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# Cosmic ray energetics and mass: configuration and progresson construction and testing

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**Abstract.** CREAM (Cosmic Ray Energetics And Mass) is an experiment being constructed to study high-energy cosmic rays from $10^{12}$ eV to over $5{\times}10^{14}$ eV using the new ultra long duration balloon (ULDB) capability under development by NASA. ULDB flights are designed to last from 60 to 100 days each. CREAM includes a sampling tungsten/scintillator calorimeter, a transition radiation detector (TRD), and a timing-based charge detector (TCD). This report summarizes the configuration expected to start flying in December 2003, and provides the status of its construction and testing, including preliminary sub-system environmental tests.

## 1 Introduction

Extra-solar matter in the form of cosmic-ray particles contains information needed to address fundamental astrophysical questions, such as the acceleration mechanism responsible for their enormous energies, their source material and their propagation through the inter-stellar medium. Reliable data on elemental spectra of ultra high-energy cosmic rays will allow us tests of the currently accepted supernova shock acceleration and leaky-box models. Due to their rapidly falling power-law spectrum, the study of high-energy cosmic rays requires very large collection power for a sufficiently large sample of events. Indirect ground-based measurements allow an energy reach well over $10^{20}$ eV. Their elemental resolution for incoming primaries, however, is very poor and inherently model-dependent. Direct measurements at the top of the atmosphere or in space resolve this issue, but their limits on weight and mission duration severely constrain their collection power, and thus their energy reach.

CREAM utilizes the ULDB capability, being developed by NASA, to maximize collection power in a balloon-borne experiment, with a possible multi-flight energy reach over $5{\times}10^{14}$ eV (Seo et al., 1999). CREAM is expected to collect almost twice the current world total of direct high-energy cosmic ray events in a single flight. With 3 flights the energy reach will overlap the low end of the ground-based range by almost an order of magnitude. Dual charge measurements using the TCD and fiber hodoscopes will allow excellent charge identification. CREAM will also be the first experiment to fly with a calorimeter and a TRD, which will provide cross-calibration of their energy scales.

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## 2 Configuration

The CREAM configuration, as shown in Fig. 1, includes a scintillator TCD, two TRD modules sandwiching a Cherenkov trigger layer, fiber hodoscopes interleaved with graphite targets, and a sampling tungsten/scintillator calorimeter with fine lateral segmentation.

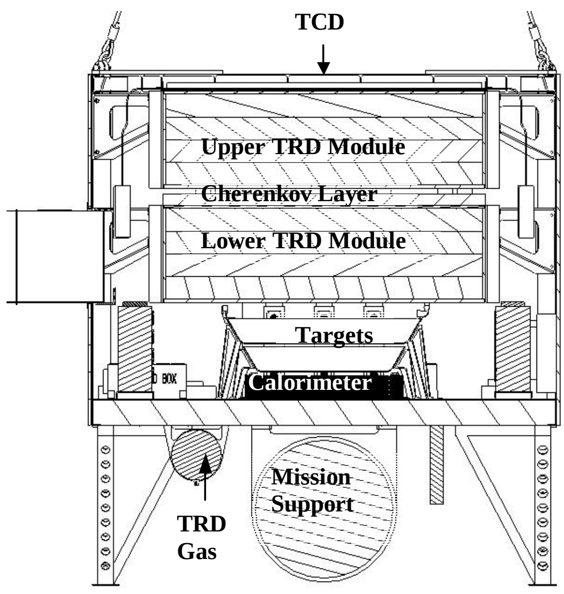


**Fig. 1.** Schematic cross-section of the CREAM payload.

The detector systems with their associated electronics and the TRD gas system are supported by an integrated structure. The support structure is based on a thick aluminum honeycomb deck, four corner posts, honeycomb shear panels on all sides, and a top structure connected to a rotator by four cables. A thermal system will maintain instrument temperatures between $0^{o}$C and $30^{o}$C in the hot case (daylight over Antarctica) and the cold case (pre-dawn over water). Power will be provided by high-efficiency solar arrays and stored for night operations in a bank of batteries sufficient for over 12 hours of eclipse. Instrument power is estimated at 350 W with 200 W additional power supplied to mission support equipment (e.g. transponders, data system, etc.).

## 2.1 Timing charge detector

The TCD (Beatty et al., 1999) is comprised of two crossed layers of 0.5 cm thick, 30 cm wide, 120 cm long paddles of fast scintillator, read out on both ends through 0.5 cm thick acrylic light-pipes by fast photomultiplier tubes (PMT). Optical components are wrapped in black Tedlar for light-tightness. Light pipes are bent to reduce the TCD lateral dimension. Figure 2 shows a paddle with one light pipe attached. An unwrapped light pipe is shown in Fig. 3.

