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# Test of the hydrogen wire chamber PC2 developed for the MUCAP experiment

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## 1 Summary

In the course of proposal R-97-05 [1, 2] (nuclear muon capture on the proton - MUCAP experiment), we have developed a special multiwire proportional chamber (PC2) with anode and cathode strip readout. The chamber which can be operated in ultra clean hydrogen gas at 10 bar will be used for the tracking of incoming muons.

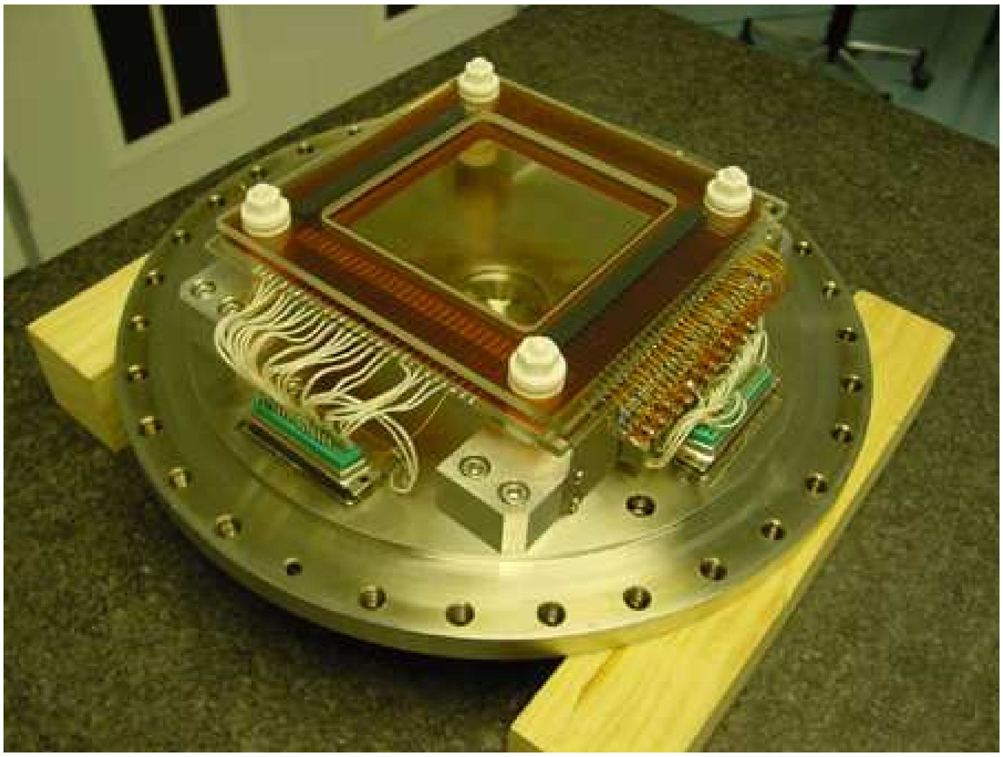

Figure 1: Photo of the fully assembled PC2 chamber mounted on the entrance flange of the hydrogen pressure tank. The plugs shown here for the signal readout were in a later phase replaced by single wire pin connectors.

Fig. 1 shows a picture of PC2 as it was used during the tests. The beam enters through a thin Havar window at the center of the flange. The chamber is entirely fabricated from borofloat glass, keramic insulators, metals and other UHV materials which can be high vacuum pumped and heated up to 130 C in order to maintain a hydrogen purity at a level of $10^{-8}$. The frame in the middle of PC2 is an anode plane on ground potential, equipped with d=25$\mu$ gold coated tungsten wires (W-Au) in vertical direction spaced 4mm. The anode frame is sandwiched between two cathode frames on negative potential, equipped with d=50$\mu$ W-Au wires in horizontal direction spaced 1mm. A view of the chamber viewed from upstream with the wire geometry is presented in Fig. 2.

