G.Cecchet, C.Leroy, G.Levman, P.Pelfer, A.Penzo, P.G.Rancoita and A.Seidman: A FORWARD CALORIMETER FOR HERA

A Forward Calorimeter for HERA

G. Cecchet[1], C. Leroy[2], G. Levman[3], P. Pelfer[4],
A. Penzo[5], P.G. Rancoita[1], A. Seidman[6],

Abstract:

A compact calorimeter for HERA is proposed. It is designed to cover the very forward region of $\pm 10°$ to the proton direction. It is expected to have a resolution of $32\%/\sqrt{E}$ for hadronic showers and $17\%/\sqrt{E}$ for electromagnetic showers.

[1] INFN-Milano, Italy
[2] McGill University, Montreal, Canada
[3] University of Toronto, Toronto, Canada
[4] University of Florence and INFN, Italy
[5] INFN-Trieste, Italy
[6] Tel Aviv University, Tel Aviv, Israel

1. Introduction

The HERA project will allow us to study collisions of 30 GeV electrons on 820 GeV protons. The huge difference between the proton and electron momenta implies that the bulk of the produced particles will be concentrated along the direction of the incoming proton. This imposes stringent constraints on the forward calorimeter.

Homogeneous calorimeters, for which the absorber and the active material which detects the shower of the produced particles are identical, become prohibitive at these energies because of cost limitations and radiation damage when they are closer to the beam pipe.

In practice, the calorimeter has to be build using a sampling method. In this type of calorimeter, the cascade developes in the absorber and the ionization is sampled in slices of an active material between the absorbers. The obtainable energy resolution is expected to be lower than the one found in homogeneous calorimeters since it is degraded by fluctuations in the energy loss in the absorbers. However the longitudinal and lateral segmentation of the detector allow for shower position measurement and easier particle identification.

The forward calorimeter one has in mind for HERA has to be long enough to contain the shower of the produced particles. It has to be as close as possible to the beam line in order to keep the minimum detectable angle small. It should present a very fine segmentation to provide precise angle measurements and allow the separation of very close jets. Such a calorimeter requires the use of a high density material for the absorber and very narrow read-out gap. A minimization of the cost would ask for a calorimeter as small as possible. However good energy resolution up to these very high energies would favor a large size in order to obtain a full containment of the showers. Tungsten and uranium appear to be the best candidates when choosing an absorber for an electromagnetic calorimeter since these two very dense materials have a very short radiation length (X_0= 0.36 cm for tungsten, X_0=0.32 cm for uranium). The compensation property of uranium selects it as the best possible absorber for an hadronic calorimeter.

2. Calorimeter requirements

The design of a forward calorimeter for an experiment at HERA should meet with several requirements coming mainly from:
   a) physics: precision of measurements, acceptance
   b) constraints from the machine construction and operation.
   c) costs.

It is generally agreed that an optimized detector for measurements of structure functions will be also adquate for most of the other searches (e.g. exotics).

In the forward direction there will be many problems arising from constraints due to the geometry of the interaction region, the beam pipe obstruction, the background noise and the longitudinal space available. In the forward direction ($\leq 10^{o}$) a very good angular resolution $\sigma(\theta_J) \sim 5$ mrad is required for resolving hadronic components. Also a high granularity would be useful for the electromagnetic part of the calorimeter in order to resolve possible complicated lepton-side configurations (exotics). The energy resolution for the electromagnetic part of the calorimeter should range between $15\%/\sqrt{E}$ and $25\%/\sqrt{E}$.

Up to 30° an angular resolution of $\sigma(\theta_J) \sim 10$ mrad and $\sigma/E \sim 60\%/\sqrt{E}$ for the hadronic calorimeter would be required [1]. The lateral size of the electromagnetic shower is given by the Moliere radius R_M; for a 95% of lateral containment the electromagnetic detector elements should cover a radius of $2~R_M$.

