Cerenkov Fiber Sampling Calorimeters

K. Arrington, D. Kefford, J. Kennedy, R. Pisani, C. Sanzeni, K. Segall, D. Wall, D. R. Winn, Contact†
Fairfield University, Fairfield, CT, 06430-7524

R. Carey, S. Dye, J. Miller, L. Sulak, W. Worstell
Boston University, Boston ,MA, 02215

Y. Efremenko, Y. Kamyshkov, A. Savin, K. Shmakov, E. Tarkovsky
Oak Ridge National Laboratory, Oak Ridge, TN, 37831

† FAX: 203-254-4277
winn@fair1.fairfield.edu

Abstract

Clear optical fibers were used as a Cerenkov sampling media in Pb (electromagnetic) and Cu (hadron) absorbers in spaghetti calorimeters, for high rate and high radiation dose experiments, such as the forward region of high energy colliders. The fiber axes were aligned close to the direction of the incident particles(1°-7°). The 7 λ deep hadron tower contained 2.8% by volume 1.5 mm diameter core clear plastic fibers. The 27 radiation length deep electromagnetic towers had packing fractions of 6.8% and 7.2% of 1 mm diameter core quartz fibers as the active Cerenkov sampling medium. The energy resolution on electrons and pions, energy response, pulse shapes and angular studies are presented

I. INTRODUCTION

Sampling fiber calorimeter techniques show much promise for sampling calorimetry at high energy colliders [1], [2], [3], [4]. Fibers are arranged on a square grid in an absorber matrix, parametrized by an areal packing fraction (p.f.), with the fibers (spaghetti) typically oriented within a few degrees of the incident particle directions. This longitudinal fiber technique is an efficient method to obtain a quasi-homogeneous mixture of absorber and sensistive material (normally scintillator fibers) compared with many other sampling methods. Special spaghetti calorimeter features for the forward region are: (i) hermetic and uniform response, (ii) projective transverse segmentation with good transverse position resolution, (iii) compensation, resulting in more Gaussian energy response with a small constant term in the energy resolution, (iv) fast temporal response; (v) linear energy response over a large range of jet energies; (vi) no active devices in the high radiation environment; (vii) possibility of replaceable media from the back of the calorimeter.

However, in the forward region at colliders or in any high dose (>1 GigaRad) experiment, conventional techniques using scintillator fibers fail because of radiation damage, with doses for existing fibers limited to hundreds of MRad. Furthermore, response speed is still limited by the scintillation decay.

On the other hand, Cerenkov light is even faster than scintillator (co-temporal with the radiation) and some transparent materials are radiation hard at GigaRad levels in highly purified forms (quartz [5], [6], [7], silicones [7], diamond, noble liquids, for example). The reduction of light output, typically by a factor of 40 compared with scintillator, is acceptable in the forward region at hadron colliders because of the boosted energies. For example, jets with the same transverse energy E_t have ~10 times the total energy E at $\eta = 3$ compared to jets at η=0.

The use of Cerenkov light is well-known in absorption calorimetry, usually as a total absorption calorimeter. Examples are Pb-glass electromagnetic (e-m) and hadron [8] calorimeters, and water e-m [9] and hadron [10] calorimeters. However, for quality hadron calorimetry a sampling technique is essential to attempt to equalize the hadronic and electromagnetic responses, especially in the case of Cerenkov light, where particles must be near-relativisitic to generate a signal, and therefore electromagnetic energy is more efficient at generating light.

A promising media are optical fibers of highly purified quartz cores (<0.1 ppm OH^- content), cladded with fluoride-doped quartz; these are used in the nuclear power industry in high radiation environments, and are readily available for use as the sampling material [5], [11].

The initial ideas for the work herein were based on work at CERN for calorimeters to use with heavy ion beams at high rates and high radiation doses (P. Gorodetzsky and collaborators at CERN and Saclay) [5], [11], [12] . The main motivation for our work is to be able to measure missing transverse energy and jet energy resulting from high mass physics signals (supersymmetry, new vector bosons, heavy quarks, compositeness) at colliders, while emphasizing simple construction. We have therefore constructed and studied prototype spaghetti calorimeter modules, using Cerenkov light as the active sampling signal in the form of clear fibers, arranged nearly parallel to the incident particle directions, in contrast to the CERN modules, arranged with the fibers at the Cerenkov angle to the incident particles. The fiber calorimeters in this study were designed to operate with the beam direction within ~3°-5° of the fiber direction. In the work at CERN the fibers are arranged close to the Cerenkov angle of ~45° to the incident particle directions, in theory to maximize the capture of Cerenkov light for particles along the axis of the absorber. (A detailed description for this choice of orientation is found in [5], [11], [12]). This would complicate the design of detectors for projective fiber calorimeters in the forward region of colliders.

