Calibration of a Digital Hadron Calorimeter with Muons

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Scope

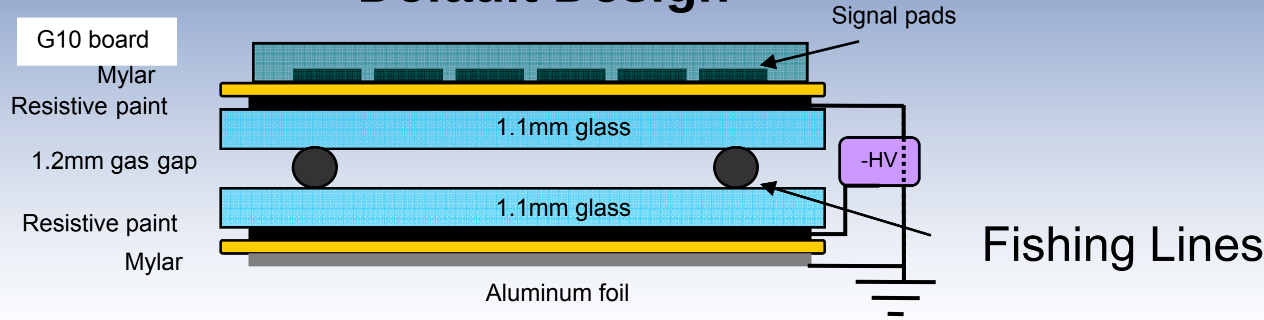
- Report on the development of a finely granulated HCAL using Resistive Plate Chambers (RPCs) as the active medium.

- In preparation for the construction of a larger prototype module, a stack of nine small chambers was assembled and exposed to the muons of the Fermilab test beam.

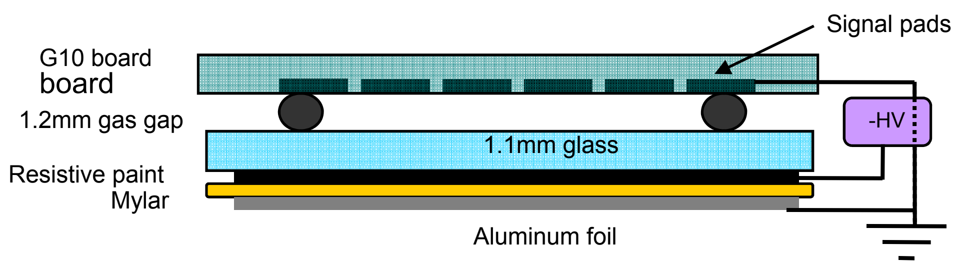
- The measurements performed with the broad-band muon beam are described in detail.

Description of the Calorimeter Stack

Default Design



Exotic Design



The calorimeter stack consisted of nine chambers interleaved with the combination of a steel (16 mm) and a copper (4 mm) absorber plates, corresponding to approximately 1.2 radiation length.

The chambers measured 20 x 20 cm^2. They were operated in avalanche mode with an average high voltage setting around 6.1 kV. The gas consisted of a mixture of three components: R134A (94.5%), isobutane (5.0%) and sulfur-hexafluoride (0.5%).

Description of the Electronic Readout System

The electronic readout system is optimized for the readout of large numbers of channels. The charge resolution of individual pads is reduced to a single bit (digital readout). The system consists of several parts:

- **Pad Board**: 20 x 20 cm^2, where the central 16 x 16 cm^2 contain 256 1 x 1 cm^2 signal pick-up pads.
- **Front-End Board:** Four front-end Application Specific Integrated Circuits (ASICs).
- **DCAL Chip:** The chip can be operated in high or low gain mode, where the latter is more suited for operating with RPCs. The threshold value is common to all channels of a chip and is set by an internal digital-to-analog converter (DAC) with a range of 256 counts. The chip can be operated in either triggered or self-trigger mode.
- **Data Concentrator:** Each data concentrator receives data from four front-end ASICs.
- **Data Collector:** Receive data from the front-end and format them for transfers to the data acquisition computer (VME-based).
- **Trigger and Timing Module:** Generates the clock and time-stamp reset signals for the readout and distributes the external trigger signals to the data collector modules.

The total number of readout channels was up to 2,304, for nine layers.

Calibration Procedure

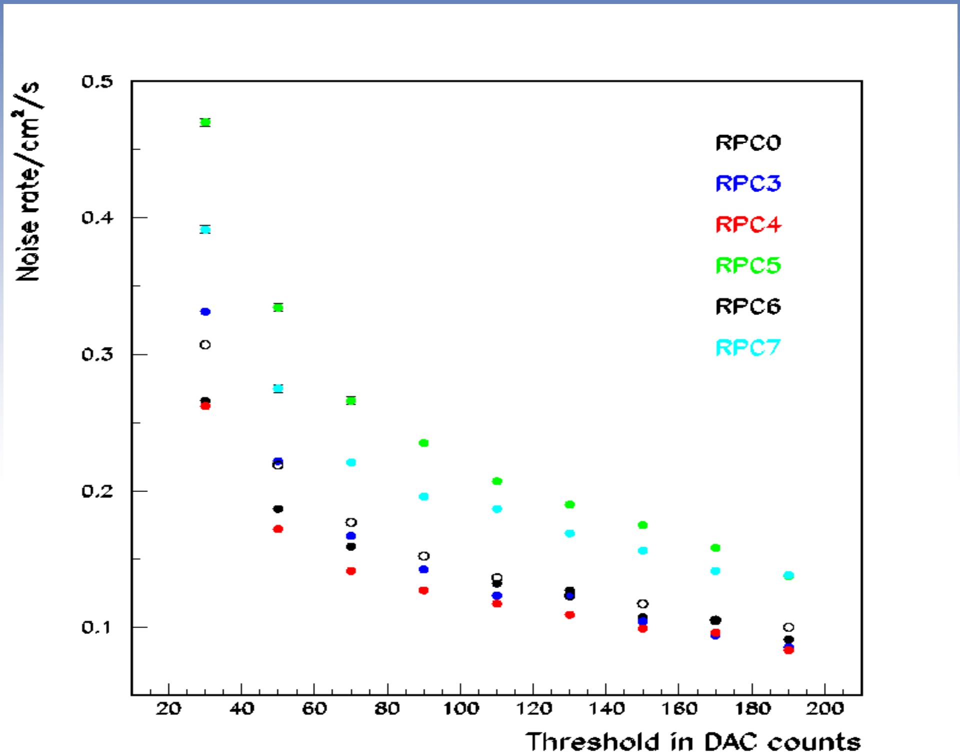
$E_{hadron} = \alpha_{samp}(\Sigma_i H_i) \cdot \Sigma_i(H_i - B_i)/(\varepsilon_i^{MIP} \cdot \mu_i^{MIP})$