For homogeneity reason, this calorimeter should be build using a single material for absorber.

The achievable resolution, the value of the ratio e/π, and the compactness are the three criteria which have to be considered when choosing the absorber. The dominant contribution to the resolution width for hadronic showers comes from fluctuations in the nuclear processes and the correlated loss in detectable energy due to nuclear binding effects and from undetected energy carried away by neutrinos or non-interacting neutrons. With conventional absorbers (like Fe) the resolution can be estimated from [2]:

$$\sigma(E)/E = (~50\%/\sqrt{E}~)~(~1 + 0.08t~)^{1/2}$$

where t is in g/cm^2 If one uses depleted ^{238}U as absorber, fluctuations in the energy deposit of the hadronic cascade are compensated by the energy gained from fission induced by the hadronic shower with the consequence that now the resolution is given by [3]:

$$\sigma(E)/E = (\ 20\%/\sqrt{E}\ )\ (\ 1 + 0.08t\ )^{1/2}$$

When using U as absorber, the ratio e/π is found varying from 1.1 at 5 GeV to ~ 1. at 10 GeV. This ratio reaches higher values when using conventional absorber; for instance in a Fe/Liquid Argon calorimeter, e/π varies from 1.5 at 5 GeV to 1.45 at 10 GeV. Combining uranium and 'classical' material one finds e/π ratio still higher than unity. An absorbing blocks made of 45 % (62 %) uranium and 55 % (38 %) copper give e/π= 1.2 (1.1) [4] at 10 GeV. Finally uranium is a very dense material (ρ=18.95 g/cm^3) with an interaction length of 10.5 cm and consequently allows building very compact calorimeters. So the hadron resolution and the e/π ratio demonstrate the advantage of a calorimeter of the fission compensated type compared to calorimeter using conventional absorber materials.

In order to build a calorimeter as compact as possible, one has also to adopt a narrow read-out gap. This requirement is satisfied by liquid argon and silicon read-outs. However liquid argon presents some disadvantages compared to silicon. Liquid argon needs a heat shield and therefore space is lost for vacuum tank and argon tank walls which increases the minimum detectable angle. Contrary to liquid argon, silicon can be operated at room temperature. The signal output from a 2 mm layer of liquid argon is roughly 3-4 times smaller than that from a silicon layer with a standard thickness of 250 μm. In addition, for that specific example, the collection time for this liquid argon layer is 5 times as large as that of this silicon layer. Thus we will consider a sampling calorimeter having uranium for absorbing blocks and with silicon read-out for an hadronic forward calorimeter at HERA.

3. The very forward calorimeter

We discuss in the following the design for a very forward calorimeter at HERA. This sampling calorimeter will have a tower structure. Each tower is made of squared layers of depleted uranium as passive material [see figs. 1 and 2] and silicon detectors as active material. The calorimeter,
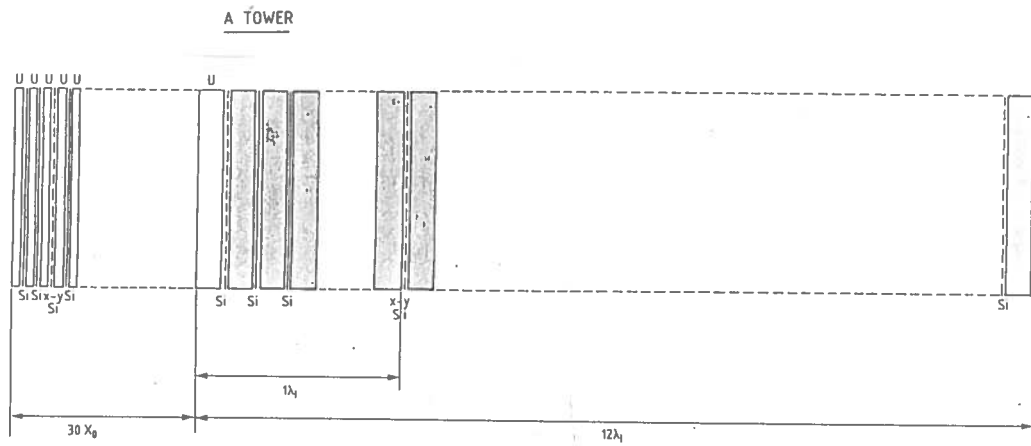
A TOWER

