Chapter 1

Hadron Calorimeter for the SBS

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1.1 Introduction

The Hadron Calorimeter (HCAL) for the Super-Bigbite Spectrometer (SBS) will be used in the Hall A 12 GeV Nucleon Form Factors experiments to detect the recoiling protons in GEp(5) [1], the neutrons and protons in GMn [2], and the neutrons in GEn(2) [3], in the momentum range $\sim$ 2.5 to 10.5 GeV/c. HCAL will be also used for the Transversity experiment [4] to detect all types of hadron jets as described in this CDR.

1.2 Requirements for the HCAL

The main requirements for HCAL are derived from the needs of the nucleon form factors experiments. In the case of GEp(5), as an example, the electron arm is located at a central angle of 39° and the proton arm is at 12°. The viability of the proton detection system with the associated polarimeter depends upon the quality of the trigger. The overall experiment trigger is a coincidence between a signal from the electromagnetic calorimeter detecting the electron, and a signal from the hadron calorimeter detecting the proton after its polarization has been measured in a dual polarimeter. The coincidence between elements of the two calorimeters will be organized in such a way that only events with an ep angle relation corresponding to elastic scattering will be accepted. This requirement imposes the dimension of the cells of both calorimeters providing good online use of the angular correlations between the proton and the electron. Furthermore, the energy deposited in the hadron calorimeter will have to be above a threshold determined by the proton energy and the resolution of the calorimeter, typically half the proton energy.

Good energy resolution of the electromagnetic calorimeter will allow for the electron arm trigger rate of 60 kHz at the maximum luminosity of $\mathcal{L}_{max} = 7.5 \times 10^{38}$ cm^{-2}/s at 11 GeV with 75 μA beam current on a 40 cm long liquid hydrogen target.

The above conditions, primarily for GEp(5), require the following for the HCAL:

1. Position resolution of <5 cm will be necessary for HCAL to play a key role in track reconstruction of the recoiling proton.

2. Sufficient energy resolution to suppress low-energy signals (<4 GeV) without significant loss for 8 GeV protons. A 5-10% loss of efficiency for the detector due to low-energy background should be acceptable.

3. A total time gate width of ∼50 ns for online use to create a coincidence time window for the electron arm and the hadron arm will be necessary.

1.3 Choice of the Technology

First we review the general characteristics of a calorimeter of the general type iron/scintillator. For the design of HCAL for SBS we do rely on the considerable experience acquired from the many exemplars built recently at high energy laboratories like Fermilab, CERN and BNL. We will present some specifics of the COMPASS calorimeter, *HCAL1*, which is the basis of the hadron calorimeter for SBS. We have developed Monte Carlo simulation programs based on GEANT4 and modeled HCAL in our energy range.

1.3.1 General features of a hadron calorimeter

In general, the shower generated by a high energy hadron in matter has two components, a hadronic one containing protons, neutrons and mesons, and an electromagnetic one due to the neutral pions created in the energy loss process, their succeeding decay into photons, which in turn trigger an electromagnetic shower. An important characteristic of shower information is the very large fluctuation, from shower to shower, between its various components, and therefore the very large fluctuation in the fraction of the initial energy deposited in the form of detectable energy (usually energy loss by the charged components in scintillator material).

Unless active stopping material is used, the functions of slowing down the initial shower and detecting its charged component are accomplished in two different materials; for example lead or iron, and scintillating plastic. In addition to the loss of information associated with the neutral component of the shower, an additional hidden energy goes to the breaking of the nuclear binding of the heavy material. So, in general, only a fraction of the total energy of the initial particle will be measured from light emitted in the scintillator component of the detector; and that fraction varies strongly from event to event. Furthermore, and unavoidably, the shower will have an electromagnetic component, and the material used in the calorimeter will more readily absorb the energy in that component than that in the hadronic part. Indeed, in iron the ratio of the nuclear interaction length, λ_{int}, for protons and neutrons, to the radiation length, X_0, is, 131.9 g/cm^2 (or 16.76 cm) / 13.8 g/cm^2 (or 1.76 cm); *i.e.*, 9.5. The corresponding numbers for lead are 194 g/cm^2 / 6.37 g/cm^2 for a ratio of 30.5.

