Studies of Multiple Tile Readout Compensated Calorimetry And Beyond

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•Dual Readout/Cerenkov Compensation first studied in GEANT MC in 1988 in a variety of media [Ex: LAr ionization, with its Cerenkov light].
["Compensating Hadron Calorimeters with Cerenkov Light", D. R. Winn and W. Worstell, IEEE Trans.Nuc.Sci.,v.1 NS-36, 334(1989]

•DR has been studied by R.Wigmans et al. (DREAM collaboration) using parallel plastic scintillating and silica Cerenkov fibers.

N.Akchurin et al., NIM A735, 130-144 (2014) *and loc. Cite*

• DREAM uses parallel, longitudinal quartz Cerenkov fibers & plastic scintillating fibers in a Cu matrix.

•D.E.Groom, showed that R.Wigmans' analysis of DR is equivalent to 1988 analysis
http://lanl.arxiv.org/pdf/1210.2334.pdf http://lanl.arxiv.org/pdf/1208.3159.pdf

Deficits in Parallel fiber Dual Readout Compensation

1. *Constant Term – unavoidable issue* - self-attenuation of the scintillator light over ~2 m.
2. *Pointing Geometry* (to interaction diamond or target) in a practical parallel fiber calorimeter over a substantial solid angle is problematic. The mechanics and fiber packing of fully projective (θ,ϕ) are (nearly prohibitively) difficult for pitch,yaw more than ~5°. Streaming down the fiber holes lowered the resolution in DREAM even at a 2° pitch.
3. *Longitudinal Segmentation:* Fiber dual readout is incompatible with longitudinal segmentation.
4. *Calibration:* The scintillator parallel geometry is difficult to calibrate, as radiation damage varies over the length. In longitudinally segmented calorimeters, longitudinal damage is far easier to quantify.
5. *Fiber Bundle & Photodetector Punchthrough:* Huge fiber bundles, ~25% of the back of the fiber dual calorimeter area, are directly behind the calorimeter. Large punchthrough backgrounds are generated by these fibers and the photodetectors (~1/800 incident π/K scatter through a 10 Lint calorimeter).
6. *Scintillator Fiber & Photodetector Raddam:* At present, there are no good examples of scintillator fibers which have proven sufficient raddam resistance to be useful for hadron calorimetry at SLHC
7. *E-M and Hadronic Components of Incident Jets:* Parallel fibers have almost no ability to detect and separate the incident *direct e-m component of a jet, since there is no longitudinal segmentation*.
8. *High Resolution EM Front End*. The parallel fiber dual readout has almost no ability to make a *compensated* high-Z high sampling fraction EM front end.
9. *Timing & Pileup:* Although longitudinal fibers store the information of jet/em showers, the signal is generated over a time for the light to traverse the fibers. The light generated *at the back of the calorimeter* arrives at the photodetector first. Fiber calorimeters measure the falling edge, a less precise measurement.
10. *Cerenkov (Fiber)Index of Refraction:* Practical clear fibers with high radiation resistance are limited largely to quartz, n=1.46, a limitation on the resolution – h/e_C ~0.25-0.2. However, tiles with lower indices (as discussed below:1.4≥n≥1.1) for lower h/e_C ratio, with better Cerenkov compensation.
11. *Particle Flow/Energy Flow Calorimetry*[30,31] is also a developing calorimetry technology, improving the angular resolution and core ID of jets, the isolation/ID of incident electrons/photons in jets and in showers, and muon and neutral particle (K^0, n) identification, all especially under pileup. *Tile* dual readout is fully compatible, and can be easily added to particle flow calorimeters via the addition of Cerenkov tiles next to the ionization sensors in particle flow.
12. *Cost:* the cost of tiles is significantly less per mass or volume of sensitive material than that of fibers, and the cost of a fabricated tile absorber matrix is considerably less than the parallel fiber Swiss cheese.
13. *Other Sensors:* Parallel fibers especially cannot readily use other hadronic, n, and e-m energy sensors. Examples beyond plastic scintillator and SiO_2 fibers include ionization detectors (solid – Si, Diamond; liquid- LArgon; gasses – micromegas et al.); other β->1 sensitive detectors such TRD, or ultra-low-index materials(aerogels, MgF_2, water, perfluoros, silicones,..); secondary emission sensors with higher response to slow particles β->0 and minimal response to minimum ionizing energy (new large MCP); inorganic non-hydrogenous scintillators (LYSO, $PbWO_4$ et al.)

