Linear colliders

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Early in November CERN, Europe's particle physics laboratory near Geneva announced that it closed down its Large Electron-Positron Collider (LEP) after its operation was extended for one month and its collision energy reached 209 gigaelectronvolts (GeV). CERN considered extending the life of LEP for another year to confirm the possible observation of traces of the elusive Higgs particle. The decision, which, as Europhysics News is going to press, still has to be endorsed by the Committee to Cern Council, meeting on 17 November. A further postponement of the dismantling of LEP will delay for a few months the start of operations of the Large Hadron Collider (LHC), which will be built in the same tunnel that now houses LEP.

The Higgs particle is the missing piece of the complicated jig-saw puzzle known as the "Standard Model", the theory for describing elementary particles and their interactions. The Higgs particle is the only remaining one described by the Standard Model that up to now had escaped detection. It also holds an important key to the whole of physics by conveying mass to the fundamental particles. For years the only other particles that were predicted but did not show up were the top quark and the tau neutrino: both were discovered at Fermilab, the first in 1995, the second in 2000.

With 209 GeV center-of-mass collision energy, LEP has reached close to the ultimate limit that it can achieve for stored electrons and positrons. Circular machines have the advantage that accelerated particles can go around and around through the same accelerating cavities, increasing their energy with every pass. However, the energy these particles can reach is limited because as their speed increases, they also start shedding energy in the form of synchrotron radiation when they are made to go in circles by bending magnets. These losses are the strongest for light particles, such as electrons and positrons, which lose 10^{13} times as much as protons of the same energy. The LHC, a circular machine, will be able to accelerate protons to a center-of-mass collision energy of 14 teraelectronvolts (TeV) because the particles have larger mass. However, because protons are made up of quarks and gluons, individual collisions between quarks will yield up to 2 TeV in available energy.

Because electrons and positrons produce collisions that are much "cleaner," they are viewed to have certain advantages above the colliding protons in the LHC for investigating energies above those reached by LEP. There is much less background, and the production rates for new particles or events are not that different from the known production rates, says Peter Zerwas, a theorist at DESY, the German particle physics laboratory near Hamburg. "You can project out the new physics elements much easier," he adds. The strength of the LHC will be as an exploratory machine, says John Ellis, a theorist at CERN.

The only machine that can produce high collision energies for electrons and positrons is the linear collider. Because there are no bending magnets, there are no synchrotron radiation losses. Electrons and positrons accelerated in straight paths by two separate accelerators facing each other, collide head-on or at very small angles. Existing designs call for two accelerators that will impart 250 Gev to the leptons, which will release 500 GeV when they collide. In a later stage, the machine may be expanded up to 800 or even 1000 GeV by upgrading the two linacs, either by adding cavities, or by increasing the accelerating power delivered to the existing cavities.

The scientific case

Recently, a group of high-energy physicists met at Fermilab (*) to discuss the "scientific case" for such a linear collider. The study of the Higgs particle will be one of the most important aims of this machine. "Since you operate with a precise energy in a nearly background-free environment, in a certain sense, such a machine can be described as a 'Higgs factory,'" says Zerwas. "We will be able to confirm that the Higgs mechanism is actually responsible for generating the mass of the fundamental particles," says Zerwas.

A second important aim is the study of so-called supersymmetric particles. Many physicists are convinced that all elementary particles that are currently known have a matching supersymmetric partner. "We will study a complete new world, and the supersymmetric world is larger than the Standard-Model world," says Zerwas. And supersymmetry would allow physicists to get a handle on gravitation--one of the fundamental forces. Gravitation has not yet been unified with the three other fundamental forces, the electromagnetic, the weak and the strong nuclear forces. Once the masses of the supersymmetric particles are determined with high precision, "we will be able to do extrapolations to scales close to the 'Planck scale'. We hope that by reconstructing the theory at such a high energy scale we will see for the first time the interaction between gravity and particle physics," says Zerwas.

Prototypes

Several particle-physics laboratories are now experimenting with prototype sections for a linear collider. The Stanford Linear Accelerator Center (SLAC) completed the Next Linear Collider Test Accelerator (NLCTA). At DESY an international collaboration of scientists from 40 institutes from 9 countries built the Tera Electron Superconducting Linear Collidér (TESLA) Test Facility, and Japan's National Laboratory for High-Energy Physics (KEK) in Tsukuba completed a test facility for the Japan Linear Collider (JLC). CERN is experimenting with the Compact Linear Collider (CLIC), with the aim of developing a linac that would reach beyond 1 TeV, possibly up to 2 or 3 TeV, farther in the future. CERN is not planning to partake in an important way with a first 500 MeV linear collider design, says Ellis.

However, the high-energy community agrees that the construction of a full-size machine can only be achieved by an international collaboration. "Even a large lab such as SLAC cannot carry this program by itself," says Gregory Loew at SLAC. This collaboration will not only have to select a site where the accelerator can be built, but also the technology that will be used to accelerate the electrons and positrons.

Key components of the future machine are the accelerator structures. These structures are arrays of cylindrically shaped cavities in which powerful radiowaves accelerate the particles that ride in the accelerating part of the electric field component of the wave. Several thousands of them will be used, and the higher electric gradient they can sustain, the shorter the machine will be. The length, probably around 30 km, will still be daunting.

