Dynamic Aperture studies for LHeC and FCC-eh

Emilia Cruz-Alaniz

Special thanks to: R. Tomas, R. Martin and B. Parker

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DA and Status of Lattices

LHeC

- Based on HL-LHC lattice (round optics $\beta^*=15$ cm in IR1 and IR5)
- New low-$\beta^*$ IR (IR2)
- ATS-scheme implemented in 3 low-$\beta^*$ IRs
- Previous DA studies were implemented for different IR options
- Update: Studies with errors in IR1/IR5 magnets and new magnet design for IR2

FCC-eh

- Based on FCC-hh lattice ($\beta^*=30$ cm in IRA and IRG)
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- Update: Implement same techniques for FCC-eh
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LHeC IR Optics

**CDR Default design**

- $\beta^*=10$ cm and $L^*=10$ m
  - $\beta^*$ to achieve luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$
  - Shorter $L^*$ to reduce chromaticity

- **New IR2 magnets** with field-free region (S. Russenschuck)

- Low $\beta^*$ achieved with extended ATS on IR2
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**Explore flexibility of design**

- **Increase $L^*$**: To minimize synchrotron radiation. Higher chromaticity
  - Cases: $L^* = 10$-20 m and $\beta^*$ fixed at 10 cm.

- **Minimize $\beta^*$**: Increase Luminosity (in particular $\beta^* = 5\ \text{cm/ } 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$). Higher chromaticity
  - Cases: $L^* = 5$-10, 20 cm and $L^*$ fixed at 10 m.
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**Chromaticity correction**

- Previous method: Allow all families to vary independently
- Updated method: Allow ATS families vary independently while non-ATS families vary by same amount.
- Chromaticity correction achieved for almost all cases. However case for $\beta^* = 5$cm seems to be over the limit of chromaticity correction.
DA studies

- DA studies: $10^5$ turns, 60 seeds, 5 angles, collision energy.
- Errors in the arcs but NOT in the new IRs: IR1, IR5 and IR2. (Error tables for IR1 and IR5 were on-going work at the time)
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$\beta^*=5 \text{ cm}$ looks challenging (no chrom correction)
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L* = 15 m looks very similar than L* = 10 m

B* = 5 cm looks challenging (no chrom correction)

**Conclusion:** Change default to L* = 15 m, B* = 10 cm

- Optics and chromaticity correction achievable
- Much better for magnet design and SR
- Little impact on DA
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**Following work**

- Repeat previous DA studies with errors in IR1 and IR5.
  - Same conclusion? (L*=15 m best compromise?)
- Validate new default with magnet design/aperture/SR (problems with present design)
  - DA with errors on IR1 and IR5 for **new design**, compare to old design
- Impact on **lowering B***
- Impact of **non-linear correctors**. Necessary?
• Study impact on DA with studies with errors in HL triplet and check if L*=15 m is still a good option.

• $10^5$ turns, 60 seeds, 5 angles, collision energy and errors in arcs.

• No errors: Decrease with L* but DA with L*=15 m and L*=10 m looks very similar.
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• Errors on IR1/IR5: Dominant effect for all cases. All similar DA of ~ 5\sigma.
DA for different $L^*$

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- Non-linear correctors: Increase DA for all cases. Following same pattern no errors case: $L^*$=10 and $L^*$=15 m very similar.
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- Non-linear correctors: Increase DA for all cases. Following same pattern no errors case: $L^*=10$ and $L^*=15$ m very similar

- Studies with HL errors and non-linear correctors show again that $L^*=15$ m is a good option with very similar min DA values than for $L^*=10$ m.
- Non-linear correctors necessary to achieve an acceptable DA.
NEW IR

- **Main motivation:** Validate $L^*=15$ m with new magnet design

- **Magnet design**
  - B. Parker Latest Developments and Progress on the IR magnet design

- **Aperture validation and integration of lattice**
  - R. Martin Progress with FCC-eh IR design and SR load

- **Chromaticity correction and beam4 lattice for DA studies**
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- **Errors**: arc and **HL IR errors**

- **Use of non-linear correctors**

- Some changes but **min DA basically the same (~12σ)**
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New design show acceptable DA with the use of non-linear correctors

