IceTop Tank Response To Muons

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The IceTop Air Shower Array

IceTop is an air shower array of ice–Cherenkov counters [1, 2]. Each of its current 26 stations shown in Fig. 1 is made up of two IceTop tanks. The tank ice is viewed by two standard IceCube digital optical modules (DOMs) (see Fig. 2). They consist of a 10" Hamamatsu R7081–02 photo multiplier tube (PMT) and processing and readout electronics. Two different types of digitizers are used to process the PMT signal: a fast pipelined ADC (FADC) with 255 samples of 25 ns each, and two Analog Transient Wave Digitizer (ATWD) chips, with three channels of up to 128 samples of about 3.6 ns each. The three channels are configured with different pre–amplification factors to extend the DOM's dynamic range (for details, cf. [3]).

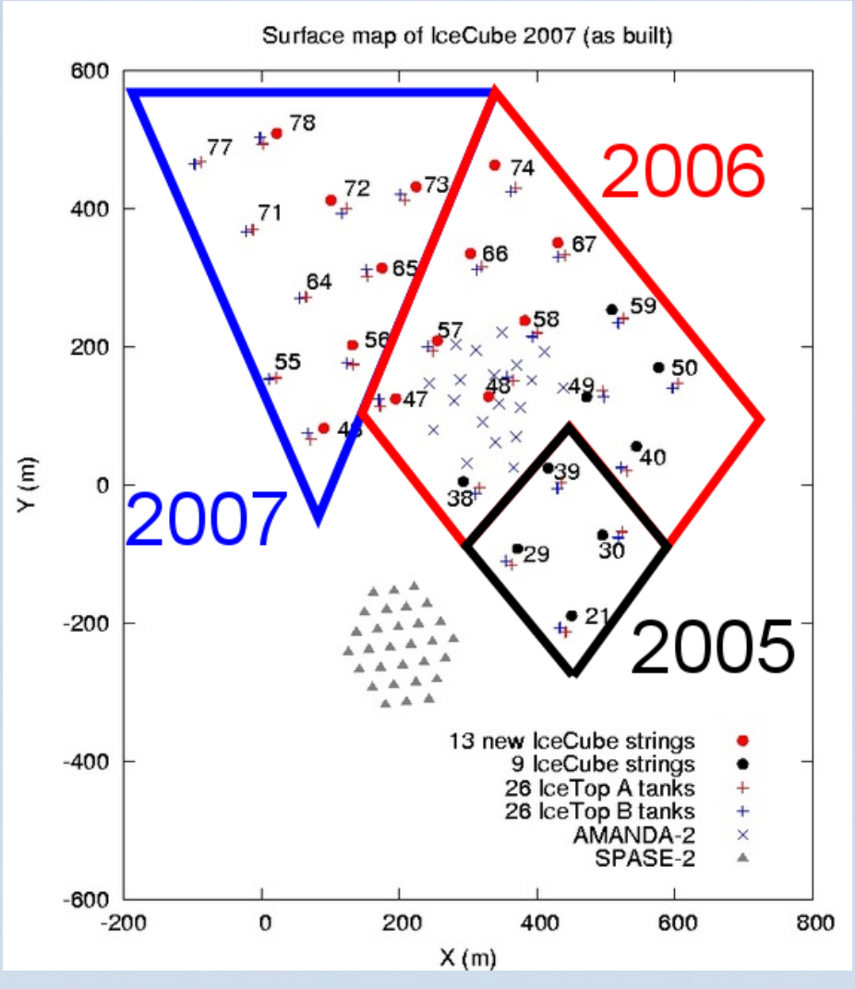

Figure 1: IceTop surface map

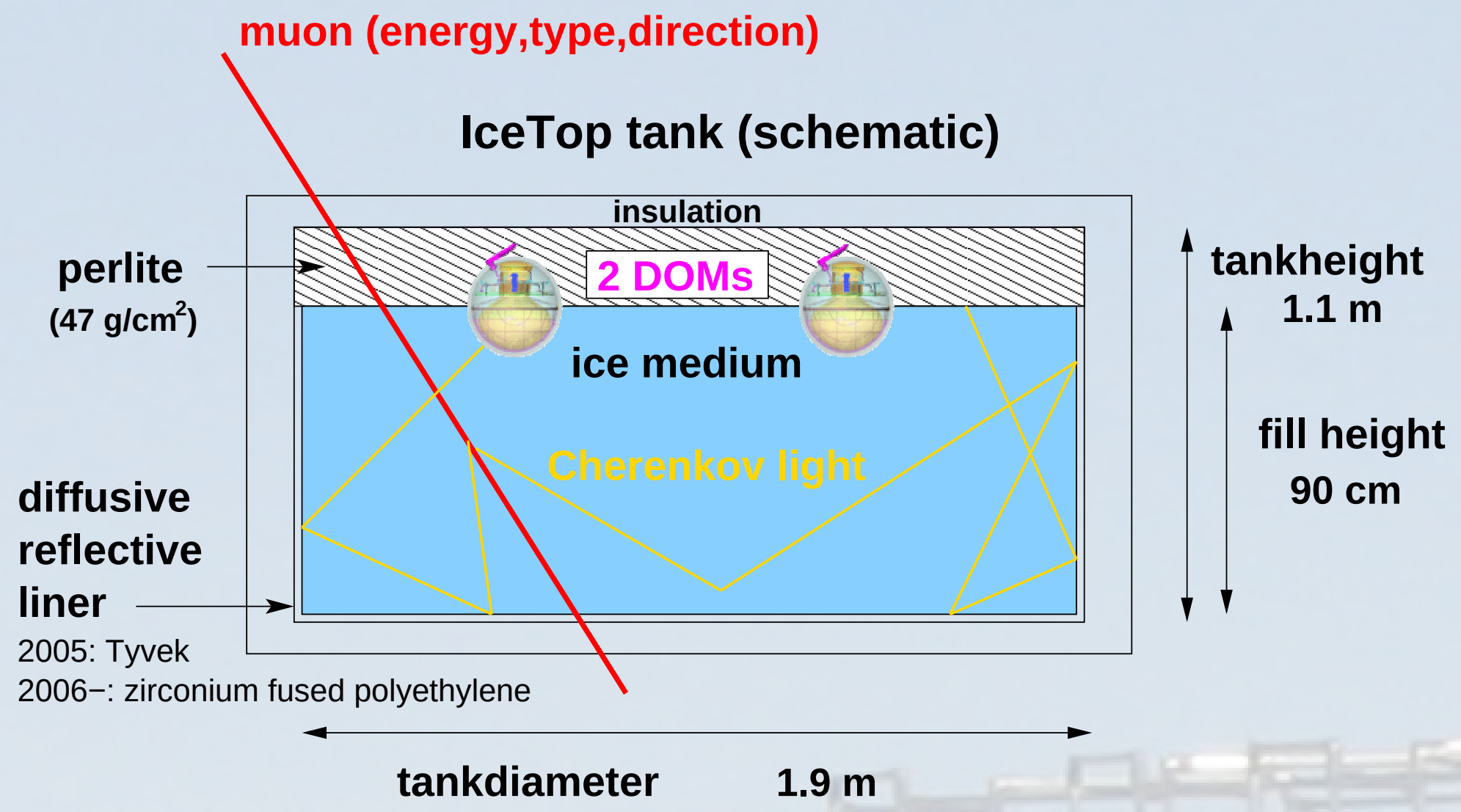

Figure 2: IceTop tank schematic

Simulating The Tank Response

The DOM responses are simulated by

- Generating showers with CORSIKA [5]:
  - hydrogen and helium primaries
  - $10\,GeV \leq E_{primary} < 415\,GeV$
  - $\Theta_{primary} < 70\,deg$
- Tank simulations (GEANT4 based, [6]):
  - generate and track Cherenkov light/secondaries in the tank.
  - account for tank properties: reflectivities of sides and top, ice quality.
  - account for PMT quantum efficiency.

Figure 6 shows the results:

- light grey: Total simulated charge spectrum
- blue: Single muons charge contribution
- black: Same, but with $\Theta_\mu < 17\,deg$
- red triangles: Total measured charge spectrum from DOM 21–63.

The total spectrum peak position is at 247 pe, the best estimate for the VEM is determined as the mean of a Gaussian fit to the black histogram, 236 pe. The ratio gives a correction factor of about five percent, which is in agreement with the correction factor obtained from the muon tagger measurements. Currently, this correction factor is assumed to be the same for all IceTop tanks.

