Beam Losses, Lifetime and Collimator Hierarchy

A. Mereghetti, on behalf of the LHC Collimation Team
This presentation will summarize the work carried out in 2017 by an extraordinary team. It is a great honor to report the operational highlights of the past year and key results for the successful operation of the LHC.
The LHC Collimation System

- **Aim:** minimize loss leakage into SC magnets;
- **Collimators** are organized in families:
  - Finite absorbance: each family absorbs the leakage from the upstream ones;
  - Hierarchy is a pre-requisite to assure desired levels of cleaning efficiency;
    → Need for operational margins between families;
- **Collimator settings** are a compromise between:
  - Protected aperture always in the shadow of collimators (dep. on conditions at IPs, e.g. $\beta^*$, xing angle);
  - Background to detectors;
  - Primary collimation cut (clean only tails and not the core, leakage to IR7 DS, …);
  - All families must fit in between primary cut and protected aperture, with margins;
  - Impedance;
- **IR7 DS:**
  - Most intense leakage out of IR7 coll. Sys., despite not being aperture bottleneck;
  - Sustainable max losses determined by:
    - quench margin, min beam lifetime, cleaning inefficiency (settings);
    - Collimator robustness;
The Art of Choosing settings: Overview on Run II

- Constraints / margins in collimators settings:
  - Protected aperture: $\beta^*$, xing angle value (i.e. normalized BB separation) and sign;
  - MKD-TCT phase advance (TCTs not hit directly by beam during Asynchronous Beam Dump);
  - Better knowledge of IT aperture;
  - Operational margins between families (avoid hierarchy violations);
  - Primary collimator cut (impedance);
  - Impedance;

<table>
<thead>
<tr>
<th>Year</th>
<th>Coll. Cut [σ]</th>
<th>Protected Aperture [σ]</th>
<th>Δ [σ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 ($\beta^*$=80cm)</td>
<td>5.5</td>
<td>15.7</td>
<td>10.2</td>
</tr>
<tr>
<td>2016 ($\beta^*$=40cm)</td>
<td>5.5</td>
<td>9.9</td>
<td>4.4</td>
</tr>
<tr>
<td>2017 ($\beta^*$=40cm)</td>
<td>5</td>
<td>9.9</td>
<td>4.9</td>
</tr>
<tr>
<td>2017 ($\beta^*$=30cm)</td>
<td>5</td>
<td>9.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Courtesy of R. Bruce
Aperture Measurements

Aperture carefully probed during 2017 initial commissioning with beam, for operation at $\beta^*=40\text{cm}$; …and in MD (MD2180), for operation at $\beta^*=30\text{cm}$;

<table>
<thead>
<tr>
<th>Date</th>
<th>Beam cycle</th>
<th>Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>7th May</td>
<td>Injection Squeezed</td>
<td>Only with pilots</td>
</tr>
<tr>
<td></td>
<td>• with/without CMS bump of -1.5 mm</td>
<td></td>
</tr>
<tr>
<td>14th May</td>
<td>Squeezed</td>
<td>Nominal + pilots</td>
</tr>
<tr>
<td></td>
<td>• with/without CMS bump</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• for 150 $\mu$rad and 185 $\mu$rad (larger crossing angle in IP5/IP1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Collision (not completed because beam was dumped)</td>
<td>Not optimized orbit after collision set up</td>
</tr>
<tr>
<td>17th May</td>
<td>Collision</td>
<td>Nominal + pilots</td>
</tr>
<tr>
<td></td>
<td>Including CMS bump and for 150 $\mu$rad crossing angle</td>
<td>Optimized collision orbit</td>
</tr>
</tbody>
</table>

