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Re-Comparing Forward Calorimetry Technologies

D. R. Winn - Fairfield University
L. R. Sulak, W. Worstell - Boston University
H. P. Paar - University of California, San Diego

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Abstract:

We discuss forward calorimetry technology choices. We demonstrate that optical fiber technologies are capable systems for Forward Calorimetry, with many superior properties to alternatives. Furthermore, they are in advanced states of R&D compared with other techniques, with broad-based international support, with both hadron and e-m modules constructed and tested, as contrasted with Tubular LArgon.

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D.R. Winn, L.R. Sulak, H. Paar, R. Webb, W.Worstell
for the SSCintCAL Fiber Hadron Calorimeter Subgroup

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Introduction/Summary:

A recent note by J. Rutherfoord, Coordinator of the Forward Calorimetry group, entitled "Comparison of Contending GEM Forward Calorimeter Technology Choices" addressed design issues of two of the possible forward calorimetry technologies, liquid argon and quartz or liquid fibers. (Other options,such as high pressure drift tubes or SEM, were not discussed.) In this note we dispute with facts many of the (apparently) official conclusions of the Fcal group as represented by and described in that memo by the group leader (hereafter referred to as the Rutherfoord Forward Memo or RFM).The RFM is attached as APPENDIX I.

The RFM focussed on conceptual designs. Most of the critique of optical techniques centered on issues easily adjusted by engineering. Essentially none of the criticism is born out in demonstrated technical performance. Further, none of the criticism would affect the ability to do physics.

Of concern in that note is the absence of discussion of some technical and performance issues of the technology choice crucial to the physics success of forward calorimeter (Fcal), in particular

(1) Demonstrated radiation hardness in the configuration needed in Fcal

(2) The enhanced temporal requirements of Fcal in view of physically overlapping showers and boosted energies

(3) The effect of jets interacting beyond eta of 5 (jets between 5-9) which are even more demanding of the technology

In this paper, we first address the points in the RFM which concentrate on issues in common with all GEM forward technologies. We then review the conclusions of the memo. In terms of radiation damage, operation at 0.1 Mrad/hour, energy resolution, and speed, the tubular 100 micron gap LArgon is not proven. We then review the M.C. and test data for e-m and hadron prototypes of quartz and liquid scintillator, including the GEM prototypes. We emphasize the experimentally proven narrow transverse shower resolution, superb temporal performance and superior radiation hardness of the quartz fiber scheme, and the superior energy resolution and temporal performance of the Liquid Scintillator.

ANALYSIS OF POINTS IN THE COMPARISON MEMO

We address each of the contested points in RFM here.

-Z-Position:

With any of the technologies proposed so far, the z-position of FCAL for GEM is completely arbitrary at this time. No technology is differentiated by this requirement. Various 'point-designs' have provided consistency checks. They were limited by engineering time and money. The more plug-like point designs presented so far for the optical forward calorimeter (Fcal) designs at lower z than liquid argon (LArgon) were motivated mainly by neutron shielding considerations for the muon system. This shielding can of course be obtained by passive absorbers.

Indeed, the LArgon may need to be further away due to the dewar, especially if the beam pipe cannot be made cold. This is only a money, design and neutron shielding question. However, the dewar may have detrimental physics implications for jets with eta ¿5, as discussed below.

- Projectivity and Longitudinal Segmentation:

Optical fiber-type (liquid scintillator or quartz) calorimeters can be made fully projective with several different methods; the particular design choice is not essential at this moment. A fully projective Fcal does not need to be extensively segmented, even though it may be desirable. For example, a 'tail-catcher' could be implemented to tag late-starting showers. We have demonstrated this in the BNL test beam for the central calorimeter with a separate PM and 10% additional fiber at the rear of the device.

The exact level of segmentation does not need to be chosen at this moment. It is not limited by any of the technologies. The basic reasons for longitudinal segmentation in the Fcal are:

(a) for position resolution, since the narrow em core develops early on in the jet induced showers,

(b) to recognize late starting showers which are not fully contained. This leads to a fake Etmiss. However, this is a small effect - not the same as muon fakes - and can be achieved with a modest tail-catcher added to the main device.

(c) with a non-projective calorimeter it is essential to measure eta. (the transverse position fluctuates with shower-start fluctuations in a non-projective calorimeter)

SPACAL has measured position resolutions of order 17.1/sqrtE mm for single electrons and 31.4/sqrtE mm for single hadrons with an 85 mm diameter tower size (20% fiber). These numbers would be better for jets and much better with smaller tower sizes as foreseen for the FCal. Once the tower size is smaller then the lateral size of the jet core, the measurement precision is independent of the tower size. It is also unaffected by the presence or absence of longitudinal segmentation. It does not matter in a projective geometry that the larger hadronic lateral size is superposed upon the narrow electromagnetic core. The latter has approximately 50% of the energy of the jet.

