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A Proposal to Study a Tracking/Preshower Detector for the LHC.

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Abstract

We describe a program of studies aimed at determining whether the track stub/preshower technique of electron identification can be used at the highest operating luminosities of the proposed LHC Collider. The proposal covers detector and electronics developments required for the construction of a track–stub and preshower detector preceding the electromagnetic calorimeter of an LHC experiment.

1 Introduction.

An important challenge for the design of a detector to operate with high machine luminosity at the LHC is the detection of leptons (muons, electrons and if possible taus) as signatures of both expected and unexpected rare physics processes.

The identification of electrons at both the trigger and analysis levels is a clear priority. The purpose of this proposal is to study the use of track/preshower techniques in electron identification, and to develop an appropriate detector prototype.

Isolated and non-isolated electrons must be identified from a background of QCD jets (including direct photons, π^0's from jet fragmentation, and conversions) that fake the signature for electron detection. Rejection can be obtained against this background by the use of a combined preshower and track stub detector preceding a highly-granular electromagnetic calorimeter. As shown in figure 1, an electron can be identified by

1. a good spatial match between a minimum-ionising reconstructed track stub, a preshower signal having a pulse height consistent with that expected for an electron, and an electromagnetic energy deposition in the calorimeter, and
2. the isolation of the electron signal from nearby charged or neutral tracks.

No track/preshower detector so far constructed satisfies the severe operational constraints imposed at LHC by the short bunch-crossing separation (15 ns), the high interaction rate ($L \approx 10^{34}$ cm^{-2} s^{-1}), and the consequent high radiation levels. On the basis of existing experience at Collider detectors (in particular UA2 and CDF), we consider that the detector response must be very fast to minimise the overlap of signals from different bunch crossings, and that highly granular space-point readout (pads) is essential for adequate pattern recognition. Additional rejection would also be possible from an accurate track momentum measurement.

Starting with the nominal detector configuration shown in figure 2 we would like to pursue the following four independent but closely related studies over a period of 2 years. We consider these four topics to be essential to understanding the use of the preshower technique in electron identification at the LHC.

1. In section 2 we present the initial results of simulating a detector in the LHC environment. We wish to pursue detailed simulations of hadronic background processes and major physics signals of interest to understand whether the required rejection against the QCD background is attainable. Test-beam measurements of prototype detectors and their associated electronics will be used as input to these studies, and results from the simulation will be used for design optimisation (granularity, number of layers, separation of layers etc.)
2. We initially propose the use of silicon as a detector material. In section 3 we explore the closely related issues of radiation damage, detector granularity, heat dissipation and mechanical constraints. We present preliminary results of calculations of the radiation levels at the LHC. We intend to make a detailed study of the damage caused by this radiation, especially the low-energy neutrons, for realistic

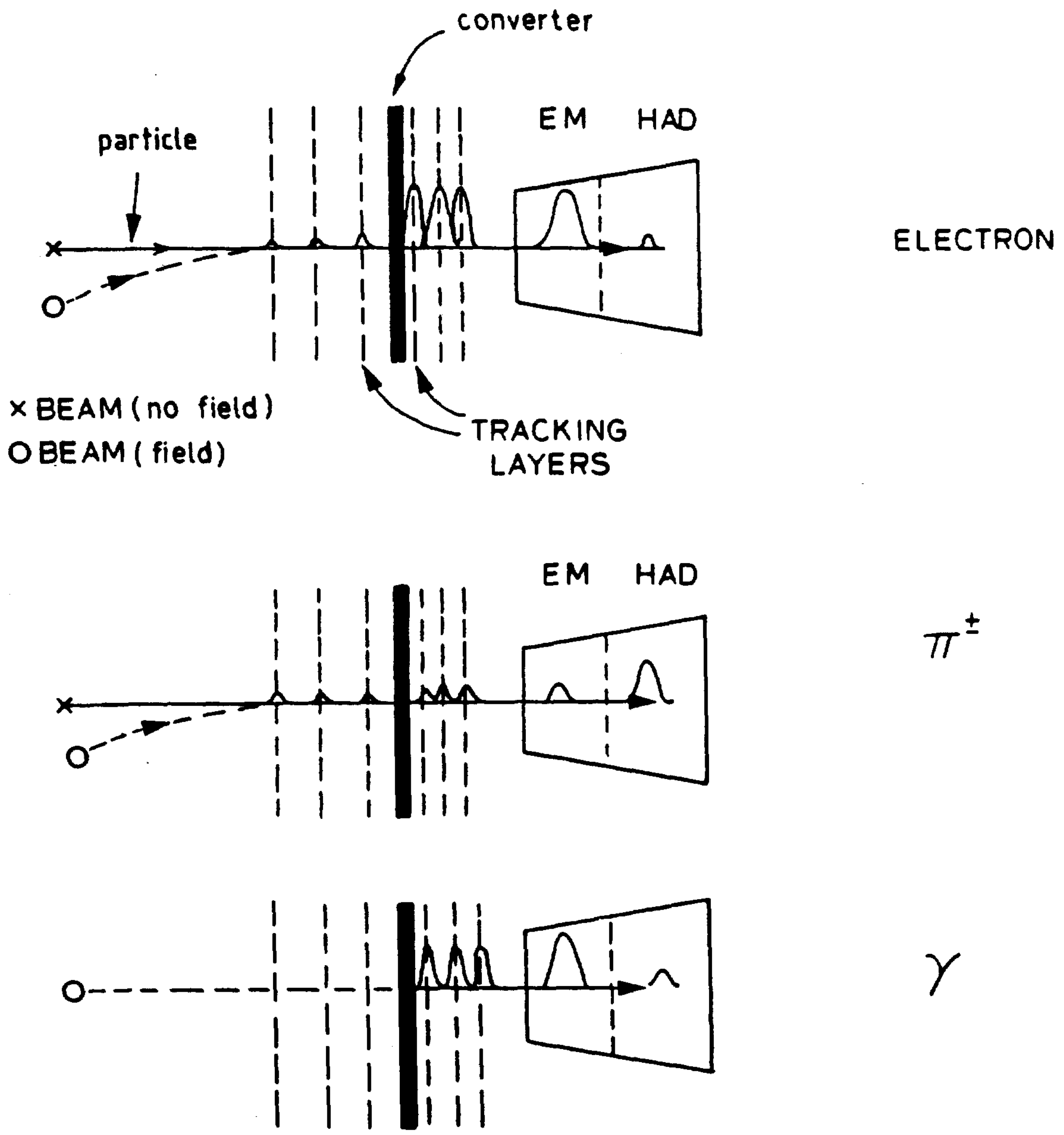


Figure 1: The identification of electrons, photons and charged pions using a preshower detector preceding an electromagnetic and hadronic calorimeter.

detector geometries that include neutron moderators. Together with measurements of radiation damage, we hope to determine within one year the suitability of silicon as a detector material at the highest LHC luminosities.

3. The development of high–density, radiation–hard electronics with fast signal response, pipeline readout and hardware trigger capabilities is crucial to the development of any preshower and/or track stub detector at the LHC. In section 4 we discuss a read-out philosophy that we believe will fulfill these requirements. We present a phased development program which will result at the end of our studies in a fully working prototype for use in test beam work.

4. We propose a program of test–beam studies that will initially concentrate on the optimisation of a detector design that is capable of meeting the required electron identification criteria. Later test–beam studies will consist of testing a prototype detector with the associated electronics developed in section 4 .

In section 6 we discuss our funding request, and the proposed activities of the participants in this development effort.

While each of the aspects discussed above is interconnected, each involves an independent research effort. In particular electronics of the type discussed in this proposal is needed for any low-capacitance detector, regardless of the detector material chosen.

2 Simulation studies for electron identification at LHC.

2.1 Expected event rates at LHC

The program PYTHIA [1] has been used to simulate inclusive QCD jet production in the central rapidity region ($|\eta| \leq 2$) at a centre of mass energy $\sqrt{s} = 16$ TeV. The same program has been used, with jet fragmentation functions consistent with data at $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1.8$ TeV, to estimate π^0 production. In addition, the cross-section for direct photon production has been estimated [2], together with the inclusive production of electrons from the two most prolific sources, namely $pp \rightarrow b\bar{b} + X$, with the b or $\bar{b}$ decaying semi-leptonically to yield non-isolated electrons [3], and $pp \rightarrow W + X$; $W \rightarrow e\nu$ producing isolated electrons [4].

These integrated cross-sections per unit central rapidity interval are shown as a function of transverse momentum (p_T) threshold in GeV/c in figure 3, where the rates in Hertz per unit rapidity correspond to a luminosity $L = 10^{34}$ cm^{-2} s^{-1}. For comparison, the measured rates at the SPS collider for a typical luminosity $L = 10^{30}$ cm^{-2} s^{-1} are shown in figure 4 [5,6].

At LHC energies the relative electron to jet rate is much less than that observed at the SPS in the p_T range of the W or Z decay electrons. Thus to identify electrons at LHC the rejection factor against QCD jets needs to be significantly higher than that necessary for the study of W and Z electronic decays at the SPS collider.

