BUILDING THE NEXT-GENERATION COLLIDER

To further investigate the intricacies of high-energy particle physics, researchers must construct a more powerful electron-positron collider

By Barry Barish, Nicholas Walker and Hitoshi Yamamoto

A new era in physics will open up when the Large Hadron Collider (LHC) extends the reach of subatomic particle investigations to unprecedented energy scales. But even before researchers initiate the first high-energy collisions in the LHC's giant storage ring, located under the French-Swiss border, they are already contemplating and working toward the next great particle accelerator. And the consensus choice of the particle physics community is a proposed facility called the International Linear Collider (ILC), a machine more than 30 kilometers long that would smash electrons and positrons together at velocities very close to the speed of light. (The positron is the antimatter counterpart of the electron, identical in mass but opposite in charge.)

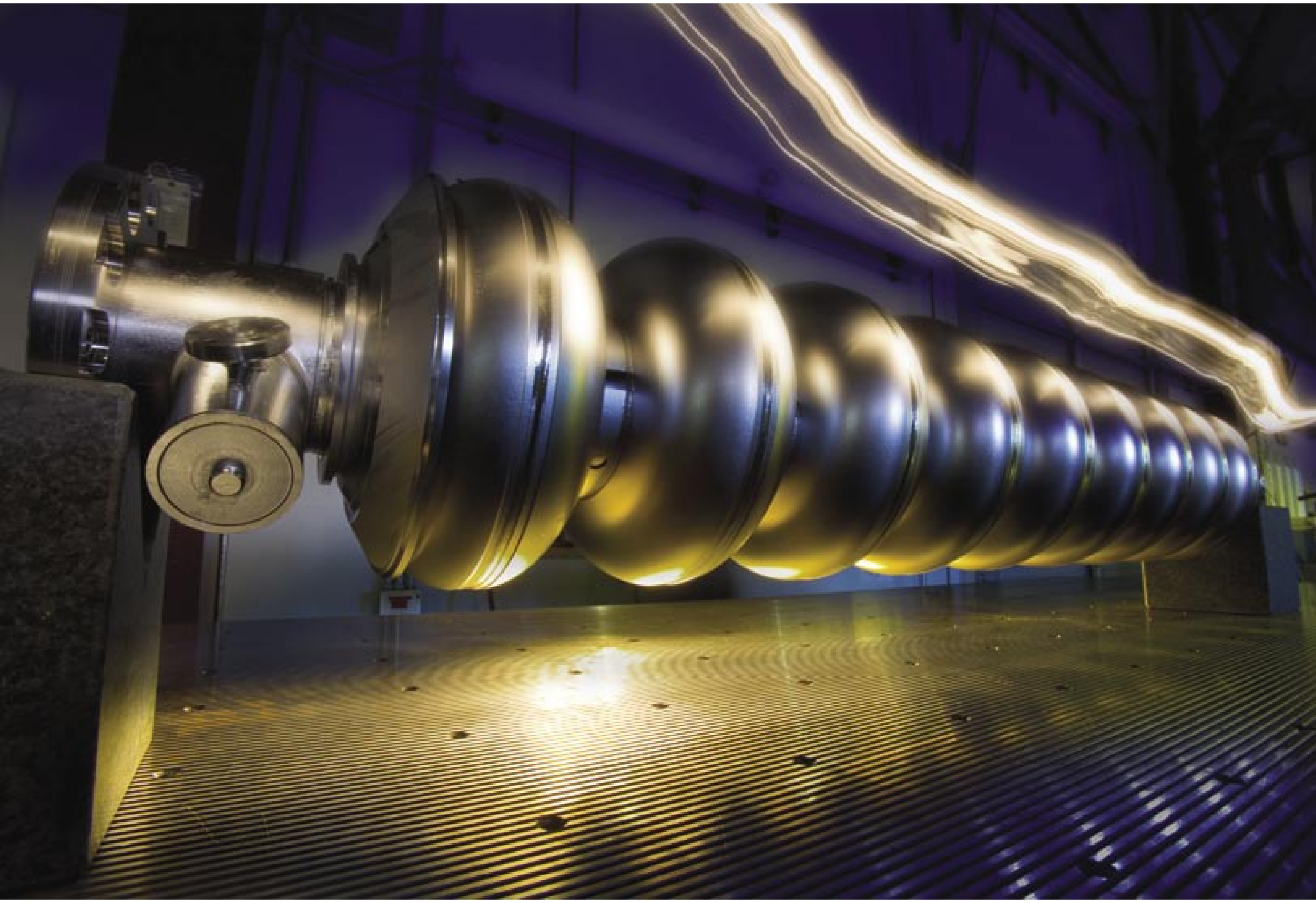
Far more powerful than previous electron-positron colliders, the ILC would enable physicists to follow up any groundbreaking discoveries made by the LHC. The LHC is designed to investigate the collisions of protons, each of which is actually a bundle of three quarks bound together by gluons (the particles carrying the strong nuclear force). Because the quarks and gluons within a proton are constantly interacting, a proton-proton collision is an inherently messy affair. Researchers cannot be certain of the energy of each quark at the moment of the collision, and this uncertainty makes it difficult to determine the properties of novel particles produced by the impact. But the electron and positron are fundamental particles rather than composites, so physicists working with an electron-positron collider can know the energy of each collision to great accuracy. This capability would make the ILC an extremely useful tool for precisely measuring the masses and other characteristics of newly discovered particles [*see box on page 58*].

