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Nuclear Instruments and Methods in Physics Research A 460 (2001) 278–288

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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A fiber-optic-based calibration system for the High Resolution Fly's Eye cosmic ray observatory

J.H.V. Girard[a], L.R. Wiencke[a,*], G.C. Archbold[a], J.A. Bellido[b], K. Belov[a], J.H. Boyer[c], A.A. Everett[a], R.C. Gray[a], C.C.H. Jui[a], B.C. Knapp[c], E.J. Mannel[c], J.N. Matthews[a], S.A. Moore[a], J.R. Mumford[a], M.D. Roberts[d], P. Shen[a], P.V. Sokolsky[a], R.W. Springer[a], S.B. Thomas[a]

[a]*Department of Physics, High Energy Astrophysics Institute, University of Utah, Salt Lake City, 115 S 1400 E 201 JFB UT 84112, USA*
[b]*Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, South Australia 5005, Australia*
[c]*Columbia University, Nevis Laboratories, Irvington, NY 10533, USA*
[d]*University of New Mexico, Department of Physics and Astronomy, 800 Yale Blvd NE, Albuquerque, NM 87131-1156, USA*

Received 10 July 2000; accepted 26 September 2000

Abstract

This article describes the fiber-optic-based calibration system installed at the High Resolution Fly's Eye (HiRes) astro-particle physics observatory. The HiRes detectors measure ultra violet scintillation light from distant extensive air showers. This automated calibration system delivers light from a frequency tripled 355 nm YAG laser to the 10,752 photo-multiplier tubes of the 42 HiRes-II detectors. © 2001 Elsevier Science B.V. All rights reserved.

PACS: 95.45. + i; 95.85.Ls; 06.20.F; 07.60.Vg

Keywords: Highest energy cosmic rays; Fly's Eye Experiment; HiRes; YAG Laser; Fiber optics; PMT

1. Introduction

1.1. *Air fluorescence measurements*

The High-Resolution Fly's Eye experiment (HiRes) studies ultra-high-energy particles that interact in the earth's atmosphere. The interaction of secondary particles traveling through the atmosphere at nearly the speed of light creates an extensive air shower (EAS). The collision of the secondary charged particles with atmospheric nitrogen generates ultraviolet scintillation light. To first order, the amount of light produced is proportional to the energy of the primary particle. The main objective of the HiRes experiment is to find what sources in the universe can accelerate particles above 10^{19} eV [1].

1.2. *The HiRes experiment*

Two observatories, HiRes-I and HiRes-II have recently been completed in the Utah west desert at the US Army Dugway Proving Grounds,

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* Corresponding author. Tel.: + 1-801-581-6058; fax: + 1-801-581-6256.
E-mail address: wiencke@cosmic.utah.edu (L.R. Wiencke).

PII: S0168-9002(00)01124-4

approximately 160 km southwest of Salt Lake City. The observatories have a total of 64 detectors and 16,384 photo-multiplier tubes (PMTs) that record scintillation light from EASs up to 50 km away under good atmospheric conditions.

Each detector has a 3.72 m^2 spherical mirror that focuses light onto a cluster of 256 PMTs. A UV filter located in front of each PMT cluster increases the sensitivity to UV scintillation lines by reducing background light from other sources such as stars and man-made lights.

Each PMT views a $1^\circ \times 1^\circ$ patch of the sky. The detectors are arranged such that the HiRes-II's 42 detectors view nearly 360° in azimuth and a range from 3° to 31° in elevation. HiRes-I, is located 12.6 km away and features 22 similar detectors and has half the angular coverage of HiRes-II (nearly 360° in azimuth and a range from 3.5° to 16° in elevation).

The data acquisition system of HiRes-II observatory uses flash analog/digital converters (FADCs) with a sampling period of 100 ns to digitize signals from the PMTs [2]. Using the pointing directions and charge distributions of each PMT associated with an EAS, the shower direction, energy and longitudinal profile can be reconstructed.

1.3. Overview of the HiRes-II calibration system

The fiber-optic calibration system [3] was designed to perform a relative calibration of the HiRes-II detectors over the anticipated 5 year observation period and track the response of each detector including changes in PMT gain, electronic response, and reflectivity of each mirror. Hence, light from the calibration system must be distributed to all detectors at the HiRes-II site in a uniform and stable manner. Stable means that the uncertainity associated with the calibration system is small compared to the typical 10–30% combined systematic uncertainities associated with scintillation measurements of air showers.

Several features of the design address the stability requirement. A single light source is used and it is located in a clean, temperature controlled environment. The relative intensity of each light pulse is measured and recorded by a monitoring system located in the same controlled environment as the source. The light is distributed to the detectors via fiber optics. Each fiber from the source to detector is a single continuous piece. This arrangement decouples the calibration system from the EAS detectors that are exposed to the ambient desert climate during observation periods.