The most striking feature, however, is the high absolute rate of electron production caused by the large proposed luminosity increase, such that an inclusive electron trigger

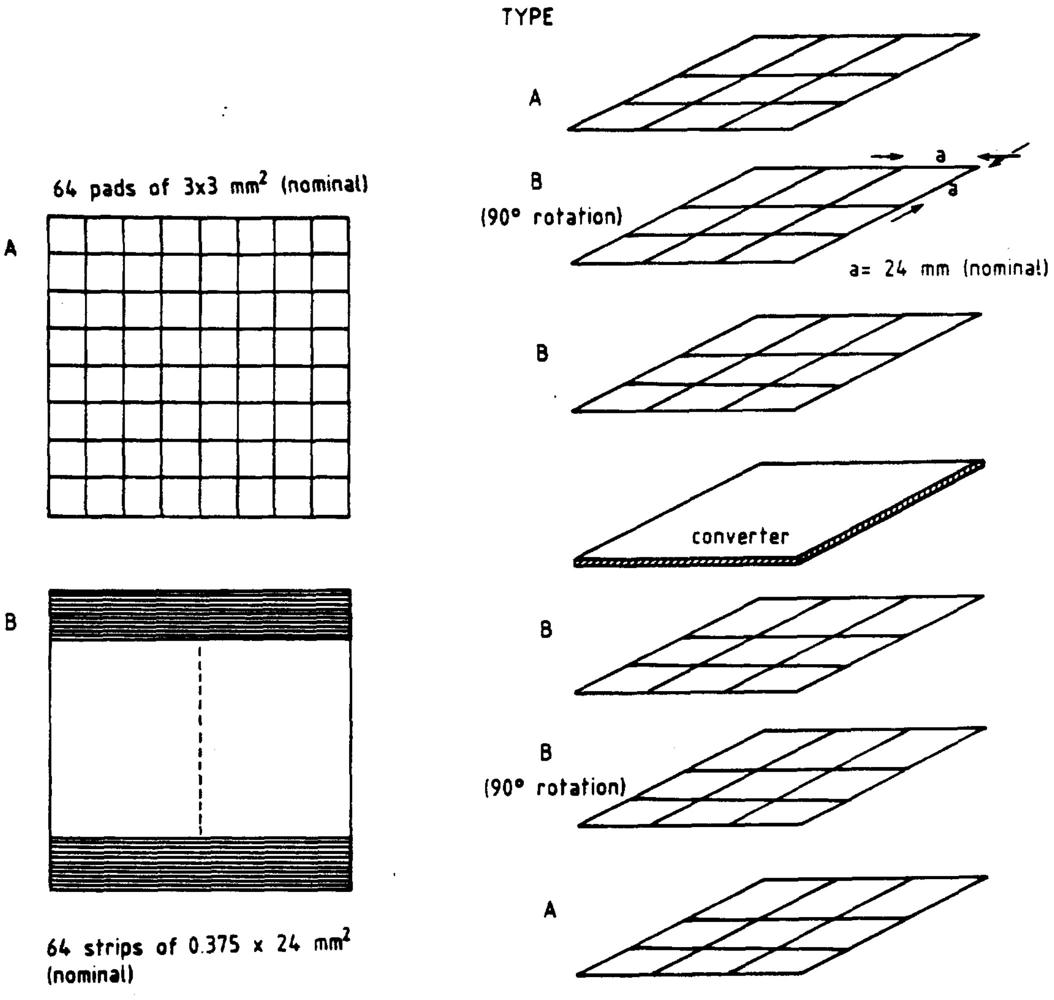


Figure 2: Schematic prototype detector arrangement.

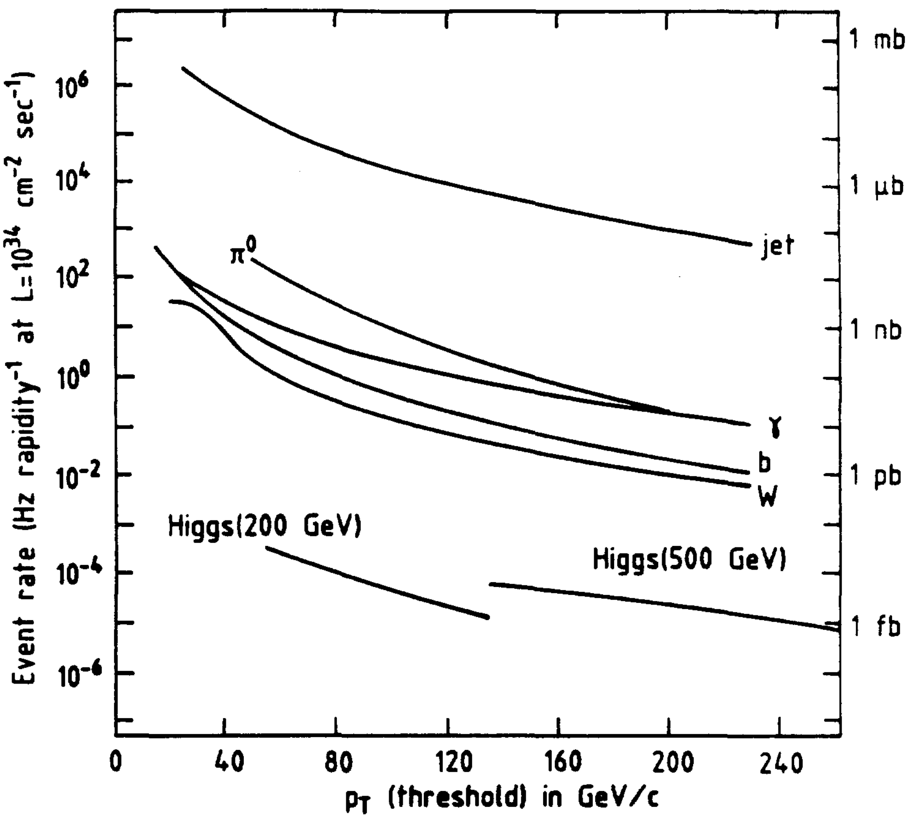


Figure 3: Expected rates from Pythia for the inclusive production of QCD jets, π^0's and photons as a function of the p_T threshold. Also shown are the expected inclusive electron rates from b-quark, W- and Higgs decay. The centre of mass energy is 16 TeV.

is outside the range of conventional data acquisition systems unless either a high p_T threshold or prescaling is applied. To exploit the available luminosity there is a clear requirement that an electron identification system should be able to reduce fake electrons to below the true electron rate at the trigger level: that is, in the case of inclusive electrons, for a rejection of order 5×10^4 to be available on-line. It is desirable that a somewhat larger rejection be available for off-line analysis although most physics topics will involve additional lepton(s), neutrino(s) or jet(s) in the final state allowing rejection factors to be compounded (for example the Z° signal which will be used for calibration studies). In combining rejection factors it is necessary to maintain a high efficiency to avoid a loss of statistical precision.

Regardless of the rejection against QCD jet background attainable by calorimetric means, a significant π^0 and photon background will fake the calorimetric electron signature since their calorimeter profiles are virtually identical. An associated charged track stub provides discrimination between genuine electrons and unconverted photons. A preshower detector provides additional rejection against charged hadron–π^0 overlaps through increased track-shower matching precision, and against the $\pi^\pm$ charge exchange background by virtue of its small interaction length. Photon conversions from π^0's and η's are backgrounds satisfying the track-preshower matching constraint. Rejection against this background can be obtained by distinguishing double tracks in the track stub detector from their ionisation deposition. Additional rejection against π^0/η decay backgrounds is available by measuring the decay opening angle using the preshower

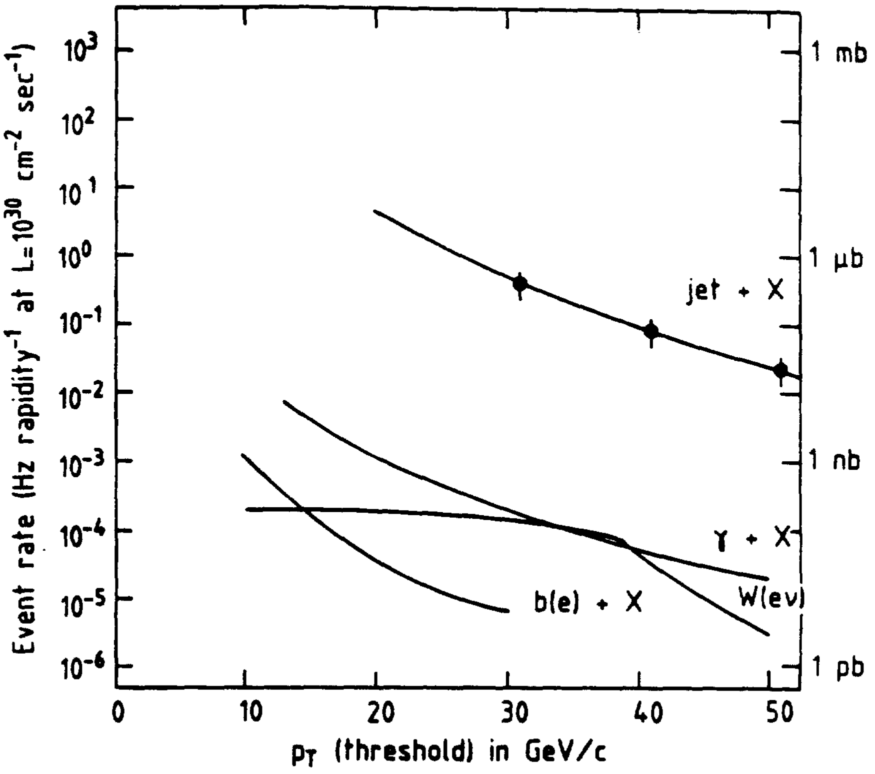


Figure 4: Measured rates for single photon production and electrons from W-decay at the UA2 experiment. The measured rate of QCD jets is shown as data points, with superimposed QCD expectations from Pythia as for figure 3. Pythia is also used to predict the electron rate from b-quark decays.

counter in conjunction with a highly granular calorimeter. The measured calorimeter impact point represents the π^0/η direction, while at $p_T = 20$ GeV/c the preshowers from the conversion electrons will be separated from this by at least 7 mm at 1 m radius.

2.2 Experience with the UA2 detector

A track-preshower detector has already been used in a Collider environment by the UA2 Collaboration as a complement to their calorimeter for electron identification [7]. This detector, which used scintillating fibres, had a projective geometry with stereo triplets, and the use of a pad layer was essential to resolve ambiguities of the pattern recognition. Figure 5 shows the rejection against electron backgrounds measured from UA2 data.

