Tune-scans for HL-LHC and LHC

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CERN-TRIUMF HL-LHC Collab.

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Optics configurations used

What's in black is kept constant including $\beta^*$ (leveling scenarios not considered)

- **HL-LHC**  V1.2  **baseline:**
  - bunch charge $N_b = 2.2$ or $1.1 \times 10^{11}$
  - IR1,5 Xing half-ang = 295 $\mu$rad, $\beta^* = 15$ cm
  - IR8 $\beta^* = 3$m, Xing half-ang =-135-250=-385 $\mu$rad (LHCb spect. pol.=-1)
  - IR2 $\beta^* = 10$m, hor. sep. = 2 mm, Xing = 170 $\mu$rad
  - $\text{emit}_n = 2.5$ $\mu$m, bunch len. = 7.5 cm, $\frac{\Delta p}{p} = 2.7 \times 10^{-4}$
  - 25 ns,  chrom = 3

- **LHC**  V6.503  at peak Lumi $1 \times 10^{34}$

conditions for tracking

- Hirata BB ON, crab cavities **OFF or ON** with fully crabbing of strong beam enforced (the default)
- standard MadX-SixTrack-SixDesk env.
Tune-scan (TS) conditions

- **tune-scan A**  HL-LHC,  
  \( \text{Nb}=1.1 \times 10^{11} \),  crabs OFF, along line \( \parallel \text{diag.} \)  \( \rightarrow \)

- **tune-scan B**  LHC  (to compare with TS A)

- **tune-scan C**  HL-LHC,  
  \( \text{Nb}=2.2 \times 10^{11} \),  crabs ON. It is 2D: looking for a better w.p. closer to diagonal in yellow \( \rightarrow \)  
  \[ (Yannis) \]

- \( Qx_{BB}=Qx_0+\Delta Qx \)  \( Qy_{BB}=Qy_0+\Delta Qy \)  
  \( Qx(y)_{BB} \) is as reported by MadX or SixTrack with CC on
Tune-scan A

HL-LHC with Nb = $1.1 \times 10^{11}$, IP1,5,2,8 and crab OFF

Nominal HL-LHC footprint at 2.2 E11

Tune-scan line

old style plot

< 2010

18 azimuthal angles
split into two plots

$Q_{xBB} = Q_x0 - \Delta Q$

Figure 1 OLD STYLE PLOT: DA-by-angle dep. on perturbed tune
New-style plots: Let’s color intervals between the constant-angle contours. Color Hue is proportional to angle value. Some overlapping unfortunately takes place..

Here color Hue is proportional to upper bound of the angle interval (4.5 deg)
Keeping all angles, just shortening the Legend (scaling the Hue).

And shifting by the approximately constant BB tune shift \( \Delta Q_x = 0.0155 \).

\( Qx0 \) is the unperturbed tune.
Tune-scan A: when in terms of $Q_{xBB}$ explains other cases:

Take $CC$ ON, $Nb=2.2 \times 10^{11}$ for two cases: 1) “no IP8” and 2) “with IP8”.

Case 2) needs a little shift to the right. The result is “best w.p. from TS A”.

**HL-LHC Lattice cases:**
- $Nb=1.1$ IR1,5,8 NO CC
- 1) $Nb=2.2$ IR1&5, CC ON
- 2) $Nb=2.2$ IR1,5,8 CC ON
DA for case 1): no BB in IR2 and 8

the only case when the chaotic border was $> 2$ at some angles
DA for cases 1) and 2). The shift for 2) works – improves DA.

*tune-scan A is quite universal*
DA for case 2) with IR2 added (still at best w.p. from TS A)

some tiny increase in $\Delta Q$ from 0.0318 to $\sim 0.033$ due to IR2

It will further improve for w.p. closer to diagonal —> pages 14+
Tune-scan B (LHC as-built with corrected tripl. errors)

Tune-scans for seeds 1–6. Color code is same as above, but only 9 angles. The three resonance dips near 64.31 are known from previous studies.