The calibration system was also designed to simulate the scintillation light emitted by an EAS. A pulsed source is used because the PMT signal from an EAS crossing the field of view is also pulsed. To perform timing calibration, it is desirable to use pulses that have a fast rise time. To check the linearity of the HiRes detector and check the PMT response over the range of light recorded from air showers of different energies and geometries, the amount of calibration light can be varied in a controlled manner. Finally, the source wavelength lies within the 300–400 nm band of nitrogen scintillation in air.

Since calibration data must be collected during each night of detector operation, the entire system is computer (PC) controlled to ensure routine operation. Diagnostic routines check the source, optical filters and monitoring system. The system is configured for remote operation. Physical access to hardware is limited to service work only. The linux operating system for the control PC was selected because of its robustness against crashes and convenient network access.

Finally, the design has the flexibility to incorporate light sources with different wavelengths and pulse durations, for example, lasers and broadband xenon flash bulbs.

2. Delivering the light

Fig. 1 shows the layout of the HiRes-II site. The 42 detectors are distributed in 21 buildings, two detectors per building. The calibration room is located in the middle of the site. Light from the source is transmitted through 168 continuous optical fibers (11 km total length) to each detector. The fibers range in length from approximately 40 to 100 m. Eight fibers are routed to each building (Fig. 2). Two fibers dubbed "mirror fibers" are routed to the center of each mirror and send light

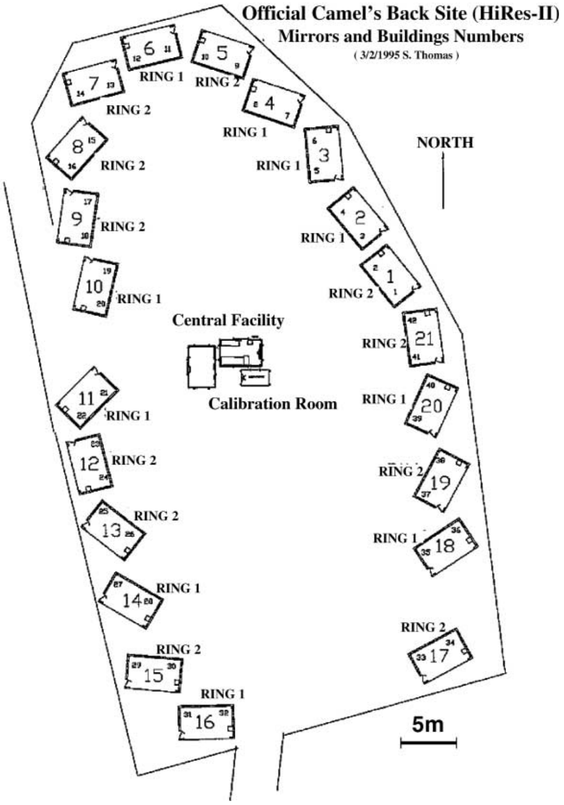

Fig. 1. The HiRes-II site layout. The numbered rectangles denote the detector buildings. There are two detectors per building. Eight optical fibers are routed from the calibration room to each detector building.

to each PMT cluster directly. A second pair of fibers called "cluster fibers" is routed to two sides of each PMT cluster. These fibers send light that is reflected by the mirrors back to the PMTs. A Teflon disk in front of each fiber diffuses the light to produce a point source.

At the source end the fibers are grouped into six bundles. Four "mirror" bundles each contain 21 mirror fibers, one from every building. Likewise, two "cluster" bundles contain 21 pairs of cluster fibers, one pair from a cluster in every building. By illuminating a single bundle at a time, the corresponding detectors (one per building) can be calibrated with no cross-talk of light from other fibers in the same building.

The light source, monitoring system, fiber bundles and associated optics are mounted on an optical table in the calibration room of the central facility. (Fig. 3). The optical table is attached to steel pillars embedded in a concrete foundation. A black-anodized aluminum box covers the table to minimize reflections, light leaks and contaminations such as dust.

The light source is a frequency tripled Nd : YAG laser [6]. It generates 8 mJ pulses of 6 ns duration at a final wavelength of 355 nm. This wavelength lies close to the 357 nm scintillation line produced by EASs and between the two other main lines of 337 and 391 nm [4].

The laser generates light at 1064 nm which is then doubled to 532 nm and tripled to 355 nm. Although dichroics mounted on the laser remove most of the 1064 and 532 nm light, the output beam still contains a small component at these wavelengths. Since the transmission efficiency of silica optical fibers increases with wavelength, it is important to eliminate the long-wavelength components before the beam reaches the fiber bundles. Otherwise, the light reaching the PMTs would not simulate an EAS properly, especially for the longest fibers. Two 45° mirrors, specially coated to reflect 355 nm light, reduce the 1064 and 532 nm components in the beam to much less than 1%.

A fraction of the beam is sampled for shot-to-shot monitoring. A beam splitter redirects 1% of the light to a photo-diode probe connected to a radiometer.

The rest of the beam passes through a motorized eight-position filter wheel that can vary the amount of light transmitted to the EAS detectors by specific amounts. The damage threshold of all filters in the system is much higher than the laser beam flux. A second filter in front of the filter wheel reduces the final output to better match the dynamic range of the detectors. This filter can be removed temporarily to allow enough light through the system so that the fiber outputs in the detector buildings can be easily measured by a portable radiometer.

