Simulation Study of the Beam Calorimeter in the GLD
Configuration for the Next Generation Linear Collider

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Abstract

The beam calorimeter, located in the very forward and backward region of the next generation
$e^+e^-$ linear accelerator, will be an important apparatus to search for or identify new particles
beyond Standard Model. One of its key design issues is to estimate the radiation dosage due
to beam related backgrounds. We used the geant-based package, Jupiter, for the proposed GLD
detector in this study. The dosage received per year for the inner most ring will be around 10 Mrad.
An algorithm for electron identification with beam calorimeter under nominal background condition
is developed and is used for the feasibility study of smuon search. The result is satisfactory.
INTRODUCTION

The International Linear Collider (ILC)\cite{1} is a proposed next generation electron-positron linear collider. It is expected to operate in an initial center-of-mass energy of 200 GeV - 500 GeV, with a peak luminosity of $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$. From previous study\cite{2}\cite{3}, the beamstrahlung contributes the dominant energy deposition in the small angle region along the beam direction. When the high energy bunches of electron and positron collide at interaction point (IP), due to the strong electromagnetic field of the opposite bunches, the beam particles would be deflected and the beam cross section would be reduced. The bent trajectory of electrons and positrons from both bunches will emit forward photons, which are called beamstrahlung photons. Simulation programs, named CAIN\cite{4} and Guinea-Pig\cite{5}, have been developed to investigate these effects.

The energy loss from the beamstrahlung photons is about 2% of beam energy on the average (Nominal beam set)\cite{6}, and this is the largest energy loss among the machine backgrounds. The beamstrahlung photons are very close to the beam line ($\theta < 0.5$ mrad). Some of beamstrahlung photons would interact with beam particles from opposite direction and produce electron-positron pairs, which are called incoherent pairs. Incoherent pairs are the main background source to the detector in the very forward and backward region. We use the full geant simulation package, Jupiter\cite{7}, for the proposed GLD\cite{8} at ILC to study the beam calorimeter (BCAL) performance. Several studies in other detector models can be found elsewhere\cite{9}.

![FIG. 1: Schematic view of the GLD detector in the forward region.](Image)

The shape of BCAL is a cylinder which consists of 33 layers of tungsten sandwiched silicon with a thickness of 3.5 mm for tungsten and 0.3 mm for silicon. It is placed at
430 cm to 450 cm from the IP (Figure 1), and the corresponding polar angle is 5 mrad to 50 mrad. BCAL can be used as a fast beam diagnostic device to analyze the activities at small angle which is crucial for the new particle search. For example, BCAL is very important for searching for the stau pair production [10]. The mass of stau particle might be able to explain the amount of dark matter in the universe.

In this paper, we choose the dominant background process, namely beamstrahlung incoherent pair, to give an order of magnitude estimation of the expected dosage received by BCAL per year under the nominal beam condition. This information is very important for the design limitation of BCAL. We also develop an algorithm for the BCAL electron identification with incoherent pairs as the principle background source. Its performance is studied by a search for smouon which is closely related to the study reported for stau.

SIMULATION PARAMETERS

Parameters in our simulation are according to the GLD configuration - 3 Tesla magnetic field, 500 GeV center-of-mass energy of beams, and 2 mrad beam crossing angle. Each layer of BCAL is sliced into 18 segments, from the inner radius (2.2 cm) to the outer radius (20.0 cm) along the radial direction. The size of azimuthal segments in each layer is 1 cm. For Nominal beam set, there are 2,820 bunches in each train (5 Hz) and the time interval of adjacent bunch is 307 ns, which is manageable with conventional pipeline readout. BCAL has about 20,000 channels, and it will produce 40 kB data for a bunch crossing if each channel needs 2 bytes in digitalization. The peak data rate will be 130 GB/s, which is practically impossible. We assume that some zero suppression techniques and low level trigger scheme will be implemented such that interesting events could be saved.

One hundred bunch crossings (BX) of incoherent pairs in Nominal beam set are generated with CAIN [11] and passed to Jupiter. For a bunch crossing, both forward and backward side of BCALs would receive energy about 8.5 TeV from incoherent pairs. The energy deposition in BCAL for both signal and incoherent pairs in each layer is shown in Figure 2. We can see that the energy from incoherent pairs is much higher comparing to a 250 GeV electron.

The energy deposition (without calibration) of HighLum [6] beam parameter set was shown for comparison in Table 1. The luminosity of HighLum beam set is $4.9 \times 10^{34}$ cm$^{-2}$s$^{-1}$. It produces much more background, and only 50 BX were used in the simulation due to long
computation time. The 100 BX should have twice events comparing with 50 BX data. Although this is just for a quick check, the mean values listed in Table I wouldn’t vary too much which is good enough for our study.

| BeamSet  | Forward E (GeV) | Backward E (GeV) |
|----------|-----------------|------------------|
| Nominal  | 108.3           | 108.2            |
| HighLum  | 603.3           | 602.2            |

TABLE I: Energy deposition of two different beam parameter sets

FIG. 2: Energy deposition in the BCAL. Left: Comparison of energy deposition in the beam calorimeter between incoherent pairs per bunch (the shadow region) and a single 250 GeV electron (the black region). Right: Energy distribution of the fifth layer of the BCAL from incoherent pairs.

