Strategic Plan for the LHC Accelerator Research Program

# Introduction

The United States has played and will continue to play a large in the Large Hadron Collider. In addition to the major role that US groups play on the LHC experiments, the US has also contributed significantly to the accelerator itself. This began with the construction of the final focusing triplets and feedboxes, and has continued through a number smaller construction and R&D projects over the years since. Much of the work has been managed by the US LHC Accelerator Research Program (LARP), but there have been some projects organized through bilateral agreements between CERN and individual US labs.

CERN is in the process of formal design study to finalize plans for a series of upgrades over the next decade, with the ultimate goals of a *leveled* luminosity of 5x1034 cm-2s-1 for at least several hours. The key components of this upgrade will be

* Large aperture, high gradient quadrupoles in the final focusing triplet. These will also have to be significantly more radiation hard than the present quadrupoles. The baseline plan is to use Nb3Sn, based on the R&D work done by LARP.
* Crab cavities to reduce the crossing angle of the bunches at collision. Crossing angle has only a minor effect on the luminosity now, but at smaller beta function the effect becomes much more important, and in fact the new quadrupoles would have little benefit without some sort of compensation. Crab cavities can also provide a straightforward method of luminosity leveling.

LARP has played a significant role in the development of both of these technologies, and the adoption of Nb3Sn as the baseline technology for the triplet upgrade is due largely to the demonstration magnets built by LARP. It would therefore be natural to assume that the US would play a role in the construction and implementation of these technologies into the LHC. However, the scope of these projects is well beyond what could be reasonably managed within the LARP infrastructure.

The purpose of this document is to summarize likely US contributions to the LHC, based both on the work of LARP and relationships between CERN and individual US labs. The cost scale of all possible contributions could exceed $200M, so it’s important to articulate a long-term plan, begin work to secure funding, and set priorities in the likely event that such funding will not be sufficient to pursue all opportunities.

The goals of the proposed projects are in harmony with those expressed in the Strategic Plan of the DOE Office of Science to “explore the fundamental interactions of energy, matter, time and space,” as well as with its mission to “keep the U.S. at the forefront of intellectual leadership” (DOE/SC-0079, February 2004). These goals have been endorsed through internal as well as external reviews of the U.S. GAD Program and LARP, and were supported by the EPP-2010 study conducted by the National Academy. For example, the first itemized finding of the EPP-2010 report states: “The study of LHC physics will be at the center of the U.S. particle physics program during the coming decade,” and the report’s major action item commends: “The highest priority for the U.S. national effort in elementary particle physics should be to continue to be an active partner in realizing the physics potential of the LHC experimental program.” This envisions full participation in LHC upgrades: “As potential upgrades to the detectors and the accelerator are motivated and defined through scientific results, the U.S. particle physics program should consider the provision of in kind contributions as appropriate.” The most recent P5 subpanel of HEPAP in its 2008 report “U.S. Particle Physics: Scientific Opportunities - A Strategic Plan for the Next Ten Years” states: “Significant U.S. participation in the full exploitation of the LHC has the highest priority in the US high-energy physics program. The panel recommends support for the US-LHC program, including U.S. involvement in the planned detector and accelerator upgrades.”

# Potential US Contributions to the LHC

There are many areas in which the US could contribute to the LHC. In this document, we are focusing on large projects, those which would cost on the order of at least $10M each. We have identified the following as the most interesting

## Nb3SN Quadrupoles for the Final Focus

The optics required to go to the design luminosity for the LHC upgrade go beyond what is possible with traditional NbTi magnets, and the baseline assumption is that the upgrade will use focusing quadrupoles with 140 mm aperture, based on Nb3Sn. The development and production of such magnets would follow naturally on the Nb3Sn work done within LARP, which has made the US a clear leader in this technology.

Significant investments in National Laboratory base programs and LARP have given the US a leadership position in Nb3Sn accelerator magnet technology. Following the successful tests of the LARP LR, TQ, LQ and HQ models, Nb3Sn technology is now regarded as the baseline for the new LHC IR. The development and construction of Nb3Sn quadrupoles for the LHC luminosity upgrade will contribute to further refining and expanding the unique US capabilities in this critical sector of accelerator technology.

We therefore consider it a high priority that the US would play a major role in the production of such magnets. The large cost of this production (discussed in the next section) make it clear that this would be the dominant US contribution in all scenarios.

