11 Electromagnetic Calorimeter

11.1 Overall System Aspects

The primary goals of the HERA – B electromagnetic calorimeter are to provide electron identification, and formation of the first level trigger. The performance requirements and design considerations are formulated in [3].

11.1.1 Description of the Calorimeter

The calorimeter is positioned at 13.25 m from the primary vertex occupying the transverse dimensions $|x| < 312$ cm and $|y| < 234$ cm with a hole for the proton beam with $|x| < 11.15$ cm and $|y| < 11.15$ cm. Four more modules are removed in order to provide free space for the electron beam pipe (see Fig. 214). The resulting geometrical acceptance to detect both electron and positron from J/ψ decays is found to be 68 %. The acceptance loss is caused mainly by the inner hole of the calorimeter.

Table 69: *Parameters of the HERA – B calorimeter.*

	Inner section	Middle section	Outer section
Outer size	156 cm×89 cm	446 cm×245 cm	624 cm×468 cm
Type	Shashlik	Shashlik	Shashlik
Number of channels	2000	1984	1768
Number of cells per module	25	4	1
Absorber	W-Ni-Fe alloy	Lead	Lead
Volume ratio	Absorb:Sc=2.2:1	Pb:Sc=3:6	Pb:Sc=3:6
Moliere radius	1.3 cm	3.5 cm	3.5 cm
Radiation length	0.62 cm	1.64 cm	1.64 cm
Cell size	2.23 cm×2.23 cm	5.575 cm×5.575 cm	11.15 cm×11.15 cm
Depth	13.6 cm (22 X_0)	33 cm (20 X_0)	33 cm (20 X_0)
Weight	1.85 tons	11 tons	36 tons
Absorb. weight	1.53 tons (2.2 mm plates)	7.8 tons (3 mm plates)	27.5 tons (3 mm plates)
Scint. weight	42 kg (1 mm plates)	1450 kg (6 mm plates)	5126 kg (6 mm plates)
WLS fibre type	Kuraray Y-7	BCF-91a	BCF-91a
WLS fibre length	1.7 km	36 km	127 km
PM type	FEU-68	FEU-115M	FEU-115M

The main parameters of the calorimeter are summarized in Table 69. An isometric view of the HERA – B ECAL is shown in Fig. 214. The calorimeter consists of inner, middle and outer sections. All sections employ the same technology of a sampling scintillator/absorber sandwich structure readout by plastic wavelength shifter (WLS) fibres ("shashlik"). The basic ECAL unit is a module (shown in Fig. 214 as a rectangular block) with transverse dimensions of 11.15×11.15 cm^2. The steep radial dependence of the track density requires a variable ECAL granularity in order to limit the number of readout channels. Thus the inner, middle and outer modules comprise 25, 4 and 1 calorimeter cell, respectively. The cell sizes, as well as the numbers of readout channels, are presented in Table 69 separately for each part of the calorimeter.

The modular geometry allows a straightforward integration into the middle HERA – B platform. Mechanically the modules form a self-support structure with 42 horizontal rows, each containing 56 modules neglecting the cut-outs for the proton and electron beam pipes. The actual weight carried by a single module in the bottom row is about 800 kg. In total, there are 2344 calorimeter modules. The total length of the calorimeter in the z-direction is 86 cm.

11.1.2 Changes since the Proposal

A considerable amount of effort has been spent in order to optimize the design of the calorimeter in terms of its performance and cost. This revision resulted in a number of changes in the ECAL design compared to that described in the HERA – B Proposal [3]. The major changes are as follows:

- The x-dimension of the ECAL has been decreased because of the reduced magnetic field of the HERA – B spectrometer.
- The modular structure of the calorimeter (instead of the super-modular one) allows a better optimization of the shape of the calorimeter sections in terms of charged particle occupancy. This simplified construction results also in some reduction of the cost. A disadvantage of the new design is the more complicated procedure of the replacement of innermost modules damaged by radiation. However, a feasible solution has been found.
- In order to improve the energy and spatial resolution (and consequently the e/π separation) the thickness of the scintillator plates of the middle and outer ECAL modules has been increased to 6 mm compared to 4 mm in the initial design. The expected energy resolution calculated using a full GEANT simulation is shown in Fig. 215 for the inner and outer ECAL modules.

  The spatial resolution for electrons from J/ψ decays is shown in Fig. 216. It has been obtained using the center-of-gravity of the energies deposited in a 3×3 array of calorimeter cells, followed by a correction of "imaging distortions". Pile-up from five minimum bias interactions has been taken into account. Such an algorithm can be implemented at the pretrigger level allowing to measure the position of the pretrigger candidate to a fraction of a cell size. The parameters of the distributions shown in Fig. 216 are listed in Table 70.

11.1.3 Radiation Environment of the Calorimeter

The expected radiation dose for the calorimeter depends drastically on the distance from the beam pipe. For the middle and outer calorimeter sections the annual dose will not exceed 0.3 Mrad (see Fig. 217 a). Various standard plastic scintillators and WLS fibres are available to operate for a few years under such conditions with only a minor decrease of light output [126, 127, 128].

For the innermost part of the inner calorimeter peak doses of up to 5 Mrad can be accumulated within one year of HERA – B operation. According to radiation damage studies [127, 128], a perforated injection molded polystyrene based scintillator will still keep more than 50% of light output after irradiation with such a dose. Standard WLS fibres such as Bicron BCF-91a or Kuraray Y-7 or Y-8 show substantial loss of light conversion efficiency and transparency after irradiation up to 5 Mrad [126, 127, 129].

The longitudinal dose distribution for the calorimeter is determined mainly by the electromagnetic shower profile. It is shown in Fig. 217 b as a function of the scintillator plate number for the ECAL tower closest to the beam axis. Since the length of WLS fibres suffering from maximum

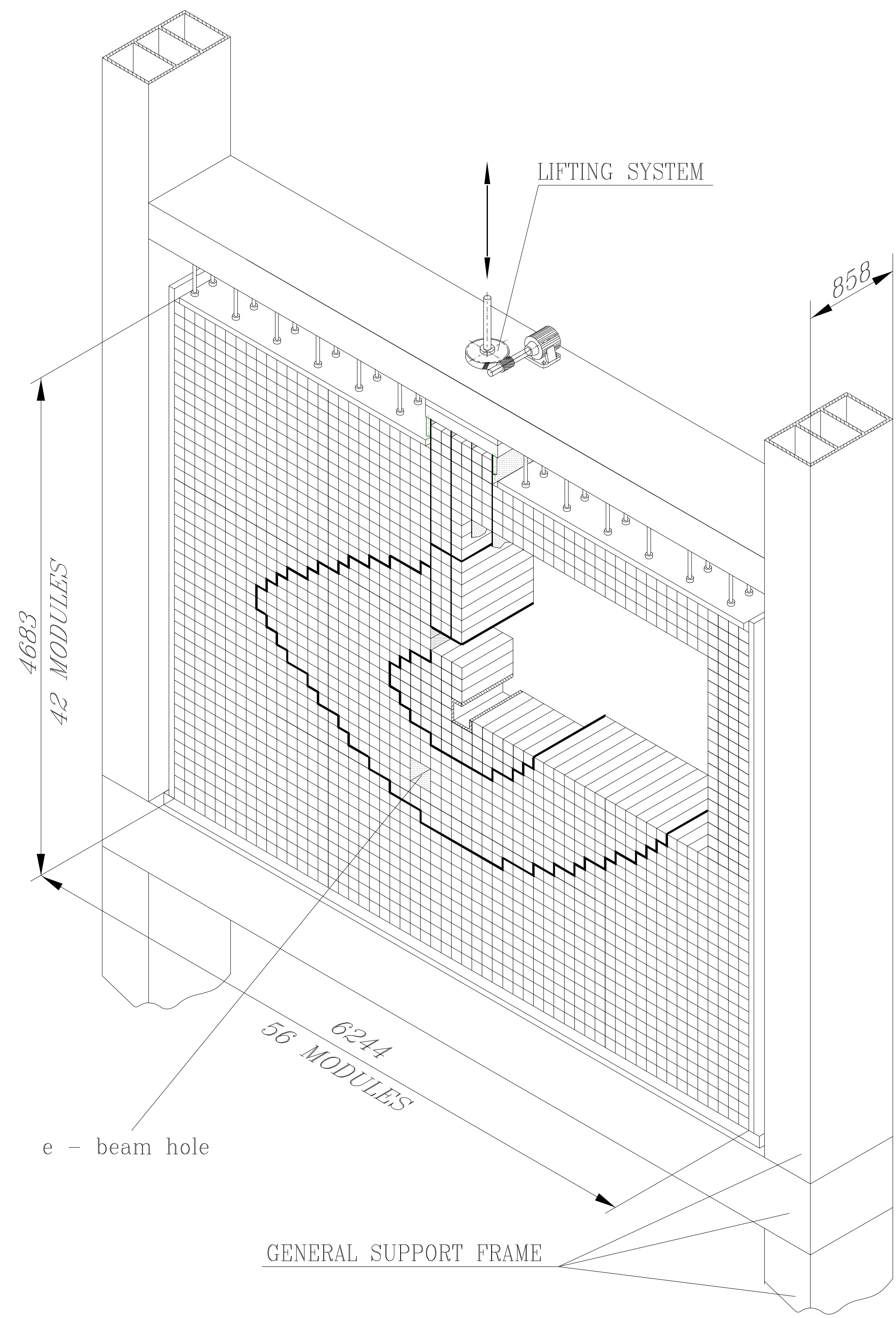

Figure 214: *Isometric view of the calorimeter. Inner, middle and outer regions are separated by the bold plotted lines. The numbers are in mm.*

