GEM TN-92-185

The Fiber Hadron Detector for GEM

H. P. Paar - University of California, San Diego
L. R. Sulak - Boston University

September 22, 1992

Abstract:

This report summarizes GEM Technical Notes that document in detail the status of scintillating hadron fiber calorimetry for the SSC. These reports demonstrate that the fiber hadron calorimeter fulfills all GEM requirements. It will operate with the baseline performance at the highest SSC luminosities.

GEM-TN-92-185

THE FIBER HADRON DETECTOR FOR GEM

H.P. Paar and L.R. Sulak
for the GEM Hadron Fiber Subgroup

September 22, 1992

ABSTRACT:

This report summarizes GEM Technical Notes that document in detail the status of scintillating hadron fiber calorimetry for the SSC. These reports demonstrate that the fiber hadron calorimeter fulfills all GEM requirements. It will operate with the baseline preformance at the highest SSC luminositites.

THE FIBER HADRON DETECTOR FOR GEM

H.P. Paar and L.R. Sulak
for the GEM Hadron Fiber Subgroup

September 22, 1992

Introduction

The scientific attributes of the fiber calorimeter in a hybrid system include the following:

1. Fast response, both rise and fall times commensurate with beam crossing time interval, assuring that measurements of both $\not{E}_t$ and bunch assignment are immune to pileup.
2. Low noise leading to isolation criteria that complement the lepton and photon measurements.
3. Hermetic registration of jets and missing $\not{E}_t$ ($\leq$2% non-active volume).
4. Fully compensated response of the combined liquid krypton electromagnetic and fiber hadronic calorimeter.
5. Robust operation, even in the high radiation environment at larger η, for at least 2 years at $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with quick replacement of damaged 3% of the fibers near the forward region ($\eta = 2.5$ to 3.0) after each 2 years of running at $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
6. Verified performance of prototype modules in test beams.
7. Long term calibration stability (better than 2%) of large scintillating systems demonstrated es at CDF and UA2 and with systems with scintillating fibers at WA89 (OMEGA at CERN) and JETSET (LEAR at CERN).
8. Compactness, which achieves active sampling with $\geq 12\,L_{\mathrm{int}}$ at $\eta = 0$ within 3.6 m radius.
9. Simplicity of construction, verified by the manufacturing of 7 prototype towers.
10. Letters of Intent with 12 international institutions, agreeing to provide over half of the U.S. value of the hadron calorimeter.

This report summarizes several GEM Technical Notes that document in detail the status of scintillating hadron fiber calorimetry for the SSC. GEM Technical Notes exist for each of the following issues:

1. Radiation Tolerance.
2. Noise, Pileup, Linearity, and Rate Capability of a Fiber Hadron Calorimeter.
3. Performance of Prototype GEM Hadronic Towers in BNL Beams.
4. Muon Energy Loss in the Hadron Calorimeter and Muon Momentum Resolution.
5. Calibration, Monitoring, and Beam Testing.

6. Photomultiplier Readout System Stability and Calibration.
7. The Forward Radiation-Hard Quartz Calorimeter.
8. GEANT Simulations of a Forward Quartz Fiber Calorimeter.
9. Simulations of the Krypton/Fiber Hybrid Calorimeter.
10. Manufacturing Engineering and Cost Estimate.
11. Anticipated Cost Sharing by International Collaborations.

Other issues have not been addressed in the Hybrid Calorimeter task force. Many of these have been studied since Spring 1987 and the results published in 13 papers by the SPACAL collaboration.

Most important among these are:

12. Signal Speed and ADC Gate Width.
13. Electron-Pion Discrimination.
14. Measuring Lateral Position of Hadronic Showers.

As a composite, these reports demonstrate that the fiber hadron calorimeter fulfills all GEM requirements. It will operate with the baseline performance at the highest SSC luminosities. The project is ready to proceed to the Technical Design Report.

We briefly summarise each of these points below.

