PRE-RADIATORS AT THE SSC/LHC

Priscilla B. Cushman
Yale University, New Haven, CT 06511, USA

ABSTRACT

An instrumented converter of less than 2 radiation lengths immediately preceding a calorimeter provides a powerful means of particle identification and a possible electron trigger based on the amount of energy deposited per unit depth by electrons, $\pi^0$'s, and minimum ionizing particles at the start of an electromagnetic shower. Such a preshower detector can be built with scintillating fibers and as such combines both tracking and energy information. At electron energies greater than 50 GeV and in a B$\geq$2T solenoid magnet surrounding the interaction region of a large hadron collider, the energy of synchrotron photons produced by the bending electron is sufficient for detection in a lead/scintillating fiber detector. Its characteristic signature (a narrow band of lower energy photons whose length is determined by the magnet parameters) can be used in conjunction with tracking to distinguish between electrons and $\pi^0$'s with overlapping charged particles.

1. INTRODUCTION

It is generally recognized that physics in the SSC/LHC energy and luminosity range, will require a precise understanding of the lepton and single-\(\gamma\) signatures. In tests of the Standard Model, searching for the Higgs particle will be a major effort. For the heavy Higgs (\(M_H \geq 2M_Z\)), the signature is expected to be one or two lepton pairs. Good electron identification is therefore required in order to recognize the pairs above the abundant QCD background. For the mass range \(M_H < 2M_Z\), the \(H^0 \rightarrow \gamma\gamma\) decay mode has been suggested as the most feasible experimental signature, putting a premium on good single-\(\gamma\)/$\pi^0$ discrimination. The ability to identify single $\gamma$'s would also allow one to search for new physics which is expected to result in an enhancement in the direct photon yield (\(pp \rightarrow \gamma + jet\)). A variety of non-standard models have important leptonic signatures as well. Heavy quarks, \(Z^*\)'s, and heavy recurrences of the $Z$, all have dilepton signatures with relatively small background. For events with accompanying jets, such as \(WW \rightarrow 2jets + lv\), certain SUSY particles, etc., a detector capable of identifying electrons inside complicated events would have a great advantage over one that has to make an isolation cut.

2. LESSONS FROM EXPERIENCE

Electron identification is generally improved by the addition of a position sensitive detector either in front of the calorimeter or at shower maximum. Over the past several years, examples of both types of detectors have been built and operated with success. The 2-shower resolution is inherently worse at shower maximum due to shower spreading and fluctuations, but the device can be made very thin. CDF installed a wire chamber with cathode pad readout at the shower maximum. The strip chamber was only .07 radiation lengths thick and was able to distinguish showers separated by 2-3 cm. Since the calorimeter towers had a granularity of 24cm x 45cm, this greatly improved the quality of the data.

A preconverter or preradiator placed just in front of the calorimeter consists of some conversion material interspersed with or followed by an active element. It must be, by definition, thick enough to start an electromagnetic shower, yet thin enough to allow shower maximum to occur well inside the calorimeter behind. For example, 1.5 radiation lengths (RL) of lead is sufficient to produce a strong signal in scintillator, but thin enough in interaction lengths (0.05 $\Lambda_{had}$) to avoid most of the hadron contamination due to processes like charge exchange. This early sampling of the electromagnetic shower gives preradiators an advantage over devices at shower maximum in the area of electron/hadron discrimination. In addition, their better position resolution is directly correlated with how well they can distinguish between real electrons and the fake signals produced by the overlap of $\pi^0$'s or $\gamma$'s and a charged track.

The active element is determined by physics requirements, detector geometry and cost. Scintillator plates or fibers, silicon pads, gas proportional tubes and wire chambers have all been used in the past. The energy deposition is small...
at the start of the shower, so gaseous detectors like wire chambers or tubes will
suffer from low efficiency and large signal variations due to the small number of
ion pairs created and gas gain fluctuations. They are therefore more appropriate
for use at shower maximum. Silicon pads generally have a high capacitance and
therefore require long integration times (0.2-1μsec) to keep the signal to noise
at an acceptable level. They thus become more susceptible to background from
multiple bunch crossings. Making them smaller reduces the capacitance, but
multiplies the number of channels and complexity of the readout. Scintillator is
ideal for the application since it is fast, relatively cheap and gives a good response
to ionizing radiation. The development of radiation resistant scintillator is still
required, but progress on this front (see these proceedings) has been rapid.

