U.S.-LHC Accelerator Upgrade Construction Proposal, LAUC

S. Peggs (editor), M. Anerella, J. Kerby, M. Lamm,
T. Markiewicz, E. Prebys, A. Ratti, P. Wanderer

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Executive Summary

CERN projects – goals, scopes and schedules

The CERN goal for the "LHC Interaction Region Upgrade – Phase 1" project (SLHC-IRP1) is to:

> Enable focusing of the beams to $\beta^*=0.25$ m in IP1 and IP5, with reliable operation of the LHC at a luminosity of 2 10^{34} $cm^{-2}s^{-1}$, [for] the physics run in 2013.

(http://slhc-irp1.web.cern.ch). The scope of the project is to:

1. Upgrade ATLAS and CMS interaction regions, maintaining the interfaces between the accelerator and the experiments at ± 19 m.
2. Replace the present inner triplet quadrupoles with wider aperture quadrupoles based on the LHC dipole cables (Nb-Ti) cooled to 1.9 K.
3. Upgrade the D1 beam separation dipoles, TAS beam absorbers and other equipment to be compatible with the larger inner triplet aperture.
4. Modify other insertion magnets (e.g. D2-Q4) and introduce other equipment in the Interaction Region to the extent of available resources.
5. Maintain unchanged the cooling capacity of the cryogenic system and other main infrastructure elements.

Major milestones for SLHC-IRP1 are (L. Evans, EDMS 905931):

June	**2008**	Conceptual Design Report
Summer	**2009**	Technical Design Report
December	**2009**	Model NbTi quadrupole
	2010	Pre-series quadrupole
	2012	String test
shutdown	**2013**	Installation

The intensity reach of the LHC is being maximized by continuing work on the LHC collimation system. Possible collimation-induced intensity limitations are being addressed in the "Phase II LHC Collimation" project at CERN. This work aims at identifying challenges and developing upgrades to the existing LHC collimation system on a similar time scale to SLHC-IRP1.

CERN is also beginning to upgrade its injection chain. Construction of the 160 MeV normal conducting H- linear accelerator Linac4 started in January 2008, is to be completed in 2012. Linac4 will double the brightness and intensity of the output beam, removing the first injector chain bottleneck, moving towards higher luminosity in the LHC, and opening the way to future injection chain upgrades, including the 4 GeV Superconducting Proton Linac (SPL) and the new 50 GeV PS2 synchrotron.

Taken together, these projects will provide the 2013 physics run with a luminosity reach 2 or 3 times greater than the nominal 10^{34} $cm^{-2}s^{-1}$.

LAUC integration with CERN and relationship with LARP

The primary component of the previous U.S. LHC Accelerator Project was delivery of the current Inner Triplets, in a region where the technical challenges were among the greatest. This region is therefore a logical location for continued participation, building on our current knowledge of the region and of its technical challenges, and building on the high standard for international collaboration that was set during the Accelerator Project. The insertions are also the most likely and cost effective location for U.S. participation machine upgrades beyond Phase 1. Continued U.S. participation in the Insertion Region upgrades provides the participating accelerator labs not only with unique technical challenges to hone system and component design and production capabilities, but also provides them with a means to increase the luminosity delivered to experimenters in an important and visible manner. Furthermore, the insertion regions are very likely to be upgraded again in the late 201x time frame, and a continued U.S. presence will enhance the probability of effective participation in further upgrades using new magnet technologies.

While the primary contribution of the U.S.-LHC Accelerator Upgrade Construction project (LAUC) is to SLHC-IRP1, it also makes secondary contributions to the other luminosity improvement project, Linac4, exploiting unique resources and "competitive advantages" that exist in U.S. laboratories.

All LAUC contributions will be completed and installed in time for the 2013 run. They will be fully integrated with CERN schedules and plans. In particular, CERN plans to release a fully integrated Technical Design Report (TDR) for SLHC-IRP1 in summer of 2009. *A crucial assumption of this proposal is that LAUC will be ready to achieve Critical Decision 2 (CD-2) in close synchrony with the release and review of the TDR, before the end of FY09.* Only then will it be possible for solid LAUC project costs, schedules and scopes to be confidently defined and agreed by all parties.

Preliminary cost estimates for LAUC are shown in Table 1. The total cost will not exceed $30M, with initial project funding in FY10 and final funding at the beginning of FY13 during installation and hardware commissioning. The maximum funding rate will not exceed about $10M in any fiscal year. Table 1 also shows expenditures in FY09, before project funds first become available. This early expenditure, necessary in order to achieve CD-2 in summer of 2009, is crucial. It must come from within the U.S. LHC Accelerator Research Program (LARP).

All six of the topics proposed, below, will have completed all crucial R&D when construction funding is assumed to begin, at the start of FY10. Because of this requirement, the proposal excludes exciting long term R&D topics – such as crab cavities, electron lenses, and Nb_3Sn quadrupoles – that show great potential for later LHC upgrades. The R&D necessary to advance such topics to a state of readiness that is robust enough for inclusion in a follow-on construction project will be performed elsewhere. Typically (but not necessarily) that R&D will be performed within LARP. However, LARP itself will perform little or no construction.

	FY09	FY10	FY11	FY12	FY13	Totals
	[$M]	[$M]	[$M]	[$M]	[$M]	[$M]
Beam Separation Dipoles	0.6	3.3	5.4	5.4	0.0	14.7
Cryogenic Feedboxes	0.6	2.9	2.9	2.9	0.0	9.3
Magnet Systems Engineering	0.6	0.5	0.3	0.3	0.0	1.7
Collimators		0.4	0.8	0.8	0.0	2.0
Laser Profile Monitors	0.1	0.3	0.5	0.4	0.0	1.3
Linac4 Low Level RF	0.2	0.2	0.4	0.4	0.0	1.2
Anual Totals						
LARP (“LAUC Planning”)	2.1					2.1
LAUC		7.6	10.3	10.2	0.0	28.1

Table 1: Coarse and preliminary LAUC budget estimate, including planning supported separately by LARP in FY09.

While LARP and LAUC would be funded separately, nonetheless their strategic planning needs to be linked, not only because of the need for “LAUC Planning” funding from LARP in FY09, but also because LARP is performing R&D on topics for potential inclusion in follow-on construction projects after 2013. Figures 1 and 2 show how LARP and LAUC activities will be co-organized in 2009, and beyond.

In FY09 LARP will have a fourth box called “LAUC Planning”, in parallel to Accelerator Systems, Magnet Systems and Program Management. The goal of this box is to achieve CD-2 in summer of 2009, synchronized with the release and review of the CERN TDR.

In FY10 and beyond LAUC will be organized on a par with LARP. Although LAUC will have an independent sub-structure, it will report to the same management superstructure as LARP (Laboratory Oversight Group, FNAL Directorate, Office of HEP, Joint Oversight Group) and may use some of the same advisory groups (CERN-U.S. Committee, LARP Advisory Committee).

