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SSC and G-2 Calorimeter and Optical Calibration

Progress Report

for Period 9/15/92 - 9/14/93

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Research Summary Abstract:

The work of this grant was in detector and detector calibration research for the g-2 experiment at Brookhaven National Lab (E821), and for SSC experiments (GEM collaboration- SciGEM subgroup). In both tasks, optical fiber calorimetry is used.

(I) Optical Calibration: The most important task of the Fairfield group was developing optical pulse calibration equipment using dye lasers pumped by a nitrogen lasers, visible semiconductor lasers, and multi-color LEDS. The light pulses generated are injected directly to the photomultipliers or to the fiber active media. These pulses are used for: (i) pmt gain stability, (ii) quantum efficiency stability, (iii) stability of optical couplings, (iv) radiation damage monitoring.

(II) Photomultiplier Systems: A second major task is to select and test photomultiplier and other electro-optic detectors for the calorimeters. Both experiments have extreme requirements for gain stability at high rates and/or dynamic range.

(III) Test Beam Operations: The Fairfield group participated in the test beam operations at BNL.

(IV) Cerenkov Fiber Forward Calorimetry: Fairfield continued to test and constructed new calorimeters using quartz cerenkov fiber sampling, in collaboration with groups from the GEM and SDC collaborations.

Report Overview:

Task A: G-2 Photomultiplier & Calibration Systems (BNL E821)

Task B: Optical Calorimeter R&D & Calibration for High Rates & Colliders

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Report Introduction:

We hereby report on our FY1993 grant ("SSC and G-2 Calorimeter and Optical Calibration"), mainly for two focussed and highly -interrelated tasks: Muon G-2 Photomultipliers and Calibration systems, and Fast, Radiation-Hard Calorimetry and Electro-Optic Calibration and Detectors for Colliders (GEM collaboration at SSC, or other applications). These two tasks were unified by their concentration on electro-optic calorimetry, electro-optic readout, and optical calibration systems.

An important goal of this program at Fairfield University was to engage undergraduates in high energy physics and experimental research. Nine students worked on the program described herein from 1992-3: Kevin Arrington, Dan Kefford, John Kennedy, Rob Pisani, Chris Sanzini, Dave Scrofani, Ken Segall. Dan Wall and Ken Segall have presented papers at the Undergraduate Research Conference. Ken and Rob will enroll in graduate school (at Yale, and Stony Brook, respectfully). Dan Wall is a graduate student in Experimental High Energy Physics at Tufts, based in part on his experiences working on G-2 at BNL and GEM/SSCintCAL at FNAL. We have instigated a mentor program where sophomores start with this program in the summer between their freshman and sophomore years, teaming with a senior. Additionally, we have supported 2 experienced seniors for the summer after graduation, before the start of graduate school (our mini-graduate program!) During the past 4 years of DOE support we have worked with a total of 13 students in this program. Figure 0 shows the Fairfield students involved in this effort working at BNL. We are very encouraged by the support of DOE for undergraduate student activities by the Fairfield Contract. Indeed, it would not be possible to continue, and our modest successes would not have been possible without their engagement in all phases of our activity.

Task A: Muon G-2 Detector and Calibration Development, BNL E821
(50% of PI Research Time)

The BNL AGS E821 Collaboration (Fig. 1a-d) has proposed and been approved by DOE and BNL for a new measurement of the muon ($g-2$) value. Figures 2-3 illustrate the basic method of measuring the anomaly. Muon $g-2$ is an important experimental measurement that has been a touchstone for the past 20 years which any new theory must address and accommodate: the gyromagnetic ratio of the muon limits the scope of new theories, and probes the existence of new forces at high mass scales ($\sim$ TeV). The muon magnetic moment acts as a sum rule for any new fields and forces in the vacuum which can interact with the muon, such as supersymmetric particle pairs or symmetry-breaking forces, such as the Higgs fields. Figures 4-7 address the underlying physics and importance of this measurement. This experiment will reach a sensitivity that will enable a measurement of the weak contribution to g directly, for the first time. It is now possible to predict the effect of a Higgs boson on $g-2$; a Higgs mass effect of $M_{\text{Higgs}} < 400\text{-}500$ GeV would be observable at the level of sensitivity proposed for BNL E 821.

The BNL AGS E821 collaboration has demonstrated to DOE & BNL review panels that it will be possible to reduce the errors on the classic (see most modern textbooks of HEP) CERN measurement by a factor of 20 (± 0.35 ppm of $g-2$), corresponding to a mass scale limit of typical of new interactions up to ~ 5 TeV, and extending the QED comparison to the available theoretical limits. Figures 8-9 illustrate the basic improvements. Note that the main contributions to the errors of the CERN experiment are reduced simply by:

- (1) accumulating more statistics by a factor of 400 compared with CERN (± 7 ppm $\rightarrow \pm 0.35$ ppm), and
- (2) improving the inherent uniformity and measured knowledge of the magnetic field in the new G-2 ring that is nearing basic completion at BNL ($\rightarrow \pm 1$ ppm B uniformity), compared with the CERN results.

This new superferric $g-2$ muon storage ring features continuous superconducting coils 14 m in diameter (world's largest superconducting magnet) and a continuous pole piece (unlike the CERN $g-2$ experiment with separate magnets). Figure 10-12 show the basic parameters of the ring. The ring operates at ~ 3.1 GeV, the "magic γ " for muons which reduces the effects of stray electric fields transforming to stray magnetic fields.

A complete review of the approved (by BNL and DOE reviewers) experiment and experimental technique is far beyond the scope of this brief proposal. Rather, we concentrate on the specific operations tasks as requested herein by Fairfield University, consistent with the $g-2$ experimental plans to help mount and analyze this important experiment. Fig. 14 summarizes some project milestones to date.

[The main results of this task to date are in the design report for the experiment, available from the DOE or from Co-Spokespersons Prof. V. Hughes at Yale, Prof. B.L. Roberts at Boston University or Dr. W. Morse at BNL - the full description of and motivation for G-2 exceeds the scope of this brief report. Prof. James Miller (617-353-6200, and in% "miller@buphyc.bu.edu") of Boston University is the task leader for the Detector Subgroup, the main group in which we participate.]

Fairfield is mainly involved in the decay electron detector systems of the g-2 experiment. The muons precess in the magnetic field of the muon storage ring. As they decay, the electron calorimeters record the time and energy of the decays. The histogram of the time of decay shows the exponential decay modulated by the precession frequency, a fit to which determines the anomaly of the muon (Fig.3). The collaboration is constructing 24 shower counter detector modules $16 \times 16 \text{ cm}^2$ in cross section on the entering face, and ~ 14 R.L. deep using scintillating fibers and Pb sheets (pioneered by SPACAL collaboration and JETSET - the calorimeters are being constructed by U. Illinois using the techniques developed for JETSET at CERN). The counter modules are placed around the 7 m radius G-2 ring (Figure 15a,b). A scintillating hodoscope (or Position Sensitive Detector, or PSD, Fast Scintillating Detector-FSD) also surrounds part of each calorimeter module to tag multiple electron hits and to allow measurement (upper limit!) of the muon electric dipole moment (Figure 16).

The performance of these electron calorimeters is technically demanding, firstly because in the first ~ 10 - $100 \text{ } \mu\text{sec}$ after injection in the muon storage ring, the (exponentially decaying) counting rates over which accurate calorimetric and superbly accurate timing measurements ($\pm 0.2 \text{ ns}$ timing, with no more than 20 ps shift of the centroid of the time distribution over $\sim 0.5 \text{ ms}$ counting period of decay cycle) must occur in the electromagnetic calorimeters, rates approaching that of the SSC (although only in the 1-3 electron energy GeV range), ie 1-10 MHz per channel. Most crucially, the centroid of a time distribution for detected decay electrons must not shift by more than $\pm 20 \text{ ps}$ from early to late times (about 10 muon lifetimes at 3 GeV or about 0.5 ms), over a steeply varying counting rate (few Mhz instantaneous rate to $\sim$ few hundred Hz instantaneous rate). This is the most difficult technical challenge we deal with for this experiment, and one that Fairfield is most directly involved in.

A second major requirement is to develop a photomultiplier system which recovers and is able to make timing measurements accurate at the $\sim \pm 0.1$ - 0.2 ns level (20 ps centroid shift) on 1-3 GeV electrons (100-1,000 p.e. pulses) after a very large "Flash" of radiation ($\sim 10^{6-7}$ neutrons, gammas, pions) hits the calorimeter over $\sim 20 \text{ ns}$ during pion injection into the G-2 ring. (The pions produced from one machine bunch are aimed along the G-2 orbit, and decay to captured muons, thus avoiding an injection kicker, which could cause time-dependent uncertainties in the integral of B along the ring larger than the fraction of a ppm that we require). During the experimental beam simulations (Fig 17a) of this Flash taken at BNL (with Yale and B.U.), signals as large as 30 V (Fig 17b) are generated by our photomultipliers during this flash, and methods must be found to relieve the photomultipliers and electronics of this burden.

[We note that the dynamic range (flash) and temporal properties -rate, timing- problems of scintillation calorimetry for G-2 have a close relationship to SSC calorimetry technique. Furthermore, the experiment will take data at mbyte/s levels, using an advanced VME system to acquire data. Additionally, sophisticated digital time recorders (similar to the CERN digitrons, but reduced to an ASIC), and waveform ADC's based on ASIC's. - see Fig. 16) will be used.]

Fairfield University was therefore responsible for:

- [1] **Test Beams:** Test beam running and testing in BNL test beams, including operation of prototype calibration systems;
- [2] **Time and Gain Calibration Systems:** Time, pulse height and PMT gain pulse laser and LED calibration systems, based on the above prototypes;
- [3] **g-2 Optical Pulse Waveform Simulator Calibration:** Optical pulse simulation tester calibration system, which generates and optical pulse train similar in size and time position to the

expected g-2 signals from the electron calorimeters, in order to ensure that the timing shift error is less than 20 ps, the g-2 requirement (with [2] above);

[4] **Photomultiplier Studies:** Aspects of the specification, selection, and testing of photomultipliers, including development of flash gating systems.

[5] **Experiment Environment Data:** Additionally, we have been a low level of participation in the design and installation of the "slow" control and measurement aspects of the experiment - We have studies particularly temperature and vibration monitors to help ensure that the integral of B along the orbit remains known to ± 1 ppm.

[1] Calorimeter Tests, in-situ Calibration Prototypes, and Installation:

Progress/Status Summary:

Over the past year Fairfield has participated in the continuing development and testing of scintillating fiber calorimeters (lead by the Boston and Illinois groups). Results from the most recent flash tests at BNL, participated in each year by 4 Fairfield students (1990-93), have indicated that the bulk of the flash comes from particles traversing the photomultiplier tube itself.

Fairfield has been involved in all aspects of the actual test beam set-up (cabling, tables, power, riggers, racks, triggers, wrapping counters, etc.) and running at BNL, in part because we are closest university to BNL (~1.5 hours by car or ~2 hours by ferry). Fig 18 shows final assembly by Fairfield students of a fiber prototype after delivery of parts to BNL in June 1992. The conceptual breakthrough that we now understand is that the flash is able to be greatly reduced at late times simply by assuring that the PMT are out of the median plane of the flash particles (but it is not eliminated). In these tests, Fairfield has supplied many of the photomultipliers, and also the calibration LED flashers and laser fiber injectors. Figure 19 shows a typical ADC spectra obtained on a fiber calorimeter prototype at BNL. We have achieved a resolution constant $\sim 15\%/\sqrt{E} + 1\%$, over the energy range 1-3 GeV, sufficient for G-2 operation.

Test beam data taken at BNL used calibration equipment supplied by Fairfield University. Before and during this test, calibration by the laser pulser of calorimeter light levels, and by LED flashers to determine the gain and photoelectron levels by a statistical method were performed by the Fairfield group.

[The LED system is used in the following manner: The average response of a PMT to a constant light pulse is $\langle R \rangle$. This response is given to first order by $\langle R \rangle = G \langle N_{pe} \rangle$, and $\sigma_R = G \sqrt{N_{pe}}$ -> gain $G = \sigma_R^2 / \langle R \rangle$, so that to first order the Gain of a PMT can be measured simply by measuring the standard deviation and the average response $\langle R \rangle$ from a constant light pulser - an LED. Corrections for the intrinsic width of the SER (single electron response) and noise are also included in the analysis.]

Fig. 20 a,b shows the schematic for, and installation of LED pulsers in prototype g-2 calorimeters by the Fairfield group. Fig. 21 a,b shows photographs of the laser pulser injector installed in BNL and in the calorimeters.

The schematic of the prototype for the 300 ps wide laser injector system shown in Fig. 21 a,b is shown in Figure 22a-c (Figure 22c shows a possible upgrade for high stability operation for precision calorimetry). A nitrogen-pumped dye laser (337-700 nm tuning) drives a non-linear GRIN lense system which injects the laser pulses into 200/240 suprasil grade quartz optical fibers.

The pulses are split 1:16 (via a commercial frustrated evanescent wave fiber-fiber coupler array) and individually attenuated to force equal power on each fiber and fed to transport fibers. A manual 0-60 dB fiber attenuator adjusts the over levels. The light pulses from the fibers are injected into calorimeters, light guides or PMT with plastic, quartz or glass diffusers or prisms, depending on the application. A dual set of photodiodes (vacuum and Si) are used to normalize the light output from pulse to pulse - the existing laser has a pulse amplitude stability of $\pm 6\%$, and normalization brings this to $< \pm 1\%$. Quartz fibers are used for their extreme stability with temperature (both N.A., n and length) and their very low attenuation (~ 1 dB/m at 337 nm, ~ 0.5 dB/km at 500 nm). Figure 23a,b show the power splitter and the assembled prototype pulser at Fairfield. Fig. 24 shows the very narrow PMT pulses capable of being generated by this device, using a special PMT with an integral coaxial connector (Hamamatsu Assy H1161), and digitized by a 2 GHz oscilloscope. (The positive pre-pulse is laser switching noise. This was been eliminated by grounding the laser housing and fiber coupler). The UV capability allows us to stimulate the tertiary dye in scintillators directly, while the visible wavelengths allow a relative and time-variation measurement of the optical couplings and attenuation of a system independently. [For collider calorimetry, this feature allows monitoring of radiation damage.] Note that the laser pulses are less than 300 ps wide. Because of the precision nature of the quartz optical delays, a constant time interval invariant over years can be created with 2 different delay fibers. This technique for precision time measurement by injection of time markers for the g-2 calibration system is planned to be installed in the experiment.