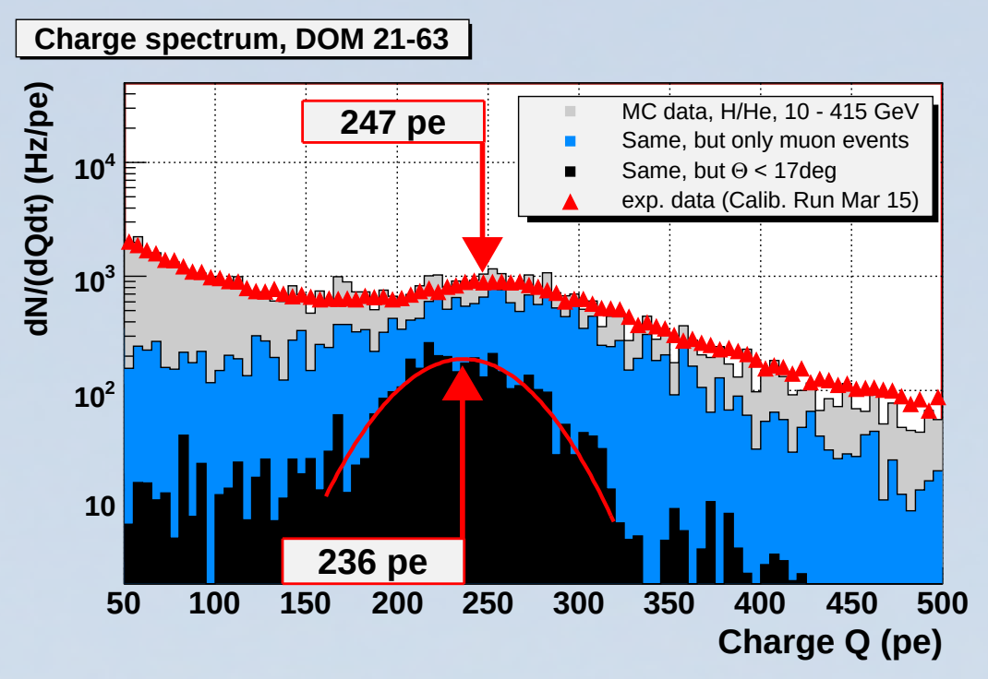

Figure 6: MC simulated charge spectrum for DOM 21–63.

VEM Calibration Run Parameters

Periodic special IceTop calibration runs serve two purposes: one, to calibrate the conversion from integrated waveform to vertical equivalent muon (VEM) for each DOM in each tank, and two, to monitor the DOM response's time dependence. The calibration run configuration differs from the regular one used for air shower data runs:

air shower mode:	singles mode (= calibration mode):
the two DOMs in the same tank are set to different gains (in 2006, $5 \cdot 10^6$ and $5 \cdot 10^4$, respectively).	every DOM is set to the same nominal gain of $5 \cdot 10^6$.
the high gain DOMs of both tanks in a station are in local coincidence (LC).	local coincidence (LC) between DOMs is turned off.
the simple majority trigger requires a multiplicity of six.	the simple majority trigger is disabled.

For the DOMs that are operated at the lower gain, the VEM might differ due to changes in the collection efficiency of the PMT. Currently, that effect is not taken into account.

Calibration using stopping muons

Stopping muons in IceTop tanks:

- $210\,\mathrm{MeV} \leq E_{kin,max}(\mu) \leq 430\,\mathrm{MeV}$
- $E_{kin,max}(e) < 53\,\mathrm{MeV}$
  ⇒ electron range less than 25 cm
  ⇒ most decay electrons contained in tank!

Are there decay signals?

- Two signal FADC traces were selected.
- Figure 11 shows Δt in blue
  ⇒ Suppress background with stringent cuts! Cuts were determined / tuned with MC studies.
- Δt for remaining events in red, fit yields a lifetime of $\tau = 2.06 \pm 0.16\,\mu s$.

The Michel spectrum is calculated by following the method outlined in [7] ("Auger method"):

1. Define a "decay" window between 1 and 2 μs.
2. Define a "crossing" window between 5 and 6 μs.
3. Collect FADC's second signal charges for both time windows.
4. Subtract "crossing" from "decay" spectrum ⇒ Michel spectrum

- Figure 12 compares measured spectrum (red symbols) with simulated spectrum.
- Qualitatively agreement between measured and simulated spectra.

