Chapter 16.
Electron Detectors

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16.1. Measurement Overview

The muon anomalous magnetic moment, $(g-2)$, is determined from the measured precession rate of the muon spin $\omega_a = 2\pi f_a$ in a uniform magnetic field, by fitting to the time distribution of detected muon decay electrons in a given energy bin. The useful time span is ten muon lifetimes, or 640 μs.

Muons are held in the storage ring at the "magic" momentum of 3.1 GeV/c ($\gamma = 29.3$). The average spin polarization magnitude is better than 95% and is initially directed anti-parallel(μ^+) or parallel (μ^-) to the muon momenta. The ring radius is 711.2 cm and the B field is 1.45 T. The spin rotates with a frequency $f_s = 6.944$ MHz about the vertical magnetic field direction, while the cyclotron frequency is $f_c = \frac{eB}{\gamma mc} = 6.715$ MHz. The net rotation of the muon spin relative to its momentum ($(g-2)$ precession frequency) is $f_a = f_s - f_c \approx \frac{aeB}{mc} = 0.229$ MHz, where $a = \frac{g-2}{2} \approx 1 \times 10^{-3}$ is the muon anomaly. In the decay process, the electron (or positron) will have energies between 0 and 53 MeV in the muon rest frame(hereafter called *"CM"*). Since the lab energy ranges from 0 to 3.1 GeV, almost all decay electrons will be swept by the magnetic field to smaller storage radii, where they can be detected.

The time distribution averaged over all decay electrons is a pure exponential, but if the detected decay electron data are divided into energy bins, the exponential will be modulated at the precession frequency

$$N = N_0 e^{(-t/\gamma\tau)}\{1 + A\cos(\omega_a t + \phi)\} \tag{16.1}$$

where $\gamma\tau = 64.4\mu s$ is the dilated muon lifetime, $\omega_a = 2\pi f_a$, and A is the energy-dependent asymmetry. To see how these oscillations come about, consider for example a band of the highest energy electrons, $E(lab) > 2.5$ GeV. These can only be produced by electrons with CM energy $E(CM) > 43$ MeV and with directions $\Theta(CM)$ within 52 degrees of the muon momenta. Because the direction of electrons with $E(CM) > 43$ MeV is highly correlated

Figure 16.1.1: The magnitude of the decay electron asymmetry, A, versus energy.

to the muon spin direction, the number of electrons with $E(lab) > 2.5$ GeV oscillates with a frequency f_a as the spin precesses with respect to the muon momentum.

The overall asymmetry parameter A is the product of the stored muon polarization (which in our case is better than 95%) and the average asymmetry in the detected muon decay electrons. The asymmetry depends on the lab energy of the electron, being a maximum of 1 for the highest energy electrons, dropping to zero at about 1.2 GeV in the lab frame, and decreasing to $-\frac{1}{3}$ at $E = 0$ (see Fig. 16.1.1).

The statistical error in the measured $(g-2)$ frequency, when data are collected over many lifetimes, is given by:

$$\frac{\Delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{A\omega_a\gamma\tau\sqrt{N_e}} \tag{16.2}$$

where N_e and A are the total number of detected decay electrons and their average asymmetry, respectively, in a given energy band. The statistical weighting of an ensemble of

Figure 16.1.2: The relative number of decay electrons per unit energy, N, versus energy.

decay electrons for determining ω_a is thus given by $N_e A^2$. The detector design goal, then, is to choose a detector system which maximizes $N_e A^2$ over the ensemble of detected electrons, within reasonable cost constraints. In Fig. 16.1.1, Fig. 16.1.2, and Fig. 16.1.3 we show the differential asymmetry, the relative number of electrons, and differential $N_e A^2$ as a function of the lab electron energy. $N_e A^2$ reaches a maximum at about 2.6 GeV, with a broad peak ranging from about 1.6 to 3 GeV. The detector system was designed for optimum acceptance and energy resolution in this energy range, although only about 14% of all decay electrons fall above 1.6 GeV. Note that there is a secondary peak in $N_e A^2$ at low electron energies. However, the average asymmetry is low while the relative number of electrons is high. Detecting such low energy electrons efficiently would require a much more expensive detector: much larger geometric coverage of the inside of the storage ring, good energy resolution at these lower energies as well as at higher energies, and higher rate capability. As is discussed later in this document, pileup and time and pulse height

Figure 16.1.3: The differential NA^2 for decay electrons, which gives their relative statistical significance, as a function of electron energy.

stability are potential problems at very high rates. We have chosen to design a system which has good acceptance for the high energy electrons, where the quality of data per electron is highest. The approach in the CERN III experiment was similar; they combined all electron data for $E_e > 1.8$ GeV. The integral distributions of A, N_e and $N_e A^2$ for all electrons above a given energy threshold versus threshold are shown in Fig. 16.1.4 and Fig. 16.1.5. These plots show curves for various radial widths of the calorimeter, with our current design having a width of 22.5 cm. The outer radial side of the calorimeter should be as close to the storage region as possible in order to minimize the number of electrons which miss the calorimeters altogether and to minimize the average time for the electron to arrive at a calorimeter. [1]

Since the highest-energy electrons have the highest average asymmetry, we could in principle gain additional statistical precision by dividing the data above about 1.6 GeV into smaller energy bins, and fitting for the precession frequency for each bin. Only modest

Figure 16.1.4: The number of decay electrons detected versus the energy threshold on the calorimeter. This is given for several widths of the calorimeter. N = relative number of electrons above threshold.

energy resolution is required, and with the expected detector energy resolution of around $11\%/\sqrt{E}$, we expect about 15% statistical improvement with energy binning of the data. However, dividing the data into smaller bins increases the potential systematic error in $(g-2)$ due to rate-dependence in the electron energy measurements.(see Ref. 1). High energy electrons travel farther in the ring and therefore have a longer "drift time", the time interval between muon decay and electron detection, than low energy electrons. If the energy gain of the detectors varied from early to late times in the spill, then, for a given electron energy bin, the true average energy in the energy bin will be slightly different at early and late times, the average drift times will be slightly different, and a timing error will be introduced. In order to minimize this problem, it is most likely that we will combine the data into one large bin, above about 1.6 GeV, in which case gain shifts need to be

Figure 16.1.5: The integral value for NA^2 (= relative statistical significance) as a function of the energy threshold on the calorimeter. This is given for several values of the detector width. Note that NA^2 vanishes for all electrons at zero threshold, but does not vanish for detected electrons, since the detectors preferentially miss low energy electrons.

controlled to about 0.2%. [1] The average asymmetry for these electrons is about 0.4, and as noted previously, the fraction of all decays detected would be about 14%.

Ultimately, the frequency of muon precession must be compared to the spin precession frequency of a proton (NMR probe) in the same magnetic field. The ratio of the clock frequencies for the detector and that of the NMR system must be kept very stable. Furthermore, the clocks which drive the electronics must themselves be stable to better than 0.1 ppm at all times. The electronics clock will be a highly stable oscillator, phase-locked to the same LORAN-C module as the NMR probes.

16.1.1. Measurement Apparatus

In order to reach our goal of 0.35 ppm measurement of $(g-2)$, we must detect about 2×10^{10} electrons above 1.6 GeV, which will require about 1×10^{11} stored muons. We must restrict systematic errors in the average detection time of the electrons to 0.1 ppm in order to keep their contribution to the overall error small. This implies that we must keep the systematic error in timing below 20 ps for any 200 μs segment of decay data, and below 60 ps over 10 lifetimes (64.4 μs=1 lifetime), after which there are very little data.

It is worth emphasizing that in order to control systematic errors in our $(g-2)$ measurement, we must avoid shifts in timing at early muon decay times compared to late decay times, *on average*. For example, individual electron arrival times will be measured to the nearest 5 ns time bin, which is the TDC+derandomizer least count. But the time of arrival averaged over a very large number of decays must be good to 20 ps. This means we must have excellent control over rate dependent shifts in the averages for PMT transit time, discriminator response, and time boundaries in our clock system. If all of these were to shift by a small constant amount from one spill to the next, it would not affect the measured $(g-2)$ frequency. Such a shift would simply introduce a shift in phase for that spill, but not a shift in the measured $(g-2)$ frequency. However, a systematic effect from early to late times in the spill would lead directly to an error in the $(g-2)$ frequency.

For the case of pion injection, a 10 ns wide bunch of about 10^7 pions is injected into the ring. Some decay into muons, but most are lost to collisions with the vacuum chamber, quads, inflector, etc. This produces an intense "prompt flash" in the detectors which can blind the PMTs. Therefore, we have designed special bases which greatly reduce the PMT gains during the flash. The gain must return to normal within a few microseconds so that timing and energy measurements can begin as soon as possible after injection. The CERN III experiment experienced, in addition to the "prompt flash", a fairly substantial "delayed flash" which produced a large DC offset in the PMT output lasting tens of microseconds after injection. They attributed the delayed flash to the effect of secondary neutrons bouncing around the area of the detectors. In pulsed beam studies by our group at BNL we saw a large long-lived tail following the flash when the PMT was directly in the pion beam, but the tail was absent when the PMT was pulled out of the beam, whether the scintillators or lightguides were directly in the beam or not. In separate tests, we found that the PMT analog signals had long tails when placed near a strong radioactive source, indicating that the PMTs themselves are quite sensitive to passing radiation. We expect to conduct further tests with pulsed test beam in August 1994 with our "final" prototype detector elements. We also plan to place the PMTs in E821 so as to minimize their exposure to traversing charged particles.

At injection time, the muons are bunched spatially over about a 20 degree arc in the ring, corresponding to the 10 ns time width of the injection pulse. Owing to the momentum range of stored muons, the muons spread out around the ring, and the bunching structure is gone after about $40\mu s$. We plan to measure the rate of debunching in order to deduce the momentum distribution of stored muons. In order to make an effective measurement of the muon momentum distribution, we must begin timing of the muon decays within 5 μs, before there is overlap between bunches. Therefore the PMT's must have recovered from gating at ~ 5 μs or less after injection, before muons at smaller radii (lower momentum) overtake those at larger radii and the beam becomes debunched. The measurement of f_a will begin at about $20\mu s$ after injection, when the PMT gains have stabilized, muon losses have subsided, and after most of the bunch structure of the stored muons is gone.

