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SiD Linear Collider Detector R&D Continuation Progress Report

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This report presents an evaluation of the progress made by the SiD university detector R&D projects, a proposal for suggested funding in the coming years and a summary of milestones for the next two years.

SiD has been designed to address fundamental questions of particle physics:

- What is the mechanism responsible for electroweak symmetry breaking and the generation of mass?
- How do the forces unify?
- Does the structure of space-time at small distances show evidence for extra dimensions?
- What are the connections between the fundamental particles and forces and cosmology?

SiD will address these questions at the next generation linear collider, the International Linear Collider, through precision measurements, such as Higgs boson properties, gauge boson scattering, effects resulting from the existence of extra dimensions, properties of supersymmetric particles, and top quark properties. Silicon detectors are used extensively in SiD and are well-matched to the challenges presented by ILC physics and the ILC machine environment. They are fast, robust against machine-induced background, and capable of very fine segmentation. SiD is based on silicon tracking and silicon-tungsten sampling calorimetry, complemented by powerful pixel vertex detection, and outer hadronic calorimetry and muon detection. Radiation hard forward detectors which can be read out pulse by pulse are required. Advanced calorimetry based on a particle flow algorithm (PFA) provides excellent jet energy resolution. The 5 Tesla solenoid is outside the calorimeter to improve energy resolution. PFA calorimetry requires fine granularity for both electromagnetic and hadronic calorimeters, leading naturally to finely segmented silicon-tungsten electromagnetic calorimetry. Since silicon-tungsten calorimetry is expensive, the detector architecture is compact. Precise tracking is achieved with the large magnetic field and high precision silicon microstrips. An ancillary benefit of the large magnetic field is better control of the e^+e^- pair backgrounds, permitting a smaller radius beampipe and improved impact parameter resolution.

The SiD R&D program aims to establish the new capabilities needed to enable the realization of this innovative detector concept. The SiD design and plan was validated by the International Detector Advisory Group (IDAG) in 2009, launching a phase of detector development that will lead to a Detailed Baseline Design (DBD) report by late 2012. Many of the technologies needed to enable this powerful detector do not yet exist. R&D over the next three years is essential to establish them. The projects are conducted by university groups in collaboration with US HEP laboratories and overseas institutions, all working toward realization of these advanced capabilities.

The set of projects includes two related to vertex detector sensor development (4.1 and 4.6), four contributing to the tracker work (5.8, 5.10, 5.22, and 5.23) and five calorimeter projects, four hardware (6.5, 6.6, 6.9, and 6.27) and two on particle flow algorithms (6.4 and 6.25). Nine of these projects were funded in year one, and this report requests a reallocation of funding to include all twelve. Direct collaboration with national laboratories is indicated just below the title of each project.

Chronopixel – Oregon/Yale (Project 4.1)

This project aims to develop a vertex sensor meeting the requirements of the ILC, with single bunch crossing time stamping. This is achieved in monolithic CMOS. A first prototype, based on 180 nm technology, has been produced, containing 80 rows and columns of pixels. Each pixel is 50x50 μm^2. To achieve high registration efficiency, a low threshold is required, placing tight demands on the pixel comparator. Each pixel contains a separate calibrator circuit, which records individual comparator offsets during a special calibration process and later subtracts this value from the common threshold. The prototype has been tested, including with a light flash and an Fe^{55} source. Comparison of the measured parameters to the design specifications/goals has been completed. The only parameter significantly outside specification is the comparator offset spread. The ultimate goal is pixel size 12.5x12.5 μm^2, which will require 45 nm feature size. Some layout mistakes were found during the tests, including the use of very thin traces for all power supplies to individual pixels. That led to unacceptable voltage drops at the majority of pixel locations and consequently operation failure of a large portion of the device. The overall design principle is working and it is expected that, in a 45nm process, the ILC design specifications can be met. Funding at the same level is recommended.

3D Sensor Simulation – Cornell (Project 4.6)

(Fermilab)

The goal of the 3D sensor simulation studies is to model the process of charge collection as a function of pixel spacing, doping profiles, pinning layers to optimize existing designs, to compare the studies with test data of real devices, and to guide the design of future devices. The modeling of the 3D pixel detector technology is intended to be matched to the Fermilab schedule of design and prototype submission for 3D devices. The work done so far includes modeling of a 3D pixel device using commercial 3D Silvaco software tools. The bulk of the work is expected to be completed over the summer of this year by a summer student. The plan for the next years is to iterate on the design and production cycle with actual devices built by Fermilab. It is recommended that this effort be supported at the same level for the following years.

