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.

The 53rd Course of International School of Subnuclear physics
E. Majorana Center – ERICE, 26 June 2015
Each bunch is ~ 30 cm < 1 mm radius cylinder
1-2 \(10^{11}\) protons/bunch
2600-2800 bunches per ring
Accelerators are very fine microscopes: we use the light of quantum mechanics to explore the acto/zeptometer dimensions!

\[ \lambda = \frac{h}{p} ; \quad @\text{LHC: } T = 1 \text{ TeV} \implies \lambda \approx 10^{-18} \text{ m} \]
CERN proton accelerator chain

- **LHC**: $2 \times (0.45 - 7)$ TeV
- **SPS**: 26 – 450 GeV
- **PS**: 1.4 - 26 GeV
- **PSB**: 0.05 – 1.4 GeV
- **Linac**: 0-50 MeV

Start the protons out here
LHC: the giant $E_{beam} \approx 0.3BR$
And its four big eyes

Exploring new frontier with hadronic collisions

LHC ring: 27 km circumference
SC : an enabling technology

- **Superconducting LHC**
  - Tunnel: 27 km
  - Field: 8.3 T
  - Cryoplant power at the plug:
    - 40 MW: *always on*
    - ~70 MW for LHC
    - 150 MW for the accelerator complex
    - 180 MW for the whole CERN complex

- **Normalconducting LHC**
  - Peak power: ~2,200 MW
  - Average power (0.4 coefficient): 900 MW only for the accelerator
Accelerators progress: SC domination
LHC; the largest instrument

- 27 km, p-p at 7+7 TeV
  3.5+3.5 2010, **4+4 in 2012**, **6.5+6.5 2015**
- 1232 x 15 m Twin Dipoles
- Operational field 8.3 T @11.85 kA (9 T design)
- HEII cooling, 1.9 K with 3 km circuits (130 tonnes He inventory).

- Field homogeneity of $10^{-4}$, bending strength uniformity better then $10^{-3}$. Field quality control (geometric and SC effects) at $10^{-5}$. 
• 392 Main Quads Two-In-One rated for a peak field of 7 T.
• About 100 other Two-in-One MQs
• 32 MQX (low-β) single bore for luminosity (design L=1·10^{34} \text{cm}^{-2}\text{s}^{-1}), 70 mm apertures, about 8 T peak field, high quality
• A «zoo» of 7600 «small» Sc magnets (correctors and higher order magnets
• Total: 9 GJ stored energy (at nominal)

• Large detector magnets
  ATLAS toroid – 25 m long 1.2 GJ
  CMS solenoid – 12 m long 2.5 GJ
The LHC Magnetic Lattice

- LHC features 112 circuits/beam + hundreds of orbit correctors
- Field errors in SC magnets vary with time & operation history
- Adjustments during operation
The LHC superconductor
1200 tonnes -7000 km of Cu/Nb-Ti cable

<table>
<thead>
<tr>
<th>STRAND</th>
<th>Type 01</th>
<th>Type 02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>1.065</td>
<td>0.825</td>
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<tr>
<td>Cu/NbTi ratio</td>
<td>1.6-1.7 ± 0.03</td>
<td>1.9-2.0 ± 0.03</td>
</tr>
<tr>
<td>Filament diameter (μm)</td>
<td>7</td>
<td>6</td>
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<tr>
<td>Number of filaments</td>
<td>8800</td>
<td>6425</td>
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<tr>
<td>Jc (A/mm²) @1.9 K</td>
<td>1530 @ 10 T</td>
<td>2100 @ 7 T</td>
</tr>
<tr>
<td>μ₀M (mT) @1.9 K, 0.5 T</td>
<td>30 ±4.5</td>
<td>23 ±4.5</td>
</tr>
<tr>
<td>CABLE</td>
<td>Type 01</td>
<td>Type 02</td>
</tr>
<tr>
<td>Number of strands</td>
<td>28</td>
<td>36</td>
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<tr>
<td>Width (mm)</td>
<td>15.1</td>
<td>15.1</td>
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<tr>
<td>Mid-thickness (mm)</td>
<td>1.900 ±0.006</td>
<td>1.480 ±0.006</td>
</tr>
<tr>
<td>Keystone angle (degrees)</td>
<td>1.25 ±0.05</td>
<td>0.90 ±0.05</td>
</tr>
<tr>
<td>Cable Ic (A) @ 1.9 K</td>
<td>13750 @ 10T</td>
<td>12960 @ 7T</td>
</tr>
<tr>
<td>Interstrand resistance (μΩ)</td>
<td>10-50</td>
<td>20-80</td>
</tr>
</tbody>
</table>
SCRF, Cryo...