At the moment, the LARP magnet program is scheduled to end with the production and testing of the “LHQ” – a 4m long quadrupole with a 120 mm aperture. CERN has agreed that this magnet will serve to “establish the technology” as viable for the production of the actual triplets. The test is scheduled to take place in 2014. By then of course, planning will already have to be well along for the production of the actual triplet magnets.

Because the aperture of the magnet has changed the production project would likely include a short demonstration magnet with a 140 mm aperture, followed by a prototype, which would include all necessary alignment and cooling features. It is currently envisioned that the production magnets will use a two layer could design with a continuously wound 18 mm wide cable. The baseline conductor is OST-RRP, although CERN is investigating PIT as an alternative.

The effective length of each magnet needs to be ~8 m, which will be assembled by combining two 4 m cold masses in a single cryostat. The construction of 8 m cold masses was discussed, but it was decided that the 4 m lengths posed less technical risk, as the infrastructure to produce these lengths already exists at US labs.

It is currently planned that the US will provide 16 cold masses and 4 spares (??), while the cryostats will be designed and built at CERN.

## Crab Cavities

Because the bunch spacing in the beams is shorter than the distance to the separation dipoles, the beams must cross at an angle to avoid parasitic collisions. This causes a reduction in luminosity, which grows as \* decreases. It is a small effect at the current value of \*, but would largely cancel out any benefit of decreasing the \* if not corrected or compensated in some way.

The baseline plan is to use “crab cavities” to transversely deflect the head and tail of each bunch, such that they collide head on in spite of the fact that the beams are crossing. It is currently planned to use a local crabbing scheme, in which each bunch in each beam is crabbed before each of the two high luminosity interaction regions, and returned to a nominal orientation by a complementary cavity afterwards. Thus, a total of eight crabbing stations would be required, each likely consisting of two cavities to provide the required transverse kick.

Crab cavities also provide a very natural way to level the luminosity, but starting out un-crabbed, or even *anti*-crabbed, and then introducing crabbing angle as the beam current is reduced.

Because of the length of the LHC bunches, the cavities will need to run at 400 MHz to avoid filamenting at the head and tail of the bunch. This presents a significant technical challenge, in that the beams are only 19.2 cm apart, and separation doglegs near the interaction regions are not feasible. This means that traditional elliptical cavities are far too large and these cavities will have to be of a novel “compact” design. As a result of an intense R&D program initiated within the LARP and EuCARD networks over the last 4-5 years, novel high performance compact deflecting cavities at 400 MHz have been proposed and are under development. These new topologies make it possible to integrate the cryomodules in the present LHC interaction region and also allow for the horizontal/vertical alternating crossing scheme which is a prerequisite.

There are currently three designs being considered: two being developed by LARP and one being developed in the UK at Lancaster University.

There is still some concern over the safe operation of crab cavities in the LHC; that is, whether there are failure modes which could result in damage to the machine. Establishing a safe mode of operation is the key milestone to the project’s moving forward.

Once the technological downselection is made, the plan is to place two prototype cavities in a cryomodule, and test them in early 2015 in the SM18 test facility at CERN. The test module would then be placed in the SPS, to be tested during the planned beam test period in 2016, just before LS2.

The final production would consist of the 8 required cryomodules (2 beams x 2 sides x 2 experimental regions) plus 2 spares. These would have to be ready for installation during LS3.

The scope of US contribution to the overall crab effort is a matter for discussion and depends largely on funding. The US could contribute to the design and R&D, or to the fabrication of just the cavities, or perhaps to complete cryomodules.

With these proposed contributions, LARP would continue to play a key role in the LHC and its luminosity upgrade, at the same time maintaining and promoting development of US expertise in the field of novel superconducting RF cavity and cryomodule design.

## 11 Tesla Dipoles

The LHC operational experience at 3.5 TeV proton beam energy and approximately 30% of the design luminosity indicates that the losses in the experimental regions from interaction debris can be an issue for both proton and for ion beams. The losses in the dispersion suppressors of interaction regions IR1 (ATLAS), IR2 (ALICE) and IR5 (CMS) have already affected the LHC operational efficiency including radiation effects on electronics, delayed access to the machine during beam operation due to radiation constraints, potential impact on magnet lifetime, etc. To improve the collimation efficiency by a factor of 15-90, additional collimators are foreseen in the DS regions around several LHC straight sections.

