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Manufacture of readout boards for a liquid argon calorimeter

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We describe techniques used for the production of large (1 m^2) printed circuit boards which are the readout electrodes of the H1 calorimeter at the HERA collider. In particular, we have developed a direct method of generating the copper image on G10 sheets to meet the multitude of board types with a very low repetition rate.

1. Introduction

H1 is one of the two experiments being prepared for the first beams at the new ep collider HERA at DESY, Hamburg. In the H1 detector design, much emphasis has been put on calorimetric measurement of electromagnetic (em) and hadronic energy of secondary particles. This is done mainly with a liquid argon (LAr) calorimeter with a fine granularity and a very good absolute energy calibration. The required energy resolutions are $0.10/\sqrt{E}$ and $0.55/\sqrt{E}$ with absolute calibration within 1% and 2% respectively for em and hadronic energy E in GeV. Both em and hadronic calorimeters are contained in one common LAr cryostat inside a superconducting solenoid. While more information on the H1 detector in general, and its calorimeters in particular, can be found in the technical proposal [1], here we will concentrate on the manufacture of the LAr hadron calorimeter readout boards.

In fig. 1 the basic hadronic calorimeter cell is shown. It consists of a thick stainless steel absorption plate and an independent ionisation chamber. A precise definition of the argon gap in the ionization chamber is required to reach the design energy resolution. The absorption plates are not a part of the detection volume because their thickness tolerances could not be guaranteed for given dimensions (1700 × 800 × 16 mm^3). The anode of the ionization chamber is formed by two copper pads on a G10 readout board (ROB). The electronic current collected on the anode flows to a preamplifier through a copper conductor on the ROB (fig. 2) and then from the ROB connector through a cable. Care is taken to minimize the cross talk between different pads by interleav-

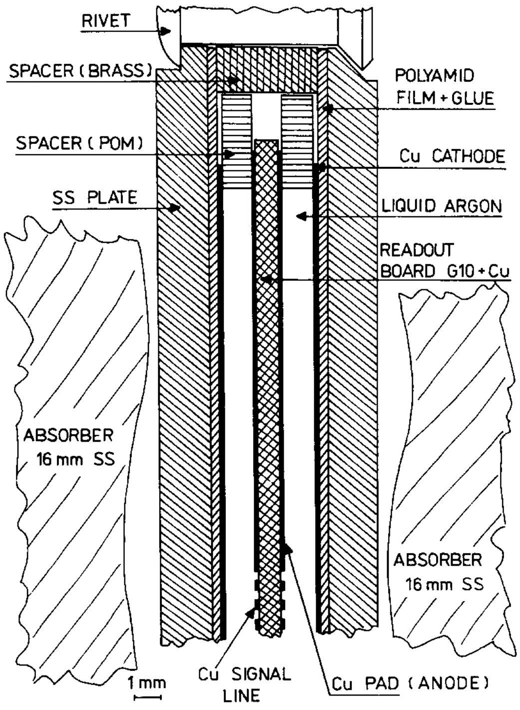

Fig. 1. Hadron calorimeter cell.