400 MHz Standing wave RF

- 4 single cell cavities in cryomodule, 2 cryom./beam. Total 16 cavities.
- Sputtered niobium design (as LEP)
- Gradient 5.5 MV/m nominal (8 MV/m available)
- Nominal 2MV, up to 3 MV at 8 MV/m

Cryo: 8 x 18 kW@4.5K which gives 8 x 2.4 kW @ 1.9 K
Magnets construction snapshots
LHC!
LHC construction timeline

1985: First ideas - Twin Dipoles and Hell cooling

1990: R&D for 8-10 T: 13 kA cables, short models, 10 m long prototypes, 1st string test

1995: Final design, industrialization start pre-series

2000: Magnet construction, performance test, tunnel preparation

2005: Installation, LHC start Incident

2010: Restart 4.2 T

8 T

Magnet designs at first LHC workshop, 1984

First LHC dipole prototype on the test bench (June 1994)

Final dipole cross section (frozen 1999)

Assembly of 15 m long coils in industry, 2003

Continuous magnet line installed in the 27 km LHC tunnel, 2006

First energy record in the proton beam, December 2009
Unprecedented stored beam energy

Nominal LHC design: \(3 \times 10^{14}\) protons accelerated to 7 TeV/c circulating at 11 kHz

At less than 1% of nominal intensity LHC enters new territory. Collimators must survive expected beam loss... Energy DENSITY is even morer dangerous....
Machine Protection

SC Coil: quench limit 15-100 mJ/cm³

Beam 140 MJ

Not a single accidental beam induced quench at 7/8 TeV (3 years Run I)
2 beam induced quenches 13 TeV (2015)

11 magnet quench at 450 GeV – injection kicker flash-over in Run I

Operations unpinned by superb performance of machine protection
Rigorous machine protection follow-up, qualification, and monitoring
Beam Collimation

- **Core**
  - > 350 MJ / beam
  - 140 MJ / beam in 2012

- **Primary halo (p)**
  - Impact parameter ≤ 1 μm

- **Secondary halo**
  - Unavoidable losses

- **Shower**
  - p

- **Tertiary halo**
  - p

- Without beam cleaning (collimators):
  - Quasi immediate quench of superconducting magnets (for higher intensities) and stop of physics.
  - Required very good cleaning efficiency.

- **Absorber**
  - CFC
  - W/Cu
  - SC magnets and particle physics exp.
The Higgs: the needle in a haystack

$Z \rightarrow \mu\mu$ event from 2012 data with 25 reconstructed vertices
Luminosity: \( L \equiv dN_{ev}/dt \times 1/\sigma \)

Integrated lumi \( \propto \) Events

\[
L = \frac{f_{rev} \, n_b \, N_b^2 \, \sqrt{4\pi \varepsilon_n \beta^*}}{R}
\]

\[
R = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^* \gamma}\right)^2}}
\]

Beam current and emittance:
- Involve Inj chain and whole ring
- \( \beta^* \) involve «only» 2 IRs, 1.2 km.

\[
L_0 = 1 \cdot 10^{34} \, \text{cm}^{-2} \text{s}^{-1}
\]

LHC has been designed for \( L_0 \)
- All systems have singularly designed tentatively for ultimate 2\( L_0 \) (to be verified...)

LRossi@Erice- HiLumi LHC
New LHC / HL-LHC Plan

LHC

LS1
spiral consolidation button collimators R2E project
experiment beam pipes

13-14 TeV
2012 2013 2014

EYETS
SPS CC

LS2
Injector upgrade cryogenics Point 4 dispersion suppression collimation
experiment upgrade phase I

14 TeV
2015 2016 2017 2018 2019

LS3
HL-LHC installation
experiment upgrade phase 2

Run III

2023 2024 2025 2035

Run I
nominal luminosity 75%

Run II
nominal luminosity

30 fb⁻¹

0.75 \(10^{34}\) cm⁻²s⁻¹
50 ns bunch high pile up ~40

Run III

150 fb⁻¹

1.5 \(10^{34}\) cm⁻²s⁻¹
25 ns bunch pile up ~40

250 fb⁻¹

1.7-2.2 \(10^{34}\) cm⁻²s⁻¹
25 ns bunch pile up ~60

Lumi saturation & Technical bottlenecks:

50 \(\Rightarrow\) 25 ns
Mantain and increase physics reach

Necessity of a jump in luminosity (useful luminosity ⇒ data quality)
c) Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.
Project Kick off meeting on 11 Nov 2013
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 fb$^{-1}$ per year, enabling the goal of 3000 fb$^{-1}$. This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Concept of ultimate performance (Oct.2013, ECFA & RLIUP) under study:

$L_{\text{peak}} \approx 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and $\text{Int. } L \sim 4000 \text{ fb}^{-1}$

LHC should not be the limit, would Physics require more...
This goal would be reached by 2035-36

What to do, to make this jump?
Luminosity $\propto$ collision rate
LIU Project Definition

• Mandate (December 2010)
  • “The LHC Injectors Upgrade should plan for delivering reliably to the LHC the beams required for reaching the goals of the HL-LHC. This includes LINAC4, the PS booster, the PS, the SPS, as well as the heavy ion chain.”

Implementation

The LIU Project will:

- Analyze the status of the injectors and the HL-LHC requirements,
- Propose an upgrade path for the injectors, exploiting the work done by the Task Forces on the “PSB energy upgrade“ and “SPS upgrade“ and by the Working Group on the SPS upgrade,
- Organize the upgrades (WBS with resources and planning) and take care of their implementation,
- Take care of hardware and beam commissioning.
PSB upgrade

160 MeV H⁻ injection

Increased intensity and brightness

2 GeV upgrade

<table>
<thead>
<tr>
<th>System</th>
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</thead>
<tbody>
<tr>
<td>Beam Dynamics</td>
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<tr>
<td>Magnets</td>
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<tr>
<td>RF Systems</td>
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<tr>
<td>Power Converters</td>
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<tr>
<td>Beam Instrumentation</td>
</tr>
<tr>
<td>Beam Intercepting Devices</td>
</tr>
<tr>
<td>Vacuum System</td>
</tr>
<tr>
<td>LINAC4 to PSB transfer line and PSB injection systems</td>
</tr>
<tr>
<td>PSB Extraction system and PSB-PS transfer line</td>
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<tr>
<td>Controls</td>
</tr>
<tr>
<td>Electrical Systems</td>
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<tr>
<td>Cooling and Ventilation</td>
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<tr>
<td>Installation, Transport and Handling</td>
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<tr>
<td>Civil Engineering</td>
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<tr>
<td>Radiation Protection</td>
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<tr>
<td>Interlock Systems</td>
</tr>
<tr>
<td>Survey</td>
</tr>
<tr>
<td>Commissioning and Operation</td>
</tr>
<tr>
<td>Half-Sector Test Project + Stripping Foil Test</td>
</tr>
</tbody>
</table>

All details are available at: [https://espace.cern.ch/liu-project/liu-psb/default.aspx](https://espace.cern.ch/liu-project/liu-psb/default.aspx)
PS upgrade

J.B. Adams – 25 Nov. 1959 – Design intensity: $3 \times 10^{11}$ p/p

- Beam Dynamics
- Magnets
- RF Systems
- Power Converters
- Beam Instrumentation
- Beam Intercepting Devices
- Vacuum System
- 2 GeV injection system
- Controls
- Electrical Systems
- Cooling and Ventilation
- Installation, Transport and Handling
- Civil Engineering
- Radiation Protection
- Interlock Systems
- Survey
- Commissioning and Operation

Increased intensity and brightness

2 GeV injection

Radioprotection
SPS upgrade

200 MHz Travelling Wave Accelerating Structures

One four sections cavity
(four power couplers and two terminating power loads)

| Beam Dynamics |
| Magnets       |
| RF Systems    |
| Beam Instrumentation |
| Beam loss control |
| Electron cloud mitigation |
| Beam transfer systems |
| Vacuum System |
| Machine interlocks |

Increased intensity and brightness
Faster kickers for ions
LHC - 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
- MCQSOX

