Final Report
Grant DE-FG02-91ER41199
Between
U.S. Department of Energy, Division of Nuclear and High Energy Physics
and
Fairfield University

Title: G-2 and CMS Fast Optical Calorimetry

Overview

Task A: Quartz Fiber Forward Calorimeter for CMS/LHC at CERN (90%)
Task B: G-2 (10%)

This proposal was for Task A: the continuation of CMS/LHC Forward Quartz Fiber Calorimetry (US-CMS), and CMS calorimeter upgrades for SLHC operation (the staged high luminosity and higher energy options of LHC). Task B: Final analysis of BNL 821, G-2. These two tasks are unified by their concentration largely on electro-optic calorimetry, electro-optic readout, and optical calorimeter calibration systems, using similar basic technologies. In this way, we leverage the abilities of our small group to be effective.

Task B, the Fairfield part of G-2, was finished in early 2002 and the results are shown in the latest publications listed at the end of this report, and in previous reports, and consumed at most 10% of time and effort. We therefore report mainly on CMS operations and development.

Task A consumes most of our time efforts, and is the only formally funded task. Task A was for i) the installation, calibration and operation of the quartz fiber forward calorimeter in CMS and the start of operation, data taking and analysis of CMS, now in the final stages of construction, on which the Fairfield group has worked on since late 1993, and quartz Cerenkov fiber calorimetry since 1991; ii) R&D to enable the operation of CMS at SuperLHC (SLHC); that is, at luminosities ~10x greater (up to 10^{35}) and energies >50% greater than LHC. This Task is already partially funded by supplements from the CMS collaboration, last year by a $5k supplement, and currently by a $16k supplement, for developing quartz Cerenkov plates to replace the scintillator plates in the endcap (between the barrel and the forward-HE) calorimeter at least for the 1st 1-2 interaction lengths where the raddam is highest. Progress on this program will be presented. Other work, the result of which may be proposed before 2007, is to develop novel rad-hard quartz fibers, some for with a high N.A. using nanoporous alumina claddings, supplemental waveform electronics for the forward calorimeter at SLHC, and other enhancements to HF, to allow SLHC operations or enhanced LHC performance.

An important program goal for this DOE grant at Fairfield University is to engage undergraduates in experimental high energy physics research. Twenty-nine students worked on the program described herein since1992. 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. We have supported 6 experienced seniors for the summer after graduation. Some of the figures below show students engaged in HEP research.

GENERAL ABSTRACT:

The Fairfield University High Energy Group proposes to continue work on a large experiment, CMS at CERN (12,500 Tons, 15 m diameter, 22 m long, ~6 million bytes of data per collision, >40 million collisions/second), which uses the talents of over 2000 physicists, from more than 150 institutes worldwide.(see http://cmsinfo.cern.ch/Welcome.html/, which we have worked on since 1993. The CERN LHC particle accelerator, 23 km in circumference, creates counter rotating colliding beams of protons at high energy, bending them in circle using superconducting magnets. The CMS experiment detector surrounds the point where the protons collide, and uses layers of specialized particle detectors inside and outside of a large superconducting magnet, to provide a fairly complete suite of information about the collisions. Large amounts of energy are deposited in a small volume of space-time during the collisions. New matter in the form of energetic particles, up to thousands in each collision, are created, which the detector measures and analyzes. We expect that new properties of the forces of nature will be revealed by these data, which may help elucidate the orgin, evolution, and fate of the universe. Remarkably, it is possible that the so-called dark matter may be produced in these collisions, and that the data will also reveal if or how the forces of nature were unified in the very early universe, near the time of the Big Bang.

The particular section of the CMS experiment being made by the Fairfield University High Energy Group is called a calorimeter. A calorimeter measures the energy of a particle by absorbing in a large block of matter all of the particle energy, and in that process of absorption creating a signal proportional to the energy; in our case it is the amount of light generated in optical fibers finely interspersed in a metal matrix. This light is detected by sensitive photomultiplier tubes, which create an electrical pulse whose size is proportional to the energy of the particles hitting the calorimeter. Our part of the calorimeter, the whole of which entirely surrounds the vacuum pipe containing the proton beams, is the very closest to the beam pipe, and receives such a large dose of radiation, that it must be especially designed to survive the radiation, without degrading. We had to invent a new technique in order to achieve this. Our group works with physicists in the USA from Boston University, University of Iowa, Iowa State, Texas Tech, and Fermilab, and internationally mainly from Hungary, Iran, Russia, and Turkey.

Project Description

Introduction:

The physics motivations for the highest possible mass scales are compelling. The object of forward calorimetry for the LHC is well-known, mainly for forward jet tags, and for measuring or signaling missing transverse energy. Physics examples where a forward calorimeter section ($3<\eta<5$) is crucial for the discovery or studies include:

(a) Heavy Higgs Searches, through the WW, ZZ fusion production channel, qq → qq+(WW or ZZ) → qqH (M_{Higgs} searches as low as 130 GeV may be possible with this method) leads to forward tagging jets from the recoiling quarks, and Higgs decays with missing energy ($\tau\tau$, bb, WW, ZZ, or $\gamma\gamma$). These tags are more essential at LHC energies, as contrasted with SSC, due to both pile-up and lower Higgs production. Moreover these "tagging" jets may be required in the trigger;

(b) WW/ZZ/WZ Scattering, crucial if there is no Higgs, greatly enhanced by forward jet tagging;