Two main types of cavity technologies now exist: 'warm' and 'cold' cavities. The warm technology has been developed first: the cavities are made of copper and sup-

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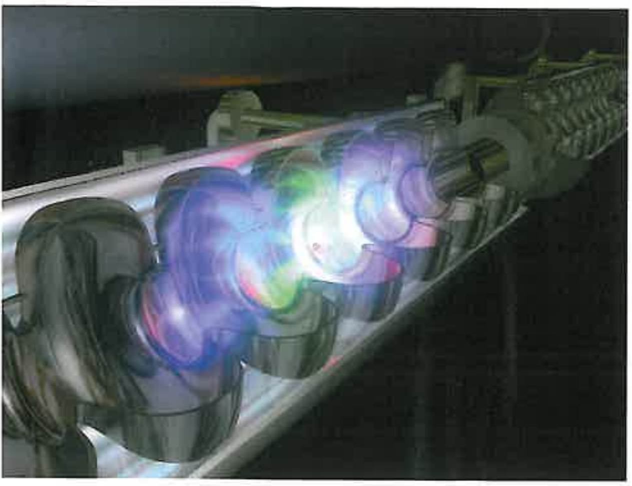

n the superconducting linear accelerator electro-magnetic 'ields accelerate the electrons to almost the speed of light. ͻ DESY Hamburg

plied with radiofrequency power at the highest frequency feasible. Both the NLC-TA and the JLC use copper cavities powered with radiowaves at 11.4 GHz (X-band) produced by klystrons, and achieve an accelerating field of about 50 megavolts per metre. Japan is also studying a machine that would operate at an alternate frequency of 5.7 GHz (C-band). Also CLIC will use copper cavities that will be powered by a 'drive linac' installed along the main linac. In this linac an electron beam supplies the rf power at a frequecy of 30 GHz, hopefully allowing a higher gradient and therefore a shorter machine for the same energy. The drive linac will also allow the machine to operate beyond 1 TeV. At these energies, driving the cavities with klystrons is expected to be problematic, says François Richard, Director of the Laboratoire de l 'Accélérateur Linéaire (LAL) at Orsay in France.

The warm cavities lose energy in the form of ohmic dissipation by induced currents in the cavity walls. TESLA uses a so-called 'cold' technology. The cavities are made from niobium and cooled to liquid-helium temperatures. At these temperatures the cavity walls become superconducting, almost completely eliminating ohmic losses. As a result, almost 100 percent of the radiowave power is transferred to the accelerated electrons or positrons. Today the cavities routinely achieve an accelerating gradient of 25 MV/m, which for an 800-GeV design would be upgraded to 35 MV/M, while 42 MV/m have been already reached in test cavities.

A difficult choice

Now as the technical problems for building a linac are being solved, the next problem the international high-energy physics community will have to deal with is the creation of an "actual machine," says Richard. First, the different participating labs will have to decide which technology will be used. Representatives of these labs have been exchanging ideas regularly at meetings organised by the International Conference for Future Accelerators (ICFA). In 1996 the International Linear Collider Review Committee, also known as the "Greg Loew" committee, compared the different designs. "I worked with about sixty scientists from all over the world--at that time there were eight different approaches to the future linear collider," says Gregory Loew of SLAC, who chaired this committee. Now the situation is somewhat simplified. "We currently have two major competing approaches: the TESLA machine at DESY in Germany, and the X-band machine studied collaboratively at SLAC in the US and KEK in Japan," says Loew. However, since complete design reports and current cost estimates are not yet available, a rational choice cannot yet be made.

And making this choice may remain a major problem for some time. "I don't think any expert can say that this one technology is better than the other," says Hirotaka Sugawara, Director General of KEK. The decision between a cold and a warm technology will depend on many factors, including who will participate in the funding of the project and who will host it, says Sugawara. "If Germany will host it, then probably they will choose TESLA, and if the US or Japan is going to host it, it probably will be the warm technology," says Sugawara, adding that the choice of technology will also depend on the decision on the expandibility of the machine. Loew argues that both designs should be explored further "until we know which of the two basic technologies is more robust and less costly". Focussing on just one design at this point could result in making a premature and incorrect choice. "In about two or three years from now we should have enough information to make an educated comparison and selection," says Loew.

The second choice will be the siting of the machine in one of the three "regions," Europe, Japan, or the United States. According to Richard, there is general agreement that this machine should be built in an existing lab to reduce overheads and to make use of an existing high-energy research infrastructure. "If any of regions would be willing to finance more more than 50 percent of the machine, it is imaginable that the other regions will accept the idea of the first region hosting the machine," says DESY's Director General Albrecht Wagner. And Loew argues that because the US is funding the LHC at a rate of about $600 million, Europe might in exchange agree with a US site.

SLAC, collaborating with KEK, the Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL) and Fermilab, and DESY are each working on their designs in great detail. According to Richard, DESY has progressed furthest in hammering out the technical specifications for a 500- 800 GeV machine and will present its Technical Design Report for the TESLA Linear Collider and Free-electron Laser in March of next year to Germany's Science Council (Wissenschaftsrat). Germany will take a final decision on its part of the funding of the international project around 2003. Last year, SLAC completed a preliminary design with a cost estimate of $7.9 billion, including detectors and all staff salaries. It was perceived by the Department of Energy (DOE) in the US as too expensive, and now SLAC is working to reduce this cost substantially, reports Loew. DESY will include its cost estimate in its Technical Design Report.

The linear collider project will also have to compete for funding with other projects, such as a possible muon collider or long-baseline neutrino project in the US, or the international fusion-energy project ITER, or a neutron source, the European Spallation Source. Wagner is confident that the free-electron laser developed conjointly with the accelerator enhances the value of the project because, in addition to the high-energy physicists, it also appeals to the X-ray synchrotron radiation community. "This is the kind of synergy you look for frequently and hardly ever find," he says." So, what's next? "Particle physics world-wide needs to develop a strategic road map," says Wagner. Loew agrees: "We must break new scientific ground to build this machine internationally."

(*) Linear Collider Workshop, Fermi National Accelerator Laboratory, 24-28 October 2000