Cold bore insulation ≈ 35 MGy

F. Cerutti, N. Mokhov, L. Esposito,...
The most straight forward 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

Smaller $\beta^* \Rightarrow$ larger IT aperture
<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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</thead>
<tbody>
<tr>
<td>Beam energy in collision [TeV]</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>$N_b$</td>
<td>1.15E+11</td>
<td>2.2E+11</td>
<td>2.2E11</td>
<td>3.5E+11</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2748</td>
<td>2604</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>
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<tr>
<td>$N_{tot}$</td>
<td>3.2E+14</td>
<td>6.0E+14</td>
<td>5.7E+14</td>
<td>4.9E+14</td>
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<tr>
<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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<tr>
<td>x-ing angle [μrad]</td>
<td>285</td>
<td>590</td>
<td>590</td>
<td>590</td>
</tr>
<tr>
<td>beam separation [σ]</td>
<td>9.4</td>
<td>12.5</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>
<td>0.15</td>
</tr>
<tr>
<td>$\varepsilon_n$ [μm]</td>
<td>3.75</td>
<td>2.50</td>
<td>2.50</td>
<td>3</td>
</tr>
<tr>
<td>$\varepsilon_L$ [eVs]</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>r.m.s. energy spread</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
</tr>
<tr>
<td>r.m.s. bunch length [m]</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
<td>7.55E-02</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>
</tr>
<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><strong>Geometric loss factor R1 with crab-cavity</strong></td>
<td>(0.981)</td>
<td><strong>0.829</strong></td>
<td><strong>0.829</strong></td>
<td><strong>0.838</strong></td>
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<tr>
<td>beam-beam / IP without Crab Cavity</td>
<td>3.1E-03</td>
<td>3.3E-03</td>
<td>3.3E-03</td>
<td>4.7E-03</td>
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<tr>
<td>beam-beam / IP with Crab cavity</td>
<td>3.8E-03</td>
<td><strong>1.1E-02</strong></td>
<td><strong>1.1E-02</strong></td>
<td><strong>1.4E-02</strong></td>
</tr>
<tr>
<td>Peak Luminosity without crab-cavity [cm⁻² s⁻¹]</td>
<td>1.00E+34</td>
<td>7.18E+34</td>
<td>6.80E+34</td>
<td>8.44E+34</td>
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<tr>
<td>Virtual Luminosity with crab-cavity: L_peak*R1/R0 [cm⁻² s⁻¹]</td>
<td>(1.18E+34)</td>
<td><strong>19.54E+34</strong></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>Levelled Luminosity [cm⁻² s⁻¹]</td>
<td>-</td>
<td><strong>5.00E+34</strong></td>
<td>5.00E34</td>
<td>2.50E+34</td>
</tr>
<tr>
<td>Events / crossing (with levelling and crab-cavities for HL-LHC)</td>
<td>27</td>
<td><strong>138</strong></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><strong>1.25</strong></td>
<td>1.31</td>
<td>1.20</td>
</tr>
<tr>
<td>Levelling time [h] (assuming no emittance growth)</td>
<td>-</td>
<td>8.3</td>
<td>7.6</td>
<td>18.0</td>
</tr>
</tbody>
</table>

**ATS required**

LRossi@Erice- HiLumi LHC
The largest HEP accelerator in construction

ATLAS CMS

Dispersion Suppressor (DS)

Matching Section (MS)

Interaction Region (ITR)

Modifications

1. In IP2: new DS collimation with 11 T
2. In IP7 new DS collimation with 11 T

Complete change and new lay-out

1. TAN
2. D2
3. CC
4. Q4
5. All correctors
6. Q5 (Q6 @1.9 K?)
7. New MQ in P6
8. New collimators

Complete change and new lay-out

1. TAS
2. Q1-Q2-Q3
3. D1
4. All correctors
5. Heavy shielding (W)

> 1.2 km of LHC!!

