DECISION APPROACHING ON CERN'S PROPOSED LARGE HADRON COLLIDER

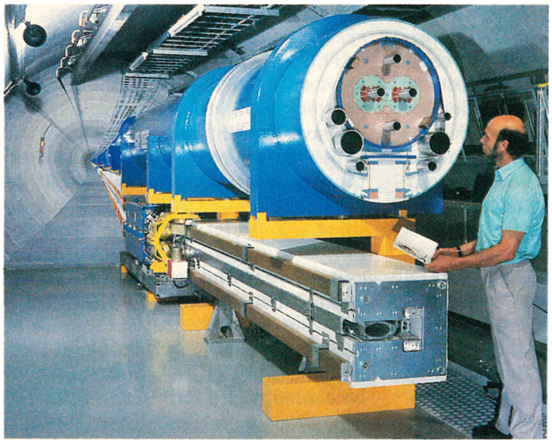
The Large Hadron Collider is Europe's answer to the Superconducting Super Collider. The final decision to build the LHC must come from the CERN Council, the governing body that represents the European laboratory's 17 member states. That decision is likely to be made at the Council's meeting in December. In the meantime, the LHC project is moving forward on several fronts.

The basic idea of the LHC proposal is to a build a proton–proton collider with 8-TeV proton beams countercirculating in the existing 27-km-circumference tunnel of CERN's LEP electron–positron collider, which has been doing physics since 1989. For light particles like electrons, the maximum beam energy one can hold in a storage-ring collider of given bending radius is limited by synchrotron radiation. LEP currently runs with 50-GeV beams, and the ultimate limit imposed by the radius of the ring is about 120 GeV. For the much heavier protons, synchrotron radiation is a secondary issue. The limit on proton beam energy is set by the limits on the strength of the bending magnets with which one tethers the protons in their circular paths. Storing 8-TeV proton beams in the comparatively modest confines of the LEP tunnel will require the mass production of superconducting bending magnets half again as strong as those being built for the 87-km tunnel of the SSC.

Ten meter-long prototype magnets of various designs are now under construction at several industrial firms. A "string test" of four of these magnets in series, with all the associated superfluid-helium cryogenics, is anticipated for this summer. In the meantime, problems of excessive quenching are being studied at CERN with the aid of model magnets that have the full cross section and field intensity but are only 1.5 meters long.

Two proton–proton collision points are envisioned for the LHC. Each of these points where the countercirculating proton beams intersect would be encompassed by a huge detector costing about $300 million. Three competing detector proposals were submitted to CERN's LHC committee last October. These hundred-page "Letters of Intent" are currently being scrutinized by teams of referees. It is expected that, by merger or attrition, the three detector proposals will have been winnowed down to two by April. The two surviving detector consortia will then be asked to prepare more technically detailed proposals, with serious cost estimates, before the December council meeting.

CERN PHOTO



Mock-up of LHC magnets (blue) on top of the existing magnets in the LEP tunnel. The 10-T LHC magnets are to keep 8-TeV protons countercirculating around the tunnel. The cutaway model shows the (copper-colored) superconducting coils surrounding the two beam pipes, held by a common (green) collar. The other pipes carry coolant.

Given the size of the LEP tunnel and the fact that the state of the magnet maker's art limits bending fields to about 10 tesla, the LHC will have to make do with a center-of-mass collision energy of "only" 15 or 16 TeV, compared with 40 TeV for the much longer SSC tunnel. Does that mean the LHC risks missing out on much of the new physics whose anticipated discovery is the *raison d'être* of both machines? That debate has been going on since the LHC idea was first broached a decade ago. The answer depends in large measure on how heavy the as-yet-undiscovered Higgs boson (or whatever else does its work) turns out to be. If the Higgs is as heavy as 800 GeV, the lower energy of the LHC will certainly be a disadvantage. But recent data from LEP and the 2-TeV Fermilab Tevatron collider suggest that the Higgs mass is less than 300 GeV, in which case the LHC's 20-times-higher design luminosity would more than compensate for the 3- or 4-times-higher Higgs production cross section at the SSC.

The LHC requires very little civil engineering, and existing CERN accelerators are to serve as the injectors. Its estimated cost is about $2 billion. (CERN cost accounting does not include staff salaries.) It was originally hoped that the machine would be ready to do physics by 1997, well ahead of the SSC. Thus the LHC could reap important results before the bigger American machine entered the arena. But Germany in particular, worried about costs, has called for a more cautious schedule. With the largest GNP of any member state, Germany is the biggest single contributor to the CERN budget. It was the Germans who insisted upon delaying a final decision on the LHC until reliable estimates of the cost of the machine *and* its two detectors were in hand. In recent months CERN Director General Carlo Rubbia, prime mover of the LHC project, has been speaking of 1999 as the target date for completion of the machine. (That's also the estimated completion date of the SSC, assuming adequate annual appropriations.) At its December 1992 meeting, the CERN Council agreed to a temporary 10% reduction in Germany's assessment for the next three years, in consideration of the financial hardships of German unification. In response Hermann Strub, head of the German delegation, thanked the council and indicated that Germany would now support an expeditious decision on the LHC.