More than 1,600 scientists and engineers from nearly 300 laboratories and universities around the world are now working on the design of the ILC and the development of the detectors that would analyze its particle collisions. In February 2007 our design team released a cost estimate for the machine: $6.7 billion (not including the expense of the detectors). We have done studies comparing the costs of locating the ILC at three possible sites—CERN, the European laboratory for particle physics near Geneva, the Fermi National Accelerator Laboratory in Batavia, Ill., and the mountains of Japan—and we are developing schemes for the governance of a truly international laboratory. Although the ILC's price tag may seem steep, it is roughly comparable to the costs of large science programs such as the LHC and the ITER nuclear fusion reactor. And if everything proceeds as hoped, the ILC could start illuminating the frontiers of particle physics sometime in the 2020s.

KEY CONCEPTS

- The logical successor to the Large Hadron Collider (LHC) is the International Linear Collider (ILC), a proposed facility that would smash electrons and positrons together.
- The ILC's design calls for two 11.3-kilometer-long linear accelerators that would use strong electric fields to accelerate particles through a string of vacuum chambers called cavities.
- In addition to overcoming technical challenges, the ILC's planners must secure funding for the project and choose a site before the collider can be built.

—The Editors



BASIC ELEMENT of the International Linear Collider design is a one-meter-long niobium cavity consisting of nine bead-shaped cells. When cooled to very low temperatures, the cavity becomes superconducting and can efficiently generate the electric fields needed to accelerate the electrons and positrons.

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Birth of a Collider

In August 2005 about 600 physicists from around the world gathered in Snowmass, Colo., to start planning the development of the ILC. But the true beginnings of the project go back to the commissioning of CERN's Large Electron-Positron (LEP) collider in 1989. The LEP accelerated electrons and positrons in a storage ring with a circumference of 27 kilometers, then smashed the particles together, producing impacts with energies as high as 180 billion electron volts (GeV). It was clear, though, that the LEP would be the largest collider of its kind, because accelerating electrons and positrons to energies in the trillion-electron-volt (TeV) scale—also known as the terascale—would require a ring several hundred kilometers in circumference and would be completely cost-prohibitive.

The major obstacle to a storage ring solution is synchrotron radiation: relatively light particles such as electrons and positrons happily radiate their energy as they speed around the ring, their paths continuously bent by the ring's many dipole magnets. Because these losses make it progressively harder to accelerate the particles, the cost of building such a collider is proportional to the square of the collision energy: a machine that doubled the LEP energies would cost four times as much. (The energy losses are not as severe for colliders that accelerate heavier particles such as protons; hence, the tunnel dug for the LEP ring is now being used by the LHC.)

