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LCDRD FINAL REPORT

REPORT ON THE

UNIVERSITY-BASED DETECTOR RESEARCH AND DEVELOPMENT FOR THE INTERNATIONAL LINEAR COLLIDER

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The U.S Linear Collider Detector R&D program, supported by the DOE and NSF umbrella grants to the University of Oregon, made significant advances on many critical aspects of the ILC detector program. Progress advanced on vertex detector sensor development, silicon and TPC tracking, calorimetry on candidate technologies, and muon detection, as well as on beamline measurements of luminosity, energy, and polarization.

The R&D of this program contributed significantly to the development of validated detector designs for ILC experiments, SiD and ILC, that were described in the following reports:

ILC Reference Design Report, Volume 4 - Detectors, 2007, 177 pages. [arXiv:0712.2356] http://ilcdoc.linearcollider.org/record/6321/files/ILC_RDR_Volume_4-Detectors.pdf?version=4

International Linear Collider interim report: Volume 2 - International Linear Collider Physics and Detectors: 2011 Status Report , 2011, 99 pages http://ilcdoc.linearcollider.org/record/35024/files/ilc_detector_report_2011_lores.pdf

ILC Technical Design Report, Volume 4, Detectors, 2013, ~337 pages.

Thirty-two projects were supported with funds, involving thirty-two institutions. These covered the main areas of detector research, including Luminosity, Energy, and Polarization Measurements (LEP), Vertex Detection (VXD), Tracking (TRK), Calorimetry (CAL), and Particle ID, including Muon Detection (PID), with the following breakdown:

Topic	Projects
LEP	6

VXD	3
TRK	7
CAL	13
PID	3

The institutions involved in the program were Argonne National Laboratory, Boston University, Brookhaven National Laboratory, Brown University, University of Chicago, Colorado State University, Cornell University, University of Hawaii, University of Indiana, University of Iowa, Iowa State University, University of Kansas, Kansas State University, Lawrence Berkeley National Laboratory, Louisiana Tech University, Purdue University, Princeton University, Texas Tech University, Tufts University, University of Michigan, Northern Illinois University, University of Notre Dame, University of Oklahoma, University of Oregon, University of Texas at Arlington, University of Colorado, UC Davis, UC San Diego, UC Santa Cruz, University of Washington, Wayne State University, and Yale University.

LIST OF PROJECTS (project number, principal investigator, topic):

Luminosity, Energy, Polarization

3.1	John Hauptman	Gas Cerenkov Cal for Lum Measm't
3.4	Eric Torrence	Extraction Line Energy Spect.
3.5	Mike Hildreth	BPM-Based Energy Spect.
3.6	Yasar Onel	Polarimetry
3.7	William Oliver	Compton polarimeter backgrounds
3.9	Bill Morse/U. Nauenberg	BeamCal and GamCal

Vertex

4.1	Charlie Baltay	Pixel Vertex Detector
4.4	Henry Lubatti	Vertex Detector Mech. Structures
4.5	Gary Varner	Pixel-level Sampling CMOS VxDet

Tracking

5.2	Lee Sawyer	GEM based Forward Tracking
5.7	Dan Peterson	MPGD Readout for a TPC
5.10	Bruce Schumm	Long Shaping-Time Silicon Strip
5.13	Stephen Wagner	Recon. Studies for SiD Trk
5.14	Richard Partridge	Sim. Studies for a Silicon Trkr.
5.15	Eckhard von Toerne	Calor-based Trk./Long-lv'd Part.
5.17	Dan. Bortoletto	Thin silicon sensors

Calorimetry

6.1	Vishnu Zutshi	Scin.-based Tail-ctchr/Muon Trkr
6.2	Uriel Nauenberg	Calorimetry R&D
6.4	Usha Mallik	Particle Flow Studies
6.5	Raymond Frey	Silicon-tungsten EM calorimeter
6.6	Andy White	Digit. Had. Calorimetry w/ GEMs

6.9	Dhiman Chakraborty	Particle-Flow Alg. and Sim.
6.14	José Repond	Had Cal w/ Digit. Readout (RPCs)
6.16	Richard Wigmans	Dual-Readout Calorimetry
6.18	John Hauptman	4th Concept Detector
6.19	A.J.S. Smith	Calorimeter and Muon ID
6.20	Tianchi Zhao	Scint/Cheren Rad Plates Cal w/ SiPMs
6.21	Satish Dhawan	Modular DAQ Development
6.22	Gerald Blazey	Scint-based Tail-catcher/Muon Tracker

Muon

7.2	Paul Karchin	Scintillator Based Muon System
7.5	Robert Wilson	Geiger-Mode APDs for Muon Sys.
7.8	Henry Band	RPC and Muon System Studies

Important advances included:

- Beamline instrumentation development, including beam tests at SLAC End Station A, for both a beam position monitor based energy measurement, and a quartz fiber based energy measurement.
- CMOS pixel detector developed in partnership with the Sarnoff Corporation, to produce a vertex detector sensor with single bunch crossing sensitivity, yielding very high immunity to background hits.
- Gaseous tracking R&D, including the development of a micro pattern gas detector TPC readout, and GEM-based forward tracking prototypes.
- Silicon tracker R&D, including simulations studies, development of a long shaping-time readout, and an alignment system prototype.
- Silicon-tungsten EM calorimeter development, including tests of prototype sensors and the development of a highly integrated readout chip.
- Hadron calorimeter RPC tests and design studies, including construction and testing of a one meter-cubed digital calorimeter prototype.
- Hadron calorimeter GEM tests, developing the basis for GEM technology applied to digital calorimetry.
- Hadron calorimetry R&D to develop modern scintillator detector technology optimized for the ILC.
- Particle Flow simulation studies to understand the limitations of jet measurements in the particle flow technique.
- Muon detector beam test preparation based on scintillator detectors.

Highlights of the DOE-supported projects are briefly described below in reports by each of the task PIs.

3.1 John Hauptman, Iowa State — Gas Cerenkov Cal for Lum Measm't

The LCDRD funds (Project 3.1) for development of a novel Gas Cerenkov calorimeter were essential for the development of this new concept in calorimetry.

1. design and construction of a simple brass-plate calorimeter

   This construction was done inside the QuarkNet program and the Iowa QuarkNet Center directed by Dr. Nural Akchurin (U. Iowa) and Dr. John Hauptman (Iowa State U.), and all work was done in the physics department lab space and department machine shop. The optics consisted of a single four-segment mirror to reflect the light for the back of the module onto a bank of small PMTs.

2. testing of this calorimeter in the CERN North Area H4 beam

   Since this was parasitic running at the CMS HF calorimeter beam test, the run was at the last moments before the testing period was finished. The Cherenkov light was seen in the PMTs, but the optics was not optimal and the energy response distribution seems to show that the PMTs photocathodes were being hit by a few shower particles.

3. travel support for test beam

4. further design, simulations, and testing of the 'ultimate' calorimeter of this type. We are now expanding the scope to an actual "dual-readout" calorimeter using the blue scintillation light from **N**2 in the gas.

   A good design requires excellent reflectivity on the inside of the tubes (or the outside of the hex rods, depending on the geometry), and we have finally identified that atomic layer deposition (ADL) can achieve this level of smoothness and reflectivity. We are discussing this with Jeff Klug at ANL.

