Photomultipliers: In-Situ High Rate Radiation-Resistant Calorimeter Sensors Cerenkov Light+Secondary Emission

Chris Sanzeni, David R Winn – Fairfield
Burak Bilki¹, Yasar Onel, Aldo Penzo, Emrah Tiras², James Wetzel - Iowa
B. Kaynak, C. Simsek, Suat Ozkorucuklu – Istanbul
Forward Region Calorimetry at future Colliders
\[ 6 \geq \eta \geq 3 \]

- Rates: 40-100 MHz beam crossing (+ gas of n, \( \gamma \))
- Hysteresis: <2% pulse-pulse for resolution
- Occupancy: High! 100% per 1cm\(^2\) cells/towers
  - e, \( \gamma \) <1 GeV, n~ MeV’s ... multiplicity >10/cell
  - Cells at \( \sim 100 \) MHz – *or higher depending on \( E_{thresh} \)*
- Dynamic range/cell: \( \sim 10^4 \) (mip-> TeV jets)
- Radiation: 100-1,000 MRad, 10\(^{16}\)-10\(^{17}\) n/cm\(^2\)
- Timing: \( \leq 30 \)ps pileup mitigation (100’s/crossing)
- Identify/Measure: jet e-m component, \( \mu \)
Calorimetry Detector Issues at large $\eta$

- **RC time constants: rate limitation**
  - Devices with $\sigma_T < 30\text{ps}$ ..... can have low rate capability
- **MCP-PMT**: inherently resistive ~ PMT resistive base
  - Typically limited by 30ns recovery
  - MCP Raddam? Yes. Lifetime? Not long enough
- **SiPM**: *Inherently resistive*
  - Excellent for low rate, low light level optical pulse timing, B.
    - But Typ Performance: 30 ns dead-time @ 3 p.e.
  - Cross-talk $>10\%$ at large light levels-$>$ hysteresis issues.
  - Radiation Damage
  - Cooling issues limit compactness near the beam-pipe
- **Si diodes**: no or low gain
  - Fast pulse risetimes - but capacitance can limit rate
  - Hysteresis from e/hole polarization at highest rates
  - Raddam at highest dose regions
  - Requires on-detector amplifier - raddam issues inside showers
Dual/Multiple Readout: 2 or more sensors with different Responses to shower fluctuations.

Cerenkov Compensation - First form of multiple readout

• 1st Quantitative MC Study:
    • Idea: Use differences in response to e-m fluctuations between
      - Cerenkov Medium (transparent – LAr, H₂O, SiO₂ ....) vs
      - Ionization Medium (scintillator, LAr ion collection, ..)
  – DREAM Collaboration/Richard Wigmans et al.
    • Parallel Scintillating+Quartz Cherenkov Fibers
    • Excellent progress in test beams - DREAM: ≥30%/√E
    • Thorough Analysis of Dual Parallel Fiber Calorimeters

• Present state of GEANT MC: 18%/√E possible....
Electrons: $E_c$ vs $E_s$ (red points) lie along line shown schematically as $E_c = E_s$.

Pions: $E_c$ vs $E_s$ scatter-plotted (blue points) lie mainly below the $E_c = E_s$ electron line with correlation between $E_c$ vs $E_s$ fitted as a line (green, 50 GeV points at an angle $\theta$). Project the points along the fitted line

As the shower fluctuates more to hadrons, $E_c$ falls faster than $E_s$. Use different Responses to Correct Calorimeter Energy... We propose Cherenkov vs Secondary emission Via PMT dynodes.
Dual Tile Correction –

**Tiles** 1cm thick each Plastic Scint, Quartz, Cu

*Cherenkov-Corrected Energy (GeV) (mean, rms) = (100, 2.66) GeV*

$\sigma_{E}/E$ enables $W \rightarrow \text{jet-jet}$ separated from $Z \rightarrow \text{jet-jet}$ at $\sim 2.5\sigma$

**Future Work:**

- Multiple Readout Tile types (aerogel low $n$, TRD, Secondary Emission, ....)
- Higher order terms - $\alpha_2(E_s - E_c)^2 + \alpha_3(E_s - E_c)^3 + ..$ & energy dependent $\alpha_n -$
  - $\rightarrow$ Continuous mapping (vector field) of the points in $E_c$ vs $E_s$ space to line $E_c = E_s = E$
Tile Dual Summary/Discussion

– Rules of Thumb:

• (0) An intrinsic limit of normal hadron calorimetry: $\sigma_E/E > 11\text{-}13\%/\sqrt{E}$, given by the ratio of detectable neutron energy to the fluctuations in lost nuclear binding energy.

