The Drift Chamber System of the MEG Experiment

Malte Hildebrandt[*,a], *on behalf of the MEG collaboration*

[a] *Paul Scherrer Institut, CH - 5232 Villigen PSI, Switzerland*

Abstract

The MEG experiment searches for the lepton flavour violating decay $\mu \rightarrow e\,\gamma$ and is aiming for a sensitivity of 10^{-13} in the branching ratio in order to probe new physics beyond the standard model. The experiment is located at the Paul Scherrer Institut (PSI) in Switzerland, where one of the world's most intensive surface muon beams is located. Physics data taking started in September 2008.

The drift chamber system is part of the innovative positron spectrometer of the MEG experiment and consists of 16 drift chamber modules. The system is designed to ensure precision measurement of 52.8 MeV/c positrons. Design, construction, geometrical alignment and performance of the drift chamber system are presented.

Key words:
low-mass drift chamber, charge division, Vernier pattern, positron spectrometer

1. Introduction

The MEG experiment [1] is a rare decay experiment. The challenging goal is the search for the lepton flavour violating decay $\mu^+ \rightarrow e^+\gamma$ with a sensitivity of 10^{-13} in the branching ratio improving the current limit [2] by two orders of magnitude.

The $\mu^+ \rightarrow e^+\gamma$ decay for a muon decaying at rest, has a clear 2-body final state in which the decay positron and γ-ray are emitted coincident in time and back-to-back each with an energy of 52.8 MeV, corresponding to half of the muon mass. Positive muons are used to avoid formation of muonic atoms and muon capture on the target nuclei. The background is dominated by the accidental coincidence of a positron originating from the normal Michel decay of the muon and a γ-ray originating from other sources, e.g. radiative muon decay ($\mu \rightarrow e\nu\nu\gamma$) or annihilation-in-flight of another Michel positron.

In order to identify $\mu^+ \rightarrow e^+\gamma$ events and to reject background events a precise measurement of energy, emission angle and time of positron and γ-ray is mandatory.

2. The MEG experiment

The MEG experiment is located at the Paul Scherrer Institut (PSI) in Switzerland. Three key elements enable the excellent sensitivity of the experiment: (i) a high rate DC muon beam, (ii) an innovative liquid xenon scintillation γ-ray detector [3], and (iii) a specially designed positron spectrometer [4] with a gradient magnetic field and a scintillation timing-counter array for fast timing and triggering.

The positron spectrometer has to fulfil several requirements. Firstly, it must cope with a very high muon stopping rate of up to 10^8 sec^{-1}. Secondly, a low-mass positron tracking system is required as momentum resolution is limited primarily by multiple coulomb scattering. In addition, accidental γ-ray background by positron annihilation-in-flight should be minimized by a low-mass construction. Thirdly, excellent position resolution is required for the tracking system, both in the r-direction (transverse) and z-direction (axial). Finally, the timing counter system has to provide excellent timing resolution as γ-ray and positron from the $\mu^+ \rightarrow e^+\gamma$ decay are coincident in time.

3. The Drift Chamber System

The positron tracking system consists of 16 independent drift chamber modules, aligned radially in a half circle with 10.5° intervals (see Fig. 1). The complete drift chamber system is placed inside the COBRA (**CO**nstant **B**ending **RA**dius) magnet [5]. This magnet provides a high gradient axial magnetic field such that positrons with the same absolute momenta follow trajectories with a constant bending radius, independent of the emission angle, while in a normal solenoidal field the radius depends on the emission angle. This offers the great advantage of selecting high-momentum signal positrons from the vast number of Michel positrons from normal muon decay. In addition, positrons emitted close to 90° are swept out of the fiducial tracking volume after a few turns, while in a normal solenoidal field such positrons undergo many turns

[*] Corresponding author. Tel.: +41-(0)56-310-2145; fax: +41-(0)56-310-2199.
Email address: `malte.hildebrandt@psi.ch` (*on behalf of the MEG collaboration*)

