

# A NEW $\mu \rightarrow e \gamma$ EXPERIMENT AT PSI

FOR THE MUEGAMMA COLLABORATION  
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A new  $\mu \rightarrow e \gamma$  experiment, which is currently being built at the Paul Scherrer Institute (PSI) in Switzerland, is described. The goal of this experiment is to measure the lepton flavor violating  $\mu \rightarrow e \gamma$  decay with a sensitivity of  $10^{-14}$ . A new detector will be installed at PSI using a stopped muon beam with a stopping rate of  $10^8/s$ . The detector will consist of a liquid xenon photon detector and a set of drift chambers contained in a 1.2T superconducting solenoidal magnet. After a short introduction to the physics motivation, details of the detector and electronics will be described.

## 1 Introduction

Fundamental theories such as supersymmetric unification (SUSY) seem to generically predict [1] that the neutrinoless muon decay  $\mu \rightarrow e \gamma$  occurs with a branching ratio somewhere above  $10^{-14}$ . On the other hand, this lepton flavor violating (LFV) process is forbidden in the Standard Model (SM). Therefore it is not “contaminated” by processes described by the SM and thus a very promising field to find physics beyond the SM. Introducing right-handed neutrinos to explain the recent discovery of neutrino oscillations is expected to enhance LFV processes such as  $\mu \rightarrow e \gamma$  [2].

The search for the  $\mu \rightarrow e \gamma$  process has a history of more than 50 years. The last measurement was performed by the MEGA collaboration at LAMPF and resulted in an upper limit for the branching ratio of  $1.2 \times 10^{-11}$  at the 90% confidence level [3]. The new experiment at PSI tries to improve the sensitivity by three orders of magnitude to  $10^{-14}$ , which is a very challenging undertaking. It will use the world’s most intense DC muon beam at the  $\pi E5$  area at PSI and requires a new detector with advanced components. The proposal for the new  $\mu \rightarrow e \gamma$  experiment [4] 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 Sensitivity and Background Rate

To reach a sensitivity of  $10^{-14}$ , detectors with high efficiencies and resolutions are required. We plan to use a muon stop rate  $N_\mu$  of  $1 \times 10^8/s$  and a running time  $T$  of

about ~50 weeks net ( $2.2 \times 10^7$ s taken into account accelerator services). With a solid angle coverage  $\Omega/4\pi$  of 9%, efficiencies  $\varepsilon_e = 0.95$  and  $\varepsilon_\gamma = 0.7$  for positron and gamma detection, respectively, and a event selection efficiency  $\varepsilon_{sel}$  of 0.8 we achieve a sensitivity for the  $\mu \rightarrow e\gamma$  decay of

$$\text{BR}(\mu \rightarrow e\gamma) = (N_\mu \cdot T \cdot \Omega/4\pi \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \varepsilon_{sel})^{-1} = 0.94 \times 10^{-14}$$

The background is two-fold. First, so-called ‘‘prompt’’ background arises from the normal radiative muon decay  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$ . Because both the positron and the gamma from this decay have energies below 52.8 MeV, it can be discriminated from the  $\mu \rightarrow e\gamma$  decay by using detectors with good energy resolution. Using the detectors described in the following sections, 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 poses the ‘‘accidental’’ background, which consists of two or more muon decays overlapping each other. Calculations show that the accidental background rate  $B_{acc}$  is described by the following relation:

$$B_{acc} \propto \Delta E_e \cdot \Delta t_{e\gamma} \cdot (\Delta E_\gamma)^2 \cdot (\Delta \theta_{e\gamma})^2$$

It is clear that a successful suppression of this background calls for good energy resolutions  $\Delta E_e$  and  $\Delta E_\gamma$  as well as good timing ( $\Delta t_{e\gamma}$ ) and angular ( $\Delta \theta_{e\gamma}$ ) resolution between the positron and the gamma.

The detectors planned to reduce this background to about  $5 \times 10^{-15}$  are described in the following sections.

