REVIEW OF FORWARD CALORIMETER TECHNOLOGIES

JOHN HAUPTMAN
Iowa State University, Ames, Iowa 50011

The forward calorimeters at an electron linear collider will cover the angular region below 50 mrad and must be able to provide a measure of luminosity bunch-by-bunch for machine tuning, and to veto events with electrons from two-γ interactions for SUSY searches. Typically, these calorimeters will absorb 20 TeV of electromagnetic energy in the form of $e^{\pm}$ pairs *per bunch crossing*, and an accumulated dose of one GRad in 10 years. We discuss five technologies proposed for this calorimeter.[1]

1 The Problem and Five Proposed Solutions

Two numbers drive the design of a forward calorimeter: the 10-year 1-GRad dose demands radiation-hard detectors, and the 1.4 ns bunch crossing interval demands very fast detectors. Wolfgang Lohmann has discussed technologies and issues mostly related to the 'cold' machine with its much longer time between bunches of 337 ns, at this meeting[2], and I will discuss the same issues for the 'warm' machine with 1.4 ns between bunches.

1.1 Silicon-Tungsten sandwich (SiW)

A calorimeter consisting of silicon sensors sandwiched between tungsten plates (SiW) is a well-understood, robust and fast technology that can be spatially segmented both laterally and longitudinally for electron shower reconstruction. This has been shown by Takashi Maruyama[4] at the SLAC meeting and both Lohmann and I have re-shown some of his work at this meeting.

Oxygenated silicon is surprisingly very radiation hard and recent data[5] show that a silicon sensitive medium can absorb one GRad with only a 20% increase in the depletion voltage. The speed of a SiW calorimeter is a concern since the electrons that constitute the signal have a mobility. Lohmann[2] and colleagues have considered diamond as a fast, radiation hard substitute for silicon in the SiW design, and it appears that diamond can have a subnanosecond response.[3]

Therefore, a potential weakness of a SiW luminosity calorimeter is the time required to extract the physical signal from the silicon and be prepared for the next wall of electrons 1.4 ns later.

1.2 Quartz fiber Čerenkov calorimeter

Quartz Čerenkov calorimeters consisting of longitudinal fibers embedded in holes in a metal absorber and read out with photoconverters at the end of bundled fibers are well-understood, thoroughly tested, and fast. Carefully prepared quartz fibers can tolerate 1 GRad with only a few percent light loss.[6] The signal is generated by electrons above the Čerenkov threshold of about 0.4 MeV/c that traverse the optical fiber near the Čerenkov angle in quartz, and the *pe* yield is ~ 0.25 *pe*/GeV times the fiber fraction in %. Transverse segmentation can be a few millimeters, since electromagnetic showers are very narrow[7], but longitudinal segmentation in depth is difficult. The transmission of the signal out of the calorimeter is fast at c/n, where $n \approx 1.58$, with a time spread of about $5X_0/c\cdot(n-1) \approx 0.2$ ns. A fast rad-hard photoconverter would be required to maintain this timing.

Therefore, the weaknesses of a quartz Čerenkov luminosity calorimeter are segmentation in depth and radiation hardness for doses exceeding 1 GRad.

1.3 Gas Čerenkov calorimeter

The Čerenkov angle in a gas is small ($\theta_C \approx 0.04$) and the light generated by relativistic electrons is channeled forward down optical conduits that are highly reflecting at grazing incidence.

Using a gas instead of a solid (quartz) for the generation of Čerenkov light solves the problems of radiation damage to quartz and radioactivation of the calorimeter mass, which gives Čerenkov light from β^- decay of radionuclides generated over 10 years.[8] The *pe* yield is about $\sim$ 3 *pe*/GeV for mm gas gaps. The time spread of the Čerenkov light is less than 20 ps since the pancake of Čerenkov light co-moves with the pancake of $e^{\pm}$ within the calorimeter mass, the Čerenkov threshold for electrons is $m_e/\theta_C \approx$ 10-20 MeV so that all the lower energy $e^{\pm}/\gamma$ debris in the interaction region is invisible, and the calorimeter consists of metal and gas and is intrinsically radiation hard. However, these simple advantages are offset by the need to extract the Čerenkov photon signal from the interior of the calorimeter mass (through optical conduits of several possible geometries) and to safely transport these photons to a fast phototube. This has proven to be difficult.

Therefore, the main weaknesses of a gas Čerenkov luminosity calorimeter are achieving highly reflecting metallic surfaces and light transport to fast radiation hard photoconverters.

1.4 Parallel plate avalanche chamber

A parallel plate avalanche chamber (PPAC)[9] operated at 750 V across a 2 mm gap filled with a low pressure 30 torr gas will have a signal generation time less than one nanosecond and, if a non-volatile gas is used, will be radiation hard. The design is to use the PPAC as the charge sensing gaps of a sampling calorimeter.

