ILC Detector R&D: Its Impact

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The Common Task Group for Detector R&D

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1 Introduction

For many years, there has been a strong international consensus that an $e^+e^-$ collider will be needed to study the underlying physics of the new phenomena in the mass range from 0.2 – 1.0 TeV, which are expected to be discovered at the LHC. This has been recognized through the support for research and development of new technologies for the ILC accelerator, detector technologies and the detector design studies. This support has fluctuated significantly over the years especially for the detector community. The R&D is considered to be far enough in advance of any defined future project that the importance and need for this effort has struggled, and continues to struggle, to be formally recognized by the agencies. Despite these struggles, the detector community has been quite successful and the impact of the R&D for ILC detectors is very real. This brief report draws attention to the significant positive impact the ILC detector R&D has had on the field of particle physics and beyond and points to the value of sustained support for basic research and development for instrumentation.

2 Vertex Detector Technologies

A key element to enable the ILC physics program is the vertex detector. Primary and secondary vertex reconstruction of unprecedented accuracy and minimal multiple scattering is required for the heavy flavor physics and Higgs channels. This puts extreme demands on the power consumption and mass budget of these detectors. Furthermore, the readout speed, detector occupancy, detector granularity and radiation hardness has to be commensurate with the experimental environment. R&D on multiple vertex detector technologies has been very active. To meet the stringent performance requirements, the Depleted Field Effect Transistor (DEPFET) active pixel sensor has been studied extensively. In the DEPFET pixel concept, the first amplifying transistor is directly integrated into a high resistivity silicon substrate. A potential minimum for electrons is created underneath the transistor channel, which can be considered as an internal gate of the FET. The signals created by an impinging particle are collected and stored in the internal gate, which results in a modulation of the transistor current. After readout the stored electrons are removed from the internal gate. The active area of the device can be as thin as 50 μm². Prototype detectors with pixel sizes of 22x30 μm² and matrix sizes of 64x128 pixels have been extensively beam tested. The data were analyzed and compared with simulation using the ILC software framework. Very good performance has been achieved to date, notably a very low power consumption and mass budget. This development has not gone unnoticed by the BELLE-II collaboration at the KEK b-factory [1]. The collaboration has adopted the DEPFET detector as the baseline design for the vertex detector for the BELLE-II detector (see Fig. 1). Because of the extensive R&D carried out under the ILC umbrella, the BELLE-II detector had a mature technology available to be taken to the detector stage.
The DEPFET concept integrates a FET directly into the silicon substrate. As such, it is an example of a Monolithic Active Pixel Sensor (MAPS), albeit a primitive one. Much more complex front-end architectures can be implemented directly in the silicon substrate in MAPS devices, such as timestamping, analogue to digital conversion and zero-suppression. The development of the MIMOSA series of CMOS pixel sensors is one example [2]. The intrinsic advantages of this technology come from the ability to implement very high granularity, very thin sensors and integrated processing circuitry in a commercial process. Driven by the ILC physics needs, more than 30 sensor prototypes have been produced in the MIMOSA series. A recent incarnation, the MIMOSA-26 sensor, is a matrix of 1152x576 pixels with a pitch of 18.4 μm resulting in an active area of 21x10.6 mm\(^2\). The chip uses a column-parallel readout architecture in rolling shutter mode. Pixels are read out at 80 MHz, resulting in a 112 μs integration time. Each column is terminated with a discriminator and offset compensation and correlated double sampling (CDS) are performed. The data were zero-suppressed before being written to a memory buffer. Beam telescopes (see Fig. 2) based on the MIMOSA26 sensors are available to the whole user community in the test beam lines at both DESY and CERN [3].
The MIMOSA-26 sensor is also the sensor of choice for the heavy flavor tracker of the STAR experiment at RICH at Brookhaven, expected to see data around 2013 [4]. It is the first application of a MAPS detector at a collider. An adapted version of this sensor also provides the baseline architecture for the micro-vertex detector for the Compressed Baryonic Matter experiment at FAIR at GSI (see Fig. 3). Also here, the long and extensive ILC R&D program has brought this technology to such a mature level that it can be readily applied in these experiments.
Vertically Integrated Electronics, or 3D technology, consists of layers of extremely thin silicon stacked on top of each other with interconnections between the layers. Each layer can be as thin as 7 μm and can be individually optimized. One of the layers could be the sensing layer, for example, whereas other layers could implement the analogue or digital front-end processing requirements per pixel. This relatively new technology was unambiguously motivated by the requirements for complex functionality in a small pixel for ILC vertex detectors \([5,6]\). 3D includes a suite of technologies, such as wafer thinning, bonding, and interconnection that can be applied to a variety of detector applications. The current 3D run at Tezzaron includes sensor integration through oxide bonding. This run includes chips for ATLAS and CMS at the LHC, Super-B and X-ray imaging as well as circuits for an ILC vertex detector. The 3D technology is currently also a serious candidate technology for the upgrades of trackers for the LHC experiments. Figure 4 shows a conceptual view of a silicon assembly for a track trigger for the LHC upgrade. Two sensors, one at the top and one at the bottom, communicate with each other through a vertical interconnect. The diagram on the right in Figure 4 shows a cross section of the connection between the sensor and a readout chip.

