TOTAL ABSORPTION HOMOGENEOUS CALORIMETER WITH DUAL READOUT
Summary

- Theoretical and experimental foundations of high resolution hadron calorimetry established more than 20 years ago.
- Progress with development of dense scintillating materials and compact photodetectors enables construction of hadron/jet calorimeters with energy resolution better than 20%/\sqrt{E}.
- Past and present generations of experiments limited by physics and not the hadron calorimeter performance, experiments at the future lepton collider may be the first ones requiring high resolution hadron calorimetry.
- Practical construction of very high resolution calorimetry is technically possible, but it requires further development of inexpensive scintillating crystals/glasses and economical large area photodetectors.
- In any realistic detector the ultimate energy resolution is likely to be limited by the leakage fluctuations and calibration accuracy. At high energies it is the constant term, what counts!
(Apparent Lack of?) Progress with Hadron Calorimeters

- More than 30 years ago: AFS hadron calorimeter 36%/sqrt(E)

**ABSTRACT**

We present results obtained with a uranium/copper scintillator fine-sampling calorimeter with wavelength shifter readout. Test beam measurements made with $e^\pm$, $\pi^\pm$ and protons in the momentum range 0.3 to 40 GeV/c are presented. The calorimeter achieves energy resolutions of $\sigma(E)/E = 0.36/\sqrt{E}$ and 0.16/\sqrt{E} for hadrons and electrons, respectively. The measured ratio of response for electrons to that for hadrons is 1.11, for energies of 2 GeV or more. The spatial resolution achieved for single particles at normal incidence is $\sim 1$ cm for electromagnetic showers and $\sim 3$ cm for hadronic showers. Operational experience over three years of running at the CERN ISR, including operation at very high luminosities ($\sim 1.4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$), is described.

- Now: with great effort we can almost as well in R&D projects, much worse in real experiments
- Compare with the progress in other experimental techniques
Huge Progress in Understanding Calorimetry and Physics of Hadronic Showers

- Nuclear effects induce dominating contribution to fluctuations of the observed signals
- Huge increase of the available computing power (GRID!) enables calculations of mind-boggling complexity
- But the complete and correct physics content must be provided
- Fundamental limitation of sampling calorimeters: 'sampling fraction depends on particle type and energy => hence they vary within the shower. This is in addition to unavoidable sampling fluctuations and this is the origin of a 'neutron problem'.
- Homogenous total absorption calorimetry (if practical and affordable) is an interesting candidate for super-high resolution calorimetry (both EM and hadron). Correlation of Cherenkov and scintillation signals can be used to correct for energy lost to nuclear binding and pions masses.
TAHCAL at Work: Single Particle Measurement

- 100 GeV $\pi^-$
- Full Geant4 simulation
- Raw (uncorrected)
- $\Delta E/E \sim 3.3\%$
- but significant non-linearity, $E \sim 92$ GeV

After dual readout correction, correction function (C/S) determined at the appropriate energy:

- Linear response: $S/B=1$ for all energies
- energy resolution scales as $\Delta E/E \sim \alpha/\sqrt{E}$ (no constant term)
- stochastic term $\alpha \sim 12-15\%$
Dual Readout Correction at Different Energies

Correlation of the fraction of 'missing energy' and Cherenkov-to-scintillation ratio for showers of different energies: 10 - 200 GeV:

- High energy showers contain more EM energy (range of C/S confined to higher and higher values)

- Width of the correlation shrinks like \( \sim 1/\sqrt{E} \) (hence the \( \Delta E/E \sim 1/\sqrt{E} \))

- Overall shape quite similar, but significant (compared to the width of the correlation) differences present. They will lead to:
  - non-optimal energy resolution
  - non-linearity of the response
  - contribution to the jet energy resolution
TAHCAL: The Energy Resolution with the Global Correction

With very crude reconstruction and non-optimal global correction function:
• energy resolution shows no constant term and scales $\Delta E/E \sim 1/\sqrt{E}$
• stochastic term in the energy resolution is $\sim 15\%$ for single hadrons, $2\%$ for electrons and $\sim 22-23\%$ for jets
• this performance is limited by the shortcomings of the current simulation programs
Total Absorption Calorimeter in a Realistic Experiment

- Functional role:
  - Measure energy of electrons/photons
  - Reconstruct jets, measure invariant mass
  - Di-jet mass
  - Event Timing
  - Particle ID
  - Provide seed for trackers
  - Provide spatial (position/angle) measurement of neutrals
  - Separate close photons
  - Trigger etc. Etc..

- Geometry and granularity of the calorimeter requires careful optimization of the overall physics capabilities of the experiment. Crystals based calorimetry offers great degree of flexibility.
Separated Functions Calorimeter

Calorimeters are expected to measure energies of particles/jets. But... They are also expected to provide topological information: positions, directions, close showers separation. These additional requirements tend to complicate the detector design and compromise the energy.

A possible solution: decouple the energy and topological measurements. Delegate the topological measurements to two-three layers of silicon pads. Negligible fraction of shower energy deposited in silicon should have no adverse effect on the overall energy resolution.