A more cost-effective solution is a linear collider, which avoids synchrotron radiation by accelerating particles in straight lines rather than in a ring. In the ILC design, two 11.3-kilometer-long linear accelerators, or linacs—one for electrons, one for positrons—are aimed at each other, with the collision point in the middle. The downside is that the electrons and positrons must be accelerated from rest up to the collision energy on each pulse of the machine instead of building up speed with each circuit of the storage ring. To obtain higher collision energies, one can simply build longer linear accelerators. The cost of the facility is directly proportional to the collision energy, giving linear colliders a clear advantage over the storage ring concept at the TeV scale.

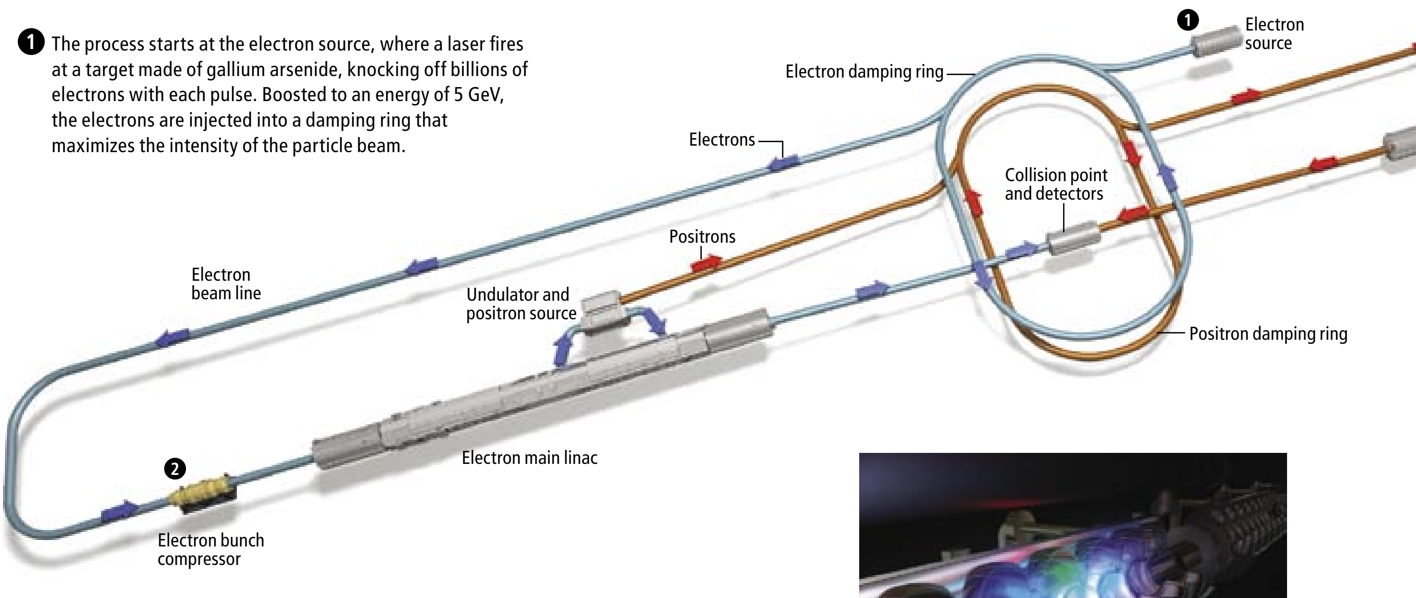
At the same time that the LEP was being constructed in Europe, the U.S. Department of Energy was building a competing machine at the Stanford Linear Accelerator Center (SLAC). SLAC's device, which was considered a proof of principle of the linear collider concept, used a three-kilometer-long linac to accelerate bunches of electrons and positrons in tandem, boosting them to energies of about 50 GeV. The bunches were then magnetically separated and bent around to bring them into a head-on collision. Although SLAC's machine—which operated from 1989 to 1998—was not exactly a true linear collider, because it employed only one linac, the facility paved the way for the ILC.