A typical calorimeter for protons should have a thickness (including iron or lead and scintillator) corresponding to 4-6 nuclear reaction lengths (depending on the energy), and 12-25 radiation lengths. Depending on actual design, the first number determines the fraction of the total energy deposited in the calorimeter as a whole, and the efficiency of response. The second determines the response to the electromagnetic component. Together these numbers determine the e/h ratio, where h is the recoil hadron, which should be kept close to 1 for optimum performance.

An ideal calorimeter will have the same (or a similar) response for electrons and protons, *i.e.*, $e/p \sim 1$. It should have a response increasing linearly with the incident energy, be nearly 100% efficient, and have a spatial resolution of order of a few cm. The electromagnetic shower size is determined by the Moliere radius of the material, typically 2 cm for iron and lead. The radial development of the shower plays a role in the fraction of energy leaking out of a calorimeter module. This energy loss affects the energy response but also improves the position resolution if the energy leaking into the neighboring blocks is used to find the entrance point.

The light generated in the scintillating plastic of the calorimeter must be led into a light detection device, typically PMTs or silicon photo-diodes. The coupling between the scintillator and the PMT photo cathode can be accomplished with wavelength-shifting (WLS) plastic light collectors connected to the periphery of the scintillator tiles, or with WLS fibers going through the stack of iron or lead and scintillator tiles (so-called "Shashlik" design).

1.3.2 Hadron calorimeter design for Super-Bigbite

The Super-Bigbite hadron calorimeter design is based on the COMPASS hadron calorimeter *HCAL1* [5]. It has a modular structure with 242 blocks arranged in a matrix 11×22 (see Fig. 1.1. A single module consists of interleaved layers of 40 iron and scintillator plates. (The total number of plates can be reduced from 40 to 30 since our hadron energies are much lower than the ones of COMPASS.) The thickness of the scintillator and iron plates is 5 mm and 20 mm, respectively. The cross sectional area of the plates are 142×146 mm^2. Figure 1.2 shows the design for a single calorimeter module. The light from the scintillator is collected using a wave shifter. The length of a wave length shifting light guide is 1200 mm with an active length of 1050 mm, and a thickness of 3 mm. The total length of a calorimeter module is 1450 mm, with an active length of 1000 mm (4.8 λ_{int}). One module weighs 150 kg. Figure 1.2 shows the design for a single calorimeter module as in COMPASS. Scintillator and iron plates and a wavelength-shifting light guide are enclosed in a rectangular container with a cover. Both are made of 1.4 mm thick steel sheets.

The main requirements for the scintillating plates are high light yield and uniform light collection over the scintillator surface. High radiation resistance of the scintillator is also important for its long term operation as it will be exposed to high intensity radiation. The light emitted in the scintillator plates is collected by a flat wave length shifting (from 420 nm to 520 nm) light guide attached to their open surfaces. (WLS with a smaller decay time than the green type used in COMPASS is being considered for SBS HCAL.) A FEU-84-3 PMT with venetian blind dynode system with 12 multiplying stages, and a multi-alkali photocathode is used in the COMPASS calorimeter. Its quantum efficiency is maximum at a wavelength of $\sim$460 nm and varies from 0.18 to 0.26 for different specimens. (PMTs with faster time response than that of FEU-84-3 are

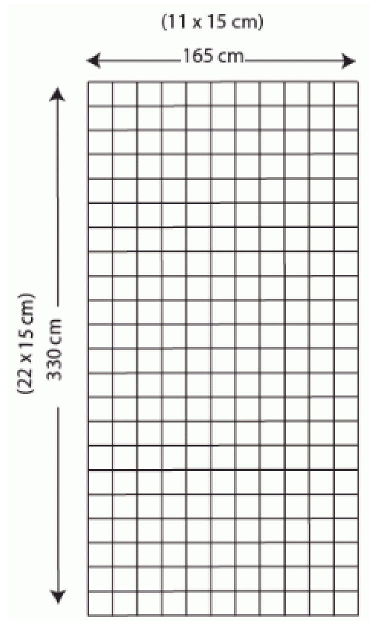

Figure 1.1: HCAL for Super-Bigbite with 242 modules of iron/scintillator plates arranged in a matrix 11×22.

