Run III Layout and Performance for Protons

A. Mereghetti, on behalf of the LHC Collimation Team
Outline

Recap of Run III Layout:
- TCSPM design and 2017 measurements with beam
- Removal of MQWA.E5[L,R]7 and installation of shielding
- TCLDs and load on downstream cold elements

Expected performance in Run III:
- Possible Run III optics
- Outlook to HL-LHC v1p4

Conclusions
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  - Removal of MQWA.E5[L,R]7 and installation of shielding
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- Conclusions
Overview of the Upgrade of the LHC Collimation System

**Partial HL-LHC Upgrade** (during LS2):
- Exchange of 2 IR7 TCPs (60cm): from CFC to MoGr;
- Addition/Exchange of 4 IR7 TCSs (1m): from CFC to Mo-coated MoGr;
- A single module MBH(11T)+TCLD+MBH(11T) in IR7 (p+ions) and a single TCLD in IR2 (ions only);
- Exchange MQWA.E5[L,R]7 with shielding (reduce dose to MQW coils and spacers);

**Run III**

**Full HL-LHC Upgrade** (during LS3):
- Exchange remaining TCSGs (7);
- IR1/IR5 TCTPs (1m):
  - Cell 4: from Inermet180 to CuCD (4);
  - Cell 6: TCTPHs in CuCD (2) + re-use TCTPVs in Inermet180 (2);
- New TCLs (6);

*Units are given per beam.*

New design of TCTPH.4 and TCL.4, with two beams in same tank!

A good fraction of the HL-LHC collimation hardware already available in Run-III, for gaining experience with LIU Beams!

A.Mereghetti, 16 Oct 2018, HLLHC Annual Meeting, CERN (CH)
Recap of TCSPM Design

**TCSPM**: new design of TCS collimators:
- MoGr jaws should stand the same BLT minima as for the nominal LHC:
  - 1MW in case of 0.2h beam life time over 1-10s (Nominal LHC: 500kW);
  - 200kW in case of 1h beam life time in steady state (Nominal LHC: 100kW);
- Mo-coated jaws: reduce impact on machine impedance budget (spare octupole current);

**TCSPM flatness not granted** for 12m beam lifetime:
- Estimation done looking at the most loaded secondary collimator in IR7 (i.e. immediately downstream of the TCPs);
- Deformation computed linearly combining (pessimistic) thermal expansion, self-weight (V) and tolerances → check performance in simulations in presence of jaw deformations;
- Gap at concerned collimator is not the smallest among all TCSs → 100μm specs may be taken not exactly strictly;

### Staged implementation, avoiding the most loaded slot and giving further time to optimize eng. design

<table>
<thead>
<tr>
<th>Stresses</th>
<th>1h beam lifetime</th>
<th>0.2h beam lifetime (DESIGN GOAL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCSP[^{CFC}] (LHC)</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>TCSP[^{CFC}] (HL-LHC)</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>TCSP[^{MoGr}] (LHC)</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>TCSP[^{CFC}] (HL-LHC)</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>TCSP[^{CFC}] (HL-LHC)</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Total sagitta</td>
<td>+83</td>
<td>-110</td>
</tr>
</tbody>
</table>
Validation of Design: Installation of TCSPM Prototype and measurements with beam

- During YETS 2016, a prototype of TCSPM was installed (LHC-TC-EC-0006) in slot D4R7.B2 (V TCSG) for tests with beam to finalise design:
  - Smallest beam $\sigma$ among TCSGs $\rightarrow$ ideal for impedance measurements;
  - Presence of a regular TCS in CFC in same slot, for direct comparisons;
  - Three stripes of different materials, to assess effect of coating on impedance;
- Extensive MD campaign of tune-shift measurements in 2017, to benchmark expectations from impedance models;

...though measurements with Mo constantly x2 expectations

...possible explanation: surface roughness / non-regular column structure of Mo coating, with effects on impedance $\rightarrow$ ongoing investigations (G.Mazzacano, CERN, BE-ABP-HSC)

Challenging measurements, with sensitivity of $\Delta Q \sim 2 \times 10^{-5}$!