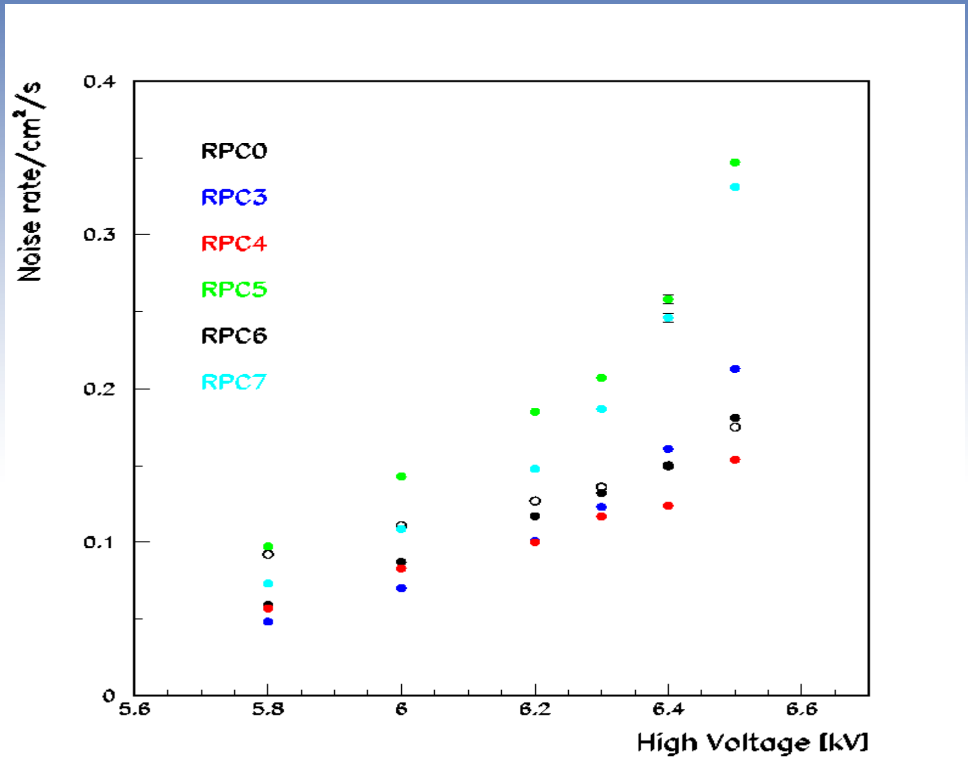
where,

- i is an index running over all pads associated with an incoming particle
- H_i is set to 1 (0) depending on whether a hit (or no hit) has been recorded in pad i
- B_i are the expected number of background hits (from accidental discharges, electronic noise or cosmic rays)
- ε_i^{MIP} is the efficiency for pad i to fire when traversed by a minimum ionizing particle (MIP)
  $\varepsilon_i = N_i^{hits>0} / N_i^{total}$ (binomial errors are calculated for efficiency)
- μ_i^{MIP} is the average number of pads firing when pad i is traversed by a MIP, where the 'zeros' are excluded from the average (standard errors are calculated for pad multiplicity) and
- $\alpha_{samp}(\Sigma_i H_i)$ is a sampling term, possibly depending on the total number of hits.

Measurement of the Noise Rate

The noise rate was measured using the self-trigger data acquisition mode of the DCAL chip.