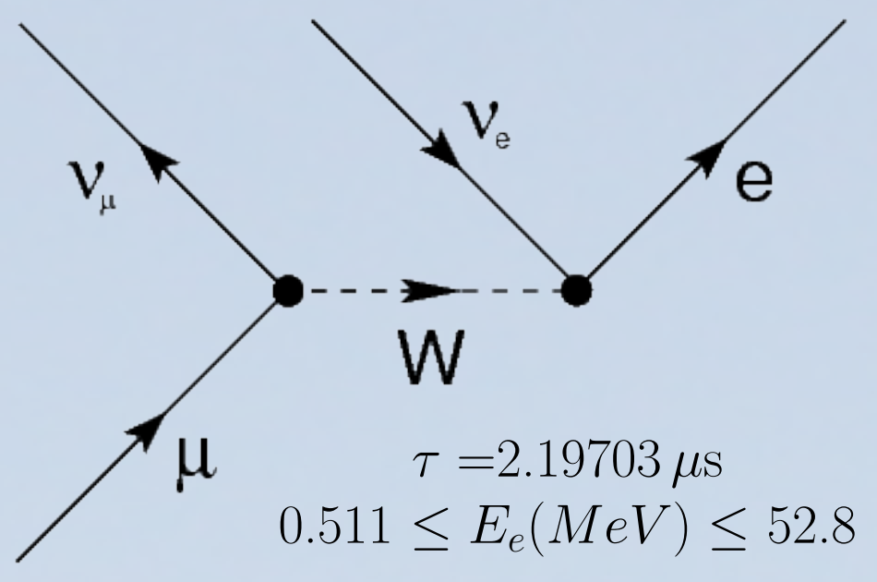

Figure 10: Feynman diagram of muon decay.

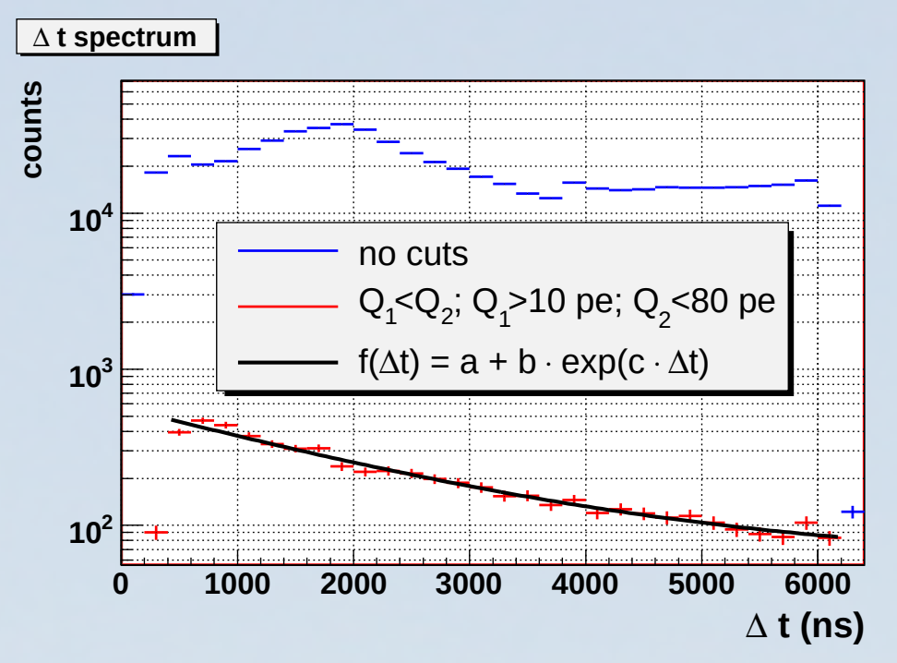

Figure 11: Δt before (blue) and after cuts (red)

