LHC Run 2 Startup Machine and Detector Performance

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The Large Hadron Collider
CMS Detector

3.8 T Solenoid

Tracker:
~1 m² Pixels (66M channels)
~200 m² Si microstrips (9.6M channels)

Iron Yoke

4 stations of muon detectors

ECAL: Electromagnetic calorimeter - 76K PbWO₄ crystals

12,500 tons
21 m long
15 m diameter

HCAL: hermetic Brass/Scintillator sampling hadronic calorimeter
Outline

• Run 1 flashback
• LHC restart
• ATLAS readiness
• CMS readiness
• Run 2 status
• Summary
Run 1 in Brief

- **20 Nov 2009**
  - First beams

- **30 Nov 2009**
  - Collisions @ 2.36 TeV

- **8 Nov 2010**
  - PbPb 2.76 TeV

- **30 Mar 2010**
  - Stable collisions @ 7 TeV

- **13 Mar 2011**
  - 7 TeV start with beam

- **Nov 2011**
  - PbPb 2.76 TeV

- **5 Apr 2012**
  - 8 TeV start with beam

- **20 Jan 2013**
  - pPb

- **Feb 14 2013**
  - Start LS1

ATLAS/CMS Pile-up

- **O(2)**
- **O(10)**
- **O(25)**

Run-1: 50 ns LHC bunch spacing
Peak luminosity of $7.8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

For Both experiments

- Integrated luminosity of $\sim 5 \text{ fb}^{-1} @ 7 \text{ TeV}, \sim 21 \text{ fb}^{-1} @ 8 \text{ TeV}$
- Data Taking efficiency $\sim 94\%$
- Data quality selection 95%
Run 1 Legacy

The Nobel Prize in Physics 2013

François Englert
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider™"
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. 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
LHC LS1 Activity Highlights

- Each sector trained to 6.55TeV (11080A) (100A above the operational field)
- Large variation in number of training quenches per sector
- Detailed analysis in Progress
LHC in Q2 2015

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<th>Week</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
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- **Start LHC commissioning with beam**
- **Recommissioning with beam**
- **Scrubbing for 50 ns operation**

**FIRST BEAM**
- **5th April**

**FIRST STABLE BEAM**
- **3rd June**

**PILOT PHYSICS**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Date</th>
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<tbody>
<tr>
<td>Circulating beam</td>
<td>Sunday 5th April</td>
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<tr>
<td>Ramp to 6.5 TeV</td>
<td>Friday 10th April</td>
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<tr>
<td>First 13 TeV collisions</td>
<td>Wednesday 20th May</td>
</tr>
<tr>
<td>First Stable beams</td>
<td>Wednesday 3rd June</td>
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</tbody>
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08/04/2015  Jinlong Zhang
LHC Restart

- Experiments ready for beam operations from Feb 2015
- First beam through transfer lines to stopper TDI in front of LHCb on March 7th
- First circulating beams on Easter April 5th 2015

CMS, Apr 5 2015 Splashes

ATLAS, Apr 5 2015 Splashes
6.5 TeV Beam for the 1st Time
13 TeV Collisions

First images of collisions at 13 TeV

by Cian O’Luanaigh

LHC Page 1
Fill: 3746
E: 6500 GeV
t(SB): 00:00:00
21-05-15 09:22:18

BEAM SETUP: ADJUST

Energy: 6500 GeV
I(B1): 1.84e+11
I(B2): 1.85e+11

BIS status and SMP flags

Comments (21-May-2015 09:22:03)
test collisions at 13 TeV

AFS: Single_2b+1p_1.1.1

Test collisions continue today at 13 TeV in the Large Hadron Collider (LHC) to prepare the detectors ALICE, ATLAS, CMS, LHCb, LHCf, MOEDAL and TOTEM for data-taking, planned for early June (Image: LHC page 1)
ATLAS Consolidation in LS1

- Insertable B-Layer (IBL) of Pixel detector
- Many other detector improvements
  - Infrastructure upgrades
  - Muon chamber completion and replacements, new readout for forward chambers
  - Calorimeter electronics repairs
  - Improvement of inner detector readout capability
  - Pixel detector new services and module repairs
  - New luminosity detectors
  - Trigger/DAQ improvements
  - Software and computing improvements
ATLAS IBL

