Facilities for High Energy Physics Detector Research and Development at the DOE National Laboratories

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Introduction

The field of High Energy Physics resides on the ability to detect the detailed properties of a wide array of particle species under vastly different energy scales – from 10^{-3} to 10^{18} eV. There is a tradition in the field of researching and developing innovative tools for this challenging environment, many of which have direct applications in related nuclear fields. Much of this innovation comes from the flow of creative ideas from the university community and the national laboratories. A successful high energy physics detector R&D program requires facilities and staff for engineering, fabrication and testing of detector technologies. The DOE National Laboratories presented here provide extensive support and infrastructure for Detector R&D in all these areas. The staff has experience in most aspects of detector R&D, gained from developing and constructing experiments for fixed target, collider and non-accelerator based research. As a result there is a strong capability for design of integrated systems in addition to developing individual detector elements. This memo is intended to highlight the available facilities at each of the national laboratories involved in High Energy Physics.

Argonne National Laboratory

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In all experiments the Division has participated in or is participating in, members of the Division have played major roles in the design and construction of the hardware and detector sensors. These span the range of design and construction of large mechanical structures, to the development and construction of superconducting sensors, to the exploration of radiation hard optical readout systems. We provide electronics, installation and commissioning of integrated detector systems and maintenance during the life of the experiment. Due to the unique multi-disciplinary nature of the laboratory, we have access to the materials science expertise and micro and nano fabrication facilities within our materials science and energy systems divisions and our center for nano-scale materials division, which are used in the development of new detector sensors. A brief description of the major facilities is given below.

- Industrial building 366, a 23,000 sq ft high bay, 35 ton crane equipped, unique assembly area for large construction projects. CDF, ZEUS, MINOS and ATLAS modules as well as moving systems for ATLAS were built here. Recently the full prototype of a 56x56ft NOvA module was assembled here. The Argonne laboratory provides and maintains this space.
- There is a mechanical design group within the Division, with two mechanical engineers, typically supported by project funds. We also have access to a lab wide engineering group in case more effort is needed.
- The Division is the home of the electronics group with a total staff of ~ 9 engineers, designers and technicians who support all Argonne divisions. This group designs, builds and maintains electronics associated with detectors provided by the Division for experiments. Typically at least 3-4 members of that group work on HEP activities.
- Machine shop including 2D CNC machining capability (plus machinist) in the large assembly building, plus two smaller machine shops. We also have access to the large Central Shop maintained by the laboratory where a full range of machining capabilities is available including multi-axis CNC, EDM, welding, and precision inspection instrumentation.
- Cosmic ray test stand and optical research lab in HEP Building 362.
- Three Atomic Layer Deposition systems in the Energy Systems Division: a Beneq reactor, a Large Substrate Reactor (LSR), and a tube reactor. The latter is only for 33mm disks. The Beneq and LSR systems are for 8" plates.
- Plasma Atomic Layer Deposition Reactor in Energy System Division used for superconducting cavity development.
- Access to the Argonne Electron Microscopy Center, and a variety of surface analysis tools such as Low Energy Electron Diffraction, X-ray Photoelectron Spectroscopy, and Ultra-Violet Photoelectron Spectroscopy.
- Access to the Argonne Glass Shop run by a 4th generation scientific glass blower with 45 years of experience.
- Access to the IBM Blue Gene Q supercomputing capabilities within the Argonne

