Lepton Flavour Violation
Search for $\mu \to e\gamma$ at Paul Scherrer Institut

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A new $\mu \to e\gamma$ experiment currently being built at Paul Scherrer Institut (PSI) in Switzerland is described. The goal of the experiment is to search for the lepton flavour violating decay of $\mu \to e\gamma$ with a sensitivity down to the level of 10^{-14}. A new detector system will be constructed at PSI using muon beam with a stopping rate of 10^8/sec. The system consists of a liquid xenon photon detector and a positron detector contained in a superconducting solenoidal magnet with 1.2 T magnetic field strength. In this article, details of the detector and electronics will be described after a short introduction to the physics motivation.

1 Introduction

Fundamental theories such as supersymmetric unification(SUSY) seem to generically predict[1] that the neutrinoless muon decay $\mu \to e\gamma$ occurs with a decay branching ratio somewhere above 10^{-14}. On the other hand, this lepton flavour violating (LFV) process is exactly forbidden in the Standard Model (SM). Therefore it is not "contaminated" by processes described by the SM and thus the signal will be a clear evidence of the new physics beyond the SM.

The search for the $\mu \to e\gamma$ process has a history of more than 50 years. The last measurement was performed by the MEGA collaboration at LAMPF, resulting in obtaining an upper limit for the branching ratio of 1.2×10^{-11} at the 90% confidence level [2]. The new experiment at PSI aims to improve the sensitivity by three order of magnitude to 10^{-14}. It will use the world's most intense DC muon beam at the πE5 area at PSI and requires a new detector system with advanced components. Figure 1 shows the overview of the detector. Details will be described in the following sections. The proposal for the new $\mu \to e\gamma$ experiment[3] was accepted in May 1999 by the PSI research committee. A collaboration was formed with about 40 physicists from Japan, Italy, Russia, and Switzerland.

2 Experimental Methods

2.1 Beam line

Surface muons with a momentum of ~28 MeV/c will be transported from the PSI production target by means of dipole and quadrapole magnets to the detector. It is expected that beam intensities of up to $8\sim10\times10^8\mu$/sec are achievable, of which $1\sim2\times10^8\mu$/sec will be stopped in a 100μm thick mylar target slanted at an angle of 22° in respect to the beam axis. Figure 2 shows the layout of the πE5 area. There are two beam transport branches in the πE5 area, "U"- and

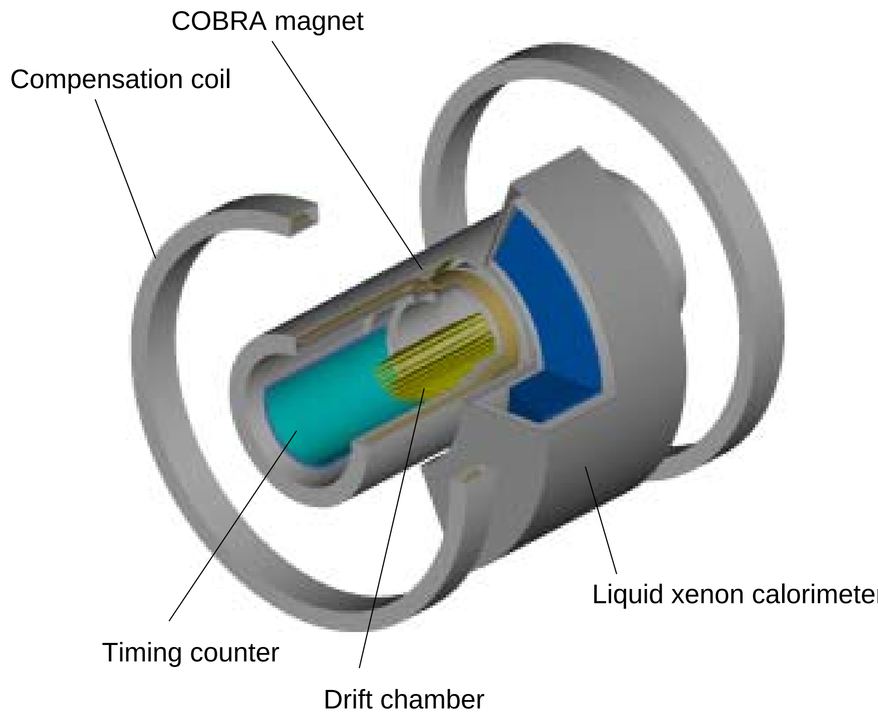

Figure 1: An overview of the $\mu \to e\gamma$ detector.