The accelerator

CERN's 450-GeV Super Proton Synchrotron, fed by the venerable 26-GeV Proton Synchrotron, is to be the LHC's injector. With relatively modest modifications, the PS and SPS are expected to deliver beam intensities sufficient to achieve the design luminosity of 2×10^{34} sec^{-1} cm^{-2}. (Luminosity is the event rate, at each collision point, per unit scattering cross section.) That's an order of magnitude higher than the SSC designers are shooting for. The choice is meant to compensate to some extent for the LHC's lower collision energy. This unprecedented luminosity is seen as posing more of a challenge to the detector designers than to the builders of the accelerator. "A collider's luminosity depends primarily on its injectors, " Rubbia told us. "In that respect the final ring is just a passive recepticle for bunches of protons. Our long experience with the PS and SPS convinces us that the injectors will be ready to deliver the requisite luminosity well before the big ring is completed. In fact, if you dumped the output of *today's* SPS, before any of the modifications we're planning, into an idealized LHC, you'd already get a few times 10^{33} sec^{-1} cm^{-2}. That leaves us less than a factor of 10 still to go." The SSC, by contrast, is being built on a site south of Dallas that has no preexisting high-energy facilities. Its injectors are being constructed from scratch.

"In building the machine itself we face only one real challenge," says Rubbia. "That is the 10-tesla bending magnets. The digging and injector construction are largely behind us, so we can really concentrate on developing and mass-producing the best magnets money can buy." Some 1300 superconducting dipole magnets, each 13.5 meters long, will have to be fabricated by industry and installed in the LEP tunnel. They are to lie just above the existing LEP magnets. CERN will thus have the option of occasionally running the LHC as a proton–electron collider—much like the HERA collider that recently began doing physics in Hamburg, but at five times HERA's center-of-mass energy. The LHC will also be a part-time heavy-ion collider. But the primary role of the new magnets will be to keep two beams of 7.7-TeV protons counter-circulating around the tunnel in their separate, adjacent vacuum beam pipes. That will require an unprecedented bending field of 9.5 tesla.

Protons circulating in opposite senses require magnets of opposite polarity. That's why the SSC will have a double ring of some 8000 bending magnets. But the LHC designers, prompted by frugality and the cramped quarters of the LEP tunnel, have opted for a more radical, "two in one" magnet design. The two oppositely polarized magnet coils surrounding the two beam pipes will share a single yoke and a common cryogenic system. (See the photo on page 17).

The 15.5-meter SSC magnets will need only 6.6 T to bend their 20-TeV protons around the much more expansive Texas ring. How can one expect to make 9.5- or 10-T accelerator magnets when the SSC people had enough trouble producing a successful 6.6-T prototype? The answer is temperature. Both magnet designs call for very similar superconducting cable made of niobium–titanium alloy. But whereas the SSC cables are cooled to 4.2 K by ordinary liquid helium, the LHC magnet cables will be cooled to 1.9 K by *superfluid* helium. Good experience with Torsupra, a new midsize tokamak near Aix-en-Provence with a pioneering superfluid-helium cooling system, has given the Europeans confidence in this rather new cryogenic technology. But at 1.9 K, the LHC will require a novel and possibly troublesome liner inside its beam pipes to insulate them from the synchrotron radiation of the high-luminosity beams.

No full-length LHC magnet has yet been tested at superfluid helium temperature. But two hybrid results have been very encouraging: Recently at Fermilab a full-length SSC magnet reached 9.4 T without quenching when it was cooled to 1.9 K by superfluid helium. At Asea Brown Boveri in Germany, an LHC magnet body, wound with the somewhat thinner HERA cable, has reached 8.3 T at 1.9 K. In both these cases the maximum field was dictated by the composition and thickness of the particular cable itself, not by any excessive quenching caused by straining under the enormous Lorentz forces to which the cable is subjected when it's wound in the magnet coil. For the LHC cable this "short-sample limit" at 1.9 K is about 10 T.

