Progress Report 2002 and Beam Request 2003

A Precision Measurement of the Positive Muon Lifetime Using a Pulsed Muon Beam and the *μLan* Detector

PSI Experiment R-99.07.1, D. Hertzog and R. Carey, co-spokesmen

(Berkeley, Boston, Illinois, James Madison, Kentucky)

Overview

The Muon Lifetime ANalysis (*μLan*) experiment[i] aims to measure the positive muon lifetime to 1 ppm precision, thus determining the Fermi coupling constant, G_F, to 0.5 ppm. The experiment requires a high-intensity pulsed muon beam, a nearly hermetic decay spectrometer, a high-precision clock system, and a fast DAQ environment. Significant progress has been made since the submission of the original proposal. The collaboration is stronger, the experiment is funded,[ii] and prototype stages have been completed. At present, major construction on all components is started or nearly started. This report summarizes our progress with technical achievements and also reports on the "lifetime" analysis performed on data obtained in a summer 2002 run. Given these facts, our plan is to run twice in 2003, once to commission the final beam line with its new kicker and, later, to commission the whole experiment. Our major data taking would follow in 2004. The official **run plan and beamtime request** is included at the end.

Four short test runs have been completed during the last three years. We have developed a new beam-line tune and measured the phase space and flux at all key locations along the beam-line appendage. We built a mock kicker to simulate the final pulsed device. The critical extinction factor, which is the ratio of beam-off to beam-on during kicker activation, was measured to be 3×10^{-4}, exceeding the design goal for the experiment. We signed a contract with TRIUMF to construct the electronics for the final kicker and work has begun. The beampipe and plates will be built by PSI. The PSI test runs were also used to make short "lifetime" trial runs using variants on the original proposed detectors and target schemes. Following several improvements, we have recently commissioned 13 percent of the detector successfully and have read it out with waveform digitizers from the *g*–2 experiment. The results are good and we have initiated full production of the whole detector. Concurrently, we have developed a new 4-channel, waveform digitizer and have successfully tested prototype boards. All major components are ordered and the final layout is being tweaked prior to ordering all boards. Our data acquisition team is designing a system to handle and analyze the large volumes of waveforms anticipated in the experiment. With the synergy between the μLan and μCap experiment, we expect that some common development will ease these tasks. We continue to explore several innovative data storage options, but we have not settled on a final format. Our Monte Carlo modeling of both beam transport and experiment is becoming more sophisticated, leading to a fine-tuning of the final beam vacuum window region, wire chambers, and target size. We now anticipate using a fast wire chamber to count arriving muons during accumulation and to monitor beam position stability.

The experiment is fortunate to have many enthusiastic postdocs and students leading crucial tasks. To date, more than 20 students have participated in the effort. We expect to establish a more permanent presence at PSI in the coming year; for now, we have kept our groups at our home institutions where the developments are taking place.

μLan Experimental Concept

The *μLan* experiment is simple in concept. A stream of approximately 20 muons is brought to rest in a thin target during an accumulation period of several microseconds. The muon beam is then "switched off" and decays are recorded by a surrounding detector during a measuring interval lasting approximately 10 muon lifetimes (22 μs). This cycle is repeated until greater than 10^{12} decays are recorded. The time-structured muon beam must be created artificially at PSI by a installation of a new custom kicker.

During the measuring interval, the Michel positrons are recorded by a multi-segmented, nearly hermetic spectrometer. The geometry features 170 independent scintillator tile pairs, with each element read out by a PMT whose signal is sampled at 500 MHz by a dedicated waveform digitizer. The time of arrival and energy deposited in each tile are derived from a fit to the signal shape. Decay time histograms are constructed from coincident hits and are then fit to extract the lifetime.

The design of the experiment is driven by systematic error considerations. Primary concerns are related to multiparticle pileup, muon spin precession, time-dependence of detector gains or electronic thresholds, and backgrounds. Pileup is minimized by the segmentation of the detector, the relatively low peak rate per element, and by the double-hit resolution enabled by recording the pulse height in both tile elements for each event. Uncontrolled precession of the stopped, polarized muon ensemble can cause a change in acceptance of the detectors during the measuring interval, which occurs because the emitted positron rate is correlated to the direction of the muon spin. We plan to minimize the residual polarization by using a depolarizing target material, such as sulfur. Further reduction is realized by a systematic dephasing of the initial spins inside a uniform magnetic field. Finally, the detector features front-back matched, symmetric segments, where the sum of elements is nearly immune to a change in spin direction.