- New pixel layer around new smaller beam pipe
  - 50×250 µm² pixel size, planar and 3D sensors
  - 130 nm CMOS technology
- More robust b-tagging, improved rejection against light jets at high pile-up
- IBL installed in ATLAS in May 2014
- Timed-in and aligned

- Suffered from wire-bonds corrosion but new modules produced in record time
- Observed a larger than expected thermally induced r-φ twisting of staves, at the level of few µm/K. It might require refinements to operating procedures, with careful temperature control at the level of ~ 0.2 K
ATLAS Inner Detector

- Pixel Detector (PIX)
  - Replacement of On-detector service patch panel
  - Module repair
- SemiConductor Tracker (SCT)
  - Replacement of off-detector optical transmitters
  - Expansion of readout capacity
- Transition Radiation Tracker (TRT)
  - Solution for gas leak
- Detector timed-in and aligned
ATLAS Tracker Performance

Impact parameter resolution improvement from IBL

Material study with hadronic interaction vertices

K\(_s\) mass as alignment & material probe

08/04/2015

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ATLAS LAr Calorimeter

- Repair of FE boards
- Installation of new LV power supplies
- Replacement of HV power supplies of EMEC and FCAL
- Timed–in with beam splash events

Cell energy distribution

Timing distribution
ATLAS Tile Calorimeter

- Installation of new LV power supplies
- Consolidation of frontend electronics drawers

Evolution of Masked Channels and Cells: 2015-06-06
ATLAS Calorimeter Performance

- Di-photon spectrum without data-driven energy scale corrections applied
- Jet $p_T$ spectrum measured with topological clusters and calibrated with the EM+JES scheme
- Missing Energy resolution, measured with topological clusters using LCW (Local Cluster Weighting) and good vertex requirement
ATLAS Muon Spectrometer

- Improvement of coverage
  - Installation of remaining EE MDT tracking chambers
  - Installation of chambers in the elevator holes and foot region
- Repair or Replacement of problematic TGC chambers
- New CSC readout system
- Double MDT readout links for endcap
- All system timed in and aligned

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ATLAS Forward Detectors

- New Minimum Bias Trigger Scintillator (MBTS),
  - Low energy/low interaction rate runs, such as first collisions, calibration scans and heavy ion runs
- New Luminosity Cherenkov Integrating Detector (LUCID)
  - High quality luminosity measurements, suitably rad-hard
- Upgraded ALFA system (4 Roman Pots on each side)
  - A new heat protection system and additional horizontal Roman Pots to improve acceptance
## ATLAS Detector Readiness

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Run 1</th>
<th>2015</th>
<th>Run 1</th>
<th>2015</th>
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<tbody>
<tr>
<td>Pixels</td>
<td>80 M</td>
<td>95.0%</td>
<td>99.0%</td>
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<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>99.3%</td>
<td>98.9%</td>
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<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>97.5%</td>
<td>97.3%</td>
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<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>99.9%</td>
<td>100%</td>
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<tr>
<td>Tile calorimeter</td>
<td>9800</td>
<td>98.3%</td>
<td>99.2%</td>
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<tr>
<td>Hadronic endcap LAr calorimeter</td>
<td>5600</td>
<td>99.6%</td>
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<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>99.8%</td>
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<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>100%</td>
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<tr>
<td>LVL1 Muon RPC trigger</td>
<td>370 k</td>
<td>100%</td>
<td>98.7%</td>
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<tr>
<td>LVL1 Muon TGC trigger</td>
<td>320 k</td>
<td>100%</td>
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<tr>
<td>MDT Muon Drift Tubes</td>
<td>350 k</td>
<td>99.7%</td>
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<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
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<td>98.4%</td>
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<td>RPC Barrel Muon Chambers</td>
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<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>98.2%</td>
<td>99.8%</td>
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</table>
CMS Consolidation in LS1

- Infrastructure upgrades
- Pixel detector overhaul on surface
- Running Tracker cold
- New photodetectors for HCAL
- Completion of 4th layer of muon system
- Beam instrumentation (Pixel Luminosity Telescope, Beam Conditions Monitor, Beam Loss Monitor, etc)
- Trigger improvements
- DAQ, computing and software improvements
- Other repairs
CMS Tracker

- Pixel system moved to surface during LS1 and overhauled
- Problems found just prior to reinstallation with 47/192 (1 quarter) of the BPIX not or only partially responding
  - Ohmic short between wire bonds pads and interconnects
  - Half-shell was reworked and short removed
- Pixel fully calibrated (-10 C)