![Fig. 4: Conceptual view of a 3D silicon assembly for a track trigger for an LHC upgrade showing a silicon sensor at the top and bottom interconnected through an interposer (left) and a cross section of a connection between sensor and readout chip (right). Image: Ron Lipton](image)

The Silicon On Insulator (SOI) technology is another vertex detector technology actively being developed by the ILC community. This technology provides monolithic integration of electronics and sensor by deploying the SOI “handle wafer” as the sensor in a multilayer stack. The ILC community has developed techniques to thin the SOI wafers to the required 50-100 microns and demonstrated a process to provide a backside Ohmic contact via implantation and laser annealing. The technology has already been applied as a conventional X-ray imager. The detector technology project at KEK has fabricated integrating pixel detectors that count the number of gamma rays that hit each pixel. The latest version of the chip, INTPIX4, has an array of 512 x 832 pixels, each with a size of 17 μm x 17 μm. Figure 5 shows a picture of a dried sardine taken with this camera \([7]\). Applications for cryogenic infrared imaging and astronomical imaging are being developed.
3 Tracking Technologies

An important element of the ILC physics program is to uniquely map the Higgs sector. The most accurate determination of the Higgs mass is achieved through the recoil mass determination, which requires excellent charged particle momentum resolution. The Time Projection Chamber is the technology of choice for the ILD detector concept, the R&D for which is being carried out by the LC-TPC horizontal detector R&D collaboration. Because conventional anode wire, cathode pad readout has limited resolution Micro Pattern Gas Detectors (MPGD) are being studied. Different technologies, such as MicroMesh Gas (MicroMegas), Gas Electron Multiplier (GEM) and direct CMOS detectors are being studied in great detail in a large parameter space by the LC-TPC collaboration. One of the groups was heavily involved in this R&D and had proved the concept of the MPGD TPC with running prototypes and a validated simulation and analysis framework. With these tools a MicroMegas based TPC inside the old UA1 magnet for the near detectors for the T2K experiment was designed and proposed. In 2009 three large T2K MPGD TPCs were installed in the near detector [8]. The photograph in Figure 6 shows one of the MicroMegas TPCs. The group readily states that without the ILC TPC R&D program, there would have been no T2K TPCs. The T2K Collaboration has recently announced the observation of electron neutrino appearance events using the neutrino beam from J-PARC to the Super Kamiokande detector. This indication that muon neutrinos oscillate to electron neutrinos could imply that the last unknown neutrino mixing angle, called theta-13, is relatively large. This is a nice example of the intricately interwoven matrix of detector development. The unconventional and unexpected marriage of a magnet used in the discovery of the W- and Z-bosons, combined with the groundbreaking R&D on a tracking detector for the proposed ILC project, has led to shedding light on a key parameter of the neutrino mixing matrix. Remarkable indeed!
An alternative solution for the construction of a Micromegas detector for a TPC with pixel readout is the integration of the amplification grid and CMOS chip by means of an advanced wafer post-processing technology. The process uses standard photo-lithography and wet etching techniques and is CMOS compatible. With this technique a thin (1 μm) aluminum grid is fabricated on top of an array of insulating pillars, which stands 50 μm above the CMOS chip. This concept of an integrated grid is called InGrid (see Fig. 7). The grid hole size, pitch and pattern can be easily adapted to match the geometry of any pixel readout chip. In September 2011 this technology will be proposed for use in the CERN Axion Solar Telescope (CAST) experiment.
4 Calorimeter Technologies

