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Optics Matching Studies

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Many thanks to K. Oide, J. Dilly and Optics Tuning Team

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FCC-ee Z Parameters

- We would like to report on two studies, I´ve been working on:
    - re-matching the baseline lattice with systematic b2 errors in dipoles
    - start the design of a lattice based on HTS combined function magnets
- For our first studies, we focused on the Z mode lattice, which has the most challenging optics due to lowest beta*.

	FCCee_z_530_nosol_23 Oide-san sequence
Length [m]	91174.117
Horizontal tune	214.260
Vertical tune	214.380
Beta*x [mm]	99
Beta*y [mm]	0.8
Horizontal Natural Chromaticity	-481.842
Vertical Natural Chromaticity	-3041.692
Horizontal Chromaticity	-1.165
Vertical Chromaticity	-1.911
Dispersion_{max} [m]	0.624

- **Baseline lattice with b2 errors in dipoles**
- HTS combined function magnets lattice

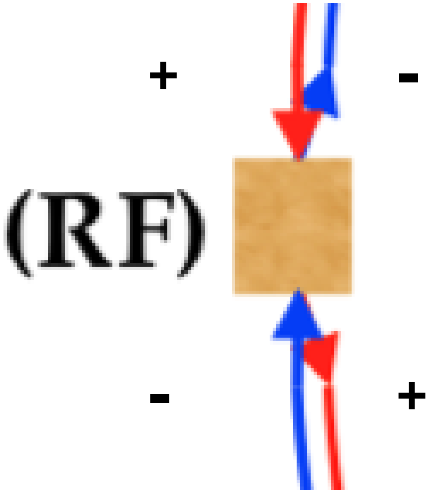
Systematic b2 error in Dipoles

- The magnet design team predicts a **systematic quadrupolar error "b2"** in the arc dipoles.

- "b2" means the normalized term for the quadrupolar error in the dipole with a specific radius **expressed in units of 10^{-4}**, not in Tesla, the estimate from magnets is 4 units.

- The sign of the quadrupolar error depends on whether the beam is on the inside or outside aperture of the dipoles but has the same magnitude in both cases.
- The beams cross in the IPs and the Intermediate Straight Sections (ISSs), moving from the inside to the outside of the ring or vice versa. Therefore the sign of the quadrupolar error depends on the arc in which the dipole is located.

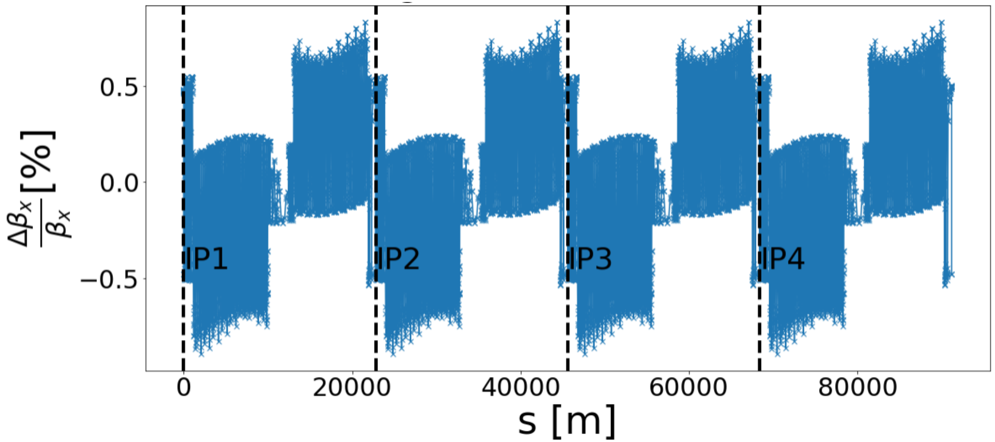
- What is it the maximum the b2 errors to get a beta beating of 1%?