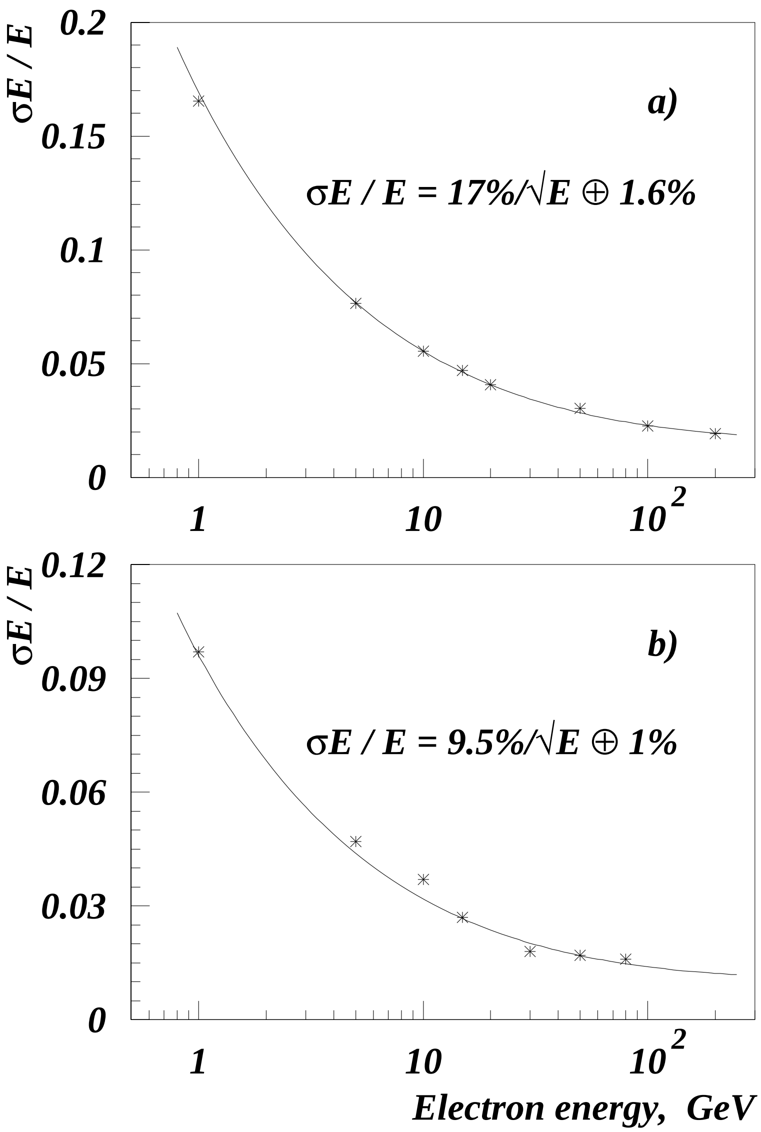

Figure 215: *Energy resolution of the inner (a) and middle/outer (b) ECAL modules.*

irradiation is rather short, we expect that the calorimeter modules of the proposed design could operate with an acceptable deterioration of their resolution up to doses of 5 Mrad. The decrease of each channel response will be monitored and compensated by adjusting the HV power supply of the photomultipliers (PMs).

Up to 16 of the innermost calorimeter modules are considered to be replaced after each year of HERA – B operation at nominal luminosity. The expected maximum doses for the rest of the inner ECAL section are 3-5 times lower; so the replacement of these modules is not foreseen.

The maximum radiation dose accumulated by the PMs in the vicinity of the beam pipe is expected to reach about 1.5 Mrad/year (see Fig. 217 b). The dose is decreasing rapidly with the increase of the distance between PM and the beam pipe. Since the conventional borosilicate glass window of a PM will lose about 15% of its transparency in the light wavelength range of 480-500 nm after an irradiation up to 0.3 Mrad [130], FEU-68 PMs with radiation hard silica windows will be used for

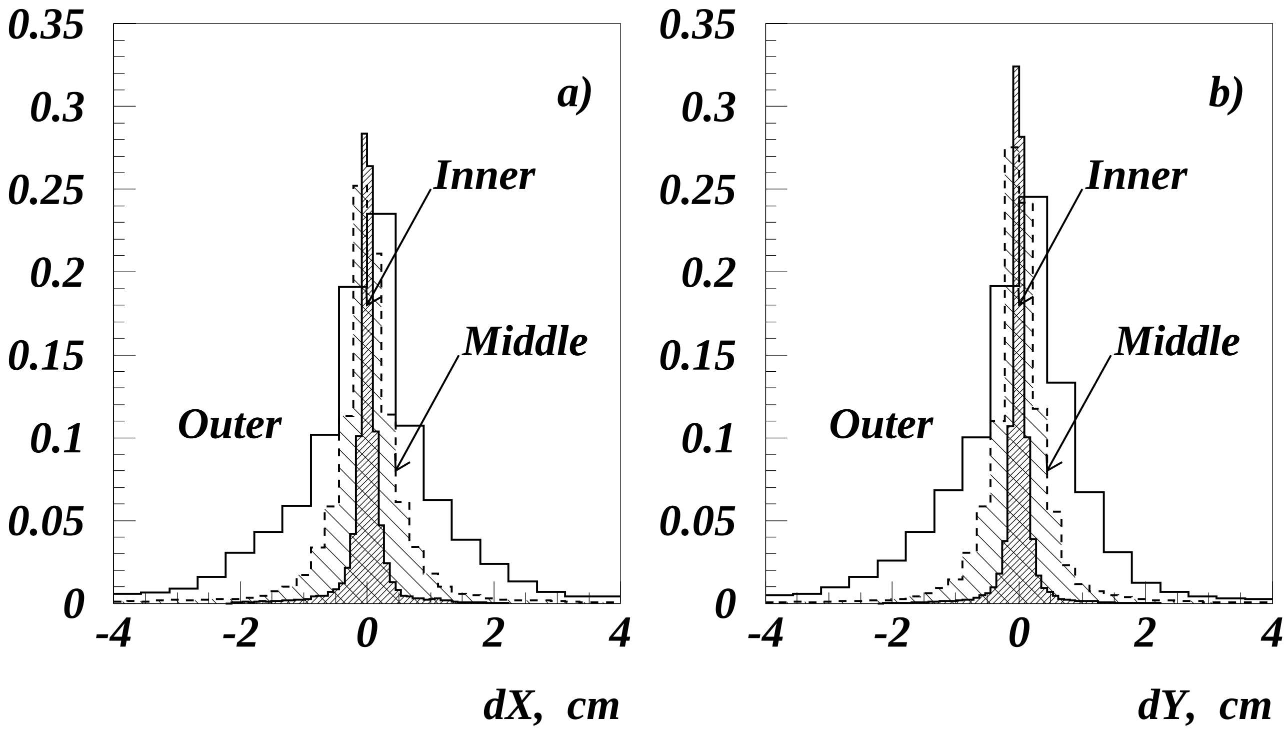

Figure 216: *Spatial resolution of ECAL modules in horizontal (a) and vertical (b) directions.*

Table 70: *Spatial resolution of ECAL modules.*

	Horizontal	Vertical
Inner module	σ=1.2 mm RMS= 3.3 mm	σ=1.1 mm RMS= 2.5 mm
Middle module	σ=4.2 mm RMS= 8.2 mm	σ=3.6 mm RMS= 6.5 mm
Outer module	σ=10 mm RMS= 17 mm	σ=9 mm RMS= 15 mm

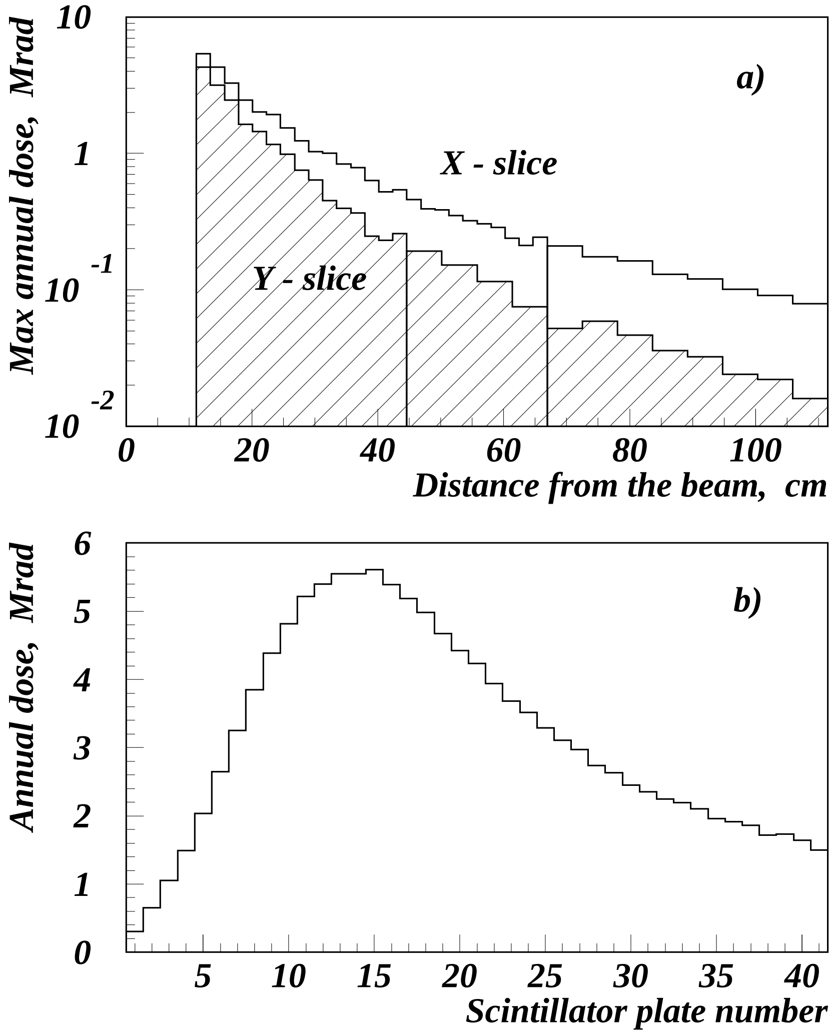

Figure 217: *Annual radiation load of the calorimeter. (a) Dose accumulated at the shower-max position; boundaries between the inner and middle sections of the ECAL are shown by vertical lines. (b) Longitudinal annual dose distribution for the most loaded inner ECAL tower.*

the inner calorimeter. FEU-115M PMs with a conventional windows will be used for the middle and outer parts of the ECAL.

11.2 Mechanics of the Calorimeter Modules

11.2.1 Construction of the Inner ECAL Module

A module of the inner calorimeter, shown in Fig. 218 and Fig. 219, has a transverse segmentation of 5×5 towers. It is constructed from alternating layers of 2.2 mm thick heavy metal alloy of W-Ni-Fe (2), white reflecting paper (6), and 1 mm thick injection molded polystyrene-based scintillator tiles (1). In total, there are 41 scintillator and 40 absorber layers resulting in a total depth of 22 X_0. The transverse granularity is achieved by assembling each module out of 25 identical scintillator tiles (A-A cross-section) with the edges aluminized to improve light collection and to prevent tile-to-tile light crosstalk. The light is readout via 1.2 mm diameter WLS fibres (3) penetrating the entire length of the module. The 1.5 mm diameter holes for the WLS fibres are arranged on a square lattice with center-to-center spacing of 11.1 mm. Thus each tower is equipped with 4 WLS fibres bound together, polished and coupled to their own PM (22). The positioning of the fibre bundles is fixed by a stiff plastic plate (16) attached to the back of the module using tie-bolts (18). There is a 1 mm air gap between the polished surfaces of the WLS bundles and the PMs. At the front of the tower the fibres are cut and aluminized. The rigidity of the complete stack is provided by front (7) and rear (4) stiff plastic plates and 0.15 mm thick stainless steel side covers (9) that are pretensioned and welded to both front (8) and rear (5) steel lids.

