Manchester accelerator group meeting: 26th January 2015

LHC dynamic aperture studies: Beam 1 at injection

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Manchester accelerator group meeting: 26th January 2015:

Outline

1. Introduction
2. Dynamic aperture
3. Measuring the LHC dynamic aperture
4. Simulating the LHC dynamic aperture
5. Comparison
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Introduction

- The linear dynamics of the LHC is well understood and corrected
  → new record for optics quality in colliders set in 2012

- Future limitations on the machine performance may then begin to arise from the nonlinear dynamics

- Expect understanding of the nonlinear sources in the LHC will become more important

- Motivated a number of beam-based studies of the NL LHC dynamics during Run 1
  → Features of the NL dynamics are measured & compared to simulation
  → Discrepancies of the model with the real accelerator can be identified & explanations sought
  → If specific sets of NL errors found to agree/disagree may be possible to refine the magnetic model
  → Aim to improve understanding of the LHC: operate more effectively / develop corrections

- Dynamic aperture (DA) is an important feature of the NL dynamics
  → studied at injection in LHC Run 1
Dynamic aperture

- Dynamic aperture is the boundary in phase space separating stable and unstable particle motion.
- Region of stability: volume enclosed by last connected invariant orbits in \((x, p_x, y, p_y)\) → excludes stable islands.
- Define long term DA \((D_\infty)\) as radius of hyper-sphere with same volume as stable region.
- Make equivalent definition for \(D(N)\) wrt region within which particles survive for \(N\) turns.
- \(D(N)\) can then be related to the evolution of bunch intensity:

\[
\frac{I(N)}{I(0)} = 1 - e^{\frac{D(N)^2}{2}}
\]

- DA can be measured via beam losses.
- Stable region can be examined in simulation by particle tracking → initial conditions distributed in amplitude along range of angles in the phase space → find amplitude of last stable/surviving particle after \(N\) turns.
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Dynamic aperture

- Typically the time spent in the beam process is longer practical to simulate
- Possibly also longer than practical to wait during DA measurements

**Operational cycle: Duration of the Different Phases**

(A. Mcpherson, CERN OP, LHC Beam Operation workshop - Evian 2012)

- Want to extrapolate tracking/measurements to longer times...
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Dynamic aperture

Tracking studies have shown that the evolution of DA with time can be well interpolated by an inverse logarithm scaling law

Most recently a law of the form:

\[ D(N) = D_\infty + \frac{b_0}{\left[\log(Ne^{-b_1})\right]^k} \]

has been shown to well interpolate LHC tracking data

“Analysis of possible functional forms of the scaling law for dynamic aperture as a function of time”
F.Lang et al

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Measuring the LHC dynamic aperture

To measure the dynamic aperture:

- Probe bunch (small, low intensity) blown up to larger emittance
  → excite with white noise from Transverse Damper
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Measuring the LHC dynamic aperture

- Settings of nonlinear correctors varied
- Beam loss monitored using the Beam Current Transformer

![Graph showing intensity and MCO current over time](image-url)
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Measuring the LHC dynamic aperture

- Intensity data converted to $D(N)$ in $[\sigma_{\text{beam}}]$ and fit with inverse log scaling law (left)
- Results converted to $[\sigma_{\text{nominal}}]$ (right)
  - Synchrotron radiation telescope (BSRT) gives continuous ($\sim$) passive measurement of relative changes in emittance
  - Wire-scanner data used to calibrate BSRT at start of injection
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Simulating the LHC dynamic aperture

Simulation of LHC nonlinear dynamics predominantly uses 3 codes:

  - Long term numerical tracking through thin elements LHC lattice
  - Scan initial conditions in amplitude along distinct angles in \((x, y)\)
  - Determine last stable condition for \(N\) turns to find \(D(N)\)
  - Post-processing tools recently upgraded to allow study of \(D(N)\) vs \(N\)

- **MAD-X**: [http://mad.web.cern.ch/mad/](http://mad.web.cern.ch/mad/)
  - “a general purpose accelerator and lattice design program”
  - Used for the construction of LHC model which can be passed to SIXTRACK for DA simulation

  - Tracking code and normal form analysis implemented as module within MAD-X
  - Rapid determination of nonlinear chromaticities, amplitude detuning... via PTC_normal module
  - Short term tracking studies (also thick lattice tracking / fringe fields...)

