LARP

U.S. LHC Accelerator Research Program R&D Plan

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Version 1c

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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.

The mission of the U.S. LHC Accelerator Research Program (LARP) is 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. Four U.S. DOE National Laboratories comprise LARP -- Brookhaven National Laboratory, Fermilab, the Lawrence Berkeley National Laboratory and SLAC. Working with the U.S. Department of Energy, and in close collaboration with our CERN colleagues, LARP enables U.S. accelerator specialists to take an active and important role in the LHC accelerator program during its commissioning and operations, and to position them to play a major role in LHC performance upgrades. In particular, LARP supports 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 is at the technological frontier and will thereby improve the capabilities of the U.S. accelerator community.

This Research and Development Plan outlines the long range guiding vision and specific goals, the plan and scope of work, and a summary of the resources being allocated in 2006 to carry out LARP activities. It also describes the management plan to guide the work, measure progress and make program adjustments. This plan 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 Advances 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 enhances 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 analysis of *High-Energy Facilities on the DOE Office of Science Twenty-Year Roadmap*[8], HEPAP recommended that three proposed projects are 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 Advances U.S. Accelerator Science & Technology

While helping to advance the world's knowledge of particle physics at the energy frontier, LARP also assists 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 Advances International Cooperation

While not a LARP goal *per se*, 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 worldwide 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, that 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. LARP Deliverables

The following LARP deliverables 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.

1.3.3. Anticipated LARP Funding

Preliminary guidance from the DOE indicates that the peak funding will be somewhat in excess of $10 million per year, as shown in Fig. 1.3-1. This limits our ability to make a vigorous start on magnet R&D, and limits the breadth of the initial suite of instrumentation that LARP will provide.

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

Deliverables / **Goals**	***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**

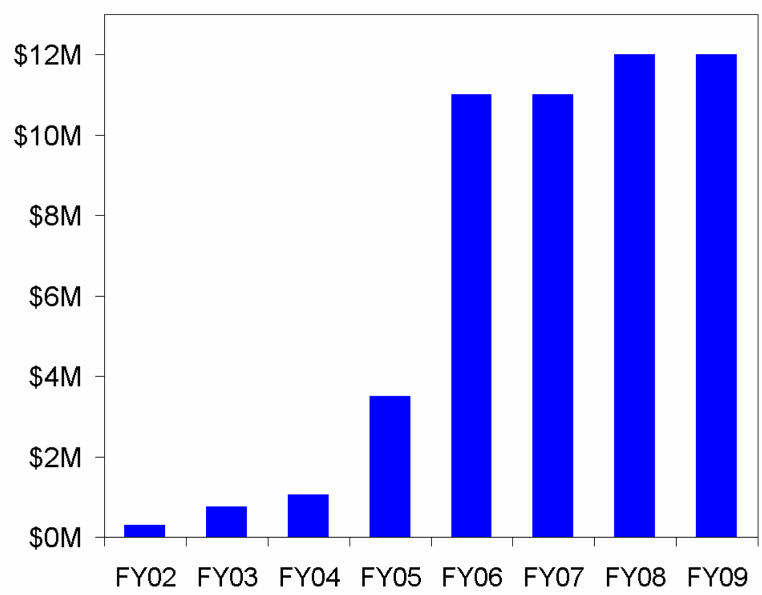

Fig. 1.3-1 Preliminary funding guidance from the DOE.

LARP is not a substitute for the core 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 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. LHC Interaction Region Upgrades

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.

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 b^*; 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 b^*, 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.

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 and large crossing angle 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, these designs reduce 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 dipole-first, and large crossing angle designs. Consistent with this, a major LARP goal is to demonstrate the successful functioning of a long, high gradient, large bore Nb_3Sn quadrupole by 2009.

1.5. The LARP Management Plan

1.5.1. The LARP Leadership and Management Structure

The LARP management and oversight structure is shown in Fig. 1.5-1. 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.

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 1.5-1 lists the organization and the current leaders of each deliverable subgroup. It is important to note that multiple institutions participate in almost every activity, and contribute to every deliverable, although some will be more involved than others.

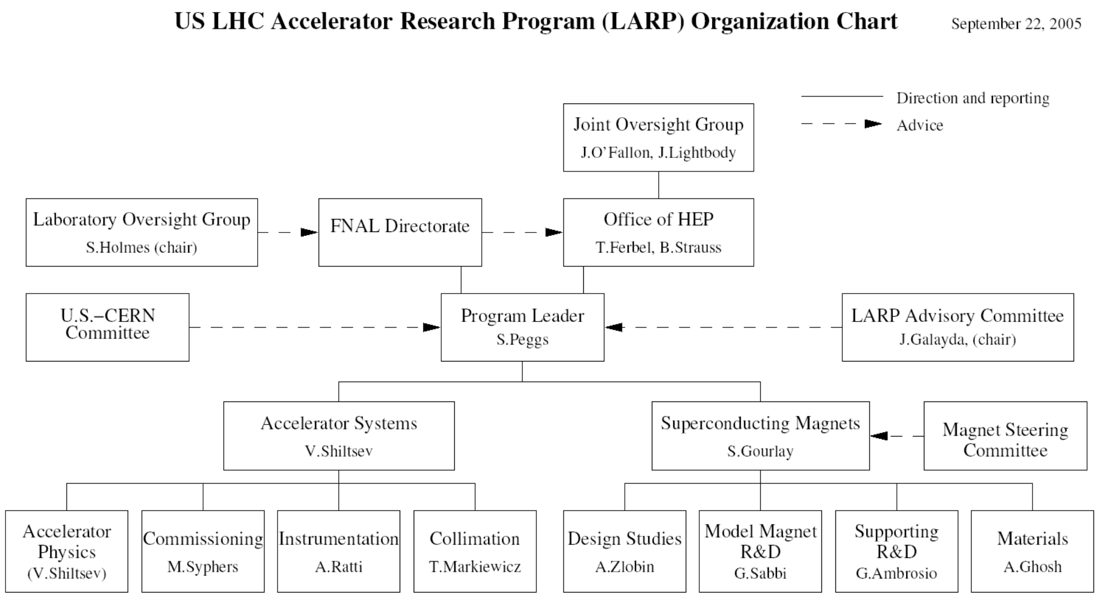

Fig. 1.5-1 LARP organizational and reporting structure, including advisory committees.

1.5.2. Advisory Groups and Peer Review

The LARP advisory groups shown in Fig. 1.5-1 are described in the following paragraphs.

Laboratory Oversight Group (LOG): The Laboratory Oversight Group provides a coordinated communication channel between the Program Leader and the directorates of the U.S. DOE laboratories in LARP. It addresses high-level inter-laboratory issues, meeting as needed, and at least once per year. This mechanism is invoked when issues of joint policy or strategy arise, or when there is need to discuss LARP access and/or use of specific laboratory infrastructures. Most meeting are by phone, email, or video conference.

Executive Committee: The U.S. members of the U.S.-CERN Committee serve as the Executive Committee, which advises the Program Leader on programmatic issues within the U.S. Labs, such as allocation of resources and division of collaborative work. It represents the leaders of the U.S. LHC Accelerator Research Program and the technical leadership and management of the U.S. laboratories in LARP. Members are either involved in, or are very familiar with, LARP activities. The Executive Committee meets in person at least twice per year. Many of its members also attend the LARP collaboration meetings that rotate between locations near BNL, Fermilab, and LBNL. Potential changes to the LARP program, proposed for example to add new program elements or to drop existing ones, are presented to the Executive Committee as part of the Change Control Process that can add, drop, or significantly modifying major LARP program components. The Executive Committee is also consulted when the LARP organization chart has to be changed, and when high-level names within organization chart boxes are changed. This committee also provides top-level coordination of the on-going work of the LARP collaboration by receiving periodic reports on the progress being made.

Table 1.5-1 The LARP Management Team

Deliverable	***Leader***	***Leader's Institution***
Overall Management & Strategy	***S. Peggs***	***BNL***
Accelerator Systems	***V. Shiltsev***	***Fermilab***
Instrumentation	*A. Ratti*	*LBNL*
Commissioning	*M. Syphers*	*Fermilab*
Collimation	*T. Markiewicz*	*SLAC*
Accelerator Physics	*V. Shiltsev*	*Fermilab*
Magnet R&D	***S. Gourlay***	***LBNL***
Design Studies	*A. Zlobin*	*Fermilab*
Model Magnets	*G. Sabbi*	*LBNL*
Supporting R&D	*G. Ambrosio*	*Fermilab*
Materials	*A. Ghosh*	*BNL*

U.S.-CERN Committee: The U.S.-CERN Committee includes all members of the Executive Committee, plus the leaders of LHC work at CERN relevant to the LARP. It is chaired jointly by the CERN LHC Project Leader and by 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 committee meets as needed, and at least once per year, usually towards the end of the fiscal year, in order to endorse current and planned LARP activities. The process of developing and evolving LARP planning involves many informal and formal contacts with CERN staff, including person-to-person meetings, phone, email, et cetera. Key in the process of developing mutually desirable and practical collaboration goals are the activities of the "LARP Liaisons" at CERN, who work closely with the Program Leader. The annual meeting of U.S.-CERN Committee formalizes the consensus building, planning, and work that has occurred on a continuous basis throughout the year. Most meetings are in person at CERN, sometimes with a video conference component.

LARP Advisory Committee (LARPAC): The LARP Advisory Committee meets on an *ad hoc* basis, determined by the technical progress of the program, approximately once per year. The committee meets in person, typically for two or three days. It 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 are conducted by the LARPAC directly, or by independent subcommittees which report to it. LARPAC may 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 Change Control Process. This internal LARP review mechanism complements the more formal program reviews called by the DOE Office of High Energy Physics, and the internal laboratory reviews that are called on occasion.

Magnet Steering Committee (MSC): LARP activities are heavily matrixed, especially in Magnet R&D. Horizontal tasks involving multiple laboratories must be integrated into the vertical coordination of resources and infrastructure at each individual laboratory. The Magnet Steering Committee provides a mechanism to manage and link the matrix for LARP Magnet activities. It meets several times a year, often by video conferencing, sometimes in person, including email and telephone exchanges.

1.5.3. Management Oversight and Performance Evaluation

Because 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 is provided by requiring periodic written reports from the leaders of each major program element, 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 submits a “task sheet” work plan for the next fiscal year, which also includes commentary on the progress made against the previous year’s plan.

