AN ACCURATE REFERENCE SYSTEM IN STACKS OF NUCLEAR EMULSION

Giorgio Romano
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ABSTRACT

A method is described which defines an accurate reference system in stacks of nuclear emulsions, as required by present-day hybrid experiments. It is based on a new reference grid and a versatile X-ray marking set-up; both devices have been developed and are in use at CERN.

The 240 mm × 120 mm grid is drawn with lines less than 20 μm wide. It has a basic 1 mm² mesh with 200 micron subdivisions. Coordinates are displayed in each square millimetre by sets of dots in binary code.

The X-ray set-up includes a high-accuracy collimator which makes it possible to obtain very sharp lines down to 15 μm wide over a length of 100 mm. Different marking schemes can easily be implemented by means of long-range micrometric translating and rotating stages.
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1. INTRODUCTION

The need to follow tracks which pass from one layer of emulsion to the next in a stack makes it essential to have a precise reference system, so that corresponding points in different layers may be found. In the past this need was satisfied by using either of the following methods: i) by machining two perpendicular edges of the stack or stacking the layers on dowels passing through holes of the same diameter, and by printing on one surface of each layer a reference grid aligned in the same way; ii) by exposing the sides of the stack to X-rays passing through a narrow slit perpendicular to the plane of the layers; the edges of the layers were thus marked with thin lines, allowing their accurate alignment [1].

The trend in the last decade has been towards large hybrid emulsion experiments, where increasingly precise reference systems are necessary not only to locate points within the stack itself but also absolutely, i.e. with respect to the rest of the hybrid system, so that incoming and exiting particle trajectories measured by external apparatuses can be used to locate an interaction vertex in the emulsion. Very often these hybrid experiments are designed to detect extremely rare events, as in the search for heavy flavours, for which typical on-line trigger rates could range between $10^{-4}$ and $10^{-3}$ per interaction, and subsequent off-line selection could reduce this figure by one or two orders of magnitude. In these conditions, and in order to keep the volume of the exposed emulsion within practical limits, the density of incident particles must be as high as possible and the uncertainty volume wherein a given interaction is to be sought must be as low as possible.

During the last 10 years there has been much progress in the domains of vertex detectors and beam hodoscopes demanding a large variety of equipment, including spark chambers, multiwire proportional chambers (MWPCs), bubble chambers, etc. In particular, silicon microstrip detectors, which are now commonly used, allow accuracies down to about 10 µm to be reached and are particularly suited to high incident-particle fluxes.

Emulsions, being continuously sensitive, can of course accept only a finite density of incident particles, limited by the average spacing between tracks and by the blackening produced by the incident beam tracks (if charged) and by primary and secondary interactions. With emulsions sensitive to minimum ionization, this limit is normally set between $10^3$ and $10^4$ incident particles per square millimetre. Such a flux produces, on the average, 2.5 to 25 interactions per cubic millimetre of emulsion. It is seen then that whereas earlier hybrid experiments succeeded in locating events within a fiducial volume of the order of 1 cm$^3$, the accuracy now required is a fraction of a cubic millimetre, which implies a very good link between emulsion stacks and external apparatuses.

It will be shown below how a reference system based on a new grid and X-ray marks meets the present requirements adequately. Figure 1 shows schematically the set-up of one of the runs of experiment WA75, which took place at CERN in 1983 and 1984 [2], and where the following technique was widely applied. The emulsion stacks, which were mounted on a movable stage, incorporated thin vertical emulsions poured on thin glass plates and fixed to the bases. In the same way as for the normal exposure, the stage was moved to preset positions where these plates were given a relatively lengthy exposure to the beam in order to form easily visible beam 'spots', indicating the position of the stage with respect to the beam axis.