The 25 PMs (22), the corresponding Cockroft-Walton bases and the electronics (23) are mounted inside a rigid aluminum housing (B-B and C-C cross-sections). The PM housing and the module are tied together with specially machined bolts (18,26).

11.2.2 Construction of the Middle and Outer ECAL Modules

The construction of the middle and outer calorimeter modules is shown in Fig. 220. Conceptually this design follows the ideas developed for the PHENIX calorimeter at BNL [131]. The outer calorimeter module consists of one individual tower; the middle calorimeter module is subdivided into 2×2 towers. Both modules are composed of a stack of 38 (6 mm thick) scintillator and 37 (3 mm thick) lead plates having a total depth of 20 X_0. White paper (0.1 mm thick) separates the lead from the scintillator surface. For the middle ECAL module each scintillator layer is assembled from four identical scintillator tiles. The lateral edges of all tiles are aluminized. The pattern of the 1.5 mm diameter holes for the WLS fibres, shown in the cross-section C-C, is the same for the middle and outer modules. The currently proposed WLS fibres are Bicron BCF-91a with a diameter of 1.2 mm. Each module comprises a total of 72 u-shaped WLS fibres, which are inserted in the holes of the scintillator/absorber stack. The bending radius of the loop is $\sim$ 14 mm; so each fibre penetrates through the holes separated vertically by two holes. Similar to the inner modules the lead/scintillator tiles are compressed together using stainless steel side covers. The PMs, Cockroft-Walton divider and electronics are housed inside the stainless steel cylindrical tubes attached to the back side of the module.

11.2.3 Assembly of the Calorimeter Modules

The assembly procedure is illustrated in Fig. 221 for an inner calorimeter module. The basic steps of this procedure are: stacking of the module (A); insertion of the WLS fibres (B); grouping the fibres into bundles and polishing (C); and connecting the PM housing (D).

The module assembly begins with the cover side welding to the front stainless steel lids (A). In order to align the lead and scintillator plates, two rods per scintillator plate are passed through the stack. These rods are calibrated steel spits of 1.3 mm diameter. After stacking, the assembly is put under cyclical compressive forces to stabilize the lead plates and paper. After this stabilization phase, the side covers are welded to the rear stainless steel lid, then the locating rods are removed.

The front edges of the WLS fibres are aluminized before the insertion into the holes. When inserted, the fibres are grouped into bundles and fixed in the fibre housing plastic plate (C). The ends of the fibres are covered with epoxy glue. After epoxy hardening the fibre bundles are trimmed and then polished. The module assembly is completed by the installation of the PM housing (D). Wrapping with a black tape provides light insulation of the module.

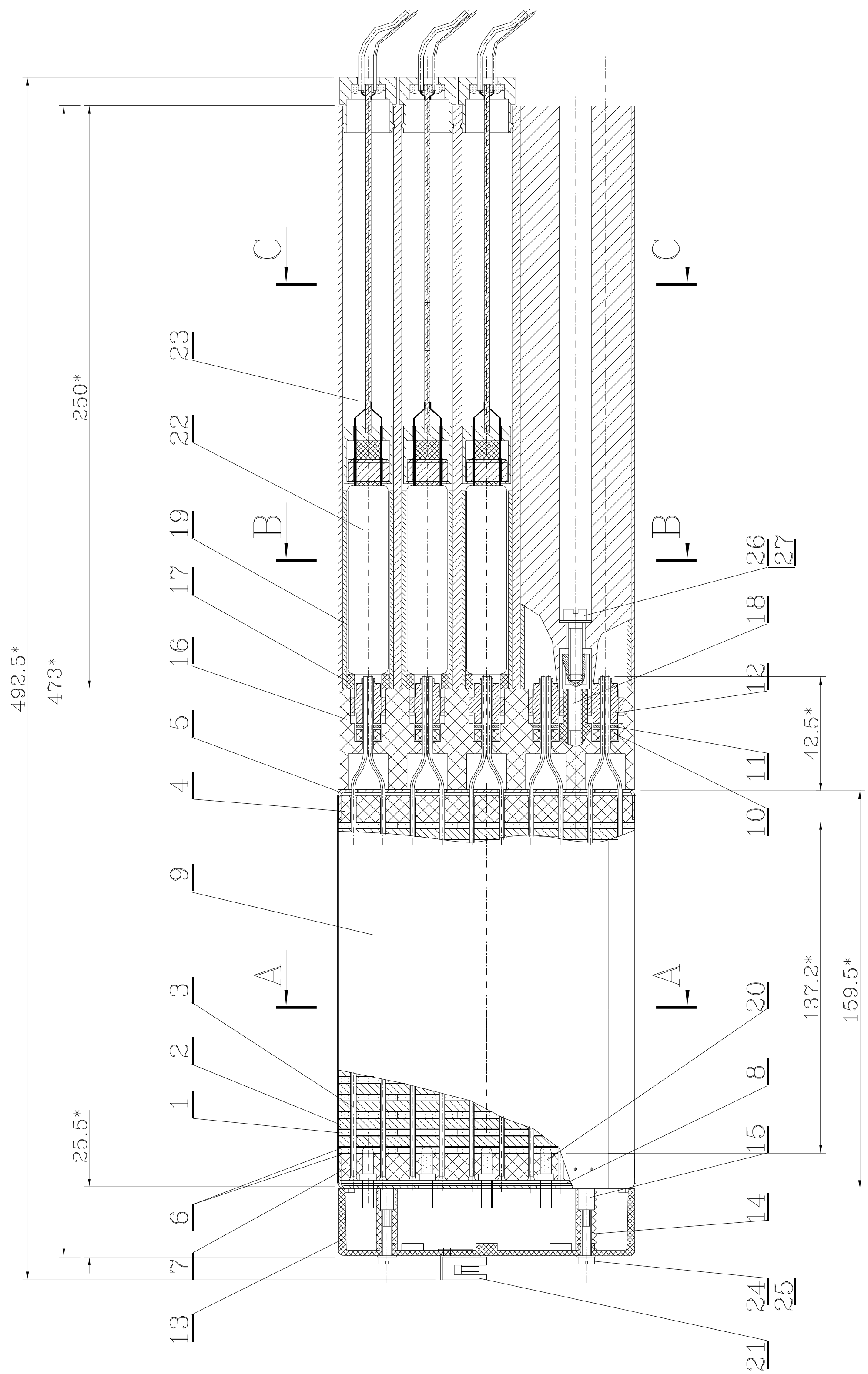

Figure 218: *Inner module (details of the base arrangement are not shown). See Fig. 219 for more details.*