An example of a high resolution preconverter is provided by the outer layers
of the UA2 fiber tracker. This type of detector has become known as an imaging
preradiator. The UA2 preshower detector consisted of 1.5 radiation lengths of
lead followed by 6 layers of 1 mm diameter scintillating fibers arranged in stereo
triplets and read out by an image intensifier and CCD chain. The track-shower
residuals obtained by this device were 0.4 mm and 1.1 mm RMS in the Rφ and Z
directions respectively.

The improved electron/hadron separation due to early sampling in preradiators
has been amply demonstrated as well. A cut at 2 MIP on the UA2 preshower
detector alone, gave an average detection efficiency of 98% for 40 GeV electrons
compared to only 7% for 40 GeV pions. The SpaCal collaboration has made
some tests with a very simple preconverter consisting of 2.6 radiation lengths of
lead followed by a scintillator plate. This was placed in front of one module of
a "spaghetti" calorimeter and improved their hadron rejection by a factor of 5
beyond that already achieved by shower development cuts.10

3. ADVANTAGES OF PRERADIATORS

3.1 Introduction A preradiator provides a link between tracking devices and
calorimeters. It can supply position information with a precision characteristic
of tracking devices while providing detailed information about the early develop-
ment of electromagnetic showers. Since it is an energy measuring device, the
energy resolution of the electromagnetic calorimeter should not be compromised.
Thus we improve momentum resolution (and relax the constraints on the tracking
device) by providing good position resolution at a long lever arm without
degrading the energy resolution. The redundancy of some of this information
may also be important when interpreting complex events in the next generation
of hadron colliders. The advantages of using a preconverter in a 4π detector can
be summarised as

1. The precise determination of the location of the starting point of an elec-
 tromagnetic shower;

2. Reduction of accidental π0/charged-track overlaps which fake electrons;

3. Distinguishing between π0's and γ's on an event-by-event basis (direct pho-
ton physics);

4. Unambiguous assignment of the shower with bunch crossing;

5. Improved electron/hadron discrimination in isolated events and electron
 identification within complicated events where isolation cuts can't be ap-
plied;

6. Tagging high energy electrons by detecting their synchrotron radiation.

3.2 Good Position Resolution The submillimeter position resolution and the
early sampling available in imaging preradiators enables otherwise confusing
events to be reconstructed. Background from charged tracks which overlap with
π0's or γ's, and are thus mistaken for electrons, could be greatly reduced. This
is particularly important for non-magnetic or forward detectors where E/p cuts
cannot be made. Material in the inner detectors will cause e+e- conversions,
some fraction of which could be recognized by their separation alone or by a
large energy deposition.

With such resolution it should also be possible to separate directly produced
single-\(\gamma\)'s from \(\pi^0\)'s on an event by event basis. An opening angle of \(\theta_{\text{min}} = 2m_e/m_\pi\) for \(\pi^0\) decay means, for example, that the two photons from a 100 GeV \(\pi^0\) are separated by \(\geq 2.6\) mm per meter of flight path. The separation should be measured before the showers begin to merge, making it a natural task for a preradiator. However, in order to insure that both photons have a chance to convert, the sampling depth must be \(\sim 3\) RL. For those magnetic detector designs which place the electromagnetic calorimeter outside a 1-2 RL aluminum coil, one possibility is to place layers of preradiator inside the magnet coil, thus optimized for \(e/\pi\) discrimination and rejection of overlapping events, and another set after the coil which are used to separate \(\gamma\)'s from \(\pi^0\)'s.

3.3 Good Time Resolution A preconverter made out of scintillator has excellent time resolution as well. If the fibers are no longer than 2 meters, then each event is assigned unambiguously to the proper bunch crossing (every 15 nsec at the SSC). Since it takes 50 nsec (spaghetti calorimeter) to 400 nsec (liquid argon) to collect the calorimeter signal, this would prove very useful in reducing calorimeter background from showers in neighboring buckets.

3.4 Electron Hadron Discrimination Requirements for \(e/\pi\) separation at the SSC have usually been quoted at \(10^4\). Separation to this order has not yet been obtained. The standard methods of electron identification exploit the differences in the lateral and longitudinal development of the electromagnetic and hadronic showers. Recent work has shown that the time development of the pulses in a scintillating fiber calorimeter can also be used to improve \(e/\pi\) separation\(^1\). With these methods, rejections on the order of 0.1%-1.0% can be achieved. However, all of the above methods are highly correlated, rejecting hadronic showers that develop later, but failing for those showers which convert most of their energy into \(\pi^0\)'s early on. This limits a natural limit to shower development cuts since there will always be fluctuations in the development of hadronic showers so that they resemble electromagnetic showers. In addition, when an electron is accompanied by an energetic hadron, such calorimetric methods fail completely and the event must be discarded. This indicates the need for additional non-correlated information.

