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MEGA: A SEARCH FOR THE RARE DECAY $\mu \to e\gamma$ AT THE LEVEL OF 5×10^{-13}

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ABSTRACT

We report on a new experiment in progress at LAMPF to measure the branching ratio of $\mu^+ \to e^+\gamma$ to a sensitivity of 5×10^{-13}, two orders of magnitude better than the existing upper limit. The apparatus has been designed and constructed to observe this process in a very high rate and high background environment, and as such employs state-of-the-art fine granularity detectors and readouts that can operate at high rates with low system deadtime and can measure the kinematic properties of positrons and photons with sufficient resolution to reject all backgrounds at the design sensitivity.

1. INTRODUCTION

The MEGA experiment is a search for the rare decay $\mu^+ \to e^+\gamma$ that is being undertaken presently at the Clinton P. Anderson Meson Physics Facility (LAMPF) in Los Alamos, New Mexico. This process is forbidden by fiat in the minimal Standard Model of electroweak interactions[1] since it violates conservation of both muon and electron number. The MEGA experiment is designed to detect this decay *with no background* at the unprecedented branching ratio sensitivity of a few parts in 10^{13} and thus is able to probe indirectly for the presence of a new intermediate state with a mass of several TeV. Direct observation of such a state will not be possible until the SSC and/or LHC are completed and operating.

The decay $\mu \to e\gamma$ is often cited as a sensitive test of the validity of many extensions of the minimal Standard Model—extensions that have been constructed to address one or more perceived deficiencies in the minimal theory. These include grand unified theories that allow for some μ-τ and e-τ mixing,[2] supersymmetric left-right gauge models,[3] and models with four or more generations of fermions (of course with neutrinos with mass above $M_Z/2$) with either an anomalous W boson magnetic moment[4] or anomalous gauge couplings.[5]

It should be noted that the "trivial" extension of the three-generation Standard Model to incorporate massive neutrinos with mixing would not give rise to $\mu \to e\gamma$ above a branching ratio of 10^{-18}. Thus, observation of this decay in the MEGA experiment would be a clear signature of significant new physics beyond the Standard Model.

The underlying and heretofore undetected physics that might give rise to $\mu^+ \to e^+\gamma$ determines the extremely low rate at which this process occurs. (The branching ratio is known to be smaller than 4.9×10^{-11} at the 90% confidence level.[6]) The experimenters' task is made somewhat easier by the clean kinematical signature of such a decay at rest—the coincident emission of a positron and photon with equal and opposite momenta of $\sim m_\mu c/2$. To isolate this decay from the copious backgrounds arising from other uninteresting muon decay modes requires very good resolutions on the relative times, as well as the directions and magnitudes of the final state momenta.

The prompt background from muon inner bremsstrahlung, $\mu \rightarrow e\gamma\nu\overline{\nu}$, where the neutrinos carry off very little energy, is suppressed to the level of 10^{-15}. The random coincidences between an energetic positron from one muon decay with an energetic photon from some other source (muon decay or bremsstrahlung) are expected to be at the level of 10^{-13} in the pulsed muon beam provided by LAMPF. Thus, the MEGA experiment has been designed to see $\mu \rightarrow e\gamma$ in a background-free environment with a sensitivity on the branching ratio of about one part in 10^{13}. The rate at which the apparatus can accept muons, coupled with the anticipated life of the experiment, imply that MEGA will reach a sensitivity of about 5 parts in 10^{13} by the end of 1995.

2. APPARATUS

The MEGA apparatus is divided into two "arms" that are contained in a superconducting solenoid with a bore of 1.9 m and a length of 2.5 m. (See Figure 1.) Muons of momentum ~29 MeV/c from the LAMPF Stopped Muon Channel are brought to rest at the center of the magnet in a thin planar elliptical target canted at a steep angle to the beam. This geometry makes the target appear thick along the beam direction (to stop muons) but thin along the target normal (to reduce multiple scattering of the daughter positrons).