The Program Leader calls 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 LARPAC are invited to participate in these reviews. It is expected that each major element in the program will be reviewed about once per year, with more frequent or specifically focused reviews scheduled as needed. The reviews report to the

Program Leader, who is responsible for informing 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, LARPAC reviews LARP at least once per year, and may organize additional reviews as needed.

1.5.4. Procedure for Proposed Changes to the LARP Work Scope

LARP is open to proposals for new program elements or major changes to existing ones. Such proposals are submitted from time to time, either by individuals or by institutions that are currently part of the LARP collaboration, or by those from outside the current collaboration. Such proposals are submitted in writing to the Program Leader, often in the form of proposed "task sheets", including a statement describing the work to be done, the schedule of the work, a cost estimate, and, if relevant, funding source. The Program Leader may then consult with relevant technical leaders in LARP and at CERN, and with the DOE, about how the proposed work would fit in with and contribute to the overall LHC program, and about 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 is presented to the LARP Advisory Committee, 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 Program Leader may then forward the proposal to the Executive Committee, which considers how well the proposal matches LARP goals, and whether it is possible to accommodate the cost of the proposed work within the existing funding guidance for the LARP. The results of the LAPAC review will be considered by the Executive Committee, who 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 submits it to the U.S.-CERN Committee for formal consideration for inclusion in LARP.

2. Accelerator Systems R&D Plan

The Accelerator Systems component of the U.S. LHC Accelerator Research Program 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. Below we give an overview of the different program elements that address these goals.

Accelerator Systems FY'06 budget: 3,960,000 USD. Level 1 manager: Vladimir Shiltsev (FNAL)

2.1. R&D on LHC Instrumentation

FY'06 budget: 1,530,000 USD. Level 2 manager: Alexander Ratti (LBL)

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 decided that the initial suite of instruments and diagnostics be operational for LHC first beam, scheduled to be in 2007. Instrumentation projects developed under LARP will help to commission LHC and will be in operational use during LHC luminosity operation.

2.1.1 Tune Feedback

FY'06 budget: 325,000 USD. Level 4 manager: Peter Cameron (BNL)

Tune, chromaticity and coupling feedback instruments and software are being developed by LARP for the LHC. 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. The goal is to control the tune during the acceleration ramp to avoid resonance crossing and beam loss. The Phase Locked Loop (PLL) method is to shake the beam and observe the resonant beam transfer function when the shaking frequency is at the fractional betatron tune. Once the fractional tune is measured with the PLL, it is used in a feedback system to regulate the quadrupole current and tune.

Encouraging results with PLL tune feedback were obtained in RHIC and in the Tevatron in 2005, with many problems addressed and solved.

Overall Plan:

FY2006: Q1 – make prototype PLL (4 planes) ready for RHIC beam
Q2 - deliver 2 planes to CERN for SPS testing
Q3 - Final Design Review, SPS testing, initial Controls integration (FESA)
Q4 - finalize architecture

FY2007: Q1 – make final system (4 planes) ready for RHIC beam
Q2 - deliver final system to CERN, system integration and testing
Q3 - system commissioning with beam

2.1.2. Luminometer

FY’06 budget: 960,000 USD. Level 4 manager: Alexander Ratti (LBL)

LARP is committed to delivering four ionization gas luminosity monitors to the LHC, to go on either side of IP1 (ATLAS) and IP5 (CMS). The devices are ionization gas monitors designed to withstand the extreme radiation levels of these interaction points. Flowing gas is needed to ensure that fresh medium is used to prevent radiation damage effects. At this point there are no plans by anyone to place luminosity monitors at IP2 (ALICE) and IP8 (LHCb), although experimenters are petitioning LHC management to do so. (The LHC philosophy is to treat luminosity monitors as standardized accelerator diagnostics, rather than as devices belonging to the experiments that are made available to the accelerator control room.) One possibility would be for CERN to "purchase" 2 or 4 additional ionization gas monitors from LARP, for use at IP2 and/or IP8. Since there are no TAN neutral absorbers at IP2 and IP8, installation and integration there would have to be developed on purpose and could not be the same as at IP1 and IP5.

In 2005 the LBL group completed and formalized the system integration document, describing the installation plan at CERN. A test of the prototype luminosity monitor at the ALS (LBL) X-ray beam line was very successful and demonstrated 40 MHz capability of the monitor, and completed the feasibility studies planned for the device.

Overall Plan:

FY2006: Design and build first unit of DAQ system
Final design of complete first unit
Test prototype at RHIC

FY2007: Build all units
Install and commission all units at CERN

2.1.3. Schottky Monitors

FY'06 budget: 245,000 USD. Level 4 manager: Andreas Jansson (FNAL)

4.7 GHz Schottky monitors will allow continuous and non-destructive measurements of LHC beam sizes, tunes, and distributions on bunch-by-bunch basis. Both narrow and wide band systems are potentially useful. Original 1.7 GHz version of VHF Schottky monitors have demonstrated their extreme operational usefulness at the Tevatron and Recycler rings at FNAL, and 4.7GHz Schottky R&D will be a natural continuation of the method for the LHC beam parameters. Under that task, LARP will deliver: a complete design and analysis, a drawing package, the analog signal processing electronics, analysis software, installation and hardware commissioning support at CERN. CERN will provide manufacturing and local installation, DAQ system and controls system integration.

Overall Plan:

FY2006:	S/N study of low intensity bunches in Tevatron
	Design pick-up structure
	Study PLL DAB board for DAQ
	Design and build front-end electronics
FY2007:	Adapt Fermilab analysis software
	Hardware commissioning at CERN without beam
FY2008:	Hardware commissioning at CERN with beam
FY2009:	Beam studies of chromaticity measurements, ramp effects

2.1.4 New Instrumentation Initiatives

FY'06 budget is 0,000 USD. Level 2 manager: Alexander Ratti (LBL)

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 current 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.

Four LHC instrumentation proposals are presently under consideration, while others are still being developed:

Zero Degree Calorimeters for Luminosity Monitoring

It is proposed to install three Zero Degree Calorimeter (ZDC) modules on either side of IP1, primarily for use by the ATLAS experiment. This makes such devices available to the accelerator also for luminosity monitoring. These ZDCs are derived from those already used very successfully in routine operation as standard devices at RHIC. Their installation at IP5 would "double up" luminosity monitors there, allowing the cross calibration of ZDCs and ionization gas devices. Sebastian White (BNL) is in the process of making a formal request to ATLAS, seeking about $140k in funds. The similarities between ZDCs and ionization gas devices makes it possible for them to share the readout electronics, which is already part of the effort underway at LBL. It is proposed that LARP extend its effort to include the readout electronics for the ZDCs.

In FY'06 the ZDC proposal will be evaluated and commitment decision will be made. Sebastian White (BNL) is leading this proposal.

Head-Tail Monitor

The head-tail chromaticity monitor. originally proposed at CERN, has been developed at FNAL and is now routinely used for chromaticity measurements in the Tevatron. In the LHC the large swing in chromaticity (> 50 units) at the start of ramp and the short decoherence time will pose additional challenges. A collaboration between V. Ranjbar (FNAL) and R.Jones (CERN) has begun to look at improvements to the method. This method also allows to measure tunes, coupling and lattice functions, and has promise to measure second order chromaticities with better precision than traditional methods.

In 2006 we will carry out collaborative machine studies in the Tevatron and SPS to measure chromaticity with reduced emittance blow up and explore possible extensions to measure higher order chromaticities and wake fields. Vahid Ranjbar (FNAL) is leading this proposal.

AC Dipole

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. 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.

In FY'06 we will evaluate effectiveness of the AC dipole for the LHC measurements, make cost estimates and schedule. M.Bai (BNL) and A.Jansson (FNAL) are leading this proposal.

2.2. LHC Commissioning

FY'06 budget: 940,000 USD. Level 2 manager: Michael Syphers (FNAL)

There is an overall benefit to the U.S. high-energy physics program if the LHC turns on rapidly and successfully. Our experimental physics groups have invested heavily in the LHC project, and the science produced there thus represents a return on the U.S. investment. A healthy and strong HEP activity at LHC will surely be necessary to secure future accelerator-based HEP projects in the U.S. The information gained during the commissioning will be available in a timely manner and will have maximum positive effect on U.S. plans for LHC upgrades.

2.2.1. Beam Commissioning

FY'06 budget: 400,000 USD. Level 4 manager: Elvin Harms (FNAL)

The Beam Commissioning task consists of :

Commissioning of LARP Deliverables: This includes the commissioning and exploitation of beam instrumentation developed with LARP funds, such as luminometers, tune feedback, and phase 2 collimators.

Generic Beam Commissioning: This includes participation in beam startup, various beam studies, and exploitation of beam instrumentation other than that developed with LARP funds. Some 30 topics for possible U.S. contributions were listed by CERN Beam Commissioning leaders and presented at the LARP collaboration meetings in 2005.

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.

Overall Plan:

FY 2006	First visits for commissioning of LARP deliverables organized and started; Long term plan (LTP) of general beam commissioning formulated, reviewed and approved
FY 2007:	First year of full involvement of LARP in the LHC beam commissioning
FY2008+	The commissioning effort continues according to the LTP

2.2.2. IR and Hardware Commissioning

FY'06 budget is 540,000 USD.

This consists of :

Interaction Region Commissioning: This relatively modest and well defined Task refers to non-beam commissioning of hardware built in the U.S.-LHC Construction Program, such as interaction region magnets, and feed boxes. LARP will support 2-3 1-year long visits for that purpose in FY06-07. The names are identified and the visits are scheduled.. Level 4 manager :Michael Lamm (FNAL).

Hardware Commissioning: Strong verbal support has been expressed by the DOE and U.S. lab directorates for additional hardware commissioning assistance to CERN, and for the idea that LARP is a natural vehicle through which this activity could be organized. Any additional hardware commissioning scope inside LARP would go beyond "following through on U.S.-built deliverables," to participation, mainly by engineers, with more general commissioning. In 2005, LARP Commissioning Task Force identified possibilities to send some 5-7 U.S. engineers to CERN for general hardware commissioning work – in addition to the IR commissioning. Effort required for this new activity is not included in the current LARP funding envelope.

The entire IR and Hardware commissioning effort will take place in FY'06 and FY'07 – until the end of the LHC installation and machine commissioning.

Overall Plan:

FY 2006: Funding issues to be cleared out and general Hardware Commissioning to be organized in the first half of FY'06.
IR Commissioning participation started.