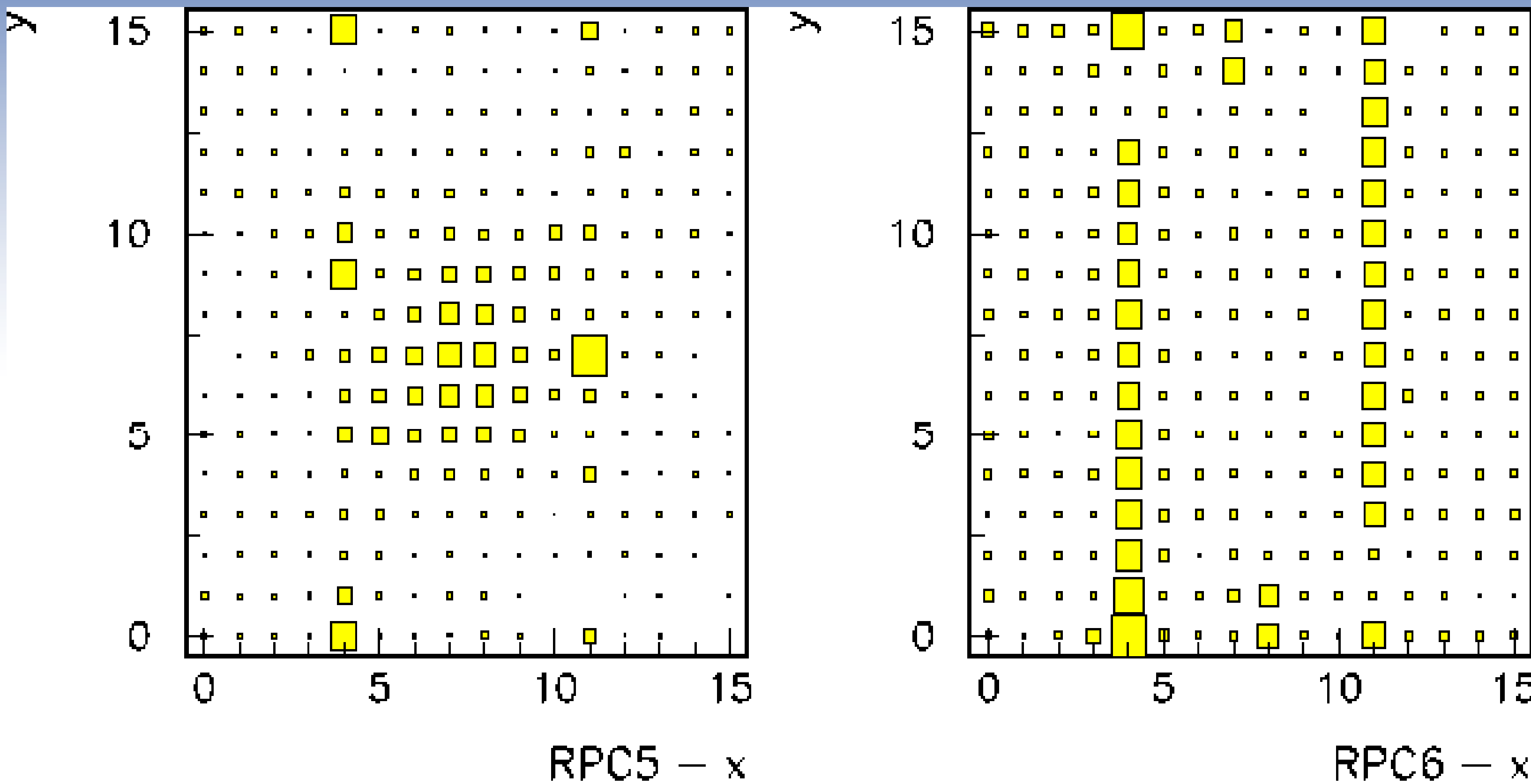




The measurements were performed with a high voltage setting of 6.3 (6.0) kV, for the default (exotic - RPC6) chambers.The rate at our default threshold setting of 110 DAC counts corresponds to about 0.15 Hz/cm^2. Extrapolated to a calorimeter with say 50·10^6 channels, as envisaged for the International Linear Collider (ILC), this rate in turn corresponds to 0.2 hits/event. With the high voltage to the chambers turned off the noise rate was found to be less than 4·10^{-5} Hz/cm^2.

The measurements were performed with a threshold at 110 counts. The high voltage values for the exotic chamber (open circles) were set at 300 V less than indicated in the plot.

Measurement of the Noise Rate



x – y map of the noise hits for a typical default (RPC5) and the ‘exotic’ (RPC6) chamber. A clear clustering along the fishing lines located approximately at x = 4.2 and 10.7 is visible.

Test Beam Setup and Data Collection

The calibration procedure was performed at the Meson Test Beam Facility (MTBF) of Fermilab.

The calibration runs were taken with the primary 120 GeV proton beam and a 9 foot (~ 3 m) iron beam blocker in place to produce muons and filter out the non-muon component.

The readout of the stack was triggered by the coincidence of two large scintillator paddles located approximately 5.0 and 0.5 meters upstream of the stack.

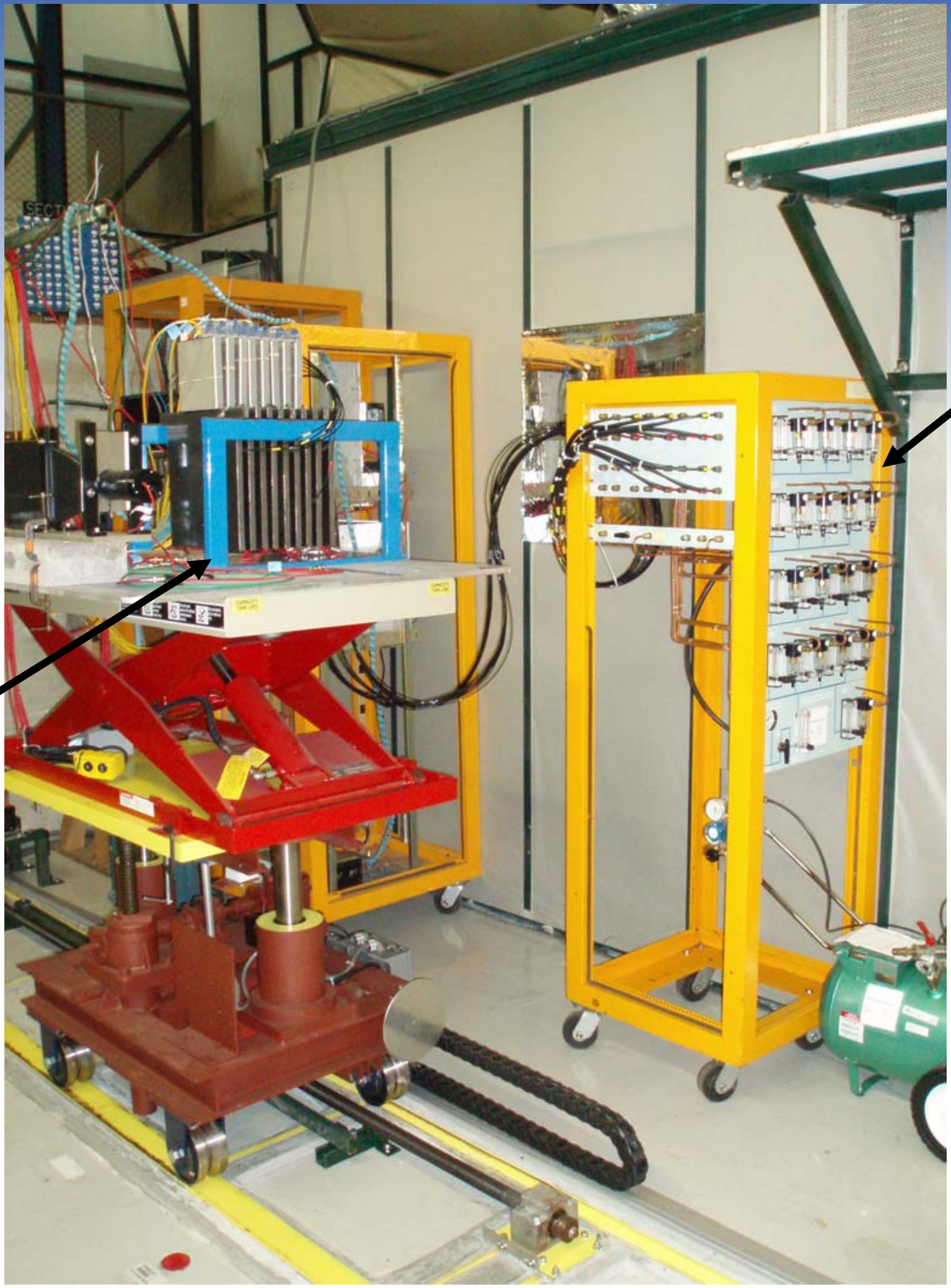
The beam came in spills of four second length every one minute.

