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LABORATORI NAZIONALI DI FRASCATI

SIS – Pubblicazioni

LNF-97/029 (NT)
23 Luglio 1997

**Construction Techniques of the High
Resolution Lead/Scintillating Fibre
Electromagnetic Calorimeter for the KLOE
Experiment**



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Abstract

The electromagnetic calorimeter of the KLOE experiment at the DAΦNE φ -factory is a lead-scintillating fibre sampling device. This calorimeter is arranged as a “barrel”, closed at both ends with an “end-cap”. The barrel consists in 24 modules defining a cylinder, 4.3 long, with 4 m inner diameter. Each end-cap consists of 32 modules running vertically along the chords of the circle inscribed into the barrel. In this paper the calorimeter construction techniques are described.

1 Introduction

The KLOE detector at the DAΦNE φ -factory of the Frascati National Laboratory is designed primarily with the goal of detecting direct CP violation in neutral Kaons decay. Fig. 1 shows two views of the KLOE detector[1]. The electromagnetic calorimeter (EmC) is a very demanding element of the detector, it is supposed to ensure: a) good position resolution, b) excellent timing performances, c) high efficiency in γ 's detection down to 20 MeV and d) good energy resolution[2]. The KLOE EmC is arranged as a “barrel”, closed at both ends with an “end-cap”. The barrel consists of 24 modules, 4.3 long and 230 mm thick, presenting a trapezoidal cross-section, with bases as long as 525.1 and 585.7 mm respectively. Each end-cap consists of 32 modules, ranging in length from 0.7 to 3.9 m and running vertically along the chords of the circle inscribed in the barrel. At the two ends each end-cap module is bent by 90° so as to ensure appropriate overlap between barrel and end-cap, to provide a hermetic coverage of the solid angle and to minimise the effects of the magnetic field on the photomultipliers' response. End-cap modules are 230 mm thick, have rectangular cross sections and are of three different widths (88, 132 and 264 mm). Schematic views of barrel and end-cap modules are shown in Fig. 2. Both barrel and end-cap modules are lead-scintillating fibres sampling devices, made of very thin (0.5 mm) lead layers and 1 mm diameter scintillating fibres. Kuraray SCSF-81 fibres were used in the inner half of the calorimeter modules and Pol.Hi.Tech. 0046 fibres in the outer half[3]. The total length of fibres used in the calorimeter is 15000 km. The calorimeter's total weight exceeds 100 tons. The first barrel module was assembled in Frascati in 1994.

After the successful test of this full scale prototype[4] ($\sigma_E/E = 5\%/\sqrt{E(\text{GeV})}$, $\sigma_T = 72\text{ps}/\sqrt{E(\text{GeV})}$), the series production started.

The construction of the whole calorimeter required 18 months. The barrel modules were built in Carsoli (AQ) by Pol.Hi.Tech., using assembling tools provided by the KLOE group. The construction of the 64 end-cap modules has been shared among three Institutions of the KLOE Collaboration (LNF, Roma I and Pisa).

This paper describes the construction techniques of calorimeter modules.

2 The Supporting Plates

Each module is supported on the outer side by a 25 mm thick aluminium plate. For the end-cap modules the supporting plate is bent by 90° at both ends (Figs.3 and 4). Each Al plate was carefully inspected before the module construction. The quality checks consisted in measuring: i) the plate thickness in six points along the plate and the corresponding values were required to stay within ± 0.1 mm; ii) for the end-cap modules, the bending angle ($90^\circ \pm 0.1^\circ$); iii) possible warpages producing a “banana” shape on the plate (any deformation of this type had to be smaller than 0.3 mm). The fulfilment of these quality checks is necessary for a correct and easy assembling of the whole calorimeter: in particular the above requirements were chosen to minimise unwanted clearances between two adjacent modules.

The plate face, where the first lead foil had to be glued, was machined to ensure planarity. On the same face a 1 mm “reference” groove was also machined in central position along the full plate to drive the first lead foil gluing.