FY 2007: IR and general Hardware Commissioning efforts continue

2.2.3. Toohig Fellowships

FY'06 budget: 160,000 USD. Toohig Fellowship Committee Chair: Peter Limon (FNAL)

It is critical that U.S. accelerator physicists and engineers make use of this relatively rare opportunity to train younger staff members on the LHC machine. In 2005, the LHC Accelerator Research Program announced Toohig Fellowships - postdoctoral research positions in accelerator science for recent PhDs in physics or engineering. These positions are explicitly for studies and activities concerning CERN's Large Hadron Collider. The term of the Toohig Fellowship is two years extendable to three, approximately half of which will be spent at CERN and the remainder at a U.S. DOE laboratory involved in the LARP collaboration. LARP could support up to two fellowships per year for remaining years of the Program.

The Fellows are expected to study and improve the operation of the LHC by helping with commissioning activities, by actively participating in accelerator research on the collider, beam physics calculations and simulations, and by pursuing R&D on instruments, magnets, and other equipment to facilitate a luminosity upgrade.

Overall Plan:
FY 2006-2010: up to 2 Toohig Fellows will be selected each year

2.2.4. New Commissioning Initiatives

FY'06 budget is 0,000 USD. Level 2 manager :Michael Syphers (FNAL)

LARP is currently considering participation in the CMS/LHC Remote Access Center at Fermilab – which will support several types of LARP activities.

- Participate in LHC hardware & beam commissioning and operations
- Monitor LHC accelerator components (e.g. systems built in the U.S.)
- Analyze the monitoring data for LHC
- Develop software for the LHC
- Provide access to monitoring data and analysis results
- Provide training and data-analysis facility for members of US/LARP
- Provide a rapid response call center to get experts located in North America connected to CERN (data access, operational status, etc.)

The ability to participate in experiments remotely from the U.S. may greatly reduce the travel strain and cost of Accelerator Physics and LHC beam commissioning activities.

Overall Plan:
FY 2006: Take part in initial discussions on that subject within framework of the LHC@FNAL Task Force initiated by FNAL Director in April 2005 and led by Eric Gottschalk (FNAL).

2.3. LHC Collimation R&D

FY'06 budget: 850,000 USD. Level 2 manager: Thomas Markiewicz (SLAC)

The LHC cleaning system must have exceptional efficiency to meet its design parameters, significantly beyond the state-of-the-art that is achieved in existing colliders. It is crucial for the success of the LHC that different paths are explored in order to optimize the design, hardware and operational procedures for the LHC collimation system. In view of the exceptional difficulty for the LHC it is essential to pursue parallel R&D studies in- and outside of CERN. The phased approach for the LHC collimation system will allow to test various proposals and to implement the best solutions in an already defined upgrade path to nominal performance. The LHC Collimator R&D will complement the work at CERN and will be performed in close collaboration.

2.3.1. Cleaning Efficiency Studies

FY'06 budget: 50,000 USD. Level 4 manager: Angelika Drees (BNL).

We plan to install and implement at BNL accelerator tracking code identical with the one used at CERN (K2, SIXTRACK with Collimators, i.e. SIXTRACKwColl) and perform detailed simulations. SIXTRACK needs to be adjusted to specific RHIC conditions (single sided collimators); this effort is currently in progress. Simulations should include apertures and result in predicted collimation efficiencies and loss maps which will then be compared to simulation results from earlier studies done at RHIC with other codes (Teapot, K2, ACCSIM) and with data. Various data sets at two energies are available.

During the RHIC proton run collimator setup procedures should be implemented into the RHIC control system and tested with beam under real operating conditions.

The ultimate goal of this sub program is to bench mark code(s), in particular SIXTRACKwColl, in a variety of aspects with RHIC beams. Once the simulation code is installed and cross checked between the labs more studies can be performed easily (such as HI scattering, loss maps and collimator efficiencies).

Overall Plan:
FY 2006: compare SIXTRACK with other simulation and data, test setup procedures, finish reports

2.3.2. Rotating Collimators R&D

FY'06 budget: 720,000 USD. Level 4 manager: Thomas Markiewicz (SLAC)

The ultimate goal of this sub-program is a successful design for low impedance, high efficiency LHC secondary collimators. The design will be validated with a sufficient but small (1-3) number of prototypes and beam tests. The design specifications and the prototypes are the primary deliverables. The time scale is set by the desirability of testing the prototypes with LHC beam in 2008/09. Based on the design study, prototype performance and overall experience with the Phase I collimation system in actual LHC running conditions, CERN will decide whether or not to proceed with the rotating collimator design. If a decision is made to proceed, this sub-project will provide an engineering drawing package to CERN and will support the effort to commission the collimators once they are manufactured and installed by CERN.

Overall Plan:
FY 2006: Tests of RC0, Design and construction of functional collimator (RC1)
FY 2007: Tests of RC1 (two rounds), design and construction of RC2
FY 2008: Non-Beam Tests of RC2
FY 2009: RC2 beam tests & final drawing package for CERN
FY 2010: Await production & installation by CERN

FY 2011: Commissioning support

2.3.3. Tertiary Collimator Studies

FY'06 budget: 30,000 USD. Level 4 manager: Nikolai Mokhov (FNAL)

The Tevatron and HERA experience says, that the backgrounds in the detectors and protection of expensive detector components is the most demanding issue to the collimation system performance and efficiency, and that the tertiary collimators in high-luminosity insertions is an absolutely necessary component here. Therefore, we plan full tracking – with the STRUCT code - of secondary halo particles up to the limiting apertures in the IP1 and IP5 insertions and farther to the CMS and ATLAS detector inner detectors followed by realistic energy deposition modeling with the MARS15 code with and without tertiary collimators.

Minimization of machine-related backgrounds and protection of the final focus and collider detector components at normal operation and accidental beam losses is to be added to the collimation system specifications. This is to be done with the appropriate simulation tools, thorough benchmarked and further developed if needed, in a close collaboration with the CERN LHC collimation team, with all the necessary iterations on the LHC lattice, detector and collimator models. The ultimate goal is a successful design for high efficient robust tertiary collimators in all the LHC experimental insertions. The design specifications are the primary deliverables.

Overall Plan:
FY 2006: First studies and optimization of the tertiary collimator performance
FY 2007: Engineering design, extension to heavy-ion mode of operation
FY 2008: Studies towards luminosity upgrade
FY 2009: Studies towards luminosity upgrade
FY 2010: Engineering design and production
FY 2011: Commissioning

2.3.4. Material Irradiation Studies

FY'06 budget: 50,000 USD. Level 4 manager: Nikolaos Simos (FNAL)

Material irradiation studies will provide indicators of how prone LHC collimator materials are to changing physical and mechanical properties, important to the beam collimating function, with the onset of irradiation. Behavior of a wide range of materials from low to high Z under irradiation and post-irradiation to be studied at BNL. The main phase of the irradiation study uses the 200 MeV beam of the BNL BLIP (~ 70μA average current). It is expected to induce approximately 0.25 displacements per atom on the materials and will provide initial screening.

To address potential issues with materials considered for Phase 2 collimators, the effects of irradiation on the driving design parameters must be established early on and thus guide the final selection and the design. Specifically, materials that are being discussed are Beryllium, Copper, Aluminum, Inconel, Tungsten, Titanium alloys and AlBeMet (alloy of Beryllium and Aluminum). Understanding of how irradiation primarily degrades thermal conductivity (as well as other physical and mechanical properties such as ductility, strength, fracture temperature, etc.) is of paramount importance in the Phase II study that is exploring a number of options.

Overall Plan:

FY 2006: Continuation BLIP studies, start of irradiation studies with high energy protons at either BNL AGS or FNAL

FY 2007: Post irradiation analysis of material properties

2.4. Accelerator Physics R&D

FY'06 budget is 640,000 USD. Level 2 manager (acting): Vladimir Shiltsev (FNAL)

LHC, as a 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 because 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. The results of these calculations, simulations and experiments will give us the knowledge to design and build with confidence the next generation hadron collider.

2.4.1. Electron Cloud Simulations

FY'06 budget: 200,000 USD. Level 4 manager is Miguel Furman (LBL)

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 SPS, RHIC, and 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.

Experimental data on electron cloud effects during recent SPS run had been acquired and they will be used for EC codes calibration. In addition, we intend to better understand the ECE in the cold sections of RHIC.

Overall Plan:

FY2006: Complete the analysis of June 2004 SPS run. Additional SPS studies including bunch length dependence
Finish LHC heat-load estimate and POSINST-ECLOUD benchmarking
Define optimal LHC conditioning scenario and fill pattern during first two years of beam operations

FY2007: Perform 3D simulations bunch trains, beam instability for LHC arcs
Report on applicability of Iriso-Peggs maps to LHC
Report on e-cloud simulations for RHIC detectors, predict BBB tune shift

FY2008: Report on e-cloud simulations for LHC IR4 “pilot diagnostic bench”

2.4.2. IR Design and Beam Beam Simulations

FY’06 budget: 260,000 USD. Level 4 manager: Tanaji Sen (FNAL)

The nominal beam parameters of the LHC take it into beam-beam territory 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. The Tevatron experience has shown importance long-range beam-beam interactions that are likely to limit the luminosity in the LHC. Experimental observations at Tevatron and RHIC to 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. 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.

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.

Overall Plan:

FY2006: Design concepts for the IR upgrade will be explored in greater detail.
Develop matched designs that can be used from injection to collision.
Develop non-linear correction schemes for both Dipole-first (DF) and Quadrupole-first (QF) designs
Energy deposition and magnet protection considerations for both designs

Study interference of TOTEM and ZDCs with IR systems
Benchmark code against Tevatron and RHIC beam-beam observations and CERN's fast-multipole code

FY2007: Application of BEAMBEAM3D to halo formation, luminosity monitor (swept beams).
Explore in simulations long-term emittance growth and working point dependencies

FY2008: Plans to be determined after obtaining previous years results.

2.4.3 Wire Beam-Beam Compensation R&D

FY'06 budget: 180,000 USD. Level 4 manager: Tanaji Sen (FNAL)

It was recently proposed to compensate LHC long-range interaction effects by placing several current carrying wires in vicinity of the beams close to main IPs. Beam experiments with wires in SPS showed that one wire can compensate detrimental effects caused by another wire. LARP is supporting an experimental test of the wire compensation at RHIC that provides unique environment to study experimentally long-range beam-beam akin to LHC operation. The experiment assumes installation of a wire compensator on a movable stand in one of the RHIC rings.