Simple calorimeter cuts give an overall rejection of 140 against centrally produced jets. This can be subdivided into a factor of about 10 from requiring the energy deposition in the e-m compartment of any set of 2 × 2 adjacent cells to be above threshold ($\Delta\eta \times \Delta\phi = 0.20 \times 0.26$ in the UA2 central calorimeter), with a further reduction of about 14 from isolation requirements (cuts on hadron leakage and cluster radius). The efficiency of this calorimeter selection is 92% [6].

The requirement of a track/preshower match in front of a calorimeter cluster gives an additional rejection of about 40 against conversions and 200 against overlaps. The matching precision, studied using electrons from a sample of unambiguous W decays,

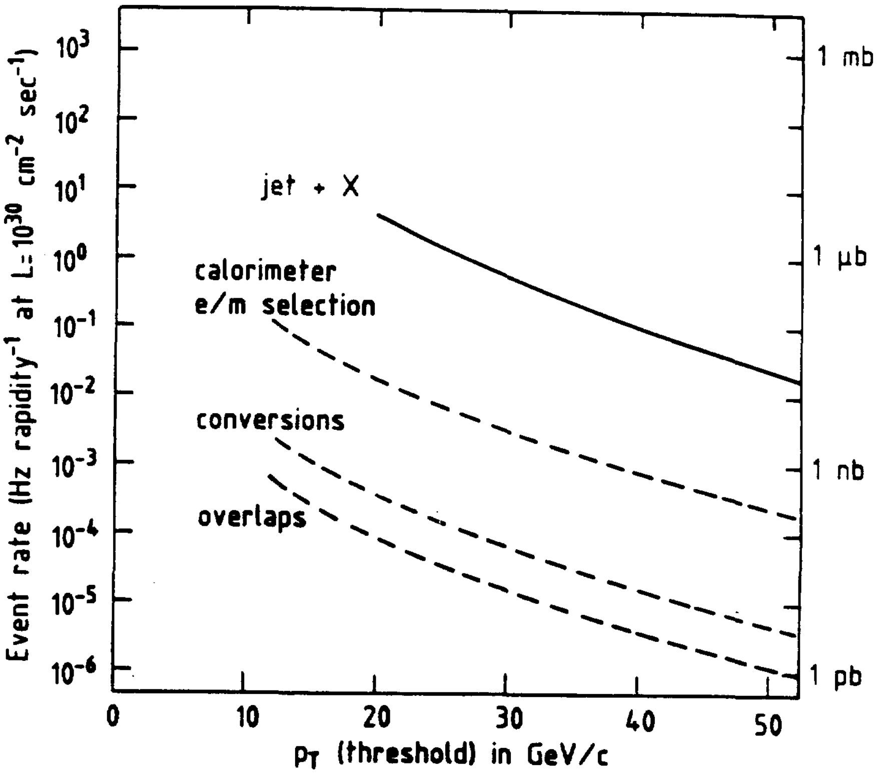


Figure 5: Event rates observed in the UA2 detector before and after calorimetric selections for electron identification. Also shown are the estimated conversion and overlap backgrounds, after additional track and preshower selection criteria.

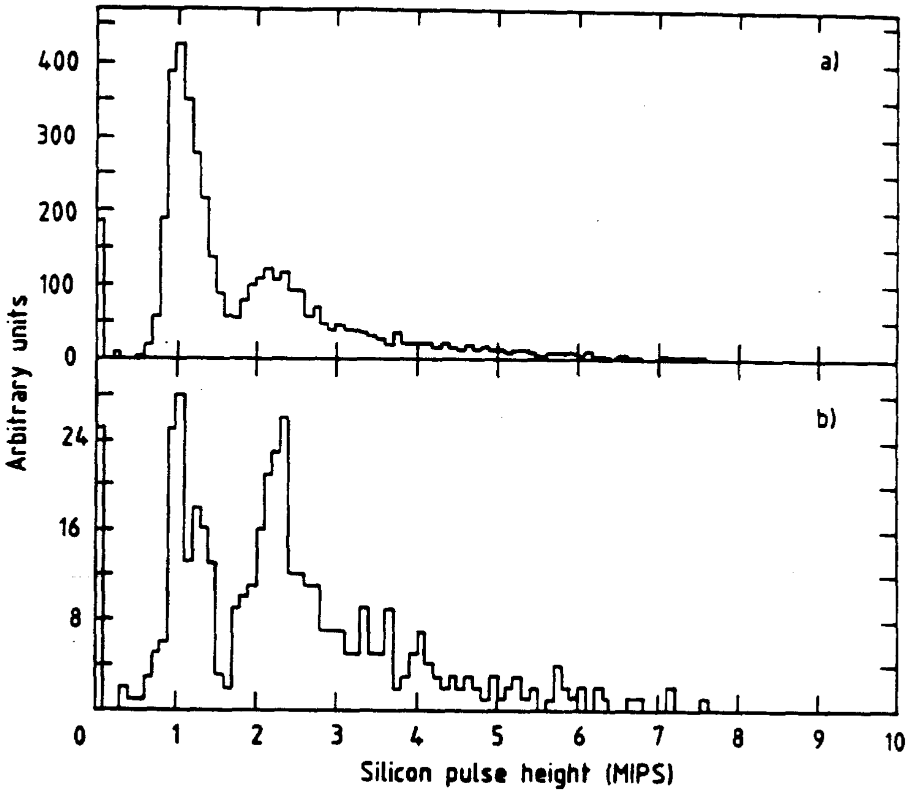


Figure 6: The pulse height distribution measured in the UA2 outer silicon detector (units of minimum ionisation) a) all tracks facing an electromagnetic cluster, b) the track selected to have the best match to the preshower and calorimeter clusters.

is found to be $\sigma_{r\phi} = 0.4$ mm and $\sigma_z = 1.1$ mm from a Gaussian fit. These data showed non-Gaussian tails which are partially attributed to other particles overlapping in the projective geometry of the detector [7]. The rejection obtained against overlaps is consistent with the ratio of solid angle subtended at the vertex by a calorimeter cell to that subtended by a preshower matching ellipse. The combined rejection against overlaps from the calorimeter and the preshower detector is about 3×10^4.

The large conversion background is due to the amount of material (almost $10\% X_0$) in front of the track-preshower detector. Figure 6 illustrates the ability of the UA2 silicon pad detector [8] to resolve double particles on the basis of pulse height. The upper pulse height distribution (in minimum ionisation or MIP units) was obtained for all tracks facing an electromagnetic calorimeter cluster, whereas the lower distribution represents the charge on the track with the best match to the preshower and calorimeter clusters. For an isolated electron the Landau tail on the 1 MIP response limits the single layer efficiency to between 70% and 80%, according to the amount of material traversed. A multi-layer detector would significantly enhance the 1 to 2 MIP separation capability.

The average multiplicity of charged tracks associated with an e-m calorimeter cluster is measured to be ~ 1.2, which was about 30 times the minimum bias occupancy. This restricts the rejection power of any track stub/calorimeter match without an associated preshower association. The local high multiplicity illustrates the limitation of a projective geometry because of 'ghost' combinations obtained in the region of a jet core [9].

2.3 Extrapolation to LHC

We assume the initial electron identification is made from a highly granular calorimeter having an interior unoccupied radius of 1 m, consisting of an e-m calorimeter with lateral cell size of the order of the Moliere shower radius ($\Delta\eta \times \Delta\phi \approx 0.02 \times 0.02$) and with a depth of 27 radiation lengths, followed by a hadron calorimeter 10 absorption lengths deep. The study of a calorimeter configuration with these parameters is the subject of a separate R & D request [10]. An electron would deposit more than 90% of its energy in a 3 × 3 cell matrix. For any given threshold E_T a requirement that the summed E_T of the matrix exceeds threshold would provide an initial rejection of about 50 against jets. A realistic simulation, including electronic noise and minimum bias pile-up (for LAr with $\sim$ 400 ns integration time), indicates that isolation and leakage cuts would result in an overall rejection of about 10^3, leaving the irreducible single π^0 and direct photon production as the major backgrounds [11]. The additional rejection needed can be supplied by requiring a track stub pointing to the centre of the electromagnetic shower. The centre of the shower can be measured by either the e-m calorimeter or by a preshower counter. Under test-beam conditions the precision obtained from the centre of gravity of a shower cluster should be $\sigma \approx 0.6$ mm from simulation studies [11,12]. In practice pile-up and noise (especially at the edges of the cluster) will lead to non-Gaussian tails which degrade the average precision. For $p_T = 20$ GeV/c it has been estimated that 95% of electrons will lie within a radius of $\sim$ 3 mm about the cluster centroid [11].

A GEANT simulation of the track/preshower matching precision of the nominal prototype detector (see figure 2), shows a fitted σ of $\sim$ 0.25 mm (see figure 7). While the track/calorimeter match is likely to be sufficient (i.e. a rejection of $\sim 2 \times 10^5$ against overlaps), the additional rejection obtained from a track/preshower match provides an important safety margin. Furthermore, a first level trigger using the good granularity of this detector will be easier to achieve than a similar trigger using the track/calorimeter match.

In the event of photon detection being necessary in rare physics processes, the preshower detector could be used in conjunction with the calorimeter to provide a measurement of the photon direction.

It will be very important to minimise the material in front of the track stub detector to ensure that the background from photon conversions is kept to a minimum. The nominal prototype has three layers of very high granularity in the track stub region, therefore enabling a much better 1 MIP/2 MIP separation than that achieved by UA2.