17th – 18th Sep 2017

Courtesy of S.Antipov

LHC nominal bunch

30th Jun – 1st Jul 2017

Courtesy of S.Antipov
Installation Slots of TCSPMs

- Slots of installation of the 4 TCSPMs chosen among a pool of 4 possible ones (CERN-ACC-2017-0088, in preparation):
  1. Reduce impedance as much as possible – collimators with largest contribution on both H and V plane;
  2. Avoid first two skew collimators – most exposed to steady-state losses;
  3. Avoid H and V secondary collimators – ABD + inj. failures;
  4. Avoid H secondary collimators only – ABD;

- 50% of the expected impedance reduction can be achieved exchanging only 4 collimators;
- Option 2 favored over the others since no TCSPM installed in most loaded location, giving time to further optimize design;
- Cleaning performance evaluated for each option, but no major differences found (A. Mereghetti, 2017 HL-LHC annual meeting);

- Chosen one: option 2

<table>
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<tr>
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<td>exchange</td>
</tr>
<tr>
<td>TCGS.B4L7</td>
<td>TCGS.B4R7</td>
<td>addition</td>
</tr>
<tr>
<td>TCGS.E5R7</td>
<td>TCGS.E5L7</td>
<td>addition</td>
</tr>
<tr>
<td>TCGS.6R7</td>
<td>TCGS.6L7</td>
<td>addition</td>
</tr>
</tbody>
</table>

Loading on coating layer still to be evaluated with detailed FLUKA simulations;

Courtesy of S. Antipov
Removal of MQWA.E5[L,R]7 and Installation of Shielding

- **Removal of MQWA.E5[L,R]7:**
  - Module subject to highest load from IR7 losses (integrated dose);
  - Measurements and simulation campaign to estimate loads for present LHC and for HL-LHC (F. Cerutti and P. Fessia, HL-LHC TCC #14);
  - Proposal (P. Fessia et al): remove the module and propose solution to limit load on following module;

- **New IR7 optics** by R. Bruce (HSS Section Meeting, 12th Dec 2017):
  - MQWB.5 reconfigured as MQWA, in addition to MQWA module removal
  - Re-matching to arc optics;
  - Verification of cleaning performance (D. Mirarchi);

- **Large simulation campaign** (C. Bahamonde et al.), to propose shielding solutions – currently: tungsten masks at each magnet + iron shielding (2m);
- **Final design** presented by L. Gentini, ColUSM 31/08/2018;

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Total peak dose accumulated by the end of HL-LHC

*Assuming 8.4 x 10^{19} protons lost in IR7 for the whole HL-LHC nominal operation
R. Garcia Ali, 7th HL-LHC Collaboration Meeting, 15/11/17
TCLDs

- During LS2, it is planned to install a single module MBH(11T) + TCLD(Inermet180) + MBH(11T) in DS downstream of IR7 (protons / ions) per IR7 side:
  - Position currently considered: MB.B8x7 → Second unit (Q10) initially foreseen removed with 2016 re-baselining;
  - In IR2, only TCLD collimator in connection cryostat;

- Large simulation campaign (D.Mirarchi, P.D.Hermes, C.Bahamonde et al.), for optimizing position of TCLD package:
  - Cleaning performance (SixTrack);
  - Endep in magnets downstream of TCLD collimators (FLUKA):
    - Quench limit due to peak endep in SC coil;
    - Total endep in coils and cold bore tube (specific to 11T dipole);
    - Total power on cryogenics;

Input relevant for evaluations of cryogenics performance and adequacy to loss scenarios
Cryogenics experts have checked that thermal design of 11 T is sufficient – 1h BLT scenario is fine, and 0.2h BLT scenario can be tolerated only for short times;

Limitations from the cryogenics system still need further investigations:

- 1h BLT: cooling of cells 10 & 11 MB-dipoles could be critical with ions;
- 0.2h BLT: adiabatic T-rise of 11-T-dipole coil (to be evaluated);

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**Intermediate 11T dipole specific summary for proposed beam-Lifetime scenarios (MBB.B8)**

<table>
<thead>
<tr>
<th></th>
<th>Continuous cooling ↔ Blt 1h</th>
<th>Transient cooling ↔ Blt 12min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak power (mW/cm²)</td>
<td>11T: coil + beam-pipe (W)</td>
</tr>
<tr>
<td>Protons</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Ions</td>
<td>4</td>
<td>21</td>
</tr>
</tbody>
</table>

For the 1h Blt the 11T dipole thermal design is sufficient

For the 12min Blt the 11T dipole thermal design is ok for peak power on coil - but overall temperature will drift during transient