Impact on the Optics

- To obtain a beta-beating of 1%, several values of b2 were reviewed, 1.6×10^{-4} gives said value.
- Apart from the change of tune, we can also look at the **change in beta function** due to the b2 errors.
- The horizontal and vertical tune changes 1.0×10^{-2} and 7.6×10^{-3} respectively.
- Integrate the errors in the lattice is possible with the matching function.

$$\frac{\Delta\beta_X}{\beta_X} = \frac{\beta_{X error} - \beta_{X ideal}}{\beta_{X ideal}}$$



- https://indico.cern.ch/event/1167740/

Matching with MAD-X

- ➔ Small beta beating is tolerable in arcs but unwanted in the insertion regions.
  - ◆ Wrong beta functions and dispersion leaking into the IP would reduce Luminosity.
  - ◆ It is important to recover baseline optics in these region to maintain the initial parameters.
- ➔ This can be done using matching in MAD-X[1], using quadrupoles close to the Arc-IR interface
  - ◆ The matching with errors and the design for a new lattice are based to minimizing the differences of optical function with respect to the baseline design by Oide-san (the ideal lattice for this study).

[1] https://madx.web.cern.ch/madx/

Symmetry in FCC-ee to do matching

- 8 Interest Region (IR)
  - 4 Interaction Point (IP)
  - 4 Intermediate Straight Section (ISS)
- 8 ARC
  - 17 super-FODO cells/ARC
  - 24 FODO cells remaining

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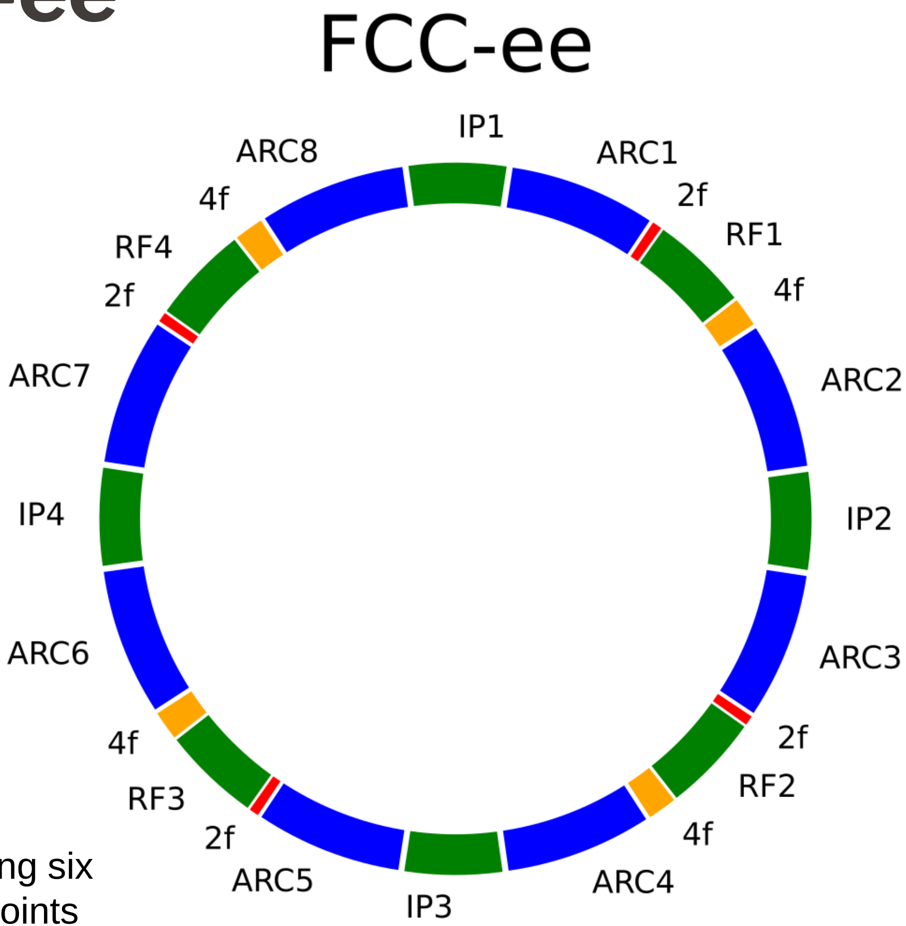
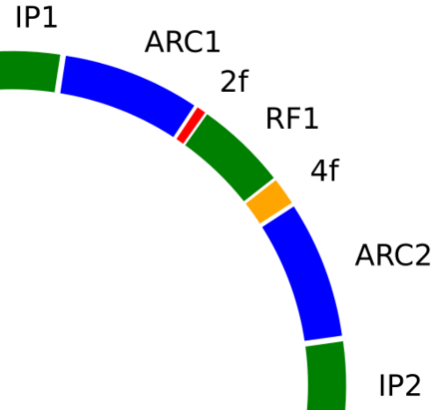
704 FODO cells in total