Overall Plan:

FY2006: Design and construct a wire compensator
Install wire compensator in RHIC in summer 2006, downstream of Q3 in IR6
Perform theoretical studies to test the compensation and robustness

FY2007: Study the wire compensation in RHIC with 1 proton bunch in each beam and nominal conditions at flat top and 1 parasitic interaction.
Beam studies to test tolerances on: beam-wire separation compared to beam-beam separation, wire current accuracy and current ripple

FY2008: Decide on scope of work for the LHC wire compensation

2.4.4 New Accelerator Physics Initiatives

FY'06 budget: 0,000 USD. Level 2 manager: Vladimir Shiltsev (FNAL)

Field fluctuation measurements

It was recently pointed out, that the beam screen inside the LHC dipole magnets is subject of microkicks due to turbulent flow of 20K Helium used for its cooling. Miniscule fluctuations of the beam screen shape caused by these kicks will result in field fluctuations at frequency range including lowest betatron lines. Emittance growth due to such fluctuations can be of concern for he LHC integrated luminosity if their magnitude exceed dB/B~1E-10. The fluctuations can be directly measured using Faraday induction coil probes.

Overall Plan:

FY 2006: elaborate preparations of the measurement coils, DAQ and LHC MTF, testing and calibration of the equipment

FY2007: Measurements begin, dB/B measured at different He temperatures and flow rates

3. Magnet Research and Development

3.1 Introduction

The start of LHC operation is planned for 2007. However, preliminary studies of possible scenarios for future LHC upgrades have already been started at CERN and in the U.S. [13] aimed at increasing the luminosity to 3-10×L_{nom} or reaching the highest possible beam energy $E=(1.5\text{-}2)\times E_{nom}$. The ranges in both parameters reflect the uncertainties in actual LHC performance as well as unknown technical limitations.

The projected lifetime of the current IR magnets is six – seven years at full luminosity. Combined with cost considerations, this makes replacement of the IR magnets an obvious scenario for an initial upgrade

Three of the four U.S. National Laboratories in LARP (LBNL, BNL and Fermilab) are now positioned to develop the next generation of high performance magnets for the interaction regions of the LHC, which can, by themselves, double or triple the luminosity, and which will be compatible with operation at full performance at a luminosity as high as 10^{35} $cm^{-2}s^{-1}$. The same magnet technology also has the potential to allow a new machine to be built in the LHC tunnel with up to a factor of two increase in beam energy. In a paper presented at EPAC2002 [11], Tom Taylor outlined a performance upgrade plan for the LHC. He points out that the current LHC relies on pushing NbTi technology to the ultimate limit, revealing the magnet systems as the limiting components for improved machine performance. Any enhancements will require the use of new materials. Replacement of the existing inner triplets is a key step toward higher luminosity. There are two fundamental inner triplet design options [12,13]: a large-aperture, single-bore inner triplet followed by beam separation dipoles or double-bore inner triplet with separation dipoles first. The present inner triplet design is based on the first option. This approach and the magnet requirements are well understood. The second one needs a new layout of inner triplet optics with twin, large-aperture high gradient quadrupoles and correctors and very high field separation dipoles. This approach requires more study in terms of accelerator physics and magnet design.

Steady improvements in the application of Nb_3Sn technology have been made over the last several years [14]. The LARP magnet program is charged with answering the question of whether it can now be considered a viable material for practical high field accelerator magnets. High gradient, large aperture quadrupoles operating under high radiation induced heat loads, require superconductor with performance parameters provided by Nb_3Sn. Development of a Nb_3Sn-based technology that can be industrialized will require a long-term, aggressive R&D program. Preliminary work has been performed by all three labs on a variety of quadrupole designs [15-17]. Study of a reference design indicates that a 90 mm Nb_3Sn quadrupole with a nominal gradient of 205 T/m, which would allow a factor of 2 decrease in β^*, is feasible with presently available material. With anticipated advances in Nb_3Sn performance and more aggressive magnet designs, even larger apertures are likely to be feasible, permitting an even larger decrease in β^* and corresponding increase in luminosity. Several innovative options exist that could meet the operation requirements and will be studied as part of the program. These magnets can operate with energy deposition levels a factor of 10 (5) higher at 1.9 K (4.5 K) than the present NbTi-based system.

In addition to basic magnet development, the program outlined in this document includes parallel development of ancillary technology to address issues that are crucial for operation of the magnets. Examples are; heat load due to secondary particles and synchrotron radiation, vacuum, quench protection, injection field quality and long coil fabrication.

The LHC luminosity upgrade provides a unique opportunity to operate magnets using Nb_3Sn technology in an accelerator. LARP will also help to strengthen collaborative ties amongst the U.S. Labs as well as with CERN and the international community.

3.1.1 Program Goals

This is a long-term R&D program to develop and demonstrate the feasibility of Nb_3Sn technology for accelerator magnets. The first phase (2006 – 2009) is highly focused on assembling the toolbox necessary to undertake further development of magnets that could eventually be used for LHC upgrades. The issues discussed above, and others that will emerge during the course of the R&D program, are addressed by the general goal of the program, to "*demonstrate by 2009 that Nb_3Sn magnets are a viable choice for an LHC IR upgrade.*" This goal is approached in a program with three overlapping phases. Each phase is implemented by a series of model magnets with specific targets:

1) *Predictable and reproducible performance (SQ and TQ series)*

2) *Long magnet fabrication (LR and LQ series)*

3) *High gradient in a large aperture (HQ series)*

At a minimum, each phase should result in a magnet that performs to within a significant fraction of the conductor potential, and which shows no significant retraining after a thermal cycle. A summary of the program is shown in Table 3.1 – 1.

3.2 Materials Issues

The program goals are structured around the numerous issues related to development of a technological base necessary to meet performance and operational requirements. Some are generic to Nb_3Sn accelerator magnet technology and others are specific to LARP applications. Of particular importance in the initial phase of the program are issues to do with conductor and cable.

Table 3.1 – 1 LARP Magnet Program Summary

Model Magnets		**Type**	**Length (m)**	**Gradient (T/m)**	**Aperture (mm)**	**FY05**	**FY06**	**FY07**	**FY08**	**FY09**
Series	Description									
TQ	**Technology Quad**	Cos-2theta	1	> 200	90		$\mathbf{3}_N + 1_R$	$\mathbf{2}_N + 1_R$		
LQ	**Long Quad**	Cos-2theta	4	> 200	90				$\mathbf{1}_N$	$\mathbf{1}_N$
HQ	**High Gradient Quad**	Cos-2theta	1	> 250	90					$\mathbf{2}_N$
Supporting R&D		**Type**	**Length (m)**	**Peak Field (T)**	**Aperture (mm)**	**FY05**	**FY06**	**FY07**	**FY08**	**FY09**
Series	Description									
SQ	**Sub-scale**	block	0.3	10 – 11	110	$\mathbf{1}_N + 1_R$	$\mathbf{1}_N + 1_R$	$\mathbf{1}_N + 1_R$	$\mathbf{1}_N$	
SR	**Short Racetrack**	block	0.3	10 – 12	N/A		$\mathbf{1}_N$	$\mathbf{1}_N$	$\mathbf{1}_N$	
LR	**Long Racetrack**	block	4	10 - 12	N/A			$\mathbf{2}_N$		
N = New Magnet										
R = Revised Magnet using existing coils										

3.2.1 Conductor and Cable

The demanding operational parameters of the upgrade magnets require the use of superconducting materials substantially beyond NbTi. Recent progress in the development of Nb_3Sn magnets has encouraged the prospects for its use in LHC upgrades. However, even though it has been available for more than 40 years, Nb_3Sn technology, as applied to accelerator magnets, is still far from fully developed and success is founded on high performance conductor.

The U.S. DOE Office of High Energy Physics has been funding the development of Nb_3Sn through the Conductor Development Program (CDP), since its establishment in 1999. The first phase has resulted in readily available conductor with critical current densities over 3 kA/mm^2 @ 12 Tesla and 4.2 K [18]. A complete list of the target parameters is shown in Table 3.2 – 1. While critical current density has improved dramatically since then, there are still several important issues remaining, such as reducing effective filament diameter, and increasing RRR and piece length, while maintaining the high critical current density.

3.2.2 Conductor Plan for LARP magnets

Magnets for LARP are designed to use high J_c Nb_3Sn wires that achieve more than 2000 A/mm^2 at 12T. Although considerable work by industry has been done in developing such strands under both the DOE's Small Business Innovation Research (SBIR) program and under the CDP, we have as of today only one reliable U.S. vendor that is able to deliver sufficient quantity of high J_c wires, namely Oxford Superconducting Technology (OST).

Table 3.2 - 1. ***Technical and cost performance goals of the US/HEP conductor development program.***

Specification	Target value
Jc (non copper,12T, 4.2K)	3000 A/mm^2
Effective filament size	Less than 40 microns
Minimum piece length	Greater than 10 km in dia. of 0.3 to 1.0 mm
Wire cost	Less than $1.50/kA-m (12T, 4.2K)
Heat treatment times	Less than 200 hrs

All high J_c conductors that have been manufactured by the internal-Sn process have large effective filament size, D_{eff}. This D_{eff} is typically the same as the geometric size of the filament bundle within the diffusion barrier. As a consequence all high Jc strands are ***intrinsically unstable*** at low field to flux-jumps. This property of the wire persists until D_{eff} is reduced below about 30 μm for high J_c strands. Industry has been developing techniques to reduce D_{eff}, by introducing distributed barriers, by increasing the number of sub-elements and by using "fins" to break-up the filament bundle. However, at present only OST can reproducibly produce high J_c wires, either by the Modified Jelly-Roll (MJR) process or by the newly developed Rod-Re-stack Process (RRP). (The MJR manufacturing process has recently been discontinued.) In either case the strand uses the 61-stacking design, which inevitably produced wires at 0.7 mm with large filament size greater than 70 μm.

The Powder-in-Tube process (PIT) has achieved filament diameters of about 50 μm in 1 mm strands, which would translate to 35 μm in 0.7 mm strands. PIT conductor development in the U.S. is being performed by small companies under the SBIR program. However, no reliable source for such wire currently exists in the U.S. The sole source of this wire (Shape Metal Innovations, Netherlands) has so far been unreliable in delivering conductor in a timely manner. Additionally, the present day PIT conductor has lower J_c than the RRP strands.

