not. This issue is particularly important in the case of a mass production for the whole detector. This can be evaluated by comparing the raw count rates measured without lead, just before a slab of lead got into the roller, after different times. This operation has been done at least once for each thickness, typically at time intervals of one hour. For each thickness, the relative variation between two consecutive such measurements has been computed. The variations of the raw count rates are shown, for the different thicknesses, in figure 9. From these results, one can conclude that the system is drifting somewhat, at a level of the order of 0.2 to 0.3% per hour. This means that the system will have to be calibrated quite often during the production for the complete detector, with about two or three calibration runs per day.

4.2 Intrinsic resolution of the system

By “intrinsic resolution” we mean the ability of the system to separate different thickness values. This can be estimated as $1/\sqrt{2}$ the r.m.s. of the distribution of the thickness difference of two gauges measuring the same lead thickness. We can easily have this situation by comparing the thicknesses measured by two different detectors at the same time, assuming that the amount of lead in front of all the detectors is the same, and that the measurements done by two different gauges are statistically independent. Figure 6 shows the distribution of such r.m.s. differences for all possible gauge combinations, for one roll of 1.13 mm lead.

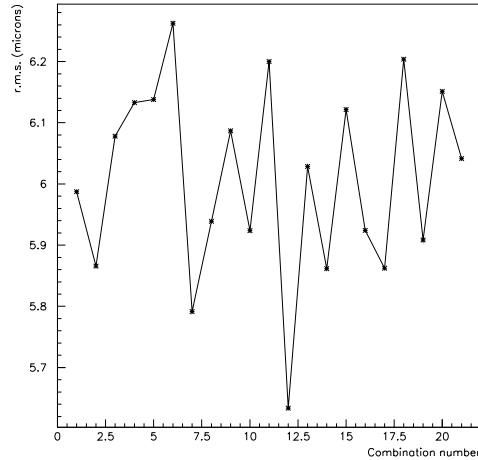


Figure 6: r.m.s. of the distributions of the difference of all possible combinations of gauge pairs, ordered in the way : combination 1=gauge 1-gauge 2, combination 2 = gauge 1-gauge 3,..., gauge 1-gauge 7, gauge 2-gauge 3...

From this figure we can see that the resolution of all the gauges are approximately equal : if all the gauges have the same intrinsic resolution, one expects the r.m.s. of all the distribution of thicknesses difference to be equal. This is only approximately the case here, due to the fact that different gauges may have different intrinsic resolutions, for various reasons, like photomultiplier efficiencies, light collection, and X-ray beam non-uniformities. From this information one can easily deduce the intrinsic resolution for each gauge, by searching for the resolution values that minimize the set of equations :

$$\delta_{i,j}^2 = \sigma_i^2 + \sigma_j^2$$

where $\delta_{i,j}$ is the r.m.s. of the distribution of the differences between gauge i and gauge j , and σ_i the intrinsic resolution of gauge i . Figure 10 gives the intrinsic resolutions obtained for each gauge with this method, for the 1.13 mm, 1.53, 1.7 mm mm lead sheets. Again, the 2.2 mm data has not been used here, because of the known problem with one gauge.

By comparing the resolutions for roll 8 and roll 9, which have the same thickness (1.7 mm), but differ by the counting times used (0.15 second per measurement for roll 8 and 0.3 seconds per measurement for roll 9)⁶, it can be inferred that the resolution is statistics dominated, since the average of the ratios of the resolutions for all seven gauge is 1.39, where $\sqrt{2}$ is expected if the resolution is of purely statistical origin. The shape of the plots giving

⁶The time used for the counting has been changed between roll 8 and 9 because it was estimated that the increasing lead thickness did not guarantee anymore a sufficient resolution on the thickness measurement.

the resolution as a function of gauge number are also well explained by a statistical origin of the resolution : the seven gauge are arranged in a fan-like pattern (figure 2), so that the central gauge (number 4) is perpendicular to the lead sheet, whereas the others see the lead with an angle increasing with the distance to the center of the lead sheet. The result of this disposition is that the counting rates are systematically lower for the gauges out of the center of the lead sheet, so that the resolution gets slightly worse when one goes from the center to the edges of the lead sheet.

4.3 Thickness distributions

Figures 11 to 14 show the thickness distributions, averaged over the seven detectors, for all the laminated rolls, and for the part of the lead that is within the tolerance interval. These figures show that the r.m.s. of the lead thickness distribution goes from 7 to 10 microns for the 1.13 mm lead, 8 to 10 microns for the 1.53 mm lead and 6 to 9 microns for the 1.70 mm lead. This could sound very good, assuming however that the thicknesses are distributed completely randomly. Unfortunately, this is absolutely not the case : Plots 15 to 18 show the thickness (averaged over all the seven gauges) as a function of measurement number (which is approximately proportional to the distance of the measurement point from the origin of the roll). One clearly notices several facts :

- At the very beginning and at the end of each roll, there is some length of roll which is often out of the tolerance intervals. This is due to the fact that it is impossible to set up a priori the roller to output lead with the nominal thickness with the precision we require. At the beginning of each roll, the worker has to look at the display provided by the X-ray system and to use this information to tune the roller. At the end of each roll, the roller brakes brutally while the lead sheet gets suddenly released, so the thickness of this part of the roll is unpredictable.
- The thickness varies slowly, staying almost constant, for quite significant amounts of time, and then jumps suddenly from time to time. This is due to the fact that the worker has to correct from time to time the tuning of his machine ; if he would not do that, the thickness would slowly drift out of the tolerance intervals. However, it takes several seconds before the effect of the corrections can be seen on the screen, because this is the order of magnitude of reaction time of the roller to corrections. Conceptually, the roller and the worker tuning it may be seen as a feedback system, where the retroaction is delayed with respect to the measurement of the difference between actual and control value. It is well known that such systems tend not to be very stable, and this is exactly what we observe here.

- If we look carefully at all the plots, we see that all of them exhibit short length but big amplitude (of the order of 20 microns) oscillations around the central value, which either stays almost constant, or jumps suddenly by 10 to 20 microns, as explained above. In the case of roll 3 (for the 1.13 mm lead), 5 (for the 1.53 mm lead) and 9 (for the 1.7 mm), the amplitude of the oscillation is so big that it dominates any over effect that may lead to thickness variations, since the r.m.s. of the thickness distributions of each of these rolls is the worst in its thickness category, and the oscillations are very noticeable by eye. These oscillations are most probably due to cylindricity defects in the rolls, or to roll axis eccentricity. We will study them with more detail in the next section.