Because the average rate of electrons incident on a single calorimeter, $20\mu s$ after injection, is about 6 MHz for muon injection, we must prepare the counters to handle the very highest rates. In addition, at the end of 10 muon lifetimes this rate has decreased to a few hundred per second, so the detectors must be stable against shifts in timing and pulse height over a very wide dynamic range(10^4). The detectors will be segmented to reduce the early-time rates per PMT, and considerable effort has gone into developing PMT and base combinations capable of stable operation at elevated rates. We have found that our base and PMT combinations are very stable at the highest rates anticipated in our measurement. One reason we are able to drive the tubes at such a high rate is that this high rate is not sustained, but instead decreases rapidly over a couple of hundred microseconds. This means that we do not exceed the manufacturer's specification for maximum average anode current. The instantaneous currents are low enough and sufficiently transient that space charge does not have time to build up in the PMTs.

For the calorimeter, a lead-scintillator combination has been chosen because of its speed, short radiation length, fairly good energy resolution, and high level of light output. The light output is large enough to have long light guides, allowing the placement of the PMT's well below the plane of the ring, where problems from the flash will be much less severe. High light levels also reduce potential background problems due to Cerenkov light produced in the lightguides by errant charged particles. The good time and energy resolution of the detectors makes it easier to monitor the rate stability and to handle pileup, which is essential to controlling systematic errors.

We are developing two different methods for recording the time of the electrons. The "T" method will use the conventional approach, used by CERN III, of recording the timing from discriminated pulses in a multi-hit time-to-digital converter (MTDC). In the "Q" method, the electron pulse height from the calorimeter is recorded at 2.5 ns intervals over the decay period using a waveform digitizer, data from all injections are added together, and the resulting spectrum, total calorimeter pulse height versus time, is fit for the precession frequency. [2]

We also plan a subsidiary measurement to establish a new limit on the muon electric dipole moment (EDM) which requires that we detect the oscillation in the average vertical component of the decay electron momenta. This can be achieved by vertically segmenting the electron detectors, as discussed below and by Miller et al. [3].

16.2. Detector Specifications

We have settled on a design where 24 detector stations are placed at equal (1.8 m) intervals around the ring (see Fig. 16.2.1). This maximizes the acceptance of the high energy electrons, which carry the most useful information on the $(g-2)$ frequency. The short radiation length of our design allows us to contain the electromagnetic showers with a short counter, and also reduces the number of undesirable side entering electrons, which tend to have much lower average energies and $(g-2)$ frequency information but larger shower leakage than front entering electrons. If the side entering electrons are not vetoed, then they are a potential source of pileup on top of the front-entering electrons, particularly when we operate at the highest rates. We have not yet determined whether we will need to veto side entering electrons (see below for the discussion of the side scintillator detector, SSD).

Each detector station will consist of a calorimeter and a horizontal array of five scintillator paddles on the front face of the calorimeter (Front Scintillator Detector, FSD) Fig. 16.2.2. Leading-edge timing for the $(g-2)$ precession frequency measurement would be taken from the FSD, and the time over threshold measurement of the discriminated FSD signal would provide information for pileup rejection, with both measurements utilizing the MTDC. For timing purposes, the FSD signal has the advantage over the calorimeter signal since the pulse height is independent of the electron energy. Pulse height and an additional measurement of the average time for a given event would come from the calorimeter and waveform digitizer (WFD).

At least one detector station will be a so-called "superstation", and will have, in addition, a scintillator along the side of the calorimeter closest to the storage region (Side Scintillating Detector, SSD), and a Position Sensitive Detector(PSD), or hodoscope, on the front of the calorimeter. The SSD would be a veto for electrons entering the side of the detector. The PSD is a scintillator fiber hodoscope with 0.7 cm segmentation in x and y. Its spatial information will be used for additional pileup suppression and to

Figure 16.2.1: Plan view of the detectors.

Figure 16.2.2: Calorimeter design.

provide information on the entrance point of the electron into the calorimeter. The vertical position information from the SSD or the PSD will provide the necessary data to place an improved upper limit on (or measurement of!) the muon electric dipole moment. The SSD performance will be evaluated for its pileup rejection capabilities, and may be incorporated at all stations for the high rate situation expected with muon injection. The PSD may be implemented at more stations if the unit cost can be reduced, mainly by finding a cheaper PMT and readout.

16.3. Proposed Detector System- Design Details

As previously mentioned, the detector system for the $(g-2)$ experiment will consist of 24 detector stations positioned at 15 degree intervals around the storage ring. Their height is limited to less than 18 cm by the pole gap. Part of the detector will be in the full magnetic field;the remainder will be in the fringe field. The task of each station is to provide a high-quality determination of the time of arrival and energy of decay electrons. The design is influenced by the high rate in the muon-injection phase of the experiment. Therefore segmentation is introduced into both the timing counters and the calorimeter. Scintillator fluors are chosen to be fast with fast decay constants. The calorimeter is physically compact to reduce the number of side-entering decay electrons (proportional to its length). Additionally, a side veto counter option (SSD) is provided, as is a highly segmented front hodoscope (PSD) to mark the entrance position of the electrons into the calorimeter. Each detector package is fully self-contained and is designed to permit detectors to be positioned as near as possible to the vacuum chamber walls of the storage ring while keeping all photomultiplier tubes and bases well out of the influence of the ring's magnetic field and out of plane from the initial flash caused by the decaying pions at injection. For ease of installation and handling, and to ensure proper and repeatable alignment, each detector package will ride in a carriage mounted on a set of precision rails. An N_2 laser-based calibration system will be implemented to illuminate all detectors with a pulse of UV light coming from a common source and, most importantly, at a common time. Laser illumination of the scintillator provides for complete system integration, a measurement of relative gain stability and a good timing standard.

An overall view of the detector package is shown in Fig. 16.2.1 The baseline plan provides for a four-fold segmented calorimeter at each station and a five-fold segmented set of front scintillator detectors (FSD). One "superstation" will include such enhancements as an SSD and a PSD.

A full prototype of the system was built and tested in the summer of 1993 (see below) from which final design changes have been made. At the time of this writing (3/94), many of the components are well under way to final construction and plans are firm for a 1994 beam test of the final design, including a mock-up of the storage ring magnet. The detector subsystems of the final design will be discussed in turn in the sections which follow.

16.3.1. Calorimeters

The calorimeters are made of 1 mm scintillating fibers embedded in a lead block. The construction of these Pb/SCIFI calorimeters consists of placing stretched "nets" of evenly spaced fibers on top of grooved lead/antimony (6%) plates. The fiber nets are held in the grooves by an optical epoxy. For the $(g-2)$ experiment, modifications have been made compared to our earlier work which results in a shorter radiation length, i.e. the detectors are more dense. This has been achieved by increasing the thickness of the lead plates while keeping the fiber-to-fiber spacing the same. An indirect consequence of this change has been the need to develop a somewhat revised assembly procedure including a new custom air-cylinder press facility which has recently been fabricated. On the whole the design of the calorimeters is based on our considerable experience with such devices and therefore represents a minimum of new or risky development. [4]

Each $(g-2)$ calorimeter is 22.5 cm wide $\times$ 14 cm high $\times$ 15 cm deep, with a radiation length of about 1 cm for a 35% packing fraction (35% plastic by volume). It is made of four separately-constructed modules which are then machined smooth and glued together to form the complete block, see Fig. 16.2.2. The fibers are oriented radially with in the storage ring coordinates which implies that the electrons enter nearly orthogonal to the direction of the fibers. The depth of approximately 15 radiation lengths is sufficient for reasonable containment of the showers, however slightly better resolution could be achieved by lengthening the blocks a few cm. This is not warranted in our application as the increase in the number of side-entering electrons and the need for larger light couplers offsets the slight resolution gain. It is expected that the resolution will be about σ = 10-13%/$\sqrt{E}$, in the final configuration. Test results on linearity and resolution are shown in Fig. 16.3.1 and Fig. 16.3.2.

One concern with the four-fold physical segmentation is the inevitable crack between modules. In the prototype version, one crack was oriented horizontally at the detector midplane. A noticeable gain loss and resolution degradation was seen there, and although a blemish in an otherwise uniform detector, we hasten to point out that it would have no direct effect on the measurement of $(g-2)$. However, substantial improvements have been made on two fronts. First, the machining and assembly procedure has reduced the effective

Figure 16.3.1: Calorimeter linearity.

Figure 16.3.2: Calorimeter resolution.

crack by a factor of three; it is equivalent to the absence of one row of fibers. Further, we have devised a method to machine oversized Pb/SCIFI blocks at 4 degree angles so that the crack now does not run horizontally, but rather, at a 4 degree pitch. From front to back, no straight-through particle path now exists.

Solid acrylic light couplers have been designed to gather the light from the inside radius of the flat and diamond-machined ends of the calorimeter and bring it to a two-inch round acrylic light pipe. The light coupler / mixer has been measured to have a uniform acceptance to approximately 1% across the entrance face. [5] Four such couplers, each $7.5 \times 8\ cm^2$ are glued to the Pb/SCIFI detector and, together with the calorimeter, are housed in a light-tight plastic box securely mounted and aligned to the detector carriage. The two-inch light pipes extend from the light couplers to the PMTs located approximately 48 inches away. Each light pipe undergoes a precise 90 degree bend having a 10 inch radius.

An important design parameter for $(g-2)$ is uniform light output, independent of the entrance position of the electron into the calorimeter. This can be problematic in a Pb/SCIFI detector because of light attenuation in fibers. For example, 2 GeV electrons entering at large and small radii will look somewhat different. We have studied this effect and determined that the detector's radial uniformity must remain better than 20% over the 23 cm width. The measured response is found to be about a factor of two better than this, as we now discuss. The attenuation length of scintillating fibers has two components; a short component (usually ignored) is thought to be associated with the trapping of light in the cladding, while the longer component is an intrinsic one dependent on the choice of fluor. In our application, light trapped in the cladding is soon lost to the lead plates through the optical epoxy which surrounds each fiber. The long component, measured by us to have an attenuation length of approximately 1 m, still yields a considerable change over the 23 cm-wide front face. We have had several iterations of fiber choice with Bicron, finally settling on a BC-404 based formula modified for our needs and embedded for the first time in a fiber. BC-404 is a known "fast" scintillator and is commonly used in timing applications.

