Dynamic Aperture studies of FCC-hh at collision

Emilia Cruz


FCC week 2019
Does the lattice meet the stability target? $10\sigma$ @ collision

- **Impact of errors:**
  Errotables of arc magnets, triplet and separation/recombination dipoles,
  Tolerances on both

- **Efficiency of corrections:**
  Use correctors on the LHC to correct for crossing, spurious dispersion,
  nonlinearities, coupling.
  What corrections schemes can we use from LHC experience?
  Which need to be updated?
  What can we improve?
Dynamic Aperture at collision

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  Which need to be updated?

  What can we improve?

- **Challenging start:** ~0 DA… How do we got it to acceptable levels?
DA studies at Collision

- 60 seeds/10^5 turns/5 angles no beam-beam (*C. Tabasco/Beam-beam effects*)

- Field errors in triplet, separation/recombination dipole/arcs

- **Baseline Corrections**
  
  (Based on scripts of A. Chance, R. Martin, and experience LHC: R. Tomas, E. Maclean and T. Persson)

  - **Chromaticity +tune correction**
    - Crossing IPA and IPG
    - Spurious dispersion (SSC and HL-LHC like)
    - Coupling correction
    - Arc dipoles correction (*B. Dalena/ DA at injection*)
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- Tune
  - Trim quadrupoles in Long Arcs (LARs)
  - Match Horizontal and vertical tune (Qx and Qy)

- Chromaticity
  - Sextupole families in LARs (vary focussing and defocussing by same ammount)
  - Match Horizontal and vertical chromaticity (dQx and dQy) to 2 units

E. Cruz-Alaniz

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- Baseline Corrections
  - Restore crossing angle in IPA and IPG with correctors in the IR
DA studies at Collision

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A. Chance/Lattice Integration

LHC-like
Orbit bumps with kickers
DA studies at Collision

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A. Chance/Lattice Integration

LHC-like
Orbit bumps with kickers

SSC-like
Quads at ends of IR

- No differenc ein DA but SSC-like chosen for aperture reasons
DA studies at Collision

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*T. Persson/CERN*

- **Previous method:**
  - Use skew quads L/R in IRA/G (KQS4.LA/g)
  - Minimize coupling matrix at ends of IR
  - Minimized coupling but problems with MADX

- **New method:**
  - Use skew quads L/R in IRA/G
  - Calculate (and minimize) coupling directly at each matching step
DA studies at Collision

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- Measure efficiency by calculating ΔQmin
DA studies at Collision

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- Baseline Corrections
DA studies at Collision

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• DA still very low <2σ
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- DA still very low <2\sigma

- Two extra corrections were needed to provided bigger increase in DA:
  - Non-linear correctors
  - Phase Advance between main IPs
Non-linear Correctors

METHOD

- Add non-linear correctors
  - Normal and skew
  - Left and right of the IP

- Location next to third corrector

- Python script that calculates the strength to minimize Resonance Driving Terms (RDTs) from the triplet

\[
c(b_n; p, q) = \int_{IR_{\text{left}}} dsK_{n-1}(s) \beta_x^{p/2} \beta_y^{q/2} + (-1)^n \int_{IR_{\text{right}}} dxK_{n-1}(s) \beta_x^{p/2} \beta_y^{q/2},
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E. Maclean
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- Integrate into the tracking mask file with other corrections

- Calculate DA for each number of correctors

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E. Maclean

E. Cruz-Alaniz

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**LIMITATIONS**

- Maximum strengths
  - MCS : about 460 - 470 T/m^2
  - MCO : about 4000 - 4100 T/m^3
  - MCD : about 35600 - 36400 T/m^4 -- no longer achievable
  - MCT : about 315000 - 325000 T/m^5
Non-linear Correctors

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  - Assuming values of errorables, not always entirely known - more on this on results
Phase optimization

- It was found that the DA had a strong dependency on the phase between main IPs

- Change the tune correction to include this

1. Use trim quads on the “right” (IPA->IPG) to set 1st phase.
Phase optimization

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1. Use trim quads on the “right” (IPA->IPG) to set 1st phase.
2. Use trim quads on the “left” to match the tune
It was found that the DA had a strong dependency on the phase between main IPs.

Change the tune correction to include this:

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High Dependency on phase between main IPs

Vertical change shows higher change (+/- 0.1 makes a big difference) and horizontal helps optimizing it.

Locate two good ‘red’ zones. Cases with beam-beam observe dependency as well. Phase fixed so it works for both.
Phase optimization

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- Change the tune correction to include this:
  1. Use trim quads on the “right” (IPA->IPG) to set 1st phase.
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- Impact of phase advance also observed in beam-beam.

- Not necessarily same “red zones”, more drastic change with horizontal phase change.