Contrast Multiple TILE readout with Dual Readout with Fibers:

, *Fully Pointing, Longitudinal Segmentation, and fully Compensated e-m front end*

- Compatible with Particle Flow/Energy Flow, unlike parallel fibers

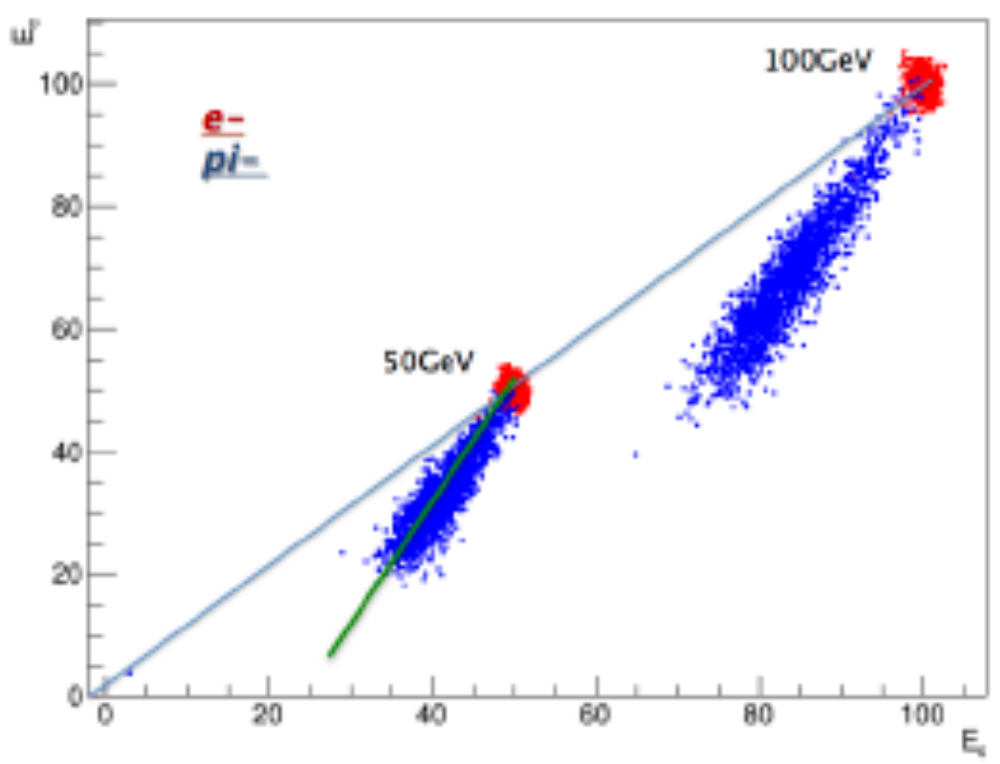
- Compatible with Triple or Quad Readout Tiles (Cerenkov, Scintillator, Secondary emission, Neutron-enhanced, ...

- Compatible with drifted ion detectors (semiconductors, noble liquids and gasses)

- Tiles more sensitive β ->1 (TRD, n~1.3) -> higher contrast to e-m showers

- more sensitive β->0 such as secondary emission -> higher contrast to hadronic showers and nuclear breakup

- Compatible with neutron-enhanced detectors -> higher contrast to hadronic showers and nuclear breakup