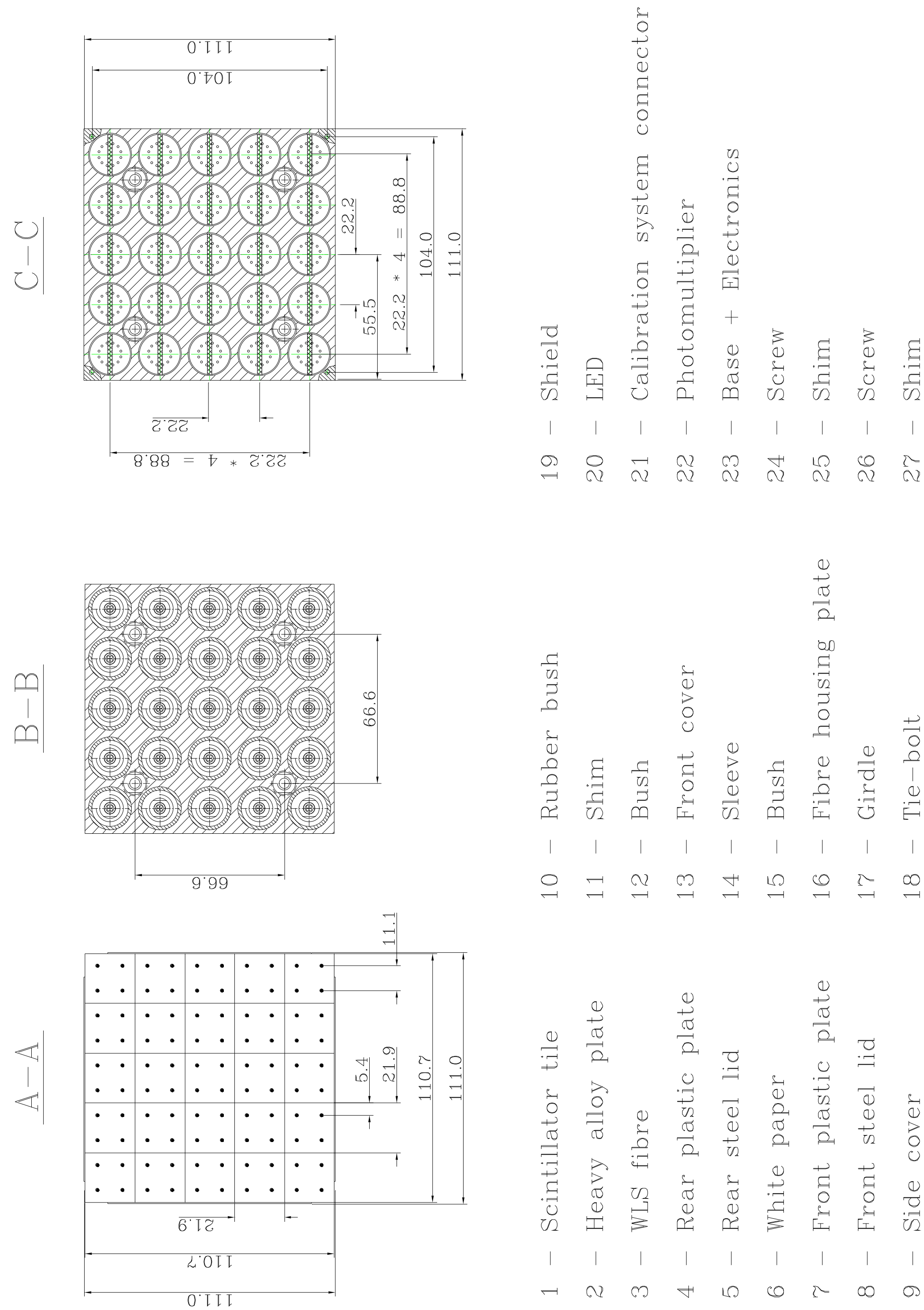

Figure 219: *Inner module (Cont. Fig. 218).*

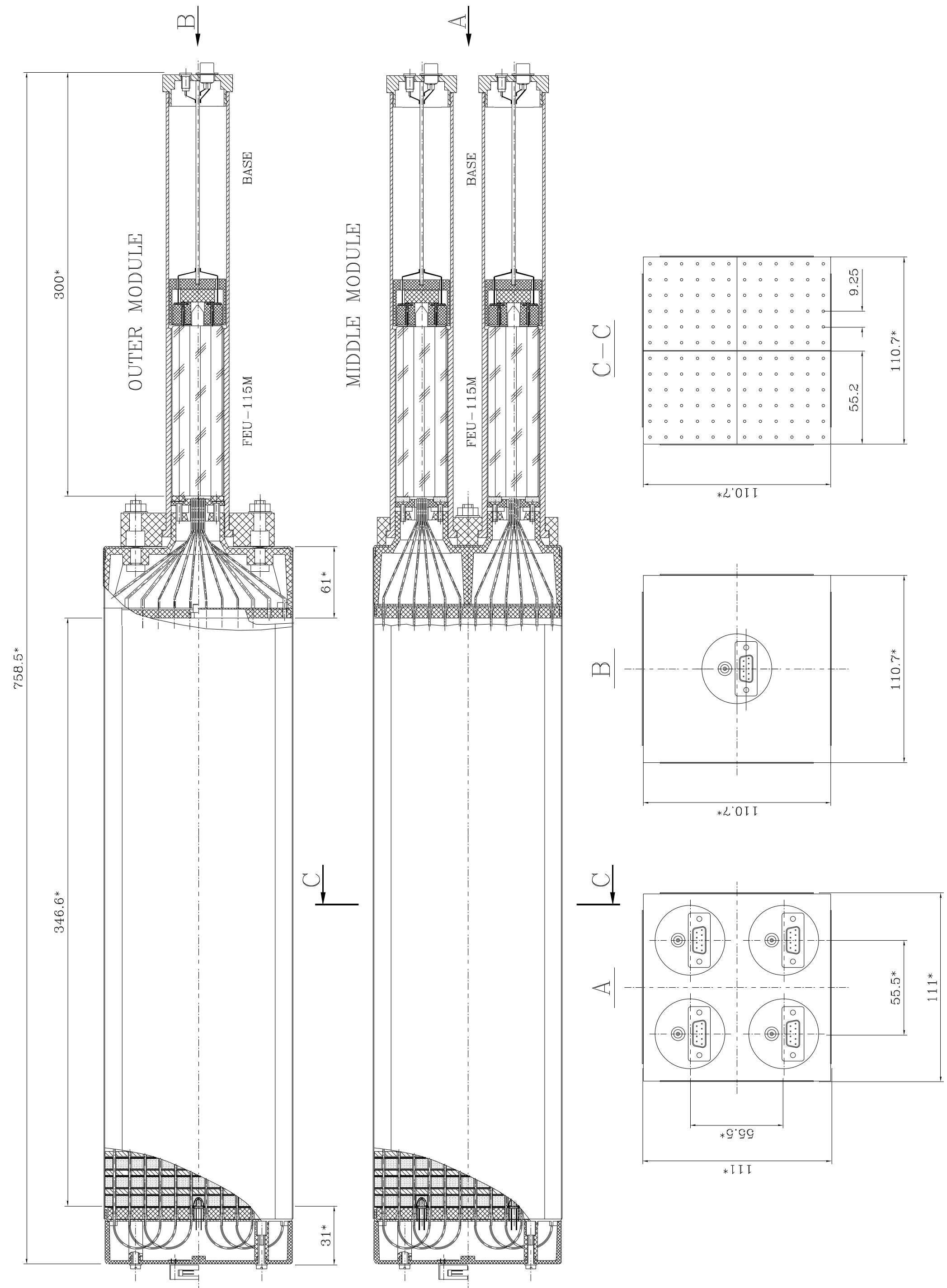

Figure 220: *Drawings of the middle and outer modules.*

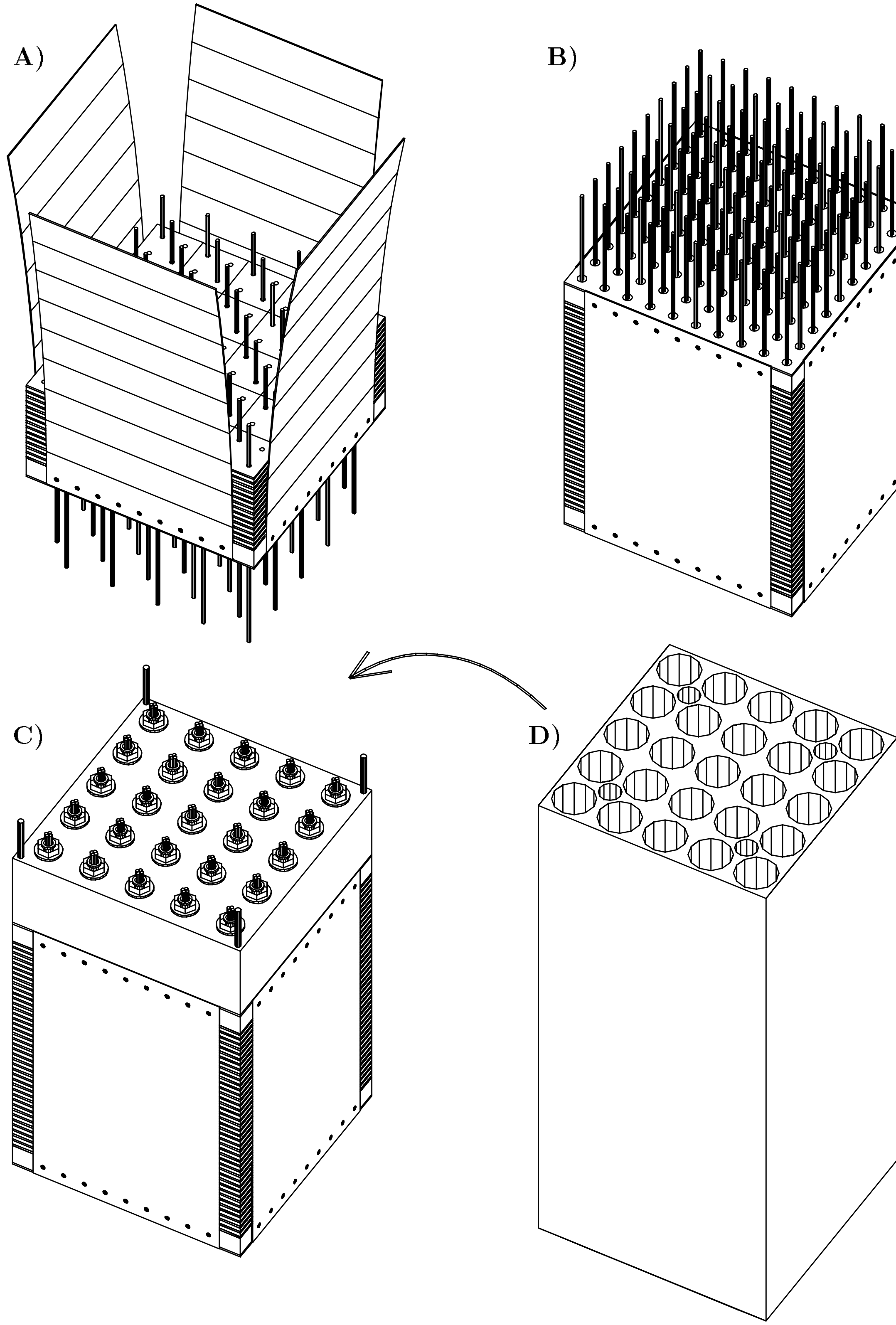

Figure 221: *Assembly procedure of the inner module. (A)-stacking of the module; (B)-insertion of the WLS fibres; (C)-grouping the fibres into bundles; (D)-installation of the PM housing.*

11.3 Support Structure and Assembly of the Calorimeter

11.3.1 Mechanics of the Support Structure

The calorimeter will be located at the end of the middle HERA – B platform. Since the design of the middle platform is not finalized, Fig. 222 illustrates only conceptual ideas of the calorimeter installation. The calorimeter is assembled inside the frame composed of stable beams (1,2,3). These beams are elements of the middle platform. The supporting beam (1) should be stable enough (maximum deformation $Y_{max} < 0.5$ mm) to carry the total weight of the calorimeter with a specific load of 8 t/m. A specially machined plate (4) is placed on the beam (1) to provide the assembly surface for the calorimeter.

The alignment cheeks (5) are arranged on the sides of the calorimeter to adjust the horizontal rows of modules laterally during assembly. The adjustment is achieved using tuning bolts (8) attached to the cheeks. The vertical stability of the assembly is ensured with two fixation plates (6,7). The lifting system (9) is attached to the upper beam (3) requiring additional space on the top of the beam (3) for service area.