Courtesy of R. van Weelderen, TCC meeting (2018-08-02)
Outline

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Expected performance in Run III:
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Conclusions
Expected Performance in Run III – 2017

- Expected performance of IR7 in Run III already presented in HL-LHC annual meeting in 2017:
  - Comparative assessment of IR7 cleaning inefficiency for the four possible post-LS2 configurations considered for installation;
  - IR7 settings: 2σ-retraction (i.e. TCPs@5.7σ, TCSGs@7.7σ);
  - Optics: v1p3:
    - $\beta^*=15\text{cm}$, no TCLD installed $\rightarrow$ max $\eta(s)$ at IR7 DS1;
    - $\beta^*=6\text{m}$, TCLD installed + removal of MQWA.E5[R,L]7 $\rightarrow$ max $\eta(s)$ at IR7 DS2;

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>$\beta^*=15\text{ cm, B1H}$</td>
<td>6.19</td>
<td>5.77</td>
<td>6.38</td>
<td>6.11</td>
<td>5.73</td>
<td>6.23</td>
</tr>
<tr>
<td>$\beta^*=15\text{ cm, B1V}$</td>
<td>5.33</td>
<td>5.12</td>
<td>5.17</td>
<td>5.32</td>
<td>5.07</td>
<td>5.34</td>
</tr>
<tr>
<td>$\beta^*=6\text{ m, B1H}$</td>
<td>2.47</td>
<td>2.41</td>
<td>2.45</td>
<td>2.34</td>
<td>2.35</td>
<td>2.25</td>
</tr>
<tr>
<td>$\beta^*=6\text{ m, B1V}$</td>
<td>3.73</td>
<td>3.52</td>
<td>3.55</td>
<td>3.70</td>
<td>3.58</td>
<td>3.84</td>
</tr>
</tbody>
</table>

Very little impact on cleaning inefficiency from TCSPM installation layout for the same settings (as expected)
Expected Performance in Run III – 2018

- Present TCSPM installation foresees to actually replace only 1 TCSG (.D4[L,R]7) out of 4;
- The other 3 TCSPMs are added immediately downstream of respective TCSGs;
- It would be possible to run with TCSGs and installed TCSPMs at the same time or separately;

Set of simulations aimed at assessing variations in cleaning performance if TCSPMs and/or TCSGs are used:
- Studies focused on a first version of possible Run III optics, developed in the framework of the Run III Configuration WG;
- Flat optics (50cm/15cm) considered – in MDs, found to be more challenging in terms of aperture margins;
- 2018-like collimator settings (pushed performance) vs HL-LHC-like settings (more relaxed settings, especially on impedance);
- CRDS beam process, i.e. telescope with tele-index at ~2.5 → increased effectiveness of octupoles in stabilizing the beam;
- Run III optics does not incorporate the new one of IR7;
- Quick look also at HL-LHC v1p4, to focus mainly on new IR7 optics;
Simulation Settings

- optics:
  - Run III Flat ($\beta^*=50\text{cm}/15\text{cm}$);
  - HL-LHC v1p4 ($\beta^*=15\text{cm}$, with IR7 optics);
- 7 TeV, B1H / B1V only, 0.04$\sigma$ halo;
- 2018 OP-like settings vs HL-LHC baseline;

<table>
<thead>
<tr>
<th>IR</th>
<th>Coll Family</th>
<th>HL-LHC [$\varepsilon=2.5\mu m$]</th>
<th>HL-LHC [$\varepsilon=3.5\mu m$]</th>
<th>2018 OP-like [$\varepsilon=2.5\mu m$]</th>
<th>2018 OP-like [$\varepsilon=3.5\mu m$]</th>
</tr>
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<tbody>
<tr>
<td>IR7</td>
<td>TCP/TCS/TCLA/TCLD</td>
<td>6.7/9.1/12.7/16.6</td>
<td>5.7/7.7/10.7/14</td>
<td>5.9/7.7/11.8/16.6</td>
<td>5/6.5/10/14</td>
</tr>
<tr>
<td>IR3</td>
<td>TCP/TCS/TCLA</td>
<td>17.7/21.3/23.7</td>
<td>15/18/20</td>
<td>17.7/21.3/23.7</td>
<td>15/18/20</td>
</tr>
<tr>
<td>IR6</td>
<td>TCDQ/TCSP</td>
<td>10.1/10.1</td>
<td>8.5/8.5</td>
<td>8.6/8.6</td>
<td>7.3/7.3</td>
</tr>
<tr>
<td>IR1/5</td>
<td>TCT/TCL</td>
<td>10.4/14.2</td>
<td>8.8/12</td>
<td>9.5/17.7</td>
<td>8/15</td>
</tr>
<tr>
<td>IR2</td>
<td>TCT</td>
<td>43.8</td>
<td>37</td>
<td>35.5</td>
<td>30</td>
</tr>
<tr>
<td>IR8</td>
<td>TCT</td>
<td>17.7</td>
<td>15</td>
<td>35.5</td>
<td>30</td>
</tr>
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</table>