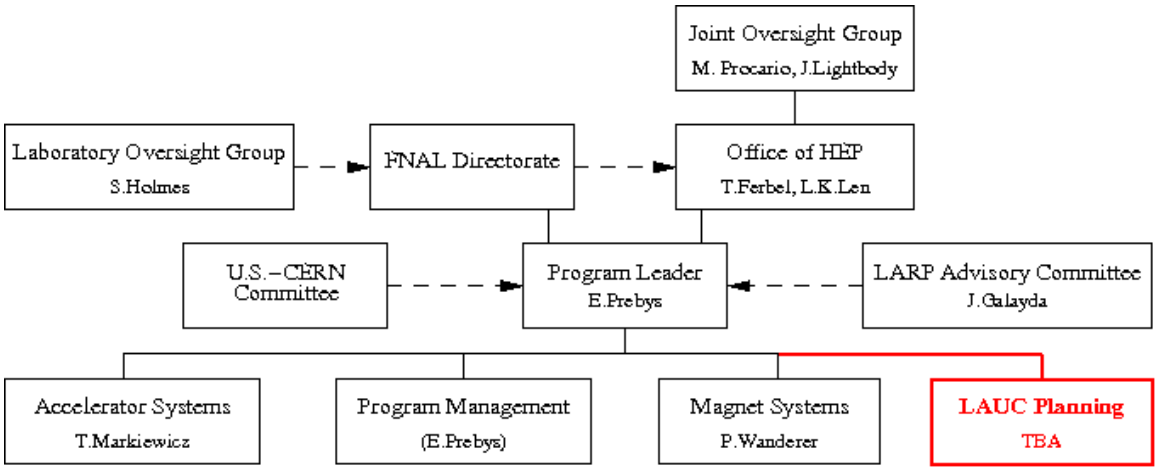

Figure 1. The organization of LARP and LAUC in FY09, before project funding begins. The goal of the "LAUC Planning" box is to achieve CD-2 in summer of 2009, synchronized with the release and review of the CERN TDR.

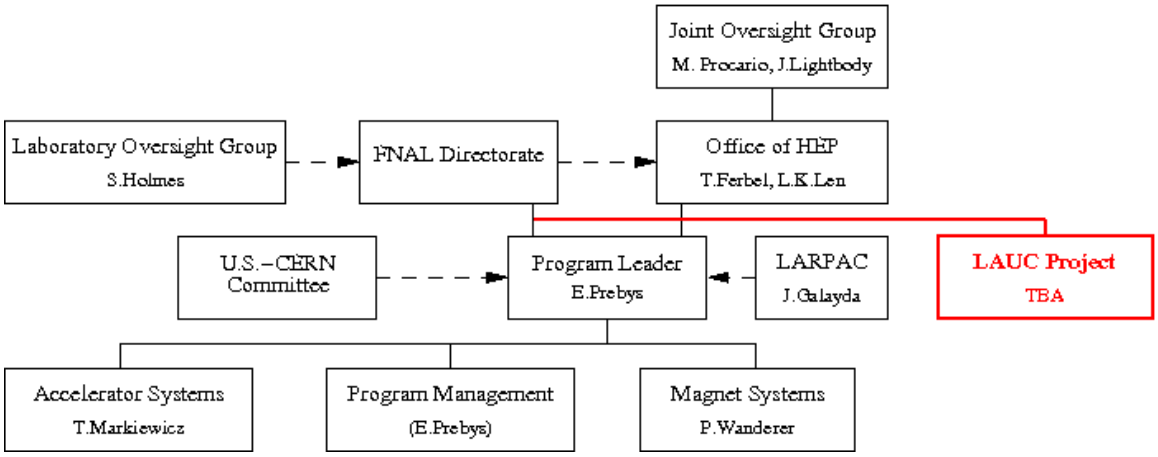

Figure 2. The relationship between LARP and LAUC in FY10 and beyond, after project funding has begun. LAUC will have an independent sub-structure, but will report to the same management superstructure as LARP, and may use some of the same advisory groups.

A brief summary of proposed contributions

Beam Separation Dipoles

The CERN LHC IR Upgrade Working Group (LIUWG) notes that superconducting Beam Separation Dipoles would have technical advantages over resistive magnets in replacing inner triplet D1 dipoles, and would be the most cost effective. Copies of the 180 mm aperture DX dipoles that have operated trouble free for almost ten years in all RHIC IR regions are suitable for this. LAUC would build ten cold masses, and assemble them at BNL into four cryostats plus one spare.

Cryogenic Power Distribution Feedboxes

LAUC would build the four cryogenic power distribution feedboxes required for the upgrade, and also the corresponding DC current links, using recent advances in materials to minimize costs and to maximize cooling efficiency. Feedboxes for the IR upgrade must be substantially redesigned in order to accommodate superconducting D1 dipoles, the new IR quadrupoles and local correctors. Current links made with HTS or MgB_2 conductors will bridge the HTS power lead box to the magnet cryostats. The U.S. is in a uniquely strong position to contribute, because the Accelerator Project designed and built the existing feedboxes, and specified and tested the existing HTS leads, and also because LARP supported a leading U.S. role in the hardware commissioning of both the CERN and U.S. supplied feedboxes.

Magnet System Engineering

Unique human resources are available at U.S. labs to participate in System Engineering for the beam separation dipoles and for the low-beta triplets, just as they were deployed for the initial inner triplet implementation. The U.S. labs can immediately contribute to complete system design efforts on topics such as cryogenics, power distribution, energy deposition, accelerator physics, and quench protection. Because the effect of the inner triplets on the luminosity is strong and complex, it is necessary to understand the integrated system, including items such as alignment, instrumentation, and controls. This involvement will exploit U.S. capabilities at the same time as developing them at the cutting edge. A complete understanding of system issues will allow the U.S. to better prepare for future upgrades in follow-on construction projects.

Collimators

One issue that is expected to challenge the LHC collimator system is the need to reduce the beam impedance. Other potential issues include cleaning efficiency, dispersion suppressor beam losses, collimator set-up time, and the desire for enhanced primary collimator deflection angles. The “Rotatable Collimator” (RC) design developed in LARP could play an important role in impedance reduction, improvement in cleaning efficiency, and enhanced radiation hardness. This assumes that an RC prototype is validated in 2009/2010 beam tests at CERN. This proposal discusses the provision of 5 RCs – 4 plus one spare – in a strawman proposal that may need alteration before CD-2, depending (for example) on the real experience with beam that will be gained in the meantime. In all scenarios – however many RCs – the LAUC effort would work in

a tight collaboration with the CERN groups.

