The state of art
Towards ILC calorimetry
Important calorimeter features

- Energy resolution
- Position resolution (need 4-vectors for physics)
- Particle ID capability
- Signal speed
The importance of energy resolution

**FIG. 7.50.** Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram a) shows the measured data points, together with the results of the best fits to the QCD background alone (dashed curve), or including the sum of two Gaussian functions describing $W, Z \rightarrow q\bar{q}$ decays. Diagram b) shows the same data after subtracting the QCD background. The data are compatible with peaks at $m_W = 80$ GeV and $m_Z = 90$ GeV. The measured width of the bump, or rather the standard deviation of the mass distribution, was 8 GeV, of which 5 GeV could be attributed to non-ideal calorimeter performance [Jen 88].
Particle ID does NOT require segmentation

\[ e/\pi \] separation using time structure of the signals

**FIG. 7.33.** The distribution of the full width at one-fifth maximum (FWFM) for 80 GeV electron and pion signals in SPACAL [Aco 91a]. The left-hand scale applies to the electron signals, the right-hand scale to the pion signals.
The importance of signal speed

**FIG. 7.19.** Oscilloscope picture of two events separated by 8 ns in the Zero Degree Quartz Fiber Calorimeter of the NA50 experiment in the CERN heavy-ion beam [Arn 98].
Important calorimeter features

✦ Energy resolution
✦ Position resolution (need 4-vectors for physics)
✦ Signal speed
✦ Particle ID capability
  ✦ but also
✦ Signal linearity or, at least
✦ Well known relationship between signal and energy (reliable calibration)

Most hadron calorimeter fall short in this respect
High resolution hadron spectroscopy

- High-resolution Hadron Calorimetry (for jet spectroscopy) very relevant for Linear high-energy $e^+e^-$ Colliders
  - Uncertainties due to jet algorithms/underlying event small
  - No constrained fits as in LEP (beamsstrahlung)
    - \( \Rightarrow \) Intrinsic detector properties limiting factor
- High-resolution Electromagnetic and high-resolution Hadronic calorimetry are mutually exclusive:
  - Good jet energy resolution \( \Rightarrow \) Compensation \( \Rightarrow \) very small sampling fraction ($\sim 3\%$) \( \Rightarrow \) poor electron, photon resolution
  - Good electromagnetic resolution \( \Rightarrow \) high sampling fraction (100% Crystals, 20% LAr) \( \Rightarrow \) large non compensation \( \Rightarrow \) poor jet resolution
Ultimate hadron calorimetry

- Why not aim for hadron calorimetry with the same level of precision as achievable in electromagnetic calorimeters?
  - ⇒ Need to eliminate/reduce hadron-specific fluctuations
  - Fluctuations in electromagnetic shower content \( f_{em} \)
  - Fluctuations in “visible energy” (nuclear breackup)
- Achievable limit: \( \sigma/E \sim 15%/\sqrt{E} \)
Fluctuations in the em shower component ($f_{em}$)

- **Why are these important?**
  - Electromagnetic calorimeter response $\neq$ non-em response ($e/h \neq 1$)
  - Event-to-event fluctuations are large and non-Gaussian
  - $<f_{em}>$ depends on shower energy and age

- **Cause of all common problems in hadron calorimeters**
  - Energy scale different from electrons, in energy-dependent way
  - Hadronic non-linearity
  - Non-Gaussian response function
  - Poor energy resolution
  - Calibration of the sections of a longitudinally segmented detector

- **Solutions**
  - Compensating calorimeters ($e/h = 1$), e.g. Pb/plastic scintillator
  - Measure $f_{em}$ event-by-event
High resolution jet spectroscopy
Compensating Pb/scintillator calorimetry

JLC prototype studies: NIM A432 (1999) 48

![Graph showing the ratio of electron to pion (e/π) corrected as a function of lead thickness for different energies (2 GeV, 3 GeV, 4 GeV). The scintillator thickness is 2 mm. The graph includes error bars for each data point. A linear fit is shown with a dashed line at e/π = 1.0.]
What compensation does and does not for you

- Compensation does **not guarantee** high resolution
  
  - Fluctuations in $f_{em}$ are eliminated, but others may be very large
  
  - Example: **Texas Tower effect**

- Compensation has some **drawbacks**
  
  - Small sampling fraction required $\rightarrow$ **em resolution limited**
  
  - Relies on neutrons $\rightarrow$ calorimeter signals have to be integrated over **large volume and time**. SPACAL’s 30%/\sqrt{E} needed 15 tonnes and 50 ns. Not always possible in practice
Compensation in a U/gas calorimeter