2.4 Required simulation studies & timescale

A phased series of simulation studies is indicated in Table 1, and is assumed to extend over 2 years. The simulations will include

1. A study of the ability to use the detector configuration shown in figure 2 to provide at high luminosity the necessary rejection against the QCD background for (initially) isolated electrons, with and without a magnetic field. If these studies are encouraging, items such as the effect of granularity, the optimisation of layer

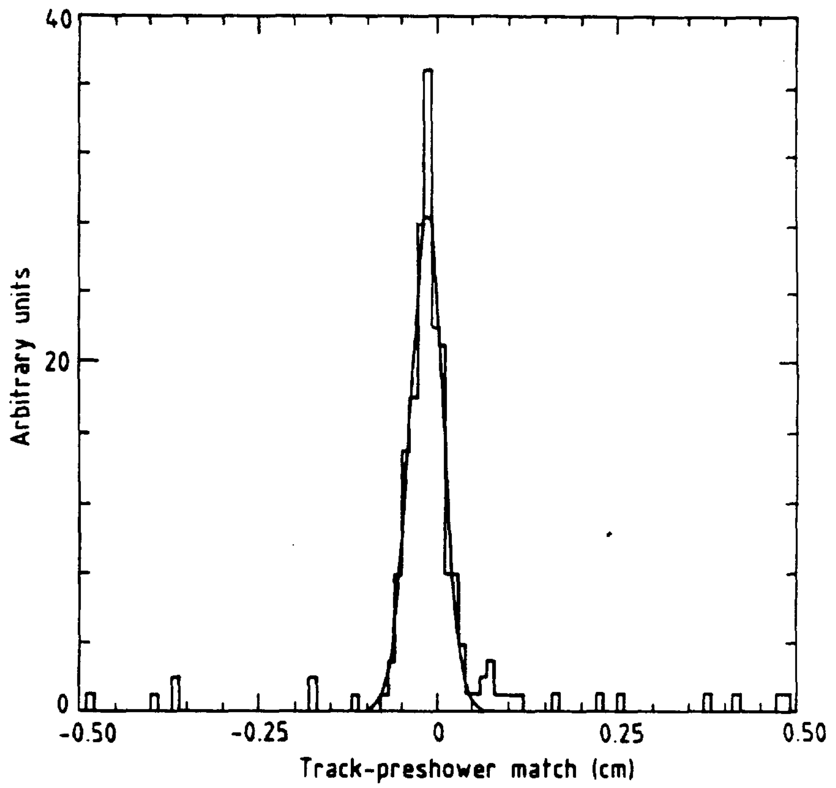


Figure 7: The expected track–preshower spatial matching accuracy of the prototype detector shown in figure 2, before applying a beam constraint. The curve is the result of a gaussian fit.

separation and the effects of gaps and overlaps will be considered. If not successful, it is important to understand whether an extended configuration would be appropriate, or whether the detector could be used to complement other detector techniques (e.g. scintillating fibres).

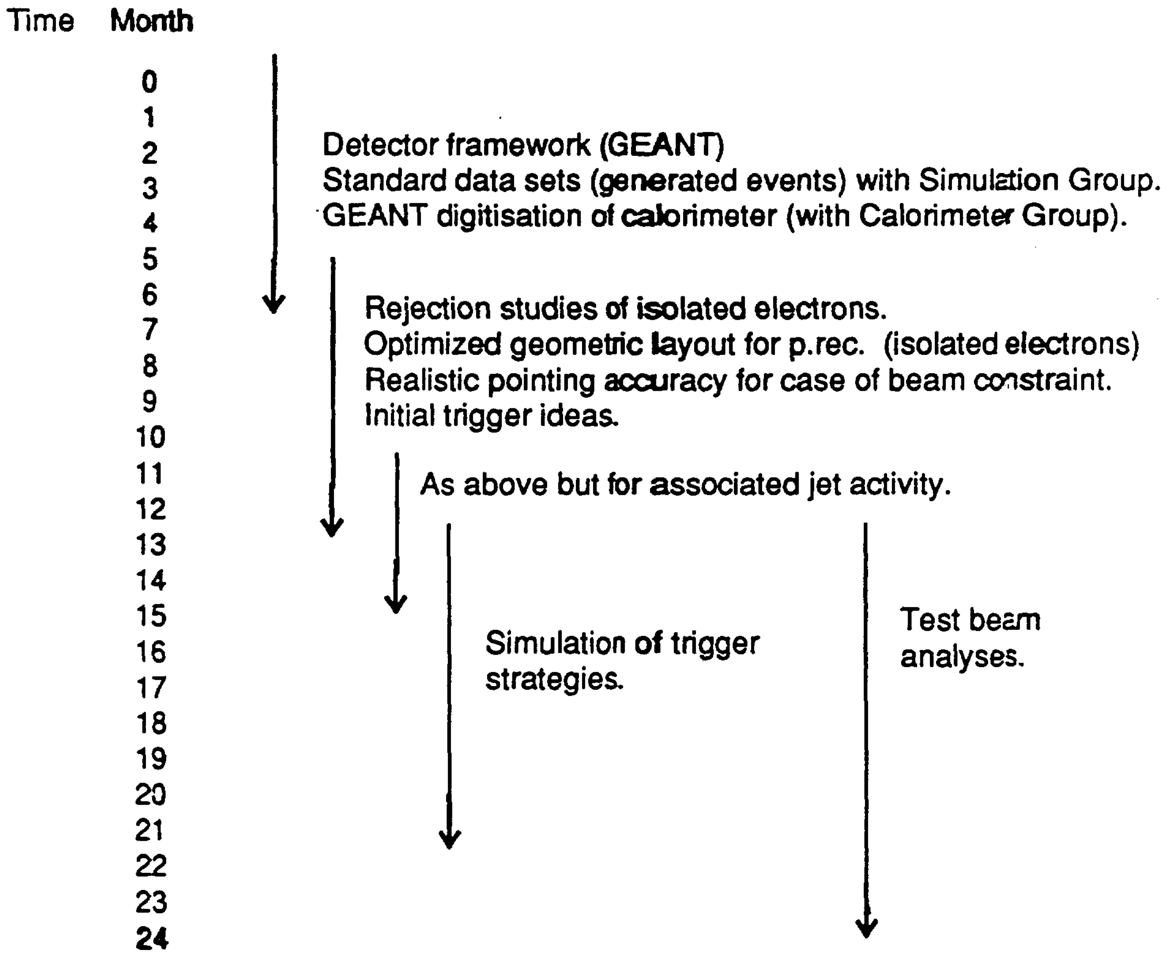
2. A full simulation of multiple-level hardware trigger strategies, on the basis of (1) above and including the compression and verification of data initially at a single plane level.
3. At a later stage a full comparison with test-beam results and an extrapolation to LHC operation is necessary.

A separate simulation requirement is that of the radiation environment, and this is described in section 3.1.

We request the following support from CERN.

1. The support of one full time analysis professional to assist in the development and maintenance of simulation and analysis software, and to maintain compatibility and complementarity with similar studies of other tracking and calorimeter detectors.
2. Professional support for the GEANT package used in simulation.
3. Adequate CPU time for simulation studies and test beam analyses, over a period of 2 years.

Table 1. SIMULATION STUDIES. Approximate time scales for simulation studies of electron identification at LHC.



Detector framework (GEANT)
Standard data sets (generated events) with Simulation Group.
GEANT digitisation of calorimeter (with Calorimeter Group).

Rejection studies of isolated electrons.
Optimized geometric layout for p.rec. (isolated electrons)
Realistic pointing accuracy for case of beam constraint.
Initial trigger ideas.

As above but for associated jet activity.

Simulation of trigger strategies.

Test beam analyses.

3 Detector design considerations.

Any detector designed as a preshower and tracking device at high LHC luminosities must satisfy the following design criteria for electron identification over an extended operating period:

1. a good detector granularity for track pattern recognition,
2. a fast signal response from the detector and from the subsequent electronics, given the 15 ns beam–crossing time and the high event multiplicities at each crossing,
3. the detector and the associated electronics must tolerate realistic radiation levels over several years of operation,
4. a good mechanical rigidity of the detector, with a small detector thickness prior to the preshower converter, and minimal dead–space or overlaps.
5. an acceptable heat output from both the detector and the associated electronics, with minimal mechanical stress due to thermal effects.

In this section, we initially discuss the resistance of silicon detectors to radiation, and propose a program of work to ascertain the suitability of silicon as a detector material. We then comment on the mechanical design criteria and describe a set of prototype counters required for R & D studies.

3.1 Radiation damage.

Radiation damage to both the electronics and the detectors is caused by ionizing radiation coming from the interaction region, and by neutrons (mainly) scattered into the cavity of the central detector by the calorimeter. Additional radiation may result from beam losses, especially during setup periods. This latter is expected to be small in comparison with interaction-generated radiation.

For a luminosity of $L \approx 10^{34}$ cm^{-2} sec^{-1} and beam storage for 10^7 sec per year, if we assume an inelastic cross section of 60 mb the number of inelastic collisions is 6×10^{15}. Assuming a charged particle rapidity density $dN_{ch}/d\eta \approx 6$ this gives a yearly fluence of charged particles at $\eta = 0$ and a radius of 1 m of $F \approx 5.7 \times 10^{11}$ cm^{-2}. The fluence varies as the inverse square of the distance from the axis. This simple calculation neglects the effects of photon conversions and could therefore be an underestimate by up to a factor of about two.

Although the neutron albedo flux is fairly homogeneous within the central cavity, the flux is strongly dependent on the calorimeter material and the calorimeter geometry. For a spherical calorimeter the flux varies as the inverse square of the calorimeter inner radius. An estimate of the flux for a cylindrical geometry is under study. From the calculations of Groom et al. [13] after renormalising for the number of inelastic collisions to be 6×10^{15}, the inner radius of the calorimeter to be 1 m and the calorimeter material to be Pb/LAr the yearly neutron fluence would be 7.7×10^{13} cm^{-2}. This fluence would be multiplied by a factor of 2.0(0.3) for a U/LAr (Pb-Scintillator) calorimeter. This neutron flux could be moderated by the existence of a neutron absorber.

The effect of radiation damage on silicon diode detectors is an increase in the reverse bias current due to the creation of bulk defects in the high resistivity silicon volume. This results in increased noise, increased power dissipation, a shift of the DC level of the front end electronics, and a voltage drop over the bias filtering resistances. For very high doses, signal losses resulting from temporary charge trapping may also occur. It is unlikely that bulk damage can be significantly reduced. However measurements of Fretwurst et al. [14] show that over long periods, natural annealing of their counters reduces the leakage current by a factor of about 2.5, and thermal annealing at 100 – 200° C might result in a further reduction of leakage current. Furthermore, by operating the counters at lower temperature it is possible to reduce the leakage current (a factor 2 per $\approx 7°$ C) subject to a constant silicon resistivity.

