U.S. Collaboration on the LHC

by GEORGE TRILLING

Forty-seven countries and 299 institutions are part of a team to build the CERN Large Hadron Collider and its detectors. This accelerator will bring protons into head-on collision at much higher energies than ever achieved. A member of the U.S. collaboration, who has been involved since its beginnings, discusses its history and participation in this effort.

THE PUSH BY PARTICLE PHYSICISTS toward ever higher particle beam energies is motivated by the fact that much of the complexity observed at lower energies may disappear when the energy becomes sufficiently high. Thus, while beta radioactivity and electromagnetism have been separately known for 100 years, it is only in the last 30 years that new accelerators have provided energies high enough to "unmask" the fundamental relationship between the two phenomena. This is because the basic force carriers involved in radioactivity, the *W* and *Z*, are very massive, and can only be produced as identifiable objects with particle beams of very high energy. By moving to yet higher energies, particle physicists hope to unmask many more of Nature's hidden secrets, including the mechanism by which our basic constituents acquire their masses. Their aspirations are currently focused on future experiments made possible by the Large Hadron Collider (LHC) facility to be built over the next eight years.

The Large Hadron Collider is a proton-proton colliding-beam facility to be housed in the Large Electron Positron Collider (LEP) tunnel at CERN. Its design energy is 7 TeV per beam, a figure seven times as large as the maximum Tevatron beam energy and seventy times as large as the maximum LEP beam energy. The enormous energy difference between the two colliders within the same enclosure arises from the fact that LEP beam energies are limited by the huge amount of electromagnetic radiation emitted by the electrons traveling in circular orbits (a limitation that linear colliders such as the SLAC Linear Collider and the Next Linear Collider are designed to avoid). Circulating protons, by virtue of being

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2000 times as heavy, emit relatively little radiation; in a tunnel of fixed circumference, their energies are only limited by the magnetic fields achievable in practical superconducting accelerator magnets (8.4T for LHC).

Up to the October 1993 cancellation of the U.S. Superconducting Supercollider (SSC) project, almost all U.S. groups interested in pursuing physics at the "energy frontier" made accessible by the LHC and SSC had been participants in one of two large SSC detector collaborations. By late 1993, the CERN management had approved two largely European detector collaborations for the LHC, ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid), to move to the preparation of technical proposals. However the overall LHC project had not been formally approved by the CERN Council because the available construction funding, based largely on the ongoing CERN budget, was about 25 percent short when summed over the proposed construction period.

In 1994 numerous U.S. groups, many of them previously involved in SSC detectors, joined the ATLAS and CMS collaborations to pursue the energy-frontier physics that had been their motivating scientific interest. Two additional detectors are planned for the LHC: LHC-B optimized specifically for studying the physics of *B*-meson decays, and ALICE aimed at the study of high-energy heavy-ion collisions. Since U.S. participation in LHC-B and ALICE is currently small, and not included within the signed agreements between CERN and the U.S. funding agencies, I shall not discuss it here.

To overcome the funding shortfall, the CERN Director General, Chris Llewellyn Smith, invited non-member-states (countries that

Countries Participating in the LHC Program

Armenia
Australia
Austria
Azerbaijan Republic
Republic of Belarus
Belgium
Brazil
Bulgaria
Canada
People's Republic of China
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Republic of Georgia
Germany
Greece
Hungary
India
Israel
Italy
Japan
Kazakhstan
Korea
Latvia
Mexico
Morocco
Netherlands
Norway
Pakistan
Poland
Portugal
Romania
Russia
Slovak Republic
Slovenia
Spain
Sweden
Switzerland
Turkey
Ukraine
United Kingdom
United States of America
Uzbekistan

