High Resolution Imaging of Cerenkov Light from Air Showers

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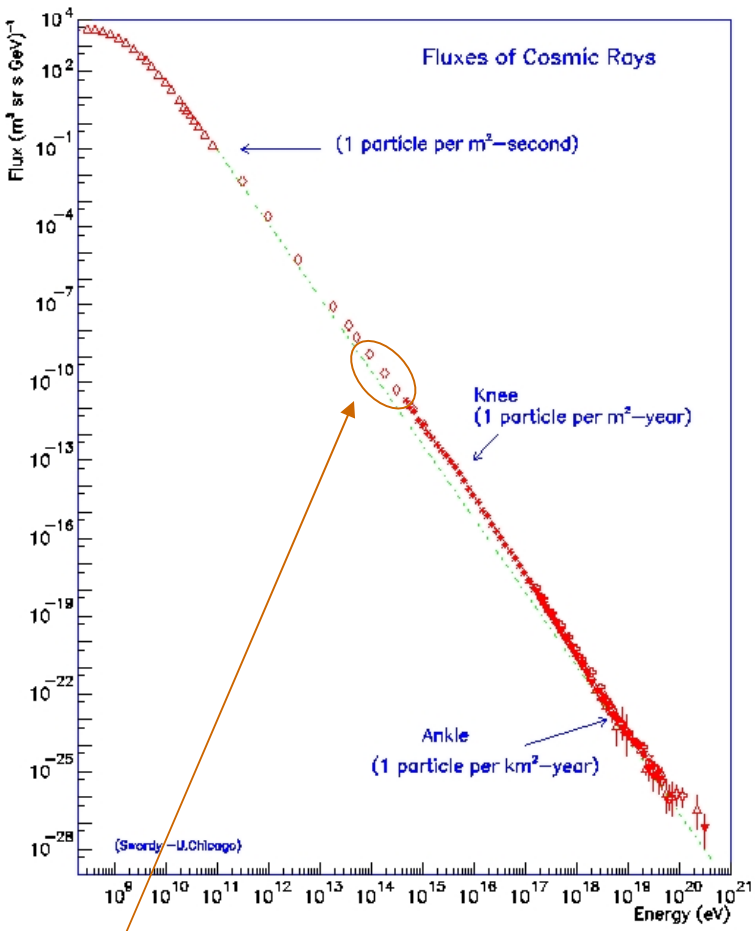
Overview

- Cosmic rays, air showers and Cerenkov light
- Imaging Air showers
- TrICE prototype
- First data

Cosmic Ray Science

- Understanding the energies and composition, and thereby the origins of cosmic rays remains a fundamental astrophysical problem
- Cosmic ray acceleration has strong ties to gamma-ray and neutrino astronomy
- Cosmic rays form a large background for ground-based gamma-ray astronomy and pose a challenge to extending observations to cosmologically interesting distances

TeV Cosmic Rays



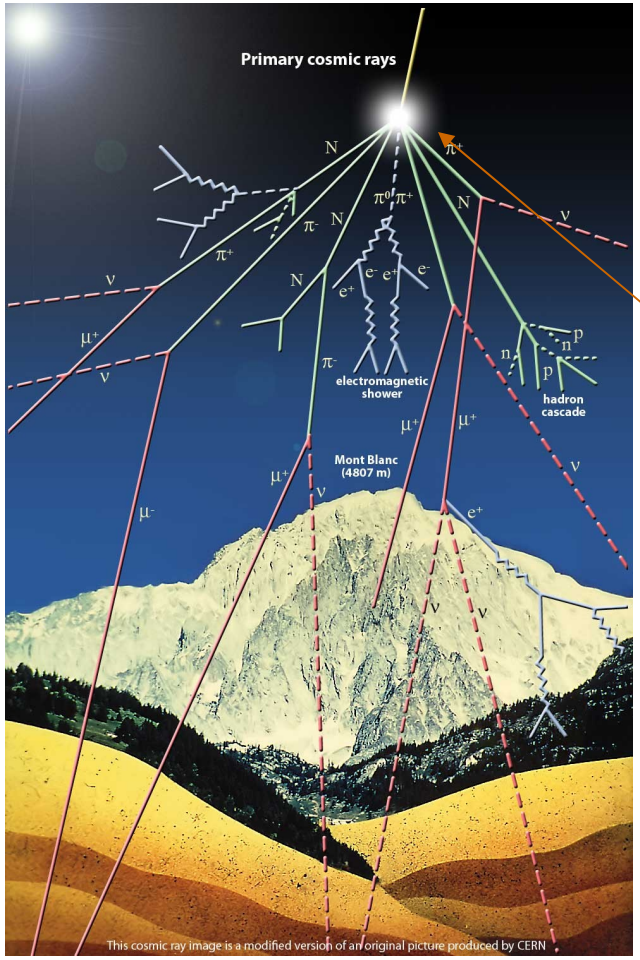
Balloon carried detectors observe cosmic rays directly at energies with fluxes at the m^2-month level.

Element composition measurements are difficult above 10^{14} eV where the flux becomes small and ground-based measurements have large uncertainties.

Apologies to SPS for something like the zillionth showing of this plot in a cosmic ray presentation...

Composition measurements difficult in this region.

Cosmic Ray-Induced Air Showers

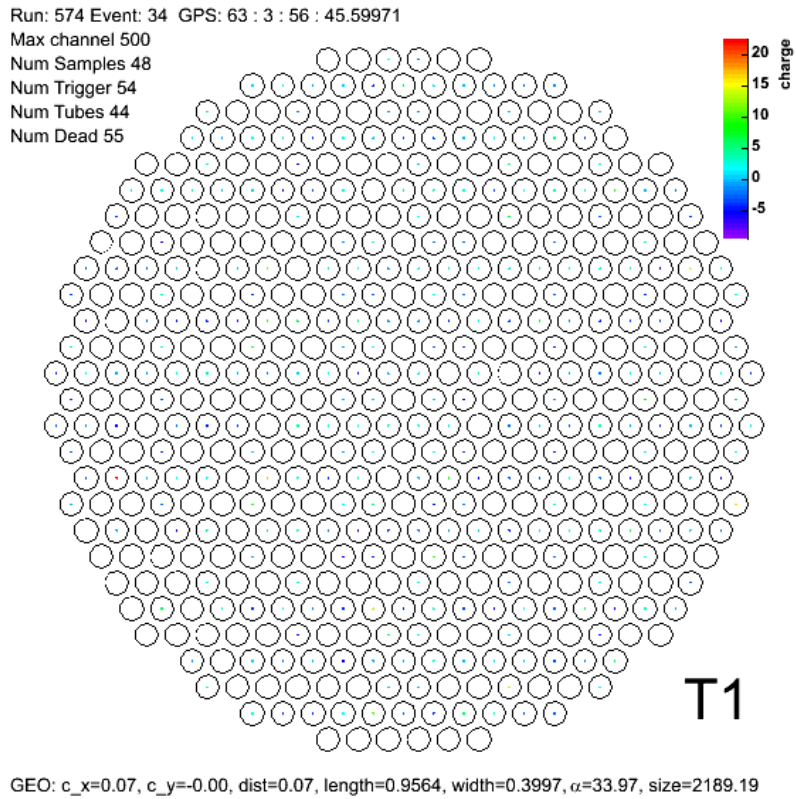


Ultra high energy cosmic rays (PeV and above, km^2-year) are observed by large ground arrays, e.g. Auger, which detect the particle component of the air shower.

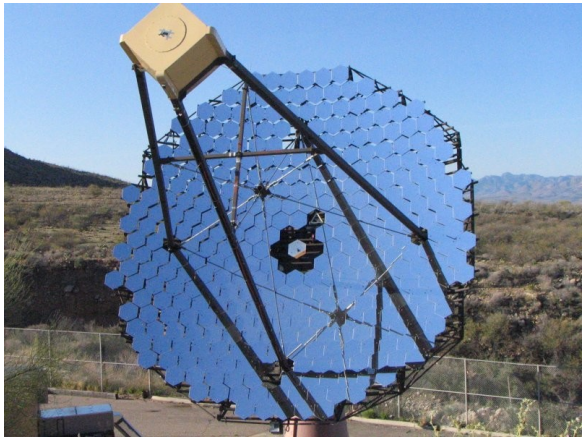
First hadronic interaction
Height ~30 km

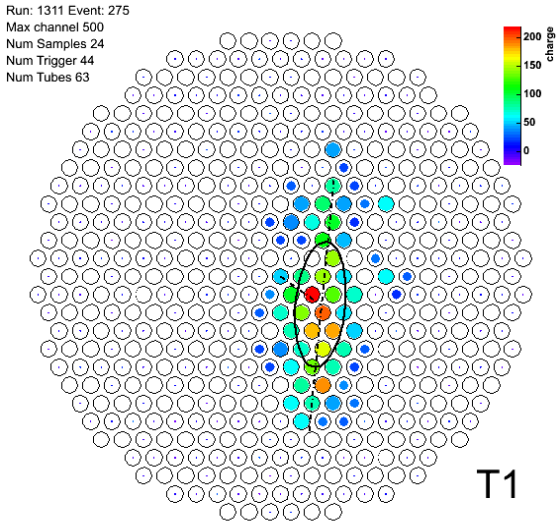
Cosmic ray-induced showers at Gev-TeV form a background for imaging air Cerenkov detectors, which look for gamma-ray induced air showers. Currently this background is rejected using angular resolution and image fitting.

Imaging Air Cerenkov Detectors



VERITAS Telescope, Mt Hopkins, AZ





Air shower images from VERITAS
3.5 deg field of view
0.15 deg pixels
2 ns sampling

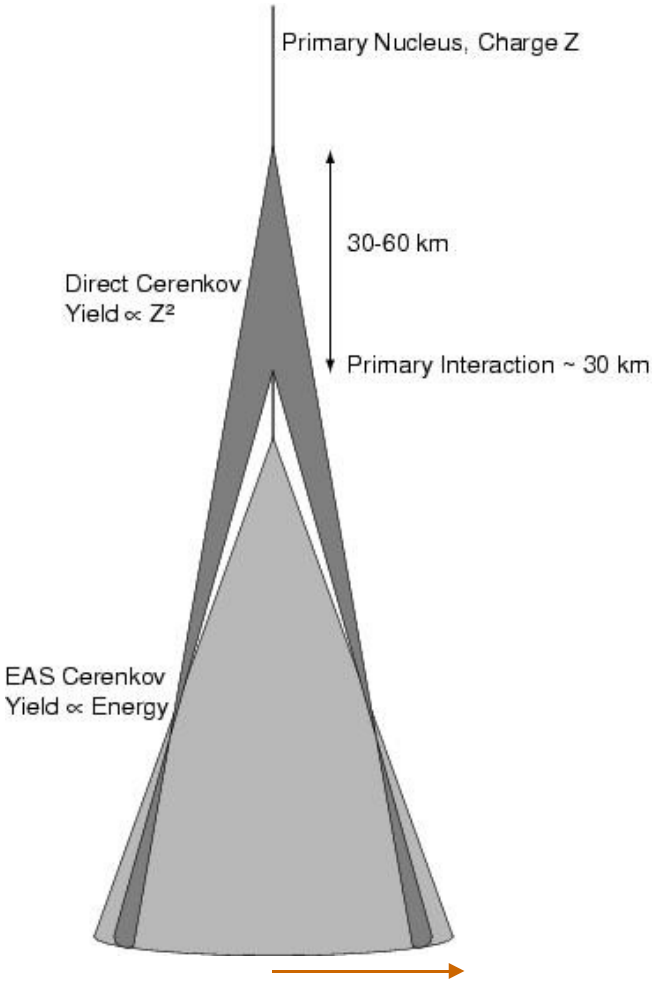
Predictions for Direct Cerenkov Emission

High altitude observations of Cerenkov light emitted by cosmic-ray nuclei before interacting in the atmosphere were originally proposed by Sitte (1965) and Gough (1976).

