Revisiting flux jumps impact on orbit

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When do we expect Flux Jumps?

- Typically, most of them well between 1-3 TeV
- 2 kA @10A/s are made in about 200 s

**Impact on beam ∝ time integral**

**Flux jump signature**

**Mechanical oscillation**

1 kA ≈ 1 T
How fast/long?

- Typically: 4.4 jumps/second
  - Only measured on 11T short model.
  - We don’t know for the quadrupoles in the triplet
    - Michele estimated about 2.5 jumps/second in this case [link]
    - We need more measurements!!!
- Rise time ~50 ms. Let’s say FWHM ~120 ms.
  - 120x4.4=~500 ms: ~half of the time a magnet is experiencing a jump, which can be either positive or negative.

From J. Coello de Portugal – Impact of flux jumps in future colliders (PRAB)
How intense?

- **Size of a Flux Jump** in single magnet:
  - **0.2 units** (for the main field)
    - i.e. B0 in 11T, B1 for quadrupoles in the triplet,…
  - **WARNING1:** we don’t know about dipole field jump on a quadrupole
  - **WARNING2:** neglected here the 0.15 units up-down gradient measured on 11T

- **Biggest PC-jump induced by flux jump:**
  - **0.06 units on whole RQX circuit** (at injection only)
    - It becomes **negligible at top energy** (<0.06 units)
    - **Note:** PC linearity+short term stability of the order of **0.2 units** at injection, even though those are variations at very low frequency (<1 Hz)
  - **negligible for 11T dipoles** (~0.06 units at injection only)
  - **WARNING3:** PC-jumps studied only for RQX and 11T trim circuits, assuming single event in a single magnet with some *arbitrary* hypothesis on scaling laws. Dedicated studies needed!
Impact of flux jump on orbit at TCPs

- Each value represents the orbit jump induced by the most effective single half-magnet affected by a jump of 0.2 units.

<table>
<thead>
<tr>
<th>Optics</th>
<th>Magnet</th>
<th>Optics sensitivity $[\sigma/10^{-4}]$</th>
<th>Jump-induced rms orbit $[10^{-3}\sigma]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>&lt; 0.01</td>
<td>&lt; 2</td>
<td></td>
</tr>
<tr>
<td>Q2</td>
<td>0.01</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Q3</td>
<td>&lt; 0.01</td>
<td>&lt; 2</td>
<td></td>
</tr>
<tr>
<td>Q1–Q3</td>
<td>0.01</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>$\beta^*=$15 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>0.06</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Q2</td>
<td>0.28</td>
<td>56</td>
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<tr>
<td>Q3</td>
<td>0.18</td>
<td>36</td>
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<tr>
<td>Q1–Q3</td>
<td>0.48</td>
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<tr>
<td>$\beta^*=$1 m</td>
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<tr>
<td>Q1</td>
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<tr>
<td>Q2</td>
<td>0.11</td>
<td>22</td>
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<tr>
<td>Q3</td>
<td>0.06</td>
<td>12</td>
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<td>22</td>
<td></td>
</tr>
</tbody>
</table>

TABLE III. R.m.s. closed orbit variation at HL–LHC TCPs under the effect of the expected flux jumps for each half quadrupole composing the triplet (Q1; Q2; Q3) and for a whole triplet (Q1–Q3) computed in units of beam sigma. The optics sensitivity in units of beam sigma per unit of magnetic field change is also reported.

TABLE V. R.m.s. closed orbit variation at HL–LHC TCPs under the effect of the expected flux jumps at the 11 T dipoles computed in units of beam sigma. The optics sensitivity in units of beam sigma per unit of magnetic field change is also reported.

Assumptions:
- 2.5 um norm. emit.
- 7 TeV for 1m and 15 cm optics
- 450 GeV for injection optics

=> A jump in some key magnet could lead to ~2% beam sigma jump at TCPs

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Some numbers

- **Affected magnets:**
  - 2 halves x 2 sides P7 of 11 T dipoles
    - Acting mainly on horizontal plane
  - 2 halves x 2 sides x 1 IP1/5 of Q1 + Q2 + Q3
    - Each IP is acting mainly on one plane due to crossing angle

- **Number of events:**
  - Over 200 s (one ramp, from ~1.2 to ~2.3 TeV), we expect 200x4.4 = **880 jumps** for each single magnet
  - Number of fills in lifetime of HL-LHC:
    - 10 years x 300 fills/year = **3000 fills**.
    - Total number of events/magnet = 2.64x10^6
Some probability of concurrent jumps

- At a given time, probability of a single magnet to be in a jump of a given sign is $\frac{1}{4}$.
- At a given time, probability that $n$ magnets are in a jump of a given sign is therefore $(\frac{1}{4})^n$

Additional assumptions:

- Assuming 1 m optics at 3 TeV (still conservative)
  - need to scale optics sensitivity values by $\sqrt{\frac{3}{7}} = 0.65$ as beam size is then bigger, i.e. size of jump in beam sigma is smaller.
- no cross-talk between magnets
- all flux jump of 0.2 units, 120 ms long, 4.4 isolated events/s
- neglected the contribution of the power converters
- Considering here only the horizontal plane
First order estimate of cases

- At least one event of $\sim 6\% \sigma_{\text{beam}}$ jump/ramp ($\sim 8\% \sigma_{\text{beam}}$ during HL-LHC lifetime)
- Similar in vertical/diagonal direction (i.e. x3 number of “bad” events)
- One can be more conservative (i.e. 0.6 units jumps $\Rightarrow$ up to $\sim 20\% \sigma_{\text{beam}}$ jumps)
Conclusions

- Typically, a few % $\sigma_{\text{beam}}$ orbit jumps at TCPs
  - For every ramp: $>1$ case with a jump up to $\sim 6\% \sigma_{\text{beam}}$
  - During HL-LHC lifetime, $>1$ case with a jump up to $\sim 8\% \sigma_{\text{beam}}$
  - Values can be scaled up to x3 to be very conservative

- We have limited knowledge on:
  - PC behavior for complex circuits like the triplet
  - Amplitude of $B_0$ jump in a quadrupole magnet

- Run3 will be fundamental to collect more data from 11T:
  - Firing 6k-turn-by-turn BPM data every “second”
  - ADT spectra
  - BPM 25Hz rms data
  - Other signals? BLM data?
  - String tests could be another place where to learn more.

Thank you for your attention and comments!
Backup
Impact of quads @TCP @1m beta* @7TeV @295 urad crossing
Impact of 11T @TCP @1m beta* @7TeV
More complicated: diagonal kick + PC effect

Actual result is very similar (within 10-20%) to horizontal plane computation only.

Still missing full analysis of PC behavior