Observations of beam-beam effects at the LHC

Giulia Papotti for the beam-beam team
outline

• layout and filling scheme, numerology
  – collision pattern effects
  – potential loss of LD
• luminosity levelling with offset (IP2/8)
• HO tune shifts in MDs
• strong-strong effects: coherent modes and orbit
• scan of crossing angle
  – effect on losses and dynamic aperture
  – PACMAN observations

HO = Head-On
LR = Long-Range
LD = Landau Damping
MD = Machine Development
ppb = protons per bunch
LHC layout

- Large Hadron Collider
  - very big, very cold, very high energy
- 8 arcs (~3km), 8 straight sections
- two-in-one magnet design

- IP2 and 8: injection
- IP6: beam dump region
- IP4: RF and BI
- IP3/7: collimators
- 4 Interaction Points (IPs)
  - IP 1 (ATLAS) and 5 (CMS): high luminosity experiments
  - 2 (Alice) and 8 (LHCb): with luminosity limitations
filling schemes

- motivation: different luminosity targets from the 4 experiments
  - filling schemes tailored to give different number of colliding pairs
    - ATLAS, Alice, CMS are located at the IP symmetry point, LHCb is 11.25 m away
    - techniques of luminosity levelling are operational
- 2.5 ns buckets, $h = 35640$, 25 ns minimum bunch spacing
- for a filling scheme we can chose:
  - bunch spacing: 25ns, 50ns, 75ns, 150ns, or >250ns
  - number of PS batches (1-4, dynamic), number of PSB rings
  - injection bucket

![INJECTION SEQUENCER v0.1.04](image)
example for ring 1

### INJECTION RING 1

<table>
<thead>
<tr>
<th>RF Bucket</th>
<th>Nbr Bnches</th>
<th>Bnch Spac [ns]</th>
<th>PS Btchs</th>
<th>Bnch Int [E9]</th>
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</table>

4 PS batches at SPS  
Injection kicker gap  
Abort gap

50 ns, 1380 bunches/ring
reminder on LHC performance

- 2010: inst. luminosity of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- 2011: did 5.5 fb$^{-1}$
- 2012: did 23.2 fb$^{-1}$
  - ~nominal $\beta^*$ thanks to excellent aperture and ‘tight’ collimators
  - very bright beams from injectors (note also SPS Q20 optics)

<table>
<thead>
<tr>
<th>parameter</th>
<th>design</th>
<th>2012</th>
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<tr>
<td>beam injection energy (TeV)</td>
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<td>beam energy (TeV)</td>
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<td>4</td>
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<td>number of bunches per beam (bunch spacing, ns)</td>
<td>2808 (25)</td>
<td>1380 (50)</td>
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<tr>
<td>$\beta^*$ at IP1/5 (m)</td>
<td>0.55</td>
<td>0.6</td>
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<tr>
<td>number of particles per bunch ($10^{11}$)</td>
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<td>1.65</td>
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<tr>
<td>norm. transverse emittance ($\mu$m rad)</td>
<td>3.75</td>
<td>2.5</td>
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<td>colliding beam size ($\mu$m)</td>
<td>16</td>
<td>19</td>
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<td>luminosity (cm$^{-2}$s$^{-1}$)</td>
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<td>0.77e34</td>
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<td>stored beam energy (MJ)</td>
<td>362</td>
<td>145</td>
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why 50 ns and not 25 ns?

<table>
<thead>
<tr>
<th></th>
<th># bunches</th>
<th>Nbunch (1e11 p)</th>
<th>ε SPS extr(μm)</th>
<th>ε LHC coll (μm)</th>
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<td>25 ns</td>
<td>2760</td>
<td>1.15</td>
<td>2.8</td>
<td>3.75</td>
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<tr>
<td>50 ns</td>
<td>1380</td>
<td>1.6</td>
<td>1.7</td>
<td>2.3</td>
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</tbody>
</table>

• 2012: 50 ns allowed more integrated luminosity while saving on scrubbing time
  - 50 ns beams are brighter from injectors
    • pile-up μ still manageable at 4 TeV (μ~30-35)
  - smaller emittance than for 25 ns allowed squeezing further
    • e.g. β^*_50=60 cm; β^*_25=80 cm;
  - 50 ns are much less affected by ecloud
    • thus less scrubbing time needed (3 days vs 2 weeks)
    • aim for more data for summer conference (July 2012)

