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Report on the Progress for the $\mu \to e\gamma$ Experiment at PSI

Collaboration for $\mu \to e\gamma$ Experiment at PSI

This document reports on the progress made in preparation for the $\mu \to e\gamma$ experiment at PSI after the approval of its proposal "Search for $\mu^+ \to e^+\gamma$ down to 10^{-14} branching ratio" [1] in July 1999. The report concentrates mainly on the developments of the liquid xenon photon detector, but also describes the progress of the positron tracker and timing counter.

1 Photon Detector

1.1 Timing resolution of small prototype

Timing resolution of the liquid Xe photon detector has been studied using the small prototype described in detail in Ref [1]. In addition to the ADCs to measure energy resolutions, high precision leading edge discriminators [2] and high-resolution TDC [3] with 25 psec least count have been introduced in the data taking system. The NIM discriminator module consists of 8 independent 300 MHz comparators. A γ-ray source of ^{88}Y and an α source of ^{241}Am are placed just outside the sensitive volume of the detector. Calibration and monitoring of photomultipliers (PMTs) were done using the signals from the α particles and LED light fed into the detector through optical fibers.

In the analysis the position of a gamma interaction is estimated by weighting the positions of the PMTs with their individual pulse heights. The γ interaction position is required to lie within a central region of 2cm $\times$ 2cm $\times$ 2cm. The PMTs are then divided into two groups by the x-z plane and in each group an average of the times measured by the TDC is calculated after ADC correction for each PMT. Timing resolution is estimated by taking the difference between the averages in two groups. Fig. 1 shows the timing resolutions as a function of number of photoelectrons. Several cases are shown for various numbers of PMTs used in the estimation. It can be seen that the timing resolution improves as $\sim 1/\sqrt{N_{\rm pe}}$ as the observed number of photoelectrons ($N_{\rm pe}$) increases. It is not straightforward to extrapolate this result to the 52.8 MeV gamma ray, since the number of PMTs involved and numbers of photoelectrons observed by individual PMTs are quite different from this small prototype. A simple extrapolation, however, indicates that a resolution of 100 psec (FWHM) is reasonably expected for a 52.8 MeV gamma ray.

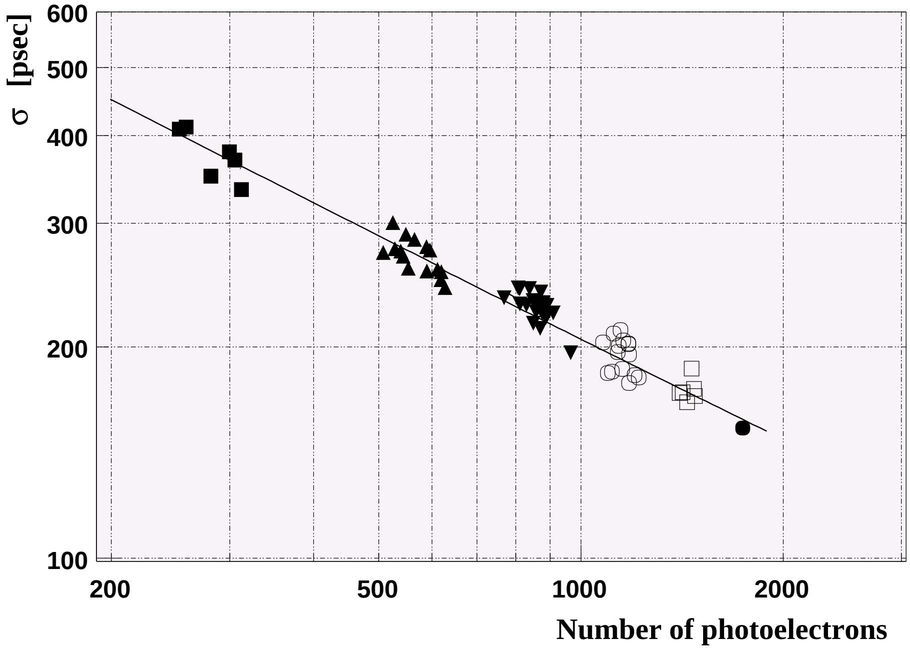

Figure 1: Timing resolution as a function of observed number of photoelectrons

1.2 Simulation of photon detector

A realistic geometry of the photon detector has been implemented in the detector simulation code. The curved structure, the positions of the PMTs and the material around and before the PMTs were simulated as realistically as possible.

