The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

This work is part of HiLumi LHC Work Package 1: Project Management & Technical Coordination.

The electronic version of this HiLumi LHC Publication is available via the HiLumi LHC web site <http://hilumilhc.web.cern.ch> or on the CERN Document Server at the following URL: <http://cds.cern.ch/search?p=CERN-ACC-SLIDES-2014-0097>
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LHC: Coming up from a 2 years shutdown - Interconnect consolidation

1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 1500 of these splices
3. Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines
7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 4 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

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Other works: R2E

- **Point 1**
  - All equipment are reinstalled and reconnected
  - Commissioning in progress

- **Point 5 & Point 7**
  - Major cabling campaign in progress

UL16 power converters

UL55 safe-room

Warm Cable installation @ P5

TZ76
And many others

- Vacuum
- UPS-RE82
- Cryo plants
- Pumping station
- 18 kV & 3.3 kV circuit breakers
- Before
- After
- RF module replacement
Key point

• We are on time for restarting Physics in LHC
• In April 2015, 13 TeV c.o.m.

• Chamonix Workshop on 22-25 September to define operating conditions and scenarii
New LHC / HL-LHC Plan

Technical limits (experiments, too) like:

- Run I: 0.75 $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  - 50 ns bunch
  - High pile up ~40

- Run II: 1.5 $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  - 25 ns bunch
  - Pile up ~40

- Run III: 1.7-2.2 $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  - 25 ns bunch
  - Pile up ~60

- 5 to 7 x nominal luminosity

- Technical limits: 50 $\Rightarrow$ 25 ns
Mantain and increase physics reach

Necessity of a jump in luminosity (useful luminosity ⇒ data quality)
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with levelling, allowing:

An integrated luminosity of $250 \text{ fb}^{-1} \text{ per year}$, enabling the goal of $3000 \text{ fb}^{-1}$ twelve years after the upgrade. This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Concept of ultimate performance: under definition:

$L_{\text{peak}} \approx 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and $\text{Int. L} \sim 4000 \text{ fb}^{-1}$
This goal would be reached in 2036

What to do make this jump?

Not to mention detector: How to cope with $\mu \sim 140$

M. Lamont,
at RLIUP workshop, October 2013
Rliminating Technical bottlenecks

Cryogenics P4- P1 –P5

8 x 18 kW @ 4.5 K
1'800 SC magnets
24 km and 20 kW @ 1.9 K
36'000 tons @ 1.9 K
96 tons of He

New Plant 8 kW in P4
New Plants for 18 kW in P1 and P5

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Availability: SC links \( \Rightarrow \) removal of EPCs, DFBs from tunnel to surface

- 1 pair 700 m 50 kA – LS2
- 4 pairs 300 m 150 kA (MS) – LS3
- 4 pairs 300 m 150 kA (IR) – LS3
- tens of 6-18 kA CLs pairs in HTS
L = 20 m
(25×2) 1 kA @ 25 K, LHC Link P7

Feb 2014:
World record for HTS
QPS boxes and intervention time

Consolidation of infrastructure!

But also new paradigm: remove from tunnel of QPS (as much as possible)
R2E improvement.
Need further for 1-3 fb$^{-1}$/day!

Workshop in October
The big technical bottleneck: Radiation damage to triplet

peak dose longitudinal profile

7+7 TeV proton interactions
IT quadrupoles
MCBX-1
MCBX-2
MQSX
MCTX nested in MCBX-3
MCOSX

Cold bore insulation ≈ 35 MGy

MCBX3 20 MGy

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The most straightforward action: reducing beam size with a «local» action