Laser Profile Monitors

Laser Profile Monitors (LPMs) are new devices that make it possible for the first time to observe H^- beams non-destructively, with no danger to the vacuum system in accident scenarios. They are fast in action – full profiles in Linac4 will be measured within a single linac pulse. We propose to deliver three complete stations, capable of measuring both horizontal and vertical profiles and emittances, for installation in the transfer line downstream of Linac4. This would build on the recent innovative success of such state-of-the-art devices, as recently installed in the SNS, and also as tested at BNL for potential use at FNAL.

Linac4 Low Level RF

LLRF control hardware and its embedded programming play a pivotal role in the performance of accelerators like Linac4 that require a tight control of amplitude and phase. Modern designs implement most of the signal processing in the digital domain. The RF group at Berkeley successfully led the technical development and implementation of the LLRF system for the SNS linac, which is very similar to Linac4 from an LLRF perspective. We propose to define the control algorithms for Linac4, based on the SNS experience, in Field Programmable Gate Array technology. This includes the feedback loop around the cavity, the adaptive feed forward, and the tuning algorithms.

1 Beam Separation Dipoles

The performance of the LHC can be improved by replacing the resistive dipoles in the IR regions near ATLAS and CMS with larger aperture dipoles. In all current versions of the optics under study by the CERN LIUWG, the D1 dipole in the new triplet is required to provide an integrated field of 27 T-m with a bore at least as large as that throu
gh the new inner triplet quadrupoles. While the LIUWG acknowledges that with the available space in the tunnel this requirement could be satisfied with superconducting, super ferric, or conventional magnets, it is also noted that superconducting magnets would have several advantages over other technologies. First, the aperture could be made as large as the aperture of the quadrupoles. Second, a longer the slot length would be available in the drift between D1 and D2 for crab cavities or other equipment that would increase the luminosity. Finally, the estimated cost of building and operating superconducting magnets is lower than the two alternatives. A strong option to satisfy the D1 requirement would be powering in series two magnets that are slightly modified versions of the DX 180 mm aperture dipole made for the RHIC IR region. The application of the DX design to the Phase I D1 requirements is demonstrated here, although the alternative designs remain under investigation.

DX (RHIC)

The DX magnet has a single-layer coil wound with 71 turns of 36-strand NbTi cable. This magnet was designed with stainless steel (Kawasaki high-Mn KHMN) collars to apply pre-stress to the coil. To minimize deflections and thus aid in assembly, a 40.1 mm wide collar was used. Iron saturation is controlled by a series of holes in the iron, near and at the yoke inner radius. Because of the rather large stored energy and the modest ratio of copper to superconductor in the cable, active protection consisting of quench detection and firing of heaters to propagate the quench of the coil was incorporated. A diode was also installed

Field @ top energy (T)	4.4
Current @ top energy (kA)	6.8
Magnetic length (m)	3.7
Yoke outer diameter (mm)	622
Inductance (mH)	49
Stored energy (kJ)	1100

Table 2: Selected parameters of the 180 mm DX dipole magnet.

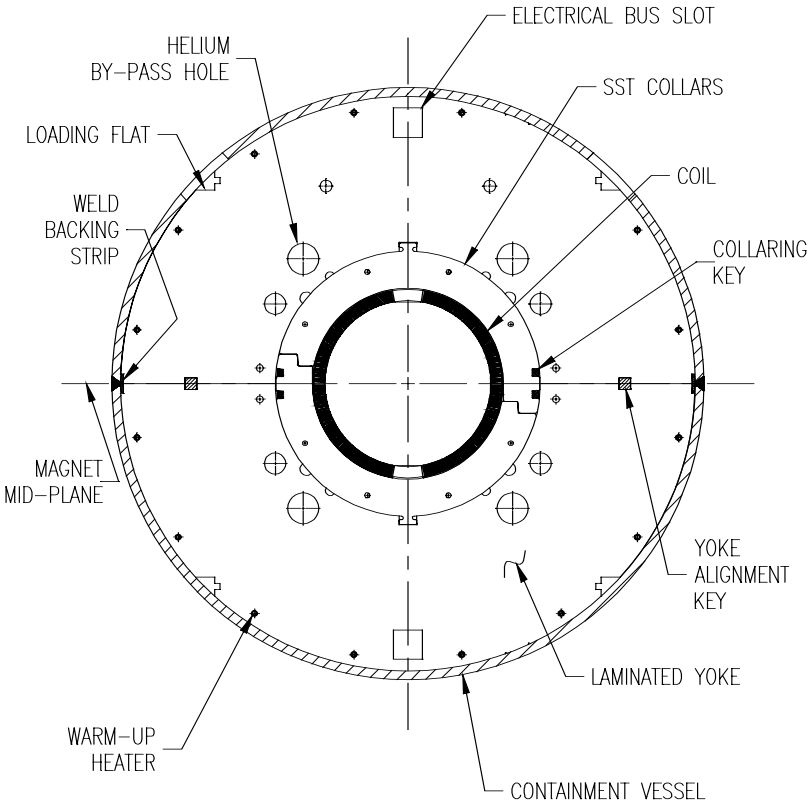

Figure 3. Cross section of the RHIC DX cold mass. The coil i.d. is 180 mm.

Modifications for use at D1 (LHC)

Yoke modification.

The o.d. of the DX cold mass is 641 mm. The LIUWG designs limited the cold mass o.d. to 570 mm vertically due to space limitations in the cryostat. For economic reasons, the LIUWG assumed the use of a standard LHC cryostat. Ramesh Gupta has made preliminary designs of two yokes that could be used with the DX coil and collars. The first design (Fig. 4), for a round yoke, has a fringe field outside the cryostat of ~ 6.5 mT and a saturation sextupole of ~ 8 units at 2/3 radius. The second design (Fig. 5), for an oblate yoke such as that used for some of the LHC separation dipoles built by BNL for the present LHC, has a smaller fringe field (0.7 mT) and saturation sextupole (~3 units). However, it would be harder to build. (Note that these designs have not been optimized.)