Cryogenics, Protection, Interface, Vacuum, Diagnostics, Inj/Extr... extension of infrastr.
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
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)

Thick boxes are magnetic lengths -- Thin boxes are cryostats
LHC low-\(\beta\) quads: steps in magnet technology from LHC toward HL-LHC

LHC (USA & JP, 5-6 m)
\(\varnothing 70\) mm, \(B_{\text{peak}} \sim 8 \) T
1992-2005

LARP TQS & LQ (4m)
\(\varnothing 90\) mm, \(B_{\text{peak}} \sim 11 \) T
2004-2010

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

LARP HQ
\(\varnothing 120\) mm, \(B_{\text{peak}} \sim 12 \) T
2008-2014

LARP & CERN MQXF
\(\varnothing 150\) mm, \(B_{\text{peak}} \sim 12.1 \) T
2013-2020

LRossi@Erice- HiLumi LHC
SHIELDING THE NEW TRIPLET – CP – D1 [II]

peak dose longitudinal profile

7+7 TeV proton interactions
HL-LHC at 3000 fb$$^{-1}$$ - 10 cm gap
LHC at 300 fb$$^{-1}$$

16 mm in Q1 and 6 mm elsewhere

larger values for increasing crossing angle

beam screen gap in the interconnects is critical

more than 600 W in the cold masses
as well as in the beam screen
(i.e. 1.2-1.3 kW in total)

tungsten inserts on the beam screen

16 mm in Q1 and 6 mm elsewhere

peak dose [MGy]
distance from IP [m]

peak dose [MGy]
distance from IP [m]

HL-LHC vs LHC
(BEFORE vs AFTER LS3)

more than 600 W in the cold masses
as well as in the beam screen
(i.e. 1.2-1.3 kW in total)
LARP Quadrupole Magnet Development

First (and only) ~4m long Nb$_3$Sn magnet in the world

Very Preliminary!
Going up to 11 or 12 T: forces doubles

HiLumi magnets!
Progress in MQXF (IT quads)

- First coil (1 m) : 2014!
- Magnet test 2015
- Long Magnets: 2016-17
- Many new technological development:
  - Magnet Protection
  - Insulation
  - Precision mechanics
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.
- Crab cavity maximizes the lumi and can be used also for luminosity levelling: if the lumi is too high, initially you don’t use it, so lumi is reduced by the geometrical factor. Then they are slowly turned on to compensate the proton burning.
Crab Cavity, for p-beam rotation at 10 fs level!

Elliptical type CC has been tested first in KEK 2008
Situation: from drawings to reality...

All Prototypes in Bulk Niobium (2011-12)

LARP-BNL  LARP-ODU-JLAB  UniLancaster-CI-CERN
And excellent results: RF dipole > 5 MV

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

Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration and allow Crab-Kiss (see later)
Crab Cavities for fast beam rotation

Present baseline: 4 cavity /cyomodule under study for Crab Kissing TEST in SPS under preparation (A. MacPherson)
Latest cavity designs toward accelerator

RF Dipole: Waveguide or waveguide-coax couplers

4-rod: Coaxial couplers with different antenna types

Dressed cavity in He tank

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

Complete criomodule for test in SPS
Low impedance collimators (LS2 & LS3)

New material: MoGr

Reduce impedance by > 2)
S. Redaelli et al.
P2 - DS collimators ions – 11 T (LS2 -2018)

LHC PROJECT

halo

Q7 Q8 Q9 Q10

11 T Nb$_3$Sn

FNAL - CERN
CERN 11 T dipole (1.8 m long model)
Integrated lumi $\Rightarrow$ availability

2012 Physics Run: Overall Availability

2012 Proton Run Efficiency 27.6%

- **Access**: 13.8%
- **Ramp**: 15.0%
- **SetUp**: 2.1%
- **Squeeze**: 5.0%
- **Injection**: 36.5%

**Hubner factor**

$H = 11.574 \times \frac{L_{\text{Del}}}{(D \times L_{\text{Peak}})}$

$\Rightarrow H = 0.175$

$D = 200.5 \text{ days}$

$L_{\text{Peak}} = 7695 \ (\mu b.s)^{-1}$

$L_{\text{Del}} = 23.269 \ fb^{-1}$

$H_{2011_{LP}} = 0.156$

**SB Time**: 73.2 days  
**Total Time**: 200.5 days

2012 Availability Compared to 2011 Production Run
Luminosity levelling

Gain: low pile up and low losses (debris) in the IT triplet
HiLumi: 3 fb$^{-1}$/day !!!
Eliminating Technical Bottlenecks

Cryogenics P4- P1 –P5

New Plant $\geq 6$ kW in P4 (LS2!)
Two new 18 kW Plants in P1 and 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
SC link to remove PC from Rad environment: High current- High temp.