The GEM Quartz Monte Carlo (Dye, Carey, Miller, Worstell) by the BU group has simulated a quartz spaghetti calorimeter. At 0 deg. to the beam direction, the collected Cerenkov photon weighted average (event by event) position of the showers is ~5 mm for 100 GeV pions. This is better than scintillator with a 9% packing fraction and no tower segmentation.

Projectivity for the optical Fcal detectors can be achieved by 2 methods:

(1) Parallel fibers can be inserted into a projective wedge of absorber, as in the barrel design. A bizarre comment in the RFM appears in the third paragraph, that the segmentation in a projective tower using this technique changes from the front to the back, which is simply incorrect. The tower absorber is designed to be a proper transverse segment from the front to the back. This method of arranging the fibers in parallel in an absorber segment is simply a convenient method to obtain a homogeneous mixture of absorber and scintillator fiber in the truncated pyramidal shape. As in a plate calorimeter, the plates get larger in area from the front to the back. One takes advantage of the variance of fiber positions to obtain extra information about the shower by separately recording the information from those fibers that penetrate fully to the front and those that terminate on the walls of the pyramid.

(2) Fibers can be fully projective from the front to the back, arranged along the incident particle

directions. The packing fraction decreases smoothly from the front to the back. Because of the Z position, the angle to the beam, and the required energy resolution compared with the barrel calorimeter, the decrease in packing fraction from the front to the back is not a problem. The packing fraction at the back decreases (depending on the Z position of the calorimeter and its total thickness) typically by a factor of 0.7-0.8. For z=5, a 20% front packing fraction would become ~15% pacing fraction in the back of the calorimeter. Sets of other fully projective fibers would be inserted from the back to various depths both to offset the the packing fraction decrease and to provide longitudinal segmentation. This is analogous to the extra fibers for longitudinal information in the back of the barrel calorimeter. For example, ~10% of the total fibers could be half length, and ~10% 1/4 length.

EFFECTS OF PROJECTIVITY/FIBER ORIENTATION RELATIVE TO THE BEAM DIRECTION ON THE QUARTZ SAMPLING CALORIMETER

Because of the directionality of the Cerenkov light and a critical angle less than the Cerenkov angle, concern has been raised about the operation of Cerenkov calorimeters with the fibers oriented at shallow angles (1-2 degrees) to the particle directions. The GEM calorimeter was operated at 9 deg. to the beam angle with a light yield of 5.3 p.e/GeV with a 6.8% packing fraction and 25% resolution on 10 GeV electrons.

The GEM simulation (S. Dye, R. Carey, J. Miller, W. Worstell) of quartz spaghetti shows that with a 9.4% packing fraction in tungsten, the resolution is the same parallel or perpendicular (0 deg or 90 deg) to the beam for 20 GeV electrons, with an RMS of 25% and 22 photons/GeV.There was only 33% more light perpendicular than parallel. The 1.6 mm fibers used ncore = 1.46 and ncladding = 1.41. Changing to Pb improved the resolution to 17%. The e-m block (18.5 cm cube) was increased to a 1.8 m cube. With 100 GeV pions in Pb, e/pi = 1.4. The resolution at 0 deg. was 30%, and at 15 deg was 18% with the same average pulse height on 100 GeV pions.

The SPACAL simulations for scintillating fiber tabulated particle directions crossing fibers in a shower. For about 1/2 of the electromagnetic energy deposition, the track direction is isotropic. We conclude that the effects of fiber orientation, while significant, do not prevent operation of the detectors with adequate performance for the forward calorimeters.

We further note in passing that methods are under investigation to further reduce these effects: (i) orient the fibers in a gentle wiggled pattern rather than completely straight; (ii) make a "1mm" fiber out of a helical 7 stranded [1 center+6 outer] braid of 250-300 micron fibers.

- Absorption Length/Density:

Any of the technologies will have an absorption length between 10.5-11.5 cm, whether projective, non-projective, or segmented, or both. A 20% packing fraction of quartz has an interaction length of 11.3 cm, and a 10% packing fraction, (the preferred fraction) has 10.5 cm. The liquid scintillator design currently has 11.3 cm. The LArgon has 10.5 cm. This difference is still of some importance, but whether a 7-8% difference is enough to base the technology choice on is open to question.

- Transverse Segmentation:

The transverse segmentation of the calorimeter is in principle arbitrary, up to the granularity of the sensitive elements (fibers or tubes of LArgon). Transverse segmentation is the sine qua non of the Fcal.

The tower size should be be chosen small enough so that JETS are spread out over several cells, in order to measure the transverse position and hence eta and Et with precision.

