SSC and G-2 Calorimeter
Optical Calibration

DOE/ER/40673-1

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Fairfield University

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Overview

Our contract was divided into two main tasks:

Task A: SSC R&D

- (1) Optical calibration generator tests of high speed photodetector pulse performance;
- (2) SSC scintillator calorimeter development & tests SSCINTCAL Subsystem R&D;
- (3) SSC EOI & LOI for GEM, and SSC Reports

Task B: Detectors for the G-2 experiment (E821 at BNL).

- (1) Detector and Calibration Tests
- (2) Photodetector and Gating Properties for G-2

Task C: Other High Energy R&D: Diamond film device development

Introduction:

Tasks A and B are highly interrelated, concentrating on high speed electro-optic particle detector techniques, mainly related to calorimetry. Another important goal of this program at Fairfield University is to engage undergraduates in high energy physics research. Five students worked on this program: Dan Keford, Bob Pisani, Dave Scrofani, Ken Segall, and Dan Wall. Ken Segall recently presented a paper at the Undergraduate Research Conference held in Minnesota in March, 1992. Dan Wall will be enrolled in graduate school at Tufts next year in Experimental High Energy Physics, based in part on his experiences working on G-2 at BNL and GEM/SSCintCAL at FNAL. Figure 1 shows one of 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.

NOTE: We mark with a RENEWAL those report sub-sections where we discuss or implicate how this work will be extended in the next year of contract renewal; these will be referred to in the contract renewal request sections following. Task C has no requests or budget and is incidental.

Task A: SSC R&D

The SSCINTCAL Subsystem R&D collaboration concentrated its efforts on spaghetti geometry scintillating calorimetry development. We briefly describe the tasks performed under this collaboration and program for SSC calorimetry, and related reports and EOI/LOI preparation for SSC experiments carried out by the support this contract that have made use of the scintillator calorimeter technology that our group has been developing over the past 2 years.

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MASTER

(1) Optical pulse generator tests of electro-optic detector performance and Calibration: SSCINTCAL Subsystem R&D.

The issues of dynamic range, hysteresis, rate and linearity for collider calorimetry photodetectors are summarized in our paper "Properties of Photodetectors for SSC Scintillating Calorimeters", published in the SSC Symposium held in Ft. Worth, in Oct., 1990. In this paper we also described the basic prototype of an optical pulse train generator that produces an optical pulse train by a set of stepped delay optical fibers driven by a single short laser pulse. This pulser can be used to inject known amounts of light into a fiber calorimeter or PMT assembly for calibration purposes. Over the past year, we have continued to construct & refine these pulsers/calibrators under the SSCintCAL/GEM SSC Subsystem R&D program for calibration of calorimeter and tests of photodetector properties. Figure 2 shows the schematic, and Figure 3 shows the module in assembly. Figure 4 shows installation of the pulser at Fermilab in Dec 1991-Jan 1992 on a large hadron fiber calorimeter prototype. The fibers inject known amounts of light into the calorimeter optical package via quartz fibers on SMA connectors. This system allows one to change optical cables as conveniently as standard electrical coax.

Figure 5 shows the use of the pulsers to study the effect of "hysteresis", the change in gain or shape with previous pulse history or rate of a PMT. The results of tests on modern good-quality PMT are discouraging for SSC high-resolution/high-speed calorimetry, both in dynamic range and in repetitive pulse gain and pulse shape. We have tested PMT under a pulse train up to an optical level equivalent to a 5 TeV deposition in a scintillating fiber calorimeter, alternating with 50 MeV minimum ionizing pulses. In Figure 5, a 62 MHz (16 ns spacing) optical pulse train is impinging on the PMT as digitized by a 2 GHz oscilloscope. Gain and pulse shapes clearly depend upon the previous pulse history (hysteresis) and are serious even at much lower dynamic conditions. The photodetector properties will be an important development problem for GEM if it adopts scintillating fiber calorimetry. Figure 6 shows a potential method to hold the light pulses from a laser stable to fractions of a percent, necessary for calibrating Higgs $\rightarrow$ 2 gammas at the SSC.