This novel calorimeter has several unique features and will find some uses in high energy physics, possibly in conjunction with the pico-second photo converters being developed at U. Chicago/ANL, or as beam monitors in fierce forward environments at an ILC collider, or Project X fixed target stations, or as forward calorimeters at the LHC.

notes and talks

1. "A 'Velocity-of-Light' Gas Cherenkov Calorimeter for the region beyond HF in CMS,"
N. Akchurin[1], J. Hauptman[2], J. Dilks[2;3], P. Bruecken[1;3], K. Ante[2], and B. von Ahsen[2]
1 Physics Department University of Iowa
2 Physics Department, Iowa State University
3 QuarkNet Program, Fermilab
CMS Note 2000-007, 16 December 1999

2. "Explicitly Radiation Hard Fast Gas Cherenkov Calorimeter,"
Oleksiy Atramentov,
CALOR02, Cal Tech, Pasadena, CA, 25-29 March 2002.

3. "Update on Cherenkov Calorimeter",
Oleksiy Atramentov,
Linear Collider Retreat, Stanford-Santa Cruz, June 2002.

4. "Fast Gas Cherenkov Luminosity Monitor: Progress Report,"
Oleksiy Atramentov,
American Linear Collider Workshop, Cornell University, 13-16 July 2003.

5. "Simulation of a Gas Cherenkov Calorimeter,"
Oleksiy Atramentov,
Geant4 International Workshop, Fermilab, October 2003.

6. "Dual-readout Gaseous Calorimeter (Cherenkov and scintillation),"
John Hauptman, Tim Overton (ISU), Jeff Klug, Rich Talaga (ANL), and
Nural Akchurin (TTU),
8 February 2013, Internal Group Note.

3.4 Eric Torrence, Oregon Extraction Line Energy Spect.

The funding for the extraction line spectrometer was used for develop the concept of an energy spectrometer capable of withstanding the intense radiation environment of the ILC extraction line and provide absolute beam energy measurements on short time scales at a relative precision of 10^{-4}. The design which was developed uses two wiggler magnets to produce synchrotron radiation stripes oriented with the beam trajectory before and after an analyzing dipole magnet in the ILC extraction line. The detector technology explored used quartz fibers read out by multi-anode PMTs to detect secondary electrons by Cherenkov radiation from the primary synchrotron radiation stripes.

The work supported by this grant was used to develop a detailed instrumentation design for the extraction line which also can accommodate a downstream polarimeter. This work included a full Geant4 simulation of the disrupted electron beam after the interaction point propagating through the ILC extraction line optics lattice. This work was the basis for the extraction line design first established in the ILC RDR (1), as was published as part of a comprehensive beam instrumentation design (2).

A second aspect of this work was a beam test of a Quartz fiber detector at SLAC in End Station A as part of a broader instrumentation test beam program. A 64 fiber prototype was constructed and saw limited beam time in 2007 using a refurbished SPEAR wiggler as T-475 (3,4). While the detector clearly sees evidence of Cherenkov photons, the quality of the data was unfortunately not high enough to warrant a publication. Unfortunately, this test beam program was terminated due to lack of funds after 2007 and no further data was collected.

(1) ILC RDR

(2) ``Polarimeters and Energy Spectrometers for the ILC Beam Delivery System," S.

Boogert *et al*., JINST **4**, P10015 (2009).

(3) E. Torrence, "Test Beam Request for a Synchrotron Stripe Energy Spectrometer," SLAC-T-475, June 2004.
http://www.slac.stanford.edu/xorg/lcd/ipbi/notes/syncspec_T475.pdf
(4) R. Arnold and E. Torrence, "Rough Layout and Rate Estimate for Beam Test in SLAC ESA of Synchrotron Radiation Detector Prototypes for LC Beam Monitor," IPBI TN-2004-7, July 2004.
http://www.slac.stanford.edu/xorg/lcd/ipbi/notes/tn_synchrate.pdf

3.5 Mike Hildreth, Notre Dame BPM-Based Energy Spect.

Project Title: A Demonstration of the Electronic and Mechanical Stability of a BPM-Based Energy Spectrometer for the International Linear Collider

The 2006-2009 (and continuation) period saw the (premature) completion of Energy Spectrometer studies at SLAC End Station A in 2007 and the relocation and commission of a new installation at the ATF2 project at KEK. The final year of running at End Station A included the installation and evaluation of a new BPM designed specifically for Energy Spectrometer Studies at University College London and Royal Holloway University London. Unfortunately, neither its resolution nor its mechanical stability achieved design goals. However, full operation of the magnetic chicane was achieved, and initial spectrometer studies were performed. This work is summarized in three publications [1],[2],[3]. BPM resolution and stability were the limiting factors in evaluating the eventual performance of the BPM-based spectrometer system.

In July, 2009, the first installation of interferometer equipment at ATF2 was begun. Three interferometer stations were completed in January 2010. (This work is partially supported by a follow-up grant to the LCDRD program.) Initial results from this configuration were shown at IPAC 2010 [4]. The LCDRD program supported the commissioning of this system.

[1] A. Lyapin, *et al.*, *“Results from a Prototype Chicane-Based Energy Spectrometer for a Linear Collider,”* JINST **6** P02002 (2011).

[2] S. Boogert, *et al.*}, *“Polarimeters and Energy Spectrometers for the ILC Beam Delivery System,”* JINST **4**, P10015 (2009).

[3] M. Slater, *et al.*, *“Cavity BPM System Tests for the ILC Energy Spectrometer,”* Nucl. Instrum. Meth. **A** 592 201 (2008).

[4] M.D. Hildreth, *et al.*, *“The Straightness Monitor System at ATF2,”* in the Proceedings of 1st International Particle Accelerator Conference: IPAC 10, Kyoto, Japan, 23-28 May 2010, pp. MOPE100.

3.6 Yasar Onel, Iowa — Polarimetry

Quartz Technology R&D for Lepton Collider Compton Polarimeter

We have developed and tested a novel Compton Polarimeter for future lepton colliders. The polarimeter was designed to make precise measurements up to multi-TeV scale colliders. The proposed electromagnetic calorimeter consists of iron rods interleaved with radiation hard quartz fibers as active medium. The fibers are read out with a single photomultiplier tube. Different radiation-hard readout options are also under consideration. The calorimeter has a linear response up to multi-TeV scale to measure the Compton scattered photons. It has sufficient containment and performance characteristics. The scattered electrons will be measured with a novel Cerenkov detector with a crystal/glass - SiPM assembly. The setup provides sufficient position measurement and is 100% efficient (compare to the limited efficiency of gas Cerenkov detectors). The radiation issues associated with the SiPMs can either be handled with a simple modular design that enables the replacement of this cheap device periodically, or replacement of the SiPMs with similar radiation hard readout options.

Compton Polarimetry for Future Linear Colliders, LCWS12, October 22-26 2012, Arlington, Texas, USA.

Total Absorption Dual Readout Calorimetry R&D, TIPP 2011, June 9-14 2011, Chicago, Illinois, USA, Physics Procedia, 37, 309-316, 2012.

3.7 William Oliver, Tufts — Compton polarimeter backgrounds

The goal of the project was to design a polarimeter to measure the polarization of the electron beam and to calculate the background to be expected in the measurement. The project began with a GEANT3 model of the magnets in the extraction line provided by the IP Beam Instrumentation Group. The extraction line featured a chicane to isolate the electrons that pass through the interaction point with minimum disruption. At the midpoint of the chicane the electrons strike a circularly polarized laser beam. The electrons back-scattered by the laser beam are bent by the downstream half of the chicane to reach a hodoscope of gas Cherenkov counters. The difference in the counting rates for opposite polarizations of the laser provides the measure of the electron polarization. Prof. Oliver was asked to calculate the analyzing power for different primary beam energies of a polarimeter operating with a fixed hodoscope, fixed magnet currents, and fixed laser energy, but with the position of the laser beam adjusted to intercept the primary electron beam at its different locations in the chicane for the different beam energies. He found that the kinematics and dynamics of Compton scattering are amazingly well suited to provide an analyzing power that is nearly independent of beam energy. With the design in hand, he proceeded to calculate some of the backgrounds to be expected in the hodoscope, adding details such as beam pipes to the model of the extraction line. The first important background discovered was due to synchrotron radiation in the magnets forming the upstream half of the chicane. There was a opening through the magnet geometry such that a narrow beam of radiation could reach the hodoscope. The trajectory was tracked and suitable shielding installed to block this radiation. The project came to a close before other background sources could be found and dealt with, but the conclusion can be drawn that the backgrounds need to be carefully calculated and the extraction line design modified appropriately before construction can commence. The work is described in detail in documents DOE/ER/40702-25 (July 15, 2005) and DOE/ER/40702-35 (July 14, 2008) submitted to the Department of Energy.

