LHC machine configurations in Run 2
(with focus on collimation and $\beta^*$)

R. Bruce

with input from N. Fuster Martinez, P. Hermes, A. Mereghetti,
D. Mirarchi, S. Redaelli, B. Salvachua
Outline

• Recap of Run 2 machine configuration evolution
• Summary of Run 2 aperture measurements
• Evolution year by year, and reasoning behind changes for
  – Collimator settings
  – $\beta^*$
• Conclusions
Combined ramp & squeeze
Matched MKD-TCT phase

RF full detuning
ATS optics
Crossing anti-leveling

Separation leveling

$\beta^* = 40 \text{ cm, } 185 \text{ µrad}$
$\beta^* = 30 \rightarrow 25 \text{ cm, } 160 \rightarrow 130 \text{ µrad}$
Evolution of key parameters

• Starting from a careful approach in 2015, ramping up to excellent performance
  – Regularly operating at twice the LHC design luminosity

• Steady decrease of $\beta^*$ over the years
  – Key to increased peak performance with total intensity almost flat in the last years
Some keys to good peak performance:

- Small emittance
  - See talks H. Bartosik, S. Papadopoulou
- Small β* at collision point
  - Focus of this talk

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2018</th>
<th>LHC Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [TeV]</td>
<td>6.5</td>
<td>7.0</td>
</tr>
<tr>
<td>No. of bunches</td>
<td>2556</td>
<td>2808</td>
</tr>
<tr>
<td>Max. stored energy per beam (MJ)</td>
<td>312</td>
<td>362</td>
</tr>
<tr>
<td>β* IR1/5 [cm]</td>
<td>30→25</td>
<td>55</td>
</tr>
<tr>
<td>Half crossing angle IR1/5 [μrad]</td>
<td>160→130</td>
<td>142.5</td>
</tr>
<tr>
<td>Normalized beam-beam separation</td>
<td>10.6→7.9</td>
<td>9.4</td>
</tr>
<tr>
<td>p/bunch (typical value) [10^{11}]</td>
<td>1.1</td>
<td>1.15</td>
</tr>
<tr>
<td>Typical normalized emittance [μm]</td>
<td>~1.9</td>
<td>3.75</td>
</tr>
<tr>
<td>Peak luminosity [10^{34} cm^{-2}s^{-1}]</td>
<td>2.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>
• Several aspects of machine configuration covered in other talks
  – Beam characteristics: beam types, bunch intensity, emittance → H. Bartosik, S. Papadopoulou
  – Optics → T. Persson
  – RF settings → H. Timko
  – Chromaticity, octupoles → X. Buffat
  – Heavy-ion configurations → J. Jowett
  – $\beta^*$
  – Collimator settings

This talk
• Collimation hierarchy sets lower limit for protection of aperture
• All elements (e.g. triplet) must have larger apertures (in $\sigma$)
• Beam size increases in triplet when $\beta^*$ is squeezed
• Smaller $\beta^*$ usually requires larger crossing angle

=> smaller normalized aperture in $\sigma$ to be protected at smaller $\beta^*$
Ways to push aperture limit

• **Tighter collimators** => protect smaller normalized aperture

• **Smaller normalized beam-beam separation** => smaller crossing angle and more aperture at any given $\beta^*$

• **Better knowledge of the aperture** allows a smaller margin on the aperture
  
  – Used to squeeze in Run I, now aperture “goldmine” is depleted

R. Bruce, 2016.12.15
Aperture measurements

• **Crucial to know aperture well** for correct determination of machine settings that ensure protection

• **Detailed aperture measurements part of standard commissioning**
  – Limited precision due to variations in closed orbit and machine movements
  – Some minor differences expected between the years

• **Measured aperture used to verify calculation parameters for predicting the aperture in new, untested configurations**
  – MAD-X aperture module – accurate 2D calculation, but need to tune many input parameters for various sources of imperfections
  – “Scaling” of aperture – fast and straight-forward method, but risk of errors if aperture bottleneck is purely horizontal or vertical
## Collision apertures in Run 2