Leadership Computing Facility

- High bandwidth electo-optical test stands with capabilities to test up to 11 Gb/s links. Bit Error Rate (BER) measurement facilities, motorized 2D stage for optical alignment, CW laser sources (650nm, 850 nm, 960nm, 1490nm, 1550nm), high speed receivers (10 Gb/s), optical power meters, Lens systems and alignment facilities.
- Femto-second UV laser test facility at the Argonne Advanced Photon Source
- Thin film synthesis tools, including two 5-targets sputtering systems (AJA, direct and con-focal gun configurations) to synthesize superconducting and thin films and heterostructures. The con-focal deposition system is dedicated for synthesis of superconducting films only, and provides film thickness uniformity of ~2% across the 6” wafer.
- Clean Rooms (Class 1000) equipped with microfabrication tools, including:
  - 100-kV electron-beam lithography (JEOL 9300 FS),
  - 30-kV electron-beam lithography (Raith 150)
  - focused ion beam/scanning electron microscopy (FEI Nova 600 NanoLab Dual Beam
  - Step-and-repeat nanoimprint (Nanonex NX-3000), and Optical mask aligner (Karl Suss MA6)
  - Reactive-ion etch (RIE) station for high resolution anisotropic etching of silicon, silicon dioxide, silicon nitride with a high degree of selectivity, anisotropic etching of refractory metals and removal of organic residue (uses CHF3, SF6, CF4 gas chemistry)
  - Inductive coupled plasma reactive ion etching chlorine chamber (Cl2, SF6, BCl3, HBr, CHF3, CO, O2, Ar) (Oxford Instruments Plasmalab 100)
  - Reactive ion etching fluorine chamber (SF6, CF4, CH4, CHF3, HCFC-124, H2, O2, Ar) (Oxford Instruments Plasmalab 100)
  - Table-top reactive ion etching chlorine chamber (Cl2, CH4, H2, O2, Ar) (March Plasma);
  - Table- top reactive ion etching fluorine chamber (SF6, CF4, H2, O2, Ar) (March Plasma);
  - Table-top reactive ion etcher (CF, SF6, Ar, O2) (Plasma Sciences 600);
  - Barrel asher system (Ar, N2, O2) (PlasmaTherm),
  - Wet Wafer Processing tools, including, Wafer rinse dryer tool (2-, 4-, and 6-inch), Electroforming (Au, Cu, Ni, Pt), Silicon anisotropic etching, membrane fabrication and wet etching.
- Metrological tools, including
  - Optical microscopes (Olympus MX-61),
  - Three-dimensional surface profilometer (Veeco Dektak 8),
  - Profilometer (Tencor Alpha Step 500),
  - Reflectometer (Filmetrics);
- X-ray diffractometers and Atomic Force Microscopes for structure of the films and devices. The AFM system is equipped with Q-control module for enhanced sensitivity and has a vibration isolation enclosure, which helps to ensure that the system has a vertical noise resolution of less than 0.5 Angstrom.
- Conventional transport and magnetic characterization tools, including Physical Properties Measurements System (PPMS, Quantum Design) for measurements of

magnetization, magnetic anisotropy, susceptibility and I-V four-probe transport measurements in temperatures 1.7K-400K, and magnetic fields up to 7 T, and Superconducting Quantum Interference Device (SQUID, Quantum Design) for high-sensitivity magnetization measurements at temperature range 1.7K - 350K, and magnetic fields up to 6 T.

- Sub-Kelvin transport characterization tools:
  - An insert-type liquid helium cryostat (CIA) with an open-cycled He3 refrigerator (280mK base temperature);
  - Liquid helium cryostat (Chase cryogenics) with a closed-cycled He3 refrigerator (230mK base temperature);
  - Four series SQUIDs arrays with home-built readout electronics;
  - NIST time domain SQUIDs multiplexing read-out system, current one column first stage SQUIDs for 32 sensors readout, expandable to 32 x 8;
  - Lakeshore temperature controllers and temperature monitors;
  - Lock-in amplifiers (Stanford Research, SR830) and one AC resistance bridges (Stanford Research, SIM921).
- Burle/Photonis photocathode growth facility for large area photocathodes, currently as large as 7’’X7’’. The facility consists of a PMT envelope tube, a turbo-pumped high vacuum system capable of 10-8 torr base pressure, oven and a control table.
- Ultra-High Vacuum Growth and Characterization Facility, designed for the study of the cathode growth process. The chamber consists of a growth chamber, an optical and electrical characterization chamber and a surface science chamber.
- Photocathode electrical and optical characterization station for reflection, transmission and quantum efficiency measurement of various thin film materials, equipped with Newport 70511 Apex Monochromater Illuminator, Newport 74125 Oriel Cornerstone 260 1/4m monochromator, enclosed beam path, Si photodiode light detector, Femto DLPCA-200 Current amplifier, Keithley 2701 Ethernet Multimeter/Data Acquisition System and 6517B Electrometer/High Resistance Meter.
- VAC HE-43-6 DRI LAB glove box which provides a working area of inert atmosphere nearly free of moisture and oxygen, which permits handling of materials sensitive to moisture and oxygen contamination. The system consists of a gas delivery system, a hermetically sealed glove box, a side-mounted load-lock chamber and a full-view window.
- In addition we have access to the user facilities at the Center for Nanoscale Materials (CNM). These include:
  - complex oxide film synthesis via molecular beam epitaxy (DCA R450 Custom),
  - physical vapor deposition (Lesker CMS 18 and PVD 250),
  - spin coating (Laurell WS-400),
  - electron beam lithography system (JEOL 9300 Raith 150),
  - focused ion beam (FEI Nova 600 NanoLab),
  - laser pattern generator (Microtech LW405),
  - nanoimprint nanonex (NX3000),
  - wafer priming oven (YES-TA series),
  - deposition facilities with AJA oxide sputtering 3-inch targets,
  - atomic layer deposition (Sundew D200),