The position resolutions obtained using the new simulation code turned out to be identical to those written in the proposal. This is no wonder, as the positions are determined by the local distributions of the PMT outputs around the photon incident position and the curved structure does not affect them in a significant way.

Using the new simulation code, the energy resolutions, with no scintillation light attenuation (i.e. the attenuation length longer than 1 meter) but with Rayleigh scattering (the scattering length of 30 cm), are also in good agreement with those written in the proposal. If it should happen that the light attenuation length be about 1 meter or shorter, corrections of the measured energy would need to be made according to the conversion point. These corrections are different for the realistic structure and the rectangular structure used in the proposal, since the solid angles of the PMTs seen by the conversion point are generally different for these two cases. Algorithms to make these corrections are currently being optimized. To clarify this issue, the attenuation length in liquid Xe must be actually measured; this is one of the most important subjects to be studied with the large prototype.

1.3 Development of a gas calibration system

It is important to establish a reliable method for testing and calibrating PMTs before constructing the photon detector. For this purpose it is proposed in Ref [1] to use gas Xe instead of liquid since it is much easier to handle. A prototype system has been developed to investigate the feasibility of this method. The system consists of a vessel filled with gas Xe and a movable

α source controlled from outside. The vessel is equipped with a liquid nitrogen cooling pipe so that the gas and PMTs can be cooled down to $-100°$C. Several test runs were performed at a room temperature with 6 PMTs. The α source was moved at 1cm and 1mm intervals. From the distribution of the pulse heights of the individual PMTs the position of the α was reconstructed. The spread of the positions is about 3.2 mm which mainly comes from the range of α particles in the gas. By subtracting the contribution the r.m.s. accuracy of the position determination is estimated to be 2.2 mm.

1.4 Further development of photomultipliers

The current version of the PMT (R6041Q) has proved to operate stably in liquid Xe for more than hundreds of hours. However, its metal channel dynodes, which make the PMT very compact, does not have a very high transmission efficiency of photoelectrons to the first dynode. By introducing a focusing dynode structure, we will improve the transmission efficiency by 12%. A new model will be delivered by spring 2000. The modification of the dynode structure also helps to facilitate the construction of the PMT, which saves production cost.

On lateral and back sides of the photon detector, where the length of the PMT is not a critical issue, we consider using PMTs with an ordinary dynode structure such as a linear focusing type which have better quantum efficiency and transmission probability.

1.5 R&D on cryogenics for liquid Xe

Conventionally liquid nitrogen has been used to liquefy and recondense xenon gas for high energy physics experiments. However, this method wastes liquid nitrogen and the handling of the cryogenic fluid might be troublesome for a long operation of an experiment. Recent developments in cryocooler (small mechanical refrigerator) provide a better alternative: a pulse tube refrigerator. It is easy to handle and has no moving part in low temperature region. The vibration at the cold part is therefore negligibly small, making a long term operation stable and reliable.

We have investigated the possibility to use the pulse tube refrigerator for the cryogenics system of the photon detector. A small commercially available pulse tube refrigerator, PR-111, made by AISIN Corp., Japan, was used for preliminary tests. It is originally designed to work efficiently at ∼80K (cooling power of 5W at 87K).

We first checked that the pulse tube refrigerator can keep its cooling power even at the liquid xenon temperature (165 K). A cold head of 25 mm diameter was installed in a vacuum insulated glass dewar of a few liters volume. A copper block equipped with a 20 Ω electric heater and a platinum temperature sensor was attached to the cold head. The glass dewar was then evacuated to a pressure below 5 mPa. Cooling power was measued at various temperatures by changing heater power. The results are shown in Figure 2. It was confirmed that the cooling power remains sufficiently high at around 165 K.

