PPS Perspectives @ HL-LHC
What we know and don’t know – A First Brainstorming

Elba Workshop
26 May 2018

Valentina Avati: simulations
Mario Deile: calculations
Dmitry Druzhkin: layout and mechanics studies
• new standard emittance $\varepsilon_n = 2.5 \, \mu\text{m rad}$ (instead of 3.5)
• for crossing angle $(\alpha/2, \beta^*) = (295 \, \mu\text{rad}, 15 \, \text{cm})$
• assuming XRP$s @ 15 \sigma$ (optimistic and simplified)

for $s > \sim 270 \, \text{m} : D_x > 0$
$\Rightarrow$ diffractive protons between the beam pipes
$\Rightarrow$ no standard Roman Pot possible $\Rightarrow$ improved technology ($\Rightarrow$ D. Druzhkin)
Free only around $420 \, \text{m}$.
Region not yet considered here.
The Only Region of Interest: 210 – 250 m
(for Classical Roman Pot Technology)

more detailed studies for
- \( s = 220 \) m
- \( s = 234 \) m
Calculate contour lines of “1-arm pseudo mass” limits $\tilde{M}_{\text{min/max}} = \xi_{\text{min/max}} \sqrt{s}$ in $(\alpha/2, \beta^*)$ plane.

Orthogonality:
- $d_{\text{XRP}}$ depends only on $\beta^*$, not on $\alpha/2$.
- $D_x$ depends only on $\alpha/2$, not on $\beta^*$.

Confirmed for nominal 2018 optics but not explicitly verified for HL-LHC optics!

Additional freedom @ HL-LHC:
- Crossing-angle can be horizontal or vertical $\rightarrow$ distinguish $\alpha_x/2$, $\alpha_y/2$
  - To do: investigate effects of vertical dispersion
- Possibility of flat optics: $\beta_x^* \neq \beta_y^*$

MAD-X simulations:
- $(\alpha_x/2, \alpha_y/2, \beta_x^*, \beta_y^*) = (295 \mu\text{rad}, 0, 15 \text{ cm}, 15 \text{ cm})$ done
- $(\alpha_x/2, \alpha_y/2, \beta_x^*, \beta_y^*) = (0, 295 \mu\text{rad}, 15 \text{ cm}, 15 \text{ cm})$ done
- flat optics scenarios not yet done; needed?

For the preliminary calculations shown here, we assume strict independence of $x$ and $y$. 
**Dispersion vs. Crossing-Angle**

**MAD-X simulations:**
- \((\alpha_x/2, \alpha_y/2, \beta_x^*, \beta_y^*) = (295 \, \mu\text{rad}, 0, 15 \, \text{cm}, 15 \, \text{cm})\):  \(D_x(220\text{m}) = -23.3 \, \text{mm}, \; D_x(234\text{m}) = -18.1 \, \text{mm}\)
- \((\alpha_x/2, \alpha_y/2, \beta_x^*, \beta_y^*) = (0, 295 \, \mu\text{rad}, 15 \, \text{cm}, 15 \, \text{cm})\):  \(D_x(220\text{m}) = -106 \, \text{mm}, \; D_x(234\text{m}) = -108 \, \text{mm}\)

Assume linearity:

\[
D\left(\frac{\alpha}{2}\right) = D(0) + D'\frac{\alpha}{2}
\]

(confirmed by 2017 data).
XRP Insertion Distance vs. $\beta^*$  \(1\)

Assume insertion rule: \(d_{\text{XRP}} = (n_{\text{TCT}} + 3)\sigma_{\text{XRP}} + 0.3\) mm

2 Options:

a. \(d_{\text{TCT}} = \text{const.} \Rightarrow n_{\text{TCT}}(\beta^*) = n_{\text{TCT}}(\beta_0^*)\sqrt{\frac{\beta^*}{\beta_0^*}}\)

b. \(n_{\text{TCT}} = \text{const.}\)

\[\sigma_{\text{XRP}} = \sqrt{\frac{\varepsilon_n\beta_{\text{XRP}}}{\gamma}}\]

We need $\beta_{\text{XRP}}(\beta^*)$!