Energetic positrons from the typical Michel decay $\mu \rightarrow e\nu\overline{\nu}$ are confined to the central region of 30 cm radius as they spiral in the 1.5T magnetic field. Their passage to the upstream or downstream end of the magnet is detected by eight thin high-rate MWPCs; their timing is measured by scintillator barrels at both ends of the solenoid.

Any photons from muon decay or positron interactions pass unhindered through the electron arm MWPCs to a set of three independent coaxial pair spectrometers. Some of these photons convert in one of these spectrometers to an electron-positron pair that is detected by drift chambers, an MWPC and scintillators. These converted photons, if they are energetic enough, trigger both arms of the apparatus and cause the information to be read into a set of FASTBUS TDCs, ADCs and latches. In the interval between LAMPF macropulses, the data are transferred from the FASTBUS modules to one of eight workstations where an online filter is applied to select candidate $\mu \rightarrow e\gamma$ events. The selected events are written to 8mm tape for offline processing.

3. ELECTRON ARM

The direction and magnitude of the momentum of a positron is measured by recording its passage through MWPCs instrumented with both axial and large-angle stereo readout. (See Figure 2.) This digitized measurement avoids rate limitations and any problems with drifts and associated calibrations that would accompany a

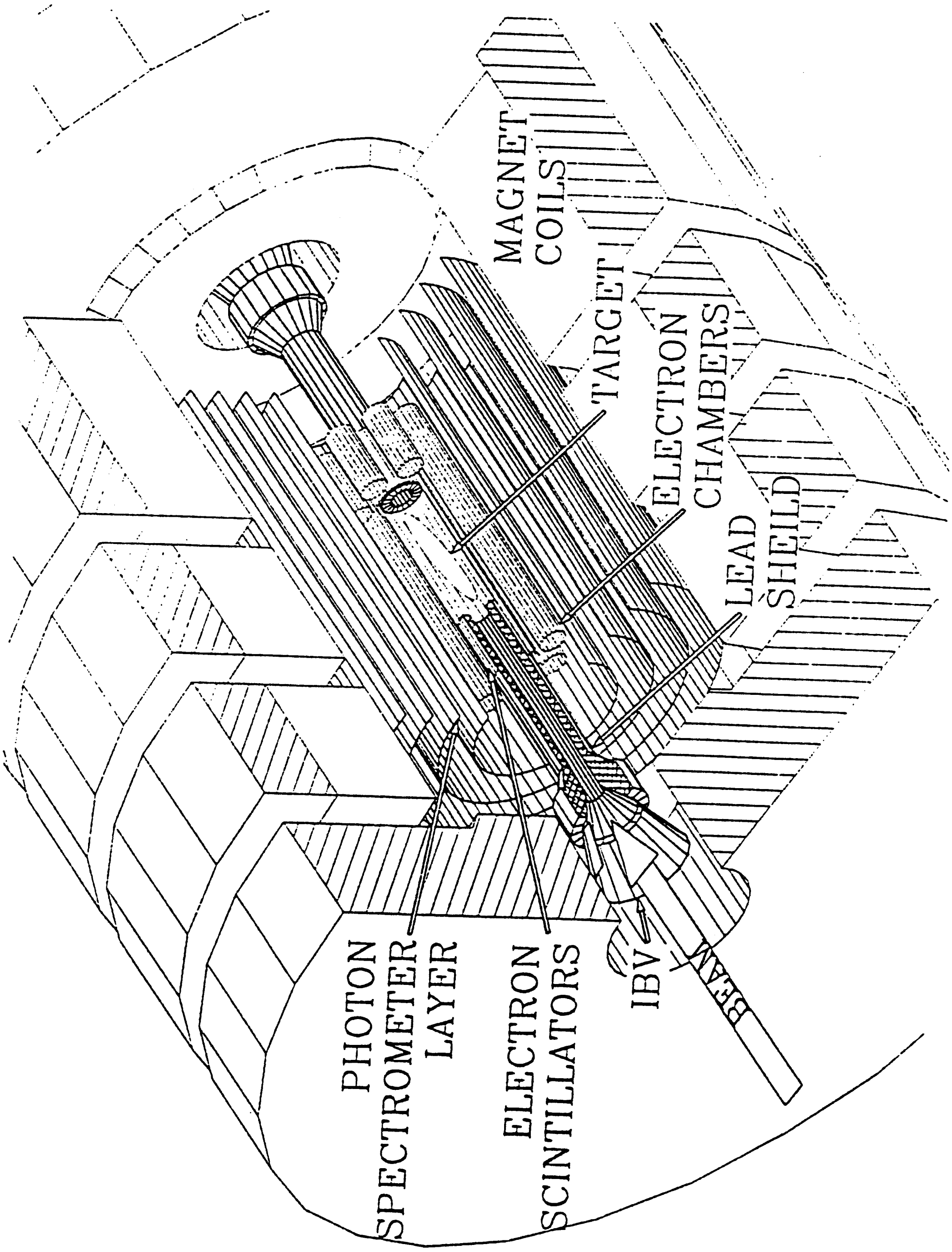

Figure 1: Cutaway view of the MEGA apparatus

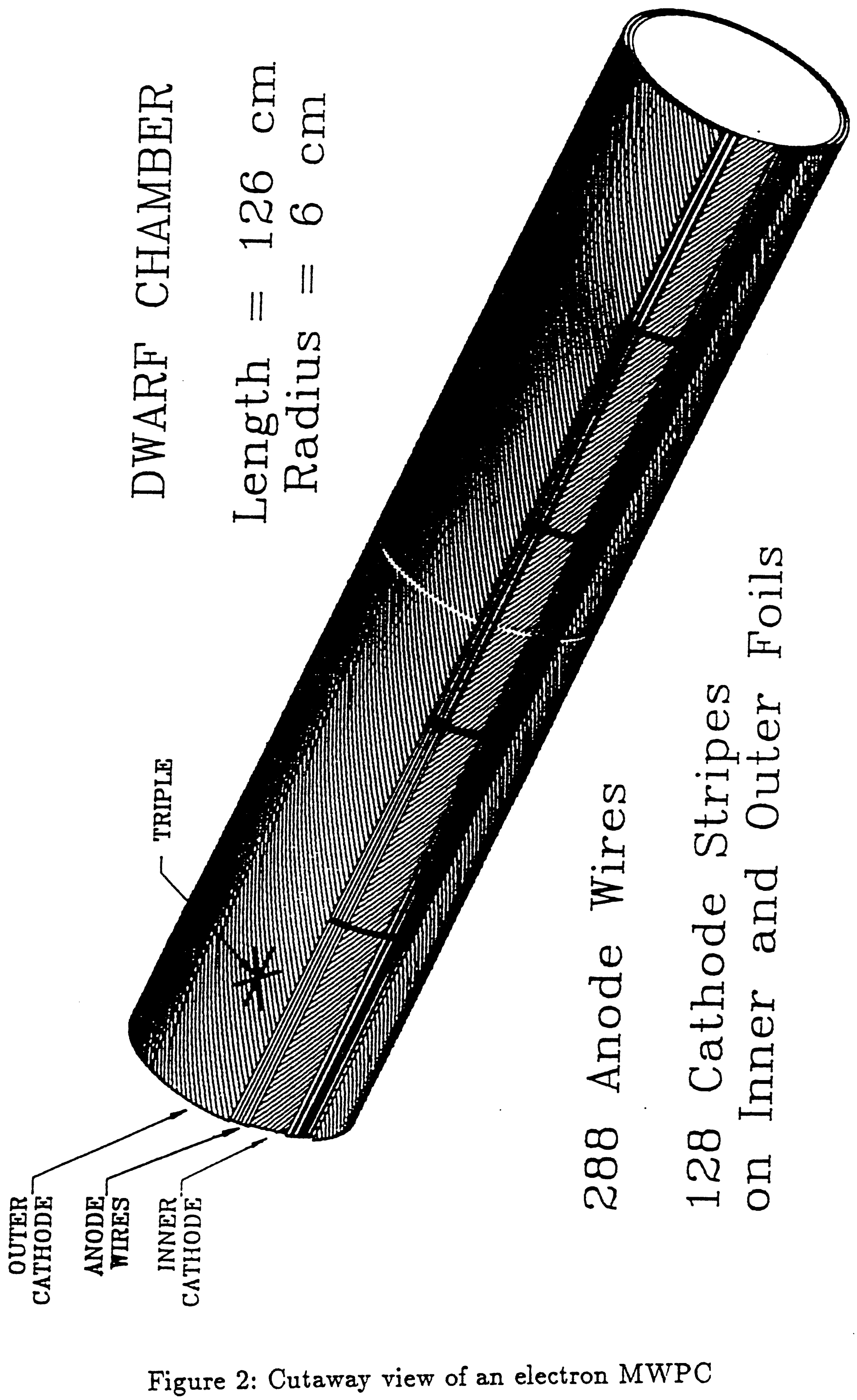