This pulser with 16 fiber outputs can also be used to generate a train of pulses by using 16 different length fiber delay lines, and recombining the ends, as shown in the schematic of Fig. 22b. This will be discussed in following sections where it was used to demonstrate hysteresis in PMT response (ie a pulse response depends on the history of previous pulses), a danger for time shifts over the g-2 decay cycle.

The group at Fairfield uses this equipment for PMT tests, and plans to test the PMT in all aspects (gain, QE, cathode uniformity, temporal properties, including hysteresis and time shifts) before installation in the g-2 experiment. Figure 25 shows a typical gain curve vs HV for a PMT before installation in a calorimeter, as supplied by Fairfield for the collaboration. Each PMT has a green LED cabled to it before installation. The LED are driven by a simple reverse bias pulser. Fig. 27 a,b show typical data that can be acquired by the test facility, including photocathode uniformity and LED test pulses. Figure 26 shows the PMT test facility at Fairfield.

During these tests we acquired waveform information from photomultipliers and their linear sum using our digital oscilloscope on both test pulses and data. Figure 28 shows a photograph of the traces of three electron calorimeters taken with the Fairfield digital oscilloscope - note the basic similarity to the LED test pulses. We have also taken timing data comparing the time of arrival of the beam electrons measured by the calorimeters, and by a separate FSD (fast scintillator detector), fabricated by an experienced technician at BNL. The Fairfield group proposed to the G-2 collaboration to use a separate system to measure the time of arrival of the electrons, to reduce the burden on a PMT to produce precise timing on signals of varying pulse height. Preliminary indications from the on-line system are that the width of the resulting TDC distribution is narrower for the FSD than for the calorimeters. A combined system of tag and veto scintillators is shown in Fig. 16. This may be an important step in guaranteeing the time measurement of the electron decay.

[2] G-2 Optical Pulse Calibration System Development and Installation

Progress/Status

This work entailed 2 basic systems:

(1) An LED gain and QE system, and

(2) A dye-laser tunable laser fiber injector optical pulse injection system, mainly for inserting precision timing optical pulses into the g-2 detectors system at early and late times to check that time resolution (± 0.2 ns) and time shifts (± 20 ps) are stable to the required precisions, in order to fit the precession frequency of the decaying muons. This system is also used for ensuring that the overall optical couplings, scintillator properties and system gain are stable - the UV-visible tuning allows an unfolding of potential problems.

Figure 29 shows the planned g-2 laser time-pulse and optical energy calibration system, based on our prototype work to date (see above). Modern optical pulse systems have achieved 0.2-0.5% long term gain stability (see the JETSET experiment which used a similar pulsed nitrogen laser as proposed here). [See Task B, following, for references, for example with the CLEO and Bugey reactor oscillation experiments. Other systems have used spark sources, and LED.] Besides reasonable/modest gain stability ($< 2\%$) over periods of months, the main thrust of the g-2 calibration is time stability (an energy resolution $\sim 10\%$ is ok for g-2), based on quartz fiber delay cable time increments. Fairfield is responsible for and will build and install this entire optical calibration system, planned for installation (see above) with the U. of Illinois Calorimeters by 1996.

The work for the past year is aimed toward the design of a rugged and reliable "strap-down" systems for use in the g-2 detector system, based on the experience with the prototypes above. The calorimeter light levels will be cross-checked with test beam data (1994-5) for each calorimeter and PMT pair before installation. The current plan is to have sets of trace-back wire chambers to be used to determine the beam position and size from the decay electron trajectories, which necessarily measure the momenta of a sample of electrons - these will be used to cross calibrate the equivalent energy level of the calibration system. [If this system were to be delayed until later running because of funding limitations, a set of removable slits to define an electron decay momentum will be used to check the cross correlation between the light in the pulse system and the decay electron energies in each calorimeter at the beginning and/or end of a g-2 run.]

[3] G-2 Optical Pulse Waveform Train Simulator System Development

Progress/Status Summary

The Fairfield group has constructed a "flight simulator" for g-2. This simulator re-creates ("simulates") the optical pulse waveform to be seen by the PMT viewing the g-2 calorimeters, in order to test that the PMT and data acquisition systems accurately reproduce the decay times of the electrons. The difficulty this addresses is that typical PMT have a large gain shift with rate, the infamous "rate effect" - [DeVincenzi et al, NIM 225 104 (1984), Yamashita Rev.Sci.Instr. 51, 768 (1980), Zhong et al., NIM A281 384 (1989), Bianco et al, Frascati rept LNF-90/038 (1990)] Figure 30a-e. We have shown similar data. Fig. 31a,b shows the effect of just 2 identical optical pulses, 20 ns apart (50 MHz) generated by the fiber pulser prototype (shown in Figs 21-24, esp 22c), on a typical 2" PMT for g-2. Fig 32 shows 15 identical amplitude optical pulses impinging on 1 PMT, separated by 16 ns of optical delay (the individual pulses were trimmed by attenuators to be within $\pm 3\%$ of each other before being combined into a pulse train). The hysteresis is evident.

These data were taken with a resistive base. For FY 1994, measurements will be repeated with high rate transistor bases. These simple test pulse trains using stepped fiber delays with the laser time calibration apparatus cannot hope to model g-2 data conditions, with varying pulse heights from the decay electrons (~ 0.5 -3 GeV accepted, by many lower energy enter the calorimeter), out to ~ 0.5 ms, and hundreds-thousands of pulses per PMT over that interval.

The danger in g-2 is that the rate on a PMT by the nature of the experiment is decaying as $e^{-t/60\mu s}$. For 10-12 lifetimes, the centroid of timing of pulses over the decay interval of ~ 0.6 - 0.7 ms from earliest to late times of the g-2 measurement must not shift by more than 20 ps (ie the centroid of a distribution - the distribution itself could be ~ 0.5 -1 ns FWHM wide). Even with high quality constant fraction discriminators being designed by the BU group and the very best active bases, it is not certain that we will be able to guarantee or detect that low a time shift due to a rate change of gain or other hysteresis effects in the PMT, without a test of these shifts during running. We must plan to continually measure time shifts due to rate effects early (high instantaneous rates) and late (low rates) in the data taking cycle during and between running by the use of the optical pulse train simulator proposed here, to apply corrections if necessary to the data. We therefore will mount on every calorimeter a system to create an optical pulse train that simulates the g-2 optical pulses created by the calorimeters during the g-2 storage cycle. During that simulated g-2 fill cycle, a flash will be inserted by the laser calibration (see above), and one or two laser test pulses will also be fired at precisely known and highly stable times or time intervals (optical fiber cable timed). A shift in the measured time for those superposed laser pulses under varying fixed fiber delays can be used to detect and to correct shifts in the g-2 late and early times.

[4] Photodetector Tests and Specifications

Progress/Status

This section describes work on the PMT, bases and gating circuits.

The flash at injection (pion injection) into the g-2 ring is a serious obstacle to subsequent precision time measurements. A pulse of 1-10 million photoelectrons for ~ 0.1 - $1 \mu s$ is followed by pulses of ~ 100 -1000 p.e. from the g-2 decay electron calorimeters. As shown previously in flash simulations using the test beams at BNL, 30 V pulses are drawn from an unprotected PMT anode during the flash. The flash duration requires that the tube be gated off or protected from the light impulse from the detectors for about 10-20 μs , before the the g-2 decay cycle can begin. A primary difficulty with the injection Flash is in the photomultiplier tube itself and in the base. A flash gating circuit which turns off the pmt must be well-matched to the electronic properties of the photocathode and dynode chains of the phototubes under test. According to our previous tests and after extensive consultations with PMT engineers, several dynodes, but not all, must be carefully matched electrically to individual pulser circuits for optimal gating; furthermore, a gating circuit must be carefully tailored to the particular PMT model being gated. In previous tests, groups at Fairfield and BU have had inadequate results trying to gate a PMT by switching off or counter pulsing the photocathode. While this has the apparent advantage of preventing the photoelectrons from ever leaving the cathode, the very high dielectric constant and resistivity of the cathode make this a poor choice. We have had excellent results with a flash gating circuit obtained by Fairfield on a custom basis from Hamamatsu Corp. which works with the Hamamatsu R2490 2" PMT. Figure 36a-d show the gating and recovery with a gating circuit which switches 2 dynodes to the same potential. A similar modification of this circuit has been made in collaboration with Hamamatsu Boston University for the R1828. Figure 37a-c shows the results of flash test gating with this circuit which shorts D7->D4 on an R 1828 2" PMT and demonstrates that the PMT can recover to a time error of ± 20 ps after the flash. The flash testing has continued to make extensive use of the

laser optical pulse systems used in the G-2 and SSC work described above, used in this case as the "flash" optical pulse. However, these tests heretofore have not addressed the issue of time shifts from the rate effect g-2 pulses themselves (as addressed above for "flight simulator" discussion).

These flash pulses must be integrated into both the flight simulator and the test pulses for a complete test of the g-2 PMT, in both the PMT selection process and acceptance process.

[5] Slow Control and Data Acquisition System:

We began basic, zeroth order work on the design of a few of the "environmental" monitoring aspects for the data acquisition system, starting with design and specifications, and contacting vendors for sensors. No hardware will be ordered until late FY 1995. These included: G-2 building temperature and gradients, floor gradient tilt, local magnetic fields, local vibration amplitude, variations in ring position. This monitor and control information is essential to maintain ± 1 ppm on the magnetic field integral of the g-2 ring. This task will become more urgent and well-defined during 1994.

CONCLUSION of TASK A:

We are playing an important role in Muon (g-2), E821, but appropriate to our size and capabilities as an undergraduate institution. Our tasks were well-matched to our experience and our other projects, concentrating on scintillation calorimetry, electro-optics and optical calibration techniques.

Task B: Optical Calorimeter R&D & Calibration for High Rates & Colliders (50% of PI Research Time)

Introduction: Status/Summary

This task was a general continuation of developments of scintillating fiber and cerenkov fiber calorimeters developed for the SSC Generic R&D and Subsystem R&D programs, and for the GEM collaboration. Over the past 3 years, we have participated in the construction and testing of large hadron calorimeter towers for colliders. In these tests, Fairfield University supplied PMT and/or optical pulse calibration equipment. The papers attached in the APPENDIX were authored by us and summarize well the progress to date.

Additionally, Fairfield also tested 5 unique radiation hard e-m calorimeters, using liquid scintillator core fibers, and using quartz cerenkov fibers. They are initially intended for the SSC in the region of $\eta > 3.5$ (forward calorimetry), but may be generally useful in any environment that uses high rates and high radiation. The results for the liquid fiber test were presented at the Nuclear Science Symposium, as attached in the Appendix. A paper on tests of the Cerenkov fiber calorimeters (both e-m and hadron) will be presented this fall at the Nuclear Science Symposium (NSS). [During the end of this calendar year and in FY 1994, we will perform further tests on a 1.5 tonne, 7 λ hadron module which uses Cerenkov light as the sampling medium.] These modules (em, hadron) were tested this past summer (1993) with good results as will be described below. A selection of figures from a talk by the PI describing this work is the last set of Figures. These projects have been supported largely by SSC-directed funds and by TNRLC.

This report is focussed on:

[1] *Calibration*: Calibration of fiber and scintillator calorimeters, such as used at colliders and in g-2 using electro-optic technology, for very high rate and high time precision applications;

[2] *Electro-Optic Detectors*: Development of the photonic detectors used for scintillation or Cerenkov calorimetry in magnetic fields at colliders or in g-2 with rate, timing and dynamic range capabilities exceeding existing PMT systems; [Results of this work in high speed electro-optics should generally be of interest to experiments requiring measurements of both precision and high dynamic range optical signals, with long term stability.]

[3] *Fast, Radiation-Hard Optical Calorimetry*: SSC/GEM and Generic research for radiation-hard fast calorimeters that may be used in heavy ion beams or very close to high intensity beams or in future collider forward calorimetry. Our work concentrates on fiber forward calorimetry using both Cerenkov sampling fibers and liquid scintillator fibers (hollow tubing acting as a cladding for a liquid core). Complete details are given below, and also in Figures 42 a-m, Figs 47a,b, Figs 48a-d and Fig 49 following summarize our progress in this field, and show photographs of devices completed in the last year. Results on energy resolution are sufficient from these modules for forward calorimetry. Details are found below, and in the Figures.

[1] Electro-Optical Calorimeter Calibration

Generic Detector R&D, and g-2: The most important aspect of this work for the immediate future was refinement and extension of the equipment for optical pulse injection calibration systems (pulsed dye laser injection on fibers, LED, and high rate laser diodes - the "flight simulator") for

both g-2 calorimeters and for SSC R&D calorimeter modules. [These systems may be especially useful for "off-beam" testing during FY94, when higher energy beams may be unavailable.] Major parts of the optical pulse systems were and will be installed in the prototype calorimeter modules for energy and time calibration during and after beam tests at BNL, FNAL and in the Texas Test Rig(TTR) at SSCL. It is possible that some quartz cerenkov fiber calorimeter modules to use this calibration will be sent to CERN for tests with P. Gorodetzky(NA38) and the ITEP groups.

GEM SSC Detector: This generic optical pulse equipment has been adapted for and used by the GEM group both for:

- (1) the GEM Scintillating Barrel Calorimeter (Figures 40a-c), to be tested in the TTR (FY 1994) and at FNAL (1995), and
- (2) the Forward Calorimeter (Figures 41a-b).