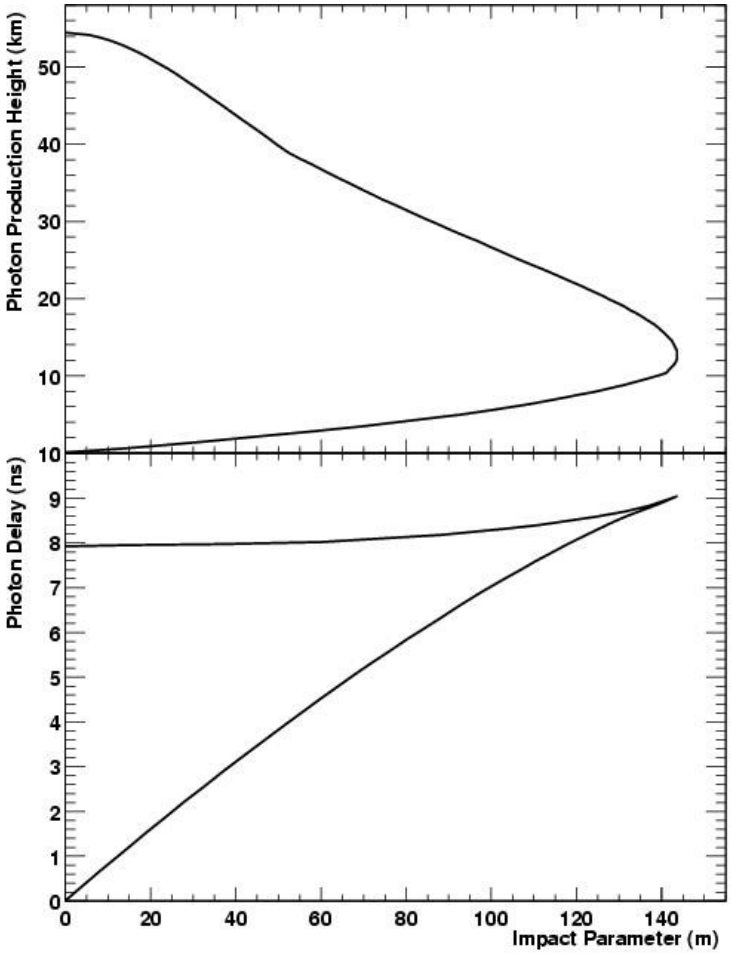
Flights were undertaken by Sood (1981) and more recently Seckel (1998) to attempt the measurement.

Kieda, Swordy, and Wakely (2001) propose this emission can be detected on the ground using the imaging Cerenkov technique developed for gamma-ray astronomy.

Direct Cerenkov Signal



Impact Parameter



from Kieda, Swordy, and Wakely, 2001

Discriminating DC Signal

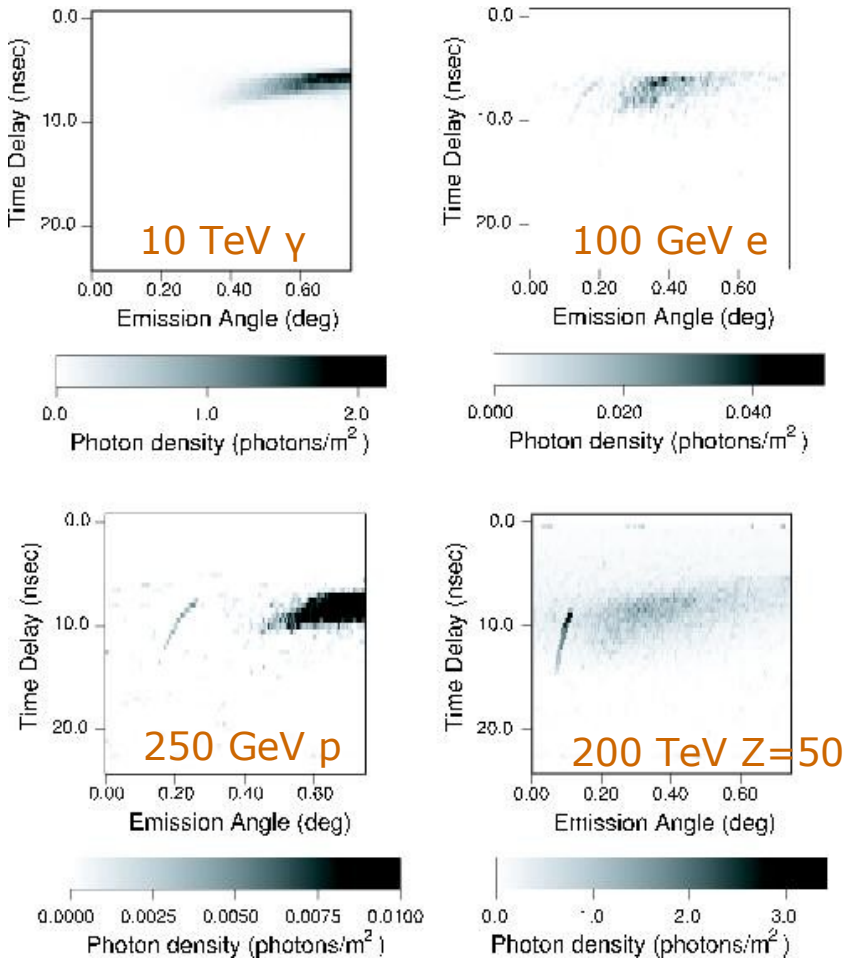
The emission angle and time delay of the Cerenkov light can be used to separate DC and air shower components.

Requires knowledge of the shower core position

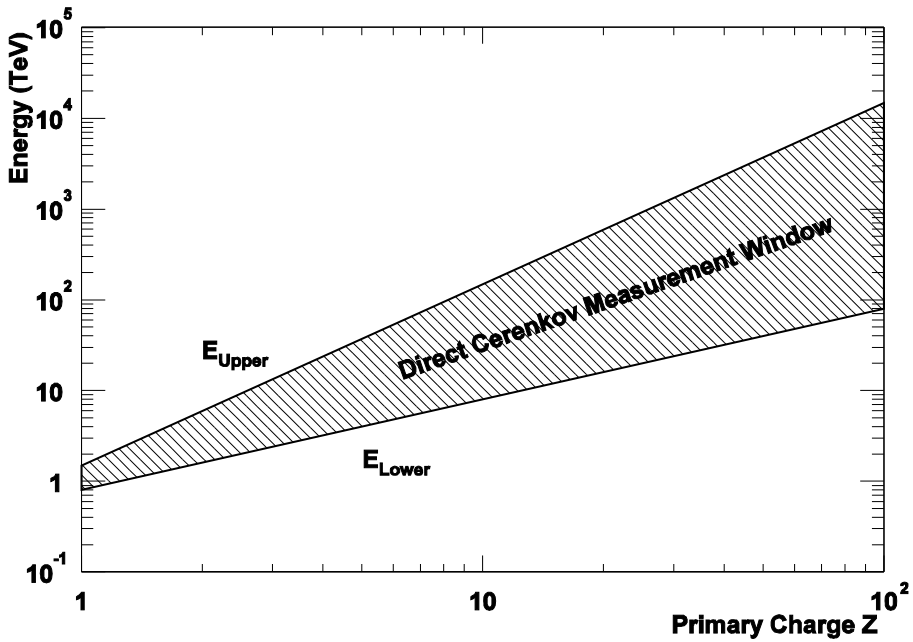
Optimal angular resolution ~0.0038 deg (VERITAS 0.15 deg)

Optimal time resolution ~1/2 ns (VERITAS 2 ns FADC)

Optimal impact parameter ~80m (VERITAS telescope separation 80m)



Direct Cerenkov Window



Lorentz threshold for Cerenkov emission depends on index of refraction (altitude)

$$\gamma_0 \propto 1/2(n-1)$$

Energy upper limit where $N_{DC} \sim N_{AS}$

$$N_{DC} \propto Z^2 \qquad N_{AS} \propto E$$

The Direct Cerenkov (DC) measurement is limited in energy of the primary particle.

The upper energy bound is set by the ability to detect the direct component over the Cerenkov light from the air shower.

The lower bound is set by the threshold for Cerenkov emission.

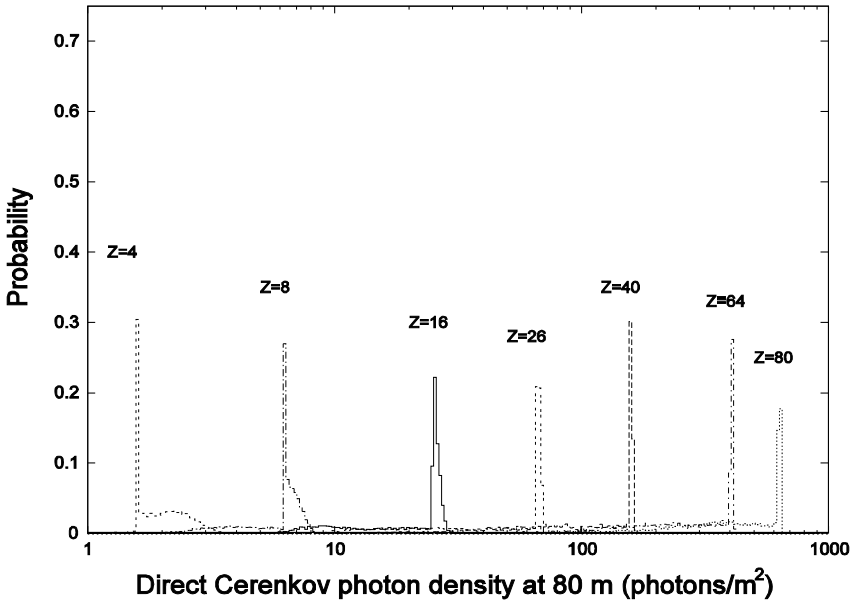
Charge Resolution

Photon density $\propto Z^2$

$\Delta Z/Z \sim 5\%$ for $Z>10$

Estimation of charge resolution includes signal contamination of by night sky background fluctuations, fluctuations in the shower Cerenkov light, and scattering of light into the direct component. Detector limitations – collection area and angular and core resolution - are also included.

There is potential for detection of exotic heavy nuclei here...



DC in Current Cerenkev Telescopes?

Current gamma-ray telescopes are not optimized to detect DC, but they're not far off.

- VERITAS uses 500 MHz sampling
  - sufficient for DC, but optics are not isochronous
- Current pixel sizes ~0.16 deg
  - reconstructed direction resolution is already good ~0.1 deg
- What could higher angular resolution provide?
  - improved background rejection for large extended and diffuse sources
  - low E background rejection
  - rejection using image fluctuations
  - DC?