For better stability there are no moving fibers or mirrors for switching the beam to a particular fiber bundle. Instead, three fixed 50% splitters and two fixed 100% reflecting mirrors divide the laser beam into four equally intense parts. Each is aligned with a different fiber bundle.

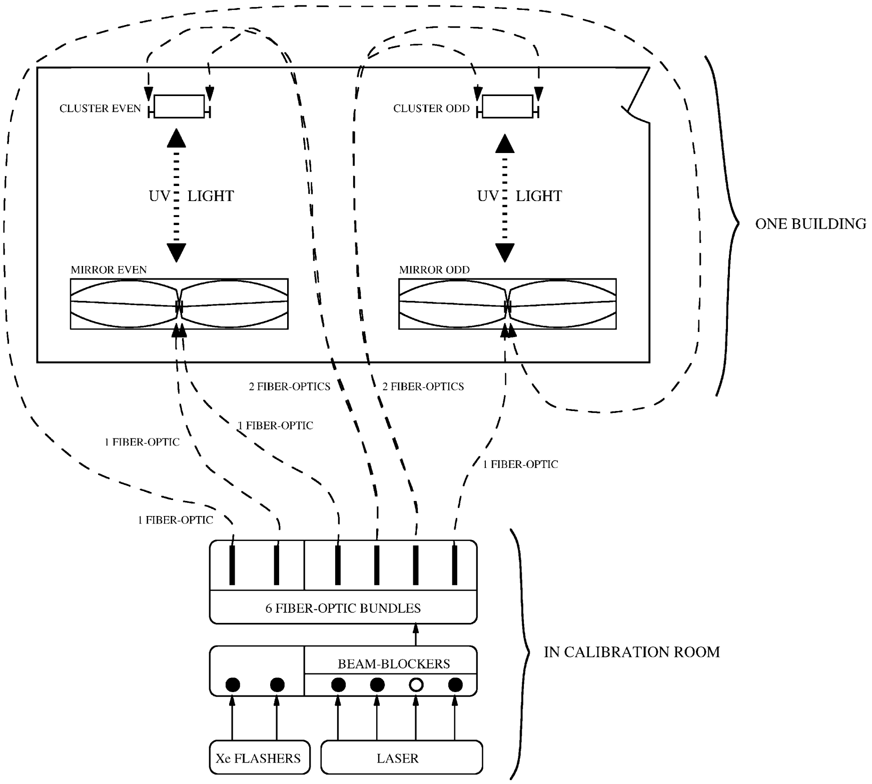

Fig. 2. Routing of the fibers of the HiRes-II calibration system from the light source to the detectors. One of 21 buildings is shown. The diagram is not to scale.

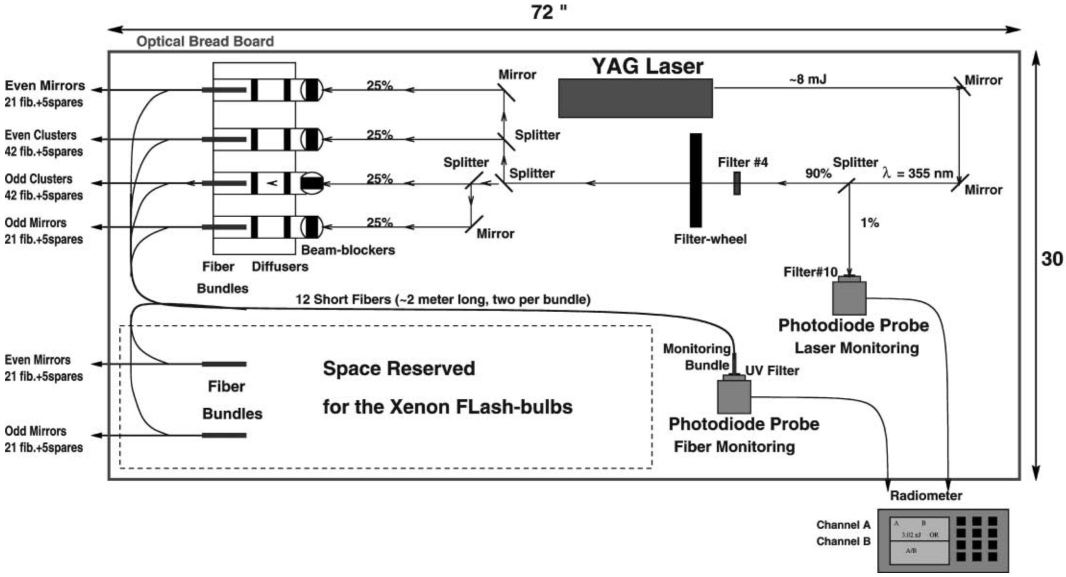

Fig. 3. Layout of the optical table located in the calibration room.