The instrumentation naturally divides into sub-systems: the muon beam and stopping target, (Illinois); precession magnet (Berkeley), the detector including scintillator tiles, lightguides, PMTs, and mechanical support (Illinois); the calibration system (JMU), the waveform digitizers and clock systems (Boston); and the data acquisition, logging and online analysis computers (Kentucky). Institutions with primary responsibilities for these items are indicated, but much of the work is shared by all collaborators.

Simulations and Measurements of the πE3 Beam

We have done extensive beamline simulations and tests over the past few years in order to optimize the transport of a "kickable" beam of sufficient flux. The layout is shown very schematically in Fig. 1. Notable in this drawing is the requirement for two sets of triplets following the kicker and separated by a third beamline slit system.

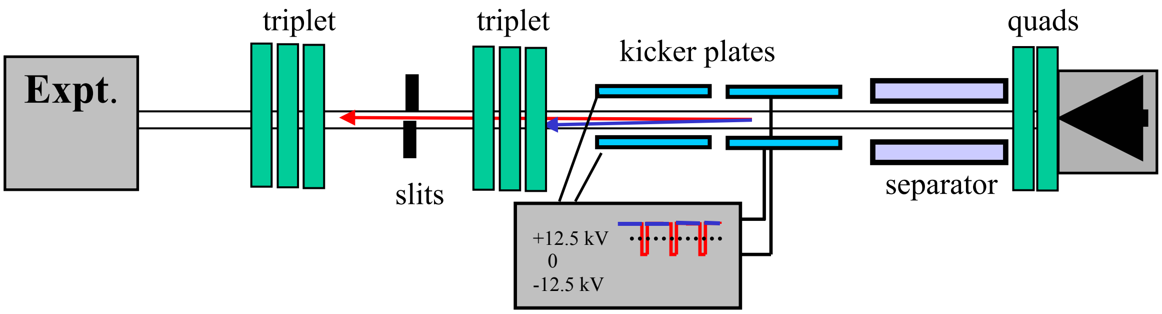

Fig. 1. Sketch of beamline components for appendage of πE3. Beam goes from right to left, with the first quad pair representing QSB71/72 in the standard πE3 drawings. The beamline length will require an extension to the area.

The optimized time structure will be created with a fast electric kick, which superposes an angular deflection on the beam. When kicked, the beam is absorbed on slits upstream of the target. The design extinction factor is a 99.9-percent. For a given applied voltage, the separation and length of the deflection plates not only determines the deflection angle, but also determines the switching time via the plate capacity. For an effective kick, the beam should have a small angular divergence in the kicker plane, but sufficient phase space acceptance to obtain the required muon flux. Thus, the kicker design requires a detailed understanding of the beam properties. We had to develop a program to measure the beam properties systematically, simulate beam behavior, and optimize a new kickable tune. In July 2002, we assembled a complete beam line for the *μLan* experiment and tested the new tune for flux, spot size, and extinction with a mock kicker on and off. The mock kicker was designed and built to produce the same deflection as the proposed electric kicker. With it, we made measurements at the focus after the kicker (i.e. the future slit position) and at the final focus on the stopping target. Figure 2 illustrates the calculated horizontal and vertical beam envelopes, and the insert depicts the box magnet mock kicker. The separator and the kick act in the vertical plane. The measured extinction factor, at 15 MHz, was found to be 3×10^{-4}, which exceeds the design criterion (See Fig. 3). At full acceptance, the measured unkicked flux was as high as 50 MHz.

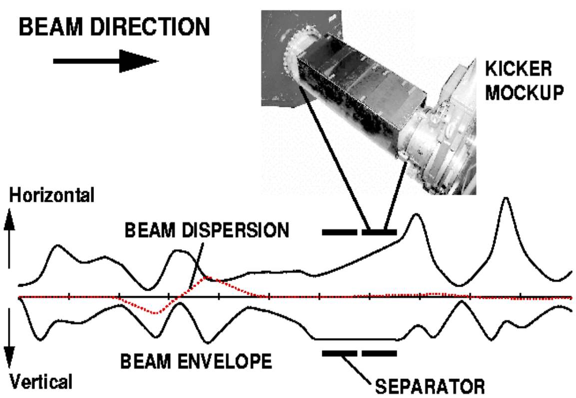

Fig 2. Beamline envelopes for our new tune for πE3 and its appendage. The mock kicker is shown in the photo.