First 6 seeds for LHC with corrected triplet. Here Qx represents Qx0 (sorry).
Tune-scans A and B compared

Top: **HL-LHC**, \( \text{Nb}=1.1 \times 10^{11} \) BB and Sext.

Bottom: **LHC**, BB+sext and corr. tripl. for seed 1

![Plot showing comparison between HL-LHC and LHC tune-scans](image-url)
detour 1/1: Tune-scans A and B, dip locations (X-plane only)

It’s a lot easier to explain the dips than the maxima of course.

red only, i.e. DA near HOR plane

The simple Two-Head-On-IPs BB model HOR plane only for the perturbed CS invariant (Poincaré surface of section) seems to explain dip locations. This invariant, when confirmed with tracking (black dots), looks like:

Near resonance it begins to oscillate fast. The blue curves on the right show module of some high-order Fourier coefficient (C10 used here).
detour 1/2: fast osc. of invariant sample lattice

0.3068
0.3072
0.3076
0.308
0.3084

0.3069
0.3073
0.3077
0.3081
0.3085

0.307
0.3074
0.3078
0.3082
0.3086

0.3071
0.3075
0.3079
0.3083
0.3087
$\Delta Q^{BB} \approx 0.033$

TS lines

Tune-scan lines parallel to diagonal and approaching it from above:

0, 1, 2 \ldots, 6 \quad \text{(TS A line is 0 here)}

step in tune $\Delta Q_x = 10^{-3}$

step in distance to diagonal (yellow) $= \sqrt{2} \Delta Q_x \approx 14 \times 10^{-4}$
(a) 1 Dist=$10^{-2}$. Min DA is 5.5 at the best w.p. from TS A. Seen to be near 45-deg plane (green).

(b) 2

(c) 3

(d) 4

(e) 5

(f) 6

(g) 7 Dist=$1.4 \times 10^{-5}$. Min DA grows to 6.5. Seen to be near VERT plane (blue).
Tune-scan C

extending the domain up and to the right (to capture best-DA region)

Min DA over 11 angles. The black dot is “best w.p. from TS C”: \((Qx0,Qy0)=(0.316,0.319)\).

Black dot tested next →
DA at the best w.p. of TS C
A sigma gained (compare with page 10)

<table>
<thead>
<tr>
<th>Wname</th>
<th>QxBB/</th>
<th>dQx/</th>
<th>CHx/</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wst1582_BP</td>
<td>62.284/</td>
<td>0.0324/</td>
<td>3.26843/</td>
</tr>
<tr>
<td></td>
<td>60.2868</td>
<td>0.0327</td>
<td>2.10872</td>
</tr>
</tbody>
</table>

w.p. set to (0.3164,0.3195) with MadX only
Tune-scan C (2D) in terms of $Q_{xyBB}$
continued Jan 2017
Tune-scan D (2D), $Nb=1.1 \times 10^{11}$

So that D is same as A, but crab ON and IR2 ON, or same as C, but $Nb=1.1 \times 10^{11}$.

Min DA over 11 angles.
Left: TS C repeated and Right: TS D

(DA at the nominal tune (red point) will be studied without and with IT field errors ⇒)
DA at nominal tune (no errors)
Tune-scan C and D shown by TS line

To see the effect of halving Nb.
Top: Nb=2.2×10^{11}  Bottom: Nb=1.1×10^{11}
from left to right – approaching the diagonal starting from Dist=0.01.
DA for nominal tune with IT field errors

Ref. for corrector limits

A table from HiLumi LHC WP3 page shows max Integrated strengths \(^1\)

and these are the corrector data

<table>
<thead>
<tr>
<th>Order</th>
<th>MCQSX</th>
<th>MCSX/MCSSX</th>
<th>MCOX/MCOSX</th>
<th>MCDX/MCDSX</th>
<th>MCTX</th>
<th>MCTSX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture (mm)</td>
<td>2</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Integrated strength (^1) (T m)</td>
<td>1.000</td>
<td>0.063</td>
<td>0.046</td>
<td>0.025</td>
<td>0.086</td>
<td>0.017</td>
</tr>
<tr>
<td>Coil length (mm)</td>
<td>841</td>
<td>123</td>
<td>99</td>
<td>107</td>
<td>449</td>
<td>102</td>
</tr>
<tr>
<td>Gradient (T/m m(^{-1}))</td>
<td>25</td>
<td>11</td>
<td>3690</td>
<td>50600</td>
<td>640000</td>
<td>613000</td>
</tr>
<tr>
<td>Number of apertures</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of circuits</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Units needed</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Spares</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