3.9 Bill Morse (BNL)/U. Nauenberg (Colorado) BeamCal and GamCal

See project 6.2 below.

4.1 Charles Baltay (Yale)/James Brau (Oregon) Pixel Vertex Detector

A monolithic CMOS pixel detector, Chronopixel, with time stamping capability has been under development, in collaboration with the Sarnoff Corporation. The design goals are derived from the requirements of an ILC vertex detector, but use with different accelerators (for example, CLIC) has also been considered. The detector contains the usual matrix of pixels organized in rows and columns. A comparator threshold is used to signal the passage of a charged particle, forcing the recording of an externally provided time stamp into a memory cell inside the hit pixel. If another charge particle is detected in the same pixel before the record has been read out, a second memory cell is used.

The ILC beam consists of about 3000 bunches of colliding particles with 330 ns bunch intervals, followed by 200 ms idle time. During bunch collisions time stamps are recorded into the pixel memory cells, and read out occurs in the 200 ms idle time interval.

The first prototype of a Chronopixel device was fabricated at TSMC using standard 0.18 μm TSMC technologies, with 50 x 50 μm^2 pixels. Comparison of the measured parameters to the design specifications revealed one parameter significantly outside specification, the comparator offset spreads. Reduction of the sensor capacitance with feature size reduction will increase sensitivity, and therefore, this parameter, expressed in the units of charge can be reduced. Sensor capacitance can also be reduced by reducing the size of the charge collection electrode or by increasing the epitaxial layer resistivity. A prototype one layout mistake resulting from the use of very then traces for power to individual pixels results in unacceptable voltage drops and operation failure for many pixels, but this error did not prevent testing of the basic features of the sensor concept.

A second prototype design was developed in light of the results of tests on the first prototype. Many new solutions were implemented, including the exclusion of PMOS transistors in the electronics inside the pixels. This was expected to significantly increase charge collection efficiency by eliminating n-wells open to detector sensitive volume. As n-wells have positive potential relative to the epitaxial layer bulk, they are competing for electron collection with the signal collecting n-well. The original concept sought to eliminate such competition by putting all in-pixel electronics on the top of the deep p-well, insulating all shallow n-wells of PMOS transistors from sensitive volume. However, deep p-well technology is not widely available. In the new concept, power consumption limits are a challenge.

Another significant prototype two feature was the use of an analog (instead of digital as in prototype one) circuit to compensate for comparator offsets spread from pixel to pixel. Use of the analog offset compensation avoids difficulties from offset granularity encountered in prototype one. The second prototype is fabricated with a 90 nm process, reducing the pixel size to 25x25 μm^2, close to the final goal of 12.5x12.5 μm^2 .

Results from the test of the first two prototypes yielded the following findings:
1. Chronopixel devices can record time stamps with the required 300 ns period.
2. The readout system does read all hit pixels during interval between ILC bunch trains (by implementing sparse readout).
3. Pulsed power can be implemented with 2 ms ON and 200 ms OFF without ruining comparator performance.
4. All NMOS electronics can be implemented without unacceptable power consumption
5. Comparators offset calibration is achievable with virtually any required precision using analog calibration circuit.
6. Tests of prototype 2 revealed that reducing feature size while maintaining performance is a challenge.
7. The all NMOS transistor approach is not yet confirmed to achieve high charge collection efficiency. This will be a goal of future investigations.

A third prototype is under development to respond to these findings. Ninety (90) nm technology is planned with reduced sensor capacitance.

Reports

"Monolithic CMOS Pixel Detectors for ILC Vertex Detection," J. Brau, O. Igonkina, N.B. Sinev, David M. Strom, (Oregon U.) , C. Baltay, W. Emmet, H. Neal, D. Rabinowitz, (Yale U.) . LCWS-2005-0810, SNOWMASS-2005-ALCPG1425, Aug 2005. 6pp. In the Proceedings of 2005 International Linear Collider Workshop (LCWS 2005), Stanford, California, 18-22 Mar 2005 and 2nd ILC Accelerator Workshop, Snowmass, Colorado, 14-27 Aug 2005, Published in ECONF C0508141:ALCPG1425,2005.

N.B. Sinev et al., "Test of the First Prototype of Time Stamping Monolithic CMOS Pixel Detector," 2010 IEEE Nuclear Science Symposium Conference Record.

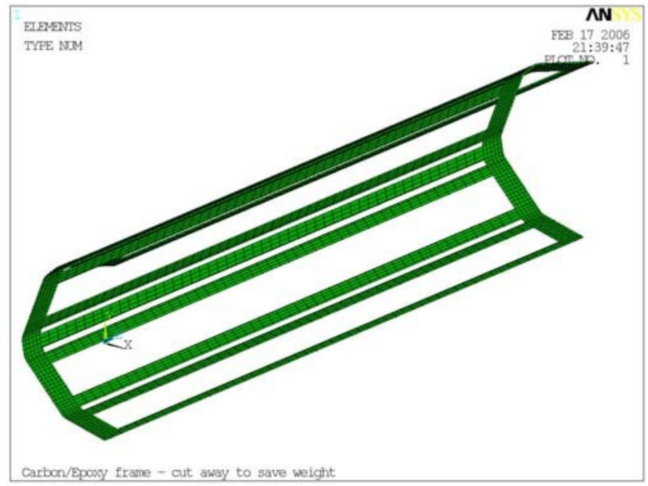
C. Baltay, W. Emmet, D. Rabinowitz, J. Brau, N. Sinev and D. Strom, "Chronopixel Vertex Detectors for Future Linear Colliders," Proceedings of the DPF-2011 Conference, arXiv:1109.2811 [physics.ins-det].

N.B. Sinev et al., "Second Prototype of the Chronopixel Detector," 2012 IEEE Nuclear Science Symposium Conference Record.

