



US LHC Accelerator Research Program
brookhaven - fermilab - berkeley

LHC Upgrades

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DOE Review

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Outline

Luminosity Upgrades: Why and When?

Luminosity Upgrade Scenarios

The US Role in Luminosity Upgrades

Energy Upgrades?

Conclusions

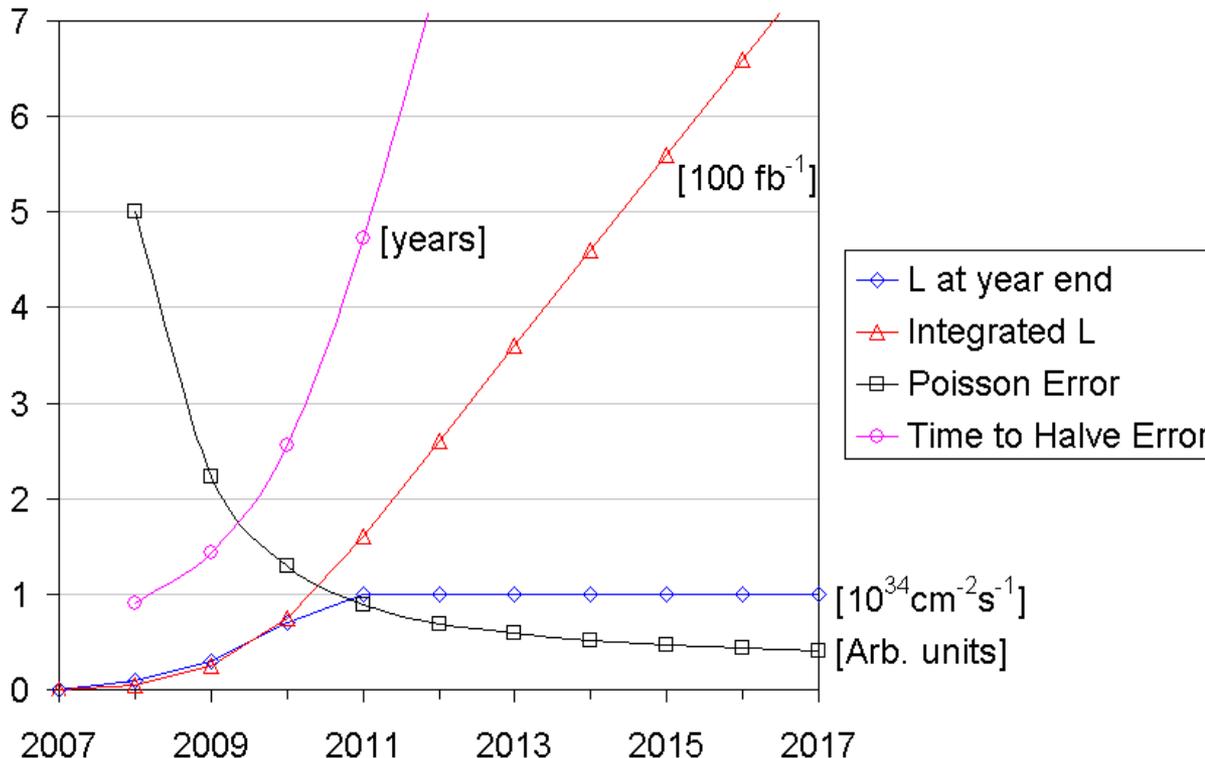


LHC Luminosity Upgrade

Why and When?

HEPAP* put R&D for a **luminosity upgrade** in its highest priority category:

The science of extending exploration of the energy frontier with the LHC accelerator and detector luminosity upgrades is *absolutely central*. The *R&D phase* for these will need to start soon if the upgrades are to be finished by the present **target date of 2014**.



*High-Energy Physics Facilities of the DOE Office of Science Twenty-Year Road Map, HEPAP report to the Director of the Office of Science, 17 March 2003.