A possible alternative: a layer of imaging crystals made of crystalline fibers? (P Lecoq)

Such a concept has been put forward, and supported by INFN and DESY. Prototype has been constructed and tested in test beams at Frascatti and at CERN: LCCAL (P. Checchia, LCWS04)

30 GeV electrons

3 layers of 0.9 x 0.9 cm silicon pads at 2, 6 and 12 X₀
Conceptual Design of a TAHCAL: an Example

- Four layers of $5 \times 5 \times 5$ cm$^3$ crystals (a.k.a. EM section): 72,000 crystals
- Three embedded silicon pixel layers ($e/\gamma$ position, direction)
- 10/16 (barrel/endcap) layers of $10 \times 10 \times 10$ cm$^3$ crystals (a.k.a. hadronic section): 70,000 crystals
- 4(8?) photodetectors per crystal. Half of the photodetectors are 5x5 mm and have a low pass edge optical filters (Cherenkov)
  - No visible dead space.
  - 6$\lambda$ at 90$^\circ$, 9$\lambda$ in the endcap region
  - Signal routing avoiding projective cracks
  - Should not affect the energy resolution
  - 500,000(1,000,000?) photodetectors
- Total volume of crystals ~ 80-100 m$^3$. 
TAHCAL in SiD: Initial Engineering

K. Krempetz, Fermilab:
... the crystal calorimeter could easily be incorporated in the SiD detector. The design that is presented has many engineering challenges which will need to be prototyped and tested before a final design could be made.

6λ at 90°, 9 λ in the endcap
- Good segmentation
- silicon photodetectors with ASIC readout electronics
- Significant imaging capabilities
Practical Limitations: Dead Volumes

Any realistic calorimeter design will induce imperfections: support structures, cables, etc..

Impact of these imperfections on the calorimetric measurements can only be evaluated within a specific detector design, and this, in turn depends on specific crystals/glasses, photodetectors, etc..

Sensitivity estimate: contribution to resolution as a fraction of energy lost in dead areas. Random distribution of dead volumes assumed.

Dead volumes absorbing up to 5% of the calorimeter volume induce negligible contribution to energy resolution.
Practical Limitations: Calibration

• Segmented crystal calorimeter involves large number of independent detector volumes which need to be inter-calibrated
• This is always a pain, but at least straightforward in principle (T1004 test beam: upper row the response of collection of crystals before inter-calibration, bottom row – after inter-calibration)
• Total number of channels ~ 10^6 - order of magnitude beyond CMS
• Calibration and monitoring will be challenging in particular for the Cherenkov component. May require some UV light distribution system.
Practical Limitation: Light Yield

- To maintain the resolution at the level of ~ 10%/sqrt(E) one needs to detect ~ 200 photoelectrons/GeV in scintillation and ~ 1-2 photoelectrons/GeV in Cherenkov.

- It is sensible to have large contingency (it is very easy to lose light). Sensible specs: 1000 photoelectrons in scintillation, 10 photoelectrons in Cherenkov.

- This is a complicated requirement involving the crystals, geometry and photodetectors (sizes, quantum efficiency, spectral response)

- Typical light yields for scintillating crystals: 100 – 50,000 photoelectrons per MeV

- Best light yield for Cherenkov: ~ 2 photons/MeV

- Maintaining the Cherenkov and scintillation light yield from a single volume is challenging.
TAHCAL: Beyond the Simulation of the Ideal Detector

- TAHCAL offers an attractive perspective for a very high resolution jet calorimeter.
- It could be constructed using the existing/nearly existing technologies, but it is not affordable.
- The principal challenges on the road to the realistic detector:
  - Cost: crystals. Several of the existing crystals can be used. None of them is close to be affordable. Need a development of inexpensive crystals optimized for TAHCAL.
  - Cost/performance: photodetectors. MPPC/SiPM must come through on their promises. Large(r) area detectors necessary (especially for Cherenkov readout).
  - Cost (of the entire detector): high energy resolution requires good containment. In a realistic case of space constrained by the superconducting coil the leakage fluctuations are likely to limit the energy resolution.
  - Calibration: to achieve the energy resolution no segmentation is necessary. Several good physics and engineering reasons demand relative fine segmentation. Summing up the individual energy deposits requires ‘good enough’ relative calibration of the response. Calibration of readout of Cherenkov light is particularly challenging.
Leakage

- A realistic detector design may provide some 120-150 cm of radial space for calorimeters (between the tracker at the coil).
- To minimize the leakage fluctuations it is important to maximize the average density of the calorimeter, including the readout. This is of particular importance in high resolution calorimeters.
- Heavy scintillating crystals and compact silicon photodetectors offer a possibility for the average interaction length of the order of 20-21 cm.
- Longitudinal segmentation an important tool to detect and to minimize the impact of leakage on the energy resolution.
The Real Challenges

- Can such crystals be designed/produced? Yes. (see A. Gektin’s talk)
- Can such crystals be affordable (target price ~ $1/cc)? Perhaps. What drives the cost of crystals?
  - Energy cost for melting (melting temperature)
  - Crucibles material wear
  - Raw materials (BGO)
- Do we need to insist on single crystals?? NO! High density scintillating glasses, metamaterials should be considered. Cost can be greatly reduced.
- SiPM’s are probably adequate to detect scintillation, but they may be insufficient for Cherenkov. Development of large area compact photodetectors very important.
Alternatives?

- Dual readout totally active calorimeter may prove to be impractical or too expensive. It is too early to focus on alternatives, but they do exist:

- Separated readout design: scintillating glass interspersed with Cherenkov radiator, like PbF2? Most of the volume filled with scintillating glass to minimize the sampling effects. Similarity of the 'inactive' and the scintillating material of great help.

- Scintillating glass only calorimeter? While inferior in the performance it may provide an interesting and affordable compromise. And the final performance, including all the systematics, may prove to be sufficient to maintain the physics capabilities of the experiment.
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