Preconverters can help in several ways. The contribution from confusing hadronic showers is greatly reduced simply by sampling the showers early before reactions like charge exchange have any significant probability of occurring. This implies, of course, that a preconverter should be made of material with a large \(\lambda_{\text{had}}/\lambda_{\text{em}}\) to minimize hadronic interactions; the use of an aluminum magnet coil as the conversion element is therefore not recommended. An imaging preradiator is, in addition, able to separate electrons from other particles at distances as small as a few mm, reducing the size of isolation cuts and opening up the possibility of electron identification inside jets.

3.5 Synchrotron Radiation (SR) Tagging In a magnetic detector, an imaging preradiator can use the SR produced by electrons as they bend in the magnetic field of the solenoid. The SR is emitted tangentially to and in the same plane as the electron orbit. Thus, it is deposited in a narrow strip in the bend plane of the magnet. The length of the strip is proportional to the bend of the electron, varying inversely with energy (see Table 1) and provides a characteristic pattern easily recognized by preradiators with position resolution of the order of a millimeter. This method of identifying electrons is uncorrelated with their shower development characteristics. Since the mean free path of the SR photons in aluminum averages 30 cm, the signal could, in principle, be observed on either side of the magnet coil, although shower spreading makes it a less favorable alternative.

The SR spectrum can be characterized by the total emitted energy \(I\) and a critical photon energy \(h\omega_c\) where the intensity becomes negligible.\(^{12}\) For electrons: \(I = 1.27E^2B^2L\) [KeV] and \(h\omega_c = 1.33E^2B\) [KeV], where \(E\) is the electron energy in GeV, \(B\) is in Tesla and the path length, \(L\), is in meters. Since the mean photon energy is \(h\omega_c/4\), the average number of photons can be estimated as \(N_e = 3.8BL\).\(^{13}\) Values for \(h\omega_c\) and strip length, \(\delta\), are shown in Table 1 for electron energies between 50 and 200 GeV for two magnet configurations.
### Table 1

<table>
<thead>
<tr>
<th>MAGNET CONFIGURATION</th>
<th>( E_0 ) (GeV)</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>5T-1M ((\bar{N}_y = 18))</td>
<td>( h\omega_0 ) (MeV)</td>
<td>16.6</td>
<td>66.5</td>
<td>150</td>
<td>266</td>
<td>416</td>
</tr>
<tr>
<td></td>
<td>( \delta ) (mm)</td>
<td>24</td>
<td>12</td>
<td>8</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>2T-2M ((\bar{N}_y = 14))</td>
<td>( h\omega_0 ) (MeV)</td>
<td>6.7</td>
<td>27</td>
<td>60</td>
<td>106</td>
<td>166</td>
</tr>
<tr>
<td></td>
<td>( \delta ) (mm)</td>
<td>15</td>
<td>7.5</td>
<td>5</td>
<td>3.7</td>
<td>3</td>
</tr>
</tbody>
</table>

A prototype scintillating fiber (SF) preradiator is presently being built by a Yale/Rockefeller collaboration to test the feasibility of using synchrotron radiation as an electron tag.\(^{14,15}\) The prototype design is shown in Fig 1. Thin (1-2 mm) layers of lead alternate with SF planes made up of 6 layers of 500 \( \mu \)m diameter fiber at 3 stereo angles \((-15^\circ, 0^\circ, +15^\circ)\). The prototype will be read out by an image intensifier-CCD chain, but in the final design this will be replace by a fast image tube incorporating a smart pixel device (see Sec 4). The prototype will be placed in an Fermilab test beam in 1990.

Results from our Geant3.12\(^{16}\) Monte Carlo simulation of the imaging preradiator indicate the power of such an approach. Fig 2 shows the electron energy deposition (including SR) after \( \sim 1 \) RL of lead/fiber layers. If a cut B perpendicular to the electron bend plane is made a distance \( \Delta x \) from line A passing through the center of the shower, and the energy deposited between lines B and C is projected onto C, then the SR appears as a peak where the bend plane intersects C. Fig 3 illustrates that the SR signal is strong relative to the tails of the electron shower in the first RL (\( \sim 6 \)mm Pb). The \( \Delta x \) cut was 1.5 mm, which in our case is 3 fiber widths. We expect to see 1 photoelectron per 40 KeV deposited. Thus, after travelling 1M in a 5T solenoid, a 50 GeV (200 GeV) electron deposits approximately 1.8 MeV (14 MeV) SR energy in the scintillator 1.5mm from the shower center, corresponding to 45 (350) photoelectrons over several fibers.
Figure (2)
Energy deposited by a 200 GeV electron and its associated synchrotron radiation in less than 1 radiation length of lead.