CERN Planning for Luminosity Upgrades



Upgrading the LHC ... the SLHC

- ◆ Initial Studies
- ◆ Physics
- ◆ Detector R&D

Roger Cashmore at the LHC Symposium, Fermilab, May 2003

15-May-03

The LHC'

93



Detectors: General Considerations

| | LHC | SLHC |
|---|----------------|----------------|
| \sqrt{s} | 14 TeV | 14 TeV |
| L | 10^{34} | 10^{35} |
| Bunch spacing Δt | 25 ns | 12.5 ns * |
| σ_{pp} (inelastic) | ~ 80 mb | ~ 80 mb |
| N. interactions/x-ing ($N=L \sigma_{pp} \Delta t$) | ~ 20 | ~ 100 |
| $dN_{ch}/d\eta$ per x-ing | ~ 150 | ~ 750 |
| $\langle E_T \rangle$ charg. particles | ~ 450 MeV | ~ 450 MeV |
| Tracker occupancy | 1 | 10 |
| Pile-up noise in calo | 1 | ~ 3 |
| Dose central region | 1 | 10 |

Normalised to LHC values

10^4 Gy/year R=25 cm

In a cone of radius = 0.5 there is $E_T \sim 80$ GeV.
 This will make low E_T jet triggering and reconstruction difficult.

Upgrade Conclusions

LHC luminosity upgrade can extend:

- physics reach of LHC at a moderate extra cost relative to initial LHC investment.
- the LHC 'lifetime'

To realise this reach, the LHC detectors must preserve performance: trackers must be rebuilt, and calorimeters, muon systems, triggers and DAQ need development. Upgrades programme, from launch to data taking will take 8-10 years

The time to start is soon **An R&D programme will be essential**



Why Should We Work on a Luminosity Upgrade?

Advance High Energy Physics

- Help bring the LHC on and up to design performance quickly.
- Improve LHC performance by advances in understanding and instrumentation.
- Use LHC as a tool to gain deeper knowledge of accelerator science and technology.
- Extend LHC as a frontier HEP instrument with a timely luminosity upgrade.

Advance U.S. Accelerator Science and Technology

- Keep skills sharp by helping commission the LHC.
- Conduct forefront AP research and development.
- Advance U.S. capabilities to improve the performance of our own machines.
- Prepare U.S. scientists to design the next generation hadron collider.
- Develop technologies necessary for the next generation of hadron colliders.

Advance International Cooperation in the High Energy Accelerators

LHC Upgrade Scenarios

- LHC Phase 0: maximum performance without hardware changes
- LHC Phase 1: maximum performance with the LHC arcs unchanged
- LHC Phase 2: maximum performance with ‘major’ hardware changes

The nominal LHC performance at 7 TeV corresponds to a total beam-beam tune spread of 0.01, with a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in IP1 and IP5 (ATLAS and CMS), halo collisions in IP2 (ALICE) and low-luminosity in IP8 (LHC-b). The steps to reach **ultimate performance without hardware changes (LHC Phase 0)** are:

1. collide beams **only in IP1 and IP5** with alternating H-V crossing
2. increase N_b up to the beam-beam limit $\rightarrow L = 2.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
3. increase the dipole field to 9 T (ultimate field) $\rightarrow E_{\text{max}} = 7.54 \text{ TeV}$

The ultimate dipole field of 9 T corresponds to a beam current limited by cryogenics and/or by beam dump considerations.

See also O. Brüning et al., LHC Luminosity and Energy Upgrade: A Feasibility Study, LHC Proj. Rpt 626, Dec 2002.

Phase 0 - Maximum \mathcal{L} without Major Upgrades

| parameter | symbol | units | nominal | ultimate | Piwinski |
|----------------------|------------------|---------------------------------|---------|----------|-------------|
| number of bunches | n_b | | 2808 | 2808 | 2808 |
| bunch spacing | Δt_{sep} | ns | 25 | 25 | 25 |
| protons per bunch | N_b | 10^{11} | 1.1 | 1.7 | 2.6 |
| aver. beam current | I_{av} | A | 0.56 | 0.86 | 1.32 |
| norm. tr. emittance | ϵ_n | μm | 3.75 | 3.75 | 3.75 |
| long. emittance | ϵ_L | eV s | 2.5 | 2.5 | 4.0 |
| peak RF voltage | V_{RF} | MV | 16 | 16 | 3/1 |
| RF frequency | f_{RF} | MHz | 400.8 | 400.8 | 200.4/400.8 |
| r.m.s. bunch length | σ_z | cm | 7.55 | 7.55 | 15.2 |
| r.m.s. energy spread | σ_E | 10^{-4} | 1.13 | 1.13 | 0.9 |
| IBS growth time | $\tau_{x,IBS}$ | h | 111 | 72 | 87 |
| beta at IP1-IP5 | β^* | m | 0.5 | 0.5 | 0.5 |
| full crossing angle | θ_c | μrad | 300 | 315 | 345 |
| lumi at IP1-IP5 | L | $10^{34}/\text{cm}^2 \text{ s}$ | 1.0 | 2.3 | 3.6 |

LHC Phase 1: Luminosity Upgrade

Possible steps to increase the LHC luminosity with hardware changes only in the LHC insertions and/or in the injector complex include the following **baseline scheme**:

1. modify insertion quadrupoles and/or layout $\rightarrow \beta^* = 0.25 \text{ m}$
2. increase crossing angle by $\sqrt{2} \rightarrow \theta_c = 445 \mu\text{rad}$
3. increase N_b up to ultimate intensity $\rightarrow L = 3.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
4. halve σ_z with high harmonic RF system $\rightarrow L = 4.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
5. double number of bunches (and increase θ_c !) $\rightarrow L = 9.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
excluded by electron cloud?

or smaller!