• (1) Contrast between $h_i/e_i$ ($i=\text{ionization}$) and $h_c/e_c$ ($C=\text{Cerenkov}$) for hadrons $h$ and e-m energy: the ratio of ratios $[h_i/e_i]/[h_c/e_c] \geq 4$ in order to reach incident hadron energy resolutions below $30\%/\sqrt{E}$, with $18\%/\sqrt{E}$ being a reasonable target to achieve using plastic scintillator and low index materials;

• (2) $h_i/e_i$: as large as possible -> hydrogenous or n-sensitized ionization detection media.

• (3) e-m energy resolution in Cerenkov light $< 70\%/\sqrt{E}$ to achieve $<20\%/\sqrt{E}$;

• (4 ) Resolution scales $\sim \sqrt{(f_{\text{sample}}/f_{\text{frequency}})}$.

• (5) Compensation achieved by enhancing neutron(hydrogenous/ n-absorbing) & ion fragment sensitivity
FUTURE Multiple Readout

- **Adding sensor tiles** relatively insensitive to MIPs, more sensitive to γβ->0
  - increases the contrast between e-m and hadronic energy (enhancing the low energy hadronic signal)

- **Secondary Emission**: Signal scales ~ dE/dx,
  - 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).

- **Homogeneous dense inorganic scintillators** (LYSO, PbWO₄,CeF₃, LAr, LXe..)... 
  - hi/ei ~ 0.4 and hc/ec ~ 0.25, or [hi/ei]/[hc/ec] ~1.6:
  -> Homogeneous calorimeters cannot achieve dual readout compensation better than ~50%/√E on hadrons, even with perfect separation between scintillator light & Cerenkov light in the homogeneous detector. [LAr/Ch4 ions instead of Scintillator]

σₑ/E ~15%-18%/VE on jets: scintillator sensors with hi/ei ~ 0.6-0.8 and Cerenkov sensors with hc/ec ≤ 0.2 are needed. To achieve hc/ec < 0.2, lower n Cerenkov radiators are required(βthresh ->1). Requires photons for e-m resolution < 70%/VE(GeV) or Nₚₑ > 2 pe/GeV.
Secondary Emission as a Calorimeter Sensor

- **Secondary Emission (SE).** Secondary Emission (SE) tiles are more sensitive to \( \gamma \beta > 0 \) particles than to MIPs - scales as \( dE/dx \). MIP SE signal \( \sim 100-200x \) less than at peak \( \gamma \beta \) SE signal – the opposite of Cerenkov light. SE tiles for correction for heavy fragments, lost neutron energies, slow hadrons. (triple/quadruple readout.) 1-2 MeV alpha particle: Max SE yield.

LHC SE Monitors:
SE Yield vs \( E_p \) (KeV)

\( 10^{20} \) p/cm\(^2\)!
(L) Secondary electron emission efficiency (L) of a single Cu cathode coated with 100 nm of Al2O3 (R) SEe yield vs \( \beta \gamma \) of 100-nm Al\(_2\)O\(_3\) cathode and SE yield of 9 stages of dynode.

The generated charge in a 9-stage secondary emission device as a result of an efficient secondary emission at the cathode.
Secondary Emission

80 GeV e⁻ Beam

Variable absorbers

SE SE SE SE SE

0 – 9 \( X_0 \)

Shower not contained laterally or longitudinally

→ Results require estimates and approximations

\( X_0 = 1.75 \text{ cm} \)

Molière Radius: 1.72 cm
Secondary Emission

Response of the SE module to 8 (left) and 16 GeV (right) electrons with tungsten absorbers. Data are shown in black and MC simulation results are shown in red.

