First LHC Emittance Measurements at 6.5 TeV

Maria Kuhn\textsuperscript{1,2} – September 16, 2015

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Introduction: LHC Cycle and Beam Parameters

- **Injection**
- **Ramp**
- **Squeeze**
- **Collisions**

- Two circulating beams.
  - Beam 1 rotating clockwise, beam 2 counter-clockwise.

- Collisions in four interaction points in the LHC.
  - ATLAS and CMS are the two large multi purpose detectors.
Introduction: LHC Cycle and Beam Parameters

- Injection
- Ramp
- Squeeze
- Collisions

### Proton beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC Design</th>
<th>2012 LHC</th>
<th>Early 2015 LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td># bunches/ beam</td>
<td>2808</td>
<td>1374</td>
<td>3 - 458</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25</td>
<td>50</td>
<td>25 and 50</td>
</tr>
<tr>
<td>Mean bunch length [ns]</td>
<td>1.3</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Bunch intensity [$10^{11}$ p]</td>
<td>1.15</td>
<td>1.1 - 1.7</td>
<td>1.0 – 1.2</td>
</tr>
<tr>
<td>Emittance at injection [μm]</td>
<td>3.5</td>
<td>1.5 – 2.0</td>
<td>1.5 – 3.0</td>
</tr>
<tr>
<td>Collision energy/beam [TeV]</td>
<td>7</td>
<td>4</td>
<td>6.5</td>
</tr>
<tr>
<td>Emittance at collision [μm]</td>
<td>3.75</td>
<td>2.4</td>
<td>1.5 – 4.0</td>
</tr>
<tr>
<td>$\beta^*$ at ATLAS/CMS [m]</td>
<td>0.55</td>
<td>0.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>
In 2012 LHC was operated with high brightness beams.
- Transverse emittance could not be preserved during the LHC cycle.
- \(\sim 0.4 – 0.9 \, \mu m\) normalized emittance growth from LHC injection to start of collisions.
- But emittance measurement precision during LHC Run 1 doubtful.

![Diagram showing wire scanner vs. ATLAS vs. IBS simulation, 144 bunches](image)

2012 LHC performance

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LHC Wire Scanner Intensity Limitations

- Several types of beam profile measurement systems in the LHC.
  - The wire scanners are the most precise and versatile instruments.
  - Two operational wire scanners per beam.
    - Horizontal and vertical.

- Wire scanners cannot be used with high intensity physics fills.
  - Synchrotron light telescope (BSRT) is used for that purpose.

- BSRT cross calibrated with wire scanners.

- Currently, wire scanners are the only instrument to measure beam sizes through the LHC energy ramp.
  - Low intensity test fills (a few bunches) are measured to evaluate emittance preservation during the LHC cycle.
Run 2 LHC Wire Scanner Accuracy

- Transverse normalized emittance $\varepsilon$:
  - (For location with no dispersion)

LHC Run 2 optics measured with k-modulation at 450 GeV and turn-by-turn phase advance method at 6.5 TeV.

- $\beta$ function accuracy better than 3 %.

Wire scanner beam size $\sigma$ accuracy

- Wire position measurement precision
  - Estimated position measurement potentiometer precision: 50 $\mu$m

- Wire position measurement calibration
  - Verified with beam by orbit bump scans at the wire scanner location

\[ \varepsilon_{x,y} = \gamma \frac{\sigma_{x,y}^2}{\beta_{x,y}} \]
Wire Position Measurement Calibration

- Using local orbit bumps to verify the wire position measurement calibration of the wire scanners.
  - Beam position measured with LHC orbit system and extrapolated to wire scanner.
  - Compared to mean position obtained from Gaussian fit to measured transverse beam profile.
  - Measurements at 450 GeV and 6.5 TeV are consistent.

Example B2V1: slope of linear fit shows + 3.3 % calibration error.

→ Overestimating B2V emittances by 6.6 %.
**Wire Scanner Emittance Measurement Errors**

- Wire scanner position calibration verification results ($\Delta \varepsilon_{\text{calibration}}$):
  - Another set of orbit bumps foreseen for the near future to check reproducibility of obtained results.
  - The results in this talk do not include a correction of the calibration.

- All wire scanner measurements show large $\sigma$ spread from scan to scan ($\Delta \varepsilon_{450\text{GeV}}$ and $\Delta \varepsilon_{6.5\text{TeV}}$).
  - Depending on scanner and energy.