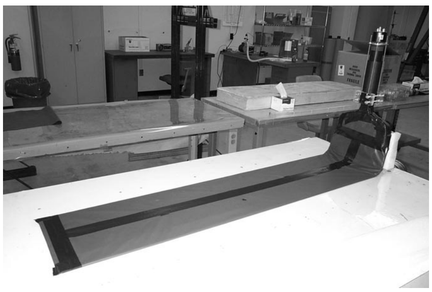

**Fig. 2.** A TCD paddle with attached light pipe and PMT. Optical components are wrapped in black Tedlar for light-tightness.

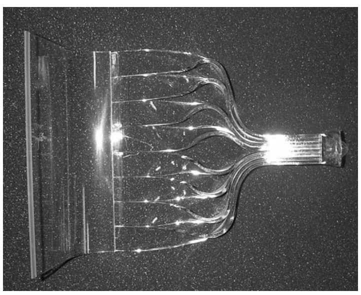

**Fig. 3.** An acrylic TCD light-pipe. The light pipe is cut into strips, which are rotated to change the cross-section from a rectangle to a near-circular cross-section sized to fit the face of the PMT.

The PMTs are read out by fast, custom-designed timing electronics that measures both the slew rate of the rising scintillation signal and the peak pulse-heights. With these two techniques the TCD electronics cover the dynamic range required to identify vertically incident protons up to iron incident at the highest angle within the CREAM geometry. The measured light-yield for cosmic-ray muons through the center of the paddle is ~100 photoelectrons.

Secondary particles scattered back from the calorimeter can distort charge measurements. One way to reduce this effect is through the use of finely segmented charge detectors to reduce the probability of a back-scattered particle hitting the same detector component measuring the primary particle charge (Ganel et al., 1999). The CREAM TCD uses time separation instead of space separation. The worst-case scenario is one in which the primary is incident on the center of a paddle and a particle back-scattered from the calorimeter impinges on the same paddle near its end. If the primary traverses the paddle at time $t_0$, the scintillation light, traveling at an effective velocity of approximately 0.6 c, arrives at the light-pipe at $t_0+3.3$ ns. The primary, meanwhile, reaches the calorimeter, 113 cm below, at $t_0+3.8$ ns. The back-scattered particle reaches the paddle-end at $t_0+8.0$ ns, 4.7 ns after the signal from the primary. The TCD electronics are designed to complete the charge measurement within 2 – 3 ns, thereby avoiding the impact of background from back-scattered particles.

Under the graphite target (see below) is a fiber hodoscope read out by fast PMTs and front-end electronics identical to those of the TCD paddles. This hodoscope provides a reference time, which allows the reconstruction algorithm to discard charge measurements for cases where the primary missed the TCD and a back-scattered particle generated a TCD trigger. This hodoscope is not used for pulse-height measurement of separate fibers, so signal distortion due to particles traversing fibers outside the target geometry is not a concern and clear fibers are not needed.

## 2.2 Transition radiation detector

Immediately below the TCD is the TRD (Seo et al., 2000). The lower TRD module supports a Cherenkov-based trigger layer read out through wavelength shifting bars by eight small PMTs. Each of the two TRD modules, with an active area of 120×120 $cm^2$, uses four active layers in each transverse orientation. Each active layer is comprised of 32 thin-walled proportional tubes. These tubes use a xenon-based gas mixture to detect x-ray transition radiation in the energy region around 10 KeV. Adequate transmission of x-rays into the tube volume requires very thin-walled devices. The CREAM TRD tubes use aluminized Mylar wound in three layers and glued together to form a tube with a 75 μm wall thickness. A central sense-wire is installed in each tube, which is operated as a conventional proportional counter to detect ionization in the tube gas. The sense wire is held in place by end fittings, which also serve to contain the gas mixture in the tube, at a constant pressure. The signal is amplified by an analog system based on the Amplex VLSI charge amplifier chip. The tubes are held in a polystyrene foam matrix. Each particle is measured by at least 6 tubes in each orientation. The foam, aside from providing mechanical support for the tubes, generates the transition radiation emitted by the charged primary particle as it repeatedly moves into and out of media with different dielectric constants. The choice of radiator is optimized for

Lorentz factors from $10^3$ to $10^4$. Since the number of TR photons is proportional to $Z^2$, TRD velocity measurements are only possible for $Z \geq 3$, with expected energy resolution of ~15% for carbon and 7% for iron at $\gamma$~3000.

