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Design and tests of the CREAM calorimeter

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The CREAM calorimeter is comprised of 20 layers of 1 radiation length (X_0) tungsten interleaved with 20 layers of scintillating fibers with fifty 1 cm wide scintillating fiber ribbons per layer. The fiber light output is read out with multi pixel Hybrid Photo Diodes (HPDs) through various optical components. Measurements of the scintillation light generated in the fiber ribbons by radio-active sources, UV Light Emitting Diodes (LEDs), and particle beams confirm that they can meet the requirements of measuring cosmic-ray particle energies from ~10^{12} to ~10^{15} eV. The calorimeter design and results of various tests of its performance are presented.

1. Introduction

The CREAM payload is designed to fly at the top of the atmosphere, suspended under a NASA research balloon, to directly measure cosmic-ray nuclei from H to Fe, in the energy range from ~10^{12} to ~10^{15} eV. The CREAM instrument, described in more detail elsewhere in this conference [1] is comprised of several complementary detector systems to measure the charge and energy of cosmic rays, including a sampling tungsten/scintillating-fiber calorimeter. Due to the limits of the balloon's carrying capacity, the instruments are tightly constrained in weight (typically 1 ~ 1.5 ton instrument weight), power (typically several hundred watts), and volume (typically several m^3). The spectra of cosmic-ray nuclei follow a power law shape, with integrated fluxes dropping approximately 50-fold for a 10-fold increase in threshold energy. The combination of constraints, limitations on flight duration, and the spectra being studied, implies that at high energies the science results gleaned from flight instruments are usually limited mostly by the statistics that can be collected. The CREAM calorimeter design is optimized to collect the maximal data sample possible, with the lowest weight and power possible. Maximizing data collection power, or effective geometry factor, requires a thin sampling calorimeter with a high density absorber (tungsten), a set of thin active layers (scintillating fiber ribbons), and a low-Z target (graphite) to induce hadronic interactions in a large fraction of incident nuclei (Fig. 1). Once an incident nucleus interacts in the graphite target, it generates a cascade of secondary particles, mostly pions. On average, a third of these are π^0s, generating an electro-magnetic (EM) shower core. The charged pions will at times interact again in the target or in the tungsten absorber, producing another generation of charged and neutral pions, with the latter enhancing the EM energy deposit. Non-flight calorimeters for measuring such hadronic showers are usually deep enough to fully contain the showers. For tungsten calorimeters this requires a depth of ~80 cm. Such a calorimeter, if it were only 50×50 cm^2 in area, would weigh a prohibitive 3 tons, and would have a very limited aperture. The CREAM calorimeter is only 20 radiation lengths (X_0), or about 10 cm in depth, keeping its weight to an acceptable 380 kg, while allowing good containment of the EM shower core produced in the initial interaction. The energy resolution of such a calorimeter, at ~45%, is sufficient for reconstructing the spectral shape being studied, and is nearly energy independent, an important quality for such a study [2]. The readout system is designed around HPDs as these devices combine extremely high linear dynamic range (up to 1:1,000,000), low power (~0.8W including front end electronics and high voltage power supplies), low weight (~30 grams per unit), high channel count (73 channels per unit), compact size (~30 cm^3 per unit), and very uniform gain between pixels in an HPD (~5% RMS) and between HPDs (~10% RMS at the same HV setting).

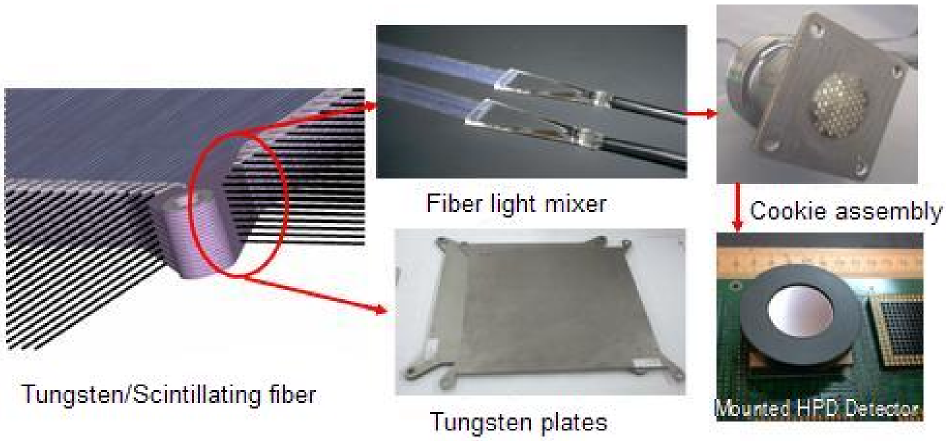

Figure 1. CREAM calorimeter components.