FIG. 1 - Side view of one of the 480 Si/U towers. The electromagnetic section extends over 30 radiation lengths (X_o) and the hadronic section over 12 interaction lengths (λ_1).
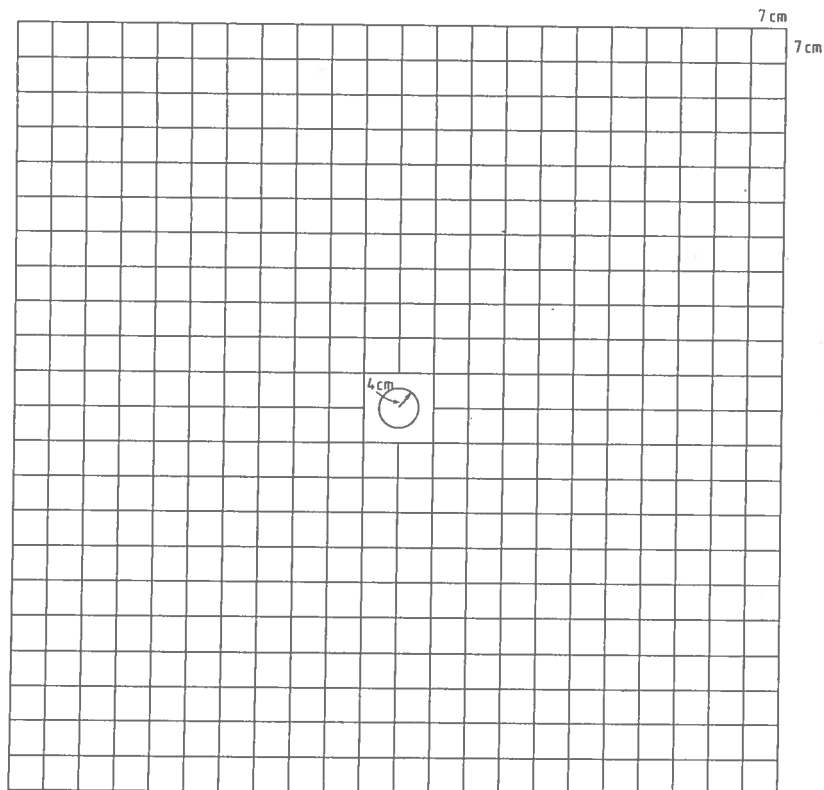

FIG. 2 - Front view of a Si/U tower. Each cell has an area of 7 x 7 cm^2.

situated at 3.6 m from the crossing point has a total lateral size of 154 cm in order to cover scattering angle up to ~ 12° [1] It will of course provide a full lateral containment for the electromagnetic and hadronic showers. The lateral containment is calculated from (in units of interaction lengths):

$$R(95\%) = 2 R$$

with R given by:

$$R = 0.5 + 0.03 \, Ln \, E$$

In the following, we neglect the thickness of the silicon in comparison with the thickness of the uranium.

Each tower will present an electromagnetic and an hadronic section.

For the hadronic section, a uranium plate is 1.05 cm thick (i.e 10 % of interaction length); 120 uranium plates are necessary since a depth of 12 interaction lengths is needed to assure a 95 % longitudinal containment of the hadronic showers. The longitudinal containment is calculated from (in units of interaction lengths):

$$L(95\%) = 1.2 + 1.62 \, Ln \, E$$

The 10 first sampling layers of the hadronic section of a tower (ie one interaction length) is followed by a x-y silicon microstrip read-out to measure the showers positions. The 120 silicon detector planes (7 x 7 cm^2), interspersed in the uranium absorbing blocks of a tower, have each a standard 250 μm thickness. The angular range covered by one cell will be ~ 1. mrad.