**Method:** beam blow-up + collimator alignment

<table>
<thead>
<tr>
<th>Date</th>
<th>Configuration</th>
<th>BI H [cm]</th>
<th>BI V [cm]</th>
<th>B2I H [cm]</th>
<th>B2I V [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/05/2017</td>
<td>without CMS bump</td>
<td>Q3R5 12.3-12.8</td>
<td>Q3L1 12.4-12.9</td>
<td>Q2R5 11.7-12.2</td>
<td>Q3R1 13.5-14.0</td>
</tr>
<tr>
<td>14/05/2017</td>
<td>without CMS bumps</td>
<td>Q3R5 12.2-12.7</td>
<td>Q3L1 13.0-13.3</td>
<td>Q2R5 13.6-14.1</td>
<td>Q3R1 12.3-12.8</td>
</tr>
<tr>
<td>14/05/2017</td>
<td>with -1.5 mm CMS bump</td>
<td>Q3R5 12.1-12.6</td>
<td>Q3L1 12.7-13.3</td>
<td>Q2R5 14.0-14.5</td>
<td>Q3R1 12.3-12.9</td>
</tr>
<tr>
<td>14/05/2017</td>
<td>with -1.5 mm CMS bump and 185 $\mu$rad crossing</td>
<td>Q3R5 10.9-11.4</td>
<td>Q3L1 12.0-12.5</td>
<td>Q2R5 12.9-13.4</td>
<td>Q3R1 11.4-11.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Configuration</th>
<th>BI H [cm]</th>
<th>BI V [cm]</th>
<th>B2I H [cm]</th>
<th>B2I V [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Q3L[S5/R1]</td>
<td>11.0</td>
<td>9.9</td>
<td>Q3R1 11.5</td>
<td>Q3R1 11.5</td>
</tr>
</tbody>
</table>

**Larger min aperture in 2017 than in 2016 by ~1.5$\sigma$, mainly thanks to reversed sign of IR1 xing angle;**

<table>
<thead>
<tr>
<th>Date</th>
<th>Configuration</th>
<th>BI H [cm]</th>
<th>BI V [cm]</th>
<th>B2I H [cm]</th>
<th>B2I V [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>14/05/2017</td>
<td>-1.5 mm CMS bump</td>
<td>Q3R5 11.5-12.0</td>
<td>Q3L1 12.4-12.9</td>
<td>Q2R5 (also Q2R5) 14.0-14.5</td>
<td>Not measured</td>
</tr>
<tr>
<td>17/05/2017</td>
<td>-1.5 mm CMS bump</td>
<td>Q3R5 11.7-12.2</td>
<td>Q3L1 12.6-13.1</td>
<td>Q2R5 14.3-14.8</td>
<td>Q3R1 12.0-12.5</td>
</tr>
<tr>
<td>2016</td>
<td>Q3R5 11.0-11.3</td>
<td>Q3L1 9.9-10.0</td>
<td>Q3R1 11.6-12.1</td>
<td>Q3R1 10.4-10.7</td>
<td></td>
</tr>
</tbody>
</table>

**No big impact from CMS bump with the given crossing conditions!!**

**Collimator (TCP for global aperture at injection / TCTP for local aperture with squeezed beams)**

**Bottleneck**
Pushing the Hierarchy

- Smaller cold apertures (for pushing peak lumi performance) at constant primary coll. cut imply reducing operational margins:
  - All collimator families must fit in the allotted aperture budget;
  - When squeezing families too much, risk of hierarchy breakage;
- Series of MDs to assess limits of hierarchy, impact on impedance, stability of alignment and feasibility of small TCP-TCSG retractions in operation (set up in reasonable time):
  - 2015 (MD314): IR7 hierarchy broken on B1V with 1σ retraction
  - 2017 (MD2191):
    - Confirm observations so far;
    - Implications on alignment procedures and time;

Angular alignment key in 2018 commissioning if we decide to push the IR7 collimator hierarchy; → Feasible in 2018, but not recommend as start-up configuration;

Same angle after 1.5y!!