"Z"-branches. In order to investigate the best way to provide a clean beam condition for the experiment, studies on the beam transport have been started in the year 2001. The first study was done to test a possibility to use a cleaning stage which consists of a degrader, two sets of quadrapole doublets, and a dipole magnet as shown in Figure 2 for improving the separation quality of surface muons over beam positrons. Further optimization of the beam transport will continue until starting the experiment.

2.2 Liquid Xenon Photon Detector

The gamma from the $\mu \to e\gamma$ decay will be detected in a liquid xenon detector. It contains $\sim$800 ℓ (2.4 t) of liquid xenon at -100^{o}C as a scintillation material, which has high light yield (75% of NaI(Tℓ)) and fast signal response (45 nsec decay time). The light will be detected by 800 photomultiplier tubes(PMTs) immersed in liquid xenon, viewing the active volume from all sides as shown in Figure 3.

The advantage of this detector is its excellent uniformity, which cannot be reached by a segmented detector. Furthermore, the light from each gamma-induced shower will be recorded simultaneously by plenty of PMTs, allowing reconstruction of the conversion point perpendicular to the front face with an accuracy of $\sim$4 mm(FWHM). Since the broadness of the light distribution on the front PMTs depend on the depth of the conversion point, the longitudinal position can also be reconstructed with a precision of $\sim$16 mm(FWHM), which in turn translates into a timing resolution of 50 psec (FWHM). Given the response of the PMTs, the overall timing resolution will be about 0.1 nsec. The energy resolution strongly depends on the light absorption length in the liquid xenon. Since this property is not known to sufficient accuracy, we will measure it with a dedicated test set-up. In the optimal case, an energy resolution of 1.4%(FWHM) can be achieved.

Two prototypes have been constructed to study the various properties of the liquid xenon detector. A "small" prototype with 32 PMTs and 2.3 ℓ active volume of liquid xenon was used to

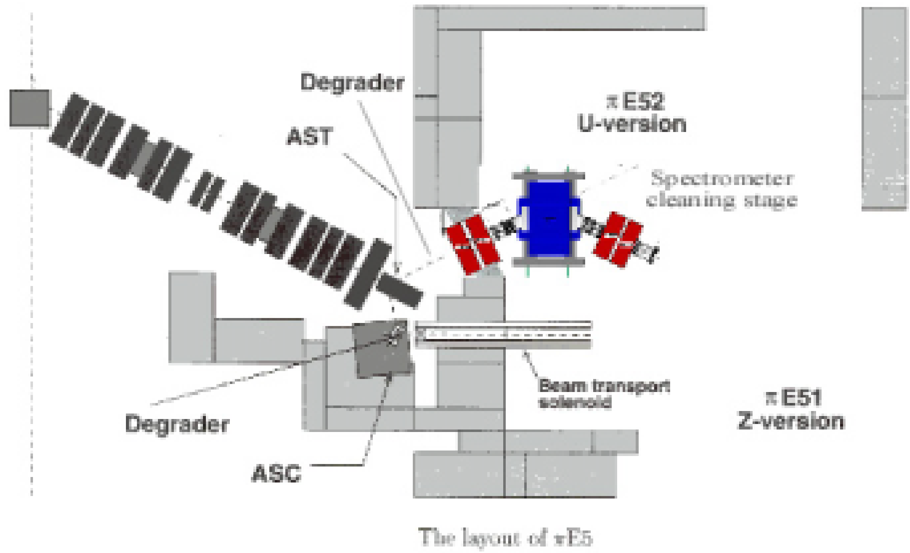

Figure 2: πE5 are show in the two branches, "U" leading to the πE52-zone and "Z" leading to the πE51-zone. Also shown is the spectrometer, used as a cleaning section.

test the general feasibility of the detector. Several radioactive sources with energies between 0.3 MeV and 1.8 MeV were used to measure the energy and position resolutions. The results agree very well with MC calculation and the extrapolation to 52.8 MeV does not disagree with our expectations, although an extrapolation of this magnitude has only limited prediction power.