Unfortunately, the typical length during which the thickness (not taking into account the high frequency oscillations) stays almost constant is non negligible compared to the size of one module. Roughly, one absorber corresponds to 24 consecutive measurements for the 1.13 and 1.53 lead plates. This means that converting the plates into absorbers in the same order as they were laminated, and mounting the absorbers in this order also will result in a calorimeter whose thickness will show jumps on scales in ϕ of the order of one module, which is the worst possible situation. To avoid this problem, it is possible to pair the plates in a way to keep the average thickness of the absorbers constant in all the calorimeters, absorbing the low frequency jumps into very high frequency jumps, on length scales smaller than the diameter of a shower, so these high frequency jumps will average naturally. This procedure will be described in details in a forthcoming note.

4.4 Study of the short-term oscillations

From the plots of figure 15 to 18, one can easily see that the oscillating pattern look quite different from roll to roll ; for example, rolls 3, 5 and 9 show oscillations with a quite high amplitude with comparison to the other rolls. The thickness distributions for these rolls also has the highest dispersion (see figure 11 to 14) Apparently, the oscillating pattern does not depend upon the thickness of lead being laminated, since the same kind of patterns can be seen whatever the thickness is.

To get a better idea of the structure of the oscillations, we performed a Fourier transform of the curves of figure 15 and 16. The data from the 1.7 mm lead and 2.2 mm lead have not been analysed this way, because there are less data points available for them, yielding less precise Fourier spectra. The results are shown in figures 19 and 20, which give the power spectra for the Fourier transform of the thickness data for each roll. From these figures, we got the following information :

- There are two families of spectra, and hence of oscillation modes :
 - The first family is characterized in the Fourier power spectrum by two close, broad peaks, corresponding to a periodicity of $\simeq 20$ measurements, or an approximate length of 0.85 absorber plate. This can be deduced from the fact that in each of the plots of figures 19 and 20, the Fourier transform has been performed on 1024 points, so that a peak at 50 corresponds to a periodicity of $1024/50 \simeq 20$ measurements. Of course, this number may change somewhat from roll to roll, due to the speed variations in the roller from roll to roll. The number we give here is only a visual estimate obtained from plots 19 and 20. To this family belong mainly rolls 3 and 5. In addition to the broad peaks, there is almost no energy in the remainder of the power spectrum.
 - The second family is characterized by one sharp peak at the approximate location of the two broad peaks of the previous family, plus some more or less noticeable harmonics up to very high frequencies (For example, the Fourier transform for roll 7 shows clear harmonics up to order 3)

In addition to these features, one often sees also very clear subharmonics (roll 2, 3, 4, 6, 7) for both families.

It is interesting to notice that the two families of spectra are quite easily distinguishable already from figure 15 to 18 : from these figures, one can see that roll 3 and 5 are very different from the other ones. These differences are also visible in figure 19 and 20.

It is impossible to identify the specific reasons why a given pattern of oscillation is being observed for one given roll. The only clear point that can be made is that the frequency that is observed on all rolls corresponds to roughly 20 measurement points, or 145 cm. Not very surprisingly, this length can be related to the diameter of the rolls, since the rolls have a diameter of the order of 45 cm, which correspond in perimeter to about 145 cm. Another fact that is very striking is that the features are unique to each roll ; one does not observe any transition from one oscillation mode to another one during the rolling of one block of lead, even during the initial phase during which the working conditions are not yet stable and the worker still makes adjustments. This indicates that the oscillatory pattern is determined largely by the initial state of the roller and does not depend much upon further adjustments.

A possible explanation of the difference of the oscillating pattern from roll to roll may be the fact that the rolls are not perfect cylinders but may exhibit some defects ; different patterns may arise from different relative phases of the defect : when the rolling starts, the phase is random, but during the rolling, this phase cannot change, explaining the stability of the pattern. A

variation of this explanation is that when the rolling starts, the axes of the two cylinders lock themselves (due to the enormous constraints exerted on them) in any random position in their cages. In a given position, these axes have some parallelism and eccentricity that stay stable until the end of the roll, where the axes get released and may choose a different position for the next roll.

Another possible explanation of the pattern constancy would have been the coil shape : if the coil is not a perfect cylinder (and it was possible visually to ascertain that most coils were quite far from perfect cylinders) it will pull periodically on the lead and change the thickness. However, if this explanation were true, the period of the oscillations would have changed during the rolling of one roll. This is not what is being observed.

The oscillating pattern may be a very annoying fact in building the calorimeter, as its period is about, but not exactly the same, as the length of one absorber. This means that there is some risk that there appears a modulation of the lead thickness as function of ϕ in the calorimeter, due to the interference between the roller period and the absorber period, if the plates are taken in the order they were laminated. This question will be studied in detail in a forthcoming note.

5 Future prospects

It is planned to laminate the lead for the whole calorimeter during November 1997. In view of the results presented here, one may ask whether it is possible to do better, from the measurement point of view and from the production point of view.

During October 1996, eleven rolls, representing approximately 5 tons of lead, have been laminated for the modules 0. This represents 6 hours of work at the factory (plus one and a half setup day) and has provided us with quite good information about the longitudinal profile of the lead we will very likely have for the whole detector. It is interesting to note that the amount of lead processed corresponds approximately to 5% of the amount of lead needed for the whole calorimeters, so we have a good idea now in terms of manpower and time needed for the full production. From the data for module 0, we can see that the r.m.s. of the thickness measurement distributions is of the order of 7 to 10 microns, depending upon the roll being considered. It has also been shown that the thickness distribution is not random at all, being characterized by several patterns that have been analyzed in detail. All the laminated lead is now in the process of offline measurement by ultrasound, whose results will be presented very soon, and compared to the present results.

As far as the measurement system is concerned, the weaknesses are identified. The biggest weakness is clearly the calibration. On this topic, the problems are identified and characterized, solutions are considered and will be implemented, as has been explained at several places throughout this note. The intrinsic resolution of the system itself is considered to be satisfactory, and could anyway not be increased much without crossing the border of admissible radiation dose emitted by the system.

Concerning the roller itself, very few things can actually be done : it must be clear that this system is an industrial system, where changing any parameter or operating procedure with respect to what people are used to do is not welcome. This means that we will have to live with the oscillatory patterns. We may understand them somewhat better than what we do for the time being, as we will have more statistics, but there is no real way to get rid of them.

Another point that could be considered, given the good quality of the lead, would be to tighten the tolerance interval. However, the impression we could get from the attitude of the workers was that they are already very close to the limit of what they can produce. Furthermore, if we look carefully how the tolerance interval is “eaten up” by the various variations we have noticed, we see that if the tolerance interval has a width of 65 microns, some 20 to 25 microns are eaten by the oscillations, some other 10 microns are taken out by the miscalibration problems⁷, leaving only 30 to 35 microns variation possible for the worker itself, which is much smaller than the interval the factory accepts to guarantee, i.e. 65 microns. This means that it will be hard to improve things much with respect to what we have now.