3.2.3 Strand Stability at Low Fields

As a consequence of the large effective filament diameter, which leads to large magnetization, flux-jumps occur as the external field is changed. The release of the magnetic energy is often sufficient to quench a wire that is carrying a transport current. Experimentally one can determine a current level above which the strand is unstable to flux-jumps. This is called the stability current I_S, with a value that is determined by "V-H" measurements on the strands.

Although wires with large filaments exhibit flux-jumps, measurements have shown that the stability current is strongly influenced by the copper stabilizer around the sub-elements. In particular the RRR of the copper influences I_S. Ultimately, though, the true low-field stability can only be achieved by reducing the filament size below the "adiabatic" stability limit, which is about 30 μm for the high J_c wires. Hence the long-term goal of Nb_3Sn development is to produce wires with small filaments, and the challenge for industry is to deliver such a conductor in long piece lengths with high J_c.

Large filament conductor can be successfully used in magnets provided that I_S is much higher than the operating current I_{OP} of the magnet. The conventional margin of a factor of two is considered to be conservative, but will probably evolve as more data is obtained on real magnet performance.

The first two magnets in the "Technology Quadrupoles" series, TQC01 and TQS01, compare two alternate ways of mechanically assembling the coils. It was decided in FY05 that they should be made from identical conductor. The only strand available to meet this requirement was the 54/61-design MJR strand that FNAL had in their core-program inventory, since there was insufficient quantity of RRP wire in the CDP inventory to proceed with the necessary cable development. Further, the width of the cable was restricted by the tooling available for building the first cos-2θ coils for these quadrupoles. The cable specifications are shown in Table 3.2-2.

Table 3.2 – 2 Cable Parameters for LARP Quadrupole Magnets

Parameters	Units	TQ Final	Tolerance
Strands in cable		27	NA
Strand diameter	mm	0.7	+/- 0.002
Width	mm	10.077	+0.000, -0.100
Thickness	mm	1.26	+/- 0.010
Keystone angle	deg	1.0	+/- 0.10

Extensive studies were performed on virgin and extracted strands, showing that the stability current is strongly influenced by the heat treat schedule. For the more aggressive heat treatment (210C/48h + 400C/48h + 665C/72h) the stability current is low (400 A – 500 A). However, by adjusting the high temperature reaction to 635C/48h, the stability current increased to over 1000 A with a loss of only 7% to 10% in J_c. The goal is to apply this heat treatment schedule independent of the thermal mass of the coils and fixture.

The "short-model racetrack quadrupole" SQ-02 uses the same MJR strand as that used for the cable for TQC01 and TQS01. However, all future magnets will use cables made from RRP strands, as OST no longer manufactures MJR strands. The question still remains as to which RRP strand stack design to consider as the main conductor for magnets to be built in FY06 and FY07.

3.2.4 RRP Strand Stack Designs

The 54/61 stack design now considered by OST as a “production wire” is also being used for high-field NMR magnets. However, 91 and 127 stack designs are also under development through the CDP program. During FY05, OST fabricated a billet (7904) with a 126/127 stack design using Nb-Ta rods, and a 90/91 stack billet (8079) which is Ti-doped using a sub-element that uses Nb and NbTi rods. Cross-sections of these wires are shown in Fig. 3.2-1.

In FY05 OST also processed (for FNAL) two smaller billets using the same sub-element as that for billet 8079. Strands from billet 7904 were rather unstable despite the smaller sub-element size, as the RRR of the wire was very low (4 to 8) even under modest reaction conditions. This indicates significant contamination of the stabilizer, due to a Nb barrier that was very thin in various regions of the strand cross-section. Either the sub-element design to produce the 126 stack needs to have an increased barrier thickness, or the Sn-content has to be reduced, in order to prevent significant reaction of the barrier. The sub-element for billet 8079 uses less Nb and Sn. This reduces the J_c but also reduces copper contamination during reaction, showing good stability for J_c around 2400 A/mm^2 at 12T.

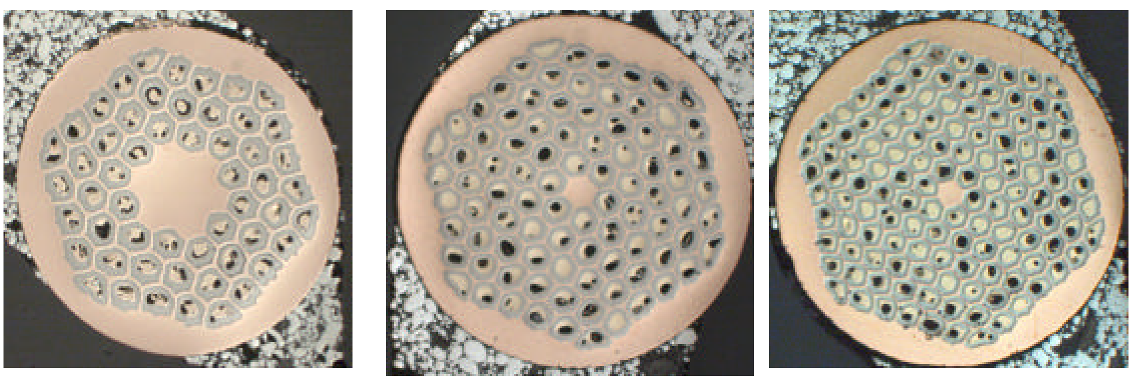

Fig. 3.2 – 1 Cross-sections of billet 7054 (54/61), billet 8079 (90/91) and billet 7904 (126/127).

The wire for FNAL using the same sub-element as that for 8079 also showed good properties at a wire size of 1.0 and 0.7 mm when reacted at lower temperatures of 635C for 50 hours. However, when rolled down, the smaller wire size was less stable than the 1.0 mm wire that was eventually delivered to FNAL. Hence, reaction optimization studies need to be made in conjunction with careful cable studies, in order to ensure that the wire stability current is above a design threshold.

In late FY05 OST delivered about 35kg of wire using the 54/61 stack design in billet 8220. Initial measurements indicate that this wire has a high Jc of greater than 3000 A/mm^2 at 12T, and a stability current Is greater than 1000A for the wire, with RRR greater than 150. A short length of TQ-type cable has been made from this wire.

Preliminary testing of strands extracted from the cable confirmed that the strand with the 54/61 design is adequate for use in LARP magnets. Table 3.2 - 3 lists some test results of round wire from billet 8220.

3.2.5 CDP Conductor

It is fortunate that LARP can "borrow" strand from the CDP inventory, with a promise to replace it at a future date. This allows for flexibility in deciding what strand to use for each LARP magnet, and it allows one to mitigate the risk of some failure at OST to deliver LARP conductor in a timely manner. The CDP inventory that has potential for use in LARP magnets is shown in Table 3.2 – 4, including R&D billets 8502, 8521 and 8466.

Table 3.2 – 3 I_c, I_s and RRR measurements of 8220 and 8079 wire

WireID	HT_Temp	HT_Time	Jc(12T)	Ic(12T)	Ic(11T)	Is	RRR
54/61-Design Round Wire							
RRP-8220-4	665	50	3022	622	750	1125	171
RRP-8220-4	665	50	3208	660	796	1012	190
RRP-8220-4	665	50	3080	634	761	1125	178
RRP-8220-4	680	48	3169	652	773		111
RRP-8220-4	650	48	2923	602	731	1075	
RRP-8220-4	650	96	3108	640	773	1125	
RRP-8220-4	635	48	2600	535	592	1150	
90/91-Design Round Wire							
RRP-8079-7	635	48	2473	561	676	1200	357
RRP-8079-7	635	36	2325	528	638	1200	344
RRP-8079-7	635	48	2457	558	670	1200	356

These three billets use rods from the same sub-element extrusion. A billet with 198 sub-elements failed to draw down. The 84/91 billet also had breakage problems with only 15 kg yield (about 50%) at 0.7 mm. The 108/127 billet is undergoing processing at the time of writing. Thus, at this point in time, strand designs with more than 61 sub-elements must be considered as R&D in nature, not yet ready for reliable production.

OST has also recently started fabricating two billets of 54/61 design to provide wire similar to that from billet 8220. Wires from these billets are expected to be delivered by 11/30/05. Also in fabrication are 2 billets of 54/91 and one of 84/91 design under a CDP purchase of 90 kg of high-J_c (3000 A/mm^2-class) strand.

Table 3.2 – 4 The CDP inventory for potential use by LARP

Billet	Type	Stack	Rod Composition	Diameter (mm)	non-Cu (%)	Weight (kg)	Length (m)	LARP Use	Delivery Date
8079	RRP	90/91	Nb-(Ti)	0.7	59	**30**	6203	R&D	**at LBNL**
8220	RRP	54/61	Nb-Ta	0.7	53.8	**36**	10776	YES	**at LBNL**
xxxx	RRP	54/61	Nb-Ta	0.7	50	**70**		YES	11/30/2005
xxxx	RRP	54/61	Nb-Ta	0.7	50	**60**		YES	11/30/2005
xxxx	RRP	84/92	Nb-Ta	0.7	50	**30**		YES	3/31/2006
8502	RRP	84/91	Nb-Ta	0.7	50	**15**		R&D	9/30/2005
8521	RRP	108/127	Nb-Ta	0.7	50	**30**		R&D	9/30/2005
8466	RRP	198/217	Nb-Ta	0.7	50	**NM**		R&D	9/30/2005

3.2.6 FY06 plan for RRP wire procurement

The plan for FY06 is to purchase 0.7 mm wire from OST fabricated using the 54/61 design using the specifications shown in Table 3.2-5, These will be fabricated using Nb-7.5a % Ta rods. Each sub-element extrusion is typically sufficient for about 90 kg of wire at 0.7 mm, provided that the billet draws down well to final size. The first procurement is for 90 kg to be delivered between March and April 2006. Since the J_c specification is not very high, OST can reduce the normal Sn-content so that the barrier reaction can be controlled. The CDP order of 70 kg of 54/61 wire will serve to increases the inventory of wire available to make TQC02. Additionally, the next CDP order of 60 kg of "production" 54/91 wire would ensure that there is sufficient wire in inventory to make all the magnets for FY06 and early FY07. This implies that magnets SR01, LR01, TQC02, TQC03 and TQS03 would all use the same 54/61-design wire, which therefore becomes the baseline wire for the program.

