A Fast Gas Cerenkov Calorimeter for Luminosity Measurement and Machine Monitoring

Classification (subsystem)

Machine Detector Interface (MDI)

Personnel and Institution(s) requesting funding

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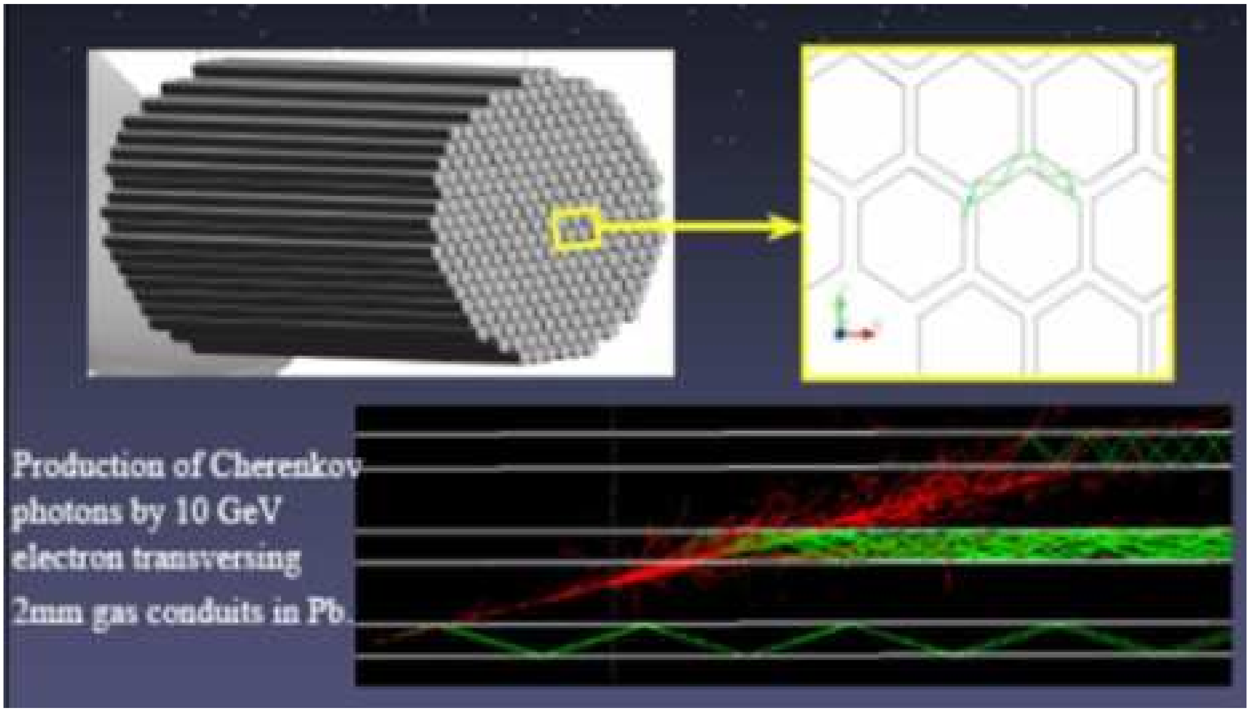
Project Overview We have proposed a gas Cerenkov calorimeter for beam luminosity measurement that is emptied of Čerenkov light in about 2 nanoseconds, thus becoming quiescent very soon after the bunches have crossed, that is explicitly radiation hard, and that is completely insensitive to both radioactivation of the calorimeter mass and to $e^{\pm}$ and γ IR backgrounds below 10 MeV. A detailed description was given in previous reports in which the main motivation was the 1.4 ns crossing time of the warm machine that is no longer relevant. Nevertheless, a fast and rad-hard detector very near the beams during commissioning of the machine, during physics running for backgrounds assessments, and even as an 'instrumented mask' deep inside 5 mrad may still be a useful device for the Linear Collider. Specifically, this instrument would provide continuous nanosecond measurements of electromagnetic activity during the collision and between collisions as a measure of machine activity during beam setup and tuning.