6 Acknowledgements

Our thanks go to Bruno Mansoulie, Patrick Perrin, Jean-Pierre Taguet from DAPNIA-CEA-Saclay, Mr Chambellan, Reverchon, Pascal and Rattoni from DAMRI-CEA-Saclay for their help during the design phase, the setup of the system and the data-taking. We would also like to thank Luis Labarga for his help during the data-taking, the people from the Autonoma University of Madrid in general and also Aurore Savoy-Navarro for their comments.

References

- [1] Performance of a large scale prototype of the ATLAS electromagnetic

⁷Since any of the gauge outside of the tolerance interval triggers the rejection of the lead, miscalibration actually reduces the effective tolerance interval !

calorimeter, RD3 collaboration, NIM 364 290 (october 1995)

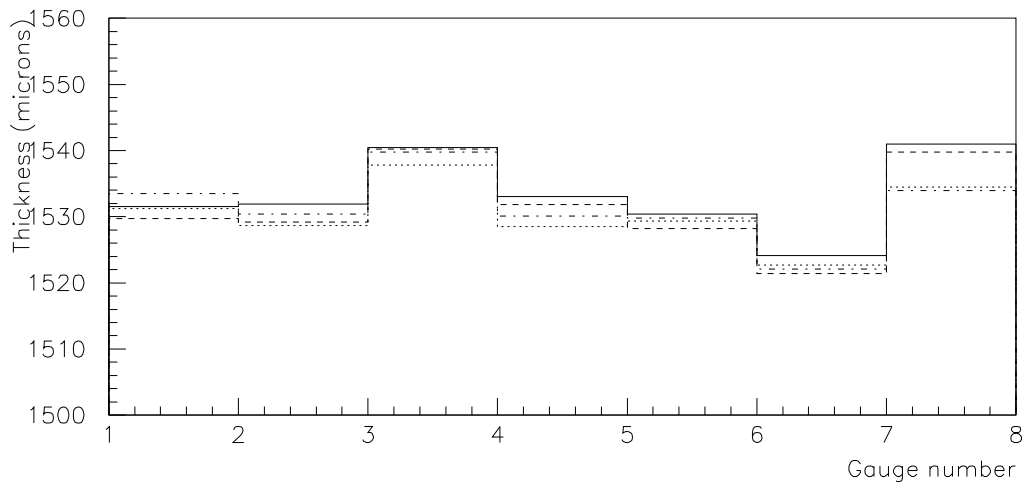
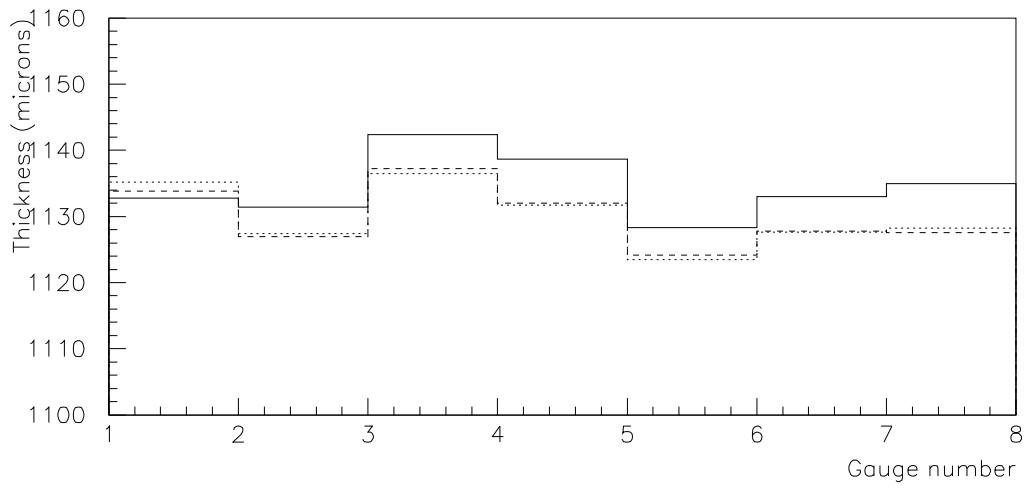


Figure 7: Average transverse profiles, according to X-ray measurements, for 1.13 mm rolls (above) and 1.53 mm rolls (below)

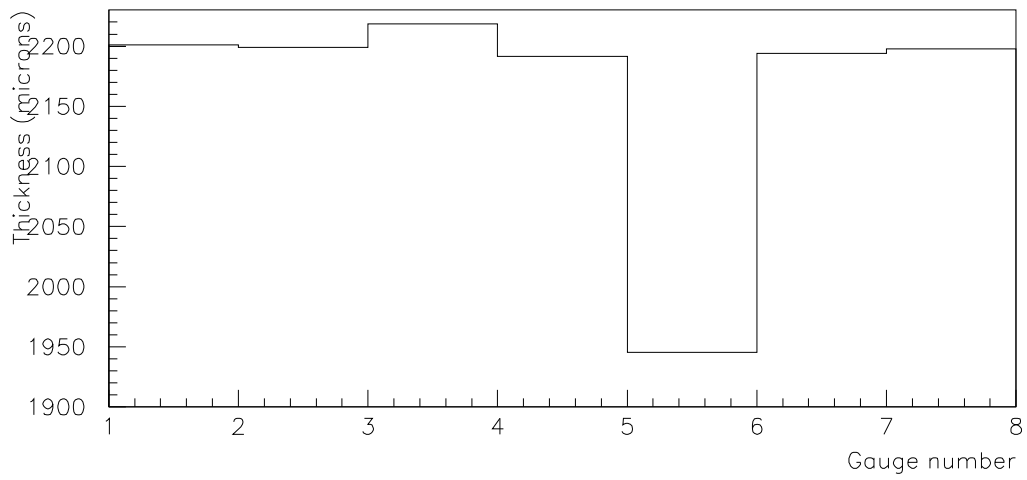
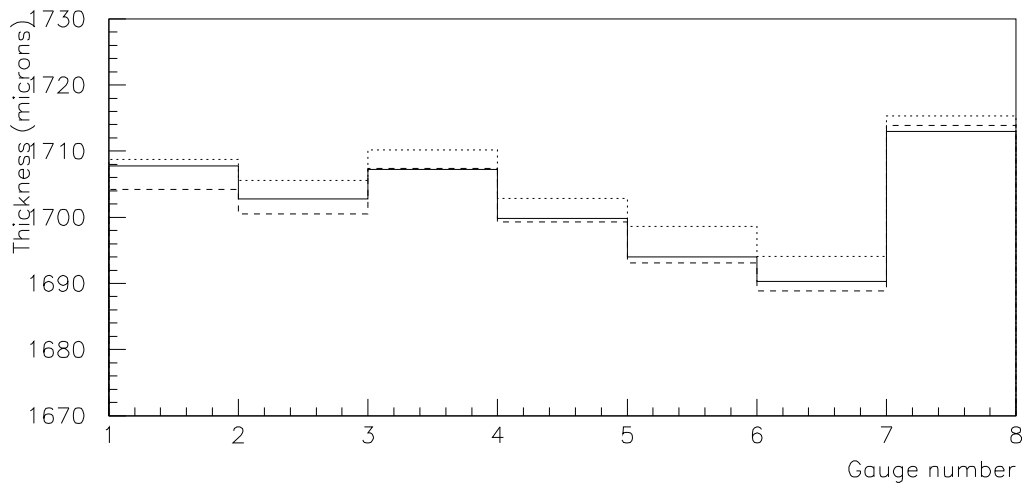