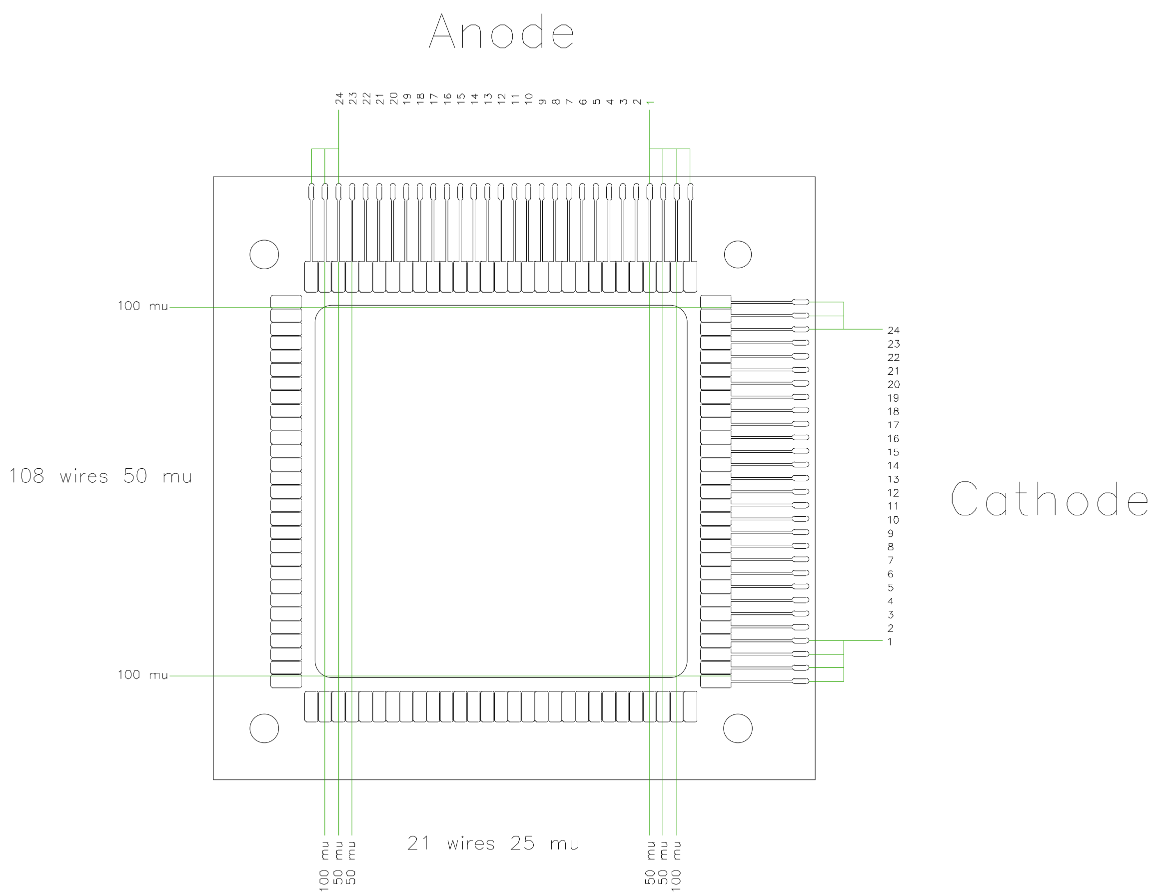


Figure 2: Wire geometry of PC2 viewed from upstream. Signals can be read out from 21 vertically positioned anode wires and from 24 horizontally placed cathode strips. Three outer anode wires on each side have larger diameters for stability reasons and give not much amplification. All outermost wires have thickness d=100$\mu$.

The signals are read out in both coordinates X-Y by making use of all wire planes: in Y direction from 21 anode wires and in X from electrically combined wires of both cathode frames. Four cathode wires are combined to one pad. This gives a 4mm spaced readout geometry in both coordinates. The total sensitive area $\Delta X \cdot \Delta Y$ of PC2 is 84mm (anodes) x 110mm (cathodes).

With an intense Sr-90 beta source the chamber was tuned and tested in the laboratory at cathode voltages up to -7.0 kV. The final performance tests were made in the $\mu$E4 beam of PSI using various incident muon momenta ($p_{\mu^+}$ = 32-73 MeV/c) with fluxes of $\sim$ 50 kHz and using a 35 MeV/c positron beam. Cathode voltages from -6.0 to -6.65 kV were applied. We have demonstrated that PC2 is at the upper voltages fully sensitive to minimum ionizing particles (electrons) traversing the chamber. Such a high sensitivity is not really needed for tracking of slow muons, however it is crucial for the development of the time projection chamber (TPC) where we will employ the same wire geometry and where a good sensitivity for electrons from the muon decay is required.