There are no essential technical or physics reason to prefer one technology over another at this time on the basis of possible transverse segmentation, with the following exceptions:

(1) Quartz calorimeters have an intrinsically narrower shower size sensitivity. The detected lateral shower extent in a quartz fiber calorimeter is smaller by a factor of ~2 or better. This has been MEASURED by Willis' group at CERN and by NA38 (Gorodetzky). It has been confirmed in Monte Carlo (MC) by the BU group (Dye, Miller, and Worstell, see Ref. 7) and by the group at CERN. Furthermore, an analysis of hadron shower data (SPACAL and Zeus data) shows that the e-m component of a hadron shower is much narrower than the full e-m + hadronic deposition. We emphasize again the GEM quartz MC results (described in the section above on longitudinal segmentation) show a factor of 2 improvement in the transverse position error compared to an ionization sampling fiber-like detector with similar segmentation and packing fraction.

The quartz is more sensitive to electrons. The narrower core response can be understood by observing that the quartz calorimeter is sensitive mainly to the e-m and high energy hadron component of a hadron shower and not to the neutron/gamma halo.

The RFM's unsupported assertion near the end (3rd from last paragraph) that a quartz calorimeter will not measure the high energy core of a shower is false by direct measurement and by MC calculations. The transverse tail of a shower consists of very low energy particles which do indeed cross fibers at large angles, but are mainly invisible. The halo of deposition is MeV neutrons and gammas. They seldom produce electrons above 0.7 MeV Cerenkov threshold, but do efficiently ionized. As is well-known, these neutrons contribute significantly to an ionization calorimeter. Indeed, the absence of this detected energy is why the energy resolution is poorer for a quartz calorimeter. But this trade-off is, in fact, the ideal tradeoff for a Fcal: narrower showers are traded for less energy resolution.

(2) Fibers in principle can be arranged to have a segmentation on the few cm scale when coupled with small or pixellated readout devices.

-Energy Resolution and Response:

The transverse energy resolution design goal as stated by the forward group is 10% or better sigma Et/Et, at Et = 100 GeV. This Et requirement translates into a calorimeter energy resolution better than 10% at E = (100 GeV Et) x (1/tan(theta)). At eta=3, 1/tan(theta) = 10; at eta = 4, 1/tan(theta) = 27.3. The calorimeter resolution must be better than 10% at 1 TeV (eta of 3) or 27% at eta of 4, etc. All of the technology choices presented so far have the capability of meeting or exceeding this requirement. Energy resolution is relatively unimportant for distinguishing the calorimeter choice of forward calorimeters at this time (without considering the new source of effective pileup for Fcals from physical shower overlaps and boosted energies).

Because the quartz is 250%/SqrtE, the RFM expressed doubt about the quartz technology. However, 250%/Sqrt1000GeV = 7.9%. Even with a 2% constant term this meets the design goal. Prototypes show a constant term closer to 1%, and MC predicts less than 1%. This resolution has been predicted by MC, and MEASURED in a hadron calorimeter prototype at CERN. The MC prediction and the high energy measurement differed by 8%= [MC- Data]/[(MC+Data)/2], using a 10% packing fraction.The predicted resolution for an "infinite" calorimeter was 3% at 6.4 TeV (=200 GeV/nucleon x 32Sulfer ions). The quartz

hadron test module was 22 x 22 x 90 cm. The prediction for the resolution in this finite module was 6% (leakage effects at 6.4 TeV). The measured resolution (Gaussian fit after calibration) was 6.5%.

Recently the BU MC group has largely confirmed the CERN resolution; they obtain 30%-18% with a 9% packing fraction for 100 GeV pions at 0-15 deg to the beam direction.They obtained (preliminary) 22 photons/GeV ~4-5 p.e./GeV at 9% packing (corresponds to ~11 pe/GeV at 20% packing) with an e/pi of 1.4. These are similar enough to Gorodetzky to give confidence in the results.

The em resolution has been measured to be between 23-35%/Sqrt E at CERN in several prototypes (20-10% P.F.), and 25% at 10 GeV by GEM. The quartz hadron prototype at CERN with a 10% packing fraction gave a corrected response of e/proton of 1.1 (data, confirming MC), with 8 p.e./GeV (corrected data), confirming the MC predictions.Again, the GEM quartz MC has obtained similar results for electrons, certainly at a level to be very encouraged by the experimental and MC results.

The RFM asserts that the GEM SSCintCAL group's e-m quartz prototype 'sees many more photons than one would predict'. This is false. In fact the photo-electrons may be somewhat lower than predictions. The exact shapes of the PMT quantum efficiency as a function of wavelength and the quartz refractive index as a function of wavelength, as well as the optical coupling efficiencies, have uncertainties in them.

Regarding the GEM prototype, RFM also states that 'the test beam results appear to be photostatistics limited'. This is false. The resolution is almost a factor of two worse than photostatistics alone, a typical situation for an optical calorimeter.

The RFM also asserts that the photostatistics are' far above...Gorodetzky'. This is false. In fact, the agreement between GEM and NA38 is most remarkable.