To study the photon detector performance at higher energies, a "large" prototype has been constructed, using 228 PMTs and an active volume of 69 ℓ liquid xenon. Liquefaction tests have been repeated to verity the stable detector operation using a pulse-tube refrigerator to recondensate xenon. The detector response have been tested using cosmic rays and alpha sources. In these tests, technical details such as a HV feedthrough, temperature and pressure sensors, and a liquid xenon surface level meter have been tested together with gain calibration method for the PMTs. It is planned to irradiate the large prototype with 40 MeV gamma ray from a Compton backscattering facility at the TERAS storage ring in AIST, Tsukuba, Japan. This will allow us to measure the position and energy resolution for gamma rays with energies close to 52.8 MeV. After completing these tests using the large prototype, the final liquid xenon detector will be constructed.

2.3 Positron Spectrometer

The decay of $\mu \to e\gamma$ has a very clean signature. Both of the positron and gamma have an energy of 52.8 MeV/c^2 (half of muon mass) and span an angle of 180^o. The gamma will be detected in a liquid xenon photon detector described above, while the positron is registered in a magnetic spectrometer consisting of a superconducting solenoid and a set of drift chambers as shown in Figure 4(right).

The magnetic spectrometer adopts a gradient magnetic field, in which the positrons with a common momentum follow trajectories with a constant radius, independently of their emission angle. This is called "COBRA spectrometer" (COnstant Bending RAdius). The constant radius leads to a more uniform drift chamber illumination and allows selecting the maximum positron momentum in the trigger by using only an outer drift chamber wire. Another advantage of this field configuration is that positrons emitted close to 90^o are swept away by this field much more quickly than with a homogeneous magnetic field, and therefore produce less hits in the

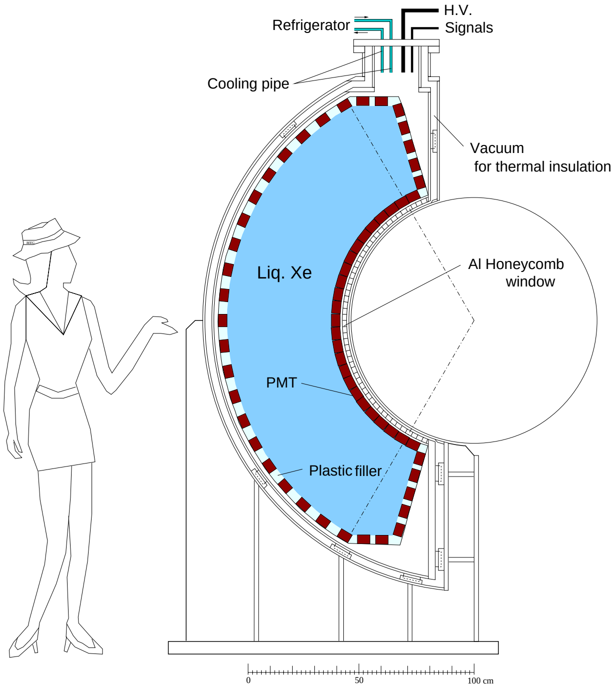

Figure 3: A cut view of the liquid xenon photon detector.