In the following chapters we discuss technical details of the chamber construction, experiences during the development and tests, and the results of our final beam studies.

# 2 Development and technical description of PC2

The PC2 hydrogen chamber will be used to define precisely the geometry of muon tracks at the TPC entrance. In combination with scintillators and MWPC's located outside the hydrogen vessel, they allow in an unambiguous way to assign to every incoming muon the correct time and track in the TPC.

This type of a hydrogen chamber was originally developed in Gatchina via several prototypes [3]. Full size chambers were also built there and tested in the muon beam at PSI during trial runs in 1998-2000 [4]. Good performance was reached during eight days of operation in December 1999, but problems with gas purity (outgasing from frames and other materials), oil contaminations, etc. caused voltage breakdowns and forced a complete redesign of the system and the chambers. To perform a real MUCAP measurement, the gas purity had to be improved by several orders of magnitude.

In 2001 a new hydrogen apparatus [2] was designed for MUCAP and constructed at PSI, with hydrogen chambers working physically according to the principles developed in Gatchina. The new chambers are fabricated from materials suitable for ultra high vacuum (UHV), i.e. with extremely low outgasing rates (no organic materials) and with the feature to heat out the system at temperatures up to 130 C.

New sets of PC2 chambers using glass frames with anode readout were manufactured in Gatchina and tested in December-01/April-02 at the PSI muon beam. It was demonstrated that the UHV proof design scheme works. Test results of the Gatchina PC2 chambers will be reported elsewhere [5].

At PSI, another UHV proof PC2 chamber was developed equipped with readout in both coordinates X-Y, in X from single anode wires, and in Y from combined cathode strip wires. Full geometrical information is provided in a sensitive region $\Delta X \cdot \Delta Y =$ 84mm x 110mm, see Figs. 1 and 2. The parameters and selections chosen for the PSI chamber are described as follows:

- The chamber consists of an anode center frame 170mm x 178mm x 2.5mm equipped with wires on ground potential. It is embedded on both sides by cathode frames 178mm x 170mm x 5mm equipped with wires at negative voltages up to 7 kV. The inner free space of the frames is 110mm x 110mm. Kapton sheets (d = 100 $\mu$) between the frames give additional electrical insulation. On each side, the cathode wires are placed in 3.5mm distance to the anode plane.

- The frames are fixed on poles with screws and washers, all made from special keramic material (Fig. 1).
- The frames are manufactured from borofloat glass polished with high mechanical precision ($\pm 0.01$mm). This material has a very low thermal expansion coefficient ($3.3 \cdot 10^{-6}\mathrm{K}^{-1}$) adjusted to that of the tungsten wires ($4.5 \cdot 10^{-6}\mathrm{K}^{-1}$). This choice prevents large changes of wire tensions during the heating process.
- For attaching the wires our technique with point welding onto an $80\mu$ Cu-Au layer was not successful, because the thermal stress of expansion during the heating ripped the coating layers off the glass surface.
- The soldering technique onto much thinner metal layers worked better: the glass frames are specially coated on the designed conduction areas by a $0.5\mu$ Ti-Au layer and by a $2\mu$ gold coated Ni layer on top of it. This method allows repeated soldering of wires under mechanical tension and heating to 130 C without loosing the tensions or ripping off the coatings.
- For the anode frame W-Au wires with diameter d=$25\mu$, spaced 4mm were soldered under tension F=0.8 N. For the cathode frames W-Au wires with d=$50\mu$, F=1.2 N and 1mm spacing were chosen. The outermost wires are made thicker (d = 50 to 100 $\mu$) in order to avoid HV instabilities at edges.

Fig. 2 gives a detailed layout of the PC2 wire geometry.

