THE HIRES-II
FIBER-OPTIC CALIBRATION SYSTEM

by

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ABSTRACT

This paper describes the fiber-optic calibration system of the the High Resolution "Fly's Eye" (HiRes) astroparticle physics observatory. The sensing elements of the second detector (HiRes-II, pictured in figure 0.0) are nearly 11,000 photo-multiplier tubes (PMT). They measure the fluorescence light, collected by 42 mirrors, from distant extensive air showers (EAS). The calibration system described here is fully automated and has begun performing nightly calibrations of the entire detector using a single light source. This detector will observe cosmic rays for the next three to five years. Its stability, and consequently, the stability of its calibration system are very important for accurate reconstruction of cosmic ray air showers parameters.

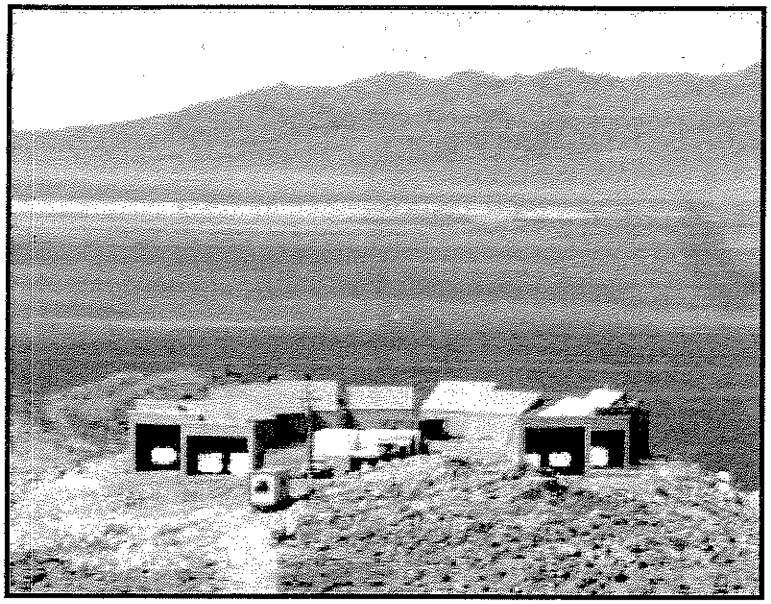

Figure 0.0. The HiRes-II Cosmic Ray Detector, Located at Camel's Back Ridge, Dugway Proving Grounds, Utah

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CHAPTER 1

MOTIVATIONS

1.1 Overview of the Air Fluorescence Technique

Previous experiments have successfully applied the Air Fluorescence Technique (AFT) to study primary cosmic rays entering the atmosphere, notably the Fly's Eye observatory [1]. In 1991, the original "Fly's Eye" experiment reported the highest energy particle ever measured (3.2×10^{20}eV) [4]. This energy surpasses by seven orders of magnitude the most energetic particle produced in earth bound particle accelerators. It is also beyond the well known Greisen-Kuzmin-Zatsepin (GZK) cut-off [5, 6] that does not predict such high energies in the cosmic ray spectrum because they are attenuated by the 2.7K microwave background radiation.

Ultra high energy particles develop a broad, thin disk of secondary charged particles traveling through the atmosphere at the speed of light [2]. This cascade process results in what is called an extensive air shower (EAS). The collision of the secondary particles with atmospheric nitrogen generates light in the ultraviolet portion of the spectrum. The AFT, described in figure 1.1, allows the measurement of the arrival direction, energy, and primary mass composition of high energy cosmic rays. The energy is determined calorimetrically using the atmosphere as a huge calorimeter. A fraction of the particle's energy is dissipated by ionizing the nitrogen molecules that fluoresce. The amount of light produced is proportional to the energy of the primary particle. The fluorescence yield corresponds to the number of photons emitted per charged particle (electron or positron in most cases) per meter. This yield depends on the pressure and temperature of the atmosphere. Most of the light is generated within a 300 nm to 400 nm band for which the fluorescence yield reaches 4 to 5 photons/m/e^- in dry air between 0 and 13°C at an altitude ranging from 0 to 20 km for a 80 MeV electron [3]. It is important to distinguish the fluorescence light from the Cerenkov light that is emitted in the cascade process. The crossing time and integrated charge for each photo-multiplier tube (PMT) triggered by the EAS's fluorescence light allows the longitudinal profile of the shower to be observed. From this profile, one can determine X_{max} which corresponds to the atmospheric depth at which the maximum number of secondary particles is produced by the shower. X_{max} is correlated with the mass of the primary nucleon.

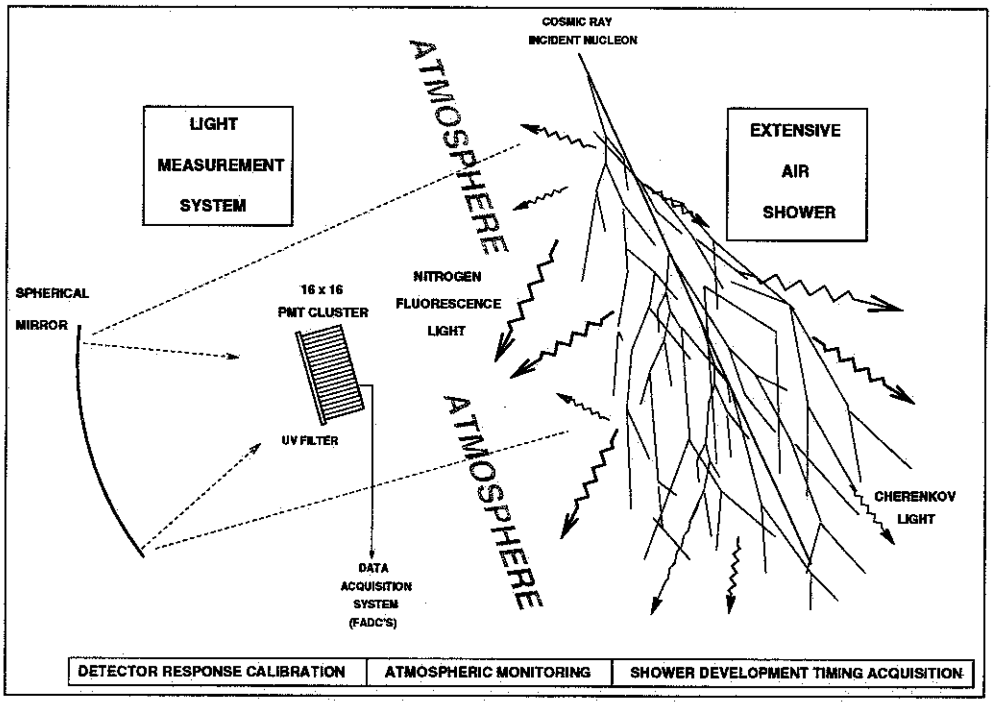

Figure 1.1. Air Fluorescence Technique.

1.2 Overview of the HiRes Experiment

The goal of the University of Utah Cosmic Ray research group is to measure more ultra high energy cosmic rays using the AFT. One of the main objectives of the HiRes collaboration is to find what sources in the universe are capable of such violent accelerations. Two new generation cosmic ray detectors, HiRes-I and HiRes-II have recently been completed in the Utah's west desert at the US Army's Dugway Proving Grounds, approximately 100 miles southwest of Salt Lake City. These detectors "see" about 30,000 km^3 of atmosphere, in which EASs occur. The HiRes detectors can record fluorescence light up to 50 km away under good atmospheric conditions. The two detectors feature a total of 64 large mirrors to collect the light associated with more than 16,000 PMTs.

HiRes-II is composed of a ring of 42 fixed fluorescence telescopes distributed in 21 buildings. Each telescope has a 3.72 m^2 spherical mirror with a cluster of 256 PMTs in its focal plane. Each PMT views a one degree cone of the sky. These telescopes are arranged such that the HiRes-II detector views nearly 360° in azimuth and a range from 3° to 31° in elevation. The other site, HiRes-I is located at 12.6 km away and features 22 telescopes. Together, HiRes-I and HiRes-II ensure good stereo reconstruction capabilities.

1.3 Requirements for HiRes Measurements

The High Resolution Fly's Eye detector (HiRes) must have the sensitivity and the speed required to measure the fluorescence light emitted by EASs and to understand the development of showers through the atmosphere.

The main requirements for HiRes measurements include a data acquisition system capable of tracking the parameters of EASs, an atmospheric monitoring system that provides useful information on the effects of the atmosphere's light scattering properties, and a detector response calibration system. The rapidly moving spot of UV light from an EAS is collected by the mirrors and focused on clusters of PMTs. Each PMT views a $1° \times 1°$ patch of the sky. The PMTs measure the amount of light generated by EASs which is related to the energy of the primary particle. The calibration of the response of the PMTs is therefore required to determine the energy of the primary cosmic ray. To perform the timing calibration, it is crucial to use short fast pulses. Longer pulses are needed to better simulate EASs. HiRes uses UV filters to maximize its sensitivity to the UV fluorescence light band and reduce the noise due to the night sky background.

1.4 Requirements for a Calibration System

The fiber optic calibration system described in this report should perform calibrations of the HiRes-II detector's response. A calibration is needed to track how each PMT is working relative to the others as well as how the reflectivity of each mirror changes as a function of time. A known amount of light must be uniformly distributed to the detectors.

The calibration system should use light sources that are well monitored over the life-time of the experiment. The system has to record and display relative information about the amount of light sent to the detectors. A single light source located in a clean, temperature controlled environment is an ideal choice. In order to use this system to verify the linearity of the HiRes detector, the calibration system also needs to vary the light intensity delivered to the PMTs.

The light source should simulate the fluorescence light emitted by an EAS. Therefore, the wavelength of the source should be within 300 to 400 nm and match the wavelength region band for which HiRes' sensitivity is maximized. In addition, the source must produce light in pulses shorter in duration than 5 μs to be comparable to the time required for an air shower to cross the field of view of a PMT.

Calibration data must be recorded every hour during each night of data taking. Therefore, the system should be computer controlled for ease of use by the detector operators. The system should also be able to run independently for self-diagnostics.

The system should also be able to provide single photons to the PMTs in order to perform a single photo-electron calibration of the detector thereby providing a calibration of the response of each PMT, and electronic readout channel. This requires very good synchronization between the HiRes data acquisition system and the calibration source. Namely, the calibration system should have the capability to trigger the detector readout.

Finally, the system has to be flexible enough to incorporate different light sources with different wavelengths and pulse durations, for example, lasers and broad band xenon flash-bulbs.