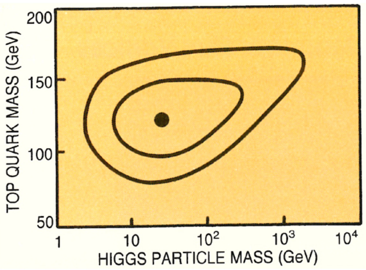
A number of the 1.5-meter-long model LHC magnets have reached 10 T, but once they get above 9 T they begin quenching excessively. The problem has been localized to the coil ends, where the cables are spliced, and the CERN magnet group is experimenting with various ways of collaring and prestressing the coils. "We have set ourselves the requirement of a successful string test of four 10-meter bending magnets as a precondition for final approval of the LHC project," Rubbia told us.

Unlike the SSC and its affiliated laboratories, CERN has no facilities for building long magnets. On the other hand, one of the industrial consortia that built the 9-meter-long, 5-tesla magnets for HERA's 820-GeV proton ring is still intact. "That's why we've involved industry from the very beginning," Rubbia explains. "If we leave them without a commitment for three or four years, their expertise and facilities will disperse, and we will have lost a great asset."

What they're looking for

The only real *terra incognita* remaining in the standard model that has served particle physics so well for two decades now is the "Higgs sector" (after Peter Higgs, University of Edinburgh), which is presumed to give the fundamental particles their nonvanishing masses and to break the underlying symmetry between the electromagnetic and weak interactions. In the minimal standard model this is done by a single neutral scalar Higgs particle of unknown mass. The theory does, however, arm advocates of the SSC and LHC with a comforting "no-fail theorem," which asserts that by the time one gets to collision energies high enough to make objects with masses of 1 or 2 TeV, one will have found either the Higgs or something else even more exotic. Short of that, there's no *a priori* prediction of the mass of the Higgs, but all its couplings to other particles are fixed by the theory. Therefore standard-model fits to experimental data, especially e^+e^- scattering at energies near the mass of the 91-GeV Z^0 vector boson that mediates the weak interactions, are telling us something about where to look for the Higgs particle. The best mass estimate at the moment is somewhere around a hundred GeV, but the uncertainties are large. (See the figure on page 19). At the 95% confidence level, the standard-model fits tell us only that the Higgs mass is less than a TeV. "We can find a Higgs as heavy as 1 TeV," says Rubbia. "Above that we'd run out of event rate and the game would belong to the SSC."

Direct searches at LEP have already excluded a Higgs particle lighter than 60 GeV. If the Higgs is indeed heavier than 160 GeV (twice the mass of the $W^\pm$, the charged siblings of the Z^0) and lighter than about 800 GeV, it should almost



Standard-model fit to LEP and Tevatron data yields mass estimates for the Higgs particle and top quark, both still to be found. The central dot, showing the best joint estimate of the two masses, is circled by two contours, indicating first 1 standard deviation and then the 95% confidence limit.

always decay into a W^+W^- or Z^0Z^0 pair. For the experimenter, the most prized events would be those in which a Higgs decays to a pair of the neutral bosons and each Z^0 subsequently decays to a $\mu^+\mu^-$ pair. All the mass of the Higgs would then be accounted for by the energy of the four emerging muons. Experimenters are particularly fond of high-energy muons: They don't participate in the strong nuclear interactions; therefore they are easily spotted by their ability to pass through considerable thicknesses of iron, and the relatively rare appearance of a muon with a high momentum component transverse to the beam direction generally signals an event of more than usual interest.

If the Higgs particle turns out to be heavier than about 800 GeV, its couplings would become very strong, and the usual perturbation formalism would be invalid. Instead of having a well-defined mass, the Higgs would manifest itself as a broad resonance between strongly interacting W bosons behaving like obese pions. "It would be a whole new phenomenology," says Rubbia, "a prospect the theorists contemplate with disgust."

For all its successes, the standard model is clearly an incomplete theory. Too many parameters have to be put in by hand. Therefore, besides searching for the Higgs, the detector groups will be on the lookout for any manifestation of physics beyond the standard model. The speculative "supersymmetric" theories, for example, predict families of exotic particles as yet unseen, among them *several* Higgs particles, charged and uncharged. Finding a very light Higgs would be construed as evidence for supersymmetry. A Higgs as light as 75 GeV could in fact be found by LEP 200, the upgrade that will double the LEP beam energies by the end of next year.

Detectors

Last spring four detector proposals were on the table. They were all designed to do essentially the same thing: identify and measure high-transverse-momentum electrons, gammas, hadron jets and especially muons with good precision. They differed primarily in the configuration of the large magnetic volume required to measure the momenta of muons by their curvature. Two of them, Ascot and Eagle—now merged as Atlas under the leadership of Friedrich Dydak and Peter Jenni—called for large toroidal magnets threaded by a small inner solenoid magnet coaxial with the beams. The solenoid's iron yoke and the hadron calorimeter inside it let only muons pass through to the outer tracking chambers. Atlas's toroidal coils, stacked like donuts in a box, encompass a cylindrical magnetic volume 26 meters long and 20 meters across.