General description of the project The calorimeter consists of a metal volume with optical conduits that can channel the Čerenkov light to the back. These conduits can be tubes, or hexagonal rods in a mosaic pattern, or several other geometries, for example, see the figure showing the hex geometry.



The Čerenkov light is generated by shower particles as they cross the gas gaps between longitudinal rods, and the gas gaps also function as the light conduits.. Since the Čerenkov angle is small, a large fraction of the light is channelled down the optical conduit. The light makes typically 10-12 small angle reflections before exiting the rear of a 30-cm deep calorimeter. Within the calorimeter medium, the Čerenkov light and the electromagnetic shower particles travel at nearly c and co-move in a pancake perpendicular to the shower axis. The shower particles are absorbed out in depth as the Čerenkov light builds up in depth, and a 50 ps pancake of light exits the rear of the calorimeter, its time dispersion dominated mostly by geometry. For a gas of refractive index $n = 1 + \delta$, with $\delta \approx .001$, the Čerenkov angle is given by

$$\cos\theta_C = 1/n\beta \to 1/n \approx 1 - \delta,$$

and expanding the cosine as $1 - \theta_C^2/2$ gives

$$\theta_C \approx \sqrt{2\delta} \approx 0.045.$$

The Čerenkov light yield in the visible is $dN/dx = 370 \sin^2\theta_C \quad \mathrm{eV}^{-1}\mathrm{cm}^{-1}$ yielding about 1 *pe* per GeV. The velocity threshold for Čerenkov light emission is $\beta_{\mathrm{th}} = (P/E)_{\mathrm{th}} = 1/n \approx 1 - \delta$ so that the Čerenkov threshold for electrons is

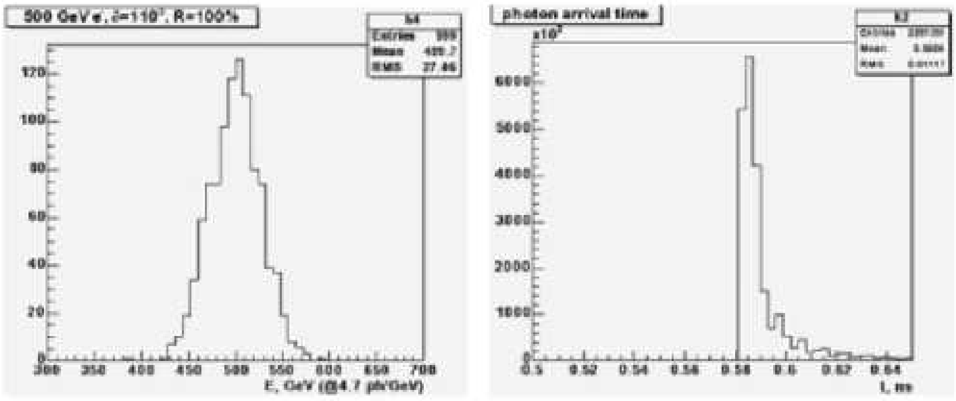
$$P^e_{\mathrm{th}} \approx m_e/\sqrt{2\delta} \approx m_e/\theta_C \approx 11 \text{ MeV/c}.$$

The critical energy of a typical metal is 10-20 MeV, comfortably above the Čerenkov threshold, and therefore most shower electrons will participate in Čerenkov light generation. The Čerenkov threshold is higher than the binding energy per nucleon, and therefore no nuclear decay, either β or γ, can generate Čerenkov light in the gas.

Therefore, this luminosity calorimeter has three unique features:

1. it is constructed wholly of metal and gas, and therefore cannot be damaged by any conceivable dose of radiation;
2. the generation of Cerenkov light is instantaneous, its transport from within the calorimeter volume is at nearly the speed of light, bunched in a 50-ps pancake, and the calorimeter volume is emptied of light in 1-2 ns; and,
3. the Cerenkov threshold is about 11 MeV, and therefore no nuclear decay from any degree of radioactivation will result in Cerenkov light, and all $e^{\pm}$ and γ IR backgrounds below this threshold are invisible.

