The First Long Shutdown (LS1) and future upgrades of the LHC machine
Frédérick Bordry
TWEPP 2013 (PERUGIA) - 23th September 2013
**LS1 and future upgrades of the LHC machine**
Frédérick Bordry
TWEPP 2013 - 23th September 2013

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**LHC Timeline**

- **August 2008**
  - First injection test

- **September 10, 2008**
  - First beams around

- **September 19, 2008**
  - Incident
    - Accidental release of 600 MJ stored in one sector of LHC dipole magnets
The LHC repairs in detail

½ machine done

1. 14 quadrupole magnets replaced
2. 39 dipole magnets replaced
3. 54 electrical interconnections fully repaired. 150 more needing only partial repairs
4. Over 4 km of vacuum beam tube cleaned
5. A new longitudinal restraining system is being fitted to 50 quadrupole magnets
6. Nearly 900 new helium pressure release ports are being installed around the machine
7. 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid
Copper stabilizer continuity problem: some examples

Sample 1 (61 μΩ)

Sample 2A left (32 μΩ)

Sample 2A right (43 μΩ)

Sample 2B (42 μΩ)

Sample 3A left (26 μΩ)

Sample 3A right (43 μΩ)
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3.5 TeV

August 2008
First injection test

September 10, 2008
First beams around

September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

November 29, 2009
Beam back

October 14, 2010
1e32
248 bunches

March 30, 2010
First collisions at

LHC Timeline
LHC main splices: busbars SC

Main Dipoles&Quads Bus, sorted by position, **2048** segments
All HWC pyramids and plus ~150 ramps to 3.5TeV analyzed

**Top 10 Splice Resistances**

- MB.A34 MB.A31L4 ↔ MB.C31L4 2.71E-09
- MQ.A81 MQ.11R8.B2 ↔ DFLAS.7R8.4 2.02E-09
- MB.A34 MB.C19L4 ↔ MB.B20L4 1.74E-09

(\textsuperscript{**}) number of splices in the quads segments corrected, 1.3 added
August 2008
First injection test

September 10, 2008
First beams around

April 2010
Squeeze to 3.5 m

November 29, 2009
Beam back

October 14, 2010
1e32 bunches

6.8e33

September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

March 30, 2010
First collisions at

November 2010
Ions

June 28, 2011
1380 bunches

4 July, 2012
Higgs discovery

18 June, 2012
6.6 fb⁻¹ to ATLAS & CMS

LHC Timeline

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Similar figures for ATLAS

2010 - Commissioning:
- 7 TeV c.m.
- 0.04 fb\(^{-1}\)

2011 - Exploring:
- 7 TeV c.m.
- 6.1 fb\(^{-1}\)

2012 - Production:
- 8 TeV c.m.
- 23.3 fb\(^{-1}\)
Some Main Beam Parameters

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<tr>
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<th>25 ns (design)</th>
<th>50 ns (2012)</th>
<th>25 ns (2012)#</th>
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<td>Energy per beam [TeV]</td>
<td>7</td>
<td>4</td>
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<td>Intensity per bunch [x10^{11}]</td>
<td>1.15</td>
<td>1.7</td>
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<td>Norm. Emittance H&amp;V [µm]</td>
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<td>1.8</td>
<td>2.7</td>
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<tr>
<td>Number of bunches</td>
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<td>1380</td>
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<td>β* [m]</td>
<td>0.55</td>
<td>0.6</td>
<td>N.A.#</td>
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<td>Peak luminosity [cm^{-2}s^{-1}]</td>
<td>1 × 10^{34}</td>
<td>7.7 × 10^{33}</td>
<td>N.A.#</td>
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</table>

# The 25 ns was only used for scrubbing and tests in 2012
Some Limitations:

Electron cloud

- Reason for running with 50 ns
- Scrubbing to suppress electron cloud build up by reducing the secondary electron yield (SEY)
- Remains still worrisome in the arcs for 25 ns bunch spacing
**Some Limitations: cont’d**

**Beam induced heating**
- Local non-conformities (design, installation)
  - Injection protection devices
  - Sync. Light mirrors
  - Vacuum assemblies

**UFOs**
- 20 dumps in 2012
- Timescale 50-200 µs
- Conditioning observed
- Worry about 6.5 TeV

**Radiation to electronics**
- Concerted program of mitigation measures (shielding, relocation...)
- Premature dump rate down from 12/fb\(^{-1}\) in 2011 to 3/fb\(^{-1}\) in 2012

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A. Gerardin, N. Garrel
EDMS: 1162034
LS1 starts as the shutdown to repair the magnet interconnects to allow nominal current in the dipole and lattice quadrupole circuits of the LHC.