Furthermore, attenuation length is wavelength dependent; short wavelengths are absorbed faster than long ones. Accordingly, we have studied the use of wavelength cutoff filters just before the PMT. A good compromise between light transmission and extended attenuation length is a Kodak #2E Wratten filter with a transmittance of 9% at 420 nm and 50% at 430 nm. This causes a 58% reduction in light from an unfiltered detector but doubles the attenuation length. The detector is uniform at the 10% level or better from the inside to the outside radius. With the configuration described, the light output corresponds to approximately 520 pe/GeV (1235 pe/GeV without filters).

16.3.2. Front Scintillation Detectors (FSD)

The FSD system consists of 5 radially oriented scintillator fingers each made of 3/8 inch BC-404 scintillator and measuring $2.8 \times 23\text{cm}^2$. Together, the five fingers cover the entire front face of the calorimeter. (See Fig. 16.2.1.) The light couplers for this system consist of three parts which ultimately, as for the calorimeters, result in the light being piped to PMTs situated near the floor more than 1.5 m away. In this case, 1 inch stock acrylic is used which matches the PMT choice, giving approximately adiabatic matching of the lightguide pieces. Care is taken to wrap them as a group and to ensure their alignment with the calorimeter and carriage. Accordingly, physical slots are prepared in the plastic light-tight box housing the calorimeter which extend to align the FSD system. Provision is made for a quartz fiber which will be attached to the front of each slab for calibration purposes.

16.3.3. Position Sensitive Detector (PSD)

The position sensitive detector (PSD) is basically a scintillator hodoscope composed of one x and one y plane each with 7 mm segmentation. Since the calorimeter has little inherent position information and the FSD provides only 5-fold segmentation in the vertical plane, a PSD is also planned for at least one station. If the unit cost can be brought down sufficiently, we may upgrade all detectors at some point in the future. The PSD provides rejection of spatially separated hits which occur within the same 2.5 ns time window, a more precise measurement of up-down asymmetry in the precession plane in the analysis of the electric dipole moment limit, redundancy in the muon distribution measurement when used in conjunction with the traceback chambers, and may be a general calibration tool to understand any non-uniformities or leakage problems in the calorimeter. In order to employ it properly as a calibration tool, the PSD should be portable and each calorimeter station should be designed to accommodate one PSD. This also allows for a possible upgrade to additional PSDs during muon injection when rates may require better pileup rejection than that achieved by the FSDs alone.

Three main considerations drive the present design: (1) Due to the segmentation, the PSD is inherently a more costly device to read out and therefore a multi-channel photosensor is the appropriate choice to keep the per channel cost low, (2) there is barely 2 cm between the top of the calorimeter and the bottom of the magnet pole tip in which to extract the light from the vertical strips, and (3) the photosensor must be removed from the midplane and placed more than a meter away from the PSD, necessitating a long light pipe. Considerations (2) and (3) imply some sort of fiber light guide with small cross

Figure 16.3.3: PSD.

sectional area and flexibility. In addition, the small size of the pixels on a multi-channel phototube also force one to abandon any simple adiabatic light guide solution. The highest light yield solution to the area reduction problem (detecting light generated in scintillator strips of cm^2 cross section by mm^2 pixels) is to use wavelength-shifting fibers. The original PSD designs used "pencil fibers" from Kuraray, so-called because the core (or lead of the pencil) was a green wavelength fiber embedded in a second, larger diameter blue fiber (the wood of the pencil). These have very good photon capture efficiency, but the mechanical problems of mating them to clear plastic light guides for transmission to the phototube outweighs the advantages. Since Kuraray has discontinued their manufacture, we have designed and built our own hodoscope elements. Each strip is formed by cutting a groove down the center of two 7mm $\times$ 4mm Bicron 404 scintillator strips, placing a 1mm diameter Kuraray multi-clad Y11 green wavelength-shifting fiber in the groove and then gluing the two halves together to form a 7 mm wide $\times$ 8 mm deep element. Each strip is individually wrapped in teflon sheeting and the bottom of the fiber is mirrored. The length of the horizontal strips is 23 cm and the length of the vertical strips is 14 cm. A custom optical coupler mates each of the green central fibers to 1.5 meter long clear plastic light guides of the same diameter. This optical connector enables one to disconnect easily or interchange the tube and light guide assembly from the PSD active elements. Fig. 16.3.3 shows an engineering drawing of the PSD assembly and mechanical support.

The PSD is a threshold device whose 53 channels will be read out by two 27-channel MTDCs. Since a typical hit in the PSD produces only a handful of photoelectrons, PSD performance is determined by how well these hits can be separated from ambient noise. Tests using a triple coincidence trigger with a Sr^{90} source have consistently shown 15 photoelectrons at the end of the light guide, as observed by a Hamamatsu R1332 photomultiplier tube which has 12% quantum efficiency in the green. This is adequate for 99% efficient sensing of minimum ionizing particles (which is what the electrons are to the thin PSD). However, any reduction in the quantum efficiency of the photosensor will lead to inefficiencies.

The commercially available multi-channel tubes have some disadvantages which make them marginal in this application. There are only two manufacturers of such devices: Philips and Hamamatsu. The Philips tube has generally poor quantum efficiency in the green, averaging 4-10%. The Hamamatsu tube has better quantum efficiency (12%), but its energy resolution is worse by a factor of 5. The poor resolution cancels out the improved sensitivity, since a broader peak due to gain dispersion is just as bad for a threshold sensing device at low light levels as a peak broadened by poor quantum efficiency. All these tubes suffer from crosstalk at the 2-5% level. However, a new multi-channel hybrid tube being developed by a member of this collaboration (P. Cushman) is well-suited to this application.

It is a proximity-focused tube with a segmented avalanche photodiode as the target. The total gain of up to 10^6 comes in two stages: from the acceleration of photoelectrons across the 6 mm gap (to which 10 kV has been applied) and an additional gain from the avalanche produced within the reverse-biased diode. Crosstalk is $< 0.1\%$ between the 64 1mm square pixels. The S20 photocathode typically yields 20% quantum efficiency in the green and we have made several Gallium Arsenide tubes with 40% quantum efficiency in the green. Read out with GaAs photocathodes, the number of detected photoelectrons at the end of the light guide will be 50. At these light levels, it is possible that the timing measurements from the PSD will surpass those from the FSD, since the hybrid tube has been measured to have a time jitter of less than 50 ps.

16.3.4. Side Scintillation Detectors (SSD)

A side veto counter system (SSD) has been developed, and may be important in attempts to keep pile-up from affecting the accurate determination of an electron's energy. The idea is to eliminate any event where a substantial amount of energy is deposited by an undetected side-entering electron entering in time with an ordinary front-entering electron. A 1/8 inch fast scintillator placed along the outside radius of the calorimeter can serve this purpose. Simulations show that electrons entering the side of the calorimeter cross this thin scintillator at such a glancing angle so as to leave a considerable energy deposit. This is in contrast to shower electrons leaking from the calorimeter itself which typically leave a small pulse height.

An SSD was incorporated into our 1993 test beam and provision for it is included in our detector carriage design. However, we were not convinced from the test beam results that the distinction between side-entering and leakage electrons could be made as reliably as we had hoped from the simulations. Accordingly, we will only provide an SSD on the superstation in time for the 1996 pion run and will continue to study its possible use.

Note that the SSD is coupled to a two-inch PMT through another adiabatic light transport system, this time through two 90 degree bends, one to turn radially, the second toward the floor.

16.3.5. PMTs and Bases

For the $(g-2)$ experiment, we need phototubes for both the front scintillation detectors (FSDs) and the electron calorimeters. Based on a series of rate, gating, and flash tests on different phototubes, the Hamamatsu R1355 and R1828-01 were selected for the FSD and the calorimeters, respectively. The R1355 is a 10-stage tube with a 28.5 mm active diameter, a 2.0 ns rise time, and a 23 ns transit time. R1828-01 is a 12-stage tube with a 53 mm active diameter, 1.3 ns for rise time, and 28 ns transit time. The transit time spread (FWHM for single photoelectron state) is about 650 ps for the R1355 and 550 ps for the R1828-01. So if the number of photoelectrons seen by the PMT is 200 for the R1355 and 500 for the R1828-01, then the transit time spread will contribute about 46 ps for R1355 and about 25 ps for R1828-01 to the FWHM of the timing histogram.

The PMT bases for both the R1355 and R1828-01 were designed by the Electronics Design Facility (EDF) at Boston University. The voltage distribution ratios were chosen from the options suggested by Hamamatsu. Different voltage distribution ratios give different rise times, gains, and linearities. The voltage distribution ratios finally used give the fastest rise time and reasonable gain and linearity for both tubes. It was necessary choose a transistorized base in order to hold the dynodes voltages stable at the highest rates. A zener diode was added between the photocathode and the first dynode to give the best possible timing stability. A transistorized switchable circuit gates off the R1355 (R1828-01) by switching the voltage on dynode 5 (dynode 7) to the same value as on dynode 2 (dynode 4). These dynode combinations were found to optimize the gain reduction and speed of tube recovery when the PMTs are switched off and on.

The output of the phototubes also poses problems. Even if the impedance of the cable and electronics input are 50 Ω, reflections at the few percent level can still be found if there is only one output from the anode. This small reflection may cause a timing shift or multiple discriminator pulsing. One way to solve this problem is to have two very short coaxial cables coming out of the anode and use a 50-Ω terminator to terminate one of the outputs so that all the reflection from the electronics gets absorbed properly by the terminator. In this way, we can have a clean signal, although its amplitude will be cut in half.