We then liquefied xenon gas with this pulse tube refrigerator. Figure 3 shows the xenon liquefaction test system. Fifty liters of pure xenon gas (99.995% purity) was used for this test. A heat exchanging fin was attached to the cold head to enhance heat transfer efficiency between xenon gas and the cold head. About 10 minutes after switching on the compressor, liquid xenon

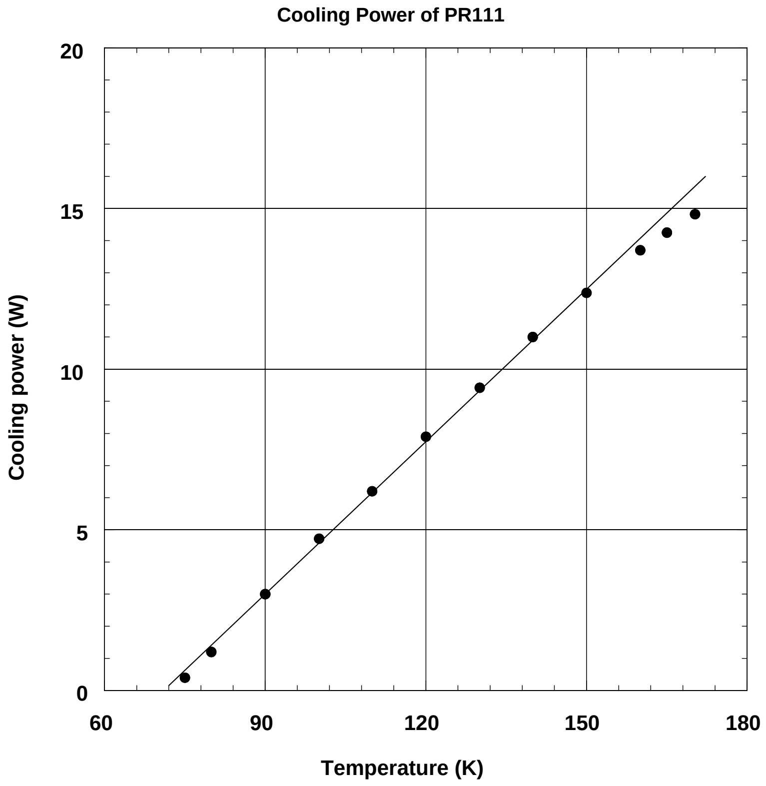

Figure 2: Cooling power of PR111

appeared on the surface of the copper fin. Liquid Xe of 70 cc accumulated in the dewar at a rate of 90 cc/hour. After the liquefaction the temperature of the cold head was kept at 165 K by the LakeShore temperature controller, Model 330. Temperature was well controlled within $\pm$ 0.1K for an hour. The pressure inside the dewar also remained stable.

