The LHC machine: Run 2 and beyond

Mike Lamont for the LHC team
LS1 - descent into the underworld again
• Total interconnects in the LHC:
  – 1,695 (10,170 high current splices)
• Number of splices redone: ~3,000 (~30%)
• Number of shunts applied: >27,000

And a lot more besides...
Superconducting Magnets and Circuits Consolidation (SMACC)

Monumental effort
• Over 350 persons involved
• Including preparation: ~1,000,000 working hours
• No serious accidents!

Collaborations with NTUA (Athens), WUT (Wroclaw) and support of DUBNA

Jean-Philippe Tock
Powering tests
Following sector by sector cool-down

• All ~1700 magnet circuits taken to nominal current level one by one
  – Rigorous checks of quench protection, energy extraction, interlocks, power converter, ELQA
  – Some circuits are more critical than others...

cumulative number of powering tests

6 months
Dipole training 1/2

- 154 dipoles per sector, powered in series
- Ramp the current until single magnet quenches - “training quench”
- Repeat as necessary
Dipole training 2/2

Training: frictional energy released during conductor motion

From this morning...

- All magnets have been trained to well over 7 TeV in SM18 before installation
- Extensive re-training was not expected
LHC - 2015

• Target energy: 6.5 TeV
  – to be confirmed at end of powering tests!!!
• Bunch spacing: 25 ns
  – strongly favored by experiments (pile-up limit around 50)
• Beta* in ATLAS and CMS: 80 to 40 cm

Energy
• Lower quench margins
• Lower tolerance to beam loss
• Lower intensity set-up beams
• Hardware closer to maximum (beam dumps, power converters etc.)

25 ns
• Electron-cloud
• UFOs
• More long range collisions
• Larger crossing angle, higher beta*
• Higher total beam current
• Higher intensity per injection
LHC bunch structure - 2015

- 25 ns bunch spacing
- ~2800 bunches
- Nominal bunch intensity $1.15 \times 10^{11}$ protons per bunch

1 PS batch
(72 bunches)

1 SPS batch
(288 bunches)

26.7 km 2800 bunches
25 ns & electron cloud

Possible consequences:

- instabilities, emittance growth, desorption – bad vacuum
- excessive energy deposition in the cold sectors

Electron bombardingment of a surface has been proven to reduce drastically the secondary electron yield (SEY) of a material. This technique, known as scrubbing, provides a mean to suppress electron cloud build-up.

Electron cloud significantly worse with 25 ns
Squeeze in ATLAS

\[ \sigma^* \propto \sqrt{\beta^*} \]

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<th>( \beta ) triplet</th>
<th>Sigma triplet</th>
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<td>1.5 mm</td>
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<td>17 um</td>
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<tr>
<td>HL-LHC</td>
<td>~20 km</td>
<td>2.6 mm</td>
<td>15 cm</td>
<td>7 um</td>
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Image courtesy John Jowett
Crossing angle

work with a crossing angle to avoid parasitic collisions.

Separation: 10 -12 σ

geometric luminosity reduction factor:

\[ F = \frac{1}{\sqrt{1 + \Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x} \]
2015: beta* in IPs 1 and 5

• Many things have changed. Start carefully and push performance later.

• Start-up: $\beta^* = 80$ cm – (very) relaxed
  – 2012 collimator settings
  – 11 sigma long range separation
  – Aperture, orbit stability... to be checked

• Ultimate in 2015: $\beta^* = 40$ cm
  – To be deployed later in the year
2015 commissioning strategy

• Low intensity commissioning of full cycle – 8 weeks
• First stable beams – low number of bunches
• Special physics: LHCf and Luminosity calibration
• Scrubbing for 50 ns
• Intensity ramp-up with 50 ns
  – Characterize vacuum, heat load, electron cloud, losses, instabilities, UFOs, impedance
• Scrubbing for 25 ns
• Ramp-up 25 ns operation with relaxed beta*
• Commission lower beta*
• 25 ns operation
### 2015 Q1/Q2

#### Controls maintenance
- **January 29**

#### First Beam
- **February 25th (at the earliest!)**

#### Scrubbing for 50 ns
- **March 12**

#### Sector test 78-67
- **April**
- **23**

#### Machine checkout
- **April 29**

####SCRUBBING FOR 50 ns
- **June 25**

#### Easter Mon
- **April 30**

#### Recommissioning with beam
- **April 5, 13, 16, 19, 20, 27**

#### Powering tests
- **February 2**

#### Whit
- **May 18, 25**

#### Ascension
- **May 1st**

#### Special physics run
- **June 1, 8, 15, 22**

#### Intensity ramp-up with 50 ns beam
- **June 25**
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**Q3/Q4 2015**

**Scrubbying for 25 ns operation**

- July 27: Scrubbing for 25 ns
- Aug 3: Intensity ramp-up with 25 ns beam
- Sep 31: Special physics run