![Graph showing compensation in a U/gas calorimeter.](image)

**Fig. 3.31.** The average signals for electrons and pions, measured with the uranium/gas calorimeter of the L3 Collaboration, for two different choices of gas with which the proportional wire chambers were operated. From: NIM A251 (1986) 258.
Compensation in gas calorimeters
Hadronic response function

**Fig. 4.57.** Signal distributions recorded with the L3 $^{238}$U/gas calorimeter, for 6 GeV electrons (a) and 6 GeV pions (b), with two different gas choices. The solid histograms were obtained with a mixture of argon (80%) and CO$_2$ (20%), the dashed histograms with isobutane. From: NIM A251 (1986) 258.
Compensation requires large integration volume!

**Fig. 4.30.** The hadronic energy resolution as a function of the effective radius of the area over which the calorimeter signals were integrated. The energy resolutions have been normalized to the value for the complete SPACAL detector. Results for 9.7 and 80 GeV $\pi^-$ that entered the calorimeter at an angle of 3° with the fiber axis (a). The same data as a function of the lateral shower leakage fraction (b). From: NIM A308 (1991) 481.
High-resolution hadron calorimetry

- **Non-solution**
  - There is no merit in “offline compensation” (e/π by weighting)
  - Resolution is determined by fluctuations, not by mean values
  - Side effect: increased signal non-linearity, response depends on starting point shower,... See NIM A487 (2002) 381
Fig. 4.59. The $e/\pi$ signal ratio at 80 GeV (a) and the energy resolution (b) of a quartz-fiber calorimeter preceded by dead material (iron), as a function of the thickness of this material [Fer 97]. The energy resolution is given for 80 GeV electrons and pions, and for multi-particle “jets” generated by 375 GeV pions in an upstream target.
Particle Flow Analysis (PFA)

- Use tracking, particle ID and calorimetry to measure 4-vectors of jets
- Charged particles represent typically 65% of the jet energy
- However, if only charged jet components are measured: \( (\sigma/E_{\text{jet}}) = 25-30\% \) independent of jet energy \( \rightarrow \) Calorimetry essential
- The problem with this method is shower overlap. Need to deconvolute contributions from showering charged particles to avoid double counting
- This problem is not solvable with a finer granularity. The showers have certain transverse dimensions and exhibit large fluctuations in all dimensions
- Larger distance vertex-calorimeter and larger B-field would help
- NIM A495 (2002) 107: Method may give improvement of \( \sim 30\% \)
Design goal ILC: separate $W, Z \rightarrow q\bar{q}$

- No kinematic constrains as in LEP (Beamstrahlung)
Example of PFA at LEP: ALEPH

Attempt to reconstruct hadronic event structure using particle identification and software compensation
PFA at Hadron Collider

- No kinematic constraints as at LEP

Figure 4: The central detector resolution $\sigma_D$ is plotted as a function of $P_T^\gamma$ for the two methods.
In order to reduce problems of shower overlap, ILC R&D focuses on reducing the shower dimensions and decreasing the calorimeter cell size.

- $X_0 = 1.8 \text{ cm}$, $\lambda_I=17 \text{ cm}$
- $X_0 = 0.35 \text{ cm}$, $\lambda_I=9.6 \text{ cm}$

**How about calibration?**
PFA method: “π” jet

✦ The circles indicate the characteristic size of the showers initiated by the jet fragments, i.e. $Q_M$ for em showers and $\lambda_{\text{int}}$ for the hadronic ones.
Improvement of energy resolution expected with PFA

Fig. 11. The jet energy resolution as a function of energy, obtained after applying the Energy Flow Method (the dots), using simulated data from a calorimeter with a jet resolution given by the dashed curve. For comparison, the jet resolution of a compensating calorimeter is given (SPACAL [7]). From: NIM A495 (2002) 107.
ILC R&D example (PFA): CALICE

164 Physicists, 28 Institutes, 9 Countries: 3 Regions

- ECAL and HCAL together, different options
- electron and hadron beams, start end 2004 at DESY

CALICE ECAL prototype

full Si/W prototype (24 $X_0$)
- 30 layers $\times$ 18 cm $\times$ 18 cm interleaved with 0.5 mm Si pads
- W absorber, 10+10+10 layers, 1.4 mm:2.8 mm:4.2 mm thick per respective layer
- readout by $1 \times 1$ cm$^2$ cells, total: 9720 channels
The DREAM principle