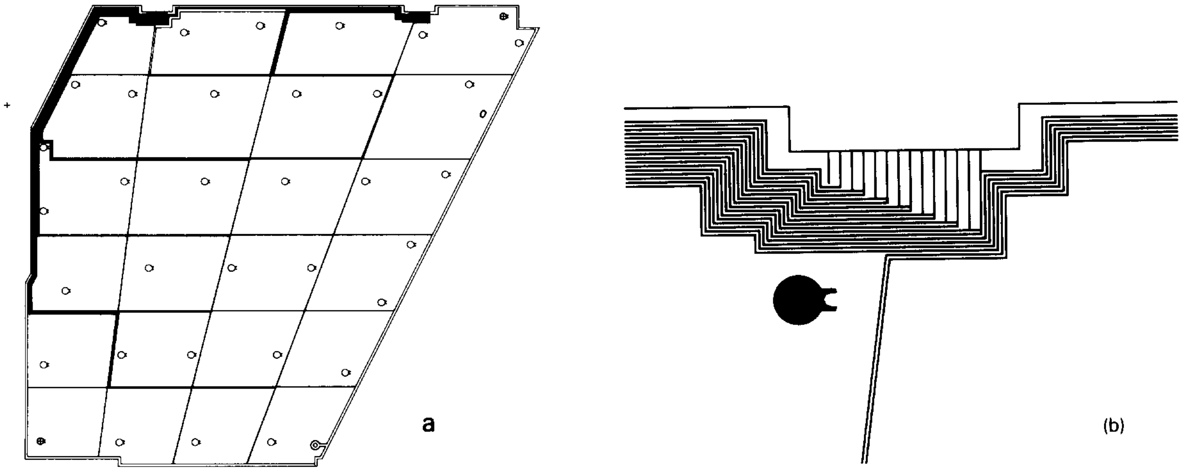

Fig. 2. G10 readout board (ROB). (a) General view: The ROB shape matches the calorimeter module mechanics. The rivet holes are distributed over the ROB area. This ROB is divided into 24 pads (LAr ionisation chamber anodes). A signal line goes from each pad to a connector. (Two connectors to be soldered at the upper ROB edge.) The signal lines are interleaved with grounded lines. High density of lines makes the dark bands seen in the figure. The complicated connection pattern is given by calorimeter trigger requirements. (b) Detailed view of a ROB connector region: Connector pins will be soldered on the vertical strips. Six signal lines (interleaved with grounded lines) come to every second strip. The odd strips get the signals from the other side of the ROB.

ing signal carrying conductors with grounded lines. The two-gap configuration of the ionization chamber has been chosen to have a symmetric structure which does not suffer from temperature deformations. The total argon gap thickness is given by precision spacers between the two stainless steel cathode planes which are riveted together every 100–150 mm. The ROB is positioned between the two cathodes by means of plastic spacers. These plastic spacers and rivet holes in the ROB allow for relative movements of G10 and stainless steel, due to temperature shrinking. As seen in fig. 2, the ROBs are printed circuit boards, each about one square meter surface with approximately 100 m of insulation lines between the pads and conductors on each side. The insulation line width is 0.4 mm, the same as the signal and ground conductor width. Rivet holes are drilled over the whole ROB surface. The required overall precision including relative displacement of the two copper images is 0.2 mm.

This article is organized as follows: section 2 covers the G10 material which was used for the ROB production. The four basic production steps, namely G10 sheet etch resist cladding, copper image generation, etching and machining are described in sections 3–6. Final operations and ROB electrical tests are summarized in section 7.

2. G10 material

Of the two commonly used laminates FR14 and G10 in printed circuit production, the latter releases fewer electrically negative ions and therefore is more suitable for a long term operation in LAr calorimeters.

For the ROB production we used a G10 copper clad laminate [#1] with higher requirements on the thickness tolerances. It was available in 1100 × 1150 mm^2 sheets. To achieve a sheet thickness of about 1.2 mm, ten layers of prepreg were glued together, with 0.035 mm thick copper foils on the bottom and top of the stack, under pressure. The prepreg was made of a sheet of glass fibercloth with a mass of 100 $\mathrm{g/m}^2$ impregnated with an epoxy resin which increased the mass of a dry prepreg to 182–188 $\mathrm{g/m}^2$. To control the polymerization during the production, one sheet with a copper foil on one side only was produced in every pressing cycle and the laminate homogeneity was visually checked. The G10 material was produced in two large batches within a period of one and a half year. The samples from every batch were submitted to a laboratory test under the Czechoslovak norm ČSN 359 004 with the following results: a surface resistance of G10 of 2.0–2.3 $\times 10^{10}$ Ω; a volume resistance of G10 of 1.2–2.0 $\times 10^{10}$ Ω m; a Cu foil peel strength for 3 mm strip width, of 5.2–5.9 N; a resistance to stripping of a control Cu surface, of 120–175 N; an absorption of water of 7.5–12.5 mg.

G10 sheet thickness measurements were done on self-made equipment with 3 dial gauges. Dial gauges were monitored as the sheet was pulled through. When a deviation outside of a preset tolerance of ±0.04 mm

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[#1] Cuprextit SEB, producer GUMON Bratislava, Czechoslovakia.

was seen, the sheet was rejected. We found that the thickness on the perimeter of a sheet is systematically lower by 0.02 mm within a band of 15 cm. This is caused by the flow of the resin during the glueing process in the press. Therefore the rule was to place the ROB in the inner part of the G10 sheet.