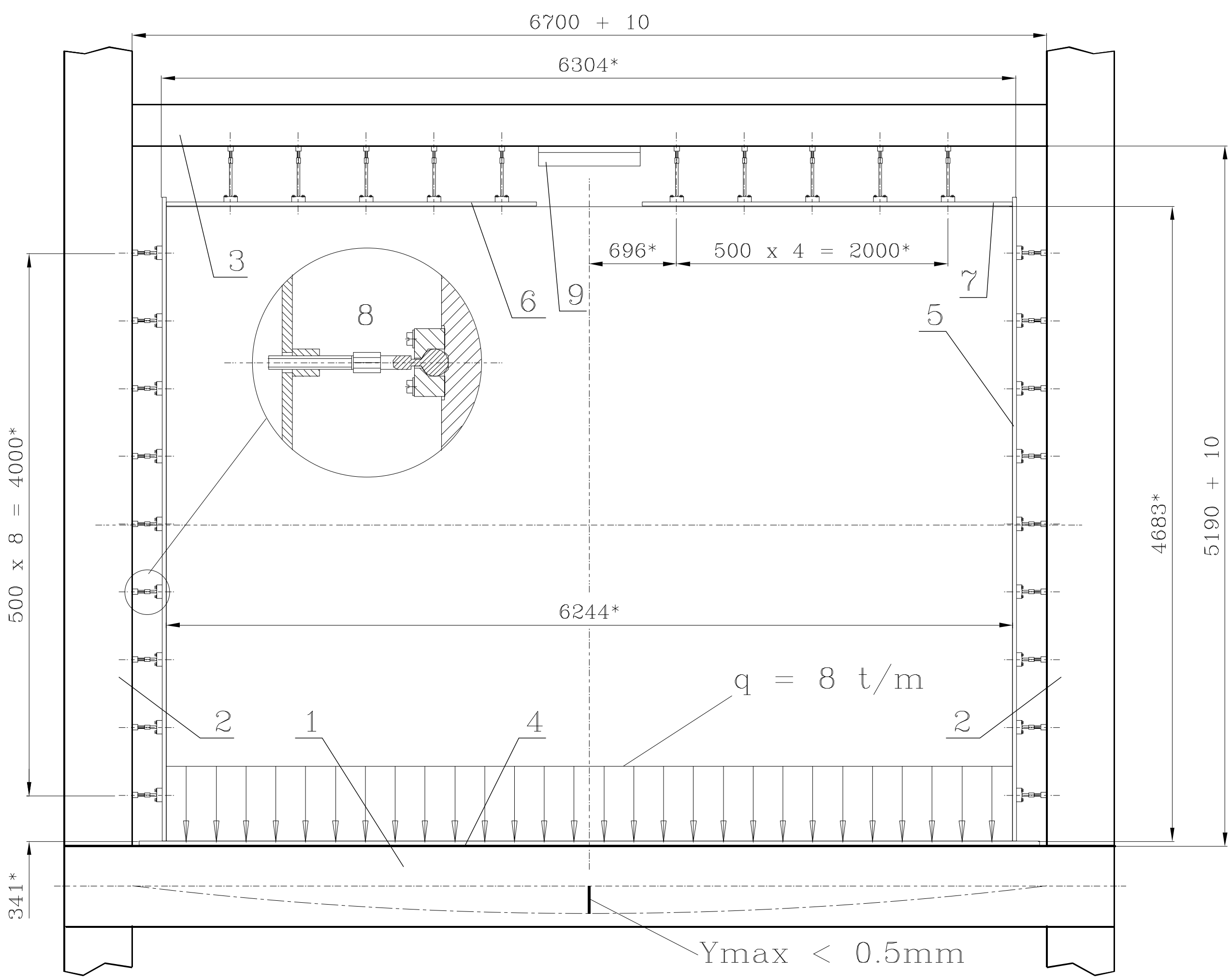

Figure 222: *Conceptual view of the support structure installed on the middle platform.*

11.3.2 Mounting of the ECAL Modules into the Support Structure

The assembly of the calorimeter is shown schematically in Fig. 223. It is assumed that there will be the possibility of access from both upstream and downstream of the calorimeter. The assembly will be done from the downstream position using a bridging fixture attachable to the side beams.

The installation procedure begins with the vertical fixation of one of the side cheeks at the reference position. The rows of modules are mounted from the bottom to the top. Each 5 rows are kept in tension adjusting tuning bolts located at the opposite side cheek. A 500 μm thick stainless steel band separates the neighboring rows of modules in order to distribute local stresses and ease lateral adjustment. To ensure a regular structure, pieces of the same band are inserted between the modules in the vertical direction as well.

In order to replace the innermost calorimeter modules damaged by radiation, there are three loops of 250 μm thick lifting bands extending from the central part of the top beam to the inner ECAL section. Each loop provides the lifting of two columns of modules. The loops are put in place after the completion of the assembly of the row corresponding to the upper edge of the inner calorimeter section. After that, the modules to be lifted are inserted into the tensioned lifting loops while the rest of the rows are assembled in the common way. In order to ease the lifting of the calorimeter modules, two extra 250 μm temporary bands are envisaged from both sides of the movable calorimeter stack. These temporary bands are used only during the assembly and will be removed at the final stage thus providing the required tolerances.

The assembly of the calorimeter is completed after the upper row is mounted. Then the whole assembly is compressed using the upper fixation plates.

11.3.3 Cabling

The cables to be connected to each calorimeter tower are: the signal cable, 5-wire flat cables to feed the Cockroft-Walton base and preamplifier and one twisted pair for the base steering current. In addition, there are calibration system cables (2 wires per tower) from the upstream edge of the calorimeter. Feed cables form chains connected in series to the PMs of each column. The cable sockets will be placed on the PM housing rear cover except for the modules of the inner section where is too little room for such a design. For the modules of the inner section cables from the PM housing are routed through tight holes to the outside and terminated only there in a connector. The calorimeter cables will be placed on a support grid and then routed to the electronics racks. The support grid is made of a steel angle profile that carries the attached cables. Such a cabling scheme allows an easy access to the PMs and their bases.

11.4 Readout of the Scintillation Light and Calibration System

11.4.1 Requirements to the Phototubes

As it was shown in prototype tests [3] the amount of light produced in the module of the middle and outer ECAL sections is equivalent to ~1,600 p.e. per 1 GeV of deposited energy. For the inner calorimeter module the expected light yield is smaller (~250 p.e./1 GeV) because of thinner scintillator plates and a smaller sampling frequency. The rather large amount of light makes it possible to use conventional PMs for the calorimeter readout provided that they meet the ECAL

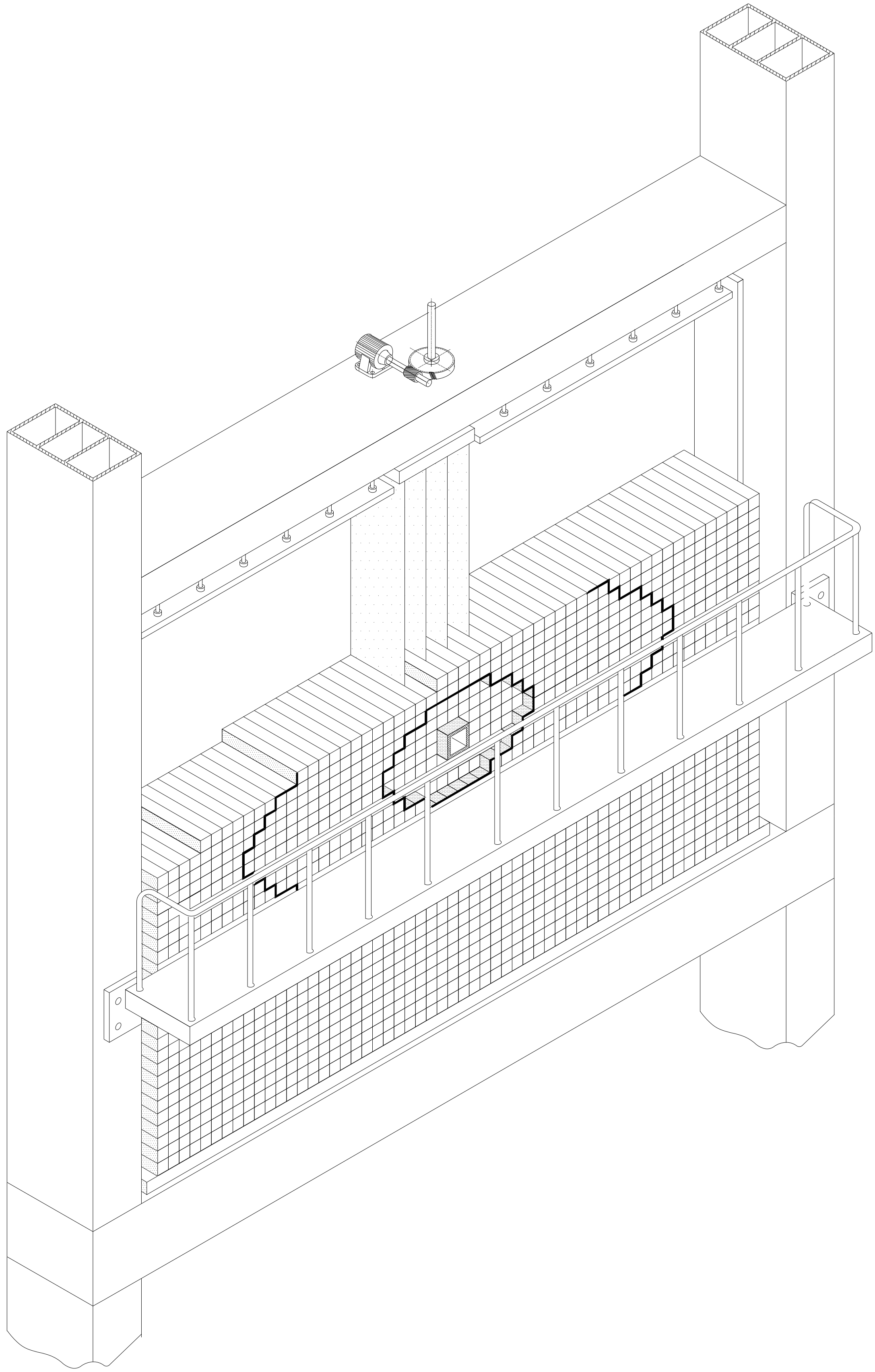

Figure 223: *Mounting of the ECAL modules into the support structure.*

requirements.

The list of requirements for the calorimeter PMs is given in Table 71. The dynamic range is determined by the maximal energy of electrons from $J/\psi \to e^+e^-$ decay and the value of the

Table 71: *Requirements to the calorimeter PMs.*

	Inner section	Middle and outer sections
Maximal E_e	300 GeV	200 GeV
Maximal $< E >$	1.6 GeV	0.3 GeV
Light yield	250 p.e./GeV	1600 p.e./GeV
$< I_A >$	$\leq 1.4 \mu A$	$\leq 4.2 \mu A$
Maximal I_A	1.9 mA	20 mA
Gain	$\leq 2.3 \times 10^3$	$\leq 5.8 \times 10^3$

calorimeter response to a minimum ionizing particle (MIP), which is equivalent to a ∼300 MeV energy deposit. The maximum energy deposit in the ECAL module and the linearity limits of the proposed PMs put requirements on the PM gain. The corresponding mean anode current is small enough to keep the gain degradation below the 10% level per one HERA − B year.

Since the light spectrum emitted from the WLS fibres used in the calorimeter modules peaks at 490 nm, PMs with a green sensitive photocathode are preferable. Another important consideration is the photocathode uniformity over the area coupled to the WLS fibres. The best choice in terms of cost and performance appears to be to use the Moscow MELS factory products FEU-68 for the readout of the inner and FEU-115M for the middle and the outer ECAL sections, respectively. The specifications of these phototubes are listed in Table 72. Both types of PM have a multi-alkali photocathode with a sensitivity range between 300 and 820 nm. The tube diameters match well the calorimeter cell sizes.

The recent results of laboratory tests of FEU-68 and FEU-115M are presented in Table 73. The PM linearity has been measured using a uniform divider for FEU-68 and a "progressive" one for FEU-115M. The use of a uniform divider for FEU-115M may decrease its linearity range by a factor of about 5. Both types of PM have a good cathode uniformity and linearity range which are well within the necessary PM requirements for the HERA − B calorimeter.