Appendix I, II are from talks given by the PI at FNAL and SSCL on PMT technology for colliders. Appendix III are slides from a talk given on scintillator calorimeter calibration at LBL in July, 1991.

RENEWAL: We will propose a development program to overcome the difficulties of present optical transducers for SSC physics requirements. We will request funding through SSCintCAL, GEM & SSCL for studying new photomultiplier technology optimized for the SSC, and for improved pulse train techniques. The systematic evaluation of optical transducers for calorimetry will be an essential program for SSC calorimetry.

**(2) SSC scintillator calorimeter development & tests:
SSCINTCAL Subsystem R&D**

Some of the results of this part of the SSCINTCAL SSC Subsystem program are outlined in a paper and abstract submitted to the IEEE Nuclear Science Symposium for last fall and for this fall, attached as Appendices IV ("Scintillating Fiber Calorimeter with Cast Absorbers") and V ("Grooved Copper Scintillating Fiber Hadron calorimeter Construction and Tests"). These papers were prepared at Fairfield and are presented by the PI for the SSCintCAL collaboration.

The salient points which may prove to be important new technologies which we have demonstrated and tested are:

- (1) the casting technique to insert scintillating fibers into low melting point lead-eutectics or into composite binder-metal powder mixtures in large hadron towers, including a full-size hadron tower tested at FNAL 12/91 (Figure 7),
- (2) a novel method to adjust the composition and thereby the radiation length, absorption length, and Moliere radius of the absorber matrix by loading the eutectic with metal or other powders/shot, including the addition of Tungsten or ceramics,
- (3) a simple grooved copper technique for producing compensated fiber hadron calorimeters at low cost, but with a lower number of photoelectrons (~ 50 p.e./GeV),
- (4) the use of polymer capillary tubes filled with liquid scintillator to replace solid scintillating fibers-liquid spaghetti scintillation calorimeters. [Appendices VI, VII show the slides from a talks to the GEM collaboration on Forward Calorimetry given by the P.I., and Appendix VIII shows the Summary of a paper on liquid core flexible fibers to be given by the PI at the Nuclear Science Symposium in the fall, 1992.]
- (5) The adaptation to fiber calorimeters of the CDF technique to use radiosources on wires to calibrate plate calorimeters.

Figure 8a-c shows the schematic and photographs of the copper towers under test at BNL. Figure 9a,b shows the first results of beam tests of the Pb-eutectic at FNAL Dec 1991, and the copper towers at BNL, June 1992. Fairfield has arranged the borrowing and installation of the CDF source driver and sources at BNL (Figure 10).

RENEWAL:

Forward Fiber Calorimetry:

A major implication of this work is for forward liquid calorimetry for the SSC, where both hadron calorimeter barrel technique and especially the liquid fiber technique that we have begun to develop for SSCintCAL are major technological contenders for the forward region in GEM [pseudorapidities of 2.7 to 5.5]. We note that forward jet tagging has become recognized as an important physics process, with forward calorimetry becoming a relatively more important physics instrument at high mass-scales, for hermetic missing E_t , and for multi-leptons from SUSY. Briefly, the detection of tagging jets in the rapidity range of 3 to 4.5 may enhance the signal/background of the heavy Higgs by factors between 4.5 -15, depending on cuts.

(3) SSC Detector and Experiment Studies: GEM EOI, LOI and Technical Studies

These tasks represented a major time commitment in 1991-92. The Fairfield group has contributed heavily to the planning of the GEM experiment in the Calorimeter part of the experiment, and continues to play a role in the preparation of the reviews for the PAC and for the Technical Design Review.[APPENDIX IX shows selected parts from the GEM LOI and Baseline design documents, as relevant to Fairfield; APPENDIX X is a study contributed to GEM for a high field solenoid option.]