I. Radiation Tolerance

The radiation levels in the hadronic calorimeter are greatly reduced relative to those in the electromagnetic calorimeter due to the fact[1] that all photons in the jets are absorbed in the electromagnetic calorimeter. They are reduced further since the location of the energy deposit in the hadron calorimeter is further from the interaction point (the dose is proportional to $1/r^2$). A third reduction comes from the fact that hadronic shower development peaks in the electromagnetic calorimeter so the hadronic calorimeter is only exposed to the tail of the longitudinal dose profile.

The radiation levels in the hadronic calorimeter stay under 1 Mrad/yr for the entire barrel/endcap region ($-3 < \eta < 3$) at the design luminosity of $10^{33}\,cm^{-2}s^{-1}$. At a luminosity of $10^{34}\,cm^{-2}s^{-1}$ for 10 years, about 5 Mrad will be accumulated at $\eta = 2.5$ and less than 25 Mrad at $\eta = 3$. The accumulated dose in the entire barrel calorimeter stays well under 1 Mrad.

Commercially available fibers today produce no unacceptable degradation in the hadronic calorimeter performance occurs up to levels of about 10 Mrad. Only 1% of the fibers ($\leq$ one row of the physical towers at η=3) would be affected in a period of 10 years of SSC running at $\mathcal{L} \approx 10^{34}\,cm^{-2}s^{-1}$. The effect of this dose is to degrade the constant term in the hadronic energy measurement by 2%.

The choice of an hydrogenous active calorimeter medium (plastic) reduces the neutron flux by at least a factor of three compared to a noble liquid hadronic system. This minimizes the problems anticipated from induced radioactivity and from spurious hits in the tracking and muon detectors. Moreover, the electronics residing upstream from the calorimeter system will suffer proportionally less from radiation damage caused by neutrons.

II. Noise, Pile-up, Linearity, and Rate Capability

Pulse shaping can be used to great advantage[2] in a fiber hadron calorimeter. Rather than speeding up the signals, it reduces the pile-up noise by a factor 2 to 3 by optimizing the pulse response of a shaping amplifier. It reduces the required PM gain from 3×10^5 to 1000 if the preamp with shaper has a gain of 300. Thus the output current from the PM is also reduced by a factor 300. This helps maintain the linearity of the PM response up to the largest energies (several TeV) and at the highest rates (at large η).

In contrast with a cryogenic liquid hadron calorimeter, thermal noise is negligibly small for the hadron calorimeter. The sum of thermal noise and pile-up noise in the fiber hadron calorimeter is likely to be a factor of 3 to 10 lower than in the cryogenic calorimeter. The factor of 3 applies if the cryogenic calorimeter successfully uses "adaptive filtering" (thus far an untried offline procedure). The factor of 10 applies to a situation without this "adaptive filtering".

III. Performance of Prototype GEM Hadronic Towers in BNL Beams

In July 1992 the SSCintCAL collaboration tested 7 prototype projective hadron calorimeter towers, each constructed with scintillating fibers embedded between copper laminations. The total mass of hadron calorimeter prototype constructed and tested in the BNL beam was 5400 kg, supported by a test stand with 4 degrees of freedom. Tests were carried out with incident electrons, pions, and muons with momenta between 1 and 20 GeV/c. The bulk of the data was for pions with 15 GeV or 20 GeV total energy. Calibrations were performed with electrons incident on each of the towers individually at 10 and 15 GeV. The results can be found in Ref. 3.

Because of time constraints in prototype construction, our fibers were not mirrored. Because of unfounded concerns about sufficient light yield, we did not use yellow filters. Both these were shown by SPACAL to increase the light attenuation length with beneficial effect on the shape of the energy spectrum. Because of readily obtainable stock, we built a calorimeter with 2.25% active fibers, rather than the 3% that has been designed and costed in Baseline I. The first two deficiencies caused our pion data to exhibit a high-energy tail. This is consistent with light attenuation combined with longitudinal fluctuations in hadronic shower development. The high energy tail has been shown not to deteriorate the performance below that of Baseline I specs for jets. This is due to the fact that the lineshape (with tail) gets sampled by the many particles in a jet and Gauss' Central Limit Theorem garantees that the resulting energy spectrum for a jet will tend to a Gaussian. We measured 60 pe/GeV. With Baseline I sampling, we would get 90 pe/GeV.