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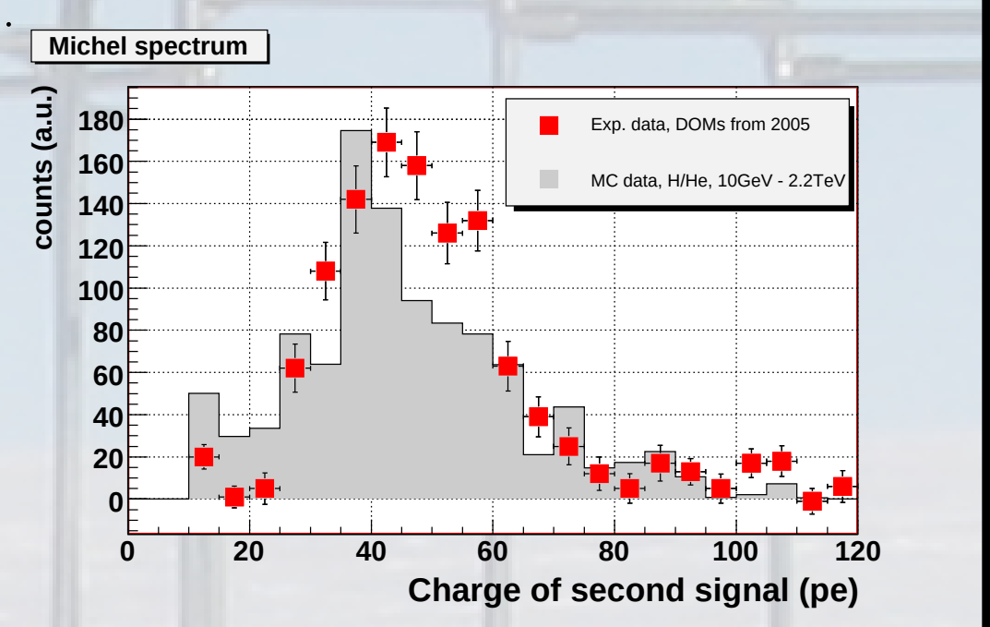

Figure 12: Measured Michel spectrum (red) in comparison with a simulated one.

What is a VEM?

A DOM's response to a vertical muon passing an IceTop tank is defined to be one Vertical Equivalent Muon (VEM). Such a muon deposits around 200 MeV in the tank ice [4]. By finding the vertical muon signal in the measured total charge spectrum, the DOM–dependent charge–to–VEM conversion factor is determined. However, single IceTop tanks cannot discriminate between different particles or incident angles. Therefore, the relation between the measured peak position of the total charge spectrum and the VEM must be determined with simulations and a tagging telescope:

1. Determine the charge contribution of nearly–vertical muons to the overall charge spectrum with the help of a tagging telescope for muons.
2. By using the zenith angle acceptance of the tagging telescope, simulate the tank response
3. Compare both results and define the VEM contribution to the total DOM charge spectrum.
4. Measure charge spectra with all DOMs and extract the VEM, monitoring its stability over time.

The Muon Tagging Telescope

Figure 3: Tagging Telescopes getting ready...

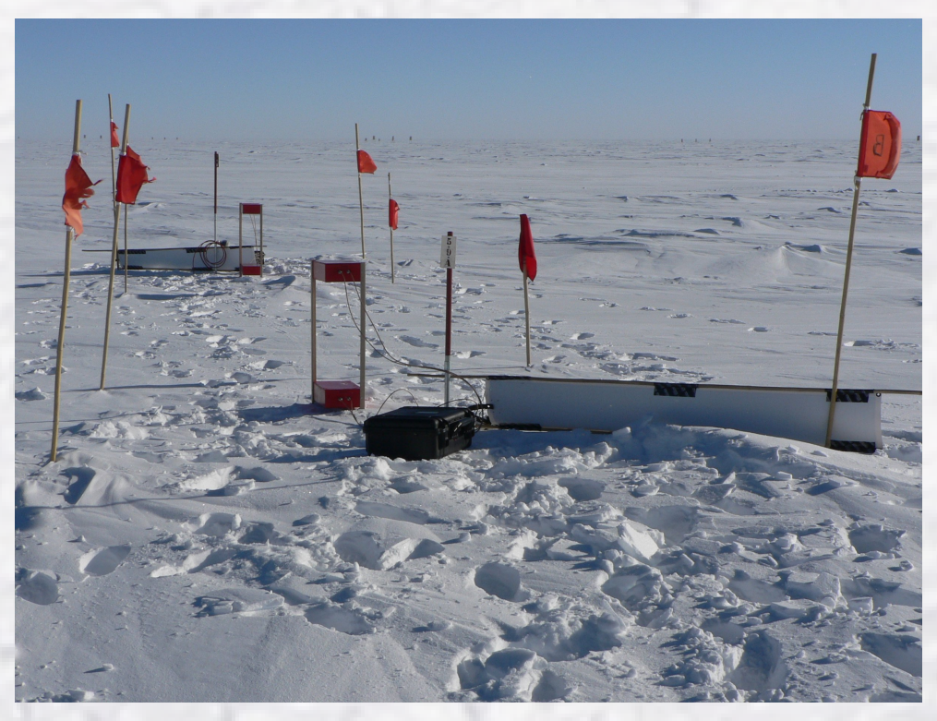

Figure 4: ... and being on duty.