Table 3.2 – 5 LARP specification for 54/61 wire

Process	Ternary RRP Nb3Sn
Diameter, mm	0.7 ± .003
J_c(12 T), A/mm^2	= 2400
D_{eff}, µm	< 80
I_S, A	> 1000 A
Cu-fraction, %	50 ± 2
RRR	= 100
RH twist, mm	'12-16
Minimum Piece length, :	350
High temperature HT d	= 48

RRP wires with larger number of sub-elements will continue development under the CDP procurement which at present is for one 30 kg of 84/91 delivered in Mar'06 and an additional 35kg of 84/91 and 35 kg of 108/127 billet to be delivered in June-July'06. LARP and the core program will evaluate these conductors for its potential use in higher performance future magnets. These billets will help OST to move this type of wire from R&D to "production" status. Tables 3.2 – 6, 7 and Figs. 3.2 – 2, 3 summarize the strand procurement and evaluation tasks.

An increase in luminosity comes with a corresponding increase in radiation from the IR's. The development and use of more radiation-hard materials such as cyanate esters, and enhanced cooling schemes to deal with the high radiation-induced heat loads, are two components of the program that will intensify as the technological base becomes better established.

Table 3.2 – 6 Total Wire Inventory by Month

	CDP	LARP	**Magnet**	Strand Req.	Inventory of strand
Oct-05	33		SR01	7	26
Nov-05	70				96
Dec-05					96
Jan-06			TQC02	40	56
Feb-06					56
Mar-06	60	95			211
Apr-06			LR01	81	130
May-06					130
Jun-06		60	TQC03, TQS03	80	110
Jul-06					110
Aug-06					110
Sep-06					110
Oct-06		60			170
Nov-06					170
Dec-06					170

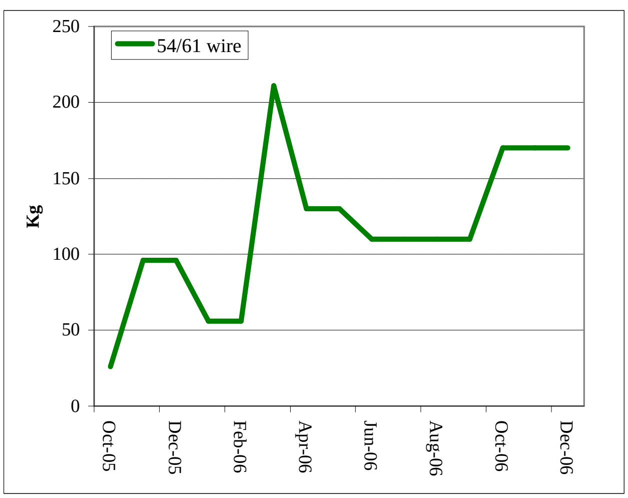

Figure 3.2 – 2 Total Wire Inventory by Month

Table 3.2 – 7 Schedule of Tasks from Strand Delivery to Finished Cable for Winding

Name	Duration	Start	Finish
Strand to Cable Delivery	62.d	9/30/05	12/26/05
Round wire tests	32.d	9/30/05	11/14/05
Strand Delivered	.d	9/30/05	9/30/05
First HT	8.d	10/3/05	10/12/05
Strand Test	14.d	10/13/05	11/1/05
Second HT	8.d	11/3/05	11/14/05
Prototype Cable	30.d	10/4/05	11/14/05
Fabrication	3.d	10/4/05	10/6/05
Extracted strand Test	21.d	10/10/05	11/7/05
Cable evaluation	21.d	10/17/05	11/14/05
Cable fabrication	29.d	11/16/05	12/26/05
Production cabling	7.d	11/16/05	11/24/05
Cable evaluation	21.d	11/28/05	12/26/05
Annealing and insulation	3.d	11/25/05	11/29/05
Coil Winding	.d	12/5/05	12/5/05

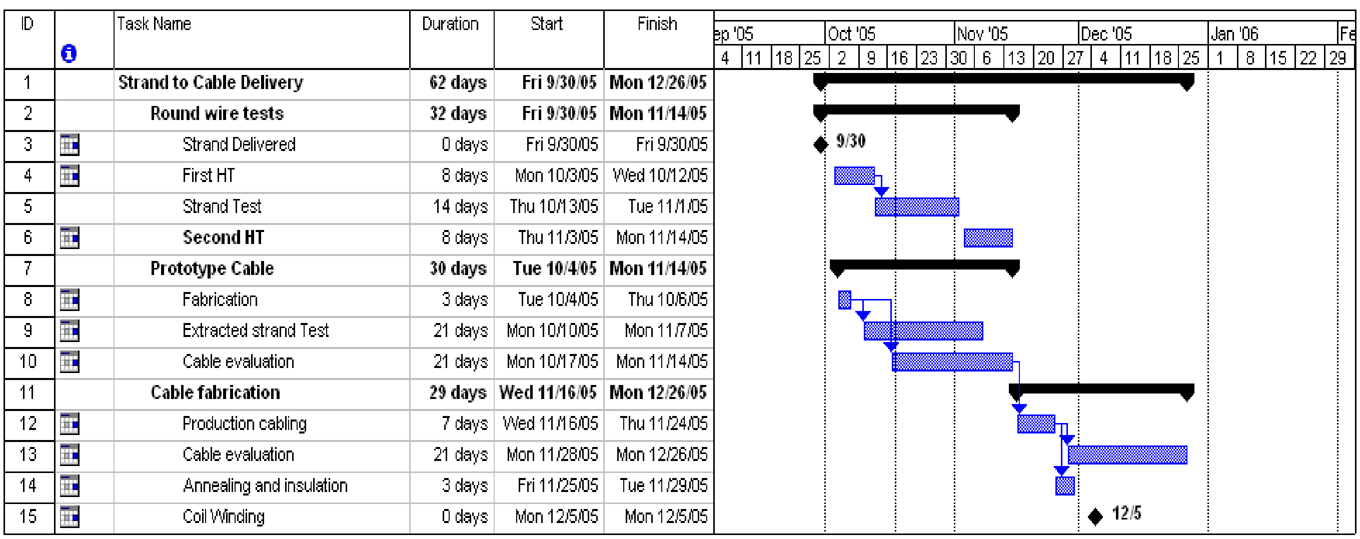

Figure 3.2 – 3 Schedule of Tasks from Strand Delivery to Finished Cable for Winding

3.3 Coil and Fabrication Issues

Since there are several plausible limitations to achieving higher luminosity, a number of upgrade options have been proposed. The actual configuration for an IR upgrade will not be known until after significant experience is gained with operating the LHC. However, large bore strong interaction region quadrupoles are required in all cases. The LARP Magnet R&D program focuses on an initial target of developing a 90 mm bore quadrupole with a gradient greater than the current design. A staged approach will be used, beginning with a simple two-layer coil design providing field gradients in the range of 210-260 T/m, then moving to more complex coil designs to increase the gradient and/or operating margin. The later part of the program may consider increasing the aperture, depending on early results of the program and ongoing studies. Figure 3.3-1 shows the potential parameter space that could be explored in terms of gradient and aperture.

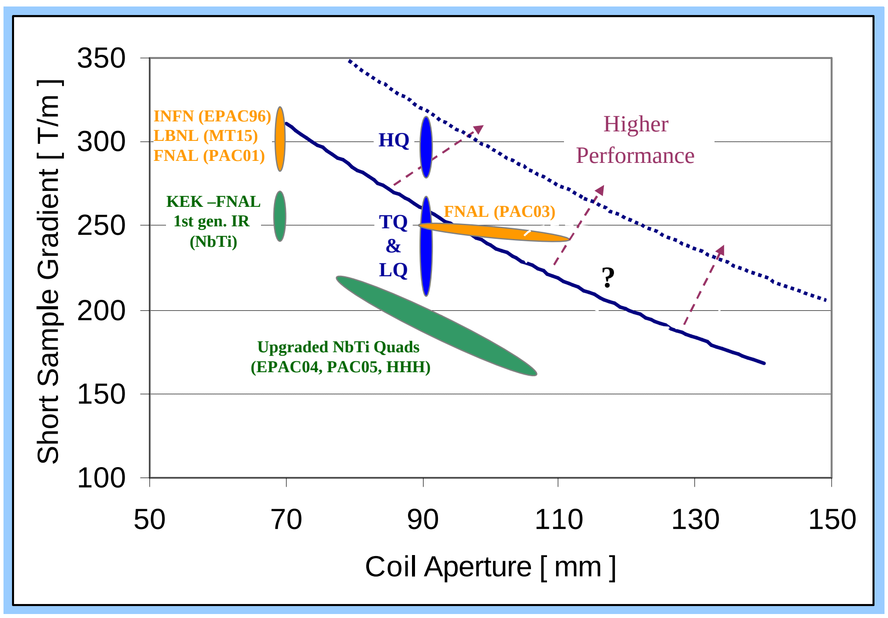

Figure 3.3 –1 Gradient versus aperture

The coil fabrication process is based on the Wind and React approach. Rutherford cable is insulated with either an S-2 glass sleeve or wrapped with ceramic fiber tape. The coil is wound and then treated with a ceramic binder, cured to size in a press to facilitate handling and inserted into a reaction fixture. After reaction the coil is impregnated with CTD-101®, an epoxy produced by Composite Technology Development. This general fabrication process has been used successfully for short models but has not yet been scaled up to coils longer than 1 meter. Length scale-up, in terms of reacting, impregnating and handling long coils, is considered to be a critical issue and is one of the three main goals of the first phase of the program.

Nb_3Sn is a brittle compound that requires careful control of stress throughout assembly, cool-down and excitation. The current accepted working limit is 200 MPa. The program is pursuing two parallel approaches; 1) conventional collars and yoke, and 2) an aluminum shell-based structure. Each of these has advantages and disadvantages that are described below.

3.4 Program Implementation

The program is implemented according to the flowchart shown in Figure 3.4 – 1 The three main near-term implementation phases are supported and developed through activities in Materials, Design Studies and Supporting R&D.