-GEM Scintillating Barrel Calorimeter: The scintillating barrel calorimeter is a scintillating plate calorimeter following the central hadron calorimeter and is used for containment, jet measurements of late showers, and muon tagging. It consists of a 0.8 m thick 11 m long barrel of Cu starting at a radius of 2.9 m, with a mass of 800T. Four layers of scintillating plates (6 mm thick) in a $\Delta\eta \times \Delta\phi$ of 0.16×0.16 read out the calorimeter using 638 PMT.

-GEM Forward Calorimeter: At present, the 2 options for the GEM forward calorimeter are liquid core scintillating fiber and quartz calorimeters. Fairfield University is the lead University on the use of Quartz Cerenkov Fibers for the sampling media of forward calorimetry, and collaborates closely with Prof. R. Webb (Texas A&M), and Dr. Yuri Kamyshkov (Oak Ridge National Lab and ITEP). We have tested 2 e-m module in summer 1992, using both quartz fiber cerenkov sampling and liquid scintillator core fiber sampling (about 30 Lrad deep each in a Pb matrix) and a second set of rebuilt e-m modules (both quartz and liquid) and a 1.5 T 7 lambda thick hadron module were tested in 1993. Spaghetti calorimetry using liquid core capillary "fibers" or quartz Cerenkov fibers offers many advantages and is especially suited to the highly collimated jets of particles in the forward region: (1) superb muon Landau measurements, (2) superior transverse segmentation, transverse hermeticity, and high uniformity across eta and phi, compared with competing technologies, (3) all optics in high radiation regions are pumpable or replaceable or intrinsically radiation hard (4) intrinsic high rate capability, (5) only active elements (PMT) are self shielded by the calorimeter.

Figures 42 a-m, Figs 47a,b, Figs 48a-d and Fig 49 following summarize our progress in this field, and show photographs of devices completed in the last year. Talks were given by the PI summarizing progress at SSCL, BNL and the NSS. Figure 49 in particular is a complete set of slides from the latest data of 1993 taken on a 7 lambda hadron module and a 30 Lrad e-m module which used these calibration systems. Note that these Figs also show a novel liquid scintillator module using hollow fiber tubes as a cladding for liquid scintillator. Results on energy resolution are sufficient from these modules for forward calorimetry. Details are found below, and in the Figures.

The optical pulsers described below and in sections [2], [3] of g-2 (Task A above) are an especially convenient way to guarantee stability. Figure 43 shows the abstracts of some papers which have demonstrated high stability achieved by optical pulsers. We plan to propose to extend these measurements with LED and laser diodes in the feed-back mode of operation.

Figures 48-49-> show a complete progress talk on the 1993 tests of a large hadron cerenkov module and improved e-m module during July, 1993.

Optical Pulsers and Optical Waveform Simulators:

• Laser Fiber Injector Prototype Improvements:

The optical pulser using a UV dye laser feeding quartz fibers was shown schematically in the Figures for Task A, and was used with g-2. Several improvements were made in this system by new connectors and fibers. This device is prepared for shipment to the TTR at SSCL for use when the SciGEM prototype is ready. It was used at BNL during the tests of the cerenkov calorimeter.

• LED Prototype System and Multi-Color Improvements:

The primary purpose of the LED system was for phototube gain stability (see g-2). We obtained prototypes for a system of blue, green, yellow and red LED mounted in the same clear package on the same chip, together with a feedback diode. Each LED was used independently to inject a light pulse on the diffuser which matches the end of a fiber bundle to a PMT. This creates a double pulse: the prompt PMT pulse, and a reflected pulse from the end of the fiber (mirrored). The ratio of the reflected to prompt pulse remains constant with no radiation damage or change in the fiber transmission.

• High Rate Laser Diode Optical Pulse Train Simulator Prototype:

(See also g-2 sub-section [3]) This consists of newly available waveform synthesizer->current driver->visible laser diode to produce an optical pulse train based on a Monte Carlo input to the waveform synthesizer time-correlated long memory. This M.C. can be from any experiment. Here we will use it both for SSC events and for g-2.

[2] Electro-Optic Detectors

A major activity was to investigate methods to extend the gain/linearity of photodetectors appropriate for fiber calorimetry in high rate and high dynamic range environments, mainly for hadron colliders.

In the above description for Task A (g-2) we have described work on hysteresis, which is similar for the SSC. We also show in Fig. 44 the time shift with pulse height over a very large dynamic range appropriate for SSC calorimeter, taken with the fiber puser prototype made for SSC/g-2.

We will propose next year to extend this work to both real SSC PMT prototypes, as opposed to the "off-the-shelf" tubes and bases used in the existing tests of the above figures, which would be insufficient for SSC operations (neither magnetic field insensitive, nor capable of the rates and dynamic range) and novel hybrid PMT which we have discussed with several vendors (Litton/AP and DEP) this year (see below). An essential part of scintillation calorimetry in high rate (above 1 MHz) precision calorimeter experiments proposed for SSC, LHC or in fixed target experiments is the dynamic range, change of gain with previous pulse history (hysteresis), and linearity capability of the photomultiplier tube, which approaches 5 orders of magnitude in dynamic range (from $\sim 1/10$ minimum ionizing on muon Landaus, ~ 50 MeV least count, to ~ 5 TeV maximum count on forward jets) at the SSC.

This included 2 basic developments and research areas:

(a) Studies for Modifications to Standard PMT;

magnetic field. The intrinsic hysteresis should be substantially lower than dynode type PMT; however this remains untested, and would be an immediate contribution of this proposal. Lastly, they require only 2 HV feeds, instead of a complex dynode chain (or at most 3 HV, with a focussing electrode which draws little current). This work will continue with the arrival of real prototypes.

[3] Fast, Radiation-Hard (Forward Fiber) Optical Calorimetry:

Status

This project was done in conjunction with the development of forward spaghetti calorimetry, and in association SSCintCAL and GEM, and with TNRLC operating funds of \$70K and \$60k, testing both liquid scintillator core fibers and quartz fibers as radiation-hard substitutes for plastic fibers, to be used in calorimetry below 5° to the beam direction.

Cerenkov fiber sampling has been pioneered at CERN by P. Gorodetzky (Saclay) for NA38. He has demonstrated radiation hardness to 3 GigaRad for high purity quartz optical fibers. For forward calorimetry, a resolution of 10-15% is acceptable at 1 TeV and has been shown to be achieved for this device. Recent MC work by us and by groups at Saclay and Oak Ridge have confirmed this analysis.

Our quartz e-m module with 6.8% packing fraction of quartz fibers, 30 Lrad thick achieved ~ 5 p.e./GeV in BNL tests, with a resolution of 25% at 10 GeV at 11° to the beam direction. We rebuilt this module with a 7.2% packing fraction. It obtained a resolution consistent with $55\%/\sqrt{E}$, 11 p.e./GeV at 5° to the beam direction, summers of 1992-1993 (see figures 42, 48, 49). We also tested a Cu hadron module 6.8 lambda thick with a small (2.8%) packing fraction on 8 GeV pions and electrons. It obtained a resolution on electrons consistent with $90\%/\sqrt{E}$ and 1.4 p.e./GeV on pions. These are sufficient for a forward calorimeter for $\eta > 3-3.5$.

Liquid Scintillator Core fibers have been pioneered by many groups using fiber tracking (see refs in papers). We have simply borrowed this technique for calorimetry. Rather than the rigid tubing used for tracking, we have concentrated on flexible rad-hard polymers and a new novel ultra-thin wall quartz, a new breakthrough design. Our e-m calorimeter with an 11% liquid core packing fraction tested at BNL obtained a resolution of 18.7% at 15 GeV.

Both types (Lscint, Cerenkov) of calorimeter had very narrow pulses, and produced beautiful Landau distributions. This is essential for calibration of forward calorimetry.

Spaghetti calorimetry using liquid core capillary "fibers" or quartz Cerenkov fibers offers many advantages and is especially suited to the highly collimated jets of particles in the forward region: (1) superb muon Landau measurements, (2) superior transverse segmentation, transverse hermeticity, and high uniformity across η and ϕ , compared with competing technologies, (3) all optics in high radiation regions are pumpable or replaceable or intrinsically radiation hard (4) intrinsic high rate capability, (5) only active elements (PMT) are self shielded by the calorimeter.

Details are available in our funded TNRLC request.

We now give a description of these new technologies in the following introduction, followed by results.

Introduction: Fiber Sampling Forward Calorimetry

(b) Studies to solicit Hybrid PMT

- (a) *Modifications to Standard PMT Technology:*

We identified several major areas of possible modifications to existing tubes which operate in ~ 1 T fields, modified especially for high dynamic range operation. This work was done by consulting with Hamamatsu, Philips and Burle. Typically these modifications trade-off gain and risetime for stability, linearity and low hysteresis. We anticipate that the gain of a PMT would be reduced from 10^6 to 10^4 , and the risetime would increase from ~ 2 ns to ~ 6 ns, still sufficient for collider operation.

Our studies indicate that the following modifications to standard PMT technology will enable PMT to perform well at Colliders:

- (1) Low resistivity photocathode ($\times 1,000$ times higher conductivity than standard);
- (2) Low carrier lifetime dynode activators - a key element in the change of gain with rate of a PMT is the carrier lifetime of the dynode secondary emission activation materials;
- (3) Dynode activators with more equal electron and hole mobilities to avoid dynode instantaneous polarization;
- (4) Defocussed anode electro-optics to limit space charge effects;
- (5) Low anode inductance to last dynode, $L < 1$ nH;
- (6) lower capacitance anode, $C < 10$ pF to all other electrodes;
- (7) Lower interdynode capacitance, < 3 pF;
- (8) Anode and last dynode heat sinking;
- (9) Lower residual gas in the envelope.

We expect to test prototypes with these proposed modifications in the immediate future..

- (b) *Hybrid PMT Research:*

Hybrid tubes using a semiconductor diode target for the photoelectron gain mechanism have demonstrated superior dynamic range (up to 10^5 at CERN and at Yale).

Recent advances have been made by Litton (Tempe, Az, private communications, and Prof. P. Cushman, Yale) in hybrid PMT technology, using new avalanche diodes produced by Advanced Photonics, which show much promise for a detector for fiber tracking (private communication, 1992, P. Cushman, Yale). However these tubes are not specifically designed for calorimetry. The gain is very good 10^5 - 10^6 , as necessary for fiber trackers. The avalanche gain, ~ 500 (2000 V supply) is multiplied by the electron bombarded semiconductor (EBS) gain. The avalanche gain mechanism in Si has a long recovery time (in contrast to the EBS mechanism), partially to resupply the depleted avalanche region with charge. The fast rising pulse therefore has a long single tail even on single p.e (~ 30 -40 ns).

We therefore have discussed possibilities for prototype hybrid PMT with modifications specifically for calorimeter operation in a magnetic field, including: (a) lower avalanche gain for greater stability and lifetime, (b) larger photocathode area with green extended performance, and (c) non-imaging photoelectron focussing. In principle, these devices may be made intrinsically more stable than PMT because the gain depends only linearly in the HV stability (vs PMT gain $\sim V^{\#}$ dynodes). The demonstrated dynamic range is a large plus for these devices. Furthermore, they are more compact than existing PMT for the same gain, and have in principle much better properties in a

The object of forward calorimetry for the SSC is well-known, and may be crucial for the discovery of the heavy Higgs, the WW scattering process, and the SUSY LSP. However, exposures above 1 gigaRad/year may be necessary for a calorimeter to survive in the $\eta=5$ region. Furthermore, the particle density below 5° is such that realistic calorimeter cells (ie 5-15 m from the interaction region, even with the interaction length of tungsten) will entrain high rates of real and leakage showers, requiring superior ability to measure calorimeter energy at high rates, especially at elevated luminosity when that becomes available.

The drawback of spaghetti calorimetry for the forward region is the insufficient radiation resistance of existing plastic scintillating fibers. However, the geometry of spaghetti fiber calorimetry has distinct inherent advantages for this forward calorimeter environment:

- (1) No active elements to fail in the high radiation region. No power is required in high radiation region. No high voltage in radiation flux.
- (2) Direct scintillator light (no tertiary waveshifter optics) or Cerenkov light is fast. Simple optical paths guarantees fastest possible optical pulses.
- (3) PMT active component survives >100 MRad (quartz envelope); also shielded by the calorimeter.
- (4) Spaghetti fibers exit the back of a calorimeter: replaceable without extensive disassembly.

In addition, spaghetti calorimetry has demonstrated compensation, speed, uniformity and good energy resolution in both prototypes (SPACAL, G-2, DAPHNE) and experiments (JetSet). Hadron energy is fully developed in 40-50 ns, and electromagnetic energy in 15 ns. In 32 ns, e/h settles to 1.2. If spaghetti fibers could be developed, which were radiation hard, and which could replace plastic fibers, then the simplicity and speed of spaghetti calorimetry would make it a viable or superior candidate for the forward region of the SSC.

Currently, several groups are intending to construct prototypes of large spaghetti calorimeters for the central regions of SSC or LHC experiments. In particular (for examples only) the SSCintCAL group, including members from SPACAL, is constructing splendid projective copper matrix hadron towers for plastic fibers, about 1.58 m in length, weighing ~1,500 lbs (~9 interaction lengths), with a 3-4% fiber packing fraction. It takes about 1 crew-day to insert by hand the ~1.5 mm fibers into the gang-sawed grooves, formed into the laminated copper sheets. Similar prototype plans are being made for SDC for forward calorimeters. Similar modules are being made at CERN for the barrel regions of the LHC (SPACAL and RD projects), and the fibers proposed for development here could be loaned for studies in beam tests.

We therefore proposed to provide two sets of fibers for forward spaghetti readout:

- (a) high index, radiation hard liquid scintillator fiber core, in a rad-hard polymer tubing cladding, (for testing, sealed with optical end plugs), and
- (b) quartz UV optical fiber Cerenkov radiators.