Correspondingly
larger!

Step 4 is not cheap since it requires a new RF system with 43 MV at 1.2 GHz and a power of about 11 MW/beam (estimated cost 56 MCHF). The changeover from 400 to 1200 MHz is assumed at 7 TeV, or possibly at an intermediate flat top, where stability problems may arise in view of the reduced longitudinal emittance of 1.78 eVs. The horizontal Intra-Beam Scattering growth time decreases by about $\sqrt{2}$.

Additional \mathcal{L} Upgrade Routes

| parameter | symbol | units | baseline | Piwinski | super-bunch |
|----------------------|-------------------------|---------------------------------|----------|----------|-------------|
| number of bunches | n_b | | 2808 | 2808 | 1 |
| bunch spacing | Δt_{sep} | ns | 25 | 25 | |
| protons per bunch | N_b | 10^{11} | 1.7 | 2.6 | 5600 |
| aver. beam current | I_{av} | A | 0.86 | 1.32 | 1.0 |
| norm. tr. emittance | ϵ_n | μm | 3.75 | 3.75 | 3.75 |
| long. emittance | ϵ_L | eVs | 1.78 | 2.5 | 15000 |
| peak RF voltage | V_{RF} | MV | 43 | 16 | 3.4 |
| RF frequency | f_{RF} | MHz | 1202.4 | 400.8 | 10 |
| r.m.s. bunch length | σ_z | cm | 3.78 | 7.55 | 7500 |
| r.m.s. energy spread | σ_E | 10^{-4} | 1.60 | 1.13 | 5.8 |
| IBS growth time | $\tau_{x,\text{IBS}}$ | h | 42 | 46 | 63 |
| beta at IP1-IP5 | β^* | m | 0.25 | 0.25 | 0.25 |
| full crossing angle | θ_c | μrad | 445 | 485 | 1000 |
| lumi at IP1-IP5 | L | $10^{34}/\text{cm}^2 \text{ s}$ | 4.6 | 7.2 | 9.0 |



Major System Upgrades

A x10 luminosity upgrade requires upgrades to a number of accelerator systems:

- **Interaction regions**
=> smaller β^* , larger crossing angle, fewer parasitic collisions.
- **RF system**
=> shorter bunches *or* crab cavities *or* superbunches.
- **Instrumentation, diagnostics, feedback systems**
=> understand and deal with instabilities limiting beam current.

The US LARP intends to

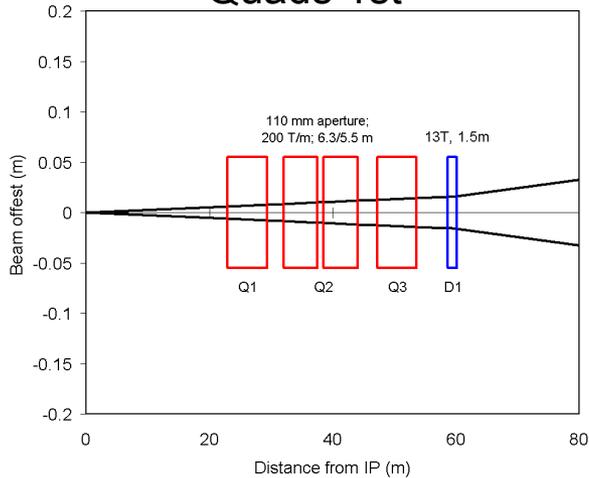
- Play a **leading role in the development of new IRs.**
- Make **significant contributions** to required **diagnostics and feedback.**

