LHC Luminosity: Operational aspects

Alick Macpherson
LHC Lumi Days 2012
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Acknowledgements: Reyes Alemany Fernandez, Helmut Burkhardt, Gabriel Mueller, Giulia Papotti, Stefano Redaelli, Georges Trad, Mariusz Sapinski, Jorg Wenninger
Introduction

- LHC in 2012: normal operation
  - Changes in Beam Conditions for 2012

- Special Runs
  - Luminosity Calibration:
    - Van der Meer Scans
    - Length Scale Calibration
  - Software changes associated with Luminosity Scans

- High $\beta$ optics
  - $\beta^*$ of 90m and 500m
The LHC in normal operation
LHC operational cycle

**Time-functions** for settings of

1. ramp,
2. squeeze(s),
3. collisions,
4. pre-cycle (without beam).

**Discrete** ("actual") settings for:

1. injection,
2. prepare ramp,
3. flat-top,
4. adjust (end of squeeze),
5. stable beams.
LHC operational cycle

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End of Fill Studies

Luminosity Optimization
### LHC in 2012: What’s new in the optics

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<th>Value at top energy</th>
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These changes require tight collimator settings: TCPs @ $4.3\sigma$, TCTs @ $9\sigma$
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**Operational Sequence: Turnaround Improvements**

- Ramp duration [ s ]: **770 s** (2010: 1020 s)
- Squeeze duration [ s ]: **819 s** (0.6 m) (2010: 548 s (1.0 m))
- Collision BP duration [ s ]: **56 s** (2010: 56 s)

Theoretical time from Start of Ramp to collisions is the same from 2012 to 2010

- Crossing angle rotation in IP8 ~ **200 s**
LHC in 2012: What else is new

- Luminosity improvements compared to starting parameters of 2011
  - $E = 3.5\text{TeV}$  \ $I_{\text{bunch}}=1.1\times10^{11}$  \ $\beta^*=1\text{m}$  \ $\epsilon_n=2.0\mu\text{m}$  \ Crossing angle =240 $\mu\text{rad}$
  - Increase $I_{\text{bunch}}$ from $1.1\times10^{11}$ -> $1.6\times10^{11}$: Luminosity Increase = 112%
  - Emittance Increase: $\epsilon_n$ from 2.0 -> 2.5 $\mu\text{m}$ Luminosity Increase = -18%
  - Decrease $\beta^*$ from 1m -> 0.6m Luminosity Increase = 56 %
  - Beam Energy from 3.5 -> 4TeV Luminosity Increase = 12.5 %
  - Crossing angle: 240 -> 290 $\mu\text{rad}$: Luminosity Increase = -4.6 %

Total Peak Lumi improvement over ‘2011 start conditions’ = 187 %
Total improvement over ‘2011 end conditions’ ($I_{\text{bunch}}=1.4\times10^{11}$) = 76 %
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Total Peak Lumi improvement over ‘2011 start conditions’ = 187%
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However: Pileup ...
- Expected Av number events/crossing \( <\mu> \) = 34.2
- Av. vertex multiplicity should scale linearly with \( \mu \)
- Expts: reconstruction algorithms not fully optimized
  => Clear feedback from Expts on useful delivered luminosity is needed
Luminosity Leveling

- Control of Instantaneous luminosity and pileup levels
  - Introduced in 2011. Now **Standard Operational Procedure**: 
    - Luminosity regulated apply transverse offset in separation plane
      - Can be applied to all experiments

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**Fill 2160: Instantaneous Luminosity**

- Date: 2011-09-27

**Fill 2240: Instantaneous Luminosity**

- Date: 2011-10-22

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Luminosity Target value, Increment size, and time between increments controlled by each experiment
The new squeeze

- **$\beta^* = 0.9$ m**: Standard
  - 2011 collimator settings. (like in 2011). No issues

- **$\beta^* = 0.7$ m**: Significant commissioning (optics, orbit, $Q'$)
  - Need to switch from **standard** to **tight** collimator settings.
  - Tight settings used in physics (EoF) in 2011 ... but some issues.
    - Orbit control in squeeze.
    - Instability/impedance control
    - Better chromaticity control.

- **$\beta^* = 0.6$ m**: Nominally straightforward once $\beta^* = 0.7$ m done
  - Tight collimator settings. Re-arrangement of TCSG6-TCDQ-TCT.