Figure (3)
Energy deposited in CF by synchrotron photons produced in a 5T-1H magnet at a distance x=1.5 mm from the electron shower center and projected onto the y-axis (line C of Fig 2).
The 3 plots are for increasing depth of detector (i.e., number of sampling layers). Each bin corresponds to one fiber width. The solid line is the SR signal, the dotted line is background from the electron shower.
Figure (4)
Cumulative energy deposited in the detector versus the fiber layers from different sources.

Figure (5)
Cumulative energy deposited in the fibers versus depth in lead.
There is also the possibility of using the signal at the trigger level without requiring reconstruction. The major background to the electron signal comes from π⁰'s where the decay photons overlap with minimum ionizing particles. Since photons from the π⁰ need to convert before they can be detected, the π⁰ shower deposits less energy at the start. The energy deposition as a function of detector thickness in RL for various initiating particles is shown in Fig 4. The presence of SR enhances the e/π⁰ energy differential. Fig 5b illustrates that, even with the overly-pessimistic assumption of Gaussian fluctuations, there is a clear separation between a 200 GeV π⁰ and an electron plus SR after 1 RL. For 50 GeV electrons the addition of SR is not significant, but enrichment of the electron sample can still be improved by the use of an early sampling preconverter.

An electron trigger such as this would be implemented by reading out bundles of fibers with a phototube from the ends opposite to the image tube. The output would be compared with a threshold level scaled by the total energy deposited in the calorimeter behind. An alternative design which optimizes the trigger aspect of SR, would be several layers of scintillator plates matched to the projective geometry of the calorimeter.

4. READOUT CONSIDERATIONS

4.1 Goals The usual method of reading out an SF imaging preradiator is to use an image intensifier coupled to a CCD and electronics for data sparsification. This method as it stands is not suitable in an SSC/LHC environment due to the long CCD readout times of several milliseconds and the fact that many events will be recorded on the same array over the 1-5 μsec it takes for the 1st level trigger decision. A SF preradiator (or tracker) readout system in a high rate environment should be able to

1. distinguish between events every 15 nsec,
2. store the events for several μsec,
3. read out the selected events at KHz rates,
4. have good spatial resolution (< 30μm for a tracker, less critical for a preconverter),
5. be capable of operating in magnetic fields of 1-5 Tesla,
6. be radiation hard,
7. not compromise the hermeticity of the calorimetry.

4.2 Some Readout Options The CCD option can be made more realistic by the development of a storage device to pipeline events for a few μsec. A device called an electro-optical delay tube is being developed by the LAA collaboration. Although it will probably work, it is limited in how small it can be made. A 40 cm tube gives a 1 μsec delay. However, if the 1st level trigger takes 5 μsec (not an unrealistic scenario), its size may become unmanageable. A delay tube does not address at all the problem of the long CCD readout time which limits the data rate to 60 Hz and eliminates the possibility of using that data in a trigger. In addition CCD's are not radiation hard.

Position-sensitive photomultiplier tubes provide a possible high speed alternative. The position information is determined by either crossed anode wires, which suffer from multi-hit ambiguities, or an array of anode cells. Whereas proximity focussed mesh dynodes can stand high magnetic fields, the position resolution of a 16x16 anode array tested to .8 Tesla is close to the limit at 3mm x 3mm for the cells. At present, B-field performance must be sacrificed in order to increase the position resolution. Even if the cell size can be reduced to a fiber diameter (500 μm for the preradiator, not even an option for a tracker), the cost will be extreme. At $60.00/channel, the readout for the SSC imaging preradiator described in Section 5 would cost $150 Million.