Both could be used as simple, direct replacements for plastic fibers (or for rigid tubing liquid fibers) used by the existing spaghetti calorimeter groups. These fibers are designed to require very little modification of the prototype hadron towers (except some minor changes in the gang-saw set ups - packing fractions or diameters), their readouts, or calibration schemes, in order to test the

energy resolution, speed and overall performance of the proposed solution for forward calorimetry (optical spaghetti) quickly and without major modification in some existing or in-construction prototypes. With proper and extensive planning and preparation, a change-over to the liquid scintillator fibers or quartz Cerenkov fibers we propose here could take less than 1 week at a beam-line. Radiation damage tests of small sets of fibers with and without recirculation can be done without hadron test beams.

A basic thrust of our proposal was that these particular types of radiation hard optical fibers are essentially available commercially, and can be upgraded to the requirements of the SSC industrially.

We now turn to the fibers proposed to be used in the spaghetti matrix.

(I) Flexible Liquid Fibers as a direct replacement for Plastic Spaghetti

Liquid Scintillants:

Organic liquid scintillators have distinct advantages for high radiation environments over polymer plastics for scintillating fibers:

- (1) Liquids are in principle replaceable by flow or pumping.
- (2) Some liquid scintillation materials are intrinsically radiation hard.

To illustrate the last statement, a typical toluene based liquid scintillator's (NE224) properties before and after 140 MRad change by less than a few % [Chiba et al p 381, CDF Conference at Tsukuba, April, 1990, KEK publ.] Bicon has also fabricated many high index liquid scintillators, with solvents which are expected to be very radiation hard. In particular, isopropyl biphenyl (index $n=1.58$) has been used as a nuclear reactor material for coolants in experimental hydrocarbon cooled reactors. It does not polymerize or coat walls of tubing, even under high neutron and radiation doses. Furthermore, benzyl alcohol ($n=1.55$) and methylnaphthlene ($n=1.62$) are similar solvent candidates. Radiation-hardened fluors produced by Bicon would be similar to those already proven.

We do not at this time propose to address the recirculation opportunity; we have decided that other performance issues are more crucial for the decision tree. At this writing, our baseline scintillator solvent is isopropyl biphenyl, and was used in tests at BNL, as acquired from Bicon. Radiation damage tests will be performed on samples of this scintillator, with and without claddings.

Additionally, liquid scintillators are typically faster than solid scintillators because of diffusive effects in the energy transfer mechanisms. Liquid scintillators using benzyl alcohols have been tested with decay constants less than 2 ns at Fairfield and Bicon [C. Hurlbut et al., IEEE TNS [1989]]

Flexible Claddings:

A number of groups have studied rigid cladding liquid fibers mainly with glass claddings, with reasonably good success [J. White & R. Webb, TAMU, private communication, J. Bahr et al., NIM A306 169 (1991)]. The attenuation length for a number of high index scintillators produced by Bicon and tested at CERN in glass capillaries is ~ 80 cm.

However, these rigid "fibers=capillary tubes" are more difficult to work with than flexible tubing, and would not be able to be a direct replacement for plastic fibers in the calorimeters without much

more extensive development and modification of the calorimeter matrix and the liquid handling. Sealing the ends optically are also more difficult. We hereby propose to separate the issue of recirculation, external liquid handling, and optical feedthrough from the immediate need for some performance benchmarks for the purposes of making a timely decision for the 2 SSC experiments.

Radiation hardness of the liquid fiber claddings is a serious issue, for both the cladding mechanical strength and optical properties. However:

(a) The development of color centers in a material by radiation usually does not affect the index of refraction, only the attenuation length. At the surface of the cladding, the evanescent wave does not penetrate significantly beyond a few wavelengths, and the absorption apparently is not very relevant. As an example, J. White and C. Johnson (private communication) have irradiated glass liquid fiber tubing until it is black; there is essentially no change in the TIR (total internal reflection) light transport properties. Similarly, black teflon (filled with carbon black) and black viton (the fluoroelastomer resin is filled with carbon black as a vulcanizer) make excellent TIR tubing [see following also].

(b) Plastic or polymer materials exist with sufficient hardness, as tested for accelerator magnet applications, for usefulness in the forward region.

We therefore proposed to use sealed flexible rad-hard polymer tubes, with the ends sealed by transparent plugs. We essentially followed the work by Chiba et al, using a Viton tube filled with liquid scintillator, and by the some of the PI (spaghetti E-M calorimeter using teflon tubes filled with liquid scintillator, tested at BNL, W. Worstell et al., IEEE TNS [1990]) and by [M. Bonesini et al., NIM A270 32 (1988) & NIM A263 325 (1988)], and by Oriel Corp (*see next section*). The difficulty with the last two devices is that (low index) teflon is not rad-hard at all, whereas in the first example Viton has some reasonable rad hardness. We have identified 6 types of semi-flexible polymer tubing appropriate for cladding for this project, with sufficient radiation hardness to be interesting to the SSC:

- (1) Halar - ECTFE fluoropolymer, tested to 200 MRads $n=1.43$
- (2) PEEK - polyetheretherketone - see figure 7 - $n\sim 1.5$
- (3) Kapton - polyimide - see figure 7 $n\sim 1.55$
- (4) Ether Polyurethane/Superthane - see figure 7 $n\sim 1.5$
- (5) Viton - fluoroelastomer - see reference Chiba et al. $n\sim 1.48$
- (6) Polysiloxanes - $n=1.4 - 1.45$

The tubing technology for Halar, PEEK, Etherpolyurethane and Viton are well-developed, down to capillary (~ 1 mm OD) dimensions commercially available, with tolerances and surface finishes of acceptable optical quality (*see next section*).

Development of these flexible claddings is a significant departure (but complementary and overlapping significantly also) from other liquid fiber groups using rigid tubing for forward calorimeters. We assert that the flexible fibers will make both the handling and engineering of the end seals and optics considerably easier (*see next section*) and result in significant cost savings.

Commercial Liquid Fibers:

Liquid optical fiber light guides (ie not scintillating at present) are available commercially from the Oriel Corporation. They have an optical attenuation length of $\sim (3) \sim 5$ meters at (400) 500 nm [$\sim 82\%/m$ at 500 nm]. The Oriel Spec-sheet shows a light guide with an outer armor for protection and the measured transmission curve. Remarkably, they have a N.A. of 0.47. These specs have

been checked by preliminary measurements at Fairfield U. These specifications confirm that standard commercial spec extruded plastic tubing used in the Oriel liquid light guides may be obtained with a surface finish acceptable to light guiding over the interesting range for SSC calorimetry (an optical attenuation > 2 m), and, with proper fluid indices, may have considerably better light trapping than existing plastic fibers. The flexible plastic tubing cladding is compression fitted with small (~1-2 cm long) cylindrical optically polished end plugs serving as the liquid core optical feed-thru and fluid containment. These plugs have essentially the same OD as the tubing ID, which may be any compatible optical material: plastic, glass, quartz (UV transmission) etc. At the far end of the calorimeter, the necessary radiation hardness of these end-plugs could be modest. At the inner calorimeter surface, these plugs could be made of stainless steel, etc., as they do not need to be optically transmissive there, a possible aid to developing a recirculation plenum. These fibers are quite flexible, and are presently available only as small as 3 mm OD; however, smaller diameters could be readily produced. Using this liquid fiber technique with Halar, PEEK, polyurethane or Viton tubing is readily possible. Preliminary discussions with a number of tubing manufacturers (pulled at random from the Thomas Register) has confirmed that surface finishes and dimensional tolerances used in the existing commercial fiber liquid light guide can be easily obtained with Halar, PEEK and polyurethane.

Recent tests of these fibers using Halar claddings and Bicon 599 are shown in our publications, as installed in a ~20 Lrad thick counter at BNL.

QUARTZ LIQUID FIBER CLADDINGS WITH ULTRA THIN WALLS:

A recent breakthrough in cladding technology has been achieved by Fairfield, based on a new commercial product. It uses a remarkable quartz capillary tube available in 0.3-2 mm ID, with 20-30 μ m thick walls! [FiberGuide Industries, Stirling NJ, Dr. Dipak Biswas] These capillary tubes have a bend radius of 10-15 cm. They are protected by a jacket of polyimide for scratch resistance. The very thin wall guarantees both: (1) superb optical surface, with the inside identical to the outside, and (2) very high dimensional tolerances. Figure 46a,b shows both a photograph of the liquid scintillator filled fiber in a dark box, and the pulse height spectra of beta particles from a collimated source traversing a 800 μ m thick core fiber. The attenuation length on a short sample (0.5 m long) was estimated to be 1.2 m.

(II) Quartz Cerenkov Fibers as a direct replacement for Plastic Spaghetti

Cerenkov light has been successfully used for hadron calorimetry in experiments where very good energy resolution is not a necessity. Non-sampling calorimeters for hadrons have been made with a water "swimming pool" at Fermilab [B.C. Brown et al., IEEE TNS NS-25 N0.1, 347 (1978)], and using lead glass blocks by a Russian group [A. Bitsadze et al., NIM A269, 115 (1988)]. Typically for hadrons, the constant term is large ~10%, and the stochastic term small ~35%/E*0.5, as is typical for total absorption calorimeters without a compensation mechanism.

Cerenkov sampling calorimeters using Cerenkov spaghetti [as developed by P. Gorodetzky of NA38 at CERN- private communications, 1992. We are extremely grateful to Dr. Phillippe Gorodetzky of the NA38 collaboration at CERN for sharing his invention, data and advice with us. This important development has also been discussed with us by Bill Willis (GEM) and by Bill Foster (SDC) for the forward region] have two principal advantages for the SSC as forward calorimeters:

- (a) very high radiation hardness
- (b) high speed

Many media for Cerenkov light can be extremely radiation hard. Although the Cerenkov light will yield a relatively low number of photoelectrons and the compensation mechanisms are poor (and constant term expected to be large ~6-10%), the radiation hardness, speed, simple construction, and (if successful) very low development costs, compared with other technologies, make Cerenkov fiber sampling an interesting candidate in the forward region, where the calorimeter deposited energies are very large.

Radiation Hardness

High purity quartz (suprasil) has demonstrated excellent radiation resistance. In tests at GANIL, over a wavelength range of 300-500 nm, the transparency of small quartz samples changes by less than 4% after 20 Gigarads, and between 300-425 nm, the change is less than 2%. For exposures above 20 Grads (up to 30 Gigarads), the transparency then improves in these samples, probably due to annealing. [H. Bernas, private communication with P. Gorodetzky, 1992]. Quartz fibers have been tested with 2 claddings; the PMMA claddings are radiation hard to 2 Gigarad, and fluorine doped quartz claddings are hard (less than 10% change) to 20 GigaRad. Further cladding and core development appears to be easily possible by quality control upgrades or pre-selection.

Quartz Fiber Cerenkov Spaghetti Prototypes

We have followed the lead of P. Gorodetzky, who is leading a group developing a quartz fiber sampling calorimeter for the heavy ion experiment NA38 at CERN [the Silical calorimeter - quartz fibers in a lead matrix]. By using readily available quartz fibers as the Cerenkov sampling medium, the convenience and advantages of Spaghetti calorimetry are adopted.

The CERN modules were tested at CERN in an Sulphur or e- beam up to an equivalent energy of 6.4 TeV. The fibers are arranged to maximize at least some of the Cerenkov emission along the fiber meridional direction, ~45° to the beam. (If an air TIR interface could be arranged, the optimal fiber orientation would be essentially the incident particle direction, except for streaming effects of the showers). Our MC shows that this is not necessary, as a large fraction of the energy deposition comes from low energy particles which are nearly isotropic.

Dr. Gorodetzky has shared with us preliminary results from the CERN tests of this small 5x5x20 module, with 1 mm quartz fibers in a 20% packing fraction read-out by 2 PMT. These tests show an electron resolution of $37.4\%/E^{*0.5} + 1.2\%$ (electrons between 10-30 GeV). The yield with hadrons (uncontained) is 3 p.e./GeV (32S at 160 GeV/nucleon), sufficient for the SSC. The good agreement between simulation and measurement give a large degree of confidence in these results. For example, the thickness of the W block was varied between 0-8 cm, with agreement between the calorimeter response & the simulated response. It is anticipated that a full hadron module may have a resolution between $(100-300\%/E^{*0.5}) + (6-10\%)$. While this is not comparable to a compensated scintillator calorimeter, it will survive and operate, and appears to be sufficient for the physics of interest.

Fairfield e-m Cerenkov Calorimetry Results 1992 [See Figures 42- 49]

Our results from last summer in our e-m module showed a resolution of 25% at 10 GeV electrons energy, with 5.3 p.e./GeV.

This summer we achieved similar results as shown in the figures 49. An interesting bonus of the Cerenkov readout technique is the speed of response. The pulses were clean, and without long tails often associated with unoptimized scintillators. The figures 42 show the waveform from a 10 GeV electron, ~ 10 ns wide at the base.

E-M Calorimeter Prototype: We have constructed a greatly improved e-m prototype for tests at BNL and CERN.[Figure 47a,b] Fig. 47b shows the cosmic ray spectra in this device. Figures 48 show the results of the recent BNL test 1993.

Hadron Calorimeter Prototype: We have also constructed a 110 cm thick Cu with 3,200 Cerenkov fibers as a hadron module, under sub-contract to the shops at Boston University. Figures 48 show the drawings of this hadron calorimeter. The hadron module which achieved a response ~ 2 GeV/p.e. on 8 GeV pions, using only a 2.8% packing fraction of 1.5 mm Cerenkov fibers. The response to electrons implies a resolution of $90\%/\sqrt{E}$ at 8 GeV, with 1-2 pe/GeV on pions (our maximum beam energy was only 8 GeV).

Conclusion Task B:

We have accomplished tasks with wide application in Collider Physics. Our basic thrust has been in electro-optics (Optical Calorimeter Calibration and Photodetectors) and Optical Calorimetry (Fiber calorimetry for the forward region), where we are strongest, and which dovetail well with our most pressing projects on Muon g-2 - Task A.

Conclusion of the Grant Technical Report:

Our group has developed a modest but highly successful program at Fairfield University, in close and productive collaboration with our colleagues and friends at Yale and Boston University for two important and difficult experiments in high energy physics: the coming of the SSC, and G-2.