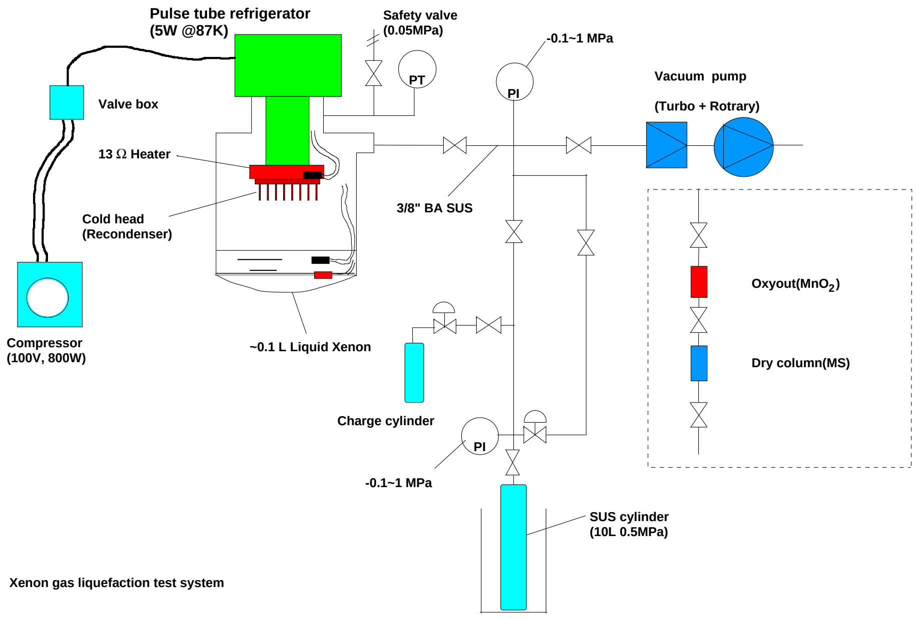

Figure 3: Flow diagram of xenon liquefaction test system

This exercise confirmed that a pulse tube refrigerator can be used for liquefaction of Xe. A pulse tube refrigerator with much higher cooling power is under development.

The PMT immersed in the liquid Xe of the photon detector dissipate heat from their small tip resistors in the bleeder circuit. It is necessary to investigate how much the heat affects the temperature homegeneity in the liquid Xe volume.

To obtain basic information on heat transfer characteristics in liquid Xe, a thin platinum wire of 0.1 mm diameter and 30 mm effective length was immersed in liquid Xe. The wire works as both an electric heater and a temperature sensor, since the resistivity of platinum has a high temperature coefficient. The amount of critical heat flux for natural convection, nucleate boiling and film boiling were experimentally measured. The relationship of heat flux, q in W/m^2, and temperature difference between the wire and the liquid, ΔT, is plotted in Figure 4.