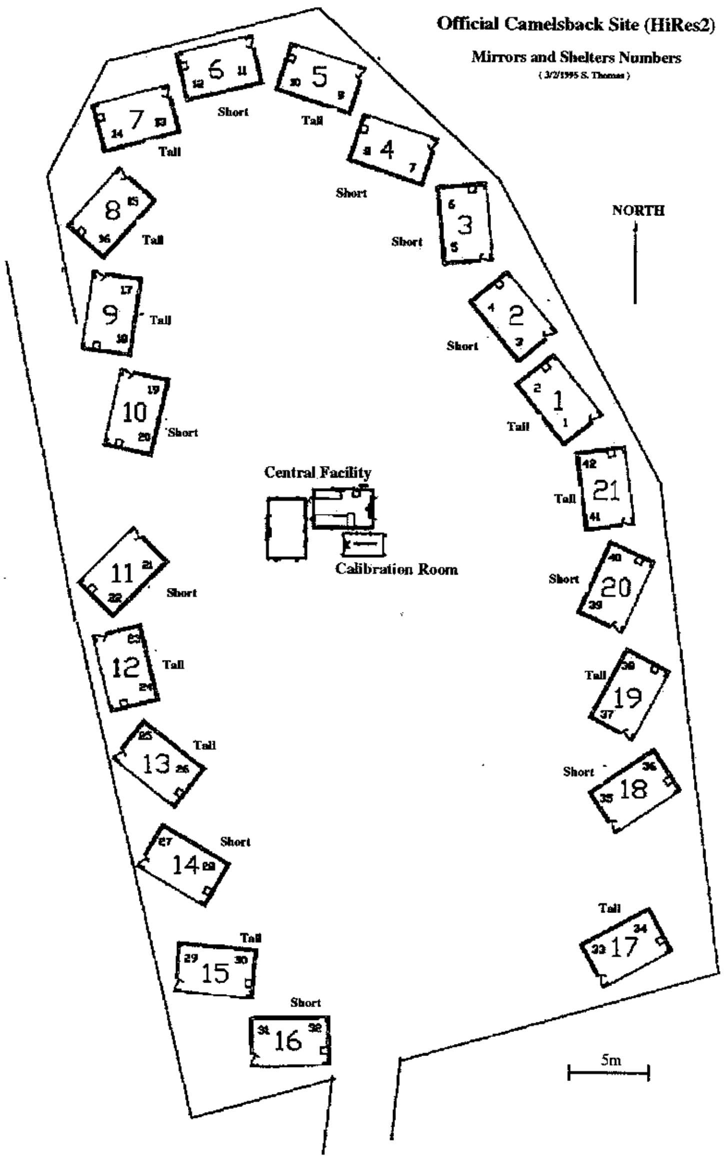

Figure 1.2. HiRes-II Mirrors & Shelters Layout.

CHAPTER 2

DESCRIPTION OF THE SYSTEM

2.1 Overview of the Detector and the Calibration System

Figure 1.2 shows the layout of the 21 buildings at the HiRes-II Camel's Back site. The calibration room is located approximately in the middle of the site. At present, the calibration light source is a frequency tripled Nd-YAG laser. Its beam is transmitted through 168 optical fibers (seven miles total length) to 42 detectors located in 21 buildings. These fibers are continuous from the light source to the detector. Two fibers have been routed to the center of each mirror to provide direct light to each PMT cluster. A second pair of fibers has also been routed to both sides of the clusters to send light pulses that are reflected by the mirrors back to the PMTs. This arrangement, which will be described in detail, can be seen in figure 2.3 and in figure 3.12.

2.2 Components of the Fiber-optic Calibration System

A schematic layout of the optics in the calibration room is shown in figure 2.1. The laser generates UV light pulses. A small fraction of the beam is split off into a photo-diode probe that monitors the output energy of the laser. Different beam energies can be selected by choosing filters of various transmission coefficients. These filters have been mounted on a wheel which can be rotated to place the desired filter in the beam. The beam is then split into four equally intense parts. Each beam can be blocked or passed to illuminate different parts of the detector. When a beam-blocker is open, its corresponding laser beam hits a bundle of optical fibers that carry the light pulses to the buildings. A diffuser in front of each bundle flattens the beam profile so that all fibers receive similar amounts of light. The light is also monitored through short fibers in each bundle that deliver light to a second probe. Hence, we know the relative variation in the energy produced by the laser and the energy coupled into the fiber bundles. This layout includes spaces for an additional piezo-electric probe to measure the beam energy at different places.

The entire setup is mounted on an optical table firmly attached to concrete pillars in the ground. A black-anodized aluminum box covers the table to minimize reflections and light leaks.

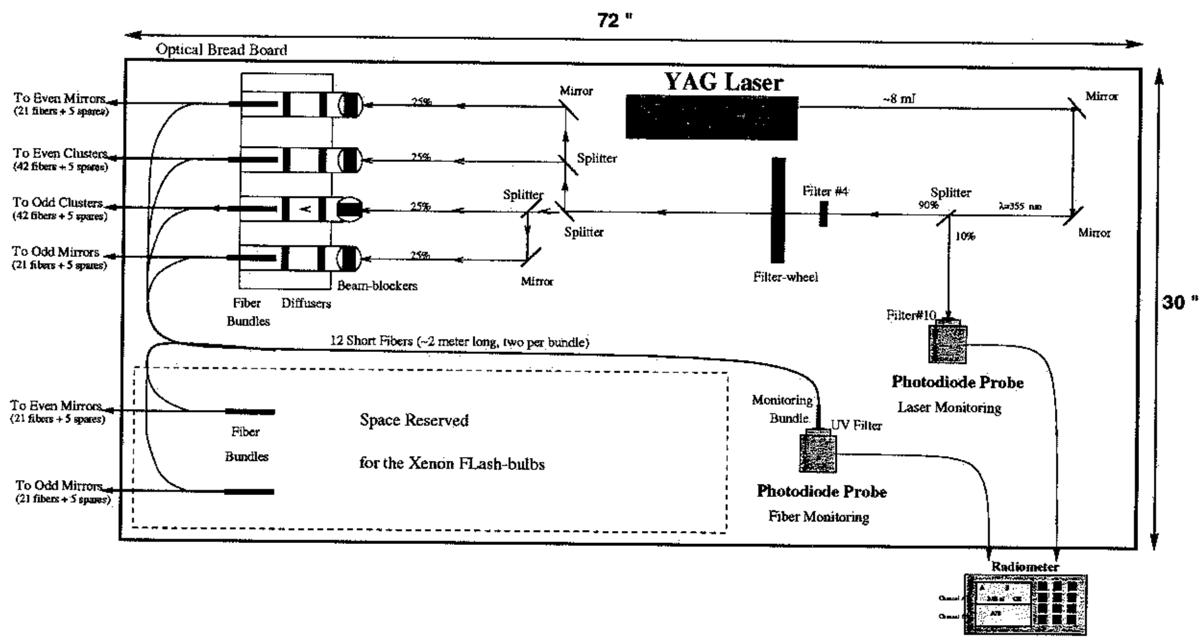

Figure 2.1. Optical Table Layout.

2.2.1 Laser

The laser is a frequency tripled Nd:YAG laser [9] that provides 6 ns pulses of about 8 mJ at a final wavelength of 355 nm. The laser first generates light at 1064 nm before doubling and tripling this fundamental wavelength using crystals. Therefore, the resultant beam may still contain longer wavelengths than 355 nm and it is important to "clean" it using mirrors with a special coating that eliminates other harmonics. The laser output wavelength falls right between the band limits of the detectors' filters that have been placed to maximize the signal to noise ratio. Also, the 355 nm wavelength of the YAG laser is very close to the 357 nm line which one of the three main components of the fluorescence signal. The signal is the fluorescence light from an EAS, the noise can be any light pollution in the sky background such as stars, houses and automobile headlights.

2.2.2 Optics

Longer wavelengths are transmitted more efficiently through optical fibers than shorter wavelengths are. Therefore, it is important to eliminate longer wavelengths before the beam hits the fiber bundles. Otherwise, the light delivered to the detector would contain these longer wavelengths and would not simulate an EAS properly.

The first optical elements in the beam are two mirrors placed at 45° so that the beam makes a U-turn. These mirrors are specially coated to reflect only the UV light at 355 nm. They reduce the 1064 nm fundamental and 532 nm first harmonic components in the laser beam to less than 1%. The first splitter placed in the beam path redirects 1% of the beam to a photo-diode probe connected to a radiometer so that it can be sampled. The rest of the initial beam is transmitted.

A motorized filter-wheel with eight filter positions allows users to select and transmit different amounts of light to the fiber bundles under computer control. All filters used in the system feature a damage energy threshold that is much higher than the laser beam flux.

To make the system as robust and stable as possible, there are no moving fibers or mirrors. Instead, the laser beam is split into four equally intense beams using three fixed splitters and two fixed mirrors. Small differences between beam intensities can be explained by the fact that one of the four beams is only transmitted and never reflected and the other three beams are reflected at least once in their path (see figure 2.1).

Four computer-controlled beam-blockers are use to select which of the four beams are sent to the detector. The beam-blockers work as "guillotines" using solenoids to lift 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 used are rated for continuous energization. The current is minimized to prevent a large dissipation of heat when a blocker is opened for long periods of time.

A diffuser is fixed in front of each fiber bundle to flatten the beam that typically has some time varying peaks in its profile. It is very important to cut these marginal hot peaks from the beam profile to send approximately the same amount of light to all fibers and to make the distribution of light stable over time. Fused silica windows have been chosen because of their extremely high damage threshold in the UV range. The diffusers consist of a pair of these windows, etched on one side and separated by 1.2 inches, and mounted in threaded 1" ID black-anodized tubes.

2.2.3 Fiber System

Fiber-optics are the key elements of the system. Dealing with them required quite a bit of thought. To optimize the transmission in the UV, 200 μm fused silica fibers were chosen. The main problem was to find a reliable and stable way to hold 30 to 50 of these fibers together and to simultaneously send the same amount of light into each one. After many trials, a bundle of 50 fibers of different lengths was prepared and successfully tested in the laboratory. This test-bundle is pictured in figure 2.2.

To prepare this bundle, the fiber ends were stripped of their nylon protection and gathered together with heat-shrink tubing. This package was glued together along the center of a stainless steel tube with a UV transparent and resistant epoxy. After 10 days of curing the end of the tube was cut off using a slow cut diamond saw. Surprisingly, the resulting surface was smooth enough and did not require additional polishing.

