High Resolution Jet Calorimetry Option

Principles of Operation: Energy Resolution

Principal limitations of the hadron energy resolution come from two sources:

- sampling nature of the conventional hadron calorimeters. In addition to the inevitable fluctuations of the energy sharing between passive and active parts of the calorimeter (sampling fluctuations) it induces additional fluctuations due to the fact that the effective sampling fractions depend on the particle type and its energy
- a significant and fluctuating fraction of the incoming hadron energy is converted into non-observable forms of energy (primarily nuclear binding energy)

These effects lead to a significant non-linearity of the response of the detector and to a difference of the response to neutral and charged pions (often referred to as e/ ratio). They are responsible for the dominant contribution to jet energy resolution, as the result of the fluctuations in the jet fragmentation.

Good jet energy resolution requires a calorimeter where both of the above-mentioned factors are eliminated or largely reduced. This can be accomplished with a homogenous, totally active calorimeter with dual readout: scintillation and Cherenkov. Totally active calorimeter eliminates all contributions related to the sampling nature of the device whereas an anti-correlation between the scintillation and Cherenkov light (see Fig.1) can be used to reduce the fluctuations of the nuclear binding energy loss.

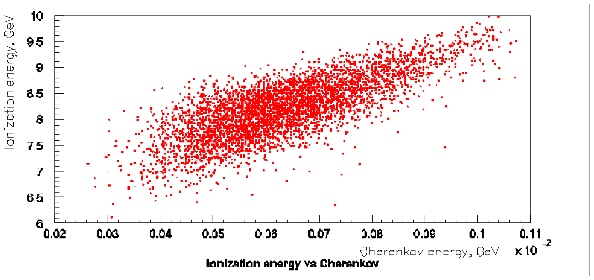

Fig. 1 Correlation of the total ionization energy loss in a hadron showers with the amount of the Cherenkov light.

Anti-correlation of Cherenkov and scintillation light can be expressed as a dimensionless fashion as a fraction of the total particle energy detected via scintillation as a function of Cherenkov-to-scintillation light, as shown in Fig. 2 (a). Application of such an event-by-event correction to a sample of hadron induced showers improves the energy resolution and makes the average hadron response equal to the beam energy (hence equal to the response to electrons on neutral pions of the same energy), as shown in Fig 2(b) .

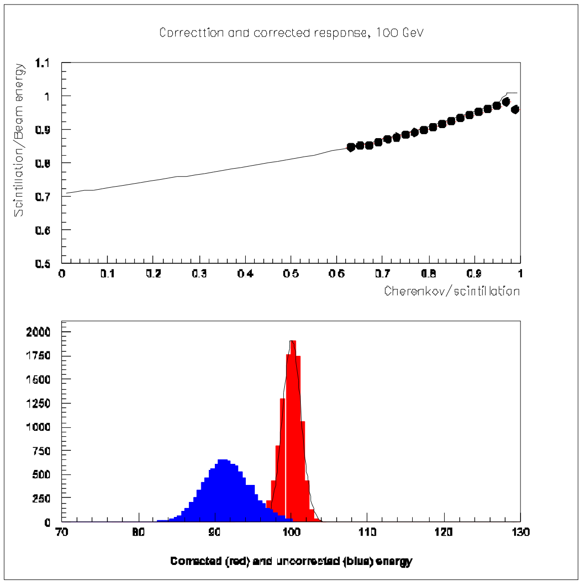

Fig. 2 (a) -top: The correlation between the average fraction of the beam energy detected via scintillation and the ratio of responses measured with the Cherenkov and the scintillation light. (b)-bottom: A response of the total absorption calorimeter to 100 GeV pion beam (blue) and the same response corrected on the event-by-event basis using the correlation from Fig. 2 (a). Both results are based on GEANT4 simulation.

The correlation function, Fig. 2(a), is very weakly dependent on the parent particle type and/or energy and even use of the same function at different energies does not spoil the energy resolution. This is of particular importance in the case of hadronic jets, where the contributions of different particles are in general summed up. Fig 3. illustrates the resulting energy resolution of the total absorption calorimeter for single hadrons and for hadronic jets (in the latter case a crude algorithm of summing up all scintillation and all Cherenkov light and applying one overall correction was used.) Figs 3 and 4 show the resulting corrected response to single hadrons and hadronic jets of different energies. The response function is to a good approximation gaussian with no visible tails of the resolution.