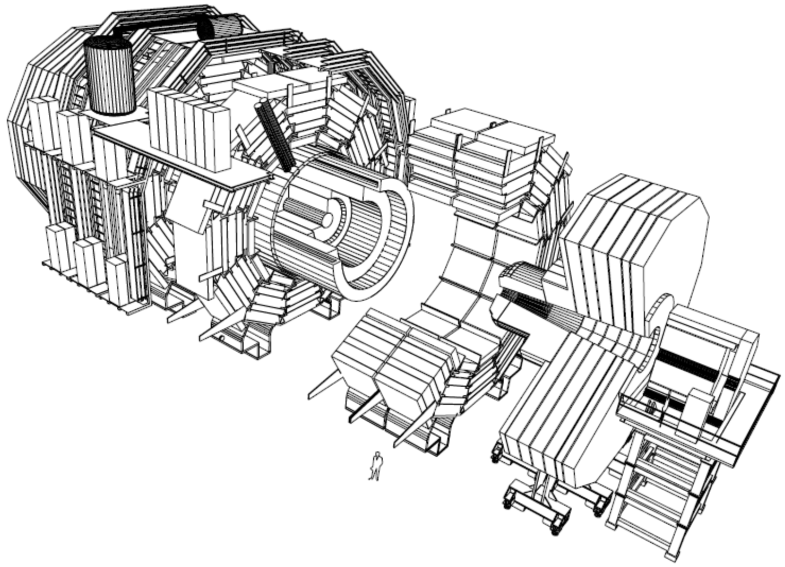
(c) SUSY LSP Searches (missing energy). Missing transverse energy from the escape of the LSP is the least model-dependent signal of supersymmetry (cascade decays from squark and gluino pair production). Missing energy is the most likely to be a robust signal at LHC for new physics, compared with any other signals, in general. A hermetic calorimeter into the forward region is essential to measure m_{LSP} below 100 GeV and gluino masses within 10%.

(d) In slepton or chargino/neutralino searchs, vetoing jets (veto tag) at larger rapidities (up to 5), as in $H \rightarrow WW \rightarrow l\nu l\nu$ are essential to suppress much larger squark and gluino production.

(e) If m_H ~170 GeV – a forward jet veto is needed to suppress ttbar production and $E_T$miss

(f) SUSY Higgs h,H,A → $\tau\tau$, bb, or $\gamma\gamma$ require missing transverse energy cuts as low as 20 GeV and rapidity coverage to 4.5. Forward energy containment is essential.

(g) Heavy Higgs Decays. For example gluon fusion production of the heavy Higgs, the largest cross-section as in $pp \rightarrow gg \rightarrow H \rightarrow WW \rightarrow l\nu jj$ require hermetic coverage and jet definition, past η of 4.5.



The CMS Detector – One of the two Hadron Forward (HF) Calorimeter arms is shown on its stand at the extreme right. Note the standard human for scale.

However, exposures above 1 gigaRad/year may be necessary for a calorimeter to survive in the

η=5 region. Furthermore, the particle areal density below 5° is such that realistic calorimeter cells (i.e. 5-15 m from the interaction region) 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.

Fairfield is participating on the CMS (US-CMS) Collaboration (Compact Muon Solenoid) at the Large Hadron Collider (LHC) at CERN. Fairfield first proposed the use of parallel quartz fiber calorimeters for the region beyond η>3 in 1994 for CMS, because of rates and radiation dose, which exceed those predicted for the SSC. The radiation-hard forward calorimeter and high speed pulsed optical calibration equipment developed at Fairfield for both SSC and g-2 are even more necessary for LHC experiments, and have been successfully transferred to LHC collaborations.

The drawback of normal scintillating 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.

Spaghetti calorimetry has demonstrated compensation characteristics, speed, very high uniformity and hermeticity, and good energy resolution (SPACAL, G-2, DAPHNE). 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 LHC. This is the motivation for the quartz fibers. Fairfield University has been at the forefront of showing that quartz fibers in the classic spaghetti geometry provide such calorimetry for the SSC and now at CMS/LHC in the Forward Region.

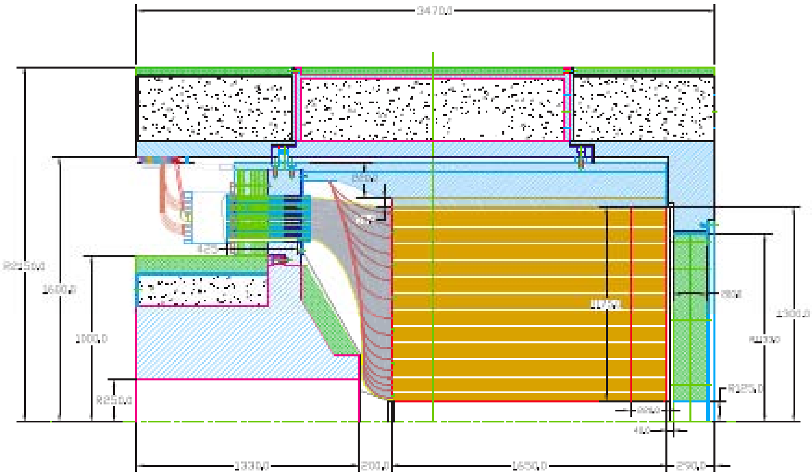


Figure 1: The cross section view of the HF calorimeter shows that the sensitive area extends from 125 to 1300 mm in the radial direction. The absorber in the beam direction measures 1650 mm. Bundled fibers (shaded area) are routed from the back of the calorimeter to air-core light guides which penetrate through a steel-lead-polyethlene shielding matrix. Light is detected by PMTs housed in the readout boxes. Stainless steel radioactive source tubes (red lines) are installed for each tower and are accessible from outside the detector for source calibration. All dimensions are in mm.

Fairfield Parallel Quartz Fiber Forward Hadron Calorimeter Chronology

1991-1993: Fairfield proposed the first SSC/GEM quartz fiber calorimeter using fibers oriented at 0°, based on MC studies of e-m shower electrons (based on pioneering work of P.Gorodetzky using quartz fibers oriented at 45°). The 1st beam tests of any 0°, parallel quartz fiber Cerenkov calorimeter were at BNL: Pb absorber e-m module, 6.8% packing fraction,1 mm fibers, 25 radiation lengths, 12 x 12 cm face, constructed at Fairfield. The next year, the first beam test of a 700 kg Cu absorber 0° Cerenkov fiber orientation hadron module, constructed by Fairfield University was completed. All test beam operations were conducted by Fairfield University. Our group consists of the PI, mechanical engineer, computer tech, and 3-6 undergraduate RA.