**Plan for Initial running**

- Prepare squeeze sequences to $\beta^* = 0.6$ m and 0.7 m
- Commission with low intensity to $\beta^* = 0.6$ m.
- **Then take a decision on $\beta^*$ value.** ie 0.6 or 0.7m
Procedure to get to Stable Beams

- After the squeeze
  - Collapse the separation bumps
  - **Optimize luminosity in crossing angle plane** (All expts simultaneously)
  - **Declare Stable beams**
  - Optimize in separation plane (All expts where Lumi leveling not used)
  - Turn on Luminosity leveling in all required IRs
  - Take reference orbit once all Lumi leveling targets are reached

- One little complication  ...
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**LHCb Request: change from horizontal to vertical external crossing angle**

- **Reason:**
  - beam-beam @ 25ns: Ensure beam separation of 1st parasitic encounter >12σ
  - New scheme: crossing angle (hence machine config) independent of spectrometer polarity
  - LHCb: Crossing angle independent of polarity removes one systematic error

- **Implementation: Not yet defined ...**
  - crossing angle rotation at injection if aperture margin
  - After LHCb squeezed to 3m and while IP1/5 squeezing to 0.6m
  - After the squeeze
From the LPC ...

- Emphasis on luminosity production
  - Concentrate special runs towards the 2nd part of 2012

- Special Runs: Two higher priority tasks
  - Luminosity calibration ... what is requested?
    - One VdM scan with $\beta^* = 11$ m to reach ultimate precision
    - Perform the scan at sufficiently low $\mu$ (~1 or 2)
    - Keep transverse luminous size larger than vertex resolution
      - to investigate correlations between horizontal and vertical beam profiles
    - May also ask for calibration at nominal $\beta^*$

- High beta physics
  - 2 physics goals:
    - Diffractive physics at $\beta^* = 90$ m (mainly TOTEM)
    - Highest $\beta^*$ to approach Coulomb interference region for elastic scattering
  - Only one of physics run is likely within the present schedule
    - Proposal: A mixed setup with 90m in IP5 and 500m in IP1

- Other requests
  - Beam splashes events at expts, 10M evts in Low pileup sample ($\mu = 0.01$), very high pileup runs, stable beams fills 25 ns
  - Sufficient advance planning required to allow for preparation and setup
### LHC Schedule

- **Re-commissioning with beam:** 21 days + 3 days of scrubbing.
- **Physics @ Easter…**
- **Earlier scrubbing, shorter 1st MD = > Maximize ∫ Ldt for ICHEP**
- **LPC to clarify when details for Special Runs in first part of the year.**

### LHC Schedule Table

<table>
<thead>
<tr>
<th>Week</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
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<tr>
<td><strong>M</strong></td>
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<tr>
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<tr>
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<tr>
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</tr>
<tr>
<td><strong>S</strong></td>
<td>28</td>
<td>5</td>
<td>19</td>
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</tbody>
</table>

**Technical stop**

- **Start partial powering tests:** 1-Feb
- **Start full powering tests:** 1-Mar
- **Re-commissioning with beam**

### LHC Schedule Diagram

- **Scrubbing run (date tbc)**
- **8 wks physics**
LHC re-commissioning and special setups

First turn, CO, capture

450 GeV

Ramp

Squeeze

Optics corrections

MPS commissioning

Injection setup & validation

Collimation setup & validation

Stable beams and intensity ramp up

Transfer line setup

Injection steering

Injection protection

Transfer line collimation

Injection protection validation

Collimation 450 GeV

Ramp settings

Collimation 4 TeV FT

Tertiary setup squeeze & collisions

Squeeze settings

Loss maps

Setup 450 GeV

Setup 4 TeV

Dump protection

Dump protection validation

Validation required after any change to standard operational setup

For simple changes the minimum setup time is ~ 2 shifts
Special Runs: Luminosity Calibration
Luminosity Calibration

- In 2011 this procedure matured and is now standard
- Luminosity Calibrations is a multi-step process
  - **Beam Size measurements**
    - Errors: 5% (Wires scans), 10% (BSRT)
  - **Van der Meer Scans**
    - Stepwise scan 1 beam across the other
    - Luminosity as a function of beam separation
    - Scan in orthogonal planes
    - Repeat VdM with scan directions reversed
  - **Length Scale Calibrations**
    - Correlate beam movement with vertex offset
  - **Other calibration effects**
    - Energy (Jorg), beam beam effects (Werner)