\(^1\) Integrated strength is the field at the 50 mm ref radius times the magnetic length
Results taken from ref. paper \(^2\) are: corr. strengths (Fig 2) and integrated mult. field at 5 cm (Table 3).

![Distribution of strength of non-linear correctors](image)

**Figure 2:** Distribution of the strength of the non-linear correctors: \(a_3, b_3\) (upper left); \(a_4, b_4\) (upper right); \(a_5, b_5\) (lower left); \(a_6, b_6\) (lower right).

my result for corr. strengths
(comp. with Fig.2 of ref. paper)

Same errors and same correctors used as in ref. paper above
my result for integrated strengths
(comp. with Table 3 of ref. paper) need to explain the difference

<table>
<thead>
<tr>
<th>correctors, mT.m</th>
<th>Computed</th>
<th>Specified</th>
</tr>
</thead>
<tbody>
<tr>
<td>norm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>15.3</td>
<td>46</td>
</tr>
<tr>
<td>5</td>
<td>9.6</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>30.8</td>
<td>86</td>
</tr>
<tr>
<td>skew</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>186</td>
<td>1000</td>
</tr>
<tr>
<td>3</td>
<td>15.1</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>11.4</td>
<td>46</td>
</tr>
<tr>
<td>5</td>
<td>12.3</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>5.5</td>
<td>17</td>
</tr>
</tbody>
</table>
DA at nominal tune with IT field errors, no A2, no D1,D2

i.e., at the red point for TS D on page 21

FIRST 40 seeds
Identify worst seeds

- “worst” seeds 38, 7, 5, 15 and 16
- good seed: 2
- may be correlated with dr. terms

next ⇒
skew driving terms, Beam1

Relative units. First of pair: IR5. Second of pair: IR1. Where terms is 0, means corrected. Bad seeds (red) are seen to correspond to near maxima for A4 (1,3), A5 all not-corrected – main cause for DA loss and A6 (3,3)
normal driving terms, Beam1
Bad seeds (red) are seen to corresp. to near maxima for B4 (2,2), B6(4,2)
Use all 60 seeds. Identify worst for each angle

3 new “worst” seeds: 36, 48 and 9

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<table>
<thead>
<tr>
<th>ang [deg]</th>
<th>seed</th>
<th>dr. term</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>38</td>
<td>A5 (2,3)</td>
</tr>
<tr>
<td>15</td>
<td>7</td>
<td>A6 (3,3) and B6 (4,2)</td>
</tr>
<tr>
<td>22.5</td>
<td>5</td>
<td>B4 (2,2)</td>
</tr>
<tr>
<td>30</td>
<td>7</td>
<td>3,3 and 4,2</td>
</tr>
<tr>
<td>37.5</td>
<td>38</td>
<td>A5 (2,3)</td>
</tr>
<tr>
<td>45</td>
<td>38</td>
<td>A5 (2,3)</td>
</tr>
<tr>
<td>52.5</td>
<td>36</td>
<td>B6 (2,4) ?</td>
</tr>
<tr>
<td>60</td>
<td>15</td>
<td>A5 2,3</td>
</tr>
<tr>
<td>67.5</td>
<td>16</td>
<td>A4 (1,3) ? check</td>
</tr>
<tr>
<td>75</td>
<td>48</td>
<td>B3 (3,0) and B5 (3,2)</td>
</tr>
<tr>
<td>82.5</td>
<td>9</td>
<td>A5 (2,3)</td>
</tr>
</tbody>
</table>
skew

![Graphs of terms A3 to A6](image-url)

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