It has now become a major shutdown which, in addition, includes other repairs, maintenance, consolidation, upgrades and cabling across the whole accelerator complex and the associated experimental facilities.

All this in the shadow of the repair of the magnet interconnects.
LS 1 (16th Feb. 2013 to Dec. 2014)

• Numerous projects and activities:
  ▪ SMACC (Superconducting Magnets And Circuits Consolidation)
  ▪ R2E (Radiation to Electronics)
  ▪ Massive shutdown maintenance after more than 3 years of operation
  ▪ Several major consolidations PSB, PS, SPS, LHC and electricity network
  ▪ A lot of projects (Linac 4, HIE-Isolde, Elena, nTof EAR 2, **High Luminosity LHC**, ….)

• Compared to previous shutdowns, an exceptional number of …
  ▪ Simultaneous activities (co-activities) – **Planning and safety**
  ▪ Non-CERN workers (FSU, collaborations, contracts,…) - **Logistics: Registration, training, transport, parking, access, dosimeter, PPE, catering, accommodation, ….)**
The main 2013-14 LHC consolidations

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. 3 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
Several shielding campaigns prior 2011  
+ Relocations ‘on the fly’  
+ Equipment Upgrades

Radiation to Electronics

- 2011/12 Christmas Break
  - ‘Early’ Relocation
  - Additional Shielding
  - Equipment Upgrades

R2E Project to reach nominal and ultimate luminosity

Aiming for <0.5 dumps / fb^{-1}

~12 dumps / fb^{-1}

~3 dumps / fb^{-1}

~400 hours Downtime

~250 hours Downtime

Annual Cumulated Luminosity

(For Run 2011, Run 2012, and After LS1 (Target))
The main key drivers are:

- Superconducting Magnets And Circuits Consolidation
- **Radiation To Electronics – R2E**

Main activities in LHC

- **Point 1** – ULs, Ujs, RRs
- **Point 5** – UJ56, UL55, RRs
- **Point 7** – UJ, TZ

In total 70 weeks and a combined effort of about 150 persons

Courtesy: A.-L. Perrot, Y. Muttoni
Main activities in LHC

The main key drivers are:

- Superconducting Magnets And Circuits Consolidation
- Radiation To Electronics – R2E
- Full maintenance of all equipment
Main activities in LHC

The main key drivers are:

- Superconducting Magnets And Circuits Consolidation
- Radiation To Electronics – R2E
- Full maintenance of all equipment

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<tr>
<th>Cabling !!!</th>
<th>Km</th>
<th>years</th>
<th>persons</th>
<th>km/person per year</th>
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<td>LHC installation</td>
<td>3’500</td>
<td>5</td>
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<td>LHC LS1</td>
<td>700</td>
<td>1</td>
<td>100</td>
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Flexwell @ P4
2013-02-16 08:25:27
*** END OF RUN 1 ***
No beam for a while
Access required
time estimate: ~ 2 years
Objective:
- Identify possible limitations (other than the splices) on the superconducting circuits for operation at 7 TeV, that could eventually be fixed during LS1

All circuits other than the main dipole and quadrupoles reached the nominal 7 TeV equivalent current (except main dipole and quadrupole circuits)

Electrical Quality Assurance (ELQA) tests
- ELQA at 1.9K and at room temperature were performed in all sectors and are just finished
- 37 NCs revealed. Most of them will be solved at warm, during SMACC.
Few perturbations (EL, CV, controls), Few issues with HW (HX-Comp-Tu)

Done in 10 weeks !!!
LS1 Slogan:  
1\textsuperscript{st} Safety , 2\textsuperscript{nd} Quality , 3\textsuperscript{rd} Schedule

LS1 Safety

- **Prevention measures**
  - Training for all categories of personal (safety, procedure, mock-up,...)
  - Common inspections CERN / Contractor before starting work
  - Safety Officer / Safety Coordination Patrols
  - Spontaneous witnesses of hazardous situations
  - Evacuation exercises