The gas gain is about 10^4 and the positive ions generated will take a fraction of a μs drifting back to the cathode. This positive ion density will build up on successive bunch crossings during the ion drift time. Maruyama calculates[4] about 10^3 e^-/cm^2 at the face of the luminosity calorimeter with a mean e^- energy of 4 GeV. For an absorber of critical energy 7 MeV (Pb), this gives $5{\times}10^5$ e^-/cm^2 at shower maximum, or $5{\times}10^9$ positive ions per cm^2.

Therefore, the main weakness of the PPAC is the generation and build up of positive ions in the gas during the $192{\times}1.4$ ns ~ 0.27 μs bunch train.

1.5 Lead tungstate ($PbWO_4$) crystal calorimeter

Lead tungstate crystals ($PbWO_4$) are being prepared in large quantities for LHC experiments, are well understood and well characterized, and are relatively fast scintillating, very dense optical media. Their energy resolution is excellent and transverse granularity is easily as small as 2cm×2cm. The scintillation time constant is τ = 5-15 ns, which is fast for the "cold" machine, but too slow for the "warm" machine. The transmission of scintillation light degrades by 10-20% under irradiation by electron beams up to one MRad.[10] These data are not hopeful for the use of $PbWO_4$ crystals in a luminosity calorimeter for a linear collider.

Therefore, the main weaknesses of $PbWO_4$ crystals are radiation damage and speed.

2 Comparisons and Conclusions

The main technology criteria for a forward luminosity calorimeter are radiation hardness ($\sim$ GRad) and speed (1.4 ns). This is met by both Čerenkov detectors (gas and fiber), and by the Si/diamond-W detector. The Čerenkov detectors are similar in signal speed and the need for fast radiation hard photodetectors. For radiation hardness, only $PbWO_4$ fails.

Secondary criteria include easy lateral and longitudinal segmentation and basic electromagnetic energy resolution, which together are related to the ability of the calorimeter to reconstruct individual showers inside the many-TeV bath of electron pair showers. Si/diamond-W is the best technology for these, and quartz fiber is next best.

Finally, all detectors require a signal path to a protected readout and processing box behind the shielding. Si/diamond-W and PPAC are easy, quartz fiber are less easy, and gas Čerenkov is difficult. Costs and convenience are not useful criteria since this detector is small.

The machine technology decision will be made soon. The 337-ns "cold" machine would allow a detailed Si detector, whereas the 1.4-ns "warm" machine would demand either one of the Čerenkov detectors, or a carefully crafted diamond detector. I thank Mike Woods and Takashi Maruyama for helpful criticism.

References

1. The transparencies for this talk are at http://polywww.in2p3.fr/-actualites/congres/lcws2004/, Tuesday, Machine-Detector Interface, 15:00-16:30. This note is IPBI TN-2004-6.
2. W. Lohmann, "Instrumentation of the Very Forward Region of a Linear Collider Detector", *Linear Collider Workshop*, 19-23 April 2004, Paris. This review included work from the *FCAL Workshop*, 16 April 2004, Prague; transparencies *ibid.*
3. P. Moritz, *et al.*, "Diamond Detectors with Subnanosecond Time Resolution for Heavy Ion Spill Diagnostics", , note RD42 Collaboration (1997).
4. Takashi Maruyama, "Background Studies", *ALCPG 2004 Winter Workshop*, SLAC, 8 January 2004. (http://www-conf.-slac.stanford.edu/ alcpg04/WorkingGroups/ BeamDeliveryInteraction-Region/ tvm_alcpg2004.pdf)
5. Michael Moll, "Development of radiation hard sensors for very high luminosity colliders - CERN - RD50 Project", *RD50 Note-001* (2003).
6. N. Akchurin and R. Wigmans, *Rev. Sci. Instr.* **74** (2003) 2955.
7. N. Akchurin, *et al.*, "Electron Detection in a Dual-Readout Calorimeter", submitted to *Nucl. Instr. Meths.*
8. J. Hauptman, *et al.*, "A velocity-of-light gas Čerenkov calorimeter for the region beyond HF in CMS", CMS-2000-007.
9. E. Norbeck, J. Olson, Y. Onel, "PPAC for luminosity monitor", IPBI TN-2004-4, June 2004.
10. V.A. Batarin, *et al.*,, "Study of Radiation Damage to Lead Tungstate Crystals Using Intense High Energy Beams", hep-ex/0210011, 5 October 2002; and, "Comparison of Radiation Damage in Lead Tungstate Crystals under Pion and Gamma Irradiation", preprint 11 December 2003.