# The U.S. LHC Accelerator Research Program:
# A Proposal


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# Introduction

The LHC will be the most important instrument for both world and U.S. high-energy physics in the second decade of this century and will provide unique opportunities for accelerator science research. Recognizing this, the United States government has made an investment of more than half a billion dollars in the collider and its detectors. Up to 50 percent of U.S. experimental high-energy physicists will be doing their research at the LHC when it is fully operational. In addition to the insights into fundamental particles and interactions at the highest energy that the LHC will enable, it will also be the most technically advanced collider in the world, and as such, will offer unique opportunities to study and advance accelerator science and technology.

We propose to fully exploit our national investment by taking advantage of the opportunities that the LHC offers in the field of accelerator science and technology, and by working with CERN to ensure the maximum performance of LHC in support of high-energy physics. The three U.S. DOE National Laboratories, that comprise the U.S. LHC Accelerator Project, Fermilab, Brookhaven National Laboratory and Lawrence Berkeley National Laboratory, working with the U.S. Department of Energy, and in close collaboration with our CERN colleagues, plan to form the U.S. LHC Accelerator Research Program (LARP). Through this program, U.S. accelerator specialists will continue to take an active and important role in the LHC accelerator program during its commissioning and operations, and to be a major collaborator in LHC performance upgrades. In particular, LARP will support U.S. institutions in LHC commissioning activities and accelerator science, accelerator instrumentation and diagnostics, and superconducting magnet R&D to help bring the LHC on and up to luminosity quickly, to help establish robust operation, and to improve and upgrade LHC performance. Furthermore, the work we do will be at the technological frontier and will thereby improve the capabilities of the U.S. accelerator community.

This proposal sets forth the guiding vision, the specific goals, the preliminary plan and scope of work, an estimate of the resources necessary to carry out the work within a reasonable schedule, and a management plan to guide the work, measure progress and make program adjustments. Following the plan put forth in this proposal, we will advance high-energy physics while increasing our own capabilities in accelerator science and technology to more effectively operate our domestic accelerators and to position the U.S. to be able to lead in the development of the next generation of high-energy colliders.

# 1. The LHC Accelerator Research Program

## 1.1. Program Goals

### 1.1.1. LARP Will Advance High-Energy Physics

The U.S. Department of Energy, through LARP, offers U.S. accelerator scientists and technologists an opportunity to stay at the forefront of their field. At the same time, LARP will enhance the HEP output of the LHC. LARP makes available the resources to collaborate with CERN to:

- **Bring the LHC on and up to design luminosity quickly, safely and efficiently.**
- **Continue to improve LHC performance by advances in understanding and development of new instrumentation.**
- **Use the LHC effectively as a tool to gain a deeper knowledge of accelerator science and technology.**
- **Extend LHC as a frontier high-energy physics instrument with a timely luminosity upgrade.**

In its recent analysis of *High-Energy Facilities on the DOE Office of Science Twenty-Year Roadmap*[8], HEPAP recommended that three proposed projects were sufficiently compelling to be called Absolutely Central to the future of particle physics. The definition of this category, to quote from the report is: "To be considered *absolutely central*, we require that the intrinsic potential of the science be such as to change our view of the universe. This is an extremely high standard, at the level at which Nobel Prizes are awarded." The three projects are a linear collider, SNAP, the Supernovae/Acceleration Probe, and a luminosity upgrade to the LHC. In the opinion of the leaders of U.S. high-energy physics, the goals of the LARP program are absolutely central to the future of U.S. high-energy physics.

### 1.1.2. LARP Will Advance U.S. Accelerator Science & Technology

While helping to advance the world's knowledge of particle physics at the energy frontier, LARP will, at the same time assist in developing a new path to better and more effective accelerators by presenting the opportunity to U.S. accelerator scientists and technologists to:

- **Keep skills sharp by helping CERN commission the LHC—a once-in-a-decade opportunity.**
- **Conduct forefront accelerator physics research and development.**
- **Advance our national capability to improve the performance of our own accelerators.**
- **Prepare U.S. accelerator scientists to design the next generation of hadron colliders.**
- **Develop the advanced accelerator technologies necessary to build the next generation of colliders after the LHC.**

### 1.1.3. LARP Will Advance International Cooperation

While not a goal *per se* of the LARP, an important benefit of extending our collaboration on the LHC is to further advance international cooperation in large science projects, and in the construction and exploitation of high energy accelerators in particular. Energy frontier accelerator facilities of the future will have to be built and operated on a fully international basis, and the deepening of our collaboration with CERN will be an important step towards the building the sort of world-wide collaboration that will be necessary for high energy physics to go to the next stage.

## 1.2. The DOE Program Guidance

The U.S. Department of Energy and the U.S. National Science Foundation, acting through the Joint Oversight Group, issued guidance for LARP in a letter dated February 5, 2003, attached as Appendix A. It spells out the vision for LARP in the introductory paragraphs:

> "The Department of Energy (DOE) anticipates providing significant funding for the U.S. LHC Accelerator research program to enable active participation of the U.S. scientific community in the accelerator physics research program of the LHC machine as foreseen by the international agreement. While this program will maintain and improve the domestic accelerator physics capabilities it must exploit the substantial U.S. investment in the LHC by providing an accelerator physics and technology basis for improvements to that machine."

The Guidance defines LARP as a world-class R&D and scientific research program at the frontier of accelerator science and technology. The deliverables of the research should improve U.S. capability and not be products or intellectual contributions that are readily available either at laboratories or in the marketplace. Although some fabricated deliverables are envisioned within the program, major physical deliverables will be separately funded as projects proposed and approved following standard procedures.

## 1.3. The LARP Scope of Work

### 1.3.1. The LARP Deliverables

In order to accomplish the LARP goals set out above within the context of the DOE national laboratory capabilities and expertise, we have constructed an initial set of deliverables. We believe that these activities satisfy all of the boundary conditions set out in the DOE Guidance.

- Help commission the hardware delivered by the LHC Accelerator Project and later by the LHC Accelerator Research Program.
- Help commission the LHC with initial beam.
- Use the LHC to perform experiments and test calculations and theories of fundamental accelerator science.

- Develop and build new instruments that will improve the operation of the LHC and help us perform accelerator physics experiments.
- Perform accelerator physics studies and advanced magnet R&D that will result in the IR designs and prototype IR magnets for a timely LHC luminosity upgrade.

In particular, all of these activities improve the LHC, lead to greater knowledge of accelerator science and technology, and help keep the U.S. accelerator community at the forefront of the field. In some cases, LARP will deliver final devices or intellectual contributions. In other cases, particularly those in which the fabrication is unusually costly, LARP will deliver the R&D, prototypes, designs, and intellectual contributions, but the actual fabrication will be separately negotiated, and the cost will be borne outside of the LARP funding.

### 1.3.2. How the LARP Deliverables Satisfy the LARP Goals

It is not possible or even desirable to organize LARP in a way that each deliverable satisfies the requirements of a single goal. In fact, the goals and deliverables overlap and intertwine. The planned R&D and the organization are motivated by the goals of the program and are strongly interconnected in the sense that many parts of the organization are involved in successfully delivering each goal. Table 1.3-1 shows the interconnections needed to achieve the LARP goals.

Not surprisingly, accelerator physics research – calculations, simulations and experiments – is needed to achieve any of the goals of the program. Some instrumentation and diagnostics will also be needed to bring on the machine quickly, and to bring it to luminosity. It is also likely that improved and novel beam instrumentation will continue to be needed for accelerator research and upgrades. Finally, the major component of an LHC upgrade will be high-performance magnets, presently beyond the state-of-the-art, for a new and improved interaction region.

***Table 1.3-1. The LARP Goals Connect with the LARP Deliverables***

| Goals \ *Deliverables* | *Hardware Commissioning* | *Beam Commissioning* | *Fundamental Accelerator Research* | *Instrumentation & Diagnostics* | *Magnet R&D* |
|---|---|---|---|---|---|
| **Maximize HEP at the LHC** | **Y** | **Y** | **Y** | **Y** | |
| **Improve LHC Performance** | | | **Y** | **Y** | |
| **Advance Accelerator Science & Technology** | | | **Y** | **Y** | **Y** |
| **Extend LHC HEP by a Timely Upgrade** | | | **Y** | **Y** | **Y** |
| **Prepare to Build the Next Generation Hadron Collider** | **Y** | **Y** | **Y** | **Y** | **Y** |

### 1.3.3. The Anticipated LARP Funding

Preliminary guidance from the DOE indicates that the peak funding will be somewhat in excess of $10 million per year. It will require a few years to get to that level, as shown in Fig. 1.3-1. The program we propose requires slightly more than $10 million per year, but begins rather modestly due to the slow start of the funding profile. This will limit our ability to make a vigorous start on magnet R&D, and limits the progress we can make on the initial suite of instrumentation.

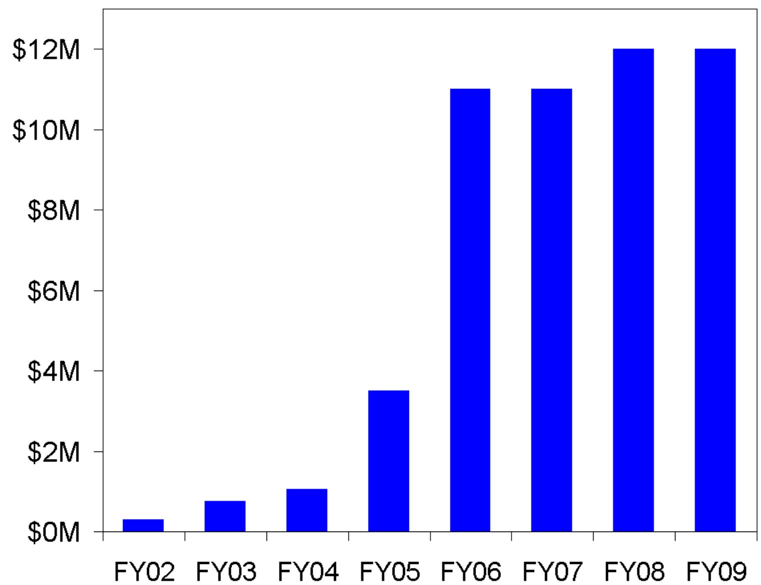


**Fig. 1.3-1** Preliminary funding guidance from the DOE.

The LARP is not a substitute for the base program, and, in fact, it assumes the existence of the base program in a number of areas. For example, LARP-funded instrumentation will be tested at the existing U.S. colliders, and the magnet R&D requires the existing R&D programs in $Nb_3Sn$ magnets and materials to continue. In addition, we have found it difficult to separate scientists and engineers from their regular responsibilities to be at CERN for extended periods. Hence, it will be necessary to add personnel to the staffs of the DOE laboratories to carry out the LARP at CERN and for extensive R&D, such as magnet development in the U.S. In order to be able to recruit and retain the best-qualified personnel, it is imperative that the LARP funding be continuous and robust, with minimum fluctuations from year to year.

## 1.4. The LARP Management Plan

### 1.4.1. The LARP Leadership and Management Structure

The initial LARP management and oversight structure is shown in Fig. 1.4-1. The LARP Program Leader sets the overall program directions and reports the status of the program periodically to the DOE-NSF Joint Oversight Group (JOG), the DOE-NSF LHC Program Office, and to the Director of Fermilab. The ultimate responsibility for the effective operation of the program rests with the Fermilab Director in consultation with the Directors of LBNL and BNL, as established in a letter of governance from John O'Fallon, Director of the Office of High-Energy Physics of DOE to Michael Witherell, Director of Fermilab, dated November 21, 2000, and included as Appendix B.

The LARP is organized along lines of deliverables rather than along lines of separate goals, because personnel capabilities, R&D infrastructure and even particular institutional directions tend to self-organize in categories of specific capabilities and technologies. Organizing in this way is also more straightforward for management, which can divide and distribute the tasks necessary for accomplishing goals into technological categories that are relatively separate and require a minimum of interconnections among the different groups doing the R&D, and whose progress is straightforward to measure. Table 1.4-1 lists the organization and the initial leaders of each deliverable subgroup.

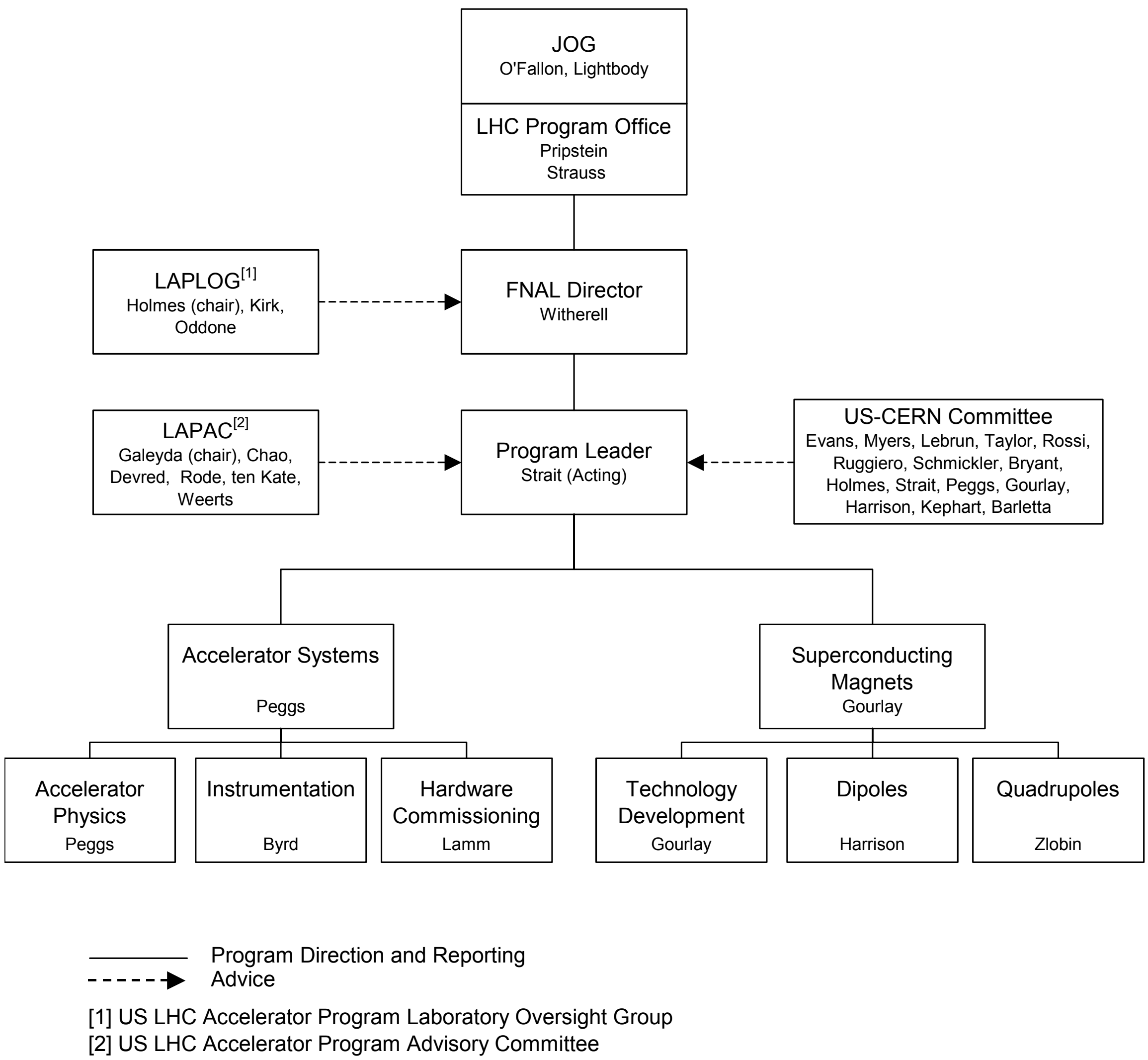


**Fig. 1.4-1** Initial LHC Accelerator Research Program organizational and reporting structure, including advisory committees.

*Table 1.4-1 The Initial LARP Management*

| <u>Deliverable</u> | Initial Leader | Leader's Institution |
|---|---|---|
| ***Overall Management & Strategy*** | ***J. Strait*** | ***Fermilab*** |
| ***Accelerator Systems*** | ***S. Peggs*** | ***BNL*** |
| *Hardware Commissioning* | *M. Lamm* | *Fermilab* |
| *Accelerator Physics* | *S. Peggs* | *BNL* |
| *Instrumentation & Diagnostics* | *J. Byrd* | *LBNL* |
| ***Magnet R&D*** | ***S. Gourlay*** | ***LBNL*** |
| *Technology Development* | *S. Gourlay* | *LBNL* |
| *IR Dipoles* | *M. Harrison* | *BNL* |
| *IR Quadrupoles* | *A. Zlobin* | *Fermilab* |

It is important to note that all three institutions will participate in every activity, and contribute to every deliverable, although some will be more involved than others. The leadership has been drawn from those people who have been most active in the initial planning of the LARP. We expect that the leaders of these groups will change and that even the arrangement and foci of the groups may change as our understanding of the work that has to be done is sharpened.

### 1.4.2. Advisory Groups and Peer Review

The Leader of LARP and the Laboratory Directors will establish advisory groups as needed. The initial advisory groups are shown in Fig. 1.4-1 and described in the following paragraphs. The initial membership of the advisory committees are listed in Appendix C.

<u>LAPLOG:</u> The U.S. LHC Accelerator Program Laboratory Oversight Group consists of the relevant Deputy or Associate Directors of the three participating DOE laboratories plus other members that the Fermilab Director may appoint. It advises the Fermilab Director in his oversight and line-management duties with respect to the LARP and addresses high-level inter-laboratory issues. It meets as needed, and at least once per year.

<u>U.S.-CERN Committee:</u> The U.S.-CERN Committee consists of the leaders of the U.S. LHC Accelerator Research Program and leaders of the LHC work at CERN relevant to the LARP. It is chaired jointly by the CERN LHC Project Leader and the U.S. LHC Accelerator Research Program Leader. Its primary function is to review the proposed topics for U.S.-CERN collaboration on LHC machine activities and advise the Program Leader on the elements of the overall program. In reviewing individual program elements, the Committee considers the technical and scientific quality of the work, how it will impact the performance of LHC, and how it coordinates with the overall LHC program. The initial program described in this proposal was approved by this group at a meeting on April 10, 2003, as indicated in a letter from Lyn Evans to Jim Strait on April

14, 2003, which is included as Appendix D. As the LARP develops, changes to the approved program may be proposed, either to add new program elements or drop existing ones. These proposed program changes will be reviewed by the U.S.-CERN Committee, which will advise the Program Leader on them before changes are made. This committee also provides top-level coordination of the on-going work of the U.S.-CERN collaboration by receiving periodic reports on the progress of the LARP. The committee meets as needed, and at least once per year.