2.3 Calorimeter module

Below the TRD is the calorimeter module, which is comprised of three hodoscopes interleaved with graphite targets cemented into composite cages, and a sampling tungsten calorimeter. Each hodoscope has two orthogonal layers of scintillating fibers. Each multi-clad, 2×2 $mm^2$ square fiber is read out via a clear fiber of identical shape and lateral dimensions, by a 73-pixel hybrid photo-diode (HPD). The clear fiber reduces the impact of particles outside the target, where they cannot be filtered out by the graphite. The top two hodoscopes, just below the lower TRD module, provide supplemental charge measurement for particles already measured in the TCD. They also provide the only charge measurement for the ~50% of calorimeter events that miss the TCD. These hodoscopes, along with another, located between the targets, also provide tracking information. Below the bottom hodoscope is the calorimeter with an active area of $50 \times 50$ $cm^2$. This detector is constructed as a stack of 20 tungsten plates, each 3.5 mm thick, a bottom aluminum plate of the same thickness, and 20 interleaved scintillator layers, with an energy resolution of ~45%. Each scintillator layer is made up of 1 cm wide, 0.5 mm thick scintillating fiber ribbons. Each ribbon is read out through an acrylic light-mixer and a bundle of thin clear fibers, by a multi-pixel HPD of the same type used in the three upper hodoscopes. While the HPD can cover the enormous dynamic range, from 5 MeV to 1 TeV (Ahn et al., 2001) expected in single ribbons, the electronic readout is limited to 11 bits. To cover the required 1:200,000 range, the clear fibers from each bundle are divided into different-size bundles to provide high-energy, mid-energy, and low-energy ranges respectively. Each range is read out by different pixels in the same HPD, with optical attenuation for the mid- and high- ranges. For mechanical reasons, alternate ribbons are read out on opposite ends. Non-readout ends are aluminized by vacuum sputtering to increase the light-yield and effective attenuation length, thereby increasing the S/N ratio and improving response uniformity over the active area. A similar scheme is used in the three upper hodoscopes.

## 3 Construction and sub-system environmental tests

All detector systems are currently being constructed in preparation for beam-tests at CERN, the European High-Energy Physics lab, in August 2001. Integration and testing of the complete instrument will take place during the first half of 2002. During the latter half of 2002 we plan to calibrate the detectors at an accelerator. Full integration of the instrument and ballooncraft, as well as final tests and reviews will be carried out in 2003, after which the payload will be shipped to the launch site, and preparations will begin for the launch campaign. Based on the current ULDB development schedule, the first launch is expected in December 2003. The launch location is not yet determined, but any of the candidate sites can accommodate science measurements. CREAM will float at an altitude above 110,000 feet for a period of 60 – 100 days. At this altitude, near-vacuum conditions cause coronal discharges between unshielded points with a potential difference as low as 100 V. The payload must be able to survive a wide range of thermal environments. Depending on the launch site and prevailing winds, the balloon's trajectory may take the payload over Antarctica, where the 24-hour daylight and the high albedo from the ice will increase thermal input and increase payload temperature. The payload may also spend considerable time at near-equatorial latitudes, where an eclipse of up to 12.5 hours will allow a great deal of heat to leak out. Thermal and vacuum testing is required to verify the payload can survive such environmental extremes.

3.1 TCD testing

Cast scintillators subjected to vacuum may be subject to fluor evaporation over time, leading to gradual signal degradation. Accordingly, the TCD paddles are made with vacuum-rated fluors. On each end of each paddle, a 0.5 cm thick acrylic light pipe is attached with BC600 epoxy. A 1 cm wide step is cut into both the paddle and the light pipe to increase the joint area. Without this step the joint may break during normal handling. Tests with a mockup of the stepped joint demonstrated that it was capable of holding 3kg and that it could withstand a slight torque. In thermal tests the joint did not lose strength when heated up to 50°C, but broke during a torque test at –20°C. This result agrees with the manufacturer's practice of breaking poor scintillator/Lucite joints after cooling the undesirable product in a freezer. The PMT is attached to the (nearly) round end of the light pipe using GE RTV615 and SS4120 primer. A plate-glass/acrylic test assembly was thermally cycled from –20°C to 50°C several times. The assembly could not be parted without breaking the glass plate.