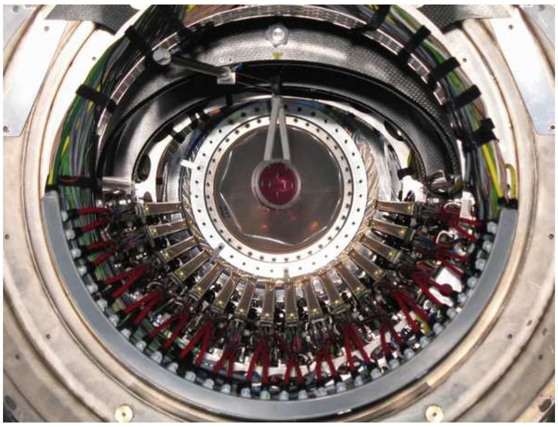

Figure 1: View of the drift chamber system from the downstream side of the MEG detector. The drift chamber modules are mounted in a half circle, whereas the muon stopping target is placed in the centre.

Figure 2: Anode frame with wires (front), "middle cathode" and "hood cathode" (back) of a drift chamber module.

in the sensitive volume, thereby causing difficulties in pattern recognition and affecting stable operation of the drift chamber.

4. Design of a Drift Chamber Module

Each drift chamber module has a trapezoid shape. It is an open frame geometry without any supporting structure towards the inner side (see Fig. 2). This open frame construction reduces the amount of material in the inner part of the spectrometer and reduces background events due to positron annihilation-in-flight.

The chamber module consists of two detector planes which are operated independently. These two planes are separated by the so-called "middle cathode" which consists of two cathode foils with a gap of 3 mm. The wire frames contain alternating anode and potential wires, stretched in the axial direction and mounted with a pitch of 4.5 mm. The shortest wire has a length of 40 cm, the longest of 86 cm and the anode-cathode distance is 3.5 mm. To resolve left-right ambiguities one wire plane is shifted in the radial direction by half a drift cell. The two detector planes are enclosed in the so-called "hood cathode".

The middle cathode, as well as the hood cathode, are made of a 12.5 μm thick polyimide foil with an aluminum deposition of 2500 Å thickness.

Thanks to such a low-mass construction, the amount of material of one drift chamber module sums to an average value of $X_{0,\text{module}} = 2.5 \cdot 10^{-4}$ of a radiation length.

5. Charge division and Vernier pattern

The determination of the z-position is based on the principle of charge division. For this reason, the anode wires are resistive wires made of nickel chromium with a resistance per unit length of 2.2 kΩ/m. In a first step, the z-coordinate is derived from the ratio of the charges measured at both ends of the anode wire. Following this method the z-coordinate can be measured to a precision of better than 2 % for each anode wire length.

In a second step, the information from the cathodes is used to achieve a more accurate z-coordinate, by using a so-called "double-wedge" or "vernier pattern" structure [6] which is etched on the cathode planes on both sides of the anode wire (see Fig. 3). The resistance per unit length of the strips is 50 Ω/m. The induced charges on each vernier strip are related to the z-position due to the double-wedge structure. In total there are four cathode signals for each anode wire and to increase the capability of this method the vernier pattern of one cathode plane is shifted by $\lambda/4$ in axial direction with respect to its partner plane.

6. Geometrical alignment

During the construction of each single frame the position of the anode wires and of the zig-zag structure of the vernier pattern was measured with respect to an alignment pin located at the bottom left edge of the frame.

Each cathode hood is equipped with two target marks placed on the most upstream and most downstream upper edge of the cathode hood. After the assembly of a drift chamber module the position of these identification marks was measured with respect to the alignment pin which allows the alignment of the different frames within the drift chamber module and which acts as a reference for the wire positions as well as the positions of the vernier structure.

All drift chamber modules are mounted in a support structure made of carbon fibre in which the modules are mounted at 10.5° intervals. The surface of the support structure between two adjacent drift chamber modules is also equipped with target marks both on the downstream side as well as on the upstream side.

