Experimental Interaction Region Optics for the High Energy LHC

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**Experimental Interaction Region**

- Need a new triplet for the final focus
  - 😕 More rigid beam
  - 😥 Increase in debris
  - 😃 FCC NbSn technology

- Separation dipoles
  - 😕 More rigid beam
  - 😥 Less space
  - 😃 FCC NbSn technology

- Space for crab cavities

- Matching section
  - 😕 More rigid beam
  - 😥 Has to fit in LHC tunnel
Algorithm

Set total length and fix required beam stay clear, $\beta^*$, $L^*$, gaps and shielding

- Initially 10 mm shielding
  
  FCC Week 2017

- $\bar{\epsilon} = 2.5 \, \mu m$, $\beta^* = 25 \, cm$

- 12 $\sigma$ Beam stay clear
  - $12 \times 1.5 = 18\sigma$ to consider crossing
Algorithm

Set total length and fix required beam stay clear, $\beta^*$, $L^*$, gaps and shielding

Use fast FOM to scan large range in parameter space

Determine sensible range $g \pm 0.005$, $l_4 \sim 2\% + 8\%$

Use PyMadX for small scan of accurate beam stay clear using current shielding ($12 \times 25$ resolution)

Find setup with largest beam stay clear

If beam stay clear larger than required

Plot ideal setup and output lengths + strengths
Optics-FLUKA interaction

- Set required $\beta^*$, $L^*$ and use initial shielding
- Use code to find shortest setup with good beam stay clear
- Use this setup for radiation studies of triplet
- Change shielding accordingly
- Work out shielding required for this setup

Integrate and match into machine for further studies

J. Abelleira
New Triplet

- Overall 8.2 m longer than HL-LHC Triplet
- Study resulted in triplet with 2 cm shielding
  - Talk by J. Abelleira
- Overall 8.2 m longer than HL-LHC Triplet
- Study resulted in triplet with 2 cm shielding
- $\beta^* = 25 \text{ cm}$
- $\theta/2 = 131 \mu\text{rad}$
- $14\sigma$ aperture
- Potentially much more shielding in Q1
- Larger crossing might be needed
  - $\theta/2 = 180 \mu\text{rad}$ possible
  - $\theta/2 = 210 \mu\text{rad}$ with 1.8 mm shielding in Q3
  - See talk by T. Pieloni
• Less space for separation than LHC due to triplet
  – 205 mm vs. 194 mm
• Larger separation than LHC
  – 205 mm vs. 194 mm
• D1 – Single aperture
  – Superconducting
  – 140 mm aperture
  – 11 T (challenging)
• D2 – Double aperture
  – Superconducting
  – 70 mm aperture
  – 7 T
Crab Cavities

- Currently space reserved between D2 and Q4
  - Adapted from HL LHC
  - Shares space with orbit corrector
  - 11 m space in front of correctors

- $\beta$ functions in this space
  - $\beta_x = 7750 \rightarrow 14360 \text{ m}$
  - $\beta_y = 4260 \rightarrow 5260 \text{ m}$

- Taking $\beta = 4500 \text{ m}$, $\beta^* = 0.25 \text{ m}$ and 130$\mu$rad crossing
  - Voltage = 6.3 MV
  - Compared to 6 MV in HL LHC

- Larger angle needs more voltage
  - See talk by T. Pieloni
Matching to Arc

- **Optics Matching**
  - Increase length of first four matching quadrupoles

- **Chromaticity correction**
  - Need to optimise this phase
  - $\pi/2 \, [\pi]$ phase from IP to sextupoles
  - $\pi/4$ between sextupoles

- **Challenging – compromise**
  - Match to second sextupole only

\[
\begin{align*}
\mu_x &= \frac{\pi}{2} \left[ \pi \right] \\
\mu_y &= \frac{\pi}{2} \left[ \pi \right]
\end{align*}
\]
Matching to Arc

• Lack of flexibility in Dispersion suppressor
  – Geometry fixed from LEP
  – TWIS constrained by arc

• Very dependant on rest of lattice including DS
  – Worked in V0.2
  – Currently no solution in V0.3
  – See talk by R. Tomas on lattice versions
Injection Optics

- HL LHC injection optics has $\beta^* = 11 \, \text{m}$
  - Use this as provisional baseline
  - Using $12\sigma$ separation
  - This gives $> 12 \sigma$ N1 in triplet
- Limit $\beta$ to 275 m – like arcs
  - Could face similar aperture problems
  - Potentially same 450 GeV beam as LHC
  - Smaller beam screen aperture
Dynamic Aperture with Triplet Errors

- Using V0.2
- Errors scaled from FCC
- Added errors one by one
  - No errors for reference
  - Added a3/b3 errors
  - Added a4/b4 errors
  - Included all errors

E. Cruz, M. Crouch
Dynamic Aperture with Triplet Errors

- Using V0.2
- Errors scaled from FCC
- Added errors one by one
  - No errors for reference
  - Added a3/b3 errors
  - Added a4/b4 errors
  - Included all errors
- Non-linear correctors
  - Package behind triplets
  - $b_3$ using $c(b_3; 1, 2)$ & $c(b_3; 2, 1)$
  - $a_3$ using $c(a_3; 3, 0)$ & $c(a_3; 0, 3)$

E. Cruz, M. Crouch
Dynamic Aperture with Triplet Errors

- Using V0.2
- Errors scaled from FCC
- Added errors one by one
  - No errors for reference
  - Added $a_3/b_3$ errors
  - Added $a_4/b_4$ errors
  - Included all errors
- Non-linear correctors
  - Package behind triplets
    - $b_3$ using $c(b_3; 1, 2)$ & $c(b_3; 2, 1)$
    - $a_3$ using $c(a_3; 3, 0)$ & $c(a_3; 0, 3)$
- Added crossing angle

E. Cruz, M. Crouch
Dynamic Aperture with Triplet Errors

- **Double tuning approach**
  - Vary phase between EIRs
  - Big impact in FCC
    - E. Cruz, Dynamic aperture at collision
  - Done using arcs

- **Coupling correction**
  - Using skew quadrupoles
  - Match $R_{11} = R_{12} = R_{21} = R_{22} = 0$ at both ends of EIR

- Increases DA to $6.4\sigma$
  - No other errors added yet
  - Need to further increase
IR4 and Tuning

• Doubled space for RF cavities
• Added another pair of quadrupoles for tuning

P. Mirave
IR4 and Tuning

• Doubled space for RF cavities
• Added another pair of quadrupoles for tuning
  – Allows one to change phase advance
  – No beating in cavities
• Doubled space for RF cavities
• Added another pair of quadrupoles for tuning
  – Allows one to change phase advance
  – No beating in cavities
• Large range of phase advance
  – Can be used as handle to increase DA
  – Aim to implement something similar in IR6
Conclusion

- Experimental IR first design iteration complete
  - Triplet optimisation
  - Separation and crab schemes
  - Further work needed on matching and dispersion suppressor

- Dynamic aperture studies with triplet errors
  - Non-linear correctors
  - Double tuning and coupling correction
  - $6.4\sigma$ achieved

- IR4 optimised for HE-LHC and tune change
Thank you!
Backup
**Triplet Optimisation**

- **Parameters affecting triplet beam stay clear**
  - $\uparrow$ Gradient = $\downarrow$ Aperture
  - Individual magnet lengths
  - $\beta$ functions in magnets
- **Scan parameter space**
  - Fixed length triplet
  - Find triplet with largest beam stay clear
  - Thin lens scan first
  - Then precise MADX scan