Six bundles were made at the HiRes-II site and arranged following the scheme shown in figure 2.3. Each bundle includes five long spare fibers in preparation for the event where broken fibers have to be replaced. Four short fibers were also included in each bundle for relative monitoring. Different fiber bundles were used for even and odd numbered mirrors to prevent cross-talk that occurs when light from one fiber reaches PMTs in both telescopes in the same building. Also, this

TEST-BUNDLE (50 FIBER-OPTICS)

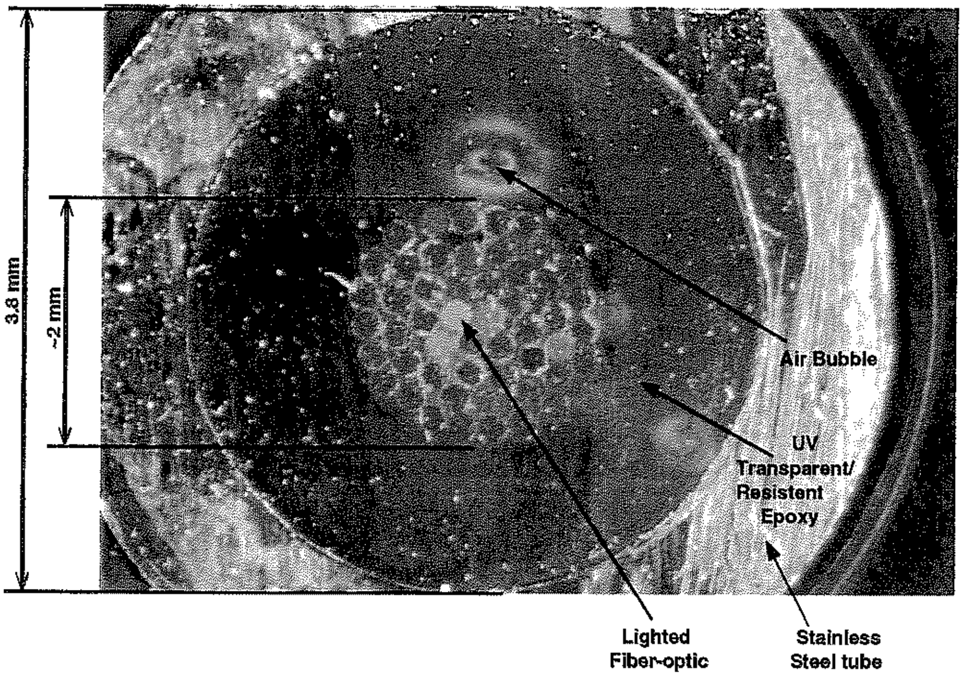

Figure 2.2. Photograph of the Fiber-optic Test-bundle.

scheme provides good methods to check if a fiber output or its diffuser is damaged. For example, if the signal measured directly from the mirror fiber has changed but the signal from the "cross-talk" fiber has not changed,, one can conclude that this mirror fiber output, not the detector, is problematic.

2.2.4 Monitoring

The shot to shot laser output fluctuates in energy by approximately 5% RMS. Therefore, it is important to monitor these pulse variations to normalize the signal measured by the HiRes detector. This monitoring is accomplished by two photodiode probes. The laser monitor measures 1% of the laser beam sampled by the first beam splitter. The fiber monitor probe measures the relative amount of light sent through two short fibers in each bundle. We chose to use two fibers instead of one to double the amount of light and reduce systematic errors due to the radiometer sensitivity.

The ratio of the two probes' measurements is sensitive to changes in the beam line optics and to the coupling of light into the fiber bundles. The two probes

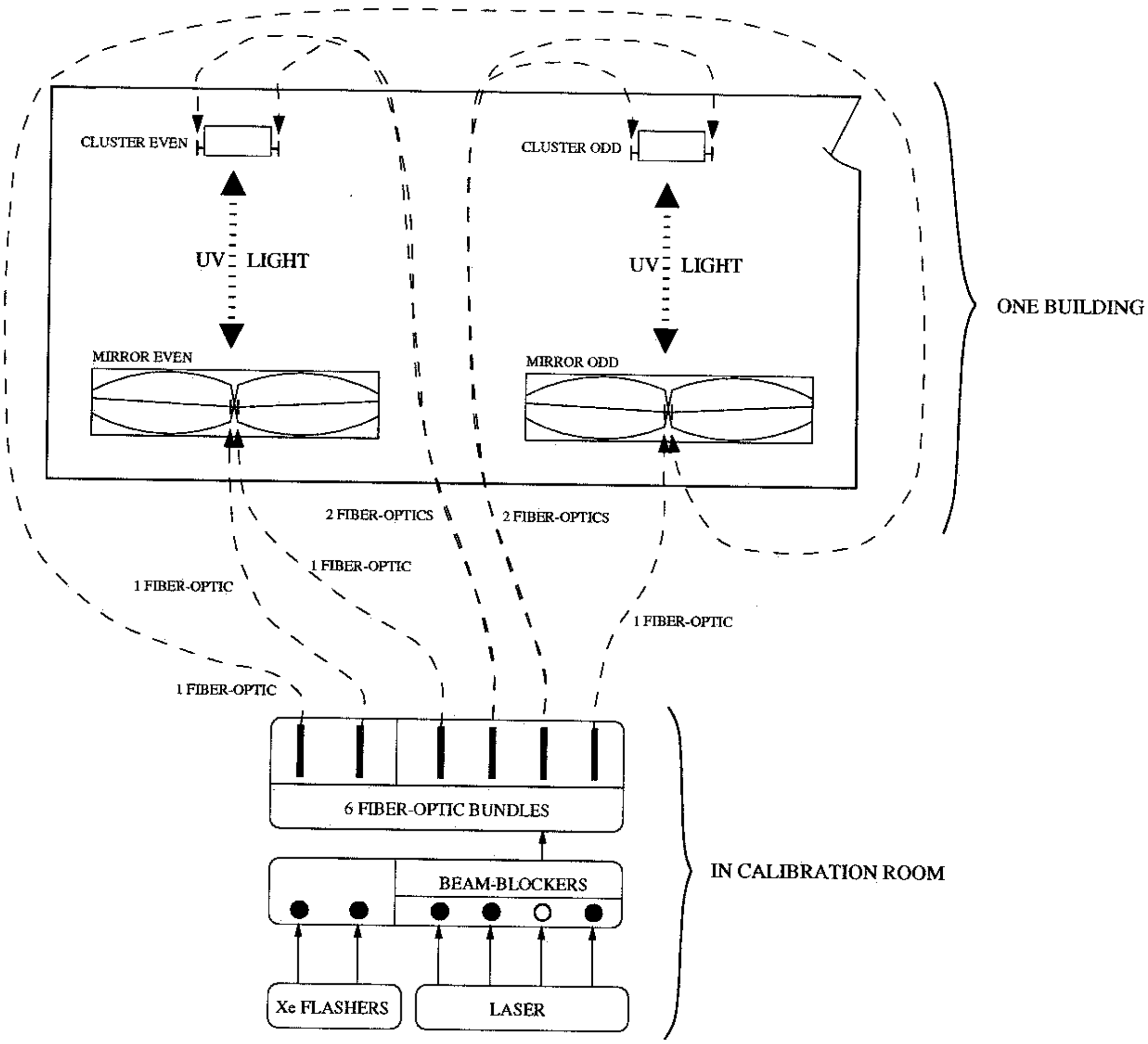

Figure 2.3. Fiber-optic System.

are connected to a two-channel radiometer that reads the energies and sends the digitized measurements to a PC where the data is recorded.

2.2.5 Computer Control

Operators can control every adjustable element of the calibration system from a PC. This includes the laser, the filter-wheel, the beam-blockers and the radiometer as shown in figure 2.4. The Linux operated PC is connected to the Internet and allows users to operate the system from remote locations. Automation helps to ensure the system runs stably. Physical access to the optics is limited to maintenance or major changes only.

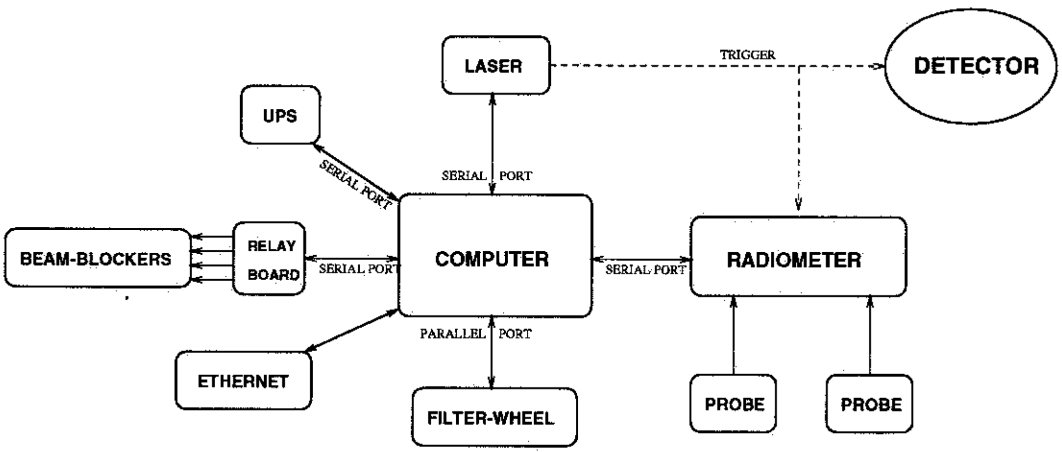

Figure 2.4. Computer Control Diagram.

It is important to mention that the data acquisition equipment for the monitoring of the delivered light uses RS232 serial connections which easily accommodate the firing rate of the laser which is about 3 Hz. It is independent from the fast data acquisition system of the HiRes-II detector which is composed of flash analog/digital converters (FADCs).

2.2.6 Equipment and Supplies Used

Table 2.1. List of the parts that are actually used in the system. Many items that have been used during tests are not included in this table.

Item	P/N	Source	Cost (US $)	Notes
YAG Laser	CFR ULTRA	BigSky Lasers, Inc [9]	14,218	˜8 mJ max
Radiometer	RM 6600	Laser Probe, Inc	3,654	2 Channels
Computer	-	-	1,800	PC 350 MHz, Linux operated
Photo-diode Probes	RJP 465	Laser Probe, Inc	1,870	2 at $935 each
Splitter	w2-pw1-1012-uv-355-45s	CVI Laser Corp. [10]	400	45°
Splitter	BS1-355-50-1012-45s	CVI Laser Corp.	400	45°
4 Mirrors	16MFB 133	MELLES GRIOT	836	45°
Filter-Wheel	fw1-100	ISI Systems [11]	1,100	8 filter positions
8 Fused-Si windows	WNL 1104	U-Oplaz Tech., Inc	200	Not etched as purchased
Optical Bread Board	78-191-02	CVI Laser Corp.	1,755	72 × 32″
Mounting optics	-	THOR Labs, Inc	˜1,000	-
Relay Board	CTPDISO 16P	Cyber Research, Inc	463	w/ cable & connection box
Serial card	EASYIO 4 ISA	Stallion Tech., Inc	250	w/ cable & connection box
4 Solenoids	69905K26	Mc Master-Carr	50.52	Beam-blockers
Epoxy	301-2FL	Epoxy, Inc	36	UV transparent/resistant
Si Fiber-optics	SFS 200/220N	Fiber Guide Ind., Inc	˜16,000	200μm Si core, $1.47/meter

Total Cost of these Items: ˜$44,000

Table 2.2. Comparison between two types of light source: YAG laser and xenon flash bulbs.

Light Source	Advantages	Disadvantages
YAG Laser	Single sharp wavelength Pulse energy Fast rising edge Constant pulse width Best for timing calibration Collimated beam, easy to direct Needed to install and test the fiber system	High cost Unstability Short pulse duration (˜6 ns)
Xe Flashers	Several wavelengths available Stable pulse area Lower cost Longer pulse duration (˜1 μs) Low maintenance	Require narrow band filters Lower pulse energy Emit light in all directions, difficult to focus

CHAPTER 3

TESTS AND RESULTS

3.1 Laboratory Tests and Results

The purpose of the laboratory tests was to determine how to build the fiber-optic system by evaluating each of its components before installation at HiRes-II. The following sections describe these tests.

3.1.1 Laser Monitoring

Figure 3.1 shows the setup used to test the laser monitoring system that would be used on the calibration system to be installed at HiRes-II. The measurement performed by the photo-diode probe was compared to a energy measurement made by a piezo-electric probe. This test verified the ability of the photo-diode probe to monitor fluctuations in laser output energy. The piezo-electric probe, insensitive to wavelength, can handle higher energy pulses than a photo-diode probe. For these reasons, it is used for absolute energy measurements. The results are displayed in figure 3.2.