Figure 8: Average transverse profiles, according to X-ray measurements, for 1.70 mm rolls (above) and the 2.2 mm roll (below). Notice the mistake in the calibration for the 2.2 mm roll (gauge 5)

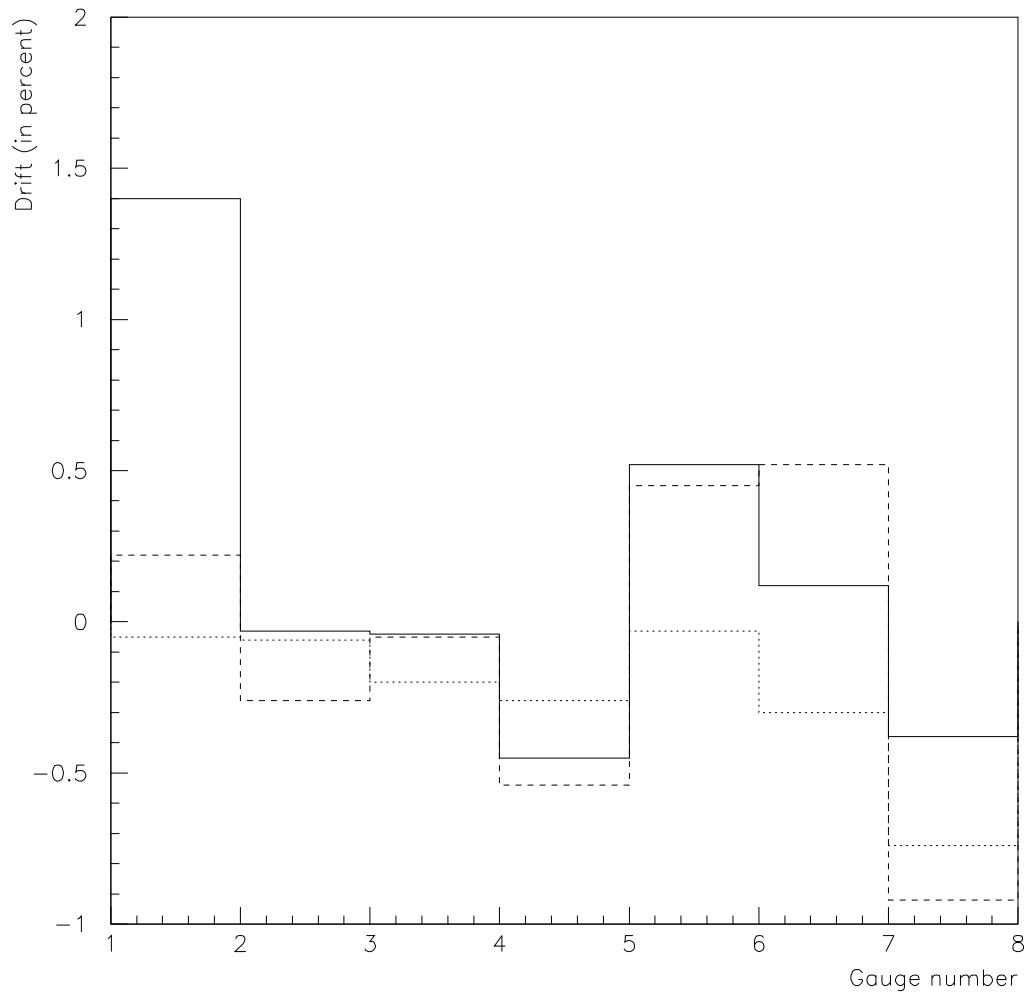


Figure 9: For each thickness, relative variation of the raw count rates, as a function of gauge number, when no lead is engaged in the roller. The 2.2 mm data is not usable because there was only one roll of this kind. Solid line is 1.13 mm lead, dashed is 1.53 mm, dotted is 1.7 mm. The raw data used to obtain each curve have been taken separated by about half an hour each.

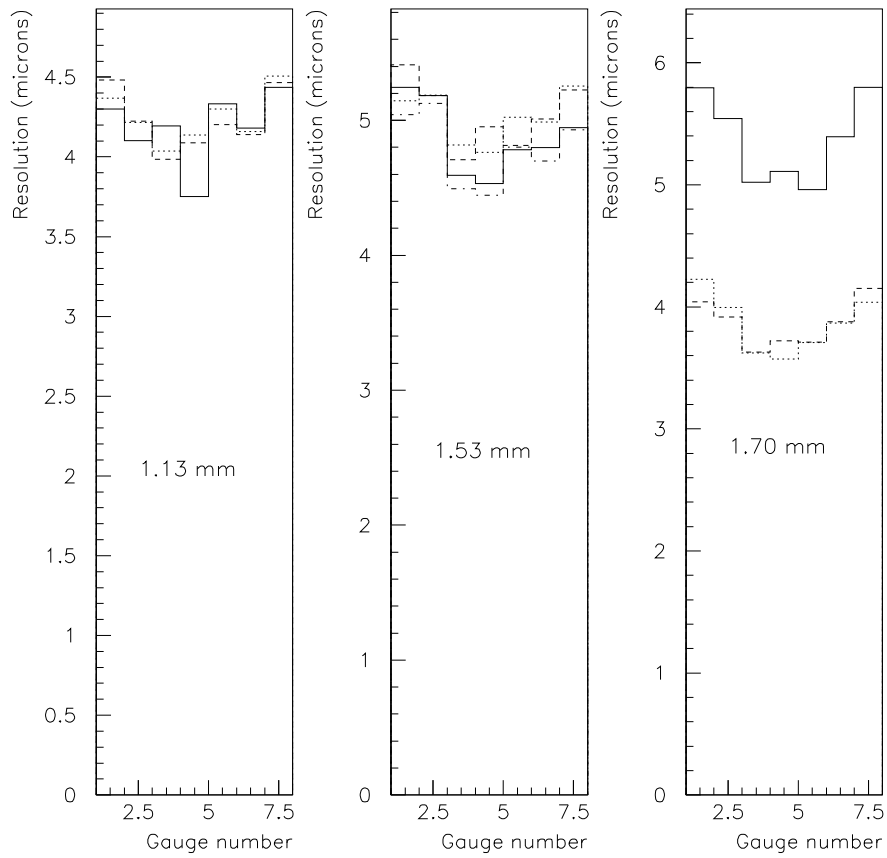


Figure 10: Intrinsic resolutions of the seven gauges, computed roll by roll and thickness by thickness. The difference among rolls for the 1.70 mm lead is due to the fact that the counting time used has been increased from 0.15 second per measurement to 0.3 second, to increase the resolution.