A portable, solar–powered muon telescope was developed to tag muons that have angles close to vertical (< 17 deg) and pass through the center of the tank. It measures signals in coincidence between two scintillator slabs 70 cm apart and records the GPS clock time stamp. Measurements were taken during the polar season 2005/2006 on tanks deployed one year earlier. The charge spectra of the tagged muon sample are shown in Fig. 5, superimposed in blue over the total charge spectra for DOMs 39–63 and 39–64 in black. The VEM is determined to be about 95% of the full spectrum peak position.

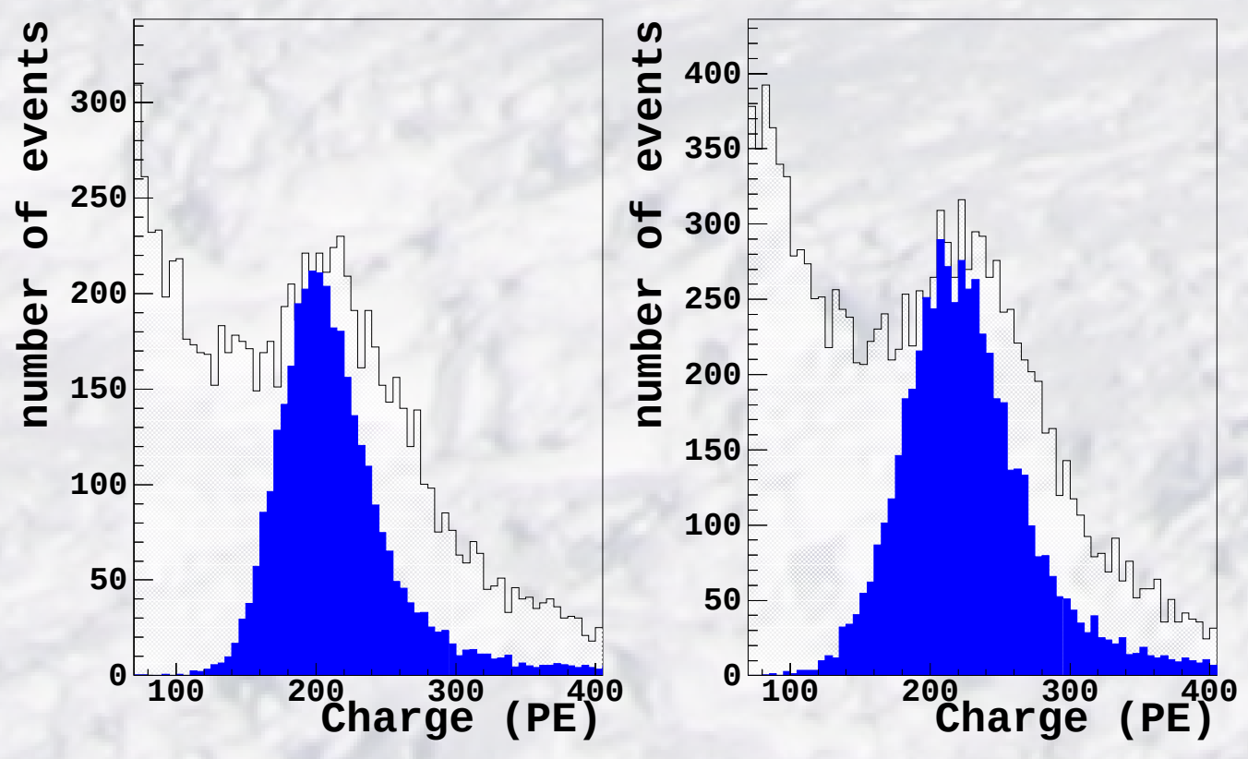

Figure 5: Total charge spectra (black) for tank 39b with tagged muon spectrum (blue) superimposed.

VEM Calibration And Monitoring Results

The calibration data is processed by

- correcting each raw waveform for the specific, ATWD chip–dependent pedestal pattern
- correcting the signal droop (implemented, but not tested)
- adjusting any residual baseline
- calibrating the charge in photo electrons
- summing the charge and plotting the charge distribution
- applying fits (e.g. [4]) to extract the full spectrum peak position
- using the conversion of that peak position value to VEM.