- lambda microwave plasma CVD System (nanocrystalline diamond deposition),
  - oxford plasmalab 100 Inductively coupled plasma enhanced chemical vapor deposition,
  - sputter deposition system (Emitech K675X),
  - thermal/PECVD System for CNT and graphene synthesis;
  - Wet Chemistry with Electroplating (Au, Cu, Fe, Ni, Pt),
  - Selective wet chemical etching,
  - Wafer Spin Rinse Dryer:
  - VERTEQ;
  - Inspection and Metrology with Atomic Force Microscope (Park Scientific XE-HDD),
  - Potentiostat,
  - Scanning Vibrating Electrode (SVET M370),
  - Three-Dimensional Contact Profilometer (Dektak 8),
  - UVISEL Spectroscopic Ellipsometer (Horiba Jobin Yvon);
  - Post-Processing facilities with Chemical Mechanical Polishing (Logitech Orbis),
  - Critical Point Dryer (Leica CPD030),
  - Thermocarbon Dicing Saw (TCAR 864-1);
  - Synthesis facilities with Complex oxide film synthesis via molecular beam epitaxy (DCA R450 Custom),
  - Physical vapor deposition (Lesker CMS 18 and PVD 250),
  - Spin coating (Laurell WS-400);
- Nanophotonics facilities such as
  - Near-field scanning optical microscopy (NSOM),
  - Confocal Raman microscopy, Ultrafast transient-absorption spectroscopy,
  - Ultrafast microscopy,
  - Nanophotonics nanoparticle synthesis laboratory,
  - Near-Infrared microscope and spectrometer,
  - NIR microscope (800-1700 nm) for electroluminescence and photoluminescence (650-nm excitation),
  - Varian Cary-50 UV/VIS spectrophotometer.

Brookhaven National Laboratory

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The Lab provides overhead support of nearly $7M/year for the Instrumentation Division, which is a great boon to the generic detector R&D program. Aside from expert technical personnel the Instrumentation Division has many useful facilities:

- Semiconductor Detector Laboratory: Clean rooms, 6" wafer capability, oxidation, mask alignment, thin film deposition, detector characterization, testing and defect analysis.
- Gas and Noble Liquid Detector Laboratory: Clean rooms, fabrication and test facilities for X-ray, neutron, and charged particle detectors.
- Optical metrology Laboratory: Digital optical surface profiler, long trace profiler, interferometers.
- Laser Application Laboratory: picosecond to femtosecond laser oscillators and amplifiers, time-correlated single photon counting. In-situ photocathode deposition and characterization for photoemission stud- ies, X-ray and particle beam monitors, Diamond based X-ray detectors
- Micro/nano Fabrication Laboratory: Fabrication of micro/nano structures, analytical electron micro- scope.
- Solid State Irradiation facility: 1.5 kCi 60Co source for radiation damage studies.
- Printed Circuit Fabrication and Assembly Facility: Design and fabrication of multilayer printed circuit boards using FR4/Poyimide/teflon/glass laminates up to 10 layers, 1m maximum dimension, wire- bonding, surface mount assembly.
- RF Communications Engineering: support intra-Laboratory spectrum management

The Collider-Accelerator Division has expertise in cryogenics. The Superconducting Magnet Division has extensive expertise in specialized magnet fabrication. The Physics Department provides substantial lab space and a 4000 ft2 High Bay with a 30T crane. A $30M building upgrade is in progress that will in the next year provide a 1725 ft2 Class 10,000 clean room (Class 100 capable) and approximately 12,000 ft2 of totally revamped lab space. The latter includes a second clean room, 448 ft2, Class 100.