Pions exhibited uniform response when scanned across boundaries between modules. Less than 1% variation, consistent with lateral leakage, was recorded when we scanned through a range of incident angles with respect to the fibers. We obtained less than 2% mean shift across module boundaries.

We obtained a fitted energy resolution of $91\%/\sqrt{E}$ for 10 GeV pions. Our measured e/π ratio is 1.08 ± 0.02 before any leakage corrections (1.03 ± 0.02 with leakage corrections), for pion energies between 10 and 20 GeV. Simulations of the fiber/copper calorimeter in CALOR89 predict an energy resolution of 93% ± 5%, and $e/\pi = 1.05 \pm 0.03$ (again, without leakage corrections). This should be compared with the $90\%/\sqrt{E}$ Baseline I goal for the resolution for hadrons.

For electrons, we obtain a fitted energy resolution of $57\%/\sqrt{E}$ at 15 GeV for a small angle between electron incidence and fiber axes. As with pions there is a high-energy tail, but for a different reason. Since the Moliere radius is 12 mm and the fiber lattice spacing 8 mm for this 2.25% calorimeter, very few fibers respond to the shower from a single electron incident on the hadron calorimeter tower. Consequently, the response is a sensitive function of electron incident position and angle. Electrons with EM shower maximum located directly on a fiber give significantly greater response. At large incident angles between beam electrons and the fibers axes the response becomes gaussian. There is no high-energy tail in response to EM shower leakage from the back of an EM calorimeter, which is distributed across many fibers; GEANT simulations for leakage of 100 GeV electrons predict a gaussian resolution of $45\%/\sqrt{E}$. This compares with our Baseline I resolution of $40\%/\sqrt{E}$ for a calorimeter with a 3% instead of a 2.25% fiber fraction. We expect the resolution to improve by about $\sqrt{1.5}$.

For muons, we observed Landau distributions well-resolved from pedestals for an incident angle of 1.5 degrees with respect to horizontal planes of fibers and 0 degrees with respect to vertical planes of fibers. An incident angle at least this large is anticipated by a "pinwheel" orientation of fiber axes.

IV. Muon Energy Loss in the Hadron Calorimeter and Muon Momentum Resolution

Muons may undergo catastrophic energy loss in the calorimeter. This energy must be added to the momentum measured outside the calorimeter. The radiative tail consists almost entirely of bremsstrahlung, including most of the 10% muons that lose more than 2.8% of their energy. Most of the 3.3% muons that experienced more than 10% of their energy lost did so by photonuclear interactions. Bremsstrahlung leads to electromagnetic showers; photonuclear interactions lead to hadronic showers. Compensation is therefore very helpful in the measurement of muon energy loss.

A detailed GEANT simulation[4] shows that the fiber hadron calorimeter with $\sigma_E/E = 50\%/\sqrt{E} + 2\%$ and no depth segmentation does not degrade the GEM muon momentum resolution for energies below 100 GeV muons where its contribution is 1.1%. This is of the same magnitude as the momentum resolution at 100 GeV To decrease the calorimeter contribution, one needs to improve the hadronic energy resolution, not the electromagnetic one.

However, the momentum resolution may not have to be better than that required to measure the Z^0 mass without affecting its resolution. Since the natural width of the Z^0 is 2.5 GeV, a deterioration of the momentum resolution from 1% to 1.4% should not matter.

V. Calibration, Monitoring, and Test Beam Plan

The calibration and monitoring plan[5] for the GEM Scintillating Fiber Hadron Calorimeter covers all phases of the experiment, procurement, fabrication, assembly, and operation. Components to be calibrated and monitored include the copper and tungsten absorber blocks, the plastic and quartz fibers, the optics package, the PMTs, and the electronics. Redundant procedures (e.g., optical light injection, movable radioactive sources, electronic pulse injection, and cosmic ray muons) are used in all phases of manufacturing to insure quality control. Intercalibration and monitoring of all modules throughout the fabrication and assembly process carries over to actual operation because these same procedures are used there as well. For example, insitu each electronic channel has a test pulse input, has an LED on its face, each optical fiber bundle has an N_2 laser fiber (with 10^5 dynamic range), and each tower has a piezo electric motor driven source that scans it diagonally for its full depth.