- **Hazardous Situations**
  - **Not wearing of the Personal Protective Equipments (PPE)**
  - Personnel crossing safety barriers
  - Smoke generation by vacuum pump motors
  - False fire alarms and evacuations

*Fire brigade exercise*  
*In SPS*
LS1 Safety

- Notified accidents in LS 1 (Accelerators)
  - **Head wound from hitting obstacles (4 x)**
  - **Hand/Fingers hurt by portable tool (3 x)**
  - **Eye irritation from glass fibre dust**
  - Fall from bicycle (during evacuation)
  - Slipping and hitting a pole
  - Electrical shock (w/o consequences)
  - Handling loads

Totaling 45 days of sick leave due to accidents for more than 150’000 man•days worked (very low gravity rate ≈ 0.04) (after 7 months)
**LS1 Personal Dosimetry**

*Collective dose for the period 1 March – 31 August 2013*

- obligatory for work in **any CERN Radiation Area** (Supervised and Controlled Radiation Areas)
- assigned after validation of a successful participation in a radiation protection course.
- presently 5989 DIS dosimeters in use
- **maximum individual doses: 0.7-1.0 mSv** (SPS LSS1 cabling, PS/PSB vacuum and magnet maintenance)

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**collective doses given in man•mSv**

- **84.6** 32%
- **64.5** 24%
- **117.9** 44%

**total:** 267 man•mSv

2011: 527 man•mSv
2012: 494 man•mSv

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**Courtesy Stefan Roesler**
LS1 Personal dosimetry
Individual dose distribution
for the period 1 March – 31 August 2013

Dose sum per class (man mSv)
Dose occurrence per class
Dose class in mSv

Courtesy Stefan Roesler
LHC Preliminary leak tests

- Arc subsectors all tested: 20 internal helium leaks identified
  - 14 identified to component (for repair).
  - For 6 leaks not identified to component, further tests to be performed in phase 2.
- QRL
  - 2 existing internal leak known
  - 5 new internal leaks – under investigation
The damaged compensator (QRL Line C)

Internal ply damage (S45, 14R4)  External ply damage (S78, 10R7)

DN100 multi-ply bellows compensators (4 plies of 0.3 mm)
The failure mode (QRL as typical)

Filling of the inter-ply space with time (3-4 years of operation)

Pressure increase of the inter-ply space during warm-up \(\rightarrow\) compensator collapsing!

Maxi pressure with conservative assumption: isochoric transformation and space initially at line conditions \((P, T)\)

- CM: 1500 bar
- Line C: 1200 bar
- Line E & F: 120 bar
- Line D: 20 bar
- Line B: 1 bar

Difficult to survive!!

Metallographic observations (EN-MME)

A “virtual” leak (not seen during global leak test)

He \((P, T)\)

Courtesy Laurent Tavian

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## Repair plan for QRL compensators

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<td>T1 T2 T1 T2 T1 T2</td>
<td>T3</td>
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<td>Sector 2-3</td>
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<tr>
<td>T1 T2 T1 T2 T1 T2</td>
<td>T3</td>
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</tbody>
</table>

**T1** Mechanical preparation (CRG)

**T2** Compensateur integration/welding and clamshell leak test (CRG & VSC)

**T1** Screen and MLI interconnect integration (CRG)

**T2** External envelop closure/welding (CRG)

Subsector pumping

**T3** Individual and global leak test (VSC)

PT - preparation for pressure test (QRL to be closed)

**T1** (Team 1): 2 persons (2 technicians)

**T2** (Team 2): 2 persons (1 welder + 1 mechnanics) (TE-VSC support to be added)

**T3** (Team 3): VSC support

---

**All existing spares fully tested prior to installation**

**Replacement of the first compensator started in S81**

**New spares to be ordered with updated welding & QA procedure**
SMACC: Cryo-feedbox (DFBA) consolidation

SMACC: DFBA Consolidation

- Baseline
- Completed

Updated 11-Sep-2013
The damaged compensator (DFBA)

DN120 multi-ply gimbal bellows
(2 plies of 0.2 mm); Identical failure process identified

DFBAK upper gimbal (Sector 5-6)

DFBAF lower gimbal (Sector 3-4)

DFBAI lower gimbal (Sector 4-5)