Executive Committee: The U.S. members of the U.S.-CERN Committee serve as the Executive Committee, which meets periodically, separate from the CERN members, to advise the Program Leader on programmatic issues within the U.S. Labs, such as allocation of resources, division of collaborative work, and disposition of proposed changes in the LARP scope of work prior to submission to the full U.S.-CERN Committee.

LAPAC: The U.S. LHC Accelerator Program Advisory Committee is a group of distinguished accelerator scientists, technologists and high-energy physicists, who are not involved in LARP, which provides the LARP Program Leader with independent scientific, technical and management advice on the performance of the program. This advice may be given through reviews of the program as a whole, or focused reviews of individual program elements. The focused reviews may be conducted by the LAPAC directly, or by independent subcommittees which report to it. The LAPAC will also be asked to provide an independent review of proposed changes to the program, for example addition of a new program element or a significant re-direction of a program task, prior to submitting the change to the U.S.-CERN Committee. An early version of the current program plan was reviewed by the LAPAC on June 17-18, 2002. The LAPAC meets at intervals determined by the technical progress of the program, at least once per year.

### 1.4.3. Management Oversight and Performance Evaluation

Because the LARP activity is focused on R&D, measuring progress and performance by traditional project management means (i.e. earned value) is not appropriate. Nevertheless, the different parts of the program do need oversight, for purposes of program direction, resource management and flexibility. This oversight will be provided by requiring periodic written reports from the leaders of each major program element, and by periodic reviews reporting to the Program Leader.

Periodic progress reports will be submitted by each major sub-program leader, either quarterly or semi-annually, depending on the scope and pace of the work. As part of the annual budget planning cycle, the leader of each major program element will submit a work plan for the next fiscal year, which will also include commentary on the progress made against the previous year's plan.

The Program Leader will call periodic technical reviews of each major program element, to be conducted by technical experts not directly involved in the work under review. Relevant members of the LAPAC will be invited to participate in these reviews. It is expected that each major element in the program will be reviewed at least once per year, with more frequent or specifically focused reviews scheduled as needed. The reviews will report to the Program Leader, and he is responsible to inform the U.S.-CERN Committee, the Fermilab Director, and the DOE of these reviews and their results.

In addition to reviews called by the Program Leader, the LAPAC, as an independent advisory committee, will review the LARP as a whole at least once per year, and may organize additional reviews as needed, as outlined in paragraph 1.4.3.

### 1.4.4. Procedure for Proposed Changes to the LARP Work Scope

Proposals for new program elements or major changes to existing ones may be submitted from time to time, either by individuals or institutions that are currently part of the LARP collaboration, or by those from outside the current collaboration. Such proposals should be submitted in writing to the Program Leader, and include a statement describing the work to be done, the schedule of the work, a cost estimate, and, if relevant, funding source. The Program Leader will forward the proposal to the Executive Committee, which will consider how well the proposal matches the goals of the LARP, and whether it is possible to accommodate the cost of the proposed work within the existing funding guidance for the LARP. The Program Leader may also consult with the LHC Project Leader and relevant technical leaders at CERN about how the proposed work would fit in with and contribute to the overall LHC program, and with the DOE concerning the availability of additional funding. If the proposal is deemed to address the LARP goals and the overall LHC program, and if it is plausible that its cost can be accommodated within available LARP funding, the proposed program will be presented to the LAPAC, who will provide independent advice on the scientific and technical merits of the proposed work, the proposed budget and schedule, and the match to the LARP goals and the LHC program needs. The results of the LAPAC review will be considered by the Executive Committee, who will advise the Program Leader as to whether the proposal should be accepted. If the Program Leader accepts the proposal, based on the Executive Committee advice, he will submit it to the U.S.-CERN Committee for formal consideration for inclusion in the LARP.

### 1.4.5. Toohig Fellowships

To allow the U.S. LHC Accelerator Research Program to benefit from the expertise of outstanding individual investigators, we are prepared to support individuals from outside the LARP participating institutions who wish to work in cooperation with LARP, either at one of the participating national laboratories, or at CERN. The specific work can involve original ideas of the investigator, or can be in the form of a desire to participate in one of the projects already approved to be part of the LARP work plan. If the proposal is in the form of assistance to an existing project, it should be submitted in writing to the LARP Program Leader and approved by him. If the proposed work is original, it must be reviewed following the procedure outlined in paragraph 1.4.3 above. To be acceptable, the proposals must satisfy the same criteria that are applied to LARP proposals.

We imagine that the assistance provided to individuals from LARP will be in the form of support fellowships. After a proposal for participation is approved, LARP will support an individual investigator for one year at one of the participating DOE national laboratories or at CERN. This support will be in the form of salary or sabbatical support and additional living and travel expenses. The investigators may be from U.S. or foreign universities, institutes or laboratories, but should not be staff at any of the LARP participating laboratories. We expect that LARP could support up to two fellowships per year.

We have named these fellowships in honor of the late Rev. Dr. Timothy Toohig, SJ, who spent his life working to foster international cooperation in high-energy physics. He was instrumental in many aspects of high-energy physics, including the original 200 BeV project, which later became Fermilab, the SSC and the LHC. In his last years, which he spent at the DOE, he inspired us to start the U.S. LHC Accelerator Research Program to help make the LHC the best instrument it could be, to help keep U.S. accelerator science at the forefront of the field, and to advance international cooperation in accelerator science in the realization that the next big machine would have to be international in scope. His vision and support was absolutely central to LARP.

### 1.4.6. Other Participation

From time to time the LARP Program Leader may choose to contract with individuals not in LARP to work on subjects of mutual interest or because an individual may have specific expertise. The methods discussed above do not exclude such contracts for consultation or other work.

# 2. Accelerator Systems Program Description

The Accelerator Systems component of the U.S. LHC Accelerator Research Program is a logical continuation of the first phase activities of the LHC Accelerator Project. It continues to address the goals of advancing High-Energy Physics and advancing U.S. accelerator science and technology, while exploiting and building on the strengths and interests of the National Laboratories. In the following paragraphs we give a brief overview of the different program elements which address these goals, and include a summary of the resources required to accomplish them. R&D towards a luminosity upgrade is described separately, since it will eventually comprise the major effort of the program.

## 2.1. R&D to Maximize the HEP Output of the LHC

### 2.1.1. Hardware Commissioning

The LHC Accelerator Project did not anticipate and does not include resources to commission the hardware delivered to CERN by the U.S. DOE national laboratories. The scientists and engineers from the U.S. labs who actually designed and built these components are more knowledgeable about their operation and integration into LHC than anyone else. A modest effort of on-site assistance to CERN during the hardware commissioning will ensure that the U.S. provided equipment is integrated efficiently with the other LHC systems, and thereby will significantly speed up the commissioning phase of the LHC. Moreover, the commissioning activity will provide important feedback on the effectiveness of the designs, and the U.S. designers will be best positioned to capture the benefits of this feedback by participating directly at CERN. The commissioning will require that a few appropriate U.S. experts be present during the hardware commissioning activities of the LHC that include the U.S. deliverables. A small contingent that will provide continuity and management oversight may be required at CERN for longer periods overlapping short term specific commissioning assignments.

The major hardware commissioning effort will take place during the U.S. fiscal years 2005 – 2007, starting with the commissioning of the first U.S.-provided inner triplet in 2005, and continuing through first operations with beam. It is expected that there will be an effective effort of two FTEs and associated travel costs during each of those years, split among a number of scientists and engineers from the three U.S. Labs. Preparatory work will begin in the second half of 2004, and some work may continue into 2008, depending on the actual schedule for LHC startup, and the extent to which hardware problems arise as the luminosity increases due, for example, to beam heating.

### 2.1.2. Beam Commissioning

Commissioning a collider requires the combined effort of many highly-trained and skilled scientists. The LHC is very complex and it will be very challenging to put into operation. The U.S. DOE laboratories operate two superconducting hadron colliders and are a rich source of the experienced scientists necessary to effectively and efficiently commission the LHC. It is clear that their participation will help bring the LHC to design luminosity more quickly. At the same time, participating in this activity is a benefit to the

U.S. program, since commissioning colliders is a once-in-a-decade opportunity. By participating fully and vigorously in the commissioning of the LHC, we will help maintain a core of experience in this area which will be important for the future capabilities of the National Laboratories in commissioning future machines at home. In consultation with CERN, we have concluded that this activity will be most effective for commissioning and optimally useful for gaining U.S. experience if LARP supports about one scientist per commissioning shift. We imagine that we will staff these shifts with a combination of long (up to a year) and relatively brief (on the order of a month) visits, and with a mix of experienced and more junior staff, in order to achieve significant breadth and depth in this effort.

The LHC is scheduled to have first beam in mid-2007. The beam commissioning activity will begin at least one year before that, in order to prepare and be sure that our scientists are fully integrated with the team at CERN. The LHC will be a very difficult machine to operate, and it is expected to take several years for it to approach its design performance. Thus we expect commissioning work to extend for about two years after first beam. By that time, the LHC should be nearing peak luminosity, and the effort will segue into analysis and fundamental accelerator physics, using the LHC as an experimental instrument.

### 2.1.3. Initial Instrumentation Suite

In order to bring the LHC up to luminosity as soon as possible, some specialized instrumentation and diagnostics beyond the usual set may be required. All of the instruments in the initial suite will be strong tools for efficient commissioning of the LHC. We have chosen to work on these because, in addition to enhancing the LHC performance, they push the state-of-the-art, and in some cases their development can also contribute to the efficient operation of our own machines. It is highly desirable that the initial suite of instruments and diagnostics be operational for LHC first beam, scheduled to be in 2007. Hence, the work must start early.

#### *2.1.3.1. Tune, Chromaticity and Coupling Feedback*

Tune, chromaticity and coupling feedback instruments and software are being developed at CERN and BNL. Such tools are crucial for efficient operations with intense beams in superconducting accelerators to help deal with dynamic effects, particularly during injection and at the beginning of the ramp. These instruments would be very useful to the operation of the Tevatron and RHIC, and even more important for the operation of LHC. Automatic and robust measurement of the tune without adverse side effects is a challenging problem and is the focus of the R&D effort. With a reliable tune measurement, a feedback system can be implemented in software and tested in a straightforward way.

#### *2.1.3.2. Real-Time Luminosity Measurements*

Also vital is a fast luminosity measurement device that can help LHC keep the beams in exact collision. Currently there are two potential technologies being proposed: an $ArN_2$ gas ionization chamber and a CdTe solid state detector. Recently the luminosity instrumentation review committee stated that *".. the decision on which technology to pursue should be made by Dec 2003. This time scale provides enough time for final* *designs and installation by Dec 2006*."  A beam and radiation hardness test of both technologies, performed jointly by LARP and CERN, is planned at the Fermilab Booster for later this year.  LARP has proposed the gas-ionization technology[2], and if that technology is chosen, we expect to be able to deliver the R&D on a time scale consistent with the luminosity monitor being available for first collisions.

#### *2.1.3.3. Longitudinal Beam-Density Monitor*

An advanced longitudinal beam density monitor, based on the non-linear mixing of synchrotron radiation with light from a pulsed laser, can be used to measure the longitudinal beam profile[3]. The longitudinal density monitor, which measures both the shape of individual bunches and the presence of other beam in "unfilled" RF buckets or as untrapped beam, will be essential for LHC, given the unprecedented stored energy in the beam.  The start of R&D on the longitudinal density monitor must be delayed until FY2005, due to the slow ramp up of expected funding.  Before that, its early conceptual development is being supported by LBNL LDRD funds, but development of a full prototype system for LHC will be carried out as part of the LARP.

### 2.1.4. Additional Instrumentation

There are a number of instruments and diagnostics that will possibly be very useful for the LHC, and for which the U.S. laboratories can supply expertise, but which are not part of the initial work scope.  Either they are more technologically speculative, their need is not well-established, or there is generally less interest in them at the present time. Some of these systems can be productively developed using the Tevatron or RHIC and be useful in improving the performance of both the LHC and our domestic accelerators. Other advanced instruments may be designed to help carry out fundamental accelerator physics experiments.  This work is a continuation beyond the initial suite of instruments, and it is estimated as a level of effort in later years.

While we cannot firmly predict now what instrumentation we will develop in the future, we list below some examples. This list is not intended to be exhaustive. Decisions about whether to support R&D on these  or other devices will be made by the Program Leader with the advice of the U.S.-CERN Committee at the appropriate time.

#### *2.1.4.1. Beam-beam compensation systems*

Beam-beam compensation systems have been proposed based on an electromagnetic wire or an electron lens. In the early phases of the LARP we will explore the feasibility of testing an electromagnetic wire system in the Tevatron in collaboration with CERN, as this both offers an early test for LHC and might yield positive results for the performance of the Tevatron.  No work on the electron lens for LHC will be proposed until its capabilities are well demonstrated in the Tevatron.

#### *2.1.4.2. High-Frequency Schottky*

High frequency Schottky monitors open the possibility of continuous and non-destructive  measurements of LHC beam sizes, tunes, and distributions.  Both narrow and wide band systems are potentially useful.  A narrow band resonant system achieves high sensitivity and can make rapid, low-noise measurements, while a broader band system, with poorer sensitivity, will nonetheless have adequate sensitivity and time resolution to measure beam size bunch-by-bunch. Coherent signals have been observed to interfere with Schottky (shot noise) signals, to some degree, at all hadron storage rings, including RHIC and the Tevatron. Reducing or ameliorating the effects of the coherent signals is a subject of current research at RHIC and the Tevatron. The results of the current R&D program could substantially affect our approach to this problem.

#### *2.1.4.3. AC Dipoles*

The installation of AC dipoles potentially aids the LHC to *non-destructively* measure the linear, near-linear, and non-linear properties of the beam, by exciting coherent betatron oscillations of the beam at frequencies very close to the betatron frequency. Perhaps most important is the potential ability of AC dipoles to rapidly and efficiently measure the optical beta-functions at the suite of collimators that are necessary to protect the LHC. Early operating experience has already been gained with AC dipoles at RHIC in the linear mode, generating preliminary beta-function measurements of varying quality. Near-linear and non-linear measurements have yet to be made. AC dipole experience at RHIC - in design, construction, and in operation - will be directly relevant to the potential installation of AC dipoles at the LHC.

## 2.2. Fundamental Accelerator R&D

### 2.2.1. Fundamental Accelerator Physics

High-energy physicists need to have experiments at the LHC because it is the collider at the frontier. Accelerator scientists must exploit the LHC for the very same reason: The frontier machine pushes the parameters to the limit where one can learn the most. Accelerator physics activities will require a mix of calculation, simulation and experimentation. Some of these activities can be done at home institutions in the U.S. Others will require presence at CERN—indeed, some experiments important for future colliders can be done only at the LHC, where the average and peak currents are high, and where synchrotron radiation is a significant effect.

At the present time, we see this as a level-of-effort activity. We expect that once funding permits, there will be about 9 FTE scientists working in Accelerator Physics, including commissioning, fundamental research and planning for upgrades, with as many as half at CERN and the rest at their home institutions. The ability to do experiments remotely from the U.S. may greatly reduce the travel strain and cost of these activities. The results of these calculations, simulations and experiments will give us the knowledge to design and build with confidence the next generation hadron collider.

Examples of some of the fundamental accelerator physics research that we expect to pursue is given in the following paragraphs.

#### *2.2.1.1. Beam-beam interaction*

The nominal beam parameters of the LHC take it into beam-beam territory well beyond current hadron colliders. The beams will have a finite crossing angle, and thus the closely spaced bunches will also undergo multiple long-range parasitic collisions at each interaction region. A RHIC based experimental program can systematically explore the major parameters associated with the head-on beam-beam interaction. Beam-beam experiments at the Tevatron[4] would complement those at RHIC[5], especially in the domain of long-range beam-beam interactions that are likely to limit the luminosity in the LHC. These experiments would be backed up by simulations using "strong-strong" beam-beam codes that are under development at LBL, which is the site for both the NERSC supercomputing center and the Sci-DAC supported Accelerator Modeling and Advanced Computing group. The results of these studies can help guide the strategies at LHC for dealing with beam-beam effects, and will help guide the design of a second generation IR for a luminosity upgrade (see Chapter 3). As the LHC comes into operation, it will become the direct focus of the experimental and theoretical programs on beam-beam effects within the LARP.

*2.2.1.2. Electron cloud*

The electron cloud effect is a significant problem in many of the current generation of high intensity electron-positron and hadron colliders. In the LHC, the electron cloud effect, if uncontrolled, is expected to cause excess power deposition on the cryogenic beam screen and an increase in beam emittance. LBL was an early participant in studying the electron cloud effect, developing one of the first simulations during the design and construction of PEPII, and then applying it the LHC. Electron clouds have been detected in RHIC, and (tentatively) in the Tevatron. RHIC and the Tevatron are cryogenic test beds similar to the LHC. Measurements, simulations, and analytical work will contribute to a better understanding of the electron cloud effect. Conversely, the ongoing efforts at CERN to describe and model electron cloud effect will benefit current and future U.S. Collider performance.

*2.2.1.3. Other Vacuum Effects*

Other manifestations of the physics of the vacuum are also important. The LHC will be the first machine with non-negligible synchrotron light emission into a cold bore environment, requiring the presence of a beam screen to intercept the synchrotron light. Future higher energy hadron accelerators will experience much more severe problems in this regard. Thus the LHC will provide a crucial test of our understanding of the physics mechanisms involved.

*2.2.1.3. Remote operations and maintenance*

We expect remote operations to become important to LARP accelerator physics activities on all time scales, and to beam instrumentation maintenance as systems developed by the U.S. labs are implemented. In the early stages of LHC commissioning most U.S. participants will spend a substantial fraction of their time on site at CERN. However, as the LHC matures an increasing fraction of effort could be done remotely, allowing a larger number of participants to stay involved with the LHC with less cost to the program. This involvement is important because it is through hands on understanding of the real limits of LHC performance that important new ideas and proposals for improving machine performance will emerge.