We are **exploring** how the US might contribute to **RF system upgrades.**

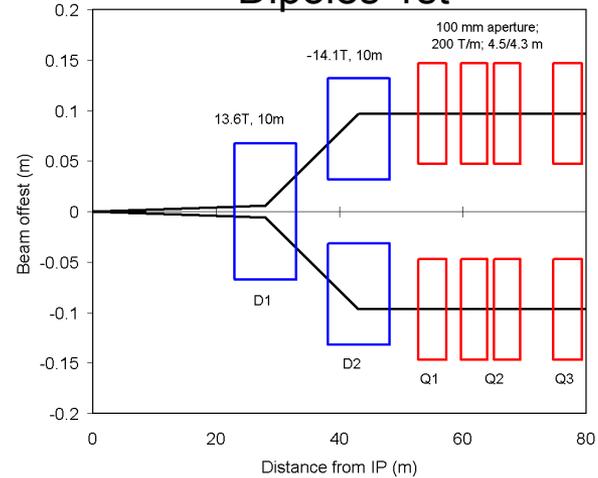


New IRs: The Major US Role in R&D for a Luminosity Upgrade

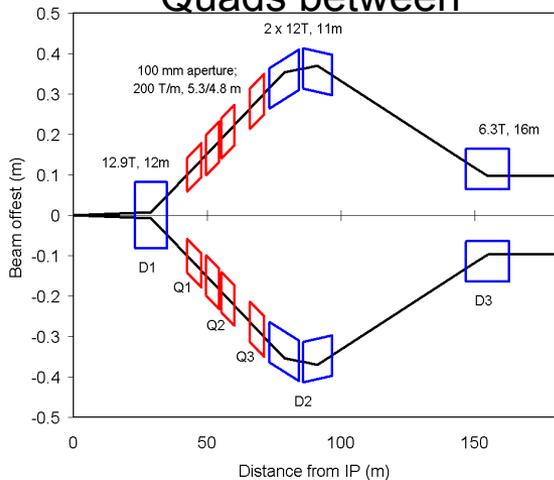
Quads 1st



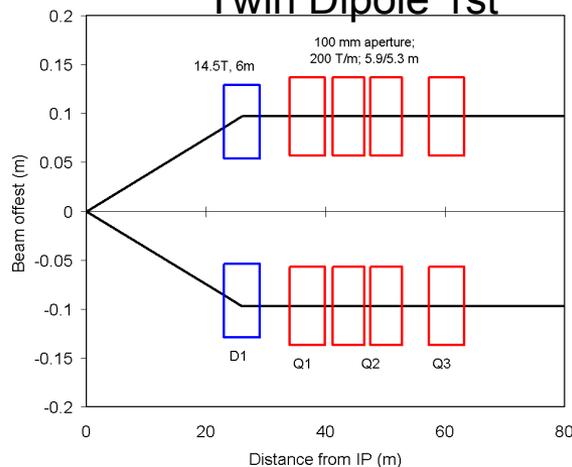
Dipoles 1st



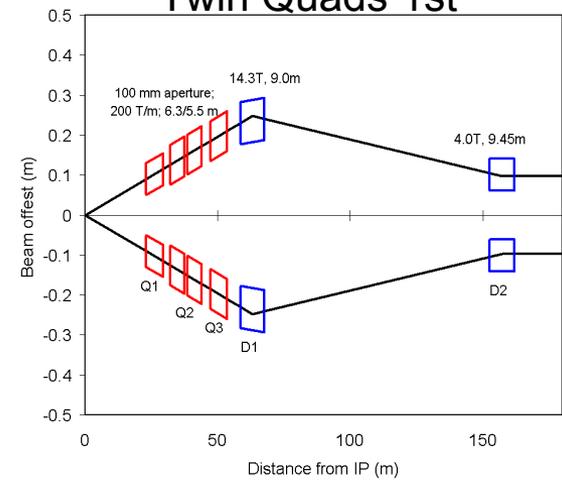
Quads between



Twin Dipole 1st



Twin Quads 1st





Key IR Parameters*

| <i>Parameter</i> | <i>Luminosity Upgrade</i> | <i>Baseline</i> |
|--|--|-----------------|
| <i>Quad Aperture</i> | 100 ~ 110 mm | 70 mm |
| <i>Peak field for G_{max}</i> | 15 T | 10 T |
| β^*_{min} | 25 cm (dipole 1 st) → 10 cm (twin quads 1 st) | 50 cm |
| β_{max} | 15 km (quads 1 st) 23 km (other layouts) | 5 km |
| <i>Dipole Aperture</i> | 135 mm (dipoles 1 st) → 75 mm (twin dipoles 1 st) | 80 mm |
| <i>Dipole Field</i> | 15 T | 2.75 T |
| <i>Crossing angle</i> | ~0.5 mrad (single bore 1 st) ~7.5 mrad (twin bore 1 st) | 0.3 mrad |

* J. Strait, et al., Towards a New LHC Interaction Region Design for a Luminosity Upgrade, PAC2003.



