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. 

Oliver Brüning, CERN

ACES Workshop March 7th 2016

HL-LHC Upgrade Plans

O. Brüning
CERN, Geneva, Switzerland
Goal of High Luminosity LHC (HL-LHC):

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:

- Prepare machine for operation beyond 2025 and up to 2035
- Devise beam parameters and operation scenarios for:
  - # enabling a total integrated luminosity of $3000 \text{ fb}^{-1}$
  - # implying an integrated luminosity of $250 \text{ fb}^{-1}$ per year,
  - # design oper. for $\mu \delta 140$ (⇒ peak luminosity $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)
- Operation with levelled luminosity!
- Ten times the luminosity reach of first 10 years of LHC operation!!
LHC Upgrade Goals: Performance optimization

Luminosity recipe (round beams):

\[ L = \frac{n_b \times N_1 \times N_2 \times f_{\text{rev}}}{4 \times * \times n} \times F(\ , \ , \ , \ , s) \]

- 1) maximize bunch intensities
- 2) minimize the beam emittance
- 3) minimize beam size (constant beam power); ➔ triplet aperture
- 4) maximize number of bunches (beam power); ➔ 25ns
- 5) compensate for ‘F’;
- 6) Improve machine ‘Efficiency’

➔ Injector complex
➔ Upgrade LIU
➔ Crab Cavities
➔ minimize number of unscheduled beam aborts
LHC Limitations and HL-LHC Challenges:

- Technical bottle necks (e.g. cryogenics) ⇒ New addit. Equipment
- Insertion magnet lifetime and aperture:
  ⇒ New insertion magnets and low-β with increased aperture
- Geometric Reduction Factor: ⇒ SC Crab Cavities
  ⇒ New technology and a first for a hadron storage ring!
- Performance Optimization: Pileup density ⇒ luminosity levelling
  ⇒ devise parameters for virtual luminosity >> target luminosity
- Beam power & losses ⇒ additional DS (cold region) collimators
- Machine efficiency and availability:
  # R2E ⇒ removal of all electronics from tunnel region
  # e-cloud ⇒ beam scrubbing (conditioning of surface)
  # UFOs ⇒ beam scrubbing (conditioning of surface)
Nominal LHC triplet: 210 T/m, 70 mm coil aperture

- ca. 8 T @ coil
- 1.8 K cooling with superfluid He (thermal conductivity)
- current density of 2.75 kA / mm²

At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm²)!!!

LHC Production in collaboration with USA and KEK
HL-LHC technical bottleneck: Radiation damage to triplet magnets at 300 fb⁻¹

**Peak dose longitudinal profile**

- **Q2**: 27 MGy
- **Cold bore insulation**: ≈ 35 MGy

![Graph showing peak dose longitudinal profile with labels for various cryomodules and a peak dose of 27 MGy at Q2.]
HL-LHC technical bottleneck: Radiation damage to triplet magnets

Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity!!!!!

- Requires larger aperture!
- 70mm at 210 T/m ➔ 150mm diameter 140 T/m
  8T peak field at coils ➔ 12T field at coils!!!
HL-LHC Magnets

- **LHC triplet:**
  210 T/m, 70 mm bore aperture
  ➞ 8 T @ coil (limit of NbTi tech.)

- **HL-LHC triplet:**
  140 T/m, 150 mm coil aperture
  (shielding, $\beta^*$ and crossing angle)
  ➞ ca. 12 T @ coil ➞ 30% longer.
  
  - Requires Nb$_3$Sn technology
    ➞ ceramic type material (fragile)
  
  - US-LARP – CERN collaboration

**US-LARP MQXF magnet design**
Based on Nb$_3$Sn technology
New Interaction Region lay out

Longer Quads; Shorter D1 (thanks to SC)

Thick boxes are magnetic lengths -- Thin boxes are cryostats
HL-LHC Challenges: Crossing Angle

Insertion Layout:

Parasitic bunch encounters:

Operation with ca. 2800 bunches @ 25ns spacing ➔ approximately 30 unwanted collision per Interaction Region (IR).

➔ Operation requires crossing angle

non-linear fields from long-range beam-beam interaction:

efficient operation requires large beam separation at unwanted collision points ➔ Separation of 10 -12 σ ➔ large triplet apertures for HL-LHC upgrade!!
HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

- Reduces the effect of geometrical reduction factor
- Independent for each IP

\[ F = \frac{1}{\sqrt{1 + \frac{c^2}{z^2}}} \]

- Noise from cavities to beam?!?
- Challenging space constraints:
  
  \[ \rightarrow \text{requires novel compact cavity design} \]
Latest cavity designs toward accelerator

3 Advanced Design Studies with Different Coupler concepts

RF Dipole: Waveguide or waveguide-coax couplers

Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017 TS

Double ¼-wave:

Coaxial couplers with different antenna types

Present baseline: 4 cavity/cryomod TEST in SPS under preparation for 2017
And excellent first results: RF Dipole
Recent results from Measurements @ CERN

Initial goal was 3.5 MV however \( \Delta V > 5-6 \) MV would ease integration
Testing Crab Cavities with Beams

Crab Cavity Test Installation in the SPS:

- Vital to gain feedback from operation with beam before launching of cavity production for HL-LHC ➔ need results before LS2!!!
- Tight and ambitious schedule but doable!
  ➔ Visualization and planning now
  ➔ Preparation in EYETS 16/17
  ➔ Installation YETS 17/18

➔ vital for project to be able to launch Carb cavity production by LS2!!! (international partners!!)

Cable and pipework length: ~150-200 m

Cold-box + SPS fire safety

200 m²

65 m

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SPS beam test: a critical step for Crab Cavities (profiting of the EYETS 2016-2017):
LHC Challenges: Beam Power

Unprecedented beam power:

Worry about beam losses:

Failure Scenarios ➔ Local beam Impact

➔ Equipment damage
➔ Machine Protection

Lifetime & Loss Spikes ➔ Distributed losses

➔ Magnet Quench
➔ R2E and SEU
➔ Machine efficiency
Collimation Upgrade Plans for HL-LHC

Collimation Upgrade Path for the HL-LHC:

• 2015 operation experience:
  ➔ up to 280MJ beam energy and no quench from beam losses

Quench test with beam:

\[ E_{b\text{-}\text{max}} > 420\text{MJ}, \ LHC_{\text{nom}} = 335\text{MJ}, \ HL\text{-}LHC = 630\text{MJ} \]

➔ 11T DS collimators in IR7 (2 per beam ➔ 4 units for LS2),
➔ connection cryostat DS collimators in IR2 (2 units total)
➔ mitigation in DS of IR1 & IR5 via orbit bumps

• Hollow e-lens: interesting for Halo depletion
  ➔ on path to Baseline
DS collimators – 11 T Dipole (LS2 -2018)
Prototyping of the by-pass crystostat (QTC) for the installation of a warm collimator in the cold dispersion

Magnet: prototypes reached 11 T field in March 2013!
R2E SEU Failure Analysis - Actions

- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact

- **2011-2012**
  - Focus on equipment with long downtimes; provide shielding

- **LS1 (2013/2014)**
  - Relocation of power converters

- **LS1 – LS2:**
  - Equipment Upgrades

- **LS3 -> HL-LHC**
  - Remove all sensitive equipment from underground installations
IR1 & IR5 Underground Civil Engineering:

P. Fessia, HL-LHC TDR
Vibration Tolerances for Operation
Lessons from Civil Engineering Test Drills and Earth Quakes
On Vibration Tolerances:

• Driven by worries about vibrations from the HL-LHC civil engineering

• GEOTHERM2020
  a renewable energy production project by the Canton of Geneva
Vibration Tolerances for Operation
Lessons from Civil Engineering Test Drills and Earth Quakes
On Vibration Tolerances:

• From Noise to Beam

- \( O(100) \) amplification to cold-mass for certain modes (\( H_0 \))
- \( O(10-100) \) attenuation \( H_1 \) and \( H_2 \)
- order of micrometer tolerance for vibrations!
- Schedule that allows CE construction during LS2!!
- Hollow electron lens for halo depletion!
New Schedule: → HL-LHC CE during LS2

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- **Shutdown/Technical stop**
- **Protons physics**
- **Commissioning**
- **Ions**

**Legend:**

- Blue: LS3
- Green: LS4
- Orange: LS5

---

**Notes:**

- For the years 2015 to 2023, the schedule includes EYETS (End of Year Early Technical Stop) and LS2 (Long Shutdown 2).
- For the years 2024 to 2032, the schedule includes LS3, LS4, and LS5.

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Performance Projections up to HL-LHC:

- **Run I**: Splices fixed
- **Run II**: Injectors upgrade
- **Run III**: New Low-β* quads
- **Crab Cavity Phase 2**: 1000 fb⁻¹
- **300 fb⁻¹**: Technical limits (in experiments, too) like:
  - Cryogenic limit, Radiation & Damage of triplet magnets
  - 5 $10^{34}$ cm⁻²·s⁻¹, 50 ns bunch, high pile up ~40
  - 1.5 $10^{34}$ cm⁻²·s⁻¹, 25 ns bunch, high pile up ~40
  - 1.5 - 2.2 $10^{34}$ cm⁻²·s⁻¹, 25 ns bunch, very high pile up > 60
  - 5 $10^{34}$ cm⁻²·s⁻¹ levelled, 25 ns bunch, very high pile up ~140
  - Energy: 6.5 TeV
  - Intensity Upgrade
  - 81 - 82\% current efficiency

**NOTE**: The diagram includes technical limits and performance projections up to HL-LHC.
The critical zones around IP1 and IP5

1. New triplet $\text{Nb}_3\text{Sn}$ required due to:
   - Radiation damage
   - Need for more aperture
   - Changing the triplet region is not enough for reaching the HL-LHC goal!