### 2.2.2. Advanced Instrumentation & Diagnostics

As the LHC program develops, as the limitations to the LHC performance and the need for more information to understand them become clearer, and as new ideas are developed, additional instrumentation research and development may be added to the LARP. Continued development of beam instruments and diagnostics is essential to the advancement of accelerator science and the delivery of the best machine performance for HEP. The efficiency of a complicated modern collider depends strongly on the quality of its instrumentation and diagnostics. Among the reasons for this is that superconducting magnetic components are not ideal, especially at injection fields, and the requirement of high-luminosity push beam parameters to the very edge of stability. Many of the effects that could make the LHC difficult to operate have already shown up in U.S. colliders. Thus new ideas for beam instrumentation can be rigorously tested at the Tevatron or RHIC, and the development of these instruments may be of great utility to those machines as well as to LHC. Most of this work is R&D that can be done at the U.S. DOE laboratories, requiring presence at CERN only during installation and commissioning of the new advanced systems.

# 3. LHC Upgrades

The recent report by HEPAP to the Office of Science on future high-energy physics facilities recognized the crucial importance of upgrading the luminosity of the LHC to the future of our field. Its report[1] states:

> Upgrades of the LHC are being envisaged. The more cost-effective upgrade is an increase in the luminosity, with the goal of a factor of 10 above the design value. This involves modifications of the accelerator (particularly the focusing magnets around the interaction regions) and the detectors (particularly the tracking systems). The science of extending exploration of the energy frontier with the LHC accelerator and detector luminosity upgrades is ***absolutely central***. The ***R&D phase*** for these will need to start soon if the upgrades are to be finished by the present target date of 2014. (Emphasis in original.)

A luminosity upgrade of the LHC is one of only three potential projects in high energy physics that the HEPAP report gave its highest rating of being absolutely central to the advancement of our science.

The U.S. DOE National Laboratories are uniquely positioned to lead the development of a new IR design, which will be a key element of the luminosity upgrade, and of the magnets that it will require. Our work on the design and construction of the existing IRs gives us important understanding of their limitations and of the measures to be taken to alleviate those limitations. The new IRs, whatever their design, will require magnets based on $Nb_3Sn$ superconductor, both to achieve the higher fields required and to provide greater temperature margin against radiation heating than is available with NbTi. The R&D programs at BNL, Fermilab, and LBNL put the U.S. DOE laboratories at the forefront in the development of high-performance accelerator magnets based on this technology. The specific magnets required for a new IR will take many years to develop, and R&D on them must begin within the next few years to ensure that they are ready when the LHC upgrades are to be implemented.

## 3.1. Time Scale for the LHC Luminosity Upgrade

After a few years of operation at the LHC design luminosity, the additional time it will take to significantly reduce the statistical errors in measurements will become prohibitively long, requiring luminosity upgrades to maintain the LHC as a discovery collider. This can be seen by considering the time required to reduce the statistical errors by a factor of two. Figure 3.-1 shows a simple model in which the first collisions in LHC take place in 2007, the first real physics run is in 2008, and the luminosity rises slowly to reach the design value of $10^{34}$ $cm^{-2}$ $s^{-1}$ by the end of 2011. The growth of the integrated luminosity is shown, assuming an effective $10^7$ seconds per year at the indicated luminosity. The statistical error on a typical measurement, which is proportional to $(\int L\, dt)^{-1/2}$, is shown in arbitrary units, as is the time required after each year to accumulate enough new data to halve the statistical error. By the time the LHC reaches the design luminosity, this "error halving time" will be at least 4-5 years. Thus, beyond about 2013-2014, the utility of additional running, without a major upgrade to the machine and detectors, will be limited. It should be noted that this conclusion does not change if the LHC luminosity is limited to a lower value than the nominal $10^{34}$ cm$^{-2}$ s$^{-1}$, or if the LHC exceeds its design parameters, since it is based solely on ratios of integrated luminosities.

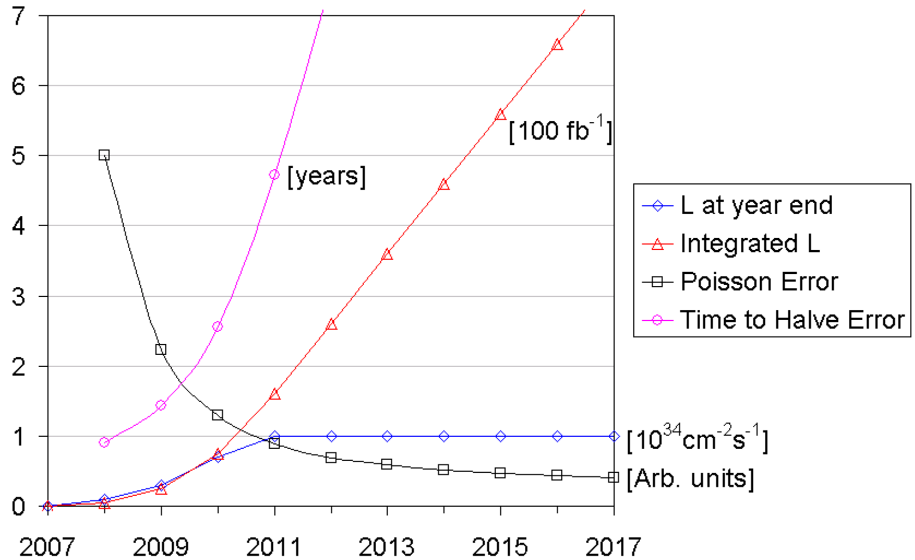


**Fig. 3.1-1** Results of a simple model used to estimate the time from LHC start it takes to halve the statistical error in a measurement. Note that after a year of operating at full luminosity, it will take more than seven years to halve the error.

## 3.2. Brief Descriptions of Possible LHC Upgrades

An increase in LHC luminosity by up to an order of magnitude, to as much as $10^{35}$ cm$^{-2}$ s$^{-1}$, appears feasible[6]. This will extend the mass reach of LHC by 20-30% and allow study of rare processes that are not accessible to the baseline machine[7,8]. Such an increase can be achieved with upgrades that involve replacement of equipment in the LHC insertions, but the large investment in the main accelerator arcs and most of the infrastructure would continue to be used. These upgrades would cost a only a small fraction of the original cost of the LHC, and would require only relatively modest down-time, on the order of a year, to install.

To achieve a factor of ten increase in luminosity, a number of accelerator systems will need to be upgraded, each of which will contribute to the higher luminosity. Substantial R&D on accelerator components, and studies to understand the limitations of the current configuration will be required before the specific modifications to the LHC can be proposed. These modifications will include replacement of the interaction region final focus system[9,10,11] with higher performance magnets to focus the beams to smaller $\beta^*$; advanced instrumentation and feedback systems to deal with higher intensity beams or new beam structure; and new RF systems to shorten the bunches, provide crab crossings, or provide novel beam structures such as superbunches. The U.S. labs expect to be deeply involved in the accelerator physics studies that will lead to decisions about the upgrade path, the development of magnets for new interaction regions, and the development of the instrumentation and control systems.

The issues to be addressed in designing a new IR for higher luminosity[12] are reducing $\beta^*$, minimizing the effects of the parasitic long-range beam-beam interactions within the region shared by the two beams, and dealing with the high radiation load that is a by-product of the very high luminosity. A number of different new IR layouts are under consideration, which address these issues in different ways and with different emphasis on each problem.

The simplest case is to duplicate the existing optics and layout, but with larger aperture quadrupoles that will permit a substantial reduction in $\beta^*$. This case is shown in Fig. 3.1-1. Assuming that the crossing angle scales with $(\beta^*)^{-1/2}$, a 110 mm aperture quadrupole[13] would allow about a factor of three decrease in $\beta^*$. This layout has the virtues representing the simplest possible change to the existing layout, and by placing the quadrupoles as close as possible to the IP, minimizes $\beta_{max}$ for a given $\beta^*$. However, it does not address the potentially severe problem of parasitic collisions. If a larger crossing angle is required to generate greater beam separation, then $\beta_{max}$ would have to be reduced and $\beta^*$ increased to compensate.

To reduce the number of parasitic collisions, the order of the beam separation dipoles and the quadrupole triplet can be reversed, as illustrated in Fig. 3.1-2. The D1 starts at the same distance from the IP as the Q1 in the baseline layout, and about 5 m is allowed between the magnetic ends of the D1 and D2 for a neutral particle absorber (TAN). A 100 mm aperture quadrupole would allow a factor of two decrease in $\beta^*$ from the baseline 50 cm. The D1 and D2 dipoles have coil apertures of about 130 mm and 100 mm respectively. The energy deposited in the D1 dipole by collision debris will be extremely high in this layout, requiring non-conventional designs[14]. Because the quadrupoles are substantially further from the IP than in the baseline, $\beta_{max}$ is substantially larger for a given $\beta^*$. Other configurations can also be considered, for example, placing twin-aperture quadrupoles with non-parallel axes between the first and second beam separation dipoles. Further details can be found in [12], and additional discussion of LHC upgrades is presented in Appendix E.

At the present time, not enough is known about the behavior of the LHC or the technical issues facing the magnet R&D to make a decision as to which type of upgrade will to be most effective. Generally, the dipole-first designs are more complicated and more challenging to the magnet R&D, because of the beam losses in the leading dipoles, the possibility of needing canted quadrupoles, and the distance to the quadrupoles from the IP. However, the dipole-first design reduces the long-range beam-beam effect, a possible impediment to higher luminosity in the LHC. Because the significance of this effect is not yet known, and probably will not be known until the LHC has operated for at least many months, we must continue to pursue R&D that supports both the conventional quadrupoles-first and the dipole-first designs.

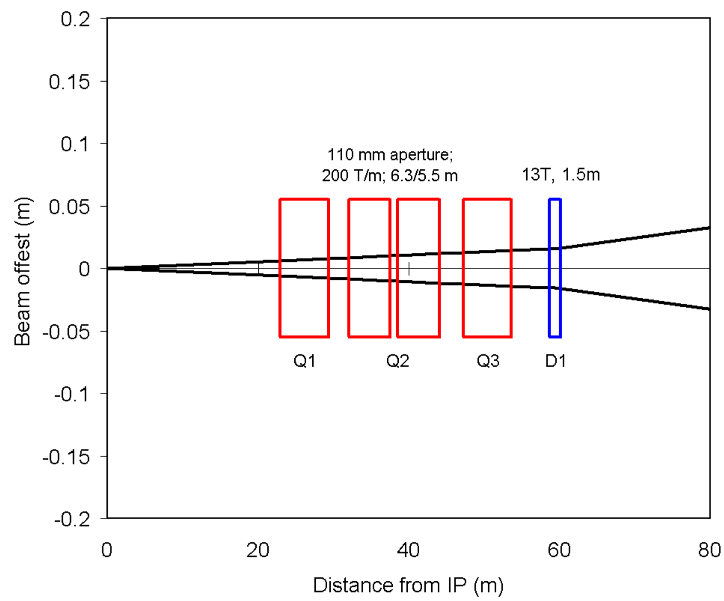


Fig. **3.2-1.** Quadrupoles-first interaction region, similar to the current LHC baseline.

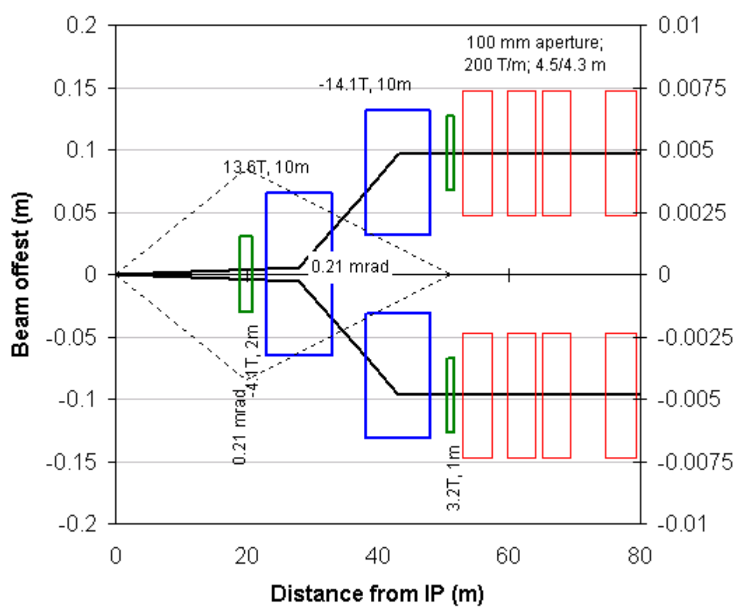


**Fig. 3.2-2.** Dipoles-first interaction region, which more than halves the number of parasitic collisions. The heavy line shows the orbits for a horizontal crossing angle generated by the D1 and D2 dipole. The dashed lines, plotted against the right axis, show vertical orbits for a vertical crossing plane generated by dipole correctors shown in green. Alternatively, the vertical crossing can be generated by rolling the large dipoles by several degrees.

Our model assumes that LARP will have vigorous programs in both quadrupole-first and dipole-first designs until about 2009. This decision is early enough to narrow the program as it enters its prototype production phase. If the choice is quadrupole-first, no dipole prototype will be fabricated. If the choice is dipole-first, a dipole and the appropriate quadrupole design will progress together toward prototype fabrication.

## 3.3. R&D Toward Major LHC Upgrades

### 3.3.1. Accelerator Physics

The luminosity upgrade of the LHC, expected to be implemented in the middle of the next decade, will require significant accelerator physics calculations and experimentation to determine its exact configuration. Handling issues that are not yet fully understood, such as long-range beam-beam interactions, the electron cloud effect, and limitations on individual bunch intensities will determine the overall design and set the requirements for the magnetic elements used in the upgrade.

The accelerator physics for upgrades effort is the earliest accelerator physics activity, since it informs the type of upgrade that can take place, and is necessary to guide the magnet R&D program, which must be launched soon and must be launched on the right path. Most of the work will take place in the U.S.

#### *3.3.1.1. Interaction Region optics*

All LHC upgrade scenarios require integrated analysis and development by accelerator physicists and magnet builders, in both the U.S. and in Europe, and the development of the Interaction Region optics is central to this integration. For example, the "dipole first" and "dipole last" scenarios depend on whether the beam is split into two beam pipes before or after the quadrupole triplet. Placing the dipole first is effective in reducing the deleterious effects of the bean-beam, interaction, but incurs a significant heat load from luminosity radiation products. Accelerator Physicists in LARP will work closely with magnet designers to generate an upgraded IR design, consistent with the timescale on which CERN is ready and able to down select from the many upgrade scenarios currently on the table.

#### *3.3.1.2. Interaction Region compensation*

It is possible to increase the good-field aperture a for a fixed set of IR magnets by better correcting the linear and nonlinear field quality with local correctors. Larger beta functions in the upgraded IRs imply that the effects of the nonlinearities will become even stronger. A local correction system will be necessary, most likely in a natural evolution from the system currently being installed in the original LHC triplets. Packages of local linear and non-linear correctors are nested close to the final focus triplet in RHIC and in the LHC, including normal and skew corrector layers. There is evidence that the Tevatron is strongly coupled, and that nonlinear multipoles in the IR quadrupoles have a significant impact on the beam. The experience gained at both RHIC[15] and the Tevatron[16] will be invaluable in implementing similar correction strategies in the LHC, and in upgraded LHC interaction regions.

#### 3.3.1.3. Energy deposition

The major effort in this area will be the analysis of the IR region for the various luminosity upgrade scenarios. Machine operation at very high luminosities results in significant particle spray from the interaction point itself into the final focus magnets. The large amount of stored energy -- 350 MJ -- in the circulating beams of the LHC will provide many operational problems, even before an IR upgrade. Analysis of energy deposition effects has been ongoing for many years as part of the U.S. collaboration on the LHC design activities. Fermilab has very strong technical expertise in this area. Many energy deposition analyses will be needed to fully optimize the protection systems, specify the magnet heat loads, and investigate the relative merits of alternative designs to go to the higher luminosities. This will include various normal operation and beam accident scenarios, and the analysis of the relative merits of the various schemes.

#### 3.3.1.4. Beam loss scenarios

Some fraction of any stored hadron beam becomes debunched during a store and circulates around the machine, eventually filling the abort gap. If no action is taken before a beam abort, or routine dump, this beam will deposit enough energy in the superconducting magnets to cause them to quench, and endangering other components, including detectors in the experiments. The cause of the debunched beam is not completely understood; possible sources are noise in the RF cavities, energy loss due to synchrotron radiation, or intra-beam scattering. The LHC is inherently more sensitive to fractional beam loss due to the higher beam energy and greater circulating beam intensity, even before an upgrade. Further studies will be pursued to better understand how these issues influence the upgrade design.

### 3.3.2. Magnet R&D For Luminosity Upgrades

The LARP magnet R&D program will build upon the existing expertise of the U.S. DOE laboratory programs to provide enabling technology, and ultimately fully developed specific magnet designs, for luminosity upgrades of the LHC. The magnet R&D for a luminosity upgrade will eventually become the largest part of the proposed LARP endeavor. It is expected that the deliverables will be the successful R&D, including the results of an intensive model magnet program, prototype magnets and the designs and specifications, leading to accelerator-ready magnet designs. Fabrication of production magnets will be considered as a separate proposal and judged using traditional procedures.

The LARP magnet R&D program will focus on magnets required for an LHC luminosity upgrade. The magnet requirements for even the simplest upgrade configurations exceed the performance characteristics of NbTi and, in fact, push the limits of $Nb_3Sn$. The principal goal of the magnet program is to produce designs for IR upgrade quadrupoles and dipoles that utilize the full potential of the highest performance superconducting materials. The program will extend and quantify the limits on key performance parameters, providing accelerator physicists with IR options that most efficiently address the beam dynamics issues that limit machine operation.

Recent progress in the development of $Nb_3Sn$ magnets[17] has encouraged the prospects for its use in LHC upgrades. However, even though it has been around for more than 40 years, $Nb_3Sn$ technology, as applied to accelerator magnets, is still far from fully developed. A program to address the integrated technological issues associated with all upgrade possibilities, in particular for high gradient, large aperture quadrupoles and high field dipoles operating in a high radiation environment, is necessary to realize the potential of this new regime.