3 Preparation of Lead Foils

The grooved lead foils were obtained by rolling 0.5 mm thick foils into special “shaping” machines[5]: a first machine was able to shape 150 mm wide foils, a second one shaped foils up to 600 mm width. In the bigger machine the two grooving rollers are made from assembling 13 disk-like pieces, 50 mm thick and

400 mm in diameter (Fig. 5). For both machines, the grooving rollers are made of hardened steel and were ground to shape by a sintered diamond tool; the rollers are fixed by means of ball bearings on a very rigid frame and are aligned and checked with a set of micrometers. The foil thickness was measured to be uniform within few ten μm 's; the grooves deviated from a straight line by less than 0.1 mm per meter of foil length. During the grooving process, the rollers were lubricated continuously with alcohol. A 1 meter long foil was processed in half a minute. The Pb foils coming out from the weaving device were polished by means of alcohol, manually rolled up and stored. A lead/fibre sample is shown in Fig. 6.

4 Blue Scintillating Fibres Manipulation

Scintillating fibres were procured from Kuraray and Pol.Hi.Tech. in 4.4 m long bunches for the barrel calorimeter, while for the end-cap calorimeter, the bunch length ranged from 1.1 to 4.8 m. Special care was devoted to handling the scintillating fibres, as they can be damaged by the ultraviolet component of natural and artificial light. This relevant effect was observed for the first time during the construction of our prototypes and was found to affect both the light yield and the fibre attenuation length[6] (see Fig. 7). As a consequence, the fibres were stored and manipulated in a room where the windows were screened by a special yellow filter[7] and the fluorescence lamps of the working areas were replaced by standard incandescence lamps.

5 Devices for Assembling Lead Plates and Fibres

Special assembling machines have been designed and built by INFN personnel for the production of barrel and end-cap modules. More precisely, for the end-cap production there were three operating machines (LNF, Pisa and Roma I), while for the barrel assembling only one machine was built and afterwards used for production at a private firm (Pol.Hi.Tech.).

One end-cap machine is shown in Fig. 8 and details of its bending sector

are shown in Fig. 9. On a vertical plane, machined to guarantee very good planarity over the full length (“A” in Fig. 8), two solid cylinders (“C1” and “C2” drums) are fixed, holding a horizontal aluminium plane (“D”). The distance between the drums is adjustable so as to accommodate securely the module supporting plate (“E”). A variable number of vertical pistons (“F”), from 2 to 18 according to the module length, is used to apply a uniform pressure on the stack of lead foils and fibres just after glueing. The stack comprises of $12 \div 25$ planes. Each piston was held by a C-shaped iron bar (“K”) fixed at the vertical plane (“A”). The pistons were driven by a high pressure gas system: the applied pressure was about 1.1 atmosphere. In the lower part of the machine, on a milled horizontal plane (“B”) two cylinders (“G1” and “G2”) hold a stainless steel belt (“H”). This belt was stretched to press the 90° bent part of the fibre/lead stack during the gluing time. The two removable plates, (“I1” and “I2” in Fig. 9) are used to support the lead-fibre pile in horizontal position before bending the two ends.

The mechanical structure of these machines resulted to be sufficiently stiff to avoid any flexing and/or torsion during construction.

The barrel calorimeter modules were built using the device shown in Fig. 10. The barrel machine has the following relevant characteristics: a) no bending part is present; b) the pressure on the barrel module, covering an area of $0.6 \times 4.3 \text{ m}^2$, is obtained by means of a rubber bag emptied by a vacuum pump; c) a mechanical arm, driven by side rails, acted as dispenser and positioning tool for fibres.

6 Construction Procedure

The first lead foil is positioned and glued on the supporting plate with maximum care so that the grooves are parallel to the “reference” groove of the plate. This first foil is glued using a two component structural epoxy adhesive, requiring about 20 hours for final bonding[8].

Then the piling procedure starts up:

1. a smooth layer of glue is applied on the Pb foil;
2. the fibres are positioned into the Pb foil grooves;

3. a new Pb foil is glued on the fibre layer.

This last operation is very critical because no fibre should move from its own groove. Correct growing of the pile is very important, in particular for the endcap it requires that the lateral sides of modules lie on two parallel planes and possible deviations must be smaller than 1 mm over the total module length. If this condition were not fulfilled, during the milling process of module (described in Sect.8) some fibre might be cut, thus producing “dead zones” in the calorimeter.