Immediately before or after these exposures, whilst the stack was still being assembled but not yet mounted on the stage, X-ray fiducial lines were marked at two different angles across the four edges of the stack, thus providing a reference system which not only linked the emulsion layers of the stack to each other, but also linked them to the glass plates bearing the beam spots and hence to the external apparatuses. An accurate grid was also printed on the bottom surface of each layer before processing. All the measurements in the emulsion were carried out with respect to this grid, which in turn was linked to the other reference systems.
2. THE GRID

In order to provide a good absolute reference system as well as a convenient and accurate local reference system for scanning and measurement, a new grid was made [3] with the following characteristics:
- overall dimensions 240 mm × 120 mm;
- elementary squares of 1 mm²;
- inner segments within each elementary square every 200 μm (Figs. 2 and 3);
- x and y coordinates displayed in binary code (sequences of 8 and 7 dots, respectively);
- line width and dot diameter around 20 μm;
- high precision of all nominal dimensions.

This grid, which is particularly well suited for use with either manual or semi-automatic measurement devices, also has the advantage of a low and constant average blackening (of about 9%) over the area of any field of view under usual magnifications.

In order to reach the required accuracy, a subset of (30 × 30) squares was drawn on a scale 25:1 (i.e. a mesh of 2.5 cm²) by means of a computer-aided drawing table, and recorded on tape. It was then printed on film by means of a photoplotter on a scale 1:2.5 (i.e. a mesh of 1 cm²). This was further reduced photographically and reproduced eight times on the same film by means of a high-precision mechanical device. One thus gets a grid of (120 × 60) squares, i.e. a quarter of the whole grid. (For technical reasons, this was the maximum size which could be handled at this stage.) The corresponding eight sets of dots displaying the binary code were drawn and printed following the same procedure. They were then superimposed photographically on the above grid. The other three quarters of the grid were produced following the same procedure and the four pieces were assembled manually in order to obtain the final negative*).

In order to check the stability of copies, several pieces of the first quarter of the grid (0 ≤ x ≤ 120; 0 ≤ y ≤ 60) were reproduced on photographic glass plates. Accurate measurements showed that over long distances the nominal dimensions are precise to better than 1 μm/mm, that some of the junctions between the (30 × 30) mm² pieces are shifted by 10 to 20 μm, but that the parallelism of the lines is maintained at the level of 10 μm/100 mm or better. According to these and other results (for instance, see Section 4) it is believed that this grid is accurate enough to be used with its nominal characteristics for most purposes, and needs to be calibrated only for extremely high accuracy measurements. Of course, in this case, other factors must be taken into account, such as thermal expansion, etc.

3. RESPONSE OF THE EMULSIONS TO X-RAYS

In view of the requirements quoted in Section 1, the use of X-ray marking seemed most appropriate since line widths of some 10 to 20 μm and penetration depths of a few millimetres could easily be achieved.

Figure 4a shows the average penetration length λ in emulsion as a function of the X-ray energy [4]. It turns out that in the interesting energy range (50 to 150 keV) the photoelectric effect dominates and the absorption is mostly due to the electrons of the K shell of the silver contained in the emulsion, whose binding energy is Iₐₖ = 30 keV. The visible line is therefore built up by the tracks of the ejected electrons (see Fig. 14), most of them with energy Eₑ = Eₑ - Iₐₖ. Since the range of the electrons increases quickly with their energy (Fig. 4b), the use of harder X-rays is likely to produce broader lines, so that a compromise must be found. As an example, X-rays with an energy of 60 and 100 keV, whose mean penetration length is 0.8 and 3.3 mm, would give rise to electrons with an average range of 6 and 25 μm, respectively.