LHC has better aperture than anticipated: now all margin can be used; however is not possible to have $\beta^* < 40$ cm
### Parameters (PLC web page)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal</th>
<th>25ns</th>
<th>50ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_b$</td>
<td>1.15E+11</td>
<td>2.2E+11</td>
<td>3.5E+11</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>$N_{tot}$</td>
<td>3.2E+14</td>
<td>6.2E+14</td>
<td>4.9E+14</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.58</td>
<td>1.11</td>
<td>0.89</td>
</tr>
<tr>
<td>x-ing angle [$\mu$rad]</td>
<td>300</td>
<td>590</td>
<td>590</td>
</tr>
<tr>
<td>beam separation [$\sigma$]</td>
<td>9.9</td>
<td>12.5</td>
<td>11.4</td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$\epsilon_n$ [\mu$m$]</td>
<td>3.75</td>
<td>2.50</td>
<td>3</td>
</tr>
<tr>
<td>$\epsilon_L$ [eVs]</td>
<td>2.51</td>
<td>2.51</td>
<td>2.51</td>
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<tr>
<td>energy spread</td>
<td>1.20E-04</td>
<td>1.20E-04</td>
<td>1.20E-04</td>
</tr>
<tr>
<td>bunch length [m]</td>
<td>7.50E-02</td>
<td>7.50E-02</td>
<td>7.50E-02</td>
</tr>
<tr>
<td>IBS horizontal [h]</td>
<td>80 -&gt; 106</td>
<td>18.5</td>
<td>17.2</td>
</tr>
<tr>
<td>IBS longitudinal [h]</td>
<td>61 -&gt; 60</td>
<td>20.4</td>
<td>16.1</td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td>0.68</td>
<td>3.12</td>
<td>2.85</td>
</tr>
<tr>
<td>Reduction factor 'R1*H1' at full crossing angle (no crabbing)</td>
<td>0.828</td>
<td>0.306</td>
<td>0.333</td>
</tr>
<tr>
<td>Reduction factor ‘H0’ at zero crossing angle (full crabbing)</td>
<td>0.991</td>
<td><strong>0.905</strong></td>
<td>0.905</td>
</tr>
<tr>
<td>beam-beam / IP without Crab Cavity</td>
<td>3.1E-03</td>
<td>3.3E-03</td>
<td>4.7E-03</td>
</tr>
<tr>
<td>beam-beam / IP with Crab cavity</td>
<td>3.8E-03</td>
<td>1.1E-02</td>
<td>1.4E-02</td>
</tr>
<tr>
<td>Peak Luminosity without levelling [cm$^{-2}$ s$^{-1}$]</td>
<td>1.0E+34</td>
<td>7.4E+34</td>
<td>8.5E+34</td>
</tr>
<tr>
<td>Virtual Luminosity: Lpeak*H0/R1/H1 [cm$^{-2}$ s$^{-1}$]</td>
<td>1.2E+34</td>
<td><strong>21.9E+34</strong></td>
<td>23.1E+34</td>
</tr>
<tr>
<td>Events / crossing without levelling</td>
<td>19 -&gt; 28</td>
<td>210</td>
<td>475</td>
</tr>
<tr>
<td>Levelled Luminosity [cm$^{-2}$ s$^{-1}$]</td>
<td>-</td>
<td>5E+34</td>
<td>2.50E+34</td>
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<tr>
<td>Events / crossing (with leveling for HL-LHC)</td>
<td>*19 -&gt; 28</td>
<td>140</td>
<td>140</td>
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<tr>
<td>Leveling time [h] (assuming no emittance growth)</td>
<td>- 9.0</td>
<td>18.3</td>
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</tbody>
</table>
The critical zone around IP1 and IP5

3. For collimation we need to change also this part, DS in the continuous cryostat

2. Deep change also matching section: Magnets, collimators and CC

1. Deep change in the IRs and interface to detectors; relocation of Power Supply

4. LR BB compensation wires

1.2 km of LHC !!
Magnet the progress

• LHC dipoles features 8.3 T in 56 mm (designed for 9.3 peak field)
• LHC IT Quads features 205 T/m in 70 mm with 8 T peak field
• HL-LHC
  • 11 T dipole (designed for 12.3 T peak field, 60 mm)
  • New IT Quads features 140 T/m in 150 mm > 12 T operational field, designed for 13.5 T).
New Interaction Region lay out

Longer Quads; Shorter D1 (thanks to SC)

<table>
<thead>
<tr>
<th>Distance to IP (m)</th>
<th>Q1</th>
<th>Q2a</th>
<th>Q2b</th>
<th>Q3</th>
<th>DFB</th>
<th>D1</th>
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<tbody>
<tr>
<td>20</td>
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<td>80</td>
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</tbody>
</table>

- Q: 200 T/m
- MCBX: 3.3 T  1.5 T m
- D1: 1.8 T  26 T m

Thick boxes are magnetic lengths -- Thin boxes are cryostats

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LHC low-β quads: steps in magnet technology from LHC toward HL-LHC