During steps 1 and 3, epoxy resin BC-600[9] was used: a 0.28 ratio between the hardener and glue weights ensured a handling time as long as 1.5 hours. With such a procedure about 200 lead foils with interleaved fibres are piled up to a total thickness of about 230 mm.

For the endcap the sequential operations described above are repeated many times up to a given thickness of the stack, ranging from 16 mm to 32 mm. Experience demonstrated that the 16 mm stack is easier to handle during the bending process. Each end of the stack (about 50 cm in length) is bent by removing the plates “I1” and “I2” and by pressing the stack against the curved part of the supporting plate. This operation requires good expertise to ensure the lead/fibres stack to be bent with perfect vertical alignment with respect to the supporting plate. To simplify this operation a compass “J” is rotated around the axis of the drums (see Fig. 9).

The epoxy used does not cause any damage to fibres: in fact, a 1 year long studies on the first module has shown that the calorimeter performances are not affected by ageing effects[10].

To check the mechanical stability of the lead-glue-fibre compound, an endcap module has been positioned in vertical position, as it will be in the experimental apparatus, for some months, and no structural modification has been observed.

7 Geometry Monitoring during Construction

During the construction the module geometry was checked. Both the growing of a single stack and its gluing onto the other layers was continuously mon-

itored. For the end-cap modules these controls were performed by means of machined aluminium bars. Five bars, fixed at the part "A", acted as a reference stop for the Pb foils on the internal side of the machine: three bars in vertical position along the straight part of the module, ensured planarity of the external side ("L" in Fig. 8); two horizontal bars, near both ends of the module were used to monitor the pile thickness ("M" in Fig. 9).

Once per day the module growth was further monitored by optical survey: a theodolite was used to measure the position of a reference groove along the full module length, thus checking any displacement with respect to an ideal straight line. The sensitivity was such that a displacement of 1/2 groove could be easily detected: this method was adopted at Frascati and Roma 1, while a "plumb" method was used in Pisa.

8 Mill Machining of the Modules

To be shaped according to the project design, each module was machined by means of a numerically controlled milling machine. Both the two end faces and the two lateral sides were milled. Due to the large module's length (up to 4.5 m) the milling operation turned out to be very delicate. A circular cutter, 150 mm in diameter, was used as milling tool. The supporting Al plate was used as reference plane for milling. Initially this plate was aligned respect to the machine horizontal motion; then one side was milled, together with the two module faces. Finally the module was rotated by 180° and the second side was directly milled. Typically a module required about three hours to be milled.

9 Light Guides and Photomultipliers Assembling

In each module the light signal coming out from the fibres is collected by photomultipliers through "perspex" light guides with about 4.5x4.5 cm² granularity. A barrel module has 60 guides on each end face as shown in Fig. 11, while an end-cap module may have 10, 15 or 30 guides per face according to its position in the end-cap assembly (see the scheme in Fig. 12). The light guides have

different cross-sections (rectangular or trapezoidal) but have almost the same area; the length of all the guides is 197 mm. The guide geometry was optimised both by numerical simulation and by experimental tests[11]. The accuracy on the side dimensions of each guide had to be $+0.0/-0.1$ mm. To reduce the dead zone between adjacent guides, no wrapping was used. The guides were positioned on the module face by means of specially designed templates and were glued using the epoxy resin BC-600. After gluing, each guide was pressed by a special tool, 0.95 kg heavy.

As each guide touches the contiguous ones, a signal cross-talk could be expected. However, tests have shown that this effect, which happens if the glue penetrates for few centimeters the space between adjacent guides, is negligible[12].

Near the end of each module an aluminium plate is bolt orthogonal to the supporting plate. These plates (see Fig. 13) were machined to accommodate the aluminium tubes containing the PMs: 60 for barrel modules, and 10, 15 or 30 for end-cap modules. Plates and tubes are black anodised to be light tight. Two gas connectors for the nitrogen inlet and outlet are also screwed to these plates: indeed nitrogen flux is expected to prevent heating of the PM's preamps, and to avoid helium leakage from the chamber penetrate the PMs.

The thin aluminium cylinders keep PMs in correct position with respect to the light guides and are provided by a cap (see Fig. 14) ensuring the needed pressure to correctly couple PM and light guide. The optical contact between PM and light guide is obtained by means of an optical gel[13]. For each PM the high voltage divider and the preamplifier are contained in a small plastic box and are located inside the aluminium tube.