Courtesy Laurent Tavian
### DFBA gimbal bellows status for all DFBAs

Endoscopic inspection through line M interconnects

<table>
<thead>
<tr>
<th>Secteur</th>
<th>Dates</th>
<th>Bellows status</th>
<th>Sector</th>
<th>Dates</th>
<th>Bellows status</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFBAB</td>
<td>07-Aug</td>
<td>ok</td>
<td>1-2</td>
<td>20-Aug</td>
<td>ok</td>
</tr>
<tr>
<td>DFBAD</td>
<td>13-Aug</td>
<td>ok</td>
<td>2-3</td>
<td>04-Sep</td>
<td>ok</td>
</tr>
<tr>
<td>DFBAF</td>
<td>25-Aug</td>
<td>damaged</td>
<td>3-4</td>
<td>29-Aug</td>
<td>ok</td>
</tr>
<tr>
<td>DFBAH</td>
<td>29-Aug</td>
<td>ok</td>
<td>4-5</td>
<td>06-Sep</td>
<td>damaged</td>
</tr>
<tr>
<td>DFBAJ</td>
<td>20-Apr</td>
<td>ok</td>
<td>5-6</td>
<td>18-Jul</td>
<td>ok</td>
</tr>
<tr>
<td>DFBAL</td>
<td>25-Apr</td>
<td>ok</td>
<td>6-7</td>
<td>-</td>
<td>ok</td>
</tr>
<tr>
<td>DFBAN</td>
<td>15-Jun</td>
<td>ok</td>
<td>7-8</td>
<td>-</td>
<td>ok</td>
</tr>
<tr>
<td>DFBAP</td>
<td>-</td>
<td>ok</td>
<td>8-1</td>
<td>07-Aug</td>
<td>ok</td>
</tr>
</tbody>
</table>

**Statistics (total 32 bellows all inspected):** 3/32 (9.3 %)

**Endoscopic inspection through line M interconnects**
In situ access by cutting the end door: possible solution

Questions/issues:
- Very limited space to cut/weld the door
- Cutting and welding of beam pipes to be done in very difficult position
- Leak tests of beam pipes?
- Extreme very difficult work positions
- Safety to be assessed

Gimbal patching (Rigid assembly)

Thanks for EN-MME contribution!

Courtesy Laurent Tavian
Collaborations with NTUA (Athens), WUT (Wroclaw) and support of JINR-DUBNA

> 6 sectors equivalent have been opened around the LHC.

LS1 and future upgrades of the LHC machine
Frédérick Bordry
TWEPP 2013 - 23th September 2013
SMACC: Opening of interconnections

Opening of Interconnections

- Sector 56
- Sector 67
- Sector 78
- Sector 81
- Sector 12
- Sector 23
- Sector 34
- Sector 45

Updated 11-Sep-2013

LS1 and future upgrades of the LHC machine
Frédérick Bordry
TWEPP 2013 - 23rd September 2013

Courtesy Jean-Philippe Tock
SMACC: Opening of busbar lines

Measurement of > 4100 splices (total 10’170)

Preliminary results of existing splices quality control (7.09.2013).

<table>
<thead>
<tr>
<th>Sector</th>
<th>Sector 56</th>
<th>Sector 67</th>
<th>Sector 78</th>
<th>Sector 81</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured [%]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>To redo [%]</td>
<td>28</td>
<td>32</td>
<td>29</td>
<td>31</td>
<td>30</td>
</tr>
</tbody>
</table>

+ 8 FTE
and
+ 2 induction machines

Collaborations with PAEC-NCP
(Pakistan Atomic Energy Commission – National Centre for Physics)
## R-8 measurement: top ten outliers

Top ten R-8 M3 (measured until the 7.9.2013)