Model is developed using MAD-X & PTC module, then passed to SIXTRACK to study the DA.
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Simulating the LHC dynamic aperture

**Ingredients for the basic nonlinear LHC model:**

- Thin element “as-built” sequence
  → 2 Beam 1 MOD + 2 Beam 2 MOF lost following September 2009

- Estimates of errors in the lattice:
  → Generated by Windows Interface to Simulation Errors (WISE)
  → based on measurements of errors and uncertainties
  → Managed by the FiDeL group at CERN.

- Apply geometric errors to the lattice
  → Measured misalignments of magnets within LHC cryostats, and cryostats within LHC
  → Estimates are updated ~annually.
  → Generally small effect for nominal, but can be large for some configurations: best keep up to date

- Apply magnetic errors to the lattice
  → \((a_2, b_2)\) up to \((a_{15}, b_{15})\)
  → low current (‘warm’) measurements on all magnets at industry
  → operational (‘cold’) measurements on some magnets at CERN
  → warm-to-cold correlation introduced for magnets not measured under operational conditions
  → Estimates based on measurements + uncertainties (eg warm-to-cold correlation)
  → 60 instances (‘seeds’) of the errors used to account for the uncertainties
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Simulating the LHC dynamic aperture

- Apply extracted settings of the nonlinear correctors
  → Landau octupoles (MO), octupolar/decapolar spool pieces (MCDO), skew sextupoles (KSS)

- Sextupolar spools (MCS) more complicated:
  → $b_3$ of main dipoles decays during injection plateau: MCS settings vary to track dynamic $b_3$
  → “Decay and Snapback in Superconducting Accelerator Magnets”
    M.Haverkamp Ph.D Thesis
    http://cds.cern.ch/record/677979?ln
  → “CERN FiDel report on LHC magnetic model: Part III:”
  → dynamic $b_3$ not included in WISE inputs
  → assume perfect correction of dynamic part: use final MCS settings

- Matching of Tune ($Q$) and chromaticity ($Q'$) to measured values
  → (dedicated measurement of $Q'$)

That defines the core nonlinear model:
now want to look in more detail at some of the features of the beam dynamics
Simulating the LHC dynamic aperture

Tune:
- Conventional $Q_{x,y}$ measurements during study were low quality (blown up beams + bad day)

- **Determine tune instead from spectral analysis of injection oscillations in LHC BPMs**
  → But small amplitude + decohere after few turns
  → Spectral analysis using SUSSIX code: https://cds.cern.ch/record/702438/files/
  → SUSSIX (interpolated FFT) allows better resolution than conventional FFT
  → Optimized SVD cleaning removes noise from turn-by-turn data

<table>
<thead>
<tr>
<th>Injection</th>
<th>$Q_x$</th>
<th>STD($Q_x$)</th>
<th>$Q_y$</th>
<th>STD($Q_y$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2809379</td>
<td>0.000015</td>
<td>0.3137475</td>
<td>0.000020</td>
</tr>
<tr>
<td>2</td>
<td>0.2812401</td>
<td>0.000010</td>
<td>0.3137648</td>
<td>0.000024</td>
</tr>
<tr>
<td>3</td>
<td>0.2815280</td>
<td>0.000013</td>
<td>not found</td>
<td>not found</td>
</tr>
<tr>
<td>4</td>
<td>0.2811773</td>
<td>0.000015</td>
<td>0.3109888</td>
<td>0.000317</td>
</tr>
<tr>
<td>5</td>
<td>0.2810539</td>
<td>0.000010</td>
<td>0.3117223</td>
<td>0.000033</td>
</tr>
</tbody>
</table>