**Events:**
- MD 1
- TS2
- MD 2
- Jeune G
- Lower Beta*
- TS3
- Ions setup
- IONS
- MD 3
- Technical stop
- Xmas

**Dates:**
- End physics [06:00]

**Months:**
- Jul
- Aug
- Sep
- Oct
- Nov
- Dec
ATLAS and CMS performance

- Conservative beta* to start
- Conservative bunch population
- Reasonable emittance into collisions
- Assume same machine availability as 2012

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<th>Beta *</th>
<th>ppb</th>
<th>EmitN</th>
<th>Lumi [cm⁻²s⁻¹]</th>
<th>Days (approx)</th>
<th>Int lumi</th>
<th>Pileup</th>
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<td>50 ns</td>
<td>1300</td>
<td>80</td>
<td>1.2e11</td>
<td>2.5</td>
<td>4.8e33</td>
<td>21</td>
<td>~1 fb⁻¹</td>
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<td>1.1e11</td>
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<td>3 fb⁻¹</td>
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<td>1.2e34</td>
<td>48</td>
<td>8 fb⁻¹</td>
<td>34</td>
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Official GPD luminosity target for the year: 10 fb⁻¹
Run 2

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<th>Peak lumi E34 cm(^{-2})s(^{-1})</th>
<th>Days proton physics</th>
<th>Approx. int lumi [fb(^{-1})]</th>
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<td>2015</td>
<td>1.3</td>
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<td>2016</td>
<td>1.5</td>
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<td>2017</td>
<td>1.7</td>
<td>160</td>
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<td>2018</td>
<td>1.7</td>
<td>40</td>
<td>10</td>
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10 year plan

- Long years – 13 weeks Christmas stop
- Interspersed with long shutdown every 3 to 4 years
- Ions very much part of the plan

Run 2: 13 to 14 TeV c.m. with peak luminosity of \( \sim 1.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)

Run 3: 14 TeV c.m. with peak luminosity of \( \sim 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)

- EYETS 19 weeks
  - Extended year end technical stop (CMS)

- LS2: 18 months
  - Connection of LINAC4 LHC Injectors Upgrade

- LS3: 30 months
  - High Luminosity LHC

LS3 2.5 years to mid 2025
HL-LHC - goals

• Prepare machine for operation beyond 2025 and up to 2035
• Devise beam parameters and operation scenarios for:
  – total integrated luminosity of 3000 fb$^{-1}$ in around 10-12 years
  – an integrated luminosity of 250 fb$^{-1}$ per year
  – $\mu \leq 140$ (peak luminosity of $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$)
How?

- **Beam from injectors**
  - High bunch population, low emittance, 25 ns beam
- **Lower beta* (~15 cm)**
  - New inner triplet magnets - wide aperture Nb$_3$Sn
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- **Crossing angle compensation**
  - Crab cavities
- **Dealing with the regime**
  - Collision debris, high radiation
  - High machine availability
  - Beam stability, losses etc.
### HL-LHC: key 25 ns parameters

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<th>Parameter</th>
<th>Value</th>
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<td>Protons per bunch</td>
<td>$2.2 \times 10^{11}$</td>
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<tr>
<td>Number of bunches</td>
<td>2750</td>
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<tr>
<td>Normalized emittance</td>
<td>2.5 micron</td>
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<td>Beta*</td>
<td>15 cm</td>
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<tr>
<td>Crossing angle</td>
<td>590 microrad</td>
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<tr>
<td>Geometric reduction factor</td>
<td>0.305</td>
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<tr>
<td>Virtual luminosity</td>
<td>$2.4 \times 10^{35}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Levelled luminosity</td>
<td>$5 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Levelled $\langle$pile-up$\rangle$</td>
<td>140</td>
</tr>
</tbody>
</table>
1. Beams from injectors

LHC Injector Upgrade (LIU): A cascade of improvements across the whole injector chain to reach the HL-LHC target.
The critical zones around IP1 and IP5

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

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

1. New triplet Nb$_3$Sn required due to:
   - Radiation damage
   - Need for more aperture

More than 1.2 km of LHC

Plus technical infrastructure (e.g. Cryo and Powering)...

2. Lower beta*; 3. crossing angle compensation
HL-LHC & LIU

Projects firmly established and key parts of CERN’s mid-term planning
Conclusions

• 2015 goal is 25 ns at 6.5 TeV
  – Scrubbing++ required – even then electron cloud could remain an issue
• Lot of stuff to sort out again but there’s a lot of Run 1 experience
• Non-aggressive parameter choice/strategy to start with, aiming to re-establish stable operation with 25 ns before pushing performance
• LIU/LHC firmly established with planning out to 2035.