H1 Backward Upgrade with a SPACAL Calorimeter: the Hadronic Section

H1 SPACAL GROUP

Abstract

The design, technological aspects, tests and first results on performance of the hadronic section of the H1 Backward Lead/Scintillating-Fibre Hadronic Calorimeter are described and discussed.

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1 Introduction

The H1 collaboration has upgraded the H1 detector [1, 2] at HERA during the winter shutdown 1994–95 with a new backward lead scintillating fiber calorimeter (SPACAL) consisting of two sections, electromagnetic and hadronic. The primary goal of the fine-grained electromagnetic (e.m.) section is the measurement of the energy and impact point of scattered electrons or positrons with high precision, down to angles of 177° with respect to the proton direction. The hadronic section aims to measure electromagnetic energy leakage from the e.m. section and, in combination with it, to determine hadronic energy flow in the backward region (see [3] and references herein). The $\sim 1\lambda$ depth of the hadronic section (λ is a nuclear interaction length) together with $\sim 1\lambda$ of the e.m. part provides longitudinally- segmented calorimetry which improves the e/π separation capabilities [4], allows the measurement of hadronic jets and, based on precise timing, provides the H1 Detector with a time-of-flight veto on proton beam-induced background. Apart from physics requirements, the design of the hadronic SPACAL is strongly constrained by the fact that the newly-developed detector should fit into the existing mechanical structures of the H1 backward region. Finally, cost considerations, particularly the high price of the mesh dynode photomultiplier tubes, further restrict the number of channels and the granularity of the calorimeter.

2 Design and Principles

2.1 Mechanical considerations

The hadronic section, with its $\sim 1\lambda$ depth, is used as an instrument for leakage measurements, and as an important timing device, rejecting huge background rates coming into H1 from upstream (w.r.t. the proton beam) region. The entire hadronic section is an assembly of 128 cells, i.e. modules, which are packed parallel to the beam line within a cylindrical shell made of light alloy (see Fig.1). The signal from each module is processed by front-end electronics and then digitized and read out. The calorimeter has a simple non-projective geometry, and almost all modules have a rectangular cross section. A schematic drawing of a hadronic module is shown in Fig.2. The geometrical sizes of the individual modules have to allow for the mechanical and geometrical constraints in the H1 backward region; namely,

- The maximum load of the hadronic section onto the H1 cryostat is 4 tons [1]. In addition, the total longitudinal size is limited to 500 mm by the massive iron yoke covering the H1 backward region.
- Another mechanical constraint is the beam pipe diameter, which is 120 mm . For final installation of the whole hadronic section around the beam pipe, a vertical column of modules has to be removable. Thus the module cross section was chosen to be $\sim$120 mm$\times$120 mm to fit the beam pipe diameter. Only six such modules are needed to form the column, and a special steel band ties and compresses the modules together.