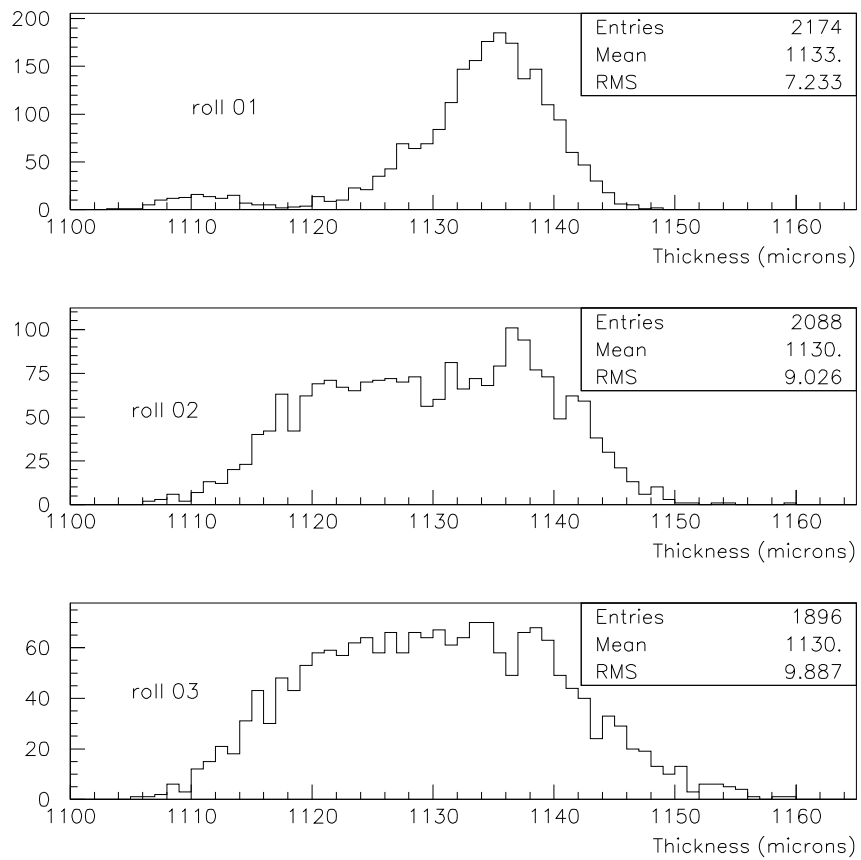


Figure 11: Distribution of the average thickness of the lead, averaged over all the seven gauges, for each roll of 1.13 mm lead.

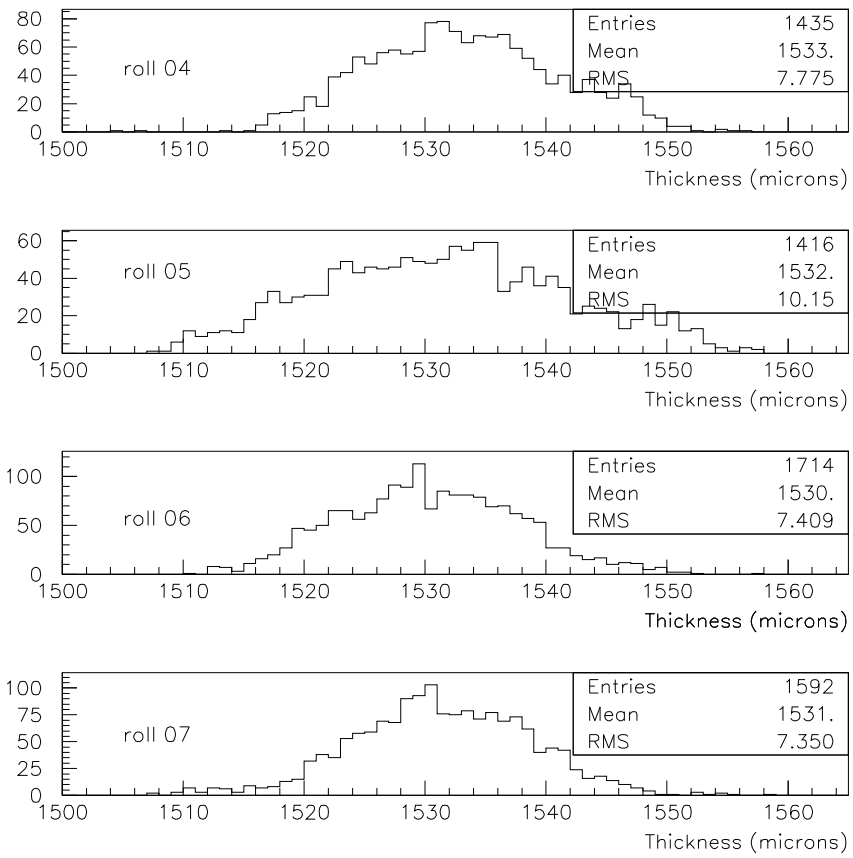


Figure 12: Distribution of the average thickness of the lead, averaged over all the seven gauges, for each roll of 1.53 mm lead.