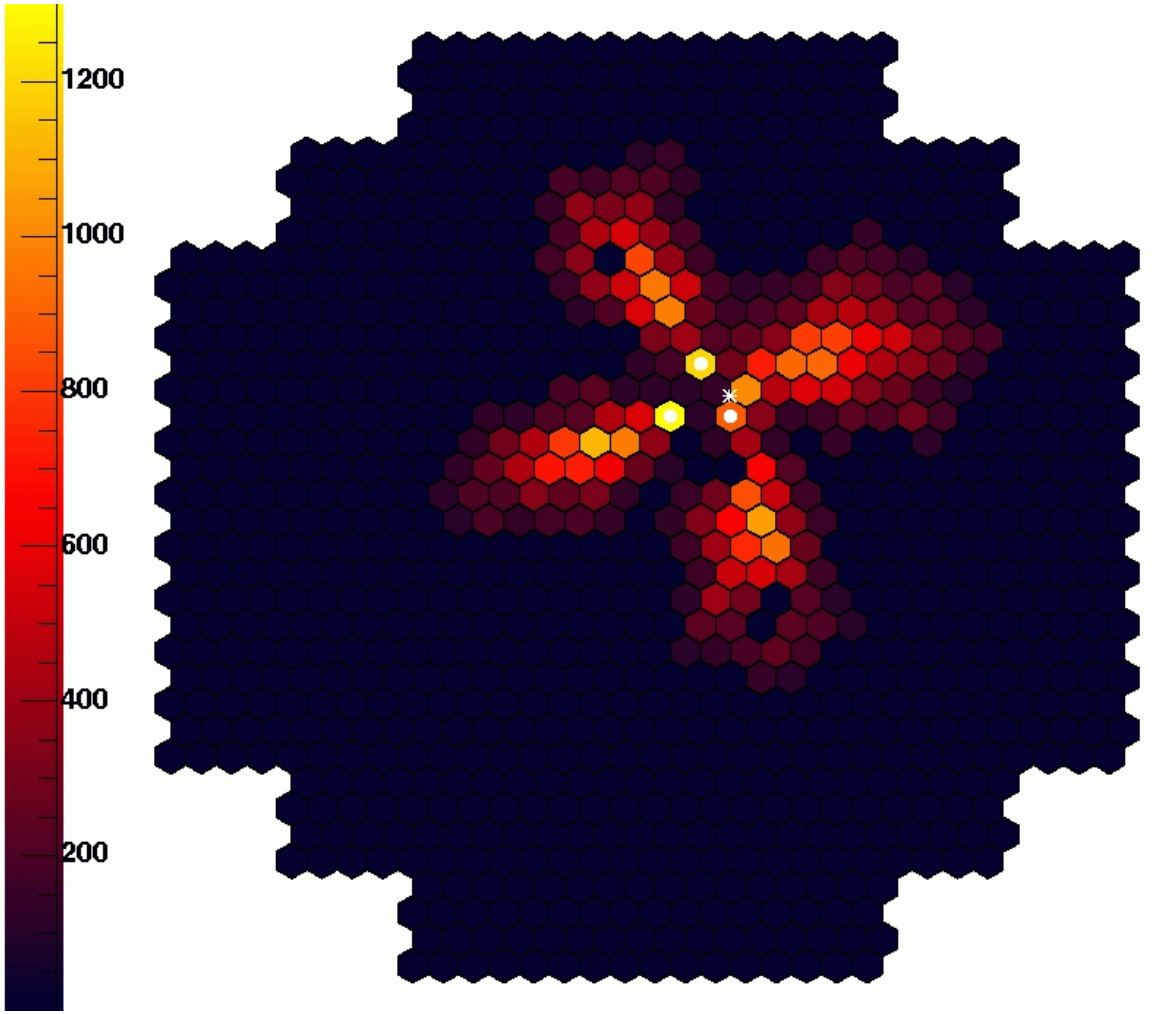
DC Detected!

H.E.S.S.: array of 4 imaging air Cerenkov telescopes operating in Namibia.

Combined camera image of an air shower viewed by all 4 telescopes (100 m apart) reveals 2 pixels with large signals

Note: This instrument is not optimal for DC detection

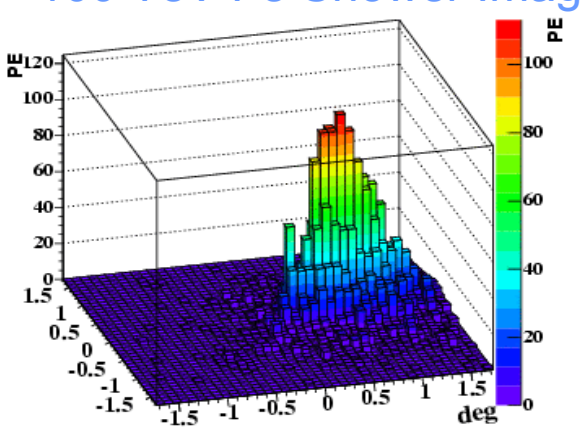
- Pixel size 0.16 deg
- No timing information



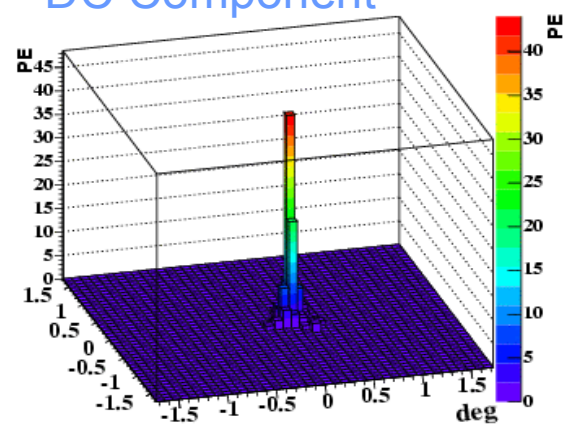
High Resolution Camera Simulations

100 TeV Iron primary
At 80 m from shower core

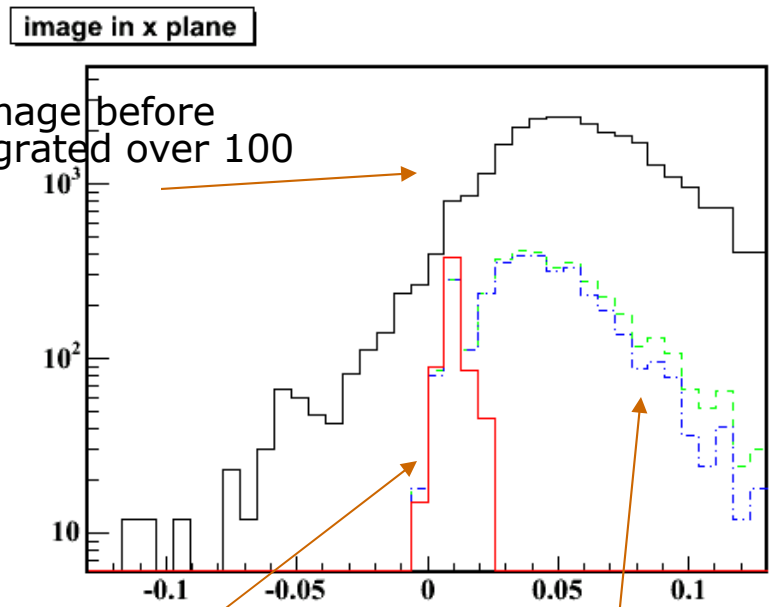
100 TeV Fe Shower Image



DC Component



Projection on axis of shower direction

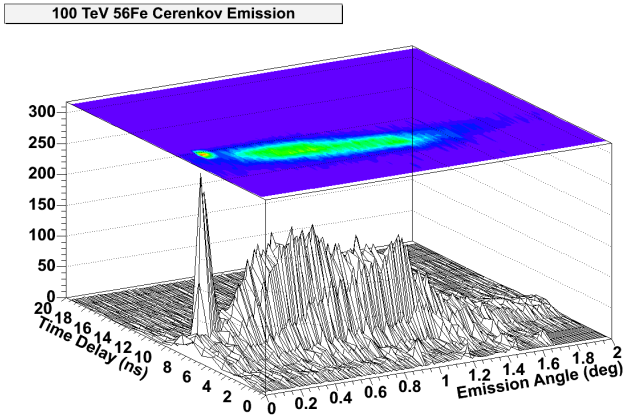


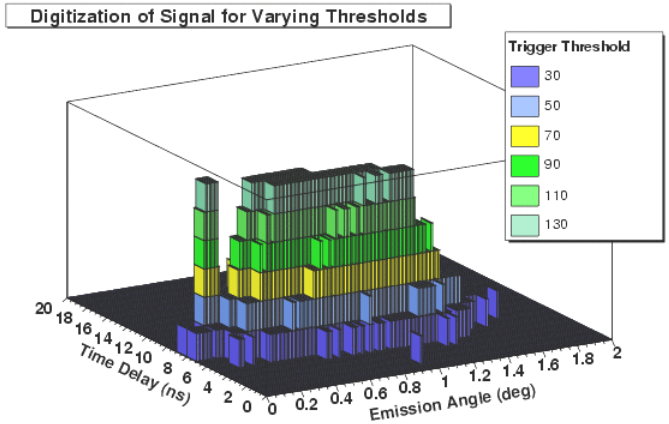
Shower image before cuts (integrated over 100 ns)

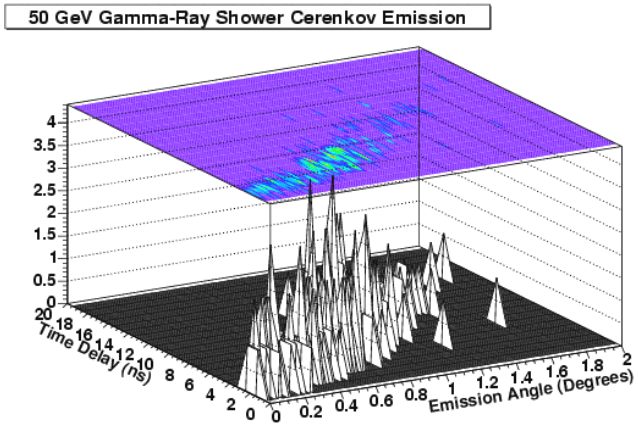
Isolated Direct Cerenkov

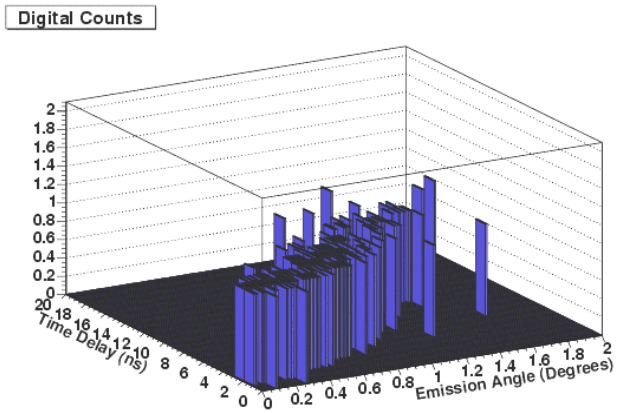
Shower image after timing and spatial cuts (remove early light, keep pixels along axis of shower direction)

More High Resolution Studies









Simulation studies of requirements for detecting DC and gamma-ray showers with high resolution detectors

from S. Wissel

TrICE – Track Imaging Cerenkov Experiment

- Prototype under development by U.Chicago, Argonne Lab, and U. Utah
  - K. Byrum, G. Drake, D. Kieda, S. Magill, L. Nodulman, S. Swordy, R. Talaga, R. Wagner, S. Wakely, S. Wissel
- Located at Argonne Lab
- Primary goals
  - View air showers with a high resolution camera
  - Develop fast and compact electronics
  - Detect direct Cerenkov signal

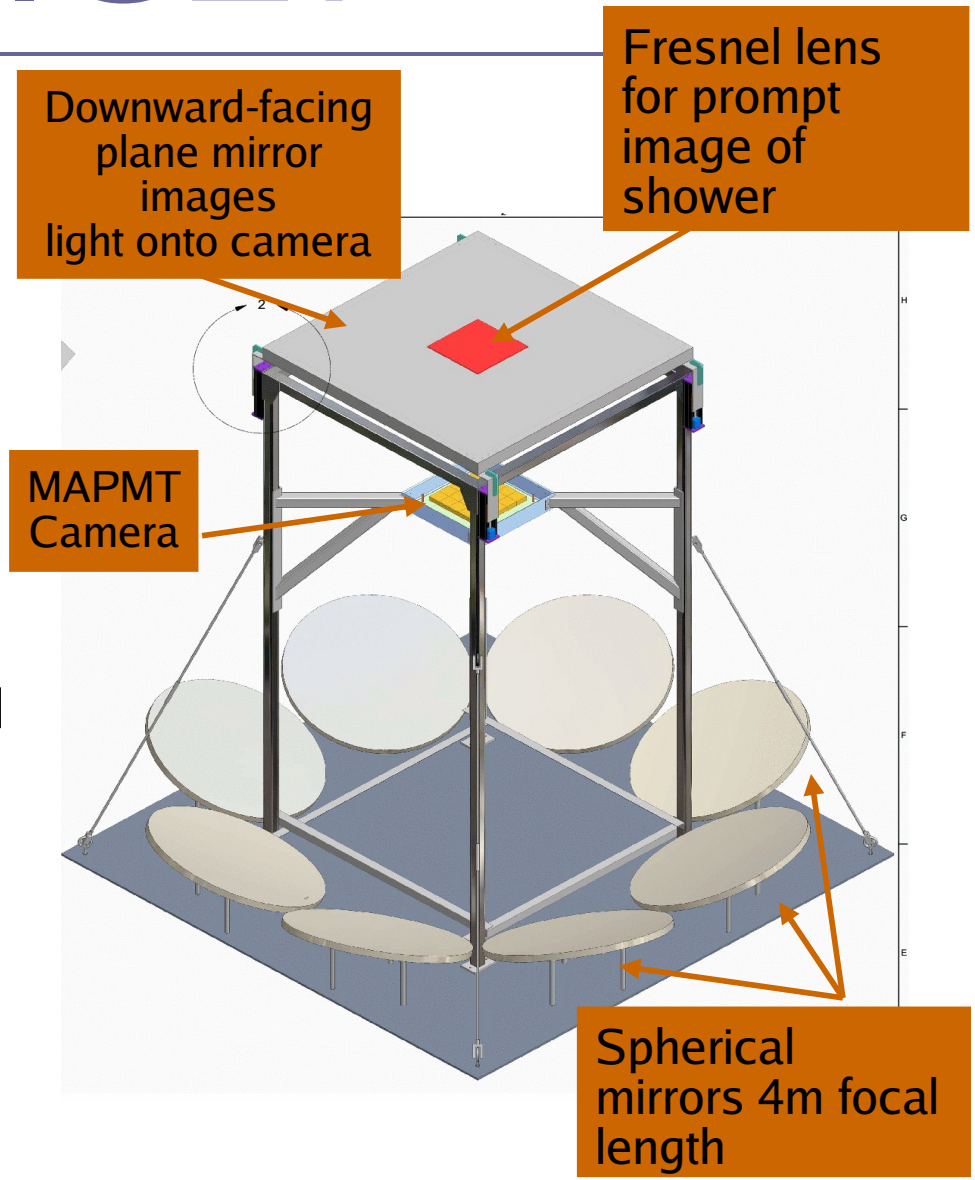
What is TrICE?