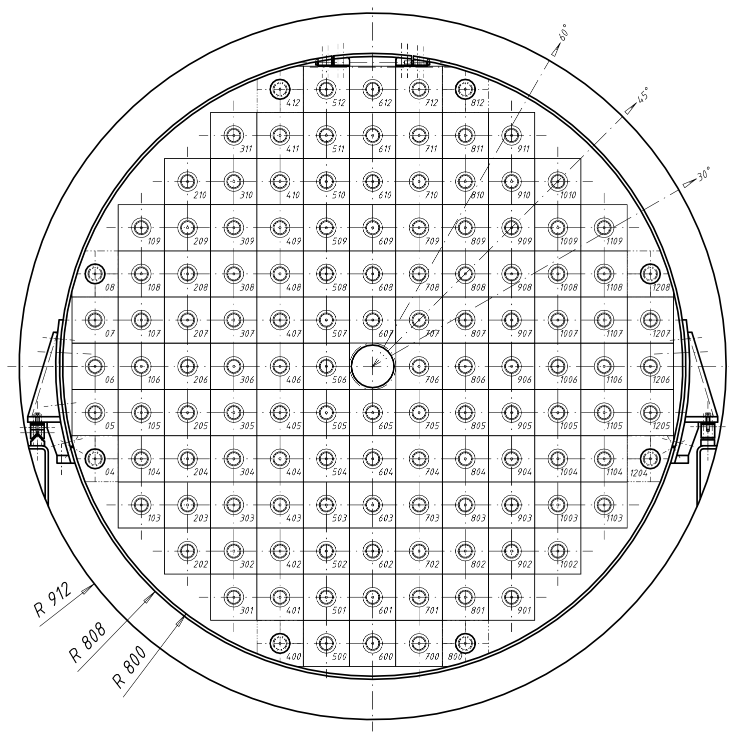

Figure 1: Rear view of the SPACAL hadronic section.

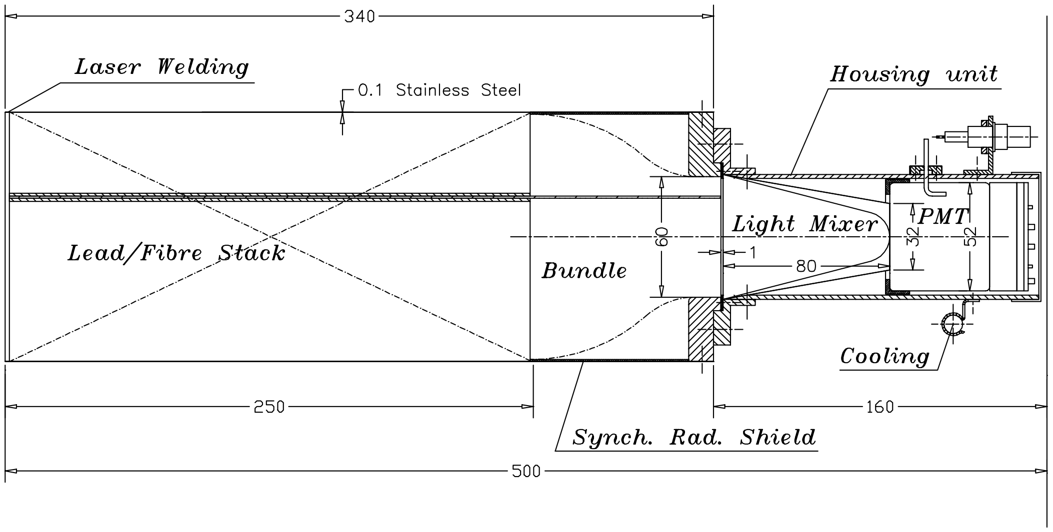

Figure 2: Schematic drawing of a hadronic module.

- The active depth of the calorimeter is limited not only by the total length mentioned above, but also by the length of the optical readout. This comprises the length of the phototube together with its active-base electronics, the light mixer, and the rear region where the fibres sticking out of the module are bundled together.

Based on these factors, we find that a good compromise was to choose a module length of 250 mm, giving an interaction depth of $\sim 1\lambda$. The cross-section of the module corresponds to $\sim 5\ R_M$ Molière radii. The final design parameters used for the module are summarized in Table 1. In the course of assembly within the cylindrical shell, thin kapton sheets (~0.1 mm) were layered between modules to smooth out the mechanical tolerances.