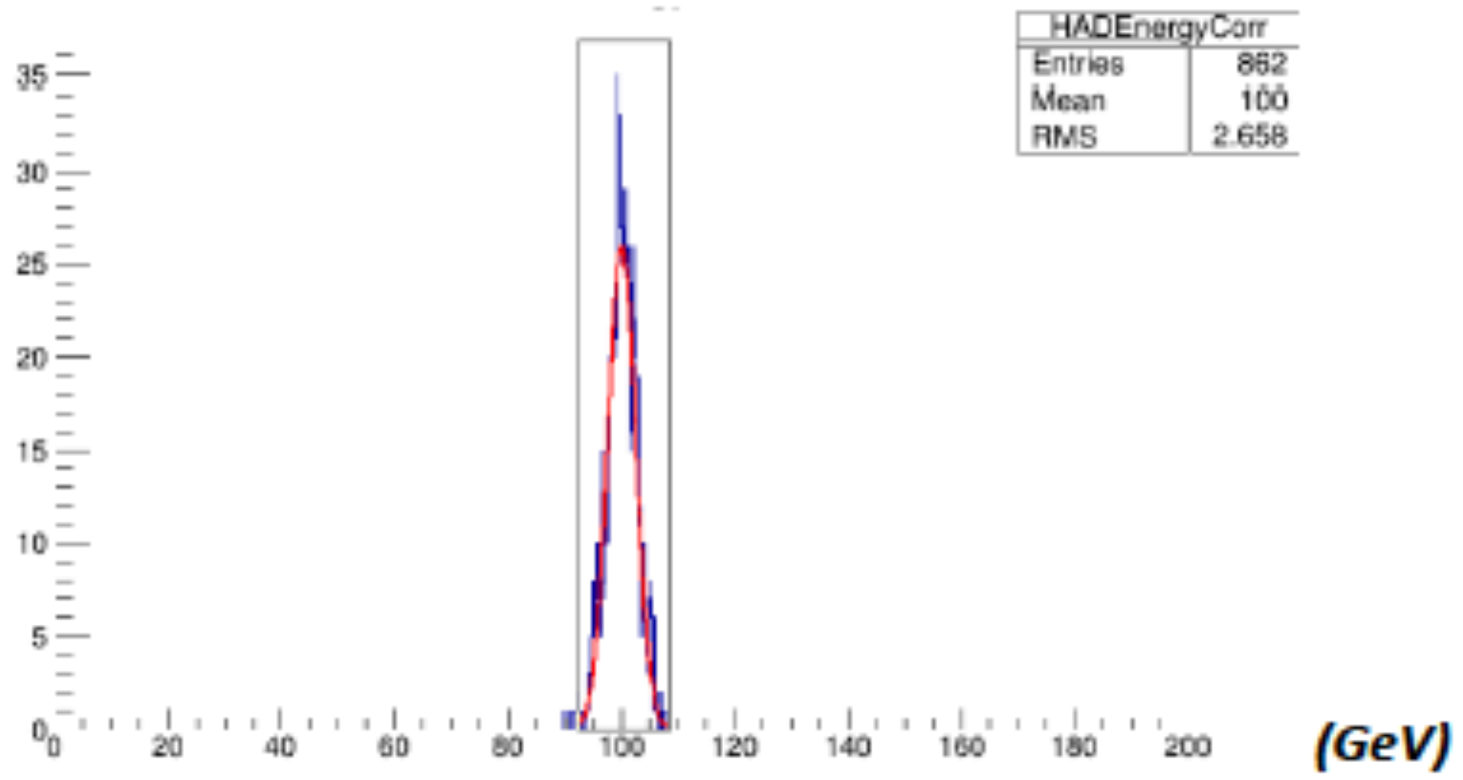


Figure 11a (Left): Tile Dual Readout GEANT4 MC: Scatter plot of $E_{Cerenkov}$ (E_C) vs $E_{Scintillator}$ (E_s) in a tile calorimeter consisting of tiles 1cm thick each of quartz, plastic scintillator, and Cu absorber. Two energies (50, 100 GeV) each of electrons (red dots) and pions (blue dots) were sent into the calorimeter. When the (E_s,E_c) points were projected onto an axis perpendicular to the green line linear fit, the resolution on hadrons is narrower and more Gaussian, as shown for 100 GeV π in Fig11b.