*) The photographic reduction and reproduction was done by Photo-Helio Brunner in Geneva.
Evidently, in order to obtain narrow lines, the X-ray beam must be collimated, with a consequent drastic decrease in intensity, and the choice of a tube instead of a radioactive source seems obligatory. On the other hand, an X-ray tube produces a spectrum, rather than a monoenergetic line, which ends at the energy corresponding to the applied voltage and has peaks characteristic of the element used as anode (at about 60 and 70 keV for W, the most commonly used). However, the low-energy part can be removed by means of low Z absorbers: in the example [5] shown in Fig. 4c a few millimetres of Al already eliminated that part of the spectrum with energy lower than 20 keV, otherwise the most abundant, while leaving almost unchanged the part exceeding 60 keV. The use of heavier absorbers allows a further hardening of the spectrum, and therefore a more uniform intensity distribution of the line with the depth, but at the cost of cutting intensity also in the useful energy range. Figures 5 and 6 show the effects of different thicknesses of Fe and Pb absorber on the 100 kV spectrum of Fig. 4c.

It is thus seen that a tube operating in the range of 50 to 150 kV, with the possibility of varying the exposure (usually the exposure time) and of inserting absorbers, would be versatile enough in order to choose the best conditions for most of the usual applications.

4. COLLIMATOR

Among several possibilities, two prototype collimators were built and tested: one consisting of two calibrated cylinders held parallel and in contact, another made up of two bars with flat surfaces, spaced by means of two strips of thin mylar sheet. The first one, used in the past in emulsion experiments [6], but for somewhat different purposes, should have as a response to a parallel incident beam (Fig. 7a) an intensity distribution

$$\frac{dI}{dx} = I_0 \exp \left[ -\sqrt{(8xR)/\lambda} \right],$$

which, although acceptable for suitable values of R and \( \lambda \), shows a long tail. In addition, the width of the line depends on the X-ray energy and on the material chosen for building the collimator. Moreover, since the incident beam usually has a sizeable divergence (extended source at a finite distance) the distribution becomes

$$\frac{dI}{dx} = I_0 \exp \left( -4xR/\lambda L_1 \right),$$

which is much less favourable. Figure 7b shows the intensity distribution that could be obtained with an X-ray tube with a small focal spot size in the configuration shown in Section 5. A test made with two ground and polished steel cylinders, 12 mm in diameter and 60 mm in length, confirmed these predictions and therefore no further tests were pursued in this direction.

Immediately after the first tests, the second type of collimator proved to be more attractive, as it was possible to produce sharp and thin lines very easily. For an ideal pair of parallelepipeds, spaced by a distance d and in the case of a parallel beam, the intensity distribution would be constant in correspondence with the window and zero elsewhere; in the case of an extended source close enough to the collimator, the distribution would become trapezoidal, i.e. (Figs. 8a and b) for \( d << \ell \ell/2L_2 \)

$$\frac{dI}{dx} = I_0 \quad \text{for } |x| \leq d/2$$
$$\frac{dI}{dx} = I_0 \left[ 1 + \ell/L_1 \left( \frac{1}{2} - x/d \right) \right] \quad \text{for } d/2 \leq |x| < d(\ell/2 + L_1/\ell)$$
$$\frac{dI}{dx} = 0 \quad \text{for } |x| \geq d(\ell/2 + L_1/\ell)$$

where \( I_0 = d/(\ell + L_1) \).
These results are roughly independent of the energy and of the material used; of course only a thick collimator ($\ell \gg \lambda$) would provide enough shielding outside the window. It is seen that in order to have thin and sharp lines it is necessary to bring the emulsion as close as possible to the collimator (Figs. 8b and c). In fact, ranging from $L_1 = 0$ to $L_1 = \ell$ the line width would increase from d to 3d and the central intensity $I_0$ would decrease by a factor of 2.