- Quartz fibers are only sensitive to em shower component!
  - Production of Čerenkov light $\Rightarrow$ Signal dominated by electromagnetic component
  - Non-electromagnetic component suppressed by a factor 5 $\Rightarrow e/h=5$ (CMS)
  - Hadronic component mainly spallation protons $E_k \sim$ few hundred MeV $\Rightarrow$ non relativistic $\Rightarrow$ no Čerenkov light
  - Electron and positrons emit Čerenkov light up to a portion of MeV
- Use dual-readout system:
  - Regular readout (scintillator, LAr, ...) measures visible energy
  - Quartz fibers measure em shower component $E_{em}$
  - Combining both results makes it possible to determine $f_{em}$ and the energy $E$ of the showering hadron
  - Eliminates dominant source of fluctuations
Quartz fibers calorimetry

Radial shower profiles in:
- **SPACAL** (scintillating fibers)
- **QCAL** (quartz fibers)
Radial hadron shower profiles (DREAM)
DREAM calorimeter

- **DREAM: Dual REAdout Module**

- **Composition:**
  - Cu : scintillator : quartz fibers : air
  - 69.3 : 9.4 : 12.6 : 8.7
  - **Filling fraction** (active material/absorber) = 31.7%
  - **Sampling fraction** for mip in Cu/scintillator = 2.1%

DREAM Collaboration: Cosenza, Iowa State, Pavia, Roma I, Texas Tech, Trieste, UCSD
DREAM prototype

Basic structure:
4x4 mm$^2$ Cu rods
2.5 mm radius hole
7 fibers
3 scintillating
4 Čerenkov

DREAM prototype:
5580 rods, 35910 fibers, 2 m long ($10 \lambda_{\text{int}}$)
16.2 cm effective radius ($0.81 \lambda_{\text{int}}, 8.0 \rho_M$)
1030 Kg
$X_0 = 20.10$ mm, $\rho_M = 20.35$ mm
19 towers, 270 rods each
hexagonal shape, 80 mm apex to apex
Tower radius 37.10 mm ($1.82 \rho_M$)
Each tower read-out by 2 PMs (1 for Q and 1 for S fibers)
1 central tower + two rings
DREAM prototype:
tested at the CERN H4 beam line
Data samples:
π from 20 to 300 GeV
“Jets” from 50 to 330 GeV
“Jets” mimicked by π interaction on 10 cm polyethylene target in front of the detector
Experimental setup for DREAM test beam

- Beam enters the setup labeled HOD, IT, and PSD.
- The DREAM module is located centrally.
- An absorber is placed on the right side.

Graphical representation:
- X-axis: Signal (mip)
- Y-axis: Events per bin
- Two curves labeled 'downstream of target' and 'upstream of target'
- A note on high-multiplicity jets
- Text: "JET" Measurements
Calibration with 40 GeV electrons

- Tilt 2° respect to the beam direction to avoid channelling effects
- Modest energy resolution for electrons (scintillator signal):
  \[
  \frac{\sigma}{E} = \frac{20.5\%}{\sqrt{E}} + 1.5\%
  \]
100 GeV single pions (raw signals)

- Signal distribution
  - Asymmetric, broad, smaller signal than for e⁻
  - Typical features of a non-compensating calorimeter
Hadronic response (non-linearity)
The (energy independent) $Q/S$ method

$$R(f_{em}) = E \left[ f_{em} + \frac{1}{e/h} (1 - f_{em}) \right]$$

$$e/h = 1.3(S), 5(Q)$$

$$S = E \left[ f_{em} + \frac{1}{(e/h)_S} (1 - f_{em}) \right]$$

$$Q = E \left[ f_{em} + \frac{1}{(e/h)_Q} (1 - f_{em}) \right]$$

$$\frac{Q}{S} = \frac{R_Q}{R_S} = \frac{f_{em} + 0.20(1 - f_{em})}{f_{em} + 0.77(1 - f_{em})}$$
DREAM: relationship between Q/S ratio and $f_{\text{em}}$
Effect of selection based on $f_{em}$