In particular, Fairfield has taken leadership roles in GEM in:

- (1) the formulation of plans and methods for calibration of the proposed fiber hadron calorimeter (Figure 11),

(2) methods to obtain a radiation hard forward fiber calorimeter, using either liquid filled capillaries or quartz Cerenkov fibers [APPENDIX XI is a proposal to TNRLC "Forward Spaghetti Calorimeter Radiation-Hard Fiber Sensor Development", approved for Fairfield], and

(3) photodetector specifications (Figure 12).

Lastly, Fairfield participated in presenting the ELMUD EOI to the PAC in the summer of 1991.

RENEWAL: the Fairfield group is: (1) preparing to fabricate, and test liquid fiber spaghetti calorimetry as part of GEM/SSCINTCAL, for the remainder of this year and next year.; (2) Continue Photodetector Development; (3) Continue Optical and Radiation Calibration.

Task B: Muon G-2, BNL Experiment 821

Introduction:

The main results of this task are in the design report for the experiment, available from the DOE or from V. Hughes at Yale - the full description of and motivation for G-2 exceeds the scope of this brief report. APPENDIX XII attaches pages from the Design Report describing the importance of the experiment and showing the collaboration and their responsibilities.

This important experimental measurement has been a touchstone for the past 20 years which any new theory must address and accomodate: g-2 limits the scope of new theories, and probes the existence of new forces at high mass scales. The muon magnetic moment acts as a sum rule for the vacuum.

We have demonstrated to several review panels that it will be possible to reduce the errors on the existing measurement by a factor of 20, 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. The main errors are reduced by accumulating more statistics and by improving the inherent uniformity and measured knowledge of the magnetic field in the new G-2 ring that we are constructing, compared with the CERN results. We will need to construct 22 shower counter detector modules $16 \times 16 \text{ cm}^2$ in cross section on the entering face, and 14 R.L. deep. The counter modules are placed around the 7 m radius G-2 ring. A scintillating fiber hodoscope tracker (Position Sensitive Detector, or PSD) surrounds part of each module to tag multiple electron hits and to allow measurement (upper limit!) of the muon electric dipole moment. Figure 13a shows the schematic of the G-2 ring and detectors and Fig 13b shows the last coil winding.

These shower counters are technically demanding, firstly because in the first ~10-100 μsec , the (~exponentially decaying) counting rates over which accurate calorimetric and timing measurements must occur in the electromagnetic calorimeter approach that of the SSC (although only in the 1-3 electron energy GeV range).

A second major requirement is to develop a shower counter which recovers and is able to make timing measurements accurate at the ~0.1 ns level on single 1-3 GeV electrons after a very large "Flash" of radiation (~ 10^{6-7} neutrons, gammas, pions) hits the calorimeter over ~20 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 would 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 14a) of this Flash taken at BNL (with Yale and B.U.), signals as large as 30 V (Fig 14b) are generated by our photomultipliers during this flash, and methods must be found to relieve the photomultipliers and electronics of this burden.

We emphasize again that the dynamic range (flash) and temporal property (rate, timing) problems of scintillation calorimetry for G-2 have a close relationship to SSC calorimetry technique.

(1) Electron Calorimetry:

Shower Counter Fabrication and Tests: Over the past year Fairfield has participated in the continuing development and testing of scintillating fiber calorimeters (lead by the Boston University group with participation by us). Results from the most recent flash tests at BNL, participated in by 4 Fairfield students in 1991, have indicated that the bulk of the flash comes from particles traversing the photomultiplier tube itself. The conceptual breakthrough that we now understand is that the *delayed* portion of the injection 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. In these tests, Fairfield has supplied many of the photomultipliers, and also calibration LED flashers. Figure 15 shows the ADC spectra obtained on a fiber prototype at BNL in summer 1991.