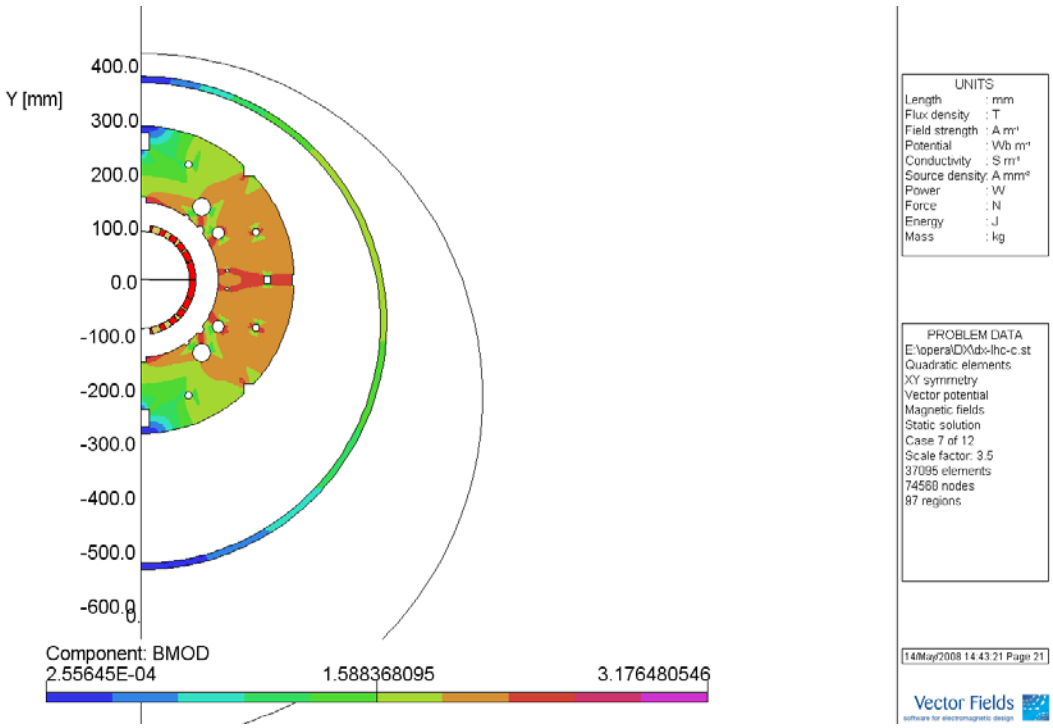

Figure 4. D1 cold mass with circular yoke, in an LHC cryostat.

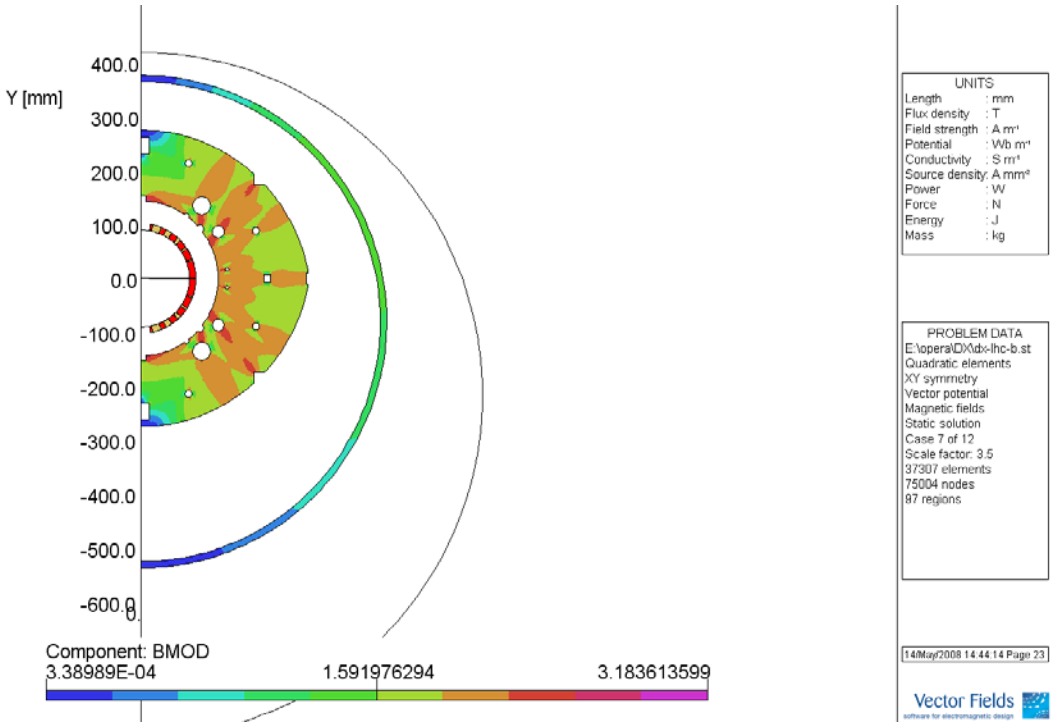

Figure 5. D1 cold mass with oblate yoke, in an LHC cryostat

Coil end modification

In the DX, because of the large number of turns and the constant perimeter path used for the design, the cable tilted significantly from the vertical. Also, the spacers between the blocks of turns were rather large. The ends were the principal source of training in DX, so it would be desirable to redesign the ends of the D1 coils to be mechanically more stable against the large axial Lorentz force by reducing the tilt of the cable and the size of the end spacers.

Interface to the LHC. Other components in DX, needed for mounting in the cryostat and interfacing to cryogenic and electrical systems, will need modification.

Schedule

A schedule, showing a construction start October 1, 2009 (i.e., no construction funding in FY09), has been developed. The schedule allows time for reconfiguring and updating some items needed for magnet production. For example, the code for the winder, written for a 286 processor, will need to be written for a modern control unit. The schedule also allows time for a practice coil, and for a cold test of the first cold mass in a vertical dewar prior to starting full production. A roll-up of the schedule is below (Fig. 6).Year-by-year highlights of the schedule include:

FY10. Design modifications for the coil ends, cradles, helium ports, and assembly of the cold mass into a cryostat. Initiate procurement of the superconductor, coil parts, and 30% of the cold mass parts. Recommission tools. Complete test coils. Start cold mass #1.

FY11. Procurement of the cold mass parts (remaining 70%). Complete assembly of cold mass #1; cold test of same. Following completion of cold test of cold mass #1, begin production of cold mass #2. Complete fabrication of all coils. Assemble cold mass #2-#6. Test cold mass # 2-#5. Assemble and ship magnet #1 and #2.

FY12. Assemble cold mass #7-#10. Test cold mass #6 through #10. Assemble and ship magnets #3-#5. The last delivery to CERN is in July 2012.

Delivery of the last magnet to CERN in the summer of 2012, six months prior to actual installation, is "just in time" (i.e., there is no schedule contingency). Contingency in the schedule can be obtained by beginning some engineering activities (in addition to CD1/CD2 planning) in FY09. These activities could include redesign of the coil ends and yoke. Overall project risk is reduced if some engineering time is available to plan the interface at LHC. Further schedule contingency can be generated if orders can be placed for some of the long lead-time items, such as superconductor.

Budget

The budget for magnet production, years FT10-FY12, is based on DX actual costs (e.g., labor hours), with updated costs on materials. The budget for FY13 includes final documentation and the detailed interfacing with LHC that will be needed for full acceptance and installation. This

budget is preliminary needs at least one thorough scrubbing.