<table>
<thead>
<tr>
<th>Wire Scanner</th>
<th>$\Delta \varepsilon_{\text{calibration}}$ [%]</th>
<th>$\Delta \varepsilon_{450\text{GeV}}$ [%]</th>
<th>$\Delta \varepsilon_{6.5\text{TeV}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1H2</td>
<td>+ 7.2</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>B1V2</td>
<td>- 5.2</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>B2H1</td>
<td>+ 9.0</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>B2V1</td>
<td>+ 6.6</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>
Photomultiplier Working Point Investigations

- Wire scanner shower product amplified by photomultiplier (PM).
  - Amplification settings (gain + filter) can alter obtained beam profile.
- LHC Run 1: strong dependence of measured $\sigma$ on PM settings.
- Optimum PM working point has to be established!
  - Scan through all available gain and filter setting combinations.

Bunches with different beam sizes were injected.

To remove natural $\varepsilon$ growth, scans with fixed reference settings done after each settings change.

$\Rightarrow$ Exponential fit

Example: B2V1 at 450 GeV
Photomultiplier Working Point Investigations

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  - Amplification settings (gain + filter) can alter obtained beam profile.
- LHC Run 1: strong dependence of PM settings on measured $\sigma$.
- Optimum PM working point has to be established!
  - Scan through all available gain and filter setting combinations.

Measured beam sizes minus the fitted growth.

Measurements with same gain + filter settings are averaged.

⇒ No sign of PM saturation at 450 GeV could be detected.

⇒ Same for 6.5 TeV.
First Emittance Measurements (1)

- Example Fill 4284 (August 28, 2015):
  - 3 bunches with different initial emittances, intensities (0.6 – 1.1 \times 10^{11} \text{ ppb}) and bunch lengths (1.0 – 1.25 \text{ ns}).

IBS simulations with MADX IBS module include measured initial beam parameters, dispersion, and radiation damping.

Measurements in the horizontal planes match IBS simulation.
Example Fill 4284 (August 28, 2015):
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Measurements in the horizontal planes match IBS simulation.

Emittance growth through the cycle of bunch 3

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon_{450\text{GeV}}$ [μm]</th>
<th>$\varepsilon_{6.5\text{TeV}}$ [μm]</th>
<th>$\Delta\varepsilon$ [%]</th>
<th>$\Delta\varepsilon_{\text{sim}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1H</td>
<td>1.90</td>
<td>2.08</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>B1V</td>
<td>1.71</td>
<td>2.04</td>
<td>19</td>
<td>-2</td>
</tr>
<tr>
<td>B2H</td>
<td>1.50</td>
<td>1.65</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>B2V</td>
<td>1.58</td>
<td>1.95</td>
<td>23</td>
<td>-2</td>
</tr>
</tbody>
</table>

Vertical emittance growth through the cycle could not be reproduced with IBS simulations.
Emittance Growth during the LHC Ramp

- Measured $\beta$ during ramp not yet available.
  - Using linear interpolation of measured $\beta$ at injection + flattop.
- Current $\beta$ knowledge results in unphysically growing/shrinking $\varepsilon$.
  - Run 1 experience: non-monotonically changing $\beta$ functions during the ramp.

Measurements in the horizontal planes consistent with IBS simulations during the ramp.

Beam 2 vertical emittances grow 20% (~0.3 $\mu$m).
Emittance Preservation during the Squeeze

- Within measurement accuracy emittances are conserved during the $\beta^*$ squeeze.
  - Result is reproducible.

Emittances measured with BSRT and averaged over several hundred measurements.

Also need measured $\beta$ functions during the squeeze.
Emittance at Start of Collisions

- Comparison of emittance from wire scans and luminosity:
  - Fill 3954 (July 4, 2015), one bunch in collision.
  - According to experts ATLAS luminosity low by ~10 % with uncertainty ±10 %.
    - 5 % error on crossing angle
    - ±1 cm error on measured bunch length.
    - $\beta^*$ measured with $k$-modulation with 1 % uncertainty.

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<th>Injection</th>
<th>Collision</th>
<th>Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS $\epsilon$ [(\mu m)]</td>
<td>2.51 ± 0.10</td>
<td>2.75 ± 0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>ATLAS $\epsilon$ [(\mu m)]</td>
<td>n.a.</td>
<td>2.97 ± 0.36</td>
<td>0.46</td>
</tr>
</tbody>
</table>

- Preliminary: ATLAS and wire scanner results agree within errors.
  - Better than during Run 1.

$L = \frac{k N^2 f \gamma}{4 \pi \beta^* \epsilon} \cdot F$

$L$ .... Luminosity
$k$ .... # bunches
$N$ .... # protons / bunch
$f$ .... Revolution freq.
$F$ .... Luminosity reduction factor
Radiation Damping at 6.5 TeV

- At high energies protons circulating in the LHC emit enough synchrotron radiation to modify the beam parameters
  - First observed during LHC Run 2
  - Counteracts IBS: reduction of vertical emittance

Simulations with MADX IBS module.