Fig. 11b(Right): Histogram of the 100 GeV π events at left vs Cerenkov projected energy, as projected perpendicularly to the linear fit to the E_c vs E_s correlation. ***The (mean, rms) = (100, 2.66) GeV shows the promise for W-> jet-jet separation, especially with higher sampling frequency (1/5 Xo) .***

Discussion: In homogeneous non-hydrogenous dense inorganic scintillators (LYSO, $PbWO_4$, CeF_3, etc) $h/e_i \sim 0.4$ and $h/e_C \sim 0.25$, or $[h/e_i]/[h/e_C] \sim 1.6$ and as such, homogeneous calorimeters *cannot* achieve dual readout compensation better than ~50-60%/√E on hadrons, even if perfect separation between scintillator & Cerenkov light in the homogeneous detector. To achieve the theoretical minimum ~15%-18%/√E on jets, separate scintillator sensors with $h/e_i \sim 0.6$-0.8 (likely hydrogenous), and Cerenkov sensors with $h/e_C \leq 0.2$ are needed, which we will both explore in MC and test in this proposal. To achieve $h/e_C < 0.2$-0.25, lower n(index of refraction) Cerenkov radiators are required(i.e. β_{thresh} ->1), but sufficiently thick for enough photons to achieve an e-m resolution <70%/√E(GeV) or N_{pe}>2 pe/GeV.

a) E-M Compartment: Homogeneous, high index scintillator e-m front sections reduce jet energy resolution substantially, but cannot be fully compensated by their own Cerenkov light. We will study in MC

b) Fused silica tiles (n=1.46; h/e_C ratio ~0.25)

c) Lower index (1.1<n<1.35) and rad-hard tiles to achieve a high contrast ratio with h/e_C->0.15: silica aerogels (n=1.05-1.3), polysiloxanes (n=1.35, 100 MRad), TeflonAF (n=1.29, 12 MRad), MgF_2 (1.37).

d) TRD (straw tubes high β threshold) tiles, interspersed w/ plastic scintillator tile and absorbers;

e) Liquids: for very large detectors such as long-baseline or cosmic neutrinos.

1) LArgon drifted ions and simultaneous Cerenkov light detection. The index is low enough that a good e/h contrast seems possible, and the scintillation light at 128nm will not penetrate PMT windows.

2) water "tiles"(using n=1.29-1.31 TeflonAF films for light piping)+liquid scintillator tiles – no absorber;

f) Drifted Ion detectors – "tiles" of Si, LArgon, high pressure hydrogenous gas or micromegas.

g) Secondary Emission (SE). Large scale glass-based thin-film activated MCP[37] (prototypes already available to our collaboration) that are directly sensitive to ionizing particles, and could serve as a "tile". Secondary Emission(SE) tiles are more sensitive to γβ–>0 particles than to MIPs - the SE signal scales as dE/dx (βγ), with a MIP SE signal~100-200x less than that of the particle at the energy of the peak SE signal – the *opposite* of Cerenkov light. SE tiles may provide further correction for binding energy effects and lost neutron energies. (See triple/quadruple readout below.)

h) Triple Readout and beyond: Extending the readout to include 3 or more materials to see if multidimensional correlations of sensors can yield an algorithm to improve dual readout: non-hydrogenous scintillator, hydrogenous or other neutron-sensitive scintillator, and 2 indices of Cerenkov tile(s), or the SE tiles above, may enable even more correction, by also comparing less-sensitive neutron scintillators (direct charged particles including nuclear fragments) such as non-hydrogenous scintillators (inorganic and perfluorcompounds) to more neutron-sensitive scintillator tiles.

- *Neutron-enhanced detecting scintillator tiles with film coatings* - ^{10}B, ^{6}Li, hydrogenous materials like ^{6}LiH, but a thin therefore clear film, buffered with alumina films; especially interesting is $Li^{6}B^{10}H_4$, transparent if deposited as thin films between clear buffers.

(0) An intrinsic limit of normal hadron calorimetry is σ_E/E~13%/√E, given by the ratio of detectable neutron energy to the fluctuations in lost nuclear binding energy.

(1) the contrast between h/e_i (i=ionization) and h/e_C (C=Cerenkov) for hadrons h and e-m e energy should be as large as feasible-that is, that the ratio of ratios $[h/e_i]/[h/e_C] \geq 4$ in order to reach incident hadron energy resolutions below 30%/√E, with 18%/√E being a reasonable target to achieve using plastic scintillator and low index materials;

(2) h/e_i as large as possible - implying hydrogenous or neutron-sensitized ionization detection media;