RADIATION DOSE

The radiation tolerance of silicon detector is an important issue. A conventional silicon detector can be operated up to the radiation dose of several Mrad [12]. For BCAL, if it received large energy deposition, meaning that the serious radiation damage happened. Figure 3 shows the radiation dosage from incoherent pairs deposited in BCAL in the z – r plane from Jupiter simulation. We could see extremely high radiation dosage (∼10 Mrad/year) at the small angle rings. For HighLum beam set, the radiation dosage can be as high as 100 Mrad per year. Radiation hard sensors are needed for this purpose [13].

ELECTRON IDENTIFICATION

When the background particles of a bunch crossing hit BCAL, they will leave energy in the BCAL cells. To check the electron identification efficiency under the beamstrahlung
backgrounds, 250 GeV electrons are randomly generated to BCAL in Jupiter and passed to the “electron finder”. The electron finding relies on a clustering algorithm and a comparison with the electromagnetic cascade shower profile. However, assuming no special treatment for background suppression, the identification of electrons below 20 mrad is totally failed because of the severe background. It can be easily understood in Figure 2 because most of the energy deposition from backgrounds is in the small angle rings.

The basic idea of suppressing the effects from incoherent pairs is to subtract mean deposition energy of bunch crossings in each cell. The following procedure was used to get the electron identification efficiency with incoherent pairs:

1. We generate 100 BX Nominal and 50 BX HighLum incoherent pairs from CAIN. The generated events were submitted to the full geometry simulator, Jupiter.

2. We calculate the mean and variance of deposited energy in each cell of the beam calorimeter, and randomly choose a bunch data. Then, we superimpose randomly generated electron signals onto this data set.

3. Finally, we subtract the mean deposited energy of each cell and set the $E_{fired}=1\sigma$ for each cell. $E_{fired}$ is a parameter of electron finder. The cell will not be included in the electron finder if energy deposition is below $E_{fired}$.

The electron identification efficiency is shown in Figure 4. Electron identification efficiency depends on incident electron energy and also the energy deposition of incoherent pairs. The smaller polar angle region shows worse efficiency. As one can expected, the beam parameter set with the larger beamstrahlung effect showed poorer electron identification efficiency. However, electron identification efficiency is generally independent to the incident energy at lower background region. Energy resolution is also affected by the background, as
FIG. 4: Electron identification efficiency (%) of a) Nominal beam set and b) HighLum beam set.

FIG. 5: Reconstructed cluster energies (50 GeV, 100 GeV, 150 GeV, 200 GeV, and 250 GeV) in Nominal beam set.

SMUON SEARCH

The masses of smuon, $\tilde{\mu}_R$, and the neutralino, $\tilde{\chi}_1^0$, can be evaluated by analyzing the energy spectrum of the final state leptons $\mu^+$ and $\mu^-$. The right-handed smuon decays isotropically according to the decay mode

$$e^+ e^- \rightarrow \tilde{\mu}_R \tilde{\mu}_R \rightarrow \mu^+ \tilde{\chi}_1^0 \mu^- \tilde{\chi}_1^0$$

where $\tilde{\mu}$ is supersymmetric partner of the muon, and it will decay into one standard model particle and one sparticle - muon and neutralino. It is believed that neutralino is the least massive supersymmetric particle (LSP). The neutralino interacts via weak force only, and it will penetrate through our detector without being detected. Since the neutralino cannot be detected directly, the experimental signature is the muon pair only. Several standard
model backgrounds are considered to be important. Those are $e^+e^- \rightarrow ZZ \rightarrow \mu^+\mu^-\nu\bar{\nu}$, $e^+e^- \rightarrow W^+W^- \rightarrow \mu^+\nu\mu^-\bar{\nu}$, $e^+e^- \rightarrow \tau^+\tau^- \rightarrow \mu^+\nu\mu^-\bar{\nu}$, and $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$. Ten thousand events are generated with SUSYGEN3 \cite{14}, and the total cross section is 86.6 fb at 500 GeV. The electron beams are 80% right-handed polarized. Assuming R-parity conservation, five parameters are used in the event generator according to SPS1a \cite{15}:

\begin{align*}
m_0 &= 100 \text{ GeV}, \ m_{1/2} = 250 \text{ GeV} \\
A_0 &= -100 \text{ GeV}, \ tan\beta = 10, \mu > 0
\end{align*}

where $m_0$ is the universal scalar constant, $m_{1/2}$ is the universal gaugino mass, $A_0$ is the universal trilinear term, $tan\beta = v_2/v_1$ is the ratio of the vacuum expectation values of two Higgs doublets, and $\mu$ represents the supersymmetry conserving higgsino mixing term. The mass of neutralino is 98.0 GeV and the mass of right-handed smuon is 144.7 GeV. In the smuon decay, the simple two-body kinematics results in a flat distribution of the observed muons.