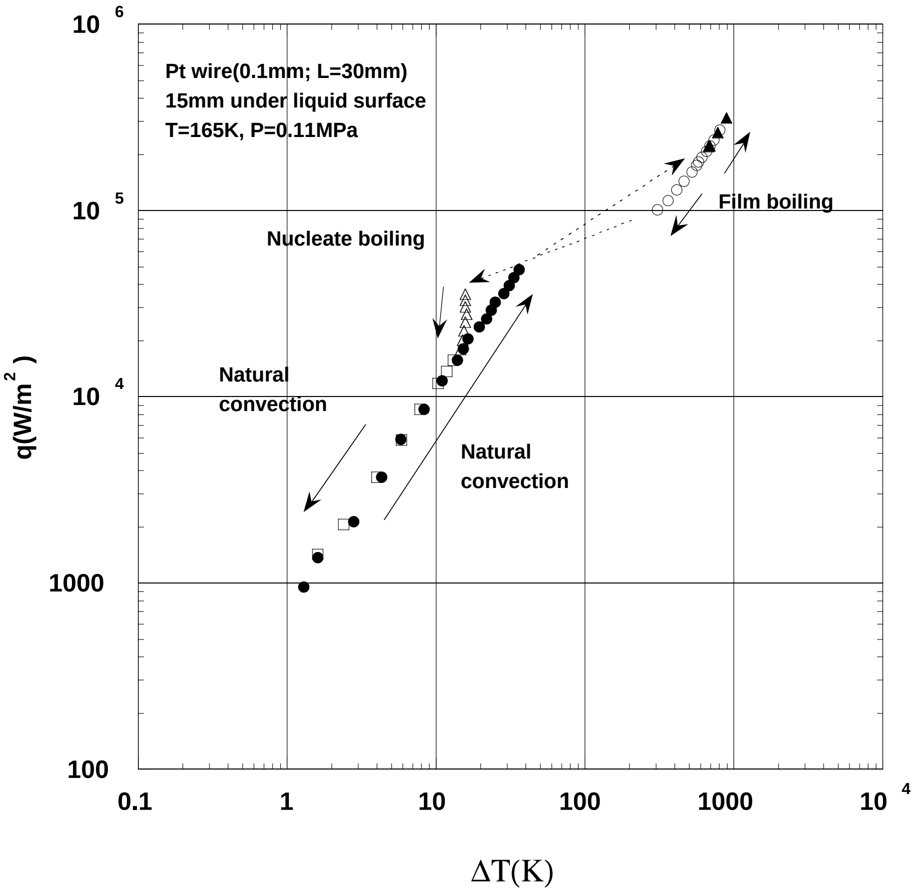

Figure 4: Boiling heat transfer characteristics of liquid Xe

In this experimental configuration bubbles were formed when heat flux exceeded about 14000 W/m^2. A more realistic simulation of heat dissipation from an actual PMT was done by immersing the same tip resistor (3.2 mm $\times$ 1.6 mm) as used for the PMT and heating it up in liquid Xe. Bubbles were formed on the surface of the resistor when heat flux reached 18000 W/m^2. Electric current was increased until many bubbles came out. Bubbles faded away when the heat flux was decreased to 10000 W/m^2. In an actual PMT operation the maximum heat flux from the tip resistor is expected to be below 5000 W/m^2. The above results imply no bubble production in liquid Xe at the expected operation mode of PMTs.

More detailed studies on heat transfer characteristics will be done by using platinum wires with different diameters and a copper plate with a wide flat surface area. The results on the heat transfer characteristics will be used for simulation of the temperature distribution in the large Xe volume of the photon detector.

1.6 Large prototype

Tests with the small prototype described in the proposal [1] are limited to a low γ energy region because of its limited volume. A prototype of a larger size is necessary to demonstrate the performance of the photon detector for a 52.8 MeV photon from $\mu \rightarrow e\gamma$ decay. We are now designing a large prototype detector and plan to start various test measurements at the beginning of the year 2001. We intend to use the γ beam produced via inverse Compton scattering at the TERAS electron storage ring of Electrotechnical Laboratory (ETL) in Tsukuba, Japan.

TERAS stores electrons up to 300 mA with their maximum energy of 800 MeV. Photons emitted from a laser of λ=256 nm collide head-on with the electrons as shown in Fig. 5. Gamma rays of energies up to 40 MeV can be delivered at a rate of 500–1000 Hz. Energy resolution of the detector will be derived by measuring the spread of the Compton edge, which has an intrinsic spread of less than 1%. With a proper collimator setup, the position resolution will be also evaluated.

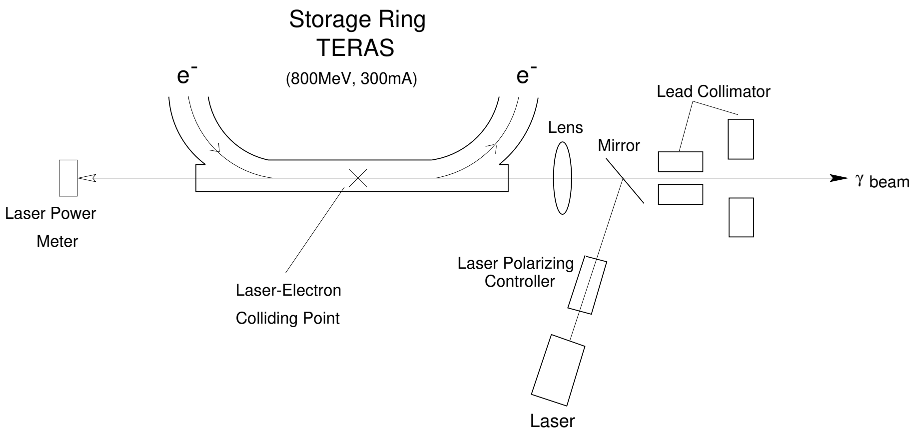

Figure 5: Laser Compton facility at TERAS of ETL

We will examine not only the performance of the liquid Xe photon detector but also various elements necessary to build the final detector, such as a Xe liquefaction system, with the large prototype detector.

Fig. 6 shows a present design of the large prototype. A total of 264 PMTs are placed inside the liquid Xe container. A honeycomb structure will be used on the front side of the liquid Xe container just like the full scale detector for the $\mu \rightarrow e\gamma$ search. The outer vessel has a thin window for the gamma beam. By placing additional materials in front of the window the effects of the material on the energy and position resolutions can be studied.

For calibration of the PMTs during data taking, α sources will be placed inside the liquid xenon volume.