Further speculation in the RFM concerned the short length of fibers (40 cm) in the GEM em prototype and specular reflection as contributing to why the GEM prototype response was so much better than CERN (which it is not). This speculation is nonsense. In fact, there is essentially no specular reflection because of the cladding design. The GEM group was very specific with the manufacturer on this point.

Nevertheless we do a "worst case" analysis of specular reflection: it would only be important for light emitted at angles with respect to the meridional ray larger than the TIR (total internal reflection) capture angle, or larger than sin(theta) = N.A./ncore. For the fibers in the GEM test this angle is 16 degrees (ie the minimal angle at which specular reflection may become important). The number of bounces for a fiber of length L is given by Ltan(theta)/D where D is the fiber diameter.This gives 2.9 bounces per cm (AT MINIMUM). If we assume 95% reflectivity (an extreme value), and that the average light is piped for 25 cm (22 cm deep em module , 40 cm fibers) then the intensity is attenuated by (0.95) ** (2.9 x 25) = 2.4%. This is a very conservative number ie is the upper limit; at larger angles the number of bounces quickly increases. Nevertheless, assuming light is created isotropically in the fiber, at most 50% more light is collected by specular reflection. A more realistic calculation would estimate the integral from 16 deg to 90 deg including the increase in bounces. We find less than 4% of the light is from specular reflection assuming the extreme reflectivity of 95%.The manufacturer claims the reflectivity is closer to 80-85%. In either case, this does not explain discrepancy with CERN as there is none. Specular reflection, as is well-known with scintillating fibers, is not a factor. [Note: if it were, then the JetSet calorimeter with short fibers could not possibly have 6%/ SqrtE resolution.]

We note in passing that the measured TIR attenuation length for 300 nm light is 9 meters in the off-

the-self un-optimized fibers used in the GEM prototype. In better quality quartz fibers it is 100 meters. At 400 nm the attenuation is 0.5 dB/km. At 200 nm it is 90%/meter. This will allow us to place the PMT very far from the calorimeter and out of the high radiation regions.

A variety of statements and rhetorical questions in the RFM make further assertions about the response of a single particle crossing a fiber which are misleading or incorrect. These assertions would begin to prove that Pb glass would not work. Note that the response of a fiber calorimeter to a mip (a muon, for example) does not require the particle to cross the sensitive element at all. The ionized delta rays emerging from the mip track have a much larger effect on the response than the track itself. The muon Landaus in SPACAL at ~0 deg. are among the best ever published.

- The Technology Choice:

In the next to last paragraph of the RFM, the Forward Group asserts that 'only one technology,liquid argon, has been investigated with sufficient care to have reasonable certainty that it will meet our physics goals'. The SDC and ASCOT/EAGLE collaborations may take exception to this statement as they are considering the different technologies (SDC-Lscint, and ASCOT/EAGLE quartz).

We believe that 'sufficient care' includes the construction and beam tests of prototypes, preferably hadronic ones, but at least electromagnetic ones. This has been done for the quartz and liquid scintillator. Only nominal constructions and no beam tests have been done for the LArgon options.

CRITICAL UNANSWERED ISSUES FOR LIQUID ARGON

Some remarks on the present feasibility and understanding of a LArgon Fcal are in order.

- Radiation Damage and Operation During Dose:

The LArgon tubing proposed has not been operated during a radiation dose of 0.1 MR ad per hour = 1 Grad/year. There is no experimental proof (i.e. the only objective "investigation with sufficient care" that these tubes will operate in the radiation conditions expected.

Will the positive ions shut off or modify the gap field significantly?

Will the radiation pump impurities into the gap to an unacceptable level?

Will the radiation dose damage or outgas the insulators?

Will the microbubbles (comparable in thickness to a human hair) form in the gap during beam heating or radiation outgassing due to radiolysis, causing sparks?

The radiation tolerance at the level needed ESPECIALLY DURING OPERATION has never been investigated. Neither has the performance change during operation been measured. The level of radiation affects the signal generation in LArgon by positive ions, modifying the field in the gap. This non-linear process is essentially absent in Cerenkov or scintillation. One cannot simply irradiate a detector, and then afterwards turn it on and claim it works. The radiation dynamically affects its operation, both in terms of gap field effects and in terms of impurity ions. No one is claiming that W or Ar damage in some permanent way themselves; rather, there is no proof of performance under dynamic dose conditions.

The very thin gap (100 microns) and the spiral wind of quartz fiber has consequences for radiation damage.

(a) There may not be sufficient circulation to remove impurities. Boundary layer effects are large compared with the 50 microns on each side, and the spacer spirals constrict fluid motion

(b) The surface to volume ratio is a factor of 10 - 20 larger than ordinary gaps, increasing the concentration of surface-born impurities by that factor.

(c) Dust and dirt particles of 10's of microns in size may affect the operation when ionized.