We have initiated a contract with TRIUMF specialists Mike Barnes and Gary Wait to produce a fast electrostatic kicker, essentially two devices in the MORE style operating in series. Each kicker has plates 0.75 m in length, 20 cm high, separated by a 15 cm gap. The risetime and falltime for switching on or off the field is approximately 45 ns. The "off" state, corresponds to a zero potential (zero field), while the kicked or "on" state has a potential difference of 25 kV. New Boston postdoc, Anatoly Gafarov, who has significant prior experience in high-voltage switching networks, will be present at TRIUMF to assist in the construction and testing stages for the kicker. Anatoly will be responsible, from the *μLan* side, for the kicker during experimental operation at PSI. The construction of the plates and housing is the responsibility of PSI.

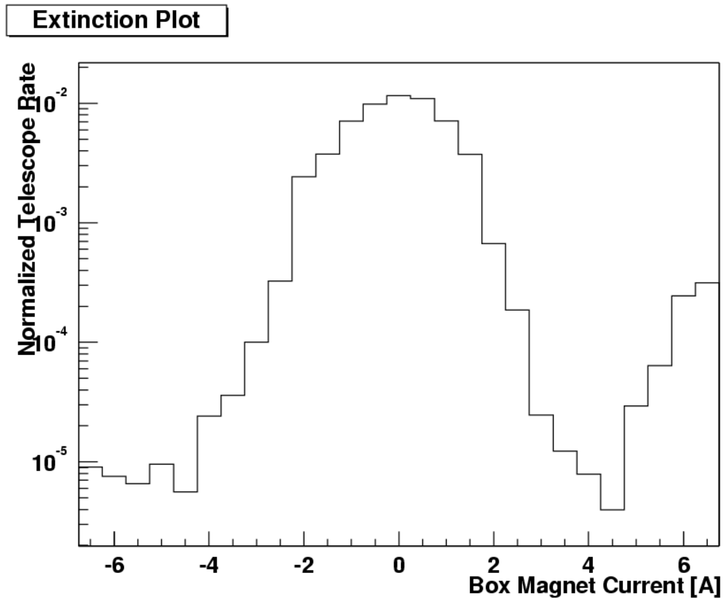

Fig. 3. Measuremetn of the muon flux at the beamline exit as a function of the pseudo-kicker (box magnet) current. The "on / off" difference exceeds 1000:1.

Note that the beamline will be longer than nominally in πE3. The experiment requires several additional meters for its footprint and to roll it downstream for access. Plans to extend the shielding are in place.

Detector Construction and Testing

Each of our PSI runs has also included extensive tests of detector prototypes and targets. The main elements of the detector are shown in Fig 4. They consist of tile pairs, which are 3-mm thick, triangular scintillators coupled to individual PMTs at 90° using mirrored beveled edges, and adiabatic lightguides. Clusters of five or six tiles are inserted into "pent- or hex-houses." The assembly of 20 hexagons and 10 pentagons forms a truncated polyhedron (soccer ball) geometry, having flat faces perpendicular to a radius from the center of the target and two units omitted for beam entrance and exit. Four of these structures were built and tested in July 2002 and were used to make realistic lifetime studies (see section below). The 44 detector elements contained therein were read out using *g*–2 waveform digitizers. Bartoszek Engineering is doing the mechanical design now for final detector housings. The overall support will likely follow that built for the *μCap* experiment. A sketch of the *μLan* Ball with such a structure is shown in Fig. 5.

Phototubes and bases have been selected for the detector following a competitive bid process. The final tube is an 11-stage, Photonis XP-2982 with a resitive divider base, optimized for count-rate stability and linearity.