In figure 3.2, the top two plots show the fluctuations in energy measured by both probes. The next two diagrams display the correlation between them. Statistical distributions of both measurements are plotted below. The RMS of the laser output variations is about 5% of the average energy. The RMS of the ratio (bottom diagram) is only 0.8% of the mean. This ensures that the laser output can be monitored to better than 1%. This test consisted of about 65,000 laser shots over a five hours duration. This corresponds to several weeks of normal operation at HiRes-II. The gentle slope in the ratio versus shots plot can be explained by

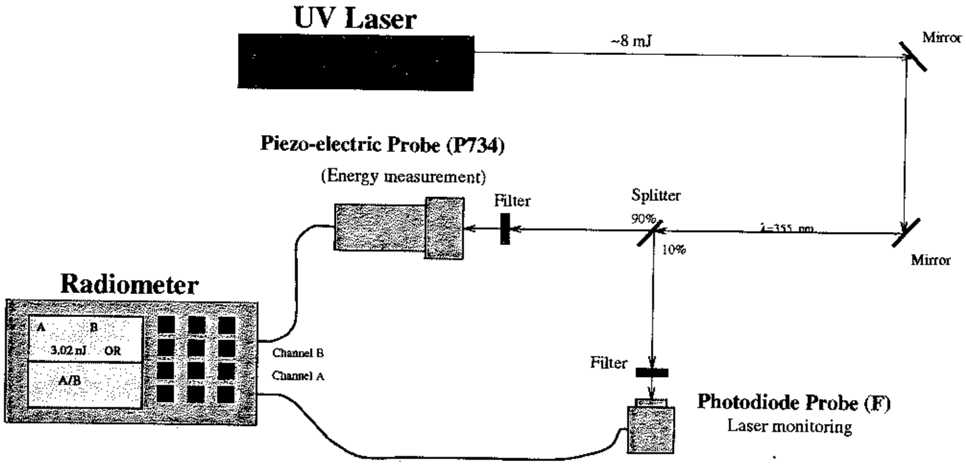

Figure 3.1. Laser Monitoring Test Setup.

inadequacies in the type of glass used to split the beam. This splitter was damaged during the first 40,000 pulses. This problem was solved when the system was installed at Dugway by utilizing a splitter with a high energy damage threshold. This test indicated that the laser monitoring probe provides a reliable measurement of the variations in laser energy output.

3.1.2 Fiber Monitoring

Two laboratory tests were performed with configurations very similar to the final setup at HiRes-II. Using the laser probe as a reference, the first test compared its measurement with that of a second probe viewing light transmitted through the longest fiber that the HiRes-II setup would use (120 m). A drawing of this setup is shown below in figure 3.3 and the results are displayed in figure 3.4. Although the laser's intensity decreased over time, the two measurements follow each other. A small change in the correlation with time is attributed to the type of glass of the splitter as described earlier. This test demonstrated the correlation between the laser monitor probe measurement and the quantity of light delivered to the detector through the entire optic system including the diffuser, the fiber bundle, a 120 meter long optical fiber and a Teflon attenuator. The RMS of the pulse to pulse ratio is better than 1% over 150000 shots.

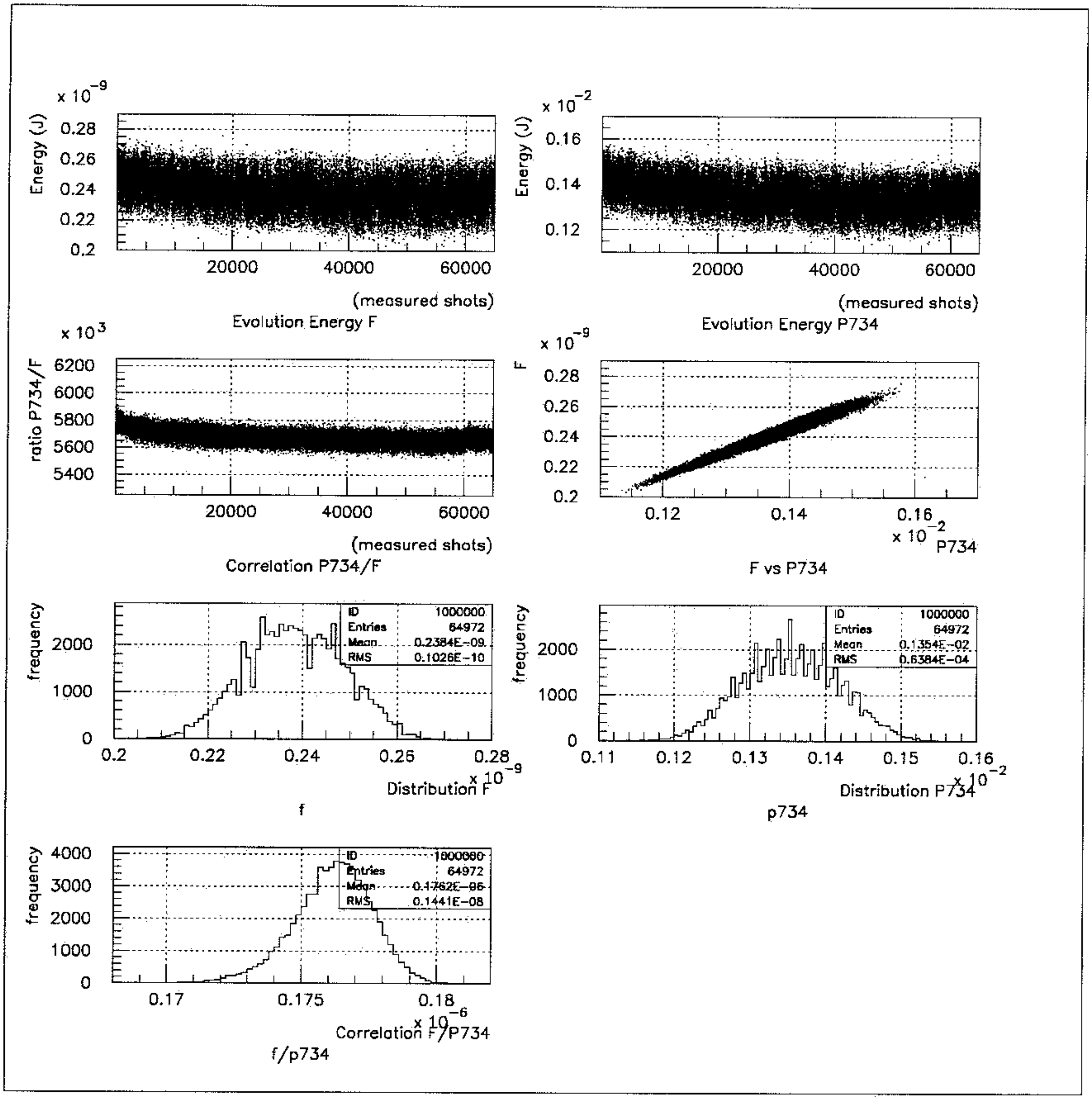

Figure 3.2. Laser Monitoring Test (Correlation with Laser Variations)

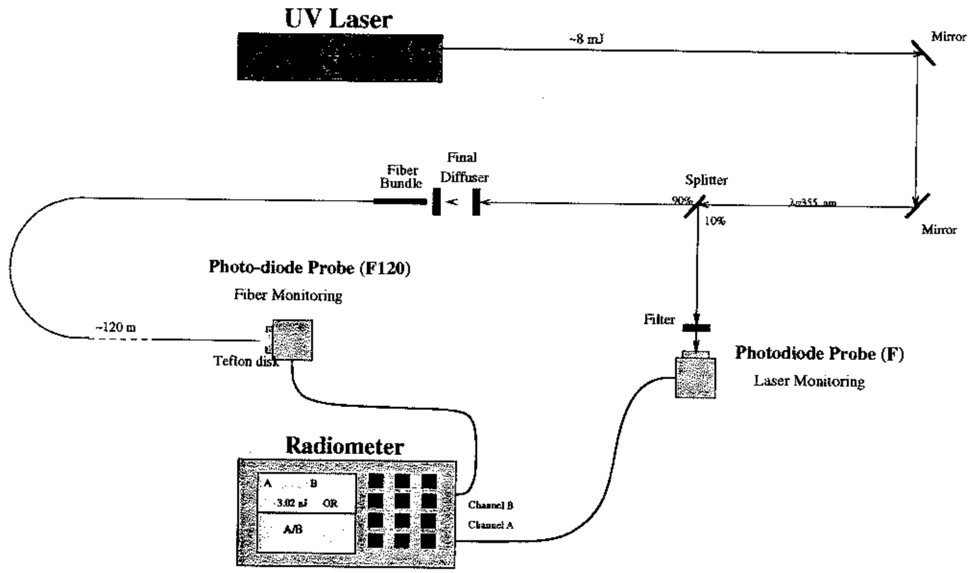

Figure 3.3. Fiber Monitoring Test Setup.

Another test performed with the configuration described in figure 3.5, determined the correlation between is the light transmitted by two fibers of the same bundle. The test was repeated many times in laboratory, using different fibers pairs of the test-bundle (figure 2.2). The results of one these measurements are displayed in figure 3.6. It was successfully verified that the correlation could be optimized by choosing two fibers very close to each other and minimized by choosing two fibers at opposite boundaries in the test-bundle. This shows that the beam profile at the output of the diffuser is not ideal but it is demonstrated later in this paper that the degree of diffusion reached in this configuration was sufficient.

For a long duration test consisting of 150,000 laser shots, the correlation fiber1 to fiber2 had a RMS of 0.3% for close pairs and 1.0% for opposite pairs. This result was encouraging because two ways to monitor the light provided to the detector were successfully demonstrated. The comparison between these redundant measurements will allow a long term check of the optics in the laser beam.