We remark on the highly unified nature of our Tasks, using similar calorimeter and electro-optic techniques for very different experiments, which in these areas have similar technological demands; this confluence helped make our effort efficient, and was by design.

We are continually encouraged by the very positive response of our undergraduate students to these developments. Fairfield University strongly supported this effort by some cost sharing with DOE. Additionally, TNRLC supported supplements the effectiveness of this Grant.

- **Personnel:**

- Principal Investigator David R. Winn, Ph.D., Professor of Physics, Fairfield University. Prof. David Winn is also a non-budgeted Research Affiliate of Yale, and a Visiting Professor at Boston University. For references, see Prof. V. Hughes or Prof. L. R. Sulak, respectively.

- 4 Undergraduate Students, during the academic year, and summers.

- The University encourages student research through research course credit offerings.

- Technician (shared with the Department, as described above).

- Computer Technicians as available.

1992-93 Fairfield University Publications Resulting from DOE Support

“Grooved Copper Scintillating Fiber Hadron Calorimeter Construction and Tests”, D. Brown et al., to be presented by D.R. Winn, Conf Proc.IEEE Nuc.Sci.Symp, 1992

“Liquid Scintillator Core Fibers with Polymer Claddings”, K. Segall et al, presented by D.R. Winn, Conf. Proc. IEEE Nuc.Sci.Symp, 1992

“Scintillating Fibers with Cast Absorbers”, D. Brown et al, IEEE Nuc.Sci.Symp., Pub Conf Record, 1992

[“ Cerenkov Fiber Calorimeters” - to be presented in the IEEE Nuclear Science Symposium, Nov 1993]

[“An Thin Wall Quartz Capillary Liquid Scintillator Core Fiber” - to be presented in the IEEE Nuclear Science Symposium, Nov 1993]

APPENDICES - Papers attached

(note: slides from a talk on cerenkov calorimeter progres are attached as the last set of figures)

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Fig. 15a: Electron Calorimeter placement with scalloped vacuum chamber (plan view)

- Fig. 15b: Electron calorimeter placement, perspective and elevation view in magnet.
- Fig. 16: Detail of calorimeters, FSD & SSD scintillator tags, and time/waveform readout.
- Fig. 17a,b: Flash-test geometry at BNL test beam, with PMT Flash Waveform.
- Fig. 18: Electron calorimeter final assembly at BNL with Fairfield Students
- Fig. 19: Electron calorimeter ADC distribution, test beam 1991.
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- Fig. 23a: Fiber power splitter
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- Fig. 24: Narrow pulse produced on fiber to fast PMT (pre-pulse is laser noise, eliminated by grounding laser housing) by laser fiber pulser.
- Fig. 25: Typical PMT gain curve taken in PMT test rig at Fairfield, used at g-2 test beam to set PMT voltages (1 ch=0.25 pC).
- Fig. 26: Photograph of PMT test facility at Fairfield University.
- Fig. 27: Typical data from PMT testing; LED pulses and photocathode uniformity.
- Fig. 28: Test pulses in calorimeters at BNL.
- Fig. 29: Schematic design of Laser Test Pulse facility for g-2 experiment.
- Fig. 30a: Rate effect - gain shifts with pulse rate and pulse history. DeVincenzi et al., NIM 225, 104 (1984).
- Fig. 30b: Rate effect - gain shifts with pulse rate and pulse history. Yamashita, Rev. Sci. Instr. 51, 768 (1980).
- Fig. 30c: Rate effect - gain shifts with pulse rate and pulse history. Zhong et al., NIM A281, 384 (1989)
- Fig. 31a: Two identical ($\pm 2-3\%$) optical pulses (20ns space) from laser pulser prototype, dithered, digitized and averaged. Note shift in 2nd pulse.
- Fig. 31b: Measured laser double pulse separation vs optical fiber separation. Measured pulse

separation deviates from linear at short pulse delays (any effects of oscilloscope electronics not removed).

Fig. 32: Hysteresis of fast PMT illuminated, by 16 pulse 62 MHz optical pulse train of 0.6 ns wide pulses, generated by the laser fiber pulser prototype. Note baseline shift.

Fig. 33: Schematic for an optical waveform synthesizer using laser diodes ("g-2 flight simulator").

Fig. 34a,b: Pulses and driver circuit for visible laser diode.

Fig. 34a,b: Pulses and driver circuit for visible laser diode.

Fig. 35a: Typical fast voltage-current converter for laser diode drive.

Fig. 35b: Typical $Z = 2\Omega$ transmission line to drive laser diode (note feedback lead).

Fig. 35c: Typical 635 nm laser diode specs.

Fig. 36a: Hamamatsu gated base specs - shorts D4-D7.

Fig. 36b: Gate pulse reducing large signals

Fig. 36c: Recovery time to full gain after gate pulse.

Fig. 37a: Test rig for flash simulation recovery using a laser to simulate flash.

Fig. 37b: Time shifts in pulses in 1000 p.e. pulses after flash gating (0= no time shift due to gating)

Fig. 38: PMT specifications proposed for g-2 by Fairfield.

Fig. 39: Fast LCD shutter which may be adapted for a Flash Gate for G-2.

Fig. 40a: GEM Experiment.

Fig. 40b: GEM calorimeters; Scintillating Barrel outer.

Fig. 40c: GEM Scintillating Barrel Assemblies and Performance.

Fig. 41a: Forward Calorimeter modules for GEM

Fig. 41b: Forward Calorimeter Detail, liquid core fibers; Quartz fiber similar.

Fig. 42a: Liquid core optical fibers as assembled at Fairfield (Halar cladding tube, 40 cm long, 3 mm ID; BC599 liquid scintillator core, 1 cm long quartz end-plugs; See APPENDIX 3 for details).

Fig. 42b: Pb plate stack for e-m calorimeter.

Fig. 42c: Liquid fibers inserted in Pb plate stack.

Fig. 42d: Liquid fiber bundle.

Fig. 42e: Assembled liquid fiber calorimeter.

Fig. 42f: Digitized single pulses of muons, electrons in liquid fiber cal.

Fig. 42g: ADC spectra for Liquid Fiber e-m calorimeter.

Fig. 42h: Summary slide of Liquid Scintillator Core Fiber e-m Calorimeter, tested summer 1992.

Fig. 42i: Quartz fiber calorimeter assembly.

Fig. 42j: Assembled quartz calorimeter.

Fig. 42k: ADC spectra for muons and electrons.

Fig. 42l: Pulse shapes for electrons.

Fig. 42m: Summary slide for Fairfield Quartz e-m Calorimeter, tested summer 1992.

Fig. 43: Abstracts of papers using optical techniques for precision gain stability.

Fig. 44: Time shift of 2nd pulse (3 GeV equiv.) following 1st pulse of 0.001-1 TeV equivalent with a delay of 350 ns between pulses, a possible difficulty for high rate PMT-based calorimetry.

Fig. 45a: Proximity focussed Hybrid PMT tested at CERN from DEP.

Fig. 45b: Hybrid PMT from Litton/Advanced Photonics with avalanche gain.

Fig. 46a: ADC distribution of 0.5 mm ID quartz fiber illuminated by collimated beta source.

Fig. 46b: Photograph of quartz cladding liquid fiber mounted in dark box with beta source.

Fig. 47a,b: Improved quartz fiber e-m cal module(bottom), and cosmic ray "Landau-like" distribution, in tests at Fairfield before beam test at BNL, summer 1993.

Fig. 48a,b: Cerenkov Fiber Hadron Module Towers (60" deep lead-eutectic) being assembled for BNL Tests, summer, 1993)

Fig 48c,d: Fibers and fiber cutter for Cerenkov Hadron Module.

FIGURES 48e->49 following: A complete talk on the results from the BNL beam test of summer 1993.

Fig. 0a: Fairfield Student installing g-2 calorimeter at BNL, with BU professor.

Fig. 0b: Fairfield Students working at BNL.

BNL AGS E821

**A New Precision Measurement
of the
Muon ($g - 2$) Value
at the level of 0.35 ppm**

**Boston University, Brookhaven National
Laboratory, Cornell University, Fairfield University,
University of Heidelberg, University of Illinois
Los Alamos National Laboratory, Max Planck
Institute für Med. Forschung - Heidelberg,
University of Tokyo, KEK, Riken, Yale University**

Gerry Bunce - BNL - Project Manager

Bill Morse - BNL - Resident Spokesman

Vernon Hughes - Yale - Co-spokesman

Lee Roberts - Boston - Co-spokesman

E821 Collaboration

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Non-U.S. Collaborators

Institution	Experimenter	Present	Future
Heidelberg	K. Jungmann	0.25	0.25
	G. zu Putlitz	0.25	0.25
MPI-Heidelberg	U. Haeberlen	0.5	0.25
KEK	K. Endo	0.15	0.15
	H. Hirabayashi	0.1	0.1
	S. Ichii	0.1	0.1
	S. Kurokawa	—	—
	Y. Mizumachi	0.2	0.2
	T. Sato	0.1	0.?
	A. Yamamoto	0.2	0.2
Riken	L. Ishida	0.1	0.?
Tokyo	M. Iwasaki	0.1	0.5
	K. Nagamine	0.15	0.15
Novosibirsk	L.M. Barkov	—	—
	B.I. Kazin	0.2	0.2
	D.N. Grigorev	—	0.2
	E.A. Kuraev	—	—
	S.I. Redin	0.2	0.2
	Ya.M. Shatunov	0.1	0.1
	E. Solodov	0.2	0.2

Institution	Present Students	+6 Months
Boston	5	- 1
Yale	1	+1
Tokyo	0	+1

Fig. 1c: Foreign Collaborators to g-2.

Fig. 1d Photograph of collaborators in front of coil-winder.

Fig. 2a: Cartoon of Muon g-2 Method

Spin Precession in a B Field

Precession frequency $\omega_a = \omega_s - \omega_c$

where the orbital cyclotron frequency

$$\omega_c = \frac{eB}{mc\gamma}$$

and the spin precession frequency

$$\omega_s = \frac{eB}{mc\gamma} + (g-2) \frac{eB}{2mc}$$

The anomalous moment a_μ is

$$a_\mu = \left(\frac{g-2}{2} \right)$$

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{e}{mc} B.$$

For both $\vec{E}$ and $\vec{B}$

$$\vec{\omega}_a = \frac{d\Theta_R}{dt} = \frac{e}{mc} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right]$$

“magic γ ”

$$\left(a_\mu - \frac{1}{\gamma^2 - 1} \right) = 0$$

This is satisfied if $\gamma = 29.3$ and $p_\mu = 3.094$ GeV/c.

It is this muon momentum which makes the AGS the ideal place for such a measurement.

Fig. 3a,b: Spin Precession and Modulation of the Muon Decay

Standard Model Contributions to Muon $g-2$

QED
 e, μ, γ

+

+

Hadrons

+

QED
 τ

Weak Bosons

+

Fig. 4a: Diagrams Contributing to $g-2$.

Higher-order Hadronic Vacuum Polarization Contributions to Muon $g-2$

**Radiative
Corrections**

0.92 (0.03) ppm

-1.71 (0.04) ppm

**Hadronic
Light-by-Light
Scattering**

0.42 (0.05) ppm

Fig 4b: Diagrams Contributing to $g-2$

Summary of Theoretical and Experimental Information

$$a_{\mu}^{QED} = 1\,165\,847\,409(46)(28) \times 10^{-12} \quad (\pm 45 \text{ ppb})$$

$$a_{\mu}(\text{had}) = 7027(175) \times 10^{-11} \quad (60.2 \pm 1.5) \text{ ppm}$$

$$a_{\mu}(\text{weak}) = 195(10) \times 10^{-11} \quad (1.7 \pm 0.1) \text{ ppm}$$

The total theoretical value of a_{μ} is

$$a_{\mu}(\text{theory}) = 11\,659\,191\,8(176) \times 10^{-11} \quad (1.5 \text{ ppm})$$

The experimental value is

$$a_{\mu}(\text{experiment}) = 11\,659\,230(84) \times 10^{-10} \quad (7.2 \text{ ppm})$$

or

$$a_{\mu}(\text{experiment}) - a_{\mu}(\text{theory}) = (38 \pm 85) \times 10^{-10}$$

Fig. 5a: Summary of experimental and theoretical information

Hadronic Contributions to the Muon Anomalous Magnetic Moment (in ppm)

(Current Uncertainty)

(Stat) (Syst)

CMD-2: $\rho, \omega, \phi, n\pi$

52.45 (0.48) (1.30)

$0.40 \text{ GeV} < \sqrt{s} < 1.42 \text{ GeV}$

$\rho, \omega \rightarrow \pi^+ \pi^-$ 43.43 (0.18) (1.29)

$\omega \rightarrow 3\pi$ 4.00 (0.41) (0.13)

ϕ 3.45 (0.15) (0.11)

4π 0.80 (0.03) (0.07)

> CMD-2: $e^+ e^- \rightarrow \text{hadrons}$

9.72 (0.13) (0.54)

$1.42 \text{ GeV} < \sqrt{s}$

$1.42 < \sqrt{s} < 2.05 \text{ GeV}$ 4.71 (0.09) (0.29)

$2.05 < \sqrt{s} < 3.15 \text{ GeV}$ 1.87 (0.02) (0.37)

$3.15 < \sqrt{s} < 7.8 \text{ GeV}$ 2.74 (0.07) (0.25)

$7.8 < \sqrt{s} < 30.8 \text{ GeV}$ 0.37 (0.02) (0.02)

$30.8 \text{ GeV} < \sqrt{s}$ 0.03

Fig 5b: Hadronic contributions

Sensitivity to New Physics of the New Muon ($g - 2$) Experiment

New Physics	E821 Sensitivity	Comments
μ substructure ^a	$\Lambda \geq 5 \text{ TeV}$	SSC domain
μ Form factors ($1 - k^2/\Lambda^2$)	$(W^\pm) \Lambda > 450 \text{ GeV}$ $(Z^0) \Lambda > 64 \text{ GeV}$ $(\gamma) \Lambda > 180 \text{ GeV}$	$\Lambda_{LEP I} > 300 \text{ GeV}$
excited muon ^b	$m_{\mu^*} \geq 6.3 \text{ GeV}$	Not Interesting
excited muon ^c	$m_{\mu^*} \geq 400 \text{ GeV}$	LEP II comparable
$W^\pm$ substructure ^d	$\Lambda \geq 400 \text{ GeV}$	LEP II $\sim 100 - 200 \text{ GeV}$
$\frac{(g_W - 2)}{2} \neq 0$	≥ 0.02	LEP II, SSC ~ 0.2
Light Higgs	$\leq 300 \text{ MeV}$	$O(10^{-3}g)$ coupling
Heavy Higgs	$\leq 500 \text{ GeV}$	$O(g)$ coupling
Supersymmetry ^e	$\leq 130 \text{ GeV}$	FNAL $\bar{p}p$ collider
$W_R^\pm$	$\leq 250 \text{ GeV}$	FNAL $\bar{p}p$ collider
$Z'(E6)$	$\leq 100 \text{ GeV}$	FNAL $\bar{p}p$ collider

^aFor substructure $\Delta a_\mu \sim m_\mu^2/\Lambda^2$

^bChiral Invariant Interaction

^cTraditional $\mu \cdot \mathbf{B}$ interaction (non-chiral)

^dGoes to 0 if $M_W \rightarrow 0$ to get proper coupling to conserved current.