Figure 2: Cutaway view of an electron MWPC

calorimetric energy measurement using, for instance, crystals. The cylindrical chambers are 1.26 m long, with an anode spacing of 1.3 mm and a halfgap of 1.75 mm between the anode cylinder and the two cathode cylinders. Each 3 mm wide stereo cathode strip makes one 360° spiral along the chamber length, and is split at the midpoint with independent readouts at both ends. The MWPCs are suspended from rigid endplates in a lightweight carbon fiber cylinder that is not reachable by even the most energetic spiraling positrons. Lacking any internal rigid support structure by design, the MWPC geometry is maintained by differential gas pressure applied across the cathode cylinders. Thus, each chamber is only 3×10^{-4} radiation lengths thick and causes very little multiple scattering of and radiation by throughgoing positrons.

Because of the high rate of muon decays in the MEGA target and the spiralling of the daughter positrons in the magnetic field, an MWPC in this environment will see an instantaneous density of about 3×10^4 hits/mm^2/s. The chambers are operated at low gain (to reduce space charge effects) with a fast gas mixture of 80% CF_4 and 20% isobutane that permits us to minimize the gating time. Still, any 30-ns snapshot of the chambers taken during a LAMPF macropulse will contain hits associated with the fragments of about 15 positron tracks. The chamber arrangement of one large central MWPC ("Snow White," with radius 11.1 cm) surrounded by seven smaller off-axis MWPCs (the "Seven Dwarfs," each with radius 6 