Aging tests of FEU-68 and FEU-115M are in progress at ITEP. Both phototubes are being exposed by the light from a green LED. The photocathode response is shown in Fig. 224 as a function of the charge collected at the first dynode of FEU-68. No degradation is observed for collected charges up to 0.3 C. This amount is equivalent to the operation in the HERA − B environment during 30 years.

11.4.2 Power Supply

The HV supply system has to provide stable PM operation at high particle rates of up to 10 MHz in the HERA − B calorimeter. We propose a Cockroft-Walton base solution which can provide an average output current as large as 0.1 mA and a current pulse amplitude of up to 200 mA. A 300 channel system had been built and tested for a gamma tomograph at ITEP. The main parameters of the proposed scheme are summarized in Table 74. In order to reduce the number of stages in the Cockroft-Walton base (due to space limitation) a uniform distribution of potentials at the last

Table 72: *Specifications of FEU-115M and FEU-68.*

PM type	FEU-115M	FEU-68
Manufacturer	MELS, Moscow	MELS, Moscow
Light sensitivity range	300-820 nm	300-820 nm
Photocathode diameter	25 mm	10 mm
External PM diameter	30 mm	15 mm
PM length	110 mm	70 mm
Number of stages	12	10
Cathode sensitivity	$\geq 80\mu A/lm$	$\geq 80\mu A/lm$
Anode sensitivity	100 A/lm	$1A/lm$
Operating voltage	2000 V	1400 V
Rise time ($20\% - 80\%$)	≤ 5 ns	≤ 5 ns

Table 73: *Results of laboratory tests of FEU-115M and FEU-68.*

PM type	FEU-115M	FEU-68
QE at WLS fibre emission spectrum	13%	not measured
Cathode uniformity over the central area	$\oslash$ 10 mm $rms = 5\%$	$\Box$ 3 mm $rms = 6\%$
Linearity at 2% level	> 50mA (100%) > 100mA (50%)	> 1mA (100%) > 1.9mA (50%)
Gain (HV[kV])	5×10^5 (1.8) 10^6 (2.0)	5×10^3 (1.0)

dynodes of the PMs is envisaged.

11.4.3 Calibration and Monitoring System

In situ calibration constants for the calorimeter will be obtained from experimental data using isolated particles that have their momenta precisely measured in the tracker. As was estimated in [3], a sufficiently large data sample ($\sim 10^3$ electrons and 10^3–10^5 hadrons) can be collected for the calibration of each ECAL cell within a few hours of HERA – B running.

The energy flow measurement provides another possibility for calibration and monitoring. A subset of calorimeter modules will be calibrated at test beams at ITEP, DESY and CERN. In situ the absolute calibration of this subset can be transferred onto the entire calorimeter by measuring the average energy deposited from all pN interactions per cell and using an interpolating procedure.

For large PM-based systems, the calibration from experimental data must be complemented by a stability monitoring system aimed to correct for the time-dependent gain variations in the PMs and

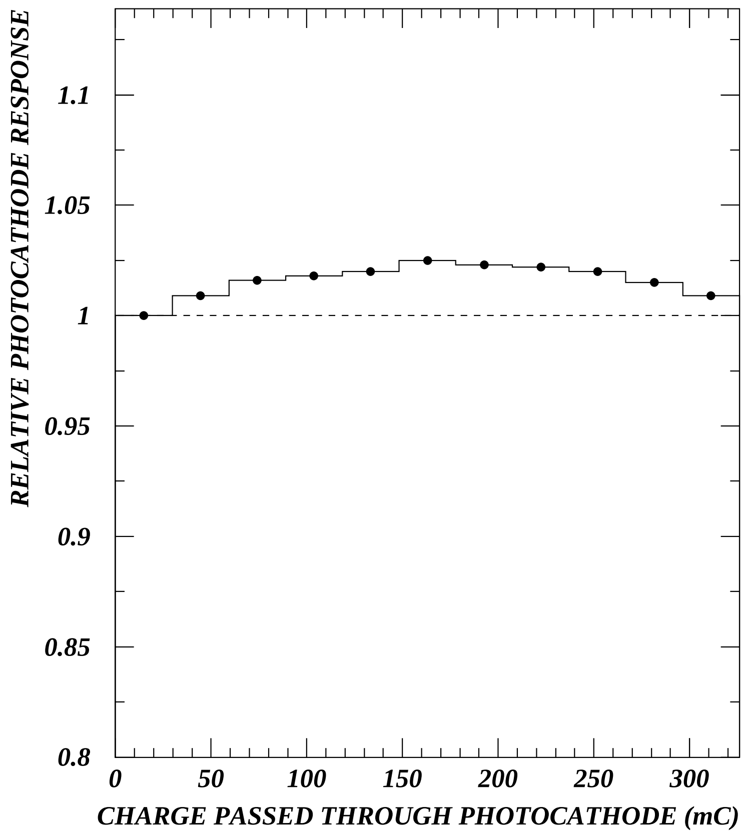

Figure 224: *FEU-68 PM photocathode response as a function of the charge collected at the first dynode.*

Table 74: *Parameters of the Cockroft-Walton base.*

HV range	0-3 kV
Step of HV monitoring	2-10 V
Power supply	100-300 V $\rightarrow$ 1-3 mA +(5-18) V $\rightarrow$ 10-15 mA -(5-18) V $\rightarrow$ 10-15 mA
Ripple	$<$100 mV at HV=3 kV $<$7 mV at HV=1.5 kV
Allowed average anode current (no change in parameters)	$15\mu A$
Long term stability	$<$0.005
Allowed distance to the remote control system	100 m

to provide a post-installation test of the calorimeter. At present we are considering two monitoring techniques based on the use of either multiple blue LED assemblies ($\sim$ 430 nm emission length) or a high intensity nitrogen laser. The mounting of the LEDs at the front surface of the calorimeter modules is shown schematically in Figs. 218 and 220. The LED light is injected into the center of the first scintillator layer of each calorimeter tower. Rescattered in the plastic, blue light gets into the WLS fibres and propagates down to the corresponding PM. For the laser-based monitoring technique, the light can be transported to the calorimeter modules using a system of quartz optical fibres.

Monitoring studies using flashing light sources report better than a few percents stability [133]. Both monitoring systems will be developed in parallel. The final choice will be made after further *R&D* studies.

11.5 Calorimeter Electronics

The aim of the front-end electronics is to ensure the calorimeter pretrigger and to provide analog signals for digitization. The pretrigger efficiency can be improved if, besides the information on the energy of the cluster candidates, the electronics is capable to give also information on the cluster centroids. Another substantial improvement would be achieved if it were possible to recover the energy losses due to bremsstrahlung photons.

Adding up all these requirements, it seems that they can be more easily fulfilled if we adopt an early digitization of the calorimeter signals. A very appealing solution in this direction seems to be the one offered by the FERMI (Front End Readout MIcrosystem) system developed for LHC by the RD16 collaboration [132]. The FERMI system is a digital multichannel data acquisition and signal processing module for high resolution calorimetry. It is implemented as a Silicon-on-Silicon multichip microsystem. A large Si substrate ($\approx 5 \times 5$ cm^2) with 4 metal layers supports the various ASICs, components, interconnections etc. At the moment there are demonstrator prototypes that handle nine complete channels. Three different ASICs have been developed for these prototypes: the "Analog", the "Channel" and the "Service" ASIC. These ASICs perform dynamic range compression, digitization at sampling frequencies up to 80 MHz, various controls on chip and digital signal processing. The latter includes data linearization, pedestal subtraction and zero suppression, trigger functions and pipelining. All these features lead to obvious advantages in stability, noise immunity, programmability and the possibility of providing absolutely normalized data. Fig. 225 shows a simplified FERMI block diagram.

The design of the FERMI prototypes was of course driven by LHC requirements. Some specifications can be relaxed in the case of HERA – B with no sacrifice in performance, for example the signal sampling frequency (due to the longer time between bunch crossings), a slight reduction in bit resolution and no specific demands for radiation damage.

11.5.1 ECAL Front-End and Readout

The electromagnetic calorimeter readout is requested to measure energies ranging from 0.3 GeV (release of a MIP) up to 300 GeV. In order to discriminate MIPs from the ADC pedestal, this implies a 14 bit dynamic range.

The front-end chain (Fig. 226) will consist of a shaping CR-RC amplifier followed by a signal compressor to adapt the signal dynamic range to the 10-bit ADC response. As an example, the response of one compressor developed by the RD16 collaboration is shown in Fig. 227.

For reasons of noise reduction we plan to have the shaping amplifier and compressor placed near

Figure 226: *ECAL front end readout chain.*

Figure 227: *Compressor response curve.*

the PM output. The readout boards will be placed around the ECAL boundaries with distances up to a few meters.

The readout ADC will be probably based on the FERMI Analog ASIC whose performances match the ones requested by our experiment at a reasonable cost. Table 75 summarizes the performance of the first complete FERMI ADC prototype.

Table 75: *PSA-ADC characteristics.*

Number of bits	10
Input range	0–2 V
Input capacitance	1.7 pF + pad capacitance
Analog bandwidth	$>$ 35 MHz
Power supply	+5 V
Core circuit size	2.7×3.3 mm^2
Sampling Clock frequency	40 MHz (70 MHz)
DNL	$\pm$0.5 LSB ($\pm$0.75 LSB)
INL	$\pm$0.68 LSB ($\pm$1.10 LSB)
Number of missing codes	0
Power consumption	225 mW (267 mW)
Technology	1.2 μm CMOS

We intend to use for our readout a simplified version of the features offered by the Channel and Service ASICs, possibly developing the essential support logic for the FERMI ADC and the proper signal extraction for our pretrigger directly on the readout board. Regarding this last point, as it will be discussed in the next subsection, the demand of the pretrigger to the readout electronics is to extract the converted data and to compare it with an energy threshold, generating a flag when the signal exceeds it. The converted data and the flag have then to be pipelined in a 128 word depth memory. The time to get the converted data and the flag to start the pretrigger analysis using this FERMI ADC (or similar) may be estimated in about 20 clock cycles, and working at 80 MHz this means about 250 ns after the bunch crossing.

11.5.2 ECAL Pretrigger

The purpose of the ECAL pretrigger electronics is to:

- find the calorimeter clusters,
- compute the cluster energy $E_c = \sum E_i$,
- compute the cluster coordinates X_c and Y_c,
- apply appropriate selection cuts, and
- pass to the FLT the energy of bremsstrahlung photons in order to reconstruct the correct electron energy.