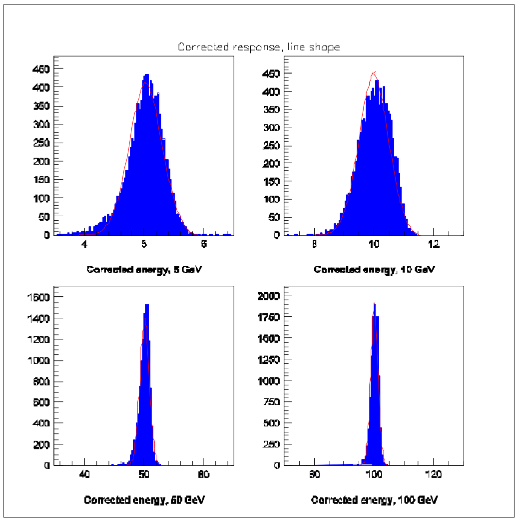

Fig. 3. Corrected response of a total absorption dual readout calorimeter to single hadrons of different energies.

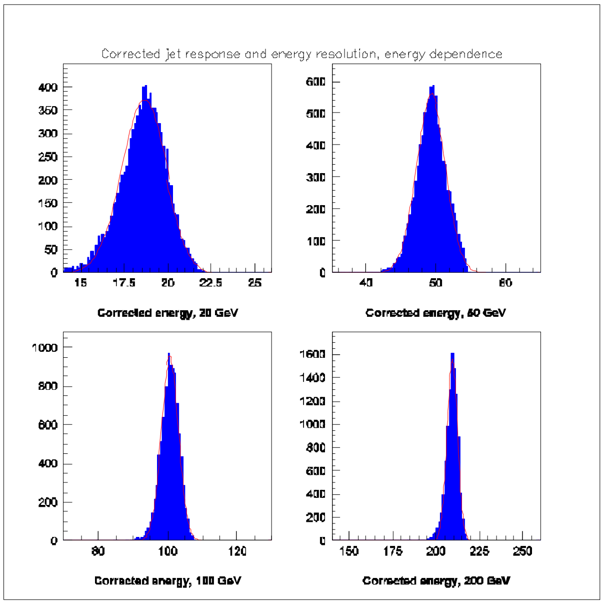

Fig. 4. Corrected response of a total absorption dual readout calorimeter to hadronic jets of different energies. Jets are generated using Pythia.

The resulting corrected response and energy resolution for single hadrons and jets energy is shown in Figs. 5 and 6. For single hadrons the energy resolution is of the order of $0.15/\sqrt{E}$ whereas for hadronic jets above 100 GeV the energy resolution is better than $0.25/\sqrt{E}$. There is no indication of a deviation from the $1/\sqrt{E}$ behavior of the resolution in the investigated energy range. In case of hadronic jets there some residual non-linearity of the overall response and a degradation of the energy resolution at low energies are probably a result of a very crude reconstruction and correction algorithm.

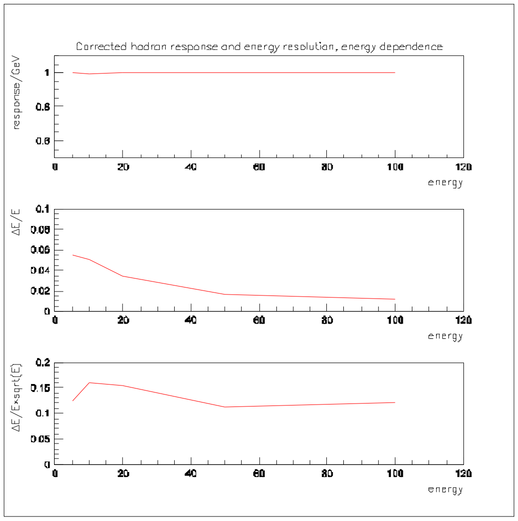

Fig. 5. Response linearity, energy resolution and scaled energy resolution for single hadrons.