- Cold operation of strip tracker to ensure efficient performance in Run 2
  - Leakage current doubles every 7C, plus with increasing radiation dose. Already at ~30% of power supply limit at the end of 2012
- Dry gas system, new seals and new bulk head panels
- Calibration @ -15 C completed early this year
CMS Tracker Performance

Strip Calibration

Run 1, +4°C

Run 2, -15°C

Pixel alignment

Link gain setting

Pixel hit efficiency

CMS Preliminary 2010

CMS Preliminary 2014

0 T at the beginning
08/04/2015

3.8 T since July 6

Jinlong Zhang
• Recovered dead channels due to LV connector fault in the endcap
• Repaired HV connector on pre-shower detectors
• Timed in for readout better than 1 ns
• Energy spectra in barrel, endcap and preshower OK

CMS Preliminary

13 TeV

\[ m_{\gamma\gamma} = 127.09 \pm 0.06 \]  
\[ \sigma = 10.56 \pm 0.07 \]

\[ m_{\gamma\gamma} = 119.93 \pm 2.73 \]  
\[ \sigma = 21.18 \pm 2.57 \]

\[ m_{\gamma\gamma} = 513.26 \pm 0.61 \]  
\[ \sigma = 26.70 \pm 0.76 \]
CMS HCAL

- SiPMs instead of Hybrid Photo Diodes (HPDs) in all of the HO Barrel
- New thin-window dual-anode readout PMTs in the HF forward region

HFPTimingVSLS

<table>
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<tr>
<th>HFPTimingVSLS</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>RMS y</th>
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<td>79608</td>
<td>1.708</td>
<td>60.86</td>
<td>0.2274</td>
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HF phase scan

Ratio of BX+1/BX

13 TeV
HB

8 TeV
HB
CMS Muon Spectrometer

- Three technologies (Drift Tubes DT, Resistive Plate Chambers RPC and Cathode Strip Chambers CSC)
  - Refurbishment and reinstalltion of ME1/1 chambers
  - Completion of the 4th layer of endcap station
  - Cosmic Runs, collision runs with and without Magnetic field

To time-in, calibrate and align the detectors
CMS Muon Performance

From inclusive and specialized dimuon triggers

- $\phi$
- $J/\psi$
- $Z$
- $Y$
CMS BRIL (Beam Radiation Instrumentation and Luminosity)

- **BCML**: new diamonds for beam abort system
- **BHM**: Cherenkov detector for high-radius background monitoring
- **HF**: new readout for proven online luminosity
- **PLT**: new silicon telescope for online luminosity
- **BCM1F**: scaled-up diamond system for online background and luminosity measurement
CMS Detector Readiness

Active Detector Fraction Run 1 to Run 2

- Pixel
- Strip
- EB+EE
- EB
- EE
- ES
- HCAL
- HB
- HE
- HF
- HO
- DT
- RPC
- CSC

Fraction (%)

Start Run 2 (May 2015)
End Run 1 (Feb 2013)

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13 TeV Stable Beams

June 3, 2015

PROTON PHYSICS: STABLE BEAMS

Energy: 6500 GeV

(B1): 2.93e+11

(B2): 2.96e+11

Comments (03-Jun-2015 10:40:01)
collapsed separation bumps in IP1 and 5
collapsed separation bumps in IP2 and 6
preparing for stable beams

First Stable Beams

proton-proton collisions at 13 TeV

08/04/2015
Jinlong Zhang
Substantial discovery potential for high-mass objects already with 1 fb\(^{-1}\)

\[ m(\text{system}) > \sim 2 \text{ TeV} \]

Increase in reach across ~all searches with 10 fb\(^{-1}\)
Run 2 to Date

\[ \mu^+\mu^- \text{ event with 881 GeV invariant mass} \]

CMS Integrated Luminosity, pp, 2015, \( \sqrt{s} = 13 \text{ TeV} \)

Run 251244 Event 204117665
\[ pp \rightarrow ZZ \rightarrow 2e2\mu \]
\[ m_{\mu\mu} = 91.1 \text{ GeV} \]
\[ m_{e\mu} = 88.2 \text{ GeV} \]
\[ m_{e_2} = 208.9 \text{ GeV} \]

\[ p_T^1 = 58.7 \text{ GeV} \] \[ \eta^1 = 1.8 \]
\[ p_T^2 = 36.1 \text{ GeV} \] \[ \eta^2 = 0.98 \]
\[ \phi^1 = 63.3 \text{ GeV} \] \[ \eta^1 = 1.2 \]
\[ \phi^2 = 25.5 \text{ GeV} \] \[ \eta^2 = 0.20 \]