FNAL and SSC test beams are required to verify physics simulations and to characterize modules of 14 different geometries. The goal is to minimize the constant term in the energy resolution and to determine the constants needed to achieve effective compensation of the composite calorimeter. The measurements for each physics tower geometry provide complete characterization of shower shapes and quantify the response (e/h) as a function of energy for electrons, pion and jets from ~10 GeV to 2 TeV. Although past experience shows that statistical sampling is sufficient to monitor production quality, the schedule assumes all modules will be checked in test beams to insure verification of the intercalibration.

VI. Photomultiplier Readout System Stability and Calibration

The stability, monitoring and calibration of a photomultiplier based calorimeter is the main issue for their operation and performance. The ZEUS collaboration maintains 1% tower-to-tower and module-to-module energy calibration with 0.2% overall stability. With 100 GeV incident particles, their calorimeter gives an energy resolution of ~ 2% for electrons and ~ 4% for hadrons. CDF reports that the difference of the calibration results done five weeks apart on 40 towers shows an RMS of 0.2 ± 0.7%. An ^{241}Am α-source monitored ~1000 channels of a Pb-glass electromagnetic calorimeter at FNAL E704. Over a 50 day period, a stability of <1.0% was achieved. FNAL Experiment E840 shows that ~ 2.3% global calibration with a mechanically driven radioactive source is easily achieved for 60 channels of a scintillating fiber calorimeter prototype . The same technique with longitudinal and transverse source scans is exploited for attenuation length, local radiation change uniformity of response and calibration monitoring. The 300 tower JETSET fiber calorimeter achieves 0.5% stability over 2 weeks with no special attempts to control temperature or high voltage in an open bay at the CERN PS. A N_2 laser normalized of PM's, and through muons and

the π^o peak provide absolute calibration.

The GEM baseline PM is a mesh dynode proximity focusing tube. It is stable for $\leq$1 Tesla of magnetic field with a gain of up to $\sim 2 \times 10^5$ and with a risetime of < 3 ns. The fine mesh dynode structure extends the current range up to 1A with 0.1% deviation over 3 orders of dynamic ranges. It remains linear within 2% at 2A. The typical temperature dependence of product of gain and quantum efficiency is $\sim 0.5\%/^\circ$C for the PMTs used in ZEUS and CDF.

From the extensive studies and the experience of the above large detectors, we conclude[6] that the stability (< 1%), monitoring and calibration ($\sim$ 1%) requirements for the GEM scintillating fiber hadronic calorimeter can be met.

VII. The Forward Radiation-Hard Quartz Calorimeter.

The kinematic region beyond η=3 at the SSC provides special challenges for high performance calorimetry. Hadron showers cover rather large regions of η and radiation levels beyond $\eta = 5.5$ exceed 10^6 Rads per standard SSC year. However, for physics processes with $\not{E}_t$ signatures, this kinematic region is of extreme importance.

A technical note[7] describes the design and performance of a fast, radiation-hard, projective quartz fiber sampling calorimeter for the forward regions in the GEM detector. This calorimeter would provide the energy and spatial resolution required for this $\not{E}_t$ physics while being robust enough to survive 3 years of operation at a nominal luminosity of 10^{34} without repairs.

VIII. GEANT Simulations of a Forward Quartz Fiber Calorimeter

The Simulation of the Čerenkov light output from a quartz fiber calorimeter shows[8] that it provides sufficient energy resolution for long-term use in the forward region at the SSC. A detailed Monte Carlo of Čerenkov light production in transparent fibers has been integrated with the GEANT3 program. Results of the simulations of electrons and photons of various energies incident both transverse and longitudinal to quartz fibers embedded in both lead and tungsten blocks is consistent with the results of the BNL test beam. The Cerenkov yield is independent of the direction of the incoming particle. This makes the results of the CERN test beams (perpendicular to the fibers) relevant to the SSC forward calorimeter (where the showers are essentially parallel to the fiber).

IX. Simulations of a Krypton/Fiber Hybrid Calorimeter

We have calculated the jet resolution with GEANT for a LKr EM calorimeter followed by the baseline fiber hadronic calorimeter with 3% active material. The Monte Carlo simulations appear to describe the BNL beam test results. The jet energy resolution is $(57\pm3)\%/\sqrt{E} + (2.2\pm0.7)\%$.