Parameter	Value
Total length of module, incl. housing	500 mm
Length of the active region	250 mm
Cell size, width × height	$119.3\times119.0\mathrm{mm}^2$
Number of lead plates per module	65
Thickness of one lead plate	1.90 mm
Number of modules	128
Angular coverage	$160^\circ \leq \theta \leq 178^\circ$
Fibre type	Bicron BCF-12
Fibre diameter	1.0 mm
Number of fibres in one layer	54
Total number of fibres/module	3510
Lead–Fibre mixture density	7.7 g/cm^3
Lead:Fibre ratio	3.41:1
Radiation length, X_0	0.85 cm
Nuclear interaction length, λ	24.6 cm
Molière radius, R_M	2.45 cm
Length of the active region	1.03 λ, 29.4 X_0
Photomultiplier tube	Hamamatsu 2$''$ R2490-06

Table 1: Design parameters of modules in the H1 SPACAL hadronic section

2.2 The lead stacks and related technology

For the H1 SPACAL hadronic section, scintillating fibres with a diameter of 1 mm have been chosen as the active medium. In order to keep the volume ratio Pb:fibre close to 4:1 [5] the fibre spacing was fixed at 2.22 mm (see Fig.3). The construction of the absorber uses a very simple technique, namely piling up of the grooved lead sheets. The sheets of lead are profiled using extrusion technology, which turned out to be optimal. Firstly, this technology provides regular spacing and longitudinal alignment of the grooves, as well as allowing them to be formed in one step on both sides of the lead sheet. Secondly,

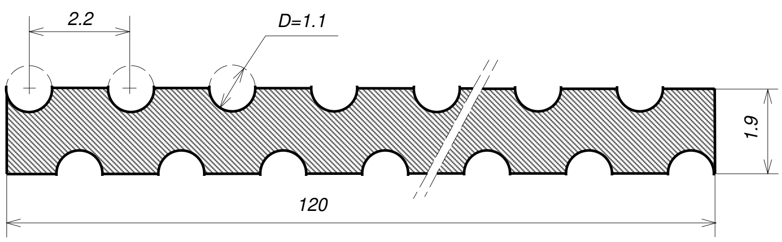

Figure 3: Profile of the lead sheets that were stacked to form the hadronic modules.

technology allows a reasonable production rate by the ITEP workshop. A special hard steel matrix with a corresponding negative profile was precisely machined at the ITEP workshop. To form the lead sheets, flat sheets 3.0 mm thick were cut from bulk rolls of lead and further rolled until 1.4 mm thick, then again cut to nominal size. With a pressing force of 180 tons the sheet is then extruded so that with the final profile it reaches an overall thickness of 1.9 mm . Each profiled plate can be made in less than one minute.

A special oil was used to lubricate the hard steel matrix. This measure prevents the plates from sticking to the matrix. Once profiled, the sheets were then washed for 10 minutes in a hot water bath to remove the residual oil.

The scintillating fibres delivered were cut to nominal size. The sheets and fibres were piled up inside the reference mould, keeping the right geometrical size of the whole stack body. Once piled and equipped with fibres, every plate was covered by a thin layer of epoxy in a narrow ~ 5 mm band. The epoxy envelopes each fibre and penetrates into the grooves of both plates. This measure was found to be necessary to prevent the fibres from dislocating and to make the module rigid. After assembly, every stack was kept under a 1 ton load while the epoxy polymerized.

After piling up of the lead sheets, the following important steps had to be carried out. To keep the module light-tight and mechanically rigid, the stack was packed in and compressed with 0.1 mm stainless steel. An industrial laser-welding machine was used to accurately weld the thin steel cover along the seams. To suppress the background from synchrotron radiation, an additional 1.5 mm-thick steel shield over the rear fibre area was installed (see Fig.2).

2.3 Optical readout

The 1 mm-diameter scintillating fibres used in the hadronic section are of type BCF-12 from Bicron. After extensive studies, the blue BCF-12 type was selected because the emission spectrum of these fibres matches the spectral sensitivity of the bialkali photo-cathode of the photomultiplier [2]. To enhance the light yield and to improve the uniformity of the fibre response, the front end of each fibre was polished and mirrored. At the rear end of the lead stack, the fibres sticking out were compressed with a special aluminum frame, bundled together and cut. One should mention here that the bundling area must be far enough from the rear end of the lead stack to prevent tight bends in the fibres, which would damage the cladding layer (Fig.2). To form a bundle, the bunch is impregnated and hardened with a black-coloured epoxy. Then the bundle is machined and the surface is carefully polished to achieve a good light yield.