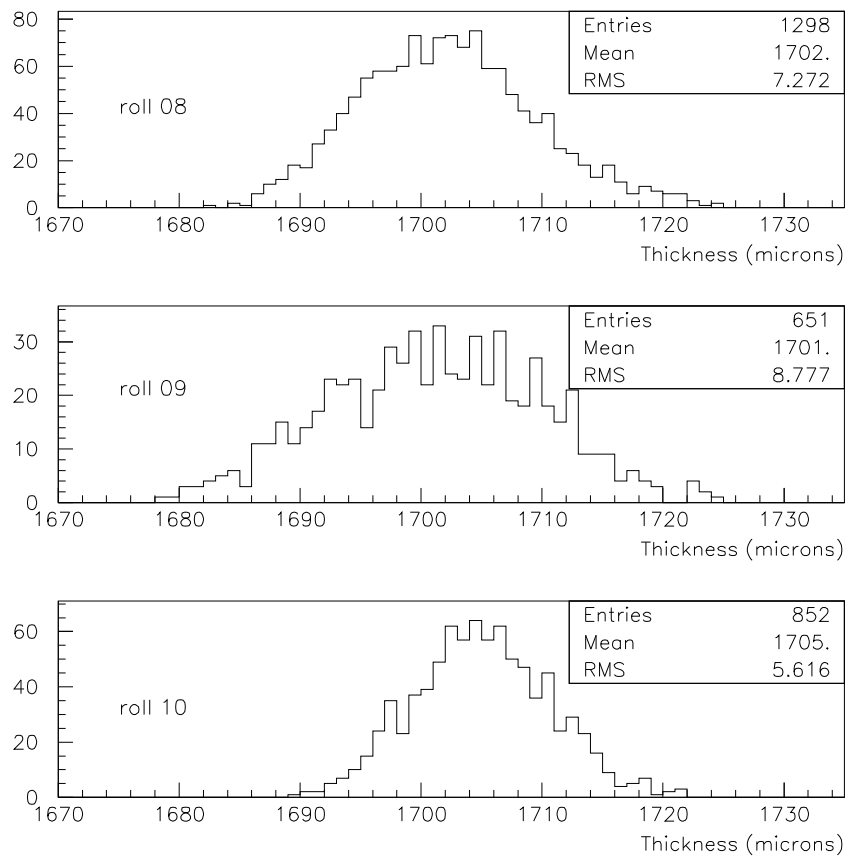


Figure 13: Distribution of the average thickness of the lead, averaged over all the seven gauges, for each roll of 1.70 mm lead.

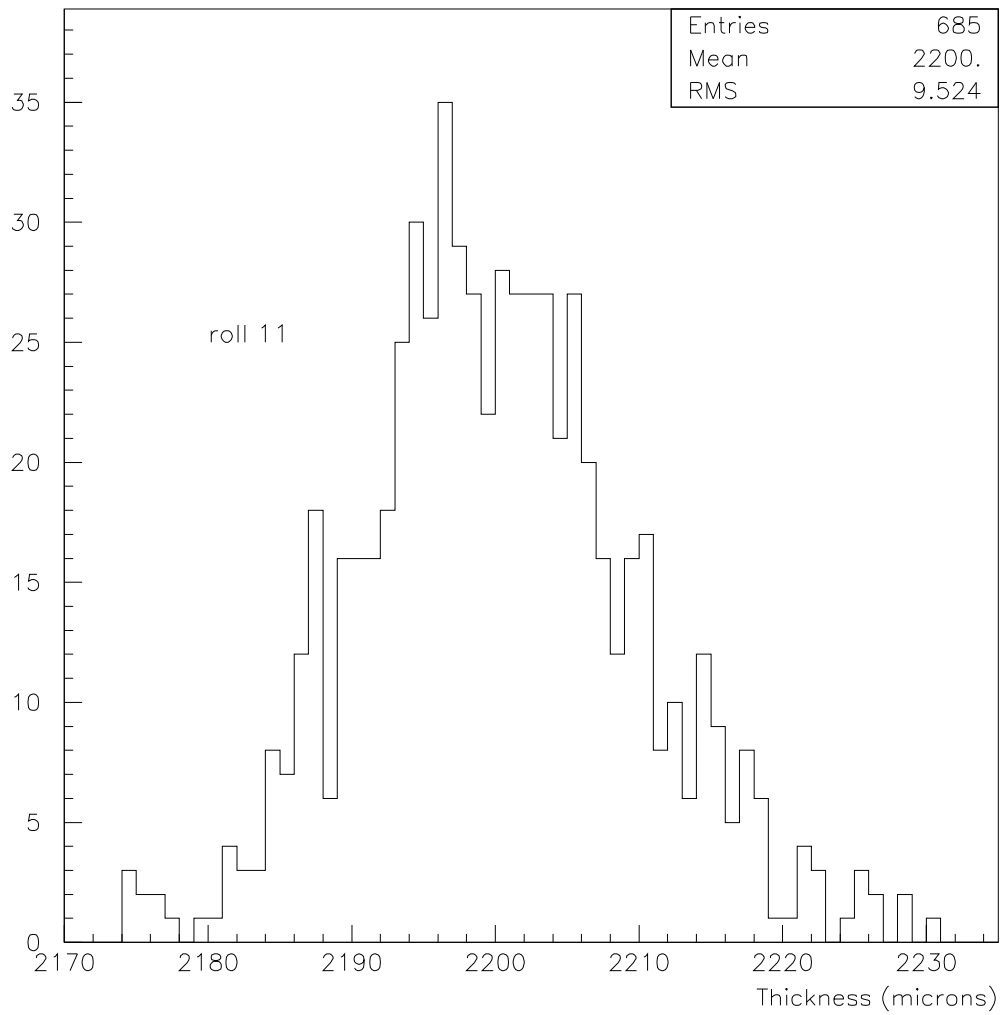


Figure 14: Distribution of the average thickness of the lead, averaged over all the seven gauges, for the roll of 2.20 mm lead.

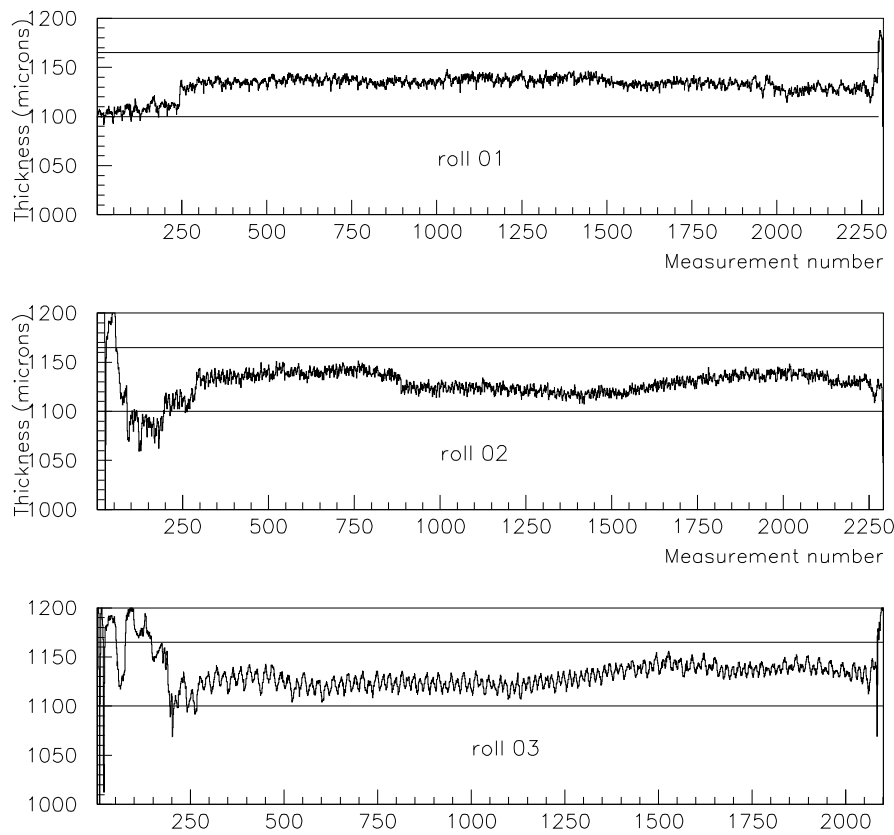


Figure 15: Longitudinal profiles of the 1.13 mm lead rolls. The horizontal lines give the limits of the tolerance interval.