2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4.

3. For collimation we also need to change the DS in the continuous cryostat: 11T $\text{Nb}_3\text{Sn}$ dipole

More than 1.2 km of LHC!!

Plus technical infrastructure (e.g. Cryo and Powering)!!
## HL-LHC Baseline Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal LHC (design report)</th>
<th>HL-LHC 25ns (standard)</th>
<th>HL-LHC 25 ns (BCMS)</th>
<th>HL-LHC 50ns</th>
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<tbody>
<tr>
<td>Beam energy in collision [TeV]</td>
<td>7</td>
<td>7</td>
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<tr>
<td>$N_b$</td>
<td>$1.15\times 10^{11}$</td>
<td>$2.2\times 10^{11}$</td>
<td>$2.2\times 10^{11}$</td>
<td>$3.5\times 10^{11}$</td>
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<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2736</td>
<td>2592</td>
<td>1404</td>
</tr>
<tr>
<td>Number of collisions at IP1 and IP5</td>
<td>2808</td>
<td>2736</td>
<td>2592</td>
<td>1404</td>
</tr>
<tr>
<td>$N_{tot}$</td>
<td>$3.2\times 10^{14}$</td>
<td>$6.0\times 10^{14}$</td>
<td>$5.7\times 10^{14}$</td>
<td>$4.9\times 10^{14}$</td>
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<td>beam current [A]</td>
<td>0.58</td>
<td>1.09</td>
<td>1.03</td>
<td>0.89</td>
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<td>x-ing angle [μrad]</td>
<td>285</td>
<td>590</td>
<td>590</td>
<td>590</td>
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<tr>
<td>beam separation [σ]</td>
<td>9.4</td>
<td>12.5</td>
<td>12.5</td>
<td>11.4</td>
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<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
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<tr>
<td>$\epsilon_n$ [μm]</td>
<td>3.75</td>
<td>2.50</td>
<td>2.50</td>
<td>3</td>
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<tr>
<td>$\epsilon_L$ [eVs]</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
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<td>r.m.s. energy spread</td>
<td>$1.13\times 10^{-4}$</td>
<td>$1.13\times 10^{-4}$</td>
<td>$1.13\times 10^{-4}$</td>
<td>$1.13\times 10^{-4}$</td>
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<tr>
<td>r.m.s. bunch length [m]</td>
<td>$7.55\times 10^{-2}$</td>
<td>$7.55\times 10^{-2}$</td>
<td>$7.55\times 10^{-2}$</td>
<td>$7.55\times 10^{-2}$</td>
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<tr>
<td>IBS horizontal [h]</td>
<td>80 -&gt; 106</td>
<td>18.5</td>
<td>18.5</td>
<td>17.2</td>
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<tr>
<td>IBS longitudinal [h]</td>
<td>61 -&gt; 60</td>
<td>20.4</td>
<td>20.4</td>
<td>16.1</td>
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<tr>
<td>Piwinski angle</td>
<td>0.65</td>
<td>3.14</td>
<td>3.14</td>
<td>2.87</td>
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<tr>
<td>Geometric loss factor R0 without crab-cavity</td>
<td>0.836</td>
<td>0.305</td>
<td>0.305</td>
<td>0.331</td>
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<tr>
<td>Geometric loss factor R1 with crab-cavity</td>
<td>(0.981)</td>
<td>0.829</td>
<td>0.829</td>
<td>0.838</td>
</tr>
<tr>
<td>beam-beam / IP without Crab Cavity</td>
<td>$3.1\times 10^{-3}$</td>
<td>$3.3\times 10^{-3}$</td>
<td>$3.3\times 10^{-3}$</td>
<td>$4.7\times 10^{-3}$</td>
</tr>
<tr>
<td>beam-beam / IP with Crab cavity</td>
<td>$3.8\times 10^{-3}$</td>
<td>$1.1\times 10^{-2}$</td>
<td>$1.1\times 10^{-2}$</td>
<td>$1.4\times 10^{-2}$</td>
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<tr>
<td>Peak Luminosity without crab-cavity [cm$^{-2}$ s$^{-1}$]</td>
<td>$1.00\times 10^{34}$</td>
<td>$7.18\times 10^{34}$</td>
<td>$6.80\times 10^{34}$</td>
<td>$8.44\times 10^{34}$</td>
</tr>
<tr>
<td>Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm$^{-2}$ s$^{-1}$]</td>
<td>(1.18E+34)</td>
<td>19.54E+34</td>
<td>18.52E+34</td>
<td>21.38E+34</td>
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<tr>
<td>Events / crossing without levelling w/o crab-cavity</td>
<td>27</td>
<td>198</td>
<td>198</td>
<td>454</td>
</tr>
<tr>
<td>Levelling Luminosity [cm$^{-2}$ s$^{-1}$]</td>
<td>-</td>
<td>$5.00\times 10^{34}$</td>
<td>$5.00\times 10^{34}$</td>
<td>$2.50\times 10^{34}$</td>
</tr>
<tr>
<td>Events / crossing (with levelling and crab-cavities for HL-LHC)</td>
<td>27</td>
<td>138</td>
<td>146</td>
<td>135</td>
</tr>
<tr>
<td>Peak line density of pile up event [evt/mm] (max over stable beam)</td>
<td>0.21</td>
<td>1.25</td>
<td>1.31</td>
<td>1.20</td>
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<tr>
<td>Levelling time [h] (assuming no emittance growth)</td>
<td>0.21</td>
<td>1.25</td>
<td>1.31</td>
<td>1.20</td>
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Reserve Transparencies
Eliminating Technical Bottlenecks
Cryogenics P4- P1 –P5