In the light of these calculations and the results of the tests, it was decided to build a collimator of this kind with a useful length of 100 mm. Technical considerations led to the choice of super high-speed steel bars with a thickness of 25 mm. They have been squared and ground exactly at CERN; suitable holes for fixing were also made by means of electro-erosion. The spacing d between the bars was achieved by inserting thin mylar sheets close to the extremities of the bars themselves. A careful check of the straightness of the line was performed by exposing a nuclear emulsion, 100 $\mu$m thick poured on glass, with the surface perpendicular to the X-ray beam at a distance of 5 mm from the collimator, which was set with 8 $\mu$m spacing. The line width turned out to be about 11 $\mu$m, and coordinate measurements of the centre of the line performed every 10 mm on a microscope equipped with step motors (1 step = 1 $\mu$m) showed a spread of the points around the fitted straight line of about 1 $\mu$m on two independent sets carried out in opposite directions of the microscope stage (Fig. 9a).

Another series of coordinate measurements was performed on the grid, which was contact-printed on the surface of the plate. The width of the grid lines turned out to be $\sim 17$ $\mu$m after processing. In this new series the distance between the X-ray line and the closest grid line was measured each millimetre (sensibility $\pm 1 \mu$m). Owing to a misalignment, the lines were not parallel and the X-ray line crossed four grids over the whole length; for clarity, Fig. 9b shows the differences between one measurement and the previous one. It is seen that the spread is consistent with the sensitivity ($\sigma = 1.9 \mu$m/mm; each point involves four measurements) and no appreciable irregularity can be detected on this scale. Possible deviations from a straight line would be at the level of radii of curvature in excess of 100 m, for both the collimator and the grid lines.

Further tests performed by varying the distance between emulsion and collimator showed a widening of the lines greater than that predicted by the analytical relations, using the nominal values of d and $\ell$. This discrepancy (Fig. 8c) is most probably due to the fact that, in grinding the steel, a slight curvature of the edges of the bars was unavoidable. The data are consistent with a lack of flatness of the order of 1 to 2 $\mu$m over the last few millimetres close to the edges, which would result in an apparent shortening of the collimator thickness.

In the following, a spacing of 12 $\mu$m will be considered as standard; this choice yields sharp lines about 20 $\mu$m wide at a distance of 5 mm, with a reasonable exposure time.

5. X-RAY SET-UP; ALIGNMENT AND CALIBRATION

Figure 10 shows the present set-up, which is more versatile than needed for a single experiment, though it does not cope with all possible needs. Up to now it has been used mainly to mark stacks as described in Section 1, but other kinds of exposures were also performed, and they needed only minor modifications. The tube was set at a distance of 50 cm from the collimator and has the following characteristics:

<table>
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<th>Characteristic</th>
<th>Value</th>
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<tr>
<td>Voltage and current</td>
<td>40 to 160 kV at 5 mA</td>
</tr>
<tr>
<td>Focal spot size</td>
<td>1.5 mm $\times$ 1.5 mm</td>
</tr>
<tr>
<td>Beam angle</td>
<td>50°</td>
</tr>
<tr>
<td>Inner filtration</td>
<td>3 mm Al</td>
</tr>
<tr>
<td>Timer</td>
<td>up to 6 min</td>
</tr>
<tr>
<td>Rise time to preselected kV</td>
<td>$\sim$ 9 s</td>
</tr>
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It proved adequate for the requirements, stable, and easy to handle.
The whole tube, apart from the beam window, is shielded by means of 5 mm Pb and the unwanted part of the beam with 30 mm Pb. The collimator described in Section 4 is mounted on a stage (BG 120 – see Fig. 10) that allows rotations up to \( \pm 45^\circ \) around a horizontal axis. The collimator is fixed on one side in order to enable an emulsion stack to be placed close to it. On the same stage lead plates are mounted in such a way as to distribute the load evenly, while leaving a window 150 \( \mu m \) wide in correspondence with the collimator.

The tube and shielding can be displaced by means of screws for fine adjustments in a vertical plane. The amount of shielding is much more than required by the CERN safety rules, and was carefully chosen to yield only a negligible background in the irradiated emulsions, even for very long exposures.