The issue of whether to clip the PMT analog signals is still under investigation. CERN III had problems with a decaying DC offset in the PMT signal just after pion injection. A short clipping stub, shorted to ground, would greatly reduce this DC offset problem. However, in tests employing a fast pion beam at BNL, we attributed the DC offset to the direct response of the PMT to traversing charged particles. By placing the PMTs out of the plane of the ring, we hope to eliminate this problem. Thus, we may be free to place a resistor at the end of the clipping stub, and to adjust the resistance and the length of the clip line until the natural tail from an individual pulse is cancelled. This will greatly reduce the time shift of a pulse which would otherwise have been sitting on the tail of the previous pulse, a circumstance which may be a significant problem at the high rates of muon injection.

16.4. Detector Electronics

16.4.1. System Architecture

The heart of the $(g-2)$ measurement is the precise, rate-independent measurement of muon-decay electron arrival times. In addition, electron energies must be measured with modest resolution, in order to to select those of highest energy (which have the highest asymmetry) and to bin the data according to energy. Both timing and energy measurement systems must operate at peak rates of up to 8 MHz per calorimeter for muon injection, and must digitize as many as 400 events per calorimeter during the 1 ms muon storage time. During the 1 or 2 seconds between AGS storage ring fills, data must be transferred to mass storage and any on-line calculations necessary for monitoring the experiment must be performed. In addition to the calorimeter and FSD readout, data must be acquired at similarly high rates from PSDs and the muon phase space reconstruction systems. Finally, data from the on-line calibration system and from the NMR magnetic field measurement system must be included in the data stream and stored for later detailed analysis. Precision field measurement and precise decay-time measurements must also be coordinated through a common high-stability clock and its associated clock signal distribution system.

Our baseline detector electronics system is built around a few modular components, a multi-hit time to digital converter (MTDC), a "derandomizer", and a wave form digitizer (WFD), each of which has a prototype currently under test. The readout electronics for the calorimeter and FSD systems are illustrated schematically in Fig. 16.4.1.

The MTDC records the times of the leading and trailing edges of logic pulses with 1.25 ns accuracy. A prototype of this device has been developed at Boston University in collaboration with the DUMAND experiment. A VME version with on-board memory is being developed at BU. The key element within this device is a new Gallium Arsenide-based ASIC (Application Specific Integrated Circuit) running with a split-phase 400 MHz clock.

Figure 16.4.1: Schematic illustration of E821 readout electronics system architecture.

The MTDC registers the time of the leading and trailing edges of the input logic pulses. If the logic pulse is time over threshold from the PMT's, then the width of the pulse can be used for pileup suppression. It also identifies piled-up pulses with small temporal separation (plus tagging anomalously wide pulses resulting from nearly simultaneous piled-up events-the width is deduced since the time of trailing edge of the logic pulse is also recorded) for each of up to 27 independent input signals. Data from the FSD and calorimeter will be read out by separate channels of the MTDC so that correlation of data from each of these devices may be readily achieved.

A $(g-2)$ prototype of the MTDC is now being tested, and the functionality of the ASIC chip has been proven. For the time being, the device sits inside a large rack-mount box along with its power supplies and an interface board. As there is no large on-board memory, the MTDC is read out into a 128 Kbyte LeCroy 1190 VME memory module. We have recently begun using our $(g-2)$ decay pulser (which produces a spectrum of pulses with the timing characteristic of our experiment, but no modulation) to exercise the MTDC and have successfully read out hundreds of pseudo-spills with UNIDAQ and VxWorks, the data acquisition and operating systems, respectively, which we expect to use in the real experiment. The MTDC ASIC, its interface and memory will be repackaged into a triple width 9U VME card in late summer 1994. We expect that much of the original design can simply be transferred to the new one, and that the VME interface can be borrowed in large part from that for the WFD, which is described below.

A second component of our electronics is a "de-randomizer" circuit which will unambiguously associate asynchronous discriminator transitions from the FSD with synchronous clock cycles. In fact, we plan to use a single 200 MHz clock for the derandomizer, MTDC, and WFD, so that they are all in phase. The MTDC board would have a x2 frequency multipler to provide the necessary 400 MHz. The derandomizer is housed in a NIM module, with 4 channels per station. Its input will be the logic pulse from a discriminated FSD signal and its output, a logic pulse whose leading edge has been shifted to the center of the proper clock pulse, which is then fed into the MTDC. The time boundaries of each 5 ns bin must be stable on average to 20 ps over 200 μs, i.e. 0.1 ppm. The derandomizer is necessary since the MTDC is not designed to be free of systematic errors to 0.1 ppm. The de-randomizer circuit will only be used for those channels requiring high-stability timing, corresponding to discriminated FSD outputs in our baseline design. By separating the functions of high stability pulse synchronization (with the derandomizer) from the time scaler (with the MTDC) we hope to isolate and minimize any sources of systematic error.

A derandomizer prototype was produced by the BNL instrumentation group, and was delivered to BU in February of 1993 but, owing to early problems with the MTDC ASIC, we have just begun to examine its performance. It was tested and certified as rate independent in isolation from the rest of the detector electronics. In particular, we have moved a pulse very slowly (fractions of a ps per step) across a clock boundary and verified that the derandomized signal moves cleanly and suddenly from one time bucket to the next and that it does so in a rate-independent manner. Naturally, this test must be repeated for a variety of ambient rates and the transition between buckets should look the same in all cases. We also plan to perform the so called synchronous random phase test, developed by by the CERN III experiment, to measure the linearity of our counters.

For the calorimeter energy measurement, we have constructed a two phase 400 MSPS (Mega-samples per second) zero-suppressed waveform-digitizer (WFD) system. The WFD was developed by the BU electronic design facility in collaboration with the BU MACRO group. The WFD is a VMEbus slave module designed to digitize and store analog input data at a rate up to 200 MHz. With a pair of channels operating 180 degrees out of phase on the same analog pulse, we will effectively sample at 400 MHz. We have indicated the internal operation of a WFD channel schematically in Fig. 16.4.2. There are four independent WFDs per VME motherboard. Each channel has in turn four analog inputs, corresponding to the four PMTs on each calorimeter. The sum of the four analog signals is digitized by a 300 MHz, 8 bit flash A/D converter, while each of the four inputs is separately discriminated. In zero-suppress mode no data throughput occurs unless at least one of the discriminators has fired. After every four conversions, the digitized data are stored as a parallel group of four bytes, allowing a 50 MHz rather than 200 MHz data storage rate. At the time each group of 4 data bytes is stored, a 16 bit time word (incremented every 5ns) plus 2 bytes of discriminator information are also stored, resulting in a total of eight bytes of information being stored at a rate up to 50 MHz. Each channel of the module is allotted 64 Kbytes of storage: 32K for pulse samples and 32K for time and discriminator data.

The MACRO version of the current motherboard is about to go into production. Any modifications for $(g-2)$ will be minor. The front end amplifier card of the WFD, a daughter card which is mounted, in turn, on the 9U mother board, is being modified for the needs of the $(g-2)$ experiment. Specifically, it should be capable of handling high rates and fast phototube signals and have good linearity characteristics. The new front end should be ready for testing in the late summer 1994.

We tried out a second generation prototype WFD card in the July 1993 beam test. The WFD worked the first time we plugged it in. The energy resolution curves were identical to those produced using conventional charge-integrating ADCs. We also tested two-phase operation by splitting the linear signals, delaying one copy and sending it off to another input channel. That, too, was a success.

Figure 16.4.2: Schematic illustration of waveform digitizer internal operation.

Several critical tests remain. We have made preliminary tests of the pulse height stability with rate which look promising, but we won't have a truly definitive answer until the new amplifier front end arrives. The same goes for the stability of the time response.

In addition to event-by-event determination of electron energies and the detection of anomalous pulse shapes (for pileup rejection), the WFD system is being incorporated into an alternative system for measuring the muon precession frequency with the same calorimeter pulses, termed the "Q-method". In the Q-method, waveform digitized calorimeter pulses are digitally summed across many fills, and the resulting pulse height/timing pattern fitted to a sinusoidally modulated decaying exponential. The timing versus rate stability and linearity requirements for the WFD system are more demanding than for the conventional energy-threshold technique (the "T-method"), and we are in the process of determining whether our WFD meets Q-method requirements for linearity and rate-independence in its digitization of pulse heights.

The baseline DAQ electronics system described thus far is for a general detector station. In addition we expect to instrument between 1 and 4 "superstations". As mentioned above, superstations will include Position-Sensitive Detectors (PSD) and Side Scintillator Detectors (SSD) for additional pileup rejection, as well as additional calibration, monitoring, and pulse measurement capabilities. Although there is no provision for waveform digitization of FSD signals from general stations, for example, our modular design allows us to outfit a superstation with this capability if we so choose, and to thereby make informed decisions on potential future electronics upgrades. The modular DAQ electronics system design allows this and other variations on the baseline design to be explored at superstations.

16.4.2. Calorimeter Readout

Each of the four PMTs on a calorimeter is split into calibration and WFD signal paths (Fig. 16.4.1). Resistive splitters are used in our conservative baseline design, but we will characterize the rate independence of commercial active splitter modules as well. Our baseline design for standard stations includes only a 2-way split, while superstations might use a further split to form analog sums of the calorimeter PMT signals. These summed signals would then be discriminated and accurately timed in the same manner as FSD signals (as discussed below). For standard stations, we will use the WFD as a multiple-hit ADC which samples the pulse height of the sum of the four PMT signals every 2.5 ns, and Lecroy CAMAC-based FERA ADCs will be used for calibration and monitoring. The purpose of the calibration ADC is to provide a high-resolution measurement of the calorimeter PMT response to a laser calibration pulse. This pulse will be generated once per storage ring fill, at varying time positions relative to injection, to monitor any gain or time shifts from early to late decay times. For our baseline design (if funding allows), we plan to have a separate FERA calibration channel for each PMT in the experiment.