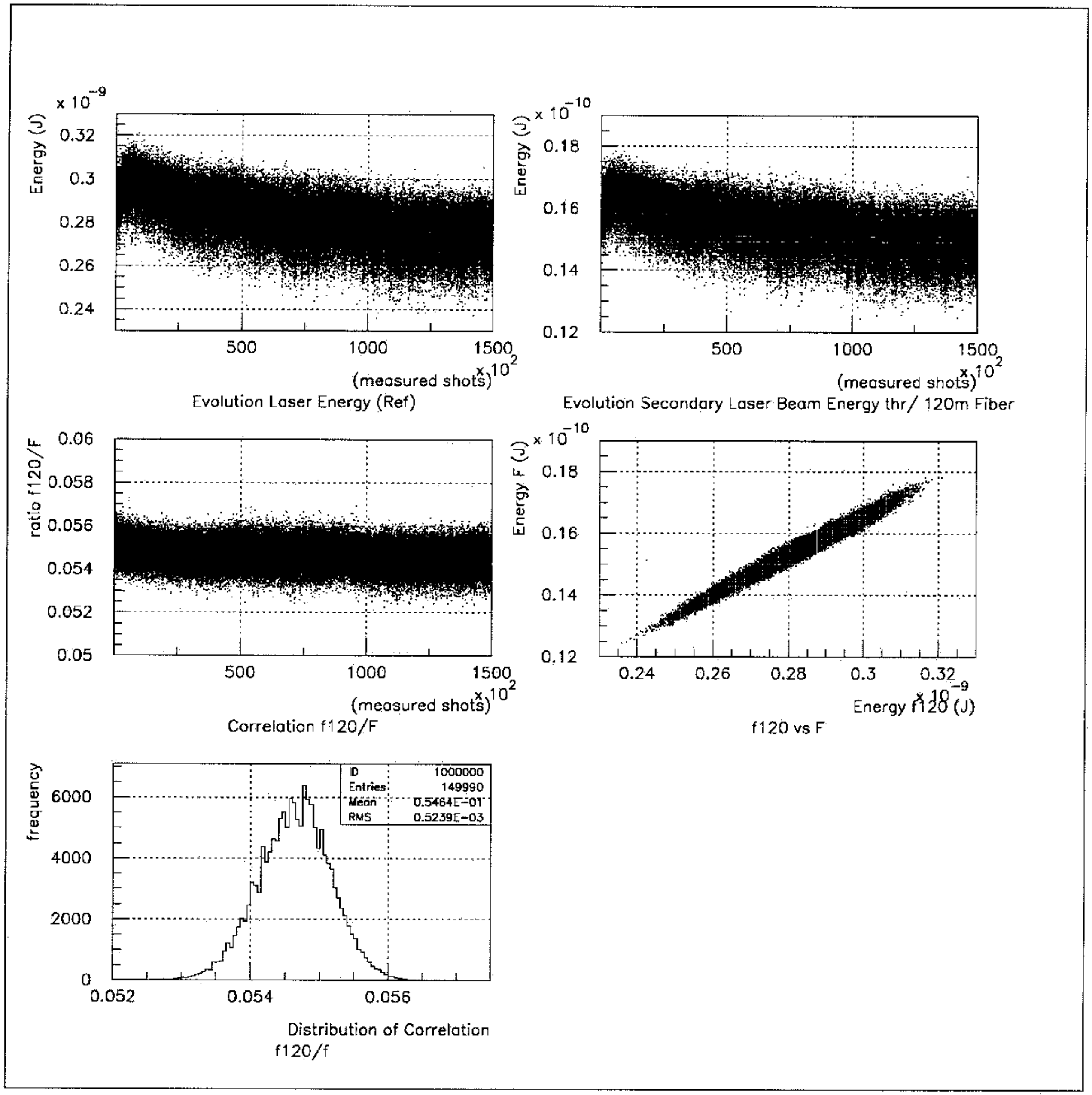

Figure 3.4. Correlation of the 120m Long Fiber Output with Laser Output over 150,000 Laser Shots.

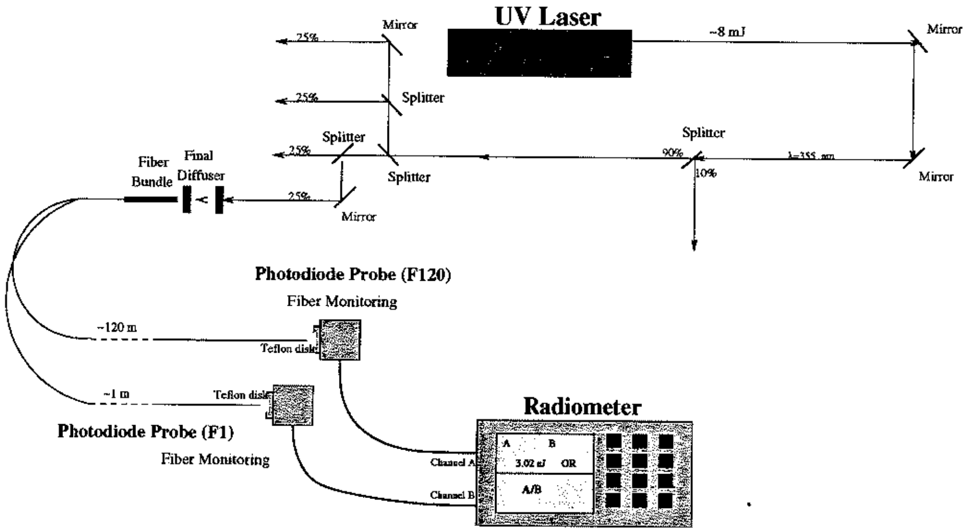

Figure 3.5. "Fiber/Fiber" Monitoring Test Setup.

3.1.3 Stability

The main source of instability of the system is the laser. Its energy varies 5% shot to shot but longer term variations can be much larger especially just after the laser is turned on. Another test examined how well the light could be monitored after different interruptions. The setup was similar to that shown in figure 3.5. Figure 3.7 displays the results from six successive tests 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 an hour.However, the fiber pair measurements are well correlated for all segments. The RMS of the ratio ranged between 0.58% and 0.70% for two fibers separated by half of the maximum separation in the test-bundle. The statistics are displayed in figure 3.8.

3.1.4 Attenuation Through Teflon

The object of this test was to understand the transmittance of the Teflon disks used to attenuate and diffuse the light at the output of each fiber. Different thicknesses of Teflon would be used to balance the amount of light delivered to each part of the detector.

Figure 3.15 displays plots of the energy measured through a single fiber normalized to the energy measured by the laser probe (see figure 3.3) versus the thickness

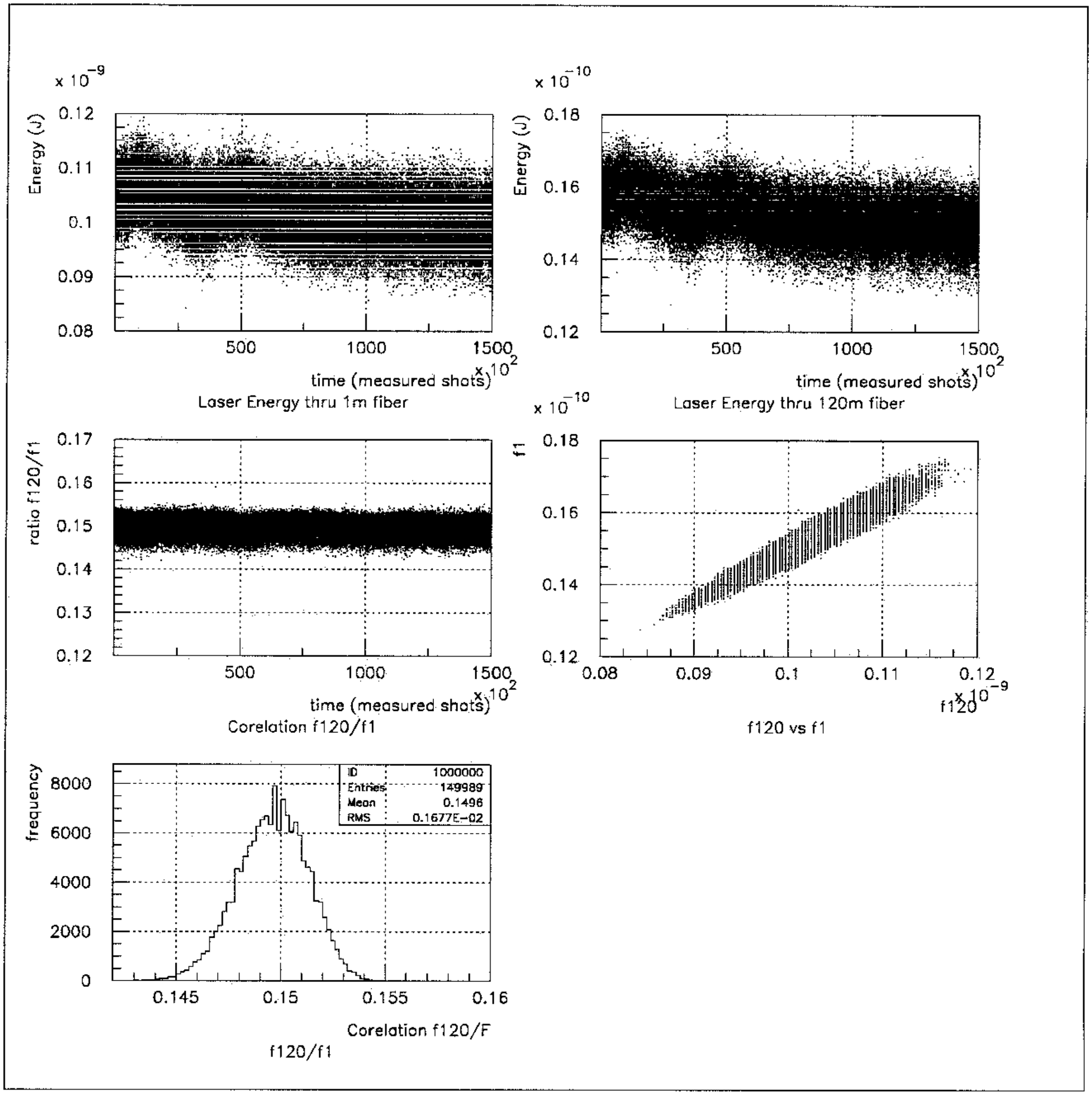

Figure 3.6. Correlation "Fiber/Fiber" over 150,000 Laser Shots.