- VdM: Must guarantee Aperture Margin at IPs and TCTs

**VdM: Aperture Margin OK for $\beta^*= 10\text{m}$ and $\beta^*= 0.6\text{m}$ @4 TeV**

- VdM for $\beta^*= 0.6\text{m}$ uses $\sim0.19\sigma$ @ TCT (Aperture budget is 0.2 $\sigma$)
Luminosity Calibration
Luminosity Calibration

**VdM Scans:**
Scans in orthogonal planes

*In 2011*  
- Horizontal plane  
- Vertical plane

*In 2012*  
- crossing angle  
- separation planes

Allows for inclined crossing angle plane (eg LHCb)

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**Maximum beam separation at IP**
- **Van der Meer Scan:** $6 \sigma$
- **Lumi Optimization:** $2 \sigma$

**Beam size ($\varepsilon_n = 3.5 \mu m$)**
- $\beta^* = 0.6 m$ @ $4$ TeV  
  $\sigma = 22 \mu m$
- $\beta^* = 1.0 m$ @ $3.5$ TeV  
  $\sigma = 31 \mu m$
Van der Meer Scans in 2011

VdM at collision settings

VdM scans: Typically 2-beam symmetric. Max Beam separation = ±6σ

VdM with offset in other plane
Off set = 160µm
Example: VdM Scan in May 2011 (Fill 1783)

- **Conditions:**
  - p-p @3.5 TeV, $\beta^*$: 1.5/10/1.5/3 m, $I_{\text{bunch}}=\sim 0.8\text{e11}$
  - Vdm Program Duration: ~11 hrs
  - Filling Scheme: Single_38b+1small_14_16_22_4bpi11inj

- **Scans per IP at collision settings:**
  - VdM 20 minutes each plane (H,V)
  - H-plane VdM with V-offset: 15 minutes
  - V-plane VdM with H-offset: 15 minutes

- **Length Scale Calibration (LSC)**
  - "Fast" LSC: 15 min per plane (full loop, and reversed)
  - ‘Leap-frog" LSC: 2 hrs per plane (Special request by ATLAS)

**Minimum time for Lumi Calibration Run**

Duration = $4\times2\times(VdM_{\text{1-plane}}) + 4\times2\times(VdM_{\text{offset}}) + 4\times2\times\text{LSC}_{\text{Fast}}$ = 400 min

=> Lumi Calibration is possible in 1 shift ... But special scan patterns take longer
Luminosity Scanning software improvements

- Ongoing ...
  - Ability to scan in crossing angle and separation planes (default)
    - implementation ongoing ...
    - depends somewhat on implementation of LHCb crossing angle rotation
  - Luminosity Leveling functionality for all IPs
  - Optimization Status to be published to Expts
  - Ability to pause/resume VdM scan sequence

- To be implemented ...
  - Ability to load predefined scan sequence
    - Each expt can define its scan procedure
      - VdM scans with single or both beam trims
      - LSC scans with leap-frog or fixed separation method.
  - Perform VdM scans at different IPs in parallel if requested
  - Make available LUMI-SCAN trims to experiments

For 2012 startup, **standard functionality assured** but testing/validation needed for more complicated requests ... end of fill tests etc.
High Pileup run - FILL 2252: \( N \approx 2.3 \times 10^{11} \) protons per bunch \( \varepsilon_n \approx 2.5 \) µm

Separation scans: all as expected
Note of caution ...

High Pileup run - FILL 2252: \( N \approx 2.3 \times 10^{11} \) protons per bunch \( \varepsilon_n \approx 2.5 \, \mu m \)

- Separation scans: all as expected
- Lumi re-optimization at EOF
  - ATLAS shows a \( \sim 10\% \) jump
  - ATLAS confirms data is correct
  - Reason: not optimised in vertical at start of fill

G.Trad – LSWG December 8, 2011
Special Runs: High $\beta$
High $\beta$ operation

- **High $\beta$ operation is classified as Special Running**
  - Physic coordinator defines priority: ~8 days of Special Runs allocated
    - High $\beta$ program: need Special Runs + Machine Development time to meet the physics program
    - Only one of physics run can be supported within present schedule
  - **Proposal:** A mixed setup with 90m in IP5 and 500m in IP1