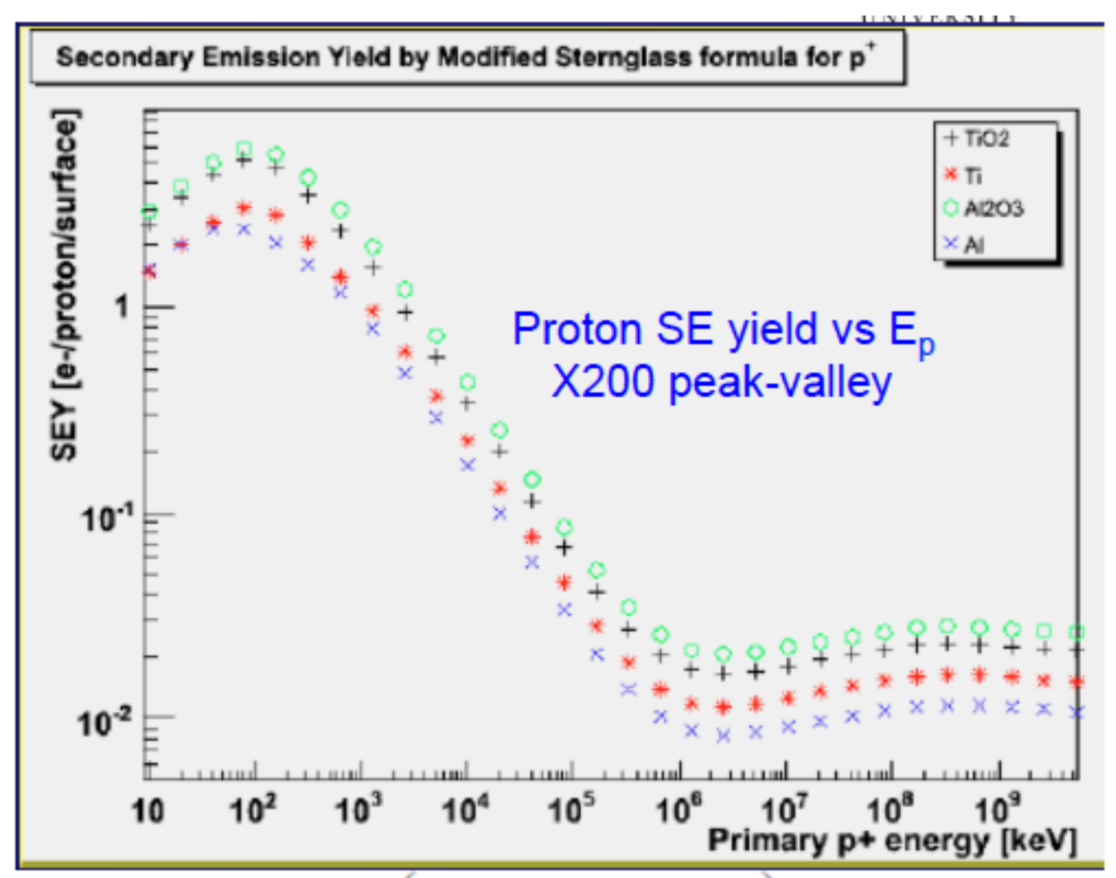
(3) the intrinsic resolution on e-m energy from Cerenkov light must be ~80%/√E or better to achieve resolution better than 20%/√E;

(4) Resolution scales ~$\sqrt{(f_{sample}/f_{frequency})}$.

(5) Compensation can be achieved by enhancing the neutron or ion fragment sensitivity (hydrogenous media) and/or by suppression electromagnetic component by tuning the absorber thickness relative to sampling media (f_{sample} typically ~1/10), but at a loss of potential ultimate resolution.

(6) Adding sensor tiles which are relatively insensitive to MIPs and more sensitive to γβ->0 will increase the contrast between e-m and hadronic energy by enhancing the low energy hadronic signal – one such sensor is Secondary Emission; its signal scales as dE/dx, with a MIP SE signal ~100x less than that of the energy of the peak signal (peak signal for protons occurs at ~200KeV - n+p->p+n knock-on protons).

Example: Ultra-low index tile – Teflon-AF n=1.3
Silica aerogel similar but 1.05<n<1.2
Sensitive to β->1



Example: Secondary emission – less sensitive to e-m showers; more sensitive to low energy Spallation fragments, hadrons.