Studies for previous lattices with errors on HL IR, although not validated with magnet design, give a good indication of how the DA would look like.
New IR with errors

- Estimate impact of triplet errors and non-linear correctors in LHeC IR
  -> No LHeC triplet error tables yet but use HL error tables as an estimate and implement them in the LHeC IR triplet
  -> Install $a_3/b_3/a_4/b_4/b_6$ correctors in LHeC IR
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  - Errors: arcs+HL+LHeC
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- Errors: arcs+HL+LHeC
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- Impact of LHeC IR errors but DA (just about) acceptable with non-linear correctors
- HL non-linear correctors but more iteration for LHeC non-linear correctors to be done.
New IR with errors

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How about the case for lower $\beta^*$?
Lower $\beta^*$

- Using previous result (lattices without magnet validation give a good DA indication) implement these on lattices with lower $\beta^*$
- Cases are not validated by magnet design and cases still have $L^*=10$ m.
- $10^5$ turns, 60 seeds, 5 angles, collision energy and errors in arcs.
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- Impact of LHeC triplet errors. Decrease with beta$^*$ although not very large.
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- Errors on IR1/IR5 and non-linear correctors: Very similar results for different $\beta^*$ (DA ~12 $\sigma$).
- Impact of LHeC triplet errors. Decrease with beta* although not very large.

- Larger DA for new triplet. (Even with $L^*=15$ m and others $L^*=10$ m)

- Decrease on DA with lower $\beta^*$, although not large.
  - New triplet works slightly better with errors.
  - Biggest challenge for lower $\beta^*$ likely to start instead from elsewhere: optics matching/ aperture, magnet design and chromaticity correction.
DA studies FCC-hh

- DA studies have been performed for FCC-hh studies
- 60 seeds/$10^5$ turns/5 angles no beam-beam
- Errors on arcs and IR magnets

- Corrections
  - Chrom+tune correction
  - Spurious dispersion (SSC and HL-LHC like)
  - Crossing IPA and IPG
  - Coupling correction

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**Main corrections**

- Non-linear correctors show steady increase:

- Phase between main IPs have a major impact on DA
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- Results for different $\beta^*$ options and impact of main corrections
  - DA of 10.6 $\sigma$ with phase optimization and no non-linear correctors
  - Large DA 19.7 $\sigma$ for default case ($\beta^*$=30 cm) with phase optimization and non-linear correction
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- Impact of FCC-eh: new low-β* of 30 cm in IRL. No errors yet on new IR

- DA of 10.6 σ with phase optimization and no non-linear correctors
  - 9.5 σ for FCC-eh

- Large DA 19.7 σ for default case (β*=30 cm) with phase optimization and non-linear correction
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  - 9.5 σ for FCC-eh

- Large DA 19.7 σ for default case (β*=30 cm) with phase optimization and non-linear correction
  - 13.4 σ for FCC-eh

- Acceptable DA with phase optimization. Increased DA with non-linear correctors
- Non-linear correctors are necessary in case errors on IRL have an impact.
Conclusions

LHeC

- A new IR design for the case $L^*=15 \text{ m}$ and $\beta^*=10 \text{ cm}$ has been made with validation of magnet design and benefits on SR. Chromaticity correction is achievable.

- New design shows a DA of $12\sigma$ including errors and non-linear correctors on HL. **Acceptable DA but only with the use of non-linear correctors on HL IR.**

- DA with an estimation on LHeC errors (using HL errortables) lowers the DA to $9.4\sigma$. Non-linear correctors crucial for HL IR and useful for LHeC IR. More iterations to be tested.

- Studies for lower $\beta^*$ (lattices with no magnet validation and $L^*=10\text{ m}$) show DA decreases when adding LHeC errors, but real **challenge** might come from somewhere else (chromaticity correction). Good news: new triplet shows better results for DA.

FCC-eh

- DA studies for the FCC-hh show that an acceptable DA of $10.6 \sigma$ was obtained with phase optimization but a bigger increase up to $19.7 \sigma$ was obtained with non-linear correctors.

- When including FCC-eh IR results without non-linear correctors show a similar value of $9.5 \sigma$, and an increase up to $13.4 \sigma$ was obtained when including non-linear correctors. **Non-linear correctors are therefore necessary** to ensure an acceptable DA in case error in LHeC IR affect the DA.