cm) was chosen to reduce the cathode occupancy and thereby maintain the pattern recognition efficiency at high rates, at the same time keeping the multiple scattering of the spiraling positrons to an acceptable level. The spectrometer resolution (FWHM) is 0.6% in energy, 0.2 cm in position, and 0.6° in angle, the latter quantities being measured at the muon decay point in the stopping target.

Scintillator barrels are located just inside and at both ends of Snow White. The 9.9 cm outer radius of these barrels dictates that only positrons above 30 MeV are able to spiral out far enough to strike these barrels. To further reduce the occupancy, each barrel is segmented azimuthally into 88 bars of rhomboidal cross section. (See Figure 3.) This shape was chosen so that most entering positrons strike only one scintillator. (About 20% pass through two or more adjacent scintillators.) The timing resolution (FWHM) is 0.5 ns after correction for light propagation along the scintillator bar. Almost all positrons, whether they pass through the scintillators or not, are absorbed in a lead-heavymet pipe inside each scintillator barrel. Again, this geometry was chosen to reduce the creation of spurious energetic photons by the showering positrons.

4. PHOTON ARM

Each of the three 1.8 m long independent photon pair spectrometers, at 34, 50 and 65 cm radius, is constructed to maximize the photon energy resolution while maintaining an acceptable detection efficiency. (A section of one spectrometer is shown in Figure 4.) Photons can convert to an e^+e^- pair in one of two thin (250