The increase of leakage current per unit volume is proportional to the particle fluence and can be parameterized by $\Delta J = \alpha_c F_c + \alpha_n F_n$ where $F_c(F_n)$ is the fluence of charged particles (neutrons). The damage constant for minimum ionising particles is $\alpha_c \approx 10^{-17}$ A cm^{-1} with an uncertainty of ±30%. Using the charged particle fluences given above and a detector thickness of 300 μm this gives an increase in leakage current due to charged particles ΔI = 170 nA cm^{-2} year^{-1}.

There is considerably more uncertainty regarding the damage coefficient for low-energy neutrons, that is around 1 MeV. Data from controlled measurements suggest damage coefficients of between 6×10^{-17} [15] and 17×10^{-17} A cm^{-1} [16] We assume a damage coefficient α_n of 10^{-16} A cm^{-1} (conservatively we do not account for self-annealing effects). Therefore using the neutron fluences quoted above gives an increase in leakage current of 230 μA cm^{-2} year^{-1}. Therefore the radiation damage effect of neutrons is far greater than that of charged particles. The net increase in leakage current in a 9 mm^2 detector is 21 μA year^{-1}. A more realistic evaluation and a minimisation of this leakage current is an important aspect of this proposal.

A DC coupled fast front-end amplifier with continuous feedback, similar to AMPLEX [17] can remain operational up to leakage currents of about several μA. AC-coupled devices would allow considerably increased leakage currents. However even using AC coupled devices a very much larger leakage current would cause a proportinal increase in power dissipation and a significant increase in shot noise.

In summary the ability to use silicon detectors for a preshower/tracker at the LHC depends crucially on the neutron flux. The basic degradation mechanism is now well understood. However, neither the neutron flux nor the neutron energy spectrum is at present well known. Alternatives to silicon, for example amorphous silicon or diamond-like carbon, are not yet practical at this stage, but their development is being followed.

In close collaboration with a working group on calorimetry [10], we propose to

1. obtain accurate neutron flux estimates for realistic cylindrical detector geometries being considered for LHC,

2. use these estimates to optimise the detector design to minimise the neutron albedo, for example by inserting forward holes in the detector and by the use of neutron moderators.

3. perform measurements of the radiation damage at neutron energies around 1 MeV (see for example [14]) for the prototype silicon detectors discussed in section 3.5.

Adequate measurements are required to have confidence in the estimated fluxes, and in addition to ongoing measurements at the SPS [18], we propose to compare neutron fluence measurements at UA2 with a simulation using the UA2 detector geometry. Finally, ideas for low-temperature operation will be actively considered as a way of reducing the leakage current following radiation damage.

The question of developing radiation hard electronics for this environment is discussed in section 4.

3.2 Detector granularity.

The detector granularity must be decided as a compromise between several competing factors:

1. resistance to radiation damage,
2. small detector capacitance and fast signal response,
3. pattern recognition capability for isolated tracks,
4. mechanical considerations and connectivity to electronics, and
5. cost.

We have initially considered a pad size of approximately 3×3 mm^2, with additional accuracy in θ and ϕ from strip detectors of the same area. To significantly decrease the pad size gives a prohibitive channel count; of all the considerations above, the question of radiation damage is dominant, and indeed prevents a larger pad size. Recent studies by the Aleph and Delphi Collaborations [19] show promise for the use of double-sided silicon readout; we therefore also intend to study the feasibility of this technique.

In addition to simulations and associated electronic development, significant R & D is needed to understand the best way to mount the detector pads, and to provide a coherent large-area readout scheme (board design, interconnections, etc).

3.3 Mechanical rigidity.

The final detector design must be thin, rigid, and have good thermal characteristics. Further, the dead space between detectors must be minimised. Figure 8 shows the mechanical assembly for the inner layer of the UA2 silicon detector (a detector with 3 times less granularity than the nominal design shown here). In this detector the readout was achieved by conductive rubber strips held under pressure against the silicon. An AMPLEX chip was supported on a ceramic holder behind the individual counters. In the LHC design, the electronics must remain mounted close to the detectors. Because of large number of channels and small granularity it is necessary to make some data sparsification and pedestal subtraction, plus if possible local trigger decisions on the chip. It is therefore necessary to develop, in parallel with the associated electronic chip developments, ideas for counter support and readout, and to test them in prototype designs.

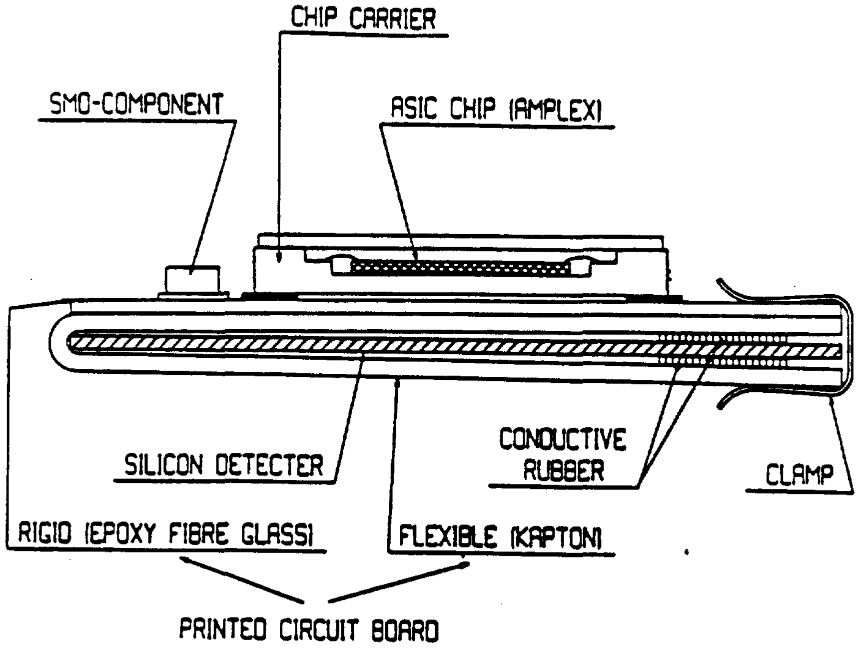


Figure 8: Assembly of the UA2 inner silicon detector.

3.4 Detector prototypes.

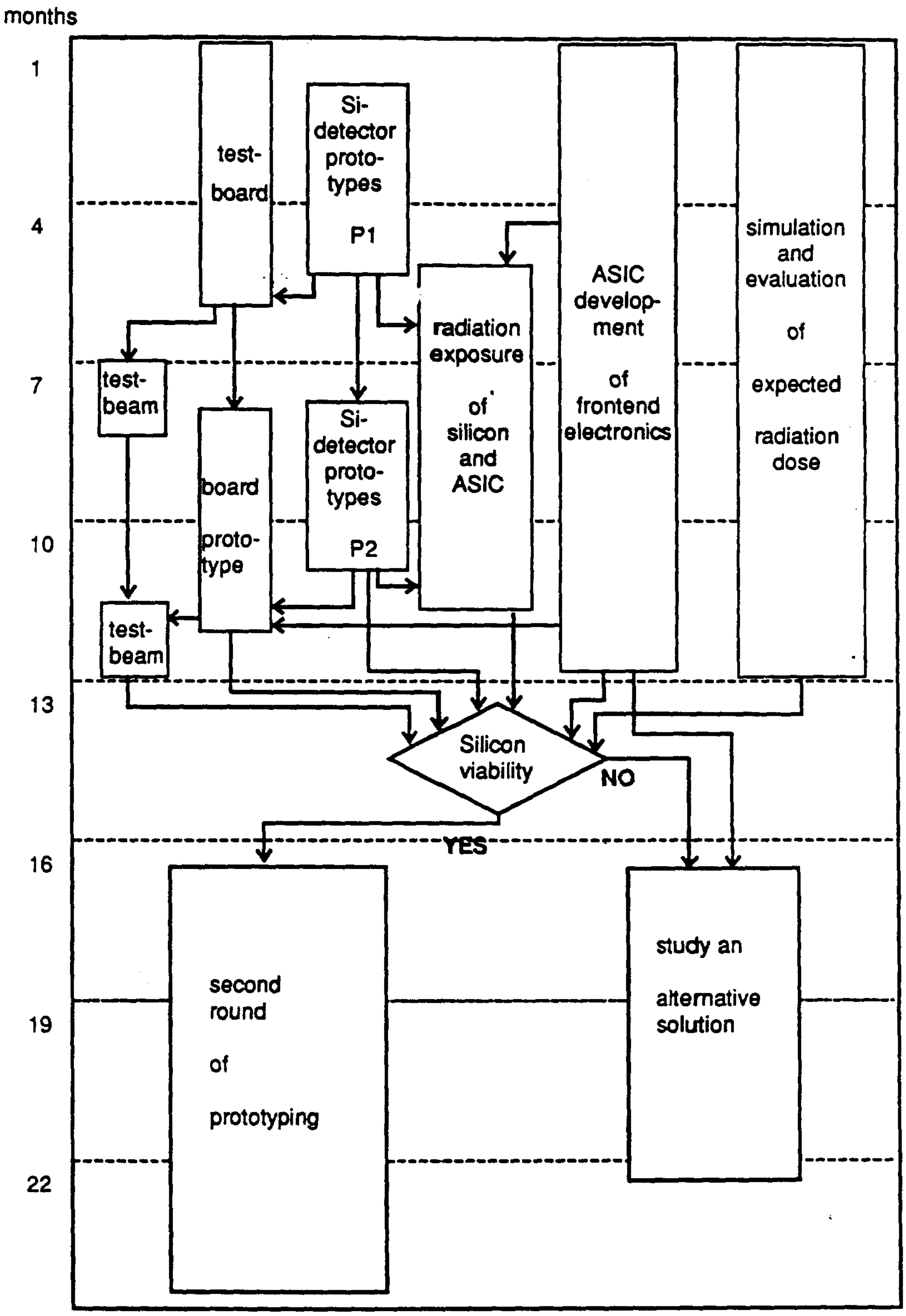
In the UA2 experiment we have successfully developed and operated pad counters for the UA2 silicon detectors [8] with pads of size 2 mm × 16 mm. We intend to build on our experience with these designs, and on working relationships that have been established with European manufacturers. We have already been able to design some double–sided prototypes and are in the process of evaluating these. An initial programme of work is summarised in Table 2. The aim is to design and manufacture silicon pad and strip detectors for our initial tests, and in parallel to explore new techniques required for the operation of a large high–density silicon array. The designs will involve detailed consideration of the read–out techniques and mechanical supports to be used, and comprehensive radiation studies will be essential to test their viability.