Speed up calculations using ¼ of ring due to the symmetry to do Matching



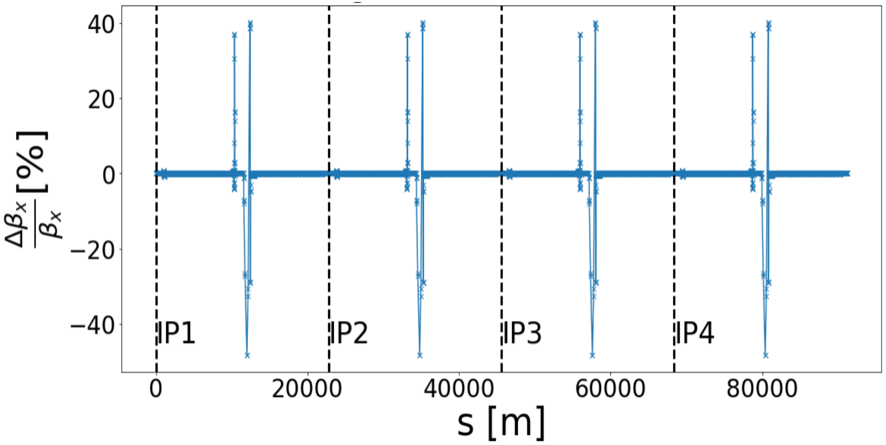
We are using six matching points

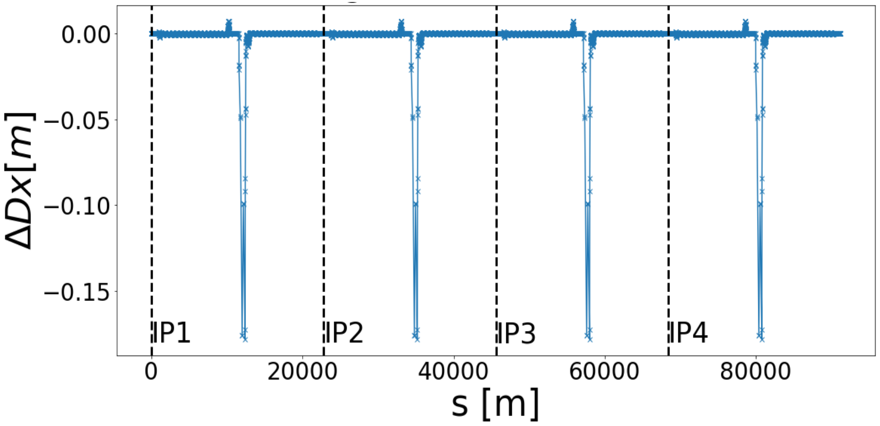
Results of Matching

- ➔ After the matching, the original tunes are recovered.
- ➔ The β* in the horizontal and vertical planes are also the same as before.
- ➔ Further analysis showed that β-beating is below 0.75% in the arcs but peaks in the ISSs. There is not a problem as there are no IPs in these regions.

$$\Delta D_x = D_{xerror} - D_{xideal}$$

- ➔ There is a change in the maximum dispersion in the intermediate straight sections. So it does not compromise the initial parameters for the IPs.





Results of Matching

- Matching was used to recover the:
  - The correct phase advance in the arcs (and the horizontal and vertical betatron tunes).
  - The periodic behaviour in the IPs.
- b2 errors in the lattices can be absorbed

Parameters	Ideal Lattice	Lattice with b2 errors	Lattice after the Matching
Horizontal tune	214.260	214.259	214.260
Vertical tune	214.380	214.379	214.380
Beta*x [mm]	99	99	99
Beta*y [mm]	0.8	0.79	0.8
Horizontal Chromaticity	-1.165	-0.986	-0.945
Vertical Chromaticity	-1.911	-3.461	-2.796
$Dispersion_{max}$ [m]	0.624	0.632	0.787

- Baseline lattice with b2 errors in dipoles
- **HTS combined function magnets lattice**

Combined Function Magnets

- Combined Function magnets[1,2] (CF) make it possible to increase the Filling Factor (FF), in order to reduce the Synchrotron Radiation
  - When introducing **CF** the total **bending angle (θ)** of the dipoles is now split among dipoles and quadrupoles, hence increasing the **bending radius** (**ρ**).