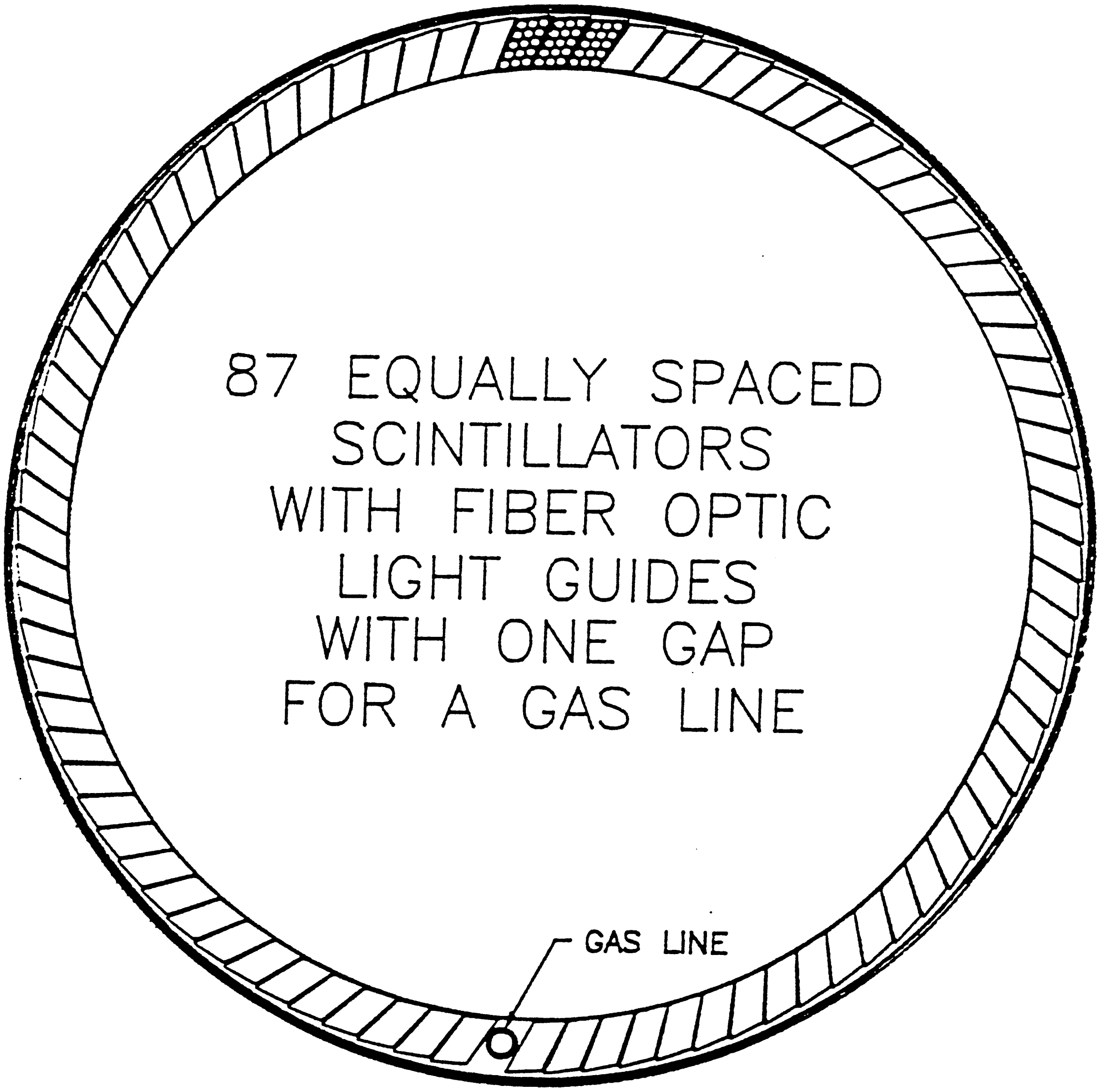

Figure 3: End view of an electron scintillator barrel

μm) lead sheets separated by a MWPC that identifies the sheet in which the conversion occurred. The daughter electron and positron spiral in the 1.5T magnetic field through three layers of drift chambers before reentering and passing through the converter sheets to an inner cylinder of scintillators. The lead sheet thickness was chosen to maximize the probability of photon conversion *without subsequent hard radiation by the daughters.* The drift chambers are of an open cell design with only axial sense wires; however, each anode in the innermost drift chamber is associated with a parallel cathode delay line that gives z readout for that channel. The drift chamber resolutions (FWHM) are 3% for the photon energy, 0.3 cm (0.5 cm) for the r-ϕ (z) coordinate of the conversion point, and 10° for the photon angle. The opening angle between the photon and a reconstructed positron is determined to better than a degree by assuming that the photon and positron originate from the same point on the target, then measuring the direction from that point to the photon conversion point.