• post LS1: 25 ns is default
  - too high pile-up with 50 ns (μ~80-120 vs μ~25-45 with 25 ns)
    • might need levelling even with 25 ns
  - “when” will depend on scrubbing efficiency
  - note: no more non-colliding bunches

Pile-up: number of inelastic collisions per bunch crossing

R. Jacobsson, “Needs and requirements from the LHC physics experiments"
luminosity levelling with offset

- LHCb and Alice limited in pile-up $\mu$
  - LHCb at $\mu \sim 2.5$
  - Alice at $\mu \sim 0.02$
    - ran also with main-satellite collisions (satellites at 25 ns)
- run with separated beams (transverse offset)
  - e.g. LHCb: running at constant $L \sim 4 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
  - trimming down the offset in small steps during the fill
  - people worried at first, but no real showstopper found

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**R. Jacobsson, “Needs and requirements from the LHC physics experiments”**

**B. Muratori, “Luminosity levelling techniques: implications for beam-beam interactions”**

**D. Jacquet, “Implementation and experience with luminosity levelling with offset beams”**

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![Graph of instantaneous luminosity over time](image-url)
collision patterns

- provide different number of colliding pairs to different experiments by shifting the injection bucket
  - examples of filling schemes used in 2012 for physics production
    - 50 ns spaced beams, IP1/5 at $\beta^* = 0.6$ m
  - Alice running with main-satellite collisions, $\beta^* = 3$ m
  - LHCb running with levelling by offset ($\beta^* = 3$ m)
    - scheme 1 to 2: shift 4 injections

<table>
<thead>
<tr>
<th>scheme</th>
<th>total number of bunches</th>
<th>number of colliding pairs</th>
<th>comments</th>
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<tr>
<td></td>
<td></td>
<td>IP 1 and 5</td>
<td>IP 2</td>
</tr>
<tr>
<td>scheme 1</td>
<td>1380</td>
<td>1331</td>
<td>0</td>
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<tr>
<td>scheme 2</td>
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<tr>
<td>scheme 3</td>
<td>1380</td>
<td>1377</td>
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</table>
• some bunches in ring 1 were losing very quickly due to instabilities
  – interlock kicked in at ~4e10 ppb, and fills terminated prematurely
  – bunches colliding only in IP8 (levelled by separation)
• changed collision pattern to have head-on collisions in IP1/5 for all bunches
  – need the beam-beam tune spread
  – kept 3 non-colliding for background studies at IP1/5
loss of Landau damping

- single bunches that become unstable
  - visible on losses, sometimes on emittance growth
  - need improvements on instrumentation for instabilities detection

R. Giachino, “Diagnostics needs for beam-beam studies and optimization"
high HO tune shift in MDs

• performed several tests:
  – dedicated MDs on head-on limitations in 2011
  – high pile-up tests in 2011 and 2012

• head-on limit MD (2011):
  – N=1.9e11 ppb, $\varepsilon=1.2$-$1.4$ $\mu$m
  – linear head-on parameter: $\xi=0.02/IP$ and $\xi=0.034$ total
    • design report: $\xi=0.0033/IP$ for (3 IPs, +1 offset)
  – no significant losses nor emittance effects observed
    • tune adjustment needed to avoid emittance blowup: $Q_H=Q_V=0.31$
high pile-up in MDs

- design report: pile-up $\mu \sim 19$
- MD: high pile-up test ($\mu_{max} \sim 31$) in 2011
  - used by experiments to study their own limitations
- MD: high pile-up test ($\mu_{max} \sim 70$) in 2012
  - $N=3e11$ ppb, $\varepsilon=2.2 \ \mu$m
    - very bright single bunches with SPS Q20 optics
  - instabilities observed during ramp and squeeze
    - despite increased chromaticity and longitudinal size
    - one beam only into collisions cleanly
    - would have needed more time and iterations

pile-up: number of inelastic collisions per bunch crossing

G. Trad, “Beam-beam effects with a high pile-up test in the LHC”
coherent modes

- observed during the head-on MDs in 2011
  - with individual bunches
- could measure $\sigma$ and $\pi$ modes