There's also a very large computing facility built to support the RHIC and ATLAS programs. It provides leveraging for small computing efforts.

Brookhaven has several accelerator user facilities that are available for test beam use.

- In the past the NSLS provided a tagged photon beam in the few hundred MeV range that was used for calorimeter development.
- The Accelerator Test Facility has high quality electron beams from 25 to 76 MeV with very flexible temporal structure, single micropulse charge from zero to a few nanocoulombs, bunch train charge up to about 50nC. There is also a Terawatt CO2 laser and other research tools. See http://www.bnl. gov/atf/core_capabilities/atf_beam_parameters.asp for more details.
- The NASA Space Radiation Laboratory employs beams of protons and heavy ions

from the Booster accelerator. It has made available 1 GeV/nucleon 56Fe , 0.3 GeV/nucleon 97Au and many other ions.

- The BNL Tandem Van de Graaff provides a vast array of low energy heavy ions that have been used for SEU and other studies. See http://tvdg10.phy.bnl.gov for details.
- The BNL Chemistry Department has a group that specializes in scintillation detectors for neutrinos. It has a number of facilities including a Liquid Scintillator development facility: 2 technicians and a Chemical analysis and Material Compatibility facility: 2 technicians.

Fermi National Accelerator Laboratory

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The Particle Physics Division of Fermilab operates a number of facilities whose focus is assembling and testing detector systems. These include 8000 ft2 of clean rooms, a vacuum and cryogenics group and scintillator development facilities and thin film deposition. Most of these facilities are part of the Technical Centers Department and were primarily developed as part of programs to construct experiments. The detector R&D program takes advantage of these facilities with relatively minor incremental cost.

The Fermilab Test Beam Facility:

- Test beams are crucial to many detector R&D projects. The Fermilab Test Beam Facility provides users from around the world the opportunity to test and calibrate the performance of their particle detectors or detector prototypes using a variety of particle beams and beam conditions. Only a few high energy test beam facilities exist and Fermilab operates the sole US facility. The goal of the Fermilab test beam program as stated in the director's handbook is "to provide flexible, equal and open access to test beams for all detector tests, with relatively low bureaucratic overhead and a guarantee of safety, coordination and oversight."
- The test beam originates from the resonant extraction of a proton beam from the Main Injector (MI). The beam spill length is variable from 0.2 to 1.2 microseconds. The extracted beam is accelerated to 120 GeV and can be delivered to the test beam area in a flexible fashion, allowing experimenters to specify the beam conditions appropriate for their particular test.
- The 120 GeV proton beam has an approximate 0.3% momentum spread and can be focused to a 7 mm RMS spot size in the user area. In addition to delivering primary protons, there are two targets on movable stages that can act as secondary beam production areas. The magnets downstream of those targets can then be tuned to deliver any secondary momentum from 0.5 GeV to 60 GeV. This flexibility gives the researchers many options in designing their tests. The momentum bite for these secondary beams is on the order of 2-3%.
- The current test beam facility (MTEST) has a number of user installation areas, and crane coverage to facilitate the installation and removal of equipment. Various instrumentation is provided to characterize the beam impinging on the detectors being tested. The test beam facility offers a pixel telescope which measures the beam direction with resolution of a few microns. This telescope can be used for tests of new pixel sensor technologies.
- The facility has a differential Cherenkov counter that can perform 3 species separation in the region between 5-32 GeV and is very efficient for tagging electrons down to 1 GeV. This particle identification can be used in a trigger system for experiments which require a pure event sample.
- For precision timing studies, Fermilab has developed a 175 psec resolution TOF system that is 10 cm x 10 cm size, as well as an advanced microchannel plate PMT system that can get 20 psec timing resolution on the proton beam.
- The facility offers the use of large lead glass module that can be used to measure the parameters such as electron content and beam momentum spread for any specific

beam conditions. As measured with this device, the beam typically delivers 2-3% resolution.