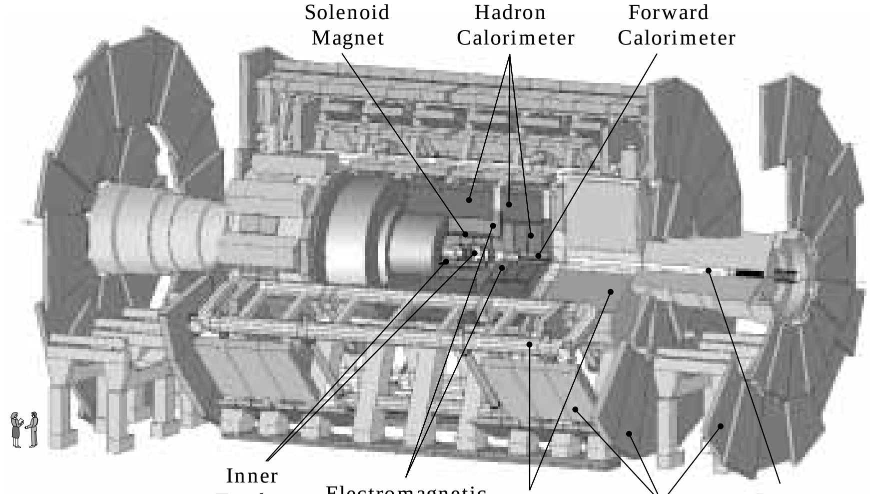
are not CERN member-states), whose physics communities had substantial interest in exploiting the LHC, to participate financially and intellectually in the machine construction. This is a departure from tradition; in contrast to detector facilities, which are built and funded internationally, accelerators are normally funded by the host country or—as in the case of CERN—the host region. The justifications for this departure, expressed from the point of view of U.S. involvement, are the following: (1) The multi-billion-dollar LHC stands at or beyond the limit of what a single region can afford to fund. If such projects are to go forward, they need interregional funding support, and such support is most naturally sought from countries whose scientific communities have strong interest in these projects; (2) The large U.S. community interested in participating in LHC experiments, currently about 600 scientists and engineers, has a strong stake in the timely completion of the accelerator project. U.S. participation in the machine can help ensure this timely completion; (3) Participation in the LHC collider effort would afford new opportunities for the continuing development of U.S. capabilities in the area of accelerators using superconducting magnets.

The proposed U.S. participation in LHC was considered by the 1994 High Energy Physics Advisory Panel (HEPAP) Subpanel on Vision for the Future of High-Energy Physics, under Sidney Drell's chairmanship, which gave a positive recommendation. Further action by U.S. funding agencies awaited CERN Council approval of the LHC project, which came in December 1994. To secure this approval, CERN management presented a staged construction plan, based solely on member-state contributions, that completed the full LHC not earlier than 2008, with the expectation that, with adequate non-member-state support for the machine, the staging might be avoided, and full completion achieved by 2004 or 2005.

Discussions between the Department of Energy (DOE), the National Science Foundation (NSF), and the CERN leadership, relative to U.S. participation in the LHC program, were initiated in April 1995. They culminated in the signing, on December 8, 1997, by Energy Secretary Frederico Peña, NSF Director Neil Lane, CERN Council President Luciano Maiani, and Director General Llewellyn Smith of a Cooperation Agreement on the LHC program. More detailed accelerator and experiments protocols were signed later in December. These various agreements set out the "rules" and funding levels under which the U.S. will participate in both LHC accelerator and detectors. The U.S. will commit $250M from DOE and $81M from NSF for the ATLAS and CMS detectors, and $200M from DOE for the LHC accelerator. The totality of NSF plus DOE detector funding is to be split about equally between ATLAS and CMS. The accelerator funding is to be split into $90M for goods and supplies from U.S. industry, and $110M for systems and components provided by three national laboratories, namely Brookhaven (BNL), Fermilab, and Lawrence Berkeley. This accelerator collaboration is principally focused on the design, fabrication, and commissioning of elements for the LHC interaction regions.

In light of the proposed U.S. and other non-member-state participation in the machine, the CERN Council, in December 1996, had approved going forward on a non-staged LHC to be completed in 2005. Needless to say, Congressional approval of these funding commitments was essential. In April, House Science Committee Chair Sensenbrenner raised a number of concerns about the proposed U.S.-CERN agreements. To satisfy these, and with the approval of the CERN Council, the agreements were appropriately modified. The full $35M request for DOE-supported LHC efforts in fiscal year 1998 has been provided.

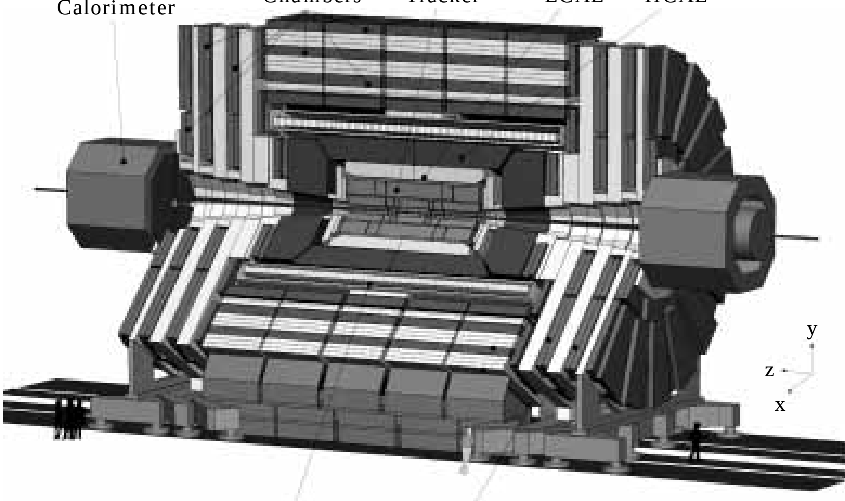
ALTHOUGH THE U.S. HAS PREVIOUSLY participated in detector projects abroad (L3, ZEUS, AMY etc.), such involvement has not yet occurred on the financial scale envisaged for LHC. Strong management is mandatory for the accelerator project and especially for the detectors, which involve collaboration by large numbers of institutions. Each detector project has a U.S. host laboratory (Fermilab for CMS and BNL for ATLAS) with management oversight responsibility given to the host lab director or his appointed representative. Because of the close coupling of DOE and NSF in the detector projects, the two agencies are forming a Joint Oversight Group (JOG) to oversee the detector fabrication efforts. Each detector program will have a U.S. Project Manager reporting to both the JOG and the host lab director.