(d) The dose level varies along the length of the tube from the front face to the back. Consequently, the positive ion buildup will be different at different z positions along the tube. How do we know that this does not affect the energy resolution? For example, at shower max the collected charge

during the sampling time maybe much reduced or spread out by positive ion buildup compared to 2 lambda deeper in the calorimeter. This may increase the constant term to unacceptable levels.

- Existing Tests of Liquid Argon Forward are Inconclusive

There is no proof that the gap 'tested' is as efficient as it needs to be, or is seeing the signal level expected (under radiation conditions). The assertion comes without explanation. We must see the data and the calculation.

Do we know that response is uniform along a tube?

Do we know that the tubes will not sag and spark when assembled in a huge stack despite the spiral standoff?

Do we know that the long cable readout works as advertised?

Do we know that the yield in manufacturing will be good at 100 micron tolerances?

Do we have any lifetime tests comparable to the SSC operation?

The data presented on the collected charge as a function of bias voltage showed slight but disturbing asymmetry with polarity - what is the origin of this? It may be explained by attachment since the field is slightly higher on the inner rod than the outer tube. If so, then the attachment in the test device was as high as this field effect is small. There is no data on the speed of these gaps other than extrapolation.

- Termination Region and Operational Problems

The termination region at the ends of these tubes apparently has not been thought out in detail. There is a layer of liquid argon at the front and back ends of these tubes.

What happens to the charges produced here which see some HV from the center rod?

In the layer of LArgon in the front of a module, do the electrons drift and stick to the insulator in the front of a tube near the center rod at +HV, and cancel the field or produce arcs?

The cables at HV at the back run out through LArgon gap between longitudinal segments - do the electrons produced in the gap stick to the insulator on these cables?

The dewar itself causes potential problems for LArgon calorimetry in the FCal. Even if the sensitive region ends at eta of 5, jets beyond eta of 5 will enter the dewar which must extend into the eta of 5-8 region. Note that at eta of 5, the thickness of a wall parallel to the pipe to the particles is multiplied by 74. This means that the high eta jets striking the dewar will traverse ~1-2 lambda (3 mm SS or 5 mm Al dewar wall). A 20 GeV Et jet has an average energy of ~2-3 TeV and a rate of 4 MHz at eta 5-8. The enormous spray rate from this in 1-2 lambda has not been fully considered.

A projective quartz tower on the other hand ends cleanly at eta of 5. Indeed, the beam pipe might be structurally linked to the tower. It therefore may be made even thinner when the vacuum is supported by the tower next to the beam pipe. Every available technological artifice must be employed to limit the jets beyond eta of 5 (5-9) from interacting near the calorimeters.

If for no other reason than the example above from spray, the speed of the forward device must be exemplary. Clearly the forward region has a large increase in rate from physically overlapping showers. We must use a technology whose intrinsic temporal properties can be exploited. LArgon is clearly not that

choice.

We question whether the shaping time will be independent of shower fluctuations enough to make good timing. This LArgon geometry is sufficiently different from a plate calorimeter to question this. In a plate calorimeter, the cables can be trimmed to length to avoid the time walk problem. In this case, shower max fluctuations add a few ns to the shape peak, potentially altering the timing characteristics.

- Liquid Ar Prototype Construction

There has been no beam test, not even of a small electromagnetic prototype showing the resolution, despite the hard work of a group of 3 faculty, 2 technical staff, a post-doc, several grad students and a term employees over 12 months.

THE ADVANCED STATE OF OPTICAL FORWARD CALORIMETRY

In contrast with the state of development of the Fcal LArgon Tubes, let us point out the results of the test beam data, which has been confirmed by detailed MC studies for Fcal Quartz and Liquid Scintillator Fiber Prototypes. These data and MC have been attained at CERN (NA38) and by GEM. Two independent M.C. of quartz sampling calorimeter have been done, one by NA 38 (Gorodetzky and students) and by GEM (BU group Dye, Carey, Miller, Worstell). M.C. of LScint is adjusted from plastic spaghetti MC by adjusting the fiber diameter and the attenuation length.

Four prototype quartz spaghetti modules have been constructed of Pb absorber: (i) NA 38 2 em modules 5 x 5 x 10 cm (20% packing fraction);(ii) NA38 1 hadron module 22 x 22 x 90 cm (both 5% and 10% packing fraction); GEM (Fairfield) 12 x 12 x 21 cm, 6.8% packing fraction).

Four prototype LScint modules: (i) GEM (TAMU) em module with rigid tubes; (ii) SDC (TAMU) e-m module with glass tubes; (iii) GEM (Fairfield) e-m module flexible halar tubing; (iv) SDC (toronto) hadron module, quartz tubes, 1 m deep.