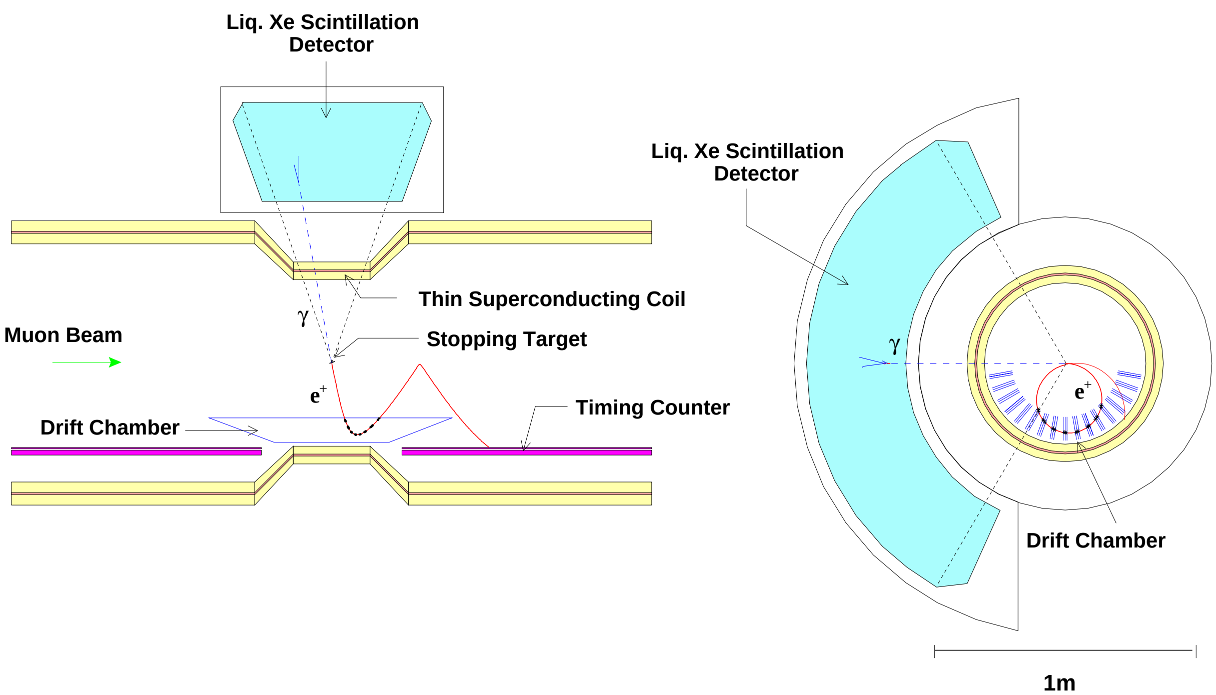

Figure 4: Cross section of the detector along the beam axis (left) and perpendicular to the beam axis (right). Also shown is one MC generated $\mu \to e\gamma$ event, where the gamma registers in the liquid xenon photon detector and the curled positron track intersects several radial drift chambers before hitting the timing counter.

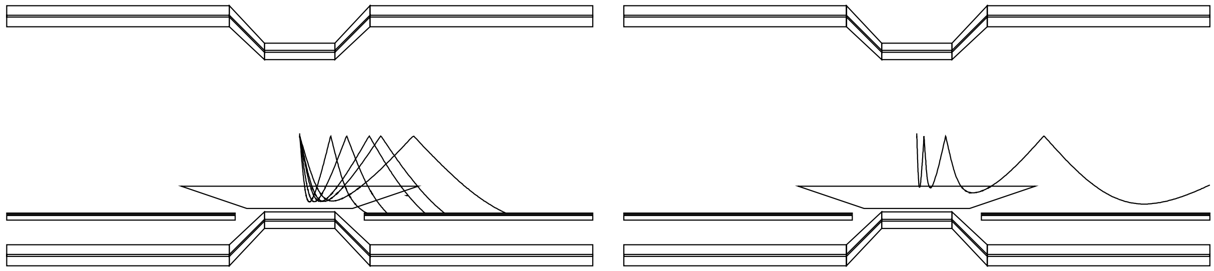

Figure 5: Principle of the COBRA spectrometer. The gradient magnetic field leads to a constant radius for monochromatic positrons (left) and sweeps away positrons emitted close to 90^o quickly (right).