In each module all mechanical pieces (including screws, springs, etc.) were selected to be of non magnetic metal. An overall view of the guides, plates and thin tubes assembling is shown in Fig. 15.

The fibre/lead part of a module is wrapped with aluminised adhesive tape of 0.16 mm thickness[14]. The module wrapping is designed to minimise the dead zone between contiguous modules.

10 Conclusions

The production rate of the end-cap modules was typically one module per week. The production of each barrel module was three times longer. A fully assembled half end-cap calorimeter is shown in Fig. 16.

The calorimeter modules were tested with cosmic rays at a dedicated set-up at the Frascati National Laboratory[10]. All the modules have performances meeting design specifications. According to the cosmic ray results, barrel and end-cap modules show an absolutely similar behaviour; their time and energy resolutions for electromagnetic showers are expected to be:

$$\sigma_T = \frac{55 \text{ ps}}{\sqrt{E(\text{GeV})}}$$
$$\frac{\sigma_E}{E} = \frac{4.7\%}{\sqrt{E(\text{GeV})}}$$

Acknowledgements

We thank F. Bronzini, S. Casani and M. Perciballi as well as G. Catitti, A. Cecchetti, S. Cerioni, B. Dulach and D. Orecchini for their invaluable support in designing the KLOE calorimeter. We acknowledge L. Andreanelli, responsible of the Roma I mechanical workshop for his help in preparing many tools.

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- [7] Yellow filter is plastic film TA81. The cut wavelength is around 530 nm.
- [8] Commercial adhesive UHU-Plus by UHU, Buhl, Germany.
- [9] Optical cement BC-600 (Part A and Part B) by BICRON, Newbury, Ohio, USA.
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- [13] Optical grease BC-630 by BICRON, Newbury, Ohio, USA.
- [14] Tape YR3633 by 3M, Hutchinson, MN, USA.

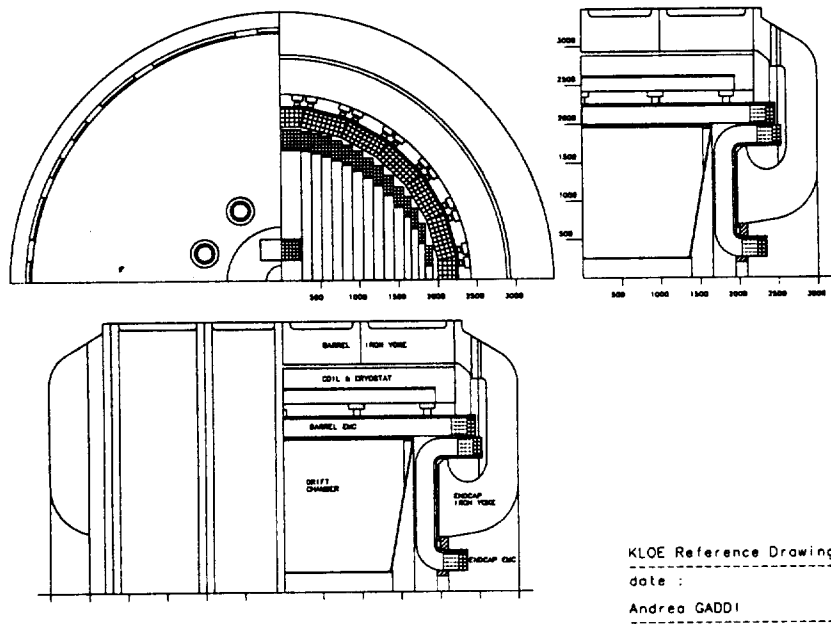


Figure 1: Partial KLOE views: (top) front view of the upper half of the KLOE detector, the part on the right is shown without the return yoke; (bottom) side view of the upper half of the KLOE detector, the part on the right is a cross-section in the vertical plane including the beam pipe. Length scales are expressed in mm.