Contingency. A budget for the labor needed to plan for CD1 and CD2 in FY09 has been guesstimated at 2-3 FTE's. Efforts are underway to improve the accuracy of this estimate. The budget includes a contingency of 25%. A review of the major items in the budget indicates that this overall contingency estimate is consistent with a contingency estimate that would be arrived at by use of the item-by-item "contingency dictionary" that was used by the Minerva neutrino collaboration.

Funding profile. As noted above, it is highly desirable to begin some engineering design and long lead-time purchases in FY09 in order generate a modest contingency in the schedule.

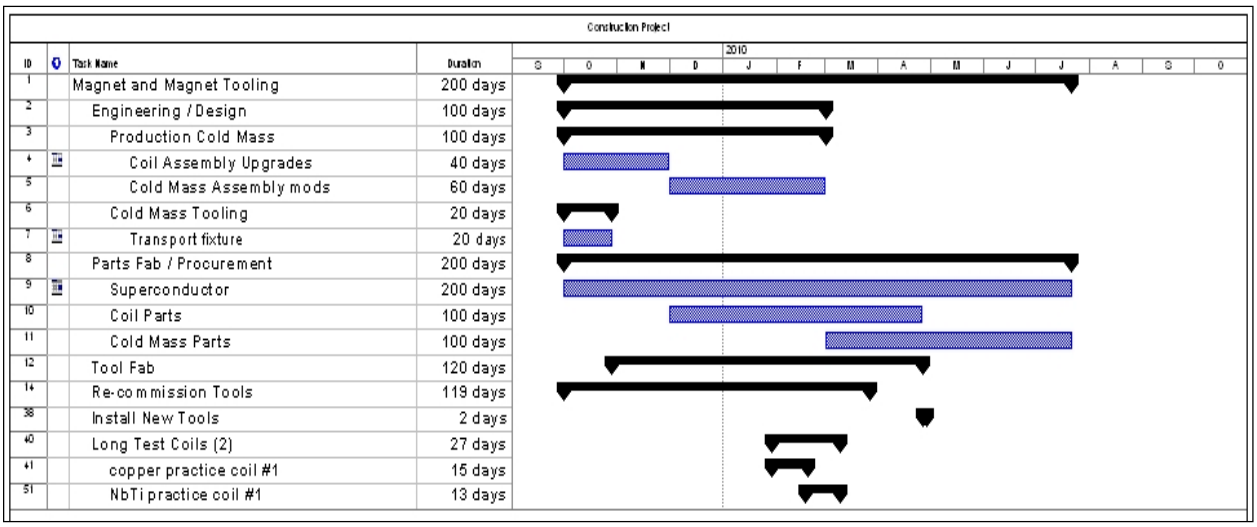

Figure 6. Roll-up of schedule for D1 magnet production.

ID	Task Name	Duration	Start	Finish
61	Magnet Assembly	490.5 days	Thu 7/22/10	Wed 7/11/12
62	Cold Mass #1	177.5 days	Thu 7/22/10	Fri 4/8/11
111	Cold Mass #2	122 days	Fri 1/28/11	Mon 7/25/11
112	Coils	20 days	Fri 1/28/11	Mon 2/28/11
113	coil #1	10 days	Fri 1/28/11	Fri 2/11/11
114	install mandrel on winder	0.5 days	Fri 1/28/11	Fri 1/28/11
115	wind coil	2 days	Mon 1/31/11	Tue 2/1/11
116	install pushers, liners	0.5 days	Wed 2/2/11	Wed 2/2/11
117	move to cure sta. & install in FB	0.5 days	Wed 2/2/11	Wed 2/2/11
118	cure	1 day	Thu 2/3/11	Thu 2/3/11
119	remove from FB & move to test	1 day	Fri 2/4/11	Fri 2/4/11
120	measure, test	2 days	Mon 2/7/11	Tue 2/8/11
121	splice, stabilize leads	2 days	Wed 2/9/11	Thu 2/10/11
122	transport to Bldg 902	0.5 days	Fri 2/11/11	Fri 2/11/11
123	coil #2	10 days	Fri 2/11/11	Mon 2/28/11
133	Cold Mass Assembly	30 days	Mon 2/28/11	Mon 4/11/11
134	assemble coils into collars	7 days	Mon 2/28/11	Wed 3/9/11
135	collar coils	3 days	Wed 3/9/11	Mon 3/14/11
136	assemble yoke	2 days	Wed 3/9/11	Fri 3/11/11
137	install coils into yoke	2 days	Mon 3/14/11	Wed 3/16/11
138	install shells	4 days	Wed 3/16/11	Tue 3/22/11
139	install end plates / apply axial load	4 days	Tue 3/22/11	Mon 3/28/11
140	wire coils	7 days	Mon 3/28/11	Wed 4/6/11
141	complete helium vessel	3 days	Wed 4/6/11	Mon 4/11/11
142	Cold Test	27 days	Mon 4/11/11	Wed 5/18/11
143	install in horizontal dewar	2 days	Mon 4/11/11	Wed 4/13/11
144	connect leads, plumbing	8 days	Wed 4/13/11	Mon 4/25/11
145	cool down	3 days	Mon 4/25/11	Thu 4/28/11
146	test	10 days	Thu 4/28/11	Thu 5/12/11
147	warm up	2 days	Thu 5/12/11	Mon 5/16/11
148	remove from dewar	2 days	Mon 5/16/11	Wed 5/18/11
149	Ship	45 days	Wed 5/18/11	Mon 7/25/11
150	Cold Mass #3	132 days	Mon 2/28/11	Tue 9/6/11
189	Cold Mass #4	142 days	Mon 3/28/11	Tue 10/18/11
228	Cold Mass #5	152 days	Mon 4/25/11	Fri 12/2/11
267	Cold Mass #6	162 days	Mon 5/23/11	Thu 1/19/12
306	Cold Mass #7	172 days	Tue 6/21/11	Fri 3/2/12
345	Cold Mass #8	182 days	Thu 7/21/11	Fri 4/13/12
384	Cold Mass #9	192 days	Thu 8/18/11	Fri 5/25/12
423	Cold Mass #10	202 days	Fri 9/16/11	Wed 7/11/12
424	Coils	20 days	Fri 9/16/11	Fri 10/14/11
445	Cold Mass Assembly	30 days	Tue 2/14/12	Wed 3/28/12
454	Cold Test	27 days	Wed 3/28/12	Fri 5/4/12
461	Ship	45 days	Fri 5/4/12	Wed 7/11/12