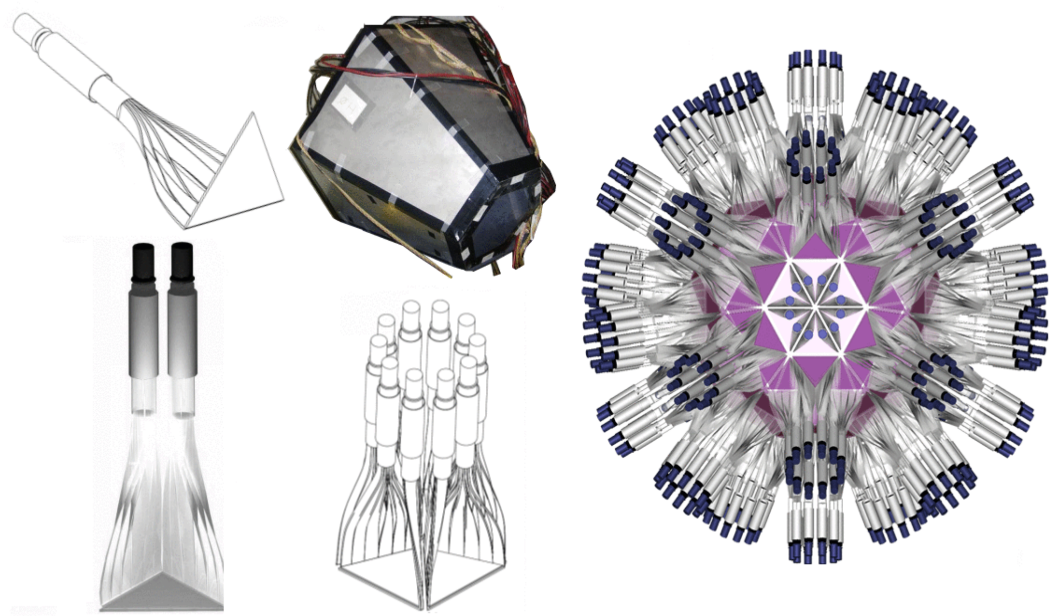

Fig. 4. The μLan detector elements. Individual scintillator element, lightguide and PMT (top left); tile pair (bottom left); pentagon cluster of tiles (bottom middle); hex-house complete structure (top middle); μLan ball (right).

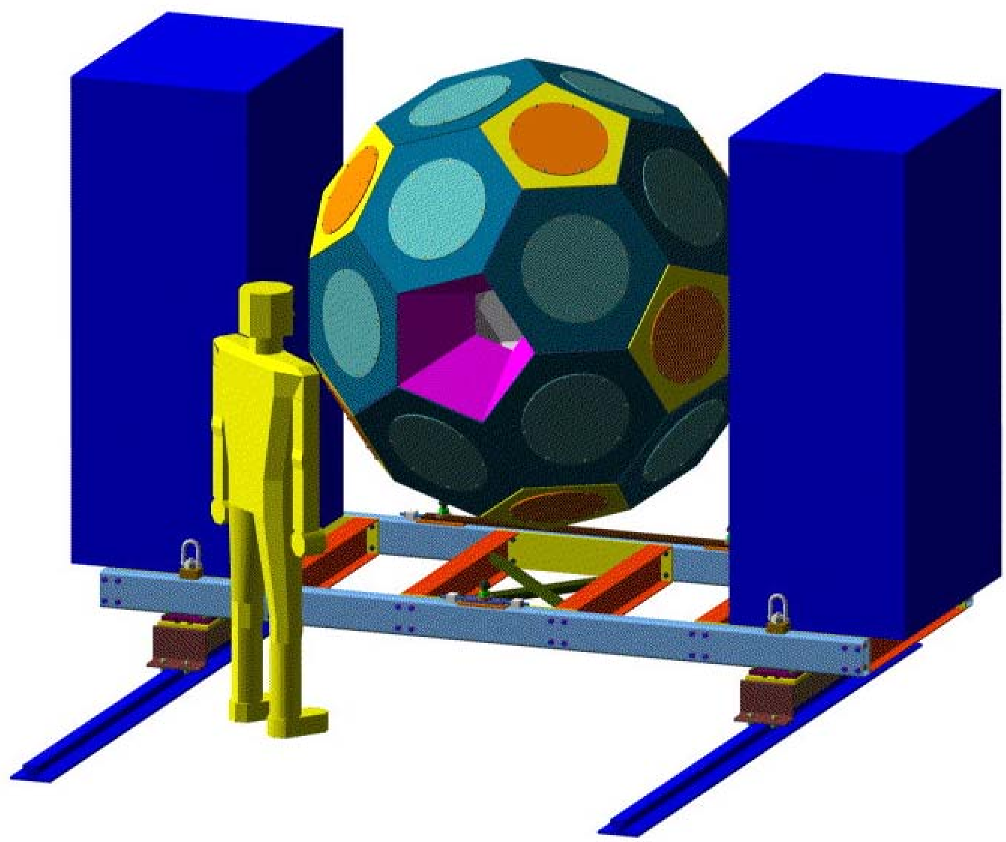

Fig. 5. The outside faces of the μLan Ball and a sketch of a support structure frame copying that used in the μCap experiment. The beam enters the exposed opening in the front of the Ball.