Cutaway view of the ATLAS detector. The inner detector, calorimeters, and muon detectors measure and identify the various collision products. Magnetic fields to deflect charged particles are produced by a solenoid (for the inner detector) and air-core toroids (for the muon detectors).(Courtesy Lawrence Berkeley National Laboratory)

The physics goals of the ATLAS and CMS detector collaborations are similar to those that motivated the SSC. While the design energy of 7 TeV per beam is one third of that for the SSC (but seven times that of the Tevatron), the design luminosity of 10^{34} cm^{-2} sec^{-1} is ten times higher. These conditions place great demands on the detectors, in terms of performance and survivability in a hostile radiation environment. At full luminosity, each crossing of two proton bunches will produce about 20 interactions, and these crossings will occur every 25 billionth of a second. A whole range of opportunities for physics discovery will open up. These include the Higgs boson or bosons, new spectroscopies such as supersymmetry, new massive gauge bosons, and searches for evidence of compositeness in what have heretofore been point particles. The Higgs sector is connected to the fundamental issue of how all our basic particles (quarks, leptons, and gauge bosons) acquire their masses, and what determines those masses. Recent work has shown that, if supersymmetry is indeed found, the LHC experiments will be capable of numerous measurements to probe its details.

Computer simulations of searches for these phenomena have provided guidance to the design of detector subsystems. Such simulations, done for a sufficiently broad array of processes, give confidence



Cutaway view of the CMS detector. The tracker, calorimeters (including HCAL and ECAL), and muon chambers are the measurement elements for the various outgoing particles. A large solenoid coil produces a very strong magnetic field for charged-particle momentum measurement.

that the ATLAS and CMS detectors can not only uncover what physicists are searching for (if it is there), but also discover unexpected and entirely new phenomena if that is Nature's way.

The main features of both detectors include: (1) high resolution and highly segmented electromagnetic calorimetry to allow detection of the two-photon decay of a light Higgs boson (below 120 GeV); (2) the ability to identify electrons and muons, and measure accurately their charges and momenta over a large angular range; (3) nearly hermetic hadronic calorimetry to measure hadronic energy flow and detect missing momentum transverse to the beam line; (4) capability to identify the presence of a *B*-hadron decay through detection of a displaced vertex with high position-resolution silicon pixel detectors; (5) operational capability, and survivability at the design luminosity of 10^{34} cm^{-2} sec^{-1}.

With such capabilities, these instruments can determine, for each proton-proton collision: the energies and directions of outgoing electrons, muons, photons, and jets; identify those jets originating from bottom quarks; and measure the total transverse momentum associated with neutrinos or other undetectable neutrals. Furthermore they can process enough of this information sufficiently quickly to select, for permanent recording and detailed analysis, just the one

Signing ceremony for the LHC project on December 8, 1997, in Washington, DC. Secretary of Energy Federico Peña, left, congratulates Luciano Maiani, president of the CERN Council. (Courtesy Department of Energy)

K. Shipp

collision in 100 million (still about 10 events/second) that may bear the seeds of an important measurement or new discovery.

Since these detectors are intended to complement each other, their similar design goals are accomplished in substantially different ways. More detailed descriptions of some specific detector subsystems in which U.S. groups have major responsibility are given by Gil Gilchriese (ATLAS) and Dan Green (CMS) in the following articles respectively.

Over the past few months, both detector collaborations have submitted voluminous Technical Design Reports for most of their detector subsystems, and these have undergone painstaking review by the LHC Committee. The U.S. groups hope to have completed their DOE/NSF baselining reviews by early 1998. The scientific and technical challenges are enormous, but powerful international teams including a strong U.S. presence are very effectively working together to meet those challenges. The future looks exciting.