We emphasize that SE is essentially unconditionally rad hard for any anticipated uses.
PMT for time/rate application requirements/properties:

- **RADDAM**: Metal Vacuum Envelopes + Quartz, Sapphire window PMT
  - **Dynodes**: metal oxide secondary emission > 10 GRAD
  - **Photocathode**: 10 nm film – energy loss ≤ 1 eV/mip.
  - no excess noise from RADDAM in metal-envelope/quartz etc window PMT.
  - Studies of glass-based PMT by ATLAS and NASA: Increased dark current entirely from glass induced phosphorescence
  - PMT survive > 20 years in satellites in the n-dose and solar wind in near-earth orbit.
- **Radiation Resistant, Thin (≤3mm) Windows**: quartz (SiO₂), MgF₂, or sapphire (Al₂O₃)
- **Gain**: \( G_{\text{eff}} \sim 5 \times 10^4 \): low gain to avoid dynode Ohmic heating @ 100 MHz. \( G_{\text{max}} \leq 2 \times 10^6 \)
- **Inductance, Capacitance** of anode plane to ground \( L < 5\text{pH} \); \( C < 0.2\text{pF} \)
- **B-Field**: Secondary Emission (SE) mesh/metal dynodes: ≥5% max Gain @1T (forward calo)
- **Compact Longitudinal Dimensions**: Glass window-to-Anode pins thickness ≤ 1.5cm
- **Multi-Anode Pixel Size**: ≤ 3x3 mm
- **Single p.e. timing**: \( T_{\text{rise}} \leq 0.5 \text{ ns}; \ T_{\text{fall}} < 0.5\text{ns}; \) Slew Rate >10 mV/ns into 300 Ω;
- **Latency/Transit Time**: \( T_{\text{trans}} < 3 \text{ ns} \) enables rate ≥ \( (2 \times T_{\text{trans}})^{-1} \sim 200 \text{ MHz} \)
- **Quantum Efficiency**: (QE) for Ultra bi-alkali photocathodes ~35%-40% (competes w/ SiPM?)
- **Tileable**: square or hex shapes
**SE+Cerenkov In-Situ Calorimeter Sensor**

- PMT: quasi-compensated calorimeter sensor
  - Cerenkov from Cerenkov tile+PMT Window
  - SE ionization from dynodes
  - Self-compensating: dynode signal adds low-E particles
  - High transverse segmented forward e-m stub-preshower calorimeter in front of CMS forward calorimeter at $3 \leq \eta \leq 5.3$?
Monte Carlo of Cerenkov radiator+PMT+ Absorber
(No Dynode S.E. included... yet)

100 GeV π

Calorimeter:  L: 1 cm quartz cubes + 1.5 cm thick PMT + 3mm W plates. R: e-m resolution

Stub Tracker/E-M PreRadiator: 5 quartz 1cm thick quartz tiles mated to 5 MAPMTs + 2 λ of Fe absorber tiles: Muon Cerenkov light trajectories/Cerenkov cones
Secondary Emission likely from $\mu$-halo, $\gamma$ or n sky-shine in the beam(?)

Preliminary Tests from DESY test beam
R7600 PMT with and without quartz block

With quartz block R7600
No quartz block

Secondary emission (?)
Showers (?)
Window

Secondary emission (?)
Showers (?)

Preliminary
Possible Application: CMS HF Forward Calorimeter
Stub Pre-Radiator/μ-Tag/Timing:30-40ps
Protects HF from Raddam
1x1 cm cells PMT+Quartz, ~1 \( \lambda \) thick W absorber, ~3m diameter
Extra Slides
Dual Correction

- A Simple analysis: Linear fit to hadron scatter points (Green line), with slope R, corrects the energy: Project the scatter points as a histogram perpendicular to the linear correlation, the energy distribution becomes Gaussian & narrower.