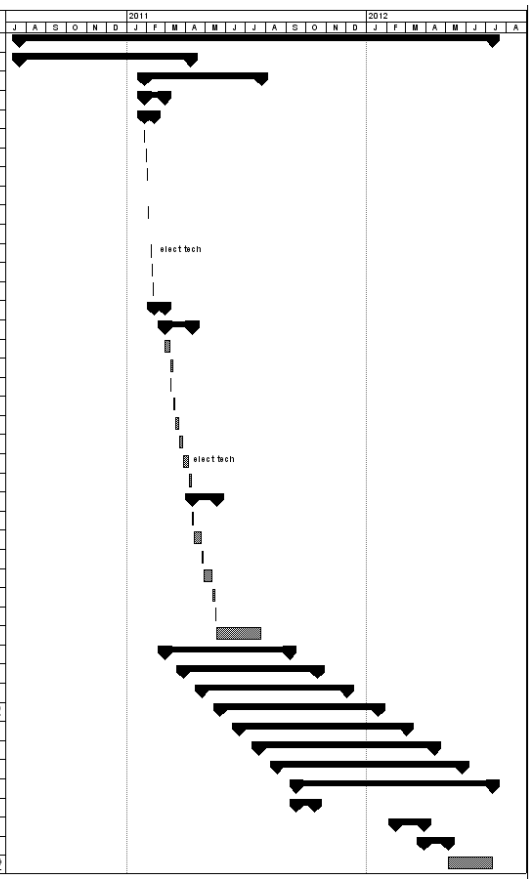

Figure 7. Schedule showing detailed production schedule for the first cold mass, and rolled-up schedules for the remaining cold masses.

2 Cryogenic & Power Distribution Feedboxes

The present inner triplet feedboxes are not matched to the proposed Phase I needs. The Phase I layout calls for 12 kA power leads for the IR quadrupoles, possibly requiring a dedicated set of leads for each cold mass plus superconducting power leads for a proposed superconducting D1. There is also a strong desire by CERN to move the power leads and cryogenic connections away from the beamline to a more accessible location. The new feedbox strategies favor building new feedboxes and placing them in personnel accessible alcoves near the inner triplets.

Proposed Solution

The optimum complete solution to this problem is still under study. Figure 8 shows one possible scenario for the box distribution, for the left side of IR 1:

1) The cryogenic and cold power connection box will be located off the beamline, but contiguous to the line of IR magnetic elements.

2) The cold connection box will contain a lambda plug for the power bus transition to helium vapor.

3) There is a separate power lead box with helium vapor cooled power lead for room temperature transition of the power bus. Where possible, this box will be located in a low radiation area with easy personnel access to room temperature interconnections.

4) The transfer "link" from the cold connection box to the power lead box is made with a helium vapor cooled line, with the conductor to be decided.

Design Deliverables

LAUC will be responsible for delivering a complete system for each side of the two high luminosity regions.

A major goal for FY09 is to deliver a complete cost estimate for the full system in time for CD-2 in the summer of 2009. This cost estimate will depend on the details of the IR design, such as the powering scheme, location, thermal mass and operating temperature of each magnetic element. Preliminarily, we estimate that the cost per distribution site is $1.2M per feedbox plus $0.4M for the superconducting link, not including EDIA. This is based on previous experience with the present IR feedboxes, the cost of cryogenic transfer lines, and the present cost of HTS and MgB_2 materials.

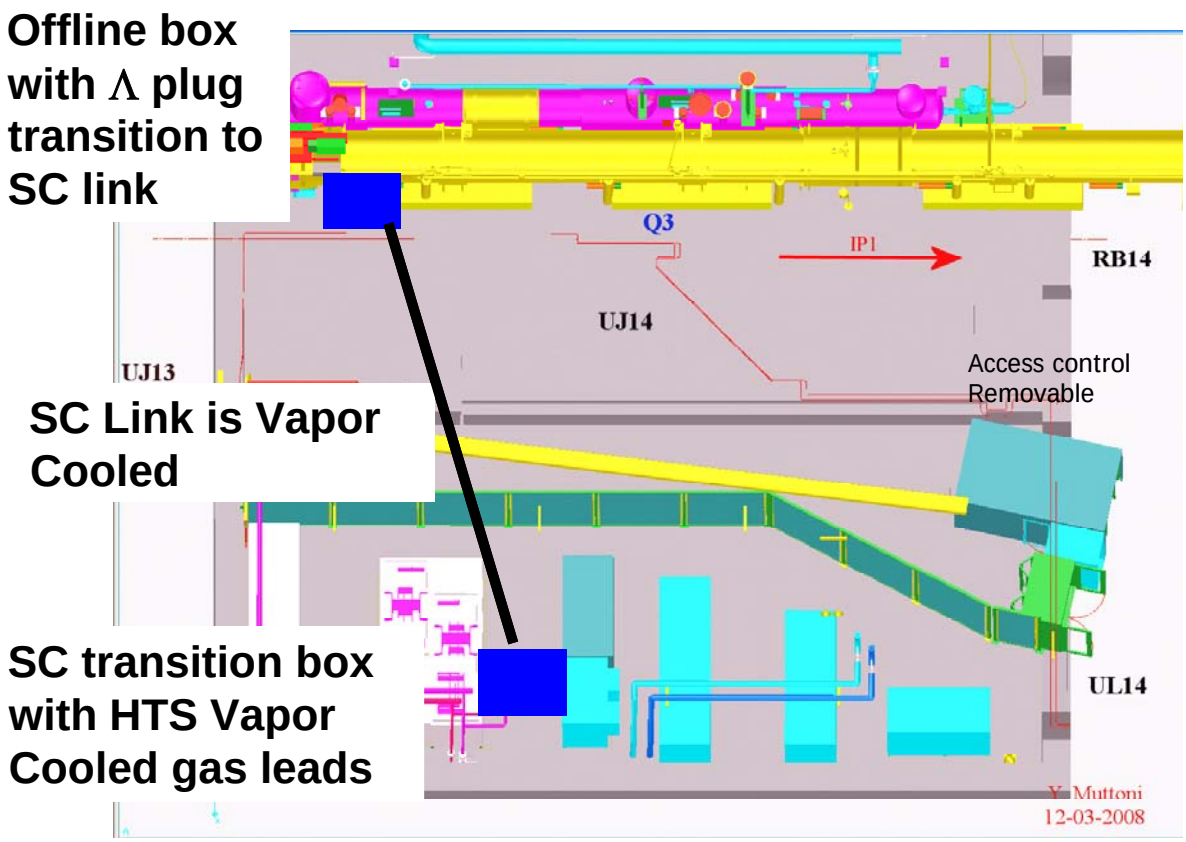

Figure 8: One scenario for the layout of the cryogenic and power distribution system for IR 1, left.

Milestones

Another deliverable for FY09 is a project schedule, with milestones tied to the Phase I project. The following tasks need to be performed:

June	**2009**	Completed interface and functional specification for systems.
		Detailed cost and schedule for delivery of feedboxes and transfer line.
June	**2010**	Demonstration of short length transfer line at Fermilab.
		Order placed for power leads.
January	**2011**	Place order for Feedboxes.
		Start power lead bench testing at Fermilab.
Fall	**2011**	Test power leads in power lead vessel using mini transfer lines.
January	**2012**	First feedbox and SC link brought to CERN for string test.
Shutdown	**2013**	Installation in accelerator.
	2013	Accelerator commissioning.