II. MONTE CARLO STUDIES

Several independent Monte Carlo (MC) studies using GEANT, EGS, and LTRANS, with user-supplied Cerenkov light generators were performed. The cut-offs were set at Cerenkov threshold. For a single fiber (core index n, numerical aperture NA) crossed by a particle, the impact energy resolution functions with a stochastic term of ~190%(170%) in Cu(Pb), a constant term of 5%(5%), and a yield of 1.8(0.9) p.e./GeV. This would imply a transverse energy resolution of 11% on E_t on a 100 GeV E_t jet at $\eta=3$ (since $E \sim 10E_t$), sufficent for forward calorimetry at colliders.

III. PROTOTYPE DESIGN AND CONSTRUCTION

A. Hadron Calorimeter

Copper as a hadron calorimeter absorber leads to a compact calorimeter because the interaction length of a quasi-compensated calorimeter is ~15.7 cm. The main draw-back compared with higher Z materials is that the electromagnetic component is less suppressed in Cu, which leads to a low packing fraction in order to achieve compensation, even with scintillator (p.f.=3.2%) [14], thus giving low light yields. This difference has a negligible effect on most of the physics of interest in the forward region at collider energies, as described above in the MC of a 2.8% packing-fraction detector.

A prototype projective hadron calorimeter tower of 625 kg was constructed with clear plastic fibers embedded between grooved copper laminations [14]. The fiber packing fraction is 2.8%, as in the MC, but with a larger fiber diameter. Fiber spacing was 8.0 mm square. Each projective tower was 22 cm x 22 cm on the front face, 31cm x 31cm on the back face, 105 cm long (6.95 λ deep), and had all fibers parallel to the tower's axis of symmetry. The clear plastic Cerenkov fibers were chosen for cost reasons only. Mitsubishi 1.5 mm diameter (NA=0.45, 4 μm cladding) clear PMMA fibers were inserted (4 hours) and gathered in a bundle at the larger tower end, then optically mated to a hexagonal light mixer and read out with a single 2" bi-alkali PMT. Figure 2a,b show the construction details. The nuclear interaction length, radiation length and Moliere radius are 15.1 cm, 1.45 cm, and 1.16 cm, respectively. The fiber effective attenuation length at 400 nm is about 3 m (manufacturers specs).

Fig. 2a: Schematic of the projective hadron fiber calorimeter, showing the PMT housing and fiber bundle (left) and the stepped Cu plate laminations (right_ . See Ref. [14] for details.

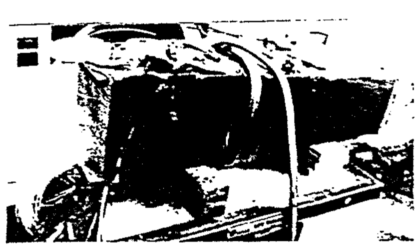

Fig. 2b: Photograph of hadron calorimeter during "stuffing".

B. Electromagnetic Prototypes

The two lead electromagnetic (e-m) calorimeters consisted of bolted together Pb sheets 13 x 13 cm x 1 cm, with a grid of drilled 3 mm(3.9 mm) holes on 5.7 mm(8mm) centers, to make a stack 19 cm deep, with an active area of 12 cm x 12 cm. Quartz fibers (1 mm core, n=1.49, NA=0.4, PEEK cladding) were inserted in bundles of 3 (the "triplet") or 5 (the "quintuplet") each hole of the 2 stacks, respectively, gathered to a bundle and mated through a UVT lucite hexagonal light mixer to a high gain quartz window PMT. These formed 2 calorimeters with 7.2% and 6.8% p.f.- the "quintuplet" fibers. The 3M quartz fibers had an attenuation length of greater than 9 m for λ>350 nm. Figures 3a,b show photographs of the e-m calorimeters under construction.

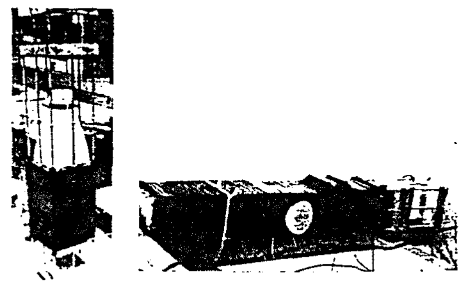

Fig. 3a, b: Photographs of the e-m calorimeters.

IV. TEST BEAM DATA

A. Beam Line and Test Conditions

Tests were carried out at Brookhaven National Laboratory (BNL), with incident electrons, pions, and muons with momenta between 6-8 GeV/c on muons, 7.5 GeV on pions, and 8 GeV on electrons (1993) and with 10 GeV electrons on one e-m module (1992). All charge ADC data was collected with a gate width of 100ns. A beam defining system consisted of 2 Cerenkov counters, muon, hole veto, and finger counters. The momentum bite was ~1-2% or better, with a 1 cm spot. Typically 5-10 electrons per spill were collected. The photomultiplier tubes (PMT) were calibrated in a dark box before and after data collection, using the statistical method (mean and sigma of a pulse height distribution with a constant light pulser). Tilt angles were measured with a digital level.