Our baseline design also calls for an MTDC for the time correlation of calorimeter signals with those from the FSD. Input to the MTDC is provided by the discriminators in the WFD. Superstations may discriminate each PMT individually and record separate times to the MTDC and may also include de-randomizers on discriminated outputs of either fanned-in or separate calorimeter PMTs. This implementation will require sufficient rate-independence from the calorimeter PMTs and might also require the use of constant-fraction discriminators (or a software correction) to eliminate the correlation between pulse-amplitude and the time of the discriminator pulse. However, the rate dependence of CFDs tested (see §16.4.3) was unsatisfactory, so this correlation will have to be corrected in software.

If the calorimeter signals are to be used to provide a second precision timing system for the superstations, it will be necessary to include more high-resolution calibration TDC channels of the type discussed below.

16.4.3. Front Scintillator Detector (FSD) Readout

The FSD system provides the precision timing measurement for the determination of $(g-2)$. As discussed earlier, we plan to isolate rate-dependent effects within the electronics to the PMT, base, and "de-randomizer" circuit. Error-free recording with the MTDC system should then be straightforward. The input to the de-randomizer will be provided by a single channel from a leading edge discriminator; initial tests are currently being carried out with a Phillips 704 300 MHz Quad leading edge discriminator. The use of constant-fraction timing would minimize the correlation between timing and pulse height from the PMTs, but the rate-dependence of a candidate CFD, the Phillips model 714, is too large at the highest rates expected in our application. By contrast, the Phillips model 704 leading edge discriminator displays no rate dependence at or beyond the highest rates anticipated in the experiment. In spite of the merits of CFD timing, we have decided to use leading-edge discriminators in the experiment. We note that the variation in the electron pulse heights in the FSD is not large and tests have shown excellent gain stability in our candidate PMTs which facilitates the use of leading edge discriminators for timing.

The direct and de-randomized FSD discriminator outputs will be sent to separate MTDC inputs. The purpose of this partially redundant readout is to preserve the 1.25 ns resolution of the MTDC for the leading and trailing edge timing of the direct discriminator output, since the derandomized pulses will only be timed with 5 ns resolution. The fine time resolution on the MTDC will be used to reject pileup through analysis of temporal and spatial hit patterns. Two pulses too close together in time could be rejected, or two pulses nearly on top of each other will produce a discriminator pulse which is over threshold too long compared to a single pulse. For superstations, we will implement precision TDCs which will monitor the FSD timing response to calibration laser pulses. The calibration TDC will be a LeCroy 2228 8-channel TDC, with 50 ps resolution. This fine time resolution permits calibration and monitoring with many fewer calibration pulses than with the coarser MTDC timing. The calibration TDCs will be operated at a low constant rate to maximize their stability. The superstation FSD readout system may also include fanning out the analog signal to a waveform digitizer and calibration ADCs.

16.4.4. SSD and PSD Readout

The side scintillator detector (SSD), which will be found only in "superstations", is used to reject decay electrons entering through the side of the calorimeter. The SSD is read out with a leading-edge discriminator whose output is fed into the MTDC system. The threshold would be set so that the discriminator fires on the large pulses from side-entering electrons but not on the smaller pulses from electrons leaking from the shower of a front-entering electron. An alternative implementation of the superstation SSD readout might include fanning out the signal to waveform digitizer and calibration ADC systems of the type used for the calorimeter signals.

The PSD is read out with the MTDC, like the FSD but without the derandomizer. The sparse nature of the PSD data is well-matched to the MTDC 27-input design. For our baseline, we have assumed that each PSD will require two MTDC modules, which will record threshold-crossing times for the summed-anode output provided by the PSD multianode PMT and/or a synchronization signal. The 1.25 ns resolution time of the MTDC system is smaller than required for the PSD and sufficient for accurate correlation of PSD, FSD, and calorimeter information. For our baseline, we plan to use Phillips model 706 100 MHz 16-channel leading edge discriminators, although an integrated preamplifier/discriminator system such as the 16-channel LeCroy 2735DC is another possibility.

16.4.5. Clock Distribution, Calibration and Test Electronics

The $(g-2)$ Clock and its distribution system are indicated schematically in Fig. 16.4.3. Our baseline precision clock for the $(g-2)$ experiment is a temperature-controlled and highly stable 200 MHz oscillator which is phase-locked to the LORAN standard. For historical reasons we still sometimes refer to this as a "frequency synthesizer", as in the figure. From this standard we must generate both a 400 MHz clock for the MTDC as well as 200 MHz signals for all the WFDs and derandomizers. We will therefore require a clock fan-out distribution system, which is currently under development. Low-dispersion cables will be used in the clock signal distribution to preserve the clock pulse integrity, and both the cabling and the fan-outs (housed in RF-shielded NIM modules) will be well-shielded from such sensitive circuits as the NMR field measurement system. The NMR system will also be locked onto LORAN, and the maintenance of a constant ratio between the frequencies of the two clocking systems will require careful verification. For testing the stability of our precision timing circuits against rate changes and other effects, we will use a precision frequency generator which can be beat against the master clock. This Synchronous Random Phase Test, developed by the CERN $(g-2)$ group, is one of many tests we will perform on the system. In connection with these tests, we have constructed two custom modules: 1) a "flight simulator", which can faithfully deliver a train of pulses similar to that expected in the detectors, and 2) a device (described earlier) which produces a logic pulse with varying time relative to the clock, in order to test the stability of the derandomizer near a clock boundary.

16.5. Calibration System

We anticipate performing PMT analog-signal calibration with our laser-based and LED-based calibration systems. The laser will be fired once per $(g-2)$ storage ring fill, with the delay between injection and laser firing controlled by a programmable pulse generator (such as the HP 8112A). The intensity of the pulse will be monitored by an isolated independent PMT. Emphasis will be placed on detecting any shifts in pulse height or timing as a function of time after injection, which appear as a direct systematic error in our $(g-2)$ measurement. The LED calibration system will be used for tests at high rates, and will require computer control over pulse amplitude and timing, whether used in single pulse or high-rate mode. It will also require LED driver pulse fan-outs to provide an LED signal at each PMT. Finally, it will be very important to analyze the pulse shapes

Figure 16.4.3: Schematic illustration of E821 clock and clock distribution system architecture.

Figure 16.5.1: Laser calibration system.

produced by both to decay electrons and the laser light source with a 1 GHz digital storage oscilloscope.

Our high-precision measurement relies heavily upon accurate calibration in order to measure those systematic effects which cannot be reduced below the 0.1 ppm level. For timing shifts which vary as a function of time after injection, a 0.1 ppm error limit corresponds to a less than 20 ps systematic timing shift over a 200 μs period, the time over which we establish half the statistical significance of our experiment. These time-shifts are expected to come mainly from rate-dependent gain effects on the PMT. In order to hold the centroid of a time distribution produced by a CFD constant to 20 ps, the gain on a PMT which slews at 0.1 V/ns must be corrected to 0.3%.

Measurement of such small shifts requires large numbers of calibration events, since we need 2500 pulses measured with a timing precision of 1 ns to measure a mean time to within 20 ps. It is clear that good time resolution would facilitate the calibration, and we expect to obtain a resolution of around 300 ps, which would require only about 200 counts per calibration point. Furthermore, calibration must be performed during actual data taking, in order to take account of the prompt and delayed flash and changes in ambient rate.

A laser calibration system designed to meet these needs is shown schematically in Fig. 16.5.1. There are two separate calibration subsystems, one laser- and LED-based, since the capabilities of these two methods are complementary. Laser pulses are very useful for time-synchronizing calorimeter channels, for generating narrow pulses (similar to an electron shower), for monitoring rate dependent time shifts, and for exciting the emission of fluorescence light from scintillating fibers. The UV laser pulses are injected into the scintillating fibers at the end of the fiber bundle farthest from the PMT, which therefore calibrates the readout system as a whole unit. The laser system will consist of 2 independent UV lasers with relatively low command jitter (1-2 ns). Each laser will have a separate vacuum photodiode monitor viewing a portion of the light for an absolute time difference and start time measurement. The lasers will be fired relative to each other at precisely measured times (using both a channel of the data electronics and an independent CAMAC system). Typically this will occur early (few μs) and late (500 mus) into the data taking to measure relative shifts in the time offset of the rate-dependent gain. A set of reference cables will be supplied to calibrate the time system. The amplitude of the laser pulses is independently adjustable.

The LED system injects light directly into the photomultiplier tube via a short coupling lucite cookie. LEDs are useful for measurements at high pulse rates, for simulating pulses from light sources with arbitrary time patterns (such as for simulating the flash), and for distributing calibration light to a large number of calorimeter channels nearly simultaneously. The LED's additionally provide an independent check of the PMT performance, as separate from the calorimeter, and are used to measure the absolute photoelectron gain via the statistical method. It is likely that the LED system will be replaced by laser diodes at the time of the experiment, which have superior temporal properties to LED's, in order to use the LED/laser diode system with a flight simulator output that directly simulates the optical pulses from the experiment. In any case, a pulser system based on avalanche transistors which can produce pulses as short as .5 ns, will be constructed for each channel.

The laser calibration system begins with pulsed nitrogen lasers (0.3-0.6 ns FWHM) as a source of UV light, which is transmitted through a collimator into a high-power UV transmitting optical fiber. From here, the laser light is directed onto four major segments which are remotely enabled by shutters; these correspond to the 4 calorimeters at each measuring station. The 4 fibers are then split into 25 quartz fibers, using a commercially available 1:25 fiber optic splitter with 3db variation in intensity between output channels and 6 dB loss overall. Each quartz fiber is 8 meters in length, and extends from the laser splitter located at the center of the storage ring to a calorimeter on its circumference. On the calorimeter, each laser fiber will excite a custom UV diffusion chamber (simple UVT lucite box) which will then distribute light by short fibers to each of the calorimeter segments, the FSD, and the SSD. The light is injected by more UVT lucite boxes or prisms using teflon reflectors. Tests have shown good uniformity (10% across a face) and low time dispersion (less than 1 ns). A time-offset on each calorimeter is anticipated to be less than 0.5 ns. Finally, one of the quartz fibers is routed to a reference PMT which is well-shielded from radiation in the ring, so that it is not subject to a rate-dependent environment. The reference PMTs provide a standard against which rate-dependent gain and time shifts are measured.