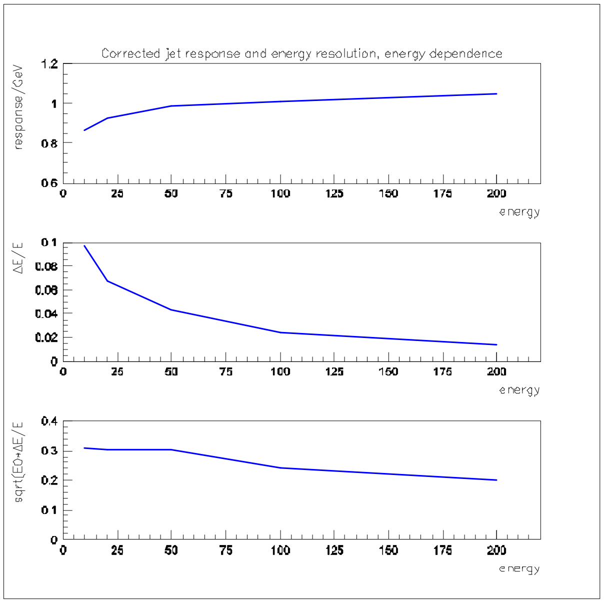

Fig. 6. Response linearity, energy resolution and scaled energy resolution for hadronic jets.

It should be pointed out that the energy resolution described above is attained without any relation to the detector granularity, only a total amount of scintillation and Cherenkov was used. Such a technique does not, therefore, require any particular segmentation of the calorimeter on one hand, but it does not preclude it other, provided that the adequate cross-calibration of the detector elements is accomplished. The calorimeter segmentation will be determined by a combination of ’other’ physics-driven requirements and practical aspects like calibration and engineering aspects. One should expect that additional information available from the spatial distribution of the observed signals may be used to improve further the energy resolution for the hadronic jets.

Particle Identification Capabilities

One of the pre-requisites necessary to attain good energy resolution is the detection of

Cherenkov light produced by particles traversing the calorimeter. At the same time this may provide unique capabilities for the particle identification, at least for some of the jet particles. Recent initiatives on the development of picosecond timing [Chicago/Argonne/Saclay offer an interesting possibilities for very precise time-of-flight measurement and the identification of lower energy particles inside the hadronic jet; fast Cherenkov signal being an enabling factor. Full exploitation of the advantages offered by very fast timing require a development of fast, large area, pixelized photodetectors, though, and such an avenue is pursued by Argonne. This, in turns opens up yet another possibility of particles identification via the ring imaging of the Cherenkov light.

Particle identification capabilities require charged particle detection and measurement before the first hadronic interaction and the start of the resulting shower. They may also be affected by the particles overlap in the detector elements, hence the full assessment of the particle identification efficiency requires a careful optimization of the detector design.

Spatial/Topological Information

Calorimeters are used to provide more information than the energy of particles and/or jets. Measurement of an angle of the detected high energy photon or separation of close electromagnetic showers are the examples such additional functions of the calorimeters and they often are used to constrain the design and the granularity of electromagnetic calorimeters. From the point of vie of the hadron/jet energy resolution this is highly undesirable: separate and different section of the caalorimeter tend to produce a significant contribution to the energy resolution.

To maintain excellent hadronic energy resolution it is necessary to find a way to provide the spatial/topological information within a concept of a total absorption calorimeter. One of the possibilities may involve very fine segmentation of the front section calorimeter. Another possibility may involve several layers of silicon pixel detectors embedded at several depth in the front section of the calorimeter, as pioneered by the LCCAL project. Yet another possibility may involve use, perhaps in the early depth segment of the calorimeter, of some of the novel optical materials, composite of crystal fibers, which have been recently developed.

Enabling Technological Developments

The concept of the dual readout calorimetry has been around for more than two decades [Paul Mockett]. The required separation of the Cherenkov and scintillation light using the timing information has been demonstrated experimentally in 1984 [IEEE Transaction]. The DREAM Collaboration has recently demonstrated such a separation by using the wavelength separation [Wigmans]. Whereas the principles underlying the possible high resolution hadron calorimetry were known and understood for a very long time, the construction of a practical hadron calorimeter, especially with the hermeticity required in the colliding beam environment, was made possible by several technological breakthroughs:

- development of affordable, high density, scintillating crystals. Good energy resolution requires an adequate depth of the calorimeter, in excess of 6-7 interaction length. The primary example here is the development of lead tungstate crystals for the CMS experiment, where the entire development and large scale production cycle was driven by the requirement of a single HEP experiment.
- advent of compact, inexpensive silicon-based photodetectors (APD’s and SiPM’s) capable of operating in a string magnetic field.