The trigger rates were typically between 100 and 200 per spill.

For a given run, all default chambers were operated at the same high voltage and threshold settings. The ‘exotic’ chamber was operated at the same threshold, but at a somewhat lower voltage.

Test Beam Setup and Data Collection

The gas distribution rack



The stack containing nine layers within the blue hanging file structure

Test Beam Setup and Data Collection

Number of Chambers in the Stack	High Voltage in kV	Threshold in DAC Counts
8	6.2/5.9	30
		50
		70
9	6.3/6.0	30
		70
		110
		150
		210
7	6.4/5.8	30
		50
		70
		110
		150
		190
		210
8	6.5/6.2	30
		120
		210

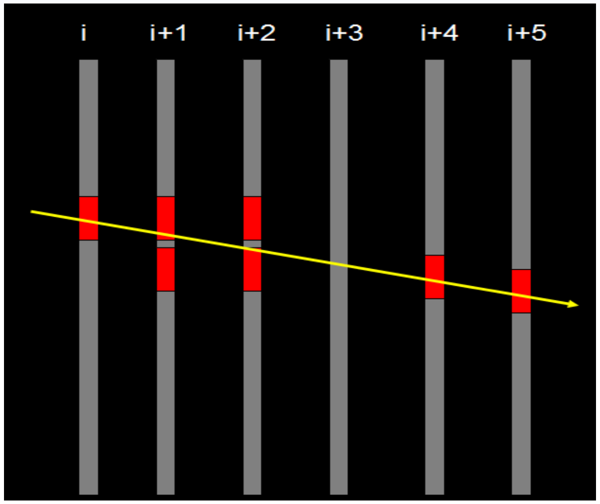
Analysis Procedures

A1 | **A2**

Rejection of events with large number of hits: Events with more than 50 hits were rejected.

Clustering of the hits in each layer: Cells that share a common side are assigned to the same cluster.

RPC	Efficiency	Pad Multiplicity
i=0	100%	1
i+1	100%	2
i+2	-	-
i+3	0%	-
i+4	-	-
i+5	-	-

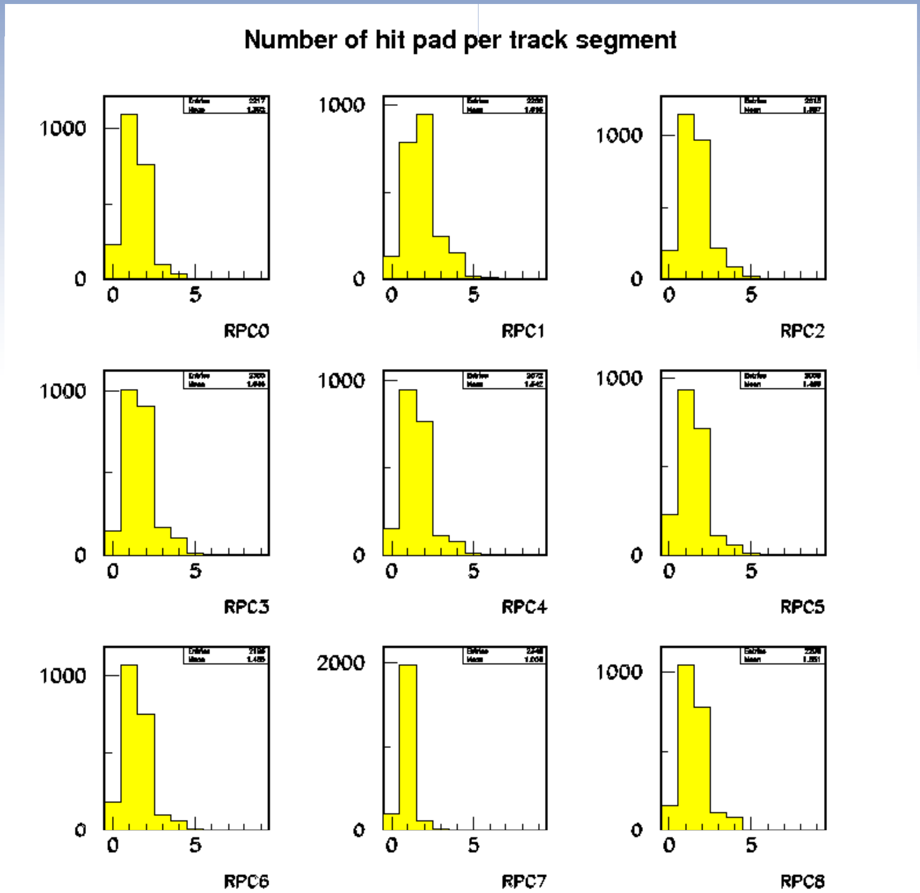


RPC	Efficiency	Pad Multiplicity
i=0	100%	1
i+1	100%	2
i+2	100%	2
i+3	0%	-
i+4	100%	1
i+5	100%	1

Cuts to avoid the readout boundaries.