One of the hallmarks of an ILC detector is a fine-grained calorimeter enabling jet energy reconstruction through the particle flow concept. These calorimeters provide an image of the evolution of the interaction of the particles in the calorimeter that was not imaginable a decade ago. It is in large part made possible through the advent of silicon photo-diodes operated in Geiger mode (SiPM), the ability to embed modern readout electronics inside the detector and for the associated data acquisition systems to handle large channel counts. The field of medical imaging has already recognized the potential of these calorimeters for Proton Computed Tomography (pCT). pCT is very much like a fixed target experiment: a proton beam is measured before it hits a target, in this case part of the human body, and its direction and energy is measured when it exits the target (see Fig. 8). CsI crystals are commonly used to measure the energy of the outgoing protons. The new pCT detector concepts use miniature ILC calorimeters with SiPM readout as range detectors for the protons [9]. This allows for cheaper experimental setups with faster readout providing more accurate images.

Fig. 8: Schematic of the principle of proton computed tomography

Another medical imaging technique with potentially huge benefits from the application of the SiPMs is Positron Emission Tomography (PET) assisted by time-of-flight (TOF) measurements for the reduction of noise and eventually the refinement of position resolution. PET is a nuclear medicine imaging technique that produces a three-dimensional image or picture of functional processes in the body. A positron-emitting radionuclide (tracer) is introduced into the body on a biologically active molecule, usually a sugar. Areas of high metabolism will absorb these saccharides and the system detects pairs of back-to-back gamma rays emitted by the annihilation process of the positron with an electron. Three-dimensional images of tracer concentration within the body are then constructed by computer analysis and allow for accurate location of, for
example, cancers. Figure 9 shows a schematic view of a typical detector block and full PET system. The conventional readout using photomultiplier tubes also dominates the overall volume of the detector.

![Schematic view of a typical detector block and detector ring used in a PET system.](image)

Several groups involved in scintillator-based calorimeter R&D for the ILC contribute with their expertise and with ILC developments to such projects. One example is a group at DESY that aims at building and commissioning a multichannel time-of-flight Positron Emission Tomography (TOF-PET) test device with SiPM read-out featuring a coincidence time resolution of about 300 ps FWHM [10]. This corresponds to an improvement by a factor of two compared to commercially available devices, which offer a time resolution of about 600 ps. A coincidence time resolution of 300 ps allows locating the origin of the two back-to-back 511 keV gamma rays with a precision of 4 to 5 cm FWHM. It has been shown that TOF information of this precision significantly improves the image quality. Due to their compact design SiPMs coupled to small size scintillating crystals allow the design of detectors with unprecedented granularity and compactness. Figure 10 shows a 3x3 array of crystals with direct-coupled SiPM readout. This array is extremely compact and shows significant improvement over the conventional readout using photo-multiplier tubes. A full test device is operational and has demonstrated the feasibility of the design with a spatial resolution of 2.5 mm for a point-line $^{22}$Na source (see Fig. 11). Since the beginning of 2011 the project has been supported by the European Union to focus on the realization of an endoscopic PET system exploiting the miniaturization possibilities offered by the SiPM technology. This work is only possible thanks to the strong synergy with the multi-channel SiPM readout of the analog hadronic calorimeter prototype for the ILC. As an aside, it should be noted that the crystals used in PET systems, generally BGO or LYSO crystals, already came out of basic detector R&D in the field of particle physics.

Not surprisingly, other high-energy physics detector teams have been encouraged by the ILC driven success and the proven advantages of SiPM readout for scintillators to consider and finally select this technology for their projects. One such example is the upgrade of the iron yoke instrumentation of CMS, which serves as muon spectrometer and tail catcher of the hadron calorimeter. In a later stage of the CMS upgrade project,
also the hadron calorimeter itself will be equipped with SiPMs and in the process provide much finer readout granularity [11]. Another example is the upgrade of the end-cap K-long and muon (KLM) detector for Belle II, a project led by the ITEP group in Moscow, who is also responsible for the scintillator SiPM systems of the CALICE hadron calorimeter prototype, which used the novel sensors for the first time on a very large scale. The upgrade of the KLM detector in the end caps of the Belle II detector has 17,000 scintillator strips read by SiPMs and has a total weight of 10 tons [1].

Fig. 10: 3x3 array of LYSO crystals with direct-coupled embedded SiPM readout for Positron Emission Tomography applications.

