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SILICON SAMPLING HADRONIC CALORIMETRY: A TOOL FOR EXPERIMENTS AT THE NEXT GENERATION OF COLLIDERS

SICAPO Collaboration

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ABSTRACT

The SICAPO Collaboration project to build a perfectly compensating hadron calorimeter using silicon as the active medium, is described. The insertion of low-Z material (G10 plates) in front or at the rear of the silicon detectors allows a fine tuning of the calorimeter response to electromagnetic showers. This is a new approach to obtaining compensation. The tuning can be exploited to obtain $e/\pi = 1$ (compensation condition). The expected performance ranks this calorimeter among the best candidates to face the severe constraints requested by the next generation of colliders.

1. INTRODUCTION

The interest of the high-energy physics community is turning nowadays to several ambitious projects, such as the Large Hadron Collider (LHC) (in the LEP tunnel at CERN) and the Superconducting Super Collider (SSC) in the USA, involving multi-TeV proton beams. The exceptional experimental conditions faced in these projects such as very high luminosity, high multiplicities, and large variety of physics phenomena to be studied, requires the construction of very complex detection systems. They will impose severe constraints on the performances of the large hadron calorimeters that will be the core component of these experiments. The following features will be required of calorimeters: compact construction, flexibility, fine segmentation, fast charge collection, easy calibration, good radiation hardness, good energy resolution, and ability to satisfy the compensating condition $e/\pi = 1$.

Among the best candidates that meet all these requirements will be a sampling calorimeter with silicon as the active medium [1]. The silicon-detector thickness ($\sim$ 400 μm) and its thin support allow sampling gaps of less than 2.0 mm. Silicon allows a flexible and very fine longitudinal and lateral segmentation, providing precise angle measurements and separation of very close jets and/or photons. The high granularity so achieved is a necessary condition to resolve possible complex interaction configurations. The very flexible construction allowed by silicon best accomodates to the small available space left by the relatively small crossing angle at the new generation of colliders. The silicon detectors have fast response; for standard silicon detectors (300–400 μm thick) the electron collection time is 2 ns or less, whereas the hole collection time is less than 6 ns. They require low operating voltages: typically less than 100 V for 200 μm depletion and a resistivity between 1 and 5 k$\Omega\cdot$cm.

The question of the silicon radiation hardness is at present under investigation [2]. It is clear that, in view of the large silicon calorimeters to be built in the future, quantitative results are certainly needed on the silicon radiation hardness, on the profiles of the generated neutron fluences inside the hadronic showers, and on a correct evaluation of the rate effect.

Electromagnetic calorimeters using silicon as the active medium have been shown to have a good energy resolution. Measurements performed by the SICAPO (SIlicon CAlorimeter and POlarimeter) Collaboration (Florence, Hamburg, McGill, Messina, Milan, Oregon, Tel Aviv, Tennessee, Trieste, Turin) with an electromagnetic calorimeter (24 radiation lengths deep) using silicon as the active material (each detector had an area of 5×5 cm^2), and tungsten and uranium as the passive material, have shown an energy response which is linear and stable to better than 1%, and an energy resolution of $\sigma(E)/E = (17.6 \pm 0.3)\% \sqrt{\tau/E}$ (GeV), where τ is the thickness of each absorber layer in radiation lengths [3].

No data are available at present for hadronic calorimeters with silicon as the active medium. However, a prototype of such a detector is being put into operation at CERN by the SICAPO Collaboration, in order to measure its energy resolution and to study the characteristics of the hadronic showers, the final aim being to build a perfectly compensating hadronic calorimeter using silicon as the active material.

In this paper, we describe the various phases of the SICAPO project of building this calorimeter and ensuring that it is perfectly compensating, i.e. that it achieves an electromagnetic (e) to hadronic (π) signal ratio $e/\pi = 1$.

2. THE MEANING OF THE e/π RATIO

The energy resolution of the calorimeter is dominated by the sampling and intrinsic fluctuations [4] and by the value of the ratio e/π:

i) The sampling fluctuation originates from the fact that only a small fraction of the energy is deposited in the active layers and contributes to the calorimeter signal. It is mainly generated by the fluctuation in the total number of charged particles crossing the active layers. Therefore, the contribution of this source of fluctuations is proportional to the square root of the thickness of the absorber plates.

ii) A large amount of the deposited energy goes into breaking nuclei (binding energy) or into low-energy neutrons and therefore is partially not visible. Photons and nucleons released in the de-excitation of nuclei are poorly sampled owing to short range and/or saturation effects in the active material. In addition, pion and muon decays produce secondary particles such as ν, which are mostly undetected. The amount of energy converted into excitation or break-up of the nuclei, of which only a fraction will result in detectable energy, fluctuates from event to event. These intrinsic fluctuations constitute, in fact, the main contribution to the energy resolution in hadron calorimeters.

iii) Decays of hadronic resonances created during the degradation of the energy of the incident hadrons and charge-exchange reactions, produce π^0 (mainly) and η, which will propagate electromagnetically without any further nuclear interactions and consequently deposit their energy in the form of e.m. showers. For instance, the total number of π^0 in a shower initiated by π^+ of energy E is $n_{\pi^0} \approx 5 \ln E(\mathrm{GeV}) - 4.6$ [4]. The average fraction converted into e.m. showers increases with energy. As a result, any hadronic shower has a purely hadronic and a purely e.m. component. The size of this e.m. component is largely determined by the production of π^0 (and η) in the first interaction, and event-by-event fluctuations around the average value are large and non-Gaussian.