Fig. 7 shows the support structure for the PMTs on the front wall. An array of PMTs are plugged into the holes of a long rectangular G10 frame. The PMT is fixed to the frame

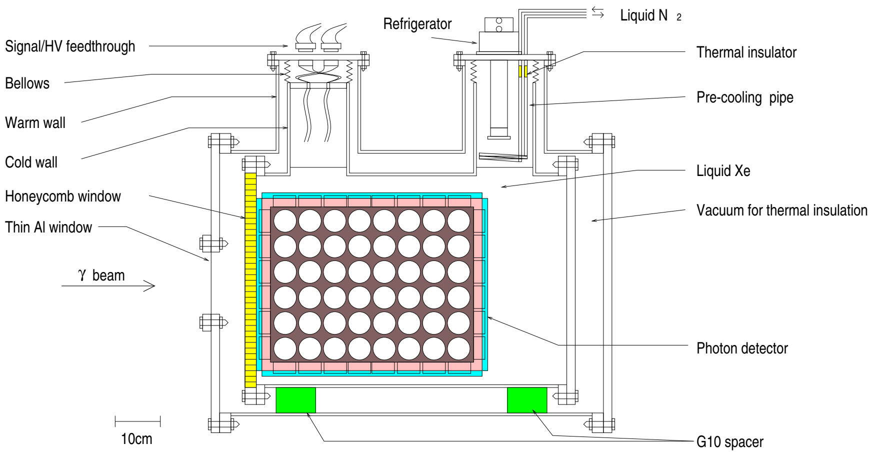

Figure 6: Schematic view of the large prototype

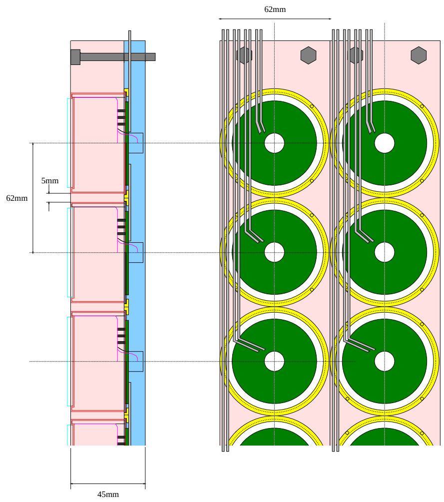

Figure 7: Support structure of PMTs on the front wall

with a metal ring. The PMT backside is sealed with another G10 plate which prevents liquid Xe from penetrating into the insensitive volume. Cables from the PMTs are connected to the feedthrough at the flange of the vessel. It is planned to use the same type of feedthrough connectors as used for the liquid Ar calorimeter of the ATLAS detector [4]. PMTs on the side and end walls will be attached to aluminum plates and together with the front wall, they will be assembled to a rectangular box shape to be placed in the cooling vessel.

The amount of liquid Xe required for the prototype test is about 150 liters. Gas Xe is filtered by Oxisorb to remove contamination before being transfered into the vessel. The gas is cooled and liquefied with a liquid nitrogen cooling system. After completion of liquefaction a pulse tube refrigerator with 50 W power takes over and keeps the liquid at stable temperature and pressure.

The vessel will be equipped with several probes to monitor local temperatures in order to study the effect of convection of liquid Xe caused by the heat dissipated by the PMTs. The temperature measurement also gives us information on the local density of the liquid from which a possible inhomegeneity of refractive indices can be studied.

2 Positron Timing Counter

Several prototypes of the positron timing counter have been constructed and tested with beams at KEK, Japan.

A simple prototype was constructed to establish the technique to achieve the ultimate timing resolution required for the $\mu \to e\gamma$ search experiment. The prototype consists of a bulk of plastic scintillator (BICRON BC404, 95 cm $\times$ 2 cm $\times$ 3.5 cm) and 2.5-inch PMTs (HAMAMATSU R6504S). The PMT has a sufficiently large sensitive area to cover the end surface of the scintillator. It is attached to the scintillator without a light guide to detect as much scintillation light as possible. The fine-mesh type PMT was employed in this study considering that the timing counters in the $\mu \to e\gamma$ search should operate in a strong magnetic field. Fig. 8 shows the timing resolutions obtained with this prototype. Resolutions of 27.8 psec (σ) for 1.0 GeV/c π^+s and 18.1 psec (σ) for 0.5 GeV/c protons have been attained.