2. Optical design

In the calorimeter, charged shower particles generated in the tungsten traverse the fiber ribbons, generating scintillation light. This light travels in the fibers to an acrylic light mixer and is transferred to a bundle of forty eight 256 μm diameter clear plastic fibers. The clear fiber bundle carries the light to the face of the HPD, where the bundle is split into three groups each with a different number of thin fibers, and through a different neutral density (ND) filter (see Fig. 2 for the transmission coefficient of the different ND filters). The sub-bundles are glued into a plastic cookie that holds them in position against different HPD pixels (Fig. 1). This arrangement forms three readout ranges to match the dynamic range of the front end electronics, while covering the 1:200,000 range needed to read out the lateral tails of the shower for ~1 TeV showers, as well as the shower core maximum for ~1000 TeV showers. For mechanical reasons, alternate ribbons in the same layer are read out on opposite ends. Aluminization on the non-readout side of each ribbon improves light collection in each ribbon, and increases the effective attenuation length in the ribbon, thereby reducing the position dependence of the ribbon response for LED (Light Emitting Diode) and even more-so for showers (Fig. 3). Each HPD reads out 25 ribbons, with 25 pixels viewing low-energy range, 25 reading out mid-energy range, and 5 more combining high-energy range signals from 5 nearby ribbons each. A pair of IDEAS VA32-HDR2/TA32C ASICs read the signals from each HPD, with the low range signals in one ASIC, and the mid- and high-range signals in the other. The low-range signals are used to form a half-layer trigger, which is then combined with the other half-layer to form an overall OR of all ribbons in the layer. Alternate layers are oriented orthogonally to each other, providing 10 measurements in

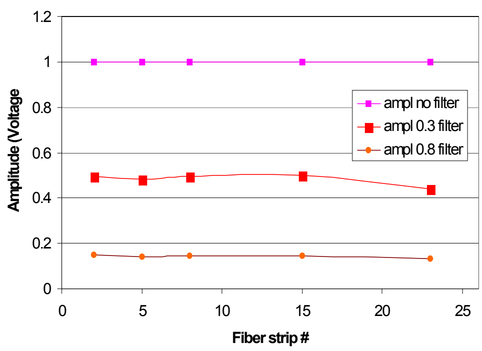

Figure 2. Measurement of transmission efficiencies of neutral density filter in different fiber strips in a cookie.

the X direction and 10 alternate measurements in the Y direction. The overall calorimeter trigger is formed by requiring trigger signals from N consecutive layers, where N is adjustable in-flight by command from the ground to 4, 6, 8, or 10 layers.

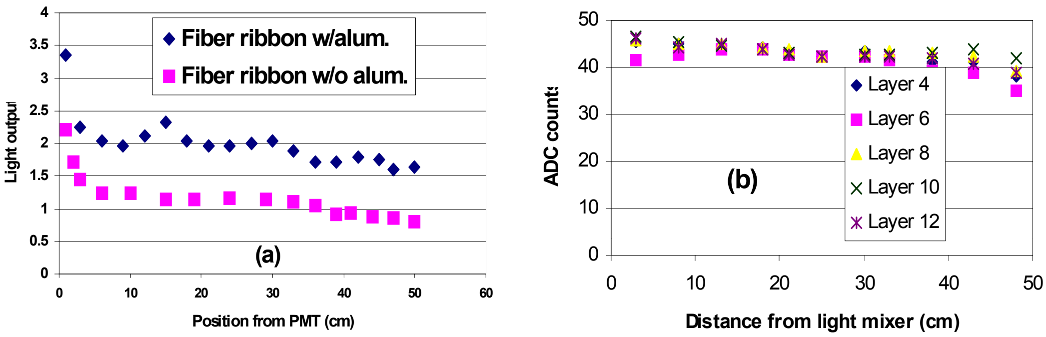

Figure 3. (a) Light outputs of fiber ribbons with and without aluminization on non-readout ends, from UV LED light source; (b) light output of aluminized fiber ribbons from electron showers.