Tested March 2014
I = 20 kA
T = 24 K
Bpeak = 1 T
Length = 2×20 m

Φext ~ 65 mm

A. Ballarino,
CERN
$L = 20 \text{ m}$

$(25 \times 2) \ 1 \text{kA} @ 25 \text{ K}, \text{ LHC Link P7}$
R2E improvement.
Need further for 1-3 fb\(^{-1}\)/day!

- 0.5 dumps/fb\(^{-1}\) means 1 dump/day, \(\Rightarrow\) 4 hours lost/day!

SC links
Rad-hard cards for msot EPC QPS
QPS boxes and intervention time

Consolidation of infrastructure!
But also new paradigm: remove from tunnel of QPS (as much as possible)
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 based on a kind of generalized squeeze involving 50% of the ring

$\beta^* = 40$ cm

$\beta^* = 10$ cm

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

ATS is not an option is critical for the upgrade; implementation in Run II or Run III is beneficial!
The "crab-kissing" (CK) scheme (2/5)

**HL-LHC w/o CK scheme:** Plan A (solid) and Plan B (dotted)
- 12.5 MV crabs in X-plane, round optics (15/15 cm), $\sigma_z = 7.5$ cm (Plan A)
- or bb wire, flat optics (50/10 cm), $\sigma_z = 10$ cm (Plan B)

**"HL-LHC+" with CK scheme** and Gaussian bunch profile
..adding crab-cavities to Plan B in X and || planes (6 MV+7 MV)

**"HL-LHC++" with CK scheme** and rectangular bunch profile
... adding a new 800 MHz RF system (still keeping $\sigma_z = 10$ cm)

(S. Fartoukh)@ECFA HL–LHC Exper. Workshop, Aix-les-Bains 7 October 2013

→ A net gain by a factor $\sqrt{2}$ at each step
.... at nearly constant integrated performance
Implementation plan

- **PDR:** Nov 2014; Ext. Cost & Schedule Review in March 2015;
- **TDR:** OCT 2015; TRD_v2: 2017
- Proof of main hardware by 2016; Prototypes by 2017 (IT, CC)
- Cryo, SC links, Collimators, Diagnostics, etc. starts in LS2 (2018)
- Start construction 2018 from IT, CC, other main hardware
- IT String test (integration) in 2019-20; Main Installation 2023-24
- Though but – based on LHC experience – feasible
LHC / HL-LHC Plan

Run I  Run II  Run III  Run IV, V...

LS1
- splice consolidation
- button collimators
- R2E project
- experiment beam pipes
- 30 fb⁻¹

LS2
- 13-14 TeV
- 14 TeV
- 14 TeV
- 2011-2014
- EYETS
-Injector upgrade Point 4
- D8 collimation IP2
- 6PS CC
- experiment upgrade phase 1
- experiment upgrade phase 2
- 2x nominal luminosity
- radiation damage
- cryostat interaction regions
- 6 to 7x nominal luminosity

LS3
- HL-LHC installation
- 2023-2025
- 300 fb⁻¹
- 2026
- 3000 fb⁻¹
- integrated luminosity

Civil engineer works for HL-LHC

Lay-out, permits, tenders, preparation

Excavation period

Surface buildings and services

Problem of vibrations makes difficult/impossible to excavate during Run III
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.
Since 2014
Future Circular Collider

First studies on a new 80-100 km tunnel in the Geneva area

- 42 TeV with 8.3 T using present LHC dipoles
- 80 TeV with 16 T based on Nb$_3$Sn dipoles
- 100 TeV with 20 T based on HTS dipoles

HE-LHC : 33 TeV with 20T magnets
Is it really possibile to go so high?

Looking at performance offered by practical SC, considering tunnel size and basic engineering (forces, stresses, energy) the practical limits is around 20 T. Such a challenge is similar to a 40 T solenoid (μ-C)
# FCC magnet catalog – HTS option