Fig. 11: One of the two PET detector modules of the test device realized at DESY consisting of a matrix of LFS crystals with SiPM readout (left); reconstructed image of two point-like sources (right). The spatial resolution amounts to 2.5 mm FWHM.
An alternative approach to ILC calorimetry that allows very fine granularity is gas based calorimetry. This type of calorimetry differentiates itself from scintillator based calorimetry, discussed above, in that the readout is digital. This means that only the passage of a particle is registered in the active medium without any information about the energy deposited. Two technologies are being investigated: Gas Electron Multiplier (GEM) detectors and Resistive Plate Chambers (RPCs). GEMs use micrometres-thin copper-cladded plastic foils with holes with a diameter of about 50 μm. Inside these holes the signal amplification takes place. Only a relatively small voltage of a few hundred volts is applied across the foil for signal amplification. The charge is collected on readout boards with pads of 1 cm². RPCs use glass plates with a small gas filled gap of about 1 mm with a relative large voltage across the gap. The passage of a charged particle will result in an avalanche. Signal readout is similar to the readout with GEM foils. Large areas of GEM foils and RPCs are needed for the ILC calorimeters. Large area GEM foils of 100 x 33 cm² have been successfully produced in the CERN workshop. The availability of these large area foils is an important advance that opens up a number of potential applications. The Florida Institute of Technology is using GEM foils in a muon tomography project to detect nuclear contraband for Homeland Security. The large area foils will be used in a system to scan cargo for high Z materials through the detection of scattered cosmic ray muons. Figure 12 shows a large GEM foils configuration. The cargo would enter a portal with GEM detectors both on top and on the bottom of the portal. Since multiple scattering is basically proportional to the atomic number Z, the deflection of the track can be used to discriminate different Z materials. As an aside, the readout of this experiment uses the APV25 chip, developed for the readout of the silicon tracker for the CMS experiment.

The Institute of Nuclear physics of Lyon and the Laboratory for Particle Physics of Clermont-Ferrand, collaborating with volcanologists from the "Magma and Volcanoes Laboratory" in Clermont-Ferrand, are using the Semi-Digital Hadron Calorimeter (SD-HCAL) technology to build a precise tool for volcano tomography [12]. The Tomuvol experiment (TOmography with atmospheric MUons of VOLcanos) uses glass Resistive Plate Chambers developed for the Semi-Digital Hadron Calorimeter (SD-HCAL) as...
trackers for transmission imaging of volcanoes. Three or four such chambers, equipped
with the CALICE embedded readout electronics are placed on the flank of a volcano.
They measure continuously the atmospheric muon flux passing through the volcano.
Comparing the measured flux with the expected flux the integrated density along the
muon path is determined: the higher the density, the more absorbed muons. If
measurements with several detectors placed around the target are available, the
radiographic images obtained by each detector can be combined into a three dimensional
density map of the volcano structure. The image accuracy depends of course on the
tracking resolution that can be attained: the larger the chamber granularity, the shorter the
distance between the chambers can be, and consequently the larger the solid angle for
viewing the target. A first prototype, made of two chambers of 1 m² and a third one of 1/6
m², placed at a distance of about 50 cm from each other, was deployed in January 2011 to
monitor the Puy de Dôme, a volcano near Clermont Ferrand that has been dormant for
over 12,000 years. Figure 13 shows a picture of the Puy de Dôme. The detector took data
continuously until July, proving high stability in out-of-laboratory conditions. The result
of the data analysis is shown in the graph on the right in Figure 13. The angle $\alpha$ is the
angle with respect to the horizon; the angle $\beta$ is the azimuthal angle with zero degrees
defined at the center of the dome. The colors indicate the rock depth in meters. A similar
project is the MU-RAY project [13], aimed at the development of muon telescopes and
analysis tools to perform volcano-radiography, in particular of Mount Vesuvius and
Stromboli. This detector is based on plastic scintillator bars with wavelength shifting
fibers. The scintillation signals are detected with SiPMs and readout with the SPIROC
chip (see below).

Fig. 13: The Puy de Dôme in the Massif Central in south-central France (left); Measured flux of particles
passing through the Puy de Dôme volcano or in its near vicinity obtained with glass RPC tracking
chambers and readout developed for the Semi-Digital Hadron Calorimeter for the ILC (right). The
geometrical shape of the volcano is represented by the black dotted line.