The absolute energy calibration is transferred from test beam data to the experiment using radioactive sources An 18 gauge stainless steel tube (hypodermic needle) will be inserted into each calorimeter. Each of these channels will be oriented transversely to the incident electron trajectories and to the scintillating fibers. Sealed miniature ^{60}Co sources on wires will be inserted into the channels at various depths in order to illuminate different sections of the calorimeter. A radioactive source of strength 100microCurie will be used during down times to provide an absolute energy shape in the calorimeters, which will correspond to testbeam data. Fiducial marks are provided on the counters to use the sources externally.

16.6. Expected Detector Performance

16.6.1. Results of Simulations

The design of the electron calorimeters and their readout has been carried out with the aid of a chain of computer simulation programs. The flow chart for this process is shown in Fig. 16.6.1. We first generate stored muons from injected pions. Large data sets of muons and pions have been generated in the past year and have been used in studies of the muon loss monitor and the flash, as well as of the decay electrons and their motion through the storage ring. S. Mane has provided the detector group with data files which are essentially a snapshot of the bunch at 22.4 μs and at other set times, as well as the phase space coordinates of these same muons at birth. However the muons are chosen, they are propagated through the ring using a simple parameterization of their betatron motion and spin rotation until they decay.

The decay electrons are then turned over to the GEANT-based simulation and propagated through the magnetic field, a map of which was calculated using POISSON. If they strike a calorimeter, PSD, quadrupole electrode, or other obstacle, the shower is simulated as well. The magnitude and spatial pattern of energy deposition in the four calorimeter segments then serves as input to several post-processing routines, which simulate the resulting pulse waveforms and the response of the data acquisition electronics. The output of the simulation includes data banks which look like those produced by the MTDC and waveform digitizer.

Given the enormous numbers of events we will collect and the small errors that we are trying to understand, the full Monte Carlo, with a complete electromagnetic shower simulation, will not be capable of delivering the number of events that we need in order to see very small systematic problems. There is considerable flexibility in the level of detail performed by the Monte Carlo, but even in its simplest useful form, it is still far too slow to generate 30 billion events. However, it may help in indicating what those problems might be. For example, a particular systematic effect can be studied with far fewer events if it is exaggerated and the effect from a much smaller systematic problem can be estimated by extrapolation. We have attempted to parameterize the results of the full Monte Carlo in a very fast and very simple Monte Carlo capable of delivering the needed number of events, but it is still largely untested.

After simulating the shower within the detectors, the next step is to simulate the time and energy response of the data acquisition electronics. The response parameters for these electronics (pulse width, energy resolution, etc.) can then be varied to find the resultant

Figure 16.6.1: Flow chart for detector simulations.

response to electron showers and pairs of nearly coincident electron showers. Preliminary studies have been completed. A phototube pulse corresponding to the energy left by a

1.5 GeV electron in a calorimeter with perfect resolution was modeled, with adjustable scintillator and phototube pulse-shape time-constants. Simulated energy measurements were made using an 8 bit 200 MHz wave-form digitizer and the corresponding 400 MHz device, where two FADCs sample the waveform at two phases of a 200 MHz clock. In each case, an FADC samples the pulse height at 4 ns intervals. Naturally, the measured resolution depends on the number of flash ADC samples taken during each pulse, and resolution improves with increasing pulse width. The results indicate that at 200 MHz, for a high packing-fraction (30%) calorimeter, with underlying resolution of 11.6% at 1 GeV, we need a phototube decay time constant of more than 6 ns, if we wish to keep the electronics' contribution to the overall resolution to less than 10% of the total. At 400 MHz, even with an uncertainty in phase of .5 ns between the two clocks, the time constant can be as little as 3.5 ns, which will make our calorimeter signals more useful for rejecting pileup. As described elsewhere, the WFD has been used on electron signals at the BNL test beam and its resolution performance was comparable to conventional charge integrating ADCs.

The second problem, that of rejecting overlapping pulses, has also been addressed in our simulations. As mentioned above, there are two approaches to pileup rejection: using geometric information from the PSD or segmented FSD, or using pulse height or pulse width measurements from a slab of scintillator (FSD) placed before or on the side of the calorimeter. Using the former method, with an algorithm which demands separate hits on two fingers of each plane in the PSD (where each finger is about 1cm wide), we obtain a rejection power, (how often it distinguishes overlap events) of about 85 %, consistent with a simple geometric estimate. Unfortunately, as we do not expect to outfit each detector station with a PSD, this approach is of limited utility. The segmented FSD could be used in much the same way. With a five-fold segmentation, we would expect a rejection power of close to 80 percent.

The alternative approach to overlap rejection involves measuring the width of photomultiplier pulses from the FSDs, that is how long the pulse remains over a carefully chosen threshold. Single particle events are expected to be narrower; overlap events, wider. The MTDC, now being developed at BU performs exactly this job: sampling an input waveform at 800 MHz and writing to a large buffer the times at which the signal rises above and falls below threshold. The results of simulation, mainly the rejection power vs. single particle efficiency, depend somewhat on the threshold chosen, but at one plausible threshold and pulse width cut, 93% of the double particle events (where the two particles arrived within 8 ns of each other) were rejected while 90% of the single particle events were retained. We have chosen to use the pulse width of the FSD signal as our primary means of rejecting pulse pileup. Hardware tests of this method have just begin at Boston University.

We have decided to install a veto counter (side slab detector, SSD) on the outside radial edge of only one of the detectors ("superstation"), at least for the time being. There are a couple of reasons why we would like to reject side entering electrons. One, these electrons carry little $(g-2)$ frequency information, since their average energy is low. Two, they are a source of signal pileup in the calorimeters, and if we do not detect them, we cannot correct for this problem. An SSD would also help give a good understanding of the level of pileup, which is needed in order to adequately model the expected shape of the time spectrum. However, this turns out only to be a significant problem at the highest rates. Therefore we have decided to leave open the possibility of running with an SSD for muon injection, but until then, to do without.

The final set of simulations uses the effects of pileup thus derived to modify the distribution of higher-energy electrons as a function of time after injection in the same way as will be the data from the future experiment. Without specifically accounting for pileup, the function would be of the form

$$f\left(t\right)=Ne^{\left(-t/\gamma\tau\right)}\left[1+A\cos\left(\omega_{a}t+\phi\right)\right] \tag{16.6.1}$$

Perturbations in the timing spectrum $f(t) \rightarrow f'(t)$ resulting from pileup or other effects operate upon the muon count rate distribution to produce perturbations in the measured muon $(g-2)$ precession frequency $D \rightarrow D'$. By requiring that D and D' agree to within 0.1 *ppm*, we can place a constraint on the maximum permissible magnitude of the perturbation f→f'. It is the ERROR in our knowledge of the magnitude of the perturbing effect $f \rightarrow f' \pm \Delta f'$ which determines the ultimate $(g-2)$ error $D \rightarrow D' \pm \Delta D'$, since one can, if necessary, subtract the known systematic errors in D'.

The fitting procedure is performed through minimization of χ^2 with t varying across all time bins and p over the n $(=5$ in Eq. (16.6.1)) parameters in the fitting function.

16.7. Rate and Pileup Studies for PMTs and Bases

16.7.1. Introduction

As mentioned above, in order to control systematic errors in the measurement of $(g-2)$ to better than 0.1 ppm, we must measure the average electron arrival times in any 200 μs interval to 20 ps and over the whole measurement time, 640 μs, to 64 ps. In addition, we must know the relative average energies of the electrons to 0.2%.

Event rates in the PMTs are as high as several MHz shortly after muon injection and decrease to hundreds of Hz at the end of the decay period (ten muon lifetimes). The large range of rates can lead to gain and timing changes in the PMTs and discriminators from early to late decay times.

In this subsection, we report the results of time stability measurements on our candidate PMTs and discriminators. We have found their time stability to be at least as good as the specification at the highest rates expected, but gain stability is about 0.4%, or twice the specification. Both gain and timing will be carefully monitored to the desired accuracy during the experiment (see §16.5 on the laser calibration). Corrections will then be applied to the gains and, if necessary, to the times, in order to meet specifications.

16.7.2. Description of the Rate and Pileup Tests

Two types of measurements were performed on candidate PMTs.

1) The timing and pulse height of the last pulse in a burst of between 100 and 2000 uniformly spaced LED pulses was measured as a function of time between the pulses in order to detect shifts which depend on average rate. Successive pulse trains were separated by 200 ms.

2) The timing and pulse height of the second of a pair of LED pulses was measured as a function of the time between the pulses. This test is a measure of shifts which depend on the spacing between a pair of pulses, e.g. pileup effects. Shifts in timing could come from a shift in the electron transit time of the PMT, or from effects of the tails of previous pulses. We will distinguish between these two effects.

We tested two different tubes: a Hamamatsu R1828-01 2 inch PMT for the calorimeters and a Hamamatsu R1355 1 inch PMT for the FSDs. These tubes are designed for high rates and fast timing.

If the gains on these tubes were set so that a typical pulse produced 200 mV into 50 Ω, then the average current through the anode for a continuous, 5 MHz, 15 ns wide pulse would be around 2 mA, far in excess of the maximum anode current ratings. Fortunately, our application does not require operating PMTs at sustained high rates. If the instantaneous rate in a detector at early decay times were 5 MHz, then the total number of electrons detected in 10 lifetimes would be 320. In order to perform realistic testing, we test timing following a burst of between 100 and 2000 closely spaced pulses, which simulates more nearly the high rate situation which we will encounter, and also does not approach the maximum rated average anode currents.

The first set of tests consisted of measuring the times between pulse "B" and a delayed pulse B in the PMT, with and without a burst(pulse train "A") in between them. To solve the problem of irrelevant long term drifts in the PMTs and electronics, we fired the B pulse every event, but the A pulse train only every other event. Thus, the time comparison, with and without the high rates produced by A, could be made over a much shorter time scale, in this case every other pulse, (0.2 Hz). This improved the stability of the measurements dramatically, and precision timing and pulse height studies became possible. For convenience, when alternate pulsing was used to measure time shifts, we will refer to it as "method 1".