- Simulation predicts slightly faster emittance decrease than measured with BSRT.
- Additional emittance growth from proton collisions + beam–beam effects not included in the simulation.
Current Performance of the LHC

- Emittance in collisions derived from luminosity.
- Injection emittance of first batch measured with SPS and LHC wire scanners.

Emittance blow-up through the cycle:

- 50 ns beams show very little blow-up (~10%), much smaller than during Run 1.
- Large blow-up for 25 ns beams (25% for most recent fills).
  - Electron cloud effects
  - Beam instabilities
Summary & Conclusion

- Good progress in understanding wire scanner emittance measurements for LHC Run 2.
  - Wire scanner calibration verified, no PM saturation effects detected.

Emittance growth during the LHC cycle:
- Horizontal emittance growth matches IBS simulations.
- Small growth in the vertical planes not yet understood.
  - Caveat: single bunch fills.
- Synchrotron radiation damping observed for the first time at 6.5 TeV.
- With still not fully calibrated luminosity data: emittances from wire scans and ATLAS luminosity agree within errors.

- Smaller emittance blow-up (~10%) through the cycle than during Run 1 for 50 ns beams.
- 25 ns physics beams show much larger growth.
  - Electron cloud effects and beam instabilities.
Outline

- LHC cycle and beam parameters
  - LHC Run 1 transverse normalized emittance blow-up
- LHC wire scanner intensity limitations
- Run 2 LHC wire scanner accuracy
  - Wire position measurement calibration
  - Photomultiplier working point investigations
- First transverse normalized emittance measurements
  - Emittance growth during the LHC ramp
  - Emittance preservation during the squeeze
  - Emittance at start of collisions
  - Radiation damping at 6.5 TeV
- Current performance of the LHC
The LHC needs most of the CERN accelerators...

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Photomultiplier Saturation Studies Run 1

- Photomultiplier (PM) gain and filter can have a strong influence on measured beam size
  - See measurements of 2012

Observed strong gain dependence at 450 GeV and 4 TeV during Run 1!

PM saturation studies at 450 GeV in 2012.  

PM saturation studies at 4 TeV in 2012.
Photomultiplier Working Point at 6.5 TeV

- Measurements at 6.5 TeV more difficult.
  - Smaller range of possible PM settings before ADC saturation.

- No evident sign of PM saturation at 6.5 TeV could be seen.

- Run 1 investigations showed significant dependency of measured beam size on PM settings.

  ➤ LHC wire scanner upgrade during Long Shutdown 1:
    - One broken wire scanner replaced (beam 2).
    - Power supply schematics upgraded.
    - PM gain dependency on light intensity reduced.
LHC Optics Measurements

- Can use results from optics measurements with the turn-by-turn phase advance method and k-modulation for:

  - Outstanding measurements:
    - K-modulation at 6.5 TeV and after the squeeze
    - Turn-by-turn phase advance measurements at 450 GeV (repeated) and during the ramp!

- For emittance plots: using measured $\beta$ where possible
  - $\beta$ function measurement error < 3 %
  - Maximum measured beta beat is 5 % at the wire scanners
  - Linear interpolation during the ramp and squeeze
**β* Measurements**

- Sinusoidal k-modulation in IP1/5 on August 8, 2015

**Measurement error on tune oscillation amplitude in sub-percent level**

- $\beta*$ meas. uncertainty $\leq 1\%$
- Beta beat $\leq 1\%$
- Compatible with turn-by-turn measurements

<table>
<thead>
<tr>
<th>Preliminary</th>
<th>IP1 [m]</th>
<th>IP5 [m]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>B1</td>
<td>B2</td>
</tr>
<tr>
<td>$\beta^* H$</td>
<td>0.81</td>
<td>0.79</td>
</tr>
<tr>
<td>$\Delta \beta H$</td>
<td>0.01</td>
<td>0.004</td>
</tr>
<tr>
<td>$\beta^* V$</td>
<td>0.81</td>
<td>0.79</td>
</tr>
<tr>
<td>$\Delta \beta V$</td>
<td>0.01</td>
<td>0.01</td>
</tr>
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</table>
Bunch Length Measurement

- Longitudinal bunch shape not Gaussian at 6.5 TeV
  - Due to controlled longitudinal RF blow-up at flattop energy
- But LHC bunch length monitor publishes 4$\sigma$ bunch length values based on FWHM algorithm assuming Gaussian profiles

\[ \text{Bunch length error } \pm 1 \text{ cm!} \]

\[ \text{“True” emittance from luminosity should be larger by 0.1 } \mu\text{m} \]

[Graph of strongly non-Gaussian profile]