The electromagnetic section of a tower, 30 radiation lengths deep, is made of 30 uranium plates (7 x 7 x 0.32 cm^3) with interspersed silicone detector planes (7 x 7 x 0.025 cm^3). The three first layers, represent-

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[1] The same criteria are in principle valid up to 30°, the difference being less stringent resolution requirements.

ing 3 radiation lengths, will be followed by a x-y silicon microstrip read-out in order to measure the position of the showers.

The total number of towers required for building the whole calorimeter amounts to 480. The amount of uranium needed to build this calorimeter is then 56,159 kg and 4,279 kg for the hadronic and the electromagnetic part respectively, so a total of 60,438 kg. The total area of silicon used is 352.8 m^2.

The expected resolution reached by this calorimeter for the hadronic showers is 32%/√E

3.1. Performance of the Si sandwiched electromagnetic calorimeter

A prototype of a Si/W electromagnetic calorimeter [5] has been tested at CERN-SPS for incoming energies between 4-49 GeV and at CERN-PS for incoming energies between 2 and 6 GeV.

At CERN-SPS, the calorimeter had 24 radiation lengths of tungsten and an active silicon (25 cm^2 of active area) sampler every two radiation lengths. The detectors were operated depleted at 200 μm. The mean depleted layer stability was better than 0.3% [6]. In fig 3, the detected energy is given. The calorimeter response is linear with the energy at better than 1%. The study of the longitudinal development indicates a two component structure, each component approximatively exponential with a log(E) dependence (fig 4). The energy resolution is

$$\sigma(E)/E=(17.6\pm0.3)\% \ \sqrt{(\tau/E)}$$

where τ is the number of radiation lengths per active sampler and E is the electron energy in GeV.

At CERN-PS, the calorimeter had 28 radiation lengths of tungsten and an active sampler every two radiation lengths (τ=2). The detectors were operated depleted at 70 μm. The stability of the mean depleted layer width was around 1%. The energy sensed by the calorimeter shows a linear dependence (and well in agreement with the CERN-SPS measurements) on the incoming electron energy. The energy resolution is

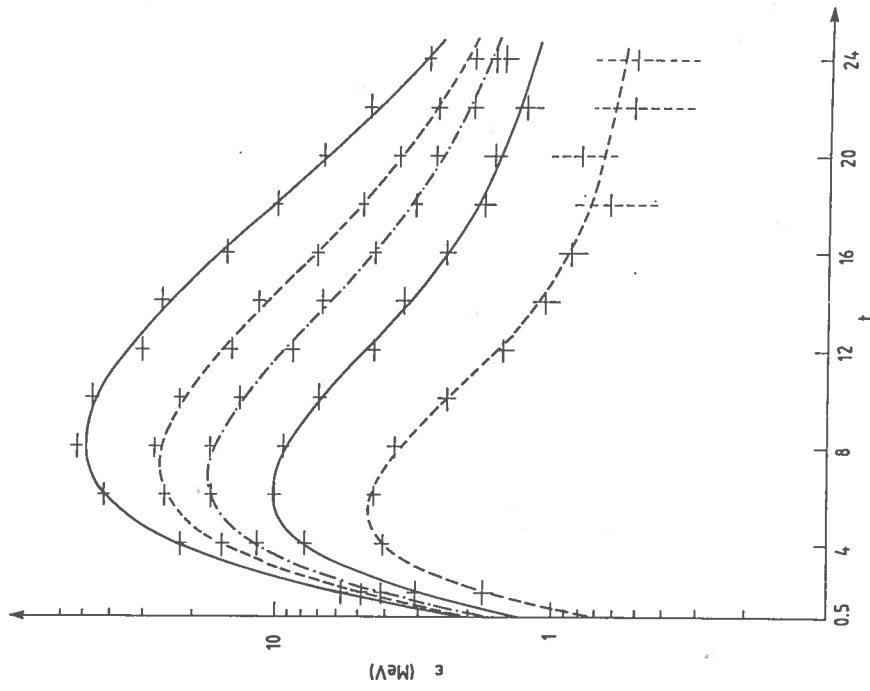$$\sigma(E)/E=(20.4\pm1.0)\% \ \sqrt{(\tau/E)}$$