As will be discussed in section 5, the nominal test set-up will consist of 6 layers each having a 3 × 3 array of detectors as in figure 2. The 2 type A layers will require counters with 64 pads 3 mm × 3 mm, and those in the type B layers will have 24 mm × 375 μm micron strips which will be used in a crossed configuration. Thus the pad area and the channel count will be the same for both types of detector. We assume that these detectors will at least initially be 300 μm thick. Additional counters will be needed for radiation studies and rejects will be required for mechanical tests. We intend to place design and manufacturing orders with 2 commercial firms (a result of our experience in UA2) to obtain detectors for our first test beam period. In addition, we will ask the manufacturers to use the same masks to make double–sided detectors, with strips on one side and pads on the other. These counters have considerable advantages in the design of a realistic full–scale detector if they can be shown to work effectively.

In subsequent phases of design and manufacture we will continue to study the possibility of detector improvements, for example detectors of reduced thickness, radiation–hard detectors and further designs for double sided detectors.

We will need to develop and extend our existing equipment for characterising and

Table 2 OVERALL TIMETABLE



testing the counters, both for acceptance tests and for studies of counter degradation. In addition we will continue to require access to CAD equipment, and the use of electronic board layout facilities, clean room and test facilities at CERN ECP Division and elsewhere.

To summarise, we request in a first manufacturing round the production of

1. 18 working detectors (3 mm × 3 mm pads) with read-out lines to the counter edge,
2. 36 working detectors having 24 mm × 375 μm strips, and
3. ten additional counters of each type for other related tests.

With the quoted dimensions we will obtain 7 detectors from each 4 inch wafer. Each run is estimated to be 30 kSF.- per manufacturer, a total of 60 kSF per manufacturing cycle. We expect 3 or 4 manufacturing cycles, including 2 during the first year. Purpose-built control and test modules are estimated to cost an additional 50 kSF. (25–30 kSF per laboratory involved). Recurrent operating budgets for essential support from groups in ECP Division are not included in our budget request.

We note that our Cambridge University collaborators are involved in an independent R&D initiative in the United Kingdom.

4 Electronics.

4.1 Speed considerations.

Silicon preshower/tracking detectors of the type discussed in this proposal have the potential to resolve, both temporally and spatially, track ambiguities that necessarily occur if large–volume and low–speed calorimeters are constructed for the high–luminosities of the LHC. We therefore intend to develop for the preshower detector a VLSI electronics readout system which

1. is capable of running at LHC cycle times, with a timing accuracy about 1–2 ns,
2. is dead–time free, and
3. has no pulse pile–up.

This speed performance is possible because of the intrinsic speed of the silicon; for a 200μm thick detector biased at 80V the collection time is less than 1.5 ns [20]. Thus for a 5 pF detector element (10 mm^2) the charge transfer between detector and amplifier can be very fast.

Two examples of recent work demonstrate that existing micro–electronic technology and analog circuit design techniques are able to cope with the speed constraints of an LHC detector. Preliminary test chips using CMOS technology [21] have already demonstrated the possibility of fast and low–noise readout. The computer simulations of figure 9 show the output response of a fast current sensitive preamplifier made in 1.2 μm CMOS technology. The peaking time is in the range 5–10 ns, for a 5 pF detector capacitance. A second approach is to use BiCMOS technology [22]. Figure 10 shows

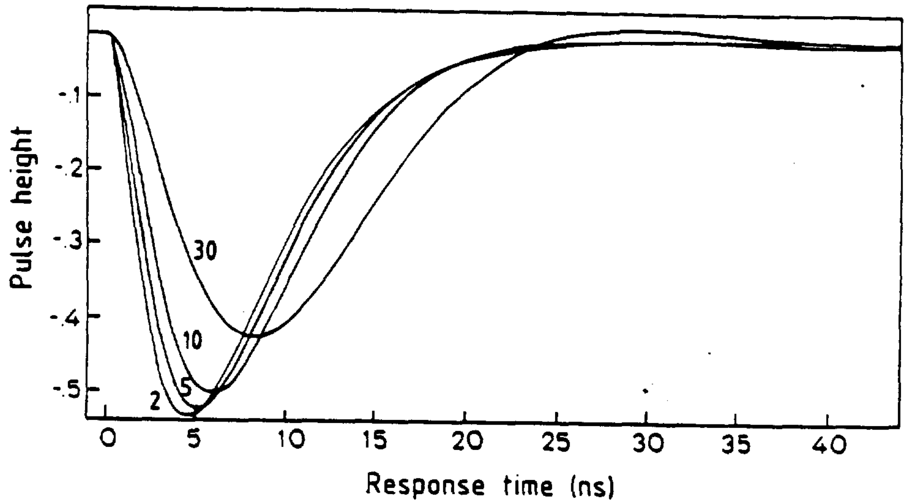


Figure 9: SPICE simulation (arbitrary scale) of the response of a fast CMOS amplifier in 1.2 μ CMOS technology, using several detector capacitances (pF).

the output response of a monolithic fast current sensitive preamplifier, implemented in 3 μm CMOS and using a lateral bipolar transistor. It has a peaking time of 15 ns for a 10 pF detector with an equivalent noise charge (ENC) of $\approx$ 1200 rms electrons.

An important feature of the readout electronics of a track/preshower detector is its ability to unambiguously associate any hit pad signal with the corresponding LHC clock cycle. The time jitter is ultimately limited by the amplifier noise, and by the pulse height distribution. The time accuracy of the signal is

$$\sigma(t_d) = \sigma(V_{out})/\sigma(dV_{out}/dt) \qquad (1)$$

where t_d is the propagation time of the signal discrimination and V_{out} is the output voltage of the preamplifier driving the discriminator. For peaking times as low as 15 ns, $\sigma(t_d)$ is less than 1 ns for ENC $\leq$ 1500 rms electrons. Landau fluctuations cause a larger t_d variation because of the spread in dV_{out}/dt; for large pulse heights t_d is shortened by the Landau distribution. Nevertheless, the timing precision is adequate for the unique association of hit pads within any 15 ns beam crossing period.

4.2 Power consumption.

Assuming a pad density of 64 channels per detector of 24 x 24 mm^2, there are 10 channels per cm^2 per layer. Each of these channels will include several active blocks such as discriminators and amplifiers with standing DC power. Each block will consume approximately 1 mW, that is 3 mW for each channel. This is similar to the power dissipation in the UA2 inner silicon array. The dynamic power of the switched capacitor used in the analog pipelines (including the switches, shift registers and control logic) is more difficult to estimate. If each channel includes 500 transistors in 1.2 μm CMOS

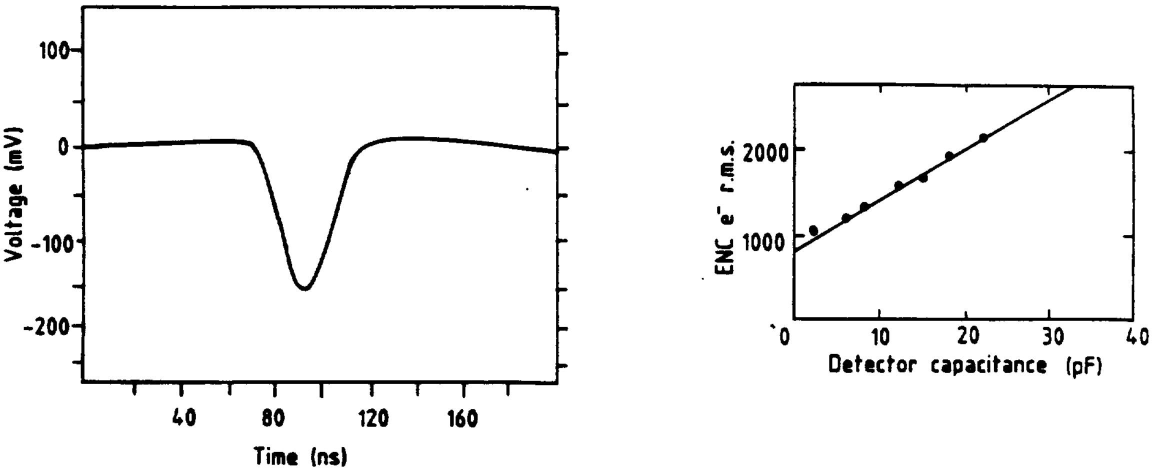


Figure 10: Measured output response of a monolithic fast current-sensitive preamplifier using the bipolar effect in CMOS.

technology the total gate capacitance to be driven becomes $\approx 2.5 \times 0.5$ pF, that is

$$P(\text{dissipated}) = NtC_gV_{DD}^2F_c = 1 \text{ mW} \tag{2}$$

for a clock frequency of 62.6 MHz, and $V_{DD} = 3$ V. This estimate is rather uncertain because of stray capacitance effects, etc. and a 1 mW uncertainty should be included. The total power dissipation is then estimated to be 5 mW ch^{-1}, that is 550 W per m^2 of detector. If the detector capacitance (including stray fields etc.) is significantly less than 10 pF, the power consumption will be correspondingly reduced.