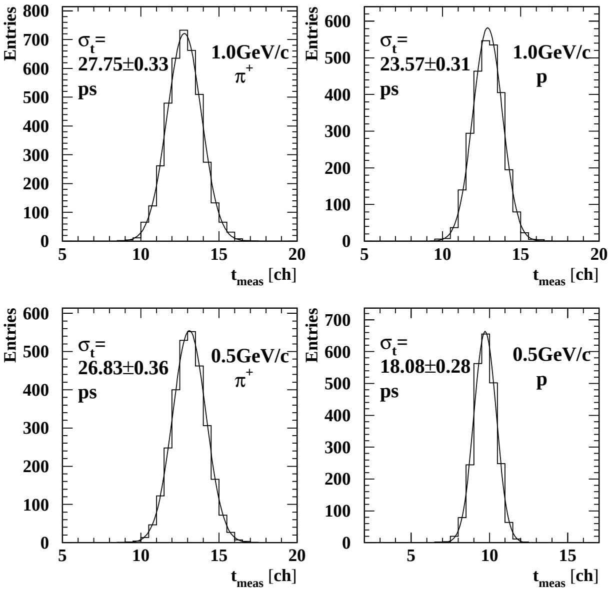

Figure 8: Timing resolutions for 1.0 GeV/c π^+, p, 0.5 GeV/c π^+, and p.

Based on the experience with this prototype, we have also constructed and tested more realistic prototypes. Taking into account the configuration of the timing counter in the $\mu \to e\gamma$ search, PMTs with a smaller diameter (HAMAMATSU R6152-01, 27 mmϕ effective sensitive area) are attached to the scintillator with lightguides of a fish-tail shape. In a preliminary analysis, a resolution of 48 psec (σ) has been obtained for mininum ionising particles. From all these test results, we believe that a timing resolution of 100 psec FWHM for a 52.8 MeV positron is feasible and could even hope for a better resolution.

It is planned in the year 2000 to test another prototype which employs lightguides and PMTs with higher gains before starting a final design of the positron timing counter.

3 Positron Tracker

To make basic feasibility studies on the positron tracker system we have designed a prototype drift chamber with a sensitive area of 290 mm $\times$ 80 mm. It roughly models one sector of the chamber system described in the proposal.

The prototype has two layers of sense wires staggered by a half pitch. Each layer has 8 sense wires to be read out at both ends to determine the hit position along the wire by charge division technique with an accuracy of ~1 cm. A cross-sectional view of the prototype is shown in Fig. 9.

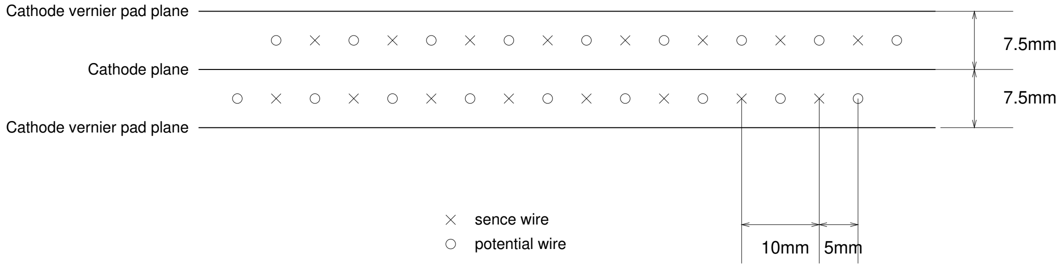

Figure 9: A cross-sectional view of the prototype drift chamber.

The chamber walls are made of thin Kapton foils. For an initial test we use a foil of 12.5 μm thickness. A thin layer of aluminum is deposited on the foil as cathode electrodes. The aluminum deposit is shaped to make a vernier pattern as shown in Fig. 10(a) for precise determination of the hit position along the sense wire.