Small fixed-mount prototype IACT

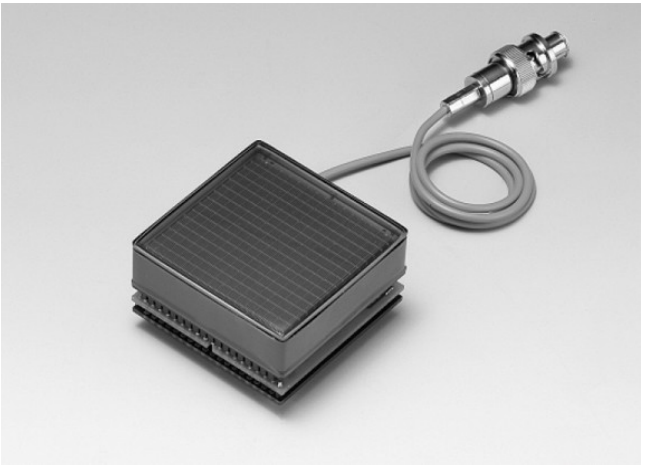
Two optical paths – prompt through fresnel lens, ~20 ns delayed from spherical mirrors

Look for direct Cerenkov signal in air shower image using appropriate delay and spatial features

MAPMTs used to attain higher angular resolution, in this optical setup 0.08 deg pixels



Candidate MultiAnode PMTs



Hamamatsu H8500 64 pixel (8x8)

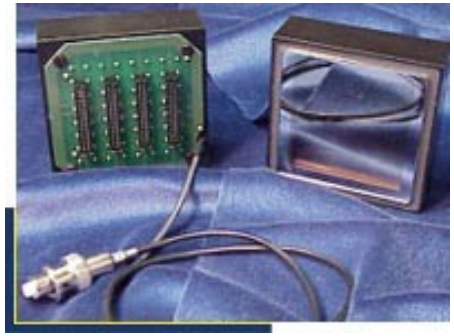
Effective area ≈ 5 x 5 cm^2
89% active

Pixel size ≈ **6 x 6 mm^2**

Quantum eff. @ 420nm ≈ **19%**

Tested at Argonne and Chicago

Burle 85011-501 64 pixel (8 x 8)



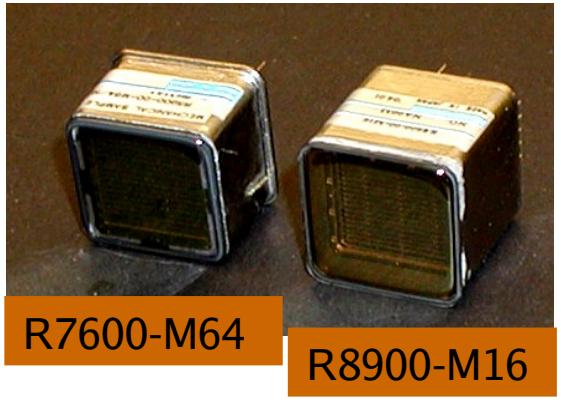
Microchannel plate (2 stages)

~70% active

Pixel size ≈ **6 x 6 mm^2**

Large frame and smaller gain than Hamamatsu tube

Tested at Chicago
Beginning tests at Argonne



Hamamatsu R8900-M16 16 pixel (4x4)

Eff. Area ≈ 2.4 x 2.4 cm^2
85% active

Pixel size ≈ **6 x 6 mm^2**

QE @ 400nm ≈ **24%**

Tested at Argonne

Selected for use in TrICE

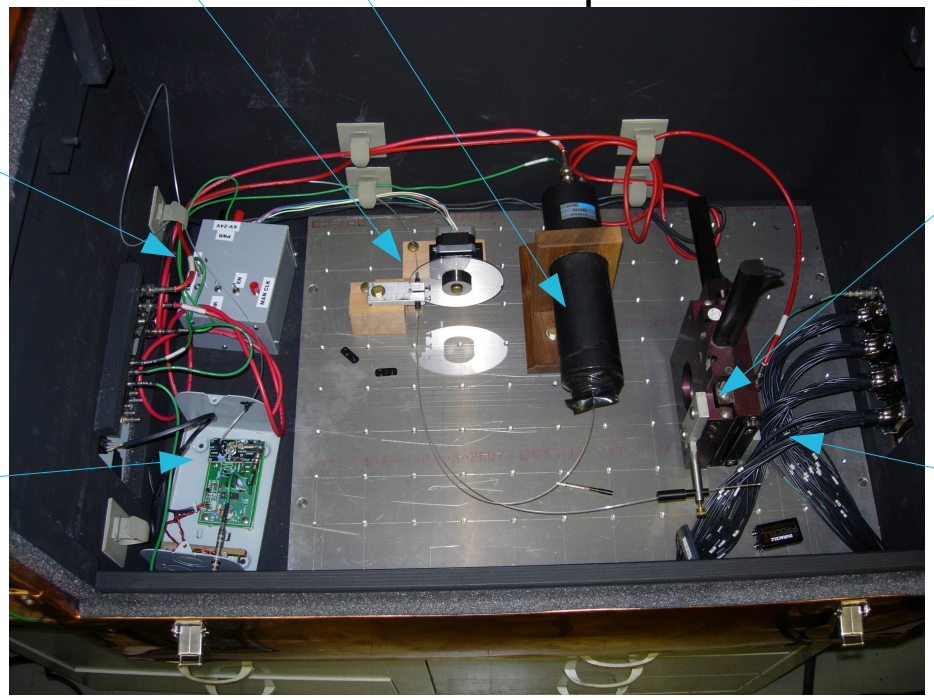
PMT Test Setup at Argonne

Our lovely dark box; complete with X-Y stager for the optical fiber to allow automated measurements for each pixel

neutral density filter Wheel

reference PMT

filter wheel motion control



X-Y stager with spring mount for fiber

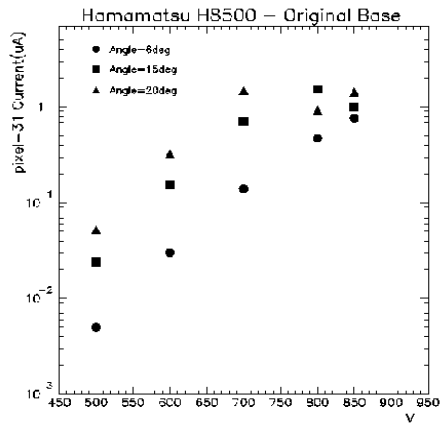
blue LED pulsed using external signal

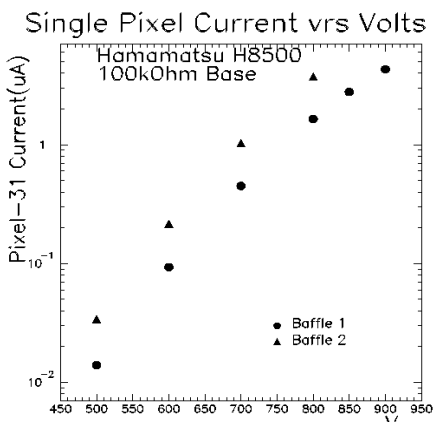
Signal cables for either H8500 (64 pixels) or R8900 (16 pixels)

Lab tests measurements made via CDF Run I electronics – 16 bit ADC, wire chamber amplifier board: 1.144fC/count

Night Sky Background

R8900 and H8500 PMT bases needed modification for high current operation (1 uA per pixel)





Dark Site?

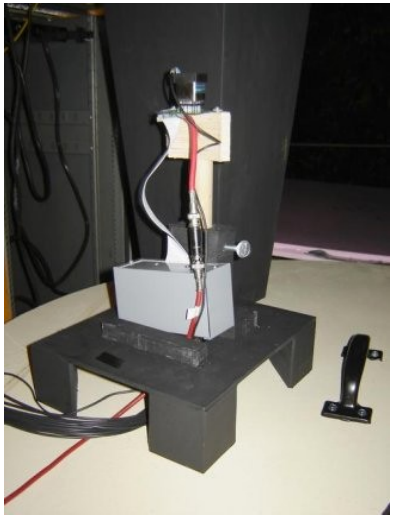
Practical Definition: *Clouds make it darker, not brighter*

Gamma-ray telescope at a dark site
2 km a.s.l.,
1 deg fov,
300-600 nm,
100 m^2 mirror area
background ~ 10 photons / ns

TrICE measurements at ANL
200 m a.s.l.,
~1 deg fov,
300-600 nm,
3 m^2 mirror area
background ~ 3 photons / ns