Fairfield Students (L) stuffing the very first HF Cerenkov Hadron Calorimeter Prototype 700 kg Cu, delivered to BNL and CERN, and (M) with first HF Cerenkov EM module prototype. (R) Fairfield prototypes in test beam.

1994: The PI with Prof. Y.Onel (Iowa) presented a proposal to CMS for a very forward quartz fiber calorimeter & joined CMS. Fairfield rebuilt the 1993 hadron module, and delivered it to CERN. The first tests Fairfield/Iowa US-CMS module at CERN were conducted at high energy, with a collaboration of Fairfield, Iowa, and BU. On the basis of beam tests, the quartz fiber concept was approved by CMS as a possible replacement for the baseline PPC (parallel plate chamber) gas calorimeters for the forward region. The US-CMS collaboration for quartz fiber very forward calorimeters was then joined by Texas Tech and Iowa State. Several Russian Institutes lead by ITEP joined the parallel QF collaboration (later Turkey, Hungary and Iran).

1995-7*:* With CERN & DOE support, design and construction of a new 1,000 kg Cu absorber quartz fiber prototype CERN (~ 31 x 31 x 150 cm – 3x3 towers) commenced, with beam tests at

CERN. The design and specification of the prototype was a collaboration mainly between BU Iowa, and Fairfield. A technical shoot-out with the competing PPC (parallel plate chamber calorimeter) group resulted in the adoption of the parallel quartz fiber technology for the very forward calorimeter of CMS at LHC.

-During FY96-1997, Fairfield first showed that an external Co source would cause counts in a bench test of an early e-m prototype at Fairfield, enabling a radiosource calibration strategy.

- A detailed report was generated (CERN CMS TN/95-207 technical note). The preparation of the HCAL TDR also represented a significant effort by Fairfield. [CMS The Hadron Calorimeter Technical Design Report", M. Della-Negra et al., CERN/LHCC 97-31, CMS TDR 2 (20 June, 1997) This ~530 page TDR is available at ftp://uscms.fnal.gov in directory .pub/hcal_tdr/] Fairfield contributed to the main text and figures for HF on: (i) the PMT, (ii) the Optics, (iii) PMT HV, (iv) integration and installation.

1998-2002*: - Prototypes*: A series of preproduction prototypes (PPP) were designed, constructed and tested at CERN to verify the design and performance, in particular the longitudinal segmentation scheme using fibers pulled back from the front by about 1 interaction length to sample mainly the hadron interactions, to be used with full length fibers to obtain a crude separation between e-m and hadronic components of a jet and correct the energy. Fairfield participated in the design of the calorimeter and introduced novel light collector/air light guide which improves the light yield by nearly a factor of 2. CMS technical Notes were prepared and submitted for publication.

– *HV and Base:* Fairfield invented a novel base system which used individual power supplies on ganged dynodes to provide high rate capability, which was adopted for by the collaboration.

- *PMT Specs and Down-select:* Fairfield was largely responsible for the PMT downselect, and we tested 9 different prototypes. Lower gain was utilized to match the low input noise afforded by the readout electronics and to increase the lifetime of the PMT (total charge drawn from the anode). The basic HF phototube properties are determined by requirements of: a) dynamic range; b) area of fiber bundles; c) average and peak currents; d) tube lifetime; f) counting rates; g) gain sufficent for 1 p.e. as a least count separated from pedestal in the readout; h) operation of HF in a hundred Gauss of magnetic field at most.

- *Radiosource Calibration*: In FY 1998, we collaborated on the design and tests of using both Co60 and Cs137 source wires to calibrate the HF quartz fiber calorimeter. These source wires were developed by V.Barnes et al., Purdue for calibrating scintillating plate hadron calorimeters used on the CDF experiment and for the CMS barrel calorimeter. For adaptation to fiber calorimeters, we developed a small test calorimeter with extra grooves in the copper plates parallel to the fibers to accept the standard source wires developed by the Purdue group. During FY1998-00, we achieved count rates of ~1-10 KHz on 1 p.e. using 10 mCi Cs sources and a precision integrator. This result shows that we will be able to fully calibrate and measure radiation damage longitudinal profiles in the forward calorimeter during off conditions, especially if higher source intensities are possible. Longitudinal scans in 1998-9 of the PPP module showed the radiosource data in the full length (em) fibers, the hadron fibers (pulled back 20 Xo from the front) and the TC or tail-catcher fibers, only in the last interaction length (to check for late showers). The count-rates are sufficient to calibrate the calorimeter in less than 1 hour to the level sufficient for good forward physics.

-*PMT Radiation Damage Tests* The HF PMTs are sufficiently shielded by the HF itself, the HF shielding, and by the bulk of CMS that radiation damage will be minimal. The HF PMT are located at over 1 m in radius, from the beam pipe and over 14 m from the IP, and are enclosed in a robust shield to absorb neutrons. During 1998 tests, we observed low levels of induced phosphorescence in the window using UV-glass from Hamamatsu, but with neutrons. The high purity synthetic quartz version did not have this effect - we supplied the new candidate PMT for this work. The candidate tubes (see below) operate at up to 10^{14} n/cm^2 with little effect on gain, far exceeding the limits of the experiment. The PMT prototype window glasses have exhibited a radiation resistance with Co60 well-sufficient for operation in HF up to and exceeding 10 years of operation.