Fig. 10(b) shows a result of Monte Carlo simulation based on this design. The figure on the left shows the correlation between the ratios of charges induced on the three pads. The right one shows the charge ratios as a function of position along the sense wire. From the simulation it is expected that the position can be determined with an accuracy of 300 μm (σ) using this vernier pad technique.

The components of the prototype are now being delivered and we will soon start systematic studies with various gas mixtures and different vernier pad patterns using radioactive sources. In parallel we will carry out further Monte Carlo studies and a detailed design of the mechanical structure of the whole tracker system.

References

[1] "Search for $\mu^+ \rightarrow e^+\gamma$ down to 10^{-14} branching ratio", Research Proposal to Paul Scherrer Institut, May 1999 (PSI Proposal R-99-05.1).

[2] Phillips Scientific, Octal 300 MHz discriminator, MODEL 708.

[3] Phillips Scientific, 16 channel TDC, MODEL 7186.

[4] ATLAS Liquid Argon Calorimeter Technical Design Report, CERN/LHCC/96-41, ATLAS TDR 2, December 15, 1996.

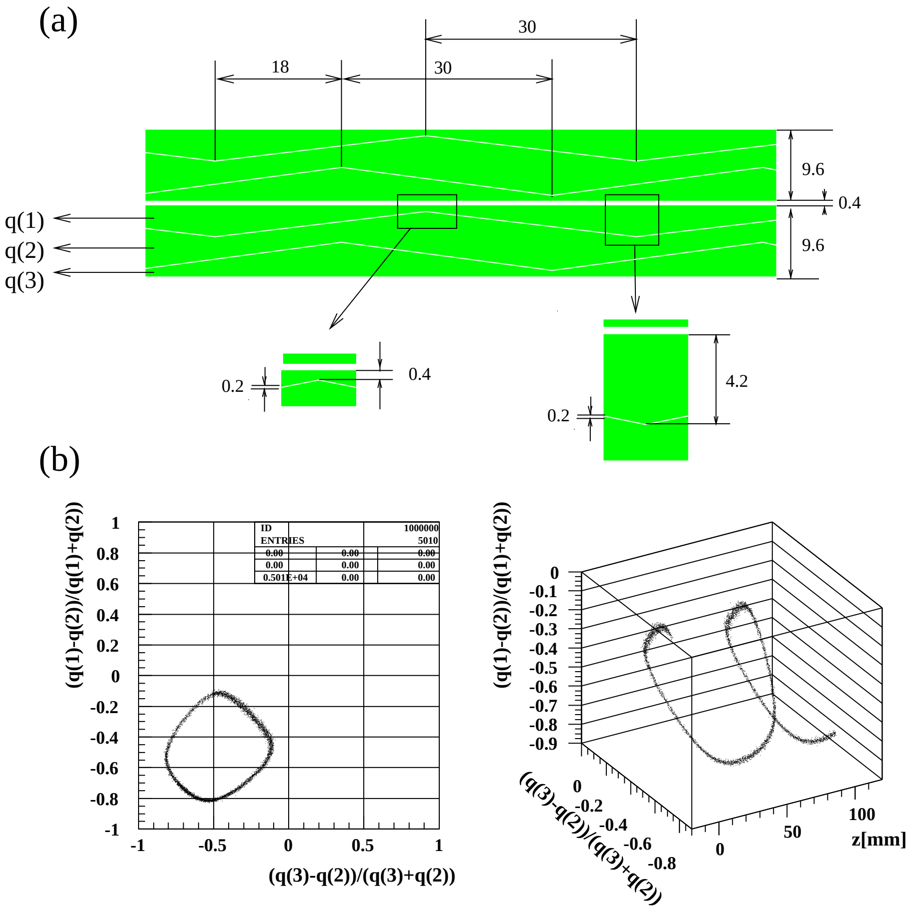

Figure 10: A design of the vernier pattern is shown in (a). In (b) a result of Monte Carlo simulation is presented. More than half of the total charge will be induced in the middle pad which is the closest to the sense wire.