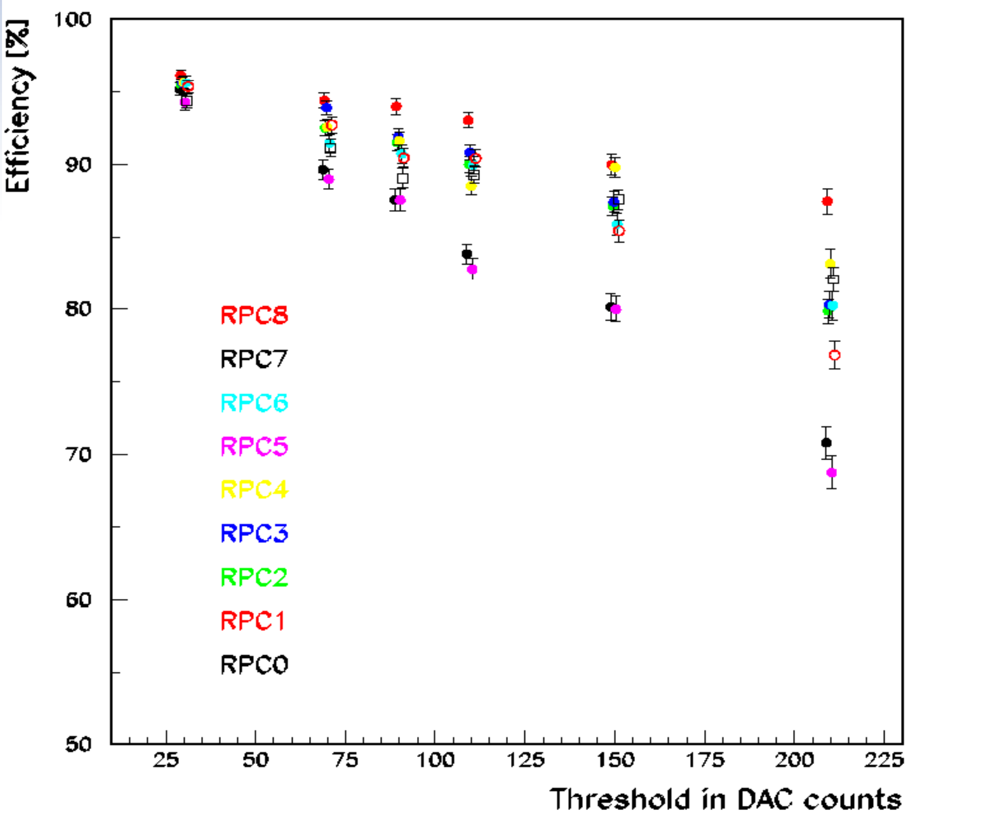
Cut associated with readout problems.