One other problem was solved in a similar manner. If we note time or gain shifts in the B pulse as a function of rate, we would like to know whether they are due to transit time shifts in the PMT, or whether they are due to the fact that pulse B is sitting on the tail produced by pulse train A. Therefore, we set up 4 different kinds of triggers:

1) A and B- simulates the full high rate environment for test pulse
2) B only- test pulse only, response when rates are low, no tail from pulse train A
3) A only- tail from pulse train A only
4) no pulse - pedestal only

Obviously, when B does not fire, there can be no timing. However, an ADC will still monitor the integrated area in the same time region, so that we can know the size of the tail relative to the pedestal, and, with a knowledge of the shape of the leading edge of the PMT analog signal, we can model the expected time shift. We refer to measurements obtained using these four different triggers as "method 2".

16.7.3. Setup for PMT tests

The setup we used for rate and pileup studies is shown in Fig. 16.7.1. The idea is to let a very low rate light source (pulse "B") define the timing and pulse height(strictly speaking the area under the pulse) and then to measure the timing shift and pulse height changes in B by firing a burst of light pulses at a high rate before B (pulse train "A"). All the signals are synchronized. A pulse generator (PG in Fig. 16.7.1) is running at about 5 Hz and one of its outputs is connected to a module (AP in Fig. 16.7.1) which generates one logic output pulse for every other input pulse. The outputs from AP were used to start a time-to-digital converter (TDC), externally trigger an LED pulser which is used to fire the low rate LED, and as an input to a pattern register which is used to tag the type of event. The other output from the PG was sent to a module (DP in the Fig. 16.7.1)which only generates logic pulses for the first two of every four input pulses. The output from this module is sent to an HP 8130A 300 MHz Pulse Generator which is used to drive the high rate LED (pulse train A) and is an input to another pattern register. A gate for the ADC (a Lecroy FERA), timed to the low rate pulse position, was driven by PG.

We used a Phillips model 704 300 MHz quad leading-edge discriminator to provide the logic signal to the TDC. This unit has very good rate stability, introducing less than a few ps timing shift at the highest rates in our tests. The octal model 708 showed equally good timing stability.

The TDC was a Lecroy model 2228A CAMAC module. Its start was derived from the gate driving the slow LED, pulse B. Its stop was derived from discriminated PMT signals. The analog input to the discriminator included both pulse train A as well as pulse B. The pulses in burst A were set to be smaller than pulse B. The discriminator threshold level was set to fire only on pulse B. This was done in order to limit the rate of pulses into the TDC, which was found to have some rate dependence. While the pulse height differed, the areas of the PMT pulses from both LEDs were about the same.

Figure 16.7.1: Part of the setup used for rate and pileup studies. PG is a pulse generator, AP is a module which generates one logic pulse every other input pulse, DP is a module which, for every four input pulses, generates two logic pulses on the first two and nothing on the second two. HP 8130A PG is a pulse generator which can generate bursts of between 1 and 10000 equally spaced pulses.

16.7.4. Results of PMT Tests

Now we describe the results of our PMT tests.

The test of timing stability was performed by using 100 signals in a burst (pulse train A) with a uniform spacing of Δt. The low rate signal (pulse B) was placed Δt after the end of the burst. For example, with a burst rate of 5 MHz, we generated 100 signals with 200 ns between the neighboring signals and placed the low rate signal 200 ns after the last signal in the burst. This required that the low rate signal be delayed by about 20 μs relative to the start of the burst. The jitter caused by this delay is about ± 4 ns, which is acceptable compared to the 200 ns or larger period between pulses. This is why we chose to limit the high rate burst to 100 successive signals; more would have introduced an unacceptable jitter of pulse B relative to pulse train A. Nevertheless, we did some tests with 2000 pulses in the burst, which we will also describe. Recall for comparison that the expected maximum total number of electrons per calorimeter per ring injection is a few hundred.

For the R1355 tube, the signal from the PMT was fed into the Phillips Scientific 704 Leading Edge Discriminator directly. For the R1828-01 tube, the signal was first led to an attenuator set at 30% before going to the discriminator. The number of photoelectrons for each high rate signal was about 300 for the R1355 and 690 for the R1828-01. The high voltage was 1325 V for the R1355 and 2300 V for the R1828-01. The parameters for the low rate and high rate signals from both tubes are listed in Table I.

Table 16.5.2-1 Signals used for rate and pileup studies: All parameters were measured by averaging over 64 pulses using the Tektronix DSA 602A Digitizing Signal Analyzer with band width set at 1 GHz. The signal from the PMT was connected by a 35 ns RG 58 cable to the scope. LD refers to the leading edge, TD the trailing edge as observed on the scope. Both LD and TD are measured from 10% to 90%.

Signals	LD [ns]	TD [ns]	FWHM [ns]	Amplitude [V]
Low Rate/R1355	2.13	2.20	2.87	2.47
HighRate/R1355	2.73	12.17	7.57	0.78
Low Rate/R1828 − 01	1.68	4.35	2.37	7.83
HighRate/R1828 − 01	2.36	11.78	7.26	2.81

Fig. 16.7.2 shows a typical timing histogram, in this case for the low rate LED with no high rate LED, indicating the intrinsic time resolution in our measurements. The peak is mainly broadened by the Poisson distribution of photons of the low rate light source and the jitter of the electron transit time in the PMT. For the rate tests here, $\sigma = 60.2 \pm 0.7$ ps for the R1355 and $\sigma = 33.5 \pm 0.7$ ps for the R1828-01. The positions of the peaks were

Figure 16.7.2: For a constant rate, this shows the time resolution on the low-rate pulse in the typical case, using a green LED under reverse bias. There are about 46 ns per TDC channel.

calculated by averaging over all the events in the peak. Timing shifts were calculated using

$$\Delta t = \bar{t}_{rate} - \bar{t}_{free} \ ,$$

where $\bar{t}_{rate}$ was the averaged time of the low rate LED when both the high rate LED and low rate signal were firing and $\bar{t}_{free}$ was the averaged time when only the low rate LED was firing (method 1).

Fig. 16.7.3 shows the timing shift for both R1355 and R1828-01 tubes at different rates up to 20 MHz. We can see that there is a weak rate dependence, but the shift is less than 20 ps at all rates.

Before we reach any conclusions, there are a few questions we need to answer.

(i) Is 100 signals in the burst enough for the $(g-2)$ rate test ?

(ii) For the timing shift above, how much does the tail from the previous pulse contribute (hereafter "the tail effect") and how much does the shift of the electron transit time in the PMT contribute?

(iii) In the actual experiment, pulses will not be uniformly spaced. How much does the timing shift as a function of the spacing between two successive pulses?

As mentioned above, for most of the tests, only 100 signals were used in a burst in order to minimize the time jitter in the low rate pulse relative to the end of the pulse train. But we also tested at 10 MHz with about 2000 signals in the burst. Both the R1355 and the R1828-01 were tested. The timing shifts are -14 and -18 ps for R1355 and R1828-01, respectively. The timing shifts were found to be almost a constant value if the low rate signal was placed anywhere within a couple hundred μs after the end of the burst. These tests were conducted at average rates well beyond those expected in the $(g-2)$ experiment.

The timing shift shown in Fig. 16.7.3 can be caused by the tail effect or by the rate dependence of the electron transit time. This becomes clear if we use Method 2 in Fig. 16.7.1, where we measure the both the timing and the integrated charge (over a 200 ns gate): of the low rate pulse, of the low rate pulse plus the tail contribution from the burst, of the tail contribution alone, and of pedestal events in successive triggers. Measuring the pulse heights concurrently allows us to determine their effect on the timing shifts. We define

$$\lambda = \frac{\bar{A}_{tail} - \bar{A}_{ped}}{\bar{A}_{free} - \bar{A}_{ped}} \times 100 \ ,$$

where $\bar{A}_{rate}$ is the measured low rate pulse height when both the high rate and low rate pulsers are firing, $\bar{A}_{tail}$ is the measured tail contribution when only the high rate pulser is firing, $\bar{A}_{ped}$ is the measured pedestal when neither the low rate nor the high rate is firing, $\bar{A}_{free}$ is the measured low rate pulse when only the low rate pulser is firing. In the case where the low rate pulse was absent, the gate falls over the same time region relative to

Figure 16.7.3: The timing shifts Δt of the R1355 and R1828 PMTs as a function of rate, by method 1: a high rate burst of pulses followed by the test pulse.

the high rate pulses. As previously mentioned, we monitored the low rate signal, the tail

Figure 16.7.4: Δt versus λ, indicating the relative importance of the tail in the timing shift as a function of rate. The tube was an R1828-01 with high voltage at 2300 V. A leading edge discriminator was used to measure the timing shift. The upper set of data points corresponds to the case where the low rate pulse was placed after a 100 signal burst of varying rate. For the other set, the low rate pulse was placed 140 $\pm$ 40 ns after 2004 signals at 10 MHz. For the 100-burst data, the timing shift Δt has a linear relationship to the size of the tail, λ, suggesting that shifts are dominated by the tail effect. The three points corresponding to 2004 signals in a burst do not lie on this line, suggesting that another mechanism has come into play, namely a shift in the electron transit time in the PMT.

contribution, and the pedestal contribution to the ADC at almost the same times, with a repeating pattern of four different triggers. To register pulse areas, we used the Lecroy Fast Encoding and Readout ADC (FERA) 4300B, which showed good stability at high rates.

Fig. 16.7.4 plots the timing shift Δt versus λ. We can see there is some correlation between Δt and λ when there are 100 pulses in the burst at different rate. This means the timing shift as a function of rate, shown in Fig. 16.7.3, arises mostly from the tail effect (The Lecroy 428F Linear Fan-in/Fan-out was found not to cause extra timing shifts at different rates). Fig. 16.7.4 also shows three data points measured by firing 2004 pulses in a 10 MHz burst. With the low rate pulse placed about 140 $\pm$ 40 ns after the end of burst (the $\pm$ 40 ns jitter is caused by the long delay), we can see that, 1) the shift is repeatable, and 2) the three data points associated with the 2000+ pulse bursts do not fall on the previous curve. Since the observed shift was larger than that expected from the tail effect alone, we concluded that a significant portion was caused by a shift of the electron transit time. Fortunately, this timing shift is small. In zero resistance clip line studies, the timing shifts for 100 pulses in the burst are always found to be positive, which is consistent the fact that the reflected pulse gives a positive tail. The electron transit time shift was found to be about constant from the highest rates down to a few hundred kHz. Our conclusion was that in contrast to the 100 burst data, we were beginning to see a transit time shift in the 2000 burst data, although the shift was still within the specification of < 20 ps.