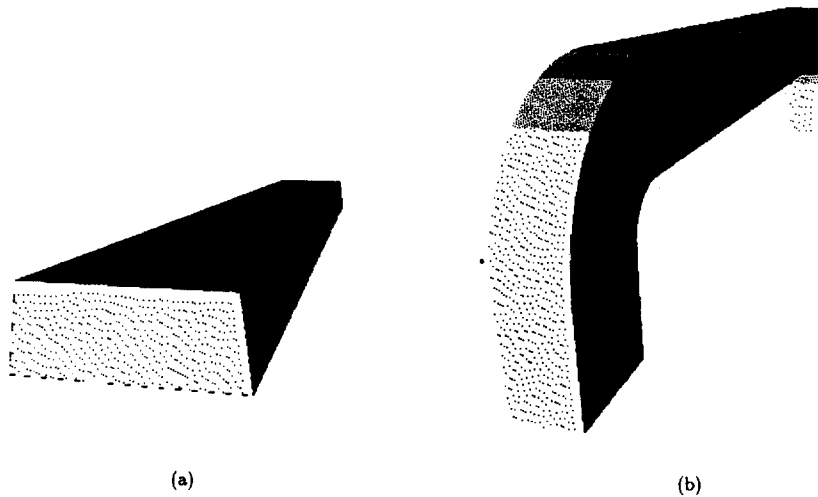


Figure 2: Schematic view of two calorimeter modules: (a) barrel module; (b) end-cap module.

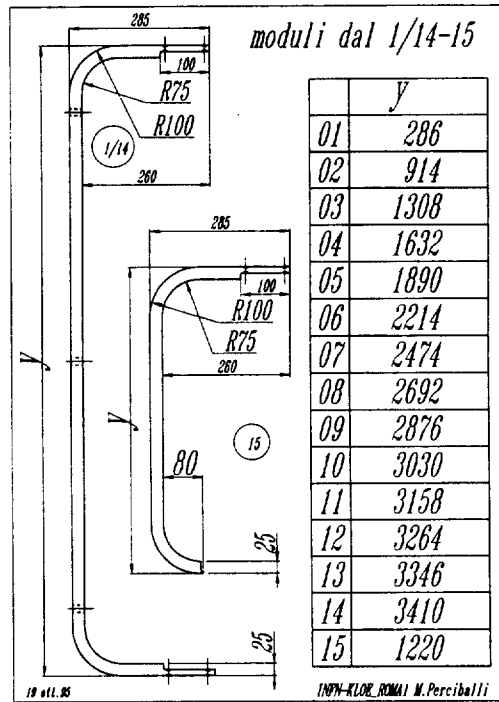


Figure 3: Design of the supporting aluminium plates of the end-cap modules

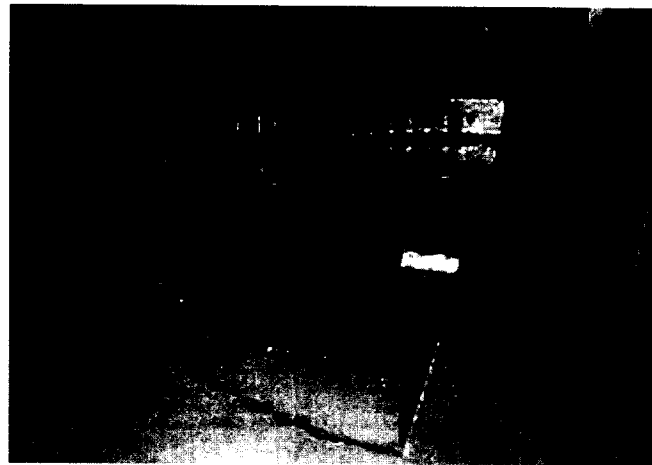


Figure 4: The 16 aluminum supporting plates for a half end-cap.



Figure 5: Machine for grooving of thin lead foils.



Figure 6: A magnified cross section of a lead/fibre sample built with the Frascati machine shown in Fig. 5. The real fibre diameter is 1 mm.