<table>
<thead>
<tr>
<th>Year, Size, Offset</th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015, 80 cm, -145 μrad</td>
<td>18.2 (D1/Q3R5)</td>
<td>15.7 (D1/Q3L1)</td>
<td>16.2 (D1/Q3R1)</td>
<td>15.7 (D1/Q3R1)</td>
</tr>
<tr>
<td>Predicted 2015</td>
<td></td>
<td></td>
<td>16.0</td>
<td></td>
</tr>
<tr>
<td>2016, 40 cm, -185 μrad</td>
<td>10.6 (D1/Q3R5)</td>
<td>9.9 (D1/Q3L1)</td>
<td>11.5 (D1/Q3R1)</td>
<td>10.4 (D1/Q3R1)</td>
</tr>
<tr>
<td>Predicted 2016</td>
<td></td>
<td></td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>2017, 40 cm, +185 μrad</td>
<td>10.9 (D1/Q3R5)</td>
<td>12.0 (D1/Q3L1)</td>
<td>12.9 (Q2R5)</td>
<td>11.4 (D1/Q3R1)</td>
</tr>
<tr>
<td>2017, 40 cm, +150 μrad</td>
<td>11.5 (D1/Q3R5)</td>
<td>12.4 (D1/Q3L1)</td>
<td>14.0 (Q2R5)</td>
<td>12.0 (D1/Q3L1)</td>
</tr>
<tr>
<td>Predicted 2017a</td>
<td></td>
<td></td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>2017, 30 cm, +150 μrad</td>
<td>10.6 (D1/Q3L1 &amp; D1/Q3R5)</td>
<td>11.1 (Q2R5 &amp; Q3/D1 L1)</td>
<td>10.9 (D1/Q3L1)</td>
<td>10.5 (D1/Q3R1)</td>
</tr>
<tr>
<td>Predicted 2017b</td>
<td></td>
<td></td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>2018, 30 cm, +160 μrad</td>
<td>10.5 (D1/Q3L1)</td>
<td>10.5 (D1/Q3L1)</td>
<td>10.0 (D1/Q3L1)</td>
<td>10.5 (D1/Q3R1)</td>
</tr>
<tr>
<td>Predicted 2018a</td>
<td></td>
<td></td>
<td>9.6</td>
<td></td>
</tr>
<tr>
<td>2018, 25 cm, +145 μrad</td>
<td>9.2 (D1/Q3L1)</td>
<td>9.2 (D1/Q3L1)</td>
<td>&gt;12</td>
<td>10.5 (D1/Q3R1)</td>
</tr>
<tr>
<td>Predicted 2018b</td>
<td></td>
<td></td>
<td>9.4</td>
<td></td>
</tr>
</tbody>
</table>

*All in σ for 3.5 μm emittance*  
*All apertures predicted within 0.5 σ*
Crossing plane aperture at top energy

- Calculating aperture as function of $\beta^*$ using scaling for fixed BB-separation
- Aperture measurements with beam largely consistent

Aperture scaled from worst measurement every year. Assuming varying crossing angle – 9.2 $\sigma$ beam-beam separation for $\varepsilon=2.5 \mu$m
Lessons learned on aperture

- **Asymmetry** in aperture between IR1 crossing angle signs
  - Gained about $2\sigma$ in the crossing plane of IR1 with positive crossing angle
    - limitation moves to other plane. Gain on limit about $1\sigma$
  - Crossing changed to distribute radiation in triplet. Change back to negative polarity in Run 3?
    - so far produced with **positive** polarity: $115\ fb^{-1}$ at 6.5 TeV, with **negative** polarity: $45\ fb^{-1}$ at 6.5 TeV + $30\ fb^{-1}$ at $\leq 4\ TeV$

- **CMS IP shift bump** predicted to cause significant degradation of vertical aperture in MAD-X calculations
  - Not observed in measurements – shadowed by IR1 crossing plane
  - Global LHC measurements: **No effect** seen in tests down to -2 mm at $\beta^*=40\ cm$
  - Operated with CMS bump at -1.8 mm in 2018
Injection aperture

- Injection aperture measured in the commissioning of every year
- See some variations and improvement over the years, in particular B1H
- Some variations of the bottleneck locations – see backup
  - Probably several bottlenecks at similar apertures
Outline

