super-fast super-sensitive detectors

by Mike Perricone

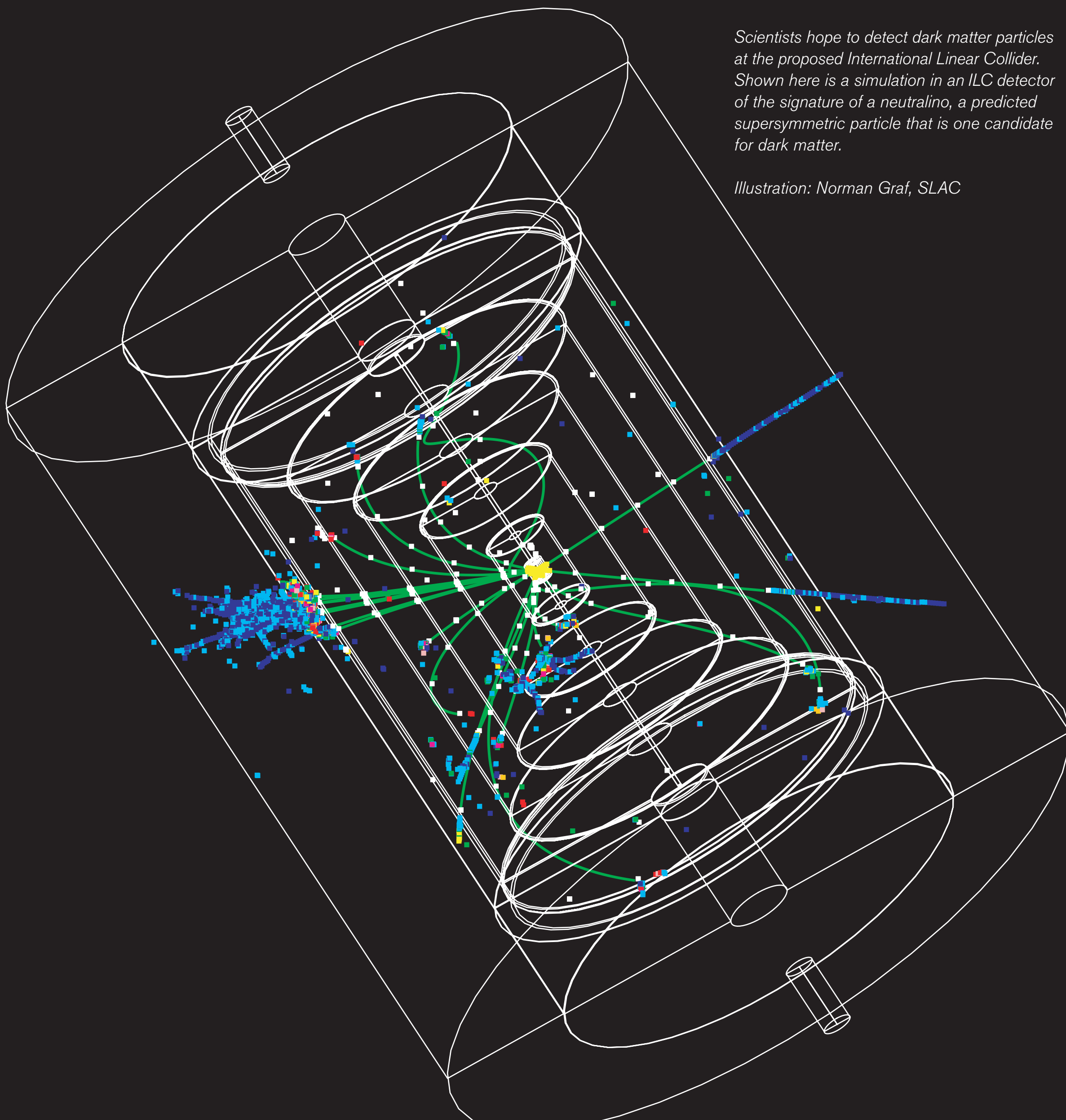
Only detectors with the greatest precision capabilities will measure up to the machine seeking to explore supersymmetry, dark matter, the Higgs mechanism, and new physics that hasn't yet been imagined. Their shapes and configurations might be familiar, but their inner workings–the materials and electronics charged with creating views of new physics–will carry a symbolic branding: "Product of the 21st century."