$$\rho = \frac{L}{\theta}$$

- Many other potential benefits from combined function magnets from discussing with colleagues (Oide-San and others)
  - More regular FODO cells
  - Better/Easier alignment
  - More effective corrections
  - Maybe less power consumption when using HTS

[1] Juchno, M. Magnetic Model of the CERN Proton Synchrotron Main Magnetic Unit. (2011), https://cds.cern.ch/record/1407908
[2] Meng, W. & Tanaka, M. Three dimensional field analysis for the AGS combined function magnets. Proceedings Of International Conference On Particle Accelerators. pp. 2907-2909 vol.4 (1993)

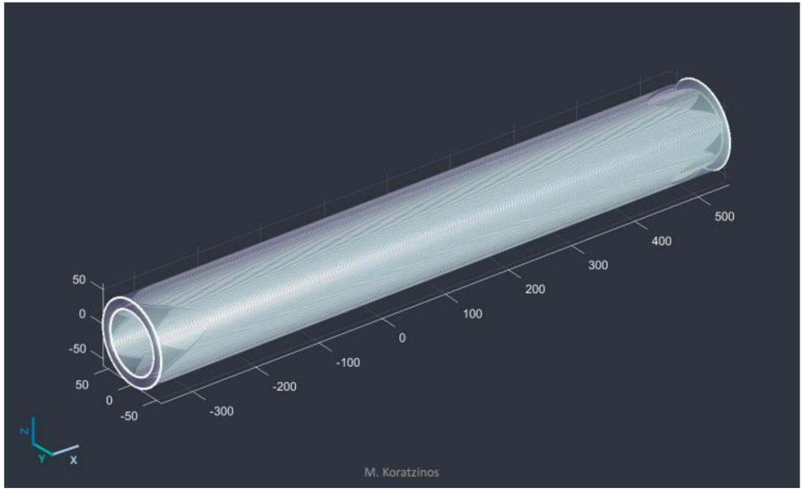
HTS Combined Function Magnets

- → Combined function magnets proposed by M. Koratzinos[1] use High Temperature Superconductors **(HTS).**

- → A project exist at PSI to explore HTS[2] Combined Function (CF) magnets for the FCC-ee.

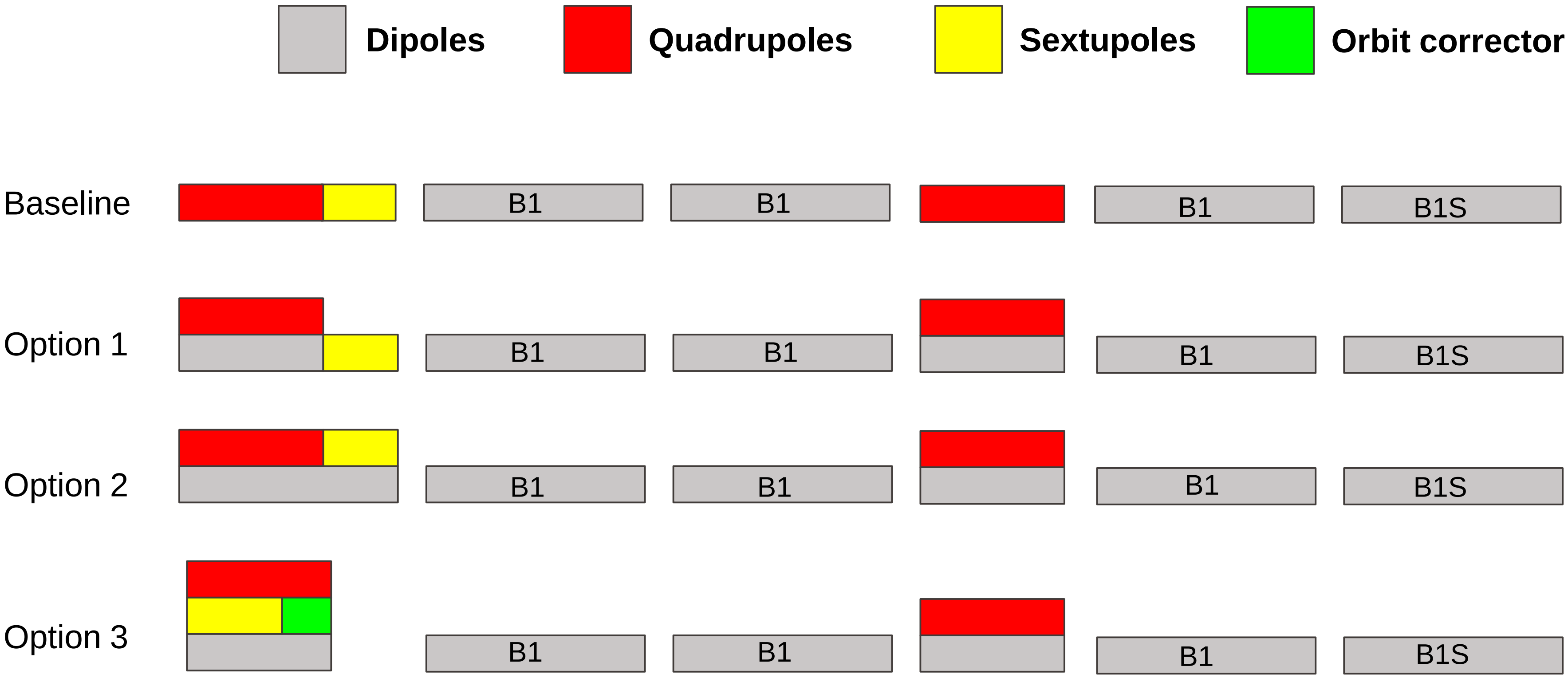
- → Our studies will allow estimating the first tolerances in the components of the magnetic errors to provide feedback to the designers.