All further elements of the optical readout, namely the light mixer and phototube equipped with an active base, were embedded and mounted in a common housing unit (Fig.2). The housing was then bolted to the rear aluminium frame of the module, keeping an air gap of 1 mm as an optical medium between the light mixer and the polished bundle surface. The $2''$ R2490-06 photomultiplier tube from Hamamatsu is coupled via the light mixer to the bundle. These tubes have a mesh dynode structure, and at the nominal high voltage of 2500 V achieve a gain of $\sim 10^5$ at a magnetic field of 1.2 Tesla (for details see [7]).

The light mixer serves as a light guide which also efficiently mixes the light to minimize effects due to non-uniform cathode response. After Monte Carlo studies, a cone of square-to-cylindrical shape was chosen. The diameter of the cylinder at one end, the length, and the side of the square at the other end, are 32 mm, 80 mm and 60 mm respectively, yielding an aspect ratio of 1.74:1, which is close to the optimum [6, 5]. The photomultiplier is glued directly to the cylindrical end of the light mixer. Then the assembled housing is carefully sealed against light.

3 Test-Beam Results and Performance

3.1 The set-up and the trigger

The measurements at ITEP were performed with a hadronic module produced in the workshop as a prototype during the R&D studies. The module was mounted on a movable table, and inclined in the vertical and rotated in the horizontal plane by 4°. The ITEP proton synchrotron delivers a beam with spills of 100 ms duration with an interval of 2.5 s between spills. The secondary beam is produced on an internal target. A system of quadrupole lenses and bending magnets provides a secondary beam with a $\Delta p/p$ of $\sim 1\%$. Data using a π^- beam with energies from 1 GeV up to 5 GeV, and electrons with energies between 1 GeV and 3 GeV, were taken. An upstream threshold gas Čerenkov counter was installed to achieve effective electron separation from the hadrons.

A conventional trigger formed with scintillation counters was used in the measurements. The coincidence of two wide upstream counters, together with crossed vertical and horizontal scintillating fingers (covering an area of $1 \times 1\,\mathrm{cm}^2$) installed near the front end of the module was demanded to trigger the event readout. Calibrated signals from an external generator were used to monitor the pedestals and the electronics. The signals from an active base, consisting of a high-voltage divider and a two-step emitter follower, were digitised by a CAMAC charge-integrating LeCroy 2249 ADC and then write out by a personal computer.

3.2 Response to electrons

The sample of data taken with the electron beam was analysed to estimate the electron response of the hadron modules. We used three energy points of 1, 2 and 3 GeV. The corresponding distributions are displayed in Fig.4 . The spectra have a nice Gaussian