*100 GeV $\pi^-$ Čerenkov signal*

- Entries: 78198
- Mean: 66.1
- RMS: 12.4

Number of events per GeV vs. Čerenkov signal (GeV)
Finally a way to measure $e/h$

\[ R(f_{em}) = p_0 + p_1 f_{em} \quad \text{with} \quad \frac{p_1}{p_0} = e/h - 1 \]

Cu/scintillator $e/h = 1.3$  
Cu/quartz $e/h = 4.7$
Dual-Readout Calorimetry in Practice

- The (energy-independent) Q/S method
  - Hadronic response (normalized to electrons)
    \[
    \frac{Q}{S} = \frac{R_Q}{R_S} = \frac{f_{em} + 0.20(1 - f_{em})}{f_{em} + 0.77(1 - f_{em})}
    \]
  - Q/S response ratio related to \( f_{em} \) value → find \( f_{em} \) from Q/S
    \[
    R(f_{em}) = f_{em} + \frac{1}{e/h}[1 - f_{em}], \quad e/h = 1.3(S'), 5(\tilde{C}')
    \]
  - Correction to measured signals (regardless of energy)
    \[
    S_{\text{corr}} = S_{\text{meas}} \left[ \frac{1 + p_1/p_0}{1 + f_{em} \cdot p_1/p_0} \right], \quad \text{with} \quad \frac{p_1}{p_0} = (e/h)_s - 1
    \]
    \[
    Q_{\text{corr}} = Q_{\text{meas}} \left[ \frac{1 + p_1/p_0}{1 + f_{em} \cdot p_1/p_0} \right], \quad \text{with} \quad \frac{p_1}{p_0} = (e/h)\tilde{C} - 1
    \]
Hadronic response: Effect \( Q/S \) correction
DREAM: Effect of corrections (200 GeV “jets”)
DREAM: Energy resolution “jets”

- After corrections the energy resolution is dominated by leakage fluctuations
CONCLUSIONS from tests

✦ DREAM offers a powerful technique to improve hadronic calorimeter performance:
  ✦ Correct hadronic energy reconstruction, in an instrument calibrated with electrons!
  ✦ Linearity for hadrons and jets
  ✦ Gaussian response functions
  ✦ Energy resolution scales with $\sqrt{E}$
  ✦ $\sigma/E < 5\%$ for high-energy “jets”, in a detector with a mass of only 1 ton! (dominated by fluctuations in shower leakage)
Published Papers

1. “Separation of scintillation and Cherenkov light in an optical calorimeter”
   N. Akchurin et al.

2. “Comparison of high-energy electromagnetic shower profiles measured with scintillation and Cherenkov light”
   N. Akchurin, K. Carrell, H. Kim, R. Thomas, R. Wigmans, J. Hauptman and A. Penzo

3. “Hadron and jet detection with a dual-readout calorimeter”
   N. Akchurin et al.

4. “Electron detection with a dual-readout calorimeter”
   N. Akchurin et al.

5. “Muon detection with a dual-readout calorimeter”
   N. Akchurin et al.
Conclusions on DREAM

- The DREAM approach combines the advantages of compensating calorimetry with a reasonable amount of design flexibility
- The dominating factors that limited the hadronic resolution of compensating calorimeters (ZEUS; SPACAL) to 30 - 35%/$\sqrt{E}$ can be eliminated
- The theoretical resolution limit for hadron calorimeters (15%/$\sqrt{E}$) seems within reach
- The DREAM project holds the promise of high-quality calorimetry for all types of particles, with an instrument that can be calibrated with electrons
How to improve DREAM performance

- Build a larger detector → reduce effects side leakage
- Increase Čerenkov light yield
  - DREAM: 8 p.e./GeV → fluctuations contribute 35%/√E
  - No reason why DREAM principle is limited to fiber calorimeters
  - Homogeneous detector ?!
  - ⇒ Need to separate the light into its Č, S components
- For ultimate hadron calorimetry (15%/√E) Measure $E_{\text{kin}}$ (neutrons).
  - Is correlated to nuclear binding energy loss (invisible energy)
  - Can be measured with third type of fiber TREAM
Conclusions

✦ In the past 20 years calorimetry has become a mature art.

✦ The next major challenge will be the experimentation at the ILC where the physics will require jet spectroscopy at the 1% level ($\sigma/E \sim 30\%/\sqrt{E}$).

✦ Two techniques (PFA and Dual Readout) are trying to cope with this challenge.

✦ An R&D project (DREAM) aims to demonstrate in the next few years that the ultimate hadron resolution ($15\%/\sqrt{E}$) is at reach.