The energy resolution and Čerenkov light arrival timing spread is shown in the figure.



Time spread ~ 11ps!

The robustness of this gas Čerenkov calorimeter allows placement very near the beam and in the most intense radiation environment.

Broader Impact The work on this project is within two single-investigator groups of a university professor and students, mainly undergraduate physics majors, working on a new problem and seeking new solutions. This explicity integrates teaching and research since our students have office space in the lab area in the Physics Department. It is a place where they can also do their problem sets.

More funds for undergraduate and beginning graduate students will allow us to hire more students. At this stage of work, several problems are available that are person-intensive, rather than equipment-costly: finding or making reflective tubes (Purdue undergraduates), GEANT4 code, reflective brass or tungsten hexagonal bars (Iowa State undergraduates), absolute measurements of reflectivity (Iowa State undergraduates), and design of a module and its optical system (Purdue and Iowa State), and in the last year, a beam test at SLAC. All of these activities are perfect for physics majors, and as we know, they are the best recruitment tools available in physics. At Iowa State, one undergraduate is female (Shauna Dennis) and two male (Sam Ose and Robert Schoene), one female having graduated. Of course, this is part time work and students are transient, but I have managed to keep individual students for 2-4 years. At Purdue, two undergraduate students have made extensive measurements of the reflectivity on the inside of SS tubes. This work by Abe Spinelli and Alvin Laasanena is critical: if we have a tube solution for the geometry, many geometric designs are easily possible.

The achievement of broad impact to enhance scientific and technological understanding and potential benefits to society at large is obtained, in these small high energy physics groups, by sending students out into the world to workshops and conferences. Last year, Oleksiy Atramentov (beginning graduate student) brought Oesa Walker and Rohit Nambyar (undergraduates) to the Cornell Workshop where he gave a talk and Oesa and Rohit watched. In my experience, the best outreach is when students talk to other students.

Results of Prior Research The request for funds last year included work on calculations, measurements of reflectivity, specific studies of metallic reflective surfaces, overall design of a luminosity monitor, and studies of performance. We have achieved most of these.

1. We have built a setup for the absolute measurement of reflectivity at grazing incidence using what we believe is a new technique. We make a very narrow, collimated light beam that bounces off one mirror at angle θ and we count photons with a fast PMT, discriminator and scaler to get a number proportional to R, the reflectivity. A second identical parallel mirror is driven by a screw so that the beam reflects three times, and we count a number proportional to R^3. A further displacement of the movable mirror brings five reflections, for R^5. This is all at fixed θ, with no movement of the PMT, light source, or first mirror. From these measurements of R^n we are over-constrained and can extract the single bounce reflectivity. This work is all done by Robert Schoene.
2. We have spent much time and effort trying to get GEANT4 to handle all the generation and reflection of Čerenkov light without success. There are clearly bugs in GEANT4, and we have recently returned to GEANT3 and will use it. Using our own detailed and exact generation and propagation of Čerenkov light, we have calculated the energy resolution and photoelectron (*pe*) response of a gas Čerenkov calorimeter in which reflecting stainless steel (SS) tubes are the light conduits, and these calculations yield about 5% energy resolution at 200 GeV for an iron (Fe) absorber. Further calculations will be for tungsten (W) with the hex geometry. This work has been done by Youn Roh and Rohit Nambyar.
3. We have searched widely for methods and processes for the manufacture of highly reflecting metallic surfaces, which is essentially equivalent to a very smooth metallic surface. Ordinarily, this is accomplished by mechanical polishing, and this can be done commercially[1], and we have also succeeded ourselves with small areas, but we are searching for a process with better control over uniformity and cost. The processes we have studied and rejected are: (*i*) ion beam melting of the surface (IBEST, Sandia Labs); (*ii*) electropolishing and electroplating;[2] (*iii*) metallic glasses;[3] (*iv*) replica techniques;[4] and, (*v*) various forms of polishing of SS, brass and aluminum.