A pedestal, where the stack can be mounted, is fixed onto a stage (RT 120 – see Fig. 10), which is able to rotate by 360° around the vertical axis, and both are mounted on a system of two stages (MT 160 – see fig. 10) equipped with stepping motors that allow independent linear displacements at 90° to each other.

The sensitivity of the stages is \((1/1000)^\circ\) for the rotating elements, 10 \( \mu m \) and 1 \( \mu m \) for the linear ones (along and across the beam, as defined by the collimator, respectively). In spite of the high accuracy of every single element of the whole set-up, the overall accuracy is about ten times worse, but some improvement has been achieved by carefully calibrating only discrete chosen positions, in particular those most commonly used (see later). The rotating stages are manually set and their position can be read by encoders and displayed. The motorized stages for the linear movements are driven at a velocity of 3.8 mm/s (10 \( \mu m \) step) and 0.27 mm/s (1 \( \mu m \) step), and their position is displayed as a number of steps.

Owing to the dimensions of the beam source, it is important to centre it with respect to the collimator to better than 0.5 mm, and indeed any misalignment would result in a loss of intensity and would give rise to asymmetrical lines, as shown in Figs. 11 and 12. The nominal values of 1.5 mm \( \times \) 1.5 mm probably refer to the area where most of the intensity of the source is confined, but specific tests showed (Fig. 12) that it extends up to \( \sim 3 \) mm \( \times \) 3 mm. As in Fig. 11 a uniform intensity of the source over 3 mm in diameter was assumed; the real situation is likely to be worse than that depicted, and indeed a misalignment of 1 mm already gives rise to a seriously distorted intensity distribution. The alignment requirement is even more stringent if a sequence of exposures with different orientations of the collimator is scheduled. In this case, in fact, the beam source, the centre of rotation of the instrument, and the collimator window should be collinear and be perpendicular to the rotation plane. In the present set-up the mechanical mounting was accurate enough to fulfil these conditions. Indeed Fig. 13 shows the position of the lines obtained by exposing a plate three times perpendicular to the beam and in a fixed position, with the collimator set at 0° and \( \pm 45^\circ \). It is seen that the centre of the collimator is shifted by \( \sim 30 \mu m \) with respect to the centre of rotation. Owing to the negligible effect of this shift on a scheme which uses only lines at 0° and \( -45^\circ \) (see Section 1), no attempt has been made to correct it further.

For the rotating stage supporting the stack, only four angles of a given face of the pedestal parallel to the linear movements were needed (say, 0°, 90°, 180°, 270°) and therefore accurately calibrated. As the linear stages were mounted perpendicularly to one another within \( \pm 5 \times 10^{-5} \) rad, it is estimated that the four positions are accurate to about \( 10^{-4} \) rad.

The zero of the collimator rotating stage has been determined by requiring two X-ray lines to be parallel after having exposed a plate perpendicular to the beam and with the pedestal rotated by 180°. The positions at \( \pm 45^\circ \) with respect to the zero also have then been determined by performing various exposures on the same vertical plate, held in a fixed position, with the angle set around the nominal value. In principle, the same could be done for any other positions. Accurate measurements of the position of the different lines in the plate with respect to the grid described in Section 2 allowed these angles to be set with an accuracy of the order of \( 10^{-4} \) rad.

For most of these fine calibrations it turned out that the use of plates rather than photographic or X-ray films was indispensable in order to avoid distortions or drifts during the exposures. Indeed, 100 \( \mu m \) thick nuclear emulsion coated on glass was normally used for this purpose.
6. CONCLUSIONS