Each G10 sheet had a number which indicated the production time and the position of the sheet in the glueing press. From the continuous thickness measurement we estimated the average thickness and the standard deviation along the lines of measurement which were in the middle and at one edge of the sheet. The distribution of the mean thickness along the central line is Gaussian. The overall thickness of the G10 material is 1.16 ± 0.02 mm. No systematic deviation was observed between the two production batches. Thickness for a small portion of G10 sheets was measured in detail on a precision device [#2] on a mesh of 5×5 or 10×10 cm^2. The comparison with a similar measurement done on our device showed that the systematic difference between both methods is less than 0.02 mm.

3. Cleaning and cladding

The purpose of the etch resist is the protection of the conductive copper surface against the etching agent. To achieve a good adherence of the etch resist over the whole surface, the G10 boards were mechanically cleaned by means of the fine powder and saponite detergent (a common means for washing up) and a manually operated pneumatic grinding machine with a felt disc. After cleaning, which took 10–15 min, the board was rinsed by water and immediately dried by compressed air to avoid copper corrosion. As this process needed much human effort, we adopted a new cleaning procedure, after thorough tests. The G10 board was agitated by a programmable arm in a bath with a neutral degreasing solution [#3] for 7 min. Subsequent washing removed the solution from the surface. The pneumatic grinding machine was used only to remove eventual copper corrosion spots with fine emery (no. 400). Final washing and drying, in an oven at moderate temperature, ended this stage.

A proper resist cladding is performed by pulling out G10 sheets of the etch resist solution at constant speed. For etch resist we used a solution of SCR 9A. The apparatus for cladding, shown in fig. 3, was installed in the dark room because of the light sensitivity of the resist. The room had to be well ventilated to extract aceton vapour from the resist thinner. The final thickness of etch resist on the board depends both on its concentration and on the pull-out speed. The thickness of 7 g/m^2 was achieved using the etch resist: thinner ratio equal to 1 : 1 and pull out speed of 12 cm/min. The flow resist out of 9 mm rivet holes drilled into the ROBs did not significantly affect the thickness of the resist layer.

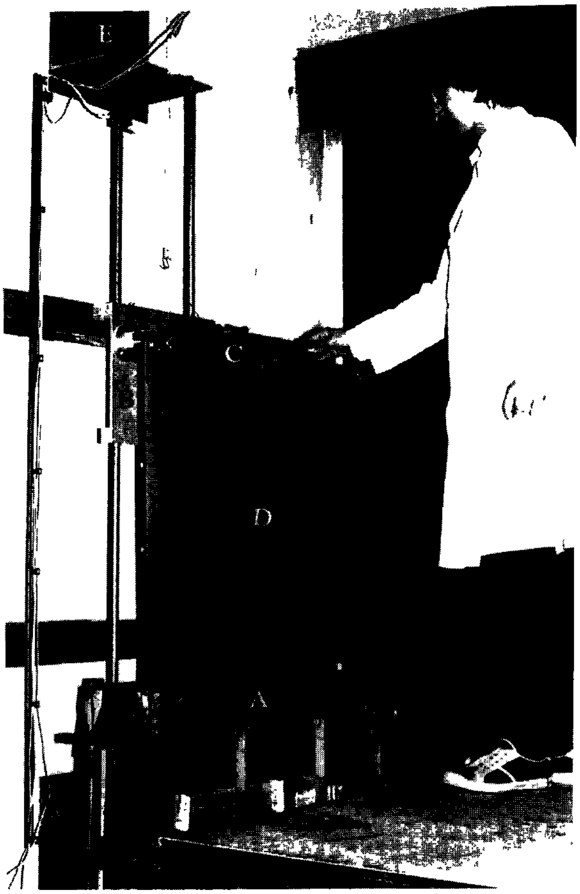

Fig. 3. Resist cladding of a G10 sheet. Vessel with etch-resist solution (A), moving part (B) with fastening jaw (C), prefabricated G10 sheet (D), electric motor (E).

The resist clad boards were stored vertically in a box stand for at least 10 h to dry. To speed up the drying of the resist one can use baking of the boards at a controlled temperature of 70 ° C for 90 min. The resist layer is very sensitive to mechanical damage and therefore extreme care must be taken during board manipulation. It is very difficult to discover fine scratches, which cause conductor cuts, at the etching stage.

4. Copper image generation

To produce large series of ROB types we have used the conventional print-and-etch method. However, out

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[#2] WMM 850, producer OPTON, D-6601 Riegelsberg.