The mission of this project is participation in and contribution to upgrades of the LHC beam collimation system planned at CERN for 2017-2021. The goal of the LHC collimation system upgrades is to provide reliable and efficient machine operation with proton and ion beams at the nominal and later at the ultimate beam intensity and luminosity. These upgrades involve installation of additional collimators in LHC lattice in the dispersion suppression (DS) areas around interaction regions (IR) in points 1, 2, and 5 and in the momentum and betatron cleaning insertions near points 3 and 7. The required space for the collimators will be provided by replacing some regular LHC dipoles (MB) with shorter but stronger dipoles with the same bending strength.

To provide a 3.5 m longitudinal space needed for the additional cryo-collimators, a solution based on 11 T Nb3Sn dipoles as a replacement for several 8.33 T Nb-Ti LHC MBs is being considered. These twin-aperture dipoles will operate at 1.9 K and be powered in series with the main dipoles. They will deliver the same integrated strength of 119 T∙m at the LHC nominal current of 11.85 kA. Recent progress in the development of Nb3Sn accelerator magnets in U.S. indicates that this technology can meet the requirements. Providing the same space for warm collimators in the cold LHC ring without using 11 T dipoles would involve design and fabrication of several complicate cryo-components as well as removing, bringing to the surface and re-installing 32 cold objects including 24 main magnets, 2 connection cryostats (new types), 2 shuffling modules, 2 DFBAs, 2 warm-cold transitions (new design). The longitudinal and radial displacement of several quadrupole and dipole magnets will certainly provide a negative impact on beam dynamics jeopardizing the LHC performance.

Technical risks for the LHC associated with implementation of 11 T Nb3Sn magnets are limited since thanks to the positive results achieved at FNAL during the past decade in the framework of core High Field Magnet R&D program and participation in US-LARP. The back-up plan to the construction and installation of Nb3Sn dipoles in LHC is the painful, but viable, relocation of existing magnets and cryoboxes in the LHC lattice.

To demonstrate the feasibility of this approach, CERN and FNAL have started in 2010 a joint R&D program with the goal of building by the end of 2014 a 5.5-m long twin-aperture Nb3Sn dipole prototype suitable for the DS region upgrade. This joint R&D effort will provide also conditions for the transfer of Nb3Sn magnet technology to CERN.

The first phase of this program is the design and construction of a single-aperture 2-m long demonstrator dipole magnet, delivering 11 T at 1.9 K in a 60 mm bore with 20% margin. The main goal of this model is to demonstrate the quench performance, nominal field, and operation margin of the Nb3Sn coils in a single aperture structure. In addition, the data on magnet field quality and quench protection will be acquired for the further optimization and selection of conductor, magnet design and fabrication technologies. The first single-aperture 2-m long demonstrator dipole has been designed and manufactured and now is being tested at FNAL.

The second phase of the program includes the fabrication and test of two 2 m long, twin-aperture demonstrator dipoles in 2013 to confirm the final magnet design, demonstrate the magnet performance parameters and their reproducibility as well as transfer Nb3Sn technology to CERN/Europe. And finally, the third phase will focus on the design scale up and prototype development and test in 2014.

Following the successful long dipole prototype and the completion of the LHC consolidation in 2014, CERN would be in the position to make a decision on the feasibility of the overall scheme to replace Nb-Ti magnets with 11 T Nb3Sn magnets for the insertion of additional collimators around the LHC ring in IR1, IR2 & IR5 and later, in IR2 and IR7. If this approach will be accepted, CERN and FNAL would share the responsibility for design, construction and collaring of the coils, while CERN would assemble the collared coils with iron yokes, install the cold masses in cryostats, and test the magnets. The construction phase would be managed by CERN with active participation by FNAL as deemed appropriate and approved by funding agencies.

Both FNAL and CERN have appropriate infrastructure including laboratories for SC strand and cable testing; cabling machines to produce multi-strand Rutherford-type cables; magnet production facilities with short and long tooling for coil fabrication and equipment for magnet assembly; magnet test facilities to test magnet models and prototypes in superfluid and normal helium. Both laboratories have skillful personnel including magnet scientists, engineers and technicians capable of designing, fabricating and testing SC accelerator magnets as well as supporting infrastructures to provide magnet and tooling design, components procurement and quality control. To perform the described R&D and later to accomplish the collared coil fabrication according to CERN schedule for LS2 and LS3, FNAL infrastructure will need some upgrades as well as the FNAL magnet group staff has to be adjusted accordingly.