Since the nuclear effects, which dominate pure hadronic showers, have no counterpart in e.m. showers, the calorimeter response to the e.m. and non-e.m. part of the hadronic shower is different, with the consequence that the e.m. (e) to hadronic (π) signal ratio $e/\pi \neq 1$. The signal ratio e/π is energy dependent as a result of the increase with energy of the average fraction of the shower dissipated in the form of e.m. showers. Therefore, one can distinguish between the energy-dependent e/π ratio and the e/h ratio which is constant with energy and only depends on the calorimeter properties. The intrinsic e/π ratio is defined [5] for an incoming e and π of the same energy as follows:

$$e/h = e/(\mathrm{ion}\, f_{\mathrm{ion}} + n\, f_n + \gamma\, f_\gamma)\,, \tag{1}$$

where e, ion, n, and γ are the signals from e.m. showers, ionizing particles, neutrons, and nuclear γ's, respectively; f_{ion}, f_n, and f_γ represent the fractions of the non-e.m. energy carried by ionizing hadrons, soft neutrons, and nuclear γ's. In eq. (1) the sum of the fractions f_i is normalized to one. This way, it is possible to analyse the case of a hadronic shower where there is no e.m. component. The relation between e/π and e/h is

$$\frac{e}{\pi}(E) = \frac{e/h}{1 - \langle f_{\mathrm{em}} \rangle [1 - e/h]}\,. \tag{2}$$

The energy resolution of the calorimeter can be quite generally be written as:

$$\frac{\sigma}{E} = \frac{C(\sqrt{t_{\mathrm{abs}}})}{\sqrt{E}} + f\left(\frac{e}{\pi} - 1\right), \tag{3}$$

where t_{abs} is the absorber thickness and $C = (\sigma_{intr}^2 + \sigma_{samp}^2)^{1/2}$ contains the contribution from the intrinsic fluctuations due to nuclear binding energy losses (σ_{intr}) and that from the sampling fluctuations (σ_{samp}). The function $f(e/\pi)$ is vanishing only if $e/\pi = 1$. This can be obtained when $e/h = 1$ [see eq. (2)]. Therefore, a ratio $e/h \neq 1$ will cause the energy resolution not to depend on the incident energy as $1/\sqrt{E}$ and the calorimeter signal not to be proportional to the incident hadron energy (non-linearity).

Linearity can be realized and an energy resolution depending on E as $1/\sqrt{E}$ can be reached if the intrinsic response of the calorimeter to purely e.m. and purely hadronic components of the showers are made equal, i.e. $e/h = 1$ which is the compensation condition [6, 5]. In this way the best resolution performance is expected for the calorimeter. Only then will the effects of the non-Gaussian event-by-event fluctuations in the fraction of energy on π^0 and η production be minimized, and the energy resolution for hadronic showers improved with increasing energy.

3. APPROACHES TO THE COMPENSATION

Two approaches are possible to realize the compensation:

i) Increase the response of the calorimeter to the pure-hadronic component of the shower.
In the case of hydrogeneous readout materials (such as scintillator), the neutrons generated at the last stage of the hadronic shower development (where processes at the nuclear level occur) can interact with the protons of the readout material. It has been demonstrated [7] in the case of this active material that $e/\pi = 1$ can be obtained by varying the relative contribution of neutrons, which can be obtained by modifying the sampling fraction [6]:
   - by changing the thickness of the absorber as a function of the thickness of the readout,
   - by changing the frequency of the sampling.

ii) Tune the calorimeter response to the e.m. component of the shower.
This can be realized by inserting low-Z (G10) planes between the silicon planes and the standard high-Z absorber [8, 9, 10]. The SICAPO Collaboration has performed a systematic investigation [9, 11] of the visible energy response for e.m. showers in a calorimeter that had 20 radiation lengths of uranium or tungsten as absorbers and a silicon detector (a 5×5 cm^2 in area and $\sim$ 300 μm in thickness) as the active medium every two radiation lengths. The usual serial coupling of five successive (along the beam direction) silicon detectors was used [9]. The detectors were operated not fully depleted, with a depletion depth of 200 μm.

The experiment was performed at the CERN PS with incoming electrons of 2, 4, and 6 GeV. Data were taken [11] for various configurations in the calorimeter: a configuration where G10 plates 0.5, 1.0, and 1.5 mm thick were inserted both in the front and at the rear of the silicon detectors; a configuration where G10 plates of 0.5, 1.0, 1.5, 3.0, 4.0, and 5.0 mm thicknesses were located at the rear only; a configuration where G10 plates 5.0 mm thick were located in between the uranium absorbers; finally data were taken without G10 plates altogether. Figures 1 and 2 show [11] the mean energy sensed by the calorimeter for Si/W and Si/U respectively, as a function of the incoming electron energy and G10 plates located at the rear only. The visible energy (E_{vis}) in the calorimeter is found to be a linear function of the incident energy. This indicates that the visible energy in the calorimeter depends on the thickness of the low-Z absorber only, thus keeping the linear (diminished) response of the calorimeter as a function of the incoming energy (E in GeV):

$$E_{vis}(U) = (5.08 \pm 0.59)E + (-1.14 \pm 1.01)\ [\mathrm{MeV}]$$
$$E_{vis}(W) = (4.25 \pm 0.49)E + (-0.88 \pm 0.86)\ [\mathrm{MeV}]$$

In fig. 3 the reduction of the visible energy (from the average of the measurements at incoming electron energies of 2, 4, and 6 GeV) is shown as a function of the G10 plate thickness [11]. The systematic difference of about 1% between the reductions of the Si/U and the Si/W calorimeters is accounted for by the difference in energy sharing (among Si detectors, low-Z, and high-Z absorbers) in the two calorimeters. The maximum reduction occurs for the maximum thickness of G10 (5.0 mm) located at the rear of the silicon detectors, where the e.m. response is reduced by 29%.

This reduction of the energy sensed by the silicon detectors is stronger than that expected to be due to the addition of G10 plates through the sharing of energy deposition. As an example, the addition of 5 mm G10 plates, every two radiation lengths, accounts for a visible energy reduction of about 10% for uranium absorbers in the case of a minimum-ionizing and non-showering particle. The reduction obtained with 5 mm of G10 absorbers located in between the uranium absorbers, but not adjacent to the silicon detector, is comparable (9.5%). In the calorimeter configurations where the silicon detectors are adjacent to the low-Z absorbers, the measurement of the visible energy is performed after the back-scattered component (for G10 plates inserted at the rear of the detectors) or/and the forward component (for G10 plates inserted in the front of the detectors) are hardened locally by the low-Z absorbers. This local hardening effect increases the reduction of the visible energy beyond that expected from energy sharing. The degree of hardening depends on the thickness of the low-Z absorber, allowing the fine tuning of the calorimeter response to e.m. showers. Using the local hardening effect due to G10 plates, 5 mm thick, located at the rear of the detectors, the response of the calorimeter to an e.m. shower can be reduced by 29%, while the response to a purely hadronic shower, not sensitive to the local hardening effect, would only be reduced by 10%. Thus a reduction of e/π by about 18% for 5.0 mm G10 plates can be achieved. This indicates the range over which e/π is tuneable by this effect with G10 plates up to 5 mm thick.