New 18 kW Plants in P1 and P5 (LS3)

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
High Luminosity LHC Participants
Implementation plan:

- TDR: OCT 2015; TDR_v2: 2017
- Cryo, SC links, Collimators, Diagnostics, etc. starts in LS2 (2018)
- Proof of main hardware by 2016; Prototypes by 2017 (IT, CC)
- Start construction 2018 for IT, CC & other main hardware
- IT String test (integration) in 2019-20; Main Installation 2023-25
- Though but – based on LHC experience – feasible
Project approval milestones:

- June 2010: launch of High Luminosity LHC
- November 2010: HiLumi DS application to FP7
- November 2011: start FP7-HiLumi DS
- May 2013: approval of HL-LHC as 1st priority of EU-HEP strategy by CERN Council in Brussels
- May 2014: US P5 ranks HL-LHC as priority for DOE
- June 2014: CERN Council approves the financial plan of HL-LHC till 2025 (with an overall 10% budget cut)
LHC Challenges: Quench Protection

Magnet Quench:

→ beam abort → several hours of recovery

HL LHC beam intensity: \( I > 1 \text{ A} \Rightarrow > 7 \times 10^{14} \text{ p/beam} \)

Quench level: \( N_{\text{lost}} < 7 \times 10^8 \text{ m}^{-1} \Rightarrow < 10^{-6} N_{\text{beam}} \)

(compared to 20% to 30% in other superconducting rings)

→ requires collimation during all operation stages!

→ requires good optic and orbit control!

→ HL-LHC luminosity implies higher leakage from IP & requires additional collimators

Which we have demonstrated during RunI
FNAL: MBHSP01 – 1-in-1 Demonstrator (2 m)

40-strand cable fabricated using FNAL cabling machine

Coil fabrication

Collared coil assembly

Cold mass assembly

MBHSP02 passed 11 T field during training at 1.9 K with $I = 12080\text{A}$ on 5th March 2013!
LHC Upgrade Goals: Performance optimization

- Levelling:

- Luminosity limitation(s):
  - Even Pileup in detectors
  - Debris leaving the experiments and impacting in the machine (magnet quench protection)
  - Triplet Heat Load
LHC low-β quads: steps in magnet technology from LHC toward HL-LHC

- **LHC (USA & JP, 5-6 m)**
  - Φ70 mm, $B_{\text{peak}} \approx 8$ T
  - 1992-2005

- **LARP TQS & LQ (4m)**
  - Φ90 mm, $B_{\text{peak}} \approx 11$ T
  - 2004-2010

- **LARP HQ**
  - Φ120 mm, $B_{\text{peak}} \approx 12$ T
  - 2008-2014

- **LARP & CERN MQXF**
  - Φ150 mm, $B_{\text{peak}} \approx 12.1$ T
  - 2013-2020

New structure based on bladders and keys (LBNL, LARP)
The HL-LHC Nb-Ti magnet zoo…

D1 (KEK)  Nested Orbit corrector (CIEMAT)  HO correctors: superferric (INFN)

D2 (INFN)  Q4 (CEA)  D2 corr

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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
3 Crab Cavity prototypes:

- RF-Dipole Nb prototype [ODU-SLAC]
- 4-rod in SM18 for RF measurements [Lancaster UK]
- 4-rod prepared for rinsing @ CERN
- DQWR prototype (17-Jan-2013) [BNL]
Scrubbing with 25ns: Heat Load Evolution

M. Giovannozzi @ LMC – September 30th

Gianni Iadarola and e-cloud team