Angular alignment key in 2018 commissioning if we decide to push the IR7 collimator hierarchy; → Feasible in 2018, but not recommend as start-up configuration;

Plenty of development on the control software for automatic angular alignment:
G. Azzopardi, B. Salvachua Ferrando, G. Valentino
Pushing Luminosity in 2017

\( \beta^* = 30 \text{cm after TS2}: \)

- TCT BPM interlocks as “condition sine qua non”;
- Carefully probing aperture (MD2180), even outside the parameter space strictly required (e.g. up to 175\(\mu\text{rad}));
- Squeezing aperture budget taken by collimation;

Xing angle “anti-levelling”:
- Gymnastics with TCTs and TCL4s – first time ever: new operational challenge! Thanks to OP (M. Hostettler and K. Fuchsberger);
- Validating collimator settings at extreme crossing configurations;

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**July (9 & 10)**

**Operation related interlocks - complement dump cause!**

**Detailed TEST results in next slides...**

- No dumps in operation, thanks to careful preparation of interlocks – thanks to all the teams involved!! (BE-ABP, BE-OP, BE-BI, MPP)

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**Loss map matrix – TS2 2017**

- 450 GeV
- 6.5 TeV

<table>
<thead>
<tr>
<th>Loss Maps</th>
<th>450 GeV</th>
<th>6.5 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inj. Prot. IN</td>
<td>Inj. Prot. OUT</td>
</tr>
<tr>
<td>B1H</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B1V</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B2H</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B2V</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>+(\delta p/p)</td>
<td>✓</td>
<td>—</td>
</tr>
<tr>
<td>-(\delta p/p)</td>
<td>✓</td>
<td>—</td>
</tr>
<tr>
<td>ASD</td>
<td>✓</td>
<td>—</td>
</tr>
</tbody>
</table>

- ✓ = done pending validation
- ✓ = done and OK
- — = not requested
- X = to be done

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*Courtesy of A. Gorzawski*
Beam Lifetime and Losses

- Loss spikes and fast drops of lifetime are a concern for operating the machine, and for the collimation system:
  - They determine the max loss rates in cold magnets and define the intensity limit for a given cleaning inefficiency;
  - At full intensity, fast losses might exceed the collimator damage limit;
  - Risk of spurious dumps for given BLM thresholds;
- Beam lifetime is used as an indicator of machine performance:
  - Monitor beam quality along the cycle;
  - Optimize working point (e.g. tune, chroma, octupoles) along operational cycle and in MDs ("is the beam happy with the last trim?");

Use dedicated server (cs-ccr-colsa3):
- Actual calculations (previously done by GUI):
- Java concentrator: lhcc-concentration-blm-lifetime;
- Subscription to raw signals (BCT, BLMs, Beam energy, Lumi);
- Logging to MDB/LDB + possible to subscribe to signals via JAPC;
- New virtual FESA class – device name: LHC.BLM.LIFETIME;

BLM signals less noisy than BCT and more sensitive to losses

Focus mainly on 2017, squeeze and adjust. Preliminary analysis by B. Salvachua Ferrando

Courtesy of B. Salvachua Ferrando
2016: $\beta^*=40\text{cm}$, 25 ns, total intensity “limited” to $\sim 250\text{MJ}$ (SPS dump, MKI).

Hit the 300 MJ barrier (280 MJ reached in 2015), towards the Nominal LHC one of 360 MJ!!

$\Rightarrow$ But then limited by 16L2;
Transmission

• 2016 transmission overall similar to 2016:
  - B1 suffers more than B2;
  - Adjust less efficient than Squeeze;

• $\beta^*=30$ cm: inverted behavior wrt $\beta^*=40$ cm

(courtesy of S. Redaelli and B. Salvachua Ferrando)

SQUEEZE

ADJUST

Courtesy of B. Salvachua Ferrando

2017 transmission overall similar to 2016:
Lifetime

Good lifetime throughout the year, as in 2016, despite some outliers!
→ B1 suffers more than B2;

Courtesy of B. Salvachua Ferrando
Overall Losses

1. Drops in beam lifetime are reflected in losses in IR7:
   - Presently, no concern for LHC operation, though increasing level of integrated losses in the last years;
   - Visible asymmetry between the two beams (reflecting asymmetry on beam lifetime);
   - Possible concerns for HL-LHC, e.g. on warm quads (removal of MQWA.E5[L,R]7 + shielding);

2. Losses induced also by Lumi:
   - IR1/IR5 RRs: presently dominating the R2E dumps, with 10-15 events (XRPs and TCL closed) per 50 fb⁻¹;
   - Strong contribution from XRPs, and also TCLs;
   - R2E failures expected to drop to <1/system/HL-LHC year after LS2, thanks to deployment of radiation tolerant electronics;

Material freely collected from R.Garcia Alia & R2E project (LMC, 6th Dec 2017) ➔ Ask the expert!