~10x higher at ANL

Single PMT mount and baffle for current measurements of the night sky background



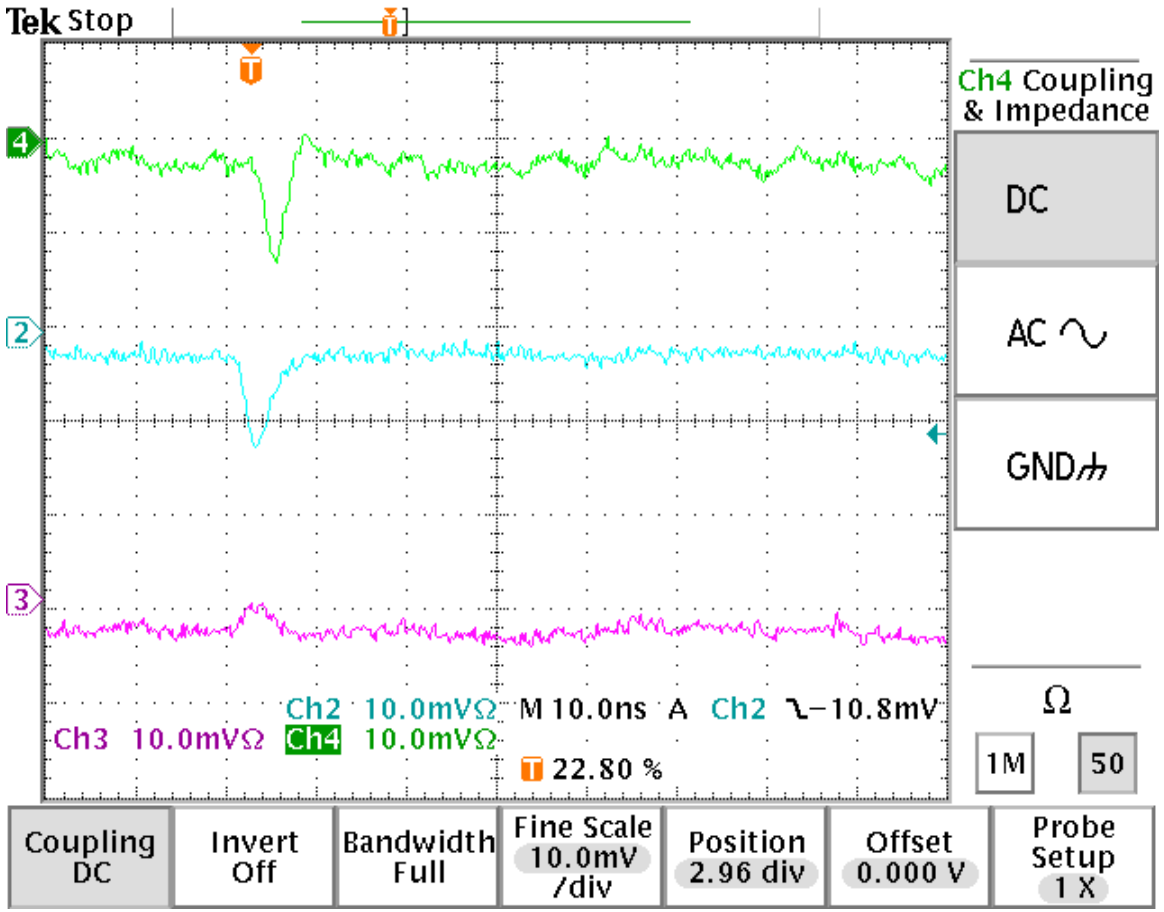
Single PMT Site Tests

Air Showers observed with R8900 at TrICE site

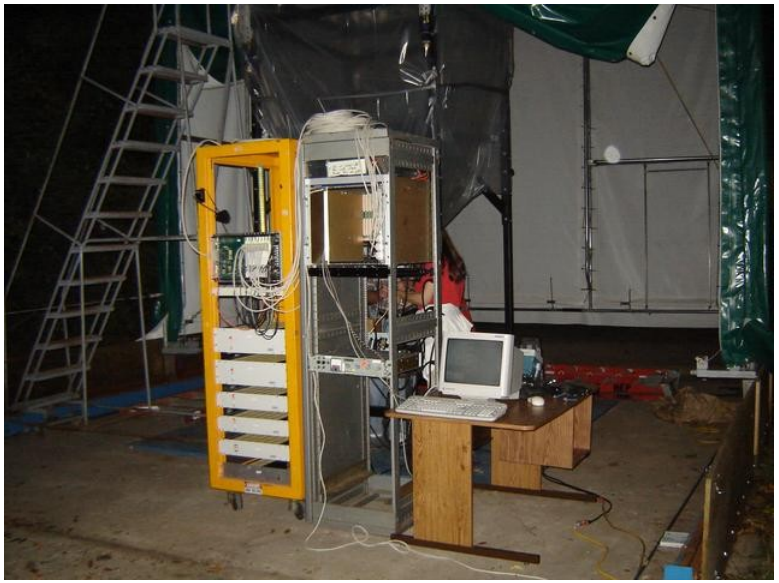
Single pixel signal

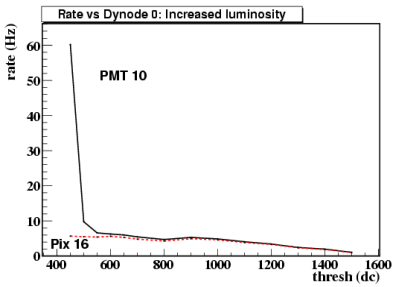
OR of other 15 pixels

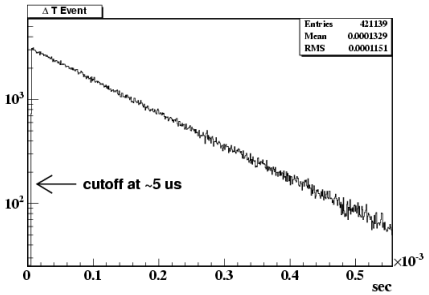
Common dynode signal (Trigger)



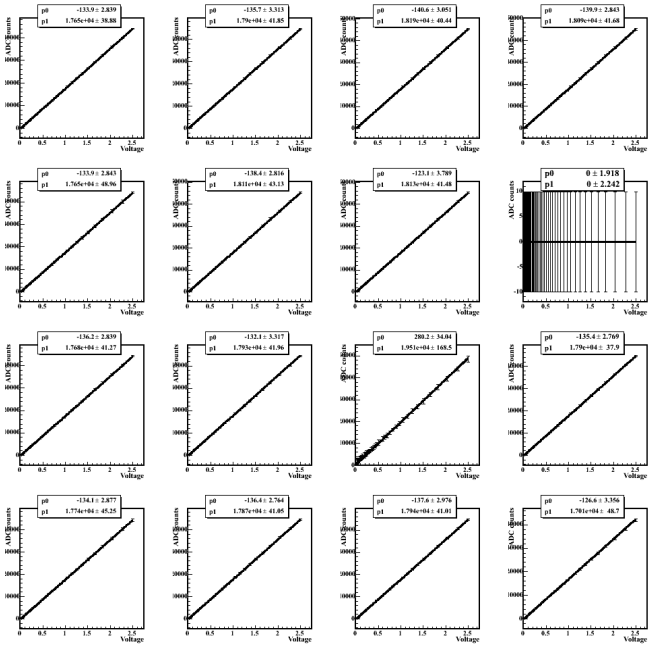
Data Acquisition Tests

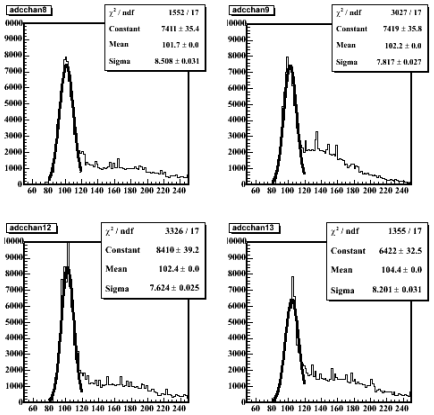


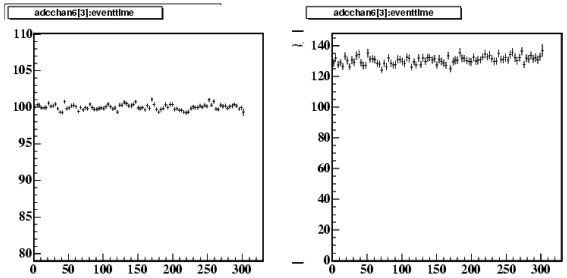




In the lab

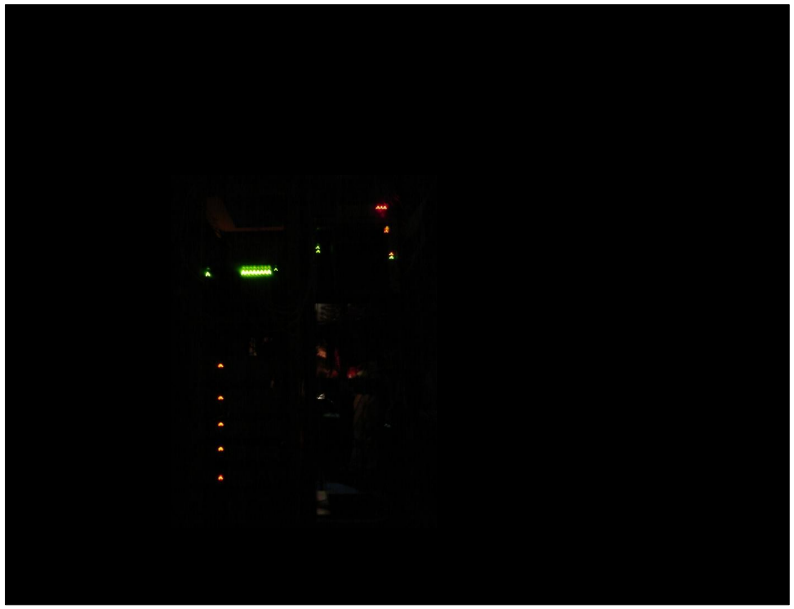


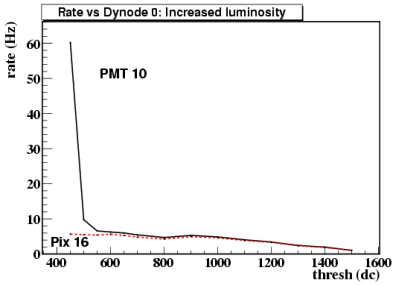


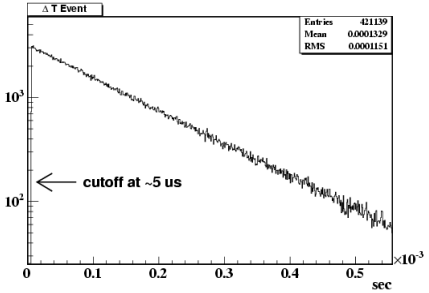


At the site...

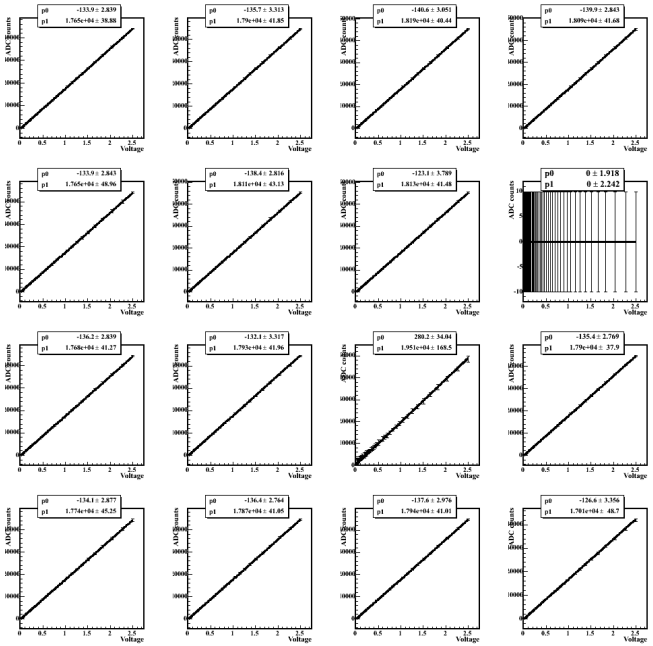
What? It's supposed to be dark?

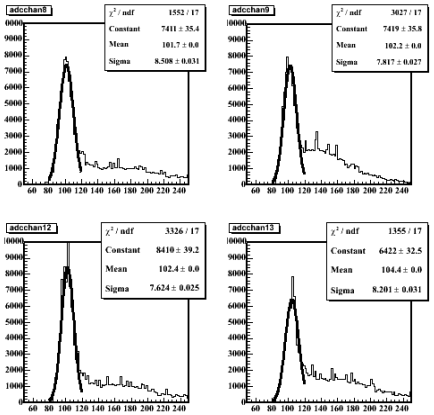


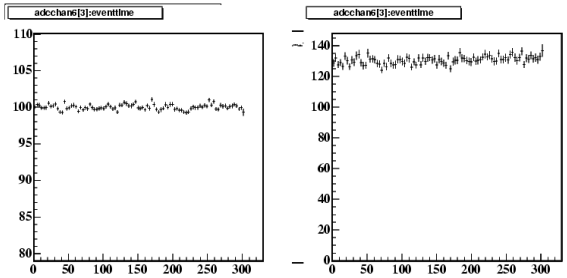




In the lab







At the site...