By Luca Bottura – CERN @ WAMHTS-1

<table>
<thead>
<tr>
<th></th>
<th>B / G (T) / (T/m)</th>
<th>B$_{\text{peak}}$ (T)</th>
<th>dB/dt (mT/s)</th>
<th>Bore (mm)</th>
<th>Length (units x m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC</td>
<td>MB 20</td>
<td>21</td>
<td>16</td>
<td>40</td>
<td>3662 x 14.3</td>
</tr>
<tr>
<td></td>
<td>MQ 375</td>
<td>10</td>
<td>10</td>
<td>40</td>
<td>610 x 6.6</td>
</tr>
<tr>
<td></td>
<td>QX 200</td>
<td>12.5</td>
<td>12.5</td>
<td>90</td>
<td>Optics ?</td>
</tr>
<tr>
<td></td>
<td>D1 12</td>
<td>13</td>
<td>13</td>
<td>60</td>
<td>4x2 x 12</td>
</tr>
<tr>
<td></td>
<td>D2 10</td>
<td>10.5</td>
<td>10.5</td>
<td>60</td>
<td>4x3 x 10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Booster in the FCC</th>
<th>MB 1.5</th>
<th>2.2</th>
<th>2.2</th>
<th>50</th>
<th>3662 x 14.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>injector in the LHC</td>
<td>MB 5</td>
<td>5.25</td>
<td>20</td>
<td>50</td>
<td>1232 x 14.3</td>
</tr>
<tr>
<td>injector in the SPS</td>
<td>MB 12</td>
<td>12.5</td>
<td>100</td>
<td>50</td>
<td>892 x 4.7</td>
</tr>
</tbody>
</table>

For ee ring also hundreds of SCRF cavities of high power SC links can become backbone of electric infrastructure.
**Nb$_3$Sn : difficult but is a must to go beyond**

- Recent 23.4 T (1 GHz) NMR Magnet for spectroscopy in Nb$_3$Sn (and Nb-Ti). 15-20 tons/year for NMR and HF solenoids. Experimental MRI is taking off.
- ITER: 500 t in 2010-2015! It is comparable to LHC!

- HEP ITD (Internal Tin Diffusion):
  - High Jc., 3xJc ITER
  - Large filament (50 µm), large coupling current...
  - Cost is > 5 times LHC Nb-Ti

0.7 mm, 108/127 stack RRP from Oxford OST

1 mm, 192 tubes PIT from Bruker EAS
The SC space

- **YBCO**
  - Parallel to tape plane, 4.2 K
  - Perpendicular to tape plane, 4.2 K

- **YBCO Bi**
  - Tape Plane
  - "Turbo" Double Layer Tape

- **2212**
  - Round wire, 4.2 K

- **Nb3Sn**
  - High Energy Physics, 4.2 K

- **Nb-Ti**
  - (LHC) 1.9 K

Maximal $J_c$ for entire LHC NbTi strand production (~) CERN T. Boutilier '07, and (~) <5 T data from Boutilier et al. MT-19 IEEE-TASC '06

Compiled from ASC'02 and ICMC'03 papers (J. Parrell OIST)

427 filament OIST strand with Ag alloy outer sheath tested at NHMFL
BHTS Coated Conductors: Basic Architecture

YBCO 225,000 x

Cu-envelope, 20 µm  SS substrate (50-100 µm)
YSZ buffer (~1.5 µm)
CeO2 buffer (~0.05 µm)
YBCO (1-3 µm)
Ag/Au protection layer (0.1-3 µm)
New (old) approach to cabling suitable for tapes: Roebel (full transposed cable)

Graphics by courtesy of A. Kario, KIT
Exploring new ideas
Aligned coil block dipole
1. Magnet design studies
   - Electromagnetic design of EuCARD2 magnet Feather-M2 and subscale model Feather-M0 completed
   - Mechanical models: Finite element models Feather-M2 and Feather-M0 ongoing
Strawman coil design for 20 T and FCC-pp numbers for conductor

From: E. Todesco, IEEE TAS, 24(3), 2014, 4004306

15 T “Snowmass” design
4578 units (+ 160 spares)
1000 tons of LHC-grade Nb-Ti
3500 tons of HEP-grade Nb$_3$Sn

20 T “Malta revised” design
3662 units (+ 120 spares)
1000 tons of LHC-grade Nb-Ti
3000 tons of HEP-grade Nb$_3$Sn
750 tons of HTS
New (old) design very suitable for Bi-2212 (ASC, LBNL, FNAL...)

Canted Solenoid Coil

Individual turns are separated by Ribs
Ribs intercept forces transferring them to the spar

Stress collector (Spar)

Canted right: Field - up dipole + right solenoid
Canted left: Field - up dipole + left solenoid

Is HE-LHC or FCC the last word?