<table>
<thead>
<tr>
<th></th>
<th>Sample ID</th>
<th>Value (μΩ)</th>
<th>Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>QBBl.B24R7-M3-Ext</td>
<td>77.5</td>
<td>R-8 right</td>
</tr>
<tr>
<td>2</td>
<td>QBBl.22L8-M3-Ext</td>
<td>52.6</td>
<td>R-8 left</td>
</tr>
<tr>
<td>3</td>
<td>QBBl.A14L8-M3-Ext</td>
<td>49.9</td>
<td>R-8 right</td>
</tr>
<tr>
<td>4</td>
<td>QBBl.16R8-M3-Ext</td>
<td>47.4</td>
<td>R-8 right</td>
</tr>
<tr>
<td>5</td>
<td>QBBl.22R7-M3-Int</td>
<td>43.3</td>
<td>R-8 left</td>
</tr>
<tr>
<td>6</td>
<td>QBQl.32R7-M3-Int</td>
<td>41.6</td>
<td>R-8 left</td>
</tr>
<tr>
<td>7</td>
<td>QBQl.31R6-M3-Ext</td>
<td>40.6</td>
<td>R-8 left</td>
</tr>
<tr>
<td>8</td>
<td>QBBl.B27R7-M3-Ext</td>
<td>39.1</td>
<td>R-8 right</td>
</tr>
<tr>
<td>9</td>
<td>QBBl.30R7-M3-Int</td>
<td>39.0</td>
<td>R-8 right</td>
</tr>
<tr>
<td>10</td>
<td>QBBl.15L8-M3-Ext</td>
<td>36.2</td>
<td>R-8 right</td>
</tr>
</tbody>
</table>

Sample 2A right (43 μΩ)

Courtesy C Scheuerlein, S Heck
Shunts are installed in more than 2 sectors-equivalent

- 50 ICs behind schedule (About one week at nominal rate)
- Delay due to 30% of IC to be redone (forecast was 15%)
- Reinforcement of the teams
- About 8 000 shunts installed (30% of the LHC)
Opening is back ahead of schedule despite closure of interconnections
Shunting starts to improve with reinforcement and optimisation of critical activities
Welding: Limited by release rate, confident that nominal rate can be achieved,
M leak test: Limited by release rate, confident that nominal rate can be achieved,
ReClosure: started ahead of schedule, now in S67
Final leak test started (Results in 2 weeks)
SMACC Dashboards

Progress:
- Baseline: 31.8%
- Completed: 25.6%
- Delay: 14 days

Updated 11-Sep-2013

Courtesy Jean-Philippe Tock
Maintenance and Consolidation of the Electrical Distribution System

Ongoing as planned

- Extensive Maintenance of all the Electrical Network
- Consolidation & Upgrade of the 66 et 18 kV Networks
  - Replacement of SPS Power Cables
  - Redundant powering of the CCC
  - Enhanced UPS solution for the LHC
  - Reconfiguration and Upgrade of the Meyrin Electrical Distribution
- Replacement of UPSs in the LHC Tunnel

French Power Source

Swiss Power Source

Courtesy Roberto Saban
Maintenance and Consolidation of the Cooling and Ventilation System

Extensive Maintenance of cooling towers, the demineralised water production station, water cooling stations and machinery. The SPS water loop will restart operation this week.

Consolidation & Upgrade

- New redundant pumps on the demineralised water loop of the LHC
- PS Ventilation System
- CCC ventilation System
- New cooling towers for the LHC to allow operation of the cryogenics during maintenance

Ongoing as planned

Courtesy Roberto Saban
Handling & Transport

- Replacement of magnets (15 dipoles + 3 quadrupoles)
- Removal and re-installation of shielding
- Removal and re-installation of components (racks, crates, collimators)
- Transport of cables

40% of the total work has been done

LS1 = 600 man • months

Baseline load: UPS, cables and CV campaigns

Transport of LHC components

Opening of the LHC

DYPB, reinstallation of LHC components

TCC2, PS units, R2E

Shielding and re-closure

Courtesy Roberto Saban
18 magnets were removed and the new ones are in place
LHC LS1 status
Booster

PS

SPS
LS 1 from 16th Feb. 2013 to Dec. 2014

LS1 and future upgrades of the LHC machine
Frédérick Bordry
TWEPP 2013 - 23th September 2013
LS1, always the same slogan:

**Safety > Quality > Schedule and Cost**

Thanks to:
- Solid preparation and dedication of numerous persons (Collaborations, industries, staff)
- Early start gave us time for debugging and going through the learning phase

So far, LS1 is on schedule for beams:
- mid-2014 for the injectors
- January 2015 for LHC

Now:
- Some issues to be solved (DFBA and QRL compensators, ...)
- Avoid routine effect

keep motivation and high level of quality
Run2: 3 years Operation Run after LS1

Run 1

LS1

Run 2

Run 2: Start with 6.5 TeV and later decision towards 7 TeV according to magnet training
Expectations after Long Shutdown 1 (2015)

- Collisions at least at **13 TeV c.m.**
- **25 ns** bunch spacing
  Using new injector beam production scheme (BCMS), resulting in brighter beams.