Detector technology for the proposed International Linear Collider (ILC) will need to surpass even the next-generation detectors nearing completion at the Large Hadron Collider (LHC) at the European laboratory CERN. "We'll have to be much better to pull the physics out of the ILC," says Harry Weerts, a former DZero co-spokesperson, now on sabbatical from Michigan State University to coordinate ILC detector research and development at Fermilab. "It's amazing how much better we'll have to be."

Particle detectors have evolved from simple foil-covered plates, used by Ernest Rutherford to discover the atomic nucleus in 1911, to gargantuan assemblies with concentric cylindrical layers of sensors and shielding weighing thousands of tons, like the ones used to discover the top quark at Fermilab in 1995.

Detectors at colliders such as Fermilab's Tevatron, SLAC's PEP-II machine, and soon the LHC, feed scientific discoveries by tracking the remnants of high-energy collisions, yielding information on the charge and momentum of particles. The closer the detector's sensors can get to the collisions and the greater the sensitivity ("granularity") they can offer, the greater their potential for discovery.

Jim Brau of the University of Oregon, along with his co-authors of a 2002 paper on ILC detector research and development, mapped several innovations for the new detector arrays that would go beyond the scope of LHC detectors. Included are an innermost layer that is 3-6 times closer to the interaction region where the collisions take place; detector pixel sizes that



Scientists hope to detect dark matter particles at the proposed International Linear Collider. Shown here is a simulation in an ILC detector of the signature of a neutralino, a predicted supersymmetric particle that is one candidate for dark matter.

Illustration: Norman Graf, SLAC

are 30 times smaller; and the ability to operate without "triggers" that filter out collision events deemed uninteresting.

A comparatively "clean" environment at the ILC will make some detector tasks simpler than at the LHC. The ILC's electron-positron collisions will involve fundamental particles, while the LHC's colliding proton beams involve more complex, composite particles.

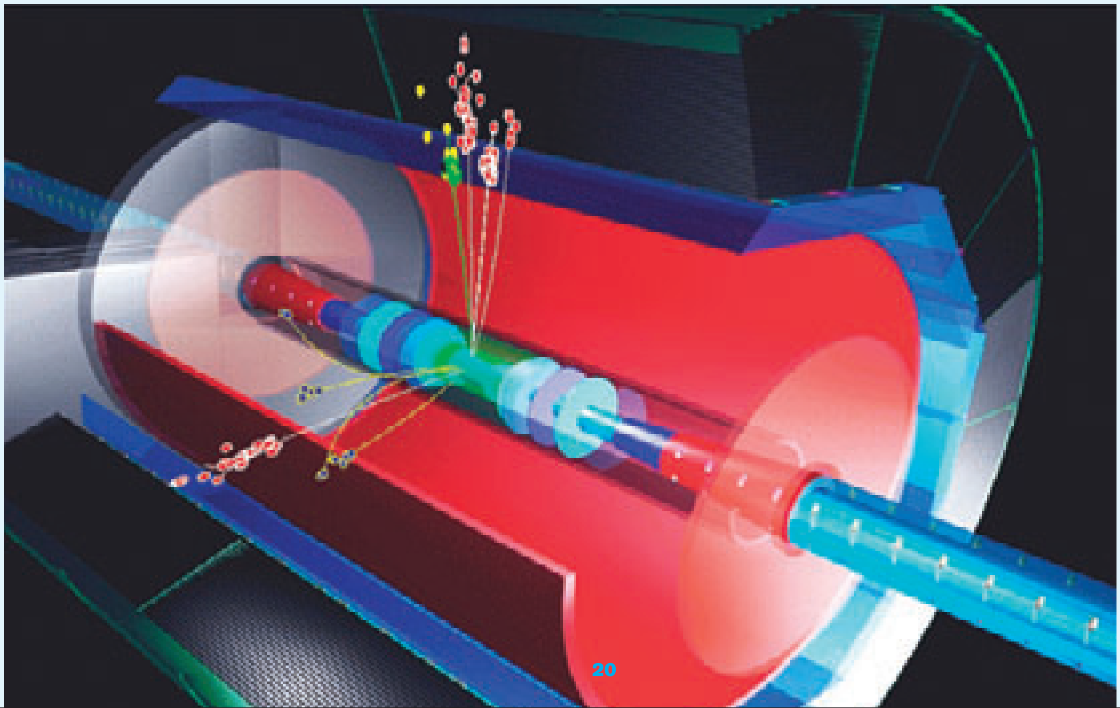
"The general features of the ILC experimental environment are quite different from the LHC, which allows us to build detectors with more precise elements," says Brau, who is also co-chair of the World Wide Study of Physics and Detectors for the ILC. "For example, the much smaller and thinner vertex detector pixels, positioned much closer to the interaction region; or the much more finely segmented calorimeters. The interaction rate at the ILC is much lower than that at the LHC, which means the background radiation is significantly lower, and the event rate is much slower. These features make such optimization of the detectors feasible. Since the event rate is low, and the density of interesting events within the full set of interactions is much higher, we can collect all the events—that is, operate without a trigger—and then separate the events off-line."