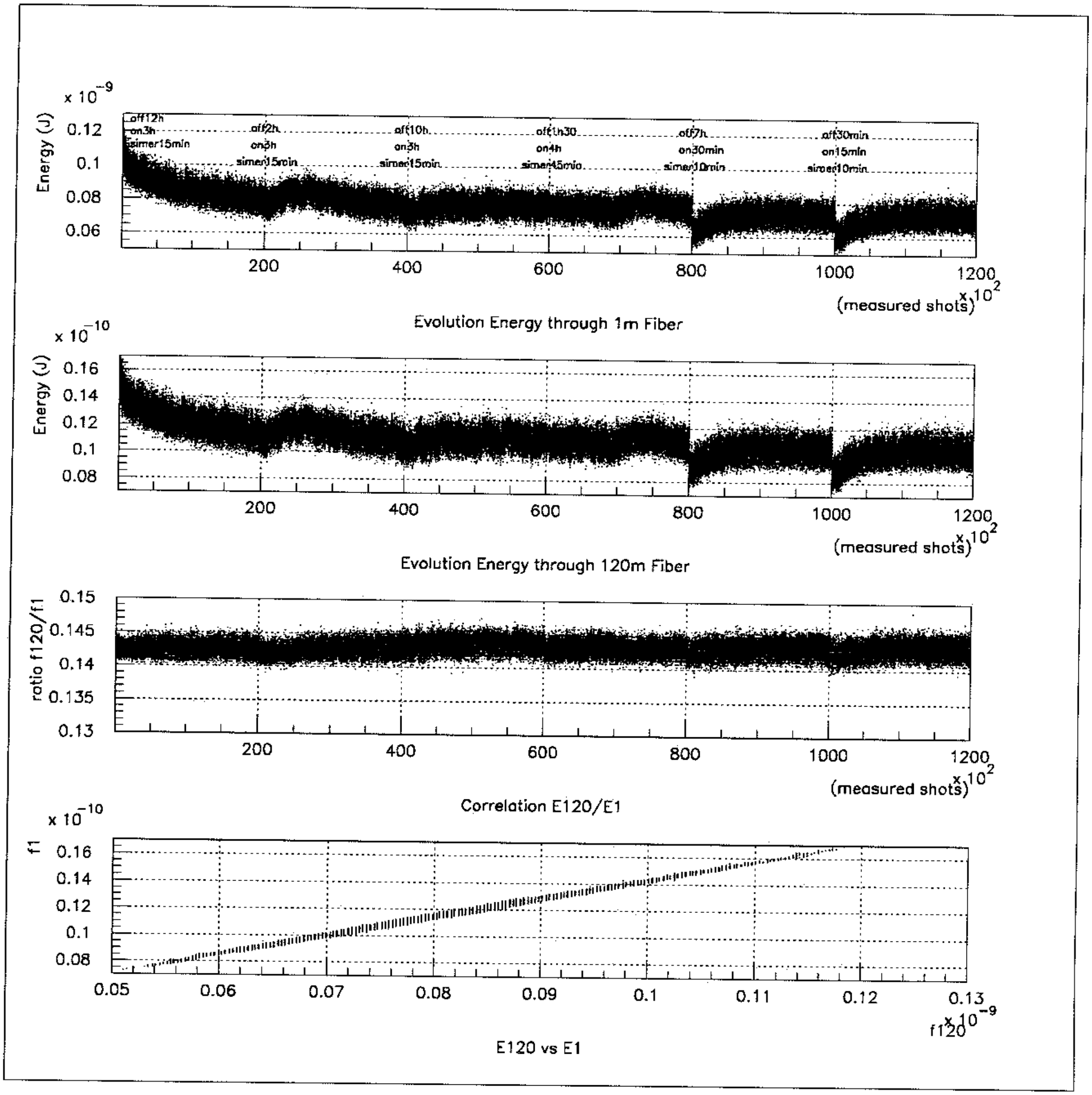

Figure 3.7. Test with Interruptions (6 Segments of 20,000 Shots).

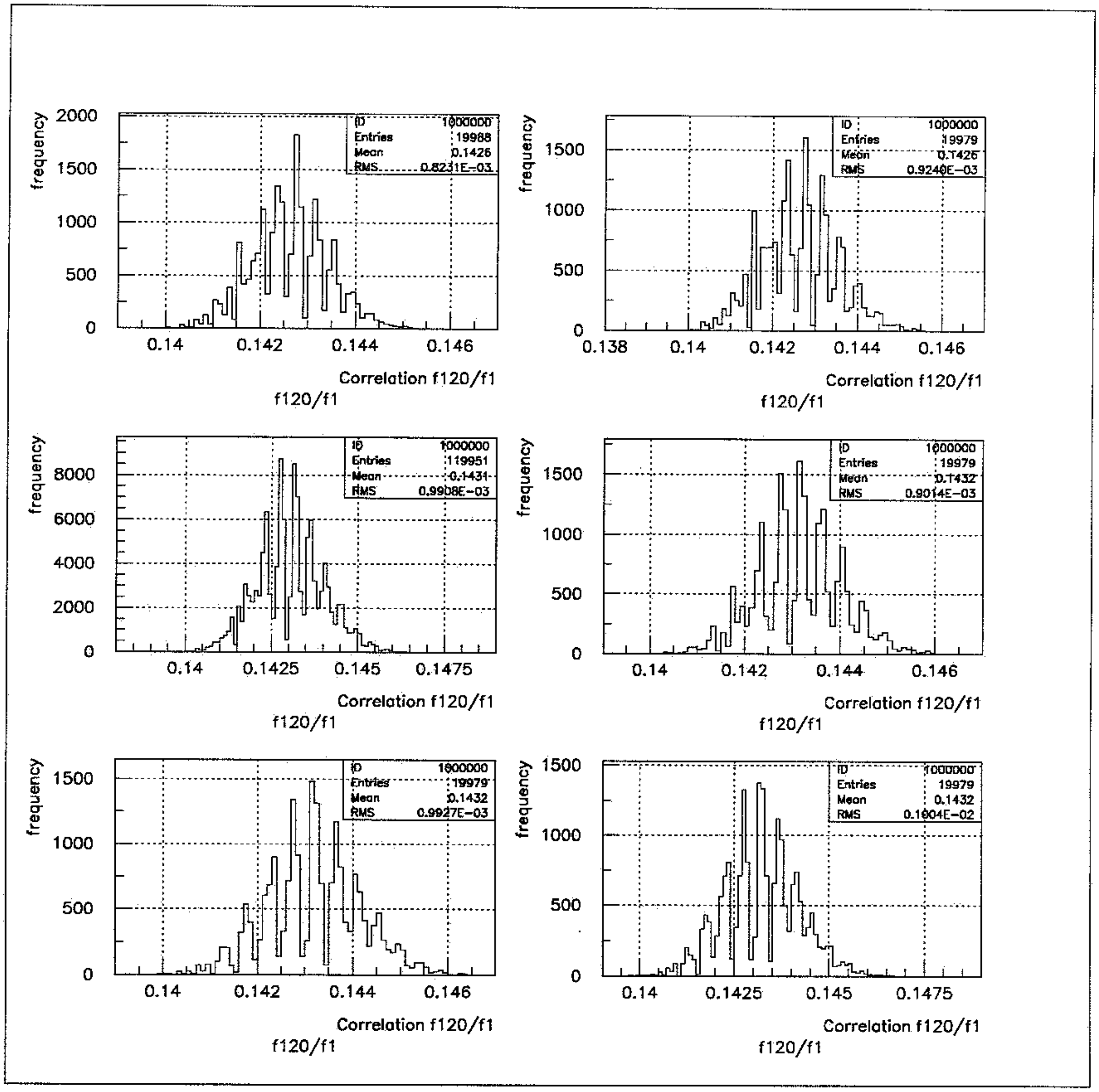

Figure 3.8. Test with Interruptions (Statistics on Each Segment of 20,000 Pulses).

of the Teflon disk. This disk is held between the fiber end and the photo-diode probe. In the plots on the left, the data point corresponding to the bare fiber (no Teflon) is included and one can see that the energy drops by a factor of about 20 by placing a 1/32″ thick piece of Teflon in front of the bare fiber. Plots on the right show that the distribution of the normalized energy(E) versus thickness(T) takes the expected form: $E = E_0 e^{-\frac{T}{\lambda}}$ where λ represents the attenuation coefficient of the Teflon used. λ also corresponds to the slope on diagram in the bottom right corner, which displays ln(E) vs T. Data points, far from the line correspond to different types of Teflon with slightly different appearance and density. We found $\lambda \approx 0.095$ inch^{-1} for most thicknesses of Teflon.

3.1.5 Uniformity

To ensure that all fibers get approximately the same amount of light and therefore illuminate the entire detector uniformly, it was necessary to make the laser beam uniform over a scale larger than the size of each bundle. Fortunately the beam spot is wider than 3.0 mm, which is large enough to contain the bundles with the largest number of fibers (50 for the cluster bundles, which makes a 2 mm diameter). The main role of the diffuser is to flatten the beam profile and lower the sensitivity to changes in beam profile over time.

Figure 3.10 shows the results of one-dimensional beam scans for five different diffusing methods. The beam was scanned by measuring the amount of light seen through a single fiber as it was moved across the beam. The first diagram corresponds to no diffusion at all. It is clear that the beam features "hot peaks" in its profile and big intensity variations within a millimeter. If a thin piece of Teflon is held 5 cm from the fiber, the beam profile adopts some sort of symmetry but it is still very sharp. Placing two pieces of UV filter glass (each sand-blasted on one side) nearly 11 mm apart and about 3 mm from the test fiber makes the beam profile more symmetric and broader but still too narrow. If the filters are set farther apart (nearly 50 mm), the flat region of the beam widens but its relative intensity drops by a factor of 10 which is too faint. A compromise was found by gluing a 50

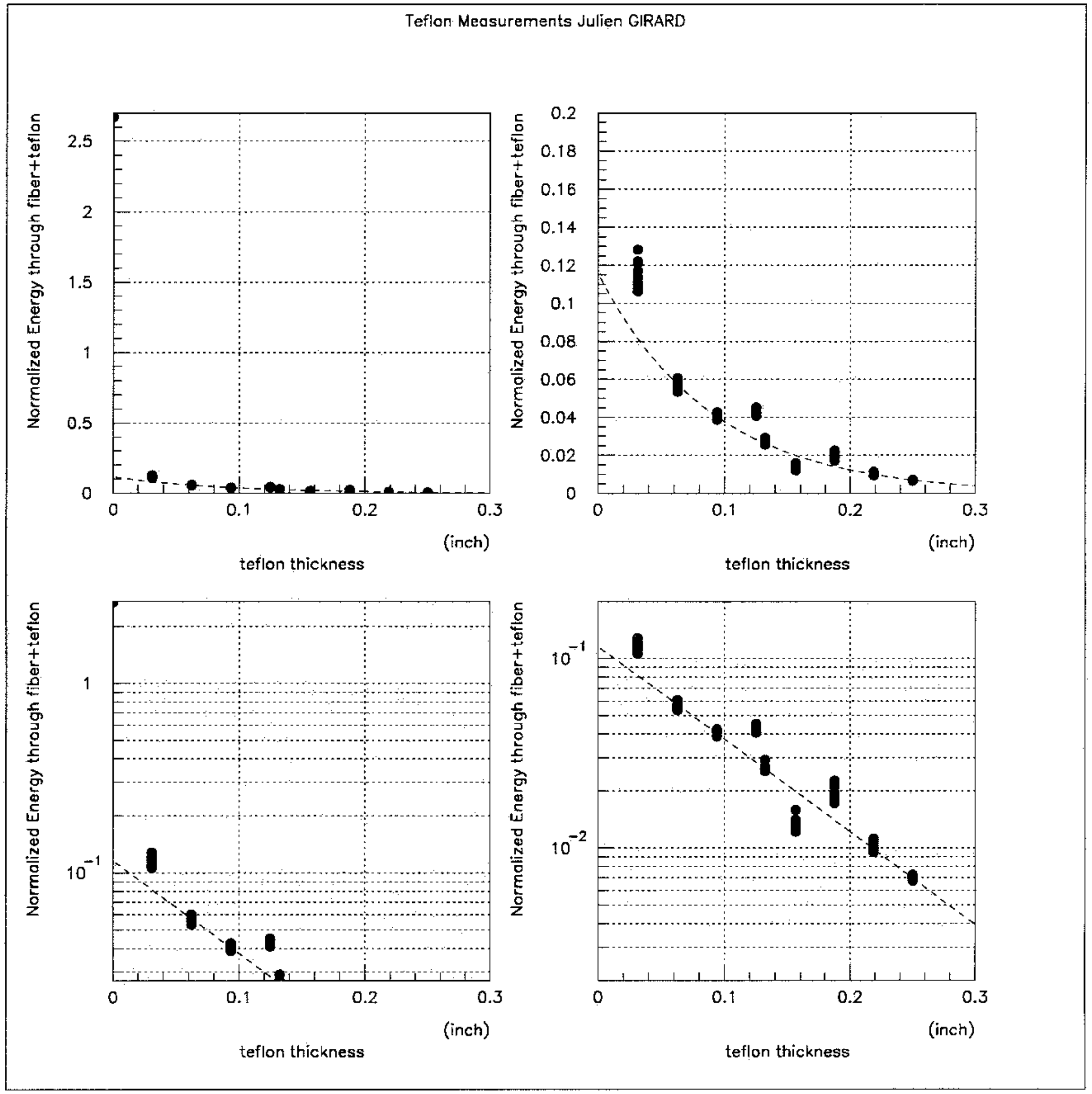

Figure 3.9. Attenuation Through Teflon (Linear & Logarithmic Scales).

mm "Vicor" tube between the filters to reduce energy loss by reflecting the beam inside the tube. The transmission was improved by about 20% by wrapping the tube in aluminum thin foil . The resulting profile featured less than 10% variations over a 4.0 mm region. Unfortunately, in the long duration tests, this diffuser was damaged by the laser beam. It needed to be replaced by a more robust type of glass.