- There is a continuous demand for improvements on the beam instrumentation at the test beam. Over the shutdown period in 2012, Fermilab is developing an entirely new data acquisition system for the 0.5 mm spaced wire chambers used for medium level tracking. Over the next 3 years, the test beam instrumentation will be continuously improved and upgraded. A new MCenter beam line will be commissioned after the shutdown and provide most of the same capabilities as MTest.

Silicon Detector Facility :

- The Silicon Detector Facility (SiDet) was constructed for the CDF and D0 Run 2 Silicon Strip detector construction and has seen incremental improvements in tools for the Run 2B upgrades, CMS construction and DECAM projects. SiDet has a permanent staff of about 15 including technicians and engineering physicists. The SiDet facility contains about 5000 ft2 of class 10,000 clean room space dedicated to the fine scale assembly of detector modules, micro- bonding and large scale assembly of complete silicon trackers. Within this space, there are clean room benches that exceed class 1000 and a new 200 ft2 internal class 100 clean room added in July 2009. An almost equal amount of space is available adjacent to the clean rooms for assembly and test stands.
- There are numerous tools for precision construction. These include Coordinate Measuring Machines of various precision optics, which are used for many applications from fine assembly to final alignment of assembled detector. The smaller CMMs are used for module assembly that is typical for detector R&D. There are several K&S wire bonders
- SiDet has been used by the R&D program to prototype mechanical assembly of low mass trackers. Recently a major focus has been assembly of CCD packages for astrophysics experiments. This work started with the DECAm project where Fermilab has partnered with LBNL. SiDet developed packaging for edge buttable assemblies that can be mounted on the camera focal plane.
- SiDet also provides support to R&D in the ASIC area with bonding capabilities. The flip-chip bonder has been used to for bonding the SPI 3D ASIC to pixel sensors for testing. This provides fast turnaround on prototype devices.
- In addition to the assembly facilities, there are significant testing capabilities at SiDet. There are several probe stations including a new automated probe station, purchased in 2011, that can handle 8” wafers and has a temperature-controlled chuck. This significantly enhances our capabilities for sensor and ASICs testing. The CCD characterization facility, developed for DECam, has multiple liquid nitrogen cooled test stations and is now actively used for a number of CCD development projects. Nearby are test stands for scintillating fiber multi-pixel PMT and SiPM characterization. Supporting equipment including electronics, ovens, vacuum equipment, robotic glue dispenser, chillers, cryo-coolers, and other temperature-control devices.

Lab 3 Clean rooms:

A separate set of clean rooms at Lab 3 cover about 3000ft2 of Class 10,000 space which was used to assemble the D0 Fiber Tracker. The primary use of this space is currently the assembly of detectors for Dark Matter searches where very low radioactive backgrounds must be achieved. This includes SuperCDMS and the COUPP bubble chambers. The facility was upgraded for this new role with an inner clean space of 120ft2 that exceeds class 100, a low radioactivity clean water supply and alpha-counting facility. Lab 3 is the primary home of many R&D projects for dark matter detectors (COUPP, CDMS, DAMIC CCDs) and the QUIET phase 1 20K blackbody source.

Lab 3 is also the home of the material structural layup facility that was used extensively for producing the carbon fiber structures of the CDF and D0 silicon trackers, the D0 fiber tracker, and the CMS forward pixel system. Layup is done with carbon fiber, PEEK and Eccsorb. This capability has been used in the detector R&D program to develop prototypes of very low mass structures for a lepton collider tracker. It is now being used to develop carbon fiber rod structures for a future CMS Tracking Trigger upgrade. A large effort is ongoing on Thermal Pyrolithic Graphite (TPG) for the CMS tracker upgrade. We have developed an encapsulation technique to make the TPG robust, and the samples of the encapsulated TPG have been provided to our European collaborators.

Cryogenics and Vacuum Instrumentation Group:

Cary Kendziora leads the Cryogenics and Vacuum Instrumentation group, which consists of one engineer and four technicians. This group has extensive experience in vacuum systems and cryogenics for experimental apparatus. The group has been responsible for implementing much of the LAr R&D at Fermilab including assembly, debugging and maintenance of the Liquid Argon Materials Test Stand and many parts of the Liquid Argon Purity Demonstrator. They also assembled and commissioned LAr Distillation column developed in collaboration with Princeton.