[#3] all chemical products mentioned in this section come from producer LACHEMA Brno, Czechoslovakia.

of 110 ROB types, 82 were needed only in small numbers (8 to 32). Photographic printing is not practical in this case because of the film cost and adjustment overhead. This has led us to develop a new technique for small series of boards. We call it the "engraving method" in the following text. For simplicity we used the same photoresist in both cases.

In the print-and-etch method a photographic mask is needed to produce the UV light latent image in the photoresist. (Developing of this image in an alcalic bath yields the required etch resist pattern.) Our photographic masks have been made from a double layer foil. The thin opaque layer is cut such that strips corresponding to insulation lines can be peeled off. The engraving method involves removing of the resist, above insulation lines, with an engraving tool. No developing procedure is needed. For both photographic mask production and the engraving we have been using the same plotter with an optional cutting and engraving head. The plotter can be operated on-line by a computer or off-line from its own tape unit.

Two Fortran 77 programs have been developed to generate and view DGF metafiles [2]. The first program is an interpreter of the designer commands. These include geometrical line definitions and a set of powerful topological Move and Draw commands. All details of the plotter real output are completely transparent to the designer. All necessary transformations, corrections and the choice between photomask cutting or resist engraving are specified when the design goes to the production.

The second program provides interactive graphics for viewing metafiles on a Tektronix compatible terminal. It has been used for design debugging and also during resist engraving when accidental defects were fixed by repeating one of thousands of DGF instructions.

4.1. Engraving method

To expose the G10 copper foil to the etching agent the resist is removed with an engraving tool of 0.3 mm width (fig. 4). This was done on a DGF1208A plotter [#4] (fig. 5). The electrostatic field of the plotter has been successfully used to hold the G10 sheets with grounded Cu foils on the plotter table. Before starting the mass production we had to solve the following problems:

- engraved line quality;
- to match the engravings on both sides of the board;
- engraving tool lifetime;
- corrections (tool finite width, eccentricity, plotter x–y nonorthogonality).

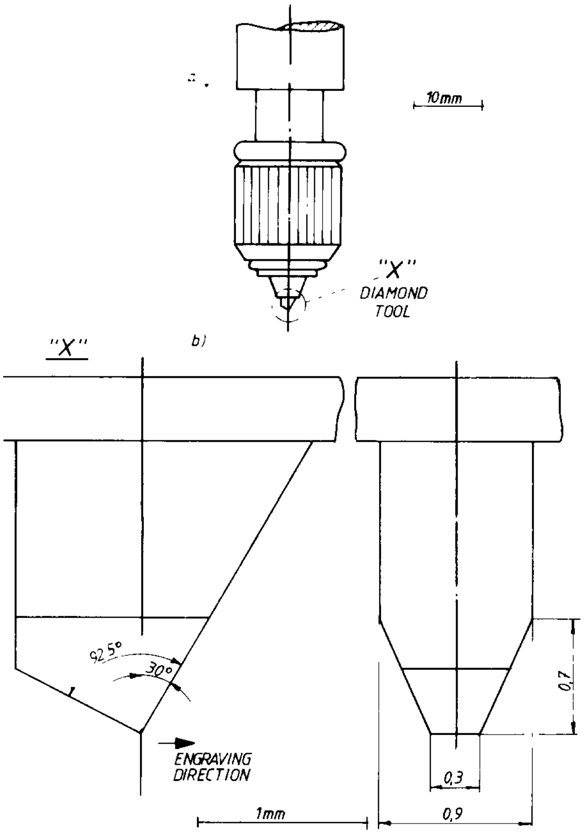

Fig. 4. Engraving tool. (a) The diamond tool seen in the plotter tool holder. (b) Geometry of the diamond tool.

To achieve good line quality with a sharp tool required optimization of the force pushing the tool against the G10 sheet, the damping for tool vertical oscillations, engraving speed and acceleration. After having reached stable results on prototype engraving we had to make further modifications to cure accidental resonant tool vibrations which occurred during the preseries production. The solution was to make a soft bed for the G10 sheet on the plotter table. This bed consists of two thin insulating layers, rubber and vaxed cloth on top of it. With this arrangement the resonant vibrations are suppressed. The plotter was used in the following conditions: a speed of 20 cm/s (maximum value); and acceleration of 20 cm/s^2 (maximum value); and a pushing force of 2.35 N. The G10 sheet is freely moving on the smooth cloth surface when its position is adjusted without electric field and is well fixed when the field is on.