ATS invariance of optical functions:

\[v_{\text{XRP}} = \sqrt{\frac{\beta_{\text{XRP}}(\beta^*)}{\beta^*}} \cos \mu_{\text{XRP}}(\beta^*) : \text{magnification independent of } \beta^*\]

\[L_{\text{XRP}} = \sqrt{\beta_{\text{XRP}}(\beta^*) \beta^*} \sin \mu_{\text{XRP}}(\beta^*) : \text{eff. length independent of } \beta^*\]

\[
\begin{cases}
\tan \mu_{\text{XRP}}(\beta^*) = \frac{L_{\text{XRP}}}{v_{\text{XRP}} \beta^*} \\
\beta_{\text{XRP}}(\beta^*) = \frac{L_{\text{XRP}}}{\sin \mu_{\text{XRP}}(\beta^*) \cos \mu_{\text{XRP}}(\beta^*)}
\end{cases}
\Rightarrow \beta_{\text{XRP}}(\beta^*) = v_{\text{XRP}}^2 \beta^* + \frac{L_{\text{XRP}}^2}{\beta^*}
\]

\[\sigma_{\text{XRP}} = \sqrt{\frac{\varepsilon_n}{\gamma} \left(v_{\text{XRP}}^2 \beta^* + \frac{L_{\text{XRP}}^2}{\beta^*}\right)}\]
XRP Insertion Distance vs. $\beta^*$  \hspace{1cm} (2)

TCT option a: $d_{\text{TCT}} = \text{const.}$

$$d_{\text{XRP}} = \left( n_{\text{TCT}}(\beta_0^*) \sqrt{\frac{\beta^*}{\beta_0^*} + 3} \right) \sqrt{\frac{\varepsilon_n}{\gamma}} \left( v_{\text{XRP}}^2 \beta^* + \frac{L_{\text{XRP}}^2}{\beta^*} \right) + 0.3 \text{ mm}$$

TCT option b: $n_{\text{TCT}} = \text{const.}$

$$d_{\text{XRP}} = (n_{\text{TCT}} + 3) \sqrt{\frac{\varepsilon_n}{\gamma}} \left( v_{\text{XRP}}^2 \beta^* + \frac{L_{\text{XRP}}^2}{\beta^*} \right) + 0.3 \text{ mm}$$

Note: $d_{\text{XRP}}(\beta^*)$ not monotonic, has a minimum!
Evolution of Parameters

- For the adaptive scenarios, include crossing angle “anti-levelling” à la LHC after the end of levelling

Slightly delay the end of levelling

max crabbing angle: 380μrad

N. Karastathis, D. Pellegrini et al., HL-LHC collaboration meeting 2017
Minimum “Mass” @ 220 m

Contour lines for \( \tilde{M}_{\text{min}} = \xi_{\text{min}} \sqrt{s} = \frac{d_{\text{XRP}}(\beta^*) + \delta}{D_x(\xi)} \sqrt{s} \)

TCT option a: \( d_{\text{TCT}} = \text{const.} \) (12.9 \( \sigma \) @ \( \beta^* = 15 \text{ cm} \))

TCT option b: \( n_{\text{TCT}} = 12.9 = \text{const.} \)

levelling trajectories:
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

Insertion distances moderate (> 1.5 mm)
Minimum “Mass” @ 234 m

Contour lines for

\[ \tilde{M}_{\text{min}} = \xi \min \sqrt{s} = \frac{d_{\text{XR}}(\beta^*) + \delta}{D_x(\xi)} \sqrt{s} \]

TCT option a: \( d_{\text{TCT}} = \text{const.} \) \((12.9 \, \sigma @ \beta^* = 15 \text{ cm})\)

TCT option b: \( n_{\text{TCT}} = 12.9 = \text{const.} \)

Levelling trajectories:
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

Insertion distances aggressive (< 1.5 mm)
Maximum Mass (1)