# 3 Laboratory studies of the PC2 performance

After the soldering the frames were cleaned in an ultra-sound water bath and carefully inspected wire by wire under the microscope for any small defects or dust particles. Deviations from a smooth surface were removed. The full PC2 was assembled in our clean room and mounted in the MUCAP pressure tank. After one week of evacuation and heating at 120 to 130 C a vacuum of $< 10^{-7}$ mbar was reached at room temperature. Even after closing the high vacuum valve a vacuum pressure below the $10^{-4}$ mbar level could be maintained for one week. This level is $10^{-8}$ of the operation pressure 10 bar, satisfying the requirements for maintaining a clean hydrogen filling. The mass spectrometer analysis showed as main components of the residual gas $H_2O$, $H_2$ and CO molecules. The presence of hydrocarbons was negligible.

Cathode voltages up to -7 kV were applied in the laboratory, and the chamber was irradiated with a 1 mCi Sr90 beta source from outside through the beam window. Dark and induced currents were measured with nA precision via a shunt resistor on the high voltage side. The analogue signals from single anodes and cathodes were read out via preamplifiers and amplifiers and studied on storage oscilloscopes.

One crucial problem which had to be solved was to make with every anode wire a perfect connection to ground. Without clean grounds we observed frequent discharges. The solution to this problem was to crimp onto each signal line its individual clip and to attach it onto the pins of the ceramaseal plugs in the flange.

A second problem was the wire stability at the edges. In order to keep a stable high voltage, edge wires of larger diameters had to be chosen (anodes $1\times100\mu$, $2\times50\mu$; cathodes $1\times100\mu$, see Fig. 2). No wires were mounted directly above the glass or at the inner edges of the frames.

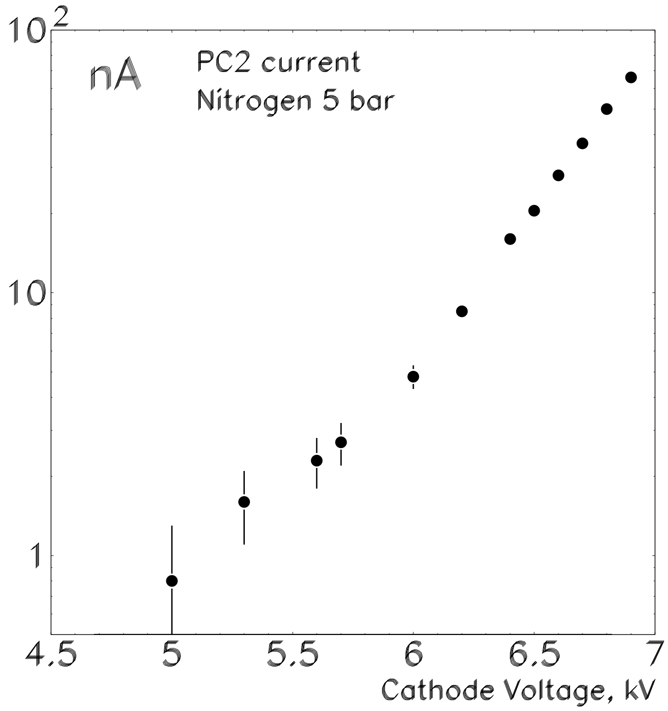


Figure 3: PC2 currents induced by the Sr-90 beta source plotted versus cathode voltage. The chamber was operated in nitrogen gas of 5 bar pressure.

A laboratory test program was performed in four steps:

(1) The pressure vessel was filled with 10 bar nitrogen. At this pressure the gas amplification of charges from ionizing particles passing PC2 was even at 7 kV below 1 nA, and no pulses from the beta source were observable. This operation mode is ideal to test the static high voltage stability of the chamber. During formation of the high voltage, care was taken to keep dark currents at or below the 10 nA level. The tripping level of the HV power supply was set to $4\mu$A. 7 kV was reached after 2 days of forming and maintained one day.

(2) The nitrogen pressure was reduced to 5 bar. At this pressure the chamber produces approximately the same signal amplifications as in 10 bar hydrogen. The chamber was tuned up to -7 kV and the characteristics of signals and Sr-90 induced currents registered, see excitation curve Fig. 3. At induced currents which exceeded 70 nA, the chamber switched into a "discharge" operation mode. In this mode dark currents of typically one to several $\mu$A (depending on the cathode voltage) appeared on "hot" wires, and the general noise level increased significantly. It turned out that the chamber needs to be carefully and slowly formed to