When the engraving program reference system is uniquely identified with the G10 sheet the engravings match on both sides of it. This identification was given by a hole in the G10 sheet (one point) and one line parallel with the y axis of the desired copper image.

[#4] DFG 1208A, producer ZPA Nový Bor, Czechoslovakia.

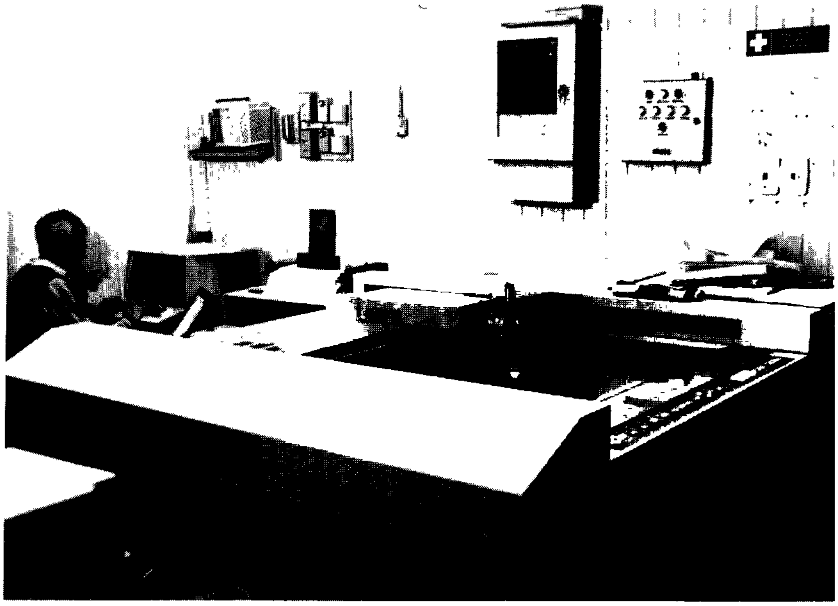

Fig. 5. Plotter used for engraving and photographic mask production.

Special equipment has been installed on the plotter table to provide for the adjustment of the board position. The microscope on the plotter head was set on the centre of the reference hole to position the tool on the starting point. With these instruments we were able to engrave on plain resist-clad G10 sheets as well as on G10 sheets which had been drilled and machined in advance.

The hard metal engraving tools available with the plotter had a very short lifetime of about one board. This was a severe problem for our mass production and we have looked for better solutions. We have found another manufacturer whose tools were about 10 times better, but finally we have ordered a diamond tool for our purpose (fig. 4). The diamond tool shape has been chosen close to the metal one and no study has been made on this subject because it worked reasonably well. We only notice here that there were incidents of a missing fragment of an engraved line. Typically a few centimeters of missing line were caused by a copper filing between the tool and the board surface. This happened much less than once per board. To correct the defect the affected line was engraved once more. This was best done after a careful visual inspection while the G10 sheet was still adjusted on the plotter table.

Corrections

Lines of final width must be longer on both ends than ideal (zero width) lines to get the angles correctly. The value of the extra length depends on angle, line width and line end (tool up or tool down). The diamond tool has in practice some eccentricity, i.e. the plotter tool holder rotation axis does not coincide with the tool symmetry axis. The correction for this on one vector level is an extra movement (with tool up) at the beginning and the end of the vector. This correction depends on angle and eccentricity vector (relative displacements of the two axis). Sometimes the plotter movements are not perpendicular enough (we needed better than 0.05 mrad); the correction in our case of reference system depends on the absolute value of the x coordinate. The latter two corrections required precision measurement procedures. All the corrections were implemented in the program which generates the DGF metafiles. They were applied on the vector level, independently of ROB design specific issues, and their parameters could be modified whenever needed.

In total about 1700 ROBs have been engraved with the total line length of about 200 km, mostly with tool without visible blunting. On average 1 h was needed to engrave one ROB. The tolerances on the resulting copper image were combined from the plotter precision (1 step = 0.01 mm, 0.02 mm reproducibility), metafile data precision (max 0.01 mm) and the reference system identification with the G10 sheet (0.05 mm, 5×10^{-5} rad). In practice the requirement of overall precision of 0.2 mm was achieved.