The scintillator barrel in each pair spectrometer is segmented azimuthally into 1 cm × 5 cm bars, each of which is read out at both ends by shielded phototubes located just outside the magnet. When combining the two or more time measurements for a single photon conversion, the photon time resolution (FWHM) is 0.5 ns.

5. DATA ACQUISITION

The 12000 detector channels are read out exclusively into FASTBUS modules. Each electron chamber MWPC anode and cathode signal is digitized then fed into a latch. Each electron scintillator signal is routed to a pair of TDCs and a pair of ADCs; readout of the common signal toggles back and forth between the TDCs and ADCs in the pair to reduce the overall experimental deadtime. Most of the signals from each photon pair spectrometer are multiplexed by either four or eight into a common channel. The scintillators are viewed by both TDCs and ADCs; the drift chamber anodes and delay lines are instrumented with TDCs; the MWPCs are read out by latches. In addition, the photon scintillators' digitized signals are fed into unmultiplexed latches so that the multiplexed data can be assigned to the proper quadrant or octant of the associated pair spectrometer.

The first stage of the MEGA trigger looks at the pattern of hits in the photon arm scintillators and MWPCs, with one independent trigger module for each pair spectrometer. A valid event demands a transverse spread of at least 16 cm in these hits, in effect requiring that the converted photon have a transverse momentum of at least 38 MeV. This trigger is implemented in programmable array logic that requires only 30 ns for a decision. A second stage trigger module looks in the two outer drift chambers for signals that overlap the scintillators and MWPC channels that fired the first stage trigger.

The limited conversion probability, the detector acceptance, and the minimum transverse momentum requirement in the trigger logic imply that only about 5×10^{-5}