Debris losses also seen deep in the arcs ➔ Further analyses ongoing, to assess possible issues to electronics;
Hardware Changes During EYETS2016 and 2017 Commissioning

- Many changes, with important hardware for HL-LHC tests:
  - TCSPM: validation of design of new secondary low-impedance collimators for HL-LHC;
  - Tungsten collimators with in-jaw wire for compensating effects of long range beam-beam (TCTPH.4R5.B2 and TCL.4L5.B2);
  - Crystals on B2;
  - TCP.C6L7.B1 (H) with embedded BPMs;
→ with no effects on availability!

- Commissioning:
  - Extensive hardware commissioning (thanks to EN-STI), including 5th axis;
  - Software improvements mostly GUI-related (e.g. LHCCollAlign FESA class stops alignment after 2 points exceeding threshold, parallel alignment per plane, …);
  - new collimators: imported in LSA DB, commissioned, aligned;
  - BPM collimator commissioning (including scans for non-linearity & updates with BE-BI);
→ Alignment still excellent, but improvements saturating!

Light weight of re-configurations thanks to embedded BPMs!
2017 Performance and Faults/Dumps

Constant improvement throughout Run II, thanks to tightening collimator settings and pushing hierarchy!!

8 dumps this year (PM DB data browser) – breakdown:
- 7 hardware faults (e.g. temperature sensors, jaw stuck, …) → all minor and isolated!
- 1 (suspected) UFO event;
+ 5 operational mistakes during tests (e.g. commissioning, MDs, …);
+ 8 OP mistakes (e.g. forgot to mask collimator movements, …);

In summary:
- 4 at injection (including prep. ramp);
- 3 during ramp;
- 1 in adjust (EoF MD);
→ None during physics!

Monitoring of IR7 performance throughout the cycle during commissioning

Courtesy of D. Mirarchi
Conclusions

• **Aperture & Hierarchy:**
  • Annual measurements during commissioning are fundamental to keep understanding alive and push performance;
  • Most relevant “knobs” for gaining aperture:
    • Playing with crossing conditions with time during fill;
    • Push the IR7 hierarchy to 1σ-retraction (IR7 TCP-TCSG), to reduce impact of collimator aperture budget → feasible, though not recommended as start-up configuration;
    • TCT-TCDQ retraction, provided that TCT-MKD phase advance stays below 30 degs;
• **Losses:**
  • Increased level of losses wrt 2016 → visible in both lifetime and integrated IR7 losses over the year, especially on B1;
  • Currently not an issue for LHC operation (dose to IR7 warm elements, dose to equipment in the arcs, SEUs in RRs, …), but for HL-LHC → mitigation actions mainly taking place in LS2;
Conclusions (II)

- Performance of collimation system in 2017:
  - Smooth commissioning with beam;
  - Improved cleaning wrt past years, thanks to tighter IR7 collimator settings;
  - Flexibility in accommodating new conditions at collision IPs:
    - Commissioning of new configuration;
    - Running conditions;
Thanks a lot!

...any questions?
Aperture Measurements – R&D

Dedicated MD (MD2180) to probe IT aperture at $\beta^* = 30\text{cm}$ and $175\mu\text{rad}$

<table>
<thead>
<tr>
<th></th>
<th>$a_{\Delta}$ at 30 cm $\beta^*$ 2017 Measurements</th>
<th>$a_{\Delta}$ at 30 cm $\beta^*$ 2017 Expectations</th>
<th>$a_{\Delta}$ at 40 cm $\beta^*$ 2017 Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1H</td>
<td>9.5-10 D1/Q3 R5 and D1/Q3 L1 ***</td>
<td>9.2 Q2L5</td>
<td>12.2-12.7 Q3R5</td>
</tr>
<tr>
<td>B1V</td>
<td>9.9-10.4 D1/Q3 L1</td>
<td>9.2</td>
<td>13.0-13.3 Q3L1</td>
</tr>
<tr>
<td>D2H</td>
<td>11.8-12.3 Q2R5</td>
<td>9.2 Q2R5</td>
<td>13.6-14.1 Q3R1</td>
</tr>
<tr>
<td>B2V</td>
<td>9.7-10.1 D1/Q3 R1</td>
<td>9.2 D1/Q3 R1</td>
<td>12.3-12.8 Q3R1</td>
</tr>
</tbody>
</table>