The specific requirements of the hadron calorimeter case are quite different from the other applications, hence there are no off-the-shelf solutions to the detector problems but the recent developments allow for an optimistic view that some additional R&D efforts may lead to a successful construction of a hadron calorimeter with unique capabilities of very high energy resolution, good particle identification and very good spatial localization of electromagnetic showers.

Conceptual Design of High Resolution Calorimeter (HRC)

A high resolution calorimeter is designed to fit into the space occupied by the ECAL and HCAL of the baseline design. It is constructed of optical ”crystals” equipped with two sets of compact silicon photodetectors at the back. One set, equipped with the low pass optical filter and short integration gate electronics, is used to detect and measure the Cherenkov light. The other set, equipped with high pass filter and long integration gate electronics is used to detect and measure the scintillation component.

The barrel section is composed of four layers of crystals with approximate dimensions of 5 5 $5cm^3$, followed by ten layers of larger crystals with approximate dimensions of 10 10 $10cm^3$. First four layers of crystals have silicon pixel detectors attached to the front face.

The endcaps are constructed in a very similar fashion, with four layers of 5 5 $5cm^3$crystals followed by sixteen layers of 10 10 $10cm^3$ crystals. Assuming crystals of density similar to lead tungstate, with the absorption length of the order of 20 cm this leads to a calorimeter with the thickness of 6 at 90^o and 9 in a forward direction.

Calorimeter is constructed by assembling the crystals into non-projective modules with the help of structural epoxy and the readout cables transported to the back planes in non-projective slots. Compact nature of the photodetectors and minimal energy consumption of the photodetectors and the associated readout electronics assures high average density of the calorimeter. The construction may result in mechanical units identical to the ones of the baseline design.

Principal Challenges of the HRC

Fundamental physics principles of the total absorption dual readout hadron calorimetry are relatively well understood. It is, naturally, highly desirable that this understanding is confirmed by a practical demonstration of the performance in the test beam, but for a construction of a practical detector there are several more milestones which need to be reached:

- development of inexpensive optical materials for the dual readout. The principal requirements are
    - short interaction length, of the order of 20 cm
    - capabilities of distinguishing the Cherenkov and scintillation light (by timing, wavelength or combination of both)
    - low cost for large scale production
    - adequate physical/mechanical properties for construction of a large detector
- availability of compact photodetectors capable of operation in a strong magnetic field and the corresponding low power dissipation front-end readout electronics. The most challenging aspects of the photodetectors include:
    - cost
    - adequate area (this is especially important for the Cherenkov component)
    - adequate sensitivity for short wavelength light. It is important to remember that the photodetector assembly may include some waveshifting elements converting the Cherenkov light to a longer wavelength, provided that it preserves the Cherenkov-scintillation separation capabilities.

In addition to these challenges, which must be met by industrial vendors, the realistic design of the detector will require detailed simulation and optimization studies as well as a complete engineering design. A realistic and robust scheme for the relative (channel-to-channel, scintillation-to-Cherenkov) as well as the absolute calibration must be developed as well.

R&D Program

In order to bring the HRC concept to the level necessary for considerations as a possible alternative calorimeter for the SiD detector it is necessary that sufficient progress is achieved along the following directions:

Task 1: demonstration of good response linearity and energy resolution for hadrons in the test beam. At the same time the capabilities of adequate measurement of the spatial characteristics, in particular two close shower separation, must be established. Although it would be desirable, it is not necessary that these studies must utilize the final crystals and/or photodetectors.

Task 2: optimization of the detector performance, including the algorithms for local dual readout corrections, jet finding and reconstruction, optimization of the detector granularity

Task 3: engineering design of the detector and its support structure. In particular the attention must be paid that the inevitable structural members do not degrade the final energy resolution.