Recently, test beam data was taken at BNL in the A-2 test beam in June 1992 using lucite light guides fabricated by BNL, with cast lead fiber calorimeters. In this reconfiguration compared with previous years, the particles enter the fiber modules at right angles to the fibers. Three modules 4 cm thick are stacked up to create sufficient thickness to absorb the electron energy. Figure 16 shows the assemblies being glued and wrapped at BNL by Fairfield students. During this test, calibration by the laser pulser and by LED flashers to determine the photoelectron levels by a statistical method were performed by the Fairfield group. [Average response of a PMT to a constant light pulse is $\langle R \rangle$: $\langle R \rangle = G \langle N_{pe} \rangle$, 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 width->sigma and the average response $\langle R \rangle$ from a constant light pulser - Figure 17].

Figure 18 shows photographs of the calibration system and counter being installed at BNL. From the on-line analysis system in June 1992, we have achieved a resolution of $13\%/\sqrt{E}$, over the energy range 1-3 GeV, sufficient for G-2 operation. During these tests we acquired waveform information from the 3 photomultipliers and their linear sum using our digital oscilloscope. Figure 19 shows a photograph of the traces of the three calorimeters taken off the digital oscilloscope in June, 1992.

During these tests (6/92), 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. During 1991-2, 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. This may be an important step in guaranteeing the time measurement of the electron decay, which will be decided in the next year.

RENEWAL: We will continue to the laser systems described in Task A above, for very precise timing tests on the G-2 calorimeters. The laser system can also be used to simulate some Flash conditions, and will be used with tests of Flash gating and PMT performance as described below.

(2) Photodetector Tests and Specifications

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. 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. We have had excellent results with a flash gating circuit obtained by Fairfield on a custom basis from Hamamatsu Corp as described in our previous Contract report. The flash testing has continued to make extensive use of the laser optical pulse systems used in the SSC work described above.

During this year we concentrated on (1) primary PMT specifications which would allow the PMT to operate under flash conditions better, (2) design of crucial bench tests to qualify PMT for G-2, (3) initial identification of fast PMT candidates for G-2, and (4) development our own active base and gating circuits. Figure 20 shows a single page summarizing the specifications for a PMT to operate G-2 successfully. Candidate PMT with 0.4 ns risetimes include the Hamamatsu R3091, R3375 for the calorimeters (transit time spread 200 ps), and the R1635 and R4124 for a separate FSD (fast scintillator detector) timing signal (transit time spread 100 ps).

A crucial test for the PMT is to eliminate any difference between the time response early and late in the G-2 decay cycle; ie the tube must not alter the pulse response at an instantaneous rate of 30 MHz of decay electrons just after injection, to an instantaneous rate of a few 10's Hz at the end of the decay cycle (~1 ms). The difficulty is to find a method to guarantee a time non-linearity of less than 0.1 ppm during those conditions. As is well-known, PMT have a serious rate effect on the gain, and G-2 has a continuously variable (exponential) instantaneous rate! Therefore, over the past year, Fairfield has developed for the collaboration a plan to construct a "G-2" simulator which generates a synthetic optical waveform which would be produced by a G-2 calorimeter, based on MC data. Basically, by loading a digital waveform synthesizer with a string (10,000) of 12 bit numbers corresponding to the amplitude of the optical pulse, with each position in the string representing a monotonically increasing time bucket (10 ns clicks), one can create an electrical waveform corresponding to the 30 MHz-> few Hz G-2 waveform. By feeding this waveform into a laser diode driver, one can then make a simulated G-2 optical waveform for studying the G-2 PMT. One can then inject an optical pulse at precisely known early and at late times on this waveform by a second laser, to study systematic variations in the time response of candidate PMT at various parts of the G-2 decay cycle.

We have also designed a high rate active PMT base for use in G-2, which includes a gate circuit making use of new HV transistors. Figure 21a,b shows the schematics of base gating systems, currently under construction. Further gating tests under way this summer include the use of an external grid biased to the opposite potential of the PMT to prevent the emission of photoelectrons during the gate-off. A pulse power supply will be available for this in late July, 1992.