The task we have set ourselves, to develop one or more magnet designs of unprecedented field strength, with very large apertures, which must operate in an extreme radiation environment, using difficult superconducting materials, and to develop the designs to the point at which they are ready operate as part of the highest performance accelerator ever built, is an extremely challenging one. We can succeed only if this program builds upon and is well coordinated with the on-going vigorous base program in high field magnet development. The DOE funded program to develop $Nb_3Sn$ will develop the fundamental superconducting material, and we count on this important program continuing. Over the past several years, a substantial infrastructure for the development of $Nb_3Sn$-based technology has been created in the U.S. DOE National Laboratories. The LHC Accelerator Research Program will benefit substantially from the existing technology base, intellectual resources and facilities at the three participating laboratories. BNL's react and wind[18] program for HTS and $Nb_3Sn$, FNAL's work on wind and react $Nb_3Sn$ $\cos\theta$ dipoles and LBNL's high field dipole program provide a complementary mix of technology that can be developed and applied by the U.S. LHC Accelerator Research Program to the specific needs of the LHC luminosity upgrade.

In addition, we must work in close collaboration and cooperation with our counterparts at CERN, and other European and Asian labs, in order to be assured that all of the magnet technologies and magnet designs required for the LHC luminosity upgrade are developed in time for implementation when the physics program of LHC will demand them. We expect that CERN, currently fully occupied with the construction of LHC, will start to devote effort on R&D for the future sometime after 2005. They will obviously become an integral and substantial part of the program. In addition, a new European collaboration has been proposed. ESGARD, the European Steering Group for Accelerator R&D, has a strong component of conductor and magnet technology development. The U.S. labs will participate in this collaboration through a networking structure that is part of ESGARD. We have already begun to organize the international collaboration through a first collaboration meeting on LHC IR upgrades, held in March 2002[19], and by sponsoring a "Workshop on Advanced Accelerator Magnets," held in March, 2003. Both included attendees from BNL, FNAL, LBNL, KEK, CERN, CEA/Saclay and a number of American and European universities. The details of our magnet R&D program will certainly be affected by how our collaboration with CERN and other labs develops.

The R&D program comprises four interdependent and overlapping phases:

1) The development of magnet requirements and conceptual designs;
2) Technology development, focused on issues generated by the requirements of possible LHC upgrades;

3) A model magnet design and development program for large-aperture, high-field quadrupoles and dipoles, that takes that technology base and directs it to the chosen upgrade applications; and

4) The construction of one or more prototypes, depending on the final choice of the new IR design, containing all of the features required for use in the LHC.

The first phase will be the major activity this year and next, but will continue at a low-level throughout the magnet program as understanding of the machine requirements and of the technological limits of potential magnet designs grows. There will be intense effort on technology development for the first several years, which will taper off as the focus shifts to model magnet R&D. Significant effort on materials (superconductor, insulation, radiation hardness, etc.), thermal properties and cooling methods, mechanical structures, and instrumentation will be required both initially to guide the model magnet design process, and later to address questions raised by the model magnet development. The model magnet program will get underway in 2005, guided by the results of the conceptual design studies and based on the initial results of the technology development program. We intend to develop both quadrupole and dipole models over the next approximately five years, focusing on the most challenging aspects of the two designs and pushing the limits on magnet parameters. In 2009 or 2010, after there has been enough running experience with the LHC to choose a final design for the upgraded IR, we will build models of the final design and launch the design and construction of prototypes, which will fully demonstrate all of the features required for the LHC, such that construction (funded outside of the LARP) of the actual upgrade magnets can begin in about 2012.

The most efficient use of resources is made by assigning the three laboratories a set of primary responsibilities and organizing these components into a coherent program. LBNL will have primary responsibility for magnet program management, integration and technology development, while FNAL will have responsibility for IR quadrupoles and BNL will focus on IR dipoles. These lines of responsibility will become more distinct in the later stages of the program.

The initial phase of developing IR magnet requirements and conceptual designs will be jointly lead by the accelerator physics and magnet leaders. This work must be done in close collaboration with CERN. Close interaction between accelerator physicists and magnet designers is required, since the magnet requirements follow from the accelerator physics calculations, but the accelerator configurations studied must be consistent with what it technologically possible. Studies include beam optics, magnet designs that can satisfy the optics requirements, expected field quality and correction methods, energy deposition, and alignment. The results will be a set of candidate IR designs, preliminary magnet requirements, and a set of magnet conceptual designs consistent with the IR designs.

A number of key R&D questions can already be identified, including the following:

- What is the highest field that can be generated within the coil winding? For quadrupoles, this translates to, what is largest possible quadrupole aperture which can operate with adequate margin at $G \geq 200$ T/m? For dipoles, the question, is what is the maximum possible dipole field with aperture > 100 mm?

- What mechanical structures can deal with the large forces from high field and large apertures?
- How can adequate field quality be maintained in twin-aperture configurations (dipole and quadrupole) at very high fields? This is particularly a question for beam separation dipoles in which the fields in the two apertures are parallel, not anti-parallel.
- What is the effect on $Nb_3Sn$ of very high radiation doses?
- What insulating materials can be used in the very high radiation environment seen by these magnets?
- How can the coils be cooled? What is the maximum possible local power deposition that can be handled?
- How can the magnet be designed or what external measures can be taken to minimize the collision debris power deposited in the coils and in the magnet as a whole?

The results of the conceptual design phase over the next year and a half will be to flesh out this list, adding additional topics and bringing the issues to be addressed into sharper focus.

The technology development program will address the issues and questions identified as key for the new IR magnets. These will include material studies, development of superconducting wire and cable for different magnet designs, radiation tests, mechanical models of coils and support structures, thermal models, sub-scale coil tests, development of computer simulation tools, and development of instrumentation both for the technology tests and for the subsequent model magnets. Some technology development will also require the construction of short model magnets, particularly related to fabrication techniques. This effort will be highly leveraged on the base program. LBNL will have primary responsibility for the technology development program.

In 2005 or 2006 we will begin building model magnets that will address the main technological issues required for luminosity upgrades. The actual choice of magnet types and designs to be developed will follow from the conceptual design studies to be done between now and then. However, it seems certain that the critical designs to study with model magnets will be a quadrupole of the largest possible aperture and a large-aperture, high-field dipole suitable for use in the extreme radiation environment of a dipole-first IR. The parameters of the magnets will be well beyond the current state of the art, in particular in terms of field strength and ability to deal with very high radiation heat loads from the p-p collision debris. Some configurations may require or strongly benefit from magnet designs or configurations that have never been tried before. For example, the dipole-first configuration may require a design with no superconductor on the mid-plane, where the radiation will be the most intense.

The exact form of the magnet R&D program – what designs will be developed, how many models of what type will be built each year, the relative efforts on complete model magnets versus simplified technology development models, etc. – cannot be determined now. The initial plans will only be fully developed following the results of the requirements and conceptual design phase and the initial technology development work. Furthermore, the fact that we will be pushing technology well beyond the current state-of-the-art means that the precise path will evolve as we encounter specific challenges and master the technology. And the details of our program will be affected by how our collaboration with CERN and other labs evolves. However, based on our extensive experience with magnet R&D programs, we can sketch below a general plan, which is representative of the likely development program. A summary of a representative program that has been used for cost estimating purposes is shown in Figure 3.3-1.

| | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 | FY10 |
|---|---|---|---|---|---|---|---|
| Sub-scale Technology Tests | | | | | | | |
| 1m Quad Models | | | 1 | 2 | 2 | 2 | 2 |
| 1m Dipole Models | | | | 1 | 1 | 1 | 1 |
| 4m Quad or Dipole Models | | | | | | 0.25 | 1 |

**Fig. 3.3-1** Representative magnet R&D program that has been used for cost estimating purposes.

We plan model magnet programs in both quadrupoles (FNAL plus LBNL) and dipoles (BNL plus LBNL). The first models, built in 2005 or 2006, may be of a simplified design (e.g. only the inner two layers of a four-layer design) or built with simplified procedures (e.g. applying LBNL's bladder assembly method to a quadrupole model). After that we plan to build about 3 model magnets per year with continuing support from the technology development program. The early models will concentrate on developing magnet technologies and demonstrating that the required field strength can be achieved reproducibly. We will also use all models to understand the reproducibility of field quality and the systematic relation between expected and measured field errors. In the later stages of the program, as the designs evolve towards ones that include most or all of the relevant features of an accelerator ready design, field quality development will become an increasingly important part of the program, particularly for the quadrupoles where the beta-functions reach their largest value in the machine. It should be noted that there will be considerable cross-fertilization between the two model magnet programs, particularly in the earlier stages, between the LARP magnet program and the base high-field dipole programs at the three U.S. DOE labs, and between the U.S. and European (and perhaps Asian) R&D programs for LHC upgrades.

As early in the program as possible, that is, as soon as we have achieved reasonable success towards achieving the field strength goals and have sufficient funding to support it, we will construct one or more long models of at least one of the magnet types (dipole or quadrupole) to understand length dependent effects. Magnets up to about 4 m long can be built and tested in the vertical dewars at FNAL and BNL. Length dependent effects have been largely mastered for NbTi magnets, but only short (~1 m long) $Nb_3Sn$ accelerator magnet models have ever been built. Length dependent effects include thermal expansion issues during coil reaction, handling of long reacted coils, and reaction of the large axial forces while minimizing the strain on the coil ends. Surprises may occur, and dealing with such issues could have critical influence on magnet designs and fabrication methods. Therefore they must be investigated as early as is practical. Unfortunately, funding limitations mean that, unless we are blessed with success in the first one or two models, it appears unlikely that we can start this phase until about 2009.

By 2009 or 2010, LHC should be approaching its design performance parameters, and the machine should be well enough understood so that the principal factors which set the limits on the achievable luminosity will be known. This will allow us, together with CERN, to determine the most effective upgrades to the machine to alleviate these limits and raise the luminosity. Depending on the specific magnet designs required for the new IR and on how successful the R&D program has been in developing $Nb_3Sn$ accelerator magnet technology, we may or may not need to build additional model magnets before starting to build prototypes.

It is certainly too early to determine the nature of the prototype program, and it is not clear whether the prototypes will be considered the last step of the R&D program and therefore part of LARP, or the first stage of a production program, and therefore funded separately. Depending on the type of IR chosen, the degree of success of our R&D on dipoles and quadrupoles, the level of funding, and the nature of our collaboration at that time with CERN and other labs, we might build prototype dipoles and quadrupoles, or only one type. Neither can we say now if these will be full-scale prototypes of full-length, which are tested in prototype cryostats, or sophisticated 4 m models, which incorporate all of the final design features but are tested in a vertical dewar. The goal, however, is clear – to have fully-developed and proven accelerator-ready magnet designs, ready for production, by about 2012, as required to support the LHC physics program.

We plan R&D programs in both quadrupoles and dipoles, so as to be ready with the required technologies for a new IR, whatever the chosen IR design is. However, the resources available to support the LARP magnet R&D effort are limited, and it will be quite challenging to develop accelerator-ready designs of two different types of magnets of unprecedented field strength, with superb field quality over a very large aperture, and which must operate in an extreme radiation environment. We will regularly evaluate the progress of the R&D, and if necessary we will concentrate most or even all of the resources of the three Laboratories on one of the magnet types, most likely the quadrupole, to ensure that we will be successful in developing it to be ready for use in the LHC upgrade.

It should be recognized, however, that while the goal is to have at least one accelerator-ready design ready for production as required for an LHC luminosity upgrade, the current immaturity of the enabling technology does not permit us to guarantee success. In the end, the R&D program will be performed on a "best effort" basis, and success will depend on, among other factors, difficulty of the technological challenges that we encounter and the level of funding over the coming years. As noted above, the likelihood of success depends also on the continuation of a vigorous base program in high field magnets, well coordinated with the LHC-specific R&D done by LARP, and on close collaboration with CERN and other labs who are aiming at the same goal.

# 4. Cost and Schedule Estimates

## 4.1 Summary

The cost of the U.S. LHC Accelerator Research Program has been estimated for the period FY2004 – FY2009. The cost estimate in then-year dollars is summarized in Table 4.1-1 and Fig 4.11, which show the estimated costs for Program Management, Accelerator Systems, and Superconducting Magnet R&D. The estimated costs are consistent with the funding guidance. The Accelerator Systems budget shows a local maximum in FY2007, corresponding to the LHC startup. This is "paid for" by a corresponding local minimum in the budget for Magnet R&D.

***Table 4.1-1 LARP Cost Estimate Summary.***

| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 |
|---|---|---|---|---|---|---|---|
| **Sub-program Costs** | | | | | | | |
| Program Management | $k | 89 | 282 | 675 | 695 | 716 | 737 |
| Accelerator Systems | $k | 638 | 1,823 | 3,623 | 4,457 | 4,098 | 3,850 |
| Magnet R&D | $k | 323 | 1,395 | 6,697 | 5,849 | 7,193 | 7,415 |
| **Total Program Cost** | **$k** | **1,049** | **3,500** | **10,995** | **11,001** | **12,007** | **12,002** |
| **DOE Funding Guidance** | **k$** | **1,050** | **3,500** | **11,000** | **11,000** | **12,000** | **12,000** |

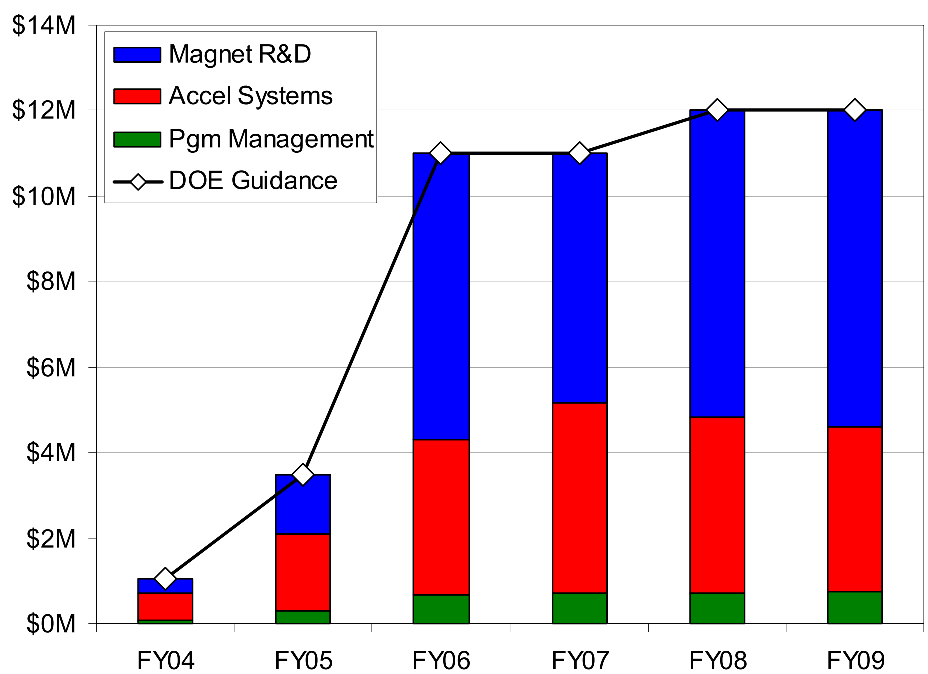


**Fig. 4.1-1** Cost estimate for the U.S. LHC Accelerator Research Program, compared with the DOE funding guidance.

The cost estimate is broken down further in Table 4.1-2, which shows the overall effort in FTEs in broad categories and cost estimates for labor, materials and services (M&S) and travel for each subprogram. Travel costs have been broken out separately, since travel is essential to the success of a multi-lab program, and even more so for one which is part of an international collaboration. Estimates are shown in constant FY2003 dollars, and with a 3% annual escalation applied to the total cost.

***Table 4.1-2 LARP M&S and Labor Cost Estimate Summary***

| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 |
|---|---|---|---|---|---|---|---|
| **Labor count** | | | | | | | |
| **Program Management** | | | | | | | |
| Scientist/Engineer | FTE | 0.4 | 1.0 | 2.4 | 2.4 | 2.4 | 2.4 |
| Administrator | FTE | 0.0 | 0.4 | 0.8 | 0.8 | 0.8 | 0.8 |
| SUB-TOTAL | FTE | 0.4 | 1.4 | 3.2 | 3.2 | 3.2 | 3.2 |
| **Accelerator Systems** | | | | | | | |
| Scientist/Engineer | FTE | 2.5 | 5.9 | 9.3 | 11.0 | 9.4 | 8.4 |
| Post-doc/Student | FTE | 0.0 | 0.5 | 4.3 | 6.5 | 7.0 | 7.0 |
| Technician/Designer | FTE | 0.1 | 0.7 | 1.0 | 0.5 | 0.8 | 0.0 |
| SUB-TOTAL | FTE | 2.6 | 7.1 | 14.6 | 18.0 | 17.2 | 15.4 |
| **Magnet R&D** | | | | | | | |
| Scientist/Engineer | FTE | 1.2 | 3.5 | 8.1 | 8.3 | 8.5 | 8.3 |
| Technician/Designer | FTE | 0.4 | 2.0 | 12.9 | 11.7 | 12.1 | 12.4 |
| SUB-TOTAL | FTE | 1.6 | 5.5 | 21.0 | 20.0 | 20.6 | 20.7 |
| | | | | | | | |
| **Materials & Services** | | | | | | | |
| Program Management | $k03 | 2 | 7 | 16 | 16 | 16 | 16 |
| Accelerator Systems | $k03 | 90 | 330 | 760 | 865 | 690 | 690 |
| Magnet R&D | $k03 | 20 | 358 | 2,920 | 2,091 | 3,010 | 3,021 |
| | | | | | | | |
| **Travel** | | | | | | | |
| Program Management | $k03 | 4 | 11 | 26 | 26 | 26 | 26 |
| Accelerator Systems | $k03 | 27 | 74 | 146 | 185 | 169 | 154 |
| Magnet R&D | $k03 | 6 | 18 | 41 | 42 | 43 | 42 |
| | | | | | | | |
| **SUB-TOTALS** | | | | | | | |
| **Labor count** | | | | | | | |
| Scientist/Engineer | FTE | 4.1 | 10.4 | 19.8 | 21.7 | 20.3 | 19.1 |
| Post-doc/Student | FTE | 0.0 | 0.5 | 4.3 | 6.5 | 7.0 | 7.0 |
| Technician/Designer | FTE | 0.5 | 2.7 | 13.9 | 12.2 | 12.9 | 12.4 |
| Administrator | FTE | 0.0 | 0.4 | 0.8 | 0.8 | 0.8 | 0.8 |
| TOTAL LABOR | FTE | 4.6 | 14.0 | 38.8 | 41.2 | 41.0 | 39.3 |
| | | | | | | | |
| **Labor cost** | $k03 | 870 | 2,502 | 6,154 | 6,550 | 6,404 | 6,104 |
| **Travel** | $k03 | 37 | 102 | 212 | 252 | 237 | 221 |
| **Materials & Services** | $k03 | 112 | 695 | 3,696 | 2,972 | 3,716 | 3,727 |
| | | | | | | | |
| **TOTAL COST** | | | | | | | |
| Constant dollars | $k03 | 1,019 | 3,299 | 10,062 | 9,774 | 10,357 | 10,052 |
| With 3.0%/year escalation | $k | 1,049 | 3,500 | 10,995 | 11,001 | 12,007 | 12,002 |

Because this is a Research and Development program, it is neither necessary nor sensible to perform detailed, "bottoms-up" cost estimates of the sort that are made for a construction project. The level of detail of the cost estimating for the LARP is different for different program elements. Accelerator physics as well as hardware and beam commissioning are essentially level-of-effort tasks. Differing degrees of detail can be given for the development of each of the instruments in the initial suite. The magnet R&D program aims to push well beyond the current state-of-the-art, and therefore it is not possible to lay out a comprehensive plan whose cost can be estimated in detail. Cost models have been developed to indicate the types and level of R&D that can be supported by the LARP budget, and these are discussed in the subsequent sections.