• Recap of Run 2 machine configuration evolution
• Summary of Run 2 aperture measurements
• Evolution year by year, and reasoning behind changes for
  – Collimator settings
  – $\beta^*$
• Conclusions
2015

• First year after LS1 – concerns for losses, stability and protection of aperture
  – Higher beam energy (6.5 TeV vs 4 TeV) and lower quench limit
  – Shorter 25 ns bunch spacing
  – Loss spikes and instabilities

• Strategy
  – Put focus on feasibility, stability and ease of commissioning. Allow comfortable margins for operation and avoid introducing too many untested features at once
  – Main priority: Get LHC running 25 ns at 6.5 TeV
  – Performance should not be main focus, but we should also not be overly pessimistic
  – Prepare for production and higher performance in 2016
• **Collimator settings**
  – Kept IR7 settings from 2012 in mm
  – Well-proven long-term stability and cleaning
  – Cleaning predicted to be satisfactory at 6.5 TeV

• Start carefully with **comfortable margins on aperture, orbit, optics, beam-beam**

• Protection of aperture: added 2 σ extra margins on top of assumption as in Run 1 [see PRSTAB 18, 061001 (2015)]
  – Risk of damage to TCTs and triplet during asynch dump driving choice of settings

• Started with conservative value of $\beta^* = 80$ cm and 11 σ beam-beam separation (150 µrad)
Development during 2015

• Started thinking of **how to push performance**

• **MDs on tighter collimation hierarchy**
  – Found that impedance and stability of cleaning hierarchy were acceptable when moving in TCSGs to 2 σ retraction from TCP
  – Found a hierarchy breakage at 1 σ retraction

• **MDs by beam-beam team** showed possibility of reduced beam-beam separation
  – 10 σ for 3.75 µm
Reducing TCDQ-TCT margin

- Relatively large margin of $4.6 \sigma$ taken between TCDQ and TCT in collimation hierarchy in 2015
  - Ensure that the TCTs and the triplet aperture just behind never risk to be damaged during an asynchronous beam dump

- Possible to reduce margin by demanding that TCTs / triplets should be close to the minimum of the oscillating miskicked beam
  - Triggered design of new optics for 2016 (R. de Maria et al.), demanding MKD-TCT phase stays below 30 deg

- MDs on aperture measurements at smaller $\beta^*$
2016 configuration

- Reduced margins in collimation hierarchy, in particular reducing TCDQ-TCT margin to $0.9 \sigma$
  - Could maybe have been reduced even more, but didn’t do it due to fear of causing higher experimental background
  - Started developing new software interlocks on phase (power converter interlock) and BPMs in IR6 and at TCTs to ensure operation within acceptable interval
    - Using built-in BPMs at collimators

- Could go to $\beta^* = 40 \text{ cm}$ and $10 \sigma$ beam-beam separation (185 μrad)
  - First time that LHC operated below the design value $\beta^* = 55 \text{ cm}$
  - Production year – start pushing performance
Developments in 2016

- Studies by beam-beam team: Reduced crossing from 185 urad to 140 urad
  - $9.3 \sigma$ for BCMS emittance 2.5 μm
  - Gave additional aperture margin – further reduction of $\beta^*$?

- Campaign of MDs in view of reduced $\beta^*$ in 2017
  - Tighter TCP setting by 0.5 $\sigma$
  - Tighter collimation hierarchy – TCSG retraction of 1.5 $\sigma$ acceptable
  - Tighter TCT setting did not show effect on experimental background
  - Aperture measurements

- Development of new ATS optics with matched MKD-TCT phase (S. Fartoukh)
• Implemented tighter IR7 settings

- **Started** close to 2016 configuration: $\beta^*=40$ cm, but with new ATS optics
  - Optics commissioned down to 30 cm to prepare future reduction
  - Asymmetric TCDQ setting required

- **Pushed** after TS2 to $\beta^*=30$ cm, based on measurements and simulations.
  - Kept same crossing angle of 150 µrad
    - decrease in normalized beam-beam separation
  - Helped in recovering performance during the “16L2 period”
• No large margins left to gain on collimators – already pretty tight
  – Primary half gaps of less than 1 mm
  – Still some room to move in tertiaries and allow smaller aperture

• Largely kept 2017 collimator settings
  – Needed to introduce tilt on TCSG to avoid hierarchy breakage even at 1.5 \( \sigma \) retraction

• Potential room to reach 27.5 cm – still started at 30 cm, but with additional \( \beta^* \)-leveling down to 25 cm

R. Bruce, 2019.01.31
• Explored a wide parameter space in Run 2

• Leveling pushes configuration later in fill when intensity-dependent constraints are relaxed

• Have gone a long way since LHC design!