RENEWAL: During the next fiscal year, we will continue the work of selecting PMT and developing methods to ensure the performance of the PMT during the G-2 experiment.

Task C: Other High Energy R&D: Diamond film device fabrication & tests

This small task is summarized in APPENDICES XIII, publications from 1991-2. Diamond thin film diode technology may have its most important application as part of a hybrid photomultiplier tube (see discussion in the papers) for scintillation calorimetry and as an important new technology for ionization calorimetry, and for switching applications. [Support for this task by this DOE grant was minimal & incidental, mainly by equipment sharing.]

Conclusion of the Report Section:

We have successfully carried out our proposed program of SSC Subsystem R&D, having generated a novel pulse train generator for scintillator calorimeters, and tested the properties of photodetectors under severe dynamic range conditions.

We have successfully tested compact shower counters for the G-2 experiment, have made important progress in understanding the injection flash with BNL and Yale Tandem tests, and have acquired in collaboration with industry a gating circuit appropriate to successfully perform the G-2 experiment.

We have carried out an extensive study of SSC detectors and physics capabilities as represented by our participation in the GEM, High Field, and ELMUD studies.

We are in a strong position to continue our detector and experimental work into the next year. We have accepted responsibilities to 2 major collaborations: G-2, and GEM Spaghetti Calorimetry/SCCINTCAL in both the central and forward regions, based on our continuing work in this contract.

We continue to stimulate a new crop of skilled undergraduate students.

Report Section Figures:

Fig. 1. Calorimeter installation at BNL with a Fairfield student.

Fig. 2: Schematic of laser-fiber pulse train/calibration systems for PMT properties and fiber calorimetry.

Fig. 3: Sixteen channel fiber pulser under assembly at Fairfield.

Fig. 4: Installation of fiber pulser on Pb-fiber hadron calorimeter module at Fermilab, Dec 1991.

Fig. 5: Hysteresis of a fast phototube when illuminated by a 16 pulse 62 MHz optical pulse train of 0.8 ns wide laser pulses. Note baseline shift.

Fig. 6: Proposed stabilized laser calibration system.

Fig. 7: Cast Pb eutectic towers as installed at Fermilab and tested with Fairfield students and personnel.

Fig. 8a: Schematic of projective laminated Cu fiber hadron towers.

Fig. 8b: Laminated Cu towers installed at BNL A-3 test beam 6/92.

Fig. 8c: Test beam trigger set up at A-3.

Fig 9a: ADC spectra for 35 GeV electrons in cast Pb-fiber calorimeter at FNAL, Dec. 1991.

Fig. 9b: ADC spectra for electrons and pions at BNL, June, 1992.

Fig. 10a,b: CDF source driver, borrowed from CDF & Purdue, as installed at BNL, 1992, and PMT assembly with LED calibration system as installed at BNL, 1992.

Fig. 11: Methods of calibration for GEM/SSCintCAL hadron calorimeters as presented to GEM by DRW, 1992.

Fig. 12: PMT specifications for a fiber hadron calorimeter presented to GEM by DRW, 1992.

Fig. 13a: Muon G-2 Ring and detector placement, with EGS display of muon G-2 decay electrons.

Fig. 13b: E821 G-2 crew in front of last coil wind in the old 80" BC building.

Fig. 14a,b: Flash test geometry with PMT flash waveform.

Fig. 15: Electron calorimeter test 1991- ADC distribution on fiber calorimeter, taken by Fairfield personnel.

Figs 16: Fiber electron calorimeters being assembled with plastic light guides and wrapped for June 1992 test beam at BNL, with Fairfield personnel at BNL.

Fig. 17 a,b: LED pulser system for determining photoelectron levels, and installation of fiber pulser and LED system at BNL, 1992, by Fairfield student.