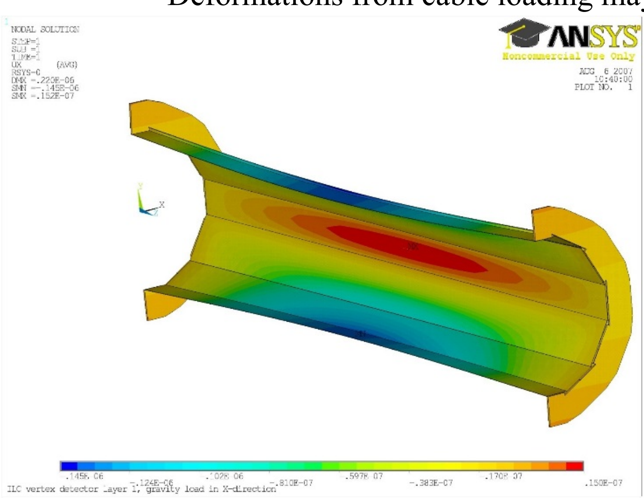
4.4 Henry Lubatti, Washington Vertex Detector Mech. Structures

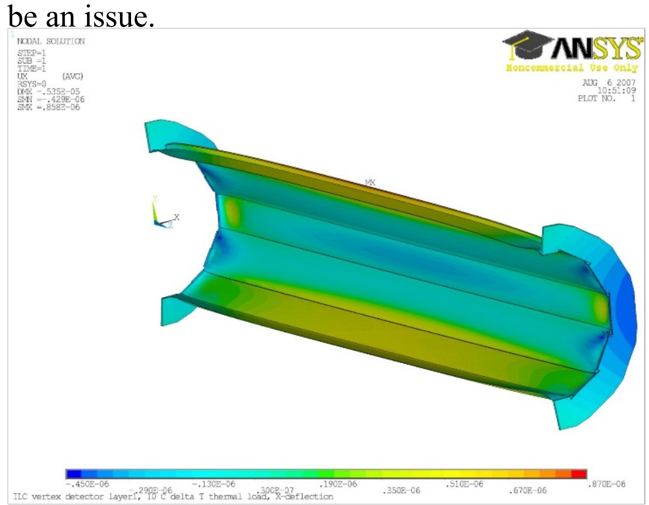
The Seattle group investigated two approaches for the design of the vertex detector:

1. Direct mounting of the sensors on very lightweight carbon fiber/epoxy composite support structure
    a. FEA calculations were done and showed that gravitational deflections were minimal. Thermal deflections appeared to be an issue
    b. A prototype structure was built using K13C2U/epoxy pre-preg.



2. An all silicon structure in which the sensors themselves are the support structure for the barrel layers.
    a. FEA analysis showed that thermal deflections would be acceptable. Deformations from cable loading may be an issue.





3. Research studies were done on CTE properties of carbon fiber/epoxy laminates to determine optimum thermal and mechanical properties.

4. All FEA studies were done for each of the 5 layers in the vertex detector.

4.5 Gary Varner, Hawaii Pixel-level Sampling CMOS VxDet

At the University of Hawaii, DOE LCDRD funding supported exploration of variants of the Continuous Acquisition Pixel (CAP) CMOS pixel architecture and its suitability to the demanding requirements of ILC detector vertexing needs. These funds supported Elena Martin and Michael Cooney in their graduate research studies of the CAP5, CAP6 and CAP7 ASIC pixel prototypes. Performance limits of the various binary-encoding architectures were explored and reported at in student presentations at the 2007 IEEE/NSS, in published references, as well as in Doctoral Dissertations.

H. Hoedlmoser, G. Varner, M. Cooney, "Hexagonal pixel detector with time encoded binary readout," Nucl.Instrum.Meth. A599 (2009) 152-160.

T. Tsuboyama *et al.,* "R&D of a pixel sensor based on 0.15um fully-depleted SOI technology," Nucl.Instrum.Meth. A582 (2007) 861-865.

G. Varner *et al.*, "Development of the Continuous Acquisition Pixel (CAP) sensor for high luminosity lepton colliders," Nucl.Instrum.Meth. A565 (2006) 126-131.

Maria Elena Martin Albarran, PhD Dissertation, UAB Barcelona, 2008.

Michael Cooney, PhD Dissertation, U. Hawaii, 2012.

5.10 Bruce Schumm, UC Santa Cruz Long Shaping-Time Silicon Strip

Several milestones were achieved from the funds received by SCIPP/UCSC.
A study of the KPIX-7 chip revealed channel-to-channel variation that limited the operating point to an uncomfortably narrow range; this was addressed in subsequent designs. A lab-bench study of charge division on resistive electrodes led to a publication [NIM-1] that raised and addressed many of the issues associated with double-ended readout of microstrip sensors and the determination of the longitudinal coordinate via charge division. A related study of load-induced noise limitations explored the effects of resistive load on readout noise, showing that network effects significantly reduce noise relative to lumped-element approximations. This work is in preparation for submission to Nuclear Instruments and Methods [NIM-2]. Finally, a simulation study of non-prompt stau production and decay [LCWS11] demonstrated good efficiency for reconstructing stau events with the SiD for staus decaying as far out in the detector as the second tracking layer. In addition, much progress was made in designing and developing infrastructure for an electromagnetically-induced radiation damage study, to be run in June 2013, that will help to select sensor technology for the BeamCal detector.

[NIM-1]:

Longitudinal resistive charge division in multi-channel silicon strip sensors,
J.K. Carman et al., Nucl.Instrum.Meth. A646 (2011) 118-125

[NIM-2]:
Microstrip Readout Noise for Load-Dominated Long Shaping-Time Systems,
K. Collier et al., to be submitted to Nuclear Instruments and Methods.

[LCWS11}:
Metastable Staus: Reconstructing Non-Prompt Tracks at the ILC with the SiD Detector,
C. Betancourt et al., Proceedings of the 2011 International Linear Collider
Workshop, e-Print: arXiv:1112.4825

5.13 Stephen Wagner, Colorado Recon. Studies for SiD Trk

Continuation of Reconstruction Studies for the SiD Outer Barrel Tracker (LCDRD 5.13)

The primary outcomes of this grant were 1) track reconstruction studies in the SiD Outer Barrel Tracker that were performed by Wagner (the PI) and 2) the development and release of a Kalman track fitter that would take estimated track parameters and a list of standard org.lcsim hits (and material) and return an optimized set of track parameters. The track reconstruction studies were an extension of earlier studies, but showed the improvement possible when the outer tracker went from long (ganged) strips to tiled strip detectors. These studies consisted of embedding hits from a track into the track hits (plus full background) of a jet and measuring the efficiency and quality of the found track as a function of the track angle from the jet thrust axis. The results of these studies were reported at various working group meetings and at the 2005 Snowmass ILC Workshop. The Kalman fitter was based on the BaBar Kalman track fitter but was developed and released into the org.lcsim framework. The Kalman fitter was the product of a Colorado postdoc (Frederic Blanc, now at Lausanne on LHCb) and was presented at the 2006 Vancouver Linear Collider Workshop. The track fitter was checked into the standard release structure, maintained through changes to the base code (hits, etc) and was shown to work with several of the track finders available at the time. The primary expense to the grant was the salary of postdoc Blanc for the time he was working on the fitter, and most of the rest went to pay for travel to attend various workshops (Snowmass, Vancouver, Albuquerque, and partial support for Hamburg and CLIC 2009). Two Colorado undergraduates were also employed at various times to work with Wagner and Blanc.

5.17 Dan. Bortoletto, Purdue Thin silicon sensors

Material minimization in the ILC detectors is important both to achieve excellent impact parameter resolution and for the precise measurement of low momentum tracks. Therefore it impacts both silicon pixels that provide precise space points near the interaction region and a silicon microstrip tracker further from the primary interaction region, and the measurement of tracks at small angle in the forward region. Our work aimed at establishing the reliability of thin silicon sensors for the ILC. DOE LCDRD funds where used to study micro-strip sensors with a thickness of 150, 200, 300 μm at Purdue University. We evaluated the electrical properties of these micro-strip sensors. Our findings show that the leakage current is dominated by the surface current instead of the bulk before irradiation. The coupling capacitance, bias resistance, and other electrical values are found to be quite uniform. The charge collection efficiency of sensors has been studied with a 1064 nm laser. As we expected, the thinner sensors collected less signal compare to the standard (300 μm thick) sensors. Nonetheless the charge is large enough to provide efficient tracking. The results obtained during our studies are documented in the Ph. D. Thesis of Seunghee Son and were presented in several meetings.

THE DEVELOPMENT OF SILICON DETECTORS FOR THE CMS EXPERIMENT AND FUTURE EXPERIMENTS, Seunghee Son, Ph.D. dissertation, Purdue University, December, 2005.