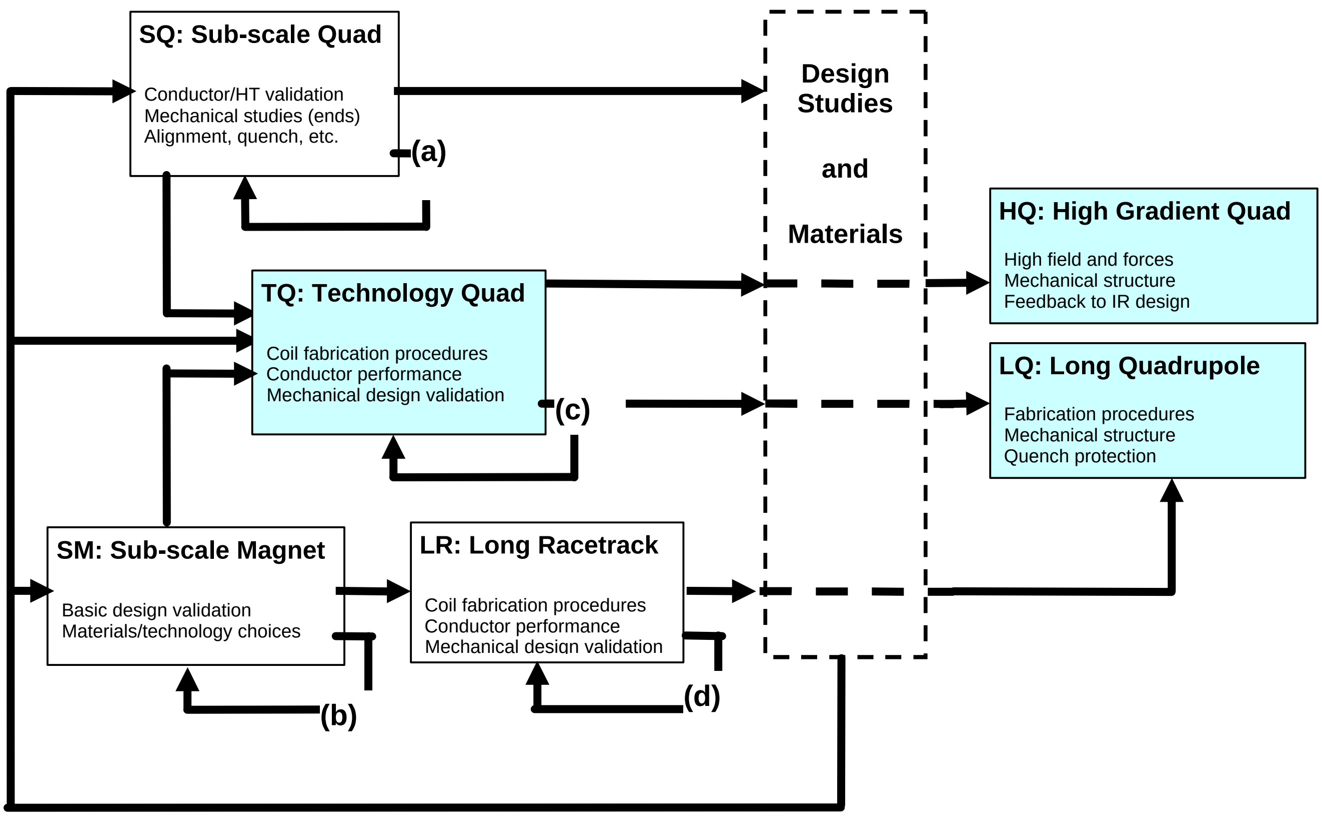

Figure 3.4 - 1. Magnet program flowchart

3.4.1 Goal 1: Predictable and reproducible performance (SQ & TQ)

The viability of any new technology application is judged on the consistent reproducibility of performance and operating parameters.

The “Sub-scale Quadrupole” (SQ) series is based on a simple racetrack coils in a quadrupole configuration, with field strengths and force distributions that are very similar to those found in the cos2θ design. The SQ series can thus be used to validate analysis models related to performance. They also provide a means of evaluating conductor and cable with operating requirements similar to the Technology Quadrupoles.

The “Technology Quadrupoles” (TQ) series is at the core of Phase 1. These quads are based on a two-layer, cos2θ geometry with a 90 mm bore. The first set of TQ's uses Modified Jelly Roll (MJR) conductor with a J_c of approximately 2,000 A/mm^2 at 12 T and 4.2 K. The expected maximum gradient is 215 T/m at 4.2 K (235 T/m at 1.9 K). The TQ’s are also used to compare two support structure designs. Magnet TQC01 (Fig. 3.4 – 2) is based on stainless steel collars supported by an iron yoke and thick stainless steel skin [19]. In contrast, TQS01 (Fig. 3.4-3) is a shell-based structure using bladders for precise, low-level pre-stress control and interference keys to retain the pre-stress, allowing bladder removal. A tensioned aluminum shell compresses internal iron and coil components, and develops substantial pre-stress on cool-down [20]. The TQ program is also an opportunity to explore end loading options that have implications for training and higher gradients and/or larger apertures.

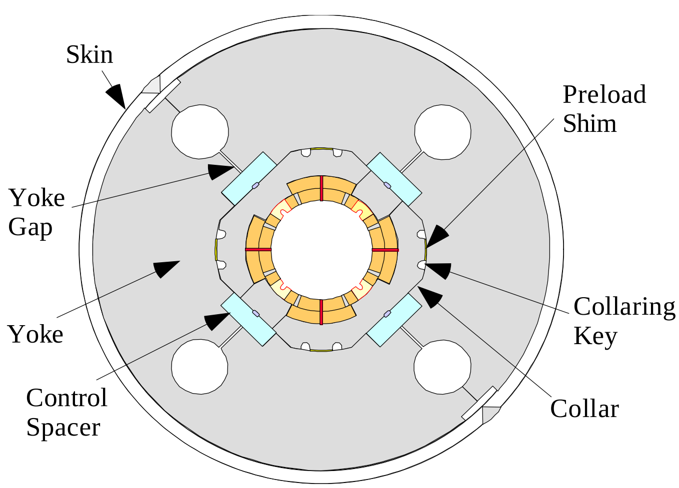

Figure 3.4 – 2. TQC (collar) mechanical structure.

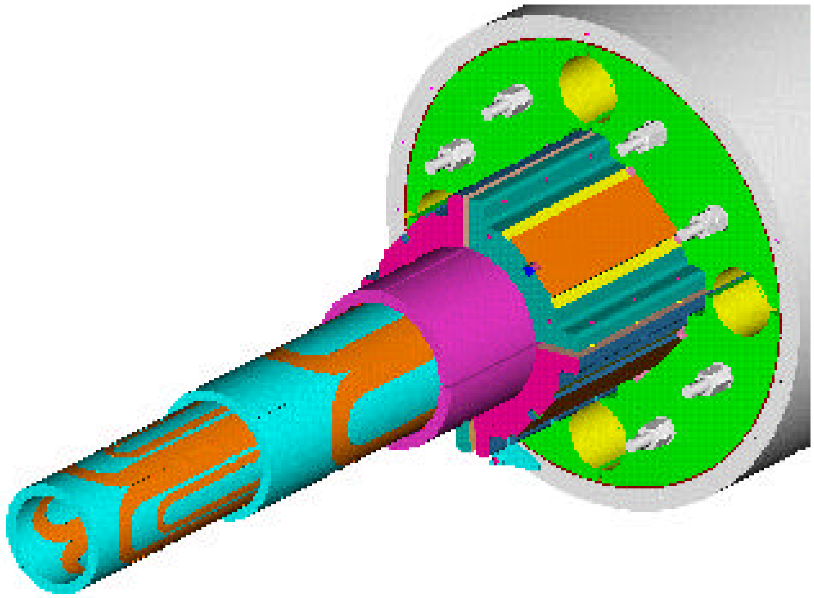

Figure 3.4 – 3. TQS (shell) mechanical structure.

The TQ series is the means by which the program demonstrates reproducibility. These magnets provide an integrated evaluation of all critical aspects of a Nb_3Sn quadrupole design, with operating parameters that significantly exceed those offered by NbTi-based technology. The TQ series also plays the critical role of exploring and evaluating mechanical support schemes and designs. A successful TQ program leads to scale-up of the cos-theta geometry via the Long Quadrupole (LQ) program.

3.4.2 Goal 2: Long magnet fabrication (LR and LQ series)

The development of fabrication, handling and assembly techniques that are required for the construction of long magnets will begin with scale-up of simple racetrack coils. The nominal length of the "Long Racetrack" (LR) coils is 3.6 m, the longest that will fit in available vertical test dewars at both BNL and Fermilab. The Long Racetrack coils are based on a well-developed 2-layer design, contained in a simple aluminum shell-type structure used extensively in the LBNL magnet program (Fig. 3.4 – 4) and similar to that used for TQS01 [21-23]. Successful completion of the LR series will be followed by construction of a 3.6 m cos-theta "Long Quadrupole" (LQ) series, based on the TQ cross section.

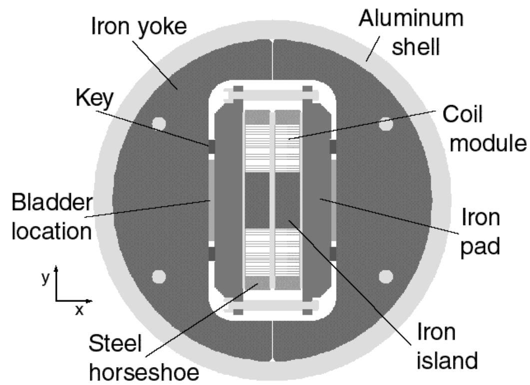

Figure 3.4-4 Subscale magnet cross section.

3.4.3 Goal 3: High gradient in a large aperture (HQ series)

In FY06 work begins on the conceptual design of a "High Gradient" (HQ) quadrupole series that will explore the ultimate performance limits in terms of peak fields, forces and stresses. The HQ design will be selected based on the comparative analysis of different options, as well as feedback from ongoing studies in the areas of materials, model magnet and supporting R&D. A 90 mm aperture over a 1 m length is sufficient to investigate the critical design and technology issues, while also being cost-efficient and offering good compatibility with existing tooling. It is expected that the HQ design will provide coil peak fields of about 15 T, corresponding to gradients of about 300 T/m in the 90 mm aperture.

3.4.4 Documentation

Documentation is an extremely important aspect of the LARP Magnet R&D program for facilitating communication and tracking progress. We are requiring weekly reports from each task manager. It will be the responsibility of the L2 managers to combine archival data from these reports and other sources into a document that includes requirements, physical parameters (e.g. cable dimensions, short sample measurements), fabrication procedures and test results and the latest schedules. These formal documents will be made available on the web for general collaboration access along with meeting notes, presentations and the usual task sheets.