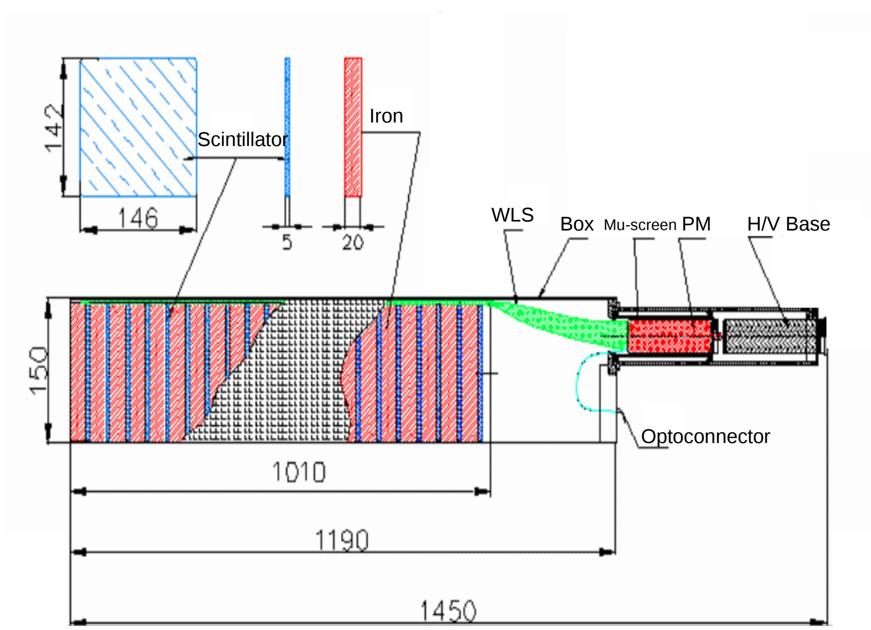

Figure 1.2: One module of COMPASS *HCAL1* hadron calorimeter [5]. All dimensions are in mm.

being considered for SBS HCAL.)

1.4 Performance analysis of hadron calorimeters

The main characteristics of the hadron calorimeter are the linearity of its response as a function of particle energy, e/h ratio, and its energy and spatial resolutions.

1.4.1 Performance of COMPASS *HCAL1*

The response of the COMPASS *HCAL1* hadron calorimeter was measured at CERN using negative hadron and lepton beams (pions, electrons, and muons) with energies in the range of 10-100 GeV. Figure 1.3 shows the spectra of energy deposited in calorimeter modules by muon and pion beams with an energy of 10 GeV. Solid lines are the Landau distribution fit for muon spectrum and the Gaussian distribution fit for pion spectrum.