The large numbers of channels of the calorimeter systems of the ILC detectors are
readout with application specific integrated circuits (ASICs) with fanciful names. The
ASIC developed to readout SiPMs for the analog hadronic calorimeter, called the
SPIROC chip, is now aiding the detection of anti-matter in the universe in a balloon
experiment. The goal of the positron electron balloon spectrometer (PEBS) is a precision
measurement of the positron and electron cosmic ray flux in the energy range from 1 to
2000 GeV. A first prototype was launched from Kiruna, Sweden, in October 2010 (see
The full experiment is scheduled to fly from the South Pole in (austral) summer 2013-2014 at an altitude of 40 km. PEBS features an electromagnetic calorimeter consisting of sandwiched scintillating layers between W absorber plates. Each layer is made of a series of scintillating bars with a small cross section. Each scintillating bar is optically isolated and equipped with wavelength shifting fibers readout by silicon photomultipliers. The readout electronics is based on the SPIROC chip [14], a 36-channel amplifier ASIC with adjustable gain and shaping time developed for ILC calorimetry.

Another ASIC, the HARDROC chip, was originally designed to readout the digital hadronic calorimeter at the ILC. It is currently being deployed in a handheld peri-operative gamma camera called TReCam (Tumor Resection Camera) developed in France [15]. The prototype camera, shown in Figure 15, offers a 49 x 49 mm² field of view. It combines a 15 mm thick parallel hole collimator with a 5 mm thick LaBr₃:Ce crystal optically coupled to a multi-anode photomultiplier tube. The read-out is established using the SPIROC chip [16]. The camera design is based on the successful clinical trials of the peri-operative compact imager (POCI) and is used to perform lymphoscintigraphy for sentinel lymph node localization in breast cancer during an operation. The imaging device has been designed so that it can easily be positioned on the surgical wound in order to locate radio-labeled tumor lesions during the surgical procedure (see Figure 15). It is currently being assessed in the context of a sentinel lymph node protocol in breast cancers. A sentinel lymph node is the first lymph node into which fluid drains from the area containing the tumor (in this case breast tissue). Because of its anatomical position, it is theoretically the lymph node most likely to contain metastases if the cancer cells have spread. In practice, the cancer is detected by injecting a radioactive solution around the tumor. Lymphoscintigraphy can then count the lymph nodes and situate them precisely. Finally, a biopsy is usually performed in the operating room using the radioactive counter probe, which allows the surgeon to check the position of the sentinel lymph node prior to making an incision, in order to identify it in the surgical wound and then, after ablation, to confirm the absence of any residual radioactivity. The study has already generated some more than encouraging results and shows the value of peri-operative imaging techniques [17].
5 Radiation Hard Sensors

The forward region of the ILC represents an extremely challenging environment. The beam-related backgrounds in this area are ferocious and the radiation levels are comparable to the LHC. At the same time, however, this region is critical to provide fast feedback on the conditions of the beam. Furthermore, it needs to provide hermetic coverage and particle identification capabilities of forward produced particles to enable studies of a certain phase space of physics. The Forward Calorimetry (FCAL) collaboration is developing novel technologies for special calorimeters in the very forward region of the ILC detectors. These calorimeters, positioned near the beam-pipe, must tolerate extremely high radiation doses, up to MGy per year and several sensor materials like poly- and single-crystal chemical vapor deposition (CVD) diamonds, sapphire and GaAs have been investigated. Similar radiation loads are faced near the beam pipe of the LHC experiments. Beam condition monitors have been foreseen to protect the inner tracking detectors from adverse beam conditions. They were designed with poly- and single-crystal diamond sensors to measure beam halo particles and collision products with time-resolutions from micro- to nano-seconds.

The experience acquired in the FCAL collaboration with extremely radiation hard sensors and the fast readout and feedback systems was essential for the completion and commissioning of the fast beam condition monitor of the CMS experiment in a challenging short time. Eight single crystal 5x5 mm$^2$, 500 μm thick diamond sensors were installed near the beam pipe on both sides of the interaction point in the CMS detector (see Fig. 16) to continuously monitor the particle flux from beam halo and interaction particles. A stand-alone readout and DAQ system delivers in addition arrival time distributions with nanosecond resolution allowing control of the beam conditions at a bunch-by-bunch level. This detector [18] has become an invaluable tool to monitor the beam conditions for a safe operation of the inner tracking detectors of CMS. The ILC-based R&D has allowed this detector to be completed much faster than otherwise
possible, mitigating the enormous risks the beams could pose to the CMS tracking detectors.

Fig. 16: A module of the beam condition monitoring detector, containing a radiation hard single crystal diamond sensor, preamplifier and laser for optical signal transmission, as installed around the beam-pipe within the CMS detector.