The other two proposed detectors, named L3P and Compact Muon Spectrometer, would employ large, high-field solenoid magnets. They're quite similar to each other except that the CMS group achieves greater compactness by daring to place the detector's innermost tracking components right up against the beam pipe. The LHC's enormous design luminosity subjects the detectors to unprecedented radiation levels. In fact all the detector groups are actively investigating new technologies that will harden their tracking and calorimetric systems against radiation damage. The problem is of course most severe for the instruments closest to the point where the proton beams collide. The L3P design cautiously keeps its innermost components further away from the collision point. Therefore it has to be somewhat larger than the CMS.

L3P is in fact a proposal by Samuel Ting and his collaborators to turn their existing L3 system, the largest of the four LEP detectors, into a proton–proton detector for the LHC. That introduces the option of housing one of the two proton–proton detectors in an existing LEP experimental hall rather than in one of the two new experimental halls planned for the LHC. One would just have to jack the rebuilt detector up a few feet into the proton beam line. This scenario would leave one of the new halls available for a more modest detector dedicated to the heavy-ion collider program. None of this excludes the very real possibility that the L3P and CMS groups will merge before the LHC committee has to make its final selection. The CMS collaboration, headed by Michel Della Negra, is descended from Rubbia's UA1 detector group, which discovered the Z^0 and $W^{\pm}$ at the SPS proton–antiproton collider a decade ago.

Each of the two proton beams circulating in the LHC will consist of several thousand needle-like bunches, with 10^{11} protons apiece. At each of the ring's two proton–proton collision points a pair of bunches will collide every 25 nanoseconds. At full design luminosity every bunch crossing will yield dozens of pp scattering events in a fraction of a nanosecond. The detectors have no hope of sorting out so many events in so short an interval of time and space. Luckily most of these scattering events are of no interest and they have the good grace to be relatively unobtrusive. Indeed the estimate is that the LHC at full tilt will produce, every second, only a few hundred events worth saving for off-line scrutiny. Therefore one needn't worry about having two interesting events in the same bunch crossing. But one does have to worry about fishing these few hundred events per second out of a 40-megaherz bunch-crossing rate.

Most of the interesting physics at high energies happens when individual quarks or gluons in colliding protons crash head on. But that's rare. Usually protons colliding at high energy interact as coherent wholes, scattering either elastically or diffractively, with the collision products going off at very small angles. The few events worth a second look announce themselves by atypically large numbers of tracks emerging from the collision (hundreds rather than dozens) or by a large transfer of collision energy to a few particles coming off at big scattering angles. If the detector records such an event, its tracks will be inextricably mingled with those of the few dozen humdrum events from the same bunch crossing. The hope is that these unwanted tracks will cause minimal confusion in detector elements designed to concentrate on particles coming out with lots of transverse momentum.

Under these high-luminosity conditions it is of course impossible to reconstruct entire events and determine precisely how much energy and momentum has escaped with undetected neutrinos. Furthermore the high density of tracks makes it essential that tracking systems near the collision point have very fine spatial resolution as well as radiation hardness and speed. To this end various groups are investigating a number of schemes for making high-resolution, high-speed silicon tracking devices.

It will certainly be more difficult to do experiments at 2×10^{34} $sec^{-1}cm^{-2}$ than at the lower design luminosity of the SSC. At 10^{33} $sec^{-1}cm^{-2}$ each bunch crossing produces only one or two background events instead of dozens. But for some purposes the lower energy of the LHC makes the higher luminosity indispensable if one is to have usable event rates. Cross sections for the production of heavy objects grow steeply with increasing energy near threshold. For Higgs production, the relevant issue is the energy of a pair of colliding gluons in their own center-of-mass frame. The typical energy of a gluon–gluon collision at the LHC would be only 2 TeV. Above that, gluon–gluon collisions become increasingly rare as they appropriate a larger share of the total 15-TeV collision energy.

"We don't always have to run at full luminosity," Rubbia told us, "but I've asked the detector groups to come up with instruments that can handle the luminosity the collider is capable of delivering. None of them has told me I'm crazy, so they must think they can do it." The groups have been pursuing novel technologies on many fronts. The goal is to have the detectors ready to go by the time the collider is commissioned.