| beam setting | momentum p MeV/c | dE/dX in $H_2$ MeV/(g/cm$^2$) | run nr. | PC2 HV kV | current nA (dark) |
|---|---|---|---|---|---|
| 32p.set | 32.0 | 59. | 3 | -6.25 | |
| 32p.set | 32.0 | 59. | 20 | -6.00 | 18 (2) |
| 37p.set | 37.0 | 26. | 2 | -6.25 | |
| 37p.set | 37.0 | 26. | 19 | -6.00 | 12.5 (2) |
| 47p.set | 47.0 | 16. | 4 | -6.25 | |
| 47p.set | 47.0 | 16. | 18 | -6.00 | 9.3 (2) |
| 73p.set | 73.0 | 8.6 | 5 | -6.25 | |
| 73p.set | 73.0 | 8.6 | 15 | -6.50 | 5.5 (2.5) |
| 73p.set | 73.0 | 8.6 | 16 | -6.65 | 7 (3.5) |
| 73p.set | 73.0 | 8.6 | 17 | -6.00 | 2 (1) |
| 35_eplus.set | 35.0 e | 4.3 | 7 | -6.25 | 10.5 |
| 35_eplus.set | 35.0 e | 4.3 | 8,9,10 | -6.50 | 60,39,30 |
| 35_eplus.set | 35.0 e | 4.3 | 12 | -6.50 | 9 (2.5) |
| 35_eplus.set | 35.0 e | 4.3 | 13-acc | -6.50 | |
| 35_eplus.set | 35.0 e | 4.3 | 14 | -6.50 | 26 (2.5) |
| beam off | - | - | 11 | -6.50 | (3) |

Table 1: Run parameters of the PC2 chamber tests. The muon momenta are given for incident particles at the channel window - the dE/dX values are calculated energy losses for muons at the PC2. The currents are given with beam on - in brackets with beam off.

high voltage during several days. With too fast powering, the chamber switches already at lower voltage to the discharge mode.

(3) After successful operation in nitrogen, the pressure vessel with PC2 was evacuated and heated up to 120-130 C for several days until a vacuum pressure $\leq 10^{-7}$mbar was reached. The mass spectrometer showed the usual residual gas components $H_2$, $H_2O$, CO as before.

(4) The pressure tank was filled with 10 bar clean hydrogen gas of purity $10^{-6}$ and the chamber tuned up to -6.7 kV. At this voltage the observed anode signals from the $Sr^{90}$ source were found to be greatly above the noise level.

# 4 Tests in the $\mu$E4 beam

On 19-21 June 2002, our apparatus (pressure chamber with PC2 under 10 bar hydrogen pressure) was positioned in the beamline of area $\mu$E4.

Two plastic scintillator counters were mounted in front of the entrance window: a 100x100x5 mm$^3$ veto counter with a 36 mm hole in the center, and a 40x40x0.5 mm$^3$ trigger counterr placed behind the hole. This arrangement provided the trigger for the chamber data aquisition (DAQ) system and was also a good beam monitor.

Muon fluxes of $\sim 5 \cdot 10^4 \mu^+ s^{-1}$ were tuned to go through the hole of the veto counter with various muon momenta ranging from 32 MeV/c up to 73 MeV/c, providing at the chamber various energy deposits per unit length, as listed in table 1. The momentum 32 MeV/c was calculated to be such that the muons just pass the PC2 chamber and stop in the hydrogen space behind PC2 where the TPC will be mounted in the final MUCAP setup.

With another tune, a pure positron beam of momentum 35 MeV/c was made consists of minimum ionizing particles. With this beam one can simulate the electrons/positrons from muon decay and thus estimate the future performance of the TPC, which must be sensitive to both slow muons and electrons. The approximate positron flux was around 100 kHz. It was not determined precisely because of some inefficiencies of the trigger counter for minimum ionizing particles.

Table 1 gives a summary of the various tunes, beam momenta, calculated energy losses in hydrogen at the location of PC2, run numbers, applied PC2 voltages and observed chamber currents (in brackets the dark currents without beam). In the following subchapters the analysis of these measurements is presented.