Planning for a TeV-scale linear collider began in earnest in the late 1980s and early 1990s when several competing technologies were proposed. As researchers developed these proposals over the next decade, they focused on the need to keep the linear collider affordable. Finally, in August 2004, a panel of 12 independent experts assessed the proposed technologies and recommended a design conceived by the TESLA group, a collaboration of scientists from more than 40 institutions, coordinated by the

[HOW IT WOULD WORK]

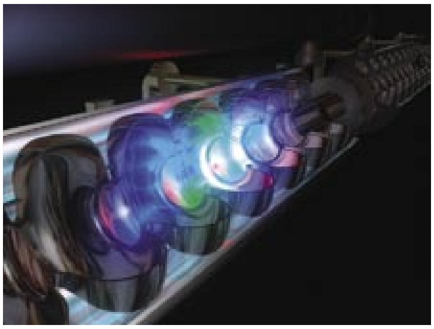
COLLIDER OF THE FUTURE

More than 30 kilometers long, the proposed ILC would be the most powerful linear collider ever built. Its linear accelerators, or linacs, would boost electrons (*blue*) and positrons (*orange*) to energies of 250 billion electron volts (GeV), then smash the particle beams into one another.



1 The process starts at the electron source, where a laser fires at a target made of gallium arsenide, knocking off billions of electrons with each pulse. Boosted to an energy of 5 GeV, the electrons are injected into a damping ring that maximizes the intensity of the particle beam.

2 The electrons are transferred to a bunch compressor that squeezes the clusters of particles and accelerates them to 15 GeV. Then the electrons proceed to one of the main linacs, which speeds the particles to 250 GeV. Midway through the linac, the electron bunches take a detour to a special magnet called an undulator, which radiates some of their energy into gamma rays. The gamma photons then strike a rotating target to produce electron-positron pairs; the positrons are captured, accelerated to an energy of 5 GeV and then shunted to another damping ring.

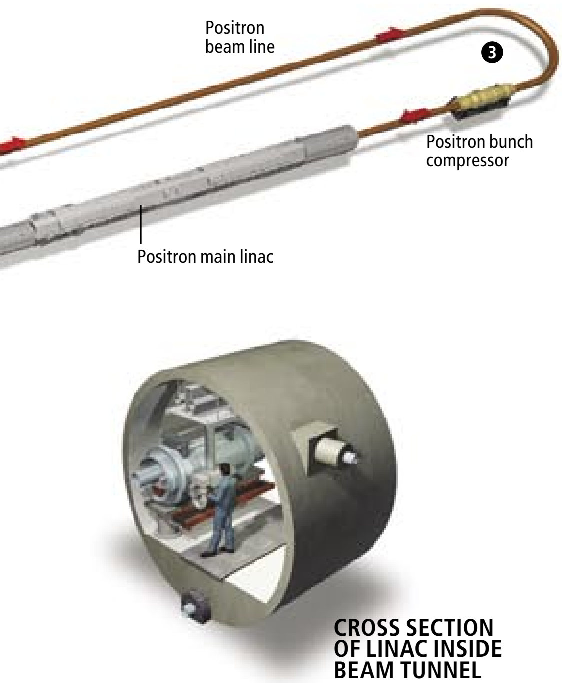


Computer simulation of the electric field inside the linac that accelerates the particles.

DESY research center in Hamburg, Germany. Under this proposal, the electrons and positrons would travel through a long series of vacuum chambers called cavities. Constructed from the metal niobium, these cavities can be superconducting—when cooled to very low temperatures, they can conduct electricity without resistance. This phenomenon would enable the efficient generation of a strong electric field inside the cavities that would oscillate at radio frequencies, about one billion times per second. This oscillating field would accelerate the particles toward the collision point.