- **Setup time for High $\beta$**
  - $\beta=90m$: Re-commission the de-squeeze for 4TeV
  - $\beta=500m$: full commission of the de-squeeze for 4TeV
    - Preparation: New optics and extended operational sequence
    - Setup:
      - Full commissioning of new de-squeeze
      - Orbit + optics checks at matched points

- De-squeeze to 90 and 500 m will be commissioned together.
**High $\beta^*$ optics: going from 90m to 500m**

- **De-squeeze to 90 m (as usual) then extend to 500m in steps**
  - At each Step (matched point)
    - Require vertical phase advance (IP to RP) $\Delta \mu_V = 90^\circ$. No constraint on $\Delta \mu_H$
    - Cabling constraint on Beam1:Beam2 ratio of Quadruple strengths (Q4 to Q8)
      - $0.5 < k_{b1}/k_{b2} < 2.0$
  - **Current basis and status :**
    - **Optics: 1st iteration exists optics for $\beta^* = 90 - 500$ m sequence**
      - All constraints satisfied, but smoothing and validating required

Talks by Helmut and Sophie
Operational Issues

- **De-Squeeze sequence**
  - ~17 match points to go from $\beta^*$ of 10m to 500m

- **Orbit control:**
  - Need regular orbit control/correction
  - Constraint
    - de-squeeze beam separation $\sim$ 2mm

- **Get Roman Pots close to beam**
  - Possibility of scraping to $\varepsilon_n \sim$ 1 µm
  - Try to probe Coulomb region

- **Setups for High $\beta$ runs**
  - $I_{\text{bunch}} \sim 3 \times 10^{10}$
  - no crossing angle $\Rightarrow$ up to 156 bunches.
  - **Equipment setup:** ADT, Feedbacks, BCTs, BPMs
    - Only standard equipment re-configurations
High $\beta$ commissioning ... time estimates

- **Fill 1:** Established feasibility, first optics measurements  *(1-2 shifts)*
  - Probe beams. Several de-squeezes probably needed

- **Fill 2:** Validate operational sequence all the way to collisions. *(1 shift)*
  - Probe beams

- **Fill 3:** Beam based alignment of Roman Pots  *(1 shift)*
  - Few nominal bunches
  - Optics measurements and checks

- **Fill 4:** Roman Pots to "physics" settings => validate stable beams  *(1 shift)*
  - 10-20 nominal bunches.
  - Complete set of loss maps in physics settings + Async dump test

- **Fill 5:** Stable beams running at High $\beta$ setting with Roman Pots in  *(1 shift)*
  - Optional: Make luminosity calibration measurements (VdM and Length Scale Calib) in IP8 & IP2 while taking physics data in IP1&5

**Total high $\beta$ setup time (optimistic): 5+1 non-consecutive shifts**
High $\beta$ running: Experience from 2011

- Total High $\beta^*$=90m time: 119 hrs - 15hrs physics = 104 hrs ~13 shifts
  - Time spread over 5 periods
  - No beam dumps directly triggered by the $\beta^*$ de-squeeze.

- Expectation for 2012:
  - Commissioning of $\beta^*$=500m should take about the same time ...
Summary

- **2012 Standard operation**
  - The 2012 LHC priority is to deliver luminosity
    - **5 fb\(^{-1}\) by June is tough**: 8 wks @ \(\beta^*=0.6\text{m}\ \ell_{\text{bunch}}=1.6\times10^{11} \Rightarrow L_{\text{DEL}} \approx 6.6 \text{ fb}\(^{-1}\)**
    - Commission to \(\beta^*=60\text{ cm}\). Decide on \(\beta^*\) then intensity ramp up
    - Adiabatic increase of \(\ell_{\text{bunch}}\) up to \(1.6\times10^{11}\) (as machine permits)
  - Optimization of operational cycle
    - Turnaround trimmed & Minimal procedure to declare stable beams
  - Rotation of LHCb crossing angle
    - Details and procedure still being finalized

- **Special runs: Priorities mostly set. Now scheduling needed**
  - Lumi Calibration: Firm up details on what and when
  - Lumi Scan and VdM software **upgrade is ongoing ...**
    - Lumi leveling functionality for all IPs
  - High \(\beta\): Only 1 run seems likely \(\Rightarrow\) confirm required configuration
    - ie \(\beta=90\text{m}\) for TOTEM and \(\beta=500\text{ m}\) for ALFA, no pilots, \(\ell_{\text{bunch}} \approx 3\times10^{10}\) etc
    - Optics for \(\beta=500\text{ m}\) is in good shape.