The group operates several facilities of within its building:

Materials Test Stand for study of impact of materials on LAr purity,

Cosmic Ray Test Stand for study of TPC and TPS electronics,

LAr Distillation column for providing a source of clean, isotopically pure Ar

The Cryogenics and Vacuum Instrumentation group has also provided critical support to the development of the COUPP bubble chambers. All of the smaller chambers have been operated in this facility and they have provided invaluable support in the development of larger detectors. Other small detectors such as ArgoNeut and the upcoming SCENE detector have also been assembled and first operated and tested in the Cryo group’s facility prior to installation at the eventual experimental site.

Scintillation Detector Development group:

The Scintillation Detector Development (SDD) group encompasses two facilities: the SDD Laboratory in LAB 6 and the Extrusion Center in LAB 5. The SDD Laboratory consists of a chemistry laboratory with three hoods and ample bench space, an analytical laboratory, and two optics rooms for light yield and optical fiber measurements. Several new instruments have been purchased over the past three years to upgrade the analytical lab including UV/Visible light spectrophotometer that is used for testing the response of plastic scintillator and a Liquid Chomatograph and Mass spectrometer for analysis of liquid scintillator.

The Extrusion Center houses the FNAL/NICADD Extrusion Line and the small, R&D extrusion line. The FNAL/NICADD Extrusion Line is used to prepare scintillator in large quantities. It normally processes polystyrene pellets at a rate of 75 Kg/hour. The R&D extrusion line is used for tests of small quantities of materials and for generic R&D such as the neutron-sensitive scintillator and the high Z scintillator. Work is progressing now on developing a method for embedding wavelength shifting fiber within the extruded scintillator.

Wire Chamber Winding:

A small group in the Technical Centers focuses specializes in winding wire chambers. This group was instrumental in the construction of many Fermilab experiments; most recently the CDF drift chamber. This group has been involved in construction of TPCs for the LAr and in wire planes for QUIET.

Thin Film Group:

The Thin Film group provides vacuum deposition and sputtering, including two vacuum systems with a magnetron sputtering gun specifically built and dedicated to optical fiber sputtering. The group also has two Programmable Vibration Resistant Diamond Polishers for “Ice Polishing” of optical fibers and connectors. Additional capabilities include UHV Bake out Facility including 1200C hydrogen degassing, Plasma Oven Cleaning Facility, RGA and Out Gassing Study Facility. The group has a staff of five technicians. This group supports R&D by responding to requests for specialized deposition and/or polishing.

In 2011, the Thin Film Group completed an evaporative coating facility to support the Large Area Picosecond Photon Detector project at Argonne. This facility is substantially wider and taller than the other vacuum coating chambers, to accommodate the 8” square microchannel plates for the LAPPD project.

DETSIM – A Computing Cluster for Detector Simulation

Fermilab also operates DETSIM, a detector simulation cluster with access to FNAL’s central Bluearc storage system. This system is used for development of linear collider detector simulation capabilities and deployment of detector simulation applications, including both ILC (early in the three year review period) and muon collider (FY11 and

FY12). It provides a flexible development environment matched to the needs of such simulations, combined with access to large storage which is essential for detector optimization studies and analysis. The entire collection of the detector simulation software tools is installed and supported there and at the same time it is used as a gateway to the grid computing resources.

Lawrence Berkeley National Laboratory

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There are a large number of unique facilities at LBNL and UC Berkeley. The KA15 program itself supports the Micro-Systems Lab (MSL), a fraction of the IC design group (via design projects), and equipment and space within the Physics Division. The MSL and its equipment along with other significant equipment maintained with KA15 funds are described in the com- panion Core document. Here, we list the LBNL and UC Berkeley facilities that we use or plan to be use in KA15-supported R&D, but are not maintained with KA15 funds. Some of these facilities are available via recharges or matrixing (such as machine shops) and others are no cost to KA15 (such as the 88" cyclotron).