These results can be understood according to the following picture. Electrons and photons transport and deposit their energy in matter through the production of e.m. cascade showers. The energy is propagated both laterally and longitudinally by an increasing number of diminishing energy particles. We know that a considerable fraction of the amount of energy deposited by e.m. showers in the calorimeter is deposited through low-energy particles. Simulations using the EGS4 [12] Monte Carlo indicate, for instance, that in the case of uranium, particles with an energy below 1 MeV account for 40% of the total deposited energy. A large fraction of the initial electron energy is going into low-energy photon production during the shower development. Compton scattering (proportional to the Z of the absorber material) and the photoelectric effect (proportional to the Z^5 of the absorber material) dominate for low-energy photons (1–5 MeV) and therefore the photon interaction cross-section is much larger for the high-Z absorber than for the low-Z readout material. As a consequence, the soft photons from the shower interact almost exclusively in the absorber and most of the soft photons will transfer their energy partly (Compton effect) or totally (photoelectric effect) to the electrons of the absorber. Low-energy photons from e.m. shower development may therefore convert into electrons sufficiently close to the surface of the absorber plate for them to escape. Normally, these electrons contribute to the measured signal. Low-energy electrons may be multiply scattered. The transverse dimensions of a shower, measured in radiation lengths, are much larger in high-Z material than in low-Z material, since the Molière length R_M/X_0 scales as 21 MeV/ϵ [$\epsilon = B(ZX_0/A)^a$ is the critical energy; X_0 is the radiation length in g/cm^2, A is the atomic mass, $B = 2.66$ and $a = 1.11$]. Thus, in a high-Z material, the low-energy electrons form larger angles [$\langle\cos\alpha\rangle = \cos(21\ \mathrm{MeV}/\epsilon\pi)$] with respect to the shower axis than in low-Z material. The number of large-angle electrons (decreasing as ϵ^2) is large in high-Z material and small in low-Z material. The multiply scattered electrons have a path length $d/\langle\cos\alpha\rangle$ in high-Z passive material which is relatively longer than their path length d in the low-Z active material. The multiple scattering can then create a flux of backward-going electrons in the absorber. Our data show that these soft electrons are absorbed by the G10 plates inserted between the active and the absorber planes, and the strongest reduction (29%) of the visible e.m. energy appears in the case when the 5.0 mm G10 absorber is located at the rear of the detectors.

4. THE SICAPO PROGRAM

The possibility to observe many of the phenomena of interest in the next generation of colliders depends critically on the intrinsic energy resolutions of the calorimeters in operation in the experiments. Calorimeters will have to serve several functions in the detector. Among the hardest tasks will be to recognize the signatures of electroweak or supersymmetric processes in a background that is dominated by soft or semi-hard hadronic interactions. In this context, a 'hermetic' calorimeter is indispensable to be able to define the 'missing momentum vector' and the 'missing energy' that would reveal the presence of a neutrino, or of a photino, for instance. The resolution requirements for both the hadronic calorimeter and the e.m. calorimeter become more and more stringent as the beam energies increase and as lower energies of the neutrinos are probed. To positively identify a neutrino, the argument of missing energy can be used only if the missing energy is larger than the uncertainty on the visible energy:

$$\sigma(E_{det})/E_{det} \approx \sigma(E_{tot})/E_{tot} < E_\nu/E_{tot} \;,$$

where E_{tot}, E_{det}, and E_ν are the total, detected (owing to particles entering the calorimeter), and neutrino energy. In other words, the multiparticle energy resolution must be better than

$$K/\sqrt{E} \qquad \text{where} \qquad K = E_\nu/\sqrt{E_{tot}} \;.$$

To detect the 40 GeV ν from the decay of a centrally produced W^+ in a $\sqrt{s} = 2$ TeV e^+e^- collider, the resolution must be better than $89\%/\sqrt{E}$. Similarly, the decay of a W^- coming from the decay of a 1 TeV Higgs into a neutrino at the SSC ($\sqrt{s} = 40$ TeV) produces on an average 250 GeV of missing energy. The resolution must then be better than $125\%/\sqrt{E}$. Even at extremely high energies, the best possible energy resolution remains a critical design consideration.

A similar discussion applies to the measurement of missing momentum. In particular, in hadron–hadron collisions, the technique of the missing transverse momentum is very sensitive. Apart from the question of resolution, this method is estimated to have intrinsic errors of the order of 4 GeV [13]. In a good design, the error caused by the resolution $\sigma(p_T) = K\sqrt{E_T}$ (where E_T is the transverse energy in the central region of the hadron–hadron collision) should not be larger than the intrinsic error. For typical transverse energies of 50–100 GeV [14], it means resolutions better than 40–$70\%/\sqrt{E}$.

The energy resolution aimed at for the hadron calorimeter being built by the SICAPO Collaboration is about $50\%/\sqrt{E}$ and therefore well within the needed conditions to achieve the physics goals at the next generation of colliders. Such a resolution is a necessary but not the only condition. Another condition is the equality of response to hadrons and electrons, $e/\pi = 1$. If $e/\pi \neq 1$, it can be shown from eq. (3) that the resolution at high energy is spoiled by an additional term. At very large energies, $e/\pi \neq 1$ would cause disastrous effects of non-linearity. In high-energy collisions, the energy of the secondary hadrons (typically coming from a jet) easily varies from 10 GeV to 1 TeV. The fraction of the energy of hadronic showers carried by the e.m. component increases noticeably in this range; the fraction carried by the hadronic component, whose response is affected by e/π, decreases. This is a source of non-linearity unless $e/\pi = 1$. In the range from 10 GeV to 1 TeV, with an intrinsic e/π of 1.1 for instance, the non-linearity thus caused would amount to 5%. Non-linearities represent a serious danger to the physics performances of these detectors, because of the biases introduced. For example, if the response to one hundred 10 GeV pions was 5% less than to a 1 TeV pion, a selection of events with missing energy/momentum could easily become a selection of high multiplicity or of particular topologies.

Another condition for calorimeters of the next generation of colliders is that the multiparticle resolution must not be much worse than the single-particle resolution. Cell-to-cell intercalibration errors, cracks, and in-flight decays can make the multiparticle resolution worse. For instance, for a distance of 4 m, the multiparticle resolution due to in-flight decay amounts to $30\%/\sqrt{E}$.

Jets represent a multiparticle situation of interest for the physics. Since an appreciable fraction of the energy of the jet can be carried by a 'leading particle' [14], the instrumental resolution for jets approaches the single-particle resolution.

