Impact of flux jumps on orbit stability

D. Gamba, L. Fiscarelli, M. Martino, J. Coello de Portugal
MBH HYBRID - Residuals and differential voltage

- Current shows peaks related to voltage spikes $\sigma = 0.3$ units.
- The difference of current minus flux shows changes $\sigma = 0.2$ units.
- Gradient (up/dw) shows changes $\sigma = 0.14$ units.

Flux jumps seems to be concentrated at “low energy”

$\sigma$ is computed in the interval [2kA, 4kA]

From L. Fiscarelli– 144th WP2 Meeting (indico)
Lucio’s conclusions

- We have tested many short models and we have data for the first full-size aperture (MBH HYBRID)

- At the field levels (2-4 T) where there is more activity from flux jumps and during ramps at nominal ramp-rate (10 A/s) we see:
  - fluctuations of the current (\( \sigma = 0.2 \) units)
  - changes on the main field not related to the current (\( \sigma = 0.2 \) units)
  - changes of the up-down gradient (\( \sigma = 0.15 \) units)

- The spectral density of the flux jumps is mainly concentrated in the interval 0.1-10 Hz

From circuit point of view, we consider “linearity” and “Short term stability – 20 min” as boundary of “tracking” performance

This is the contribute of flux jumps according to Lucio

In this range PC don’t have a detailed specification! -> still under discussion how to use “Noise”
\[ \sigma = 6.04 \text{ ppm} \]

I guess this value is computed in the 0.1 – 100 Hz range.
\[ \sigma = 0.0084 \text{ ppm} \]

\[ \text{pk} - \text{pk} < 0.1 \text{ ppm} \]

From M. Martino – 144th WP2 Meeting (indico)
Putting numbers together (11T)

- **flux jumps** given in unit – worst case (in equivalent ppm) at top energy
- **PC specs** given in ppm of $I_{\text{rated}}$ – worst case at injection
- **Impact of PCs in units** computed as \([\text{ppm}] \times 10^{-2} \times \frac{I_{\text{PC \, rated}}}{I_{\text{dipoles \, inj.} / \text{nom.}}}\)

<table>
<thead>
<tr>
<th></th>
<th>11T Magnet/Trim</th>
<th>Main Dipoles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PC class</strong></td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$I_{\text{rated}} , [\text{A}]$</td>
<td>600</td>
<td>13000</td>
</tr>
<tr>
<td>$I_{\text{injection}} , [\text{A}]$</td>
<td>(0)</td>
<td>728</td>
</tr>
<tr>
<td>$I_{\text{nominal}} , [\text{A}]$</td>
<td>(250)</td>
<td>11850</td>
</tr>
<tr>
<td><strong>Short term stability , [r.m.s. , ppm]</strong></td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Linearity , [r.m.s. , ppm]</strong></td>
<td>4.6</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Flux jump -&gt; PC -&gt; circuit , [rms , ppm]</strong></td>
<td>6.04</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Flux jump ,[rms units , of 1e-4]</strong></td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td><strong>Tot. PC ,[rms units , inj.} / \text{nom.}</strong></td>
<td>$0.063 / 0.004$</td>
<td>$0.217 / 0.013$</td>
</tr>
</tbody>
</table>

Concerns here: flux jump on itself has an about 50 times bigger effect than PC stability at top energy

Comparable values!

performance dominated by short term stability and linearity
Comparison: flux jumps statistics for RQX

From a manual selection. Very probably biased towards larger strengths (easier to spot…).

145 jumps measured in the error of the magnetic flux ($\Delta \phi$).
- Average ± Std strength: $0.2 \pm 0.1$ units.
- Average ± Std length: 40±10 ms.

244 jumps seen in the current deviation ($\Delta I$) of the regulation circuit.
- Average ± Std strength: $0.06 \pm 0.03$ units.
- Average ± Std length: 60±40 ms.

Comparable effect as 11T trim (due to comparable inductances?)

*From J. Coello de Portugal – 147th WP2 Meeting (indico)*
Putting numbers together (Triplet)

- **Impact of PCs in units** computed as $[\text{ppm}] \times 10^{-2} \times \frac{I_{\text{PC rated}}}{I_{\text{RQX(inj./nom.)}}}$

<table>
<thead>
<tr>
<th></th>
<th>RQX</th>
<th>RTQX1/3</th>
<th>RTQXA1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PC class</strong></td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>$I_{\text{rated}} [\text{A}]$</td>
<td>18000</td>
<td>2000</td>
<td>60</td>
</tr>
<tr>
<td>$I_{\text{injection}} [\text{A}]$</td>
<td>1059</td>
<td>(0)</td>
<td>(0)</td>
</tr>
<tr>
<td>$I_{\text{nominal}} [\text{A}]$</td>
<td>16470</td>
<td>(1647)</td>
<td>(35)</td>
</tr>
<tr>
<td><strong>Short term stability [r.m.s. ppm]</strong></td>
<td>0.2</td>
<td>0.6</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Linearity [r.m.s. ppm]</strong></td>
<td>1.2</td>
<td>2.9</td>
<td>5.2</td>
</tr>
<tr>
<td><strong>PC Short + Lin. [rms units] inj. / nom.</strong></td>
<td>0.207/0.013</td>
<td>0.056/0.004</td>
<td>0.003/ &lt;0.001</td>
</tr>
<tr>
<td><strong>Flux jump -&gt; PC -&gt; circuit [rms units]</strong></td>
<td>0.06/ &lt;0.06?</td>
<td>???</td>
<td>???</td>
</tr>
<tr>
<td><strong>Tot. PC [rms units] inj. / nom.</strong></td>
<td>0.22/ &lt;0.06?</td>
<td>???</td>
<td>???</td>
</tr>
</tbody>
</table>