Alignment – University of Michigan (Project 5.8)

(SLAC)

The frequency scanned laser interferometry alignment project remains a high priority for SiD, and has significant generic impacts. ILC detectors will operate in a push-pull arrangement and precise realignment after movement is essential to achieve the required physics performance. The frequency scanned laser interferometry was not funded in the first year. The first year budgets of other projects included some major equipment purchases, notably the equipment needed for the m^3 DHCAL RPC tests. The projects are commended for delivering within budget and on time. Since these were one-time large deliverables, there is now more overall flexibility in the allocation of funding. It is recommended that the laser frequency interferometry get funded at a level half the original request.

Silicon Development - UC Santa Cruz (Project 5.10)

(SLAC)

The effort at SCIPP, UCSC, has focused on many aspects of the development of a silicon microstrip tracker for SiD. The LSTFE readout ASIC has reached a relatively advanced stage of development. After confirming the basic functionality of the chip it was discovered that the chip took much longer than the expected 1 ms to achieve its quiescent operating levels after receiving a power-on signal. This was traced to a failure of a relatively 'standard analog memory cell' block used to retain operating levels in the power-off state. Test structures to allow further understanding of the memory-cell failure mode have been designed and submitted parasitically within an unrelated fabrication run. It is expected to have a full characterization of the ASIC, as well as progress on understanding the analog memory-cell failure, by the end of the calendar year.

The majority of the funding was designated to the development of testing of the KPiX/Double-Metal implementation of the silicon sensors, and exploration of radiation-hardness properties of several candidate silicon sensor alternatives for far-forward calorimetry (BeamCal). The group is ramping up contributions to the international BeamCal effort. The group has studied results on radiation hardness of various detector materials and is familiarizing itself with the NIEL (non-ionizing energy-loss) framework. The group is also working closely with SLAC collaborators to begin to establish an explicit plan to test conventional float-zone and Czochralski sensors, and possible sensors formed with epitaxial-deposited active zones. This work is generic to any implementation of a high-energy linear collider, as well as to numerous other potential high-radiation applications of segmented silicon sensors.

The group has also been active in testing the KPiX/Double-Metal tracking baseline design for the SiD detector. The primary concern is cross-talk between the digital functions of the KPiX and its analog inputs, conducted through the upper-metal traces on which the KPiX will be mounted. Of particular concern is the clock signal, which will need to remain active during the power-on, data-accumulation phase. Characterization of the sensors and tests on the unloaded KPiX chip have been carried out. A particular point of focus is channel-to-channel variations, which might be large for the low-gain KPiX.

The group has been active in two areas of simulation studies. A study of curvature resolution shows that there is room for further improvement in the fitting algorithm. The second study involved a simulation study of stau events, for which the staus have a mean decay length of approximately 20 cm. The efficiency of the track reconstruction for such a signal is being studied.

A study of readout noise vs. load was carried out using an old CDF sensor to mimic long strips. Measurement as a function of ladder length for lengths of up to 125 cm, which are expected to be dominated by the series resistance contribution for lengths over 50 cm, were found to be smaller than expected, suggesting that network effects may come into play.

The exploration of the use of charge division to derive longitudinal information from silicon microstrip sensors has been mimicked using a printed circuit board due to a mistake in sensor processing. This work should be completed by the end of next winter, and submitted for publication by summer, 2011. The UCSC group also has a laudable track record of engaging many graduate and undergraduate students in their efforts.

The recommendation is that this effort be supported at the same level for the following years. Work on the LSTFE chip has reached a point where it could be closed-out and priority could be shifted towards the characterization of the SiD baseline tracking electronics with the KPix readout chip and sensors for high radiation environment.