Using four computer-controlled "beam blockers" each beam part can be blocked or passed to illuminate its corresponding fiber bundle. The beam blockers work as guillotines. A solenoid lifts a movable stop out of the beam. If the induced current in the solenoid is interrupted, the stop drops and blocks the beam. The solenoids are rated for continuous energization.

A diffuser fixed in front of each fiber bundle flattens the beam profile and removes any time varying local peaks. It is important to smoothen these marginal hot spots so that all fibers receive approximately the same amount of light and the distribution of light is stable over time. Fused silica windows were chosen for their high damage threshold in the UV range. Each diffuser consist of a pair of these windows, etched on one side and mounted in a threaded black-anodized tube.

The etching process of the silica windows required some trial and error. Chemical etching with hydro-fluoric acid could remove half the material but did not provide a rough enough surface. Tests with sand paper and fine sand blasting produced an irregular opaque surface that failed to flatten the laser beam profile. The best result was obtained by roughening the Si windows manually on one side using 220 grain silicon carbide abrasive powder mixed with distilled water. Random polishing motions for 15 min against flat plastic surface were sufficient.

Fibers of 210 μm diameter fused silica were selected for their transmission properties in the UV. These fibers are encased in a 390 μm nylon jacket. The HiRes technical staff cut the fibers to length, and for additional protection in the field placed them in 6.35 mm $\frac{1}{4}''$ plastic "poly-flo" tubing.

At the source end, it was necessary to find a reliable and stable way to bundle 30–50 fibers together. After many trials, a bundle of 50 fibers (Fig. 4) was prepared and successfully tested in the laboratory. The fibers form a closepacked 2 mm diameter circle which is smaller than the 3 mm diameter of the laser beam. To prepare the bundle, the fiber ends were stripped off their nylon jackets and gathered with heat-shrink tubing. This package was glued along the center of a 6.35 mm OD stainless-steel tube with a UV transparent

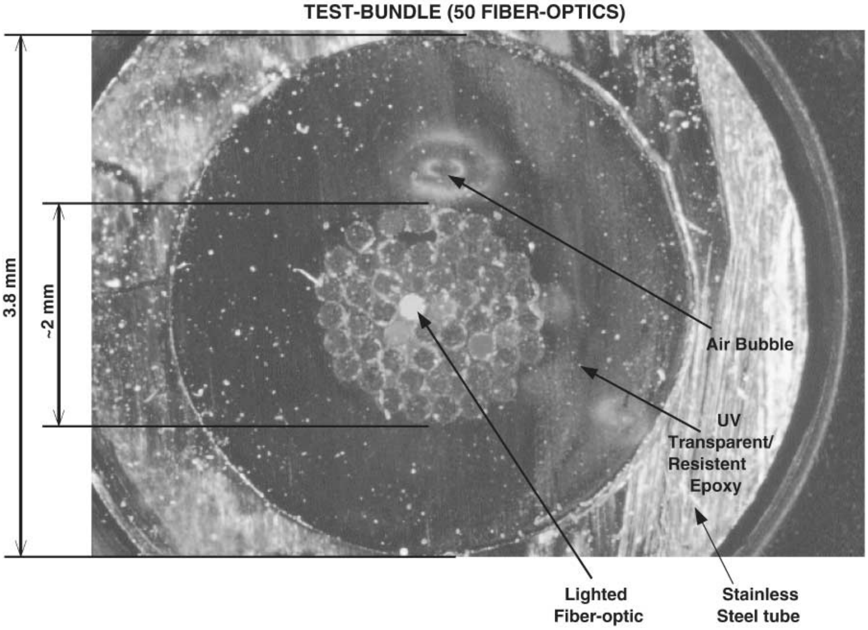

Fig. 4. Photograph of the fiber-optic test-bundle.

and resistant epoxy. After curing, the end was cut by a slow cut diamond saw. The resulting surface was smooth enough and did not require polishing.

One-dimensional scans with the silica windows in various configurations were performed by moving the test bundle across the diffused beam. The best combination of profile shape and amplitude was obtained with two windows each etched on one side and separated by 30.5 mm. The test bundle was held 3 mm behind the closest window and the etched surfaces faced the laser.

The light from two fibers, separated by 1 mm, were measured. The beam profile (Fig. 5 plots A and B) smoothly varies by less than ± 10% over 4 mm. The ratio of B/A (plot C) has a much smaller shot-to-shot fluctuation and varies by less than ± 5% across the same region. The scanned region is larger than the fiber bundle and larger than the original laser beam. Therefore, we expect that even if the bright spots observed in the original beam change with time, changes in the ratio of light coupled to one fiber and light coupled to another fiber will be limited to a few percent.

Six fiber bundles were assembled at the HiRes-II site and arranged as shown in Fig. 2. In addition to the fibers routed to the detectors, each bundle included four short fibers for monitoring purposes and five long spare fibers.