Besides the detection of missing energy and momenta, the best possible resolution is also critical to the detection of narrow large-mass resonances decaying into jets. Indeed, the signal to background ratio at the peak is inversely proportional to the calorimeter resolution, and the statistics required to find a resonance are proportional to the square of the resolution. Note that if a resolution of $50\%/\sqrt{E}$ can be maintained for jets, W and Z particles decaying into jets could be distinguished by their mass event by event (while with a resolution of $100\%/\sqrt{E}$, the mass peaks of centrally produced W and Z would overlap).

To summarize, the physics goals and the processes that limit the effective resolution fix the required calorimeter resolution at $\approx 50\%/\sqrt{E}$.

A possible way to measure the ratio $E_{det}(e)/E_{det}(\pi)$ of the detected e.m. energy $[E_{det}(e)]$ to the detected hadronic energy $[E_{det}(\pi)]$ would be to measure $E_{det}(e)$ and $E_{det}(\pi)$ separately by exposing the calorimeter to an electron beam and afterwards to a hadron beam of the same energy.

The 95% radial containment (R_e) and the 95% longitudinal containment (L_e) for e.m. showers are respectively [in units of radiation length (X_0)]:

$$R_e(95\%) = 2\,R_M$$

$$L_e(95\%) = (t_{max} + 0.08\,Z + 9.6)\,[X_0]\,,$$

where $t_{max} = 1.0\,(\ln E/\epsilon - 1.0)$ for electrons and $1.0\,(\ln E/\epsilon - 0.5)$ for photons (E in GeV), and ϵ is the critical energy.

The 95% radial containment (R_π) and the 95% longitudinal containment (L_π) for hadronic showers are respectively [in units of interaction length (λ)]:

$$R_\pi(95\%) = 2\,(0.5 + 0.03\ln E)\,[\lambda] \qquad \text{(E in GeV)}$$

$$L\pi(95\%) = (1.2 + 1.62\ln E)\,[\lambda] \qquad \text{(E in GeV)}\,.$$

Therefore, for a calorimeter with uranium (for instance) as absorber material ($X_0 = 0.32$ cm, $\epsilon = 6.6$ MeV, and $\lambda = 10.5$ cm), it means that $E_{det}(e)$ is contained in 6.4 X_0 radially and in 24 X_0 longitudinally, and that $E_{det}(\pi)$ is contained in 1.14 λ (= 37 X_0) radially and in 5 λ (= 164 X_0) longitudinally. The parts of the calorimeter used for detecting e.m. and hadronic showers are not the same. This difference in the fiducial volumes leads to considerably different systematics (intrinsic and readout errors) for the e.m. and the hadronic beams. A global measurement is needed. Therefore, we will rather adopt the following approach.

We can rewrite eq. (3):

$$\left(\frac{\sigma}{E}\right)\sqrt{E} = C(\sqrt{t_{abs}}) + \sqrt{E}\left[f\left(\frac{e}{\pi} - 1\right)\right]. \tag{4}$$

At first, *at a given energy,* we can vary the thickness of the absorber in order to minimize $(\sigma/E)\sqrt{E}$ {and since $f[(e/\pi) - 1)] = 0$ when $e/h = 1$, the minimum of $(\sigma/E)\sqrt{E}$ will be reached when $e/h = 1$}. As we have seen before, we will at first introduce low-Z G10 absorbers and vary their thickness. For each G10 thickness we will measure $(\sigma/E)\sqrt{E}$ for various thicknesses of high-Z absorbers. All $(\sigma/E)\sqrt{E}$ curves (corresponding to a G10 thickness) plotted as a function of high-Z absorber thickness ($\sqrt{t_{abs}}$) should be parallel to and above the line $e/h = 1$ (see fig. 4). So, a measurement of $(\sigma/E)\sqrt{E}$ will be performed for various thicknesses of the low- and high-Z absorber and a minimum will be searched for. At this minimum, the best achievable resolution will be obtained with $e/h = 1$ (perfect compensation).

In a second step, *at a given thickness* (of G10 and absorber) (that corresponds to the minimum at the first investigated incoming hadron energy), in order to control the value of e/π, data will be taken at various energies. If $e/h = 1$, then $(\sigma/E)\sqrt{E}$ will remain *constant* when the energy is changed. On the contrary, if $e/h \neq 1$, then $f[(e/\pi) - 1] \neq 0$ and $(\sigma/E)\sqrt{E}$ will vary as $\sqrt{E}$.

This approach will be followed in our program, which involves *two phases.*

5. THE PRESENT AND FUTURE SICAPO PHASES

5.1 The present SICAPO phase

The calorimeter will involve 60 silicon planes interspersed with uranium plates (10 mm thick initially). A silicon plane is a mosaic consisting of 18 detectors (each of a surface of $\sim 28\ cm^2$) and represents an area with an effective radius of 1.2 λ. The active mosaic area can be enlarged up to about $1000\ cm^2$ (i.e. 36 detectors), if this is required by the lateral containment of the hadronic shower. The 60 samplings represent about 5.7 λ (for U plates 10 mm thick).

This calorimeter will be operated at PS beam energies ranging from 2 to 10 GeV (and even up to 15 GeV). At 10 GeV, the radial containment will be $R_\pi = 1.14\ \lambda$ and the longitudinal containment $L_\pi = 5\ \lambda$. Therefore the calorimeter will completely contain the incoming shower at these energies.

We will then apply the program described above, i.e. at a fixed energy of 10 GeV, we will minimize $(\sigma/E)\sqrt{E}$ by varying the G10 and U thicknesses and then we will check on e/π at 4 GeV, for instance. Note that for U plates 10 mm thick, the number of samplings strictly needed at 10 GeV for longitudinal containment is 53.

5.2 The future SICAPO phase

The same approach as in the present SICAPO program is followed, with three major modifications: a) a change of the absorber from U to Fe; b) an increase of the number of detectors per plane; and c) a move to higher energies.

The number of detectors per plane will be increased to 48 (see fig. 5) and the absorber will be Fe (instead of U). In the case of a Si/U calorimeter, the number of neutrons released per GeV of incident energy is ≈ 44. The released neutrons contribute to radiation damage. They are going everywhere and this feature is bad for the granularity. In addition, the use of U is always submitted to safety regulations which, most of the time, enforce its shielding (by nickel) and therefore its radioactivity used for calibration purpose (the only remaining advantage of U) is lost.