   Presently, we are communicating with New Castle Industries on their 'chill roll' process for producing large, uniform, controlled and very smooth metallic surfaces of any kind. This looks promising, but also expensive.
4. Extensive measurements of the net reflectivity down SS tubes, both small diameter for the interior of the calorimeter and larger diameter for the transport of light to the photodetectors, has been done at Purdue by undergraduate students Abe Spinelli, Matthew

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[1] For example, by Finished Surfaces, a local company in Chicago.

[2] Poligrat, GmbH, Munchen, DE.

[3] Liquidmetal Technologies, Lake Forest, CA, *Science News*, **166**, Nov. 6, 2004, "Metal Makeover", p.298.

[4] J. Diebel, *et al.,* "Fabrication of large-scale ultra-smooth metal surfaces by a replica technique", Appl. Phys. A **73** (2001) 273.

Barnett and Alvin Laasanena with Virgil Barnes. Some of this work was reported at the SLAC meeting in Jan. 2004.[5]

5. We gave a talk at the April 2004 Paris meeting on the Linear Collider and written a critical paper on five technologies for the forward region. Two other talks were given on dual-readout fiber calorimetry and on the reconstruction of $W \to jj$ and $Z \to jj$.
6. We have made extensive studies of the energy pattern in this gas Čerenkov calorimeter using the calculated input of low-energy e, γ that will hit the front face,[6] and attempted to reconstruct the beam electron. Attempts were made to reduce the background e, γ by inserting various depths of W absorber. More work is required here.
7. Samples of metallic reflectors have been obtained by us from Sandia, Finished Surfaces, and local researchers in the Ames Laboratory, and tested in our lab. This work has been done by Sam Ose and Robert Schoene.

This work was done under the LCRD grant to "An Explicitly Radiation-Hard Gas Čerenkov Calorimeter for Bunch-by-Bunch Luminosity Measurement at the Next Linear Collider", covering the period from June 2004 to May 2005.

Talks at LC meetings

1. Oleksiy Atramentov, "Update on Čerenkov Calorimeter", Linear Collider Retreat, SLAC-/Santa Cruz, June 2002.
2. Oleksiy Atramentov, "Fast Gas Čerenkov Luminosity Monitor: Progress Report", American Linear Collider Workshop, Cornell, 13-16 July 2003.
3. Oleksiy Atramentov, "Simulation of a Gas Čerenkov Calorimeter", Fermilab, Geant4 International Workshop, October 2003.
4. John Hauptman "Gas Čerenkov Calorimeter as a Luminsoity Monitor", *Linear Collider Workshop*, SLAC, 7-10 January 2004.
5. John Hauptman, "Dual Readout Calorimeter", SLAC, *ibid.*
6. Virgil Barnes, "Mirror Finish: Stainless Steel Tubes for Gas Čerenkov Calorimetry", SLAC, *ibid.*
7. John Hauptman, "Review of Luminosity Calorimeter Technologies", *Intl. Conf. on Linear Colliders*, Paris, 19-23 April 2004.
8. John Hauptman, "Dual Readout Calorimetry", Paris, *ibid.*
9. John Hauptman, "Importance of $W \to jj$", *ibid.*

Publications

1. "Review of Luminosity Calorimeter Technologies", proceedings of the *Intl. Conf. on Linear Colliders*, Paris, 19-23 April 2004.
2. "Dual Readout Calorimetry", proceedings, Paris, *ibid.*

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[5] www-conf.slac.stanford.edu/alcpg04/WorkingGroups/ BeamDeliveryInteractionRegion/Virgil-SLAC-Jan04.pdf

[6] Calculations and data file from Takashi Maruyama, SLAC.

3. "Importance of $W \to jj$", proceedings, *ibid.*

This request is for a continuation of this work on a novel, but difficult optical calorimeter.

Facilities, Equipment and Other Resources

At ISU we have three laboratory rooms, one a 'clean room' for the optical measurements, one a hardware lab room for mechanical equipment, and a third for mostly computers and people.