DC-DC Conversion – Yale (Project 5.22)

This project addresses the fundamental aspect of increasing the efficiency of power delivery for future experiments without adding to the material budget. A study is being carried out for the powering of the front-end of the vertex detector readout, focusing on commercially available air core conductors and transformers, working towards an input-output voltage ratio more than ten, with a conversion efficiency exceeding 85%. DC-DC converter plug-in cards with air coils have been developed and tested. Two different commercial chips are used: one is monolithic while the other is a 3-die multi chip module (MCM). Tests have shown that the converter chips are not radiation resistant. The studies have led to studying technologies for radiation resistant devices. The focus has been on commercial devices as there is very little power device ASIC design capability available in the US HEP community. The future research program will address radiation hardness and will explore the use of Gallium Nitride devices, which offer high frequency and very high radiation resistance, as some of the transistor structures do not use oxide insulator. The plan also calls for load tests with the kPiX chip with power pulsing. The topic under study is extremely important for the next generation of experiments and the study of commercial devices is very appropriate. It is recommended that this effort be supported at the same level for the subsequent years.

Sensors and Connects – University of New Mexico (Project 5.23)

(Fermilab)

To achieve the tight requirements on material budget, the silicon tracker of the SiD detector employs a hybrid-less sensor design. Traces are routed to bump-bonded KPiX chips through a double-metal layer. Signal and control lines run from the KPiX chip to a flex cable, which carries the signals outside of the tracking volume. Although this design has been proposed by the SiD detector, its crucial features are very generic. A viable silicon-based low-mass tracker design could benefit a large array of future experiments. Full characterization of the noise performance of this unique design is required to verify its feasibility. Full readout will be established on the bench and the performance characterized. The sensors will then be tested in beam tests including power pulsing in a strong magnetic field. This project will address these issues, which are at the heart of the low-mass tracker design. Due to the flexibility created in the funding allocation because of the phase-out of one-time non-recurring charges, it is recommended that the University of New Mexico be funded and proceed with the tests described above.

Silicon-tungsten EM calorimetry – Oregon/UCDavis (Project 6.5)

(SLAC, BNL)

The goal of this project is to produce a test module using the same technology that would be employed in a collider detector. The silicon sensors for the test module have been received at Oregon from Hamamatsu, SLAC is testing a 512-channel version of the KPiX readout chip (with the final 1024-channel version planned for late 2010), and Davis is developing the necessary interconnects: KPiX to sensor bonding, and the flex cables. Davis is carrying out critical work on gold-stud bonding for prototype detectors with promising results. Davis is also working with a new material for flex cable-pad connections with promising results for the resistance of connections.

Oregon is continuing the evaluation of the KPiX chip, with the goal of bonding a 512-channel version to a sensor this Spring.

The overall target is assembly of the module in 2010 and testing in a beam (possibly the new electron beam at SLAC) in 2011.

Both universities in this project are carrying out essential R&D and should continue to be supported at the present level.

GEM-based Digital hadron calorimetry - UT Arlington (Project 6.6)
(SLAC)

To develop digital hadron calorimetry, UTA has constructed and tested several 30cm x 30cm double-GEM chambers with anode layers divided into 1cm x 1cm pads. Readout is via the SLAC KPiX chip (64-channel version used so far). Successful operation of these chambers has been demonstrated with Fe-55 and Ru-106 sources, and with cosmic rays. A gain of O(6000) has been obtained with an Argon-CO2 80:20 gas mixture, giving a mean MIP signal of 20fC. Beam tests of these chambers are planned in 2010. The next major goal is the construction of several 1m x 1m layers of GEM-DHCAL to be tested in the CALICE absorber stack together with RPC-DHCAL planes. To this end 1m x 33cm foils have been developed for UTA by CERN and an initial order has been placed for five of these foils. Prototype 1m x 33cm chambers will be built and tested as a precursor to assembling 1m x 1m planes (each consisting of three 1m x 33cm chambers).

This project provides an essential alternative to RPC-based digital hadron calorimetry. In addition, this project depends critically on the services of Dr. Seongtae Park who has been responsible for most of the prototype assembly and testing. We recommend support to continue the work of year one, and an increase to add partial support for Dr. Park.

RPC studies – Princeton (Project 6.19)

This work was motivated by the need to study aging effects in RPC's built from a new type of Bakelite developed by the BES-III Muon group of IHEP(Beijing) and a company , Gaonengkedi Inc. (Beijing) for use in the BES-III and Daya Bay muon systems. Aging effects have been found that must be understood and resolved before this technology can be used, for instance, in the SiD muon system.

These studies would be enhanced if they were extended to the study of aging effects in glass RPC's – relevant to the RPC DHCAL project for instance.

Now that the microscope to study RPC damage has been purchased, we recommend that the remainder of the budget stay the same as for the first year.