Accelerator Physics for Luminosity Upgrade

Accelerator Physics for luminosity upgrades is the earliest AP activity.

- It informs the type of upgrade that can take place.
- **It is necessary to guide the magnet R&D program, which must be launched soon and must be launched on the right path.**
- Close cooperation with CERN required.

Currently planned work:

- Interaction region optics.
- Energy deposition.
- Beam-beam calculations.
- Interaction region field error compensation.
- Beam loss scenarios.
- Effects of and requirements for other machine upgrades.



Magnet R&D for a Luminosity Upgrade

- Magnet R&D will eventually become the largest part of the US LHC Accelerator Research Program.
- Plan to pursue R&D on both quadrupoles and dipoles:
 - Quads with the largest possible aperture^[1] with $G_{op} > 200$ T/m, required for any new IR. (FNAL + LBNL)
 - Large-aperture dipoles for the extreme radiation environment^[2] of a dipole-first IR. (BNL + LBNL)
 - Vigorous program to develop Nb₃Sn magnet technology is required.
- Deliverables will be successful R&D, leading to accelerator-ready magnet design(s), ready for production on the time scale required for a luminosity upgrade.
- This work is a stepping stone to the magnets required for the next, higher energy hadron collider.

[1] A.V. Zlobin, et al., Aperture Limitations for 2nd Generation Nb₃Sn LHC IR Quadrupoles, PAC2003.

[2] N.V. Mokhov, et al., Energy Deposition Limits in a Nb₃Sn Separation Dipole in Front of the LHC High-Luminosity Inner Triplet, PAC2003.



Strategy for Luminosity Upgrade R&D

- **FY2004-05:**
 - Accelerator physics studies of IR issues.
 - Magnet design studies, to identify feasible designs and critical R&D issues.
 - Start technology R&D focused on critical topics.
- **FY2006-09:**
 - Model magnet R&D to develop quad and dipole technologies and learn what are feasible goals for IR upgrade designs.
 - Continue focused technology development.
 - Continue AP studies, including beam studies with LHC.
 - Choose IR design for upgrade by end of 2009.
- **FY2010-12:**
 - Develop final designs to production ready state.

All work to be done in close collaboration with CERN.



Energy Upgrade?

We expect that **our science will require a higher energy hadron collider**, once the LHC has been fully exploited.

A **higher energy machine in the same tunnel is one option**.

- Virtue of an “energy doubled” LHC: Uses CERN infrastructure.
- Concerns:
 - It will be **expensive** and require a **long shutdown**.
 - Nb₃Sn fundamental properties limit energy step to **only < x1.8** .

HEPAP has set a lower priority on an energy than a luminosity upgrade:

A challenging and more costly upgrade of the LHC would involve doubling the total collision energy from 14 to 28 TeV. This requires a multi-year shutdown of the machine during which the original magnets would be removed and a new collider, employing bending magnets with twice the field strength, would be installed and commissioned. It is possible that the physics found in the next decade at the LHC will be such that it will demand such an upgrade, but at this point we don't know enough yet either about the science or about the specifics of the facility that might be proposed. It will require an extensive R&D phase.



R&D Towards Higher Energy

The **US Labs are the world leaders** in Nb₃Sn magnets, the enabling technology for higher energy hadron colliders – **EDLHC or VLHC**.

Implementing the **new IRs** for a luminosity upgrade will be **an important step** in developing this technology **for the colliders of the future**.

- The **first use of Nb₃Sn magnets** in a high energy accelerator.
- In some respects they are **more challenging than the main magnets** of an EDLHC or VLHC.

Key issues for main magnets for a future hadron collider are being **addressed by the base program**:

- Push to the **highest possible field** (e.g. the LBNL program).
- Develop **economical production** techniques (e.g. the FNAL program).
- Explore **alternate technologies** and materials (e.g. the BNL program).



Conclusions

- A Luminosity Upgrade is a high priority goal both for US HEP and for CERN.
- The US Labs can play (and are playing already) a leading role in the R&D towards the Luminosity Upgrade.
 - AP studies of key machine issues and of new IR designs.
 - Magnet R&D for new IRs.
 - Development of instruments to understand and overcome beam limitations.
- The R&D on the Luminosity Upgrade by the US Labs will
 - Bring the upgrade into being sooner.
 - Strongly advance our capabilities in accelerator science.
 - Develop the technologies required for any future higher energy hadron collider.