In order to measure the change in pulse height with rate, we define

$$R = \left(\frac{\bar{A}_{rate} - \bar{A}_{tail}}{\bar{A}_{free} - \bar{A}_{ped}} - 1 \right) \times 1000 \ ,$$

Fig. 16.7.5 shows R as function of rate. The total error from the FERA measurement can be estimated by examining the data points in the figure. The total error (standard deviation) should be less than 1.63 for R1355 measurements and less than 1.16 for R1828-01 measurements. Similar to the timing test, we put 2000 pulses in 10 MHz burst and placed the low rate pulse about 150 ns after the end of the burst. The ratio was measured to be 3.41 for the R1355 and 4.36 for the R1828-01. This is two times larger than the specification $R < 2$, and a correction based on calibration data may be necessary during the experiment.

For the pileup studies, the setup is the same as that for the rate tests. Instead of a high rate burst, a single pulse (pileup pulse) was placed before the low rate signal, and the time shift was measured as a function of spacing between the pulse pair. Again the threshold of the leading edge discriminator was set high enough to block the pileup signal

Figure 16.7.5: The ratio R as a function of rate for the R1828 and R1355 PMTs, indicating the shift in the measured pulse height for bursts of pulses at varying rate.

from going to the TDC. The timing shift Δt is defined in the same way except $\bar{t}_{rate}$ is replaced by $\bar{t}_{pile}$.

In order to get an idea of the systematic error for the timing shift measurement, we used an R1828-01 with high voltage at 2300 to test 41 continuous runs with a time separation between pulses of 14.8 ns. The standard deviation on our measurement was 3.34 ps.

Fig. 16.7.6 shows the timing shift as a function of the time separation between the low rate and the pileup pulse (measured from the peak position). Again, as in the rate test, we needed to understand any shift caused by the discriminator, the electron transit time and the tail effect. To test the discriminator, we again put an adjustable attenuator before the Phillips 704 discriminator and adjusted the attenuator setting from 10% to 100%. The maximum change for the timing shift was found to be about only 6 ps for a time separation of 15.5 ns using the R1355 tube.

The analysis of the tail effect is more complicated. It is reasonable to assume that the timing shift from the tail effect is linear with the size of the tail. If the timing shifts are due mainly to the tail effect, then with a reasonable delay and multiplying factor, a pulse height curve of the tail from the first pulse should follow the time shift data points.

The timing shifts as shown in figure Fig. 16.7.6 and a plot of the tail of the first pulse are overlaid in figure Fig. 16.7.7 by multiplying the tail pulse height by 930 and shifting it 2 ns to the right. The scaling and offset factors are consistent with the pulse parameters listed in Table 16.5.2-1 and the discriminator threshold we used. The wave form was taken with a Tektronix DSA 620A Digitizing Signal Analyzer (DSA). It fits the data very well. This gives us confidence that the timing shifts we saw in Fig. 16.7.6 arise mostly from the tail effect.

We used the same setup for the pileup pulse height stability measurement as for the timing rate test. R is defined in the same way except $\bar{A}_{rate}$ is replaced by $\bar{A}_{pile}$. Fig. 16.7.8 shows the results. R for some of the data points is found to be close to 1% and the reason is not clear. The shift is larger for the R1355, and is larger than 0.2% for pulse spacing less than about 50 ps. It is believed to be due to the fact that the FERA is not able to measure the tail contribution accurately, perhaps due to baseline instability. However, since the probability of two pulses being within 50 ns at 4 Mhz (the expected rate at early times in the FSD,) is about 0.2, the effect is again at about the level of 20 ps.

Besides the PMTs and bases, we also studied the timing shift caused by the Lecroy 428F Linear Fan-in/Fan-out, the EG&G 50-Ω splitter, and a long cable under high rate and pileup. They were found to be rate independent but do add to the tails of the pulses and therefore increase the timing shift caused by the tail effect.

Figure 16.7.6: Timing shifts from pileup vs pulse separation for the R1355 and R1828-01. The separation is the time between pairs of pulses. The lines are to guide the eye.

Figure 16.7.7: The line represents the pulse height of the tail from ADC data (suitably scaled and shifted) overlaid with timing shifts from pileup. Data points are for the R1355 as shown in Fig. 16.7.6. The waveform was recorded by a digital scope with a 1 GHz bandwidth.

Figure 16.7.8: R as function of separation for both tubes: the relative shift of the pulse height as a function of the time spacing between a pair of pulses.

The studies above help us understand many issues about timing stability at the several picoseconds level and pulse stability at the several 0.1% level for different devices. From the measurements, we reach the following conclusions:

(a) The electron transit time shift for both R1355 and R1828-01 is less than a couple of picoseconds firing a 100-pulse burst at rates well in excess of those expected in $(g-2)$. The parameters for the tested signals are given in Table 16.5.2-1.

(b) The pulse height change is less than 0.4% at different rates for evenly spaced pulses.

(c) When a pair of pulses are brought together(as close as 10 ns), the resulting timing shift in the second pulse is almost purely due to the presence of the tail from the first pulse.

(d) When a pair of pulses are brought as close as 10 ns apart, the pulse height change from the photomultiplier tubes is less than 1%.

16.8. Data Stream

In this section we discuss the word structure coming from the various electronic elements and the initial on-line event building.

As mentioned earlier, we expect to mount the $(g-2)$ experiment in two phases: first a lower-rate (maximum about 1 MHz/calorimeter immediately after injection) data run at our proposed intensity using pion injection, followed by a later high-rate (8 MHz/counter immediately after injection, 6 MHz after 20 μs) high-statistics data run with muon injection. We anticipate that the online data stream will also make a transition between these phases, from initial logging of all data in a raw format (while compression algorithms are being developed) to later logging of mostly "compressed" events and a small percentage of "raw" events.

The bulk of the data will come from the WFDs and MTDCs. Each of the 27 channels in an MTDC module accepts logic inputs from a discriminator. An output word is generated for the current clock cycle whenever a leading or trailing edge in the input logic pulse is encountered. The output format consists of a 10 bit time field, a 5 bit channel number, and one up/down flag bit. The output words are packed in pairs and are combined with parity data to give 40 bits/pair. We are designing a 256 Kbyte on-board memory to store all of the timing information for a single ring injection. The memory would be read out between injection pulses. We plan to assign one MTDC module per two calorimeter stations. For each detector, there will be five discriminator (up and down logic transitions) and five derandomizer (1 leading edge transition) inputs from the five FSD elements, and one of each from the sum of the wfd signal as well, Typically there will be a total of two transitions recorded per electron, the calorimeter plus one FSD element. Each pair of level-transitions (rising or falling discriminator threshold-crossings) on at least one of 27 parallel inputs results in a 5-byte output record into fast memory (80ns cycle time). We therefore expect 10 bytes per decay electron from the MTDC. Compression is achieved by co-ordinating arrival times between the 4 devices and the calorimeter WFD information, and by encoding pile-up rejection information from the FSD into flag bits. As with the WFD system above, experience with off-line raw data compression in early running will be used to develop algorithms for on-line compression and ultimately hardware pre-processors for in-line compression.

Each WFD consists of 4 analog inputs. For the calorimeter, these would correspond to signals from each of the four PMTs on the calorimeter. Each input has a separate discriminator; if one or more cross a threshold, then output is generated. The analog signals are summed internally and input to two FADCs. The two FADCs are operated at 200 MHz with their relative phase shifted by 2.5 ns, to give ADC values every 2.5 ns. The output consists of information from a 20 ns time slice: 16 bits of time, 4 successive 8 bit ADC values spaced 5 ns apart and 4x4 bits of discriminator patterns. There are two 32 Kbyte memory banks, one for the times, and one for the pulse heights. Like the MTDC, the memory is large enough to store data for a single ring injection, and would be read out between injection cycles.

We anticipate 20 bytes of raw MTDC data and another 32 bytes of raw WFD data per pulse with our baseline system, yielding 2.5 kByte/fill/cal from the 50 hits/calorimeter/fill in our lower-intensity mode. Multiplying this by 24 calorimeters, 12 fills/AGS cycle, and an AGS cycle frequency of 0.6 Hz, we obtain an average raw data rate of 500 kbytes/s. An additional 25% should be added to this for the readout of PSDs and the wire chamber system (5 PSDs x 48 channels + 112 wires implies 15 additional MTDC modules).

While the calorimeter systems will contribute the bulk of the data stream, provisions must be made for reading out PSDs, wire chambers, the calibration system, the NMR magnetic field data, environmental records of ambient experimental conditions, high voltage monitoring, etc. Muon losses will also be measured as coincidences between scintillation detectors (SD) and/or wire chambers accompanied by small coincident energy deposits in a pair of calorimeters. While this analysis will initially be carried out off-line, it may well be necessary to implement it on-line before final high-intensity running proceeds.

In summary, since it is impossible to anticipate all the subtle uses of the mass of raw data we will accumulate, we are developing a modular and easily upgradable system of data acquisition electronics with a flexible on-line data processing system. For our first engineering and physics runs, this system will be capable of a maximum sustained event rate of 1 MHz/calorimeter, corresponding to our proposal conditions. For later higher-statistics and high-intensity running, the baseline front-end data acquisition electronics will be capable of 6 MHz/calorimeter operation, while the second-level VME on-line and in-line processing system will require minimal upgrading. Upgrade capability for additional instrumentation of either calorimeters or SD systems, and for the introduction of a complete set of PSDs, is provided for in a straightforward and cost-effective manner. Further developments await our experience with prototypes of our baseline DAQ system, and ultimately our experience with muon decay electrons in the storage ring.

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