QUARTZ SAMPLING FORWARD CALORIMETER PROTOTYPE AND MC SUMMARY:

- sigmaE/E: (Hadrons)

  <10% for Ehadron ¿700 GeV for 10% packing fraction Quartz
  250%/SqrtE + 1%, or better
  (90 x20x20 cm module, tested at 6.4 TeV, consistent w/ MC)

- sigmaE/E: (electromagnetic)

  23%/SqrtE +1% for electrons (20% packing fraction)

- Response: 16 p.e/GeV @ 20% packing fraction

- e/p: 1.1 (10% packing fraction- analysis of measurements NA38), 1.0-1.4, 5-20% (MC results CERN, GEM)

-Speed:
  - Operated at 20 MHz heavy ion rate at CERN (NA38)
  - Hadron energy developed to 99% of full energy in 25-30 ns (since quartz is neutron blind)
  - Hadron calorimeter risetime less than 10 ns (NA38)

  Sub-ns time-resolution obtained with e-m module.

- Radiation Damage:
  - Detector fibers OPERATED at exposure of 3 Grad/day.
  - Quartz hard at least to 20 Grad (i.e. ~ no damage at that level - not tested beyond)

GEM e-m Quarts Prototype Results:

- Confirms CERN e-m results as tested at BNL
- Extends measurement results to low beam angles, consistent w/ GEM MC
- 5.3 p.e./GeV, and 25% energy resolution at 10 GeV (6.8% packing frac)
- Pulse waveforms: rise/fall ~5 ns; FWHM = 10 ns
- Muon Landau distributions observed, consistent with energy loss
- Simplicity: Design to tested done by 1 faculty +3 undergrads,in 7 weeks
- Response not critically dependent on incident angle (see below)

GEM Quartz Fiber Monte Carlo (Dye, Carey, Miller, Worstell - BU)

- E-M resolution same for 0 deg or for 90 deg. to beam; (17% at 20 GeV; 9% packing fraction in Pb, 1.6 mm fibers)
- 100 GeV pion resolution changes from 18% at 15 deg to 30% at 0 deg with no change in pulse height
- e/pi ~ 1.4 and 20-30 collected photons/GeV at 9% packing fraction [NOTE: 1.6 mm fibers are too big..at a given Packing, spacing big]

Resolution Improvements Suggested by Quartz Prototypes Results:

- 10% to 20% packing fraction (x2)
- improved UV quantum efficiency tubes (GaAs cathode-¿x2)
- fiber numerical aperture (x1.2-1.4)
- light coupling/mixing (x1.1)

Conclusion: we could obtain 40(80) p.e/GeV @10% (20%) packing fraction

LIQUID SCINTILLATOR FORWARD CALORIMETER RESULTS

GEM e-m Liquid Scintillator Results:

- GEM has produced 2 separate em prototypes that worked well in the test beam
- Resolutions were within x 2 of plastic fiber calor w/ similar optics
- The components used in the tests (liquids, tubes, etc.) have been operated at 200 Mrads or more
- Prototype liquid fibers have achieved light attenuation lengths of 2-3 m in 3 mm ID (tested by Frascati group and Farifield group).

SDC LScint Results:

- Large Toronto hadron module works well on cosmic rays
- Uses quartz tubes (rad hard) with isopropyl biphenyl scintillator (nuclear reactor coolant)

THE CHOICE

If one had to build a calorimeter tomorrow, guaranteed to meet the requirements for a forward calorimeter, it would have to be quartz. It is the only technique sufficiently tested for radiation hardness, resolution and rate at this time. The liquid argon technique is an extrapolation.

Quartz offers a significant advantage of separating overlapping showers. As correctly pointed out in RFM, this is essential to reach the highest values of eta.

A fast calorimeter is more important in the forward region than anywhere else. The physical overlap and energy of showers increases the effective pileup of showers by an order of magnitude or more below eta of 4 compared to eta=0. Quartz or scintillator are much superior to liquid argon in this regard. The specs on speed are not discussed in RFM. We have trouble envisioning counting at 20 MHZ with LAC, as was done with quartz at CERN, much less measuring energies at those rates.

CONCLUSIONS

In conclusion, we believe that it is premature to decide on a forward technology. We emphasize, however, that if the choice had to be made today, the only choices with sufficient testing are the optical fiber technology, with quartz having the only proven radiation resistance in operating conditions. Furthermore, we assert that the choice of LArgon is associated with a large degree of risk until operational questions are answered.

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APPENDIX I - Memo on Forward Calorimetry by John Rutherfoord

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From: UAZHEP::RUTHERFO "John Rutherfoord - (602)621-2657 Univ. of Az" 28-SEP-1992 11:34:13.46
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CC:
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COMPARISON OF CONTENDING GEM FORWARD CALORIMETRY TECHNOLOGY CHOICES
John Rutherfoord

GEM forward calorimetry (FCal) has rather strict requirements. ANY detector operating at large eta faces serious obstacles. But, in addition, GEM is the ONLY collaboration to attempt a design with the FCal very close to the interaction point (IP). Not only SDC (at 14 m) but also the LHC collaborations (outside the muon tracking volume) have their FCal's located as far from the IP as possible, for good reason. GEM cannot afford to be so daring without VERY careful scrutiny. Figures 1 and 2 show the SDC and LHC cartoons with forward calorimeters well into or outside of their forward muon systems.