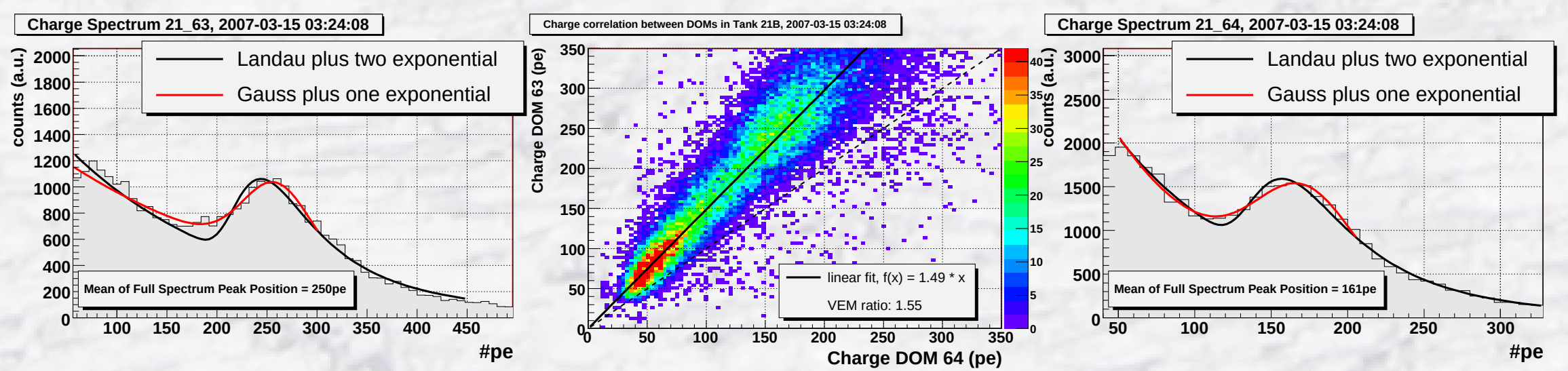

Figure 7: Measured total charge for tank 21B (DOMs 63 and 64, left and right) and the charge correlation.

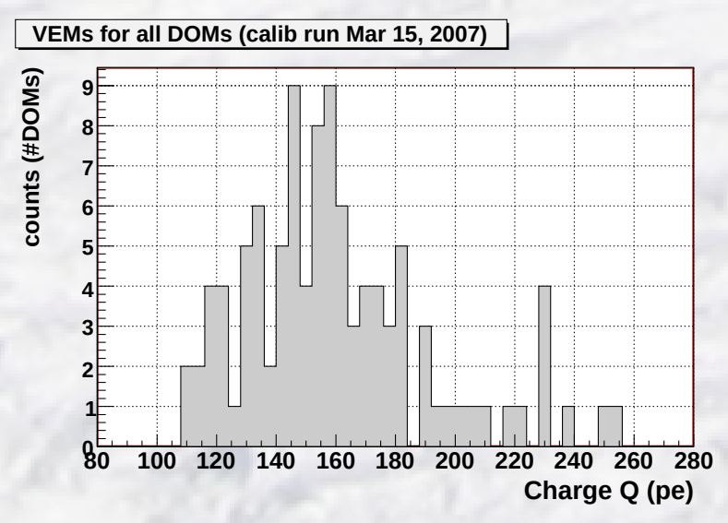

Figure 8: The spread in VEM is shown for one calibration run. The fluctuations in the response, even between DOMs in the same tank, are the main reason to introduce the VEM as a uniform, array–wide unit.