Assembly: sextupole



- [1]https://indico.cern.ch/event/1118297/
[2]https://www.psi.ch/en/science/scientific-highlights/stronger-magnets-faster-particles-new-physics

FODO Cells with Combined Function Magnets



Lattice with Combined Functions Magnets

- Option 1) Split the total bending angle of dipoles in dipoles+quadrupoles with CF
  - We take in consider the super FODO cell as the reference for the bending angle
  - The total sum of bending angle in the super FODO cell with CF is the same

- Option 2) Split the total bending angle in dipoles+quadrupoles+sextupoles
  - The bending angle for the quadrupoles and sextupoles is the same
  - The total sum of bending angle for the dipoles, quadrupoles and sextupoles is the same as the beginning.
  - The sextupoles has only dipolar component.

- Option 3) Split the total bending angle in dipoles+quadrupoles+sextupoles and the quadrupole strength in quadrupoles and sextupoles
  - To have three layers the quadrupolar component in the sextupoles and the sextupolar component in quadrupoles is added. Only in the quads next to sextupoles.
  - Best option for alignment and corrections

Synchrotron Radiation for Z-mode

- ➔ The **decrease in synchrotron radiation** for **Option 1** thanks to the increase in bending radius is quantifiable by means of the energy loss per turn.

- ➔ A reduction of 6.4% was achieved in the **4 modes** for the FCC-ee.

- ➔ This reduction **could increase** a bit more if the **combined function** could be **applied to sextupoles (Option 2)** and then obtain a FF of 74.14%**.**

- ➔ There is the possibility of putting a dipole at the location of the tt quadrupoles, that would actually double the 6%.

Parameter	FCC-ee current lattice	FCC-ee with CF (Option 1)
Circumference [m] C_0	91,174.11	91,174.11
Bending radius [m] ρ	9,936.69	10,618.09
Filling Factor (FF)	68.47%	73.17%
E [GeV]	45.6	45.6
I beam [mA]	1400	1400
SR power / beam [MW]	53.88 ➔	50.43 **(-6.4%)**

Lattice with Combined Functions Magnets

- The new θ will be obtained splitting the sum of all dipoles in the super-FODO cell (because there are three types of them) and the distribution is not regular.