In the following we will consider that the development of an electron shower is contained within a 3x3 matrix of calorimeter cells, so the i index, in the formula above, has to run from 1 to 9. The necessary operations will be performed on dedicated circuits that read the data from the readout system. A conceptual design of the ECAL pretrigger is shown in Fig. 228.

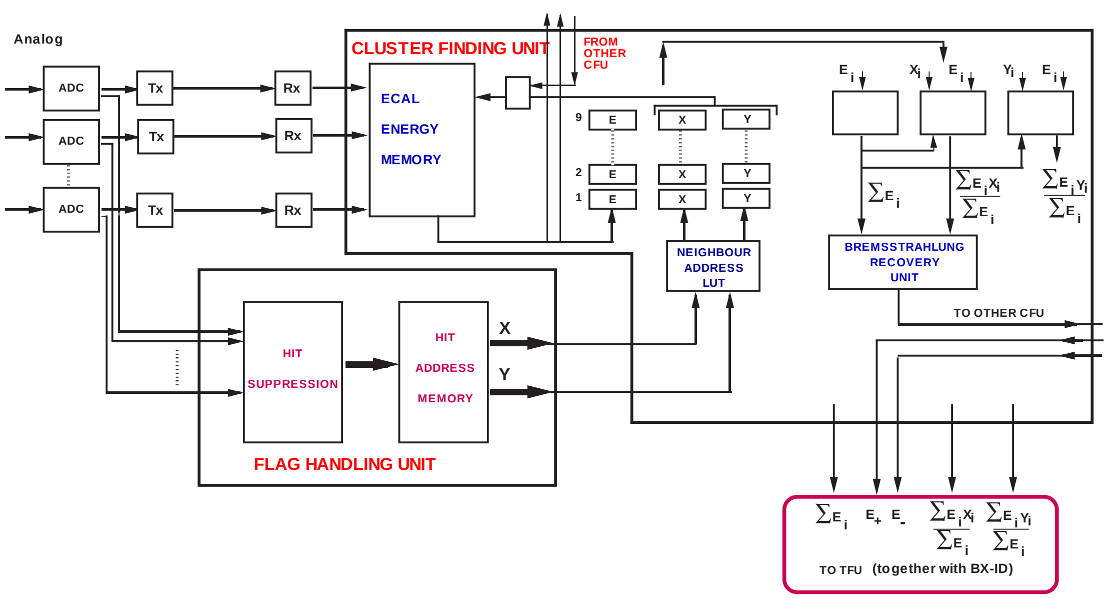

Figure 228: *Block diagram of a possible ECAL pretrigger electronics scheme.*

In order to get the relevant quantities for the electromagnetic shower, a fast handling of the digitized data is performed by flagging the release of energy above a preset threshold E_{cut}^{trig} in the calorimeter towers. In the following we will refer to a tower with a flag set as a *hit tower*.

The first block we find in Fig. 228 is a Flag Handling Unit (FHU) that converts the flag coordinates in absolute coordinates for the hit tower in the calorimeter. To perform this action the flags are processed in parallel by a Hit Suppression Unit (HSU) and by a Hit Address Memory (see Fig. 229). The HSU is necessary in order not to load heavily the data processing of the CFUs, and to perform the reduction of two (or more) hit towers close to each other into one. While the flags are processed by the FHU the energy data are stored into the ECAL Energy Memory in the Cluster Finding Unit (CFU). So in this scheme there is no need for a fast transmission of the digitized data and a straightforward 100 MHz data transmission is sufficient.

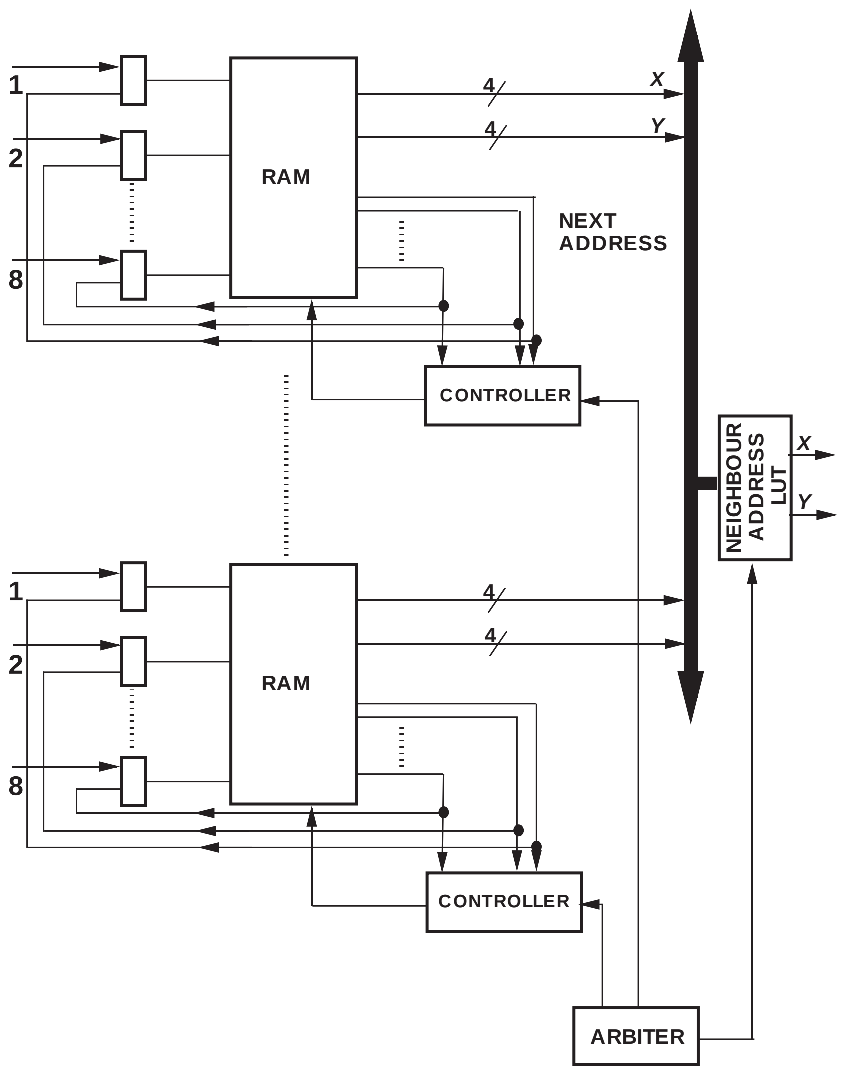

Figure 229: *Schematic diagram of the Hit Address Memory block in the HFU.*

The coordinates from the HFU are fed into a Neighbour Address look-up table (LUT) where as an output the coordinates of the 8 towers that are first neighbours to the hit one are given. The coordinates of the hit tower and of the 8 first neighbours are used to recover the information on the released energy in the ECAL Energy Memory. At this point, for each hit tower there are nine triplets consisting of (x_i, y_i, E_i). Arithmetic logic units implemented with LUTs perform the calculation of the total energy E_c and of the energy centroids (X_c, Y_c) for the 3x3 matrix centered around the hit tower. The centroids algorithm implemented in the LUTs will take in account the corrections for the cluster shape. The two quantities E_c and X_c are used by the Bremsstrahlung Recovery Unit (BRU) to start the search for a possible deposit of energy of bremsstrahlung photons. This information can be recovered inside the same CFU or in some other CFU. The possibility to have access to the ECAL Energy Memory of other CFUs has been foreseen only for the bremsstrahlung recovery phase, in order not to load too much the communication bus among CFUs. Since at the pretrigger level there are two possible solutions due to electron charge sign ambiguity, BRUs have to recover two values of energy for the bremsstrahlung photons, E_+ and E_-. Finally, E_+ and E_- together with E_c, X_c,Y_c and the bunch crossing identifier are sent to the proper TFU to start the FLT. The handling of the bunch crossing identifier is managed by the readout chip.

The CFU circuit shows the feasibility of an efficient ECAL pretrigger using the possibility offered by a fast digitization of PM signals. All the components in the board are standard ones, and the overall response time for the FLT can be kept below 2 μs.

One problem that has to be faced to have a good clustering efficiency is related to the towers that constitute the border for the CFU, i.e. the towers whose first neighbours are located in another CFU. This problem can be solved by splitting the signals of these towers into two CFUs. In one of these CFUs this signal will be used only in the calculations when it is not the central tower in the 3x3 matrix; in the other CFU this signal will be used only when the tower to which it refers is a hit tower. Of course one CFU must handle only the flags relative to hit towers that have their first neighbours inside the CFU itself; if we design CFUs that handle 100 channels this fact will imply an increment of the number of CFU channels of about 40%.

The scheme shown in Fig 228 is open to some possibilities, related to the design of the readout boards, that are now under study. For example, one could think to implement this electronics (or part of it) in the readout board itself: this would probably lead to a reduction of the cost of the pretrigger system and to a simplification (the ECAL Energy Memory block, together with the data transmission system would not anymore be necessary). Waiting for these developments, we will refer in the cost analysis of the system to an implementation of the CFUs on standard 9U VME boards. The cost evaluation therefore represents an upper limit for the cost of the ECAL pretrigger electronics.

11.6 Slow Control

The slow control system should provide the following functions for each calorimeter channel:

- The monitoring of the high voltage supply for the Cockroft-Walton base.
- The monitoring of the low voltage supply for the Cockroft-Walton base.
- The monitoring of the Cockroft-Walton base steering current.
- The stability of the calibration pulse system.
- The digital control of the ECAL threshold setting.

11.7 Mass Production

The organization of the calorimeter modules mass production must assure the necessary production rate (about 10 modules per day). The major part of the module components will be ordered in industry; assembly itself will be performed at ITEP. Various checks and tests are planned at each stage of the module assembly.

All module components: absorber plates, scintillators, reflecting paper, fibres will undergo visual inspection for any imperfections.

During the production of the scintillator tiles the quality control procedure will be as follows:

- Control of the chemical dopants by chemical methods.
- Control of the light yield of the tiles before the edge metalization. This will be done using a wavelength shifter setup, a FEU-115M PM and a radioactive source.
- Control of the metalization quality which includes a measurement of the light yield of selected tiles from each batch after the metalization procedure.

The light yield and transmission of selected WLS fibres will be checked for each batch of fibres. Tests of the photomultipliers include a photocathode area uniformity tests, a quantum efficiency test and linearity tests. All HV-distributors will be checked electrically.

As a final check a cosmic ray test is planned for all produced modules of the middle and outer calorimeter sections. Particles crossing the modules perpendicular to the fibres produce about 100 p.e. and 200 p.e. response for modules of the middle part and of the outer part respectively. The MIP peak position is determined with an accuracy of $\sim$ 1% for statistics of several thousand events per tower which could be collected in several hours. During this test the module light yield and response uniformity along the fibres will be checked. All modules of the central part (80 pieces) are planned to be tested at the ITEP and DESY accelerator beams.