6.1 Vishnu Zutshi, NIU Scin.-based Tail-ctchr/Muon Trkr

Tile-Fiber Optimization: Prototype cells of various shapes, sizes, thicknesses, surface treatments and fiber groovings were machined and evaluated together with fibers of different shapes, dimensions and optical treatments to carry out comprehensive studies of cell processing, light response, response uniformity, efficiency, cross-talk, aging and radiation hardness. The results of these studies, demonstrating that small scintillating cells are appropriate for a finely-segmented hadron calorimeter have been published in refereed journals.

Photodetectors: We propose to use SiPMs/MRS devices as the photodetectors for the hadron calorimeter. During the course of our investigations we also studied other solid state photodetectors like APDs and VLPCs but found that the SiPMs are the most suitable for the finely-segmented calorimeter we have in mind. SiPMs are multi-pixel photo-diodes operating in the limited Geiger mode. During the course of our investigations into these photodetectors we studied their operating bias voltage, dark rate, linearity of response, temperature dependence, stability, radiation hardness and immunity to magnetic fields.
The results of our studies, showing that SiPMs/MRS are suitable for a scintillator hadron calorimeter have been published.

CALICE Test Beam: A silicon-tungsten electromagnetic calorimeter and a steel-scintillator hadron shower imager took beam at CERN and Fermilab in the 2006-2008 period. The hadron shower imager physically consists of two devices; a hadron calorimeter (HCAL) and a tail-catcher/muon tracker (TCMT). Both devices use SiPMs to read out scintillator with embedded WLS fiber. NIU was intimately involved with their design, optimization, construction, commissioning and operation and in fact had primary responsibility for one of them (TCMT).

The active layers of the HCAL prototype consist of 5 mm thick scintillator tiles sandwiched between 2 cm thick steel absorber plates. Each tile comes with its own 1mm diameter WLS fiber mated to a SiPM embedded in it. The tiles come in three

granularities: 3 cm x 3 cm, 6 cm x 6 cm and 12 cm x 12 cm. The granularity of the prototype has been optimized to achieve the physics goals within a reasonable budget. As the initial proponents of the finer granularity we were responsible for the instrumentation of two-thirds (i.e. 20 layers) of the inner core. A 1 mm thick co-axial cable runs from each photodetector to a charge integrating amplier channel. This single co-axial cable carries both the bias (on its shield) and signal (on its core). The cables are mounted on a G-10 plate which also has the reflective VM2000 glued to its inner, tile-facing side.
The active layers of the TCMT consist of 1m long, 5 cm wide and 5 mm thick extruded scintillator strips. A 1.2 mm outer diameter Kuraray WLS fiber is inserted into the coextruded holes that run along the length of the strips. The strips and their associated SiPMs in each layer, are enclosed in a light tight sheath or cassette. The top and bottom skins of the cassette are formed by 1 mm thick steel with Al bars providing the skeletal rigidity. The cassettes are inserted, alternately in the X and Y orientation, in a steel absorber stack which has a fine and coarse section. The upstream fine section consists of eight 2 cm thick steel plates while the coarse section is comprised of 10 cm thick steel absorber for a total of approximately six interaction lengths. Both the HCAL and TCMT use common electronics and DAQ boards developed by the CALICE collaboration as a whole.

Analysis of this data has successfully addressed the many goals of our R&D program namely technology demonstration, validation of hadronic shower models in Monte Carlo, particle flow algorithm development, muon reconstruction, energy leakage and reconstruction. Results of these analyses have been documented in numerous CALICE publications.

Papers based on research funded in part by LCDRD funding:
"Investigation of a Solid-State Photodetector", Beznosko et al, NIM A545:727-737, 2005.
"Effects of a Strong Magnetic Field on LED, Extruded Scintillator and MRS Photodiode",
Beznosko et al, NIM A553:438-447, 2005.
"Modular Design for Narrow Scintillating Cells with MRS Photodiodes in Strong Magnetic
Field for ILC Detector", D. Beznosko et al, NIM A564:178-184, 2006.
"Studies of Silicon Photodetectors for Scintillator-based Hadron Calorimetry at the ILC", D.
Chakraborty et al, NIM A567, 2006.
"Construction and Commissioning of the CALICE Analog Hadron Calorimeter Prototype",
CALICE Collaboration, JINST 5 (2010) P05004.
"Construction and Performance of a Silicon Photomultiplier/extruded scintillator Tailcatcher
and Muon Tracker, CALICE Collaboration, JINST 7 (2012

6.2 Uriel Nauenberg, Colorado Calorimetry R&D

We carried out a detail study to determine whether, by using the design of the BeamCal, we can observe the two photon process above the beamstrahlung background and whether we can observe the Stau decays from the Supersymmetric processes above the two photon process. The results carried out by Gleb Oleinik, Jack Gill and Connors are shown in the web at

http://hep-www.colorado.edu/~uriel/Beamstrahl_TwoPhoton-Process/grp_results.html

and the work by Alec Jenkins and Kevin Fiedler presented at

http://hep-www.colorado.edu/SUSY/grpwk_anal.html

where they show that after using the BeamCal to remove the two photon production of taus by using the signal in the BeamCal we can see the stau signal.

Both results were critical in determining the effectiveness of the BeamCal in allowing us the observe the Stau signal in the limit where the mass difference between the Stau and the Neutralino is small.

6.4 Usha Mallik, Iowas Particle Flow Studies

The University of Iowa group (Task A) was involved in the Particle Flow Algorithm (PFA) with the Silicon Detector (SiD) design, and successfully completed one in 2009 which was used for the Letter of Intent (LOI) to validate the SiD design. All of the benchmark physics processes for the LOI were obtained by using the Iowa-SID PFA. Mat Charles from Iowa primarily envisioned and executed the Iowa-SiD PFA. Ron Cassell from SLAC National Laboratory helped with the interface between the algorithm and the SID software.

Several talks were given at various International Collider meetings and workshops; here is a list of some of the write-ups.

1) The SiD LOI (arXiv:0911.0006), specifically the PFA appendix
2) A generic description is available in the ILC Reference Design Report on Detector (arXiv:0712.2356)
3) arXiv:0901.4670 (by M.J. Charles, from LCWS08)
4) arXiv:0901.4532 (by M.J. Charles, U. Mallik, T.J. Kim, from LCWS08)

6.5 Raymond Frey (Oregon)/Mani Tripathi(UC Davis) Si-W EM calorimeter

Development of a Silicon-tungsten Test Module for an Electromagnetic Calorimeter

The primary goal of this support was to design, develop, and procure the key components necessary to construct a test module which uses the technologies which would plausibly be used in a detector at a linear collider. This was successful. Oregon designed and procured the required silicon sensors. Davis developed the design for the flexcables and began the development of the interconnect technologies. In parallel, our collaborators at SLAC made progress in the design of the KPiX readout ASIC and the procurement of initial KPiX prototype test chips. Oregon spend considerable effort in bench testing these initial KPiX chips. The development of both the final KPiX chips and the bump-bonding interconnect technology continued past this period of support. But the test module is currently being constructed and we expect to test it in a beam at the refurbished SLAC End Station A facility in summer 2013.

Publications resulting from this support:

Most of the progress during this period was reported to the community in the form of conference and meeting presentations. However, the following publications represent a reasonable snapshot of the effort.

1. R. Frey, et al., "A Silicon-Tungsten Electromagnetic Calorimeter with Integrated Electronics," Proc. International Workshop on Linear Colliders, Paris, World Scientific, 2005.

2. D. Strom et al., "Fine grained silicon-tungsten calorimetry for a linear collider detector," IEEE Trans. Nucl. Sci. 52, 868 (2005).