- \( \beta^* \leq 0.5 \text{m} \) (was 0.6 m in 2012)
- Other conditions:
  - Similar turn around time
  - Similar machine availability
- Expected maximum luminosity: \( 1.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \pm 20\% \)
  - Limited by inner triplet heat load limit, due to collisions debris

<table>
<thead>
<tr>
<th>Number of bunches</th>
<th>Intensity per bunch</th>
<th>Transverse emittance</th>
<th>Peak luminosity</th>
<th>Pile up</th>
<th>Int. yearly luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 ns BCMS</td>
<td>2320</td>
<td>( 1.15 \times 10^{11} )</td>
<td>1.9 \text{ \mu m}</td>
<td>( 1.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} )</td>
<td>( \sim 43 )</td>
</tr>
</tbody>
</table>

Batch Compression and Merging and splitting (BCMS)

Courtesy of the LIU-PS project team
### Potential performance

<table>
<thead>
<tr>
<th></th>
<th>Number of bunches</th>
<th>Ib LHC [1e11]</th>
<th>Collimat or scenario</th>
<th>Emit LHC (SPS) [um]</th>
<th>Peak Lumi [cm⁻²s⁻¹]</th>
<th>~Pile-up</th>
<th>Int. Lumi [fb⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 ns</td>
<td>2760</td>
<td>1.15</td>
<td>S1</td>
<td>3.5 (2.8)</td>
<td>9.2e33</td>
<td>21</td>
<td>24</td>
</tr>
<tr>
<td>25 ns low emit</td>
<td>2320</td>
<td>1.15</td>
<td>S4</td>
<td>1.9</td>
<td>1.6e34</td>
<td>43</td>
<td>42</td>
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<tr>
<td>50 ns</td>
<td>1380</td>
<td>1.6</td>
<td>S1</td>
<td>2.3 (1.7)</td>
<td>1.7e34 levelling 0.9e34</td>
<td>76 levelling 40</td>
<td>~45*</td>
</tr>
<tr>
<td>50 ns low emit</td>
<td>1260</td>
<td>1.6</td>
<td>S4</td>
<td>1.6 (1.2)</td>
<td>2.2e34</td>
<td>108</td>
<td>…</td>
</tr>
</tbody>
</table>

- 6.5 TeV
- 1.1 ns bunch length
- 150 days proton physics, HF = 0.2

*All numbers approximate

* different operational model – caveat - unproven

---

LS1 and future upgrades of the LHC machine
Frédérick Bordry
TWEPP 2013 - 23th September 2013

Courtesy Mike Lamont
Comments

• 50 ns implies the existence of a robust levelling technique

• Electron cloud at 25 ns?
  - *bench marked very recently… scrubbing time?*

• The 25 ns will bring issues:
  - *UFOs, beam inducing heating, vacuum*

• Low emittance 25 ns option is attractive for a number of reasons
  - *lower total beam current, performance…*
Possible scenarios for the beam commissioning in 2015

Initial Beam commissioning
~2 months

First stable beams at 6.5 TeV
low number of INDIVs

Scrubbing for 50 ns
(50 & 25 ns)
~7 days

Phased intensity increase to
pile-up limit
~1 to 2 months

50 ns operation

The way of the devil
(levelled 50 ns)

Scrubbing for 25 ns

25ns physics
(intensity ramp up and
further scrubbing)

Scrubbing for 25 ns
<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
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<td>2012</td>
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<td>6</td>
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<tr>
<td>2013</td>
<td>IONS</td>
<td>IONS</td>
<td>LS1 - SPLICE CONSOLIDATION</td>
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<td>RECOM</td>
<td>RECOM</td>
<td>RAMP-UP</td>
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<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
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<tr>
<td>2018</td>
<td>LS2 (LIU UPGRADE: LINAC4, BOOSTER, PS, SPS...)</td>
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<td>4</td>
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<td>6</td>
<td>7</td>
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<td>3</td>
<td>4</td>
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<td>7</td>
<td>8</td>
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<tr>
<td>2021</td>
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<td>2</td>
<td>3</td>
<td>4</td>
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<td>8</td>
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<td>2022</td>
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</tr>
</tbody>
</table>

Legend:
- Blue: Technical stop or shutdown
- Purple: Proton physics
- Red: Ion Physics
- Green: Recommissioning
- Orange: Intensity ramp-up

LS1 and future upgrades of the LHC machine
Frédéric Bordry
TWEPP 2013 - 23th September 2013

Courtesy Mike Lamont
"Baseline" luminosity

- Peak luminosity
- Integrated luminosity

~300 fb⁻¹
The workshop will focus on:

Review of the parameters of the LIU and HL-LHC projects following the experience and changes in the beam parameters experienced in the past two years.