- 88" Cyclotron The 88" is now specialized in ion mixes to simulate the space radiation environment. We test components expected to operate in space, such as CCDs. In the past we also used 55 MeV proton beams for total dose irradiation, but for current and future high rate and radiation work, approaching the Grad level, the 88" intensity is no longer appropriate.
- Engineering Division Composites Lab This is a cornerstone of our integrated structures development, now fully maintained by the Engineering Division. A more detailed description is given in the companion Core document because it is so central to our program, and also had its origin in HEP instru- mentation. The Composites Lab is sited next to the main shops, which allows seamless integration of machining, stereo lithography, and metrology with composites fabrication.
- Engineering Division Mechanical Fabrication Shops LBNL has extensive fabrication facilities including conventional NC machining, wire EDM, stereo lithography, glass, ceramics, etc., with expert staff that can work not only on large projects but also for small scale R&D.
- Engineering Division Metrology Department The Metrology Department has a host of coordinate measurement equipment (both contact and non-contact), but more importantly expert staff for making high precision mechanical measurements.
- Engineering Division Assembly Clean Room This is a 1,400ft2 class 1000 clean room available for projects and R&D on an as-needed basis. It is available for projects requiring more space than we have in our permanent clean room space (MSL and CCD test lab).
- ICP Mass Spectrometer System This tool belongs to the Earth Sciences Division, but we have open access to it. It is in- creasingly in demand by underground experiments for detecting radioactive contamination at the PPT level.
- Low Background Counting Facilities LBNL has a low background counting facility on site and one at Oroville Dam in the Sierra Nevada foothills. These are extensively used for underground detector R&D.

Lawrence Livermore National Laboratory

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- 12,000 sq. ft. integrated detector development facility including:
  - High bay for multi-ton-scale detector construction and testing
  - Clean room and noble liquid test-bed
  - SQUID electronics/readout development

- Center for Accelerator Mass Spec.
  - Van De Graff and pelletron 1-10 MeV proton sources, capable of creating, e.g. high flux (2 microamp protons on target), low energy (100 keV) neutron beams for ionization yield measurements, and other applications (cams.llnl.gov)

- In January 2013 – Second multi-purpose space, similar to 1. in the Open Campus area of LLNL/SNL – fully accessible to all academic groups with ties to LLNL

SLAC National Accelerator Laboratory

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Introduction

In this document a number of facilities at SLAC and on Stanford University main campus are described, all of which are available for the detector R&D effort without funds required from KA15, with the exception of a small nominal per person fee for use of the Stanford Nanofabrication Laboratory.

Semiconductor Fabrication, Circuits Design, Test and Analysis Resources.

SLAC has two clean rooms, a detector assembly facility in Building 84, and a larger clean room in Building 33, the latter consisting of a main cleanroom of ~ 3500ft2 and a high bay clean room of ~ 850ft2. The main clean room area in Building 33 is shown below in **Error! Reference source not found.**. Each clean room provides a full complement of basic electronics required for R&D work: low and high voltage power supplies, function generators, oscilloscopes, etc. A high-end Keithley 4200 semiconductor test system has been recently added, greatly enhancing our ability to characterize sensors and other devices. Our group has access to three standard probe-stations at SLAC and an additional station in the Stanford Nanofabrication Laboratory (SNF). We can also use a vacuum cryogenic probe station that is shared within the Stanford Electrical Engineering Department. All probe stations are outfitted with micro-manipulators, and most are mounted within dark cabinets. The SLAC detector group has a vacuum test chamber implemented with roughing and turbo pumps as well as a Cryotiger, a cooling system capable of maintaining temperatures as low as 70K without the need for liquid nitrogen or other gasses/liquids. It utilizes a refrigerator compressor and is controlled by a Lakeshore thermal module. In addition, a set of six solid-state chillers in combination with Peltier plates provides cooling at temperatures and power loads that are complimentary to those enabled by the Cryotiger.

A suite of software tools is available for use in thermal, electrical, mechanical, and system-level modeling of detectors. The Synopsys CAD collection provides advanced semiconductor device and circuit simulation abilities, complemented by L-Edit for circuit-side design. Thermal-mechanical modeling is performed using the ANSYS multi-physics program. For specialized calculations, a range of custom software, such as ab initio code libraries, is accessible within SLAC and at the Stanford NNIN Computing Facility.