Figs 18: Installation of Fairfield laser fiber pulser system on G-2 electron calorimeters at BNL, 1992.

Fig. 19: Waveforms from 3 electron calorimeters stacked along the beam direction, together with the summed waveform at BNL on 3 GeV electrons, June 1992 on Fairfield digital oscilloscope. (Currently under analysis.)

Fig. 20: Specifications proposed to G-2 collaboration for PMT.

Fig. 21a: Photocathode gating circuit using opto-coupler.

Fig. 21b: Active gated base circuit under construction.

Fig. 22: Light guides proposed for fiber calorimeters on G-2.

Report Figures

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LASER/FIBER OPTIC CALIBRATION SYSTEM

Fig. 2: Schematic of laser-fiber pulse train/calibration systems for PMT properties and fiber calorimetry.

Fig. 3: Sixteen channel fiber pulser under assembly at Fairfield.

Fig. 4: Installation of fiber pulser on Pb-fiber hadron calorimeter module at Fermilab, Dec 1991.

Fig. 5: Hysteresis of a fast photodiode when illuminated by a 10 pulse 62 MHz optical pulse train of 0.5 ns wide laser pulses. Note baseline shift.

STABILIZED TUNABLE PULSED LASER CALIBRATION LIGHT SOURCE

Fig. 6: Proposed stabilized laser calibration system.

Fig. 7: Cast Pb eutectic towers as installed at Fermilab and tested with Fairfield students and personnel.

TYPICAL COPPER LAMINATED TUBE AND PLATE TOWER

AS ASSEMBLED, BEFORE FINAL MACHINING

NOT TO SCALE

(NUMBER OF LAMINATIONS
REDUCED FOR CLARITY)

Fig. 8a: Schematic of projective laminated Cu fiber hadron towers.

Fig. 8b: Laminated Cu towers installed at BNL A-3 test beam 6/92.

SCCintCAL Trigger for 1992 BNL Tests

Summary of the Two-level (for possibly late Cerenkov signals) SCCintCAL Trigger:

A coincidence between 3 beam counters (BA, BB, BC) with a veto on a hole counter (BH) defines a beam signal (BEAM) and, if within the computer ready (DA-RDY) and beam gates (BGATE), sets the pretrigger latch (PRETLTCH). The output of the PRETLTCH will stay on (via feedback) until reset by the RST veto input. A 20ns pretrigger pulse (PRETRGR) is used to generate a stop for the TDCs (in coincidence with the RF-clock), a gate for the ADCs, and, if there is no trigger, a delayed signal to clear the ADCs and TDCs (FASTCLR) and a reset (RST) for the pretrigger latch. A pretrigger in coincidence with the appropriate Cerenkov logic (CLOGIC and CTRG) will set the trigger latch (TRGRLTCH) which, if set, will block the formation of a clear (FASTCLR). A 20ns pulse (READ) will initiate the CAMAC readout sequence, while another pulse (DONE) will signal its completion and will generate a reset (RST) for both the latches.

LRS module number and functions:

- 364 4-fold logic w/overlap width
- 365 4-fold logic w/fixed width
- 622 binary logic and/or
- 623 discriminator w/bar-output
- 821 discriminator

Fig. 8c: Test beam trigger set up at A-3.

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Fig: 9b: ADC spectra for electrons and pions at BNL, June, 1992.

Fig. 10a,b: CDF source driver, borrowed from CDF & Purdue, as installed at BNL, 1992, and PMT assembly with LED calibration system as installed at BNL, 1992.

SSCintCAL CALIBRATION

1. Absolute:

- Radiosources, cross calibrated with beam tests
 - Cs or Co source capsules on wires in tubes (like CDF)
- Landau Distributions
 - See SPACAL reports; detailed difference $40 < E_{\mu} < 250$ GeV
- Pion Punch-thru
 - Tracker + min. ionize in BaF2 + isolation $\rightarrow$ E pion known.
- Neutron Generator Activation, cross calibrated
 - 14 MeV D-T neutron generators (10^{10} /s) (like UA-1)
 - Generator: 6 terminal metal-ceramic 5 cm dia x 25 cm long
 - 1 μ sec pulses, 1% D.F.