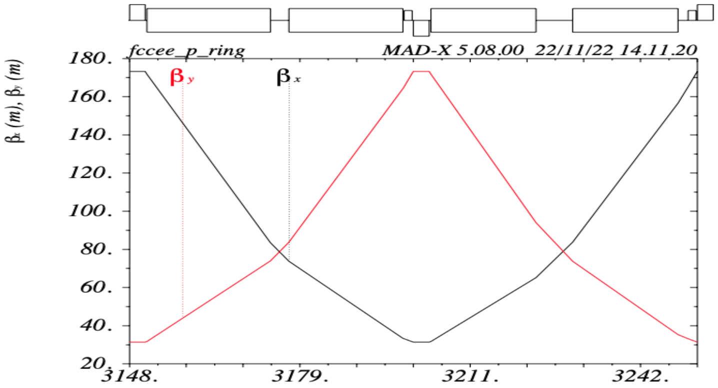
- To the sum of the length of the dipoles (in the super-FODO cell) is added the 10X length quadrupole (2 for each FODO cell), obtaining:

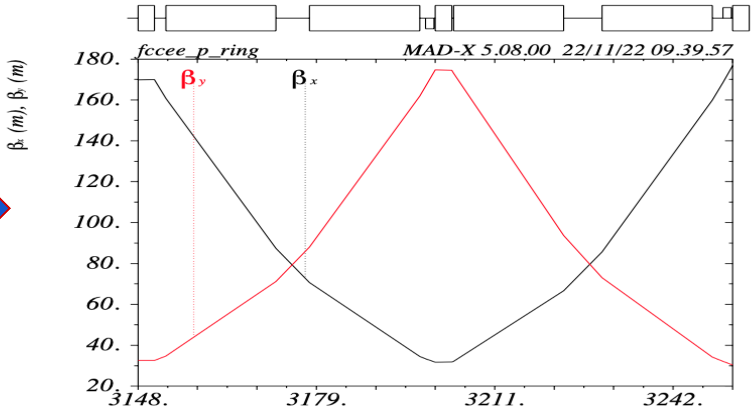
Dipolar component	Normal magnets [radians]	Combined Functions [radians]	Length [m]
θ Dipole B1	0.00227	0.00213	22.65
θ Dipole B1S	0.00194	0.00181	19.30
θ Dipole B1L	0.00210	0.00197	20.95
θ Quadrupole	0	0.00027	2.9

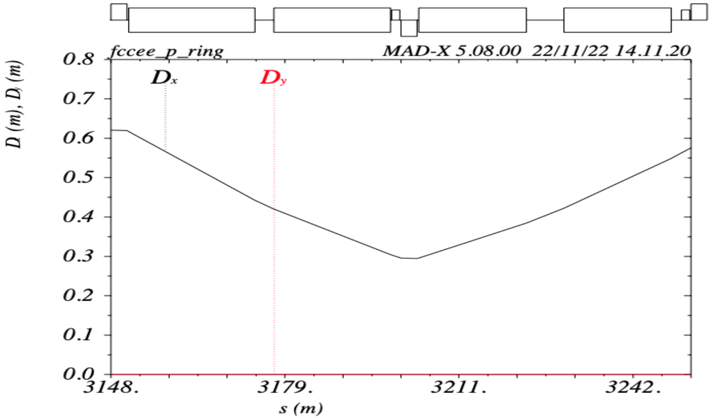
FCC-ee_Z Parameters from MADX	Lattice with normal magnets	Lattice CF (Option 1)
Length [m]	91174.117	91174.117
Horizontal tune	214.260	214.260
Vertical tune	214.380	214.379
Beta*x [mm]	99	99
Beta*y [mm]	0.8	0.8
Horizontal Chromaticity	-1.165	-0.824
Vertical Chromaticity	-1.911	-2.446
$Dispersion_{max}$ [m]	0.624	0.634

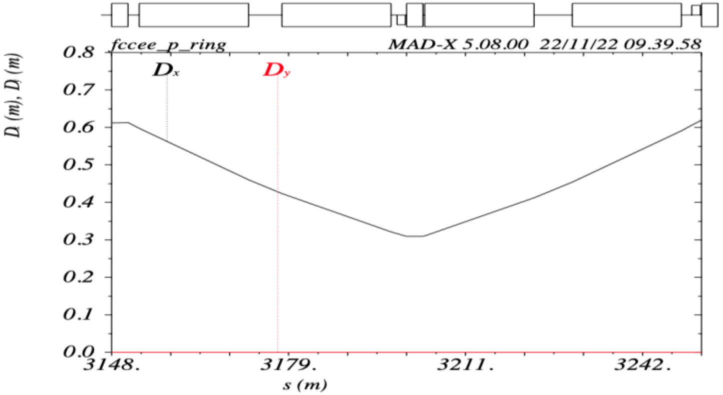
New Lattice with Combined Functions Magnets