TrICE Construction

Site Development February/March 2005

TrICE Construction

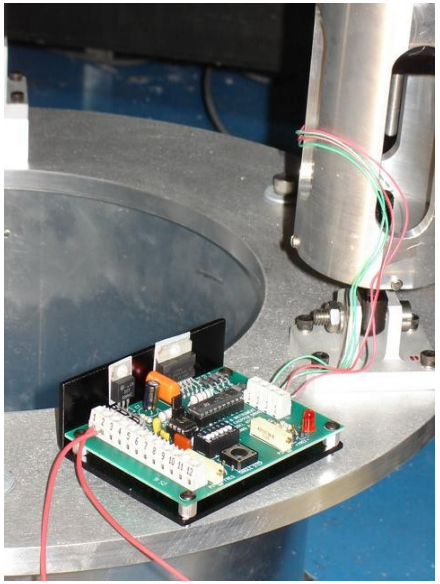
Site Development February/March 2005

Mounting the Top Plate

Adjustable height honeycomb aluminum plate holds Fresnel lens and flat mirrors.

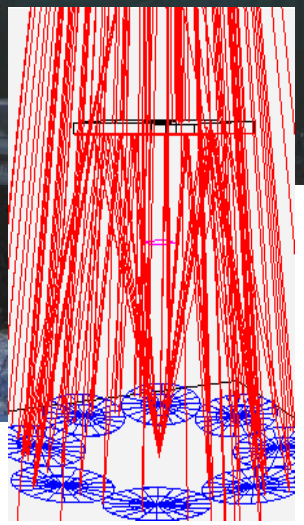
Installed at ANL August, 2005

Installing Spherical Mirrors



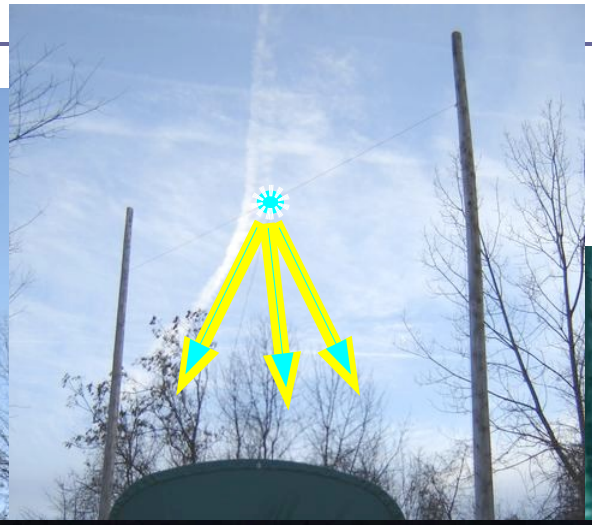
Fall 2005

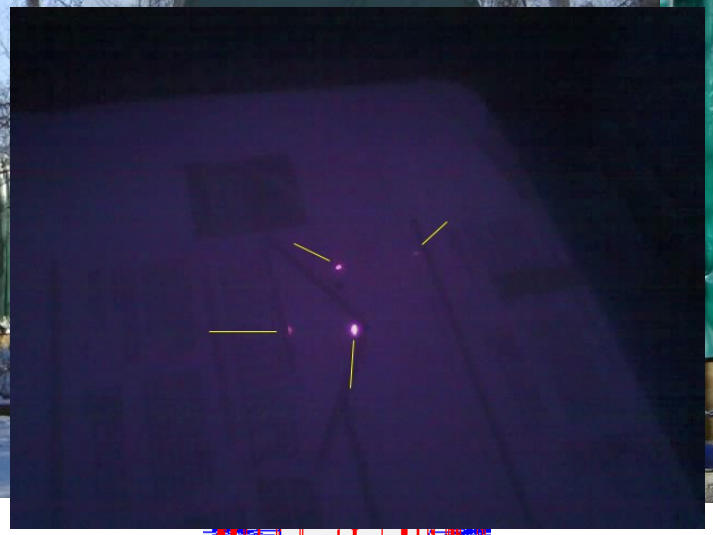
Optical Alignment



January/February 2006

Optical Alignment





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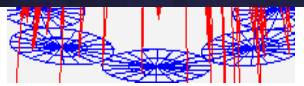
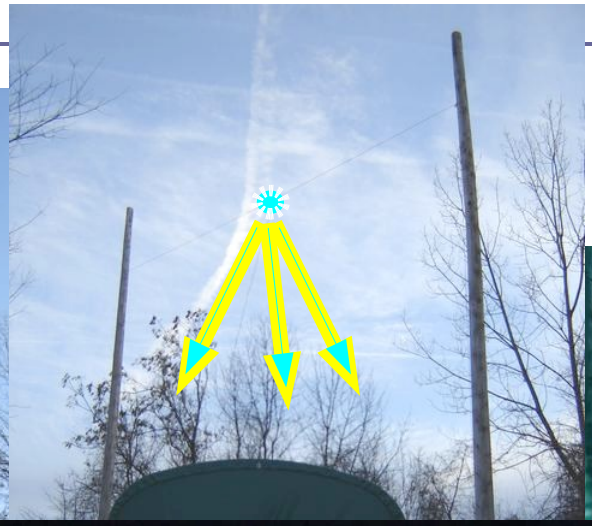


Optical Alignment



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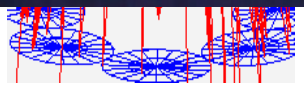
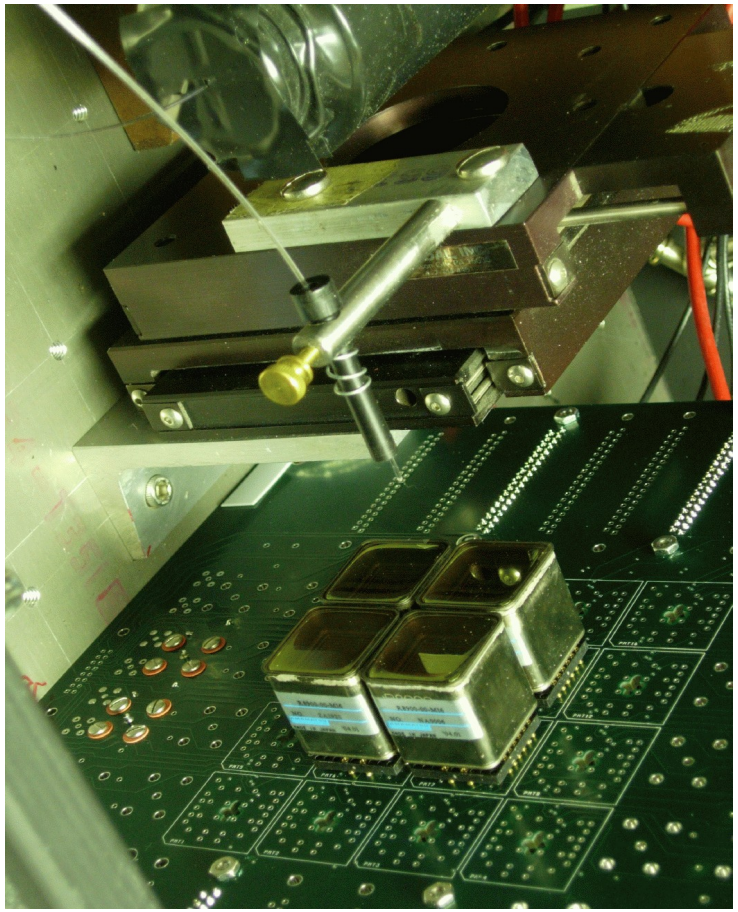
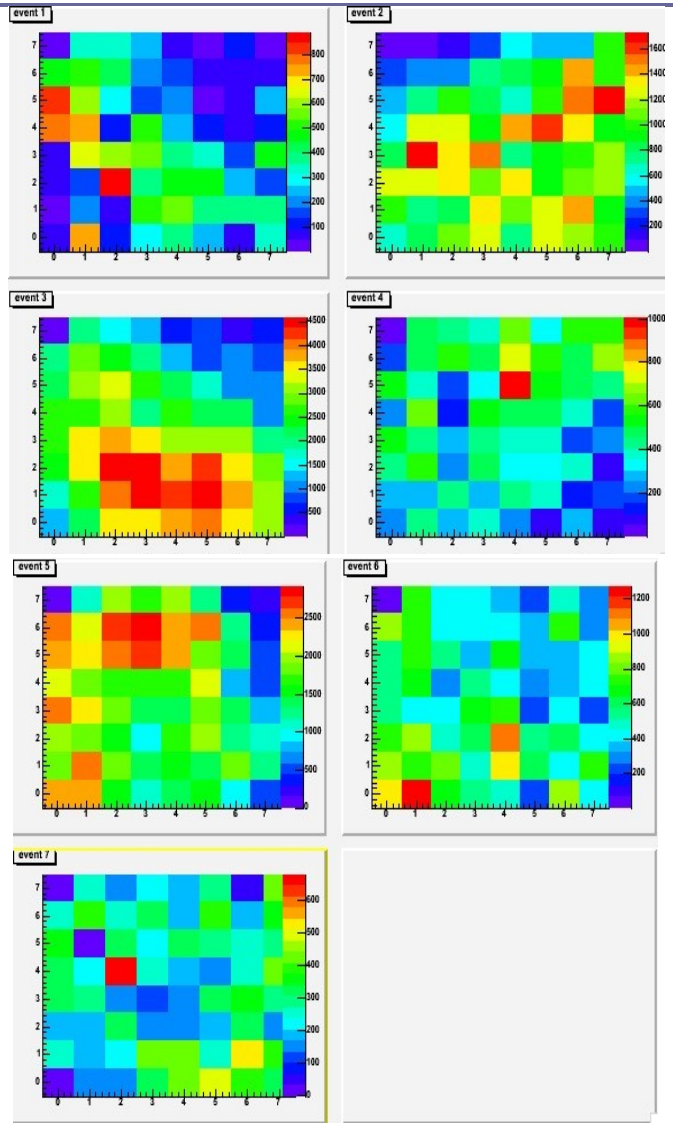


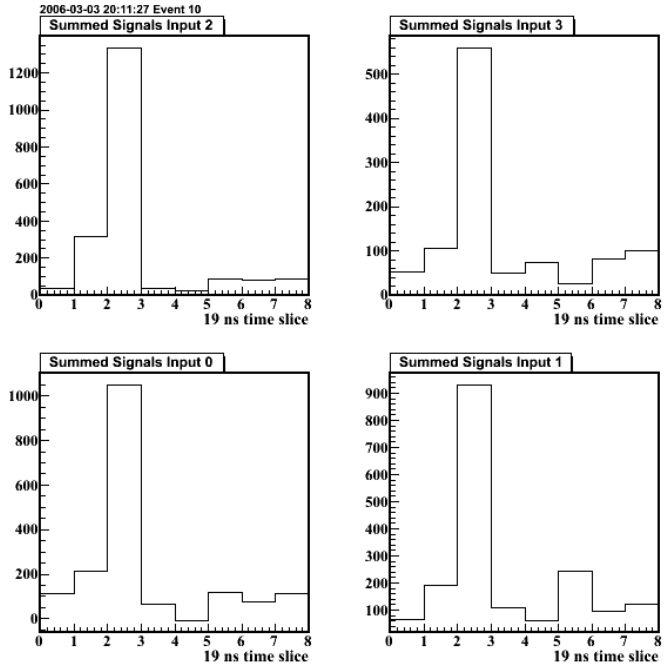
Add a Camera and Some Electronics…



Voila! First Light.



First data only includes 4 of 8 spherical mirrors and 4 of 16 PMTs (64 of 256 pixels).
Initial alignment, single PMT trigger,and initial stab at gain calibration already sufficient to see some reasonable looking showers



Lots more to do...

Noise background is large – upgraded trigger to multiplicity, requires 2/4 PMTs.
Another trigger upgrade likely.

Upgraded camera to 9 PMTs in May. Soon to be increased to full complement of 16.

Additional projects for the summer
- Fine tune alignment
- Complete camera monitoring systems (currents, moisture, light levels)
- Installation of remaining mirrors
- Calibration studies
- TrICE Simulation studies

More data and results to come...