For each program element, labor has been estimated in FTEs in broad categories: scientists, engineers, post-docs, students, designers, technicians and administrators. Because we do not have a rigid plan for where each piece of work will be performed in each year, we have estimated the cost of labor based on labor rates averaged over the three labs. These averages are based on the direct cost labor rates from the U.S. LHC Accelerator Project baseline, escalated from FY2001 (used in the current Project baseline) to FY2003 at 3% per year. The overhead and G&A rates appropriate for an R&D program are applied to the labor rates at each lab. Finally the fully-burdened labor rates are averaged across the three labs and applied to the FTE estimates. We have chosen to further group the labor categories listed above into three composite labor rates: scientists and engineers ($200k/year), designers, technicians and administrators ($120k/year), and post-docs and students ($100k/year).

Similarly, the direct cost of materials and services has been estimated for each program element. A burden rate of 30% is then applied, which is the average of the rates at the three labs appropriate for an R&D program. Travel cost is estimated as being proportional to the number of FTE scientists and engineers, with different rates for the different subprograms.

## 4.2 Program Management

Program management costs are estimated in Table 4.2-1. The central Program Office consists of 1 FTE scientist and 0.5 FTE administrator. The costs of administering the accelerator systems and superconducting magnet programs are estimated to be a 0.7 FTE scientist and a 0.15 FTE administrator for each. These are the asymptotic levels of effort for FY2006 and beyond, with proportionately smaller efforts in earlier years when the funding and therefore level of program activity is less. A nominal M&S budget, proportional to the level of effort, is allowed (burdens included) and a travel budget of $10k and $2k per year respectively is assumed for each FTE scientist and administrator. This yields a management cost that is about 8.5% of the total budget in FY04, and that drops to about 6% in later years.

***Table 4.2-1 LARP Management Cost Estimate***

| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 |
|---|---|---|---|---|---|---|---|
| **Labor count** | | | | | | | |
| **Program Office** | | | | | | | |
| Scientist/Engineer | FTE | 0.2 | 0.5 | 1.0 | 1.0 | 1.0 | 1.0 |
| Administrator | FTE | | 0.2 | 0.5 | 0.5 | 0.5 | 0.5 |
| SUB-TOTAL | FTE | 0.2 | 0.7 | 1.5 | 1.5 | 1.5 | 1.5 |
| **Accelerator Systems** | | | | | | | |
| Scientist/Engineer | FTE | 0.1 | 0.3 | 0.7 | 0.7 | 0.7 | 0.7 |
| Administrator | FTE | | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 |
| SUB-TOTAL | FTE | 0.1 | 0.4 | 0.9 | 0.9 | 0.9 | 0.9 |
| **Magnet R&D** | | | | | | | |
| Scientist/Engineer | FTE | 0.1 | 0.2 | 0.7 | 0.7 | 0.7 | 0.7 |
| Administrator | FTE | | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 |
| SUB-TOTAL | FTE | 0.1 | 0.3 | 0.9 | 0.9 | 0.9 | 0.9 |
| | | | | | | | |
| **Materials & Services** | | | | | | | |
| Misc. Supplies ($5k/FTE) | $k03 | 2 | 7 | 16 | 16 | 16 | 16 |
| | | | | | | | |
| **SUB-TOTALS** | | | | | | | |
| **Labor count** | | | | | | | |
| Scientist/Engineer | FTE | 0.4 | 1.0 | 2.4 | 2.4 | 2.4 | 2.4 |
| Administrator | FTE | 0.0 | 0.4 | 0.8 | 0.8 | 0.8 | 0.8 |
| TOTAL LABOR | FTE | 0.4 | 1.4 | 3.2 | 3.2 | 3.2 | 3.2 |
| | | | | | | | |
| **Labor cost** | $k03 | 80 | 248 | 576 | 576 | 576 | 576 |
| **Travel** | $k03 | 4 | 11 | 26 | 26 | 26 | 26 |
| **Materials & Services** | $k03 | 2 | 7 | 16 | 16 | 16 | 16 |
| | | | | | | | |
| **TOTAL COST** | | | | | | | |
| Constant dollars | $k03 | 86 | 266 | 618 | 618 | 618 | 618 |
| With 3.0%/year escalation | $k | 89 | 282 | 675 | 695 | 716 | 737 |

## 4.3 Accelerator Systems

The Accelerator Systems cost estimate is summarized in Table 4.3-1, which shows the labor effort, and labor, travel, M&S, and total cost estimates for Instrumentation, Beam Commissioning and Accelerator Physics, and Hardware Commissioning. The travel budget allows $10k/year (FY2003 dollars) for each FTE scientist, engineer, post-doc or student. The burden are included in the travel and M&S costs shown. Further details of each of these subprogram are displayed in Tables 4.3-2, 4.3-3 and 4.3-4 respectively.

The instrumentation program (Table 4.3-2) consists of three initial systems, followed by additional instrumentation. The initial instruments are tune and chromaticity feedback, luminosity monitor development and construction, and longitudinal density monitor development. The tune feedback R&D is largely a level of effort task, which ramps up to 1 FTE each scientist and post-doc or student once the LHC begins operation in 2007. The M&S budget covers a prototype tune measurement system, the full complement of TAN luminosity monitors (but no TAS monitors), and two longitudinal density monitors. All of these devices will be delivered and installed for routine operation in the LHC, perhaps after initial testing in a US accelerator. In each case the delivered system is integrated and complete, up to and including a software interface into the LHC control system.

***Table 4.3-1 Accelerator Systems Cost Summary***

| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 |
|---|---|---|---|---|---|---|---|
| **Labor Count** | | | | | | | |
| Instrumentation | FTE | 1.1 | 2.4 | 5.6 | 6.5 | 6.7 | 5.9 |
| Beam Comm & Acc Phys | FTE | 1.0 | 2.7 | 7.0 | 9.5 | 9.5 | 9.5 |
| Hardware Commissioning | FTE | .5 | 2.0 | 2.0 | 2.0 | 1.0 | .0 |
| TOTAL | FTE | 2.6 | 7.1 | 14.6 | 18.0 | 17.2 | 15.4 |
| **Labor Cost** | | | | | | | |
| Instrumentation | $k03 | 202 | 424 | 860 | 960 | 976 | 880 |
| Beam Comm & Acc Phys | $k03 | 200 | 490 | 1,150 | 1,550 | 1,500 | 1,500 |
| Hardware Commissioning | $k03 | 100 | 400 | 400 | 400 | 200 | 0 |
| TOTAL | $k03 | 502 | 1,314 | 2,410 | 2,910 | 2,676 | 2,380 |
| **Travel** | | | | | | | |
| Instrumentation | $k03 | 10 | 17 | 46 | 60 | 59 | 59 |
| Beam Comm & Acc Phys | $k03 | 10 | 27 | 70 | 95 | 95 | 95 |
| Hardware Commissioning | $k03 | 8 | 30 | 30 | 30 | 15 | 0 |
| TOTAL | $k03 | 27 | 74 | 146 | 185 | 169 | 154 |
| **Materials & Services** | | | | | | | |
| Instrumentation | $k03 | 80 | 260 | 680 | 800 | 650 | 650 |
| Beam Comm & Acc Phys | $k03 | 10 | 20 | 30 | 40 | 40 | 40 |
| Hardware Commissioning | $k03 | | 50 | 50 | 25 | | |
| TOTAL | $k03 | 90 | 330 | 760 | 865 | 690 | 690 |
| **TOTAL COSTS (escalated)** | | | | | | | |
| Instrumentation | $k | 300 | 744 | 1,733 | 2,048 | 1,953 | 1,897 |
| Beam Comm & Acc Phys | $k | 227 | 570 | 1,366 | 1,896 | 1,895 | 1,952 |
| Hardware Commissioning | $k | 111 | 509 | 525 | 512 | 249 | 0 |
| **GRAND TOTAL** | **$k** | **638** | **1,823** | **3,623** | **4,457** | **4,098** | **3,850** |

The luminosity monitor cost estimate assumes that the results of beam tests, to be conducted later this year comparing the ionization chamber developed by LBNL with a CdTe solid state detector, identify the ionization chamber as the preferred technology. In this case, LBNL will finish the R&D and detailed design for this device largely during FY2004 and 2005. The cost estimate assumes that eight 4-channel devices will be built during FY2005-2006, for use in the neutral absorbers on both sides of all four interaction regions, and implemented in LHC in FY2007

Initial R&D on the longitudinal density monitor is being supported at LBNL by LDRD funds. The first work supported by LARP will be in FY2005, and serious work to develop the design for use in LHC will be carried out principally in FY2006 and 2007.

*Table 4.3-2 Instrumentation Cost Summary*

| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 |
|---|---|---|---|---|---|---|---|
| **Labor count** | | | | | | | |
| **Tune feedback** | | | | | | | |
| Scientist/Engineer | FTE | 0.5 | 0.5 | 1.0 | 0.8 | 0.5 | |
| Post Doc/Student | FTE | | | 0.6 | 1.0 | 0.5 | |
| Designer/Technician | FTE | | | | | | |
| SUB-TOTAL | FTE | 0.5 | 0.5 | 1.6 | 1.8 | 1.0 | |
| **Luminosity monitor** | | | | | | | |
| Scientist/Engineer | FTE | 0.5 | 0.7 | 1.0 | 0.8 | 0.5 | |
| Post Doc/Student | FTE | | | 0.7 | 1.0 | 0.5 | |
| Designer/Technician | FTE | 0.1 | 0.7 | 0.7 | | | |
| SUB-TOTAL | FTE | 0.6 | 1.4 | 2.4 | 1.8 | 1.0 | |
| **Longitudinal density monitor** | | | | | | | |
| Scientist/Engineer | FTE | | 0.5 | 0.8 | 1.0 | 0.8 | 0.5 |
| Post Doc/Student | FTE | | | 0.5 | 1.0 | 0.8 | 0.5 |
| Designer/Technician | FTE | | | 0.3 | 0.5 | 0.8 | |
| SUB-TOTAL | FTE | | 0.5 | 1.6 | 2.5 | 2.4 | 1.0 |
| **Additional Instrumentation** | | | | | | | |
| Scientist/Engineer | FTE | | | | 0.4 | 1.1 | 2.4 |
| Post Doc/Student | FTE | | | | | 1.2 | 2.5 |
| Designer/Technician | FTE | | | | | | |
| SUB-TOTAL | FTE | | | | 0.4 | 2.3 | 4.9 |
| | | | | | | | |
| **Materials & Services** | | | | | | | |
| Tune feedback | $k03 | 40 | 70 | 180 | 180 | 50 | |
| Luminosity monitor | $k03 | 40 | 150 | 300 | 250 | 100 | |
| Longitudinal density monitor | $k03 | | 40 | 200 | 300 | 200 | 50 |
| Additional Instrumentation | $k03 | | | | 70 | 300 | 600 |
| | | | | | | | |
| **SUB-TOTALS** | | | | | | | |
| **Labor count** | | | | | | | |
| Scientist/Engineer | FTE | 1.0 | 1.7 | 2.8 | 3.0 | 2.9 | 2.9 |
| Post Doc/Student | FTE | | | 1.8 | 3.0 | 3.0 | 3.0 |
| Designer/Technician | FTE | 0.1 | 0.7 | 1.0 | 0.5 | 0.8 | |
| TOTAL LABOR | FTE | 1.1 | 2.4 | 5.6 | 6.5 | 6.7 | 5.9 |
| | | | | | | | |
| **Labor cost** | $k03 | 202 | 424 | 860 | 960 | 976 | 880 |
| **Travel** | $k03 | 10 | 17 | 46 | 60 | 59 | 59 |
| **Materials & Services** | $k03 | 80 | 260 | 680 | 800 | 650 | 650 |
| | | | | | | | |
| **TOTAL COST** | | | | | | | |
| Constant dollars | $k03 | 292 | 701 | 1,586 | 1,820 | 1,685 | 1,589 |
| With 3.0%/year escalation | $k | 300 | 744 | 1,733 | 2,048 | 1,953 | 1,897 |

The effort required on each of these instruments is relatively well understood between now and the first year of LHC operations. We show a constant level of labor effort, and a modestly decreasing M&S budget in FY2008 and FY2009. We expect that during the later years, not all of the resources will be required for the three initial devices. The remainder will be devoted to the development of additional instruments, as discussed in

Section 2.1.4. However, since we do not know now what instruments will be required for the LHC in those years, we cannot provide a specific cost estimate. Thus the estimated cost in FY2008-09 is to be considered a level of effort devoted to LHC instrumentation development. Up to half the effort on instrumentation development is expected to involve post-docs or students.

The cost estimate for Beam Commissioning and Fundamental Accelerator Physics is shown in Table 4.3-3. A rough estimate of the fraction of the effort that will take place in the U.S. Labs versus at CERN is indicated. Significant work starts at CERN in 2006, when we plan to participate in the injection test in the first LHC sector (sector 7-8). This is not only a crucial first test for all of the LHC systems, but also involves beam being injected through the U.S.-provided interaction region systems on both sides of IR 8.

***Table 4.3-3 Beam Commissioning and Accelerator Physics Cost Summary***

| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 |
|---|---|---|---|---|---|---|---|
| **BEAM COMMISSIONING** | | | | | | | |
| **Labor count** | | | | | | | |
| *At a U.S. Lab* | *FTE* | *0.5* | *1.1* | *2.0* | *1.0* | | |
| *At CERN* | *FTE* | | *0.5* | *2.0* | *5.5* | *6.5* | *6.5* |
| Scientist/Engineer | FTE | 0.5 | 1.1 | 2.5 | 4.0 | 3.5 | 3.5 |
| Post Doc/Student | FTE | | 0.5 | 1.5 | 2.5 | 3.0 | 3.0 |
| SUB-TOTAL | FTE | 0.5 | 1.6 | 4.0 | 6.5 | 6.5 | 6.5 |
| **Cost sub-totals** | | | | | | | |
| Labor | $k03 | 100 | 270 | 650 | 1,050 | 1,000 | 1,000 |
| Travel | $k03 | 5 | 16 | 40 | 65 | 65 | 65 |
| **FUNDAMENTAL ACCELERATOR PHYSICS** | | | | | | | |
| **Labor count** | | | | | | | |
| *At a U.S. Lab* | *FTE* | *0.5* | *1.1* | *2.0* | *2.0* | *2.0* | *2.0* |
| *At CERN* | *FTE* | | | *1.0* | *1.0* | *1.0* | *1.0* |
| Scientist/Engineer | FTE | 0.5 | 1.1 | 2.0 | 2.0 | 2.0 | 2.0 |
| Post Doc/Student | FTE | | | 1.0 | 1.0 | 1.0 | 1.0 |
| SUB-TOTAL | FTE | 0.5 | 1.1 | 3.0 | 3.0 | 3.0 | 3.0 |
| **Cost sub-totals** | | | | | | | |
| Labor | $k03 | 100 | 220 | 500 | 500 | 500 | 500 |
| Travel | $k03 | 5 | 11 | 30 | 30 | 30 | 30 |
| **BEAM COMMISSIONING + FUNDAMENTAL ACCELERATOR PHYSICS** | | | | | | | |
| **Labor count** | FTE | 1.0 | 2.7 | 7.0 | 9.5 | 9.5 | 9.5 |
| **Labor cost** | $k03 | 200 | 490 | 1,150 | 1,550 | 1,500 | 1,500 |
| **Travel** | $k03 | 10 | 27 | 70 | 95 | 95 | 95 |
| **Materials & Services** | $k03 | 10 | 20 | 30 | 40 | 40 | 40 |
| **TOTAL COST** | | | | | | | |
| Constant dollars | $k03 | 220 | 537 | 1,250 | 1,685 | 1,635 | 1,635 |
| With 3.0%/year escalation | $k | 227 | 570 | 1,366 | 1,896 | 1,895 | 1,952 |

Work during FY2004 and FY2005, as well as a substantial fraction of the effort in FY2006 is devoted to preparations for LHC commissioning. To have the maximum impact on the performance of the LHC, and to gain the maximum benefit to the U.S. accelerator physics community from participation in the machine commissioning, it is desirable that U.S. physicists take real responsibility for some aspects of the commissioning work. This in turn requires that our scientists be well integrated with the CERN team, and laying the groundwork to make this possible is a major goal of the next few years. Significant effort on beam commissioning is shown through FY2009, since we expect LHC to be a difficult machine to bring to its full operational parameters. About half the effort is expected eventually to involve post-docs.

Early accelerator physics work will concentrate on problems related to planning the LHC upgrades. The AP effort will increase in FY2006 and beyond, as LHC comes into operation and as increased funding becomes available. About 1/3 of the effort is expected to be post-docs.

Major activity on Hardware commissioning (Table 4.3-4) begins in FY2005, when the first two U.S.-provided interaction region systems (IR8 L and IR2 R) are scheduled to be commissioned together with the adjacent straight and arc sections of the machine. A small effort is budgeted in FY2004 for pre-commissioning preparations. Commissioning of 6 more regions containing U.S.-provided magnet systems will take place in FY2006, and the remaining two IR systems will be commissioned in early FY2007. An additional hardware-commissioning effort is expected to be required to learn how to operate the IR systems, which are subject to significant heating by the secondary particles from the *p-p* collisions, as the luminosity rises from first collisions in FY2007 to a substantial fraction of the nominal luminosity in FY2008. A modest M&S budget is provided during the years of peak activity to allow us to deal with hardware problems that may arise with our equipment during the commissioning process.