At the detector end each fiber end was stripped off its nylon jacket and its silica core was cleaved to maximize light emmission. A Teflon disk of a nominal thickness was placed in front (Fig. 6). After removing all filters in the beam path, the energy at all fiber outputs was measured with a portable radiometer and a photo-diode probe. The attenuation coefficient of the Teflon

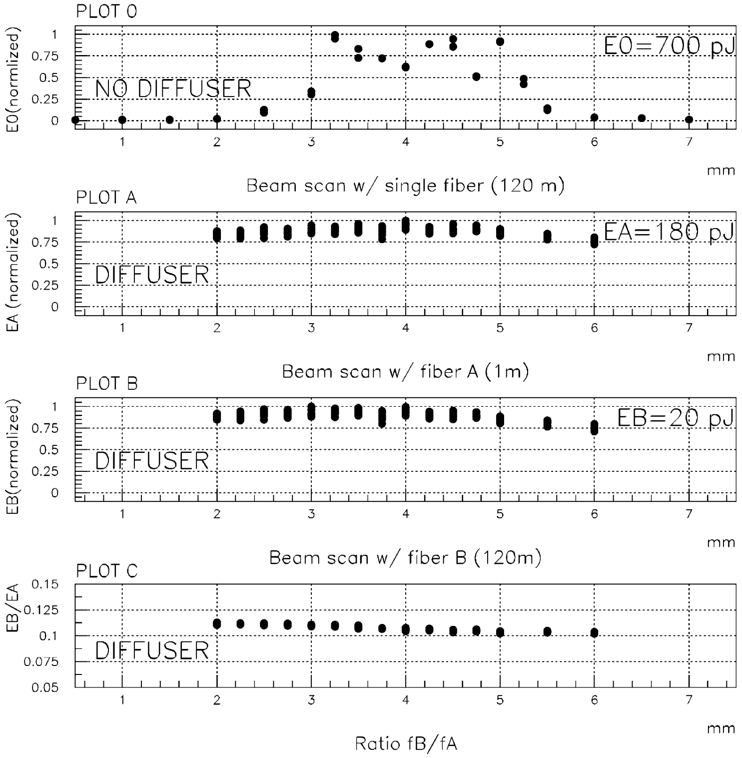

Fig. 5. Scans of diffused laser beam. Plot A shows the profile measured by a 1 m long fiber. Plot B shows the profile measured by a 120 m long fiber that is located 1 mm from fiber A in the same test bundle. Plot C shows that the ratio B/A fluctuates by less than 5% over this 4 mm region.