The End…

MAPMTs: Requirements

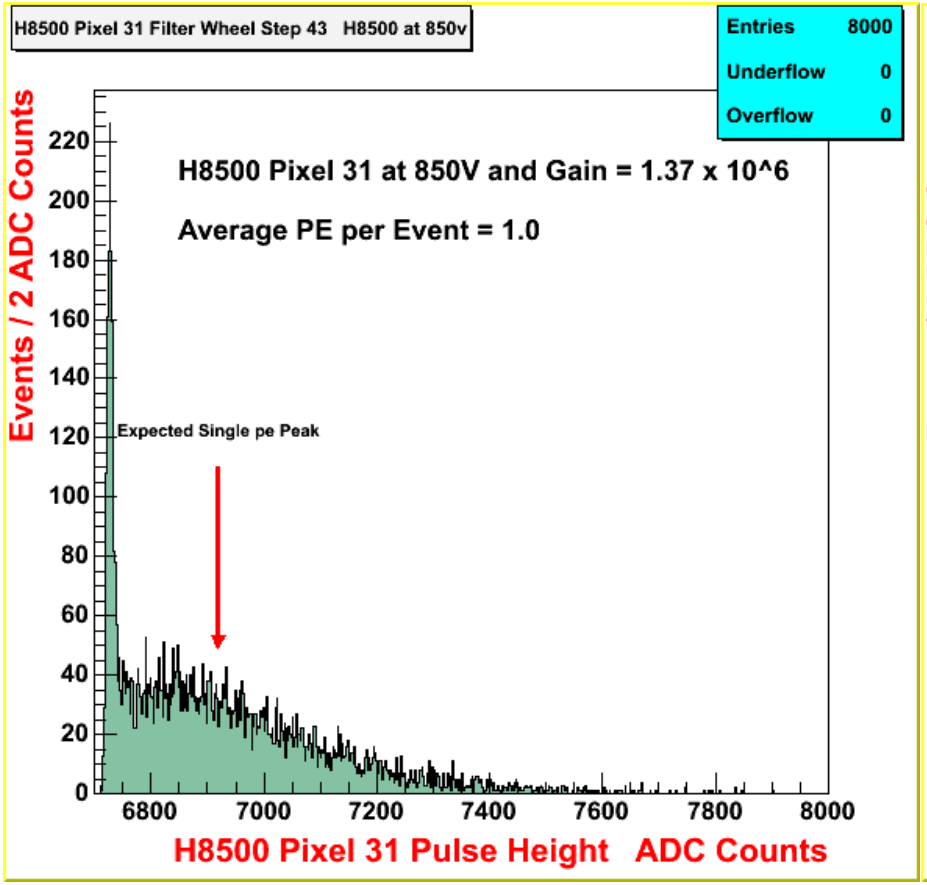
PMT Requirements similar to those for VERITAS:

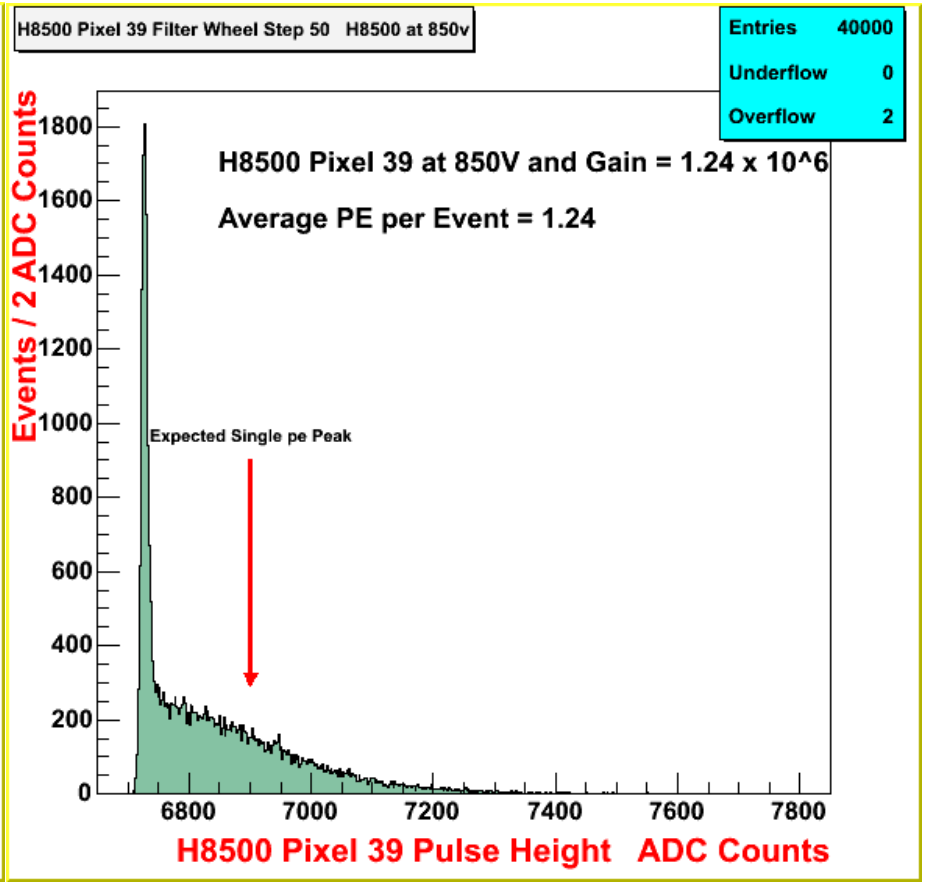
- Good single photoelectron resolution
- Linearity over full dynamic range
- Quantum efficiency as high as possible
- Good long-term gain stability

Multi-anode PMT and high background light levels at Argonne add additional demands:

- Pixel-to-Pixel gain uniformity throughout single tube
- Low crosstalk
- High current operation without significant gain loss
- Ability to trigger on dynode signal (TrICE constraint with current electronics)

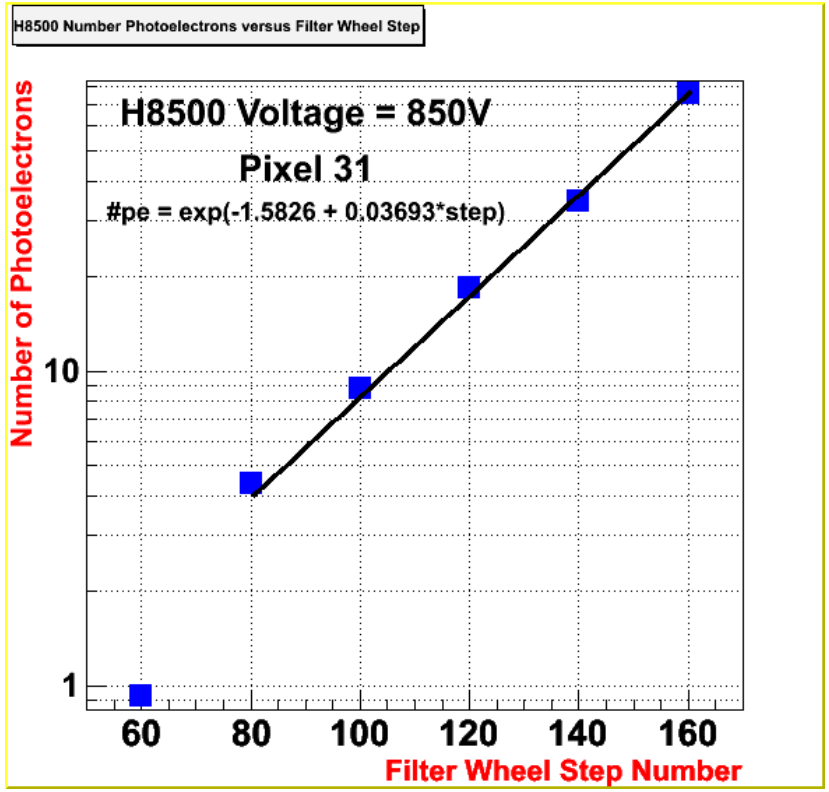
Single Photelectron Signals on H8500





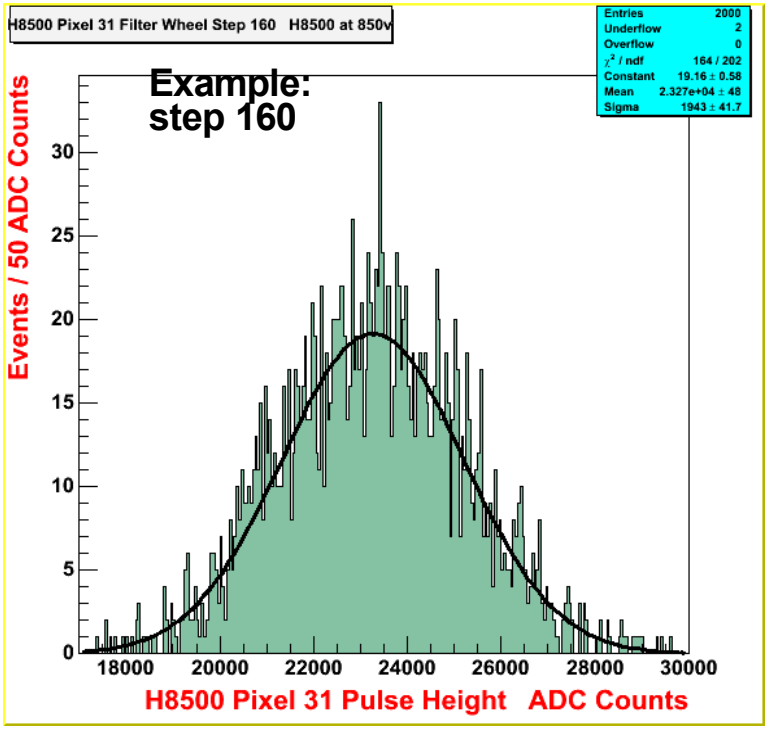
Single pe measurements shows no distinct peak - probably broadened by loss of electrons in initial dynode stages. Hamamatsu has indicated they are working on improvements to this model.

Single Photelectron Signal on H8500 (cont)



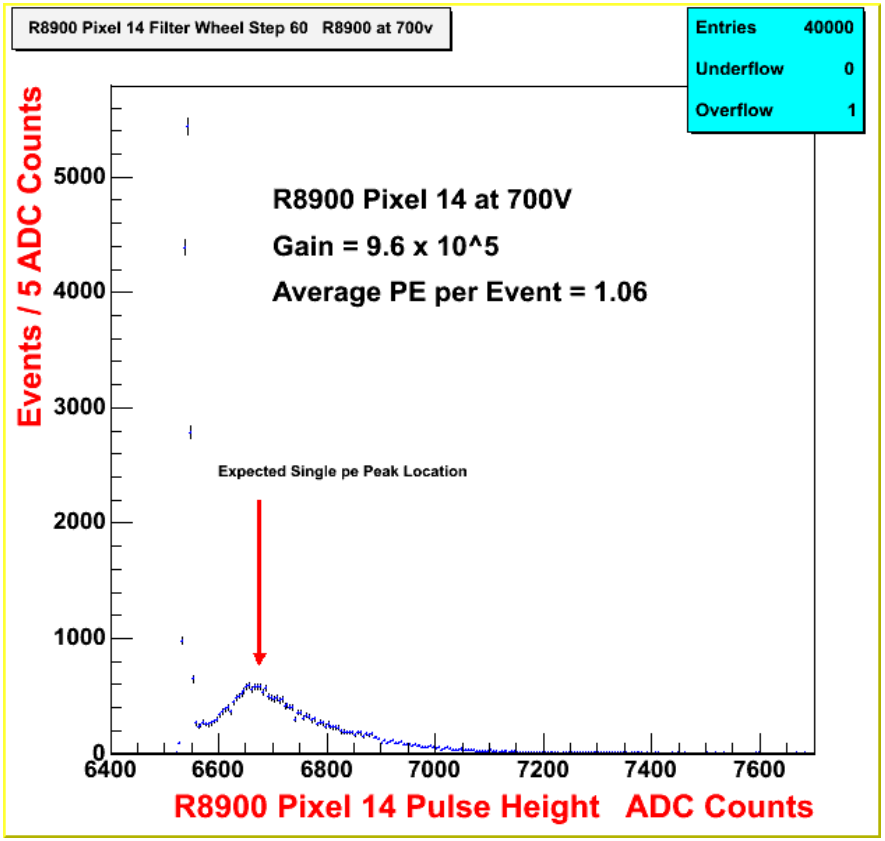
pe = [(Mean – Pedestal)/σ]^2

Gain = (7141e/ADC)[σ^2 / (Mean – Ped)]