***Table 4.3-4 Hardware Commissioning Cost Summary***

| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 |
|---|---|---|---|---|---|---|---|
| **Labor count** | | | | | | | |
| *At a U.S. Lab* | *FTE* | *0.5* | *0.5* | | | | |
| *At CERN* | *FTE* | | *1.5* | *2.0* | *2.0* | *1.0* | |
| Scientist/Engineer | FTE | 0.5 | 2.0 | 2.0 | 2.0 | 1.0 | |
| **SUB TOTALS** | | | | | | | |
| **Labor count** | FTE | 0.5 | 2.0 | 2.0 | 2.0 | 1.0 | |
| **Labor cost** | $k03 | 100 | 400 | 400 | 400 | 200 | |
| **Travel** | $k03 | 8 | 30 | 30 | 30 | 15 | |
| **Materials & Services** | $k03 | | 50 | 50 | 25 | | |
| **TOTAL COST** | | | | | | | |
| Constant dollars | $k03 | 108 | 480 | 480 | 455 | 215 | |
| With 3.0%/year escalation | $k | 111 | 509 | 525 | 512 | 249 | |

## 4.4 Superconducting Magnet R&D

For the magnet R&D program, reasonable estimates can be made for the costs of labor, materials, components, and tooling required to design, build and test a particular type of magnet. Likewise, detailed cost estimates can be made for particular "sub-scale" technology tests. However, the design parameters for LHC upgrade magnets are not yet well defined, and the technology of $Nb_3Sn$ magnets is not sufficiently developed to allow us to specify a particular sequence of technology experiments and model magnet tests. The actual R&D we will do – the specific tests, mix of sub-scale and full-scale models, and the types of model magnets to be built – will evolve as our understanding of the LHC requirements and of $Nb_3Sn$ technology develop.

To estimate the cost of the magnet R&D program, or more correctly, to illustrate the scope of work that is possible within the funding available, we have developed a cost model that assumes, of necessity, a particular program. This program was sketched in Section 3.3.2 and summarized in Fig. 3.3-1. The cost estimate is summarized in Table 4.4-1, with additional details being given in Tables 4.4-2 (M&S) and 4.4-3 (labor and total costs). For the sake of summarizing the results of the cost model, we have shown estimates for technology development, quadrupole R&D, and dipole R&D. As will be discussed below, the divisions between these are somewhat arbitrary, and, as noted above, the actual course of the work will almost certainly be different from the plan assumed here. In these tables, the 4 m model program, which is essential to test our understanding of how the behavior of $Nb_3Sn$ magnets and the constraints on the magnet technology depend on coil length, is assumed to be part of the quadrupole program. The 4 m models may, of course, be dipoles, depending on the choice of IR layout type and which of the model magnet programs advances most quickly.

The magnet R&D effort is limited in FY2004 and FY2005 by the available funding. A relatively constant level of 20-21 FTEs is maintained in FY2006 and beyond. The budget dip in FY2007, required by the peak in Accelerator Systems work as the LHC starts up, is accommodated within the M&S budget. The increased funding in FY2008 and FY2009 is sufficient to maintain an overall flat level of effort and M&S purchases, assuming 3% annual escalation.

The technology development program peaks in FY2006, and rolls off slowly after that, as more of the development shifts to addressing technological problems through model dipoles and quadrupoles. The labor budgets for dipoles and quadrupoles are comparable to each other in FY2006 and FY2007, as the first models of each type are built and tested. The increase shown for quadrupoles in FY2008 and FY2009 is to support the 4 m program, which is arbitrarily included here as part of the quadrupole program. More M&S is provided for quadrupoles than for dipoles, based on the larger number of models assumed and the assumption that the 4 m coils will be quadrupoles. A travel budget of $5k/year (FY2003 dollars) per FTE scientist or engineer is provided.

The program that forms the basis for this cost model is shown at the top of Table 4.4-2, and reproduced at the top of Table 4.4-3. (Figure 3.3-1 is a simplified version of this part of the Tables.) The cost estimates are carried out through FY2009. The number of technology tests and model magnets is shown through FY2010, since some costs in a given year depend on the planned activity for the following year, in particular design work, and tooling and cable purchases.

***Table 4.4-1 Superconducting Magnet R&D Cost Estimate Summary***

| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 |
|---|---|---|---|---|---|---|---|
| **LABOR COUNT** | | | | | | | |
| Technology Development | FTE | 1.0 | 2.4 | 4.6 | 3.5 | 2.9 | 2.4 |
| Quadrupole R&D (1m + 4m) | FTE | 0.3 | 2.2 | 8.9 | 8.5 | 10.0 | 10.8 |
| Dipole R&D (1m) | FTE | 0.3 | 0.9 | 7.5 | 8.0 | 7.7 | 7.5 |
| TOTAL | FTE | 1.6 | 5.5 | 21.0 | 20.0 | 20.6 | 20.7 |
| | | | | | | | |
| **LABOR COST** | | | | | | | |
| Technology Development | $k03 | 168 | 392 | 760 | 564 | 468 | 392 |
| Quadrupole R&D (1m + 4m) | $k03 | 60 | 368 | 1308 | 1300 | 1520 | 1616 |
| Dipole R&D (1m) | $k03 | 60 | 180 | 1100 | 1200 | 1164 | 1140 |
| TOTAL | $k03 | 288 | 940 | 3168 | 3064 | 3152 | 3148 |
| | | | | | | | |
| **TRAVEL** | | | | | | | |
| Technology Development | $k03 | 3 | 7 | 13 | 9 | 8 | 7 |
| Quadrupole R&D (1m + 4m) | $k03 | 2 | 7 | 15 | 18 | 20 | 20 |
| Dipole R&D (1m) | $k03 | 2 | 5 | 13 | 15 | 15 | 15 |
| TOTAL | $k03 | 6 | 18 | 41 | 42 | 43 | 42 |
| | | | | | | | |
| **MATERIAL & SERVICES** | | | | | | | |
| Technology Development | $k03 | 13 | 104 | 143 | 195 | 182 | 169 |
| Quadrupole R&D (1m + 4m) | $k03 | 7 | 247 | 1601 | 1270 | 2459 | 2397 |
| Dipole R&D (1m) | $k03 | 0 | 7 | 1176 | 626 | 369 | 455 |
| TOTAL | $k03 | 20 | 358 | 2920 | 2091 | 3010 | 3021 |
| | | | | | | | |
| **TOTAL COSTS (escalated)** | | | | | | | |
| Technology Development | k$ | 190 | 533 | 1001 | 864 | 762 | 678 |
| Quadrupole R&D (1m + 4m) | k$ | 70 | 659 | 3195 | 2912 | 4636 | 4816 |
| Dipole R&D (1m) | k$ | 63 | 203 | 2501 | 2072 | 1795 | 1922 |
| | | | | | | | |
| **GRAND TOTAL** | **$k** | **323** | **1395** | **6697** | **5849** | **7193** | **7415** |

The technology development program is estimated based on a series of sub-scale tests. These could be, for example, small coils to test particular materials or manufacturing processes[20], mechanical models of magnet structures, radiation tests of materials, etc. Clearly the costs of different sub-scale tests will vary greatly. However, for the sake of this cost model we assume that one sub-scale test requires 0.6 FTE-year of scientific or engineering labor and 0.4 FTE-years of designer or technician labor, plus $10k of M&S (direct cost, FY2003 dollars). As more sub-scale tests are done per year, the labor per experiment is expected to decrease such that 6 tests per year require 2.6 FTE scientist or engineers, and 2 FTE technicians. The number of sub-scale tests per year grows from one in FY2004 to six in FY2006, limited initially by the available funding, and then declines slowly as emphasis shifts to solving magnet technology problems with model magnets. Also part of the technology development program is the development of specific components in support of the model magnet development.

The cost estimate for the model magnet programs is based on our experience with the R&D program for the baseline LHC quadrupoles and on the high-field magnet programs at the three labs. Cable, component, tooling, and test material costs are all based on actual costs for similar items in the existing magnet programs, scaled according to the expected differences in size and volume of these magnets. The cost of cable, components and tooling for the 4 m models ranges between 2.4 and 4 times the cost of that for the 1 m models, since some costs scale with length and others do not. The cost model is based on an assumed quadrupole design with a large aperture (≥100 mm) and a four-layer coil[13]. For simplicity, and because the aperture requirements and peak field are similar, the cost of a dipole model is assumed to be the same as that of a quadrupole model. An independent estimate of the cost of a dipole model is consistent with this assumption.

The model magnet program is initiated with the construction of two simplified 1 m models, which are assumed here to be quadrupoles. The simplified models use half the superconductor as the standard models (for example, they may be made from the inner two layers of a four-layer design), and are assembled using simplified techniques that require less tooling than the full-featured models (for example, they might be assembled using LBNL's bladder technique for preloading the coils[21]). Coil tooling is bought in FY2005 and FY2006 for assembly of the first simplified model in FY2006. Cable for this and all models is bought in the year before the model is built.

The first full-featured models are built in FY2007, which requires that additional coil tooling, as well as collaring and cold-mass assembly tooling be procured in FY2006 for quadrupoles, and all tooling for the dipoles in FY2006 and early FY2007. Three model magnets per year are built in subsequent years. In this cost model these are shown as two quadrupoles and one dipole, but the actual split between the two types may be different. Beginning in FY2007, we begin investing in the tooling necessary to make 4 m models, beginning with non-design-specific items such as a long oven and coil retorts. Design-specific coil tooling is bought only after there has been sufficient success with the 1 m models to justify it. Here we assume that this will be in FY2008, after several 1 m quadrupole and dipole models and have been built and tested. Practice coils of 4 m length are made in FY2009, represented in Tables 4.4-2 and 4.4-3 as one-quarter of a 4 m model, and the first complete 4 m model is built and tested in FY2010.

### *Table 4.4-2 Superconducting Magnet R&D M&S Cost Details*

| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 | FY10 |
|---|---|---|---|---|---|---|---|---|
| Subscale Tests | | 1 | 3 | 6 | 5 | 4 | 3 | 2 |
| Simplified 1m Q | | | | 1 | 1 | | | |
| 1m Q | | | | | 1 | 2 | 2 | 2 |
| 1m D | | | | | 1 | 1 | 1 | 1 |
| 4m D or Q models | | | | | | | 0.25 | 1 |
| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 | FY10 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Materials & Services** | | | | | | | | |
| Technology | | | | | | | | |
| Subscale tests | $k03 | 10 | 30 | 60 | 50 | 40 | 30 | |
| Component Development | $k03 | | 50 | 50 | 100 | 100 | 100 | |
| **Technology total** | **$k03** | **10** | **80** | **110** | **150** | **140** | **130** | |
| tooling | | | 1m | 1m | 4m | 4m | 4m | |
| long oven | $k03 | | | | 250 | | | |
| cable | $k03 | 5 | 5 | 5 | 5 | 5 | 5 | |
| D | $k03 | | 5 | 5 | 5 | 5 | 5 | |
| coil, Q | $k03 | | 123 | 368 | | 1200 | 520 | |
| D | $k03 | | | 490 | | | | |
| collared coil, Q | $k03 | | | 74 | | 3 | | |
| D | $k03 | | | 74 | | | 3 | |
| cold mass, Q | $k03 | | | 144 | | | | |
| D | $k03 | | | 72 | 72 | | | |
| total tooling, Q | $k03 | 5 | 128 | 591 | 5 | 1208 | 525 | |
| D | $k03 | | 5 | 641 | 77 | 5 | 8 | |
| **Tooling total** | **$k03** | **5** | **133** | **1232** | **332** | **1213** | **533** | |
| models | | | 1m | 1m | 1m | 1m | 1m | |
| cable, Q | $k03 | | 63 | 188 | 375 | 125 | 250 | |
| D | $k03 | | | 125 | 188 | 63 | 125 | |
| coil, Q | $k03 | | | 254 | 254 | 254 | 254 | |
| D | $k03 | | | 127 | 127 | 127 | 127 | |
| collared coil, Q | $k03 | | | 35 | 23 | 23 | 23 | |
| D | $k03 | | | 12 | 12 | 12 | 12 | |
| cold mass, Q | $k03 | | | 130 | | 86 | 86 | |
| D | $k03 | | | | 43 | 43 | 43 | |
| test, Q | $k03 | | | 35 | 70 | 70 | 70 | |
| D | $k03 | | | | 35 | 35 | 35 | |
| total models, Q | $k03 | | 63 | 641 | 722 | 558 | 683 | |
| D | $k03 | | | 264 | 404 | 279 | 342 | |
| **Models total** | **$k03** | | **63** | **904** | **1126** | **838** | **1025** | |
| 4 m Models | | | | | | 4m | 4m | |
| cable | $k03 | | | | | 125 | 500 | |
| coil | $k03 | | | | | | 90 | |
| collared coil | $k03 | | | | | | 12 | |
| cold mass | $k03 | | | | | | 26 | |
| cryostat | $k03 | | | | | | | |
| test | $k03 | | | | | | 9 | |
| **4m Models total** | **$k03** | | | | | **125** | **636** | |
| Total M&S | $k03 | 15 | 275 | 2246 | 1608 | 2316 | 2324 | |
| **Total M&S + 30% G&A** | **$k03** | **20** | **358** | **2920** | **2091** | **3010** | **3021** | |

*Table 4.4-2 Superconducting Magnet R&D Labor and Total Cost Summaries*

| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 | FY10 |
|---|---|---|---|---|---|---|---|---|
| Subscale Tests | | 1 | 3 | 6 | 5 | 4 | 3 | 2 |
| Simplified 1m Q | | | | 1 | 1 | | | |
| 1m Q | | | | | 1 | 2 | 2 | 2 |
| 1m D | | | | | 1 | 1 | 1 | 1 |
| 4m D or Q models | | | | | | | 0.25 | 1 |
| | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 | FY10 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Labor** | | | | | | | | |
| Technology | | | | | | | | |
| Scientist/Engineer | FTE | 0.6 | 1.3 | 2.6 | 1.8 | 1.5 | 1.3 | |
| Designer/Technician | FTE | 0.4 | 1.1 | 2 | 1.7 | 1.4 | 1.1 | |
| **Technology Total** | **FTE** | **1.0** | **2.4** | **4.6** | **3.5** | **2.9** | **2.4** | |
| Quad+4m | | | | | | | | |
| Scientist/Engineer D&F | FTE | 0.3 | 1.3 | 2.5 | 2.5 | 3 | 3 | |
| Designer D&F | FTE | | 0.6 | 2.4 | 1.5 | 2 | 1.8 | |
| Scientist/Engineer Test | FTE | | | 0.5 | 1 | 1 | 1 | |
| Technician Fab | FTE | | 0.3 | 3 | 3 | 3 | 4 | |
| Technician Test | FTE | | | 0.5 | 0.5 | 1 | 1 | |
| Dipole | | | | | | | | |
| Scientist/Engineer D&F | FTE | 0.3 | 0.9 | 2.5 | 2.5 | 2.5 | 2.5 | |
| Designer D&F | FTE | | | 2 | 1.5 | 1.2 | 1 | |
| Scientist/Engineer Test | FTE | | | | 0.5 | 0.5 | 0.5 | |
| Technician Fab | FTE | | | 3 | 3 | 3 | 3 | |
| Technician Test | FTE | | | | 0.5 | 0.5 | 0.5 | |
| Dipole+ Quadrupole | | | | | | | | |
| Scientist/Engineer D&F | FTE | 0.6 | 2.2 | 5 | 5 | 5.5 | 5.5 | |
| Designer D&F | FTE | | 0.6 | 4.4 | 3 | 3.2 | 2.8 | |
| Scientist/Engineer Test | FTE | | | 0.5 | 1.5 | 1.5 | 1.5 | |
| Technician Fab | FTE | | 0.3 | 6 | 6 | 6 | 7 | |
| Technician Test | FTE | | | 0.5 | 1 | 1.5 | 1.5 | |
| **Dipole + Quad Total** | **FTE** | **0.6** | **3.1** | **16.4** | **16.5** | **17.7** | **18.3** | |
| **Labor Total** | **FTE** | **0.6** | **3.1** | **16.4** | **16.5** | **17.7** | **18.3** | |
| **Labor Cost** | **$k03** | **288** | **940** | **3168** | **3064** | **3152** | **3148** | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Travel ($5k each S/E)** | **$k03** | **6** | **18** | **41** | **42** | **43** | **42** | |

| **Total Cost** | | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 | |
|---|---|---|---|---|---|---|---|---|
| **Constant dollars** | **$k03** | **314** | **1315** | **6128** | **5196** | **6205** | **6210** | |
| **Escalated at 3%/year** | **$k** | **323** | **1395** | **6697** | **5849** | **7193** | **7415** | |

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# Appendix A

# DOE Guidance for LARP

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# *U.S. Department of Energy*
# *and the*
# *National Science Foundation*

U.S. LHC JOINT OVERSIGHT GROUP February 5, 2003

Dr. James Strait
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, IL 60510-0500

Dear Dr. Strait:

At the December 2001, Department of Energy/National Science Foundation (DOE/NSF) Large Hadron Collider (LHC) Joint Oversight Group (JOG) meeting, the agencies agreed to provide guidance on potential funding to the two detector collaborations, as well as to the U. S. LHC Accelerator Construction Project regarding the U.S. LHC Accelerator Research Program. This guidance is for the U.S. LHC Accelerator Research Program (LARP).

The Department of Energy (DOE) anticipates providing significant funding for the U.S. LHC Accelerator Research Program to enable active participation of the U.S. scientific community in the accelerator physics research program of the LHC machine as foreseen by the international agreement. While this program will maintain and improve domestic accelerator physics capabilities it must exploit the substantial U.S. investment in the LHC by providing an accelerator physics and technology basis for improvements to that machine. The scope of this program is broadly described in the DOE/NSF Memorandum of Understanding (MOU) on U.S. Participation in the LHC Program,

> "The U.S. LHC Research Program will require additional resources for the laboratories and universities, analogous to the pre-operational and operational phases of a new research facility. These resources are complementary to the funding provided in Article VIII of the International Agreement."

To proceed with this program the LARP collaboration should submit a proposal to the Department of Energy, suitable for peer review, which describes the program in detail and identifies the required resources. The proposal should be in keeping with the guidelines stated in this letter.