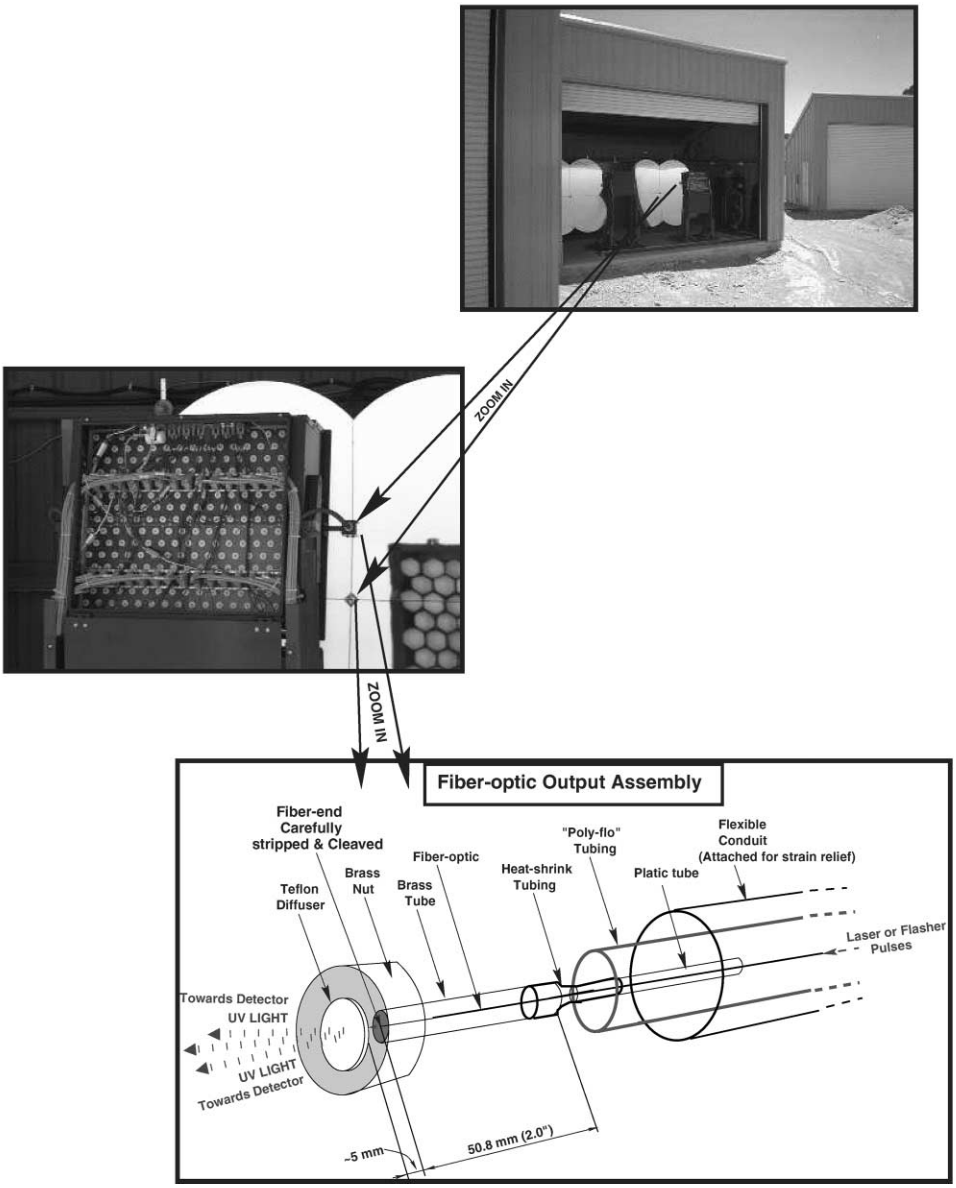

Fig. 6. One fiber output assembly.

in laboratory measurements at 355 nm was found to be $\lambda \approx 2.4\,\mathrm{mm}^{-1}$. The Teflon disks were exchanged with those of different thicknesses so that the output energies of all 168 fibers were between 40 and 60 pJ. This adjustment compensated for fiber to fiber differences in length and light coupling.

3. Monitoring the light pulses

Two photo-diode probes monitor variations in the amount of light delivered to the fibers to normalize the corresponding signals measured by the HiRes detectors. The “laser monitoring” probe measures 1% of the laser beam sampled by a beam splitter. The “fiber monitoring” probe measures the relative amount of light sent through two short fibers in each bundle (Fig. 3). The two probes are connected to a two-channel radiometer that measures the pulse energies and sends the digitized measurements through a RS232 connection to the PC.

The laser monitoring probe is sensitive to changes in the laser output. The laser varies by about 5% RMS shot to shot. Measurements of this probe were compared to measurements of the remaining beam by a piezo-electric probe. In a lab test of 65,000 laser shots corresponding to several weeks of normal operation at HiRes-II, the RMS of the ratio between the two measurements was less than 1%.

The fiber monitoring probe is sensitive to changes in the laser output and to changes in all the beam line components including splitters, mirrors, filters, diffusers, and fiber bundles. Shot-to-shot measurements from the two monitors were correlated to better than 1% RMS over 150,000 laser shots. This places an upper limit on the contribution of the beam line components to the overall uncertainty of the monitoring system.

Fiber monitoring measurements were found to track the amount of light delivered to other fibers in the same bundle at the level of 1%, even when