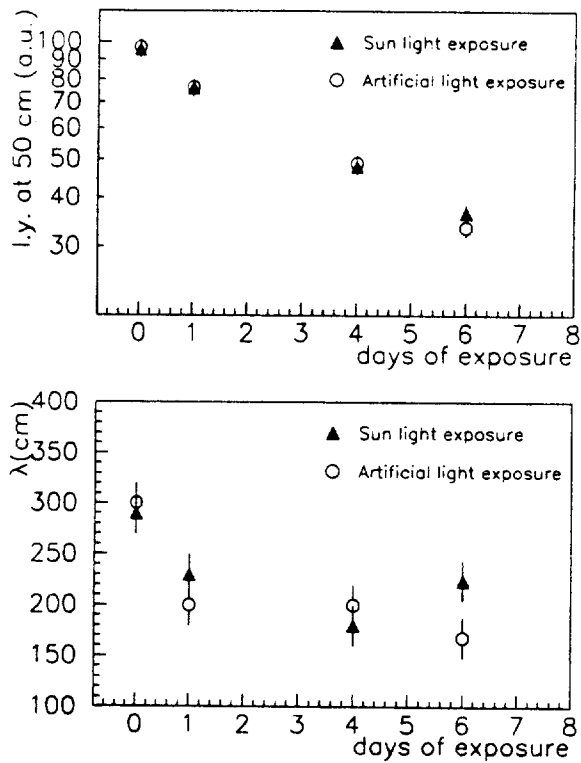


Figure 7: Damage induced by light irradiation on Kuraray SCSF-81 scintillating fibres. Light yield (arbitrary units) at 45 cm distance from photomultiplier, and attenuation length (cm) are measured as a function of the exposure time (days).

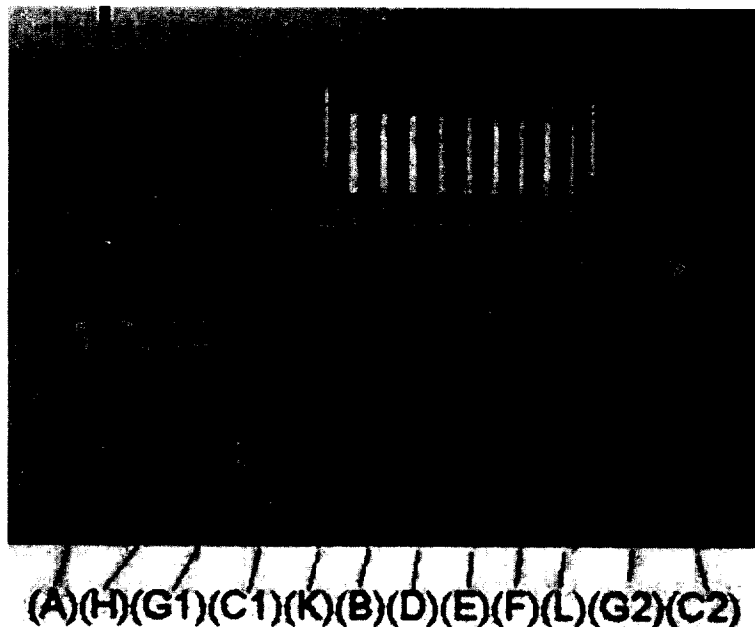


Figure 8: Device utilised for the construction of end-cap calorimeter modules. The capital letters indicate various tools which are described in Sect.5, 6 and 7.

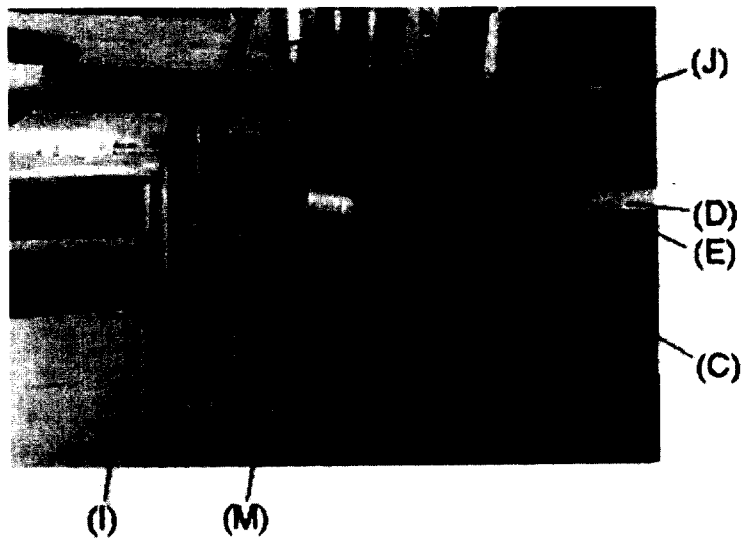


Figure 9: Detail of the device shown of Fig. 8, illustrating the method of bending an end-cap module. The capital letters indicate various tools which are described in Sect. 5 and 7. A lead/fibre stack is ready to be bent.