- $Q_y$ shift at Inj 4 ($0.3137 \rightarrow 0.311$) associated with recovery from machine protection dump
  → will need to be accounted for in the simulations

- See tune drifts of $\sim 5 \times 10^{-4}$ between injections: relevant for DA?
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- **Nominal model:**
  Large shifts at some angles, small impact on mean (w.r.t. angle) DA
  
  \[
  \Delta \bar{DA}_{\text{short}} = 11.8830 - 11.8962 = -0.0132 \\
  \Delta \bar{DA}_{\text{long}} = 11.1906 - 11.2548 = -0.0642
  \]

- **Very non-linear model:**
  Large shifts at some angles, small impact on mean (w.r.t. angle) DA:
  
  \[
  \Delta \bar{DA}_{\text{short}} = 10.0502 - 10.0316 = +0.0186 \\
  \Delta \bar{DA}_{\text{long}} = 8.5304 - 8.5048 = +0.0256
  \]

Don’t need to worry about drift of the base tune
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Closed Orbit (CO)

- Inclusion of geometric and magnetic errors in the lattice generates large CO
- Needs to be corrected for realistic model: two strategies
  - Mimic operational behaviour (use orbit correctors to match orbit towards zero)
  - Add virtual correctors to lattice, attempt to match orbit to measurements

Operational behaviour gives RMS CO $\sim 0.1$ mm:

![Graph showing horizontal and vertical closed orbit](image)
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Comparison to measurement suggests an over correction in the model:
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Can relax tolerances on the matching to give a better RMS in the model:

![Graph showing dynamic aperture (DA) vs. number of turns]

Suggests RMS CO on this scale has little influence on dynamic aperture
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But not just RMS: Mean CO + local bumps may be important for feed-down!

→ H orbit excursion at 15km due to broken corrector right of IP7
→ This bump accounts for ~ 30% of $Q'$ dependence on MO powering

$$
\Delta Q'_x = \frac{1}{4\pi} \left( N_{\text{MOF}} (\beta_x D_x)|_{\text{MOF}} K_4 L_{\text{MO}} (\overline{CO}_{\text{MOF}} - \overline{\Delta x}_{\text{MOF}}) 
+ N_{\text{MOD}} (\beta_x D_x)|_{\text{MOD}} K_4 L_{\text{MO}} (\overline{CO}_{\text{MOD}} - \overline{\Delta x}_{\text{MOD}}) \right)
$$

(1)

So 0.1 mm mean orbit in MO would give $\Delta Q' \sim 0.25$.

More significantly $\Delta KCO = 30$ could give $\Delta Q' \sim 2$, which is significant for DA.
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So match to the measured orbit...

- Routines developed for LHC online model to correct CO to target using virtual correctors
- Currently requires special version of MAD-X
- Works well in arcs, currently not working well in experimental insertions
- For NL model chosen to match to measured CO in arc, & zero at BPMs affect by IR bumps
- Post-correction apply the nominal IR bumps in the model
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\textbf{Beta-beat ($\Delta \beta / \beta$)}

- Linear optics quality characterized by ‘beta-beating’

\[ \Delta \beta / \beta = \frac{\beta_{\text{actual}} - \beta_{\text{nominal}}}{\beta_{\text{nominal}}} \]

- Global scale of model $\Delta \beta / \beta$ agrees well with measurements before beam-based correction

- “Beta-beating in the effective model of the LHC using PTC”
  https://cds.cern.ch/record/1397343?ln

- But: specific shape of $\Delta \beta / \beta$ around ring varies significantly between seeds
  → Typically won’t give same local shape of the beta-beat as real machine
  → Can’t just apply settings from real machine...