SiD + LDC + GLD

The three ILC detector concepts under development around the globe—called SiD, LDC, and GLD—have largely grown through interdependent collaborations, independent of any central direction. They overlap the three regions serving as the basis for ILC organization; there is no "European design," nor "Asian design," nor "American design." Groups working on sub-assemblies and components often contribute to all three concepts—three early concepts, as researchers are quick to emphasize, avoiding any implication that one has a leg up on the others.

The challenge of oversight was recognized early, and the World Wide Study (WWS) was formed in 1998 to help coordinate regional efforts. The immediate goal for detectors, says WWS co-chair David Miller of University College London, is to "make sure that enough R&D work is being done now on the key technologies so that we can be sure to have the precision needed for the ILC to deliver its full physics program. It would be very sad to start up a new collider in 2015, for example, and know that the physics performance was limited unnecessarily by the detectors."

All three detector concepts seek the best system for tracking large numbers of particles in magnetic fields, which would be stronger than in existing detectors. The Silicon Detector (SiD) would use silicon technology



Simulated particle collision in the TESLA detector, which was developed at DESY in Germany and has served as a basis for several aspects of ILC detector concepts. In the center of the detector are various devices to trace the paths of the particles: the vertex detector (green), tracking chamber (red), electromagnetic calorimeter (blue), and hadronic calorimeter (black). The particle bunches are made up of electrons and positrons, which hurtle in opposite directions through the beam pipe (blue), entering the detector from both sides and colliding in the center of it. The results of this "collision event" are symbolized by the colored tracks and points.

Illustration: DESY Hamburg

exclusively; the Large Detector Concept (LDC), would have a large, gaseous Time Projection Chamber (TPC), which can observe particles moving in real time, for its outer tracker; and the GLD (approximately Global Large Detector, "depending on who you ask," says one researcher), would include both a gaseous TPC outer tracker and an inner tracker of silicon strips. All three detector concepts will attempt an innovative whole-detector approach for calorimeters called "particle flow."

"Behind the trackers we slam the particles into dense calorimeters and convert their energies into electronic pulses," says Miller. "The new thing at the ILC is to combine the results from tracking and calorimetry to get at the 'particle flow,' where the tracks and clusters are combined to reconstruct what the quarks were doing before they turned into untidy jets of mesons and other particles. [In simulations,] the clusters in the calorimeters are small, which means we can identify which of them are associated with tracks and which of them are separate because they were made by neutral particles."

Silicon-tungsten calorimetry was first developed at SLAC for the SLD experiment, and at CERN for the OPAL and ALEPH detectors. Brau says those detectors used small silicon-tungsten calorimeters to monitor luminosity, "and we now aim to extend the approach to a much larger scale." Achieving excellent particle flow measurements drives the development of very fine-grained silicon-tungsten calorimeters of the kind being studied by the CALICE (CAlorimeter for the LInear Collider with Electrons) collaboration, encompassing 190 physicists and engineers from 32 institutes and 9 countries spread out among all three regions (America, Asia, and Europe).

A collaboration of SLAC, University of Oregon, and Brookhaven National Laboratory is advancing an electromagnetic calorimeter with somewhat different electronics and mechanical design; another group in Asia has completed some beam tests of a silicon-tungsten calorimeter as a start on studying this technique.

Organizing information

The cross-connections among all these detector groups prompted the appointing of a nine-member ILC Detector Research and Development Panel in March 2005, before the Linear Collider Workshop at Stanford Linear Accelerator Center. Membership draws from all three regions. (In particular, members come from the United States, United Kingdom, Japan, Korea, France, and Germany.) The mission is simple but critical: gather definitive information to find out what's going on, and where, and post it on the Web.