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LHC Performance to Date

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</tbody>
</table>

50 ns intensity ramp-up: up to 476 nominal bunches

<table>
<thead>
<tr>
<th></th>
<th>Fill</th>
<th>Stable Beams</th>
<th>Peak lumi [cm^-2s^-1]</th>
<th>Int. lumi pb^-1</th>
<th>Nc</th>
<th>Ibunch</th>
<th>emittance [micron]</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 13th</td>
<td>3392</td>
<td>5h18</td>
<td>1.32 × 10^{33}</td>
<td>20.6</td>
<td>414</td>
<td>1.10 × 10^{11}</td>
<td>2.1</td>
</tr>
<tr>
<td>July 14th</td>
<td>3396</td>
<td>4h40</td>
<td>1.60 × 10^{33}</td>
<td>18.9</td>
<td>414</td>
<td>1.12 × 10^{11}</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Challenges to tackle

- **UFOs (small falling debris in beam pipe), e-cloud, beam induced heating, instabilities,...**
  - UFOs gradually diminish with running at high energy (past experience)
- **R2E: Single Event Upsets (SEU) in Quench Protection System (QPS) electronics cards**
  - To replace all faulty boards with old ones in TS2
- **ULO (Unidentified Laying Object)**
LHC 2015 Projection

- Priorities for the 2015 run
  - Establish proton-proton collision at 13 TeV with 25ns and low $\beta^*$ (5-8 fb$^{-1}$), to prepare production run in 2016 and onwards
  - Pb-Pb run at the end of 2015
- The goal for Run 2 luminosity is $1.3 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ and operation with 25 ns bunch spacing, with estimated pileup of 40 ($\sim$120-140 fb$^{-1}$)

Special runs

Possible $\beta^*$ reduction (80 cm towards 40 cm) plus fast ramp-up

50 ns MD & 25 ns scrubbing TS2

08/04/2015 Jinlong Zhang
Summary

• Beams back in the LHC machine since the beginning of April after a very intense LS1
• Major maintenance, consolidation and upgrade work completed for ATLAS and CMS
• Machine and experiments ready for 13 TeV collisions
• Run 2 just started so stay tuned
# Current 2015 LHC Schedule

<table>
<thead>
<tr>
<th>Phase</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Commissioning</td>
<td>59</td>
</tr>
<tr>
<td>Scrubbing</td>
<td>23</td>
</tr>
<tr>
<td>Special physics run 1 (LHCf/VdM)</td>
<td>5</td>
</tr>
<tr>
<td><strong>Proton physics 50 ns</strong></td>
<td>7 + 16</td>
</tr>
<tr>
<td><strong>Proton physics 25 ns</strong></td>
<td>69</td>
</tr>
<tr>
<td>Special physics run 2 (TOTEM/VdM)</td>
<td>7</td>
</tr>
<tr>
<td>Machine development (MD)</td>
<td>15</td>
</tr>
<tr>
<td>Technical stops</td>
<td>15</td>
</tr>
<tr>
<td>Technical stop recovery</td>
<td>6</td>
</tr>
<tr>
<td>Ion setup/Ion run</td>
<td>4 + 24</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>253 (36 weeks)</td>
</tr>
</tbody>
</table>

08/04/2015 Jinlong Zhang
CMS Magnet

• Most likely cause of the incident
  – Poorly functioning oil separator
  – Wrong coalescer cartridges loaded Nov 14 by maintenance mistake (corrected Feb 15)

• Implications
  – Contaminated 300m warm He line to cold box
  – Contaminated cold box during warm gas regenerations
    • Pressure drop across input filter to first expansion turbine
    • Anomalously large Breox oil contamination through most of cold box

• Actions
  – Replaced or cleaned the contamination of adsorber, filter and turbines
  – Mitigate with N2 pre-cooler for the contamination of heat exchangers
  – Keep temperature below Breox m.p for the contamination of thermal shield

• Cold box restarted 30 May
• Magnet @3.8 T on July 6
• Prepare thorough cleaning and He line replacement in YETS 2015-16 or sooner