3. J. E. Brau, M. Breidenbach, C. Baltay, R. E. Frey and D. M. Strom, "Silicon detectors at
the ILC," Nucl. Instrum. Meth. A 579, 567 (2007).

4. R. Frey et al., "A Silicon-Tungsten ECal with Integrated Electronics," In the Proceedings of
2007 International Linear Collider Workshop (LCWS07 and ILC07), Hamburg, Germany, 30 May - 3 Jun 2007, pp CAL16. [arXiv:0710.2373 [physics.ins-det]].

5. J. E. Brau et al., "An electromagnetic calorimeter for the silicon detector concept," Pramana 69, 1025 (2007).

6. D. Freytag, et al., "KPiX, an array of self triggered charge sensitive cells generating digital
time and amplitude information," Nuclear Science Symposium Conference Record, 2008. NSS
'08; IEEE, 3447. ISBN 978-1-4244-2714-7, DOI 10.1109/NSSMIC.2008.4775080.

6.6 Andy White, UT Arlington Digit. Had. Calorimetry w/ GEMs

The UTA High Energy Physics Group has been developing GEM DHCAL detector prototypes of sizes up to 30cm x 30cm. We have also been working with SLAC colleagues to use 13bit kPiX analog chips to read out the signal from GEM prototype detectors and to characterize the detectors and the chip in real detector environments. We have built several 30cm x 30cm prototype chambers and characterized them in the lab, using radioactive sources, cosmic rays and in particle beams. We constructed one 30cmx30cm chamber with the 13bit KPiX9 readout board with 64 active channels in the center and three chambers with DCAL boards that have center 16cmx16cm active area in the center. We expose these chambers to particle beams in August 2011 at Fermilab Beam Test Facility (FTBF). We took a total of 7 million events with 32GeV muon and pion as well as 120GeV protons. The data were taken to measure chamber responses, gains as a function of high voltage across each GEM foil, position dependence of the response and threshold dependences of efficiencies. In addition, we were able to take a 32GeV pion shower run with 8inch steel bricks causing the pions to shower in front of the detector array. This allowed us to complete characterization of these chambers. We are in the process of understanding the long term stability of the chambers both with 13 bit KPiX and 1 bit DCAL readout systems.

In addition, the UTA team has jointly developed 33cm x 100cm large GEM foils with CERN GDD to construct 33cm x 100cm unit chambers. We have received and qualified five 33cmx1m GEM foils and completed constructing a 12’x8’ class 10,000 clean room for construction. We have completed jig plates for large size detector components and have constructed two 33x100cm detectors ready to accept anode boards.

In a parallel activity with colleagues from the Weizmann Institute and Portugal, we have also been developing thick-GEM detectors which offer potential advantages in terms of handling and spark protection. We have tested small prototypes in test beam at CERN and have defined a future development program based on a promising configuration using a one-sided thick-GEM and a resistive layer between it and the anode/readout layer.

Publications:

1. J. Yu, E. Baldelomar, K. Park, **S. Park**, M. Sosebee, N. Tran, A. P. White, “Development of Large Area GEM Chambers,” Physics Procedia, 590 (2012).

2. J. Yu, E. Baldelomar, K. Park, **S. Park**, M. Sosebee, N. Tran, A. P. White, “Application of Large Scale GEM for Digital Hadron Calorimeter,” Physics Procedia, 394 (2012).

3. **Seongtae Park**, Edwin Baldelomar, Kwangjune Park, Mark Sosebee, Andy White, Jaehoon Yu, "Measurement Of Gas Electron Multiplier (GEM) Detector Characteristics", AIP Conferance Proceedings, 1336, 193, 2010.

4. Kwang June Park, Edwin Baldeloma, **Seongtae Park**, Andrew P. White and Jaehoon Yu, "Radiation Effect On Gas Electron Multiplier Detector Performance", AIP Conferance Proceedings, 1336, 677, 2010.

5. **S.T.Park**, J. Yu et al., “Development of Large Scale Gas Electron Multiplier

Chambers," IEEE NSS10, Knoxville, TN (2010).

6. J. Yu et al.,, "Development of GEM Based Digital Hadron Calorimeter," published in the proceedings of IEEE NSS08, Dresden, Germany (2008)

7. J, Yu et al., "Status of GEM Digital Hadron Calorimeter," Proceedings of International Linear Collider Workshop 2007, Hamberg, Germany, 567 – 572 (2007).

*A **University of Washington** team led by **Tianchi Zhao** has collaborated with UT Arlington on this work, and has the following report:*

A sensor development aimed at the digital hadron calorimeter based on gas electron multiplier (GEM) technology is led by Andy White (UT Arlington). Progress has been made on the development of a capability for construction of large GEM foils, with the required features of small anode pads with the required characteristics (signal sizes, efficiency, hit multiplicity, magnitude and frequency of crosstalk, rate capability) Following construction and operational experience with small GEM chambers, large-area GEM foils have been obtained, characterized, and made into GEM detectors. These double GEM chambers use jointly developed 30cm x 30cm 3M GEM foils. The chambers were exposed to radioactive sources and cosmic rays for their initial functionality and characteristics studies. In order for the chamber's characteristics and functionalities properly tested with sufficient statistics, the chambers have also been exposed to particle beam, and such beam tests continue.

Publications of U. Washington group

Bulk MicroMegas with Resistive Anode, Conference Record, IEEE Nuclear Science Symposium, Oct. 30, 2009, Orlando, Florida.

Micromegas prototypes with thermo-bond film separators, Chinese Physics C 2011 Vol.35(2): 163-168

Study of a bulk-Micromegas with a resistive anode, Chinese Physuics C, 2012 Vol.36(9): 851-854.

6.9 Dhiman Chakraborty, NIU Particle-Flow Alg.(PFA) Devel.

The main accomplishment by the NIU group that was achieved through support received from the LCDRD grant was the development of the calorimeter-based "directed tree" clustering algorithm. We attempted to identify and tackle the essential challenges and analyze the effects of several different approaches to the reconstruction of jet energies and the Z-boson mass. A number of possibilities were studied, such as analog versus digital energy measurements, hit-density-based clustering and the use of single or multiple thresholds. An independent survey found this PFA-based reconstruction to be

the best performer in identifying photons inside jets. As such, it was used as the default choice in PFA-based physics studies for the SiD concept development.
The NIU PFA was developed around the Directed Tree clustering algorithm. The procedure involved identifying a cluster of energy in the calorimeters as either charged, photon, neutral or fragment. Track matching was required for charged clusters, and a longitudinal H-matrix test was used to identify photon clusters. Once the clusters are identified, they are used as seeds to absorb neighboring fragments. This association is performed by taking into account the cluster shapes and directions first, then distances between fragments and primary clusters. By itself, this PFA achieved jet energy resolutions of $41\%/\sqrt{E}$, which was competitive with other contemporary PFA's produced by single groups. Picking the best-performing elements from those allowed one to improve the resolution by ~10%.

6.14 José Repond (ANL), Yasar Onel (Iowa) Had Cal w/ Digit. Readout (RPCs)

The DOE LCDRD grant enabled the development of Resistive Plate Chambers and an electronic readout system for use in a novel imaging hadron calorimeter. A small scale prototype calorimeter was built and was tested in the Fermilab test beam. The results were published in refereed journals. Based on the success of this small prototype the large Digital Hadron Calorimeter (DHCAL) prototype with close to 500,000 readout channels was designed and built.

Publications:

"Resistive Plate Chambers for Hadron Calorimetry: Tests with Analog Readout", G.Drake et al., Nucl. Instr. Meth. A578, 88 (2007).