X. Buffat, “Coherent beam-beam modes in the LHC”
head-on collisions and losses

• 2010, $\sim0.9\text{e}11$ ppb
• used to have a tune split
  – had problems initially, possibly with coherent modes
  – first: $\Delta Q1: -2.5\text{e}^{-3}; \Delta Q2: +2.5\text{e}^{-3}$
    • lifetime beam 1 worse than beam 2
  – here inverted: $\Delta Q1: +2.5\text{e}^{-3}; \Delta Q2: -2.5\text{e}^{-3}$
    • lifetime beam 2 worse
  – finally tune split removed

expected burn-off: $\sim0.5\text{e}9$/collision after 500 minutes
scans of crossing angle: settings

- crossing angle reduced in steps until losses or lifetime reduction is observed
  - in successive MD sessions, with different $\beta^*$, intensity and number of LR interactions
  - record separation for onset of losses
- results used to confirm simulations and predict required separation with future settings

<table>
<thead>
<tr>
<th>scan</th>
<th>$\beta^*$</th>
<th>crossing angle</th>
<th>intensity</th>
<th>transverse emittance</th>
<th>bunch spacing</th>
<th>energy</th>
<th>IPs and comments</th>
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<tr>
<td>1</td>
<td>1.5</td>
<td>120</td>
<td>1.2</td>
<td>2-2.5</td>
<td>50</td>
<td>3.5</td>
<td>IP1 then IP5</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>120</td>
<td>1.2</td>
<td>2-2.5</td>
<td>50</td>
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<td>3</td>
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<td>IP1 then IP5</td>
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<td>3.1</td>
<td>25</td>
<td>4</td>
<td>IP1+IP5</td>
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</table>
scan of crossing angle: losses

- scan 1
  - 3.5 TeV
  - $\beta^*=1.5$ m
  - xing angle=+-120 $\mu$rad
  - $N=1.2e11$ ppb
  - $\varepsilon=2-2.5$ $\mu$m
- scan of IP1 only

- 12 non-colliding +
  - 50 ns train of 36

D. Kaltchev, “Analysis of long range studies in the LHC - comparison with the model”

W. Herr, “Long range beam-beam effects and experience in the LHC”
scan of crossing angle: results

- clear dependence on bunch position in batch (anti-PACMAN)
  - dependence on number of head-on collisions highlighted also
- evidence for alternate crossing effectiveness
  - crossing plane: IP1 V, IP5 H (to compensate first order LR effects)
  - scan in IP5 after IP1: lifetime seemed best when separation and crossing angles are equal for the two IPs
- proven that it is a dynamic aperture effect
  - no effect on emittance
  - losses recover if wider crossing restored

emittance from scan 2
scan of crossing angle: 25 ns

• 25 ns have twice the number of LR interactions
  – thus need bigger separation

• LR studies with 25 ns in 2012 (scan 5)
  – crossing reduced simultaneously in IP1/5
  – losses monitored
    • asymmetry B1/B2 not observed with 50 ns and to be understood
  – e-cloud effects visible
orbit effects

- different orbit due to LR collisions
  - fully self-consistent treatment developed
  - e.g. vertical offset in IP1
    - LHC orbit measurement cannot resolve these effects
    - qualitatively verified by ATLAS vertex centroid measurement
      - note the different filling scheme

W. Herr, “Long range beam-beam effects and experience in the LHC”
M. Schaumann, “Observed beam-beam induced orbit effects at LHC”
missing LR deflection

- beam dump of single beam in collisions leads to missing LR deflections
  - consequent single-turn trajectory perturbation of other beam
    - 25ns spacing, 72 bunches, \( \sim 1.1 \times 10^{11} \) ppb, \( \sim 65\mu \text{rad} \) crossing angle
    - B1H perturbation in the arc of \( \sim 230\mu \text{m} = 0.6\sigma \ 3.5\mu \text{m} \cdot \text{rad} \)
- leads with physics beam to beam losses above BLM dump thresholds
  - effect observed throughout 2012
conclusions

• long list of observations
  – LR and HO, orbit, PACMAN, loss of Landau damping, coherent modes, ...

• this was just a teaser, all details will come in the presentations in the next days

• enjoy this workshop!