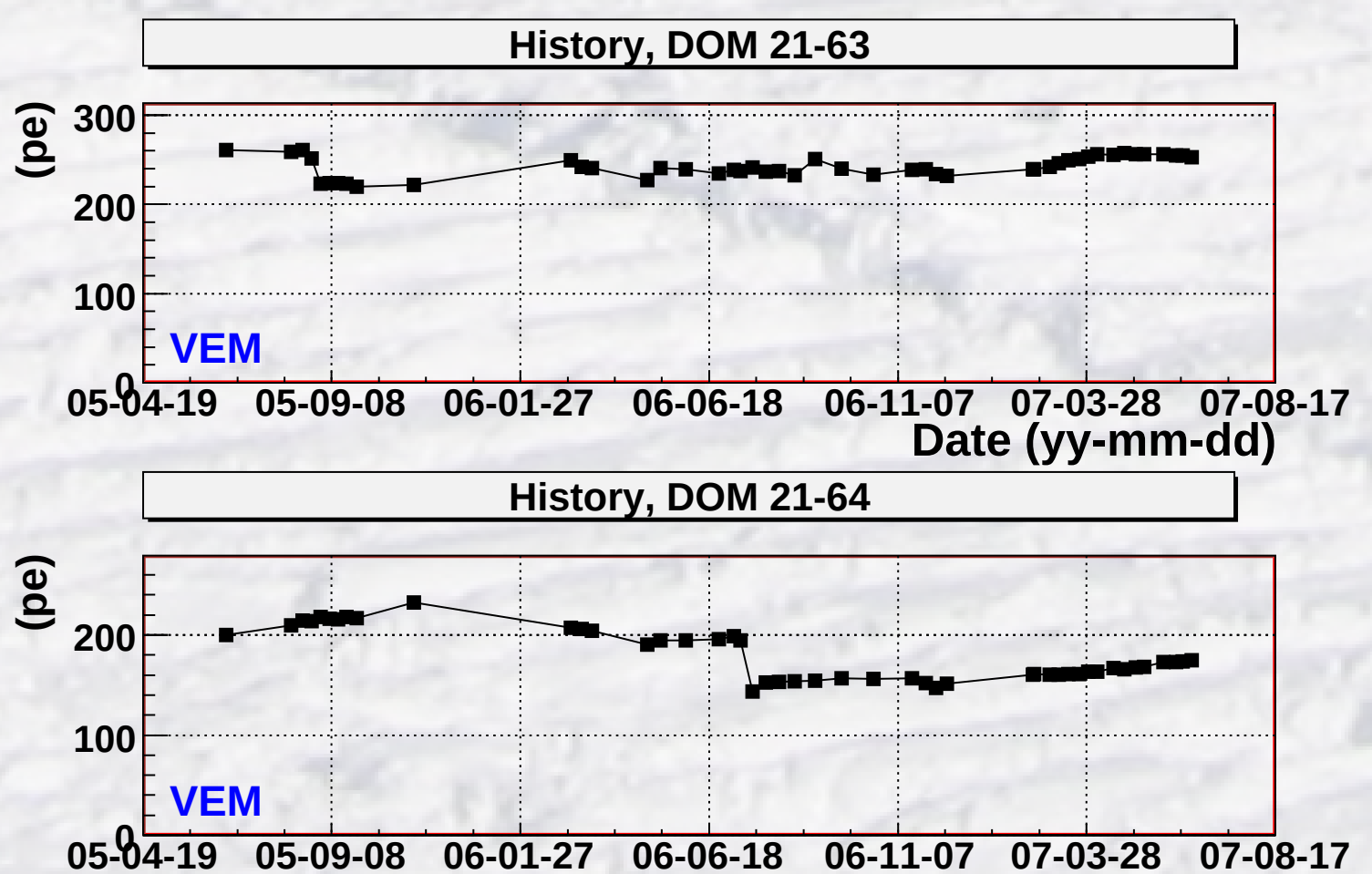

Figure 9: History of charge to VEM conversion for DOMs 21-63/64. The sharp drop in DOM 21-64 around July 2006 is observed in about half of all DOMs in tanks deployed in 2005. The specific cause of these changes in the DOM response is unknown and believed to be related to seasonal effects, i.e. the change in temperature during the Antarctic winter.

Conclusions

VEM calibration:

- Procedures and tools have been established and well understood.
- Periodic calibration runs keep track of IceTop DOM's response stability.
- Muon telescope measurements and tank simulations agree well on the nearly vertical muon contribution of the total charge spectrum.
- More muon tagger measurements will help fine tune the relation between total charge spectrum peak position and VEM.
- Simulations with higher statistics will make more realistic muon tagger cuts possible.
- Significant decrease in the VEM of several DOMs is not understood yet, but at current level does not limit the array's performance.

Stopping muons:

- Feasibility study was completed.
- Comparison between data and simulation looks promising.
- Further improvements in both the analysis and the simulation needed
  ⇒ supplementary calibration method

Acknowledgments

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Photographs by J. Roth and L. Demirörs

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