It is our firm intention that the LARP activities serve to explore the limits of the technologies described herein. While the end products of LARP will be applied to the LHC, LARP is not intended to be an engineering and construction service organization to that facility.

Rather, it is intended to enable U.S. scientists building upon their existing base, developed and broadened by their recent work on the LHC, to continue their efforts to maintain and expand world wide technological leadership in accelerator physics and superconducting magnets. Accelerator physics activities in the LARP program are expected to include but not necessarily limited to commissioning of the advanced superconducting magnets and support equipment provided by the U.S., design and fabrication of advanced beam diagnostics to optimize LHC luminosity, and machine simulation studies. All of these will directly lead to increased luminosity and physics productivity.

Members of the CERN staff, as well as U.S. scientists, have already proposed upgrades to the LHC at international conferences. These upgrades cover improved interaction region final focusing as well as an energy doubler. The U.S. team is in an excellent position to play a leading role to both of these activities because of the expertise developed in the U.S. LHC Accelerator Construction Project as well as the base program in high field magnet development. Importantly, should there be electron cloud effects in the LHC, the next generation final focus quadrupoles will be essential to achieving design luminosity.

The United States has taken early leadership in high field dipole and high gradient quadrupole design. A program of engineering development will enable the community to be ready to construct the next generation of upgrades at the appropriate time.

Preliminary guidance on the scope and funding of these activities has been provided. Our ultimate goal is to enable U.S. accelerator physicists to participate in the forefront accelerator physics and technology program of the LHC. The U.S. LHC Accelerator collaboration plans must be consistent with and focus on this goal.

We have adopted the following definitions for the scope of the DOE funded U.S. LHC Accelerator Research Program activities:

> Base Program Support - The LARP effort is not intended to replace existing base program support at the various laboratories in superconducting magnet development and other ongoing areas.
>
> LHC Accelerator R&D - This area includes but is not limited to magnet R&D, beam diagnostics, and accelerator physics. Specific R&D projects aimed at enhancing physics and machine capabilities beyond the baseline design would be appropriate. Actual construction and fabrication projects growing out of such R&D projects would be proposed to DOE and will be reviewed on a case-by-case basis following standard procedures. Therefore, funding for them should not be included in the R&D proposal.
>
> Program Management - The planning and execution of the U.S. LHC Accelerator Research Program of activities described above requires strong management. Funding for managers, program office support personnel, and other activities that are required to establish and operate a well-coordinated and effective program are to be included. To optimize the agency's investment in the U.S. LHC Accelerator

Research Program, this effort should be kept to a minimum level consistent with responsible management.

While we do not wish to prescribe any particular management structure for the U.S. LHC Accelerator Research Program, there are some elements of the management of this program that we would like to recommend to facilitate its successful execution. In particular, we feel that a Program Manager who can serve as the single point-of-contact with the agency on budgetary and management issues for that Research Program would best oversee the program. This person would have authority and responsibility to make requests from the agency, through the appropriate institutional channels, and in turn allocate the provided resources across the several laboratories, without bias and in such a way as to optimize the overall physics output of the U.S. LHC Accelerator Research Program. Of course final funding authority rests with the agencies who will carry out strong oversight regarding the distribution and use of the funds. The Program Manager thus has responsibility for a national program. We envision that the management structure should be similar to the structure of the present U.S. LHC Accelerator Construction Project. As in the present structure the program leader will report directly to the Director of the DOE Division of High Energy Physics (HEP) on programmatic matters. It should be possible to achieve such a management structure well in advance of LHC turn-on later this decade. We understand that during the transition from LHC Accelerator Construction Project to the LHC Accelerator Research Program there may need to be interim arrangements to address these issues. The proposal should outline how to do this.

It is important to the agencies that the U.S. efforts exploit the best science and technology available in the national laboratory complex and universities. We suggest that a program advisory committee that is at least chaired by a person outside the three laboratories, Brookhaven National Laboratory (BNL), Fermilab and the Lawrence Berkeley National Laboratory (LBNL), which are presently members of the LHC Accelerator Collaboration, would be appropriate.

It is the goal of the DOE Division of High Energy Physics to provide sufficient funding for the U.S. LHC Accelerator Research Program so that the U.S. effort in LHC accelerator physics and technology is consistent with its high priority in the long-term U.S. HEP program.

The preliminary funding profiles for this program will be provided by the Department of Energy in a separate communication. We also intend to annually review the U.S. LHC Accelerator Research Program. These reviews will assess the program status and plans and support decisions on actual program funding.

We expect that program management will use these scope definitions and the funding profiles to refine their project planning in preparing the proposal and in preparation for the planned review. The plans in the proposal should reflect the technical needs of the evolving CERN LHC machine. These plans and the review may also provide an important input to CERN as they develop their overall plans. The proposal should reach us well in advance of the review. We look forward to working with the U.S. LHC Accelerator Research Program to exploit the full physics potential of the LHC.

Sincerely,

John R. O'Fallon
Co-chair
U.S. LHC Joint Oversight Group
Department of Energy

John W. Lightbody, Jr.
Co-chair
U.S. LHC Joint Oversight Group
National Science Foundation

cc: S. P. Rosen, SC-20
A. Byon-Wagner, SC-223
M. Procario, SC-223
M. Pripstein, SC-223
B. P. Strauss, SC-224
D.F. Sutter, SC-224
J. Yeck, FRMI
J. Dehmer, NSF
M. Goldberg, NSF
T. Kirk, BNL
M. Witherell, FNAL
P. Oddone, LBNL

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# Appendix B

# Letter Establishing LARP

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# *U.S. Department of Energy*
# *and the*
# *National Science Foundation*

JOINT OVERSIGHT GROUP

NOV 21 2000

Dr. Michael Witherell
Director
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, IL 60510-0500

Dear Dr. Witherell:

The U.S. Department of Energy (DOE) and the National Science Foundation (NSF) are supporting the construction of the Large Hadron Collider (LHC) at the European Center for Particle Physics (CERN) under the terms of the International Agreement between CERN and the U.S. with its Protocols. Under that Agreement, the U.S. LHC Accelerator Project has been carried out by Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, and Fermi National Laboratory (Fermilab), with Fermilab as the Lead Laboratory. As Lead Laboratory, Fermilab has provided the project management required to coordinate and oversee the project activities, in addition to executing specific elements of the project.

The International Agreement provides that, beyond the LHC Construction Project, U.S. scientists will participate as full partners in the LHC Research Program. The DOE and the NSF are now considering the elements necessary for successful U.S. participation in the Research Program. In particular, there must be a formal management structure with clear lines of authority to coordinate the planning and implementation of the continuing U.S. role in the accelerator-related aspects of the LHC Research Program. Accordingly, we request that Fermilab serve as Host Laboratory for U.S. participation in these aspects of the Research Program, consistent with the International Agreement and its Accelerator Protocol.

As Host Laboratory, Fermilab would take the lead role with the U.S. accelerator community in developing plans and budgets for U.S. involvement in the accelerator-related aspects of the LHC Research Program. In this role, Fermilab would also provide management oversight for these activities including the preparation of a Project Management Plan. The draft Project Management Plan should be submitted to the DOE/NSF Joint Oversight Group for approval.

The research program should be planned to make optimal use of the infrastructure and expertise within the participating U.S. National Laboratories and should be worked out with CERN on the basis of mutual interest. The planned research could be expected to include:

Participation in beam commissioning and ongoing optimization of beam parameters;

Beam experiments, including construction of specialized instrumentation, aimed at both improved LHC performance and fundamental beam physics questions;

Design and development of equipment for improvements to the LHC, such as 2nd generation IR quads and advanced instrumentation.

Funding will be identified to carry out the U.S. LHC Accelerator Research Program. We expect that the methods for allocating the designated funding within the Research Program will take cognizance of those used for the U.S. LHC Accelerator Construction Project. The methods of allocation should be specified in the Project Management Plan.

Sincerely,

John R. O'Fallon
Co-chair
Joint Oversight Group
Department of Energy

John W. Lightbody, Jr.
Co-chair
Joint Oversight Group
National Science Foundation

***********************************************

On behalf of Fermilab, I accept the role of Host Laboratory for the U.S. LHC Accelerator Research Program.

Dr. Michael Witherell
Director
Fermi National Accelerator Laboratory

cc:

Mildred Dresselhaus, SC-1
Robert Eisenstein, NSF
Lyn Evans, CERN
Marvin Goldberg, NSF
Stephen Holmes, FNAL
Kurt Hubner, CERN
John Marburger, BNL
S. Peter Rosen, SC-20
Thomas Taylor, CERN
Charles Shank, LBNL
James Strait, FNAL
Bruce Strauss, SC-224
Jim Yeck, CH/Fermi

# Appendix C

# Membership of LARP Advisory Committees

May 2003

U.S. LHC Accelerator Program Laboratory Oversight Group (LAPLOG)

Stephen D. Holmes (Chair), Fermilab, Associate Director for Accelerators
Thomas B. Kirk, BNL, Associate Director for High Energy and Nuclear Physics
Piermaria J. Oddone, LBNL, Deputy Director for Science

U.S. LHC Accelerator Program Advisory Committee (LAPAC)

John Galayda (Chair), SLAC
Alex Chao, SLAC
Arnaud Devred, CEA/Saclay and CERN
Claus Rode, Jlab
Herman ten Kate, CERN
Hendrik Weerts, Michigan State University

U.S.-CERN Committee for the LARP

Lyndon Evans (Co-chair), CERN, Director, LHC Project Leader
Philippe Lebrun, CERN, Accelerator Technology (AT) Division Leader
Steve Myers, CERN, Accelerators and Beams (AB) Division Leader
Lucio Rossi, CERN, AT Division, Magnets and Superconductors Group Leader
Francesco Ruggiero, CERN, AB Division, Accelerator and Beam Physics Deputy Group Leader
Hermann Schmickler, CERN, AB Division, Beam Diagnostics & Instrumentation Group Leader
Thomas Taylor, CERN, AT Division, Official liaison to the United States Collaboration.
Philip Bryant, CERN, Assistant to the LHC Project Leader for Non-Member States Collaborations
Stephen D. Holmes, Fermilab, Associate Director for Accelerators
* James Strait (Co-chair), Fermilab, Technical Division, U.S. LARP Leader
* Michael Harrison, BNL, Superconducting Magnet Division Head
* Stephen Peggs, BNL, Collider Accelerator Department, U.S. LARP Accelerator Systems Leader
* Robert Kephart, Fermilab, Technical Division Head
* William Barletta, LBNL, Accelerator and Fusion Research Davison (AFRD) Head
* Steve Gourlay, LBNL, AFRD, U.S. LARP Superconducting Magnet Leader

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* Member of U.S. LARP Executive Committee

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# Appendix D

# Letter Summarizing Conclusions from the First Meeting of The U.S.-CERN Committee for the LARP

**ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE**
**EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH**

Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics

GENEVE, SUISSE
GENEVA, SWITZERLAND

Mail address: Dr L.R. Evans
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CERN
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Dr James STRAIT
Fermi National Accelerator Laboratory (FNAL)
P.O. Box 500
**Batavia, IL 60510**
Etats-Unis

Votre référence/Your reference:
Notre référence/Our reference: DG/DI/LE/jf/2003-058

Geneva, 14th April 2003

Dear Dr Strait,

I am writing to communicate to you my conclusions after the first meeting of the US-CERN Committee for the U.S. LHC Accelerator Research Program, held at CERN on 10 April 2003, at which you and your colleagues presented the draft of the proposal that you will submit to US Department of Energy within the next few weeks. I note that this meeting was attended by T. Taylor, N. Siegel (representing Ph. Lebrun), L. Rossi, F. Ruggiero, H. Schmickler, P. Bryant, and myself from CERN; and S. Holmes, S. Peggs, S. Gourlay, R. Kephart, P. Limon and yourself, representing the U.S. laboratories. S. Myers, M. Harrison, and R. Barletta were excused.

On behalf of CERN, I should like to express my strong support for continuing, after 2005, the very valuable collaboration that we have currently with the U.S. laboratories. Your proposed programme that engages the US laboratories on 'a best effort' basis in hardware and beam commissioning will be particularly appreciated by CERN. Similarly, the proposed collaboration in accelerator physics studies and R&D for beam instrumentation with the appropriate CERN groups will certainly have an important and positive impact by both speeding the start-up of the machine and by helping to optimise its performance. It is also clear to me that the proposal by the U.S. laboratories to work on accelerator physics and high-field superconducting magnets for an eventual luminosity upgrade would be invaluable to CERN, no doubt making it possible to start such an upgrade at an earlier date than would otherwise be conceivable. To increase the luminosity beyond the nominal value will be an extremely challenging task and the American contribution to this effort, done in close collaboration with CERN and other partners, will help to ensure that this upgrade can be done in a timely way and on the time-scale required by the physics programme.

I am particularly pleased to see the evident close cooperation with CERN with which this proposal has been developed.

Yours sincerely,

L.R. Evans
Director, LHC Project Leader

C.c.: Director-General

# Appendix E

# LHC Upgrades

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# LHC Upgrades

To fully exploit the large investment in the LHC made by the world high energy physics community, including the United States, upgrades to substantially increase the its capabilities will need to be undertaken after several years of operation at the design luminosity[8]. This requirement can easily be seen by considering the time required to reduce the statistical errors by a factor of two. Figure 1 shows a simple model in which the first collisions in LHC take place in 2007, the first real physics run is in 2008, and the luminosity rises slowly to reach the design value of $10^{34}$ cm$^{-2}$ s$^{-1}$ by the end of 2011. The growth of the integrated luminosity is shown, assuming an effective $10^{7}$ seconds per year at the indicated luminosity. The statistical error on a typical measurement, which is proportional to $( \int L\, dt )^{-½}$ is shown in arbitrary units, as is the time required after each year to accumulate enough new data to halve the statistical error. By the time the LHC reaches the design luminosity, this "error halving time" will be at least 4-5 years. Thus, beyond about 2013-2014, the utility of additional running, without a major upgrade to the machine and detectors, will be limited.

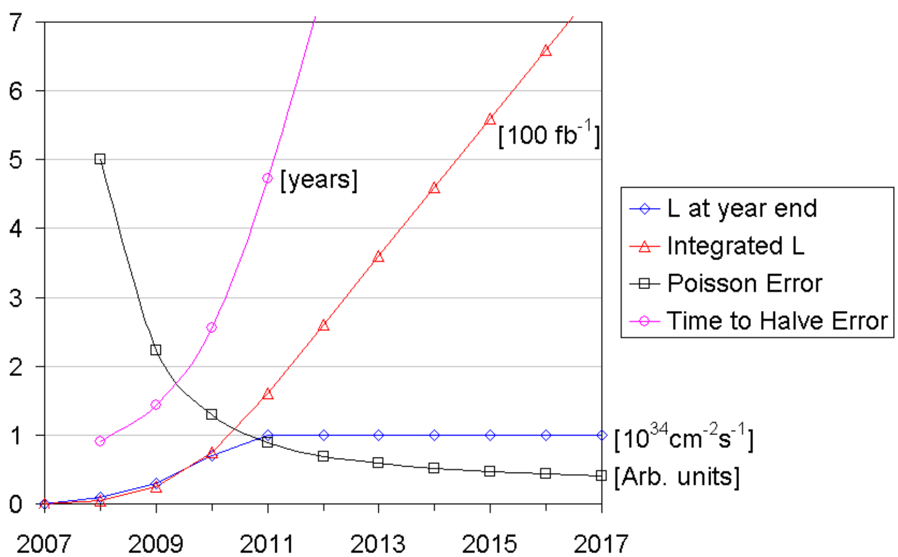


**Fig. 1** Results of a simple model used to estimate the time from LHC start it takes to halve the statistical error in a measurement. Note that after a year of operating at full luminosity, it will take more than seven years to halve the error.

**Luminosity Upgrade**

An increase in LHC luminosity by up to an order of magnitude, to as much as $10^{35}$ cm$^{-2}$ s$^{-1}$, appears feasible[1]. This will extend the mass reach of LHC by 20-30%, and allow study of some rare processes that are not accessible to the baseline machine[6,7]. Such an increase can be achieved with upgrades that involve replacement of equipment in the LHC insertions or in the injector complex, but the large investment in the main accelerator arcs and most of the infrastructure would continue to be used. These upgrades would cost a only a small fraction of the original cost of the LHC, and would require only relatively modest down-time, on the order of a year, to install.

To achieve a factor of ten increase in luminosity, a number of accelerator systems will need to be upgraded, each of which will contribute a factor to the higher luminosity. Substantial R&D on accelerator components, and studies to understand the limitations of the current configuration will be required before the specific modifications to the LHC can be proposed. These modifications are almost certain to include replacement of the interaction region final focus system[12,2,3] with higher performance magnets to focus the beams to a smaller $\beta^*$; advanced instrumentation and feedback systems to deal with higher intensity beams or new bunch structure; and new RF systems to shorten the bunches, provide crab crossings, or provide novel beam structures such as superbunches. Upgrades to the injector complex may also be required. The US labs expect to be deeply involved in the accelerator physics studies that will lead to decisions about the upgrade path, the development of magnets for new interaction regions, and the development of the instrumentation and control systems.

The U.S. National Laboratories are uniquely positioned to lead the development of the new IR design and of the magnets that it will require. Our work on the design and construction of the existing IRs gives us important understanding of their limitations and of the measures to be taken to alleviate those limitations. The new IRs, whatever their design, will require magnets based on $Nb_3Sn$ superconductor, both to achieve the higher fields required and to provide greater temperature margin against radiation heating than is available with NbTi. The R&D programs at BNL, Fermilab, and LBNL put the U.S. laboratories at the forefront in the development of high-performance accelerator magnets based on this technology. The specific magnets required for a new IR will take many years to develop, and R&D on them must begin within the next few years to ensure that they are ready when the LHC upgrades are to be implemented.

*IR Layouts*

The issues to be addressed in designing a new IR for higher luminosity[11] are reducing $\beta^*$, minimizing the effects of the parasitic long-range beam-beam interactions within the region shared by the two beams, and dealing with the high radiation load that is a by-product of the very high luminosity. A number of different new IR layouts are under consideration, which address these issues in different ways and with different emphasis on each problem. These are illustrated in Figs 2-6. Their parameters are summarized in Table 1, which shows the distance from the IP to the first quadrupole, the quadrupole coil aperture ($D_{quad}$), the minimum possible $\beta^*$, the maximum $\beta$-function in the quadrupoles for $\beta^*_{min}$, and the strength ($B_{D1}$), length ($L_{D1}$) and coil aperture($D_{D1}$) of the first beam separation dipole. These are compared with the values for the baseline LHC IR.