For Fe, the number of neutrons released is smaller ≈ 6 neutrons per GeV (1 or 2 according to recent measurements). We have seen above that the factor C appearing in eqs. (3) and (4) has, in fact, several contributions: a contribution from the intrinsic fluctuations owing to nuclear binding energy losses (σ_{intr}) and a contribution from the sampling fluctuations (σ_{samp}). In a calorimeter (for experiments at the hadron colliders of the next generation) aiming at an energy resolution of $50\%/\sqrt{E}$, when U is used as the absorber, the sampling fluctuations term is $\approx 20\%/\sqrt{E}$ for $\sim$ 25 samplings per λ (U 4 mm thick) and the term for binding losses is $\approx 40\%/\sqrt{E}$. For Fe, these values can be interchanged since the term for sampling fluctuations is $\approx 40\%/\sqrt{E}$ for $\sim$ 8 samplings per λ (Fe absorber plates $\approx$ 20 mm thick as expected from ref. [4]) and the term for binding losses is $\approx 20\%/\sqrt{E}$. This will lead to a sampling Si/Fe calorimeter with an energy resolution of $\sim 45\%/\sqrt{E}$, as typically requested for the next generation of machines, with the advantage that using Fe instead of U requires 3 times *less* silicon planes (25 samplings per λ and 8 samplings per λ respectively). In both cases, however, the $e/h = 1$ condition has to be achieved.

This calorimeter (fig. 6) will be operated at two energies at the SPS (10 and 100 GeV according to our approach for determining compensation). An energy of 100 GeV requires a radial extension of about 1.3 λ and a depth of 10 λ [15] (8.7 λ if we apply standard formulae). Therefore, the number of samplings needed in that case will be around 80. The thickness of Fe advocated above is, of course, as expected from Monte Carlo and activation studies [6, 15]. The exact tuning of the Fe thickness will be done according to the approach described before.

The lateral containment will require that the active samplers (for a calorimeter depth greater than 2 λ) be silicon mosaic planes consisting of square detectors (2.3 cm $\times$ 2.3 cm) making 46 cm $\times$ 46 cm active planes.

As a final remark, it is worth noting that Cu could be used instead of Fe with few modifications and the same advantages.

6. CONCLUSIONS

Measurements performed by the SICAPO Collaboration with a Si/U and a Si/W calorimeter at the CERN PS (at 2, 4, and 6 GeV) with inserted G10 plates of various thicknesses support the view that the signal equalization, which provides the condition $e/\pi = 1$, can be obtained with a silicon readout by tuning the calorimeter response to the e.m. component of the hadronic shower. This can be achieved by inserting in front and/or at the rear of the silicon detectors, low-Z absorber (G10 plates). The fibre-glass absorbs soft electrons and realizes a local hardening of the e.m. shower, thus reducing the total energy sensed. The low-Z absorber is used to reduce the calorimeter response to the e.m. component in a hadronic shower, while the pure hadron component (most of which is relativistic or quasi-relativistic) is expected to be only slightly affected. Silicon, which does not contain hydrogen has a prompt response, limited by the intrinsic transit time of the detector, and a narrow lateral hadronic shower containment.

On this basis, the building of a perfectly compensating hadron calorimeter of the size needed for the LHC and SSC projects, using silicon as the active material, is feasible. The SICAPO Collaboration has started this project, foreseeing two phases: a first phase where U is used as absorber and a second phase where Fe is the passive material, with the final goal of demonstrating that a Si/Fe hadron calorimeter is well adapted to the needs of the future generation of colliders; this view is supported by our present knowledge of hadronic calorimetry.

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Figure captions

Fig. 1 Mean energy deposited in the Si/W calorimeter as a function of the incoming electron energy. The highest points correspond to the case where there is no absorber in front of the detector. The other points correspond to a configuration with increasing thickness of G10 at the rear of the detectors : (from top to bottom) 0.5, 1.0, 1.5, 3.0, 4.0, 5.0 mm, respectively.

Fig. 2 Mean energy deposited in the Si/U calorimeter as a function of the incoming electron energy. The highest points correspond to the case where there is no absorber in front of the detector. The other points correspond to a configuration with increasing thickness of G10 at the rear of the detectors: (from top to bottom) 0.5, 1.0, 1.5, 3.0, 4.0, 5.0 mm, respectively.

Fig. 3 Reduction of the visible e.m. energy sensed by the calorimeter [(□) for Si/U and (*) for Si/W] as a function of the thickness of the G10 plate inserted in front and at the rear of the silicon detectors.

Fig. 4 For each G10 thickness $(\sigma/E)\sqrt{E}$ is measured for a set of high-Z absorber thicknesses. At 10 GeV, all curves corresponding to a G10 thickness and a set of high-Z absorber thicknesses are parallel: a) $e/\pi = 1.0$, b) $e/\pi = 1.1$.

Fig. 5 A mosaic plane of 48 trapezoid silicon detectors. Each detector, 400 μm thick, has an area of 28 cm^2 and is operated at a depletion of 200 μm. (These detectors were built by ANSALDO).

Fig. 6 SICAPO calorimeter. The absorber plates have a transverse size of up to 60 cm $\times$ 60 cm. The total depth available is 4 m.