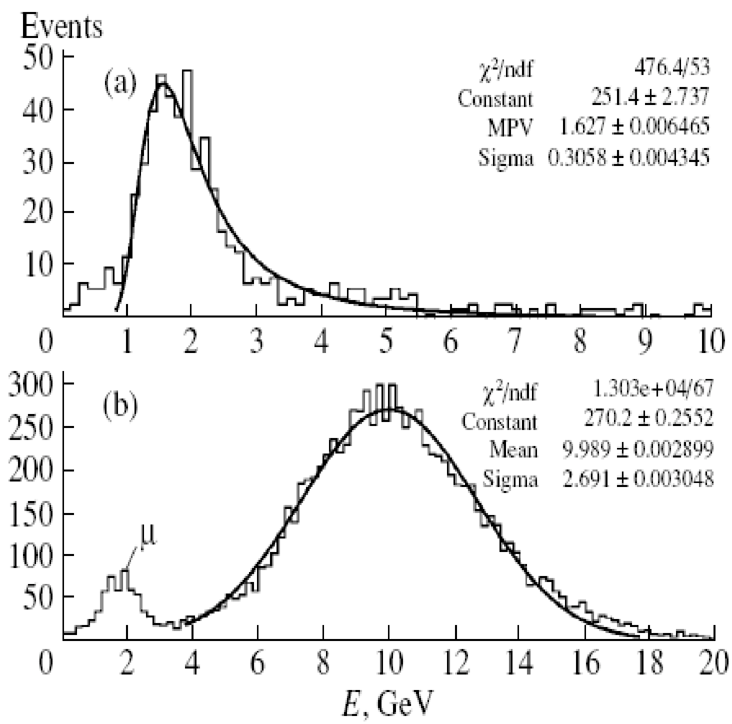

Figure 1.3: Spectra of the energy deposited in a *HCAL1* module by (a) muons and (b) pions at a beam energy of 10 GeV [5].

The experimental energy resolution of the calorimeter for hadrons (pions) and electrons were approximated by:

$$\frac{\sigma_\pi(E)}{E} = \frac{(59.4 \pm 2.9)}{\sqrt{E}} + (7.6 \pm 0.4)\%$$

and

$$\frac{\sigma_e(E)}{E} = \frac{(24.6 \pm 0.7)}{\sqrt{E}} + (0.7 \pm 0.4)\%,$$

with energy E in units of GeV. The spatial resolution was measured to be $\sigma_{x,y} = 14 \pm 2$ mm. The average value of the e/h ratio that characterizes the amplitude response of the calorimeter to electrons and hadrons with equal energies is 1.2 ± 0.1 (for an ideal calorimeter the ratio e/h=1).

Figure 1.4 shows the COMPASS *HCAL1* energy reconstruction and energy resolution as a function of momentum for identified hadrons.

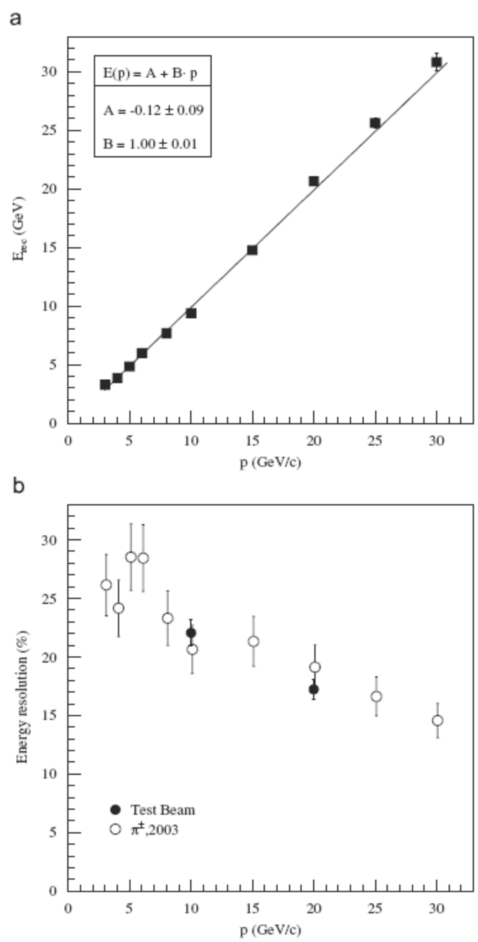

Figure 1.4: COMPASS *HCAL1* (a) energy reconstruction and (b) energy resolution as a function of momentum for identified hadrons (the full symbols denote test beam results) [6].

1.5 Simulations of Super-Bigbite HCAL

A complete GEANT4 simulation [7] code for the Super-Bigbite spectrometer including an array of 11×22 HCAL blocks has been written. Muons, pions, protons and neutrons were generated in the simulation. In this section we will focus on protons and neutrons simulation results.