6 Software

The physics and detector response simulation software developed for ILC detector studies was written with flexibility as well as functionality in mind. Many years have been invested into the development of the software and the construction of a library of analysis tools. Almost all of the substantial amounts of test beam data have been analyzed within the ILC software frameworks. It therefore does not come as a surprise that the adaptation of ILC technologies to other areas of science have benefited from the substantial software chest available. For example, the evaluation of the performance of the DEPFET technology as vertex detector for the BELLE-II detector was carried out with the lcsim Monte Carlo framework [1]. Similarly, scientists on NOvA are using elements of the reconstruction software, first developed for Particle Flow Analysis at the ILC, to reconstruct showers in their detector. In Europe, the just-launched AIDA project will include, among many other things, common software development for future accelerators, much of it seeded by development done in the context of ILC.

In addition to these opportunistic uses of the ILC software, new experiments have fully adopted the lcsim software framework for their experiment. The recently proposed Heavy Photon Search (HPS) experiment [19] at Jefferson Laboratory (JLab) employs silicon trackers and a crystal electromagnetic calorimeter in a fixed target topology. The lcsim
based ILC software, with only minor modifications, is now being used for simulations intended to optimize the performance of the detector, and will be used for the event reconstruction, including the online trigger. DarkLight, another "heavy photon" search experiment proposed at JLab [20], is also investigating the use of this software to optimize its detector, which employs a gas-jet target surrounded by a gaseous tracker. The ILC software framework was also used by a group at SLAC to study the upgrades to the ATLAS inner detector. At the time, the official ATLAS simulation framework was limited to 32-bit identifiers, limiting the number of pixels, which could be studied. The ILC software was able to perform a number of initial studies during the months it took to modify the official ATLAS C++ framework.

The Muon Collider physics and detector design study has also recently decided to adopt this framework for its initial studies, aimed at producing a performance document for the proposed 2013 DPF Snowmass meeting.

The development of the ILC software suite has also had a major impact on the development of the detector design concepts and subsequent preparation of the conceptual design report for CLIC as well as the development of the GEANT4 Monte Carlo simulation framework. Although both are in some sense part and parcel of the broader ILC physics program, they deserve to be highlighted. The Physics and Detector Study Group for the Compact Linear Collider (CLIC) considered two detectors for their conceptual design and undertook an evaluation of their performance in the CLIC environment. The two detector concepts were based on the ILC detector concepts. The readily available ILC software enabled the group to evaluate the physics capabilities of the two concepts in a record time [21]. Another impact to the larger particle physics community of the availability of the ILC software is its contribution to the further development of the GEANT4 Monte Carlo code. Hadronic showers are notoriously difficult to simulate and the Monte Carlo simulations rely heavily on extrapolated parametrizations. The unprecedented insight the ILC test beam campaigns have had on the understanding of the development of hadronic showers directly feeds into an improvement of the Monte Carlo simulations, which benefits the community at large.

7 Summary

Our record of forecasting science and technology research impacts is very poor. Sometimes, often in these economically challenging times, the impact of basic fundamental research is being questioned. We are often asked to better explain to the public what we do and what we learn, to explain what benefits there are to society and what society can expect from continued investment in fundamental research and, lastly, to organize the research in such a way to maximize its benefits to society. The word spin-off is often used to capture these concerns. Scientific activities are in our current view connected to four major activities of humankind: the development of a unique scientific culture and the growth of a patrimony of wetware, software and hardware technologies [22]. The ‘spin-off’ of the detector research and development for the ILC is clearly apparent in all four areas, as highlighted through a few selected examples in this report. Through the unique characteristics of lepton colliders, the community plays a
complementary role in the particle physics culture. Its creativity in pursuing new paradigms, such as particle flow, and the application of ideas to areas outside the realm of particle physics are all manifestations of its contribution to the further development of wetware. The construction of real detectors and deploying them in the field contributes to the software and hardware development. Though the funding for ILC detector R&D has ebbed and waned, the community has consistently demonstrated the widespread benefits resulting from inquiry-based research, for the field of particle physics and beyond.

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9 References


[2] Mimosa is an acronym that stands for Minimum Ionizing particle MOS Active pixel sensor. See also http://www.phc.cnrs.fr/-PICSEL-.html


G. Deptuch, M. Demarteau, J. Hoff, R. Lipton, A. Shenai, R. Yarema, T. Zimmerman, “Pixel detectors in 3D technologies for high energy physics”, 3D Systems Integration Conference (3DIC), 2010 IEEE International, 10.1109/3DIC.2010.5751483, 2010, Page(s): 1 – 4