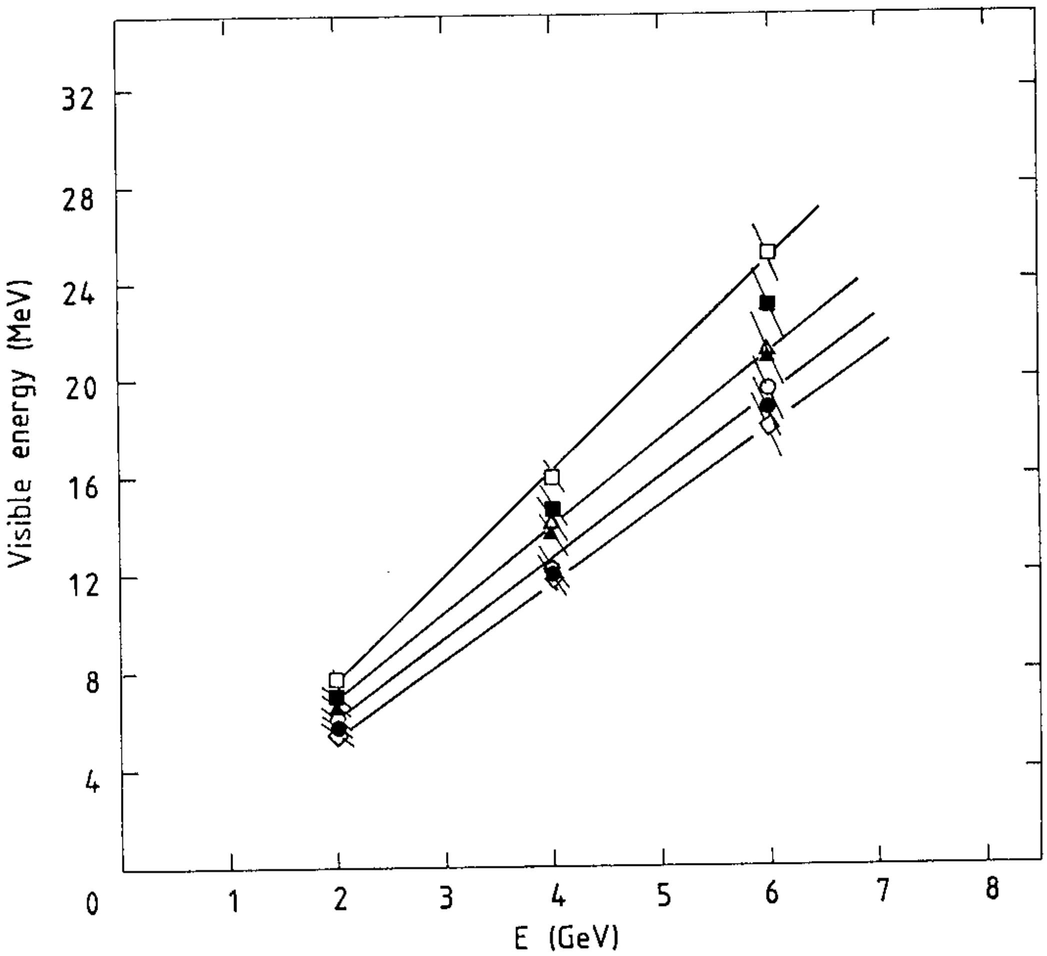

Visible energy (MeV)
E (GeV)
0
1
2
3
4
5
6
7
8
4
8
12
16
20
24
28
32

Fig. 1

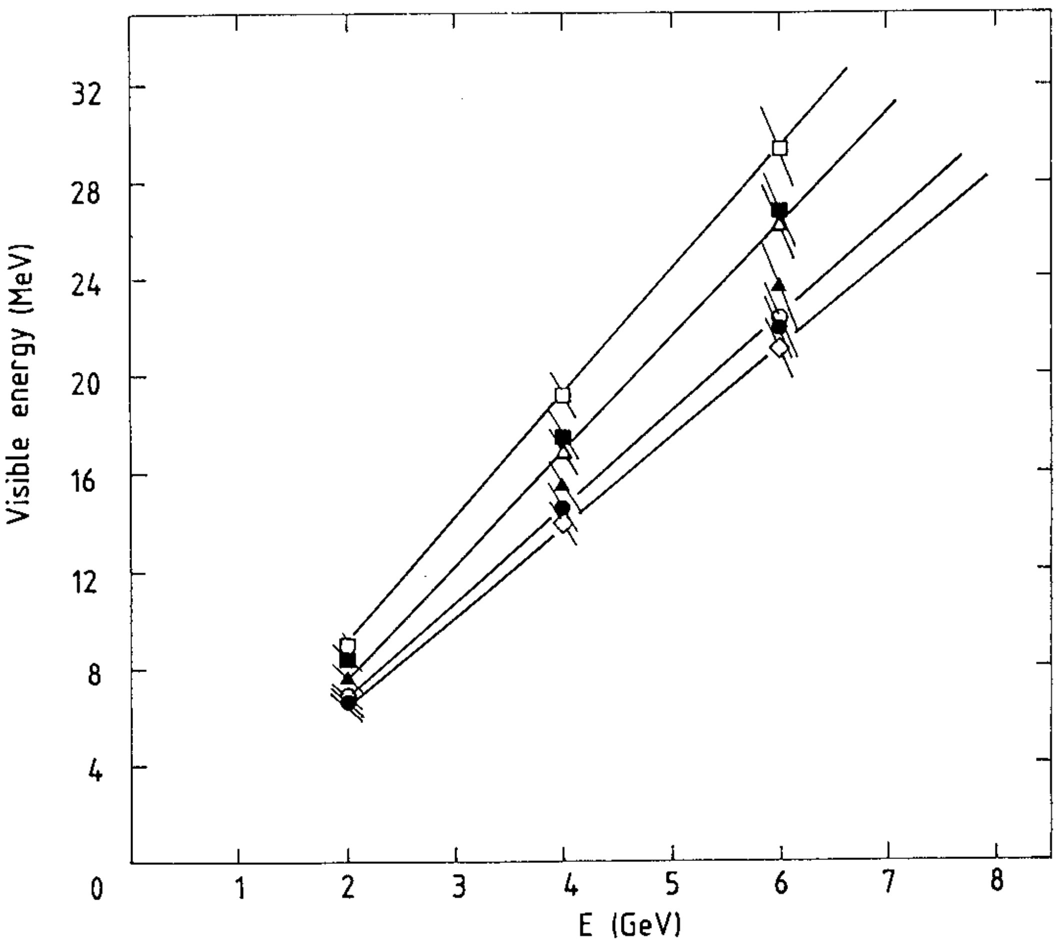
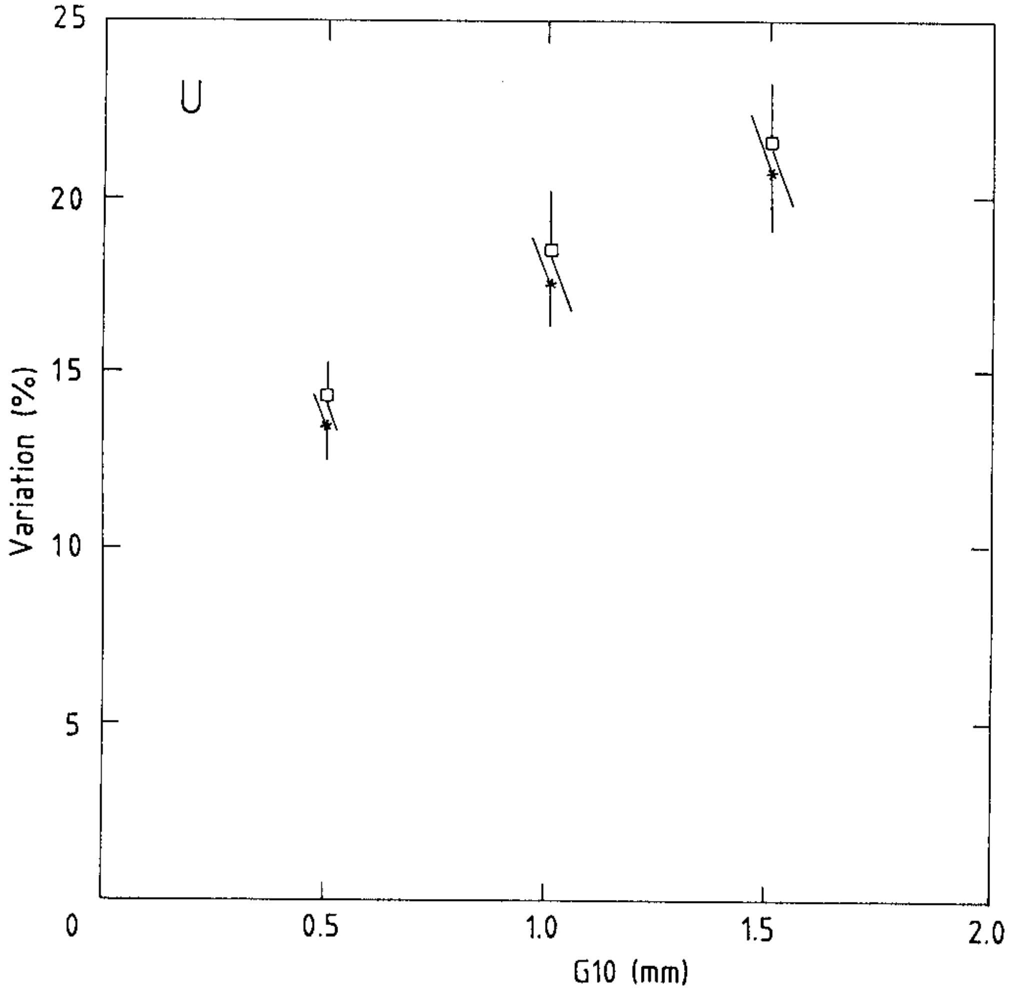