FY2002-2005:

- **FY2002-4 Test Beam Operations** During FY2002-4 we participated in test beam runs at CERN on the preproduction prototypes during June-September, supplying equipment and/or manpower to these tests. During these tests, we proved that the preproduction prototype PMT the Hamamatsu R6347 has sufficient capability to meet all requirements for the forward calorimeter, but that the variant first obtained by Fairfield in 2001, the R7525, with 8 instead of 10 stages, would be better than the R6347 in terms of lifetime(see plots) because of a) lower gain (x10) at optimal operating conditions (timing, linearity) as enabled by the low noise high sensitivity electronic DAQ developed by Fermilab, and b) the transit time is less, important for linear operation above 40 MHz (25 ns beam crossing + background pulses).Most recently, during FY2003-4, a Fairfield research assistant was resident at CERN for 8 weeks in the summers, and the PI attended 3 weeks each of test beam. During 2004, a full production version of 2 modules was fully tested. A series of test beam results in 2002 tested the preproduction prototypes for the final assembly. In 2003, the first 2 modules, fully complete as will be installed in the experiment, were mounted at CERN in summer 2003, and were tested in the test beam.
- **FY2002-3 HF PMT Selection, Procurement, and Testing:** In FY2002-3, the Fairfield Group in close collaboration with the U.Iowa group continued responsibility for the HF PMT selection, testing, and procurement, and inc luded sample tests of rate capability,quantum efficieny and lifetime on the bench at Fairfield, and radiation-induced background tests with sources and at the test beams. We note that the Fairfield Group was not funded by CMS for major construction projects since our group consists of a single PI, undergraduate students, and a fraction of an engineer with no graduate students nor post-docs. Nevertheless, we are considered part of the PMT acquisition and test effort, and have maintained this effort in close collaboration with U. Iowa, having helped design and build the test stand at Iowa, and built entirely the test stand at Fairfield.
- **FY2004-5: R&D/Prototyping for SLHC Upgrade to higher luminosity and higher beam energy**

During FY2004, Fairfield began to participate in planned upgrades for the hadron calorimeters to reach luminosities of 10^{35} and 14 TeV/beam. We have been funded by US-CMS to provide this summer at CERN tests for a possible upgrade for the endcap calorimeter, replacing the non-rad-hard plastic scintillator tiles, grooved for readout by fixed WLS plastic fibers, to rad-hard quartz Cerenkov plates, read out by either liquid WLS-filled quartz capillary tubes (about 1mm diameter, 50 micron thick walls), or by continuously replaced looped WLS plastic fibers, or by possible rad-hard inorganic fibers (ZnO or other). During FY2004, we are producing a proof of concept package for the CERN test beam, consisting of UV-transmitting clear plastic 20x20x0.6 cm tiles, with a serpentine ~1mm groove capable of moving a WLS fiber smoothly through the tile. These were delivered to CERN by Fairfield/Iowa in July-August, 2004. The estimates are that 0.5 p.e. per mip per plate is detected.

Major contributions by Fairfield to the design and construction of the current modules as being

installed in CMS today which are adopted for the CMS forward calorimeter or prototypes were:
(i) Fibers: Specification of ultra fine quartz fibers (300 μ core) both for flexible fiber bundle bending to be able to avoid readout-induced backgrounds (see below), and to have very fine sampling despite a low volume packing fraction. The smallest fibers used heretofore for large spaghetti geometry hadron calorimeters was 1 mm.
(ii) No-Component Base – extension cord PMT power. We designed and constructed the first "extension-cord" bases, where the base itself is removed from the PMT by an extension cord bundle consisting of wires for the dynode and cathode HV and the signal coax. This bundle connects a remote base outside of the HF shielding with a simple passive socket at the PMT inside the shielding, greatly reducing the necessity to open the shield to replace blown bases. In other words, there are no active nor passive components inside the radiation shielding to fail, except for the PMT pins and socket.
(iii) Air-Light Guides and Shielding: Recognition that air light guides were essential to avoid backgrounds induced in fiber bundles from beam-associated particles. We developed the concept of high aspect ratio penetration of shielding. Radiation calculations indicate that the HF PMT should receive a radiation dose of about 1 krad/year, with about 10^{10} n /cm^2/year. We developed air light guides using aluminized films for low background readout, including Winston cones, and novel high reflectivity materials. These guides are essential to avoid radiation leakage induced backgrounds in the optical package which would overwhelm the weak Cerenkov signal from the calorimeter itself. Fairfield supplied the hexagonal and ~1 m long air light guides and the conical concentrators matching 8 mm PMT photocathodes to 30 mm diameter bundles. Introduction of a novel new reflector material for the air light guides.
(iv) Readout Optics Design: Development of a readout system where the fiber bundles emerging from the calorimeter are immediately bent 90° and oriented mainly perpendicular to the beam direction to minimize Cerenkov light induced in and captured in the readout fibers bundles. (Note: Cerenkov light is best captured for charged particles traversing the fibers at ~ 45° to the fiber axis, i.e. ~ Cerenkov angle - but because the cladding has $n>1$, no Cerenkov light is captured for particles traversing the fibers at 90° to the axis.) The fiber bundles terminate in PMT when they are well away from the calorimeter. This design thus removes the PMT from the highest punch-through region, where traversing particle will also add spurious photoelectrons to the calorimeter signal. Based on beam tests, this design is now accepted as the baseline design for CMS. Fairfield was responsible for major parts of the design of the optical package for the Quartz Fiber Hadron Forward (QF-HF) Calorimeter collaboration.
(v) Radiation-Induced Background in PMT: Radiation induced background tests of PMT's. Tests with the PMT at BNL and CERN in hadron beams and with radioactive sources indicated a low level of pulses induced by traversing beam particles provided the window was thin (<1-2 mm). Fairfield also spec'ed and tested the first quartz window PMT with low phosphorescence from neutron induced changes in borosilicate glass. The HF PMT should receive a radiation dose of about 1 krad/year, with about 10^{10} n /cm^2/year.
(vi) Calibration: That gamma sources could be used to calibrate a based on single p.e. counting, or current integrating. We demonstrated this at Fairfield in 1996-7 with the first e-m prototype, achieving a 20 Hz counting rate with a tiny 10 microCi Cobalt source. This became the basis for a wire calibration system similar to that employed by the CDF collaboration at FNAL (V.Barnes, Purdue).
(vii) Individually powered ganged dynode ganged rate high linearity HV PMT system: We constructed the first system to power PMT by ganging tubes to the same HV power supplies on