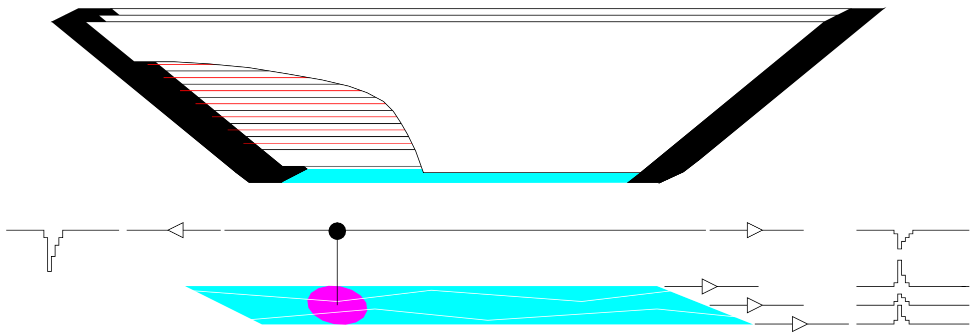

Figure 6: One drift chamber sector (top) with two staggered layers of ten wires each and a close-up of the cathode strip vernier pattern (bottom) used to determine the axial hit position.

drift chamber, avoiding track ambiguities as shown in Figure 5. The superconducting magnet produces a field of 1.2 T. The compensation coils are employed to reduce the strength of magnetic field around the PMTs of the photon detector as indicated in Figure 1.

The drift chamber system consists of 16 radial drift chamber sectors aligned radially at 10^o intervals in azimuthal angle. Each sector contains 20 wires in a staggered configuration, which makes it possible to measure both the position of a hit and its time with a precision of 5nsec. Given several hits per positron, its energy can be reconstructed with a resolution of 0.7%(FWHM). A gas mixture of He and C_2H_6 will be used to reduce multiple scattering. The charge ratio observed at both ends of the wire and at a vernier pattern at the cathode strips (Figure 6) allows the determination of the axial hit position with a sub-milimeter resolution.

A prototype of the drift chamber was constructed and tested with particle beam at the πM1 area at PSI inside a dipole magnet to measure the chamber parameters in the presence of a magnetic field. The data is currently analyzed and will be published soon.

2.4 Positron Timing counter

While the liquid xenon detector will determine the timing of the photon with a precision of about 100 psec, the drift chamber has a timing resolution of 5 nsec, which is not enough to suppress accidental background sufficiently. Therefore, positron timing counters are installed at both ends of the solenoid, where they will be hit by outgoing positrons (see Figure 4) above a certain momentum threshold. The positron timing counters will cover a range of 120^o in ϕ and a longitudinal position of 27 cm $\leq \mid z \mid \leq$ 125 cm. Positrons with an energy of 52.8 MeV will hit this counters after 1.5 turns if they are emitted between $5^o \leq \mid 90^o - \theta \mid \leq 20^o$. The positron counter consists of two layers of scintillator hodoscopes, orthogonally placed along ϕ and z directions respectively (Figure 7). All scintillators will be viewed by fine-mesh PMTs attached on both ends to be operated in high magnetic field.

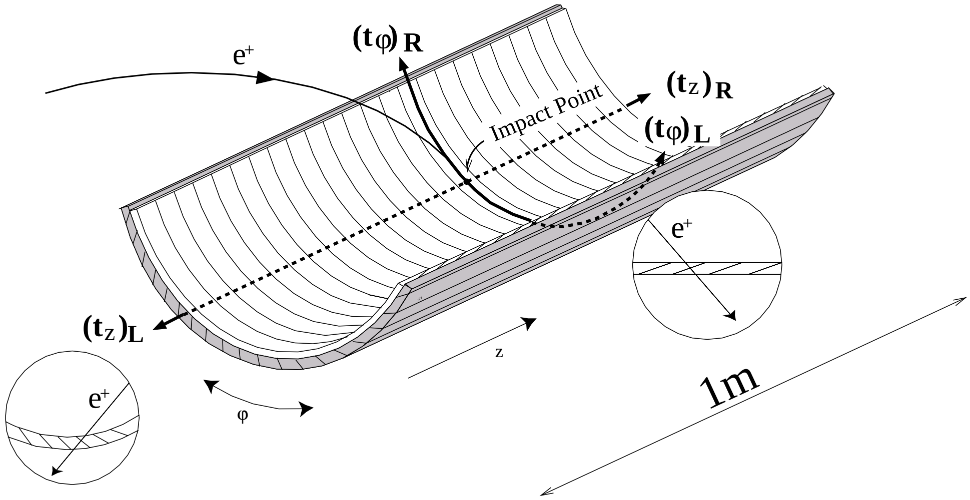

Figure 7: Configurations of the positron timing counter. Scintillator edges are slanted so that incident positrons hit several staves simultaneously. The signal ratio of adjacent staves gives a position resolution that is better than the width of an individual stave.