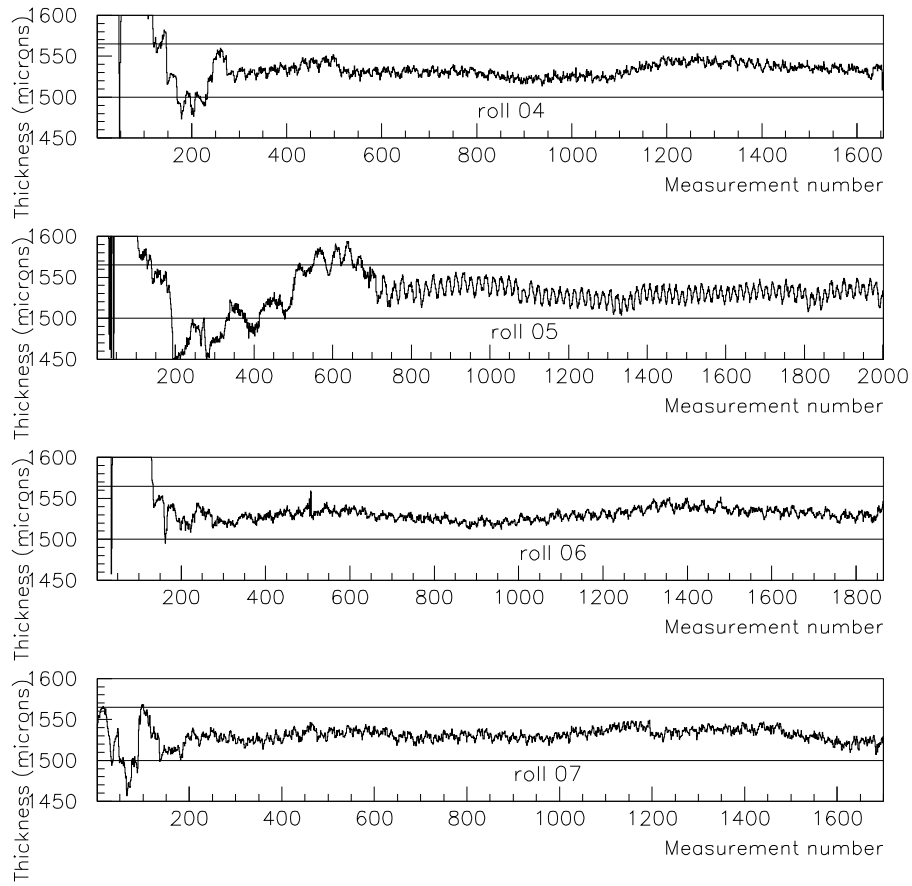


Figure 16: Longitudinal profiles of the 1.53 mm lead rolls. The horizontal lines give the limits of the tolerance interval.

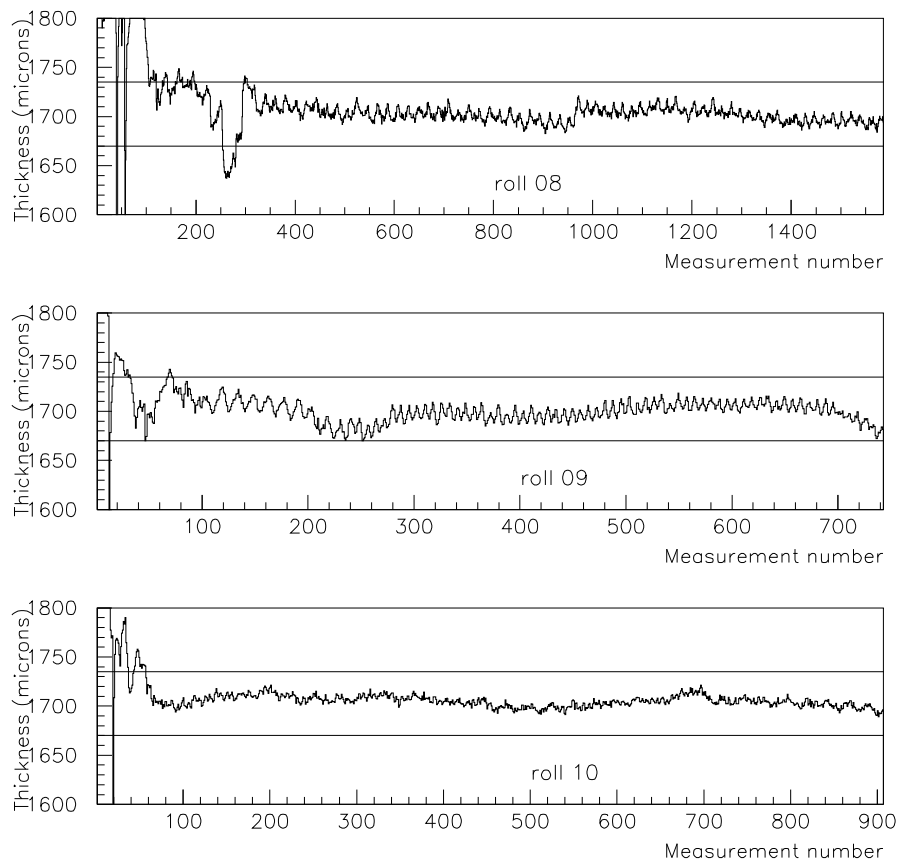


Figure 17: Longitudinal profiles of the 1.70 mm lead rolls. The horizontal lines give the limits of the tolerance interval.