2. Relative:

- Light Injection on Fibers
 - Achieved $< 0.5\%$ in CLEO, Bugey Neutrino Expt., etc.
 - Long term: several months
 - Cross-calibrate in lab, on bench, & w/ radiosource
 - CDF, UA-1, UA-2: $\sim 1\%$ long term
 - lasers, plasma pinches, LED's, stable arcs, laser diodes, etc
 - [- Tunable ring laser, phase locked machine RF
 - $\rightarrow$ sub ns pulse, stability: 10^{-4}
 - [- Inject front/rear at several wavelengths
 - $\rightarrow$ rad damage, separate fibers from PMT stability]
- Symmetries of Energy Deposition
 - Towers of constant $\pm\eta$ (a ring of towers): same Energy.
 - Sets of towers of constant ϕ : same $\delta E / \delta\eta$ (Energy profile)
 - Compute Entropy; anneal
 - Use tracker to correlate with absolute $d^3E/d\eta d\phi d\eta$.

Summary

GEM Hadron Calorimeter PMT Specifications

Photocathode:

Photocurrent: 2% linearity for 10^7 p.e. in 10 ns
Lifetime: 1 mC for 50% gain loss
Uniformity: $\pm 10\%$ over 25 mm circle

Multiplier:

Gain: $> 10,000$
Pulsed Current: 25 mA in 10 ns with $< 0.5\%$ non-linearity
200 mA in 10 ns $< 2\%$ non-linearity
Risetime (Δf^n pulse, 20%-80%, 10ma in 50 Ω): $< 4\text{ns}$
Falltime (Δf^n pulse, 80%-20%, 10ma in 50 Ω): $< 6\text{ns}$
Width at Baseline (5%): $< 12\text{ ns}$
Pulse Shape Change: $< 20\%$ for pulses between 0.1 -100 mA
Average Anode Current: 1 μA
Lifetime: 2 C w/ 50% loss
Anode Capacitance: $< 10\text{ pF}$ to all other electrodes combined
Anode Inductance: $< 45\text{ nH}$

Noise:

Single p.e.: $< 100\text{ kHz}$ at 0.5 pe peak
Afterpulsing: $< 0.1\%/p.e$ for afterpulses $> 10\text{ p.e.}$
Pre Pulsing: Arrival $< 5\text{ ns}$ early
amplitude $< 0.5\%$ of signal

Stability:

Long Term: $< 1\%/month$
Hysteresis: $< 1\%$ gain shift within 100 ns after pulse of 10 ma x 10 ns

Magnetic field: Operates parallel to 0.7 T

Full Scale: 5 TeV jet

Min Scale: 0.1 min ionizing $\sim 50\text{ MeV}$

Gain: Max Charge = 200 mA x 10 ns = 2 nC, 100 p.e./GeV $\rightarrow$ Gain = 12,000

Fig. 12: PMT specifications for a fiber hadron calorimeter presented to GEM by DRW, 1992.

ELECTRON CALORIMETER DETECTORS

Fig. 13a: Muon G-2 Ring and detector placement, with EGS display of muon G-2 decay electrons.

Fig. 13b: E821 G-2 crew in front of last coil wind in the old 80" BC building.

Fig. 14a,b: Flash test geometry with PMT flash waveform.

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

Fig. 15: Electron calorimeter test 1991- ADC distribution on fiber calorimeter, taken by Fairfield personnel.

Figs 16: Fiber electron calorimeters being assembled with plastic light guides and wrapped for June 1992 test beam at BNL, with Fairfield personnel at BNL.