"Calibration of a Digital Hadron Calorimeter with Muons", B.Bilki et al., 2008 JINST 3 P05001.

"Measurement of Positron Showers with a Digital Hadron Calorimeter", B.Bilki et al., 2009 JINST 4 P04006.

"Hadron Showers in a Digital Hadron Calorimeter", B.Bilki et al., 2009 JINST 4 P10008.

"Measurement of the Rate Capability of Resistive Plate Chambers", B.Bilki et al., 2009 JINST 4 P06003.

IOWA - DHCAL

We have contributed significantly to the design, construction and testing of the large Digital Hadron Calorimeter (DHCAL) prototype. We tested the prototype in Fermilab in several successful test beam campaigns and the results were presented in various international conferences. The results are now in final preparation for publication. The small-scale prototype data analysis were completed during this funding and the results are published in several journal articles. The funding was particularly important for the frequent travels between Iowa and Argonne/Fermilab which was crucial in the test beam operations and data analysis. The funding was also utilized in purchases of small electronics and computing resources. Overall, this funding was successfully turned into a unique calorimeter which enabled us to observe the hadronic showers with unprecedented spatial resolution. The project raises high reputation and interest among the high energy physics community.

1. B.Bilki et al., Response of the DHCAL to Hadrons and Positrons, RPC 2012, Feb 5-10 2012, Rome, Italy, PoS (RPC2012) 040, 2012.

2. B.Bilki et al., DHCAL Response to Positrons And Pions, TIPP 2011, June 9-14 2011,Chicago, Illinois, USA, Physics Procedia,37,317-324, 2012.

3. J.Repond et al., Tests of a Digital Hadron Calorimeter, CALOR 2010, May 10-14 2010, IHEP,Beijing, China, J. Phys.: Conf. Ser. 293 012075, 2011.

4. Q. Zhang et.al., Environmental dependence of the performance of resistive plate chambers, JINST 5 P02007, 2010.

5. B. Bilki et.al., Hadron showers in a digital hadron calorimeter, JINST 4 P10008, 2009.

6. B. Bilki et.al., Measurement of the rate capability of Resistive Plate Chambers, JINST 4 P06003, 2009.

7. B. Bilki et.al.,Measurement of positron showers with a digital hadron calorimeter, JINST 4 P04006, 2009.

8. B. Bilki et.al.,Calibration of a digital hadron calorimeter with muons, JINST 3 P05001, 2008.

9. G.Drake et al., Resistive Plate Chambers for hadron calorimetry: Tests with analog readout, Nucl. Instrum. Meth. A 578, 88, 2007.

10. CALICE analysis notes: CAN-030, CAN-031, CAN-032

6.18 John Hauptman, Iowa State 4th Concept Detector

The LCDRD funds for development of the Fourth Concept detector were essential for the development of this new concept in collider detectors, and the work so developed has found application in other detectors: ILD uses our dual-solenoid concept of 'end coils' to remove 1 meter of axial flux return iron, and the machine detector interface (MDI) design uses some of the developments of A. Mikhailichenko for beam stability at the interaction point. Experimental groups at both JLab and BNL have expressed interest in these ideas. These funds were expended on the following work:

- engineering studies of the dual solenoid, including forces and deformations of the supporting structures. This work was done and directed by Bob Wands, as detailed in the internal notes at http://www.4thconcept.org/appendixc.dwt

- support for undergraduate physics students working on the cluster-counting chamber and on several aspects of the calorimeter.

- travel support for members of the collaboration to attend ILC meetings.

- MDI studies by Mikhailichenko in appendix A of the LoI, detailed in the internal notes http://www.4thconcept.org/appendixa.dwt

- collateral and cooperative work on the dual-readout calorimeters (DREAM, now RD52, at CERN) are given also in appendix A, including relevant and related DREAM papers and publications at http://www.4thconcept.org/appendixa.dwt

We received substantial in-kind support from INFN, Lecce, directly by F. Grancagnolo, in-kind support from LNS, Cornell University, for the work of A. Mikhailichenko, in-kind support from KEK on dual solenoids for the work of Wake, and in-kind support from Iowa State University through the RIF account of J. Hauptman. The results of this funding are summarized and organized in the 4th Letter of Intent (http://www.4thconcept.org/4LoI.pdf) and in the technical engineering and scientific papers listed in the appendices. Most ideas are already tested in beams and experiments (dual-readout/DREAM and cluster-counting/KLOE). The Fourth concept detector contains about 20 new ideas in particle identification, high precision momentum and energy particle measurements, MDI and beam stability, and a novel magnetic field configuration. Fourth is not yet a complete detector, but the final path to complete design of a buildable detector is not far.

publications

"Muon identification and pion rejection in the 4th Concept", *Pramana Jour. Physics*, **69** December 2007, p. 1047-50.

"The 4th Concept Detector", {\it Pramana Jour. Physics}, **69** December 2007, p.1037-46.

"Particle Identification in 4th," *Proc. Linear Collider Workshop*, LCWS08, Chicago, IL, Nov. 2008.

"Dual-readout, Particle Identification, and 4th," *Proc. Technology in Particle Physics*, TIPP09, *Nucl. Instr. Meths.* **A623** (2010) 237.

"The 4th Concept Detector for the International Linear Collider," Lepton-Photon Conference, Daegu, Korea, 13-18 August 2007, arXiv:0708.0142v2 [hep-ex] 6 Aug 2007.

"Measurement of the Contributions of Neutrons to Hadron Calorimeter Signals", N. Akchurin, *et al.*, *Nucl. Instru. Meths.* **A 581** (2007) 643-650.

"Neutron Signals for Dual-Readout Calorimetry", *Nucl. Instr. and Meth.* **A598** (2009) 422-431.

"Dual-readout Calorimetry with a Full Size Electromagnetic Section," *Nucl. Instr. and Meth.* **A610** (2009) 488-501.

"The Evolution of Lepton Colliders Detectors," 8th International Conference on Nuclear Physics at Storage Rings-Stori11, October 9-14, 2011, Laboratori Nazionali di Frascati, Italy; *Proceedings of Science*.

6.19 A.J.S. Smith, Princeton Calorimeter and Muon ID

Aging Study for the RPC used in SiD Hcal and Muon system

Collaborators:
New material development, Jiawen Zhang, IHEP, Beijing, China,
Mingfa Su, Xianhu, Inc. Beijing (Beijing Kadesh Boild Materials Co. Ltd), China

In this project aging phenomena were investigated for BESIII-type ("Bakelite") resistive plate chambers (RPCs), which effects important for RPCs operated in high-rate environments. It was confirmed that in chambers operated with a Freon gas as a quenching agent, the formation of HF (hydrofluoric acid) as a byproduct of ionizing radiation is the main source of the aging. The effects of the HF on the Bakelite surface are not localized to the point of production, but occur wherever the HF molecules are transported by the chamber gas flow; consequently the aging can be more pronounced near the gas outlet of the chambers. The surface damage by HF can be mitigated by various surface treatments, including the classic linseed oil coating. A search for oil-free surfaces with comparable resistance to aging did not produce definitive results, but remains a topic for future R&D. Freonless gas mixtures were explored, and result in lower aging, but also in poorer detector performance; this approach also remains a topic for further R&D.

C. Lu, RPC electrode material study, NIM A602, 761 (2009)
C. Lu et al., Aging study for the BESIII-type RPC, NIM A661, S229 (2012)

C. Lu et al., Microscope Study of BESIII-type RPC Aging Phenomena, (Sept. 8, 2010), http://puhep1.princeton.edu/~mcdonald/ILC/MicroscopeStudyOfAging.pdf

6.20 Tianchi Zhao, Washington Scint/Cheren Rad Plates Cal w/ SiPMs

I received a DOE LCDRD grant for developing crystal calorimeter for ILC. For the TASK 6.20, I worked together with A. Para and his group at FNAL and we developed a concept of total absorption calorimeter using dense crystal materials. I also formed collaboration with a group at Ningbo University in China to develop dense scintillating glasses that would be suitable to implement this concept. A number of samples with different formulation were developed. This effort is still continuing with funding from Chinese National Science Foundation.