3. Test results of calorimeter fiber ribbons

The light mixer geometry has been optimized to transfer the light as efficiently as possible, with a UV transmitting acrylic allowing more of the mostly blue and near UV scintillation light through (see Fig. 4 for a comparison of overall signal transfer efficiency for a previous design, as well as the design flown with both UVT and non-UVT acrylic). Comparing the signal from 25 ribbons in the same layer, each about 45 cm away from the light mixer (Fig. 5) we find that the response is uniform across ribbons within ~15%, which includes effects such as ribbon optical response, aluminized mirror reflectivity, glue joint transmission efficiency, beam position vs. ribbon location, and pixel gain response. All but the beam position can be expected to remain the same in flight, and are addressed through calibration corrections. The remaining effect of beam position is expected to have a negligible impact, given that much of the 15% non-uniformity will be equalized by the gain correction. Tests of the optical strings using photo multiplier tubes, with a gain of ~10^6 (vs. ~2000 for HPDs) allowed single minimum ionizing particle signals to be seen, so that the gain of the front end electronics could be measured (Fig. 6). These measurements show that the gain is typically 1 ADC unit per MeV.

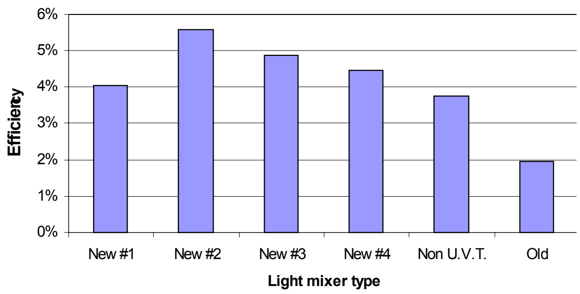

Figure 4. Measurements of transfer efficiencies for various types of light mixers. "New" are those used in flight

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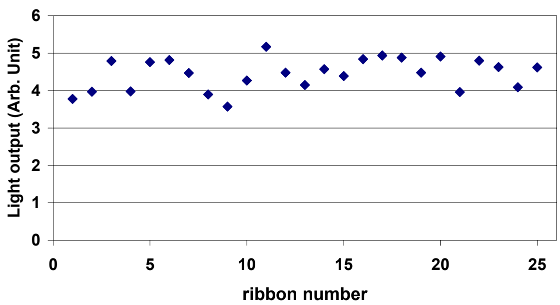

Figure 5. Light output from 25 ribbons in a cookie by UV LED illumination at 45 cm from the light mixer.

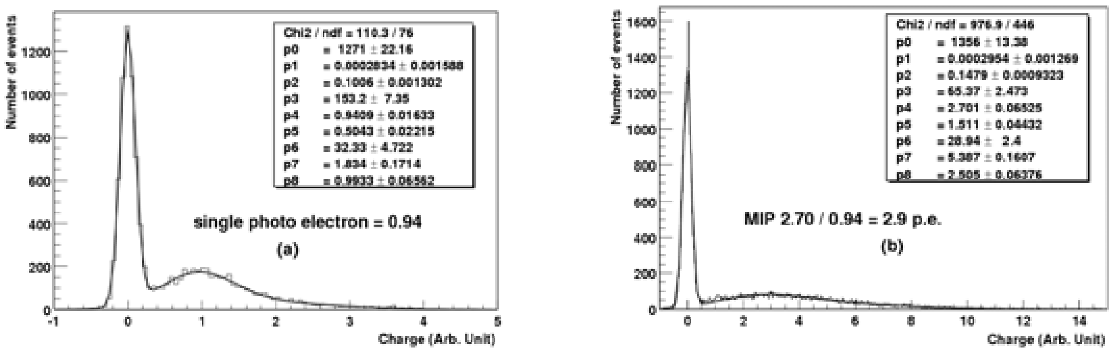

Figure 6. (a) PMT measurement of single photo electron from a blue LED light source; (b) PMT measurement of light output of a fiber ribbon from a MIP electron signal using a collimated ^{106}Ru source.

4. Conclusions

The CREAM calorimeter is optimized to be flyable, provide sufficiently accurate direct measurements of cosmic-ray nucleus showers, while collecting as large as possible a sample of events for a given flight duration. Lab measurements and beam test results show that the optical design of the calorimeter is highly uniform both along the fiber ribbons and between different ribbons. These measurements also show that the calorimeter can cover the requisite 1:200,000 dynamic range within the power and volume constraints of a flight instrument.

5. Acknowledgements

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References

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