The simplest case is to duplicate the existing optics and layout, but with larger aperture quadrupoles that will permit a substantial reduction in $\beta^*$. This case is shown in Fig. 2. Assuming that the crossing angle scales with $(\beta^*)^{-1/2}$, a 110 mm aperture quadrupole[9] would allow about a factor of three decrease in $\beta^*$. This layout has the virtues representing the simplest possible change to the existing layout, and by placing the quadrupoles as close as possible to the IP, minimizes $\beta_{max}$ for a given $\beta^*$. However, it does not address the potentially severe problem of parasitic collisions. If a larger crossing angle is required to generate greater beam separation, then $\beta_{max}$ would have to be reduced and $\beta^*$ increased to compensate.

Table 1: Parameters for the baseline LHC compared with five candidates for a luminosity upgrade

| | Base-line | Fig. 2 | Fig. 3 | Fig. 4 | Fig. 5 | Fig. 6 |
|---|---|---|---|---|---|---|
| IP to Q1 (m) | 23 | 23 | 52.8 | 42.5 | 34 | 23 |
| $D_{quad}$ (mm) | 70 | 110 | 100 | 100 | 100 | 100 |
| $\beta^*_{min}$ (cm) | 50 | 16 | 26 | 19 | 15 | 10 |
| $\beta_{max}$ (km) | 5 | 15 | 23 | 23 | 23 | 23 |
| $B_{D1}$ (T) | 2.75 | 15.3 | 15 | 14.6 | 14.5 | 14.3 |
| $L_{D1}$ (m) | 9.45 | 1.5 | 10 | 12 | 6 | 9 |
| $D_{D1}$ (mm) | 80 | 110 | 135 | 165 | 75 | 105 |

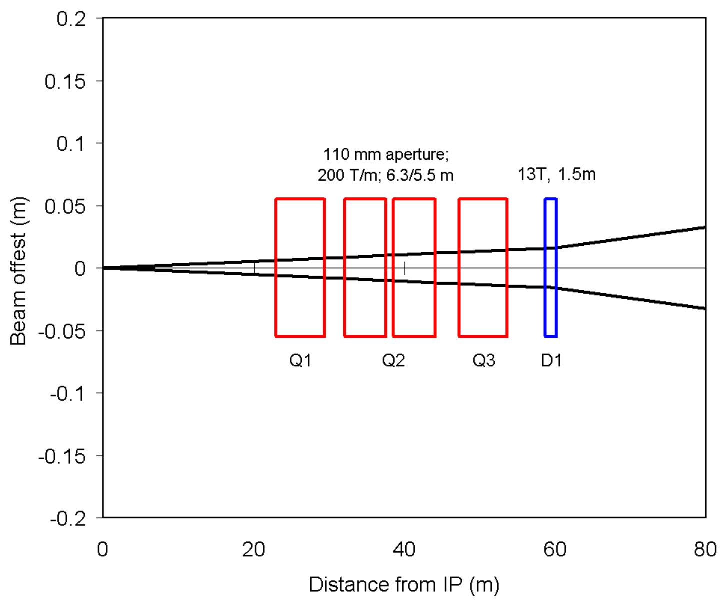


**Fig. 2.** Quadrupoles-first interaction region, similar to the current LHC baseline.

To reduce the number of parasitic collisions, the order of the beam separation dipoles and the quadrupole triplet can be reversed, as illustrated in Fig. 3. The D1 starts at the same distance from the IP as the Q1 in the baseline layout, and about 5 m is allowed between the magnetic ends of the D1 and D2 for a neutral particle absorber (TAN). Quadrupoles with a 100 mm aperture, the largest possible in a dual-bore configuration, would allow a factor of two decrease in $\beta^*$ from the baseline 50 cm. The D1 and D2 dipoles have coil apertures of about 130 mm and 100 mm respectively. The energy deposited in the D1 dipole by collision debris will be very high in this layout, requiring non-conventional designs[10]. Because the quadrupoles are substantially further from the IP than in the baseline, $\beta_{max}$ is substantially larger for a given $\beta^*$.

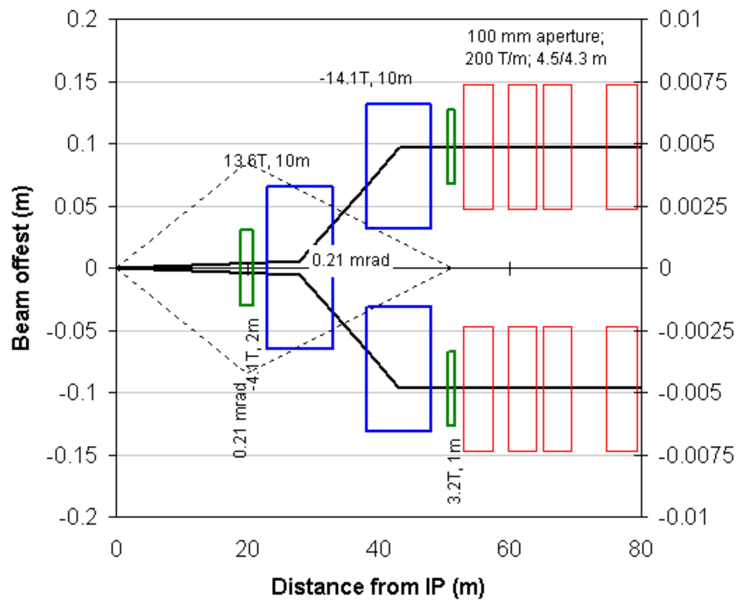


**Fig. 3.** Dipoles-first interaction region, which roughly halves the number of parasitic collisions. The heavy line shows the orbits for a horizontal crossing angle generated by the D1 and D2 dipole. The dashed lines, plotted against the right axis, show vertical orbits for a vertical crossing plane generated by dipole correctors shown in green.

To try to maintain the advantage of separating the beams promptly with a D1 placed closest to the IP, while not allowing $\beta_{max}$ to grow so large, the quadrupoles could be placed just after the D1 and before the D2, as illustrated in Fig. 4. The ratio of $\beta_{max}$ to $\beta^*$ is intermediate between the two previous cases, so a factor of about 2½ reduction in $\beta^*$ would be possible. This has the interesting feature of twin aperture quadrupoles with non-parallel axes, and requires a more complex set of beam separation dipoles than in the previous cases.

If the crossing angle could be increased by an order of magnitude, then the D1 in the dipole-first scheme could be eliminated, as shown in Fig. 5. This case might be favored by the superbunch option, in which a large crossing angle maximizes the luminosity and minimizes the length of the luminous region, or could be implemented with strong crab cavities to rotate the bunches to compensate for the large crossing angle. In this case the parasitic collisions are essentially eliminated, and all crossings can be in the horizontal plane. The ratio of $\beta_{max}$ to $\beta^*$, and therefore the minimum possible $\beta^*$, is similar to the case in Fig. 4. This IR has the interesting feature that the forward going neutral particles, which follow the outgoing beam direction, are aimed at the coil of the dipole in the outgoing aperture. Either the aperture must be made large enough to allow these particles to pass out the back of the dipole, or the dipole must withstand this radiation load in addition to the forward-going charged particles that are swept into the coil in all of the dipole-first configurations.

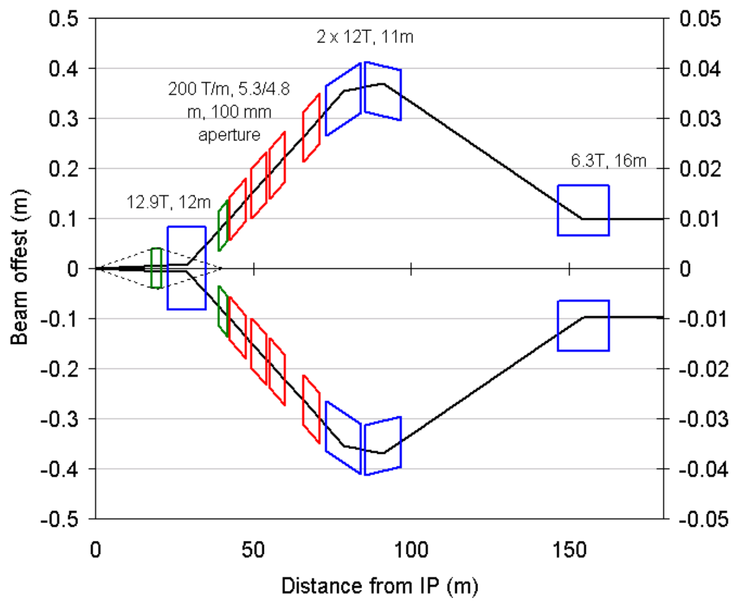


**Fig. 4.** An IR layout with quadrupoles between the beam separation dipoles. The heavy line shows the orbits for a horizontal crossing plane, and the dashed line shows the case of a vertical crossing plane.

If the crossing angle could be increased by an order of magnitude, then the D1 in the dipole-first scheme could be eliminated, as shown in Fig. 5. This case might be favored by the superbunch option, in which a large crossing angle maximizes the luminosity and minimizes the length of the luminous region, or could be implemented with strong crab cavities to rotate the bunches to compensate for the large crossing angle. In this case the parasitic collisions are essentially eliminated, and all crossings can be in the horizontal plane. The ratio of $\beta_{max}$ to $\beta^*$, and therefore the minimum possible $\beta^*$, is similar to the case in Fig. 4. This IR has the interesting feature that the forward going neutral particles, which follow the outgoing beam direction, are aimed at the coil of the dipole in the outgoing aperture. Either the aperture must be made large enough to allow these particles to pass out the back of the dipole, or the dipole must withstand this radiation load in addition to the forward-going charged particles that are swept into the coil in all of the dipole-first configurations.

Yet another variant, combining the features several of the previously presented layouts, aims the two beams directly into twin aperture quadrupoles with non-parallel axes as shown in Fig. 6. Because there is only one beam per aperture, a given $\beta^*$ does not require as large an aperture as in the single-aperture quadrupoles first case, and the 100 mm aperture illustrated in Fig. 6 could support up to a factor of 5 reduction in $\beta^*$ below the baseline 50 cm.

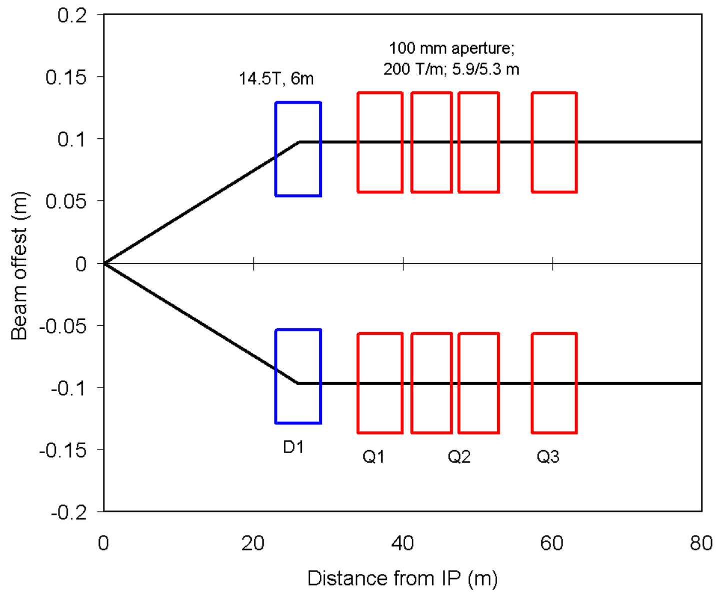


**Fig. 5.** A dipole-first IR with large crossing angle. With no parasitic collisions, alternating vertical and horizontal crossings are not required.

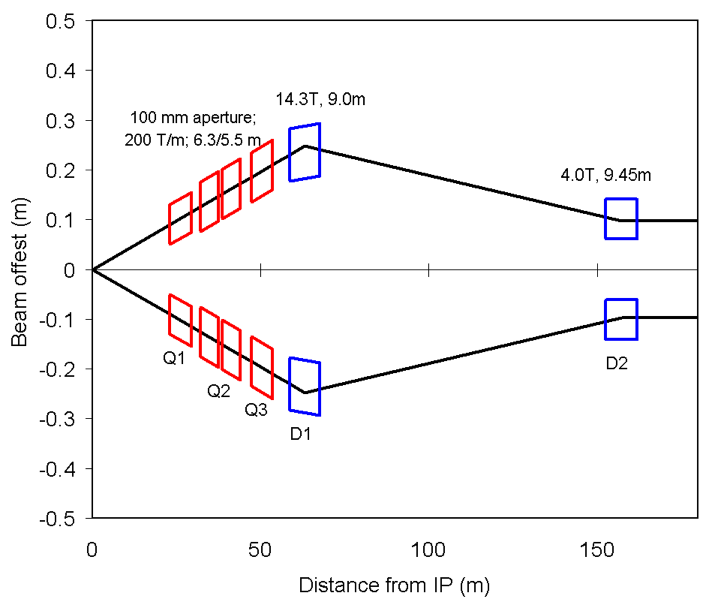


**Fig. 6.** A quadrupoles-first IR with large crossing angle.

*Magnet R&D for a Luminosity Upgrade*

The initial program will be the exploration of several possible optics and layouts of new interaction regions, including investigation of relevant accelerator physics issues and the studies of conceptual designs of the magnets required by them. Conceptual design studies have begun on several IR magnet types. We have conceptual designs for quadrupoles which, with the improvement of $Nb_3Sn$ performance expected in the coming years, provide the same gradient as the IR quadrupoles currently being built by Fermilab and KEK, but with an aperture as large as 110 mm[9]. These could allow at least a factor of three decrease in $\beta^*$, depending on the IR layout, with corresponding increase in luminosity, and would be able to operate with the expected radiation heating from up to a factor of ten increase in luminosity. Studies are also being done for the beam separation dipoles for the "dipoles first" layout, in which there is no superconductor on the mid-plane, where the peak energy deposition occurs.

Following these studies, we will begin R&D to develop one or two of the key magnets required by the chosen IR layout, most likely a large aperture quadrupole and a dipole that can survive in the intense radiation environment of a dipole-first layout. A focused R&D effort to develop the specific designs, including all features required for installation and operation in the accelerator will begin in 2005 or 2006, culminating in the construction of one or two full-scale prototype magnets in the first years of the next decade. The deliverable from this work would be the design of a new interaction region, and a fully engineered design for at least one of the new IR magnets, ready for manufacturing.

The R&D funds currently expected to be available for the US LHC Accelerator Research Program are unlikely to permit us to develop all of the new IR magnet designs required, such as correctors or all the varieties of separation dipoles required in some of the layouts, and therefore we would count on our collaborators at CERN or other laboratories in Europe or Asia to develop and provide these components. The actual construction of the new interaction regions is outside the scope of the U.S. LHC Accelerator Research Program, and the degree US involvement in the construction will be decided at the time.

**Towards Higher Energy**

Once the LHC with upgraded luminosity has been fully exploited, it will be necessary to go to higher energy to extend our understanding of nature. The LHC nominal energy of 7 TeV is achieved with a dipole field of 8.3 T. The "ultimate" field of the main dipoles is 9 T, which if reached would yield a beam energy of 7.54 TeV. To increase the energy further, it will be necessary to replace the LHC with a new machine based on higher field magnets. Using $Nb_3Sn$ superconductor, it appears possible eventually to reach a dipole field approaching 17 T. Allowing a reasonable margin, this would allow accelerator operations at 14-15 T, corresponding to a beam energy of around 12.5 TeV in the LHC tunnel. Although this yields somewhat less than a factor of two increase in beam energy, this is often called the "Energy Doubled LHC" or EDLHC.

The goal of 17 T, however, is well beyond the current state-of-the-art, the highest field yet achieved in a dipole-like geometry being 14.7 T[5]. Thus an extended and vigorous R&D program will be necessary before a higher energy machine can be proposed for the LHC tunnel. This R&D program must both achieve the very high field required and result in cost effective magnet designs for main arc dipoles and quadrupoles.

An EDLHC is likely to be a very expensive machine to build. In addition to building an entirely new machine in the existing LHC tunnel, a new high-energy injector will be required, either replacing the SPS or intermediate between the SPS and the higher energy LHC. The cost of building the EDLHC complex is likely to be comparable to or higher than that of the LHC itself, and involve a shut-down for construction of comparable length to that between the end of LEP operations and the turn on of LHC. Assuming that the EDLHC would be built only after the full exploitation of the luminosity upgraded LHC, construction is unlikely to start before the early 2020's. It is not yet clear whether the additional physics reach of the increased energy will justify the cost of this machine. No decisions can be made before the necessary R&D has been done, physics results from LHC and from a possible companion $e^+e^-$ collider are known, and the potential for building a higher energy p-p collider in a dedicated tunnel is understood[8].

The U.S. National Laboratories are currently the world leaders in the development of high field superconducting dipoles based on $Nb_3Sn$ technology, making them potential leaders in the development of magnets for a EDLHC. If a decision is made some day to proceed with the construction of such a machine, it would be natural for the U.S. to play a major role in the development of the main magnet designs, given our leadership in the enabling technology, and of the interaction region magnets, based on our extensive experience in this area.

The magnets for the luminosity upgrade, which will be the first use of $Nb_3Sn$ in a high energy accelerator, will be an important step towards the development of the technology for higher energy hadron colliders of the future. Indeed, in some respects, the IR upgrade magnets are more challenging than the main magnets for an EDLHC or VLHC, given the large apertures required and the extreme radiation environment in which they must operate. The key issues for the main magnets for any future higher energy hadron collider are being addressed now by the base program in high field magnet R&D at the three US Labs. These are how to generate the highest possible dipole field (the main goal of the LBNL program), to develop practical magnet manufacturing processes and technologies to allow economical production (a focus of the FNAL program), and to explore alternates to wind-and-react, $Nb_3Sn$, Rutherford cable technology, that might yield dividends in either field or cost (the focus of the BNL program). Based on the luminosity upgrade work of the LARP on magnets, instrumentation and accelerator physics, and on the base program on high field dipole R&D, the U.S. National Laboratories will be well placed to play a leading role in the construction of the next generation of hadron colliders, whether it be an EDLHC or a VLHC.

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