4.3 Local on-chip intelligence.

The expected channel count makes it unacceptable to read out all signals in each clock cycle (most signals are only pedestals). We hope to develop a readout based on the HARP [23] system (initiated as a CERN-LAA project) where the analog information is stored on the chip for about 1 μs until a trigger decision (local or remote) chooses to accept relevant analog signals for digitisation.

One important component of the HARP system is the charge sampling integrator (CSI) which is organised as an analog pipeline memory (figure 11). An experimental 4-channel prototype with 64 memory cells per channel has already been fabricated in 3μm CMOS technology and shown to work functionally at a clock speed of 20 MHz [24]. It is based on the charge amplifier principle in which the feedback capacitance has been replaced by a capacitor bank (see figure 11). The writing clock can be synchronised to the LHC machine cycle and switches the feedback loop of the integrator to the following capacitor at each cycle. The capacitor voltages therefore represent the last 64 sampled charges from a particular pad. It thus acts as an analog pipeline storage element. With a depth of 64 memory elements (that is 15 ns $\times$ 64 $\approx$ 1 μs), analog information can be retrieved as determined by the trigger decision during that period. The value is read out for digitisation by the read amplifier which is connected to the correct capacitor by the read control unit. The readout of such a chip effectively suffers no deadtime or pileup, because the charge sampling is running continuously. If the system is DC coupled base line fluctuations are minimised and pedestal subtraction is feasible by subtracting 2 consecutive samples. Circuitry is also being developed to compensate for increasing leakage currents due to detector radiation damage. Finally, it is possible to tune the timing of each channel by reading a charge spread over successive samplings.

The complete readout system is shown in figure 12. Each silicon pad will connected to a preamplifier which will in turn be connected to the CSI and a discriminator. The fast readout will deliver a signal to the 1st or 2nd level trigger. The CSI unit performs data compression in the time domain. The sparse data readout unit should allow data compression in the space domain. The size of the readout system will be optimised for the expected pad occupancy rate.

Considerable R & D is required, however, to master gain and calibration uncertainties resulting from the capacitor inaccuracy and pedestal spread; the use of VLSI should enable much improved reproducibility.

4.4 Radiation hardness.

The radiation hardness of the VLSI chips is directly related to processing details of the microelectronics technology used. The gate oxide quality for CMOS and the basewidth for bipolar devices are significant parameters determining the radiation hardness.

In particular, SOI CMOS technology has been developed, for example by Thomson TMS, Sandia, Hitachi and Hewlett-Packard. Very radiation-hard versions used for military applications remained operational after an $\approx$ 100 kGy photon dose and a neutron fluence $\approx 10^{15}$ cm^{-2} with a threshold shift of only a few hundred mV. This indicates an operational lifetime of many years in the central tracking cavity of LHC. Access to this technology is not easy; nevertheless Thomson TMS has recently opened the technology for research applications, with some confidentiality restrictions.

A number of performance criteria must be met for this radiation-hard electronics to be used:

1. the speed of 1.2 μm SOI CMOS technology (0.8 μm in 1992) must be compatible with LHC requirements,
2. the power dissipation at reasonable noise levels must be small,
3. the V_t shift must be small, and
4. the noise etc. must be compatible with LHC needs.

4.5 Program of work.

We wish to develop a readout system based on the CSI principle, initially with 16- or 32-channels per device. This would first be designed to operate at half the LHC clock speed (33 MHz) in a 1.2 μm CMOS process. If this step proves satisfactory, the readout will be implemented in 1.2 μm SOI CMOS technology. It is expected that in 1992 0.8 μm SOI CMOS will become available, enabling a 66 Mhz clock speed.

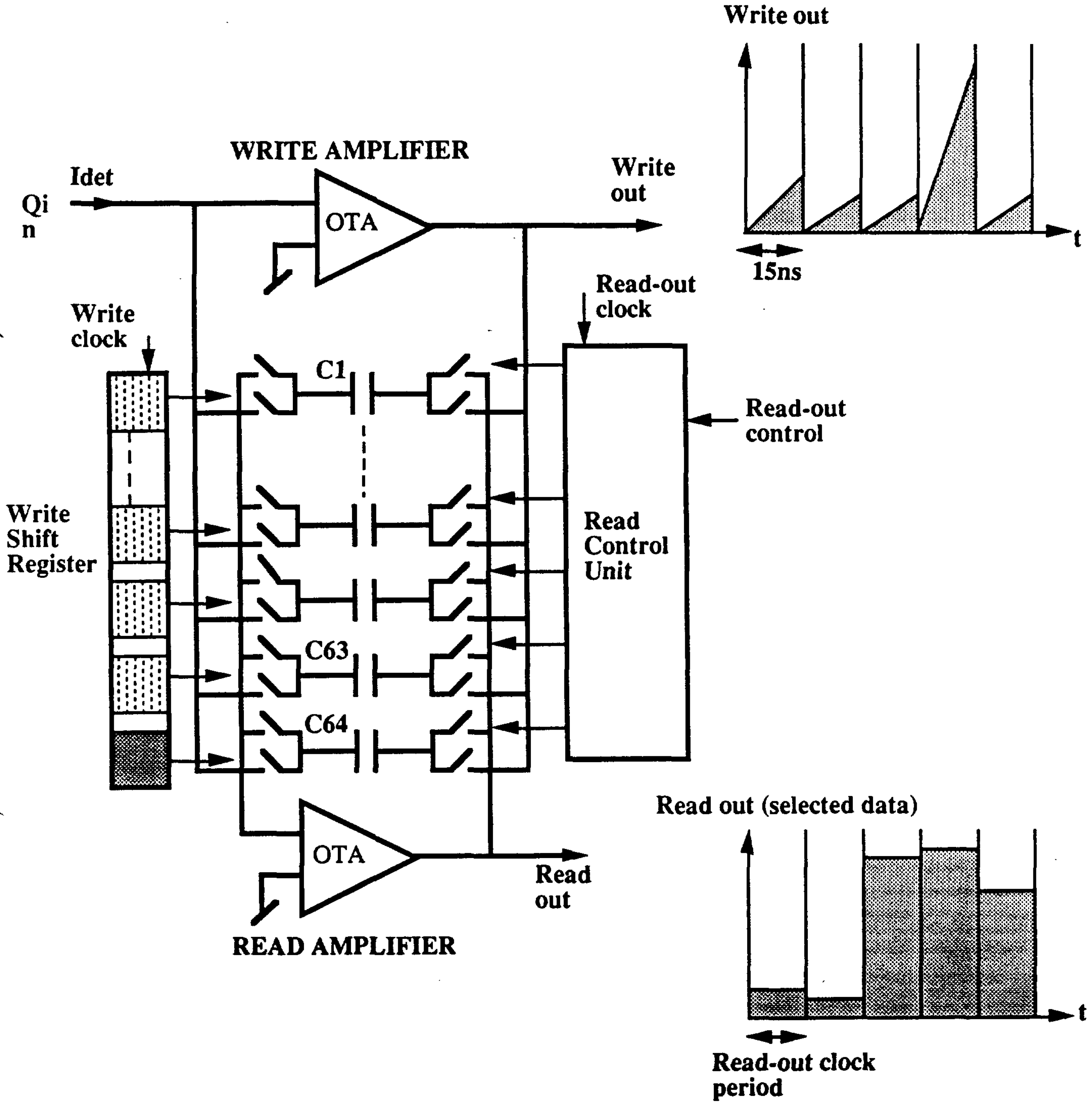


Figure 11: The charge sampling integrator (CSI) principle.