The design and manufacturing of assembling equipment (assembly tables, tools for welding, test devices) will start in 1995. At the same time the preparation of the drawings of the module components, tools for module component production and their manufacturing will take place. The module mass production will start in mid 1995. The first batch of 500 assembled modules will be ready in the fall of 1995.

11.8 Transport and Acceptance at DESY

Modules produced and tested at ITEP will be packed in wooden boxes and transported by truck to DESY based on experience gained by the transportation of the H1 SPACAL calorimeter assembled at ITEP. In order to store the manufactured modules at DESY one needs shelves with a total area of about 250 m^2. The corresponding floor area has to be at least 50 m^2 if the shelves are arranged in 5 rows.

For the module acceptance tests at DESY a cosmic stand similar to the facility at ITEP will be used. For a module in the vertical position the cosmic counting rate is about 1 count per minute. Cosmic particles deposit about 600 p.e. in one module of the middle and outer sections and about 100 p.e. in one module of the inner section in this geometry. In order to test all modules within 6 months one needs to test 20 modules every day. The cosmic ray stand will be equipped with four hodoscope planes of scintillators (20 trigger counters of 11×55 cm^2), 20 channels of discriminator, 10 coincidence units, 20 HV channels, 30 channels of ADC and the necessary DAQ.

All inner calorimeter modules will be tested at one of the DESY test beams.

11.9 Cost Estimate and Time Schedule

The results of a detailed cost estimate for the electromagnetic calorimeter are summarized in the following. Table 76 shows the cost of the three different types of modules and Table 77 the cost of the complete system including readout electronics. A tentative time schedule for the design, production and test of the calorimeter is given in Fig. 230.

11.10 The Calorimeter *R&D* Program

11.10.1 Prototypes

Because of the large amount of calorimeter modules to be produced on a rather short time scale the *R&D* program is focussed on the development of the construction procedures for the middle and outer ECAL modules such that mass production can begin not later than in summer of 1995. The milestones of this effort are as follows:

- The middle ECAL pilot module assembled at ITEP will be mechanically tested with a load of up to 800 kg corresponding to the weight of one column of the calorimeter wall. Possible deformations of the lead absorber plates and the WLS fibres are subject of these studies. Experience gained with injection molded polystyrene based scintillator showed no effect on the scintillator surface quality when held under a similar pressure.
- Assembly and full beam tests of 3×3 matrices of pilot modules for the middle and outer ECAL sections. The testing program will make use of beam time at ITEP, DESY and CERN.

The inner calorimeter section consists of 80 modules which can be fabricated and assembled within 1 year. However a dedicated *R&D* study is needed prior to the production phase. The key issues being addressed for the inner ECAL modules are:

- Development of a technology for the fabrication of absorber plates made out of either tungsten or heavy metal alloy with a density larger than 17.3 g/cm^3.
- Development of the technology for the production of holes in the absorber plates.
- Test of the injection molding technique for 1 mm thick scintillator tiles.
- Study of the light collection efficiency in 2×2 cm^2 scintillator tiles of 1 mm thickness read out with 4 WLS fibres.

A prototype of the inner calorimeter module is being manufactured at ITEP. The module is composed of 40 tungsten plates of 2 mm thickness interleaved with 1 mm thick scintillators. The transverse dimension is 80×80 mm^2. Tungsten plates have been produced by rolling and then grinding to ensure the required flatness. The holes have been pierced using an electro-erosion method.

Table 76: *Calorimeter Cost, Cost per Module in DM.*

Inner module (5x5 cells)	Total	10 387
	Scintillator (rad. hard)	442
	Machining	208
	Tungsten	1 520
	Machining	3 230
	WLS fibres	112
	PM (FEU68) + Ampli.	1 875
	HV divider	2 125
	LED	25
	Connectors	325
	Cabling	475
	Add. equipment	50
Middle module(2x2 cells)	Total	2 269
	Scintillator	58
	Machining	870
	Lead	19
	Machining	157
	WLS fibres	122
	PM(FEU115M)	480
	HV divider	340
	LED	4
	Connectors	52
	Cabling	124
	Add. equipment	43
Outer module	Total	1 502
	Scintillator	58
	Machining	870
	Lead	19
	Machining	157
	WLS fibres	122
	PM (FEU115M)	120
	HV divider	85
	LED	1
	Connectors	16
	Cabling	34
	Add. equipment	20

Table 77: *Calorimeter cost for the complete system (in kDM).*

Inner section	Total	1 246
	80 Inner modules	831
	40 Spares	415
Middle section	Total	1 191
	500 Middle modules	1 135
	25 Spares	56
Outer section	Total	2 731
	1768 Outer modules	2 656
	50 Spares	75
Design, mechanics	Total	1 520
	Design, prototypes	500
	Tools for assembly	950
	Support structure	70
Readout system	Total	1 775
	6300 Front-end channels	945
	90 Pretrigger boards	630
	6 VME crates	90
	Monitoring	60
	Prototypes	50
Transportation	Total	50
Front-end + readout	Total (cost/channel in DM)	150
	Shaper/compressor/ADC	20
	Memory, LUT	20
	Control logic	20
	Assembly, cables, tests	90
Pretrigger board	Total (cost/board in DM)	7 000
	Board	2 500
	Components	3 000
	Assembly	1 500
Total cost		**8 513**

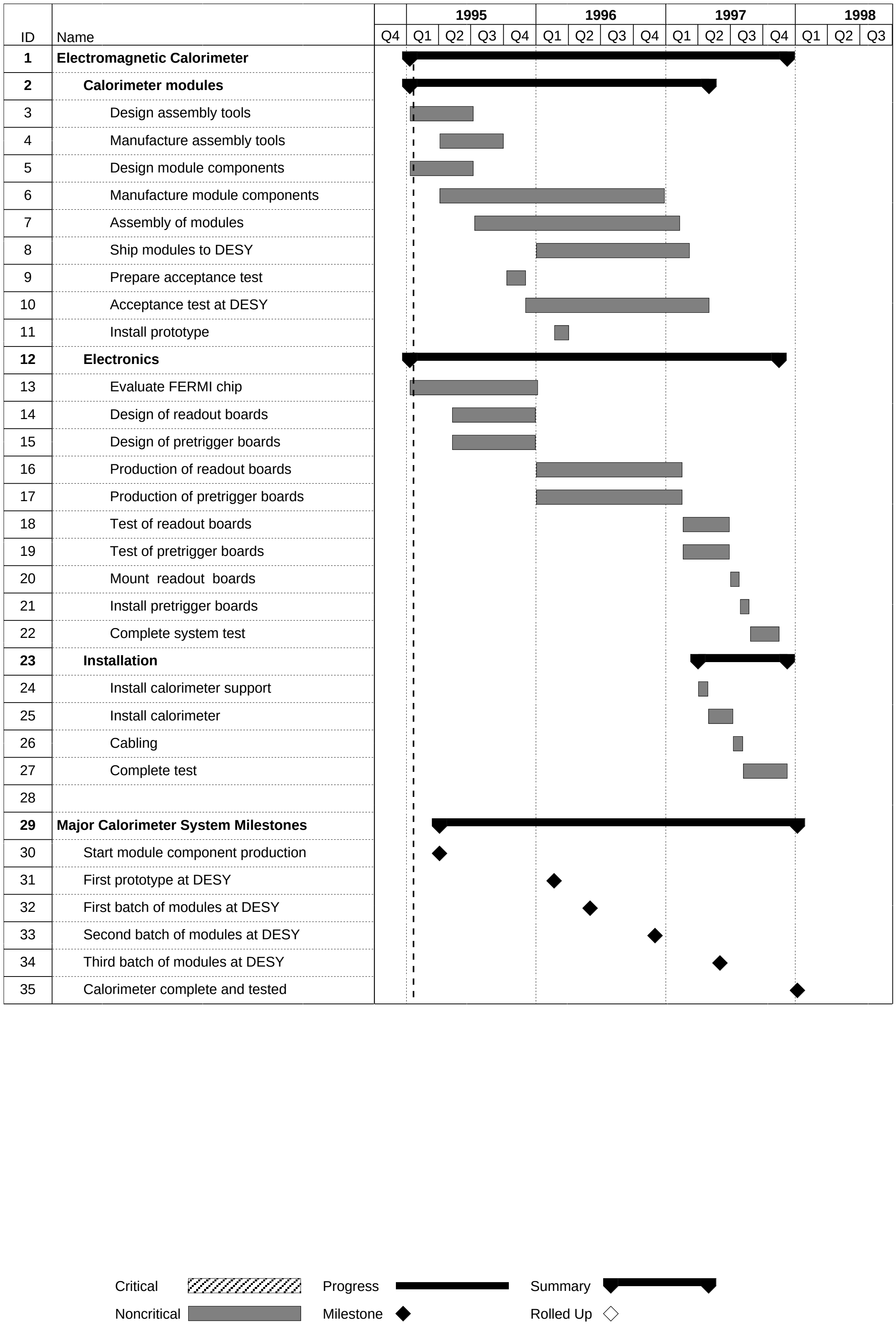

Figure 230: *Tentative time schedule for building the calorimeter.*

As an alternative technology we have ordered in industry a set of absorber plates made out of heavy metal alloy (W-Ni-Fe) containing 93% of tungsten. A heavy metal powder will be baked in a device incorporating a 1.5 mm hole pattern on a 11.1 cm grid. Each scintillator plane is subdivided into 16 cells of 20x20 mm^2 size. Each cell contains 4 WLS fibres which are viewed by a FEU-68 PM.

The response to electrons and MIPs as well as the energy resolution and uniformity over the module front face will be measured at ITEP and DESY test beams. A measurement of the lateral shower profile for electrons is of particular importance to confirm the expected Moliere radius for the inner calorimeter module.

11.10.2 Radiation Hardness

In order to validate the expected radiation hardness of the proposed design of the ECAL we plan to irradiate in 1995 one module of the inner ECAL in a high energy electron beam up to doses of 10 Mrad at the EM shower maximum and to measure the decrease in light output and the deterioration in energy resolution as a function of the accumulated dose. If the light output will decrease by more than a factor of three or the energy resolution will deteriorate by more than 30% after irradiation up to maximum dose of 5 Mrad, one should consider a backup solution of using existing scintillator/fibre combinations with longer wavelengths in order to provide improved radiation resistance [1].

The beam test of the prototype will be complemented by a radiation test using a container equipped with a Co^{60} source. The light yield degradation of the scintillator/WLS fibre assembly and the darkening of the PM window will be checked for doses up to 10 Mrad.