Can apply pre-defined correction routines for $b_2$ errors in MAD-X...
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... but they underperform relative to the applied beam-based corrections
(left shows beta-beat immediately after linear optics commissioning March 2012)

No dedicated measurements on the day: but can measured $\Delta \beta/\beta$ via injection oscillations
$\rightarrow$ seems to show increase in H beta-beat between March and June, better agreement with model
$\rightarrow$ would expect some drift, but 5% is large
$\rightarrow$ small oscillation + few turns, gives large uncertainty, no good vertical data
$\rightarrow$ also don’t see similar increase in Beam 2 or measurements later in year
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Does the beta-beat matter?

<table>
<thead>
<tr>
<th></th>
<th>Horizontal plane [%]</th>
<th>Vertical plane [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured (2012 commissioning)</td>
<td>2.2 ± 0.6</td>
<td>2.4 ± 0.7</td>
</tr>
<tr>
<td>Measured (DA studies)</td>
<td>5 ± 13</td>
<td>-</td>
</tr>
<tr>
<td>Modelled ($b_2$ on)</td>
<td>5 ± 1</td>
<td>6 ± 1</td>
</tr>
<tr>
<td>Modelled ($b_2$ off)</td>
<td>2.0 ± 0.7</td>
<td>1.9 ± 0.4</td>
</tr>
</tbody>
</table>

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How to handle beta-beat?

- Turn $b_2$ off and let feed-down give decent approximation for EMS
  → used for LHCB2 studies, but not very satisfactory

- Match beta-beat
  → but really don’t have a target & doesn’t seem very critical

- Mimic operational behaviour
  → take tracking data from 60 seeds
  → analyze with OMC software (treat each seed like single kick from beam-based study)
  → calculate ‘beam-based’ corrections for the model, using same magnets from 2012 commissioning
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**Linear coupling**
- Simulation of LHCb2 showed linear coupling to have a very large impact on nonlinear dynamics
  “Measurement of nonlinear observables in the Large Hadron Collider using kicked beams”
  https://journals.aps.org/prstab/abstract/10.1103/PhysRevSTAB.17.081002
- Measured linear coupling Resonance Driving Terms (RDT) via analysis of the injection oscillations

Uncertainty too large to see local variations
- but can estimate coupling coefficient $|C^-| \approx 4|Q_x - Q_y| \langle |f_{1001}| \rangle$
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Simulated coupling ($|\delta Q_{\text{min}}|$) much larger than measured, so some matching required

- Ideally treat coupling by local matching of $f_{1001}$. But really needs larger amplitude kicks.
- settle for global matching and estimate uncertainty
  → try to imitate operational behaviour
  → match amp and phase of $f_{1001}$ near IP1 using LHC global coupling knobs
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Coupling has a big effect on the DA!

|C| = 2 × 10^{-3}
|C| = 4 × 10^{-3}
|C| = 6 × 10^{-3}
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But want to check if tracking data makes sense wrt the measured $f_{1001}$

Restricting to cases with $f_{1001}$ inside the measured envelope have effect $< 0.5\sigma$ and $\sim 1\sigma$ for nominal and most nonlinear configurations respectively.
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**Chromaticity / $b_3$**

- Being matched in the model
- Hopefully matching of CO means feed-down correctly handled
- But: quality of local MCS corrections never checked with beam
- could influence the DA:
  M. Hayes, TOLERANCES OF THE SPOOL PIECE CORRECTION SYSTEM FOR THE LHC

**Chromatic coupling / $a_3$**

- Measured via momentum dependence of $f_{1001}$ in November 2012
- Excellent agreement found between model and measurements
  T. Persson et al, Chromatic coupling correction in the Large Hadron Collider
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**Nonlinear chromaticity ($Q''$, $Q'''$)**

- NLchroma measurements in June 2011 found large second & third order chromaticities ($Q''$, $Q'''$)

![Graph showing nonlinear chromaticity](image)