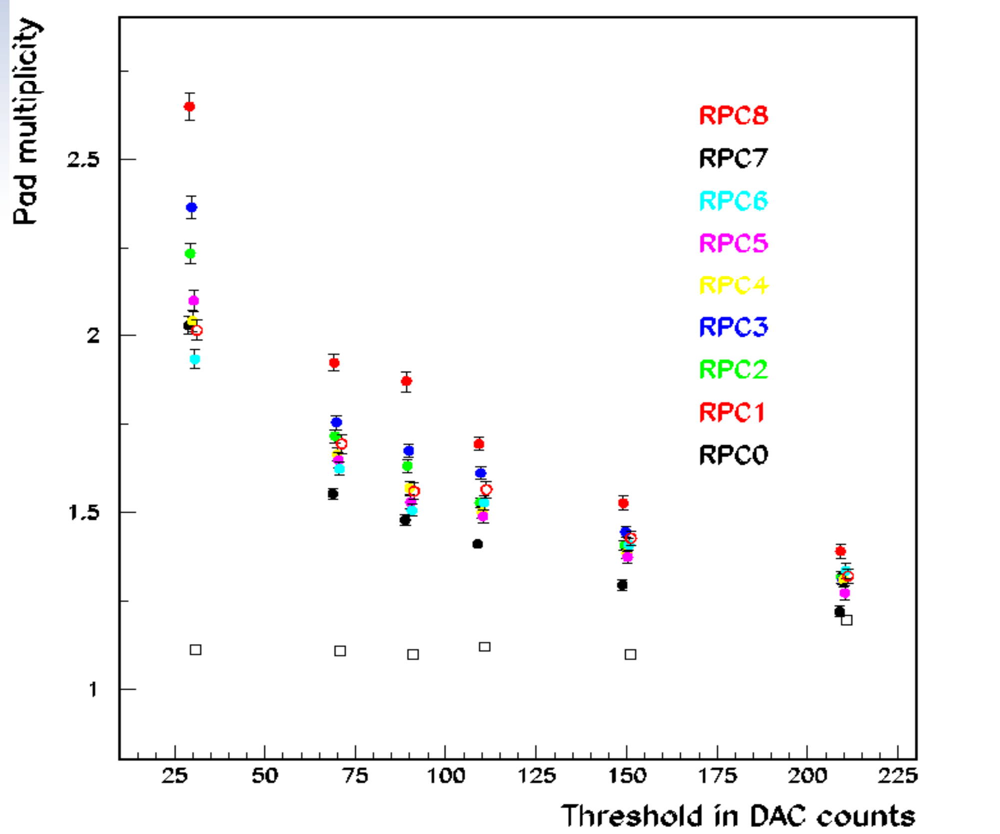
Number of Hits



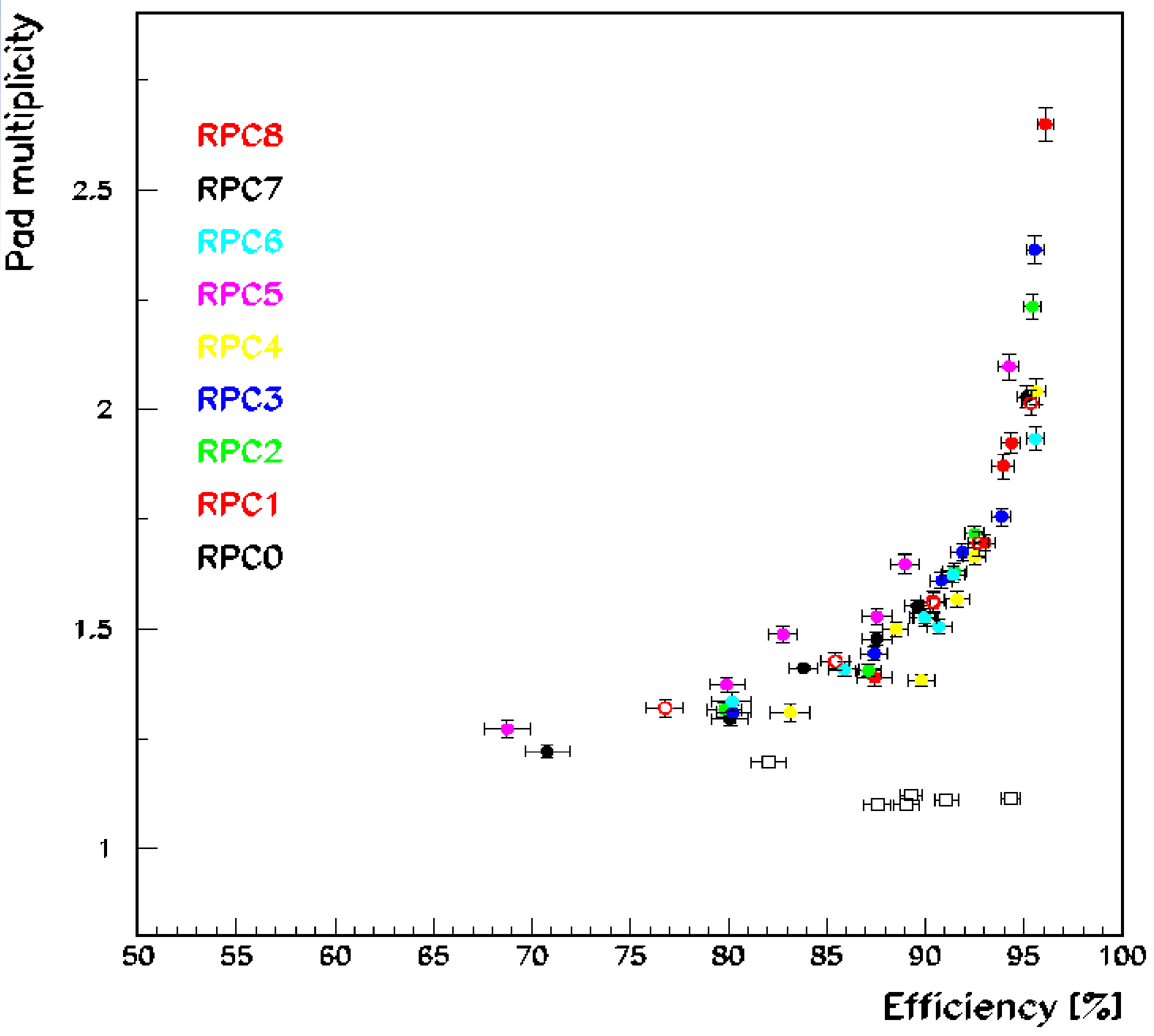
The chambers were operated with a high voltage of 6.3/6.0 kV. The threshold was set at 110 counts.