Task 4: development of novel inexpensive optical materials

Task 5: development of compact photodetection scheme and associated readout electronics

Task 1

Demonstration of an excellent energy resolution in the test beam is a very challenging project and it will require detailed preparations and several intermediate steps. They will include:

establishing a single crystal evaluation setup to perform the complete characterization of scintillation and Cherenkov light emission and collection. The principal results of these studies will be the measurement of absolute and relative light yields from scintillation and Cherenkov as a function of the particle angle.

studies of light propagation and collection in crystals, methods of optimizing the collection efficiency and uniformity

development of adequate crystal-to-crystal calibration scheme

demonstration of the energy resolution of the segmented and calibrated calorimeter for electrons

demonstration of the precision of measurement of spatial characteristics of an electromagnetic shower and two shower separation

This phase of the program will serve as learning ground to identify and understand possible practical problems and issues associated with segmented crystals calorimetry. It will evolve into a design and construction of a full scale hadron calorimeter prototype. The size and shape of such a prototype must be carefully optimized to ensure the adequate containment of the hadronic showers in a fiscally affordable. The full scale prototype may be constructed using the newly developed inexpensive crystals, but it is far more likely that it will use some of the currently available crystals. The same comments apply to the photodetectors and the front-end electronics. A particular attention must be paid to the development of the calibration scheme enabling precise cross-calibration of crystals and scintillation-to-Cherenkov response.

Task 2

Detailed Monte Carlo simulation studies will be continued to further the understanding of the dependence of the calorimeter performance on the detector design details. Possible use of local Cherenkov-to-scintillation ratio may improve the energy resolution. Jet identification and reconstruction algorithm will be studied to optimize the detector design, and in particular its spatial granularity. Possible use of particle flow algorithm to further improve the energy resolution and its relation to the detector granularity will be investigated. Particle identification capabilities via time-of-flight and by ring imaging will be studied to optimize the detector design.

Task 3

Conceptual design of the calorimeter will be carried out to identify all the factors affecting the detector performance. In particular they will include structural members (dead materials), cracks for the cables and services and cables themselves. These design details will be implemented into the detailed detector simulation program to evaluate the impact on the detector performance. Practical constraints imposed by the solenoidal magnet will likely lead to some of the energy leaking out from the calorimeter. Use of the muon system as a backing calorimeter will be evaluated and it may impact details of the design of the muon system.

Task 4

Practicality of the optical calorimeter depends in a critical manner on the cost of the crystals. None of the crystals produced at present in large quantities present an affordable possibilty. Performance requirements, in particular the scintillation light yield, are substantially different from the specification of of the current generation of crystals, making it quite plausible that there are some potential crystals which can be produced at affordable cost.Search for crystals optimized for a dual readout has already begun, and some initial results have been presented at IEEE conference. The leand tungstate/lead molybdenate crystals have been produced in Bogoroditsk and offer attractive advanteges for the separation of Cherenkov and scintillation light [Korzhik]. Lead fluorite is a very good Cherenkov radiator several attempts to dope it with a scinitillating agent have been tried. The process is in its infancy, though and it will require closer contactes with the crystal making industry.

While single monocrystals offer the most promising material in terms of thei optical properties it may well be that recent advances in production of heavy scintillating glasses offer an adequate solution. We expect to survey the current status of the R&D and perhaps initiate some new efforts.

It should be also noted that there is a significant progress in the area of design and production of novel optical media: sintered ceramics and single-crystal fibers are good examples. We expect to develop closer contacts with this efforts, evaluate the existing materials and possibly stimulate some new studies.

The development of inexpensive optical materials is the key to high resolution calorimetry therefore we expect to deveop a comprehensive program of studies with the relevant industrial parters.

Task 5

Silicon-based photodetectors and in particlar Geiger mode Avalanche Photodiodes offer a very attractive possibility for a compact readout of light in a hermetic calorimeter. These detectors are relatively new and we are actively engaged in the efforts to eveluate and characterize them with the goal of improving their performance and establishing some fundamental principles of their use. Their principal limitation, especially for the purpose of the detection of Cherenkov light is their small size. Larger size detectors are becoming slowly available and we will keep evaluating them.

Development of the front-end electronics suitable for the use in hermetic calorimeter is one of the significant challenges in using these photodetectors. We expect to contribute here by developing a dedicated ASIC chip.

A separate effort to develop large area inexpensive fast photodetectors at Argonne is of great interest here and we envisage an active participation in it. Such detectors are likely to be enabling factors for the possible particle identification capabilities of the calorimeter.