^eSignature for SUSY in 100-200 GeV region is a value of a_μ below the SM value

Fig.6: Sensitivity of $g-2$ measurement to new physics

Contributions of supersymmetric theories to the muon anomalous g-value: (a), (b) Feynman diagrams; (c) contribution to a_μ in the renormalization group SUSY model. The zero is at $a_\mu(\text{theor}) = a_\mu(\text{QED}) + a_\mu(\text{had})$. $a_\mu(\text{weak})$ is the weak contribution.

Fig. 7: Possible SUSY contributions to g-2

Outline of Technique

- Use the AGS with Booster to make 3.1 GeV π
- 72 m decay length in beamline $\Rightarrow$ 34% μ
- Choose π or μ at a momentum slit
- Bring Beam through Inflector
- Store μ in Ring by $\pi \rightarrow \mu\nu$ decay or by kick
- Count Decay Electrons as a Function of Time
- Fit Time Spectrum to Determine $(g-2)$ Frequency

We will use both π injection ~ 1 to 0.7 ppm
($\times 10$ on CERN)

μ injection - 0.35 or better

Fig. 8: Outline of the g-2 technique

Improvements and Differences with CERN

<u>AGS</u>	<u>CERN</u>
pion and muon injection	pion injection
continuous yoke & poles	40 separate pieces
superconducting coils	warm
$\pm 1\text{ppm B}$ uniformity	$\pm 20\text{ ppm}$
circular storage region	rectangular
measure B inside storage region <u>without</u> removing vacuum	remove vacuum chamber
deadtimeless data acquisition	queuing losses
segmented detectors	monolithic detectors
single bunch from AGS	multiple P.S. bunches
superconducting inflector	pulsed coax line
μ distribution measured directly at all times by electron tracking	only fast rotation
serrated vacuum tank eliminates most pre-showering	smooth tank, electrons can preshower in pipe
four-fold symmetry in quads room for inflector and kicker $\beta(\text{min}) \simeq \beta(\text{max})$	two-fold symmetry only inflector 30% difference
statistics $\times 400$ better ($\pm 0.35\text{ppm}$) full AGS Booster intensity	statistical $\pm 7.0\text{ ppm}$
Systematic error $\pm 0.12\text{ ppm}$	$\pm 1.5\text{ppm}$
Dominant systematic error E	B

Fig. 9: Improvements of E821 compared with CERN experiment.

Systematic Errors

Source of Error or Correction	Magnitude of Correction (ppm)	Error (ppm)	Comments
Magnet calibration, Averaging B over muon population	—	0.1	Continuous monitoring Circular aperture, measured muon distribution
Radial E field	0.69	0.03	Rotation frequency to measure distribution of equilibrium orbits
Pitch Correction	0.40	0.02	Measured muon distribution
Differential decay	0	0.01	
a_μ phase change due to muon losses	0.1	0.05	Measured at larger loss levels with no scraping
Timing errors at early times	0.09	0.03	Measured at higher rates by combining signals from several counters
Errors added in quadrature		0.12	

Fig. 10: Systematic Errors

Muon (*g-2*) Ring Parameters

Parameter	Value	Comments
(<i>g-2</i>) Frequency	$f_a \sim 0.23 \times 10^6/s$	$\omega_a = 2\pi f_a$ $\tau_a = 1/f_a = 4.37\mu$
Muon Lifetime	$\tau = \gamma\tau_0 = 64.4\mu s$	
Muon kinematics	$p_\mu = 3.094 GeV/c$ $\gamma_\mu = 29.3$	
Cyclotron Period	$\tau_{cyc} = 149ns$	
Central Radius	$\rho = 7112mm$	(280'')
Magnetic Field	<u>$B = 1.45T$</u>	<i>Super Ferric</i>
Storage Aperture	9.0cm circle	
Stored μ /fill ($4.2 \times 10^{12} pot$)	3,500 31,000	π^+ injection μ^+ injection
Initial Rate One Detector	$\sim 6.7 \times 10^6$	μ injection
In one lifetime:	432 revolutions around ring 14.7 (<i>g-2</i>) periods	

Fig. 11: Muon Storage ring parameters

General arrangement of AGS muon g-2 experiment.

YOKE WITH CONTAINMENT VESSELS AND COILS

Fig. 12a,b: Ring and magnet cross-sections

Fig. 12c: Monte Carlo of Decay Electron Trajectories with Synchrotron Light

Recent Progress on E821

- Magnet yoke machining finished at Ranor.
- Pole piece iron being machined at Ranor
- Two coils installed in their cryostats
- Double coil will be installed in cryostat by July 93
- Cooling plan for storage ring magnet completed
- Storage ring magnet assembly to begin in July 93
- NMR mapping electronics tested at LAMPF
- Inflector 50cm prototype successfully tested at KEK.
- Prototype vacuum chamber ready for assembly at BNL
- Final electron calorimeter/FSD/SSD package to be tested in 7/93
- Phototubes have been successfully operated at M Hz rates.
- CERN Digitrons up and running at Illinois
- Waveform Digitizer prototype ready at BU
- Derandomizer prototype built at BNL, ready for tests
- MTDC prototype ready by September 93
- Power supply ordered, to be delivered soon.

Fig. 14: Summary of Recent Progress on g-2

World's Largest Superconducting Coil Completed

The world's largest superconducting coil "on a string" (photo on front page) is hanging, not on anyone's finger, but from a massive crane just outside Bldg. 919. Here, in barely six months, the coil was completed by engineers and technicians from the Alternating Gradient Synchrotron (AGS) Department, assisted by members of the Central Shops Division.

The enormous ring, 15 meters in diameter, is really two coils fixed together. They make up the third and fourth of four similar coils that will help power a precision superconducting magnet to be used in AGS experiment 821 on muon magnetism.

Muons are electrically charged particles that spin on their own axes, acting like tiny magnets. E821 will measure g minus 2, the minute effect — only 0.1 percent — that virtual particles such as the W boson and the photon, which carry the weak and electromagnetic forces respectively, have on muon magnetism when the muons travel in a magnetic field. With the particle intensity made possible by the new Booster (see photo background), the AGS is the ideal accelerator for this experiment.

The coils were constructed inside Bldg. 919. To get them outside, the finished structure was hooked to a hoist and lifted onto special tracks (photo at right). The building's removable wall was taken away, allowing the coil to be pulled outside by a small portable winch until the center of its "spider" support lay under an outside hoist. Once attached to this mammoth crane, the coil was lowered

— Photos on this page by Roger Stoutenburgh

into its position on the foundation holding the two previously completed inner coils.

But that was last month. In Bldg. 919, work is already well under way on the vacuum tanks for a huge coil cryostat that will keep the superconducting magnet cool when the storage ring is commissioned in December 1993.

— Liz Seubert

Fig. 13: Description and photograph of ring assembly

ELECTRON CALORIMETER DETECTORS

Fig. 15a: Electron Calorimeter placement with scalloped vacuum chamber (plan view)

Fig. 15b: Electron calorimeter placement, perspective and elevation view in magnet.

E821
ELECTRONICS
BLOCK
DIAGRAM
decay $e^\pm$
→
OVERALL

Fig. 16: Detail of calorimeters, FSD & SSD scintillator tags, and time/waveform readout.

Flash Test Geometry

Fig. 17a,b: Flash-test geometry at BNL test beam, with PMT Flash Waveform.

Fig. 18: Electron calorimeter final assembly at BNL with Fairfield Students

Run 1069, ALG E=3 GeV, PSD0, 10 deg, x= 0, y= 0

Fig. 19: Electron calorimeter ADC distribution, test beam 1991.

Fig. 20a,b: LED pulser schematic as used at Fairfield, and installation of LED and laser fiber injectors at BNL test beam.

Fig. 21a,b: Laser fiber pulser at BNL and laser fibers installed in electron calorimeters in the test beam, 1992.

LASER/FIBER OPTIC CALIBRATION SYSTEM

Fig. 22a,b: Schematic of laser fiber pulser, and schematic of conversion of parallel multichannel pulser into pulse train with stepped fiber delays.

STABILIZED, TUNABLE PULSED LASER CALIBRATION LIGHT SOURCE

Fig. 22c: Schematic of future plans to stabilize laser pulser by feedback tuning.

TOTAL EXCESS LOSS = 3.47 Db.

INPUT = 54.4 μ W

1.) 1.255 μ W	9.) 1.585 μ W
2.) 1.655 μ W	10.) 1.420 μ W
3.) 1.395 μ W	11.) 1.030 μ W
4.) 1.350 μ W	12.) 1.050 μ W
5.) 2.085 μ W	13.) 1.650 μ W
6.) 1.780 μ W	14.) 1.920 μ W
7.) 0.880 μ W	15.) 1.285 μ W
8.) 1.920 μ W	16.) 2.210 μ W
TOTAL = 24.47 μ W	

Fig. 23a: Fiber power splitter

Fig. 23b: Assembled laser fiber pulser on bench at Fairfield.

0.1 V/div

10 μ s/div

Fig. 24: Narrow pulse produced on fiber to fast PMT (pre-pulse is laser noise, eliminated by grounding laser housing) by laser fiber pulser.

Tube 4340 Gain v. Tube Voltage

Fig. 25: Typical PMT gain curve taken in PMT test rig at Fairfield, used at g-2 test beam to set PMT voltages (1 ch=0.25 pC).

Fig. 26: Photograph of PMT test facility at Fairfield University.

Fig. 27: Typical data from PMT testing; LED pulses and photocathode uniformity.

Fig. 28: Test pulses in calorimeters at BNL.

Fig. 30c: Rate effect - gain shifts with pulse rate and pulse history. Zhong et al., NIM A281, 384 (1989)

Fig. 2. (a), (b), (c) Three examples, among the fifty observed of PM gain behaviour during the simulated burst. (d) The behaviour of the only PM found to have a negative gain variation.

Fig. 30b: Rate effect - gain shifts with pulse rate and pulse history. Yamashita, Rev. Sci. Instr. 51, 768 (1980).

Fig. 2. Gain variation with counting rate. Open circles, pure resistor type; triangles, Zener diode type; full circles, transistor emitter follower type. Supply voltage = 2000 V.

Fig. 1. (a) Time dependence of pulse height measured with Tube A

Fig. 1. (a) Time dependence of pulse height measured with Tube A

Fig. 30a: Rate effect - gain shifts with pulse rate and pulse history. DeVincenzi et al., NIM 225, 104 (1984).

Fig. 31a: Two identical ($\pm 2-3\%$) optical pulses (20ns space) from laser pulser prototype, dithered, digitized and averaged. Note shift in 2nd pulse.

Fig. 31b: Measured laser double pulse separation vs optical fiber separation. Measured pulse separation deviates from linear at short pulse delays (any effects of oscilloscope electronics not removed).

16 Fiber Signals

LeCroy

⊕ TRACE1.017
50 ns 5 mV

Fig. 32: Hysteresis of fast PMT illuminated, by 16 pulse 62 MHz optical pulse train of 0.6 ns wide pulses, generated by the laser fiber pulser prototype. Note baseline shift.

Optical Waveform Synthesizer
("Flight Simulator" for g-2)

Fig. 33: Schematic for an optical waveform synthesizer using laser diodes ("g-2 flight simulator").

Driver Circuit

FIG. 1. Circuit design of rf oscillator and power amplifier. The two stages of this circuit are inductively coupled together at point (a). Point (b) indicates a place to insert a switching transistor for amplitude modulation of the pulse train.

625 MHz 100 ps pulses

5/15/87

ANALOG MODULES, INC.

Specialists in Analog Electronics and Electro-optics

MODEL 775 WIDEBAND PROGRAMMABLE VOLTAGE TO CURRENT CONVERTER

- CONVERTS 0 TO +5V INTO 0 TO -150mA
- DC TO 100MHZ RESPONSE
- LOW NOISE
- LOW CAPACITANCE
- IDEAL FOR DRIVING LED'S OR LASER DIODES FROM A PULSE GENERATOR

The Model 775 is a wideband voltage to current converter. A positive voltage or pulse is converted into a proportional negative current ideal for driving grounded anode LED's or laser diodes.

SPECIFICATIONS:

INPUT:

Power: -15V at up to 0.2A.
 Voltage Range: 0 to +5VDC or pulsed.
 Impedance: 50 ohms standard.
 20K (with 600uA bias current, specify -20K.)

OUTPUT:

Current Range: -5 to -150mA.
 Current Risettime: 4nS typ. to 150mA.
 Wideband Noise: 2nA/Hz.
 Capacitance: 20pF typ.
 Reverse Voltage Protection: Standard.
 Voltage Compliance: 0 to -5V.
 Accuracy: $\pm 1.5\%$.