- Order of magnitude discrepancy with simulation

<table>
<thead>
<tr>
<th></th>
<th>measured $-\text{modelled}$ (10^3)</th>
<th>measured $-\text{modelled}$ (10^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta Q''_x$</td>
<td>$-1.7 \pm 0.1$</td>
<td>$-1.2 \pm 0.1$</td>
</tr>
<tr>
<td>$\Delta Q''_y$</td>
<td>$0.7 \pm 0.1$</td>
<td>$0.6 \pm 0.1$</td>
</tr>
<tr>
<td>$\Delta Q''''_x$</td>
<td>$10^6$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$\Delta Q''''_y$</td>
<td>$10^6$</td>
<td>$10^6$</td>
</tr>
</tbody>
</table>

- Checked reference measurement from MO polarity checks in November 2012
- Discrepancy was unchanged within the measurement uncertainties
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Significant contribution to $Q''$ discrepancy believed to come from MCO hysteresis
→ MCO nested within MCD so no precycle possible
→ low current at injection means MCO can have substantial hysteresis effects
→ Adjust MCO settings in model to include estimates of MCO field including hysteresis, provided by CERN FiDeL group

<table>
<thead>
<tr>
<th>Family</th>
<th>Expected field [Tm]</th>
<th>Actual field [Tm]</th>
<th>Discrepancy [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc 12</td>
<td>0.000069</td>
<td>-0.000005</td>
<td>-108</td>
</tr>
<tr>
<td>Arc 23</td>
<td>-0.000160</td>
<td>-0.000234</td>
<td>46</td>
</tr>
<tr>
<td>Arc 34</td>
<td>-0.000134</td>
<td>-0.000208</td>
<td>55</td>
</tr>
<tr>
<td>Arc 45</td>
<td>-0.000120</td>
<td>-0.000194</td>
<td>62</td>
</tr>
<tr>
<td>Arc 56</td>
<td>0.000063</td>
<td>-0.000012</td>
<td>-119</td>
</tr>
<tr>
<td>Arc 67</td>
<td>0.000088</td>
<td>0.000014</td>
<td>-84</td>
</tr>
<tr>
<td>Arc 78</td>
<td>0.000018</td>
<td>-0.000056</td>
<td>-417</td>
</tr>
<tr>
<td>Arc 81</td>
<td>-0.000139</td>
<td>-0.000214</td>
<td>53</td>
</tr>
</tbody>
</table>

→ explains $\sim 30\%$ of $Q''_x$ and $60\%$ of $Q''_y$ discrepancies
→ still leaves substantial $Q''$ and $Q'''$ discrepancies
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To match nonlinear chromaticity:
- examine unmatched $Q''$ & $Q'''$ distributions
- select seed close to center of all 4 distributions
- match NLchroma of selected seeds using PTC_normal module in matching macro
  - match $Q''$ via MCO and MO powering (limits on allowed MO trim)
  - match $Q'''$ via MCD
  - re-match $Q''$ in case of feeddown
- apply MCO, MCD, MO trims to all seeds
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This defines the limit on how well we can assess / expand upon the basic model using beam-based data.

It is worth highlighting that in LHCB2 there is known to be a significant discrepancy in the second order amplitude detuning, but there is no equivalent data available for Beam 1.

This is the model which will be passed to SIXTRACK to assess the DA, however it is first necessary to consider the required parameters for those simulations...

Need to ensure we include a sufficient number of angles in SIXTRACK to give a robust value of the DA.
Also observe differences between SIXTRACK simulations dependent on the writebinl parameter (after how many turns data is written to output)
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Fits to the simulated DA vs Turns appear to converge once sufficient number of turns at start are excluded
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Final stage of the analysis is to compare model and measurement.

Preliminary studies with basic NL-model are in the correct ballpark → but definitely something missing ($\sim 2\sigma_{\text{nominal}}$ discrepancy)!

Now waiting on results from the model including the beam-based aspects, to see if agreement improves...