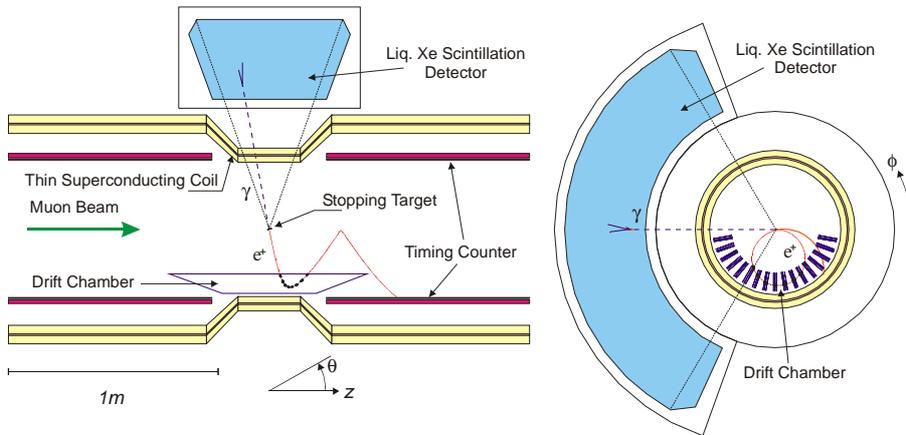
### 3 Experimental Method

#### 3.1 Beamline

Surface muons with a momentum of ~28 MeV/c will be transported from the PSI production target by means of dipole and quadrupole magnets into the detector. Measurements indicate that beam intensities of up to  $8 \sim 10 \times 10^8$   $\mu/s$  are achievable, of which  $1 \sim 2 \times 10^8$   $\mu/s$  will be stopped in a 100  $\mu\text{m}$  thick mylar target slanted at an angle of  $22^\circ$  in respect to the beam axis. It is currently under investigation if a beam transport solenoid will be used for the last section of the beam line before the detector, or if a pair of quadrupole magnets together with an electrostatic separator gives a better suppression of the positron background in the beam.

### 3.2 Positron spectrometer

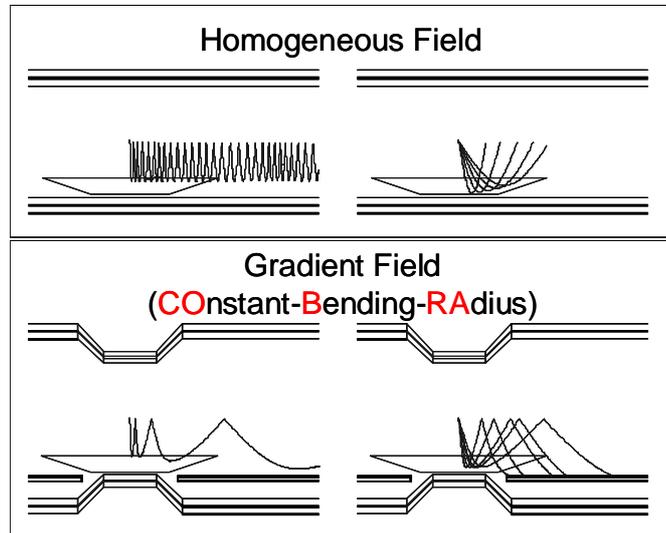
The decay  $\mu \rightarrow e\gamma$  has a very clean signature. Both the positron and the gamma have an energy of  $52.8 \text{ MeV}/c^2$  (half muon mass) and span an angle of 180 degrees. The gamma will be detected in a liquid xenon calorimeter, while the positron is registered in a magnetic spectrometer consisting of a superconducting solenoid and a set of drift chambers as shown in Fig. 1.



**Figure 1:** Cross section of the MUEGAMMA detector along the beam axis (left) and perpendicular to the beam axis (right). Also shown is one MC generated  $\mu \rightarrow e\gamma$  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.

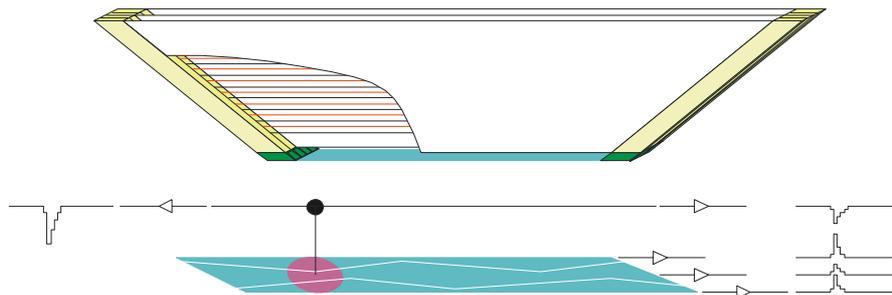
The magnetic spectrometer adopts a graded magnetic field, in which the positrons with a common momentum follow trajectories with a constant radius, independently of their emission angle. We call this COBRA spectrometer (CONstant Bending RADIUS). The constant radius leads to a more uniform drift chamber 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  $90^\circ$  are swept away by this gradient field much more quickly than with a homogenous magnetic field, and therefore produce less hits in the drift chamber, avoiding track ambiguities (see Fig. 2).