We have shown that the combination of a non-compensating electromagnetic calorimeter and a compensating hadronic calorimeter can still give effective compensation[9] for jets over 100 GeV. One can use an algorithm that takes into account the event-to-event fluctuations in the energy deposits in the electromagnetic and hadronic sections of the calorimeter. All input data required for the method can be measured in beamtests of prototype calorimeter modules, using single electron and pion beams, and multiparticle beams (obtained from a target in a single pion beam). The method can be tested by varying that target thickness, thereby in effect changing the "fragmentation" function. The energy measurement should be independent of the target thickness. A small non-linearity on the level of a few percent needs still to be corrected for.

For non-compensating electromagnetic and hadronic calorimeters additional knowledge is required regarding the jet fragmentation function and the electromagnetic energy fraction in hadronic shower development at SSC energies.

X. Manufacturing Engineering and Cost Estimate

A conceptual design for a GEM hybrid calorimeter has been completed[10] (GEM TN-92-165, Draft Two). The proposed system is composed of a two vessel liquid krypton EM calorimeter (in a "cup" configuration), a fiber hadron calorimeter and a quartz fiber forward calorimeter. This system is shown in Figure P1-1050. The total cost of the proposed system is estimated to be $134 M.

This conceptual engineering study shows that the hybrid calorimeter is a reasonable option for GEM. Design solutions were developed to address several specific concerns, for example, cryogenic utilities routing and vacuum pumping. In some cases (e.g., the shape of the accordion plates) physics analysis and confirmation is required to complete the conceptual design. Remaining issues with the hybrid system are generic to the liquid krypton EM and quartz fiber calorimeters and not to the integration into a combined system.

An important new issue is the specification of a preradiator system. Although a preradiator is assumed in the concept, with space and feedthroughs provided, a real design is needed to fully understand the implications and the cost.

XI. Anticipated Cost Sharing by International Collaborations

The GEM hadronic calorimetry subsystem has been designed[11] from the outset to be manufacturable by international partners. Some 50% or more of the total U.S. estimated cost is expected to be born by twelve collaborating institutions. "Letters of Intent" and "Interlaboratory Collaborative Agreements" from physics institutes in Albania, Belarus, the Czech Republic, China, Ecuador, India, and Russia have been signed. (Copies appear in Ref. 11). Dual source commitments have been obtained for almost all detector elements.

The LOI's cover cost sharing for the design, construction, and data analysis at the home institutions, as well as assembly at the SSC. The Letters also pledge to supply copper,

tungsten, quartz and plastic fibers, phototubes, electronics and a test beam line. These agreements pertain directly to the scintillating fiber hadron calorimeter, including barrel, end cap and forward segments. To date, bilateral scientific exchanges have occurred between collaborators in each of these countries and the GEM Hadronic Subgroup (except for the Czech inspection trip, scheduled for this fall.

Belarus is currently preparing a $7 \times 7 \times 7\,\mathrm{cm}^3$ prototype EM quartz/tungsten calorimeter. Albania is rolling and milling prototype plates for the copper barrel $\eta = 3$ tower. The Czech Republic is launching an R& D effort to mate the green extended photocathode developed by their Phillips partner with a mesh dynode amplifier similar to that produced by Hamamatsu. Russia is preparing plastic fibers to test here this fall. Belarus is producing 8 prototype ASK/ASL board with the prototype GEM electronics. All of these prototype projects are scheduled for completion by January 1993.

XII. Speed and ADC Gate-Width.

The SPACAL Collaboration has studied the effect of the ADC gate width[12] upon energy resolution, e/h, and other factors, using beamtest results obtained with a prototype hadron calorimeter. It is found that the energy resolution and e/h are negligibly affected for ADC gate lengths as short as 32 ns.