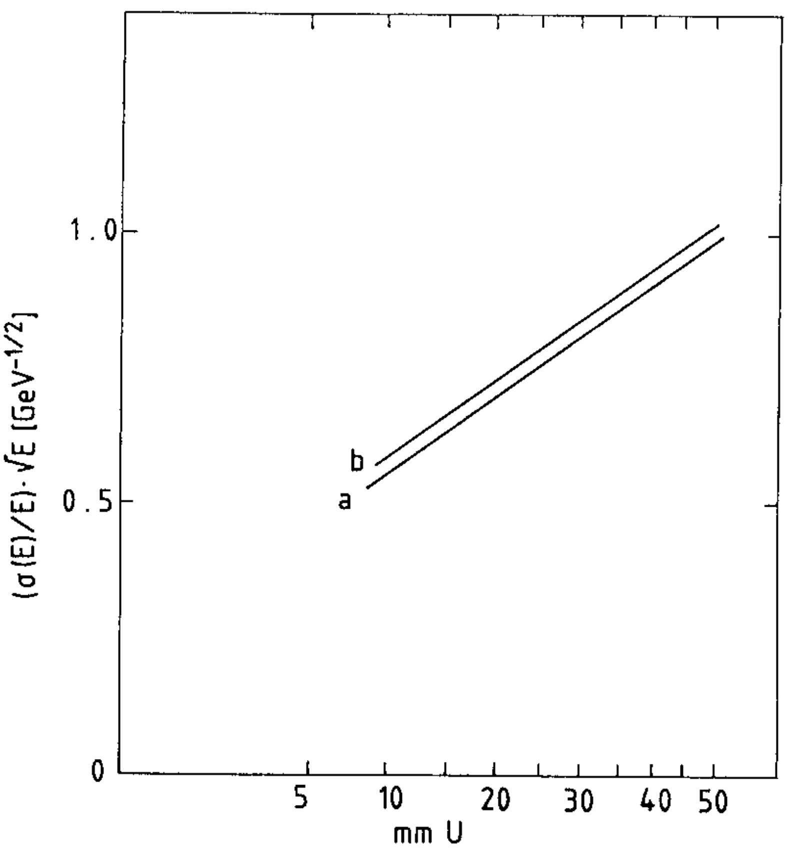

Visible energy (MeV)
E (GeV)
0
1
2
3
4
5
6
7
8
4
8
12
16
20
24
28
32

Fig. 2



25
20
15
10
5
0
Variation (%)
U
0.5
1.0
1.5
2.0
G10 (mm)