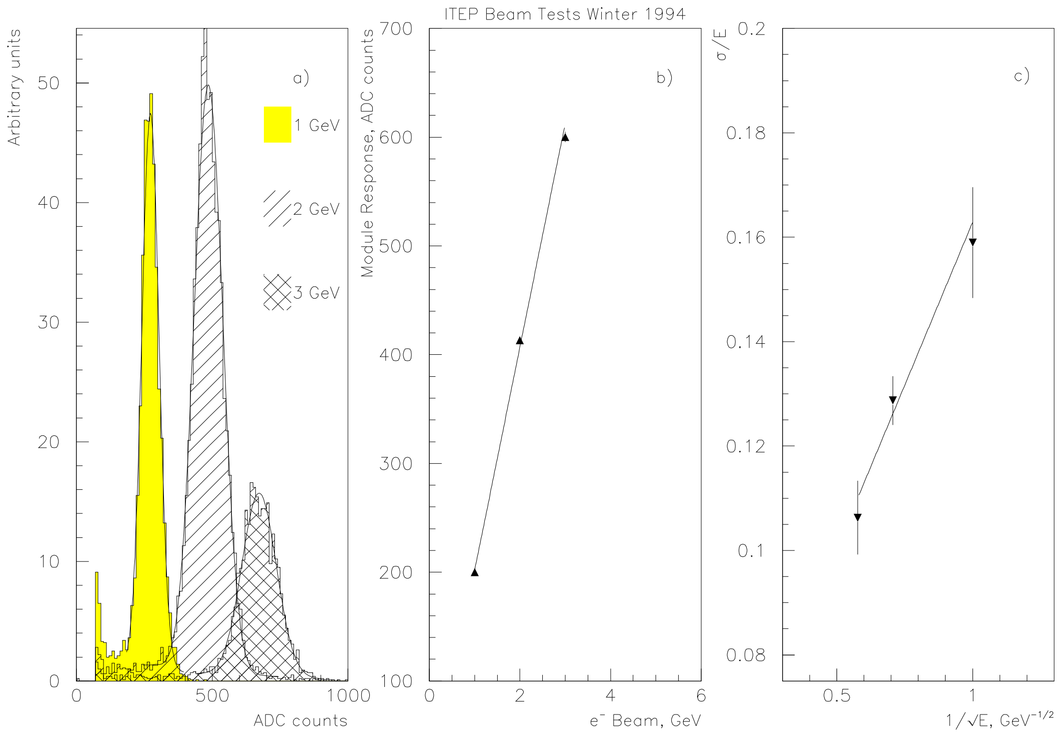

Figure 4: Response of the hadron module to the ITEP electron beam: a) signal spectra in ADC counts, b) linearity of the response, c) fit to the electromagnetic resolution.

shapes, and after pedestal subtraction were fit by a Gaussian function (Fig.4a). The fitted mean values are plotted versus the incident electron energy, and reveal quite good linearity as shown at Fig.4b. The resolution as a function of energy is parametrised as

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus c \, .$$

The fit of this function to the data yields

$$\frac{\sigma}{E} = \frac{(12.5 \pm 3.0)\%}{\sqrt{E}} \oplus (3.8 \pm 2.2)\%.$$

(see Fig.4c). The beam-energy smearing of $\sim$ 1% has been subtracted quadratically from the initial σ. The contribution of the sampling term is in good agreement with the results from the beam tests of the hadronic modules carried out at CERN later (see [4]). This measurement agrees with the results found in other projects utilizing lead/fibre calorimetry [5].