CONNECTIONS:

Input: BNC -B) Add to part number.
 PINS -P) Add to part number.
 Output: BNC.
 Power: Filter feed-thru and ground lug.

SIZE:

See Outline Drawing on reverse side.

HOW TO ORDER:

Example: Model 775-B: BNC input and output.
 50 ohms input.

Example: Model 775-P-20K: Pins input and BNC output.
 20K ohms input impedance.

Specifications subject to change without notice.

126 BAYWOOD AVENUE • LONGWOOD, FLORIDA 32750 • USA
 (407) 339-4355 • FAX (407) 834-3806

Fig. 35a: Typical fast voltage-current converter for laser diode drive.

1508 TOWERS IN
ONE END CAP

SPAGHETTI CALORIMETER END CAP FACE CONFIGURATION

Fig. 41b: Forward Calorimeter Detail. liquid core fibers: Quartz fiber similar.

Quarter view of the detector showing the calorimeters.

FIG. Details of the capillaries which hold the liquid scintillator in the hadronic section of the forward calorimeter.

FIG. Front face of the EM section of the forward calorimeter showing the readout segmentation. The scale at the left gives the dimensions in mm and the η coverage.

Fig. 41a: Forward Calorimeter modules for GEM

TIP-04025

FIG. Detail of tile/fiber arrangement in the readout tower.

TIP-04128

FIG. Details of scintillating barrel calorimeter module – side view.

TIP-04127

FIG. Details of scintillating barrel calorimeter module – end view.

TIP-04291

FIG. Distribution of number of photoelectrons per MIP (GEANT-LTRANS MC simulation).

Fig. 40c: GEM Scintillating Barrel Assemblies and Performance.

TIP-03871

FIG. Assembly of scintillating barrel calorimeter. One of 44 modules is shown being assembled. Another module is shown outside the support tube for scale.

TABLE Characteristics and Parameters of the Scintillator Barrel Calorimeter.

Outer radius of the system	3700 mm
Inner radius of the system	2923 mm
z-extent of absorber	± 4840 mm
Number of Absorption Lengths	4.5λ
Total z-extent (including readout)	± 5500 mm
Number of Mechanical modules (total) ($\phi \times \eta$)	$44=22 \times 2$
(of the same type)	$(14+2+2+2+2) \times 2$
Total weight (SS support and modules)	1143 Mg
Weight of outer SS support tube	195 Mg
Weight of outer barrel passive absorber	223 Mg
Weight of 44 modules	948 Mg
Weight of the largest (smallest) module	24 (8) Mg
Thickness of Scintillator/Copper stack	586 mm

Thickness of each Copper layer	64 mm
Maximum weight of one Copper layer	3 Mg
Number of Scintillator layers	4
Gap for scintillator in the absorber	12 mm
Thickness of scintillator tiles	6 mm
Number of scintillator tiles in one module layer	$12 (\phi) \times 8 (\eta)$
Tile size	$0.026 (\phi) \times 0.16 (\eta)$, or ≈ 80 mm (ϕ) $\times$ 400-870 mm (η)
η coverage	± 1.28 (31° – 149°)
Number of WLS fibers per tile	2
Average WLS fiber length	610 mm
WLS fiber diameter	1 mm
Total number (length) of WLS fibers	30,800 (18.8 km)
Transport fiber length (average)	350–4850 (2600) mm
Transport fiber diameter	1 mm

Fig. 40b: GEM calorimeters; Scintillating Barrel outer.

FIG. Perspective view of the GEM detector.

FIG. Vertical section of the GEM detector.

Fig. 40a: GEM Experiment.

High Speed Commercial Grade Shutter

These shutters are suitable for applications where their higher transmitted wavefront distortion is acceptable. Sheet-type polarizers and a polymer compensator retarder are attached directly to the external faces. This configuration is optimized for high contrast ratios and low voltage operation. An optional cable is available with alligator clips and a BNC connector. The B1020 and D1040 electronic controllers are compatible with these shutters. Shutters with improved image quality are available on a custom basis; please call for a quotation.

Contrast ratio:	400:1
Transmitted wavefront distortion:	3-5 waves peak to valley per inch at 633 nm
Wavelength range:	400-700 nm
Electrical drive requirements:	2 kHz square wave AC voltage of amplitude from 0 to 20 volts
Temperature range:	10° C to 50° C
Damage threshold:	1 watt/cm ² CW
Axial thickness:	0.07"

C.A.	OUTSIDE DIMENSIONS	STOCK NUMBER	U.S. PRICE
High Speed Commercial Grade Shutter			
1.70" x 3.75"	2.00" x 4.25"	HSC-2X4	\$295
Commercial Cable		LCC-BA	19

Fig. 39: Fast LCD shutter which may be adapted for a Flash Gate for G-2.

Proposed G-2 PMT* Specifications:

Basic Parameters:

Gain:	$>10^5 - 10^7$
QE: (400-600 nm)	$>10\%$
Diameter:	$1\text{ cm} \leq d \leq 5\text{ cm}$ (smaller better)
τ_{rise} (50 p.e./ns optical pulse):	$<2\text{ ns}$ (10%-90%)
τ_{fall} (50 p.e./ns optical pulse):	$<4\text{ ns}$ (90%-10%)
Pulse Width (FWHM)	$<3\text{ ns}$
Base Width (5%)	$<8\text{ ns}$
Slew Rate (1 p.e. optical pulse):	$>1\text{ mV/ns}$
t.t.s. (1 p.e.):	$<200\text{ p.s.}$
Gain Shift:	$<10\%$ after 10 ns (200<p.e.<2000)
Noise:	$<100\text{ KHz @ }0.5\text{ p.e.}$
After-Pulsing:	$<0.1\%/p.e + <1\%$ of pulses in $<5\text{ ns}$
Pre-Pulsing:	$<0.5\%$ of signal in $<5\text{ ns}$
Linearity:	$\pm 10\%$ over 100-3,000 p.e.
Stability:	$<2\%/Month$
Anode Capacitance:	$<10\text{ pF}$ to Σ all other electrodes
Anode-Last Dynode Inductance:	$<1\text{ nH}$

Specific G-2 Targets:

[I] Timing Errors:

For a 250 p.e. x 10 ns 1/2 width optical pulse fired during pulses of 50-3000 p.e., coming at average rates $\langle R \rangle \sim 30\text{ MHz} \times e^{-t/60\mu s}$, for a period of $t \sim 1\text{ ms}$:

- (a) $\Delta [T_p]$: Peak of the PMT pulse time distribution $<20\text{ ps}$, for $1\text{ kHz} < \langle R \rangle < 30\text{ MHz}$
- (b) $\Delta [\sigma]$ of PMT pulse time distribution $<100\text{ ps}$, for $1\text{ kHz} < \langle R \rangle < 30\text{ MHz}$
- (c) $\Delta [(\sigma_s - \sigma)/(\sigma_s + \sigma)] < 10\%$, for $1\text{ kHz} < \langle R \rangle < 30\text{ MHz}$ (tail remains stable)
- (d) Temperature Stability: Timing Errors shift $<1\%/C^\circ$
- (e) Voltage/Gain Stability: Timing errors shift: $\delta T_p / \delta G < 10^{-4}$

[II] Flash Immunity:

- (a) Pulse Recovery: $<10\% \delta \text{Gain}$, 200 ns after 100 mA x 30 ns
- (b) Gating Cycle: $\sim 10\text{ Hz}$

* $\equiv$ PMT + BASE/HV + GATING

Fig. 38: PMT specifications proposed for g-2 by Fairfield.

Fig. 37a: Test rig for flash simulation recovery using a laser to simulate flash.

200 ns/div

↑
30 V pulse

Both pulses arrive
at gate

gate shutting off
first pulse but not
second pulse

Fig. 36b Gate pulse reducing large signals

Fig. 36c Recovery time to full gain after gate pulse.

C 1392MOD. FOR R2490

SUITABLE PMT ----- R2490-01 (2" HEAD-ON)
HIGH VOLTAGE INPUT ----- -2000 V RECOMMENDED
 -2700 V Max.
 ([-HV] INDICATION ON PANEL)

MIDDLE VOLTAGE INPUT ----- +250 V TO +280 V RECOMMENDED
 +300 V Max.
 ([+HV] INDICATION ON PANEL)

GATE PULSE INPUT ----- WIDTH:200 nsec TO 20 usec RECOMMENDED
 VOLTAGE:+2 V TO +5V RECOMMENDED +6 V Max.

BLEEDER CURRENT ----- 1.5 mA (AT -HV=-2700 V)

SWITCHING RATIO ----- 1:10⁴ Min (AT -HV=-2500 V,+HV=+300 V)

CONNECTORS

-HV (-2700 V Max.) ----- MHV-RB
+HV (+300 V Max.) ----- BNC:UG-625B/U
GATE(GATE PULSE INPUT) ----- BNC:UG-625B/U
SIG.(SIG.OUTPUT) ----- BNC:UG-625B/U

DIMENSIONAL OUTLINE ----- SEE "Fig.1"
GATING TIME CHART ----- SEE "Fig.2"

GATING CHARACTERISTICS

T_w [GATE PULSE WIDTH]:200 nsec to 20 usec RECOMMENDED
(RECOMMENDED DUTY RATIO ON:OFF=1:MORE THAN 500)
T_r [PMT ON TO OFF TIME]:200 nsec Typ. 500 nsec Max.
T_{n1} [SWITCHING NOISE WIDTH AT PMT ON TO OFF]:500 nsec Typ.
T_{n2} [SWITCHING NOISE WIDTH AT PMT OFF TO ON]:1.4 usec Typ.
T_f [PMT OFF TO ON TIME]:500nsec Typ. 800 nsec Max.
T_{stg} [CONTINUAL TIME OF GATE PULSE TURNED OFF TO PMT TURNED ON]
GATING OPERATION ON C1392 SERIES ACTS TO HAVE TRANSISTOR SWITCHED.
WHEN GATE PULSE IS GIVEN TO THE TRANSISTOR, NON-OPERATION CONDITION AT PMT
CONTINUES IN DEFINITE TIME OWING TO ELECTRONIC COULOMBS CHARGED INTO BASE
ELECTRODE OF THE TRANSISTOR EVEN IF GATE PULSE IS OFF THEREAFTER.
CONTINUAL TIME; T_{stg} DEPENDS UPON INPUT TIME AND WIDTH OF GATE PULSE, AND AS
RESPECTIVE VALUES (TIME & WIDTH) GET BIGGER, T_{stg} BECOMES LONGER.

FIG.1 DIMENSIONAL OUTLINE

Fig. 36a: Hamamatsu gated base specs - shorts D4-D7.

Limiting values

Limiting values in accordance with the Absolute Maximum System (IEC 134). $T_{case} = 25^{\circ}\text{C}$ unless otherwise specified.

Symbol	Parameter	Min.	Max.	Unit
Laser diode				
P_o	CW optical output power	—	3	mW
$V_{R(L)}$	laser diode reverse voltage	—	1	V
$V_{R(M)}$	monitor diode reverse voltage	—	30	V
$I_{F(M)}$	monitor diode forward current	—	10	mA
T_{op}	operating temperature range (T_{case})	-10	+40	$^{\circ}\text{C}$
T_{stg}	storage temperature range (T_{amb})	-40	+85	$^{\circ}\text{C}$

Preliminary specifications

Philips Optoelectronics Centre

COL840/D
635 nm visible laser diode

Mechanical data

Dimensions in mm

Pinning

Pin	Description
1	laser cathode
2	common case
3	monitor diode anode

Pin configuration

Fig. 2. Pin configuration

Fig. 35c: Typical 635 nm laser diode specs.

Low Impedance TRANSMISSION LINE for Laser Diodes

The low impedance Transmission Line is ideal for remotely powering diode lasers while preserving pulse fidelity and minimizing losses over distances of inches to 100 feet. One of the important applications is the powering of diodes in diode pumped solid state lasers (diode pumped YAG).

Specifications

PARAMETER	
Line Impedance	2.0 ohms
Conductor Size	0.010 x 0.400" each
Circular Mills	5092
Nearest Equivalent AWG	#13
DC Current Capability (@ 25°C ambient, 100°C conductor)	40A
Pulsed Current Capability (@ 1μS pulse width, 1000 pps)	2000A
Insulation between Conductors	0.001 Kapton ¹
Rated Voltage @ Kapton ¹	7000V/mil.
Maximum Temperature	-105°C
Capacitance/ft.	-650pF
Rated Voltage Vinyl Jacket	700V/mil.
Jacket Material	105°C PVC ²
Jacket Dimension	0.065 x 0.435"
Maximum Length	random to 100 feet
Minimum Bend Radius (preferred) ³	1 inch

Fig. 35b: Typical $Z = 2\Omega$ transmission line to drive laser diode (note feedback lead).

Fig. 42a: Liquid core optical fibers as assembled at Fairfield (Halar cladding tube, 40 cm long, 3 mm ID; BC599 liquid scintillator core, 1 cm long quartz end-plugs; See APPENDIX 3 for details).

Fig. 42b: Pb plate stack for e-m calorimeter.

Fig. 42c: Liquid fibers inserted in Pb plate stack.

Fig. 42d: Liquid fiber bundle.

Fig. 42e: Assembled liquid fiber calorimeter.

Fig. 42f: Digitized single pulses of muons, electrons in liquid fiber cal.

LScint EM ADC

Fig. 42g: ADC spectra for Liquid Fiber e-m calorimeter.