Another option which combines speed with good spatial resolution and a startling 60% quantum efficiency is the Solid State Photomultiplier (SSPM).20 The fact that it must be operated at 7° Kelvin is equally startling. Along with the disadvantages of cryogenic complications is the cost of the system. Optimistic estimates put the cost of the SSPM and read out at $10.00 per fiber.
4.3 A Possible Solution We are presently investigating a low cost option which may fulfill the goals mentioned above. Electrons produced by the photocathode of an image tube are electrostatically accelerated to approximately 10 KeV and strike the surface of a pixel device placed inside the vacuum tube. The pixel detector being developed by Nygren is particularly well-suited to this task. It consists of a silicon PIN diode array, indium bump-bonded to a readout chip developed by Hughes Aircraft which has been tested radiation hard to 1 Mrad. The position resolution is only limited by how small you can make the preamp chips; 10 x 10 μm² is easily realizable. The optimum size for the preradiator is more like 100 x 100 μm². A shift register clocked every 15 nsec, with a bit set for every row and column hit, keeps track of the events. It is deep enough to await the 1st level trigger decision and then only the selected pixels are read out at a rate of 200 μsec/pixel.

The image tubes can be placed inside the solenoid since their performance should only be improved in an axial magnetic field (due to its focusing properties) unlike the microchannel plates used in most image intensifiers. If the magnet is long, several 2-meter sections of cylindrical preconverters could be placed end to end with the image tubes overlapping the next fiber section. Since the information is read out serially there are very few cables to be brought out.

4.4 Occupancy Clearly, such a device will only work if it is not always on. The intrinsic noise of the diode array is not a problem, since the noise level is at ~100 equivalent electrons due to the low capacitance (F’s) of the anodes. For an imaging preradiator at a radius of 2 meters from the beam axis and consisting of 2 meter long layers of 500 μm diam fiber, the event rate in a single fiber (assuming L=10^3) is approximately 20 KHz. If each fiber is mapped to 10 pixels in a 2 x 2 cm² array, this translates into 1 pixel hit per bunch crossing per image tube. Correlations in hits due to bundling neighboring fibers into the same image tube may increase this by a factor of 10 for any particular bunch crossing, but on average only 70 pixels out of 40,000 (occupancy = 0.002) will be hit after waiting 1 μsec for a trigger decision. The readout is therefore able to operate quite comfortably. Occupancy calculations for a fiber tracker using a similar readout scheme, but with a smaller pixel size, give comparable results.

5. CONCLUSIONS AND FUTURE DIRECTIONS

In Fig 6, I present one possible scheme for an SSC/LHC imaging preradiator. Our preferred choice, a compact, high field solenoid has the following advantages: a high field (ST) gives a strong SR signal for the electrons. The small size implies a 1/4 reduction in volume, further reducing calorimeter and muon detector cost. The submillimeter position resolution and early sampling of the imaging preradiator offsets the fact that the Moliere radius remains the same despite the scaled reduction in calorimeter cell size. However, since radiation damage to scintillating fiber 1 meter from the interaction region may be the limiting factor, a more conservative design based on a 2T-2M solenoid is presented.

In our design the preradiator would consist of ~ 2 m long fibers forming a cylindrical shell just inside the solenoid coil. Four such cylinders would be required for an 8m long solenoid. Layers of fibers would be aligned at angles of -15º, 0º and +15º to the magnet axis. The 500μm fibers would be read out individually with an image-tube inside the magnetic field. There would be 4 super-layers, each consisting of 6 layers of fibers and a lead plate. The total thickness would be 1.5 RL at the center, tapering at the ends in order to ensure that particles incident at an angle pass through the same number of RL of material. Assuming the magnet to be 8m long and to have an inner radius of 2m there would be 600k fibers for each super-layer or 2.4 million fibers in all. The total sensitive photocathode area that would be required for the preradiator would be 6000 cm². This would require 1500 image tubes, each with a 2cm x 2cm active area.

The choice of preradiator has an impact on the required granularity of the calorimeter and the complexity of the tracker. Costs could be considerably reduced on both fronts with the suitable addition of an imaging preradiator. The spaghetti calorimeter, for example, is easy to build and has a convenient geome-
try, but lacks longitudinal segmentation. However, with an imaging preradiator to improve e/h separation, this becomes less of a disadvantage. Therefore, it may be suggested that, instead of adding just those aspects of a preradiator that will improve the quality of data collected by some previously designed tracker and calorimeter, the detector as a whole be optimized. Combined with the preradiator scheme presented above, a more cost-effective, yet powerful system may emerge.

ACKNOWLEDGEMENTS

I would like to thank Dr. Roger Rusack for many a scintillating discussion which has contributed to my better understanding of these issues. This work is supported by the U.S. Dept. of Energy under the SSC Generic R&D Program.

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