LHC (USA & JP, 5-6 m)
Ø70 mm, \(B_{\text{peak}} \approx 8\) T
1992-2005

LARP TQS & LQ (4m)
Ø90 mm, \(B_{\text{peak}} \approx 11\) T
2004-2010

LARP HQ
Ø120 mm,
\(B_{\text{peak}} \approx 12\) T
2008-2014

LARP & CERN MQXF
Ø150 mm,
\(B_{\text{peak}} \approx 12.1\) T
2013-2020

New structure based on bladders and keys (LBNL, LARP)

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Progress in MQXF (IT quads)

- 1.9K SSL 18.25 kA 205 T/m
- 80% of 1.9K SSL
- 80% of 4.5K SSL
- HQ02b (1.9K)
- HQ02a2 (2.2K)
- HQ02a (4.5K)
- HQ02a (1.9K) (*) 15 more quenches to 16.1 kA
- HQ02a (1.9K) (+) Reached 15 kA current limit

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The **Achromatic Telescopic Squeezing (ATS) scheme**

Small \( \beta^* \) is limited by aperture but not only: **optics matching & flexibility** (round and flat optics), chromatic effects (not only \( Q' \)), spurious dispersion from X-angle,..

A novel optics scheme was developed to **reach un-precedent \( \beta^* \) w/o chromatic limit** based on a kind of **generalized squeeze involving 50% of the ring**

\( \beta^* = 40 \text{ cm} \)

\( \beta^* = 10 \text{ cm} \)

➔ **Proof of principle demonstrated in the LHC down to a \( \beta^* \) of 10-15 cm at IP1 and IP5**

Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS “pre-squeezed” optics (left) and “telescopic” collision optics (right)

The new IR is sort of 8 km long!

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Effect of the crab cavities

- RF crab cavity deflects head and tail in opposite direction so that collision is effectively “head on” and then luminosity is maximized.
And excellent results: RF dipole > 5 MV

¼ w and 4-rods also tested (1.5 MV)
cleaning & vacuum issues: new test under way
Latest cavity designs toward accelerator

Coupler concepts

RF Dipole: Waveguide or waveguide-coax couplers

Double ¼-wave: Coaxial couplers with hook-type antenna

Concentrate on two designs

Present baseline: 3 cavity /cryomodule
4 cavity/cryomod is under study for Crab Kissing TEST in SPS under preparation (A. MacPherson)
P2 - DS collimators ions – 11 T (LS2 -2018)

11 T Nb₃Sn

FNAL - CERN
Low impedance collimators (LS2 & LS3)

New material: MoGr
Controlling diffusion rate: hollow e-lens

Promises of hollow e-lens:
1. Control the halo dynamics without affecting the beam core;
2. Control the time-profile of beam losses (avoid loss spikes);
3. Control the steady halo population (crucial in case of CC fast failures).

Remarks:
- very convincing experimental experience in other machines!
- full potential can be exploited if appropriate halo monitoring is available.
The **Crab-kissing (CK) scheme for pile-up density shaping and leveling** (S. Fartoukh)

Baseline: CC in X-plane “only”

Crab-kissing & variants: CC also in ||-plane

\[ \frac{\partial \mu}{\partial z} \text{ [mm}^{-1}\text{]} \]

... Work on-going together with the machine experiments (S. Fartoukh, A. Valishev, A. Ball, B. Di Girolamo, *et al.*)
The HL-LHC project formally started in 2010; however it is the focal point of 20 years of converging International Collaboration.

Collaboration: the long way
High Luminosity LHC Participants

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In-kind contribution and Collaboration for HW design and prototypes

- Q1-Q3: R&D, Design, Prototypes and in-kind USA
- D1: R&D, Design, Prototypes and in-kind JP
- MCBX: Design and Prototype ES
- HO Correctors: Design and Prototypes IT
- Q4: Design and Prototype FR

CC: R&D, Design and in-kind USA
CC: R&D and Design UK
Implementation plan

- All WP active, from diagnostics to Machine Protection;
- Integration started with vigour as well as QA (workshop soon)
- Cryo, SC links, Collimators, Diagnostics, etc. starts in LS2 (2018)
- Proof of main hardware by 2016; Prototypes by 2017
- Start construction 2017/18 from IT, CC, other main hardware
- IT String test (integration) in 2019-20; Main Installation 2023-24
- Though but – based on LHC experience – feasible
- Cost: 840 MCHF (Material, CERN accounting)