Figure 10: Device utilised for the construction of the barrel calorimeter modules.

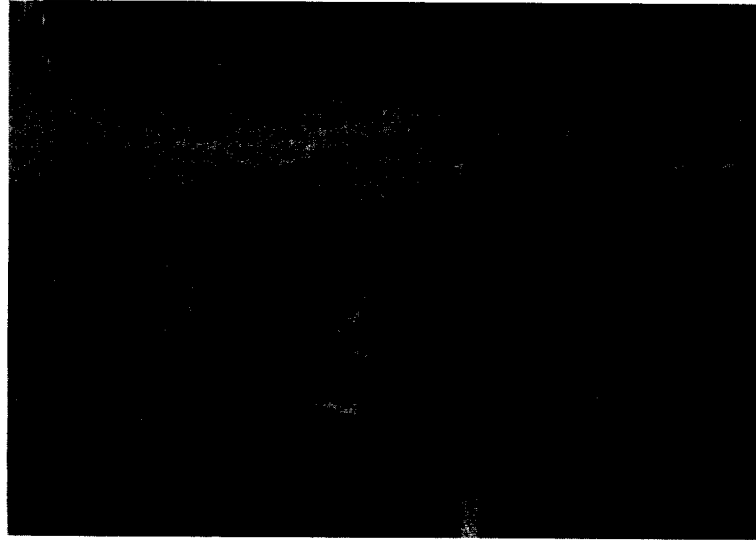


Figure 11: The 60 light guides glued to the end of a barrel module.