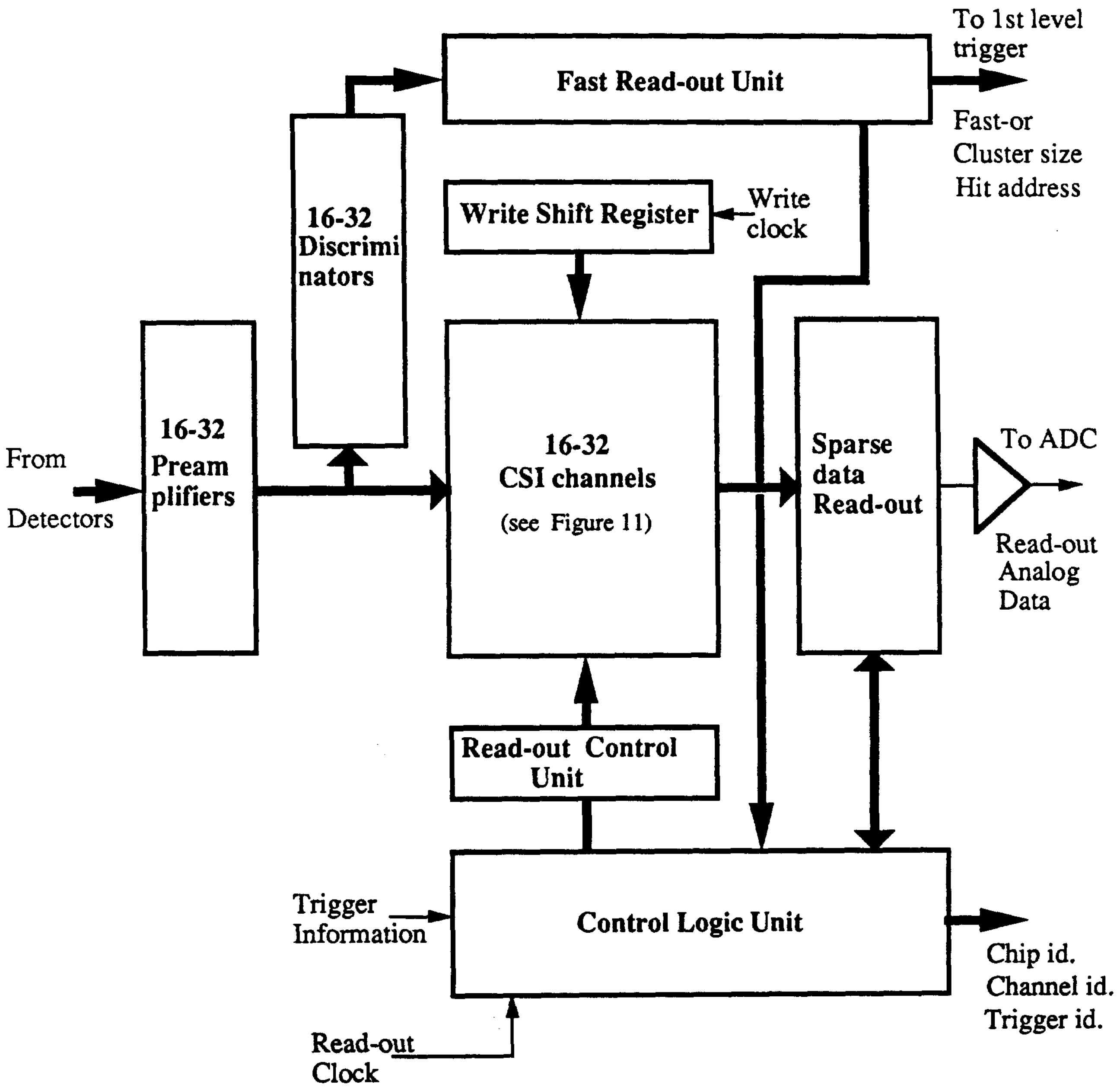


Figure 12: Schematic of a possible full readout chain for the track/preshower detector.

It is intended to develop the preamplifier and readout systems in standard CMOS technology and radiation–hard technology, in parallel. These designs will be used for performance studies of radiation–hard technology.

Work is also in progress on the possible use of the track stub/preshower signal in the first–level trigger, where a fast output (possibly including cluster identification) from the detector would, if correlated with a calorimeter cluster, enable rejection of fake electron signatures from π^0's and photons.

In support of the VLSI and detector development, an overall DAQ and monitoring strategy must be developed, and if possible implemented for test–beam studies. This will be done in close consultation with a working group on data acquisition for LHC (see next section).

5 Test beam facilities and requirements.

The following test beam measurements are foreseen to study the properties of the detector prototype and to optimise the detector design.

1. Measurements are required of the track pointing precision and of the track–preshower matching precision, including realistic amounts of material corresponding to readout electronics and cooling between layers. This study should be performed using an electron beam over a range of energies, and a muon beam to measure the intrinsic precision with a minimum of scattering and showering.

2. Measurements of the pulse height detected in the preshower layers, using electron and pion beams of various energies. This study will lead to a measurement of the rejection against single pions as well as indicating how much material could be tolerated between preshower layers if more than one is used. It will also indicate the dynamic range needed in the readout.

3. Studies of the pattern recognition properties of various arrangements of strip and pad detectors, using a pion beam onto a plastic target to create high multiplicity showers. This study will be used to choose the best combination of pad and strip layers to give high precision and minimal ambiguity.

4. If double sided detectors remain an option, the charge correlation between the two sides can be measured in a muon beam in order to find out how much this information would aid pattern recognition by removing ambiguities.

The test setup will consist of 6 layers of prototype counters arranged in a 3 by 3 array as in figure 2. The tracking and preshower parts each have one layer of pads and one of crossed strips allowing a full test of the pattern recognition properties with showers. This arrangement is also the smallest which allows studies of centroid finding and matching in the preshower, taking into account edge effects and showers incident from various angles. In a real detector many showers will be split across one or more counters. The granularity (9 mm^2) is equal for all counters, allowing the use of common electronics, though the actual pad dimensions are chosen to give the best possible match between the preshower signal and the associated track stub.

We also intend to measure the shower profile behind the lead converter with high precision, using microstrip detectors, to determine the optimal granularity given that the shower fluctuations are large. Studies in UA2 (with 1 mm granularity) have shown that the highest pulse height detected is a better measure of the shower center than the centre of gravity [7]. Measurements with microstrips would allow us to determine the best algorithm for any realistic granularity.

We estimate that four dedicated running periods are required, with two periods of five days early in 1991 to perform initial measurements of new detector prototypes with existing readout electronics. The development of readout chips and detectors will continue in parallel leading to a further two periods of five days to study a prototype module with state-of-the-art readout and taking into account initial test results and prototype choices. For a number of studies of background rejection the use of a calorimeter in conjunction with the track-preshower is essential.

We therefore request time in a beamline that provides electrons, pions and muons in the relevant energy range. Initially that should be the H2 beamline where we have already completed silicon studies for the UA2 detector, and we request that the data acquisition system (DAQ) at the H2 beamline be upgraded to allow the use of IBM cartridges. We strongly support efforts to set up a dedicated high-intensity beam line for the simultaneous test of detector prototypes, trigger and readout schemes, and data acquisition architectures for LHC. In particular it is extremely important to schedule time in coordination with the calorimeter working group [10]. The use of parasitic time with the calorimeter would allow extra studies to be performed and would ensure efficient use of the main user periods.

We are currently evaluating possible readout systems (FASTBUS, VME, CAMAC) and we request 40 kSF. to be spent on crates, readout controllers and driver modules (see section 6). We note that these modules will be available to pursue long term tests as the program develops.

6 Budget and responsibilities.

We have in preceding sections identified major complementary activities that we intend to pursue in our investigation of the use of preshower techniques for electron identification at LHC. These activities are summarised in Table 3, where we show major areas of activity and a preliminary distribution of major responsibilities within our working group. This division is subject to continuing technical discussions. In addition to the institutions participating in this study, a group from Saclay intends to join following the agreement of their management.

Our budget request is summarised in Table 4. This request excludes personnel and travel support and assumes adequate and recurrent support for the computing and microelectronics expertise needed from CERN for the successful completion of our proposal.

We wish to emphasise the following points, taking into account the budget request and the timescale schematic shown in Table 2.

1. We consider the major uncertainty in the use of silicon as a preshower detector is

TABLE 3

Division of responsibilities

	Cambridge	Oxford	Geneva	Dortmund/ Hamburg	Melbourne/ Sydney	CERN	Oslo	Perugia	RAL
SIMULATION									
• support	x					x			
• studies	←	- - -	- - -	- - -	- - -	- - -	- - -	- - -	→
RADIATION									
• simulation studies					x	x			
• measurements				x	x	x			
DETECTORS									
• Si detector prototype/test	x			x		x	[x]	x	
• Initial prototype mechanics (MX)		x							
• FINAL prototype mechanics (CSI)	[x]		[x]	x					
• Full-size detector considerations		[x]				x			
ELECTRONICS									
• Frontend (CSI)						x			x
• Control and test logic			x			[x]			
• Trigger						x			x
TEST BEAM/TEST BEAM PREP.									
• mechanics			x						
• DAQ/control room (MX)		x					x		
• DAQ/control room (CSI)	x		x			[x]			
• Running	←	- - -	- - -	- - -	- - -	- - -	- - -	- - -	→
• Analysis	←	- - -	- - -	- - -	- - -	- - -	- - -	- - -	→

TABLE 4

ESTIMATED BUDGET (FINANCIAL AND MATERIALS) FOR DEVELOPMENT OF TRACKING/PRESHOWER DETECTOR.

(Personnel and travel requests not included).

		years 1 [kSF]	years 2 [kSF]
SIMULATION AND ANALYSIS.			
1. Adequate simulation CPU cycles			
Adequate test-beam analysis CPU cycles			
2. Miscellaneous		3.	3.
		3.	3.
RADIATION LEVELS.			
1. UA2 radiation level measurements		15.0	
2. Rad hardness of prototype counters		15.0	
		30.0	
DETECTORS.			
1. Si-detector prototypes		120.0	90.0
test-bench measurement equipment		50.0	
2. Test board	A) board design/production	5.0	
	B) cooling/mechanics	5.0	
3. Board prototype	A) board design/production	25.0	50.0
	B) cooling/mechanics	15.0	15.0
		220.0	155.0
ELECTRONICS (PROTOTYPE DEVELOPMENTS etc.)			
1. ASIC electronics (Note 1)		140.0	120.0
2. Radiation hardness (Note 2)		50.0	50.0
3. Trigger studies.		25.0	25.0
4. Control and test-signal logic, counting-room, DAQ electronics		15.0	20.0
		230.0	215.0
TEST-BEAM and TEST-BEAM PREPARATION			
1. Mechanical		10.0	5.0
2. Electronics and DAQ		40.0	
3. Running and test-beam involvement.		5.0	5.0
		55.0	10.0
		533.0	383.0

Note 1 : This is additional to equipment and recurrent expenditure of the Heijne/Jarron Group.

Note 2 : This is additional to a separate financial request for general radiation hard electronics development.

its ability to sustain high radiation levels. We hope to reassess this after 1 year of studies. To meet this time schedule funds for counter prototypes are essential (120kSF in year 1). A fraction of these counters will be subjected to controlled radiation tests, plus annealing and cooling tests. Secondly, detailed simulation studies are required to optimise the detector design to result in minimal radiation damage. Associated test–beam normalisation measurements are also required for these studies, undertaken by this group and the calorimeter working group. We request CERN personnel support in these activities.

2. Simulation studies must be coordinated with other detector activities (for example calorimeter studies). We request professional CERN support for program development and maintenance.
3. Necessary funding for technical support at peak periods of activity for counter assembly, testing, etc. is requested from CERN. From experience with UA2 this should be one full time equivalent.
4. We believe that the development of small–area pad detectors is essential for reliable track–stub pattern recognition (and therefore electron identification) at LHC. A major emphasis is therefore put on funding the development of fast VLSI electronics for pad detector readout, and essential ancillary electronics. The estimated budget in year 1 is 230 kSF.
5. The estimated 40 kSF expenditure for crates, readout controllers, etc. at the test–beam is considered an essential long–term investment in an important CERN facility.

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