The superconducting magnet produces a field of 1.2 T and will have a thickness of about  $3 \text{ g}/\text{cm}^2$  including the cryostat walls which corresponds to a transmission of 95% for 52.8 MeV photons.



**Figure 2:** Principle of the COBRA spectrometer. The gradient magnetic field leads to a constant radius for monochromatic positrons (right) and sweeps away positrons emitted close to  $90^\circ$  more quickly (left).

The drift chamber system consists of 16 radial drift chamber sectors aligned radially at  $10^\circ$  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 5 ns. 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 (Fig. 3) allows the determination of the axial hit position with a sub-millimeter resolution.



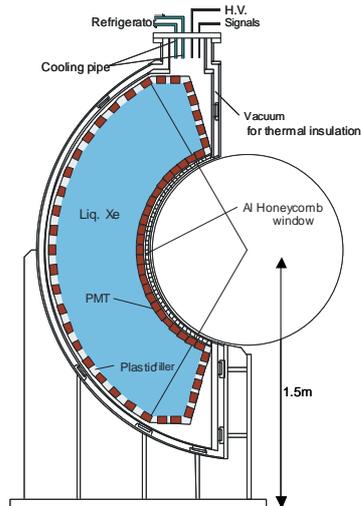
**Figure 3:** One drift chamber sector (top) with two staggered layers of ten wires each and a close-up of the cathode strip vernier pattern (bottom) used to determine the axial hit position.

Two prototypes of the drift chamber have been built so far. One was used to confirm the feasibility of the vernier pattern scheme. In a first test with a collimated  $^{90}\text{Sr}$

source an axial resolution of 400~800  $\mu\text{m}$  was achieved using the vernier pattern and a transversal resolution below 200  $\mu\text{m}$  was obtained by measuring the drift time. The second prototype was tested with a particle beam at the  $\pi\text{M1}$  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.

### 3.3 Liquid xenon photon detector

The gamma from the  $\mu \rightarrow e\gamma$  decay will be detected in a liquid xenon (LXe) detector. It contains ~800 l (2.4 t) of liquid xenon at  $-100^\circ\text{C}$ , which has high light yield (75% of NaI(Tl)) and fast signals (45 ns decay time). The light will be detected by 800 photomultiplier tubes (PMT), which are immersed in the LXe viewing it from all sides (Fig. 4), similar to the Kamiokande detector. No attempt will be made to collect the ionizations, which makes the operation of the detector much easier. The fiducial volume of the detector starts at 65 cm from the target, has a depth of 47 cm and covers a solid angle of 12%.



**Figure 4:** Cross section of the LXe photon detector perpendicular to the beam direction, showing the PMTs immersed in the liquid xenon.

The advantage of such a detector is its excellent uniformity, which cannot be reached by a segmented detector. Furthermore, the light from each gamma-induced shower will be recorded by most of the PMTs. This allows a reconstruction of the conversion point perpendicular to the front face with an accuracy of ~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 ~16 mm (FWHM), which in turn translates into a timing resolution of 50 ps (FWHM). Given the response of the PMTs, the overall timing resolution will be about 0.1 ns. The energy resolution strongly depends on the light

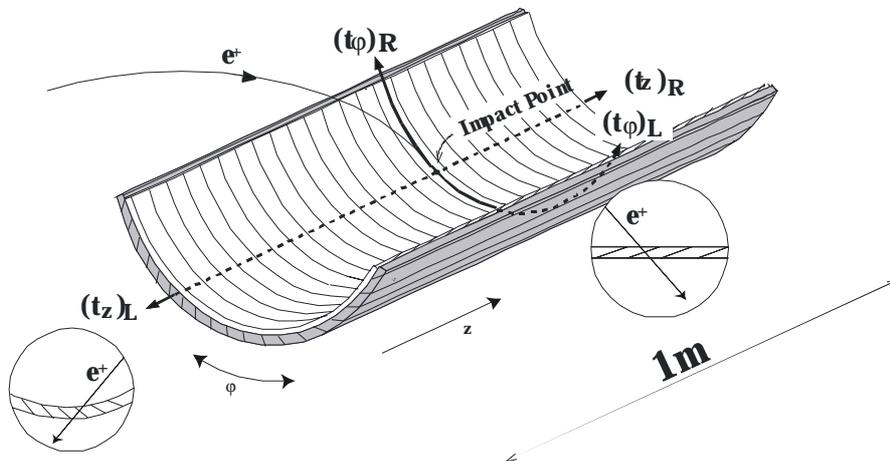
attenuation length in the LXe. Since this property is not known to sufficient accuracy, we will measure it with a dedicated test set-up. In the optimal case, a energy resolution below 2% (FWHM) can be achieved.