FIG. 4 – Longitudinal shower development structure detected by the Si/W calorimeter.
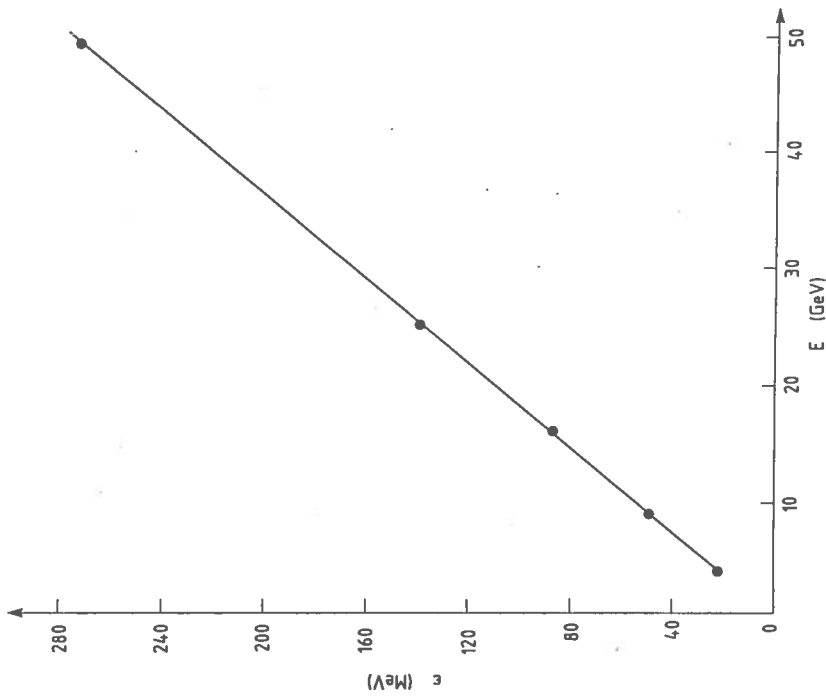

FIG. 3 – Visible energy in the Si/W calorimeter.

The slight degradation of the energy resolution is expected because the energy sensed is less (for about the ratio of the depleted layers) when the detectors are operated at 70 μm.

The performance of the calorimeter is expected to be similiar when uranium is used as passive material.

These measurements show that an energy resolution of (15 - 20)%/$\sqrt{E}$ of the calorimeter to be designed for HERA (chap.2) is obtained by using 28-30 radiation lengths of uranium (for homogeneity reasons) and an active sampler every radiation length. The detectors might be operated at a depleted layer width as thin as 70 μm. The reduction in the actual depleted layer has the advantage of requiring bulk silicon of resistivity lower than 1kΩcm.

4. Conclusion

Silicon detectors may find a specific application in a forward calorimeter (along the proton direction) in a HERA experiment.

The proposed device has a resolution of $\sigma(E)/E \sim 32\%/\sqrt{E}$ for hadrons and of $\sigma(E)/E \sim 17\%/\sqrt{E}$ for electrons and photons.

The 7x7 cm^2 tower structure complemented by the microstrip detectors provides an angular resolution of a few mrad on particle trajectories. Thus an angular resolution of better than 5 mrad on the jet direction can be achieved.

The use of silicon detectors, which can easily be adapted to these geometrical requirements, enables the construction of a compact (about 1 m long) and stable electromagnetic and hadronic forward calorimeter.

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