The basic element of this superconducting radio-frequency (SCRF) design is a one-meter-long niobium cavity consisting of nine cells that can be cooled to a temperature of two kelvins (–456 degrees Fahrenheit). Eight or nine cavities would be attached end to end in a string and immersed in ultracold liquid helium in a tank called a cryomodule [*see illustration on page 59*]. Each of the two main linacs in the ILC would require about 900 cryomodules, giving the collider about 16,000 cavities in all. Researchers at DESY have so far constructed 10 prototype cryomodules, five of which are currently installed in FLASH, a laser at DESY that employs high-energy electrons. The SCRF technology will also be incorporated into DESY's upcoming European X-Ray Free-Electron Laser (XFEL), which will string together 101 cryomodules to form a superconducting linac that can accelerate electrons to about 17.5 GeV.

Because the ILC's linacs can be shorter (and hence less expensive) if the cavities can generate a stronger electric field, the design team has set an aggressive goal of improving the performance of the SCRF system until it can give the particles an energy boost of 35 million electron volts (MeV) for every meter they travel. Several prototype cavities have already exceeded this goal, but it remains a challenge to mass-produce such devices. The key to high performance is ensuring that the inner surface of the cavity is ultraclean and defect-free. The preparation of the cavities and their installation in the cryomodules must be done in clean-room environments.



3 The positrons travel to the opposite end of the ILC, where they are compressed and accelerated to 250 GeV by the other main linac. Magnetic lenses focus the electron and positron beams as they race toward one another, and detectors at the collision point analyze the particles hurtling from the high-energy impacts.

DON FOLEY (*collider schematic*); DESY HAMBURG (*field simulation*)

The ILC in a Nutshell

The ILC design team has already established the basic parameters for the collider [*see box at left*]. The machine will be about 31 kilometers long, with most of that length taken up by the two superconducting linacs that will set up electron-positron collisions with 500 GeV energies. (A 250-GeV electron striking a 250-GeV positron moving in the opposite direction will result in a collision with a center-of-mass energy of 500 GeV.) At a rate of five times per second, the ILC will generate, accelerate and collide nearly 3,000 electron and positron bunches in a one-millisecond-long pulse, corresponding to an average total power of about 10 megawatts for each beam. The overall efficiency of the machine—that is, the fraction of electrical power converted to beam power—will be about 20 percent, so the two linacs will require a total of about 100 megawatts of electricity to accelerate the particles.

To produce the electron beam, a laser will fire at a target made of gallium arsenide, knocking off billions of electrons with each pulse. These particles will be spin-polarized—all their

[THE AUTHORS]

Barry Barish, Nicholas Walker and Hitoshi Yamamoto are all well versed in the science of electron-positron collisions. Barish is director of the global design effort for the International Linear Collider (ILC), as well as Linde Professor of Physics Emeritus at the California Institute of Technology. His research interests range from neutrinos to magnetic monopoles to gravitational waves. Walker, an accelerator physicist based at DESY in Hamburg, Germany, has worked 15 years on linear collider design and is one of three project managers for the ILC Engineering Design Phase. Yamamoto, a professor of physics at Tohoku University in Japan, has worked on collider experiments conducted at the Stanford Linear Accelerator Center, the Cornell Electron Storage Ring and Japan's High Energy Accelerator Research Organization (KEK).

SAMPLE SITES

The ILC's planners have analyzed the costs of locating the collider at three possible sites:

EUROPE
At CERN, the European laboratory for particle physics near Geneva.

U.S.
At the Fermi National Accelerator Laboratory in Batavia, Ill.

JAPAN
Along a mountain range in an unspecified part of the country.

spin axes will point in the same direction—which is important for many particle physics investigations. The electrons will be rapidly accelerated in a short SCRF linac to an energy of 5 GeV, then injected into a 6.7-kilometer storage ring at the center of the complex. As the electrons circulate and emit synchrotron radiation, the bunches of particles will be damped—that is, their volume will decrease, and their charge density will increase, maximizing the intensity of the beam.