RPC-based Digital hadron calorimetry – Boston/Iowa (Project 6.27)
(ANL)

The essential task for the next year is the construction of the 1m^3 Physics Prototype, consisting of 40 layers of 1m^2 RPC digital hadron calorimeter planes. Nearly all the material has been acquired and following a development program, all the assembly steps have been defined. The chamber assembly work is occurring at ANL, while the University of Iowa is providing the gas mixing/distribution system and the HV system, and Boston U. is providing the Data Collector boards (DCOL).

U. Iowa: the gas mixing system, which provides gas flow for the whole $1m^3$ stack has been designed, assembled, and tested. The gas distribution system from the earlier Vertical Slice Test prototype module will be used to test the individual chambers that comprise the $1m^3$ stack. A new system, now assembled, will provide mixed gas to the completed RPC cassettes. This work was scheduled to be completed by April 2010. The HV system, which provides 120 channels, has been developed and commissioned with a new control system. This completes the hardware contributions from Iowa to the $1m^3$ stack. While design studies will continue, further hardware developments of gas and HV systems are not in line with SiD priorities for the DBD.

Boston U.: 30 DCOL have been produced and successfully tested. 20 DCOL boards are needed for the $1m^3$ stack – the others for spares and test stands. This completes the Boston hardware contributions to the $1m^3$ stack.

Continued support is recommended to enable completion of the $1m^3$ stack and subsequent testing.

SiD Particle Flow Algorithm Development – Iowa/MIT (Projects 6.4 & 6.25)
(SLAC)

The U. Iowa group (with two members based at CERN), has been working to improve the performance of the SiD/Iowa Particle Flow Algorithm. MIT (as yet unfunded) is contributing to the detector optimization work using the existing PFA and plans to also work on algorithm development. SLAC is contributing many basic studies to support algorithm development and is working on a new version of the SiD geometry with more realistic subsystem configurations.

PFA development follows three lines at present:

1) Reduction of confusion by incorrect assignment of hits, with a focus on the use of a cone algorithm in early and later stages of the PFA. A correlation matrix between cone algorithm parameters is being used to search for variables that have discriminating power – such as the distance of closest approach between a cluster and the seed.

2) A study of outlier events that contribute to the tails of the energy resolution. This involves a detailed study of individual events while trying to identify trends in those events that contribute to poor resolution.

3) A study of leakage through the back of the calorimeter system at 500 GeV and 1 TeV. This study uses hits in the muon system as an indicator and measure of possible energy loss through leakage, and attempts to separate leakage from confusion. The study also includes an investigation of alternative HCal absorbers such as copper replacing steel.

The SiD PFA development is critical and should be supported, with expanded resources if at all possible. SiD has not derived any effective benefit from the NSF funding supplied to U. Kansas for support of U.S. PFA development. We strongly recommend that some of this support be awarded to MIT, which is being very productive in optimization studies using the SiD/Iowa PFA.

Table of recommended funding for year two.
$895,000 from DOE and $60,000 from NSF.

Project number	Project	University	Year 1 Funding (DOE/NSF)	Recommended Yr. 2 Funding -DOE	Recommended Yr. 2 Funding -NSF
4.1	Chronopixel	Yale Oregon	103,000 64,500	$ 103,000 59,500	
4.6	Sensor Simulation	Cornell	27,500		$ 27,500
5.8	Alignment	Michigan	0	45,000	
5.10	Silicon Sensors	UC Santa Cruz	97,500	92,500	
5.22	DC-DC Power	Yale	47,500	47,500	
5.23	Sensors/Connect	New Mexico	0	27,500	
6.4	Particle Flow Alg	Iowa	127,500	127,500	
6.5	Silicon-tungsten EM Calorimetry	Oregon UC Davis	50,000 72,500	54,400 68,100	
6.6	GEM Hadron Cal	UT Arlington	47,500	77,500	
6.19	RPC	Princeton	37,500	25,000	
6.25	Particle Flow Alg	MIT	0		27,500
6.27	RPC Hadron Cal	Iowa Boston	133,600 61,400	95,000 15,000	
	Admin	Oregon	30,000	30,000	
	F&A on subs	Oregon	25,000	27,500	5,000
	TOTAL		925,000	895,000	60,000