For the final version of diffuser, we chose fused Silica windows because of their extremely high energy damage threshold to UV light. To obtain the degree of diffusion desired for our purposes, the fused silica windows required etching. The etching process proved to be difficult. Chemical etching with hydro-fluoric acid removed half the thickness 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. A company specialized in glass etching for art performed a fast and regular sand-blasting but without the fineness required to diffuse the laser beam as desired. The best result by far was obtained by roughening the Si windows manually on one side using silicon carbide abrasive powder (grain size: 220) mixed with distilled water. 15 minutes of random polishing motions on a flat plastic surface were sufficient.

We then performed more beam scans with these roughened windows in different configurations. The best combination of profile shape and amplitude was obtained with the following configuration: Two windows each etched on one side were used. The fiber-optic bundle was held about 3 mm behind the closest window. The windows were 30.5 mm apart with their etched sides facing the laser beam. The "Vicor" tube was eliminated to prevent any risks of long term darkening from the beam. Plots A and B of figure 3.11 show the beam profile sampled by two fibers in the test-bundle that was moved across the diffused beam. The two fibers were separated by about one millimeter. Plots C and D display the profile with the same scale as in figure 3.10. Plot E demonstrates that the ratio of light sent to the two fibers varied by less than 10% when the bundle was moved over a 4 mm region. Several such diffusers were prepared for the use at HiRes-II in the real system.

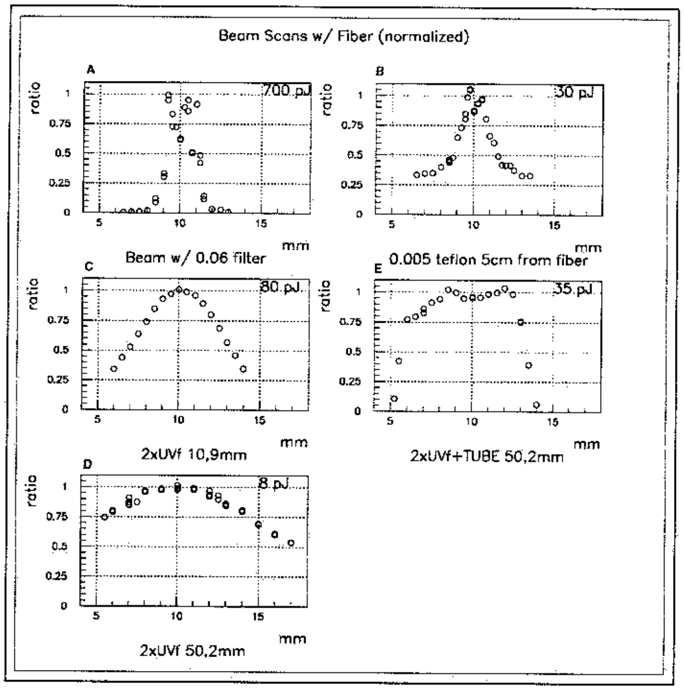

Figure 3.10. Laser Beam Scans with Different Diffusers.

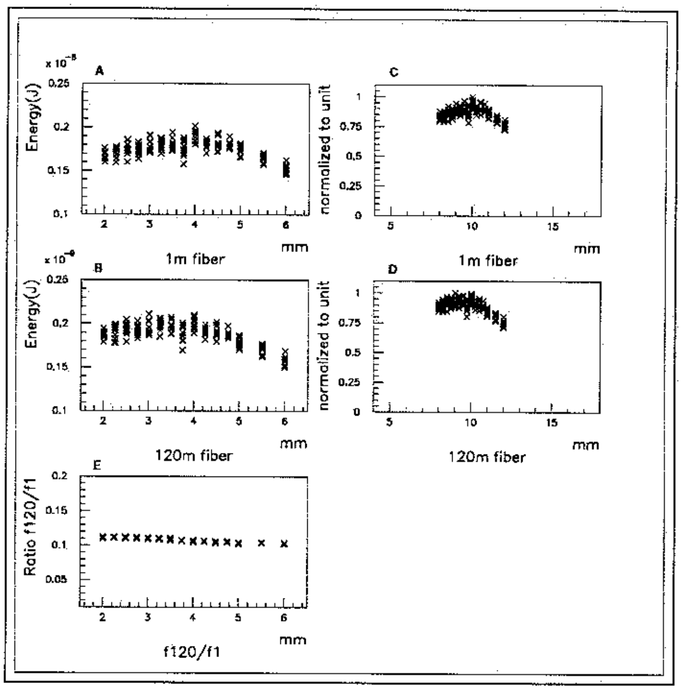

Figure 3.11. Laser Beam Scan with Final Diffuser.

3.2 Installation and First Tests at HiRes

Much of the installation work was handling and preparing the 7 miles of fragile fiber-optics. HiRes technical staff cut the optical fibers to length and placed them in 1/4" plastic "poly-flo" tubing. All 198 fibers protected by "poly-flo" (1 to 4 fibers per tube) were pulled through pipes from the calibration room to the 21 shelters and to the spare-fiber storage facility (30 spare fibers, 5 per bundle). Eight fibers were routed to each shelter. Each of the 168 fiber ends had to be prepared and assembled as shown in figure 3.12. At the same time, the delicate bundle-making process was started in the calibration room.

The fibers were carefully divided into six groups following the scheme shown in figure 2.3. It was crucial to strain relieve the poly-flo rather than the fibers because the fibers, if pulled back from their bundle, could easily break.
Unfortunately, the initial temperature of the calibration room was below the reaction temperature of the epoxy used in the bundle fabrication and the epoxy did not cure properly. The six bundles had to be prepared a second time. To make sure that all the fibers had been placed in the correct bundles and also to identify broken or damaged fibers, a very bright light was focused into each bundle to check the fiber continuity.

The rest of the hardware was then incorporated to the system: Laser, radiometer, probes, computer, mirrors, etc. Everything was mounted on the 32 $\times$72 inch optical bread board (see figure 2.1) and the laser beam was cautiously aligned. A Teflon disk of standard thickness was also installed in front of each fiber-output to proceed with the first tests.

3.2.1 First FADC Measurements with the Calibration System

Before adjusting the Teflon disks thickness, the HiRes-II detector was triggered with the calibration system and we measured the laser pulses. The data acquisition system was started and the laser was fired into mirror fibers to get a direct measurement from the PMTs. Figure 3.13 shows the average responses of PMTs to 50 lasers pulses measured in FADC counts versus position of the PMTs in the

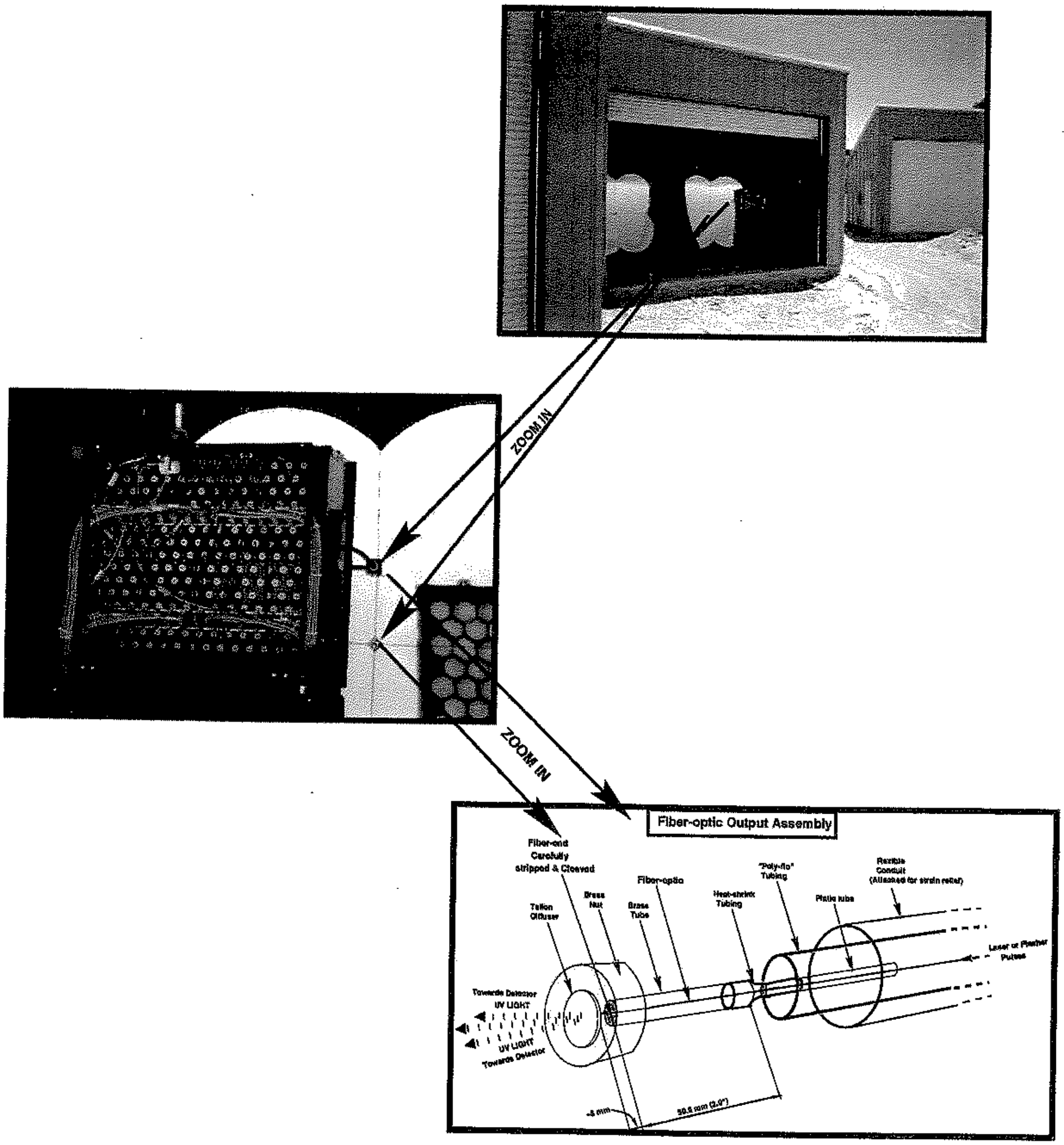

Figure 3.12. Example of One Fiber Output Assembly.

cluster. 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 (by crosstalk) recorded less light with a non uniform distribution.