The incident position will be determined with two independent methods. First, the scintillators are slanted so that incident positrons hit two or three adjacent scintillator staves. The signal ratio of the hit staves will provide a position resolution that is estimated to be ±1 cm in z and ±3 cm in ϕ direction. Second, the time difference $t_L - t_R$ provides an independent measurement of the position, while the mean time $(t_L + t_R)/2$ gives the absolute impact time.

2.5 Trigger

The trigger uses the clean signature of the $\mu \to \mathrm{e}\gamma$ events. A threshold of 45 MeV applied to the energy sum of the photon detector produces a trigger rate of about 2 kHz which mainly arises from radiative muon decay $\mu^+ \to \mathrm{e}^+\nu_e\overline{\nu}_\mu\gamma$. A time correlation between the photon detector and the positron timing counter with a window of 10 nsec reduces this rate by one order of magnitude. The positron incident point on the timing counter is strongly correlated to the positron emission angle. Therefore the signals from the positron counter can be used not only for the time but also for the angular correlation between the positron and gamma. A loose angular correlation between the gamma and positron yields to a final trigger rate that is estimated by MC simulations to be about 20 Hz. This low rate gives us some margin in case of possible backgrounds not taken into account in the simulation.

We are currently investigating possibilities to accomplish the above trigger requirements in hardware in the most flexible way by means of 100 MHz flash ADCs and field-programmable gate arrays (FPGAs). First studies have shown that with today's fast and complex FPGAs it is possible to calculate the photon detector energy sum and the position of the gamma interaction point in less than 200 nsec, thus making it possible for a signal level trigger to achieve the adobe mentioned rate of 20 Hz. In a higher level, the information from the drift chamber can be used to restrict the positron energy, but simulations have shown that this will only reduce the trigger rate further not more than by a factor of two.

Implementation of the algorithm will be done by using two dedicated electronics boards that are called as Type-1 and Type-2 boards. The Type-1 board receives and digitizes the signals from the PMTs of the photon detector and timing counter. The digitized information is transmitted to the Type-2 boards, which completes the trigger algorithm. Interconnection between the Type-1 and Type-2 boards will be achieved through LVDS connections. The estimated trigger latency will be 350 nsec, which can be accommodated in the memory depth of the main waveform

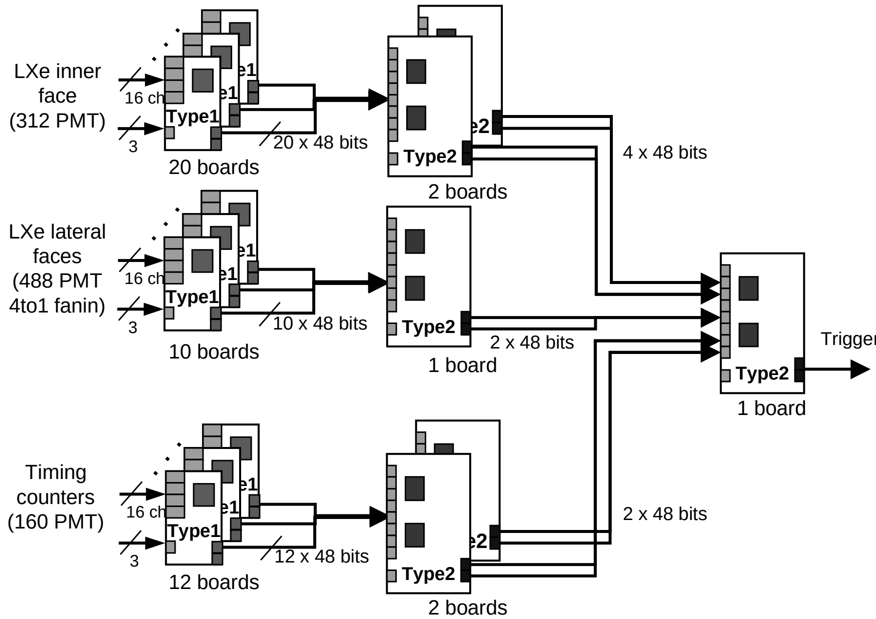

Figure 8: The trigger system structure: the 2 boards are used for the photon detector and for the positron tracker. The boards are arranged in a tree structure.

digitizer of the experiment.