Figures 1.5 and 1.6 represent the energy deposited by protons and neutrons, respectively, with momenta from 2.6 GeV/c up to 10.5 GeV/c. We notice some similarity of the shapes of the spectra for protons and neutrons although the distributions for neutrons are a bit wider.

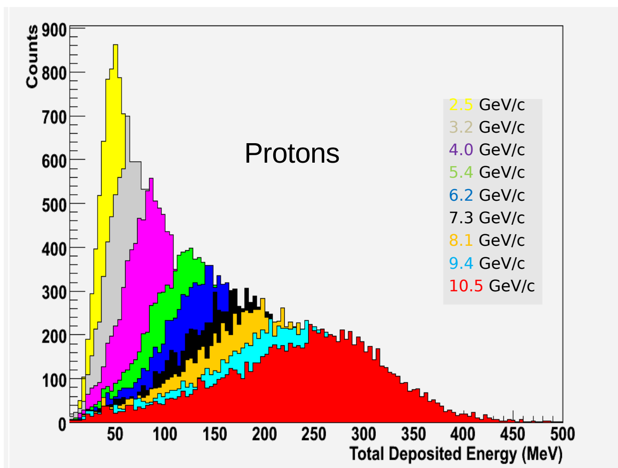

Figure 1.5: Energy deposited in a 3×3 cluster in the hadron calorimeter corresponding to protons for GMn [2] kinematics. Results are from GEANT4 simulations.

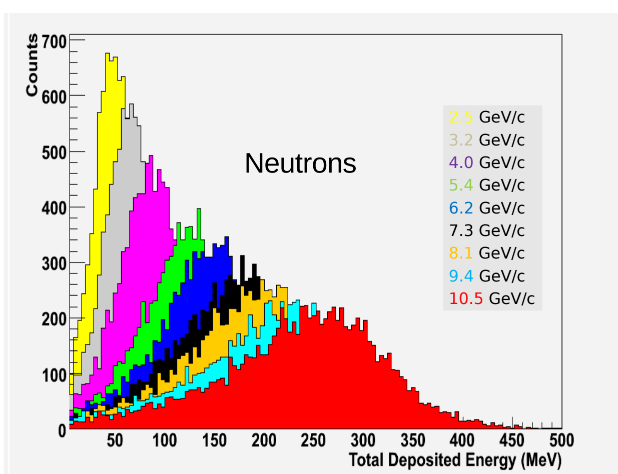

Figure 1.6: Energy deposited in a 3×3 cluster in the hadron calorimeter corresponding to neutrons for GMn [2] kinematics. Results are from GEANT4 simulations.

Energy resolutions were also extracted and they are shown in Fig. 1.7. These good energy resolutions allow high thresholds in the HCAL to eliminate background and lower the experiment trigger rates.

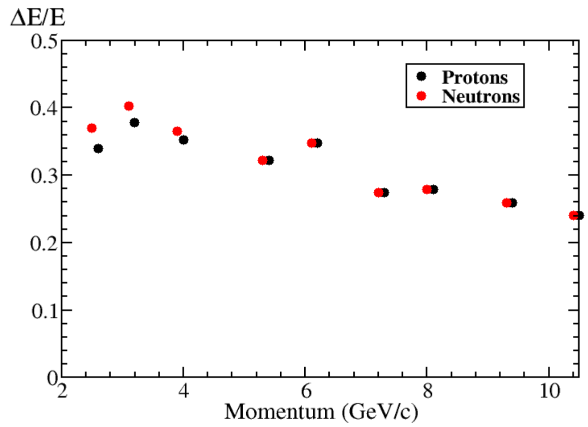

Figure 1.7: Resolution of the deposited energy in a 3×3 cluster in the hadron calorimeter for protons and neutrons for GMn [2] kinematics. Results are from GEANT4 simulations.