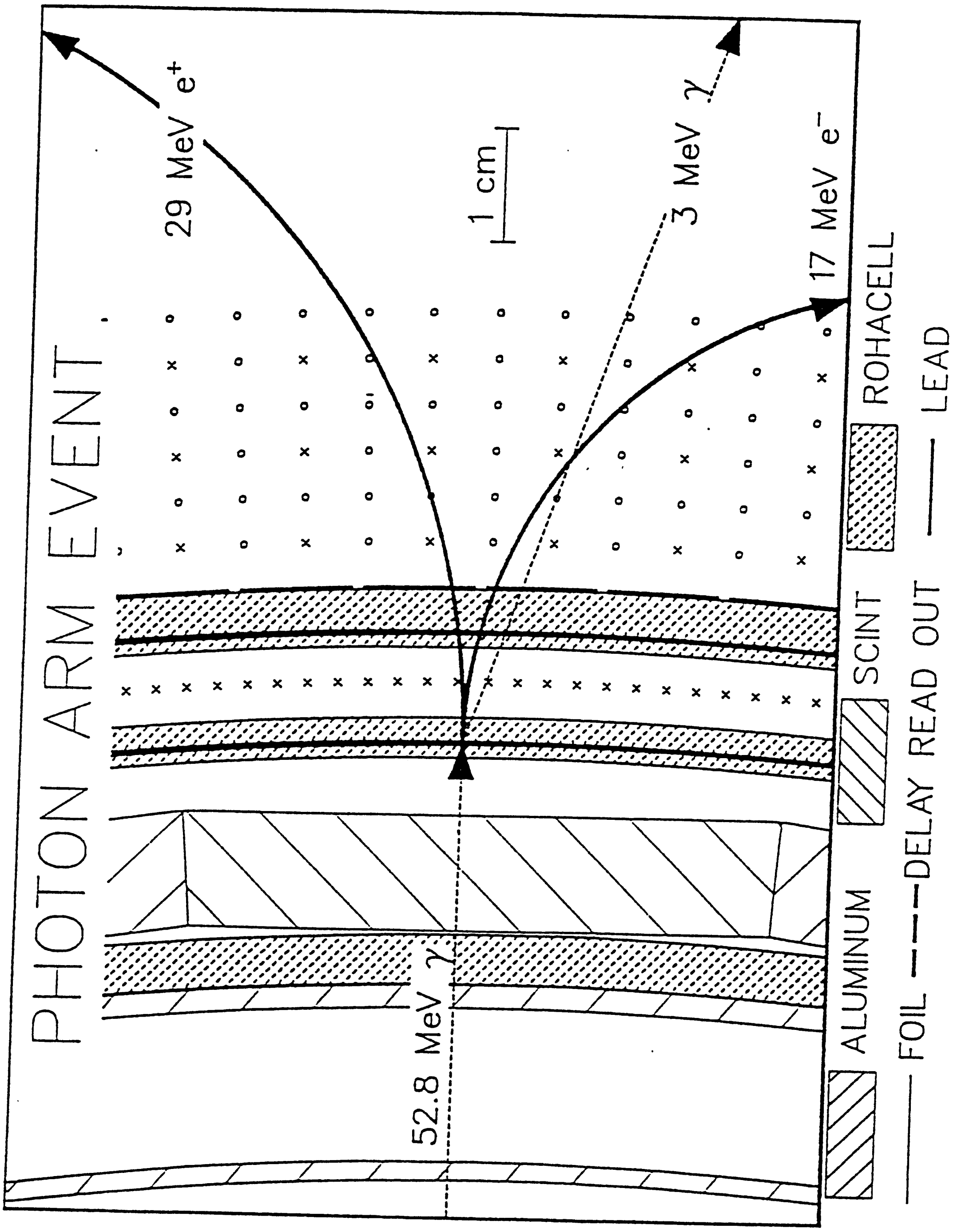

Figure 4: End view of a typical conversion in a photon pair spectrometer

of all muon decays trigger the apparatus. Thus, the instantaneous muon decay rate of 500 MHz is cut to a trigger rate of only 25 kHz. A valid trigger causes the data from the triggering pair spectrometer and the entire electron arm to be stored in the FASTBUS modules. At the end of each LAMPF macropulse, the stored data—from roughly 20 events—is transferred by VME to one of eight DECstation 5000/240 processors. From this point, the data acquisition is decoupled from the LAMPF beam structure, and the 25 kHz instantaneous rate translates into an average rate of about 200 events per workstation. A partial reconstruction of each event is attempted in these workstations to see how well it matches the characteristics of a true $\mu \rightarrow e\gamma$ event. The selected events (between 1 in 100 and 1 in 200, depending on the matching requirements) are transferred to a host VAX and immediately written to 8mm tape for subsequent analysis. (See Figure 5.)

6. CALIBRATION

Some of the detector elements require initial calibration of their outputs to enable conversion of the raw TDC and ADC signals to meaningful physical quantities, or to align the various detector components. Cosmic rays and normal muon decays (both with and without the magnetic field), as well as pion beams ($\pi^- p \rightarrow \pi^\circ n$; $\pi^\circ \rightarrow \gamma\gamma$) are used for these calibrations.

The inter-element calibration of the scintillator timing is performed three times a day to avoid broadening of the positron-photon relative timing distribution. This timing calibration uses two ring-shaped scintillators embedded in the upstream and downstream lead absorbers of the electron arm. A small fraction of the muon beam stops in a degrader mounted near each ring counter. Some of the decay positrons pass through the ring counter and then through a crack in the lead to the neighboring electron scintillator barrel, typically radiating a soft photon along the way. These events are detected by triggering on the coincidence between the ring counter and any photon arm scintillator. The triple coincidence between the ring counter, a struck electron scintillator, and the triggering photon scintillator provides the needed inter-element timing calibration.

7. STATUS

Data taking with the full electron arm and two photon pair spectrometers was begun in 1992 after a lengthy commissioning period. The data from 1992 is being analyzed presently, with a $\mu \rightarrow e\gamma$ branching ratio limit comparable to the Crystal Box value expected in Spring 1994.