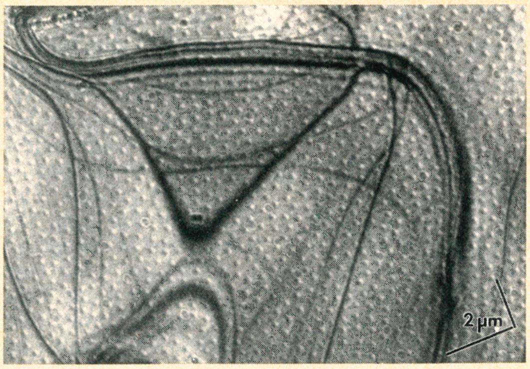
Electron and heavy-ion beams

Whether or not the LHC will ever run as an electron–proton collider depends on what kinds of interesting results are discovered at HERA. LEP 200 will begin doing e^+e^- physics at 200 GeV toward the end of next year, when all the superconducting rf cavities necessary for doubling LEP's beam energies have been installed. It is scheduled to run for at least three years, until the beginning of the yearlong shutdown required for the completion of the LHC. Does LEP have any future after the LHC is built? That depends on what the 200-GeV e^+e^- collisions unearth by then.

By contrast, the LHC's heavy-ion program is not a contingent question. "The LHC *will* be a heavy-ion collider from the start," says Christopher Llewellyn Smith, who takes over from Rubbia as CERN director general next January. The SPS has already served as a heavy-ion accelerator for fixed-target experiments. An injector capable of inserting beams of ions as heavy as Pb is in place. The LHC design calls for heavy-ion beam energies of 3 TeV per nucleon. That's 30 times the energy experimenters will get at RHIC, the heavy-ion collider now under construction at Brookhaven.

—Bertram Schwarzschild

Video Tracks Motion of Magnetic Flux Vortices



The photo shown above is just one frame of a video that tracks the motion of magnetic flux vortices in a type-II superconductor as the temperature or magnetic field is varied. The video has received thumbs-up reviews from condensed matter viewers, many of whom have studied the behavior of such vortices, especially in the high-temperature superconductors.

The video was made by Akira Tonomura of Hitachi Advanced Research Laboratory in Saitama, Japan, and his colleagues from Hitachi and the University of Lecce, Italy, who produced the images in an electron microscope.[1] They sent an electron beam vertically downward through a film of niobium 700 Å thick that was tilted at a 45° angle and placed in a horizontal magnetic field.

The reserchers obtained images of the flux lines by extending the technique of Lorentz microscopy to the realm of quantum interference. Electrons passing on opposite sides of the magnetic flux lines experience different phase shifts as a result of the Aharonov–Bohm effect, and these phase shifts bend the beams in different directions. The effect of these phase shifts is seen only when the microscope is defocused: The differently directed beams then either separate or overlap, decreasing or increasing the intensity. Thus, a given vortex line appears in the photographs as a small bump that is dark on one side and light on the other. (The dark lines running through the photograph above are contours along which atomic planes have been bent to a favorable angle for imaging.)

The phase shifts produced by magnetic vortices are formidably small—on the order of 10^{-6} rad. To detect such small shifts, Tonomura's group developed a 300-keV field emission tip that produces a coherent electron beam with a divergence angle much less than 10^{-6} rad.

The instrument records the vortex motion at the rate of 30 frames per second as the magnetic field is slowly increased. The video shows that, vortex lines suddenly appear when the field reaches the lower critical field H_{c1}, at which the magnetic field can begin to penetrate a type-II superconductor. The vortices increase in number as the field grows stronger, forming the predicted hexagonal lattice. Occasionally one sees a vortex hop to or from a weak pinning site.

The films are not only an impressive technical feat but also a powerful observational tool. One can study how fast vortices move and by what mechanisms, what defects pin them and what collective motions they have. It would be particularly interesting to image high-temperature superconductors, where there is evidence of phase transitions in the vortex configurations (see PHYSICS TODAY, October, page 17). So far the Hitachi–Lecce team has not applied its technique to such materials. The challenge will be to produce a high-T_c film no more than 1000 Å thick. Tonomura hopes to extend the technique to fields as high as 1 tesla.

The dynamic displays will complement static images produced by older methods. These include the Bitter technique of decorating the surface with magnetic particles to reveal the spatial arrangement of the vortices; scanning tunneling microscopy, which probes the electron densities of state; Hall probes mounted in place of the tip of an STM to sense the magnetic field directly; and a magneto-optical technique that has good time resolution but limited spatial resolution.

—Barbara Goss Levi

Reference

1. K. Harada, T. Matsuda, J. Bonevich, M. Igarashi, S. Kondo, G. Pozzi, U. Kawabe, A. Tonomura, Nature **360**, 51 (1992).