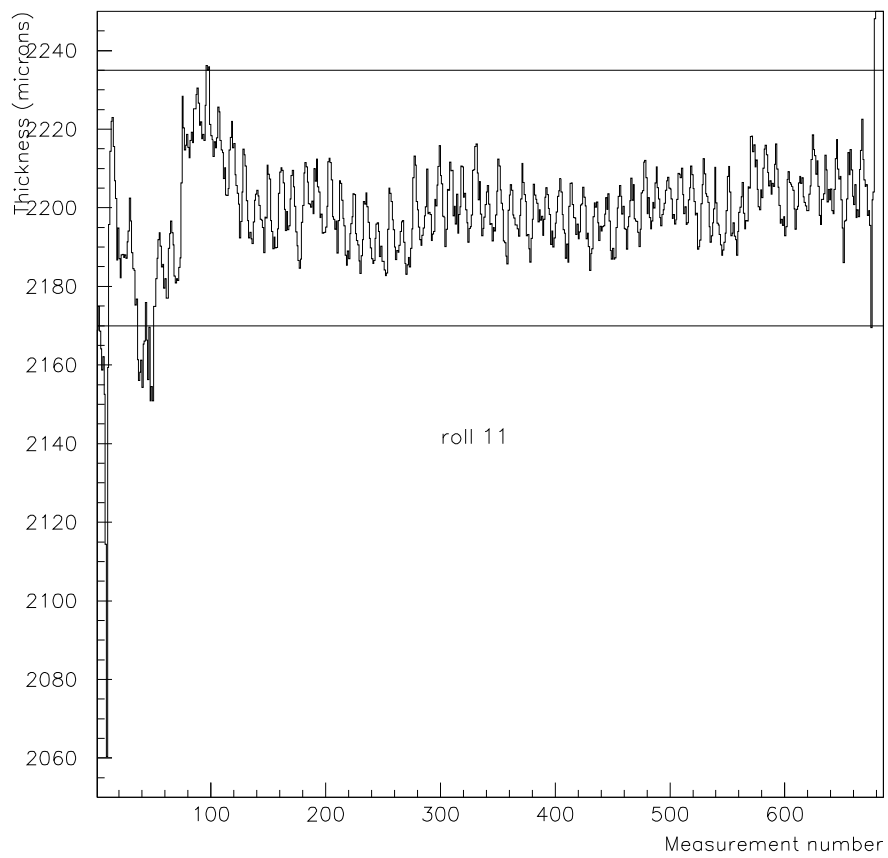


Figure 18: Longitudinal profile of the 2.20 mm lead roll. The horizontal lines give the limits of the tolerance interval.

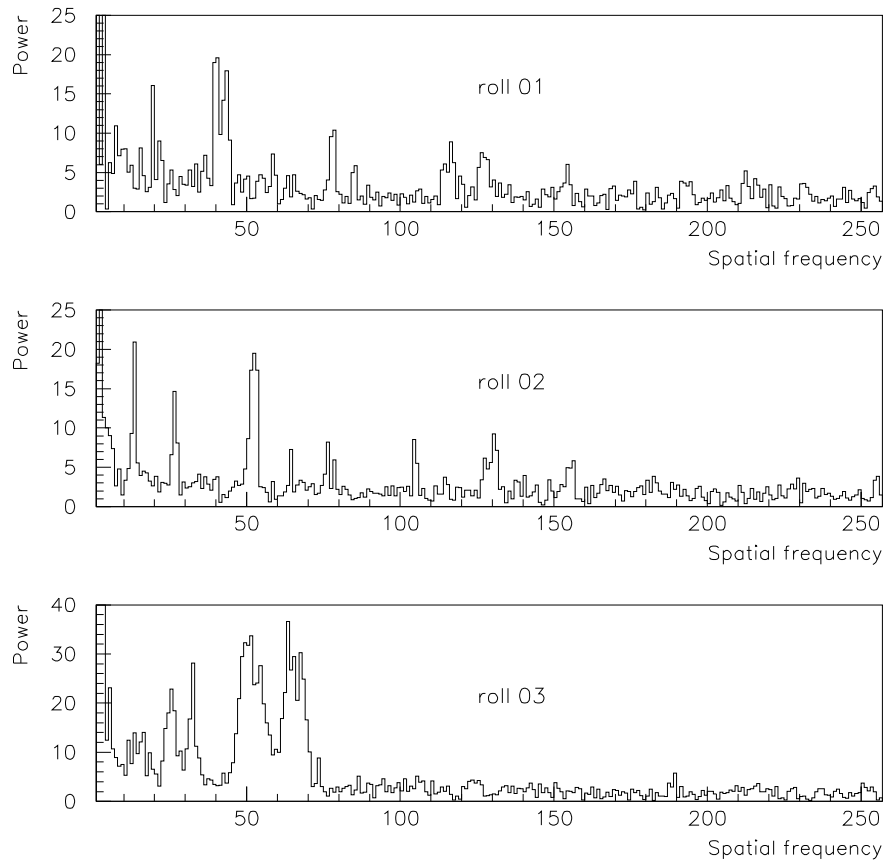


Figure 19: Power spectrum of the thickness measurements of the 1.13 mm lead rolls. 1 unit in abscissa corresponds roughly to 7 cm^{-1} .

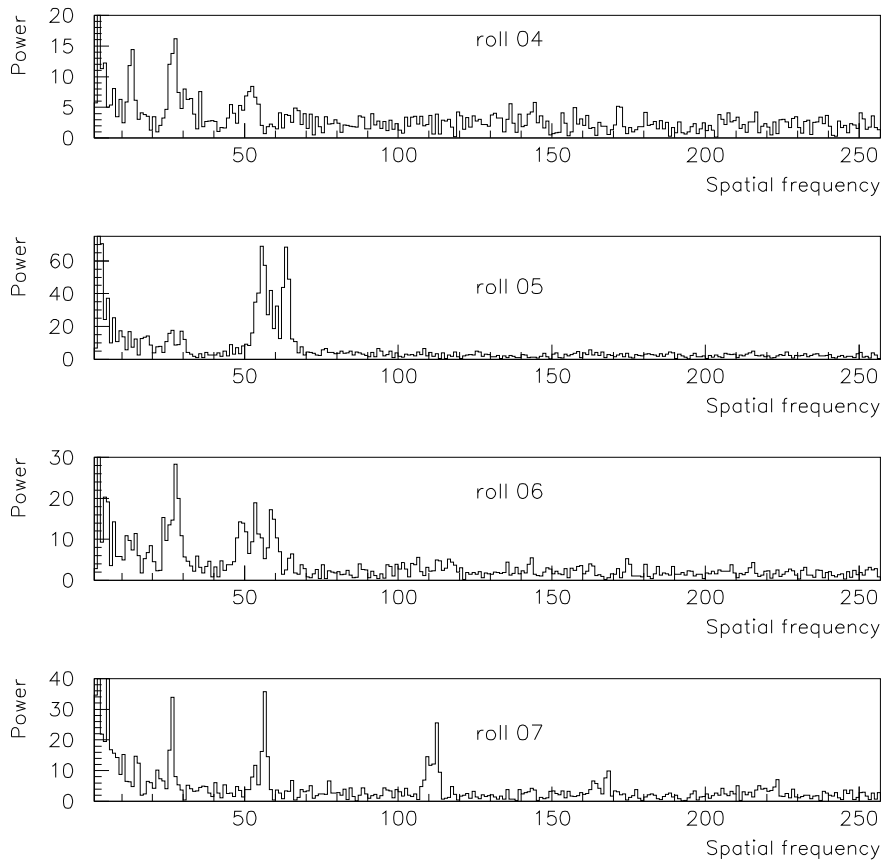


Figure 20: Power spectrum of the thickness measurements of the 1.53 mm lead rolls. 1 unit in abscissa corresponds roughly to 7 cm^{-1} .