• Pion Energy $E$ (first order): $E = E_s + \alpha (E_s - E_c)$ with a given by slope $R$ as $R = (1 + \alpha)/\alpha$ or $\alpha = 1/(1 - R)$.
  - The angle between the line $E_c = E_s$ and fitted $\pi$ scatter plot line: $\theta = \arctan(R) - \pi/4$.

• $(E_s - E_c)$ grows as shower fluctuates into nuclear/hadronic energies.

• As slope $R$ gets steeper, the correction term $\alpha (E_s - E_c)$ becomes more important.
  - When Cerenkov $E_c$ is the same as scintillation $E_s$ (example: e’s or $\pi$’s exchange to $\pi^0$’s),
    then $(E_s - E_c) \sim 0$, $E = E_s = E_c$

• This analysis can be easily shown to be equivalent to that of Wigmans using D.Groom’s analysis of dual or Cerenkov readout.
Multiple Tile Readout

- MTR can be tuned for best $\sigma E/E$, timing, rate, and radiation resistance
- MTR can enhance Energy, Intensity, and Cosmic Experiments
- MTR enables Radiation-Resistance
- MTR compatible with Energy Flow high granularity calorimetry.
- MTR can be added to Calice or the CMS endcap HGCal and other existing calorimeters
- MTR can be selected with Rad Resistant tiles.
Beyond: Multiple Particle Flow Readout -3

- **Triple Readout and beyond**: 3+ tiles to improve dual readout:
  - non-hydrogenous scintillator,
  - hydrogenous/neutron-sensitive scintillator,
  - 2 indices of Cerenkov tile(s), SE tiles....
  - Compare less n-sensitive scintillators [non-hydrogenous] to more n-sensitive H or n-converting scintillator tiles.
- **Combined Dual/Triple Readout with Particle Flow**: Add Cerenkov tiles, TRD tiles, SE tiles, or others to existing Particle/Energy flow calorimeter prototypes.
- **Neutron-enhanced detecting scintillator tiles** thin film coatings - $^{10}$B, $^6$Li, hydrogenous materials [$^6$LiH] – thin clear film, buffered w/ alumina films; interesting: $\text{Li}^{6}\text{B}^{10}\text{H}_4$ which would be transparent if deposited as thin films between clear buffers. $^{10}$B SE yield dynodes.
- **Liquids**: very large homogeneous detectors: LB, cosmic neutrinos or proton decay
  - 1) water “tiles” (n=1.29-1.31 TeflonAF light pipe) + LS tiles – no absorber
  - 2) LArgon drifted ions + Cerenkov light detection. The index n good e/h contrast; scintillation light at 128nm will not penetrate PMT windows.
A Physics Example: Calo Precision jets

- **Jet-Jet masses:** Goal for future experiments: $Z \rightarrow \text{jetjet}$ vs $W \rightarrow \text{jetjet}$
  
  Ratio $W,Z \rightarrow \text{jj} : W,Z \rightarrow \text{leptons} \sim 6-7$

- Reconstruct AND Separate ($E_{\text{miss}}, \text{jet tags, V-V scattering, BSM, W' Z'…}$)

- Separation of $W$ from $Z$: $\sigma_{E_{\text{jet}}/E_{\text{jet}}} \sim 3\%$ necessary at 100 GeV, with typical single particle energies $\sim 10$ GeV [ASIDE: during collision crossing times which may be a small as $\sim 10$’s of ns, pileup events $\sim 200$/crossing and raddam exceeding 50-100MRad.] A 3%-4% jet energy resolution from 50-500 GeV gives 2.6-2.3σ $W/Z$ separation. J-J mass resolution is important in searches for heavy $W'/Z'$, vector boson scattering, triple VVV…

- $W/Z \rightarrow \text{jet-jet separation: } \textbf{Left} -$ calorimeter $\sigma_{E/E}=60%/\sqrt{E}$; $\textbf{Middle} \sigma_{E/E} 22%/\sqrt{E}$ (3% @ 50 GeV) $\sim 2.6\sigma$ separation; $\textbf{Right}$ -perfect resolution: $\sim 4.5\sigma$ separation. (from M. Terwort)