## D2 Separator Magnets

As part of the High Luminosity Upgrade of the LHC (LHC-HL), CERN plans to increase the aperture of the D2 IR dipoles located near ATLAS and CMS. Present CERN plans call for a twin-aperture dipole with an integral field of 40 T·m, an effective length of 9.45 m (the same length as that of the 80 mm-aperture dipoles previously supplied by BNL), a central field of 4.23 T, and an aperture separation of 186 mm. The operating temperature is 1.9 K. The RHIC D0 dipole, which has an aperture of 100 mm, has been used as the D2 starting point for optics studies for the HL upgrade, and it is assumed that if these magnets are built in the US, they would be built entirely at BNL. Optics studies reported at LARP-LHC CM18 point to a coil aperture of 105 mm as being optimal. However, there are engineering and cost/schedule issues related to a 5 mm increase in aperture that need careful evaluation.

Production at BNL would take advantage of the 10 m coil production tooling (winding machine, cure press, ancillary tooling) that is being restored for use of the APUL project. The 10 m cold mass assembly tooling (collar, yoke, helium vessel, cryostat insertion) has been retained following its use in the US-LHC Project (although collaring tooling would need to be modified for the larger collars). The cryo test facility is also being modified for the APUL project, to accept 10 m magnets. The floor space in the production area now used by the NSLS II light source project will be vacated early in 2013, so there will be sufficient floor space for both D2 dipole and Nb3Sn quadrupole production. The coils for the two types of magnets will most likely be wound and cured on separate fixtures.

The existing RHIC D0 coil tooling is available for use in building a 3.6 m model magnet with 100 mm coils. This tooling would need to be designed and purchased if the coil aperture is 105 mm.

If the coil i.d. is 100 mm, no design work for the coil or its components has to be done, except to extend the length from 3.6 m (RHIC D0) to 9.45 m where appropriate. A complete new design would be needed for 105 mm coils. A new collar design is needed for either coil, since the RHIC D0 used the yoke as collar. If the yoke perimeter does not change from that used for the US-LHC twin-aperture magnets, no design work will be needed for the heat shield, cryostat, etc. The wall thickness of the coil’s cold bore tube needs study. An initial check of vendors found none who would make 10 m lengths of seamless tube in non-standard sizes.

Magnet components that require Long Lead Procurement include NbTi cable, yoke, shell, cold bore tube, collars, and cryostat. (Yoke material should probably be purchased at the same time as the yoke material for the quads.) LLP tooling includes the mandrel and coil form block.

The final production would be 4 cryostated magnets (2 sides x 2 experiments) plus 2 spares. These would be completed in time for LS3.

## High Bandwidth Feedback System

One significant area of R&D within LARP has been low level RF (LLRF). LARP provided to tools to characterize and optimize the RF in the LHC. This work has continued as an investigation of the possibility of a high bandwidth feedback system for the SPS. This would nominally be to compensate for electron cloud instabilities, but could be useful for other instabilities as well.

The instability feedback program addresses intra-bunch instabilities in the injector chain, and potentially LHC, that arise from high currents and interaction with electron clouds and impedances. The task combines accelerator physics, simulation models of particle motion, control of dynamic systems, and high speed digital signal processing. The task requires an active machine measurement and development program as part of the research. The project continues to provide excellent material for Ph.D. students in accelerator physics and engineering throughout the task plan, including MD measurements and dynamics simulations as well as technical development of system functions.

The project builds and continues the LARP effort for SPS instability control. This HL and upgrade path will use the proof-of-principle testbed and SPS machine measurements to specify a system architecture and system design for scalable and reconfigurable Instability signal processing. The high bandwidth Feedback project will develop a full-function prototype intended for an operational control system in SPS and LHC .

The major system elements include:

Wideband beam motion pickups ( vacuum structures)

Wideband beam kickers ( vacuum structures)

Beam motion receiver and processing electronics

4 – 8 GS/sec. digital signal processing for intra-bunch instability control

High-power GHz bandwidth RF amplifiers for beam excitation

Signal processing firmware and data flow hardware

System Timing and synchronization system to interface with SPS or LHC RF and accelerator systems

Operator interfaces, control and monitoring software

Beam diagnostic software and beam instrumentation systems necessary to configure and adjust the instability control system

The work must continue the machine measurement and technology development program building on the proof of principle system to be tested at the SPS in 2012 and continuing with wideband kicker installation in the 2013 shutdown. The dynamics measurements and achieved performance of the demonstrator will guide the functions and architecture of the full-function prototype

This is an area of particular US expertise and potentially a high impact contribution to the LHC upgrades. There is a significant range in the possible scope of US contribution. It could consist simply of modeling and design specifications, in which case it could probably be supported entirely within LARP. Work could extend to the low level control hardware for the feedback system, or it could include the pickups and kickers needed by the system, in which case the cost would be fairly large and would have to be supported by an independent project.