- Found a point that works for both. This might change for newer version of lattice but (hopefully) enough flexibility allows to optimize both.

J. Barranco/ C. Tabasco
-Beam-beam effects
Results

• All errors were included in studies: arc, triplet and separation/recombination dipole errors.
• Explore different options of lattice
  - Different $\beta^*$ options ($\beta^*$=0.15, 0.2, 0.3 and 1.1 m)
  - Normal and Alternative Design
  - Round and Flat beams
  - FCC-eh
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  Check what cases are feasible
  Draw line where non-linear correctors are needed
Results - nominal case

Updates in lattice and errors in magnets
  - Lattice, dipoles in the arcs (summer 2018)
  - New erortable for arcs (sept-Oct 2018)
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Baseline Ultimate case ($\beta^*=0.3$ m)

- Increase of 2-4 $\sigma$, from previous errortable
- Dependency in phase is less than before (to be checked)
- Main result is still:
  - $DA > 10\sigma$ w/o non-linear corr
  - $DA > 20\sigma$ w/ non-linear corr
- Steady increase of non-linear corr
- Non-linear corr case is “ideal”. Check what happens when corrector strengths are off.
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- Non-linear corr case is “ideal”. Check what happens when corrector strengths are off.
- Correctors strengths were purposely off by 10%. Look for effect on DA.
- Even when correctors were off DA stays very similar.
Results - Different $\beta^*$

- Explore different options of $\beta^*$ for the baseline design ($\beta^*$=0.15, 0.2, 0.3, 1.1 m)

  \textit{R. Martin/Overview of the IR}

- $\beta^*$=1.1 m ok even w/o non-linear corr
- Increase of 5-10$\sigma$ for other cases
- Non-linear correctors crucial for acceptable DA for cases $\beta^*$=0.15 and 0.2.
- Final results w/non-linear correctors:
  - DA $> 20\sigma$ for $\beta^*$=0.3 and 1.1 m
  - DA $> 10\sigma$ for $\beta^*$=0.15 and 0.2m
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- Final results w/non-linear correctors:
  - DA $> 20\sigma$ for $\beta^*=0.3$ and 1.1 m
  - DA $> 10\sigma$ for $\beta^*=0.15$ and 0.2m
- Chromaticity for lower cases above limits of correction
Results for the alternative design for round ($\beta^*=0.3\,\text{m}$) and flat beams ($\beta^*=0.15$ and 1.2 m) \textit{L. Van Riesen/Alternative IR for FCC-hh}

- Round case ($\beta^*=0.3\,\text{m}$) really stable
  - DA=$16.4\sigma$ w/o non-linear
  - DA=$25.4\sigma$ w/ non-linear

- Flat case less table but still good DA:
  - DA=$12.2\sigma$ w/o non-linear
  - DA=$20.4\sigma$ w/ non-linear

- No tests done for other $\beta^*$. But likely to follow same principle than normal design: stable for $\beta^*=1.1\,\text{m}$ (even w/o non-linear), non-linear correctors for acceptable DA for $\beta^*=0.15$ and 0.2m.
Repeat studies for case including FCC-eh ($\beta^*=0.3m$ in IPA, IPG and IPL)

- Min DA is similar to case for FC-hh
  - DA = 11.4$\sigma$

- Similar errors were added to the new triplet (IRL) to check impact and DA stay the same
  - DA = 11.6$\sigma$
Repeat studies for case including FCC-eh ($\beta^*=0.3\text{m}$ in IPA, IPG and IPL)

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  - DA = 11.6$\sigma$

- Surprisingly when non-linear errors were added DA went down (only case when this happens)  
  - DA = 8.55$\sigma$

FCC-eh is the case where phase impacts the most, so more tests will be made with non-linear correctors.
Summary

- The **DAs at collision** including errors (but no beam-beam): $\beta^* \geq 30$ cm round beams (for both normal and alternative design) and flat beams results in:
  
  - $\text{DA} > 10\sigma$ w/o non-linear corr
  - $\text{DA} > 20\sigma$ w/ non-linear corr

- The case for **FCC-eh has also $>10\sigma$** w/o non-linear correctors (even when mock errors are implemented in the new IR), but the case with non-linear correctors needs to be checked.

- The most challenging cases of $\beta^* = 15$ and 20 cm results in a $\text{DA} > 10\sigma$ but only when **non-linear correctors** are included. **Chromaticity correction** needs to be addressed.

- **Use of non-linear correctors recommended.** Just about necessary for ultimate case but they do offer steady increase (even when not correcting 100%) and also they become necessary if ones wishes to push the beta* below 0.3 m.

- In the case of **compatibility with beam-beam**, a phase between main IPs was found that worked for both. This errortable seems to have a less dependency on the phase so its likely that a new phase can be found that works for both if the current one doesn’t work.