New: aperture and offset directly from MADX when generating fort.2!

Preliminary results!

In 2018 operation we actually had:
8.5$\sigma$@30cm, 7.8$\sigma$@25cm

In 2018 operation we actually had:
37$\sigma$@IR2, 15$\sigma$@IR8
Results – LMs – Run III Flat, OP-2018 Like Settings, B1H

TCSGs only

No major differences on patterns!

TCSPMs only
Results – Cleaning Inefficiencies

- **18 simulated cases:**
  - TCSGs and TCSPMs vs only TCSGs vs only TCSPMs;
  - 2018-OP like settings vs HL-LHC settings;
  - B1H / B1V;
  - Run III Flat vs HL-LHC v1p4;

- Little variation in cleaning inefficiency when choosing between TCSGs and TCSPMs (as expected);
- Worse cleaning inefficiency with HL-LHC settings than with 2018-like settings (as expected);
Results – Collimator Losses – B1H

Run III Flat optics

- 18 simulated cases:
  - TCSGs and TCSPMs vs only TCSGs vs only TCSPMs;
  - 2018-OP like settings vs HL-LHC settings;
  - B1H / B1V;
  - Run III Flat vs HL-LHC v1p4;

- TCSGs + TCSPMs:
  - TCSPMs in shadow of upstream TCSG;
  - Least load on TCLAs and TCLD;

- TCSGs only:
  - Highest load on TCLAs and TCLD;
  - No major differences in patterns between 2018-OP-like and HL-LHC settings, or between Run III flat and HL-LHC v1p4;

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<tr>
<td>TCSPM.6R7</td>
<td>TCSPM.6L7</td>
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</table>
Asymmetric Collimator Settings

- Impedance of collimation system is comfortably under control in Run III (N. Mounet, 5th Run III Config. WG meeting):
  - Partial IR7 collimator upgrade (4 TCSPMs/beam) introduces already 50% of gain from full upgrade (11 TCSPMs/beam);
  - CRDS with tele-index of ~2.5 enhances the octupole effectiveness;
  - Ok for pushed settings (as in 2018-OP) with beam brightnesses foreseen for Run III;
- In 2018, asymmetric collimator settings explored in simulations and MDs as a mean to further decrease collimator impedance at the expenses of limited worsening of cleaning inefficiency;

B1V: measurements vs simulated cleaning inefficiency (LHC)

D. Kodjaandreev, LSWG, 11/10/2018

Measured inefficiency reasonably match expectations for B1, whereas discrepancies are found on B2; → To be understood;

Considered asymmetric configurations (IR7):
- TCPs (C1/C2);
- The 4 TCSGs of the LS2 upgrade (NPNN/ANTI-);
- Almost all IR7 TCSGs (MANY/ANTI-);

Estimation of impedance reduction based on resistive wall term, dominant for LHC collimators;
→ To be refined, in view of Run III and (especially) HL-LHC, for having a final word;

D. Kodjaandreev
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- Expected performance in Run III:
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  - Outlook to HL-LHC v1p4

- Conclusions
Conclusions

- LS2 will see the installation of the partial LHC Collimation Upgrade for HL-LHC:
  - Many changes already taking place during LS2;
  - Extended and detailed studies to converge on present baseline;
  - Different areas covered (e.g. cleaning performance, thermo-mechanics, cryogenics, radiation to equipment, …);
  - Many thanks to all teams involved!
- It will be possible to get acquainted to the new HL-LHC hardware already in Run III;
  - The staged installation of the TCSPMs (4/beam in LS2) will allow a further improvement of the design (e.g. to decrease the collimator sagitta for 0.2h BLT);
- Sound hardware for a good start-up in Run III:
  - More robust TCPs / TCSGs;
  - (Mo-coated) MoGr jaws will limit impact on impedance;
  - It should be possible to swallow the LIU beams once available in the LHC;
Thanks a lot!
Results – Collimator Losses – B1V