When the electron bunches exit the damping ring 200 milliseconds later, each will be about nine millimeters long and thinner than a human hair. The ILC will then compress each electron bunch to a length of 0.3 millimeter to optimize its acceleration and the dynamics of its subsequent collisions with the corresponding positron bunch inside the detector. During the compression, the bunches will be boosted to an energy of 15 GeV, after which they will be injected into one of the main 11.3-kilometer-long SCRF linacs and accelerated to 250 GeV.

Midway through the linac, when the particles are at an energy of 150 GeV, the electron bunches will take a small detour to produce the positron bunches. The electrons will be deflected into a special magnet known as an undulator, where they will radiate some of their energy into gamma rays. The gamma photons will be focused onto a thin titanium alloy target that rotates about 1,000 times per minute, and the impacts will produce copious numbers of electron-positron pairs. The positrons will be captured, accelerated to an energy of 5 GeV, transferred to another damping ring and finally sent to the other main SCRF linac at the opposite end of the ILC. Once the electrons and positrons are fully accelerated to 250 GeV and rapidly converging toward the collision point, a series of magnetic lenses will focus the high-energy bunches to flat ribbon beams about 640 nanometers (billionths of a meter) wide and six nanometers high. After the collisions, the bunches will be extracted from the interaction region and removed to a so-called beam dump, a target that can safely absorb the particles and dissipate their energy.

Every subsystem of the ILC will push the technological envelope and present major engineering challenges. The

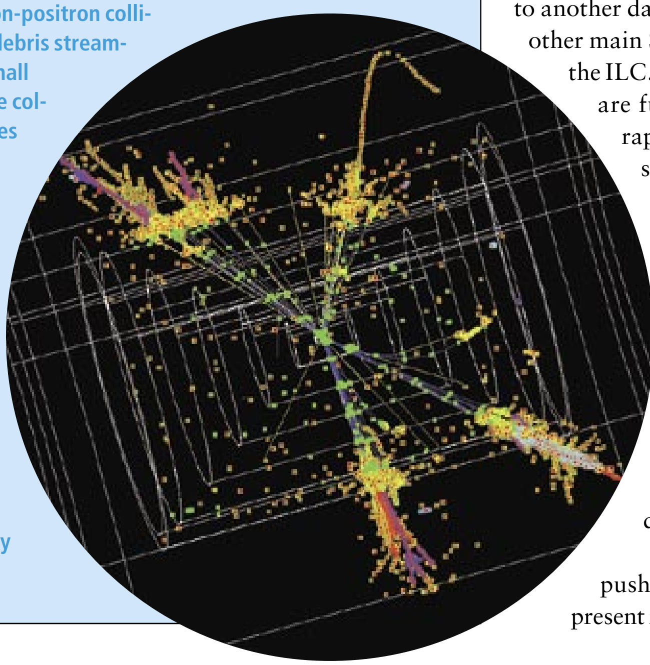
[A COLLIDER COMPARISON]

The Hammer and the Scalpel

To understand the complementary relation between the Large Hadron Collider (LHC) and the proposed International Linear Collider (ILC), imagine the former as a hammer that breaks open a walnut and the latter as a scalpel that carefully slices the bits of meat inside. The LHC will accelerate protons to energies of seven trillion electron volts (TeV), giving each head-on proton-proton collision a total energy of 14 TeV and providing researchers with their first direct look at physics at this energy scale. The collisions may generate the production of particles whose existence has been hypothesized but not yet observed. One such particle is the Higgs boson. (According to the Standard Model—the widely accepted theory of particle physics that can explain electromagnetism and the weak and strong nuclear forces—the Higgs endows all other particles with mass.) Other examples are the supersymmetric particles, which are hypothesized partners of the known particles. (The putative partner of the electron, for example, is called the selectron; the photon's partner is the photino.) Furthermore, the LHC may find evidence for extra dimensions that can be detected only by observing high-energy events.