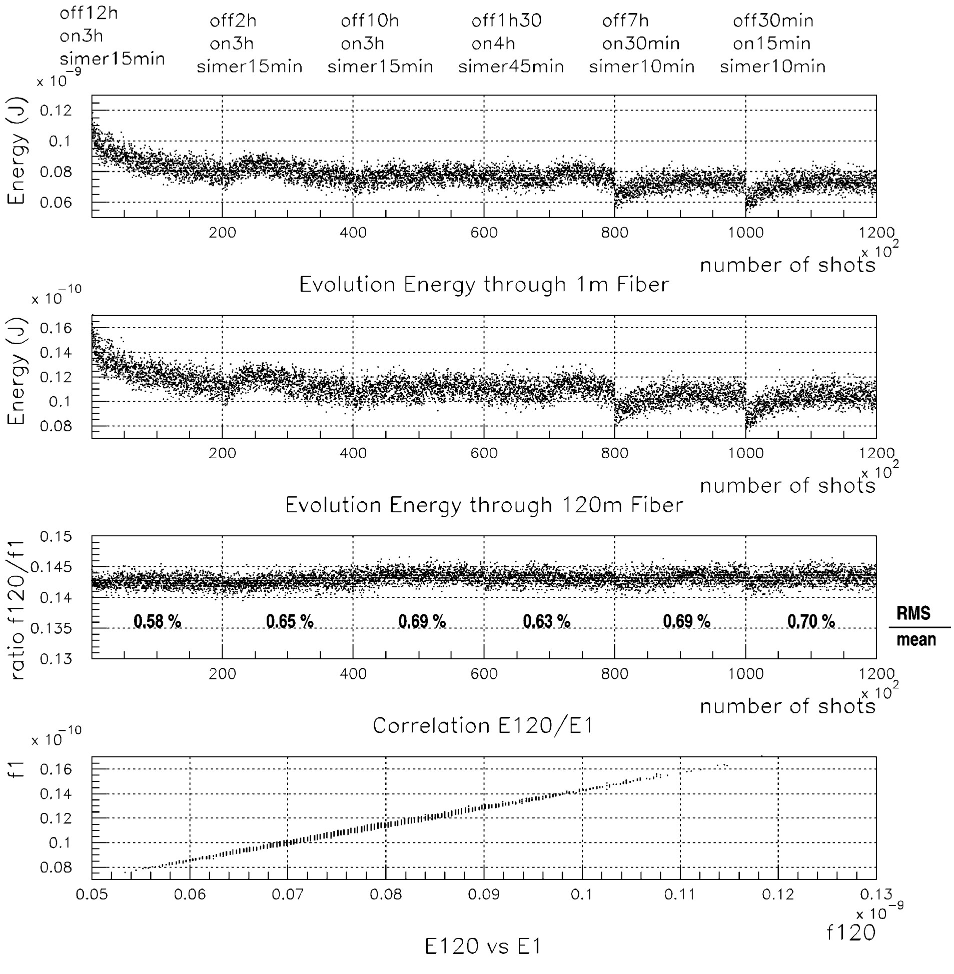

Fig. 7. Long test with interruptions (six trials of 20,000 shots). The measurements performed by two fibers of the test bundle are well correlated despite their difference in length and the laser fluctuations.

fluctuations in the laser output were quite large. For these lab tests two photo-diode probes were used, one connected to a short monitor fiber and the second to a single 120 m long fiber. These fibers were separated by 1 mm in the test bundle. Fig. 7 displays the results from six successive trials of 20,000 laser shots each. Generally, the laser output energy for the six segments showed discontinuities if the laser warm-up time was shorter than 1h. The RMS of the ratio of light transmitted through these two fibers was between 0.58% and 0.70% for each trial. In another test, the correlation was found to vary from 0.3% for adjacent fiber pairs to 1.0% for fibers on opposite sides of the test bundle.

4. Preliminary measurements at HiRes-II

Measurement by one channel of the HiRes-II detector of six consecutive laser pulses are shown in Fig. 8. The plots show the responses in FADC counts versus time. The sampling period is 100 ns. The laser provides short pulses of about 6 ns. The data acquisition system is optimized for microsecond scale pulses. A four-pole filter stretches short pulses to 120 ns before they are sampled and digitized. Some error is introduced by the alignment of the FADC sampling bins with the pulse maxima. Averaging over a large number of pulses lowers this uncertainty. (An EAS produced from a cosmic ray generates a signal of the order of 0.5–5μs, which matches the detector sampling rate.)

Fig. 9 shows the average responses of four PMT clusters to 50 laser pulses versus the position of the PMTs in the clusters. The gains for all 256 channels were previously set to produce a uniform response for the same number of photo-electrons. The Y-axis represents the integrated pedestal subtracted pulse area in FADC counts. The plot indicates that the light is uniformly distributed across each even-numbered cluster (right plots). One can distinguish that the odd-numbered clusters (left plots) that were indirectly illuminated

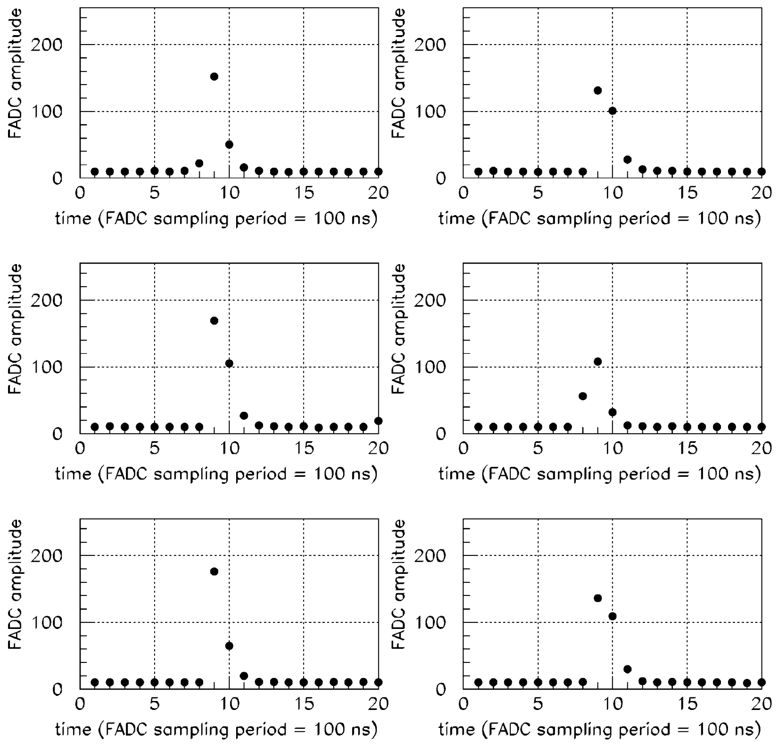

Fig. 8. 6 FADC pulses of the tube #12 of the mirror #2.