3.2 TRD testing

A key part of the TRD construction is development of the proportional tubes. A major technical concern is the prevention of gas leaks at altitude, where the differential pressure across the tubes and end fittings is ~1 atmosphere. The O-ring based system illustrated in Fig. 4, provides a more than adequate seal. Leak tests were conducted by filling a sealed tube with helium at various absolute pressures. The leak rate of this tube into a surrounding evacuated volume was measured with a helium mass spectrometer leak detector. The results of tests on prototypes of this device are shown in Fig. 5, along with the tolerable leak rates for helium- and xenon-filled tubes. Based on the amount of makeup gas carried by the CREAM payload, a leak rate tolerance was calculated for a 100-day flight. The limiting rate for helium-filled tubes is shown by the straight dotted line. Since the leak rate for the xenon flight mixture is expected to be at least an order of magnitude smaller than for pure helium, the effective tolerable leak rate for xenon (solid line) is much higher. The measured values lie significantly below both lines, indicating that the makeup gas supply should more than adequately compensate for the leakage expected during the flight. Measurements with different length tubes have shown that the leak rate of the present seal design is comparable to that of the wall material of a 1m tube.

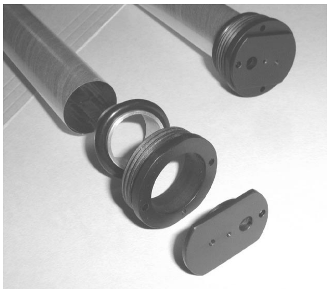

**Fig. 4.** TRD proportional tubes (2 cm diameter) with o-ring based end fittings shown both assembled and prior to assembly.

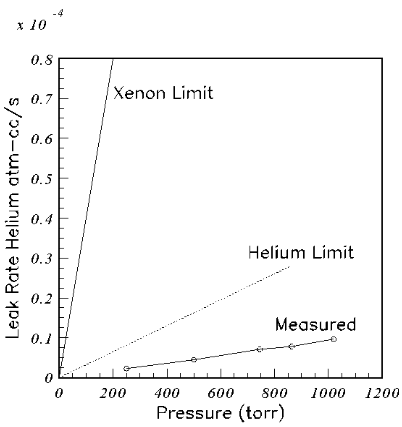


**Fig. 5.** Test results of gas leak from a TRD proportional tube. Test results are displayed as empty circles, with the limiting cases for Helium and Xenon shown by dotted and solid lines, respectively.

### 3.3 Calorimeter testing

The HPDs used for calorimeter module readouts require a voltage of up to 12 kV. The HPD and HV supply illustrated in Fig. 6, are potted by the vendor with space-grade potting. However, the HV wires have Teflon insulation, making adhesion of the potting compound difficult. An HPD and HV supply were subjected to a weak vacuum (~2 Torr) comparable to that found at an altitude of 135,000 feet. The HV supply current showed spikes suggestive of HV breakdowns, and coronal discharges were visible. To address this issue an alternate power supply with Silicone-insulated HV wires was tested up to 15 kV with good results. The vendor independently tested its potting with Silicone-insulated wires, showing adequate adhesion. We are confident that HPDs and HV supplies with Silicone-insulated wires should survive the conditions expected at float altitude, which will be verified by testing. Testing will also verify that fluor evaporation should not impact fibers.

An additional concern was the thermal stability of the graphite-based cement holding the target blocks in the composite cages, especially in case of recovery on the ice in Antarctica. Vendor data based on testing shows this cement should survive temperatures from $-100^{o}$C to over $800^{o}$C, more than adequate for CREAM. Both the graphite and the cement have also reportedly flown in the vacuum of space. Thermal testing is also being carried out for the joints from fiber ribbons to light-mixers, light-mixers to fiber bundles, fiber bundles to HPD cookies, hodoscope scintillating fibers to clear fibers, and clear fibers to cookies.

## 4 Summary

The CREAM experiment will allow direct measurement of cosmic ray nuclei with sufficient statistics for a substantial overlap with ground-based measurements. Depending on the number of balloon flights realized, CREAM should be capable of detecting evidence for a 'knee' in the proton spectrum, if such exists. With dual measurements of charge and of energy, CREAM will allow cross-calibration of both for a large sub-sample of events. Construction is on track for launch late in 2003, preliminary environmental testing shows promising results, and further testing is in progress.

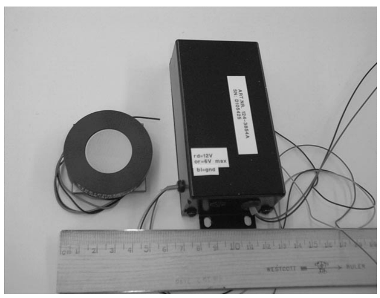

**Fig. 6.** A 73-pixel HPD (left) with 12 kV power supply (right).

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