XIII. Electron-Pion Discrimination.

The SPACAL Collaboration has studied electron-pion discrimination[13] using beamtest results obtained with a prototype hadron calorimeter. Despite the fact that the calorimeter has no longitudinal segmentation, rejection factors of several thousand were easily obtained for isolated electron candidates. Several tools are described in Ref. 13, not all of which are necessary to obtain the stated hadron rejection. In GEM the situation will be even better because there are at least three longitudinal segments: two in the electromagnetic and at least one in the hadronic calorimeter.

XIV. Measuring Lateral Position of Hadronic Showers.

The SPACAL Collaboration has studied[14] with what precision the lateral position of an incident particle can be measured, using beamtest results obtained with a prototype hadron calorimeter. The tower size was 85 mm, not at all optimum for good position resolution. The measured position resolution for single incident pions can be described by $\sigma = 2.4 + 31.4/\sqrt{E}$ mm for single incident pions. The precision depends very much upon shower energy sharing between neighbouring calorimeter towers. Smaller towers would improve the position resolution if required for the forward calorimeter for example. For the same reason, the centroid of jets may be expected to be measured much more precisely than single incident pions for the same tower size.

XV. Conclusions.

In conclusion, all open issues relative to the fiber hadron calorimeter for the GEM Hybrid Calorimeter have been addressed satisfactorily. The subgroup team is scientifically and technologically ready to proceed to the preparation of a Technical Design Report.

REFERENCES

1. "On Radiation Damage and the Hadronic Calorimeter Choice of GEM.", R. Wigmans, *GEM Technical Note* GEM-TN-92-189.

2. "Noise, Pile-up, Linearity, and Rate Capability of a Fiber Hadron Calorimeter.", H.P.Paar, *GEM Technical Note* GEM TN-92-196.

3. "Preliminary Beam Test Results for Copper/Scintillating Fiber GEM Hadron Calorimeter Prototype.", R. Kroeger and B. Worstell, *GEM Technical Note* GEM-TN-92- .

4. "Muon Energy Loss in the Hadron Calorimeter and Muon Momentum Resolution.", J. Branson, H.P. Paar, *GEM Technical Note* GEM TN-92-197.

5. "Scintillating Fiber Hadron Calorimetry: Calibration and Monitoring Plan.", J. Sullivan, C.C. Eberle, H. Paar, D. Winn et al., *GEM Technical Note* GEM-TN-92-186.

6. "Hadronic Calorimeter Photomultiplier Readout System Stability and Calibration.", N. Akchurin and Y. Onel, *GEM Technical Note* GEM-TN-92-184.

7. "The Design and Performance of Scintillator/Cerenkov Fiber Forward Calorimeter for GEM.", B. Webb, *GEM Technical Note* GEM-TN-92- ; "Re-Comparing Forward Calorimetry Technologies.", D.R. Winn, L.R. Sulak, H. Paar, B. Webb, and W. Worstell, *GEM Technical Note* GEM-TN-92-209.

8. "Simulation of the EM Response of a Quartz Fiber Calorimeter.", S.T. Dye, J. Miller, and L.R. Sulak, *GEM Technical Note* GEM-TN-92- .

9. "Jet-Energy Measurements with a Non-compensating Calorimeter System.", H.P. Paar and R. Wigmans, *GEM Technical Note* GEM-TN-92-67; "Compensation, Resolution, Linearity, and the GEM Hadron Calorimeter Decision.", R. Carey and W. Worstell, *GEM Technical Note* GEM-TN-92- .

10. "Manufacturing Engineering and Cost Estimate of a Krypton/Fiber Hybrid Calorimeter.", M. Rennich, *GEM Technical Note* GEM-TN-92-165.

11. "Status of Anticipated Cost Sharing by International Collaborators.", L.R. Sulak, *GEM Internal Note* GEM-IN-92-17, revised.

12. "The Performance of a Lead/Scintillating-Fiber Calorimeter at LHC/SSC Compatible Gate Widths.", D. Acosta *et al.*, Nuclear Instruments and MethodsA314, 431 (1992).

13. "Electron-Pion Discrimination with a Scintillating Fiber Calorimeter.", D. Acosta *et al.*, Nuclear Instruments and MethodsA302, 36 (1991).

14. "Localizing Particles Showering in a Spaghetti Calorimeter.", D. Acosta *et al.*, Nuclear Instruments and MethodsA305, 55 (1991).