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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 ($200 < \text{p.e.} < 2000$)
Noise:	$<100\text{ KHz @ } 0.5\text{ p.e.}$
After-Pulsing:	$<0.1\%/ \text{p.e.} + <1\%$ 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:	$<2\%/ \text{Month}$
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 $\langle R \rangle \sim 30\text{ MHz}$ x $e^{-t/60\mu\text{s}}$, for a period of $t \sim 1\text{ ms}$:

- (a) $\Delta [T_p: \text{Peak of the PMT pulse time distribution}] < 20\text{ ps}$, for $1\text{ kHz} < \langle R \rangle < 30\text{ MHz}$
- (b) $\Delta [\sigma \text{ of PMT pulse time distribution}] < 100\text{ ps}$, 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 $< 1\%/^\circ\text{C}$
- (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

Light Guide Alternatives

Fig. 22: Light guides proposed for fiber calorimeters on G-2.

1990-92 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, IEEE Nuc.Sci.Symp, 1992

"Liquid Scintillator Core Fibers with Polymer Claddings", K. Segall et al, to be presented by D.R. Winn, IEEE Nuc.Sci.Symp, 1992

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

" Properties of Photodetectors for SSC Scintillating Calorimeters", D.R.Winn, K. Segall, D. Wall, P. Cushman, D. Grigoriev, Proceedings of the SSC Symposium, in press, June 1991

" Cast Lead Eutectic Solid and Liquid Scintillating Fiber Shower Calorimeters", , with W. Worstell et al., Conference Record - IEEE Trans. Nuclear Science, published Feb 1991

" Diamond Film Optical, X-Ray and Particle Detectors", C.P. Beetz, B. Lincoln, D. Winn, K. Segall, M. Vasis, D. Wall, Conference Record- IEEE Trans. Nuclear Science, published Feb 1991

"The Manufacturing Engineering of a Hermetic Cast Fiber Calorimeter", with T. Coan et al, Proceedings of the SSC Symposium, published by the SSCL and DOE, in press, June 1991

"Electromagnetic MUon Detector for the SSC", M. Fortner, D. Hedin, S. Linn, E. Wang, D. Winn, H. Yamamoto, Supercomputer Computations Research Center Publication FSU-SCRI-91T-15, Feb 1991

"Sub-Bandgap Excited Photoconductivity in CVD Diamond Films", C.P. Beetz, B. A. Lincoln, and D.R. Winn, Proceedings of the SPIE, SPIE paper code 1325-29 in press 1991.

"Diamond Film Optical Detectors", C.P. Beetz, B. Lincoln, D. Winn, K. Segall, D. Wall, LEOS '90 Conference Proceedings, p95, IEEE publication 1991

"TEXAS: a calorimeter-based high-rate detector for the SSC", with G. Alvorsen et al, Nuclear Instruments and Methods, paper code NIMB 0237D, in press 1991.

"High Frequency Betatrons", D. R. Winn, presented May 1991, to appear in the Conference Record, IEEE Particle Accelerator Conference, San Francisco, in press 1991,

" Applications of Diamond Films to Photocathode Electron Guns and Accelerators", C. Beetz et al., presented by D. R. Winn, Conference Record, IEEE Particle Accelerator Conference, San Francisco, 1991

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- APPENDIX II: Slides of Talk, "PMT for Calorimeters", 1991
- APPENDIX III: Slides of Talk, "Scintillator Calorimeter Optical Pulse Calibration", 1991
- APPENDIX IV: "Scintillating Fiber Calorimeters with Cast Absorbers"
- APPENDIX V: "Grooved Copper Scintillating Fiber Hadron Calorimeter Construction and Tests"
- APPENDIX VI: Slides of Talk, "Forward Calorimetry R&D: Scintillating Liquid Spaghetti"
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- APPENDIX VIII: "Liquid Scintillator Core Fibers with Polymer Claddings"
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 - "High Frequency Betatrons"
 - "Applications of Diamond Films to Photocathode Electron Guns and Accelerators", C.

Reprints removed.

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