## Collimation

Over the years, LARP has supported a number of R&D projects related to collimation. The most significant effort in terms of time and resources had been the rotatable collimator project. The collimators contained two multi-faceted jaws in which successive faces could be rotated into place in the event the previous face had been damaged by beam loss. These were originally conceived as a possible technology for secondary collimators around the ring, but now are being considered as protection devices for the experiments. At the moment, no concrete plan for production or installation is in place.

Another area of LARP R&D involved the use of bend crystals which could be used as primary collimators to direct beam halo more cleanly into secondary collimators than an ordinary scattering collimator could. Beam tests of this technology at both Fermilab and CERN have shown promising results.

More recently, hollow electron beams have been investigated as a potential tool to remove beam halo. This work grew out of the studies of electron beams as a method of compensation for beam-beam effects. Collimation by hollow beams was demonstrated at the Tevatron, and plans are underway to possibly transfer the system to CERN for tests in the SPS and/or LHC.

Although crystal collimation and hollow electron beam collimation show promise, they are not yet part of the base line plan. Nevertheless, we must prepare for the possibility that they will be part of our long term planning.

## Cost Estimates

In this section we will

From the LARP Review:

*“…develop a strategic plan for LARP R&D that supports the LHC schedule, and meets out year budgets, and work with DOE and CERN to establish a formalism for the dialog and protocol which will provide the needed specifications in time to meet agreed upon milestones.”*

*“Provide a detailed plan, including budget profile, to DOE on transitioning from LARP R&D into HL-LHC by February 1, 2012. A similar recommendation was stated last year.”*

**Outline**

1. Introduction
   * *Background, LHC HiLumi plans, nearer-term upgrades (collimation system and dispersion suppressor modifications), LHC schedule and working shutdown schedule-E.Prebys*
2. Potential U.S. Contributions to LHC Upgrade Scope
   * *Technical descriptions of the elements*
     1. *Interaction Region Quadrupole Magnets-G.L. Sabbi*
     2. *Crab Cavities-R. Calaga*
     3. *11T Dipole magnets-A. Zlobin*
     4. *D2 Dipole magnets-P. Wanderer*
     5. *Feedback System- J. Fox*
     6. *Other-T. Markiewicz*
3. Cost Estimates for LHC Upgrade elements in the development, prototyping and construction phases
   * *We should rack up cost ranges for the R&D, prototyping and construction of full assemblies as well as partial assemblies, and include independent funding profiles, for* 
     1. *Interaction Region Quadrupole Magnets*
     2. *Crab Cavities*
     3. *11T Dipole magnets*
     4. *D2 Dipole magnets*
     5. *Feedback System*
     6. *Other*
4. Potential U.S. contributions in various funding scenarios
   * *Need a table or tables of various options (a la Giorgio’s table) for $100M, $150M, $200M and “Complete Package”*
5. Schedule and Milestones for Decision-Making

* *Needs to include schedule, milestones and decision points for each of the potential contributions, presented as independent timelines. Should clearly establish the required timeline needed for in-time delivery to CERN. Should spell out things like:* 
  + *Establishing specifications for quadrupoles*
  + *Establishing R&D plan for quadrupole magnets*
  + *Technology Selection for quadrupoles*
  + *Establishing specifications for crab cavities*
  + *Establishing an R&D plan for crab cavities*
  + *Etc., etc.*

1. Formalism and Protocol for US/DOE/CERN decision-making
   * *We should suggest an approach. I offer some ideas:*
     1. *Recommend that DOE and CERN establish some sort of joint coordination body for LHC upgrades empowered by each to establish the mechanism and process for decision-making (but obviously not the funding agreements) for the US Contribution to the LHC Upgrades.*
     2. *Empower some existing body to serve that function right now. The key is DOE/CERN actually empowering people to do this.*
     3. *We could propose a process in which “we” (Eric, Lucio, Giorgio, Stuart, ….) in the form of LARP/HiLumi jointly take responsibility in a formal way for doing this.*
2. Summary