Assumptions
For lumi calculation:
- 2544 bunches
- 1.1E11 p/bunch
- 1.9 μm emittance
- 8 cm bunch length

Beam-beam:
- 10.6 σ, for 1.9 μm

Aperture:
- 8.5 σ protected, +0.5 σ margin, positive IR1 crossing

Max pileup = 60

Triplet - max. lumi:
- 2.2E34 cm⁻² s⁻¹

For visibility, including only starting configuration for each year
Conclusions

- Explored a large parameter space for the Run 2 machine configurations
- Pushed towards higher performance every year
  - Relied on good knowledge of the aperture
  - Aperture measurements part of standard commissioning
- Collimators continuously tightened during Run 2
  - Can now protect aperture that is close to the LHC design value
  - Used MD results to determine the next machine configuration
- Pursued options to improve machine performance while staying safe and not reducing machine availability
- Achieved $\beta^*$ less than half of the LHC design value
  - Reduced $\beta^*$ by more than factor 3 since 2015
Thanks for the attention.

Questions?
Summary of Run 2 collimator settings

<table>
<thead>
<tr>
<th>Collimator</th>
<th>2015</th>
<th>2016</th>
<th>2017a</th>
<th>2017b</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCP IR7</td>
<td>5.5</td>
<td>5.5</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>TCSG IR7</td>
<td>8.0</td>
<td>7.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>TCLA IR7</td>
<td>14.0</td>
<td>11.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>TCP IR3</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>TCSG IR3</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
</tr>
<tr>
<td>TCLA IR3</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>TCSP IR6</td>
<td>9.1</td>
<td>8.3</td>
<td>7.3</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>TCDQ IR6</td>
<td>9.1</td>
<td>8.3</td>
<td>7.3</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>TCT IR1/5</td>
<td>13.7</td>
<td>9.0</td>
<td>9.0</td>
<td>8.5</td>
<td>8.5→7.8</td>
</tr>
<tr>
<td>Aperture 1/5</td>
<td>9.9</td>
<td>9.9</td>
<td>9.5</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>β* IR1/5</td>
<td>80 cm</td>
<td>40 cm</td>
<td>40 cm</td>
<td>30 cm</td>
<td>30 cm→25 cm</td>
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<tr>
<td>TCT IR2</td>
<td>37.0</td>
<td>37.0</td>
<td>37.0</td>
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<tr>
<td>TCT IR8</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Settings in σ with ε=3.5 μm

R. Bruce, 2019.01.31
### Injection apertures in Run 2

<table>
<thead>
<tr>
<th>Year</th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>MBRC.4R8: 11.6</td>
<td>Q6L4: 11.5</td>
<td>Q4L6: 12.5</td>
<td>Q4R6: 12.0</td>
</tr>
<tr>
<td>2016</td>
<td>MBRC.4R8: 12.5</td>
<td>Q6L4: 12.0</td>
<td>TCDQM.4L6: 12.5</td>
<td>Q4R6: 12.5</td>
</tr>
<tr>
<td>2017</td>
<td>Q6R2: 13.1</td>
<td>Q4L6: 12.2</td>
<td>Q6L8: 13.2</td>
<td>Q4R6: 12.8</td>
</tr>
<tr>
<td>2018</td>
<td>Q4R6: 13.3</td>
<td>Q4L6: 12.2</td>
<td>Q4L6 &amp; Q6L8: 13.0</td>
<td>Q4R6: 12.5</td>
</tr>
</tbody>
</table>
2016 beam tests of asynch dump

- MDs: Verified experimentally TCT losses during asynchronous dump tests in different optics

![Graph showing the impact of TCT setting on proton counts]

- As expected, do not see dependence on TCT setting at 40 cm
  - TCT still intercepts secondary beam out-scattered in IR6 – more spread out → not problematic