Efficiencies for detection of protons and neutrons of HCAL are also extracted and shown in Fig. 1.8. These efficiencies were extracted for thresholds of one-half and one-quarter of the deposited peak energy, respectively.

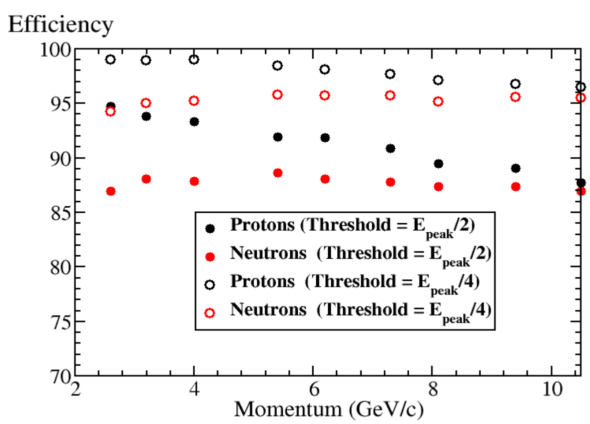

Figure 1.8: Detection efficiency in a 3×3 cluster in the hadron calorimeter for protons and neutrons for GMn [2] kinematics. Results are from GEANT4 simulations.

Spatial resolution (in x or y direction) was also extracted for both protons and neutrons in the momentum range 2.6-10.5 GeV/c and are presented in Fig. 1.9. Position is found as the square-root of the energy weighted mean position in a 3×3 array of blocks centered on the block with greatest energy-deposited. These position resolutions allow for a good angular resolution and are needed in all form factor experiments to separate the (quasi-)elastic from the inelastic and especially needed in GEp(5) to help with tracking in a large low-energy background environment.

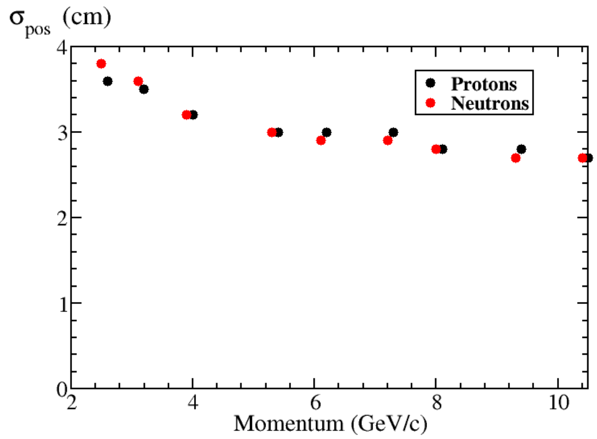

Figure 1.9: Position resolution for a 3×3 cluster in the hadron calorimeter for protons and neutrons for GMn [2] kinematics. Results are from GEANT4 simulations.

Timing resolution for the HCAL is currently under study.

1.6 Development plans for the HCAL

The development plans for the SBS hadron calorimeter is to construct one that is very similar to the working COMPASS *HCAL1* calorimeter optimized for experiments with the Super-Bigbite apparatus. our experiments. In fact, about 25 modules of the COMPASS calorimeter are in Dubna (JINR) and underwent preliminary testing with a mixed beam of 13.8 GeV ^{6}Li and 9.2 GeV ^{4}He ions from the Nuclotron May 2008. Such tests will be continued, in particular in combination with a modified configuration of the polarimeter POMME to test the hypothesis that the analyzing power can be improved by detecting the leading particle with a hadron calorimeter located downstream from the polarimeter.

1.7 HCAL Collaboration

Currently, the hadron calorimeter collaboration consists of members from Carnegie Mellon University in the U.S.A., Laboratory of High Energies, JINR, Dubna, Russia, and University of Glasgow, Glasgow, Scotland. JINR is an integral part of the collaboration and they will facilitate the construction of the HCAL modules and their prototyping and testing together with the collaborators from the U.S.A. Carnegie Mellon University is taking the leading role in organizing the HCAL design, development, construction, and commissioning of the hadron calorimeter.

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