each dynode. This proved to operate at high linearity and with high rate capability at low cost. *(viii) PMT Issues*: Fairfield took major responsibility for specifying and testing PMT optimized for HF. We recognized that beyond linearity, the critical spec for many calorimeters, PMT lifetime, hysteresis, and rate capability was a significant issue for the forward calorimeter, and prepared detailed specs and tests. In particular, we first demonstrated a stable gain for a forward calorimeter PMT operating at 50 MHz, showed that the gain-lifetime was sufficient for 5 year operation even at the highest eta, and also found that transit times as short as possible maintained good hysteretic properties. Fairfield tested 9 PMT for possible use in HF, before specifying a custom PMT from Hamamatsu with a thin quartz window, 8 stages, and a transit time < 12 ns (beam crossing =25 ns).

- ***Quartz Fiber Forward Calorimeter Prototype Beam Test and Analysis Results***

Quartz Fiber Calorimeter Test Beam Data Analysis Summary (typical results in Figs below):

a) The best electromagnetic energy resolution using a quartz window PMT is ~200%/ $\sqrt{E}$ with 9% constant term.

b) The best light yield is 0.87 photoelectrons/GeV for electromagnetic showers in the case of a quartz window PMT. For hadronic showers, the light yield depends on the energy. For example, 100 GeV pions give on the average 52 photoelectrons. For 1 TeV, the extrapolated data suggest that the average signal will be 610 photoelectrons.

c) The hadronic energy resolution stochastic term is ~280%. The total constant term from statistics and systematics is ~11% at 1 TeV.

d) The calorimeter response was found to be dependent on the impact position of the incident particles due to the coarseness of the packing fraction, and leads to a constant term in the energy resolution ~1%.

e) The expected jet energy resolution based on electron, pion and jet trigger data is ~35% at 1TeV

Forward Calorimeter HF Absorber, Assembly, Performance Status

Absorber production

Grooved Iron Plate Absorbers produced in Snezensk (Russia).

All wedges produced, and delivered at CERN

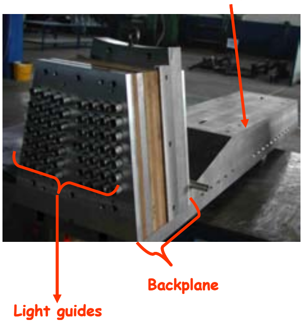
Built out of 'bricks', made of 5mm Fe plates with fiber grooves every 5 mm Assembled by diffusion welding.

Bricks are machined and kept together by welded steel straps

Geometry OK (well within tolerances) checked by templates and verified by metrology at CERN on a sample of wedges.

Strongback and backplane production

- Contract signed with Turkish firm in December 2001.
- First 9 strongbacks and 6 backplanes delivered: geometry verified by mounting the first 9 wedges on a jig simulating the geometry of final shield.
- Delivery was completed
- January 2003

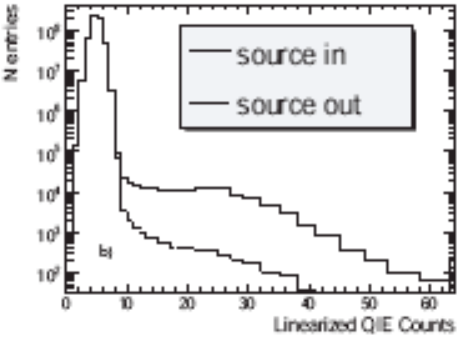


Fully stuffed wedge modules – now complete awaiting installation

Test beam

- Two wedges assembly (H2 Test beam, CERN)

Test Beam modules CERN during 2003 and 2004



Source Calibration, Cross-Calibrated with Beam Tests

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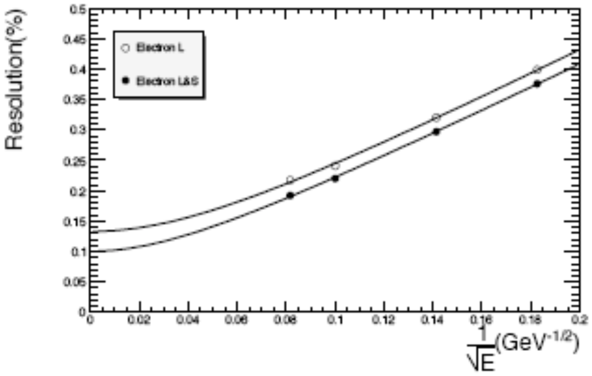
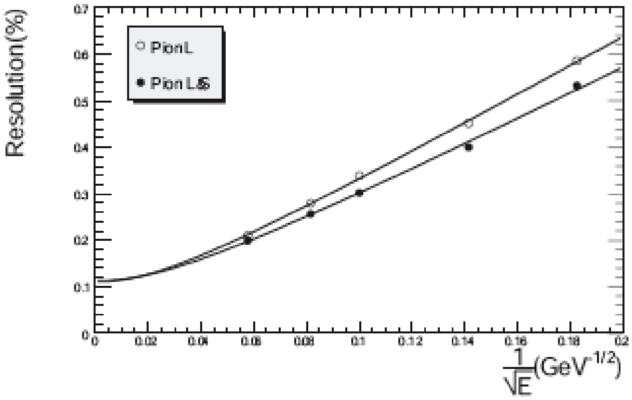
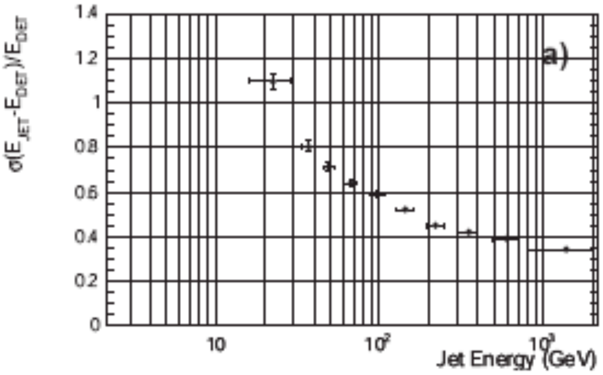


Electron resolution



Hadron Resolution



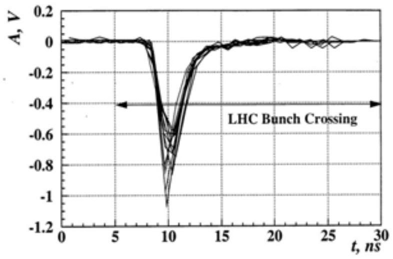
Expected Jet-Energy Resolution
the calorimeter.