B. Electromagnetic Energy Response and Energy Resolution

Figure 4a shows the measured ADC response spectra (histogram, pedestal subtracted) to 8 GeV electrons at 5° to the incident beam direction for the hadron calorimeter. The fitted resolution is consistent with a resolution function stochastic term of $\sigma/E=94\pm9\%/\sqrt{E}$, with the simple assumption of no constant term. (We were able to take data at low energy; the σ of the distribution is simply multipled by $\sqrt{E}$ for convenience in comparing to other calorimeter resolutions. The resolution function is crude enough that only extreme constant terms would affect the general trend of the stochastic term.) The response is equivalent to 3.7 photoelectrons (p.e.) per GeV, within a factor of 2 of MC predictions for fibers with an NA=0.45.

Figure 4b, c shows the pedestal-subtracted ADC spectra for the quartz e-m calorimeters at 5°(9°) tilt to the 8(10) GeV incident electron beam direction, consistent with of $\sigma/E = 55\pm7\%/\sqrt{E}$, ($76\%/\sqrt{E}$) assuming no constant term. The response is 11.3(5.3) p.e./GeV, consistent within 20% to the

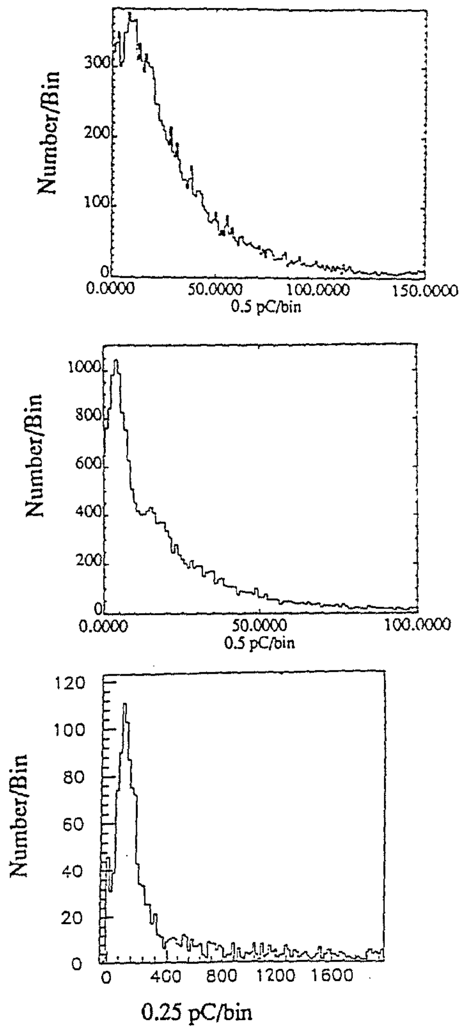

Fig. 6a-c: Muon energy loss ADC spectra in: a) hadron (3°), b) "triplet" e-m (5°), c) "quadruplet" e-m (9°) calorimeters.

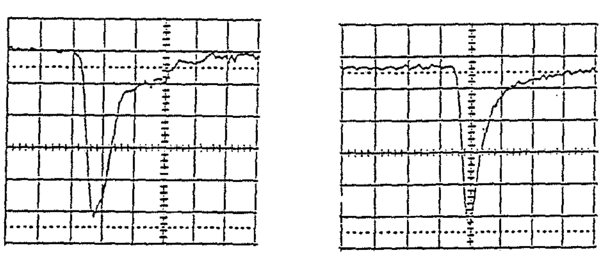

Fig.7a,b: PMT pulses from π (L), e(R). (10 ns/div, 50 mV/div)

F. Pulse Shapes

Figure 7a,b shows a π(e) pulse from a hadron (e-m) tower, with a risetime of 4(2.5)ns (10% - 90%) and a FWHM of 11 ns. The hadron pulse integrates to 95% in 42 ns. The fall-time response is due to dispersion in the delay cables (200ns).

V. CONCLUSIONS

We have demonstrated a fast, projective fiber hadron and electromagnetic calorimeters, suitable for forward jet measurements at hadron colliders, using the novel technique of Cerenkov fiber sampling. In these tests, calorimeters with very low packing fractions and coarse fiber-fiber spacings achieved e-m stochastic energy resolution terms of ~50%-60%/$\sqrt{E}$, and hadron stochastic terms of ~300%/$\sqrt{E}$ at tilt angles of 5° to the incident particles. The responses (~1-10 p.e./GeV, depending on numerical aperture and packing fraction) are close to MC predictions; the resolution on electrons is about 2 times worse than photostatistics would predict. The temporal responses are superior to almost every other calorimeter technique.

A primary result of this work is the experimental demonstration of the technique at shallow angles (3°-7°) to the incident particle direction, comparable to tests by the CERN group at 45°; there is no essential reason to align the fibers along the Cerenkov angle so that a fraction of the Cerenkov cone is aligned along the meridional ray of the fiber for operation, provided that a factor of 2 in response loss is tolerable.

Additionally, we have demonstrated that calibration with muon Landau distributions may be possible, a very important feature in the forward region of colliders where other physics signals will be difficult.

VI. ACKNOWLEDGEMENTS

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