The accuracy in determining the centre of both a grid line and an X-ray line can be of the order of 1 \( \mu \text{m} \), as seen from the measurements shown in Section 4. However, especially for the X-ray lines, this accuracy can be worsened by several factors, if they are not properly taken into account. In particular, distortions of any kind can shift the position of an X-ray line sideways up to several tens of microns (Fig. 14), unless the measurements are done on the emulsion surface stuck to the physical support of the emulsion, or when a suitable grid is printed before processing. In both cases some experience is needed to perform an accurate measurement. Moreover, the accuracy depends on the width of the line, on its sharpness, and on its absolute blackness; these effects are obviously correlated and it is easily seen that the best results are obtained by irradiating the emulsion as close as is possible to the collimator using an exposure time such that at the point chosen for the measurement, the line appears as ‘grey’. This last requirement is essential when measuring on the bottom surface of the emulsion, in order to avoid the disturbing effect of shadowing from the upper part of the line itself. Figure 14 shows photomicrographs of X-ray lines at different distances from the edge of the 600 \( \mu \text{m} \) thick emulsion sheet, for a particular exposure; of course, different choices of voltage, exposure time, and filtration allow different penetrations, blackening, etc. to be obtained.

Skew lines show themselves intrinsically larger by a factor sec \( \alpha \) (Fig. 14), and the effect is enhanced by the depth of focus. However, as the sensitivity of a \( Z \) measurement increases with the angle \( \alpha \), it turns out that \( \alpha = 45^\circ \) is a good choice for most purposes.

Systematic measurements of the distance between a perpendicular and a skew X-ray line performed on a stack of 60 pellicles, 600 \( \mu \text{m} \) thick (both lines picked up once per plate, on the glass surface), allowed the determination of their individual thicknesses, which were also measured independently. The spread of the differences between the two measurements was about 15 \( \mu \text{m} \). An independent measurement was also performed on single pellicles by measuring the distance between the crossing points of the skew lines with the two surfaces, and correcting for distortion, and it showed an average discrepancy of less than 10 \( \mu \text{m} \). It should be stressed that the method based on the set of X-ray lines is also able to determine absolute coordinates within the assembled stack, independent of the accuracy of piling up and gridding (misalignments up to \( \pm 150 \mu \text{m} \) were found in the same sample).

It is therefore estimated that an absolute reference system based on a set of X-ray lines could easily yield an accuracy better than 20 \( \mu \text{m} \) over distances of the order of 100 mm.

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REFERENCES

Fig. 1 Schematic set-up of a 'horizontal' exposure at the WA75 experiment: target, beam hodoscope, and vertex detector.

Fig. 2 Design of a new grid with coordinates displayed in binary code, particularly suitable for automatic measurement devices.
Fig. 3 Microphotographs at different magnifications of the grid reproduced on the surface of an emulsion plate exposed to the air.
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**Fig. 6** Computed energy spectra from a tube operated at 100 kV with Pb filters.
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Fig. 8 Collimator made of two flat bars spaced at a distance d from each other: a) the geometry of the system for an extended source; b) intensity distribution across the direction of an X-ray beam (extended source) as a function of the distance between collimator and detector; c) predicted and experimental line width s as a function of the distance for the collimator used in this work (25 mm thick), with the bars set at a distance of d = 12 \( \mu \text{m} \).
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Fig. 10 Set-up of the X-ray apparatus. On each stage the useful range and the nominal sensitivity are shown.

Fig. 11 Possible effects of misalignments: an increasing misalignment of the collimator with respect to the beam source gives rise to a loss of intensity and to distorted distributions (f is the dimension of the beam source and h the part of it as seen by the collimator).
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Fig. 13  The centre of rotation C of the stage does not include the collimator slit (σ is the distance), and inclined exposures produce lines intersecting at different points.
Fig. 14 Trace of X-ray lines on a thick emulsion sheet: vertical and skew lines allow accurate measurements of position and thickness; distortion shifts the lines but can be accounted for. The microphotographs show vertical (left) and skew (right) lines 2 and 2.5 mm away from the edge. The exposure conditions were: 100 kV, 1 mm Fe filter, 45 s, d = 12 μm, L₁ = 5 mm. This high magnification (100 ×) shows clearly the short electron tracks building up the line, and is not the best choice for measurements.