## 4.1 Gas amplification

With a 50 kHz beam of 32 MeV/c muons, we measured a current of 16 nA delivered by the power supply. The muons have in the chamber a calculated energy loss of

$$\mathrm{dE/dX} = 59.8\ \mathrm{MeV/(g/cm^2)}\ .$$

In 10 bar $H_2$ (density: 0.899 mg/cm$^3$), we get dE/dx = .0538 MeV/cm. In $H_2$ gas, an energy of 37 eV is necessary to produce an ion pair. We finally get 1454 $e^-$/cm. With 50 kHz muons passing the chamber, this represents a current of $1.16\mathrm{x}10^{-11}$A for a track length of 1 cm. This yields a gas amplification of

1376 at -6 kV chamber voltage.

The same calculation was made for the other chamber voltages used in this run. The resulting amplification factors and the produced electrons per cm are plotted in Fig. 4. The positron value on the bottom histogram of Fig. 4 is plotted as the last point at 100 MeV/c.

## 4.2 Noise levels

The anode signals were measured with an AD811 (8 channels) which is peak sensitive. The noise level was found to be $\sigma_{anode} = 5$ mV .

The cathode signals were measured with LRS 2249W units (28 channels) using 400 ns time gates. The noise level was found to be $\sigma_{cathode} = 2.5$ pC .

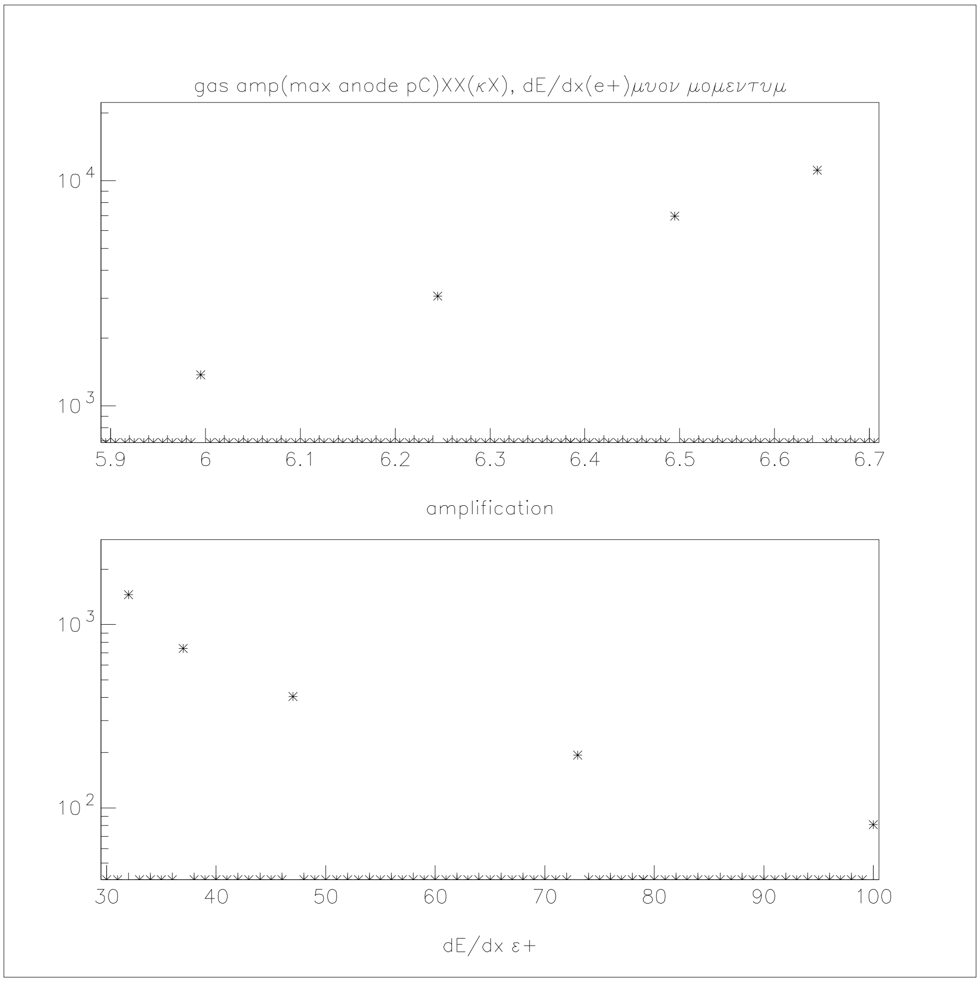


Figure 4: top: evaluated gas amplification factors plotted versus PC2 chamber voltage (kV) - bottom: electrons produced per cm in 10 bar $H_2$ gas plotted versus channel momentum (MeV/c).