10ns.

Experimental Photodetector Selection Data Lead by Fairfield
HF Group
Hadron Shower Signal Fully Developed in <10 ns

R6427

350 GeV Pion Signal



Note the remarkable speed of

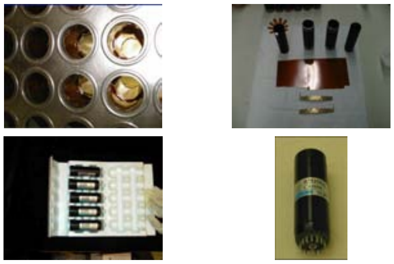
The full signal develops in <

PMT prototypes and tests

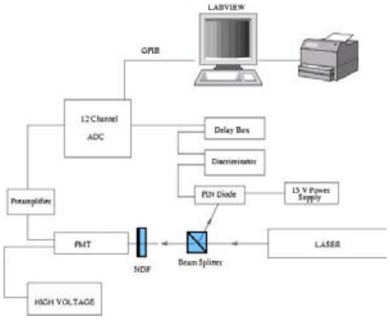
Tasks of the Test System
(Fairfield Designed Specifications)

- **For one tube in every batch:**
  - Double-pulse linearity,
  - Gain vs HV for each batch
  - Single photoelectron spectrum
  - X-Y scan (spatial uniformity)
  - Lifetime
- **For each tube:**
  - Pulse width
  - Pulse rise time
  - Transit time
  - Transit time spread
  - Anode dark current
  - Relative gain coupled with cathode sensitivity,
  - Pulse linearity
  - Quality control decision on each tube.

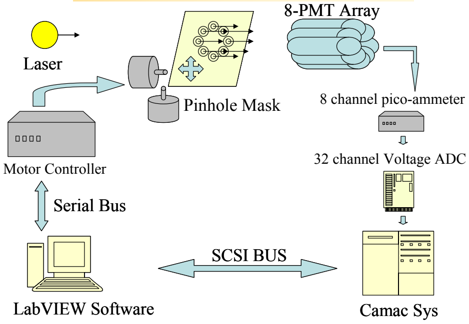
PMT's



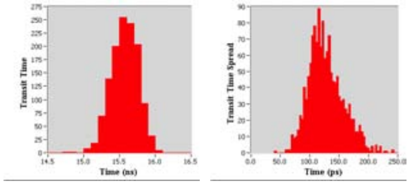
Single Photoelectron Setup
(fourth generation)



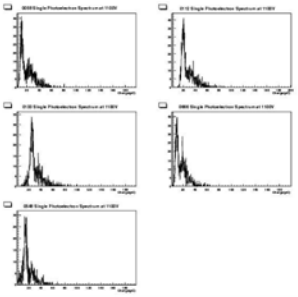
XY Uniformity, Dark Current, Relative Gain



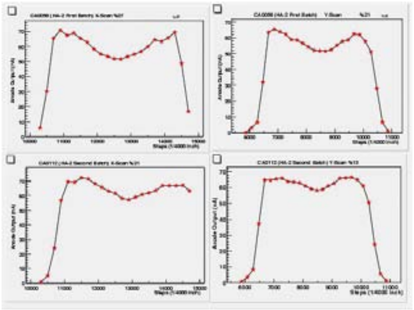
PMT Timing Data (2000 PMT's)
Transit Time, Transit Time Spread

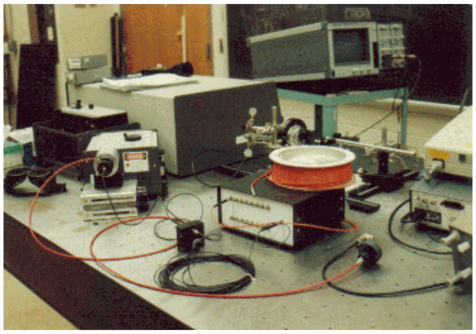


Single Photoelectron Spectrum at 1100V



XY Uniformity





Fairfield Optical Pulse System (1-16 pulses, 0.6 ns PW, 1-200 ns pulse interval) UV-Vis-IR

• FY2004-5: R&D/Prototyping for SLHC Upgrade to higher luminosity and higher beam energy

During FY2004, Fairfield began to participate in planned upgrades for the hadron calorimeters to reach luminosities of 10^{35} and >10 TeV/beam. We have been funded by US-CMS to provide at CERN and FNAL tests for a possible upgrade for the endcap calorimeter, replacing the non-rad-hard plastic scintillator tiles, grooved for readout by fixed WLS plastic fibers, to rad-hard quartz Cerenkov plates, read out by either liquid WLS-filled quartz capillary tubes (about 1mm diameter, 50 micron thick walls), or by continuously replaced looped WLS plastic fibers, or by possible rad-hard inorganic fibers (ZnO or other). During FY2004, we produced a proof of concept package for the CERN test beam, consisting of UV-transmitting clear plastic 20x20x0.6 cm tiles, with a serpentine ~1mm groove capable of moving a WLS fiber smoothly through the tile. These were delivered to CERN by Fairfield/Iowa in July-August, 2004. A mechanism to repeatedly pull out a replaceable fiber, replace it, and optically terminate it to the readout it out is still under development, with several possible opto-mechanical solutions under discussion. The estimates are that 0.5 p.e. per mip per plate is detected. We have proposed other upgrades for both the endcap (HE) and the HF-forward quartz fiber calorimeter, as described below, which will be the subject for FY2006-9, described in Task B, following.