Related conference talks and papers

A study of a new Concept of Compensating Calorimeter, Conference Record, IEEE Nuclear Science Symposium, Oct. 31, 2006, San Diego.

Active Absorber Calorimeter, Invited talk, Linear Collider Workshop March 11, 2006, Bangalore, India.

A study of a new concept of compensating calorimeter, The 9th ACFA ILC Physics & Detector Workshop & ILC GDE Meeting, Feb. 04, 2007, Beijing, China.

Heavy Scintillating Glasses for Future, High Energy Particle Physics Experiments, CIAW07, Nov. 5, 2007, Beijing, China.

Development of Gd2O3 Based Dense Scintillating Glass, Conference Record, IEEE Nuclear Science Symposium, Oct. 30, 2009, Orlando, Florida.

Study of Dense Scintillating Glasses, Zhang Yuepin and T. Zhao, 14th International Conference on Calorimetry in High Energy Physics, May 2010, Beijing, China.

Scintillating properties of Ce3+-doped high density oxide glasses, Chinese Physics 2012, Vol. 61 Issue (19): 192901.

6.21 Satish Dhawan, Yale Modular DAQ Development

Powering of LC Detector Front End Electronics

Under this R&D, we have developed a buck converter (a DC-DC transformer) using a 2D (planar) air core (non-magnetic) inductor buried in a 4 layer PCB. The inductor is used to store energy from the high input voltage for a short time and discharge at a lower voltage (and over a longer time). This DC-DC converter has no magnetic material and is suitable for operation in high magnetic fields (that would saturate iron or ferrite cored inductors).

This development uses PCB (printed circuit board) spiral patterns on all 4 layers. The inner two are connected in series to form the inductor and the outer two are grounded and become an electro static shield. Silicon strip detectors collect the charge deposited in the silicon by ionizing particles. One end of the inductor in a buck converter is alternately tied to the input voltage (e.g. 12V) and ground at several MHz. This can inject substantial charge into the Silicon strip if not shielded, and can be a noise source that can interfere with particle detection.

In addition to the electrostatic coupling, there is a magnetic field from the inductor at the buck frequency (1 to 20 MHz). We are continuing to develop various buck converter designs and PCB patterns that will reduce both electrostatic and magnetic fields without causing excessive eddy current losses. Converters using an inductor consisting of traces on a PC board can be quite small (a few square cm) and very low mass while still providing 5 A of output current at low voltage.

Future detector systems will be using small feature size (<130 nm) chips to achieve small size and high-speed operation. These will require 1 V or less at very high current. For these systems a two-stage converter is a promising option. The power will be brought inside the detector to near the front end chips at 48 V. The first stage will convert this to 5-10 V and distribute it to a second DC- DC converter next to the chips that will produce the final low voltage and high current. There are many design trade-offs to be studied and optimized to produce a practical 2-stage power delivery system.

Publications

[1] Why DC-DC Converters for High Energy Physics?
PowerSoC2012: The 3rd International Workshop on Power Supply on Chip, San Francisco, CA
Poster: http://shaktipower.sites.yale.edu/sites/default/files/PowerSoC2012 _Poster.pdf

[2] Why stay stuck with the Good old 20th Century methods?. S. Dhawan and R. Sumner, TIPP (Technology and Instrumentation in 2011 Conference 9-14 June, 2011 Chicago, Il. Physics Procedia 37 (2012) pages 181–189 (PDF)

[3] Commercial Buck Converters and Custom Coil Development for the Atlas Inner Detector Upgrade, S. Dhawan, O. Baker, R. Khanna, J. Kierstead, D. Lynn, C. Musso, S. Rescia, H. Smith, P. Tipton and M. Weber, ", IEEE Trans. Nucl. Sci., vol, vol. 57, no. 2, pp 456-462 April 2010

[4] . Design considerations for high step-down ratio buck regulators. Ramesh Khanna, Satish Dhawan, Proceedings of the 2008 Topical Workshop on Electronics for Particle Physics, Naxos, Greece

7.5 Robert Wilson, Colorado State Geiger-Mode APDs for Muon Sys.

Continuing Studies of Geiger-Mode Avalanche Photodiodes for Linear Collider Detector Muon System Readout

The goal of this project was to investigate the feasibility to use the new (then) generation of solid-state photodetectors, Geiger-mode Avalanche Photodiodes (GPD) for readout of a scintillator-based muon or calorimeter systems for a Linear Collider detector (LCD). In the conceptual design for these systems large area scintillator planes or strips are readout through embedded plastic fibers doped with a wavelength-shifter (WLS). A component of the project was to work with a small US company aPeak Inc., to produce devices that were more closely matched to the requirements of an LCD. At the time (mid-2000's), aPeak was the only domestic concern involved in such developments. With a combination of Small Business Innovative Research award sub-contract to the CSU group and LCD Research (LCDR) funding we successfully characterized single-pixel and multi-pixel devices over a modest range of temperatures using piezoelectric cooling. The positive results of that work encouraged aPeak to produce a device to our specification capable of reading out 64 1-mm diameter fibers on a chip 1 cm on a side. Each pixel (fiber readout) consisted of sixteen 160x160 micron-square GPDs, that produce a single output with a signal proportional to the number of sub-pixels activated by photons incident on the surface. We demonstrated single photon resolution and proportionate response with cosmic ray source and pulse 550-nm light. An outcome of this initial work was for the CSU group to be invited to participate in the scintillator-based pi-zero detector (P0D) for the T2K neutrino experiment. This detector had many characteristics that overlap with development needed for LCD systems. Supported in part by LCDR funds, we performed a beam test at Fermilab of three candidates devices mounted on MINERvA-style triangular scintillator with 1-mm diameter WLS fibers threaded down the center. The devices were: GPD from aPeak, MRS from Russian supplier CPTA, and the MPPC from Hamamatsu Photonics (HPK). The MPPC was clearly the best performer, and unfortunately, the aPeak was not competitive (it was never developed beyond the first phase due to lack of funding). MPPC was selected by T2K and has now become a worldwide standard (CSU did QA performance measurements on over 10,000 devices). Also partially funded by LCDR funds, the CSU group developed an apparatus to measure the response of individual 50 micron-square sub pixels by scanning a few-micron diameter photon beam across. This allowed detailed understanding of relative quantum efficiency across the pixels and crosstalk between pixels. The work supported by LCDR has been presented in ILC-US meetings, the International Workshop on Photon Detector (Japan, 2007), in the "Industrial Applications of Physics" session of the annual APS Four-Corners section meeting in 2009 and the "Applied Physics" session of the 2010 meeting, and Advance in Neutrino Technology (Santa Fe, 2010).

Coordination

All the efforts have been conducted within the context of a global linear collider detector R&D program, in some cases in direct collaboration with activities abroad, and in all cases informed and guided by the broader world-wide program.

The projects were also very well coordinated with R&D efforts at the laboratories. In many cases, there is direct collaboration. As a result, this support is well leveraged into the laboratory detector R&D programs.

Conclusion

This multi-year R&D program resulted in significant developments in detector R&D, primarily designed to address the requirements of the ILC, but also applicable in many other areas of research, both within high energy physics and in other fields.

The R&D contributed significantly to the ILC Technical Design Report that is being published in 2013.