## 4.3 Muon pulse height distributions

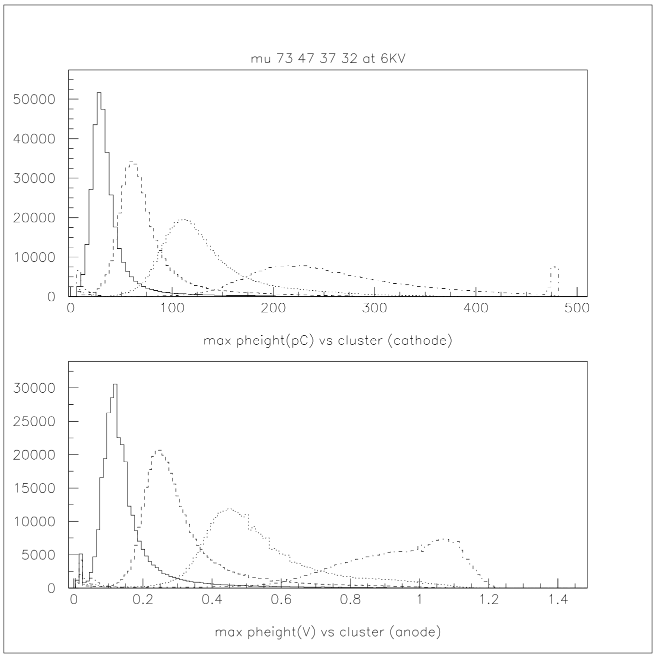


Figure 5: top: pulse height distributions of the cathode wires for various incident muon momenta - bottom: anode pulse height distributions. Cathode voltage -6.0 kV

Fig. 5 shows the evaluated pulse height distributions for muons of various incident beam momenta (73, 47, 37 and 32 at -6 kV cathode voltage). The lower the momentum, the higher are the energy deposits and the pulse heights. The top picture gives the measured cathode pulse integrals on the LRS 2249W (50 Ohm input) in pC. For each event the highest cathode pulse is used for the plot. The bottom picture shows the same for the anode signals. The saturation at $\sim$1 V comes from the preamplifier.

Fig. 6 shows the pulse height spectra as before, but for various chamber voltages. The muon momentum is fixed to 73 MeV/c. This corresponds to about twice the pulse height of minimum ionizing particles.

Fig. 7 makes a comparison of the measured pulse heights for 35 MeV/c (minimum ionizing) positrons with 73 MeV/c muons.

## 4.4 Histogram Show

Two groups of histograms covering all details of our analysis are given in separate files:

(a) file PC2-mu47.eps: 47 MeV/c $\mu^+$ measured at -6.25 kV chamber voltage. This situation corresponds approximately to a measurement of 32 MeV/c "stopping" muons

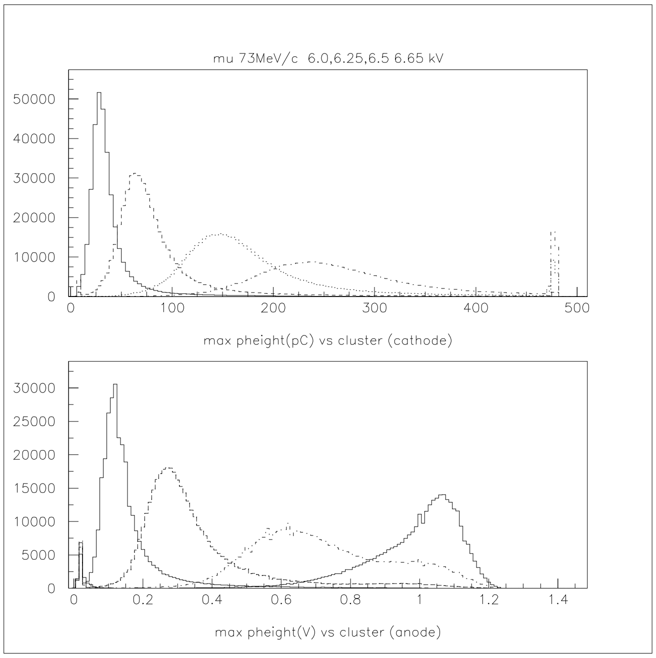


Figure 6: Pulse height distributions of 73 MeV/c incident muons for various cathode voltages, top cathodes - bottom anodes.