No strategy for TCL4, 5, 6 known yet $\rightarrow M_{\text{max}}$ calculated under assumptions

$$\tilde{M}_{\text{max}} = \frac{d_{TCL}}{D_{TCL}\left(\frac{\alpha_x}{2}\right)} \sqrt{S}$$

High-mass acceptance depends only on $\alpha_x/2$, not on $\beta^*$!
(unless $d_{TCL}$ varies during $\beta^*$ levelling; to be followed up)

Dispersion at TCLX.4, TCL.5, TCL.6 vs. crossing-angle
Maximum Mass (2)

- 220 m Location:
  Only TCL4 and TCL5 relevant
  Consider for simplicity constant distances
  \(d_{\text{TCL4}} = 15 \text{ or } 20 \sigma(\beta^*=15\text{cm})\)

\[d_{\text{TCL5}} = 15, 20, 25, 30, 35 \sigma(\beta^*=15\text{cm})\]

Comparison: Run 2: TCL4 @ 15 \(\sigma\), TCL5 @ 35 \(\sigma\)
• 234 m Location:
  Additional cut from TCL.6
  Consider for simplicity constant distances
  \( d_{\text{TCL6}} = 15, 20, 25, 30, 35 \sigma(\beta^*=15\text{cm}) \)

Severe upper mass cut by TCL.6!
Note: This affects all locations \( s > 221 \text{ m} \), of course \textbf{also the 420 m region}!
Using Both Locations?

higher masses

lower masses

220 m from IP5

235 m from IP5

Timing1

Timing2

Tr1

Tr2
Preliminary Conclusions

- Only 3 relevant locations:
  - just before TCL6 (~ 220 m)
  - just after Q6 (~ 234 m): space not impossible! (better low-mass performance!)
  - 420 m: $D_x > 0 \rightarrow$ diifr. p between beam pipes $\rightarrow$ needs improved technology not yet studied

- Main driving factor for acceptance: dispersion!
  $\rightarrow$ vertical crossing is essential!

- With present HL-LHC preview optics:
  Playing with $\beta^*$ and Roman Pot distance gives insignificant improvements.
  Flat optics won’t save the day.
  $\rightarrow$ ask to pursue improvement ideas

- Details still very uncertain and changing
  (e.g. levelling trajectory, collimator positions throughout levelling),
  but main trends become visible.

- Upper mass cut by TCL5 (and TCL6) could be a problem.

- We should work on our self-imposed 1.5 mm insertion limit (for the 234 m location).
Outlook: Other Issues to be Studied

• Debris showers → BLM rates:
  max. lumi 2018: $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
  max. lumi HL-LHC: $20 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
→ factor 10

At $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$: BLM of cylindrical pot is below threshold by factor 15 → should be ok
But all designs will change → to be watched

• Impedance:
  - max protons / beam 2018: $3.2 \times 10^{14}$
    HL-LHC: $6 \times 10^{14}$
→ factor 2 in current → factor 4 in heating
- bunch length? → impact on power spectrum
- RP distance: already studied down to 1 mm
- impedance budget of the machine might become tighter

• Influence from crab cavities on scattered p trajectories should be negligible (H. Burkhardt)

• For detector instrumentation: the pileup:
  $\mu \leq 200$ (w/o levelling, w/o crab cav.)
  $\mu \leq 140$ (w/ levelling, w/ crab cav.)