SUMMARY: Liquid Scintillator Fiber Forward Calorimeter Prototype

Absorber: Pb matrix 12x12x21 cm;

15 x 15 array of 3.93mm diameter holes on 8 mm centers

197 instrumented holes

Total hole PF ~19%

Fibers: Oriel/Fairfield

-Core: 3 mm diameter Core

isopropyl biphenyl based scintillator; $n_{\text{core}}=1.54$

Bicron 599; ~\$100/liter in one liter quantity

- cladding: Halar; $n \sim 1.42 - 1.44$

3.3 mm OD x 40 cm; \$0.48/m in small quantities

- 1/e point ~ 1.8 m

- Plug: 2cmx3mm OD quartz; saw cut & flame polished (\$1.5 each)

- Core Packing Fraction: 11%

PMT: Hamamatsu 2" R329 bialkali {g.v. tube}

Performance:

Orientation: fibers $80^\circ \pm 4^\circ$ to beam

- $\sigma/E = 18.7\%$ @ 15 GeV electrons
- 36 p.e./GeV @ 15 GeV electrons
- Pulse: Risetime ~20 ns; FWHM ~ 30 ns @ 15 GeV electrons
- Muon Landau (15 GeV) ~ 150 MeV; Mean ~ 11 p.e.; Peak ~ 4.5 p.e.

NOTE: Contributions to energy resolution

- (1) Fiber bundle "dished" on end (not flat) and air-coupled
- (2) No light mixer
- (3) Low precision in holes; not granular enough for packing fraction (5/hole)
- (4) end plugs only flame polished - rounded ends, not optically polished flat
- (5) $n_{\text{plugs}} < n_{\text{core}} \because 1.49 < 1.54$ (dumb mistake)

Fig. 42h: Summary slide of Liquid Scintillator Core Fiber e-m Calorimeter, tested summer 1992.

2 of 2

Fig. 42j: Assembled quartz calorimeter.

Fig. 42k: ADC spectra for muons and electrons.

Quartz fibers

LeCroy
 TRACES.013
 10 ns .5 V

10 GeV e^-

NB: ~50 m cables

Quartz fibers

LeCroy
 TRACES.023
 5 ns 1 V

40 GeV e^-

Fig. 421: Pulse shapes for electrons.

SUMMARY: Quartz Fiber Forward Calorimeter Prototype

Absorber: Pb matrix 12x12x21 cm;

13 x 13 array of 3.93mm diameter holes on 8 mm centers

~1.5 cm wide uninstrumented side layers

Total hole PF ~18%

Fibers: 3M: TECS hard-clad quartz fiber FP-1.0-UHT

- 1 mm core, 1.4 mm cladding, 1.6 mm buffer diameter, 40 cm long

- N.A. = 0.40; $n_{\text{core}}=1.49$ @ 200nm; cladding: polyimide/kapton

- 1/e point > 9 m for $\lambda > 350$ nm

- Bend radius: 18 cm long term

- Cleave on PMT end (no polish). Far end: scissor cut (fractured).

- 5 fibers/hole

- Core Packing Fraction: ~6.8%

PMT: Hamamatsu 2" quartz window, GaP dynode, bialkali, 1-8 pC/p.e.

Performance:

Orientation: Fibers $9^\circ \pm 2^\circ$ to beam

• $\sigma/E = 25\%$ @ 10 GeV electrons

-> scale Gorodetzky @ 20% PF @ 10 GeV: ~ 22%

• 5.3 p.e./GeV @ 10 GeV electrons

-> scale Gorodetzky @ 20% PF: $16 \text{ p.e./GeV} \times 6.8\%/20\% = 5.5 \text{ p.e./GeV}$

• Pulse: Risetime ~ 5 ns; FWHM ~10 ns @ 10 GeV electrons

-> Note: Signals after Cables > 50 m long

• Muon Landau ~ 0.25 GeV: Mean ~12 p.e.; Peak ~3-4 p.e.

NOTE: Contributions to energy resolution

(1) Fiber bundle "dished" on end (not flat) and air-coupled

(2) No light mixer

(3) Low precision in holes; not granular enough for packing fraction (5/hole)

(4) Fibers crudely cleaved (no modern super precision cleave or polish); cut on far end; no mirror

Fig. 42m: Summary slide for Fairfield Quartz e-m Calorimeter, tested summer 1992.

Time Shift of 2nd pulse (350 ns delay, 3 GeV)

Fig. 44: Time shift of 2nd pulse (3 GeV equiv.) following 1st pulse of 0.001-1 TeV equivalent with a delay of 350 ns between pulses, a possible difficulty for high rate PMT-based calorimetry.

Fig. 46b: Photograph of quartz cladding liquid fiber mounted in dark box with beta source.

Fig. 46a: ADC distribution of 0.5 mm ID quartz fiber illuminated by collimated beta source.

Fig. 47a,b: Improved quartz fiber e-m cal module(bottom), and cosmic ray "Landau-like" distribution, in tests at Fairfield before beam test at BNL, summer 1993.

Fig. 48a,b: Cerenkov Fiber Hadron Module Towers (60" deep lead-eutectic) being assembled for BNL Tests, summer, 1993

SSC FIBER CALORIMETER
TOWER END VIEW

Fig. 48a,b: Cerenkov Fiber Hadron Module Towers (60" deep lead-eutectic) being assembled for BNL Tests, summer, 1993)

Fig. 45a: Proximity focussed Hybrid PMT tested at CERN from DEP.

Fig. 45b: Hybrid PMT from Litton/Advanced Photonics with avalanche gain.

Eska ExtraTM Optoelectronic Grade

Product Code: EK (Fiber), EH (Cable)

Attenuation: $\leq 180\text{dB/Km}$ at 650nm collimated light

Heat Resistance: 85°C

Fiber Diameter: 250 ~ 1,000 μ

Main Applications: $\circ$ data transmission

Numerical Aperture and Acceptance Angle

Core Refractive Index: 1,492 (n_1)

Clad Refractive Index: 1,417 (n_2)

Numerical Aperture: $0.47 \pm 0.03 (\sqrt{n_1^2 - n_2^2})$

Acceptance Angle: $56^\circ (2 \sin^{-1} (\text{N.A.}))$

Heat Resistant Grade

Product Code (Cable)	DH	FH
Attenuation	$\leq 300\text{dB/km}$ (650nm)	$\leq 700\text{dB/km}$ (770nm)
Heat Resistance (Dry)	115°C	125°C
Fiber Diameter	500 — 1,000 μ	500 — 1,000 μ

Main Applications

- $\circ$ Short-distance data transmission in automobiles
- $\circ$ Sensor-heads for photo-electric switches in high am-

Fig 48c,d: Fibers and fiber cutter for Cerenkov Hadron Module.

Fig 49 ff

1993 BNL Beam Tests

Forward Optical Calorimeters for GEM

K.Arrington, A.Chatelain~~e~~, D.Kefford, J.Kennedy,
R.Pisani, V.Podrasky, C.Sanzeni, D.R.Winn

Fairfield University

- 7 λ Cu Hadron Cerenkov Module (2.8% clear 1.5 mm fiber)
- 30 Lrad Pb Quartz Cerenkov E-M (7.2% 1 mm quartz fiber)
- 30 Lrad Pb Liquid Scintillator E-M Module (11% core)

Fig 49 FF

Summary - E-M Cerenkov Calorimeter:

Physical Parameters

Packing Fraction (Core):	7.2%
Fiber Bundle-Hole Spacing:	5.7 mm
Fiber Core Diameter:	1 mm, 3 fibers/bundle/hole
Fiber Material:	Quartz core 1 mm, PEEK clad (1.6 mm OD) ($n=1.49$, $NA=0.4$, attenuation: >9 m for $\lambda > 350$ nm)
Absorber:	Pb
Length:	22 cm
Area:	12 cm x 12 cm active
Mass:	~ 25 kg
Readout:	2" diag. hex UVT light guide, 6" deep 2" PMT, gain $\sim 10^{**7}$, quartz window

Results (8 GeV incident energy)

e^- :	
p.e./GeV:	~ 11.3
σ/E :	$\sim 55-60\%/\sqrt{E}$ (5°)

μ Landau (~ 0.35 GeV @ 7.5 GeV):

peak:	~ 2.6 p.e.
centroid:	~ 8.6 p.e.

Pulse

Risetime < 10 ns, Fall-time < 25 ns

Summary - Hadron Cerenkov Calorimeter:

Physical Parameters

Packing Fraction (Core):	2.8%
Fiber Spacing:	8 mm
Fiber Core Diameter:	1.5 mm, 4 μ cladding
Fiber Material:	Mitsubishi purified PMMA ($n=1.49$, $NA=0.47$, attenuation: 0.3 dB/m @ 600 nm)
Absorber:	Cu
Interaction Length:	15.5 cm
Radiation Length:	1.47 cm
Length:	105 cm
Front Area:	22cm x 22 cm [25 x 25 fiber array]
Back Area:	33 cm x 33 cm [33 x 33 fiber array]
Mass:	~550 kg
Readout:	2.25" flat-flat hex UVT light guide, 6" deep 2" PMT, gain $\sim 10^{*7}$

Results (8 GeV incident energy)

σ^- :	
p.e./GeV:	~ 3.9
σ/E :	$\sim 90-100\%/\sqrt{E}$ ($2^\circ-7^\circ$)
π^- :	
p.e./GeV:	~ 1.4 (peak channel) - 2 (centroid)
σ/E :	$\sim 230-330\%/\sqrt{E}$ (5°) $\rightarrow 300-400\%/\sqrt{E}$ (2°) (2 x HWHM / Peak / 2.35) x $\sqrt{7.5}$ GeV
π/π :	$\sim 2.9 - 1.9$

Landau (~ 1.8 GeV @ 7.5 GeV):

peak:	~ 5 p.e.
centroid:	~ 11.5 p.e.

Pulse Risetime <10 ns, Fall-time <25 ns

Comments/Caveats:

- *Quartz E-M Energy Resolution:*

- Coarse Sampling: (Fiber Space)/Lrad ~ 1
 - > degrades shallow angle performance
 - > much improvement possible, to spacing/Lrad $\sim 1/4$
- "Thick Fibers": (3x1 mm ~ 1.73 mm single fiber)
 - > 0.5 mm fibers possible in e-m compartment at high P.F.
- Low Packing Fraction - can increase from 7.2% by x2-3 easily.
 - > $\sim 30\text{-}40\%/\sqrt{E}$ stochastic term appears possible for e-m calorimeter.

- *Hadron CerenCal:*

- Only 2.8% Packing Fraction, $\sim 1/2$ Lrad sampling distance, 1.5 mm fibers
- Compensation *in 1 uniform device* almost impossible in Cu (even w/ scintillator)
- e/π too high (in Cu) for good jet resolution, *without weighting by sections*.
 - > Expect 10-15% p.f. + 0.7-1 mm fibers -> $\sim 200\%/\sqrt{E}$ stochastic term

Main Results of Cerenkov Sampling Calorimeter Tests - 1993

- Cerenkov Sampling Technique Works at Shallow Angles to Beam:

- > No need for fiber alignment along "cerenkov angle" or meridional ray.
- > E-m, hadron, & μ calorimetry with coarse (0.5-1 Lrad) sampling: 3° - 5°
- > Degradation at shallower angles similar to SciFi calorimetry results.
- > Smaller fibers (closer spacing) should scale to smaller angles.

- Energy Resolution Promising:

- > E-M calorimetry achieved $\sim 60\%/\sqrt{E}$
- > E-M Resolution ~ 2 times worse than photostatistics (typ. optical cal.)
- > Indication that hadron calorimetry can achieve $< 300\%/\sqrt{E}$.
- > Packing Fractions can be increased by $\times 2$ -4, decreasing stochastic term.
- > Fiber diameters can be decreased by $\times 2$ -4, decreasing stochastic term.
- > E-M resolutions similar to NA38 (Gorodetzky) when scaled by PF.
- > Muon Landaus easily detectable, providing energy scale/calibration.

- Speed:

- > E-M (Hadron) signals integrated to ~ 90 - 95% in $\sim 1(2)$ beam crossings.
- > Risetime ~ 5 ns, both π , e, μ .

- Simple, Rugged, Reliable:

- > Once absorber matrix fabricated, hadron module completed in 12 hours, by 2 undergraduate students, on 1st & only attempt.
(cut fibers; stuff; bundle; polish; install PMT; light tight; cosmic ray test)
- > No failures during test beam run.
- > E-M modules (32 Lrad) fully portable by 1 person
"Out of the trunk - Into the test beam"

Hadron Ceren Cal - 105 cm long Cu.

Calorimeters in test beam.

top - Quartz e-m

bottom - Hadron Ceren Cal

Pb plate stack for e-m calorimeter

Exact position of the .25" holes is not critical.
 .12" hole corresponds to a #31 bit

7.2% Gre

3-fibers, 1mm core/hole

Hadron Cal - 4 GeV μ , 0.4°

Hadron Cal - 8 GeV μ , 1.9°

Hadron Cal - 8 GeV μ , 3°

μ Landau
Hadron CerenCalorimeter
 $0.4^\circ - 3^\circ$

E-M Cal-8 GeV μ 5°

E-M Cal-8 GeV μ 7.1°

μ Landau
QE-M Calorimeter
5°, 7°

Liquid E-M-8 GeV μ , 5.2°

μ Landau
Liq. Scint. Calorimeter
5.2°

E-M Cal - 8 GeV e-, 5°

8 GeV e-
Q E-M Calorimeter
5°

R1019 Q-Cal 8 GeV electrons

Hadron Cal-8 GeV e-, 3°

Hadron Cal-8 GeV e-, 5°

Hadron Cal-8 GeV e-, 7.1°

8 GeV e⁻
Hadron CerenCalorimeter
3°-7.1°

HCal, 7.5 GeV π^- , 2°

HCal, 7.5 GeV π^- , 5°

7.5 GeV π^-
Hadron CerenCal
2°, 5°

HCal, 7.5 GeV π , 5°

7200 Precision Digital Oscilloscope

LeCroy

⊕ TRACE 4.002
10 ns 50 mV

Cerenkov hadron - 8 GeV e^-

7200 Precision Digital Oscilloscope

LeCroy

⊕ TRACE4.013
10 ns 10 mV

Cerentov Hadron - 7.5 GeV π

7200 Precision Digital Oscilloscope

LeCroy

⊕ TRACE3.012
10 ns 50 mV

Quartz e-m 8 GeV e⁻

(150' cable)

LC_8_Mu_N?_T7.1_V20_1015

typical Pedestal Run

*reprints removed,
ds*

**DATE
FILMED**

2 / 2 / 94

END