The LXe detector uses new technologies and cannot be build in one step from scratch. Therefore, two prototypes have been built to study various properties of an LXe detector. A “small” prototype with 2.3 t LXe and 32 PMTs was used to test the general feasibility of immersed photomultipliers operating at  $-100^{\circ}$  C. Several radioactive sources with energies between 0.3 MeV and 1.8 MeV have been used to measure the energy and position resolutions. The results agree very well with MC calculations 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 an LXe detector at higher energies, a “large” prototype is currently being built, using 150 t LXe and 264 PMTs. Once completed, it will be irradiated with  $\sim 40$  MeV gammas from a Compton backscatter facility at the TERAS storage ring at ETL, Tsukuba, Japan. This will allow us to measure the position and energy resolution for gammas with energies close to 52.8 MeV. Also technical details like high voltage feed-through connectors and details of the PMT gain matching will be worked out with this prototype. After completion of these tests, the final LXe detector will be constructed.

#### 3.4 Positron timing counters

While the LXe detector will determine the timing of the photon with a precision of about 100 ps, the drift chamber has a timing resolution of 5 ns, 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 Fig. 1) above a certain momentum threshold. The positron timing counters will cover a range of  $120^{\circ}$  in  $\phi$  and a longitudinal position of  $27 \text{ cm} < |z| < 125 \text{ cm}$ . Positrons with an energy of 52.8 MeV will hit this counters after 1.5 turns if they are emitted between  $5^{\circ} < |90^{\circ} - \theta| < 20^{\circ}$ . The positron counter consists of two layers of scintillator hodoscopes, orthogonally placed along  $\phi$  and  $z$  directions, respectively (Fig. 5). All scintillators will be read out by PMTs attached on both sides. We will use ultra-fine-mesh PMTs that can operate in high magnetic field.



**Figure 5:** Configuration 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  $\pm 1$  cm in  $z$  and  $\pm 3$  cm in  $\phi$  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.

### 3.5 Trigger

The trigger uses the clean signature of the  $\mu \rightarrow e\gamma$  events. A threshold of 45 MeV applied to the energy sum of the LXe calorimeter produces a trigger rate of about 2 kHz which mainly arises from radiative muon decays  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$ . A time correlation between the LXe detector and the positron timing counter with a window of 10 ns reduces this rate by one order of magnitude. A loose angular correlation between the gamma and the positron yields to a final trigger rate that is estimated by MC simulations to 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 (FPGA). 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 the gamma. First studies have shown that with today's fast and complex FPGAs it is possible to calculate the LXe

energy sum and the position of the gamma interaction point in less than 200 ns, thus making it possible for a single level trigger to achieve the above 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.

### 3.6 Data Acquisition

In addition to normal digitization techniques like ADCs and TDCs, we need a good suppression of pile-up events, which makes waveform digitizing mandatory. Based on an earlier development at PSI [5], a new analog sampling chip is currently designed. It will contain 1024 analog cells, which sample the input signal with 2.5 GHz and are read out with 40 MHz using cheap 12-bit commercial FADCs. Using interpolation techniques and proper baseline subtraction, this device will give us ~40 ps timing resolution and a double hit resolving power of a few ns. While this device will be used for both the LXe and the positron timing counters, the slower drift chamber signals will be directly digitized with 100 MHz 10-bit FADCs. If this development is successful, the usage of traditional ADCs and TDCs can be omitted, making the experiment much cheaper.

## 4 Conclusions

The preparations of the new  $\mu \rightarrow e\gamma$  experiment are going well in all areas so far. The next major milestone will be the test of the large prototype with high energy gammas planned in spring 2001. While the R&D will continue until 2002, it is planned to assemble the detector in 2003, so that the first commissioning run can start in late 2003. New techniques are currently under development, which could very well be used for other experiments. The most recent information can be obtained from the MEG Web site [6].

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