"We have an embryonic Website," says panel chair Chris Damerell of Rutherford Laboratory in the United Kingdom, "and our initial task is to get all the detector R&D groups worldwide to complete an information page on that Web site. Once this is done, users will be able to find out all that has been achieved recently, and is going on now, in terms of detector R&D for the ILC, categorized in terms of vertexing, tracking, calorimetry, and all other areas. An additional role [for the panel] is to obtain, from the three 'concept studies' for ILC detectors, reports on the detector R&D they need to have completed, and on what timescale, in order to turn their studies into proposals."

Finding funding

Advancing the R&D, establishing time-scales, turning studies into proposals—all require funding as the common and indispensable ingredient. Efforts in the United States currently can draw on approximately $800,000, underwritten jointly by the Department of Energy Office of Science ($700,000) and the National Science Foundation ($100,000).

Detector funding in Europe is characterized as "uneven" by WWS co-chair Miller, who says it varies by individual countries. The United Kingdom,

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he observes, has been receptive to linking the ILC with technology that enables the application of accelerators, and superconducting linacs in particular, to many fields of science. “Both SLAC and DESY have demonstrated this [link] by their development of free electron lasers which could only work because of the demands for beam quality which were set–and met–by the ILC program,” Miller says. “In the UK, it has been accepted that some of the R&D funding should go into detector development, though the larger share is going into accelerator technologies. Over the last three years the European Union has also stepped in with useful funding for linear collider developments across the continent, and they also have recently added a detector development component to complement the accelerator R&D.”

Detector efforts may need to mature before following the Asian funding model for research, which encompasses close connections with industry. “In Japan, once the project is approved and the detector conceptually designed, industries would play important roles from the detailed design of the sub-detectors to actual installation,” says Hitoshi Yamamoto of Tohoku University, co-chair of the World Wide Study with Brau and Miller. “However, at this stage, there is no serious involvement by industries.”

Testing, testing

Detector concepts and subassembly efforts will eventually move toward convergence, much as the August 2004 report of the International Technology Recommendation Panel chose superconducting radio-frequency technology to end the dual tracks of “warm” and “cold” accelerator R&D. The August 2005 Snowmass workshop, sponsored by the American Linear Collider Physics Group, aimed to establish common reference points (“baselines”) to guide development of the three concepts. Barry Barish, head of the ILC Global Design Effort, is asking for three significant detector planning documents: an early review of essential detector R&D; then, by the end of 2006, the outline of a Reference Design Report, and a clear case for building one detector or two.

There are also plans to begin beam testing of major detector sub-assemblies in summer 2006, with a significant effort underway by the ILC Calorimeter Test Beam Group of Jae Yu (University of Texas-Arlington), Felix Sefkow (DESY, Germany), Vaclav Vrba (Prague University, Czech Republic), and Kiyotomo Kawagoe (Kobe University, Japan). A planning document has been filed for the use of the Meson Test Beam Facility at Fermilab, but test beams at CERN and at IHEP-Protvino in Russia are also being considered. “You can do many simulations,” says Yu, “but in the end you need beam. Nothing is better than data.”

Beam testing is also an important symbolic step. Yu cited one scaled-down hadron calorimeter, with a volume of one cubic meter, which could be ready for beam testing in about a year: it would consist of 40 active layers, with 10,000 channels in each layer for a total of 400,000 channels. In comparison, there are 50,000 total channels in the calorimeter of the 5000-ton DZero detector at Fermilab. Beam testing brings the future even closer.

“It’s something tangible, and that’s important,” Yu says. “It will mean lots of students, lots of papers, lots of training. That’s good for the future of field.”

For the next generation of physicists, it will mean careers that are products of the 21st century, searching for 21st-century science.

Detector basics

Cross-section view of a typical particle detector, looking along the beam pipe for a colliding beam of electrons (e^-) and positrons (e^+). Each detector component tests for a specific set of particle properties.

Tracking chamber: Determines trajectories of charged particles.

Electromagnetic calorimeter: Measures total energy of electrons (e^-), positrons (e^+), and photons. These particles produce showers of e^+/e^- pairs in the material. The number of final *e*-pairs is proportional to the energy of the initiating particle.

Hadron calorimeter: Measures total energy of hadrons (particles made of strongly-interacting constituents, quarks and/or gluons). Hadrons interact with dense material in this region, producing a shower of charged particles. Energy deposited by these charged particles is then measured.

Muon chamber: Only muons and neutrinos traverse the entire detector and get this far. This chamber detects muons, but neutrinos escape without leaving a trace. The presence of neutrinos is inferred by "missing" energy.

Magnet: Forces charged particles to travel along a curved path. Radius of curvature and direction indicate the momentum of particle and the sign of the charge (positive or negative).