Publications Summary:

The results of G-2, and the development of quartz fiber calorimetry with the fibers oriented at 0° by the Fairfield group from 1994 to the present is documented below. Server sites (ftp or WWW) where the above documents can be retrieved are available upon reasonable request (winn@mail.fairfield.edu).

TASK B: Muon G-2

• Electromagnetic calorimeters for the BNL muon (g-2) experiment.
S.A. Sedykh *et al.* 2000. Nucl.Instrum.Meth.A455:346-360, 2000. Cited 33 times

•**"The Brookhaven Muon Storage Ring",** G.T.Danby et al. Nucl.Instrum.Meth.A457:151-174 (2001) *Cited 21 Times*

• Improved measurement of the positive muon anomalous magnetic moment. By Muon (g-2) Collaboration (H.N. Brown *et al.*).. Phys.Rev.D62:091101, 2000. TOPCITE = 100+ Cited 103 times

• PRECISE MEASUREMENT OF THE POSITIVE MUON ANOMALOUS MAGNETIC MOMENT. Muon g-2 Collaboration (H.N. Brown *et al.*) Phys.Rev.Lett.86:2227-2231 (2001) *Cited 530 times*

TASK A: CMS and Cherenkov Fiber Publications from DOE Support

- K.Arrington et al., Cerenkov Fiber Sampling Calorimeters, IEEE Trans.Nuc.Sci.,V.41, 840 (1994)
- K.Arrington et al., 1994 CERN Test beam Results of a 0° Fiber Cerenkov Calorimeter, CMS TN/94-327, December, 1994.
- CMS Technical Proposal. Sections on the quartz fiber VFCal (Very Forward Calorimeter), Report CERN 94-38 (1994)
- S. Doulas et al., Preliminary Results from a Fine Sampling Quartz Fiber Calorimeter Beam Test Analysis. CERN

Technical Note CMS TN/95-144. Dec. 1995.
- "The HV Decision for CMS: Requirements and Technical Performance of the Quartz Fiber Calorimeter", The CMS HV-QF Collaboration, CERN CMS TN/95-207 technical note
- "Beam Test Results from a Fine-Sampling Calorimeter for Electron, Photon, and Hadron Detection", with N.Akchurin et al., NIM A399, 202 (1997)
- "Test Beam of a Quartz Fibre Calorimeter Prototype with a Passive Front Section", N.Akchurin et al., NIM A400, 267 (1997) CERN Pub. - CMS Note/97-041 (2 June 1997)
- "On the Differences between High-Energy Proton and Pion Showers and their Signals in a Non-Compensating Calorimeter", with N.Akchurin et al., NIM A408, 380 (1998) and CMS Note
- "Test beam results of CMS quartz fiber calorimeter prototype and simulation of response to high energy hadron jets", N. Akchurin et al. NIM A409, 593 (1998)
- CMS HCAL Technical Design Report, Submitted to CERN LHCC Committee, summer 1997. CERN/LHCC 97-31 This 800 page TDR can be viewed as uncompressed .ps or .doc (MS Word) files at: www.uscms.fnal.gov, in directory /pub/hcal_tdr.
- "Test Beam of a Quartz Fibre Calorimeter Prototype with a Passive Front Section", N.Akchurin et al., NIM A400, 267 (1997) CERN Pub. - CMS Note/97-041 (2 June 1997) Submitted to NIM.
- "Beam Test Results from a Fine-Sampling Calorimeter for Electron, Photon, and Hadron Detection", with N.Akchurin et al., NIM A399, 202 (1997)
- "Test beam results of CMS quartz fiber calorimeter prototype and simulation of response to high energy hadron jets", N. Akchurin et al. NIM A409, 593 (1998)
- "On the differences between high-energy proton and pion showers and their signals in a non-compensating calorimeter", N.Akchurin et al., NIM A408, 380 (1998)
- "Results from the Beam Test of the CMS Forward Quartz Fiber Calorimeter Pre-Production Prototype PPP-1", A.S.Ayan et al., CMS Note 2002/021
- "Beam Test results of a Longitudinally Segmented Quartz Fiber Prototype with High Energy Electrons and Pions", N.Akchurin et al., CMS-Note 2002/017 (in prep. to be submitted to NIM 2006)
- "Radiation Effect Studies on High Efficiency Mirror (HEM) and Aluminized Mylar for the HF Optical Design, P.Bruecken et al. CMS Note 2002/031 (2002) (still in preparation for publication)
- "CMS-HF PMT Test and Quality Control System", U.Akgun et al., CMS-Internal Report (2003)
- "Comparison of PMT's from three different manufacturers for the CMS-HF Forward Calorimeter", U.Akgun et al. IEEE Trans.Nuclear Science 51:1909-15 (2004)
- "Selection and Testing of 2000 Photomultiplier Tubes for the CMS-HF Forward Calorimeter" E. Gulmez et al., IMTC 2004 Instrumentation and Measurement Technology, IEEE Trans. Instr. & Measurement, (2004)
- "Energy Resolution and Linearity of the CMS Forward Quartz Fibre Calorimeter Pre-Production Prototype (PPP-1) A.S.Ayan et al., J.Phys.G: Nuclear and Particle Physics, N33-N44 (2004)
- "On the After-Pulses of the R7525", U.Akgun et al., April 2005, submitted to CMS Technical Notes, in preparation fos submission to NIM. 2006
- "Design, Performance, and Calibration of CMS Forward Calorimeter Wedges", 41 pages, HCAL COLLABORATION, CMS IN-2005/000 CMS Internal Note, in prep. for submission to NIM 2006