Status of the Custom Electronics

The heart of the front-end electronics is a waveform digitizer being developed at Boston University. Each digitizer channel will sample PMT waveforms every 2 ns, writing data to memory when it exceeds a programmed threshold, either analog or digital. The conceptual design of the board is very simple. A flash ADC produces 2 8-bit samples every 4 ns and presents them to a Field Programmable Gate Array (FPGA). The FPGA decides whether or not to keep the samples and assigns them a time. Samples are taken and the data transferred to the data acquisition system in a steady stream, without deadtime.

The principal challenge in the design is programming the FPGA to handle the high rate of data produced by the flash ADC. This past summer, we designed a single-channel prototype board as a proof of principle. For a test, we ran a relatively low-frequency sine wave into the device and reconstructed the waveform, as seen in the Fig. 6.

Building on that success, we have recently finished the design of a four-channel board with a full VME interface, external memory, and the other necessary I/O signals required by a real experiment. Moreover, we have tried to leave the device as flexible as possible. The data format is set only in the FPGA and setting aside a half-dozen of its input pins for user-specified logic signals should make it useful for a wide variety of projects. We expect to complete the final testing and deliver the working boards by early Summer, 2003.

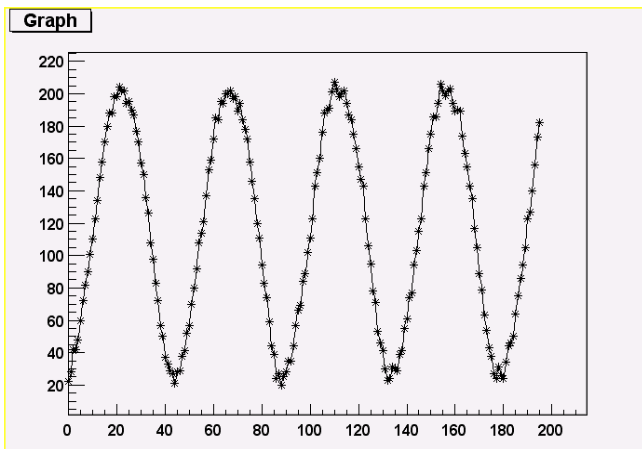

Fig. 6. Sample of a 10 MHz sine wave using prototype WFD at 500 MHz samples rate.

Status of Data Acquisition System

During the 2002 summer run we used a prototype DAQ that was based on the Midas data acquisition package and the ROOT analysis package. The hardware comprised one VME crate containing 12 WFD channels and 1 MTDC module, with a SIS3100/110 Struck interface from the VME crate to a 500 MHZ P4 rack processor. Data was acquired in "periodic mode", i.e. via a sequence of data collection and data read cycles, with the processor clock setting the collect-read frequency. The data rates were typically 1-2 MB/sec. The Midas package stored these raw data on hard disk and our MuRoot package converted these data to ROOT branches that contain both pulse shape and pulse parameters. We used a combination of the PSI archive and a DLT drive for the long-term data storage.

The mini-MuLan DAQ worked for MuLan, however we will require 1) data compression by the Midas front-end, 2) a cluster of ten front-ends feeding back-end processors, 3) better coupling of the Midas data acquisition and the ROOT online analysis, and 4) a way to store about 10 TB of data per run. These components must handle about 100 MB/sec on the front-ends and 10 MB/sec on the back-end(s).

The Kentucky group is primarily responsible for coordination and the main manpower for these developments. They will be aided by efforts from Boston and Illinois for specific tasks. We do not go into detail here the extensive number of tests being performed already, but summarize briefly that we believe a multi-crate system is capable of handling the rates, that either a disk archive system or a DVD “jukebox” type storage system is capable of handling the storage of the data, and that the modules are all “off the shelf.” We expect to do significant data throughput test runs in Summer, 2003, in parallel with the beam tuning tests requested, and with the detector in stand-alone mode using fast-pulsed LEDs.