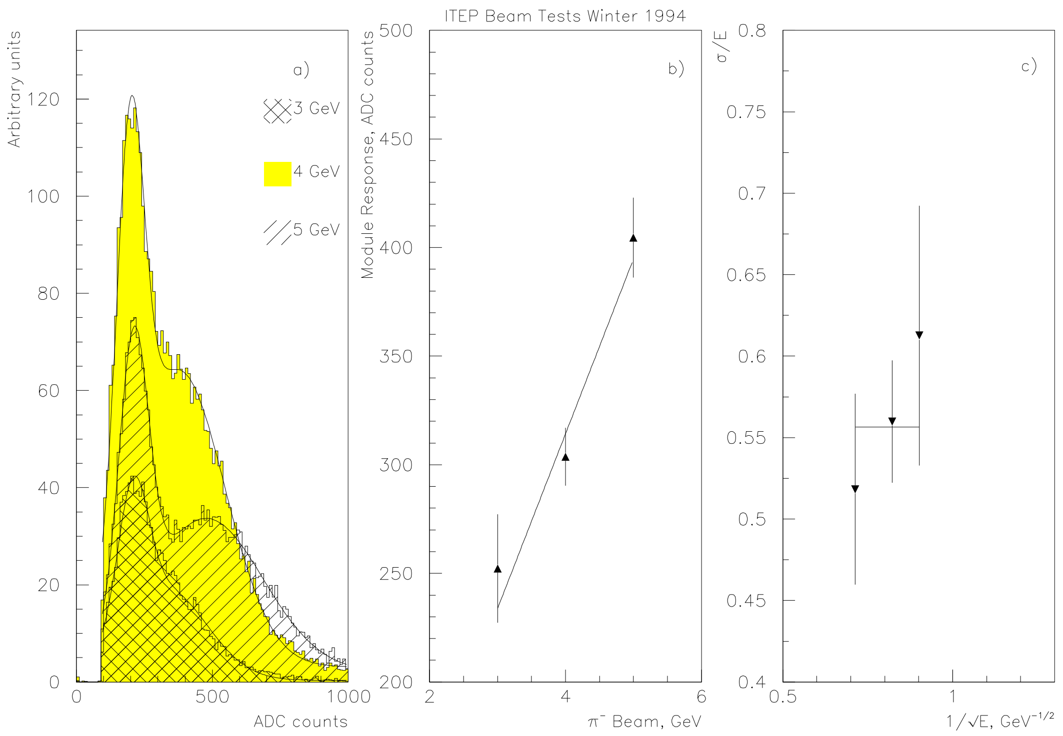

Figure 5: Response of the hadron module to the ITEP π^- beam: a) signal spectra in ADC counts, b) linearity of the response, c) the hadronic resolution.

3.3 Response to pions

The signal spectra of the module response to the π^- beam for three different energies are shown in Fig.5*a*. The minimum-ionising particle (m.i.p.) peak is described by a Landau distribution, while the hadron shower is assumed to be Gaussian-like.

Fig.5*b* displays the fitted mean position of the hadron shower against the incident π^- beam energy. The points seem to behave linearly. Taking account of the experimental uncertainties of the data points displayed in Fig.5*c*, we estimate the mean resolution of hadron shower to be

$$\frac{\sigma}{E} = (56.0 \pm 3.0)\%.$$

This figure is in agreement with the CERN test measurements, where the set of 3×3 hadronic modules were tested [4].

4 Summary

The design and production technology for the hadronic modules were developed at ITEP. The modules were produced, tested and assembled within a tight timescale and now form the hadronic section of the H1 SPACAL Calorimeter. The ITEP test beam measurements showed that the modules produced performed in accordance with the physics requirements.

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References

[1] H1 Collaboration, *The H1 Detector at HERA*, DESY 93–103.

[2] H1 Collaboration, *Technical Proposal to Upgrade the Backward Scattering Region of the H1 Detector*, PRC 93/02, March 8, 1993.

[3] H1 SPACAL GROUP,
Performance of an Electro-magnetic Lead/Scintillating Fibre Calorimeter for the H1 Detector, submitted to Nucl. Instr. and Meth.

[4] H1 SPACAL GROUP, *Hadronic Response and e/π Separation with the H1 Lead/Fibre Calorimeter*, to be submitted to Nucl. Instr. and Meth.

[5] R. Wigmans, *Performance and Limitations of Hadron Calorimetry*, CERN-PPE/91-205;
M. Livan and R. Wigmans, *Scintillating-Fibre Calorimetry*, CERN 95-02.

[6] D. Acosta et al., *Results of Prototype Studies for a Spaghetti Calorimeter*, Nucl. Instr. and Meth. A294(1990) 193.

[7] Hamamatsu Photonics Data Sheet;
R.D. Appuhn et al., *Performance Tests with a Large Sample of Fine Mesh Photo-multipliers for Use at 1.2 Tesla*, Proceedings of the IV International Conference on Calorimetry in High Energy Physics, La Biodola, Elba, Italy (1993) 118;
J. Janoth et al., Nucl. Instr. and Meth. A350(1994) 221;
H1 SPACAL GROUP, *Test of a Large Number of Fine-Mesh Photo-multiplier Tubes for Usage in a Magnetic Field of 1.2 Tesla,* To be submitted to Nucl. Instr. and Meth.