If the Higgs boson does exist, physicists expect that the LHC will detect the particle, measure its mass and determine its interactions with other particles. But scientists will not be able to specify the detailed properties of the Higgs from the LHC's messy proton-proton collisions. The more precise ILC would be needed to measure important characteristics such as the strength of the Higgs's interactions. This information would be invaluable to physicists because it could test the validity of the Standard Model: Does it correctly describe high-energy events, or are other theories needed? Investigations of supersymmetric particles in the ILC could also help physicists flesh out the details of new theories. The results may reveal whether some of these particles could be constituents of the so-called dark matter that makes up one quarter of the energy content of the universe.

Yet another particle that could be revealed by the LHC is the hypothesized *Z*-prime boson, a counterpart to the *Z* boson, which is one of the carriers of the weak nuclear force. Because the discovery of the *Z*-prime particle would indicate the existence of a new fundamental force of nature, physicists would be very interested in determining the properties of this force, its origins, its relation to the other forces in a unified framework and its role in the earliest moments of the big bang. The ILC would play a definitive role in addressing such issues. Finally, if history is any guide, it seems very likely that the LHC and the ILC will discover unanticipated new phenomena that are at least as interesting and important as the ones already discussed. ***—B.B., N.W. and H.Y.***



COMPUTER SIMULATION of an electron-positron collision in the ILC shows the particle debris streaming from the impact point. Each small square indicates a hit on one of the collider's detectors; a group of squares with the same color represents a particle shower. From these data, researchers deduce the nature of the debris: the yellow lines are the paths of neutral particles (mostly photons), and the blue lines are the trajectories of charged particles (primarily pions, consisting of pairs of quarks). This simulation predicts what researchers would see if the electron-positron collision produced a Higgs boson and a *Z* boson, both of which would rapidly decay to lighter particles.

NORMAN GRAF

CRYOMODULES will bathe the ILC's string of niobium cavities with liquid helium to make them cold enough to become superconducting. The devices shown here were tested at the DESY research center in Hamburg, Germany.

collider's damping rings must achieve beam qualities several times better than those of existing electron storage rings. What is more, the high beam quality must be preserved throughout the compression, acceleration and focusing stages. The collider will require sophisticated diagnostics, state-of-the-art beam-tuning procedures and a very precise alignment of its components. Building the positron production system and aiming the nanometer-size beams at the collision point will be demanding tasks.

Developing detectors that can analyze the collisions in the ILC will also be challenging. To determine the strengths of the interactions between the Higgs boson and other particles, for example, the detectors will need to measure the momentum and creation points of charged particles with resolutions that are an order of magnitude better than those of previous devices. Scientists are now working on new tracking and calorimeter systems that will allow researchers to harvest the rich physics of the ILC.

The Next Steps

Although the ILC team has chosen a design for the collider, much more planning needs to be done. Over the next few years, while the LHC starts collecting and analyzing data from its proton-proton collisions, we will strive to optimize the ILC design to ensure that the electron-positron collider achieves the best possible performance at a reasonable cost. We do not yet know where the ILC will be located; that decision will most likely hinge on the amount of financial support that governments are willing to invest in the project. In the meantime, we will continue to analyze the sample ILC sites in Europe, the U.S. and Japan. Differences in geology, topography, and local standards and regulations may lead to different construction approaches and cost estimates. Ultimately, many details of the ILC design will depend on exactly where the collider is built.

In any event, our planning will allow us to move forward at full speed as soon as the scientific discoveries at the LHC reveal the best targets for follow-up research. In parallel with the technical design work, we are creating models for dividing the governance of the ILC project so that each constituency of physicists will have a say. This ambitious undertaking has been truly global in its conception, development and design, and we expect it to be thoroughly international in its construction and operation as well. ■

Every subsystem of the International Linear Collider will push the technological envelope and present major engineering challenges.

➥ MORE TO EXPLORE

More information about the design, technology and physics of the International Linear Collider can be found at:

www.linearcollider.org

www.linearcollider.org/gateway

www.linearcollider.org/cms/?pid=1000437

www.fnal.gov/directorate/icfa/ITRP_Report_Final.pdf

http://physics.uoregon.edu/%7Elc/wwstudy/lc_consensus.html

DESY HAMBURG (*cryomodule*); DESY (*superconducting TESLA cavity*)