Produce a staged plan (beam parameters, technical work, all machines) of how we proceed from the performance at the end of 2012 to the required performance for the HL-LHC. In order to do this we need to know at what level of integrated luminosity will necessitate replacement of the inner detectors and the insertions. Also to see the importance of 3000 fb⁻¹ and what level of minimum integrated luminosity would be tolerated.

- Chairman: Steve Myers
- Co-Chairman: Frédéric Bordry
- Deputy Chairman: Mike Lamont
- Scientific Secretary: Frank Zimmermann
- Deputy Scientific Secretary: Brennan Goddard
- Technical Support: Pierre Charrue

Editor of proceedings: Frank Zimmermann and Brennan Goddard

DRAFT timetable and session information

***Deadline for registration: Friday 27 September 2013***
LINAC4 – PS Booster:
- H⁻ injection and increase of PSB injection energy from 50 MeV to 160 MeV, to increase PSB space charge threshold
- New RF cavity system, new main power converters
- Increase of extraction energy from 1.4 GeV to 2 GeV

PS:
- Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
- Transverse resonance compensation
- New RF Longitudinal feedback system
- New RF beam manipulation scheme to increase beam brightness

SPS
- Electron Cloud mitigation – strong feedback system, or coating of the vacuum system
- Impedance reduction, improved feedbacks
- Large-scale modification to the main RF system

These are only the main modifications and this list is far from exhaustive

Project leadership: R. Garoby and M. Meddahi
Why High-Luminosity LHC? (LS3)

Goal of HL-LHC project:
- 250 – 300 fb^{-1} per year
- 3000 fb^{-1} in about 10 years

By implementing HL-LHC
Almost a factor 3
By continuous performance improvement and consolidation
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.

**HL-LHC from a study to a PROJECT**

300 fb\(^{-1}\) → 3000 fb\(^{-1}\)

including LHC injectors upgrade **LIU**

(Linac 4, Booster 2GeV, PS and SPS upgrade)
The HL-LHC Project

- New IR-quads (inner triplets)
- New 11 T Nb$_3$Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- ...

Major intervention on more than 1.2 km of the LHC

Project leadership: L. Rossi and O. Bruning
Squeezing the beams: High Field SC Magnets

13 T, 140 mm aperture Quads for the inner triplet
(LHC: 8 T, 70 mm)

More focus strength, $\beta^*$ as low as 15 cm
(55 cm in LHC).
*In some scheme even $\beta^*$ down to 7.5 cm are considered

Dipoles for beam recombination/separation capable of 6-8 T with 150-180 mm aperture
(LHC: 1.8 T, 70 mm)
LARP (US LHC program) Magnets

LS1 and future upgrades of the LHC machine
Frédérick Bordry
TWEPP 2013 - 23th September 2013
Setting up International collaboration

with national laboratories but also involving industrial firms

Baseline layout of HL-LHC IR region
Luminosity Levelling, a key to success

- High peak luminosity
- Minimize pile-up in experiments and provide “constant” luminosity

- Obtain about 3 - 4 fb\(^{-1}\)/day (40% stable beams)
- About 250 to 300 fb\(^{-1}\)/year
Aim: reduce the effect of the crossing angle

Without crabbing

\[ \theta_c \]

With crabbing

\[ \theta_c \]

- 3 prototypes available
- Cavity tests are on-going
- Test with beam in SPS foreseen in 2015-2016
- Beam test in LHC foreseen in 2017
R2E: Removal of Power Converter (200kA-5 kV SC cable, 100 m height)

- Power converter hall
- Current leads
- Tunnel

φ = 62 mm

7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables – Itot~120 kA @ 30 K

- MgB₂ (or other HTS)

Also DFBs (current lead boxes) removed to surface

Final solution to R2E problem – in some points

Make room for shielding unmovable electronics

Make the maintenance and application of ALARA principle much easier
“to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update”

d) CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.