Appendix: Milestones

Milestones		
Project 4.1	2010	Finish testing of Chronopixel 1. Write report on results of Chronopixel 1 test. Design Chronopixel 2 with improvements. Initiate submission process for fabrication of Chronopixel 2.
	2011	Fabricate Chronopixel 2. Complete Tests of Chronopixel 2. Write report on results of Chronopixel 2 test. Design Chronopixel 3 with hi-res epi. Initiate submission process for fabrication of Chronopixel 3.
	2012	Fabricate Chronopixel 3. Complete Tests of Chronopixel 3. Write report on results of Chronopixel 3 tests.
Project 4.6	2010	First simulation results for the sensors from Fermilab.
	2011	Few iterations on those simulations, working closely with Fermilab.
	2012	Compare device and simulation results and contribute to testing.
Project 5.8	2010	-- not funded --
	2011	Design and begin prototyping elements of multi-interferometer, dual-laser demonstration FSI system to address remaining critical technology and methodology issues. Develop conceptual design and layout of system.
	2012	Complete specification and initial demonstration studies of a multi-interferometer, dual-laser demonstration FSI system. Prepare technical report.
Project 5.10	2010	Evaluation of channel-to-channel variations in KPIX-9. Exploration of attachment of KPIX-7 to prototype sensor using cutting laser to mitigate shorts from over-glass failure. Initial characterization of LSTFE-II chip. Estimation of longitudinal resolution from resistive charge division. Measurement of readout noise in the series-resistance limit, including both end- and center-readout. Simulation studies supporting the design of a high-fluence electromagnetic radiation damage study of various silicon sensors. Acquisition and characterization of sensor samples to be used in damage studies. Simulation studies of SiD tracking efficiency performance in forward region.
	2011	Characterization of 'analog memory' test structures and assessment of

		suitability for implementation of power-cycling for LSTFE. Assessment of effects of digital/analog interference effect in KPIX/double-metal assembly. PSpice simulation of series-noise readout limit and comparison with observation. Publication of charge-division results. Test-beam study of radiation damage to various silicon sensor types. Simulation studies of SiD momentum reconstruction performance in forward region.
	2012	Re-optimization (for forward region) and fabrication of LSTFE ASIC. Follow-up test-beam run to confirm radiation hardness of selected Si sensor. Determination of radial extent of sensitivity for reconstruction kinks fro stau decay in the SiD detector. KPiX/double-metal yield and reliability studies.
Project 5.22	2010	DC-DC Converter with embedded air coil (Vin = 16V, Vout = 2.5V). Pulse power from power supply side. Prototype GaN HEMT FETs for high radiation & High voltage converter. Understanding thin oxide CMOS for radiation hardness. Evaluate LDMOS Thin Gate oxide (~ 5 nm) devices Track commercial Thin Gate oxide DC-DC Converters. Radiate 11.8 nm National semiconductor Corp. converter with Gammas. Radiate 7.0 nm gate oxide XySemi FET with Gammas & Protons.
	2011	Low mass air core coils for > 10 MHz operation. Pulse load with 1 Ω power wires – Twisted pair; limit overshoot. Drive 42.5 V to deliver 2.5 V @10 amp load. Remote sense to keep voltage variation across kPix to <5%. GaN Converters 48 Vin to 1 Vout, study radiation effects.
	2012	Develop 48 to 2.5 V converter with low mass air core coils. GaN HEMT FETs for higher power & Higher voltage ratios. Report on commercial thin Gate oxide LDMOS Converters. Irradiate candidates. Identify commercial DC-DC Converters for various radiation levels and magnetic fields. Goal is power delivery efficiency improvement by x2. Reduce power supply current by > x8.
Project 5.23	2010	-- not funded --
	2011	Test present version of the cable. Iterate cable once if necessary. Design extension cable. Fabricate extension cable. Test extension cable. Iterate extension cable once if necessary.
	2012	Design adaptor board. Fabricate adaptor board. Test adaptor board.