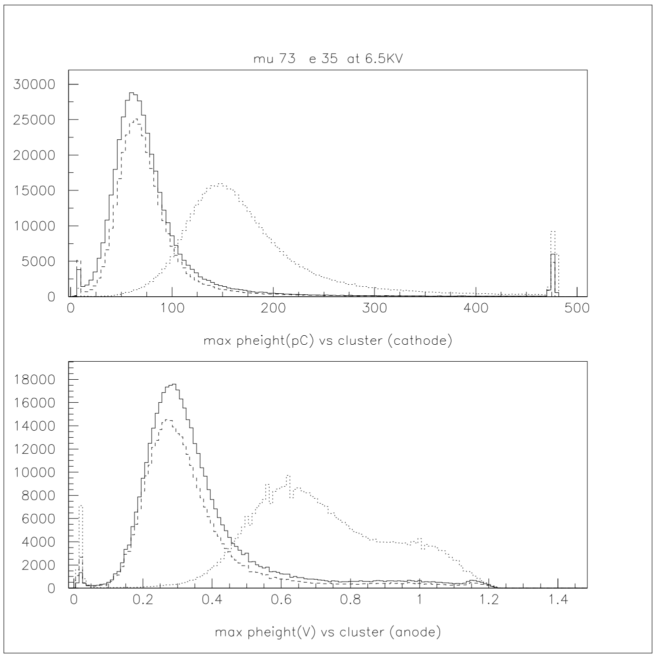


Figure 7: Comparison of 73 MeV/c $\mu^+$ pulse height distributions with that of minimum ionizing positrons. Both were measured at -6.5 kV chamber voltage, top cathodes - bottom anodes.

at -6.0 kV which is the foreseen "nominal" operating point in the MUCAP experiment.

(b) file PC2-e35.eps: 35 MeV/c positrons at -6.5 kV chamber voltage. This situation indicates what can be expected from the TPC for electron detection at this voltage. Of course, the data have to be scaled with the length of charge collection which is 7 mm in PC2. The charge collection in the TPC can vary in length from 1 mm (vertical tracks) to many cm (horizontal tracks along the wire direction).

Each histogram group presents on 6 pages a number of variables:

page 1 (top): wire hit distribution (wire0: cathode, wire1: anode)
page 1 (bottom): cluster distribution (calculated as center of mass of compact group of wires)
page 2 (top): number of clusters per event
page 2 (middle): cluster size (typically 4-5 for cathode)
page 2 (bottom): number of wires per event
page 3 (top): two-dimensional distribution of the integrated cluster pulses per event as a function of position
page 3 (bottom): two-dimensional distribution of the highest pulse per event as a function of position
page 4 (top): projection of distribution page 3 (top) on y axis
page 4 (bottom): projection of distribution page 3 (bottom) on y axis
page 5: correlation between anode and cathode pulse height
page 6: two-dimensional distribution of the hits for events with only one cluster for anode and cathode.

Remark: The run with 35 MeV/c positrons had a larger rate than originally expected. For this reason one anode wire became hot (anode 1 on the top spectrum page 1 and bottom spectrum page 3. This had practically no influence on any of the other variables. The effect disappeared with reduced positron rate.

# References


[1] D.V. Balin et al., *"High Precision Measurement of Singlet $\mu p$ Capture in $H_2$ Gas"*, proposal R-97-05.1, PSI (1996), unpublished.

[2] V.A. Andreev et al., *"Precision Measurement of Singlet $\mu p$ Capture in a Hydrogen TPC"*, technical proposal R-97-05.2, PSI (2001), unpublished.

[3] V.A. Andreev et al., *"Study of MWPC performance in 10 bar $H_2$ gas"*, int. Gatchina report (1997), unpublished.

[4] V.A. Andreev et al., progress report to PSI proposal R-97-05, PSI (2000), unpublished.

[5] V.A. Andreev et al., to be published (Gatchina).