4.2. Print-and-etch method

We mention this classical method here because it was applied to unusually big printed circuits boards (up to 1100 × 1050 mm^2) using cheap equipment developed in our home laboratory with perfectly acceptable results and performance [3].

To produce the photographic mask we have used the same software and hardware as for engraving into resist directly, except for a knife which was used instead of the engraving tool. Boundaries of insulation lines were cut with the knife into a double layer stripping foil [#5] and then stripped off manually. An exposure frame for printing on up to 1200 × 1200 mm^2 surface was designed. It is a closed box with a slot to introduce a frame with two photographic masks and a photoresist clad G10 sheet in between (fig. 6). There were 4 UV light sources on each side of the box. These were internal discharge tubes from standard 250 W street lamps. The exposure time was 5 min. The big heat load and ozone production required intensive ventilation of the box.

The photographic masks were glued on 6 mm splinter proof glass panes. Their relative position was adjusted using a microscope to observe reference crosses on the two masks and screws to fix the glass panes in the frame. Then the photomasks have been protected with a 10 μm Mylar foil. When a G10 sheet was inserted into the frame, the frame was closed and evacuated before being inserted into the exposure box.

The developing of the latent image was proved to be the most sensitive step in the series production. To guarantee well defined conditions, a programmable machine has been constructed to immerse the lightened G10 sheet into the developing bath, to agitate it in the bath for about 1 min and then remove the loose photoresist with clean water in a rinser. The developing tank contained a 1.2% water solution of NaOH (3.6 kg in 300 l). The solution was exchanged after every 40 sheets developed or every week. Four developed G10 sheets were simultaneously baked at 80 °C for 20 min. Baking hardens the developed photoresist layer and is important for obtaining sharp line boundaries.

4.3. Comparison of photographic and engraving method

The photographic contact printing, including developing, required only about 10 min for each of 40 ROBs which could be typically printed with one set of masks. Producing a new set of Rubylith masks (which we eventually preferred to using film copies) took two days and adjusting them on the frame took another one. So 40 ROBs could be processed in four days which was about two times faster than the engraving method. The engraving method is much better suited for small series (compared with 40 pieces) and has the advantage of being insensitive to dust, which produces shorts when the photographic method is used. In practice we have also about half the number of cuts with the engraving method (about 1 cut per 20 ROBs). The precision of the two methods is about the same.

5. Etching

Before etching, the board was visually inspected thoroughly. Lines with breaks on the resistive coating were retouched with a waterproof pencil. Imperfectly exposed isolation lines were repaired by scraping. The amount of these local defects depended on the quality of the preceding operations. With tuning the time needed to retouch one board was limited to 10 min. Finally a sequence number was engraved into the resist by hand.

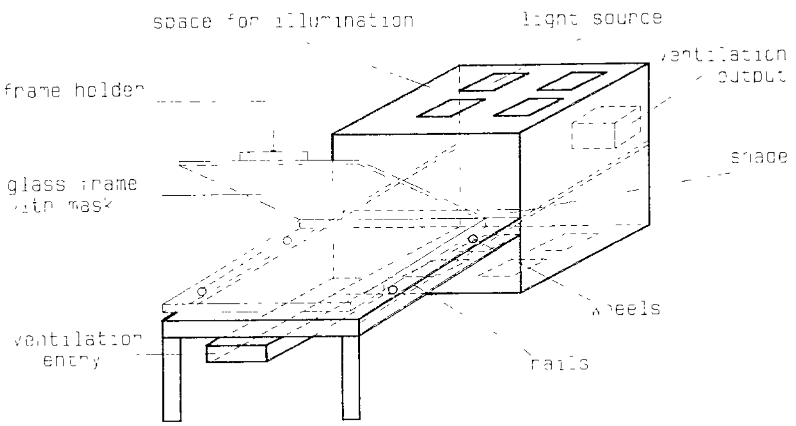

Fig 6. Exposure device for photographic contact printing. One mask is adjusted on each splinter-proof glass of the frame. The closed and evacuated frame will a photoresist clad G10 sheet inserted between the two masks is introduced into the box and both sides are illuminated simultaneously.

[#5] Rubylith, ULANO, Brooklyn, NY 11217, USA.