Individual flash analog/digital converter (FADC) measurements of six laser pulses by one PMT are shown in figure 3.14. The plots show the responses in FADC counts versus time. The laser provides short pulses of about 6 ns. The data acquisition system of the HiRes detector is optimized for microsecond scale pulses. An electronic filter stretches short pulses to 200 or 300 ns before they are sampled by the FADCs. The sampling period is 100 ns.
Some error is introduced as a result of how the FADC sampling bins match the pulse' maxima. Averaging over a large number of pulses would lower the uncertainty of measurement of the pulse area.
It is important to note that an EAS produced from a cosmic ray generates a signal of the order of 0.5 to 5 μs, which match the detector sampling rate.

The fiber-optic calibration system will also use xenon flash bulbs to compliment the present laser. Both types of source present different advantages as shown in table 2.2. The flashers produce pulses of about 1 μs, which is long enough to be well resolved by the detector. The comparison between data collected with the laser system and data collected with the flasher system will monitor the electronic filter.

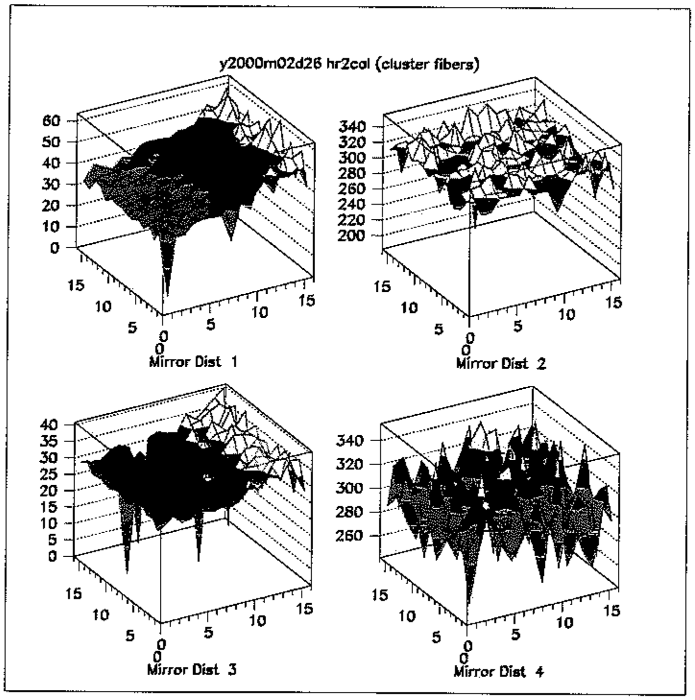

Figure 3.13. PMTs Response for Four Telescopes (Preliminary).

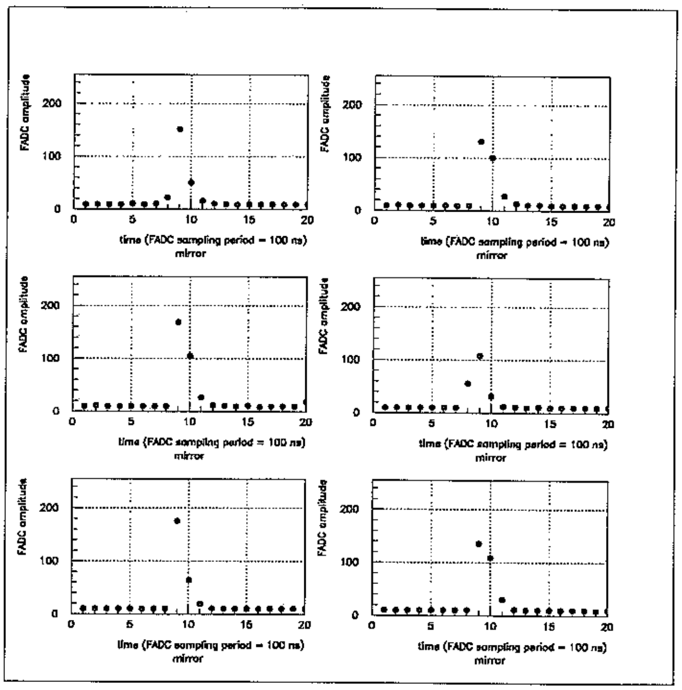

Figure 3.14. 6 FADC Pulses of the Tube #12 of the Mirror #2 (Preliminary).

3.2.2 Balancing Teflon Attenuator

The individual channels of the HiRes-II detector have a 8 bit dynamic range. One bin corresponds to approximately one photo-electron. Therefore it necessary to keep the pulses generated by the fiber-optics outputs within this range. This required high energy optical filters in the path of the laser to reduce the intensity of the light sent in the system by a factor of about 400. These filters were removed to measure the fiber outputs when balancing the Teflon.

A single disk of Teflon is held in front of each of the 168 fiber-optic terminations to diffuse the light. We used a portable one-channel radiometer and a photo-diode probe to measure the relative energy at each fiber-output by firing the laser into all six bundles with no filters. Changing the thickness of all these Teflon disks in steps of 1/32″ normalizes all the outputs to about the same energy despite the discrepancies between fibers (length, cleaving, separation from Teflon disk).
Figure 3.15 shows the comparison before and after adjusting Teflon thicknesses. The left histograms show the fiber-outputs measured with the nominal Teflon disks. The right histograms display the final result after fixing damaged fiber-ends, replacing three broken fibers with spare ones, and adjusting the Teflon. All 168 fibers emit approximately the same amount of light (between 40 and 60pJ).

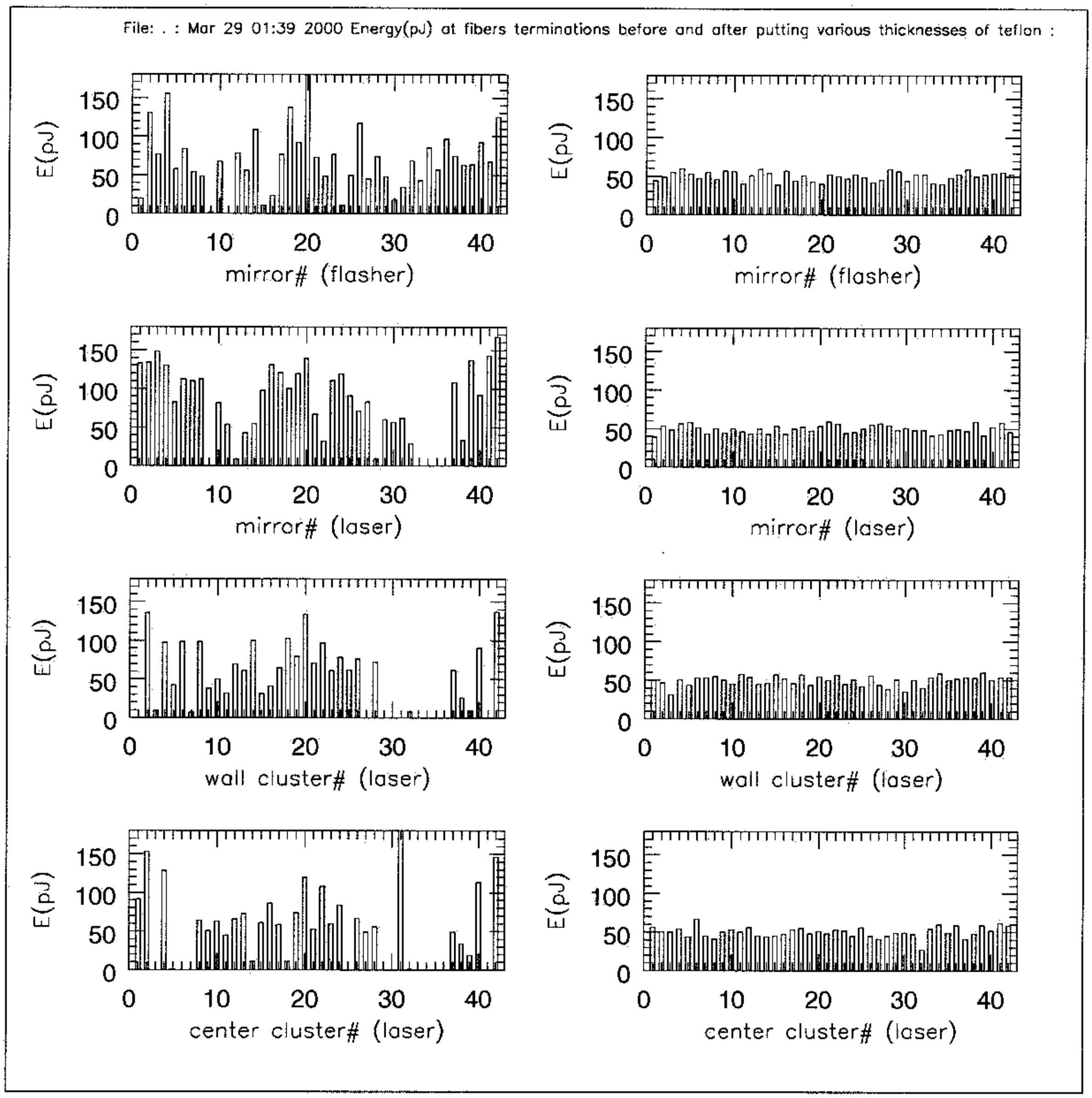

Figure 3.15. Initial and Final Energies at Fiber Terminations for All 168 Fibers.

CHAPTER 4

CONCLUSION

4.1 Status and Upgrade of the System

A few things remain to be done to complete the system such as:
-Incorporate the operation of the system in the main program that is used to run the HiRes-II detector.
-Make a graphical user interface (GUI) to facilitate the use of the control program.
-Test and install the xenon flash bulbs as additional light sources.
-Synchronize the light sources with a global positioning system (GPS clock) to trigger the detector at specific precise times.
-Set up a data base of calibration constants to track the HiRes-II detector's performance.

4.2 Satisfaction of the System Requirements

The fiber-optic calibration system was successfully installed at HiRes-II. The system provides uniform light pulses to all the telescopes of the detector in the desired ranges. Differences in the amount of light delivered between telescopes are within $\pm 10\%$. The relative shot to shot variation in the amount of light delivered is monitored to better than one percent by two different measurements. The amount of light delivered can easily be varied and the entire system can be operated remotely. Each component, as tested in the laboratory, proved to be stable over hundreds of thousands of laser shots. We believe the fiber-optic system performance is enhanced by the use of continuous fiber-optics from the light source to the detectors. The installation would certainly have been easier if we had used shorter fibers and industrial made connectors but the system would have probably lost stability and intensity because of time varying parameters such as temperature or humidity. The system is flexible because different light sources can be installed to send light pulses to the detector through the two extra fiber bundles.

A good and well understood calibration system can be a proof of quality for any experiment. Over the next three to five years, the HiRes-II detector will probably be responsible of many measurements of particles with energy above 10^{19}eV. This fiber-optic calibration system will play an important role in the accuracy and the credibility of the events reported by HiRes. An exciting time is arriving in experimental cosmic ray research particularly in the field of extremely high energies. For the first time, these particles may indicate sources in the universe that are mysterious to our present knowledge.

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