In the last engineering design I saw, the quartz and liquid scintillator FCal's are at 3.5 meters from the IP and are non-projective. This configuration simply will not meet our physics specs. However it is possible that a projective design might. I understand that work is in progress on a projective design. My concerns about previous projective designs were 1) the segmentation at the front face of the forward calorimeter was not fine enough to yield the required angle resolution and 2) the density, measured in lambda, was not high enough.

I've been trying to understand the fundamental limits on position resolution of hadronic showers. I don't know enough to be authoritative, but I worry that one might not get the required angular resolution at 3.5 meters no matter how fine the segmentation or, alternatively, I don't know how hard it will be to achieve. I can't say that some design, not yet on the table, would not work. The previous spaghetti design, which was projective, had a very funny feature (shared by the hadronic barrel and endcap spaghetti designs) that the eta-phi segmentation is 4 times better at the rear of the module than at the front. For the FCal, this is a VERY bad feature since we place a premium on spacial resolution EARLY in the shower, not later. In that previous Spaghetti design for the projective FCal, the segmentation in eta-phi at the front face was inadequate and the segmentation at the back face was acceptable if it could be maintained throughout. But it is not. Mike Shupe can simulate this situation but we have not yet figured out how to best analyze the data.

The latest non-projective spaghetti design had a good density, 11.3 cm lambda, but earlier projective designs had closer to 15 cm lambda. This is a qualitative difference. (The LAC design has 10.5 cm lambda.) We need the high density in order to contain the shower laterally. But it is hard to design a projective

spaghetti calorimeter with the required density.

Since the LAC simulations are fairly far along I can say, with confidence, that the LAC design will meet the GEM design goals. We are exploring how far we can back off in the beampipe diameter and absorber density and still satisfy our physics goals. I'm also worried about the eta coverage for a calorimeter at 3.5 meters from the IP and a beam pipe of 8 cm diameter. We will try to simulate this shortly but I can't say if we will have results in time for Wisnewski's panel.

Since angular resolution (i.e. position resolution at the FCal face) and eta coverage are the critical parameters for missing ET resolution let me make some comparisons regarding these parameters.

1) The LAC FCal front face is at 5 meters from the IP

The spaghetti FCal's are at 3.5 meters

The LAC therefore has a better lever arm for angle resolution. And for

a given beam pipe diameter, the eta coverage is better for the LAC.

If Delta theta/theta=10% at 5 m, then Delta theta/theta=14.3% at 3.5 m.

If eta(cutoff)=5 at 5 m then eta(cutoff)=4.65 at 3.5 m.

2) The LAC FCal has longitudinal segmentation (2.5 lambda in the "EM" section).

The LAC therefore can pick up the high energy core of the shower early on.

The Spaghetti FCal's have no longitudinal segmentation.

Longitudinal segmentation also allows a special design for the first module where the density of radiation is the highest but where energy and angle determinations are easier.

3) The LAC FCal is a bit denser, in absorption lengths, than the Spaghetti options so transverse fluctuations are smaller in real space and angle resolution is better. However in the latest designs I've seen this is a rather small difference. But I worry that the quartz option, in particular, may have to back off in its density quite a bit in order to achieve adequate energy resolution (see below).

4) The LAC FCal has pseudo-projectivity.

The Spaghetti FCal's are not projective.

This is fatal and they must come up with a projective design.

Once they come up with a projective design then we will have to investigate, via Monte Carlo, the channeling effects on EM showers.

With a projective geometry the quartz option might be sensitive to the high energy core of the shower and therefore have better angle resolution

than the liquid scintillator option. But we need to simulate this and no

one is even close to doing this as far as I know.

If one were to stagger the Spaghetti FCal modules in z with modules at larger eta located at larger z, then one would have effects similar to the "eta=3 crack problem" with which we are familiar. Showers near a module boundary (all showers would be near a boundary since "near" means within one lambda) would leak transversely into the front face of the tower at larger eta and give a false angle measurement. Of course it's the fluctuations in this effect, not the effect on average, that is the problem. Again this must be simulated to estimate the magnitude of the effect.

The Gorodetsky hadronic calorimetry results, to the extent I can glean them from poor quality transparencies and remarks from Dave Winn, gives 250%/sqrt(E). This is so poor that energy resolution might also be a critical factor for a quartz fiber FCal. This stochastic term might be driven by photoelectron statistics (0.2 to 0.6 photoelectrons per GeV). Dave Winn says that it is trivial to get of order 5 photoelectrons per GeV in Gorodetsky's setup. He was forced to use plastic fibers to join the quartz to the phototube and to use phototubes without quartz windows. Also his hadronic calorimeter (of which I haven't even seen a transparency) was not fully containing. So he lost several factors of 2. I've beat on Dave Winn to produce even a few words in print on the quartz fiber calorimeter but, so far, he has been unable to comply. He himself has nothing other than copies of transparencies. I can't take a technology seriously which has nothing in print. I think a paper exists but since neither I nor Dave Winn has seen it I can't comment. For instance I don't know if this paper addresses the hadronic results.