Selected Recent Publications Also Resulting From DOE Support

- "Muon Colliders", R.B. Palmer *et al.*. BNL-62740, SLAC-PUB-7119, LBL-38308, CAP-140-MUON-96C, Oct 1995. 28pp. AIP Conf.Proc.372:3-30 (1996) Also in ICFA Beam Dynamics 1995:0003-30 (QCD183:A32:1995) *Cited 29 times*
- "Muon Collider Design" with R.Palmer et al., Proc. 3rd Workshop on Physics Potential and Development of Muon-Muon Collidrs, San Fransisco CA Dec. (1995). Also in Mu+ Mu- Colliders 1995:61-84 (QCD183:I595:1995) e-Print Archive: acc-phys/9604001 Nucl.Phys.Proc.Suppl.51A:61-84 (1996) *Cited 58 times*
- "An e+e- Top Factory in a 50 + 50 TeV Hadron Collider Tunnel", J. Norem, J. Jagger, S. Sharma (Argonne), E. Keil (CERN), G.W. Foster, E. Malamud (Fermilab), E. Chojnacki (Cornell), D. Winn (Fairfield U.),. ANL-HEP-CP-99-44, 1999., 17th IEEE Particle Accelerator Conference (PAC 97)
Published in Vancouver 1997, Particle Accelerator, vol. 1 363-368 (1997)
- "Status of Muon Collider Research and Development", C.Ankenbrandt et al., Physical Review Special Topics Accelerator Beams, (3 August 1999) BNL-65-623; Fermilab-PUB-98/179; LBNL-41935; e-Print Archive: physics/9901022 Physical Review Special Topics Accelerator Beams, (3 August 1999) *Cited 287 times*
- "Silicon Micromachined Microchannel Plates", C.P.Beetz et al., NIM-A, 442, p. 443-451 (2000)
- Silicon Microchannel Plates: Initial Results for Photon Counting Detectors, O.Siegmund et al., , X-Ray and Gamma-Ray Instrumentation for Astronomy XI, Kathryn A. Flanagan; Oswald H. Siegmund; Eds. Proc. SPIE Vol.

4140, p. 188-198 (2000)
- "Expression of Interest for R&D towards a Neutrino Factory Based on a Storage Ring and a Muon Collider", K.T.MacDonald, Ed. et al., (11/7/1999) Neutrino Factory and Muon Collider Collaboration (D. Ayres *et al.*). FERMILAB-PUB-99-389, (Nov 1999) 50pp. e-Print Archive: physics/9911009 *Cited 75 times*
- "Electromagnetic Calorimeters for the BNL Muon (g-2) Experiment", S.A.Sedykh et al., Nucl.Instrum.Meth.A455:346-360 (2000)
- STATUS OF NEUTRINO FACTORY AND MUON COLLIDER RESEARCH AND DEVELOPMENT AND FUTURE PLANS. By Muon Collider/Neutrino Factory Collaboration (Mohammad M. Alsharoa *et al.*). FERMILAB-PUB-02-149-E, Submitted to PRSTA (Jul 2002). 103pp. e-Print Archive: hep-ex/0207031
- THE ROLE OF NANOSTRUCTURED MATERIALS ENABLING MINIATURIZATION OF PHOTOMULTIPLIERS, Charles Beetz, Robert Boerstler, Robert Wright, James Agresta, NanoSciences Corporation, and Christopher Sanzeni, David R. Winn, Fairfield University, Invited Talk, Proceedings of the Wire and Cable Conference, July 2002, IEEE Proceedings (Dec. 2002)- TESTING CPT AND LORENTZ INVARIANCE WITH THE ANOMALOUS SPIN PRECESSION OF THE MUON. M. Deile *et al.* hep-ex/0110044, Proceedings of 2nd Meeting on CPT and Lorentz Symmetry, 6pp (Jan 2002) U.Indiana, Bloomington *Cited 2 times*
- RECENT PROGRESS IN NEUTRINO FACTORY AND MUON COLLIDER RESEARCH WITHIN THE MUON COLLABORATION, 103 pp, Muon Collider/Neutrino Factory Collaboration (Mohammad M. Alsharoa *et al.*). Phys.Rev.ST Accel.Beams 6:081001 (2003) *Cited 77 times*

Report Conclusion:

Fairfield has made important contributions to the very forward calorimeters at LHC and requests support to continue the work largely initiated by our group. We have shared responsibilities for the optical package & photodetectors from the end of the fibers through the base & HV for the quartz fiber HF Calorimeter. Because the Cerenkov signal is low, only about 0.5 p.e. per GeV, the optics transporting the light to a photodetector, and the photodetector properties and operation are crucial elements to being able to measure the energy and position of forward jets accurately, without background signals being introduced by stray particles traversing the optics of the readout. The novel methods developed by us using air lightguides and 90° bends in the fiber bundles has solved this problem, but it is crucial for us to continue the tests at high energy and high rates with the rest of the calorimeter system in order to understand the signals during real data taking in 2007-8, and to complete installation and calibration, and to prepare for operations. The construction phase of the calorimeters up to the readout electronics will be complete by the end of calendar 2006, with installation largely complete. However, many small tasks remain (the infamous last 10%) in order for the device to function (including controls, alignment, calibration). Our group is developing a modest but successful program at Fairfield University, in close and productive collaboration with our colleagues on the CMS experiment/US-CMS, the hadron calorimeter Level 2 (HCAL) sub-group, and most particularly the quartz fiber (QF) forward hadron calorimeter (HF). The latter project was largely the invention of the Fairfield University Group at the start of the US-CMS collaboration with CERN in late 1993-early 1994. We remark on the highly unified nature of our proposal's Tasks, using similar electro-optic calorimeter and calibration techniques for very different experiments, which in these areas have similar technological demands; this confluence helps make our effort efficient, and is by design. We are continually encouraged by the very positive response of our undergraduate students to these developments, and request your continued support by your positive reponse to this funding document request. Fairfield University strongly supports this effort by agreeing to negotiate some cost sharing with DOE, as outlined at the end of the Budget Explanation pages.