2.6 Slow Control System

Long-term data acquisition in the $\mu \rightarrow e\gamma$ experiment requires a reliable and integrated control of variables such as temperature, pressure, and high voltage, commonly referred to as "slow control". A constant monitoring of these values, integrated into the main data acquision system, is crucial to ensure long-term stability of the experiment.

To achieve these requirements, a new slow control system is currently under development at PSI. This system uses an RS485 network with dedicated slow control nodes containing microcontrollers with both analog-to-digital and digital-to-analog converters, thus allowing a distributed acquisition and control the parameters. A prototype of this system has been implemented and successfully tested at the PSI drift chamber test facility.

Based on the slow control system a high voltage power supply for PMTs is also under development. This system is not only cheaper by a factor of four compared to commercial units, but also the high voltage stability and accuracy of $\pm$0.3 V over the full temperature range is significantly better than in other systems, which is crucial in a high resolution calorimeter. A first prototype with 12 channels was successfully tested, the full system with 1200 channels is now in production.

3 Sensitivity and Background

To reach a sensitivity of 10^{-14}, detectors with high efficiencies and resolutions are required as described in the previous sections. We plan to use a muon rate N_μ of 1×10^8/sec and a running time T of about $\sim$50 weeks net (2.2×10^7 sec taken into account accelerator services). With a solid angle coverage $\Omega/4\pi$ of 9%, efficiencies ϵ_e=0.95 and ϵ_γ=0.7 for positron and gamma detection, respectively, and an event selection efficiency $\epsilon_{\rm sel}$ of 0.8, we achieve a single event sensitivity for the $\mu \to {\rm e}\gamma$ decay of

$$\mathrm{BR}(\mu \to \mathrm{e}\gamma) = (N_\mu \times \mathrm{T} \times \Omega/4\pi \times \epsilon_{\rm e} \times \epsilon_\gamma \times \epsilon_{\rm sel})^{-1} = 0.94 \times 10^{-14} \tag{1}$$

The background is two-fold. First, so-called "prompt" background arises from the normal radiative muon decay $\mu^+ \to {\rm e}^+ \nu_e \overline{\nu}_\mu \gamma$. Because both the position and gamma from this decay have energies below 52.8 MeV, it can be discriminated from the $\mu \to {\rm e}\gamma$ decay by using detectors with good energy resolutions. Using the detectors described above, the prompt background rate is expected to be of the order of 10^{-17}, far below the sensitivity of the experiment.

A more severe problem arises from the "accidental" background, which consists of two or more muon decays overlapping each other. Calculations show that the accidental background rate $\mathrm{B}_{\rm acc}$ is described by the following relation[4]:

$$\mathrm{B}_{\rm acc} \propto \Delta E_e \times \Delta t_{e\gamma} \times (\Delta E_\gamma)^2 \times (\Delta\theta_{e\gamma})^2 \tag{2}$$

It is clear that a successful suppression of this background calls for good energy resolutions ΔE_e and $\Delta \mathrm{E}_\gamma$ as well as good timing $\Delta t_{e\gamma}$ and angular $\Delta\theta_{e\gamma}$ resolutions between the positron and the gamma. The detectors described above are expected to reduce this background to about $5{\times}10^{-15}$.

4 Conclusion

A new experiment searching for the lepton flavour violating decay of $\mu \to {\rm e}\gamma$ is in preparation at PSI, aiming to achieve a single event sensitivity of 10^{-14} branching ratio. The detector consists of a liquid xenon photon detector and a positron spectrometer with a gradient magnetic field. R&D works using prototypes of the detectors are in progress and construction of the detector will be started in the year of 2002.

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