Analysis of Summer 2002 Muon Lifetime Data

This summer we tested 44 detector elements (22 pairs) comprising 13% of the final detector. A uniform electromagnet was used to produce an 85 G magnetic field in the region where surface muons stopped. A 250 micron thick scintillator was used for muon identification just before the 2 mm thick stopping targets of either silver or sulfur.

The point-like symmetry of our detector pairs significantly reduces the μSR oscillations when the data from all pairs is summed. The result is that a simple fit function is able to be used to obtain a muon lifetime of 2196.9 +/ 0.3 ns (see Fig. 7). This is a 136 ppm measurement in good agreement with the PDG. In addition, if only the sulfur target data was used, a functional form without an oscillation term could be used to give a consistent chi squared minimization result.

The asymmetry for the different targets, sulfur and silver, is obtained by taking the differenced between the count rates in matched pairs. The “Forward – Backward” divided by the sum gives an indication of the residual polarization of the stopping muon ensemble. The results are shown in Fig. 8. To obtain these plots, the phases of each detector have first been carefully aligned to establish the overall asymmetry. The result is that sulfur has a depolarization factor of 11.5 over silver, exeeding the desired amount from our original proposal.

In addition to the above, the analysis led to other results. We can now identify pileup better than anticipated in the proposal. We learned to use software to compensate for detector alignment problems and inefficiancies between detectors. And our senstitivity to gain variations within the detectors, and gain stability have also been studied. Our practice with this small data set has confirmed our design specifications, relieved fears about some systematic issues, and prepared us for the full data set. We are in production of the final detectors with no changes being made.

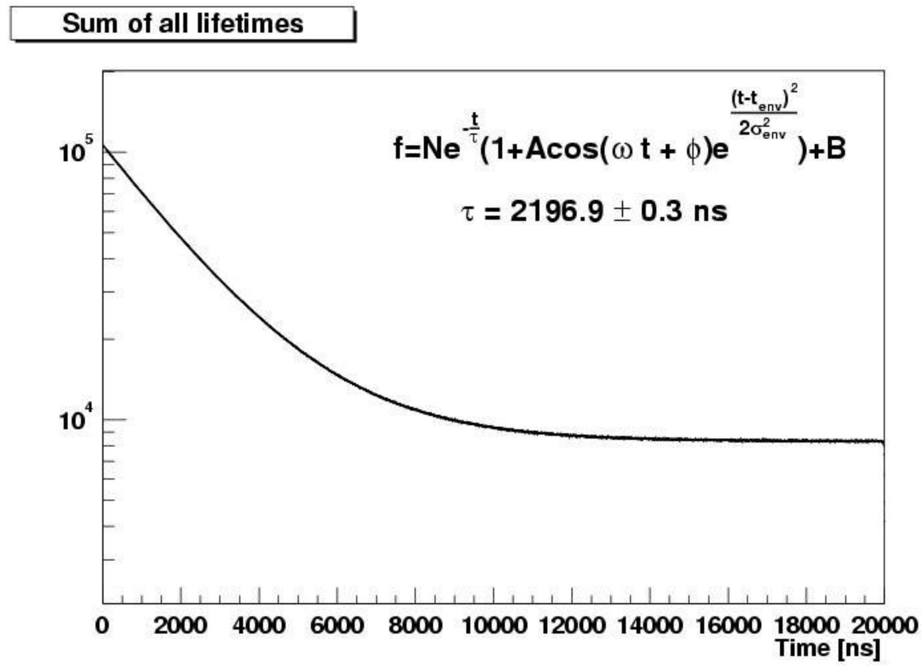

Fig. 7. Fit to the sum of all of the data obtained during the tests in Summer 2002 with both silver and sulfur targets.