### 2018-OP like settings

- **B1**
  - TCSG.D4L7
  - TCSPM.B4L7
  - TCSPM.E5R7
  - TCSPM.6R7

- **B2**
  - TCSG.D4R7
  - TCSPM.B4R7
  - TCSPM.E5L7
  - TCSPM.6L7

- **TCSGs + TCSPMs:**
  - TCSPMs in shadow of upstream TCSG;
  - Least load on TCLAs and TCLD;

- **TCSGs only:**
  - Highest load on TCLAs and TCLD;
  - No major differences in patterns between 2018-OP-like and HL-LHC settings, or between Run III flat and HL-LHC v1p4;

### HL-LHC settings

- **TCSGs + TCSPMs:**
  - 18 simulated cases:
    - TCSGs and TCSPMs vs only TCSGs vs only TCSPMs;
    - 2018-OP like settings vs HL-LHC settings;
    - B1H / B1V;
    - Run III Flat vs HL-LHC v1p4;

- **TCSGs only:**
  - 18 simulated cases:
    - TCSGs and TCSPMs vs only TCSGs vs only TCSPMs;
    - 2018-OP like settings vs HL-LHC settings;
    - B1H / B1V;
    - Run III Flat vs HL-LHC v1p4;
Results – LMs – Run III Flat, OP-2018 Like Settings, B1V
Results – LMs – Run III Flat, HL-LHC Settings, B1H

- **TCSGs only**
  - **Entire ring**
    - Local cleaning inefficiency vs. (L/v)
    - Longitudinal Coordinate (m)
    - Data points and markers for different conditions

- **TCSGs + TCSPMs**
  - **Entire ring**
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- **TCSPMs only**
  - **Entire ring**
    - Local cleaning inefficiency vs. (L/v)
    - Longitudinal Coordinate (m)
    - Data points and markers for different conditions

- **B1H - Run III Dev - Flat - IR7**
  - Local cleaning inefficiency vs. (L/v)
  - Longitudinal Coordinate (m)
  - Data points and markers for different conditions

- **B1H - Run III Dev - Flat - IR7**
  - Local cleaning inefficiency vs. (L/v)
  - Longitudinal Coordinate (m)
  - Data points and markers for different conditions

- **B1H - Run III Dev - Flat - IR7**
  - Local cleaning inefficiency vs. (L/v)
  - Longitudinal Coordinate (m)
  - Data points and markers for different conditions
Results – LMs – Run III Flat, HL-LHC Settings, B1V

TCSGs only

IR7 only

TCSGs + TCSPMs

B1V - Run III Dev - Flat - IR7

TCSPMs only

B1V - Run III Dev - Flat - IR7
Results – LMs – HL-LHC v1p4, B1H

TCSGs only

**Entire ring**

- Local cleaning efficiency vs. (T/Lm)
- Longitudinal Coordinate (m)
- Cold, Warm, Collimator
- Data points: 2.10E-06, 3.55E-06

**B1H - HL-LHC v1p4 - Round - IR7**

- Local cleaning efficiency vs. (T/Lm)
- Longitudinal Coordinate (m)
- Cold, Warm, Collimator
- Data points: 2.00E-06

TCSGs + TCSPMs

**Entire ring**

- Local cleaning efficiency vs. (T/Lm)
- Longitudinal Coordinate (m)
- Cold, Warm, Collimator
- Data points: 2.34E-06, 5.3E-06

**B1H - HL-LHC v1p4 - Round - IR7**

- Local cleaning efficiency vs. (T/Lm)
- Longitudinal Coordinate (m)
- Cold, Warm, Collimator
- Data points: 2.34E-06, 5.3E-06

TCSPMs only

**Entire ring**

- Local cleaning efficiency vs. (T/Lm)
- Longitudinal Coordinate (m)
- Cold, Warm, Collimator
- Data points: 2.06E-06, 3.43E-06

**B1H - HL-LHC v1p4 - Round - IR7**

- Local cleaning efficiency vs. (T/Lm)
- Longitudinal Coordinate (m)
- Cold, Warm, Collimator
- Data points: 2.06E-06, 3.43E-06
Results – LMs – HL-LHC v1p4, B1V