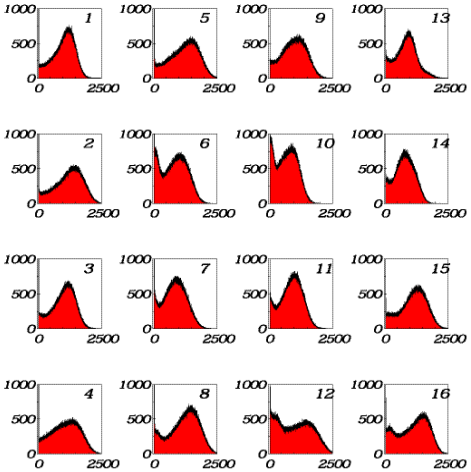
Measure number pe versus neutral density filter wheel position. For low #pe signal is non-Gaussian and blends into pedestal. Extrapolate fit to determine setting for average pe ≤ 1

Single Photelectron Signals on R8900



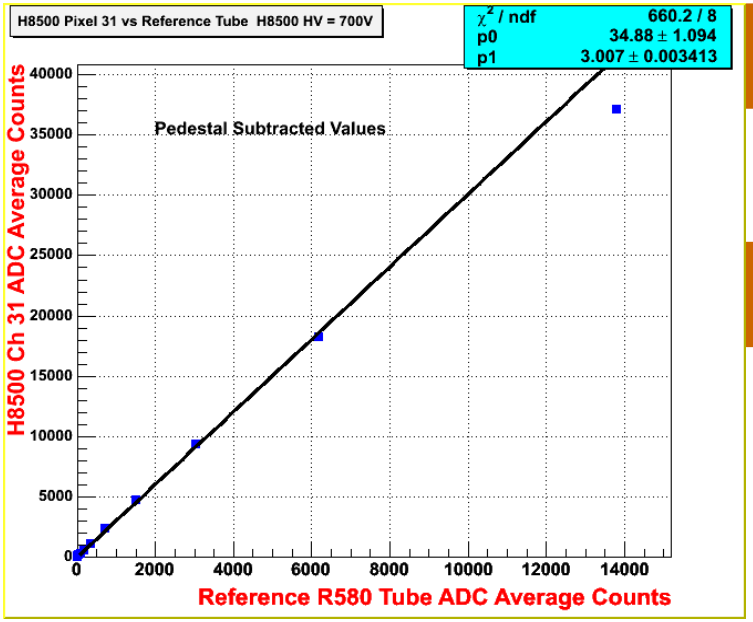
- 16 pixel R8900 shows good single photoelectron signal
- Smaller but similar in construction to H8500, tube has been around longer and been developed further

Tomasz Skwarnicki, RICH2004



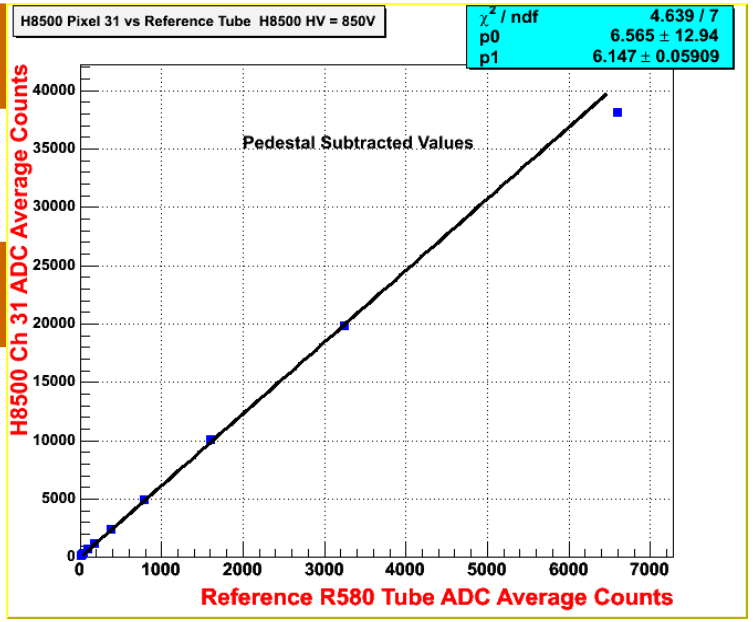
Single pe signal in all 16 pixels for bench test of R8900 at Syracuse Univ. for BTeV RICH detector

Linearity for H8500



HV = 700V

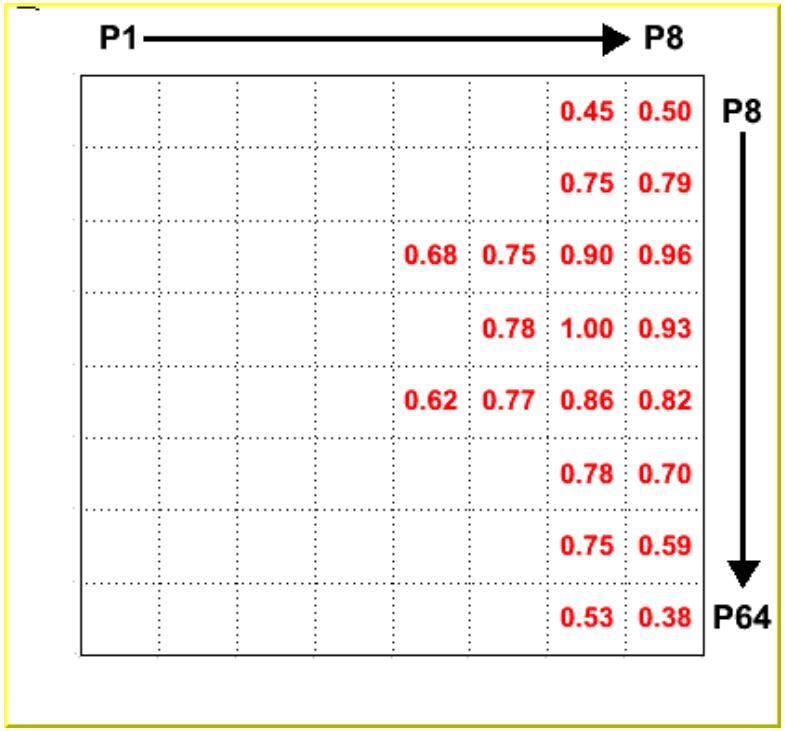
HV = 850V



Measure H8500 pixel response to flashed LED versus reference Hamamatsu R580 for varying filter wheel positions. R580 assumed linear response. Experience with tubes over 20 years in Collider Detector at Fermilab supports assumption.

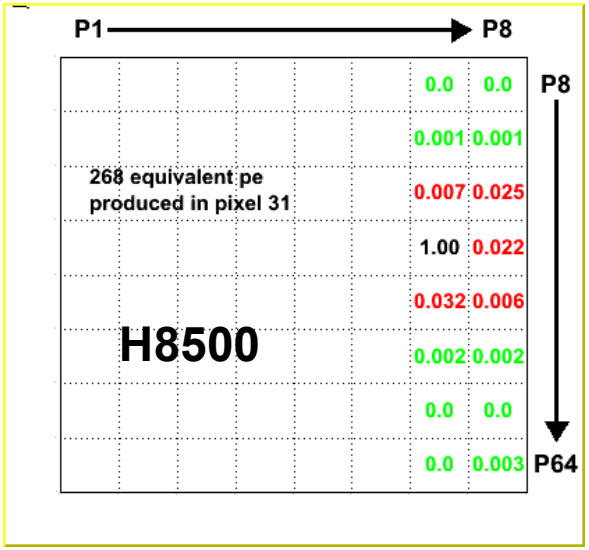
Observe ~5% deviation from linearity at highest light levels -- ~200-500 pe.

Gain Uniformity: H8500



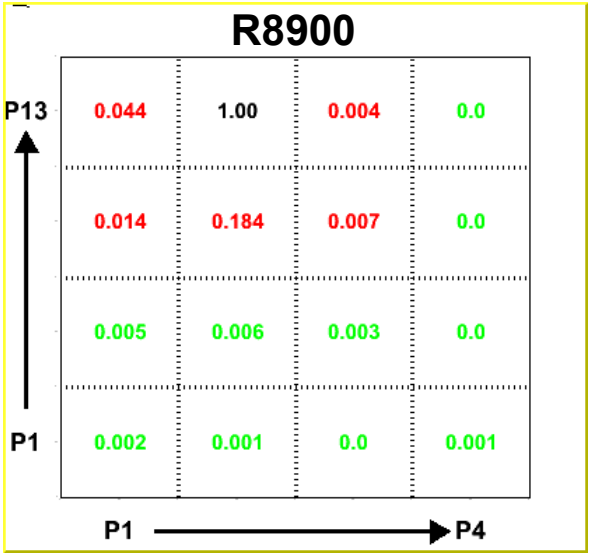
- Measure average gain over linear response range
- Largest gain pixel is 31
  - Normalize to 1.00
  - Gain of other pixels shown relative to 31
- Smallest gain observed is in corner pixel
- Variation is 2.6 : 1
- Gain stable over periods of at least 60 days

Crosstalk: H8500 and R8900



- Illuminate pixel 31. Fiber centered in pixel but not shielded
  - Crosstalk includes possible leakage of light from fiber into neighbor pixels and electronic crosstalk ~ 1%
  - Upper limit of crosstalk
- Measure relative signal in surrounding pixels

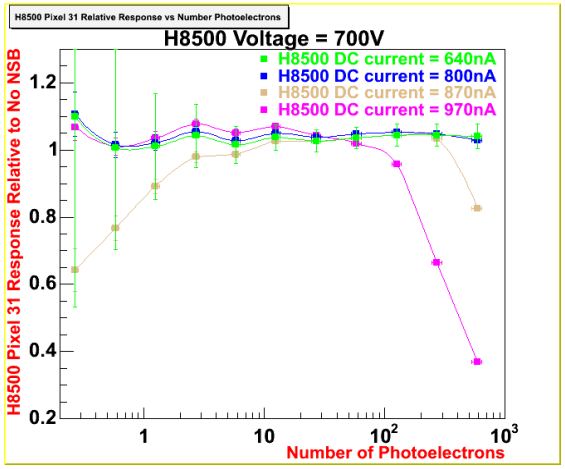
- Crosstalk in R8900
- Setup did not allow for accurate vertical centering of fiber in pixel
  - Large signal in pixel under illuminated one due to vertical offset in fiber **NOT** large crosstalk

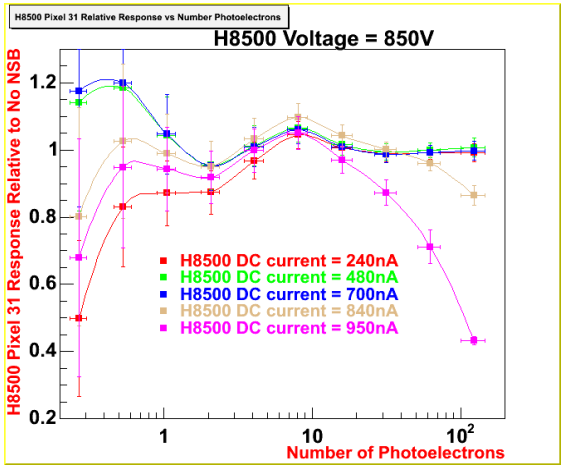


Simulation of Night Sky Background

- Use DC light source (incandescent bulb or blue LED) to simulate constant background
- Observe gain relative to no background as DC illumination is increased
- Have measured both H8500 and R8900
  - See similar results in both
- H8500 base supplied by Hamamatsu modified to allow higher DC current operation
  - Lower all resistor chain values by $\times 5$

Simulation of Night Sky Background (cont)





- Unmodified H8500 base
- Pixel 31 response relative to no background as function of equivalent number of pe incident
- No "roll-off" of gain seen up to 0.7-0.8μA depending on HV
- At 700V ($G=5.5\times10^5$) no change observed up 100 pe. For I =0.8μA, no change up to 800pe
- At 850V ($G=2\times10^6$) no change observed up 20 pe. For I = 0.7μA, no change up 100pe.