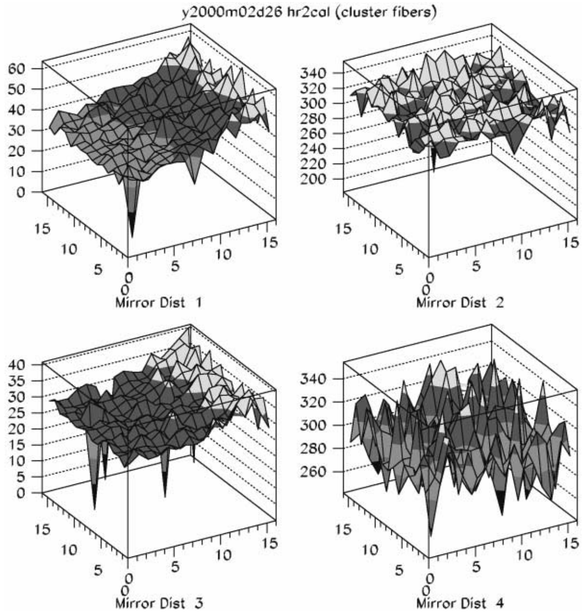

Fig. 9. PMT response for four detectors. The PMT clusters were illuminated by light pulses coming directly from mirror fibers.

recorded less light with a non-uniform distribution.

The laser fluctuates by 3% RMS to mean ratio. The corresponding fluctuation in the global pulse area measured by the 256 PMTs in a cluster is about 6%. This is consistent with an uncertainty of about 5% in the FADC measurement of the area of narrow laser pulses.

The light flux from a fiber-optic output can be estimated. The fiber outputs have been attenuated to produce 50 pJ as measured by a calibrated photo-diode probe. Treating the Teflon as a point source, the flux at the probe is 1.6×10^6 355 nm photons/sr. After calculating the corresponding number of photons hitting a PMT in the detector by including the PMT area and distance and transmission of the additional filters in the beam ($T = 0.0086$), and using the 28.5% nominal PMT quantum efficiency one finds that a single laser pulse should produce about 150 photo-electons/PMT. This is in reasonable agreement with FADC measurements of 200–300 photo-electrons/PMT obtained from similar laser pulses. The PMT calibration in this case was based on photo-electron statistics using a 1% stable portable xenon flash-bulb source.

Although this calibration system was intended for relative rather than absolute calibration, the system can be configured for a single photo-electron calibration of the entire system. This can be accomplished by selecting optical filters to reduce the flux per PMT to less than one photo-electron per pulse on average and triggering the FADC readout externally from a TTL output on the laser [5].

5. Conclusion

The fiber-optic calibration system was installed at HiRes-II. Light (355 nm) from a single YAG laser is distributed to more than 10,000 PMTs distributed in 21 buildings.

Differences in the amount of light delivered between detectors are within ± 10%. The relative shot-to-shot variation in the amount of light delivered is monitored to better than 1% by two different measurements. The amount of light delivered to the entire system can be varied by rotating a single filter wheel. The entire system can be operated remotely. The ratio of light delivered between fibers was found to be stable at the 1%

Table 1

Item	P/N	Source	Notes
YAG laser	CFR ULTRA	BigSky Lasers, Inc [6]	∼ 8 mJ max
Radiometer	RM 6600	Laser Probe, Inc	Two Channels
Radiometer	RM 3700	Laser Probe, Inc	One Channel, portable
PC	—	—	350 MHz, Linux operated
Photo-diode probes	RJP 465	Probe, Inc	Two
Splitter	w2-pw1-1012-uv-355-45s	CVI LaserCorp. [7]	45°
Splitter	BS1-355-50-1012-45s	CVI Laser Corp.	45°
Four Mirrors	16MFB 133	MELLES GRIOT	45°
Filter-wheel	fw1-100	ISI Systems [8]	Eight filter positions
Eight Fused-Si windows	WNL 1104	U-Oplaz Tech., Inc	Not etched as purchased
Optical bread board	78-191-02	CVI Laser Corp.	72 × 32″
Mounting optics	—	THOR Labs, Inc	—
Relay board	CTPDISO 16P	Cyber Research, Inc	w/ cable & connection box
Serial card	EASYIO 4 ISA	Stallion Tech., Inc	w/ cable & connection box
4 Solenoids	69905K26	Mc Master-Carr	Beam-blockers
Epoxy	301-2FL	Epoxy, Inc	UV transparent/resistant
Si fiber-optics	SFS 200/220N	Fiber Guide Ind., Inc	200 μm Si core, ∼ 11 km

level over 150,000 laser shots which would correspond to 6 months of operation at the observatory.

Two upgrades are anticipated. There are two additional fiber bundles that could be illuminated by xenon flash-bulb systems to provide a microsecond long pulse. Different wavelengths could be selected using narrow band filters. The laser will be synchronized with a Global Positioning system based clock so that the detector can be triggered at precise times to check the overall timing calibration.

A well-understood calibration system can be a proof of quality for any experiment. Over the next 5 years, the HiRes-II detector will measure particles with energy above 10^{19} eV. This fiber-optic system will track the HiRes-II detector calibration and performance.

Acknowledgements

This work was supported by US NSF Grants PHY-9322298, PHY-9974537, PHY-9904048, and by the DOE Grant DE-FG03-92ER40732. We gratefully acknowledge the contributions from the technical staffs at our home institutions. The cooperation of Colonel Fisher and Dugway Proving Grounds staff is appreciated.

Appendix A. Equipment and supplies used

The list of the parts that are used in the system is given in Table 1.

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