Micro-packaging is a critical, but often overlooked, ingredient in the manufacture of large-scale, practical detector systems. Wire bonding can be done using in-house equipment and expertise, or contracted out to a set of local assembly houses. A Finetech

Lambda flip-chip machine with 0.5 micron alignment precision is installed in the detector cleanroom and several types of bumps can be deposited and patterned at SNF. SLAC has the tools and knowledge to perform a variety of advanced micro-assembly in house.

Finally, a suite of optical-, electron-, and ion-based microscopes are accessible at SLAC and on the Stanford campus. In particular, a high-resolution, large-stage, programmable optical metrology machine is located in the detector cleanroom. A pair of versatile, programmable robots, which have been employed on previous projects, can facilitate positioning of parts and dispensing of adhesives, and so enable higher-throughput manufacturing.

Silicon Detector Laboratory

An ISO7 standard clean room has been constructed at SLAC, shown in **Error! Reference source not found.**, to provide 500 ft2 of common space for the assembly and testing of semiconductor detectors. The room has been provided with power, vacuum, Ethernet, phone, and nitrogen, and includes a separate antechamber for gowning. The facility has been carefully designed to eliminate the danger of electrostatic damage to sensitive electronics. Characterization of devices can be performed using an automated laser test stand, a semiconductor probe station complete with supporting electronics, and an optical and stylus-based three-dimensional profiling system. A wire bonder and adhesive dispensing station allow for packing of prototypes. For more advanced systems, a stud bump bonder and flip-chip bonder have been added. Moving forward, this facility will significantly enhance SLAC's ability to achieve its detector development goals.

Electronics Laboratories

There are several electronics test laboratories as well as assembly shops available to support the SLAC's detector R&D program. **Error! Reference source not found.** shows data acquisition equipment racks in one of these labs.

Test Beam

As already described in this report, SLAC will have a test-beam available for characterization of sensors and detector electronics by FY13.

Stanford Nanofabrication Facility

The Stanford Nanofabrication Facility (SNF) is a shared resource serving academic, industrial, and governmental researchers. SLAC has full access to SNF for a small nominal per person fee. SNF has a 10,000 square foot, Class 100 cleanroom housing a complete suite of tools for the micro- and nano-fabrication of semiconductor devices. A full-time staff provides equipment and process support to keep the facility operational 24 hours a day, 7 days a week. Processing capability includes photo-lithography, dry etching, diffusion and deposition furnaces, and ALD.

Semiconductor detector processing imposes more stringent contamination control requirements than other applications of semiconductor technology. SNF has demonstrated the required level of cleanliness through successful silicon detector projects.

Although SNF is traditionally known for its strength in silicon device fabrication, including extensive research in silicon germanium, there has also been significant work in pure germanium. Process equipment supports both silicon and germanium wafers.

Stanford Nanocharacterization Laboratory.

The mission of the Stanford Nanocharacterization Laboratory is to assist researchers in acquiring high quality, useful data and insight using modern facilities for the characterization of materials. The Laboratory's analysis instruments and facilities include: focused ion beam, transmission electron microscope, scanning electron microscope, electron microprobe analysis, scanning auger spectroscopy, X-ray photoemission spectroscopy, X-ray diffraction, and scanning probe microscope.

Stanford Nano Center.

The Stanford Nano Center shared facilities include some of the most advanced nanoscale patterning and characterization equipment available, complementing the SNL and SNF. The new facilities have been built to meet cutting-edge requirements on the control of vibration, acoustics, electromagnetic interference, light, and cleanliness that are essential for nanoscale instrumentation. Available instruments and facilities include: TEM with environmental cell, scanning electron microscopy, JEOL 6300 electron beam lithography system, flexible cleanroom, and Microfab Shop.

Ginzton Crystal Shop.

The Ginzton Crystal Shop specializes in the custom fabrication and modification of crystalline and amorphous materials, including germanium. Services include: lapping, grinding, polishing, slicing & dicing, core drilling, OD grinding, crystal orientation.

Silicon Valley

If additional resources are needed, SLAC is located in Silicon Valley, where semiconductor processing, test and measurement, and materials analysis services are all available locally.