Dependence on Threshold

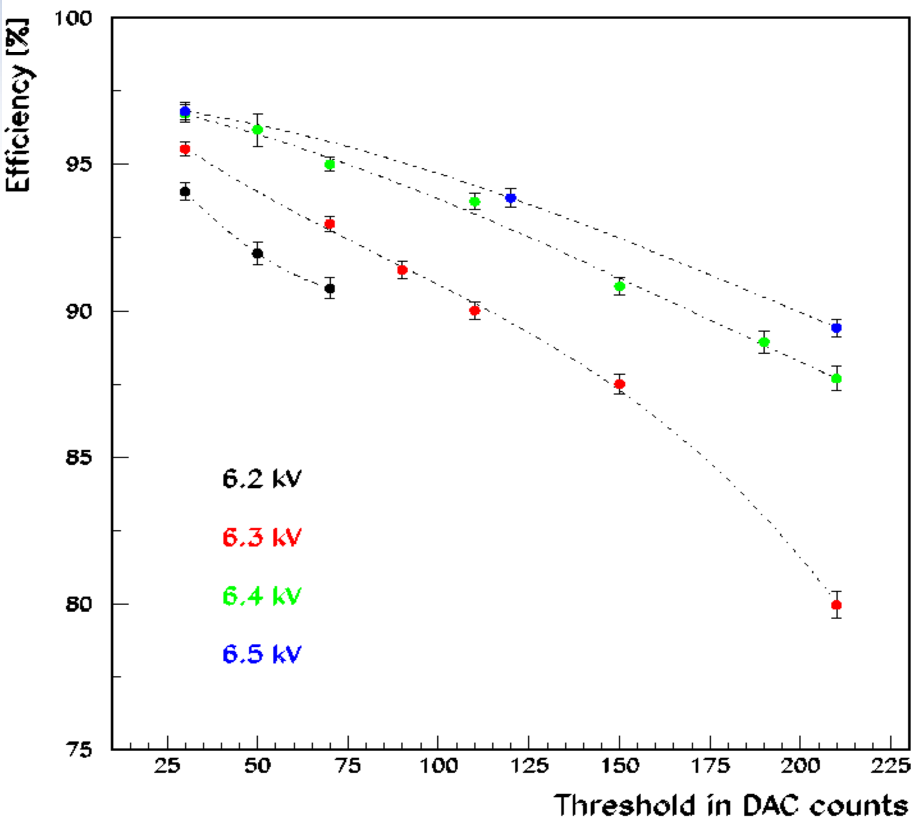


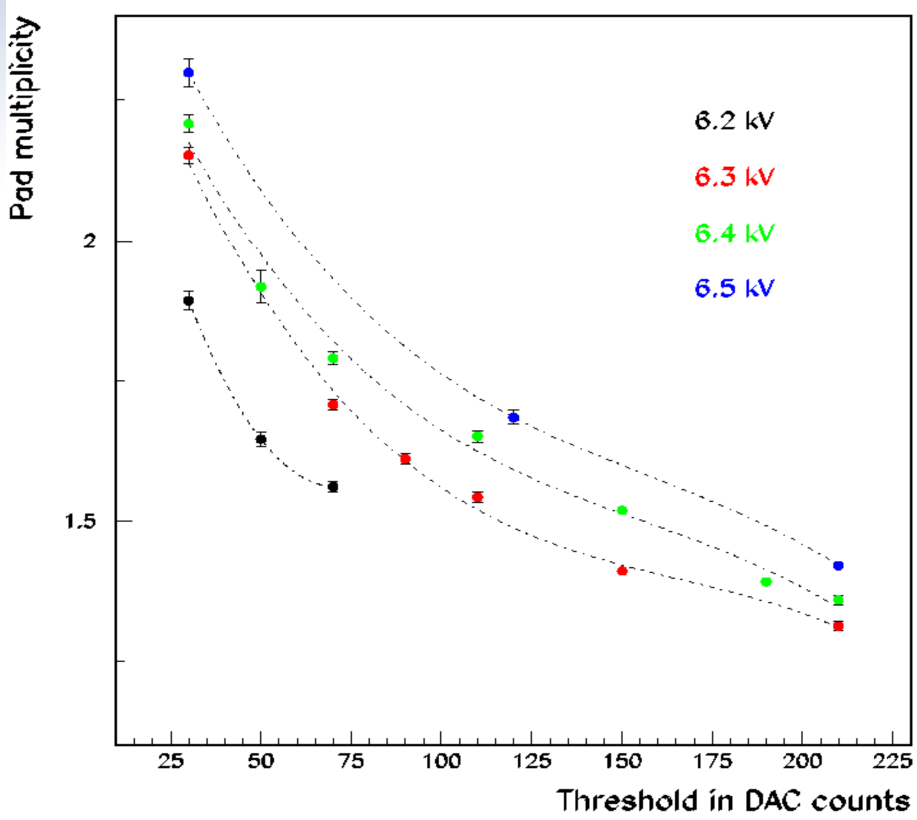


Dependence on Threshold

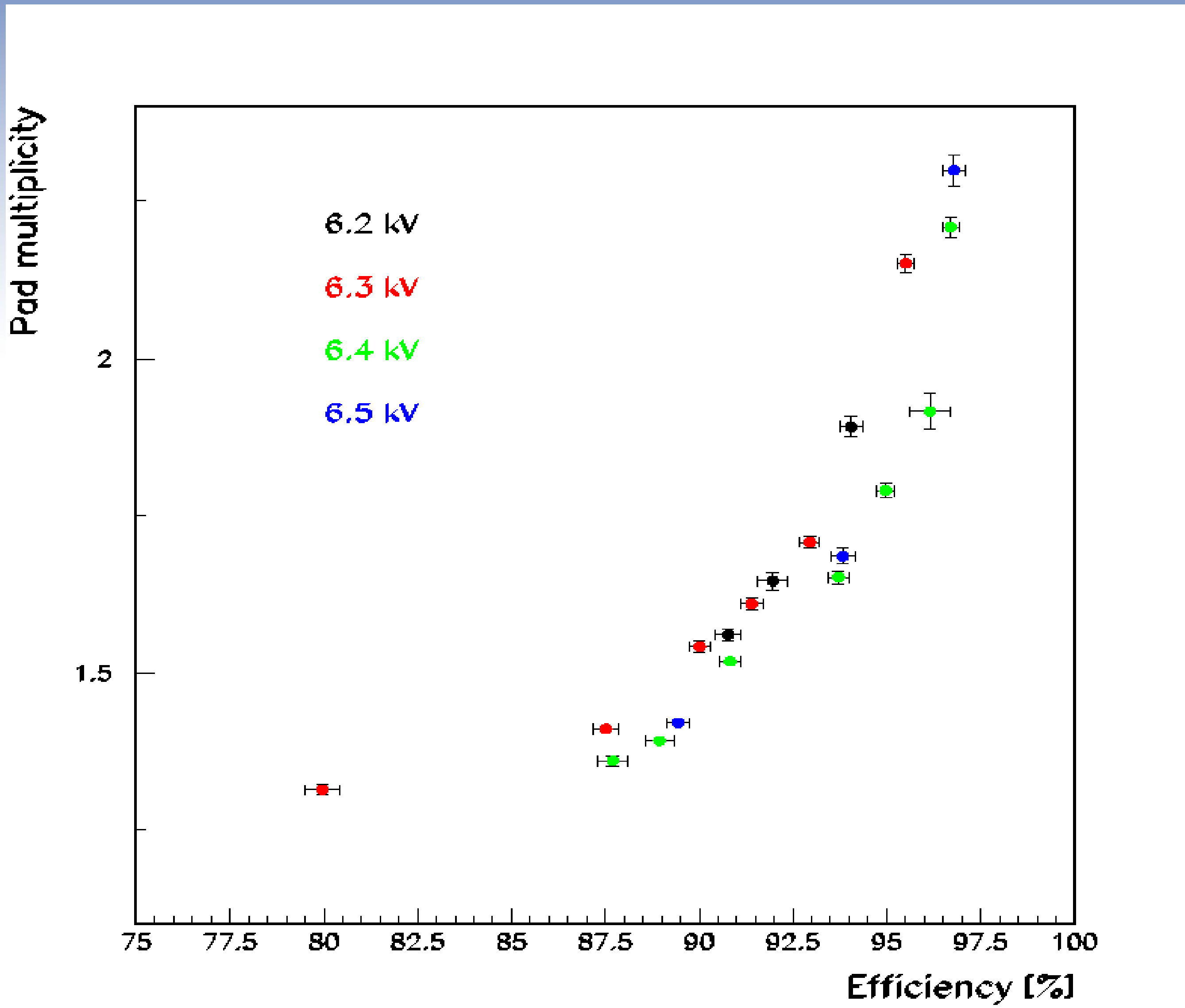


Dependence on High Voltage

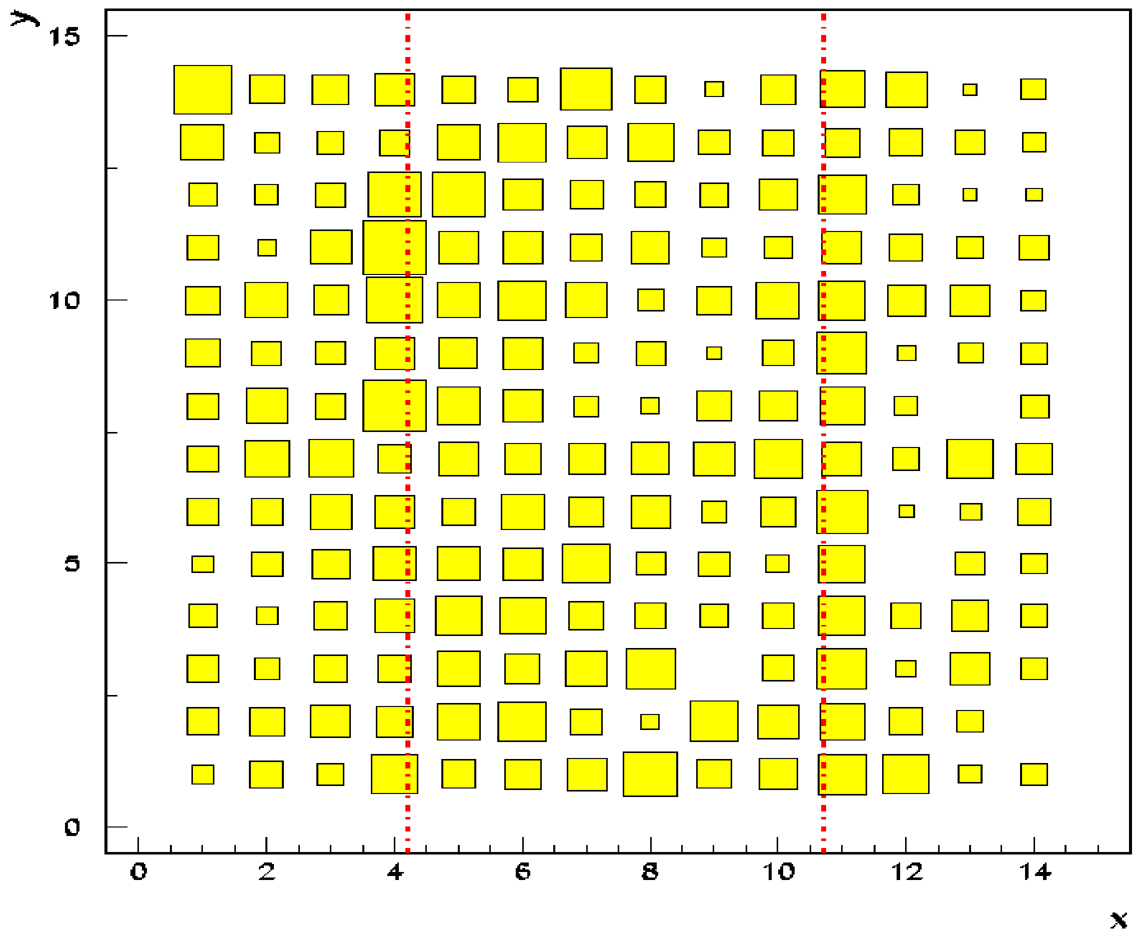




Dependence on High Voltage



x-y Map of Inefficiency



The data were collected with a high voltage of 6.3 kV and a threshold of 110 counts.

Conclusions

- **Background Noise:** Using the self-triggered mode of the front-end readout, the rate was established to be typically 0.15 Hz/cm^2. The probability of such a noise hit overlapping with a 300 ns readout window, as used in triggered mode, is negligible.

- **MIP Detection Efficiency:** Depending on the high voltage and threshold settings, efficiencies in the range between 80% and 96% were obtained using track segments reconstructed in neighboring layers. As expected the efficiency drops around the location of the two fishing lines located in the gas volume. Lower values of the efficiency observed in two of the chambers were later explained as being related to the particular grounding scheme used during the test beam data taking.

- **Pad Multiplicities:** Depending on the high voltage and threshold settings pad multiplicities between 1.2 and 2.2 were measured using track segments in neighboring layers. With the ‘exotic’ chamber pad multiplicities around 1.1 were obtained, independent of the operational conditions.

Conclusions

For a given high voltage, the pad multiplicities versus MIP detection efficiencies lie on a common curve. Operation at a higher high voltage results in a relatively larger gain in efficiency than in pad multiplicity.

Enhanced losses of efficiency are observed at the location of the fishing lines in the gas volume.

Overall, the ‘exotic’ compared to the default RPC design offers two distinct advantages: a lower average pad multiplicity and a reduced height.

In a colliding beam experiment, a RPC fine-grained digital calorimeter is largely self-calibrating, as any track segment within a hadronic shower can be used to obtain a measurement of the efficiency and pad multiplicity. This technique eliminates the need of an additional calibration or monitoring system.