And also R&D on Proton-Driven Plasma Wakefield Acceleration (AWAKE Expt at CERN)
Magnet design (20 T): very challenging but not impossible.
300 mm inter-beam
Multiple powering in the same magnet (and more sectioning for energy)
Work for 4 years to assess HTS for 2X20T to open the way to 16.5 T/beam.
Otherwise limit field to 15.5 T for 2x13 TeV
Higher INJ energy is desirable (2xSPS)

The synchrotron light is not a stopper by operating the beam screen at 60 K.
Beam stability looks «easier» than LHC thanks to dumping time.
Collimation is possibly not more difficult than HL-LHC. Reaching 2x10^{34} appears reasonable.

Beam handling for INJ & beam dump: new kicker technology is needed since we cannot make twice more room for LHC kickers.
80-100 km tunnel in Geneva area – VHE-LHC
with possibility of e⁺-e⁻ and p-e⁻

CDR and cost review for the next ESU
(including injectors)

16 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km
“CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines.”

FCC Study: p-p towards 100 TeV
Kick-off meeting: mid-February 2014

FCC: Future Circular Colliders
Conclusion

- Run 2 : 13 TeV – 25 ns – up to $1.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 40-45 fb$^{-1}$ per year
- LS2 (higher intensity) [2018 or 2019] and Run 3 (up to $1.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$)
- HL-LHC : R&D => now a construction project (LS 3) (300 to 3000 fb$^{-1}$)
- Vigorous R&D and preparation of two alternatives for post-LHC machine (CDR and Cost-Schedule)
  Higher energy hadrons (VHE LHC with TLEP)
  and
  highest possible energy $e^+e^-$ with CLIC
  to be ready for the next European Strategy Update
  (multi-lateral collaboration approach)

Thanks for your attention
VHE-LHC Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>VHE-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m. energy [TeV]</td>
<td>14</td>
<td>14</td>
<td>33</td>
<td>100</td>
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<tr>
<td>circumference C [km]</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
<td>80</td>
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<td>dipole field [T]</td>
<td>8.33</td>
<td>8.33</td>
<td>20</td>
<td>20</td>
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<tr>
<td>injection energy [TeV]</td>
<td>0.45</td>
<td>0.45</td>
<td>&gt; 1.0</td>
<td>&gt; 3.0</td>
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<tr>
<td>no. bunches $n_b$</td>
<td>2808</td>
<td>2808</td>
<td>2808</td>
<td>8420</td>
</tr>
<tr>
<td>Bunch population $N_b \times 10^{11}$</td>
<td>1.15</td>
<td>2.2</td>
<td>0.94</td>
<td>0.97</td>
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<tr>
<td>init. transv. norm. emittance [μm]</td>
<td>3.75</td>
<td>2.5</td>
<td>1.38</td>
<td>2.15</td>
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<tr>
<td>stored beam energy [MJ]</td>
<td>362</td>
<td>694</td>
<td>701</td>
<td>6610</td>
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<tr>
<td>arc SR heat load [W/m/aperture]</td>
<td>0.17</td>
<td>0.33</td>
<td>4.35</td>
<td>43.3</td>
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<td>longit. SR emit. damping time [h]</td>
<td>12.9</td>
<td>12.9</td>
<td>1.9</td>
<td>0.32</td>
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<tr>
<td>Horiz. SR emit. damping time [h]</td>
<td>25.8</td>
<td>25.8</td>
<td>2.0</td>
<td>0.64</td>
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<td>peak events per crossing</td>
<td>27</td>
<td>135 (lev.)</td>
<td>147</td>
<td>171</td>
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<tr>
<td>peak luminosity [$\times 10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>1.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
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<tr>
<td>optimum run time [h]</td>
<td>15.2</td>
<td>10.2</td>
<td>5.8</td>
<td>10.7</td>
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<td>opt. av. int. luminosity / day [fb$^{-1}$]</td>
<td>0.47</td>
<td>2.8</td>
<td>1.4</td>
<td>2.1</td>
</tr>
</tbody>
</table>

The tunnel can also be equipped with a Lepton ring to provide p – e$^-$ collisions

A circumference of 100 km is being considered for cost-benefit reasons

20T magnet in 80 km
16 T magnet in 100km

100 TeV