3.4.5 Schedule and Milestones

An overview of the schedule is shown in Figure 3.4 - 5. An explanation of the program components, a few of the issues associated with them and their relationship with other tasks is shown in Table 3.4 - 1.

Table 3.4 - 1. Program components

	Application	Predecessors	Milestones
SR/SQ	Conductor evaluation Fabrication techniques Rad-hard materials Model validation Establish baseline performance	Ongoing as required for program support Design Studies Introduction of new conductors	SQ-02 10/05 SR-01 4/06
TQ	Goal #1 - Reproducible performance Fabrication techniques Mechanical structure LQ baseline	SQ – analysis validation Conductor evaluation	First test 5/06 Evaluation Review 8/06 Support Structure 7/07
LR	Long *coil* fabrication issues reaction handling impregnation Long shell and bladder validation	Based on well-understood design SR-01	SR-01 Evaluation rev 5/06 LR-01 complete 11/06 LR-02 complete 9/07
LQ	Goal #2 – Long magnet fabrication Integration of TQ and LR program Demonstration of long magnet technology with field and aperture	LR-01 TQ's Design Studies	Coil Design Review 11/06 Mech Design Review 7/07 1st completion target 9/08 2nd completion target 1/09
HQ	Goal #3 – High gradient/large aperture Push limit on field (~ 15T) Precursor to larger aperture	SQ/SR TQ's Design Studies Conductor & Cable R&D	Coil Design Review 11/06 Mech Design Review 7/07 1st completion target 10/08 2nd completion target 2/09

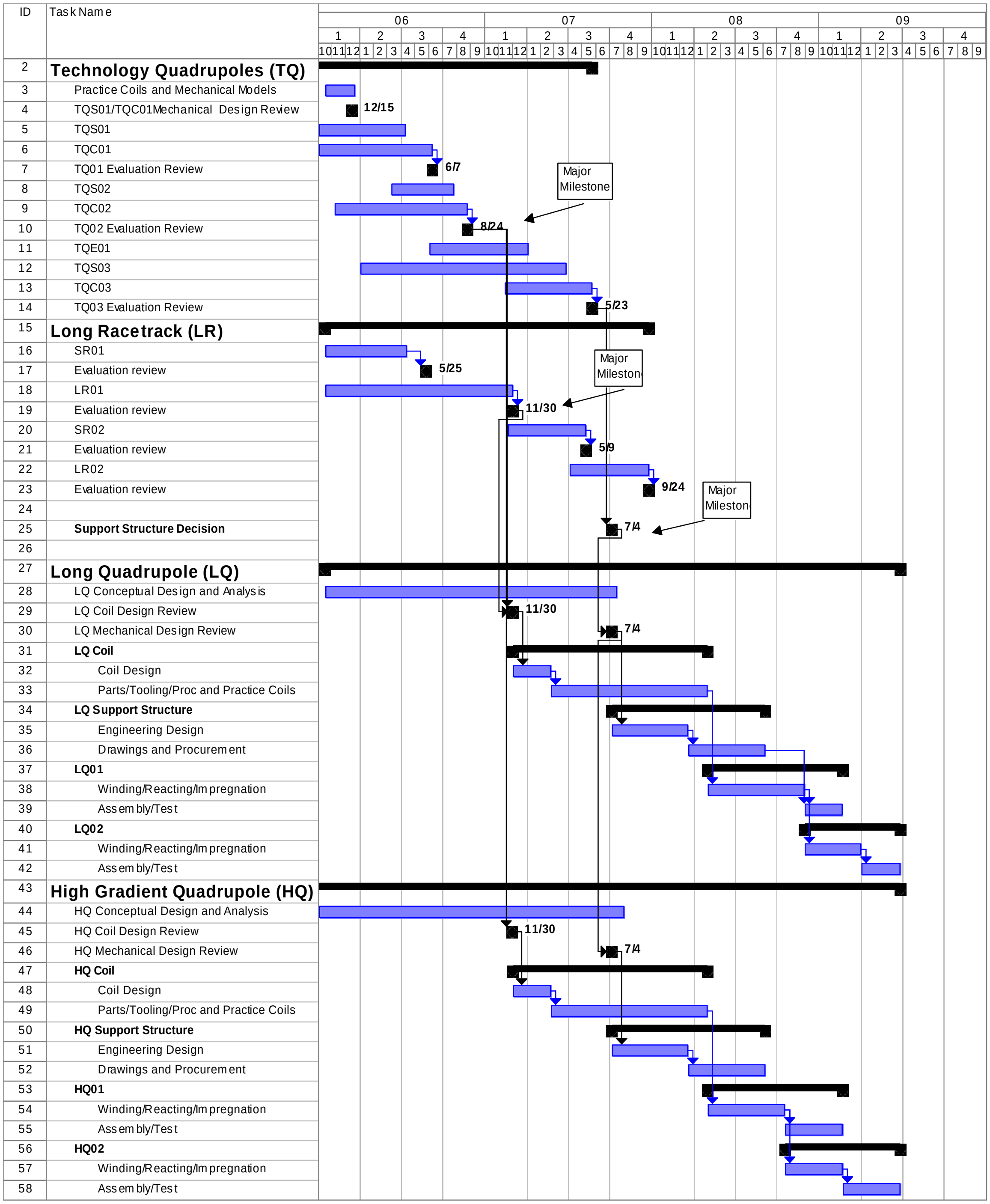

Fig. 3.4-5. Magnet program schedule overview.

3.5 Program Management and Organization

Magnet Program activities are integrated and organized around four general areas; Design Studies, Model Magnet R&D, Supporting R&D and Materials (Fig. 1.5-1). They form the basis of a Work Breakdown Structure. Activities in each of these areas is coordinated by a "Level 2" managers, whose main responsibility is to chair a Working Group associated with that topic, to provide a forum for discussion, and in so doing to provide a means to integrate tasks under Level two. Level three WBS elements are labels while Level four elements are work tasks. The responsibility for coordination and execution of a particular task resides with specific "Task Managers."

The *Design Studies* activity is generally intended to provide input on magnet parameters and lay the groundwork for the program. It covers a broad range of activities; conceptual magnet designs, radiation deposition studies, cryogenic and cooling issues and provides an interface for communication with the Accelerator Physics section of LARP.

Model Magnet R&D integrates input from the other three areas to produce model magnets that directly apply to the program goals. The current focus is on the TQ's and it will eventually house activities to build the LQ's and HQ's.

Supporting R&D covers a wide range of technical issues, primarily related to fabrication and operation. The largest task in this area is long magnet scale-up. Other tasks include sub-scale quadrupoles (SQ's) to study performance-related issues, verify analysis models, incorporate rad-hard materials and support structure development [24].

Materials: conductor is a critical component of the program. The responsibility of the Materials activity is two-fold; provide sufficient quantities of well-characterized strand for magnet development and carry on the necessary R&D to support development of material that will ultimately be used for the upgrade [25].

3.5.1 Advisory and Support Committees

The main activity of the Magnet Steering Committee (MSC) is to help the magnet program manager (Gourlay) to define and monitor the program, and to help him generate and recommend tasks and task manager assignments and evaluate petitions for changes to program tasks and goals. Lab representatives on the MSC serve as liaisons for their respective laboratories. The MSC also includes all Level Two Coordinators.

The magnet program manager is ultimately responsible for all aspects of the magnet program, consistent with the LARP Research Program Management Plan. Along with direction and guidance from the LARP program manager and advice from the MSC, there are a number of other sources of program input; DOE program reviews, US-LARP Executive Committee, US-CERN Executive Committee and the external LARP Advisory Committee. In addition, a number of *ad hoc* reviews are called by the magnet program manager to evaluate progress and provide advice at key decision points. The committees consist primarily of LARP collaborators with the addition of selected experts from the community.

3.5.2 Facilities and Infrastructure

The program is based on a well-coordinated joint U.S./European effort that is fully leveraged by the existing technology base, consisting of intellectual resources and facilities at the three participating laboratories. BNL's react and wind 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 all provide a complementary mix of technology that can be developed and applied to LARP. General magnet issues will continue to be investigated through the existing core programs. LARP will focus on issues specific to the needs and time-frame required for application to LHC upgrades.

3.5.3 Risk and Risk Management

The LARP Magnet Program is perhaps one of the most ambitious accelerator R&D programs ever attempted. On the other hand, the U.S. magnet program is better prepared for such a challenge now than at any time in the past. The near-term goal of the program is quite straightforward; "demonstrate by 2009 that Nb_3Sn magnets are a viable choice for an LHC IR upgrade." This goal is being approached by the three phase R&D program described above. The initial program plan relies on recent results of the US core magnet R&D programs and can accommodate a moderate number of difficulties that any R&D program might encounter with reasonable risk. Beyond this expectation, the schedule could be maintained through risk trade-off.

3.5.3.1 Technical

Materials

The magnet program is supported by an extensive materials evaluation program. The primary activities of the Materials Group are to provide sufficient quantities of "workhorse" conductor that is well-characterized and support as necessary, the R&D effort for continued strand and cable development.

Parametric studies

The sub-scale series of magnets provide an excellent means of risk mitigation by allowing an early start when program funding was extremely limited and maximizing the leverage provided by the core programs. Continued throughout the program, they effectively add to the number of magnets produced, contributing significantly to the experience base. As already described, these are opportunities to validate analysis models against magnet performance, narrowing the number of options to choose from.

3.5.3.2 Schedule

Schedule risk is minimized by focusing on the main program goals, and by distributing tasks according to technical competence, resources and facilities. In addition, the main goals of the program are targeted for completion well before the end of 2009, with additional magnets already scheduled. Schedule risk can also be mitigated by accepting additional technical risk. Inherent in our planning is the assumption of a robust budget and healthy core programs that can be called upon to furnish critical effort and resources when and if required.

3.6 Summary

The U.S. LHC Accelerator Research Program has launched an aggressive program to develop accelerator magnet technology for upgrades that will enhance the physics potential of the LHC. LARP is an excellent opportunity to extend high field accelerator magnet technology, and to create and strengthen national and international collaboration that will continue into future projects.

LARP will enhance the long-term physics potential for the large contingent of U.S. physicists working on ATLAS and CMS. It builds on the substantial experience of the existing magnet programs and is an excellent opportunity to extend the U.S. leadership in high-field magnets, develop a strong technological base for future projects and add vitality and diversity to the overall U.S. program. In addition to the technical aspects of the program, it will also serve to develop and strengthen collaborative ties between the U.S. programs and CERN, laying a strong foundation for future endeavors.

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