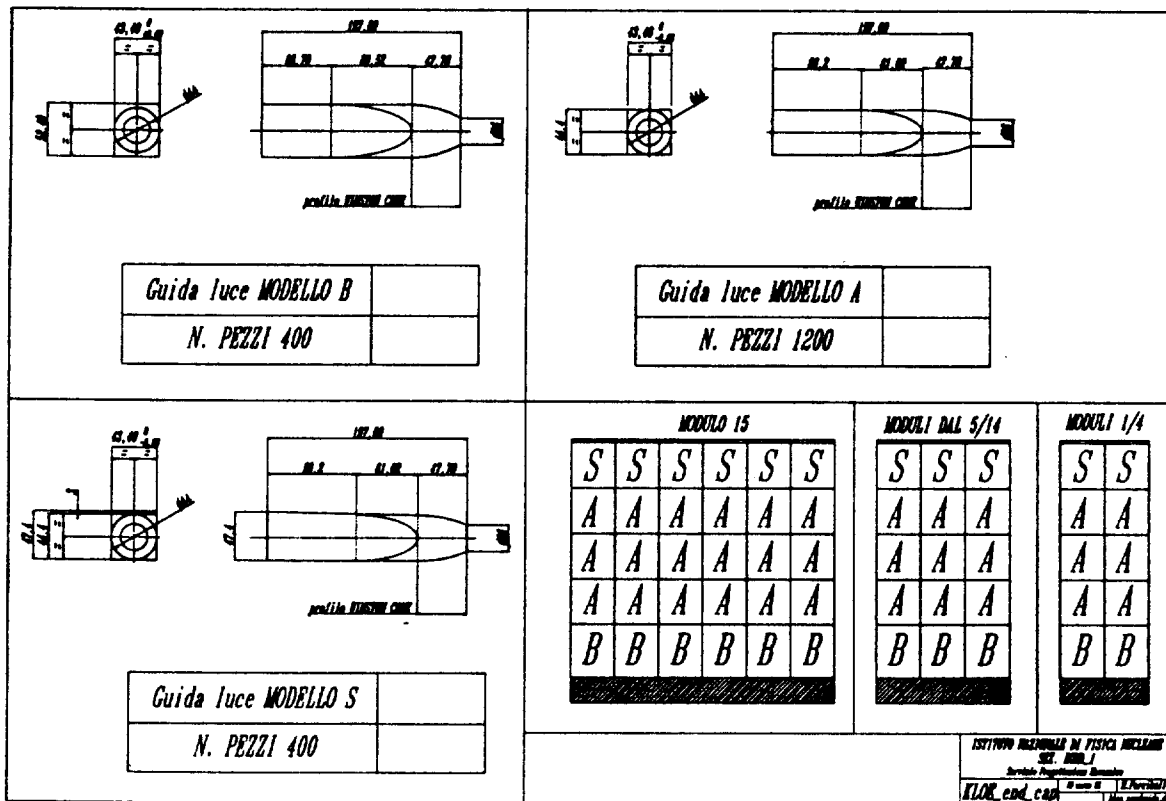


Figure 12: Light guides for the end-cap modules.

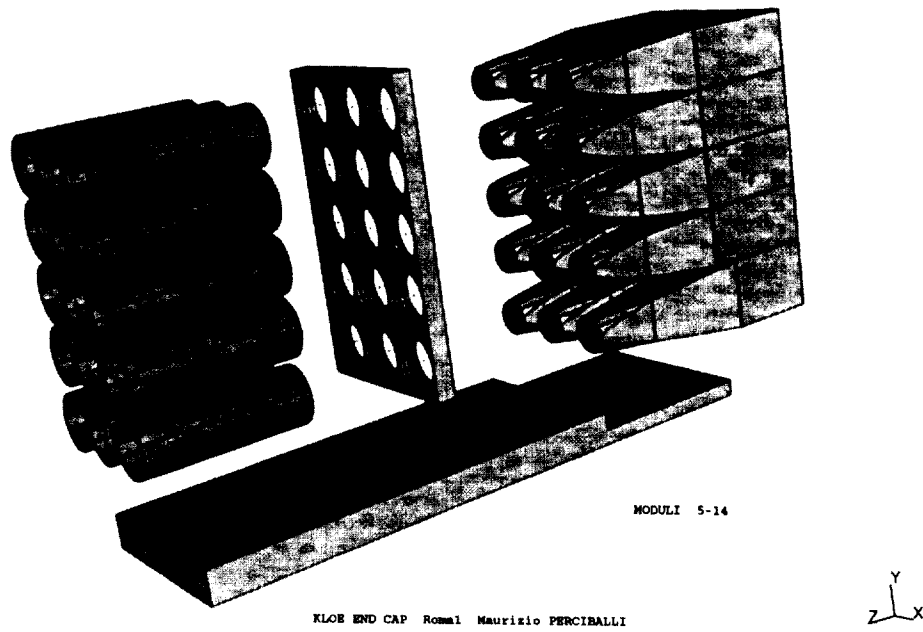


Figure 15: Exploded view of an end-cap module assembling of light guides, plates and tubes.

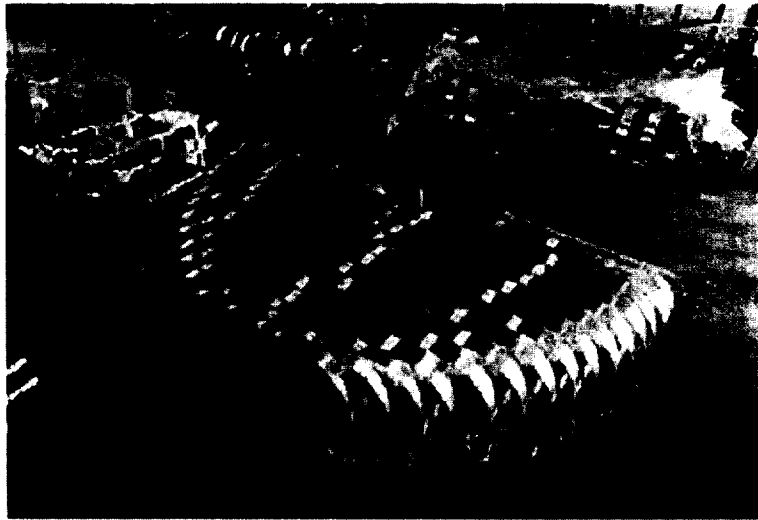


Figure 16: Half an end-cap calorimeter, composed of 16 modules, assembled at the Capannone Gran Sasso in Frascati (the shortest module is not included).