At Yuri's urging I have tried to understand the fundamentals of the quartz fiber calorimeter. I have communicated with Jerry Dodd at Nevis and have tried to understand some of Gorodetzky's transparencies. The first thing which confused me is how the quartz fibers at zero degrees transmit Cerenkov light. It is well known that with no cladding, the Cerenekov angle equals the total internal reflection (TIR) angle for beta=1 particles travelling along the fiber, i.e. Cerenkov light from a particle travelling along the fiber is emitted at an angle of 48 degrees and the TIR angle to the normal to the side of the fiber is the compliment of this, i.e. 42 degrees. Thus Cerenkov light is just at the limits of the "numerical aperture" for light generated within the fiber. But the index of a typical cladding material is 1.41 while the index of the polysilicate (quartz) is about 1.49. So Cerenkov light is far outside the "numerical aperture" for light generated inside the fiber. For particles close to the inside edge of the fiber some small fraction of Cerenkov light can spiral around the perimeter of the fiber, suffering many more reflections than is usual, but staying within the "numerical aperture".

Gorodetzky's 2-D plot of light output from a single fiber versus particle angle to the fiber axis and versus impact parameter is actually consistent with this observation, although it takes some time to appreciate this. The plot has been misused to suggest that the light output near zero degrees is roughly the same as at the Cerenkov angle. But this is a misreading of the plot. The plot applies to a single fiber traversed just once by a particle. A particle at 42 degrees and zero impact angle (where the peak appears) travels through a path length of fiber of about 1.4 mm. But the particle at zero degrees travels a path length of fiber equal to its complete length. To see how misleading this can be, imagine a calorimeter made only of a very large bundle of fibers, no absorber material. A particle at 42 degrees to the fiber axis would cross many fibers. The light output would be that read off the Gorodetzky plot multiplied by the number of fibers the particle crossed, a large number. But a particle near zero degrees would cross only one fiber and so the number read off the Gorodetsky plot would be multiplied by unity. So the light yield from a CALORIMETER as opposed to

a single fiber looks quite different from the Gorodetzky plot. One would predict many fewer photons from a calorimeter with fibers near zero degrees than from fibers oriented at 42 degrees based on Gorodetzky's plot. Since Gorodetzky was approximately photostatistics limited in his test calorimeters, changing the fiber orientation would only exacerbate this photostatistics problem. And we're not talking about a small effect. This is a VERY large effect. WE MUST UNDERSTAND WHAT WE ARE DOING and we don't.

Dave Winn's test beam results appear to be photostatistics limited but at a level far above what one would predict from Gorodetzky's plot. I.e. Dave Winn sees many more photons than one would predict. Why? His fibers are quite short compared to what we would use in a real calorimeter. Perhaps the fibers have appreciable flaws at the interface between the quartz and cladding so that specular reflection is large. This specular reflection might bring the Cerenkov photons out through the short fibers. But this light might not make it out though the longer fibers we will eventually want to use. In any event the light output will be very sensitive to imperfections.

Does a quartz fiber calorimeter measure the high energy core of a shower? I don't think so. Lower energy fragments will be scattered at large angles and some will cross the fibers at angles nearer the Cerenkov angle where their Cerenkov light will fall within the "numerical aperture" and be transmitted to the phototube. So I suspect that a quartz fiber calorimeter will be sensitive to the transverse tails of a shower and therefore have poorer position resolution. This has to be Monte Carlo'ed.

Many of the issues identified above could be investigated via simulation. In the meantime it is not responsible to assume that various suggested solutions to one problem will not create a bigger problem elsewhere. Only one technology, liquid argon, has been investigated with sufficient care to have reasonable certainty that it will meet our physics goals.

The GEM liquid argon forward calorimetry group at Arizona includes three faculty, two permanent technical staff, a post doc, some students, and term employees who are dedicated to the project and a test beam run next summer. And a visitor from Nanjing University (who intends to stay with us for two years) who is an expert in electronics has just arrived. This is a strong group which has accomplished a great deal over the last 12 months. We have a design which has been fairly stable for some time now, allowing the proponents and competitors to examine all the parameters and to identify weaknesses. The engineering is in a fairly advanced state and an attractive construction scheme is laid out.

Note: I use "numerical aperture" in quotes since the term actually applies to light which enters the end of the fiber from a medium of index=1. Our light is produced within the fiber so the fraction of light which will be transmitted within the TIR angle (which I designate as being within the "numerical aperture" for light generated within the fiber) is much smaller.