Retouched boards were fixed in a frame to be vertically immersed into a tank filled with 300 l of a commercial ferric-chloride etchant. Up to four boards were etched simultaneously. The addition of 2 kg of $CaCl_2$, as recommended in the literature, in order to achieve better adhesion of etch to boards, did not improve etching significantly. In order to keep the etch factor d/s (where d and s are the etching rates in depth and sideways, respectively) well above one and to achieve uniform etching over the whole area of all plates an intensive agitation by percolating air was used. The optimal etching time was found to be 20 min at room temperature. Then the boards were visually inspected and manual etching was applied where necessary. This happened more often in the print-and-etch method. Imperfections were caused by local overbaking in the baking oven. The etched plates were washed in the rinser and dried in the baking oven or in an intensive stream of compressed air.

6. Drilling and machining

All ROBs have rivet holes over their whole surface, as mentioned above. Also all of them have notches for connectors and about half of them have a more complicated shape. Numerical control drilling and milling machines have been used for the ROB mechanical processing. The ROBs were processed in stacks of up to 37 on drilling machines, up to 25 on vertical milling machines and up to 120 on horizontal milling machines. The main problem is to press the stack against the machine table so that it behaves more like a compact block of material. Here, again, practical solutions were different for big series and small series ROBs.

Two iron plates, 20 mm thick and plane-grinded, were used in case of big series. Up to 37 ROBs were stacked in one pack using two manually predrilled holes for clamping them between the iron plates. Such a pack was then used on the drilling and then the horizontal milling machine.

For small series ROBs we were able to make all the processing on a vertical milling machine when an 800 mm range was sufficient in one direction. For the bigger ROBs a drilling machine and then horizontal milling was used. In both cases cheaper plates made from a 20 mm thick cotton laminate have been used for clamping the stack of ROBs.

Machining was performed either before or after the production of the copper image. In the latter case the photoresist film was left as a protective layer on the ROBs. Peripheral speed of 0.4 m/s was used for drilling and milling. The required overall precision of 0.2 mm was more comfortably met for big series where thick iron plates were used.

7. Final operations and board properties

The ROBs of final shape were stripped of the resist layer. This was done by exposing the ROB to UV light and then dissolving and removing the resist in an alkaline degreasing solution. The ROB was then washed and dried. Holes of 0.6 mm diameter for the connection of both sides of each pad were made with a hand drilling machine (20000 rpm). This was easy because the copper was etched from a square of 0.4×0.4 mm^2 which marked the position of each contact hole. The contact was made with a 0.5 mm diameter silver plated wire which was soldered to both sides of the pad. All connections are done close to rivet holes (figs. 1 and 2) and are shielded by the plastic spacer not to disturb the electric field. At the end, pin connectors were soldered on each ROB (position precision of 0.5 mm).

Electrical tests of all ROBs were done to detect shorts and cuts. A voltage of 600 V was applied to each connector signal pin and currents above 2 μA, to ground or neighbour pins, were monitored with a beeper. All the shorts detected were either identified and removed or the ROB was cleaned with alcohol to get rid of distributed leakage current. This test is very sensitive to the air humidity. The current limit was approached only on humid summer days. When the ROB was free of shorts and leakage current, connection of each pad to the corresponding connector pin and the integrity of ground lines was checked with low voltage. Pad and cross talk capacity measurements were made on a subset of ~ 300 ROBs.

The overall loss of ROBs during the production was below 7%. The loss was equally distributed between loss caused by mechanical damage due to manipulation and transport and loss due to more than two cuts of copper

Table 1
Average ROB properties

Property	Typical value
ROB dimensions	850×1000 mm^2
Mechanical tolerances	0.2 mm
ROB thickness	1.16 ± 0.02 mm
Number of pads	24
ROB surface used for rivets	~ 1%
ROB surface used for leads	~ 3%
ROB surface used for connectors	~ 0.3%
Undisturbed ionization chamber area	> 95%
Insulation line length	80 m
Insulation line width	0.40 ± 0.02 mm
Pad capacity [a]	170–510 pF
Total crosstalk capacity [a]	6–40 pF
Maximum copper displacement on opposite sides of ROB	0.2 mm
Min resistance of the insulation	2 GΩ

[a] In the sensing structure geometry.

conductor per ROB. Some characteristics of ROBs are given in table 1.

8. Conclusion

We conclude that producing big surface printed circuit boards, such as high energy particle calorimeter readout electrodes is perfectly feasible in a physics laboratory and at a low cost. This is true for both small and big series types. We have produced, in total, 3200 ROBs of 110 types with a typical surface of about 1 m^2.

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