After the installation of the complete drift chamber system inside the bore of the COBRA magnet there was an optical survey done. The position of the target marks

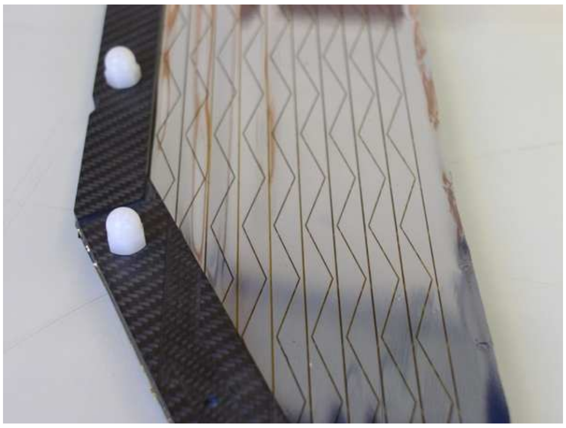

Figure 3: Double wedge or vernier pattern structure etched in the aluminum layer of the cathode foil.

on the hood cathodes and on the support structure were measured with respect to the beam axis and COBRA magnet.

The combination of all three measurements allows the determination of the wire positions in the absolute coordinate system of the experiment. The wire shift during "software alignment" with cosmic rays and Michel positrons was on average less than 50 μm, which stresses the power of the geometrical alignment procedure described above.

7. Counting Gas and Pressure Control System

In order to reduce the amount of material inside the spectrometer along the positron trajectory, a helium-based gas mixture ($He : C_2H_6 = 50 : 50$) was chosen as the counting gas for the drift chambers. The initial tests with this gas mixture were based on positive results with helium-based gas mixtures in high luminosity and high resolution experiments using magnetic fields [7].

The small primary ionisation and the large diffusion of helium is balanced by a high primary ionisation and good quenching properties and HV stability of ethane. The main advantages of this helium-ethane gas mixture are a rather fast and saturated drift velocity around ~ 4 cm/μs and a Lorentz angle smaller than 8° in the region of nominal operational voltage and magnetic field as well as a long radiation length ($X_0/\rho = 640$ m).

A specially designed pressure control system manages the gas flows and the gas pressure inside the drift chamber modules. The so-called pressure regulation value, which is the pressure difference between the inside and outside of the drift chamber modules is regulated to a precision of better than 0.2 Pa. This sensitivity is required as pressure differences would lead to large expansions of the thin cathode foils and consequently would lead to distortions of the anode-cathode distance and huge gain inhomogenities along the anode wire as well as from wire to wire.

8. Performance

In summer 2007 all 16 drift chamber modules were installed in the MEG experiment and operated during two commissioning runs in 2007 and 2008. Finally, physics data taking started in September 2008. During the commissioning runs dedicated cosmics ray and Michel positron data were taken with the drift chamber system in order to calibrate and optimize the performance of the system.

The intrinsic position resolution of the drift chamber was studied first with prototypes in the laboratory and later with the full-size modules in the MEG experiment itself. A position resolution of $\sigma_z = 900$ μm was achieved in the z-direction (axial) and on average of $\sigma_r = 230$ μm in r-direction (transverse). The latter value of σ_r corresponds to a timing resolution of 5-6 ns. By back tracking of the positron trajectory to the muon stopping target a vertex resolution of $\sigma = 3$ mm could be achieved.

Michel positron data were taken to also determine the momentum resolution of the drift chamber system. The high momentum edge of the theoretical Michel spectrum was convoluted with a detector resolution function, yielding a momentum resolution of $\sigma_p = 0.9$ %.

An improvement of spatial and momentum resolutions is expected with the new generation of the DRS (Domino Ring Sampler) chip [8], used to digitize all drift chamber signals and which is foreseen to be installed this year.

9. Conclusion

The MEG experiment searches for the lepton flavor violating process $\mu \to e\gamma$ and is aiming for a sensitivity of 10^{-13} in the branching ratio. After two commissioning run periods, physics data taking started in September 2008.

The drift chamber system, which is part of the innovative positron spectrometer, has to cope with challenging boundary conditions, e.g. a low-mass and open frame construction, limited space availability inside the COBRA magnet and a high rate environment leading to a high accumulated charge on the anode wires. Nevertheless the drift chamber system in the main fulfils these demanding requirements within the MEG experiment.

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