- **Circuit performance still dominated by PC stability** (at least for RQX)
- **Values to be compared with 0.2 units flux jump expected in each single magnet**, independently
  - Comparable at injection for RQX circuit
11T: impact on B1 orbit at 15 cm $\beta^*$, 7 TeV

Main observation:
- $< 0.2 \, \sigma_{\text{beam/unit}}$ @ TCPs
- Main dipoles have a stronger local impact
- same result for 40 cm $\beta^*$ at top energy

At injection:
- Not very different behavior
  - Optics around P7 is basically constant
  - about x4 less sensitive due to scaling of beam size with energy

TCPs

x4 wrt injection

Main dipole circuits

TCPs
Feed-down from IR1/5 triplet: impact on orbit

- Assuming pessimistic case of 295 urad half-crossing for all optics
  - Kick linear with crossing angle

- The lower the $\beta^*$ the most sensitive to "jumps"
  - Kick goes like $\sqrt{\beta}$ in the quadrupole
  - 40 cm $\beta^*$ is x1.6 less sensitive than 15 cm $\beta^*$

- Dominated by Q2.L1 (for B1)
  - $\sim 0.25 \sigma_{\text{beam/\text{unit}}} @ \text{TCPs}$
  - per Q2L magnet!
  - ($\sim 0.15 \sigma_{\text{beam/\text{unit}}} @ \text{TCPs per Q3R magnet}$)

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![Graph showing orbit impact](image-url)
D1/D2: impact on B1 orbit at 15 cm \( \beta^* \), 7 TeV

- D1/D2 other main players for orbit stability
- Based on Ni-Ti technology
  - No flux jumps expected
- Class 0 PC; 13 kA \( I_{\text{rated}} \)
  - Basically, same performance as RQX
Conclusion: impact on orbit at TCP @ inj / 15 cm $\beta^*$

<table>
<thead>
<tr>
<th></th>
<th>TCP orbit var. from optics [$\sigma_{\text{beam/unit}}$]</th>
<th>Expected jitter [rms units]</th>
<th>Expected TCP orbit var. [rms e-3 $\sigma_{\text{beam}}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11T magnet (flux jump)</td>
<td>0.02 / 0.07</td>
<td>0.2</td>
<td>4 / 14</td>
</tr>
<tr>
<td>11T trim circuit</td>
<td>0.04 / 0.14</td>
<td>0.063/0.004</td>
<td>&lt;1 / &lt;1</td>
</tr>
<tr>
<td>RB.A78 circuit</td>
<td>0.06 / 0.21</td>
<td>0.217/0.013</td>
<td>13 / 3</td>
</tr>
<tr>
<td>Q1 single magnet</td>
<td>$&lt;0.01 / 0.06$</td>
<td>0.2</td>
<td>&lt;2 / 12</td>
</tr>
<tr>
<td>Q2 single magnet</td>
<td>0.01 / 0.28</td>
<td>0.2</td>
<td>2 / 56</td>
</tr>
<tr>
<td>Q3 single magnet</td>
<td>$&lt;0.01 / 0.18$</td>
<td>0.2</td>
<td>&lt;2 / 36</td>
</tr>
<tr>
<td>RQX main circuit</td>
<td>0.01 / 0.48</td>
<td>0.22 / &lt;0.06?</td>
<td>2 / 29*</td>
</tr>
<tr>
<td>Q1 trim circuit</td>
<td>$&lt;0.01 / 0.10$</td>
<td>~0.056? / ~0.004?</td>
<td>&lt; 1? / &lt; 1?</td>
</tr>
<tr>
<td>Q3 trim circuit</td>
<td>0.01 / 0.33</td>
<td>~0.056? / ~0.004?</td>
<td>&lt; 1? / 1?</td>
</tr>
<tr>
<td>D1/D2 circuit</td>
<td>0.02 / 0.63</td>
<td>0.205 / 0.013</td>
<td>4 / 8</td>
</tr>
</tbody>
</table>

- The impact of flux jump at **top energy** for a 15 cm $\beta^*$ with 295 urad half crossing can reach up to 5.6% $\sigma_{\text{beam}}$ (MQX2) or 1.4% $\sigma_{\text{beam}}$ (MBH).
- At **injection** energy dominated by **main dipole PC (1.3% $\sigma_{\text{beam}}$)**
  - in this case it should be a slow variation (<< 1 Hz), which can be corrected by orbit feedback, while a flux jump is a sudden variation (a few Hz)!

* Note: during stable beam, PC “linearity” should not play a role, i.e. about x6 better stability.

Thanks for your questions and comments!
11T: impact on B1 orbit at injection

- Assuming 1 unit variation on RTB8L7 circuit (2x11T magnets), RB.A78 and RB.A67 circuits, single MBH.A8L7.B1 magnet
- Impact on orbit at TCPs within factor 2 to 4 for a given amplitude.
11T: impact on B1 orbit at 15 cm $\beta^*$, 7 TeV

- Not very different behavior than at injection
- About 4 times more sensitive due to smaller beam size
11T: impact on B1 orbit at 40 cm $\beta^*$, 7.5 TeV

- Computed on more recent optics with 11T in cell 9 instead of cell 8
- No major differences wrt 15 cm $\beta^*$
- (In all cases, optics is the same around P7)
Feed-down from IR1/5 triplet (295 urad xing)

15 cm \( \beta^* \)

Injection

\[ |\Delta x| \text{ [m]} \]
Feed-down from IR1/5 triplet (295 urad xing)

15 cm $\beta^*$

40 cm $\beta^*$ - 7.5 TeV
Impact of D1/D2 elements

15 cm $\beta^*$

Injection