• Radiation issues
The End.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal LHC (design report)</th>
<th>HL-LHC (standard)</th>
<th>HL-LHC (BCMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy in collision [TeV]</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Particles per bunch, $N \times 10^{13}$</td>
<td>1.15</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>2808</td>
<td>2748</td>
<td>2604</td>
</tr>
<tr>
<td>Number of collisions in IP1 and IP5</td>
<td>2808</td>
<td>2736</td>
<td>2592</td>
</tr>
<tr>
<td>$N_{\text{tot}} \times 10^{13}$</td>
<td>3.2</td>
<td>6.0</td>
<td>5.7</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.58</td>
<td>1.09</td>
<td>1.03</td>
</tr>
<tr>
<td>Crossing angle in IP1 and IP5 [μrad]</td>
<td>285</td>
<td>590</td>
<td>590</td>
</tr>
<tr>
<td>Normalized long-range beam–beam separation [$\varphi$]</td>
<td>9.4</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Minimum $\beta$ [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$\sigma_{b}$ [μm]</td>
<td>3.75</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>$\sigma_{l}$ [eVs]</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>r.m.s. energy spread [0.0001]</td>
<td>1.13</td>
<td>1.13</td>
<td>1.13</td>
</tr>
<tr>
<td>r.m.s. bunch length [cm]</td>
<td>7.55</td>
<td>7.55</td>
<td>7.55</td>
</tr>
<tr>
<td>IBS horizontal [h]</td>
<td>105</td>
<td>18.5</td>
<td>18.5</td>
</tr>
<tr>
<td>IBS longitudinal [h]</td>
<td>63</td>
<td>20.4</td>
<td>20.4</td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td>0.65</td>
<td>3.14</td>
<td>3.14</td>
</tr>
<tr>
<td>Total loss factor $R_0$ without crab cavity</td>
<td>0.836</td>
<td>0.305</td>
<td>0.305</td>
</tr>
<tr>
<td>Total loss factor $R_1$ with crab cavity</td>
<td>(0.981)</td>
<td>0.829</td>
<td>0.829</td>
</tr>
<tr>
<td>Beam–beam/IP without crab cavity</td>
<td>0.0031</td>
<td>0.0033</td>
<td>0.0033</td>
</tr>
<tr>
<td>Beam–beam/IP with crab cavity</td>
<td>0.0038</td>
<td>0.0011</td>
<td>0.0011</td>
</tr>
<tr>
<td>Peak luminosity without crab cavity [$10^{34}$ cm$^{-2}$ s$^{-1}$]</td>
<td>1.00</td>
<td>7.18</td>
<td>6.80</td>
</tr>
<tr>
<td>$L_{\text{peak}} \times R_1/R_0 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>(1.18)</td>
<td>39.54</td>
<td>18.52</td>
</tr>
<tr>
<td>Events/crossing without levelling and without crab cavity</td>
<td>27</td>
<td>198</td>
<td>198</td>
</tr>
<tr>
<td>Levelled luminosity [$10^{24}$ cm$^{-2}$ s$^{-1}$]</td>
<td>-</td>
<td>5.00↑</td>
<td>5.00↑</td>
</tr>
<tr>
<td>Events/crossing (with levelling and crab cavities for HL-LHC)²</td>
<td>27</td>
<td>138</td>
<td>146</td>
</tr>
<tr>
<td>Maximum line density of pile-up events during fill [event/mm]</td>
<td>0.21</td>
<td>1.25</td>
<td>1.31</td>
</tr>
<tr>
<td>Levelling time [h] (assuming no emittance growth)²</td>
<td>-</td>
<td>8.3</td>
<td>7.6</td>
</tr>
<tr>
<td>Number of collisions in IP2/IP8</td>
<td>2808</td>
<td>2452/2524**</td>
<td>2288/2396**</td>
</tr>
<tr>
<td>$N$ at LHC injection [$10^{13}$]†</td>
<td>1.20</td>
<td>2.30</td>
<td>2.30†</td>
</tr>
<tr>
<td>Maximum number of bunches per injection</td>
<td>288</td>
<td>288</td>
<td>288</td>
</tr>
<tr>
<td>$N_{\text{tot}}$/injection [$10^{13}$]†</td>
<td>3.46</td>
<td>6.62</td>
<td>6.62</td>
</tr>
<tr>
<td>$\sigma_{t}$ at SPS extraction [μm]²</td>
<td>3.40</td>
<td>2.00</td>
<td>&lt;2.00**</td>
</tr>
</tbody>
</table>

[from Design Report, CERN-2015-005]
[P. Fessia: HL-LHC coordination group meeting 10.07.2017]