		Iterate adaptor board once if necessary. Compare device and simulation results and contribute to testing.
Project 6.4	2010	Improved algorithm, based on sharing cluster hits between tracks.
	2011	Reorganize PFA code to incorporate the improvements. Verify code at 1 TeV. Fix outlier events where mistakes in pathological cases have been identified and corrected. Evaluate switch from SiD2 to SiD3 geometry and establish the resolution obtained with the SiD2 software.
	2012	Perfect the PFA, taking care of specific categories of events which add confusion. Build into code more sophistication and flexibility. Improve speed of algorithm. Test code on physics benchmarks.
Project 6.5	2010	Finish evaluation of gold-thermocompression for KPiX attachment to sensor wafer. Finish characterization of sensor mechanical properties for bump bonding. Evaluate KPiX-v9 (512 chan) for noise under load. Evaluate electro-less Ni-Au and solder attachment of KPiX to sensor wafer. Evaluate attachment of flex-cable to dummy sensor wafers using solder-ball technique.
	2011	Make technology choices for sensor to KPiX and sensor to flex-cable attachments. Commission 32-channel probe card for testing KPiX. Fabricate flex-cables for version 2 sensors. Evaluate 1024 channel KPiX (KPiX-1024) for noise under load. Complete first fully loaded sensor assembly (with KPiX-1024 and flex-cable attached using chosen interconnect technologies). Bench test first assemblies.
	2012	Construct 30+ loaded sensor assemblies (i.e. 30+ readout layers). Develop data buss for 30 assemblies. Construct a 30-layer sensor-tungsten stack. Test in beam.
Project 6.6	2010	Production, delivery and quality test of the first five 33cmx100cm GEM foils. Data analysis of 30cmx30cm GEM prototype chamber read out with DCAL chip. MiP characteristics of 30cmx30cm GEM prototype chamber read out with KPiX chip. Construction and bench test of three 30cmx30cm GEM prototype chambers. Completion of GEM detector response tests after irradiation. Delivery of 10 additional 33cm x100cm GEM foils

	2011	Delivery of remaining twenty 33cmx100cm GEM foils (depends on the funding). Beam test and analysis of three 30cmx30cm GEM chambers with KPiX and DCAL read out. Development of 50cmx33cm KPiX anode board together with SLAC team. Set up DCAL DAQ system at UTA. Completion of mechanical design and construction of a 33cmx100cm prototype chamber. Bench test of a 33cmx100cm prototype chamber w/ KPiX board. Begin construction of remaining 33cmx100cm unit chambers with DCAL boards. Beam test and characterization of the first 33cmx100cm GEM prototype unit chamber using KPIX.
	2012	Design and integration of the first 100cmx100cm DCAL plane. Beam test of the first 100cmx100cm DCAL plane. Complete construction of remaining four 100cmx100cm planes using DCAL readout. Beam test of five 100cmx100cm planes in the CALICE stack together with RPCs. Begin data analysis for GEM performances in a digital calorimeter.
Project 6.19	2010	Perform aging tests on 5 new RPC prototypes made of a new variant of BESIII Bakelite sheet – oil embedded Bakelite – with the total aging dose surpassing previous aging test. Characterize this new material.
	2011	Conduct a new round of aging tests to characterize material based on insulation type Bakelite, which uses a different resin from past RPCs. In parallel further study the oil embedded Bakelite to improve its surface smoothness.
	2012	Deliver 5 full size RPCs made out of the new BESIII Bakelite and another 2 full size RPCs coated with Linseed oil and Tung oil internally, and compare their general/aging performance. Make final conclusions on either using new form of Bakelite or adopting Italian oil-coating techniques for the RPC to be proposed for the SiD Hcal and Muon systems.
Project 6.25	2010	-- not funded --
	2011	Complete studies of PFA behavior and intrinsic limitations due to SiD HCAL and ECAL designs. Explore improvements in pattern recognition performance to reduce confusion. Investigate differences between PandoraPFA/ILD and PFA/SiD02, identifying roles of hardware and algorithmic differences.
	2012	Complete SiD detector global optimization study, including detector length, tracking system radius, calorimeter depth, segmentation and readout technology. Solenoid field strength and muon "tail-catcher" performance will also be

		investigated.
Project 6.27	2010	Complete data analysis for Vertical Slice Test. Complete construction of the DHCAL prototype calorimeter (including Resistive Plate Chambers, detector layer cassettes, front-end electronics, back-end electronics (BU), high voltage system (Iowa), low voltage system, gas mixing and distribution system (Iowa), and data acquisition software). Start cosmic ray testing of individual layers. Develop offline analysis tools. Complete efforts on gas recycling and high voltage distribution system.
	2011	Complete data taking in Fermilab test beam. Publish DHCAL instrumentation paper. Complete DHCAL calibration. Prepare first physics results from DHCAL. Design new approaches to gas recycling and high voltage distribution system (ANL).
	2012	Publish first physics from the DHCAL. Complete design of gas recycling system and new high voltage distribution system (ANL).