**ELOISATRON:** 300 km collider proposed by A. Zichichi in 1989!!! 200 TeV with HiLumi technology - 300 TeV with FCC technology

The bridge to the superworld
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.
Circular accelerators and magnets

- We need energy supplied by RF cavities (sometimes SC as well).
- Beam has to recirculate through them to build up energy: circular or racetrack accelerator concept (based on DIPOLAR FIELD)
- Low Energy Physics (Cyclotrons)  HEP (Synchtrons. Colliders)
19 settembre 2008: 
Il grande guasto: interconnessione
Connessione in dettaglio

http://www.ilsussidiario.net/
Electrical arc between C24 and Q24

M3 line

V lines
Collateral damage: magnet displacements
Collateral damage: magnet displacements

QQBI.27R3
V2 line

QQBI.27R3
N line

17 Sept 2009

L. Rossi - CERN @ EUCAS2009
Collateral damage: magnet displacements

QBBI.B31R3
Extension by 73 mm

QBQI.27R3
Bellows torn open

17 Sept 2009
L. Rossi - CERN @ EUCAS2009
Collateral damage:
ground supports
Precursor: temperature drift @ 7 kA current flat top
Riquadro tecnico: Il guasto nella connessione tra magneti superconduttori LHC

Interconnessione tra magneti. In evidenza i cavi superconduttori prima di essere uniti.

Cavi superc.

Interconnessione eseguita: i cavi superconduttori sono racchiusi in una “scatola” di rame e uniti con una lega Stagno-Ar Sergio (azzurro nel disegno)

Parte di giunzione eseguita male: mancanza di Sn-Ag e i cavi superconduttori rimangono isolati

Foto a raggi γ di una giunzione di LHC con lo stesso difetto del disegno di lato (mancanza di Sn-Ag, a destra, tra cavi e tra loro e il Rame).

Il difetto che ha causato l’incidente in LHC era molto simile a questo ma non limitato a un lato, bensì esteso a tutta la lunghezza della giunzione, circa 150 mm. Il difetto ha fatto dissipare nell’arco elettrico 275 MegaJoules, quanto basta per fondere 375 kg di rame, corrispondente all’energia di un TIR lanciato a oltre 500 km/h!
La riparazione di LHC in dettaglio

1. 14 magneti quadrupoli sostituiti
2. 39 magneti dipoli sostituiti
3. 54 interconnessioni riparate, altre 150 riparate parzialmente.
4. Pulizia di oltre 4 km di tubo a vuoto del fascio
5. Nuovo sistema di contenimento longitudinale per 50 magneti quadrupoli
6. Circa 900 nuove porte per fuoriuscita dell’elio installate nella macchina
7. 6500 nuove carte elettroniche aggiunte al sistema di protezione dei magneti, con 250 km di cavi posizionati
Le riparazioni sono terminate
L’anello e’di nuovo tutto freddo
Stiamo ripetendo i collaudi elettrici;
A Novembre si riparte con il fascio
LIU planning during LS2

For implementing all LIU upgrades during LS2:

20.5 months (→LHC Pilot)

22 months (→LHC Production beams as before LS2)

| L4 connection + 2 GeV upgrade | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| PSB         | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| PS          | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| SPS         | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| LHC         | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Protons     | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |

PSB LS2 works - 15 months

PS LS2 works - 14.5 months

SPS LS2 works - 16.5 months

Shutdown - 20.2 months

Beam commissioning LHCPROBE

Beam comm. LHCPROBE

Beam comm. LHCPilot

LHC prod. beam (scrubl)

Recommission LHC with beam

Need to reduce by (at least) 3.5 months

⇒ reduce time for cabling in the PSB during LS2
⇒ make optimum use of all stops and shutdowns before LS2
⇒ more during Chamonix 2014...
The LHC lumi harvest in 2012

LHC 2012 RUN (4 TeV/beam)

Peak luminosity ($10^{32}$ cm$^{-2}$s$^{-1}$)

- ATLAS
- CMS
- LHCb
- ALICE

Preliminary

Delivered integrated luminosity (fb$^{-1}$)

- ATLAS 23.269 fb$^{-1}$
- CMS 23.269 fb$^{-1}$
- LHCb 2.192 fb$^{-1}$
- ALICE 9.678 pb$^{-1}$

Preliminary

Higgs boson!

(generated 2013-01-29 18:28 including fill 3453)
Path to HL-LHC
HL-LHC: the international collaboration