Fig. 3



1.0
0.5
0
(σ(E)/E)·√E [GeV-1/2]
b
a
5
10
20
30
40
50
mm U

Fig. 4

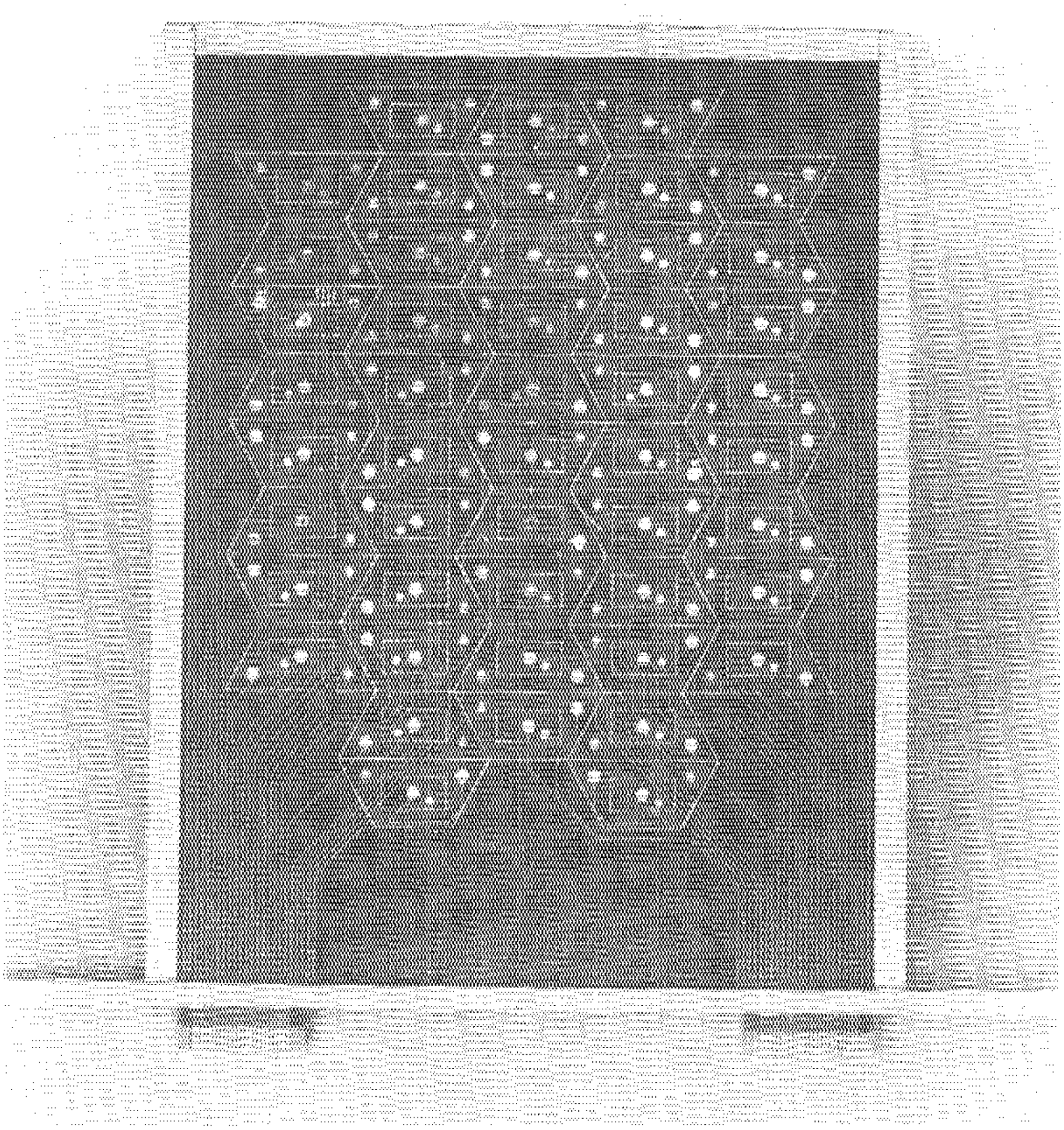


Fig. 5

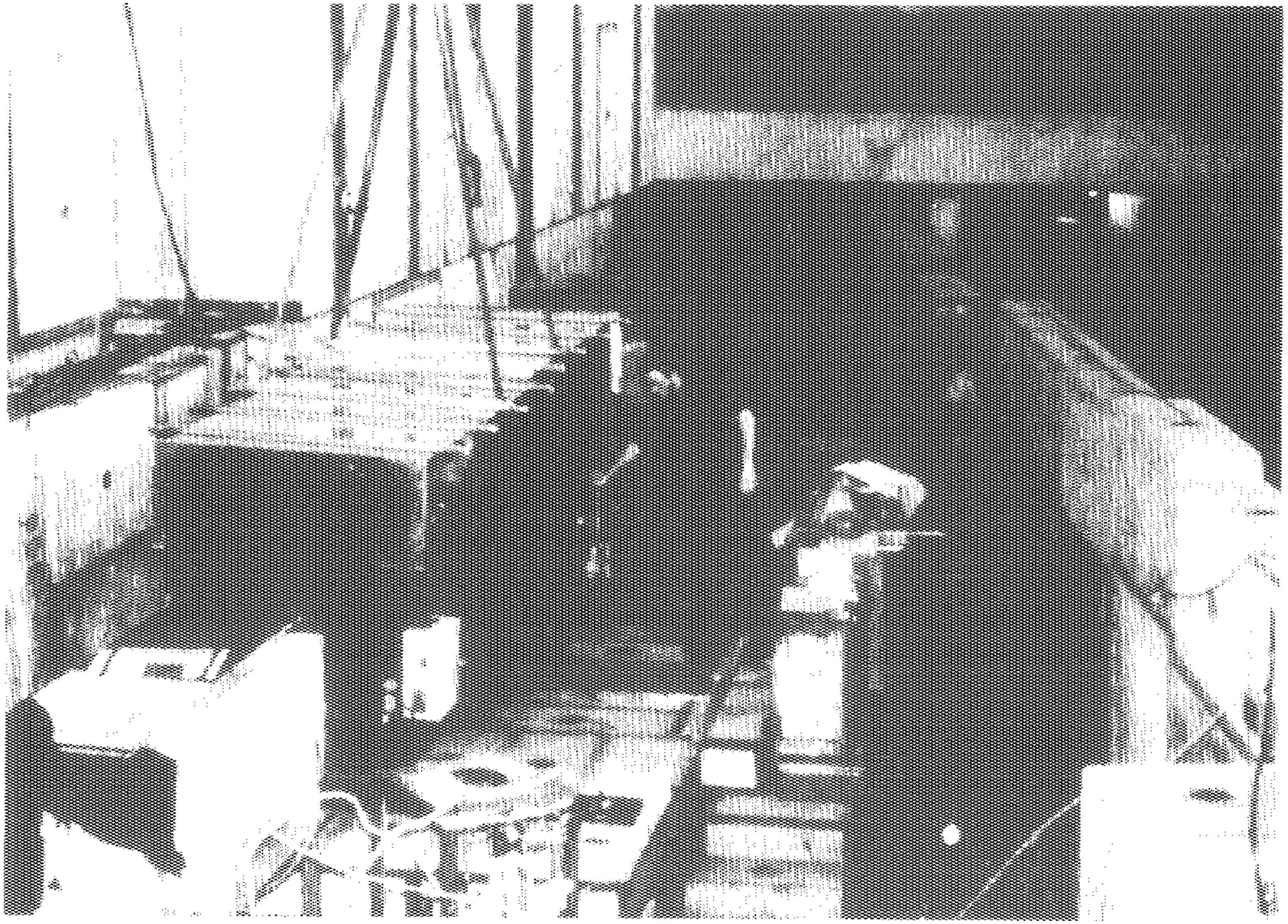


Fig. 6