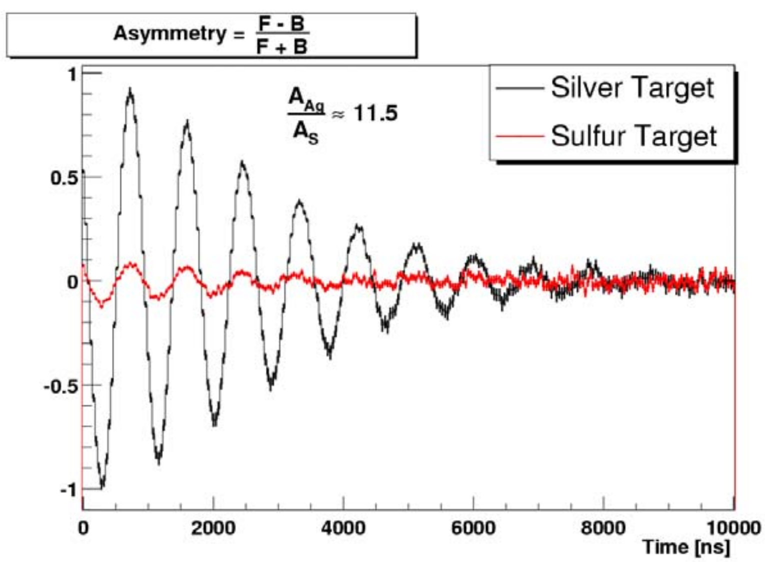

Fig. 8. Asymmetry of matched pair differences for silver and sulfur targets. This figure demonstrates the relative depolarization of the stopping muon ensemble when using sulfur compared to silver, where the polarization is expected to be retained.

Beamtime Request for 2003

The MuLan Collaboration, in coordination with the MuCap group, has been discussing our beam request for next year. The goals of the beam time requests for MuLan are:

1) BEAM TUNE RUN

To construct the final extended beamline with the new TRIUMF kicker and measure all properties: transmission, extinction, muon-on-request. The cyclic operation with μ^+ will be developed for MuLan. The muon-on-request (MORE) with μ^- will be developed for MuCap. We envision that the MuLan Collaboration will lead this effort, but some participation of MuCap people is welcomed (and necessary).

Total time anticipated: 4 weeks. Ideal schedule: July 2 - 30

2) COMMISSIONING / PHYSICS RUN for MuLan

To commission the MuLan experiment and obtain first physics measurements along with a program of systematic studies. This run will use the completed MuLan detector, electronics, DAQ, and Kicker. More than half of the time will be spent in systematic tests, debugging the first setup, and normal commissioning. We will reserve at least two weeks of "production" running at the end to obtain a significant data set in order to carry out realistic physics anslysis prior to the main production run in 2004. Goal: 3 ppm on the lifetime.

Total time requested: 5 weeks. Ideal schedule Nov. 12 - end of PSI operation

Meeting the Schedule:

The kicker will be ready by June 1st and will be shipped from TRIUMF to PSI. We must install it, along with the full beamline, which requires two triplets, a third slit, and the vertically-oriented separator used last year in πE3. Dieter Renker and Konrad Dieters are aware of these requests and must guarantee that these elements will be reserved for the requested running period. It is our understanding that there may be difficulty in obtaining a second triplet. This needs to be resolved soon.

The commissioning / physics run should be at the end of the year for two important reasons. First, we want to be confident that all components will be ready. Note, most items are in production now or nearly so. Many will be ready for the summer run. Secondly, late Fall works best for our many senior teaching faculty (Hertzog, Carey, Debevec, Roberts, Miller, Gorringe, Giovanetti). If we can reserve the end of the U.S. semester, many of us can obtain course assignments that will free up most of this time in order to be present maximally. In contrast, none of us could be at PSI from approximately mid August to mid September due to course startup duties.

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[i] R. M. Carey, M. Hare, W. Earle, E., Hazen, J. Miller, O. Rind, B.L. Roberts, *Boston University,* P. Debevec, F. E. Gray, D.W. Hertzog, C.J.G. Onderwater, C.C. Polly, M. Sossong, D.C. Urner, S. Williamson, *University of Illinois at Urbana-Champaign,* P. Cushman, *University of Minnesota*; *"A Precision Measurement of the Positive Muon Lifetime Using a Pulsed Muon Beam and the μLan Detector,"* Expt. R-99-07.1. Available on the Web at http://www.npl.uiuc.edu/exp/mulan/muLanMain.html

[ii] NSF Major Research Instrumentation award PHY-0079735, *Collaborative Research: The μLan Project-Development of instrumentation for a new high-precision determination of the Fermi coupling constant*, D. Hertzog and P. Debevec, *University of Illinois at Urbana-Champaign*, and R. Carey, *Boston University*.