One million two photon background $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ events are generated with GRC4F \cite{16}, a four-fermions event generator. Several selections are applied at the generator level to save computing time to generate useful background events:

1. $E_{\mu^\pm}^{min} = 10$ GeV
2. $E_{\mu^\pm}^{max} = 130$ GeV
3. $7^\circ < \theta_{\mu^\pm} < 173^\circ$ (Detector acceptance for muon identification)

Other backgrounds listed in Table II are generated with PANDORA_PYTHIA \cite{17} which includes the ISR and beamstrahlung effects. The electron beams are set with 80% right-handed polarization. The detector acceptance for electron identification without BCAL can be down to 35 mrad.

The event selection criteria are listed below:

1. Muon pair acoplanarity, $|\phi_{aco}| < 2.9(166^\circ)$. Acoplanarity is the $\phi$ difference of $\mu^+\mu^-$ pair.
2. Transverse momentum of $\mu^\pm$ ($P_T > 10$GeV).
The events which don’t fit above criteria are regarded as backgrounds. To suppress two photon background, there is a special veto that if an electron or a positron is found by the main detector and the total missing $P_T$ of the event is less than 2 GeV, that event will be identified as two photon background and will be vetoed.

Table II shows different physical cross sections before and after the event selection.

| Process                          | $\sigma$ (fb) | Efficiency | Visible $\sigma$ (fb) |
|----------------------------------|---------------|------------|------------------------|
| $e^+e^- \rightarrow \mu^+\mu^-$   | 86.6          | 0.798      | 69.15                  |
| $\rightarrow \mu^+\chi^0_1\mu^-\chi^0_1$ |               |            |                        |
| $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ | 53.09 $\cdot$ 10^3 | 8.24 $\cdot$ 10^{-3} | 437                    |
| $\rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$ | 17.29 | 8.91 $\cdot$ 10^{-2} | 1.54                   |
| $e^+e^- \rightarrow ZZ$          | 4.70          | 0.13       | 0.62                   |
| $\rightarrow \mu^+\mu^-\nu\bar{\nu}$ |               |            |                        |
| $e^+e^- \rightarrow \mu^+\mu^-$   | 1213.29       | $< 10^{-5}$ | $< 0.012$              |
| $e^+e^- \rightarrow \tau^+\tau^-$ | 41.69         | $< 3 \cdot 10^{-4}$ | $< 0.013$              |

**TWO PHOTON VETO**

After the event selection, there are still 8,241 out of 1 million $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ events cannot be separated from the signal. The visible cross section is still quite large (437 fb) comparing to the signal, and we need to identify the escaped two photon events further, in order to get pure muon pair decayed from smuon.

In Figure II, it shows that the polar angle of either electron or positron of the escaped two photon events falls in the region between 5 mrad to 35 mrad. The event is identified as two photon event if either muon pairs and one of the electron pairs are detected at the same time, and therefore the hermeticity of the beam calorimeter down to 5 mrad is just enough.
for our purpose.

There are 8,241 events selected to do full simulation. With the consideration of beam-strahlung effect, there are 7,845 (95.2%) events being identified. The visible cross section is then eliminated down to 21 fb, as shown in Figure 7.

FIG. 7: Muon energy spectrum of the signal and background. The left figure is before two photon veto, and the right one is after two photon veto from simulation. Blue (dotted) line is two photon background, Red (dashed) line is the signal, and black line is the superposition of signal and background. The MC data corresponds to $18.8 \text{ fb}^{-1}$

CONCLUSION

Constructing the beam calorimeter placed at a very small polar angle is a challenging technology. The major radiation source is from secondaries of beamstrahlung. It leaves about 8.5 TeV to each beam calorimeter for a bunch crossing. The radiation dose of the detector varies with the rings and the depth. At low background region, the dosage per
year will be in the order of krad. At very low angle rings, the dosage per year will be as high as 10 Mrad. It is the maximum radiation tolerance of silicon sensor. To design such detector, radiation hard sensor is preferred. Some people consider radiation hard diamond sensor sandwiches instead of silicon sensor in the sampling calorimeters [13]. Beside radiation damage, electron identification is also challenging due to large energy deposition from incoherent pairs.

Electron identification efficiency generally depends on the severeness of background. It depends on the beam parameter set and the region in the beam calorimeter. In this study, beam calorimeter plays an important role in the search of the supersymmetric particle - smuon $\tilde{\mu}_R$ to reject major background events. With the help of beam calorimeter, all of $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ can be identified ideally. But the beamstrahlung effects would affect the veto efficiency and the electron finding efficiency would also vary with the finding method. A simple and basic electron finding method is used in this study to check its performance. From the simulation results, 95% of the two photon background events are vetoed with the consideration of the beamstrahlung effect using BCAL. The result is satisfactory.

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