3 Magnet System Engineering

With the new high luminosity IR region optics and subsequent magnetic elements comes a completely new set of requirements for cryogenics, quench protection/energy extraction, electrical powering and quench protections systems. Interfaces with existing LHC tunnel space and infrastructure must be designed to meet these requirements. Real alignment and field quality of accelerator components will affect the local as well as the global beam optics.

The U.S. was responsible for the cryogenics and the electrical layout of the present inner triplet, and took responsibility for the commissioning of both the DFBX feedbox and the cryogenics of the CERN DFB feedbox during LHC hardware commissioning. Similarly, two U.S. commissioners are leaders in the HC Quench protection team, and so are thoroughly familiar with CERN standard quench protection, electronics and extraction hardware. Through the US LHC Accelerator Project, the U.S. labs were responsible for several accelerator physics studies including the relative alignment of the IR quadrupoles, the integral strengths of corrector magnets and absorber placement and expect heat loads on the IR magnets

We propose to take leading roles in the following tasks:

1) **Cryogenic design,** including positioning and redesigning the cryogenic feedbox and distribution lines in the IR including cryogenic instrumentation, leading to the Phase I cryogenic feedboxes. Required inputs for this study are: layout of the IR's including which operating temperatures for each magnet; thermal mass of the magnet system; expected static heat and dynamic heat loads; proposed methods for intercepting beam energy; tunnel space availability and evaluation of radiation zones; re-evaluation of the existing IR cryogenic system in light of the ongoing commissioning.

2) **System powering and quench protection.** Based on the Phase I magnet designs, and required powering configurations for various LHC physics programs, propose a powering and energy extraction plan for the safe operation of the superconducting magnets. Validate quench protection for internal magnet bus work and expansion loops.

3) **Accelerator Physics.** Participate in specific accelerator tasks, such as generating corrector magnet specifications based on IR quad magnet error tables; setting alignment specifications for the IR quads including tolerances of mechanical supports, beam tube placement and relative alignment of magnet axes of quadrupole elements; calculating heat loads based on proposed absorber schemes.

As the system engineering must be largely completed prior to construction, much of this effort must take place prior to the CERN technical design review and the Critical Decision 2. A smaller but non-negligible effort is expected through Phase I installation and commissioning. The following table gives an estimate of the effort required in FY09-FY12. The design for the cryoboxes is closely coupled to the system design so the EDIA for this is included with the system design effort.

4 Collimators

The LHC collimation system is expected to require lower beam impedance and higher collimation efficiency in order to safely and to stably contain nominal and ultimate beam currents. The "Rotatable Collimator" (RC) design developed in LARP could play an important role in impedance reduction and improvement of efficiency, while improving UHV behavior and radiation hardness.

Ultimately the collimator-induced impedance and the collimation efficiency shall be improved by a factor 10, addressing predicted limitations for both proton and ion operation. Additional issues that could challenge the collimator system include dispersion suppressor beam losses, collimator set-up time, the desire for enhanced primary collimator deflection angles and radiation damage to collimator materials. The CERN Phase II LHC Collimation program (which overlaps the Phase-1 Interaction Region upgrade project) addresses these issues. Space has been left for additional secondary collimators to address these limitations, at thirty locations around each ring. Cables and base supports have already been installed for the "Phase II" locations for fastest possible installation.

Finding a technical solution that balances impedance, efficiency and robustness against accidental beam damage is challenging. The Phase II project has the following key aspects:

1. The R&D and prototyping of at least three different concepts for advanced collimation designs, each addressing different possible limitations to LHC luminosity.

2. Operational experience of the LHC with the Phase I collimation system to understand the nature of any luminosity limit and the best ways to ameliorate deleterious effects with already installed systems.

3. Testing of collimator prototypes at CERN to their technological limits before any installation in the LHC

4. Installation and testing of qualified Phase II prototypes in the LHC during the second full year of LHC operation with a decision on Phase II design and production, which may require more than one technology, at the end of the year.

5. Production of the collimators during years 3-4 of LHC operation, installation during regularly scheduled shutdowns and use beginning with year 5 of LHC operation.

The plan of studies outlined above will allow determining the optimum collimation solution for the LHC. Even if the still-to-be-determined reduction in impedance due to the copper Rotatable Collimators is sufficient to allow increased beam current to reach 10^{35} luminosity, the improvement in collimation efficiency from Rotatable Collimators alone is insufficient. The Phase II collimation upgrade MUST involve more than one

kind of device. Even though there is considerable uncertainty in the number of Rotatable Collimators to be built, nonetheless, given the urgent need to begin planning, the experience at SLAC can serve to outline the level of effort, cost and schedule of an eventual collimator construction project.

In 2005 SLAC began R&D on a Rotatable Collimator to serve as one of the three complementary designs to be considered and tested. The first cylindrical collimator jaw will soon be completed and thermal-mechanical tests will be performed. Assuming it behaves as calculations predict, a fully functional 2-jaw collimator will be constructed and shipped to CERN for beam testing in mid-2009. A schedule based on this plan is shown in Figure 9.

Key milestones are the removal of risk factors through thermal mechanical testing of the first jaw at SLAC, vacuum and mechanical testing of the first full unit at SLAC and then again at CERN, operational beam tests under normal operation conditions at the SPS and LHC, and damage testing in an external beam line at CERN.

Early indications are that the production cost of a Rotatable Collimator unit (2 adjustable, rotatable jaws in a vacuum tank) is $250k. To this one would need to add the rack and pinion jaw adjustment system, stepper motors and LVDTs and the system integration costs required to assemble, test and qualify the units. Production would be scheduled to begin in FY11. While a detailed analysis of the resources required permitting a 2 year construction period has not been carried out, informal discussions confirm that a timely conclusion is possible, even for 36 Rotatable Collimators. A more likely strawman proposal would be to provide 5 RCs – 4 plus one spare. This number may need alteration before CD-2 in summer of 2009.

If a decision is made to use Rotatable Collimators, then there are a number engineering details regarding its interface to the LHC control system, cable plant, installation tooling, et cetera, that will need to be agreed with the CERN team. While the overall mechanical design of the Rotatable Collimator has been kept “plug-compatible” with the Phase I devices, the delivered devices will require pre-installation qualification at the CERN site and installation by CERN staff. In all scenarios – however many RCs – the LAUC effort would work in a tight collaboration with the CERN groups.