Construction of the MEGA experiment apparatus was completed with the installation of the third photon pair spectrometer in Summer 1993. The analysis of the 1993 data, when combined with the 1992 result, is expected to improve the sensitivity on the branching ratio to about 3×10^{-12}.

If the U.S. Department of Energy continues to operate LAMPF for two more

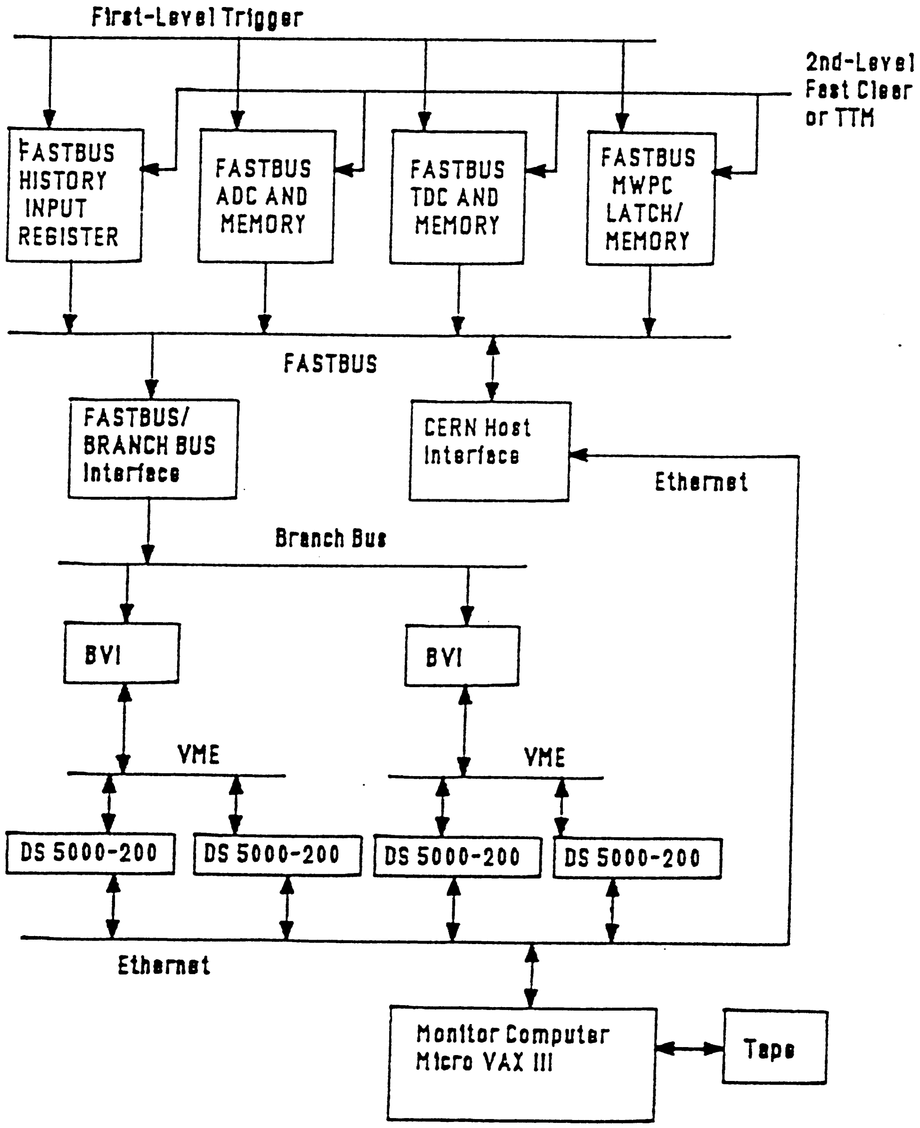

Figure 5: Schematic of the MEGA data flow architecture

years, then the MEGA experiment will take enough data to reach its goal of a sensitivity on the $\mu \rightarrow e\gamma$ branching ratio of 5×10^{-13}.

8. ACKNOWLEDGEMENTS

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