Dedicated MD (MD2396) to test new method of measuring aperture via AC-dipole;
Asset: combine optics and preliminary aperture measurements, gaining commissioning time;

• Good agreement with expectations but for B2H;
• Aperture at $\beta^* = 30\text{cm}$ smaller than that at $\beta^* = 40\text{cm}$ by $2\sigma$;
• Smallest measured aperture at $9.5\sigma \rightarrow$ good for TCT settings at $7.5\sigma$ (protected aperture at $8.5\sigma$);

• Example: aperture scan at injection;
$\rightarrow$ Measurements in very good agreement with each other;

Courtesy of N.Fuster-Martinez
Pushing the Hierarchy – R&D

Stability of alignment (centres) is essential for reliably operating the system throughout the year

Centre shifts between MD and initial commissioning

Remarkable stability of alignment over months! → Ok for 1 alignment per year

Automatic angular alignment:
- Three different algorithms under test;

Method 1
Method 2
Method 3

On-going development on the control software:
G. Azzopardi, B. Salvachua Ferrando, G. Valentino

BLM spike recognition with methods based on machine-learning (MD2720 during MD4);
- Essential to properly identify spikes from jaws touching the beam;

- BLM spike pattern recognition (12:00 – 18:00)
- Machine learning was quite accurate 41/43 tests correct.

…the challenge between humans and machines continues…
## 2017 Collimator Settings

<table>
<thead>
<tr>
<th>IR</th>
<th>Coll. Family</th>
<th>Inj</th>
<th>FT</th>
<th>$\beta^* =$40cm</th>
<th>$\beta^* =$30cm</th>
<th>Coll.</th>
<th>XRP\text{\text{s IN}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR7</td>
<td>TCP/TCSG/TCLA</td>
<td>5.7/6.7/10</td>
<td>5/6.5/10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR3</td>
<td>TCP/TCSG/TCLA</td>
<td>8/9.3/12</td>
<td>15/18/20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR6</td>
<td>TCDQ/TCSP</td>
<td>8/7.5</td>
<td>7.4/7.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR1/5</td>
<td>TCT/TCL4/TCL5/TCL6</td>
<td>13/-/-/-</td>
<td>15/-/-/-</td>
<td>9/-/-/-</td>
<td>8.5/-/-/-</td>
<td>8.5/15/15/-</td>
<td>8.5/15/35/20</td>
</tr>
<tr>
<td>IR2</td>
<td>TCT</td>
<td>13</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR8</td>
<td>TCT</td>
<td>13</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Pushing the Hierarchy – BPM Interlocks

• Interlock the beam position as read by TCT BPMs;
• Based on good orbit reproducibility (analysis by G. Valentino);
• Announced in Evian 2016…
• "Conditio sine qua non" for running at $\beta^*=30\text{cm}$ after TS2;

From first proposal…

to thorough tests and final implementation!

…thanks to the good orbit reproducibility!

July (9 & 10)

Operation related interlocks - complement dump cause!

SIS Tests @ Injection (9 July)

SIS Tests @ FT (10 July)

IR

<table>
<thead>
<tr>
<th></th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR1/IR5</td>
<td>1</td>
</tr>
<tr>
<td>IR2</td>
<td>4</td>
</tr>
<tr>
<td>IR6</td>
<td>1.5</td>
</tr>
<tr>
<td>IR8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Thanks to all the teams involved!! (BE-ABP, BE-OP, BE-BI, MPP)

LogBook 14:06: RCBH16.RBB1 tripped with feedback off. Lost beam 1 therefore. We will refill directly and re-attempt.

Courtesy of A. Gorzawski