ID		Task Name	Duration	Start	Finish
1		Construct 1st SLAC RC Jaw	87 days?	Tue 1/1/08	Wed 4/30/08
2		Thermal Testing of RC Jaw 1	20 days	Thu 5/1/08	Wed 5/28/08
3		Construct RC1 Prototype	197 days?	Tue 7/1/08	Wed 4/1/09
4		SLAC Mechanical & Vaccum Te	30 days	Thu 4/2/09	Wed 5/13/09
5		Ship RC1 to CERN	10 days	Thu 5/14/09	Wed 5/27/09
6		Testing of RC1 off beam at CEF	20 days	Thu 5/28/09	Wed 6/24/09
7					
8		Development & Construction of	370 days?	Tue 1/1/08	Mon 6/1/09
9					
10		Testing 3 protoypes at TT??	30 days	Thu 6/25/09	Wed 8/5/09
11		Installation & Testing of qualifie	125 days	Mon 3/22/10	Fri 9/10/10
12		Decision on number & type of c	5 days	Mon 9/13/10	Fri 9/17/10
13					
14		Preparation for Construction	60 days	Mon 9/20/10	Fri 12/10/10
15		Construction	505 days	Mon 12/13/10	Fri 11/16/12
16		Installation in LHC	72 days	Mon 1/14/13	Tue 4/23/13
17					
18		LHC Run 0 (Commissioning)	86 days?	Fri 8/1/08	Fri 11/28/08
19		LHC Run 1	152 days?	Fri 5/1/09	Mon 11/30/09
20		LHC Run 2	152 days?	Mon 5/3/10	Tue 11/30/10
21		LHC Run 3	152 days?	Tue 5/3/11	Wed 11/30/11
22		LHC Run 4	152 days?	Thu 5/3/12	Fri 11/30/12
23		LHC Run 5	152 days?	Fri 5/3/13	Mon 12/2/13

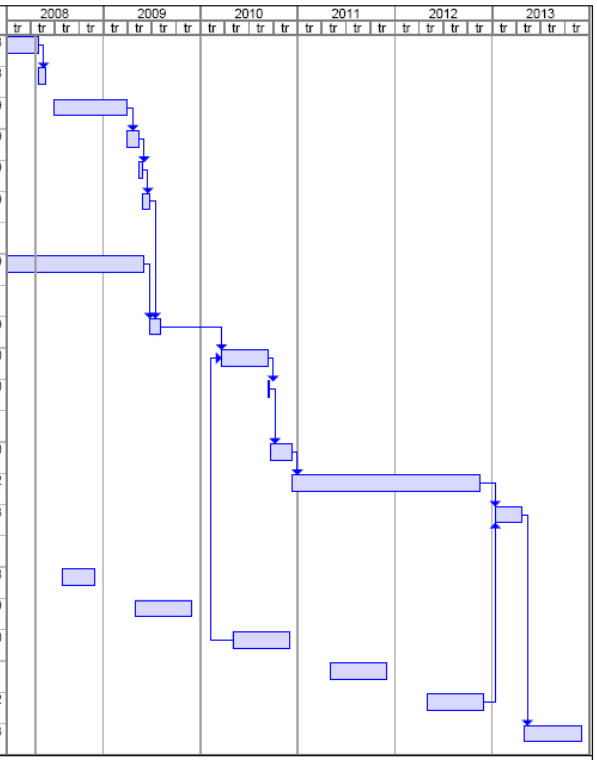

Figure 9: Schedule for the Phase II Collimator project.

5 Laser Profile Monitors

The basic principle of a Laser Profile Monitor rests on neutralizing the H^- beam with 1500 nm wavelength light. Profiles are measured by moving a narrow laser beam across the ion beam, while measuring the detached-electron current as a function of the laser position. Profiles of 750 keV beams and 200 MeV beams have been measured at BNL, and the profile of the 2.5MeV beam in the SNS MEBT has been measured at LBNL.

As an improvement over the SNS system, we propose deflecting the photo-detached electrons from the accelerator beam and measuring them with a high-gain detector. This reduces the required peak photon flux by several orders of magnitude, and permits a fiber-optic diode laser to be used. The light is piped into the accelerator tunnel by a fiber lying in a cable tray. Alignment consists of clamping a focusing head at the beam line. The light beam is scanned across the accelerator beam by a rotating 45° mirror in a linear ramp timed to scan across the accelerator beam during a portion of a machine cycle. A full profile will be measured within a single linac pulse.

The best detector for the Linac4 beam is a Si surface-barrier detector operated as a solid-state ionization chamber. The choice of laser will depend on the energy of the beam to be measured and the detector to be used – higher energy beams spend less time in the light path and relativistic effects shift both the wavelength and the photon flux in the beam frame. The same overall approach and the main components can also be configured for emittance measurements, so an integrated package will be designed to allow for both profile and emittance measurements.

We propose to deliver to CERN three complete stations, capable of measuring both horizontal and vertical profiles and emittances in the transfer line between Linac4 and the PS Booster, at an energy of 160 MeV. These devices will be used to diagnose the Linac4 beams during injection into the PSB rings.

6 Linac4 Low Level RF

Low-level RF (LLRF) control hardware and its embedded programming play a pivotal role in the performance of an accelerator that require a tight control of amplitude and phase. Modern designs implement most of the signal processing in the digital domain. This reduces the size and cost of the hardware, but places the burden of proper operation on the programming. Field Programmable Gate Arrays (FPGAs) and communications-grade ADCs and DACs enable sub-microsecond delay for the LLRF controller feedback signal. The virtue of simplicity is easy to apply to the hardware, but more of a challenge in the context of programming. Digital signal processing, combined with dedicated hardware, controls and maintains the cavity phase (relative to an absolute reference) unaffected by drift or 1/f noise of any long cables or active components. Developing and testing that programming is also a very real challenge.

The RF group at Berkeley successfully led the technical development and implementation of the LLRF system for the SNS linac, which has demonstrated a high level of cavity and beam controls and high reliability in its first years of operation. Linac4 (and SPL) are very similar to the SNS from a LLRF perspective, including both warm and superconducting RF cavities operating in a pulsed structure with comparable repetition rates. The frequencies are also quite similar (352/704 MHz vs. 402.5/805 MHz). This makes the SNS system a natural starting point from which to develop the implementation for Linac4.

Digitized signals are processed in a single FPGA in the SNS LLRF system, enabling the full potential of digital signal processing to be exploited. The processor implements a number of other tasks, including feed forward adapted on a pulse to pulse basis, as well as pulse to pulse calibration, so that all reference are corrected during the time when there is no beam. In addition, the FPGA also performs all the networking and data transfer tasks required to integrate the system into an operational accelerator.

The proposed contribution is to define the control algorithms for Linac4, based on the SNS experience. This includes the feedback loop around the cavity, the adaptive feed forward, and the tuning algorithms. We propose to contribute to the development of these algorithms and their implementation in FPGA technology, in full collaboration with CERN.