The university supports a High Performance Computing (HPC) cluster that we use extensively and at esentially zero cost to us, for all of the GEANT work and any other compute-intensive work.

The Chemistry Department maintians an excellent machine shop that we have used (at $20/h) for many small equipment projects, and we would use this shop for mounting the metal mass inside the gas volume for this calorimeter.

At Purdue, laboratory space, shop facilities and computing infrastructure exists for this project.

FY2005 Project Activities and Deliverables We will have a conceptual design for the reflecting surfaces, the GEANT3 code will be finished for the hex geometry (already works for tube geometry), and full measurements of the SS tube option. We will continue throughout the year to search for viable technologies to produce highly smooth metallic surfaces.

FY2006 Project Activities and Deliverables Construction and assembly of a beam-testable module, light transport measurements; physics simulations of performance, both as a luminosity monitor at ±3m and as an 'instrumented mask'.

FY2007 Project Activities and Deliverables Assembly of final module for test, purchase of fast PMTs, and beam test of module. The configuration of the module and its readout will depend up its final use, and therefore we will be consulting with interaction region and machine colleagues.

Budget justification: Iowa State University: The small-scale testing of reflecting surfaces, identification of processes for the manufacture of metallic reflectors, and the calculations and design of a module are all within the capabilites of this group. Most funds in the first and second year are for hourly wage support of undergraduate physics majors ($8K/y), a month of summer support for a beginning graduate student ($2K/y) and nominal equipment, travel and supplies for a lab. (Most equipment, e.g. NIM bins and fast electronics, are borrowed from Fermilab). In the third year we will purchase the metallic reflective absorber, assemble it in the local machine, instrument with PMTs, and prepare for a beam test ($30K equipment, $4K travel).

Three-year budget, in then-year K$

Institution: Iowa State University

Item	FY2005	FY2006	FY2007	Total
Other Professionals	0	0	0	0
Graduate Students	2.0	2.0	2.0	6.0
Undergraduate Students	8.0	8.0	8.0	24.0
Total Salaries and Wages	10.0	10.0	10.0	30.0
Fringe Benefits(11.3%)	0.2	0.2	0.2	0.7
Total Salaries, Wages and Fringe Benefits	10.2	10.2	10.2	30.7
Equipment	2.0	3.0	20.0	25.0
Travel	2.0	2.0	4.0	8.0
Materials and Supplies	2.0	2.0	2.0	6.0
Other direct costs	0	0	0	0
Total direct costs	16.2	17.9	36.2	69.6
Indirect costs(46% of TMDC)	6.5	6.5	7.5	20.5
Total direct and indirect costs	22.7	23.7	43.7	90.1

Budget justification: Purdue University: The manufacture of SS tubes as light conduits, testing and measuring reflectivities, and the design and manufacture of $(3\text{cm})^2$ conduits for the transport of light to PMTs is mostly done by undergraduate physics majors ($8k/y). In the third year, funds are for construction of final conduits and preparation and testing of components for a beam test ($12K equipment, $4k travel).

Three-year budget, in then-year K$

Institution: Purdue University

Item	FY2005	FY2006	FY2007	Total
Other Professionals	0	0	0	0
Graduate Students	0	0	0	0
Undergraduate Students	8.0	8.0	8.0	24.0
Total Salaries and Wages	8.0	8.0	8.0	24.0
Fringe Benefits (11.3%)	0.2	0.2	0.2	0.7
Total Salaries, Wages and Fringe Benefits	8.2	8.2	8.2	24.6
Equipment	2.0	4.0	6.0	12.0
Travel	2.0	2.0	4.0	8.0
Materials and Supplies	2.0	2.0	2.0	6.0
Other direct costs	0	0	0	0
Total direct costs	14.2	16.2	20.2	50.6
Indirect costs	5.6	5.6	5.6	16.8
Total direct and indirect costs	19.8	21.8	25.8	67.4