➔ Option 1) Quadrupoles are replaced by elements with a quadrupole and dipole component in the same object. In this way we have a combined function magnet effect for the simulations:



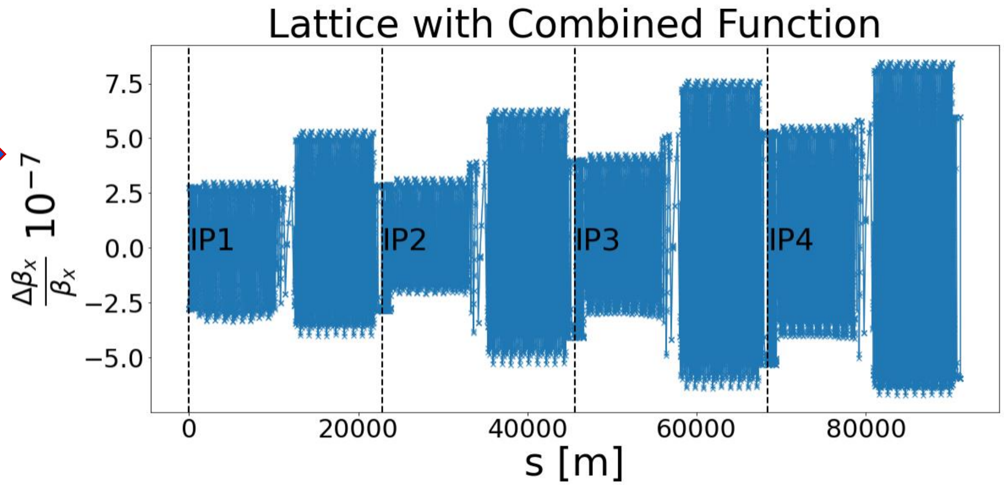






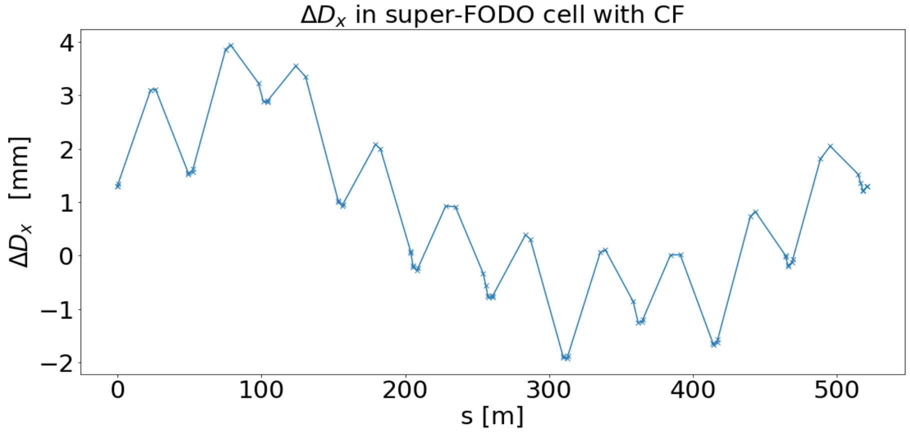
Optical Functions in HTS CF Lattice

- Beta-beating with the lattice with Combined Functions in the quadrupoles taking as reference the lattice with normal magnets.



- The beta-beating is very close to 0%, indicating that the discrepancy between the two lattices is very small.

- The average dispersion has increased by ~1 mm.



Emittance with Combined Function Magnets

	Baseline	Option 1	Option 1 (modified)
Horizontal tune	214.260	214.260	214.260
Vertical tune	214.380	214.380	214.380
Horizontal Chromaticity	-1.165	-1.165	-1.165
Vertical Chromaticity	-1.911	-1.911	-1.911
$\text{Dispersion}_{\text{max}}$ [m]	0.624	0.634	0.634
Emittances [pi micro m]	0.33E-06	-0.36E-06	0.10E-04
J_x, J_y, J_E	0.999&1.00 2.00	-0.866&1.00 3.86	0.031& 0.999 2.968
I4 / I2	0/0.00064	0.00110/0.0006 0	0.00058/0.00061

- Obtain unphysical "negative" emittances with this new lattice using EMIT module
- Due to negative horizontal partition number (no damping)

$$\epsilon_u = C_q \frac{\gamma^2}{J_u} \frac{\mathcal{I}_{5u}}{\mathcal{I}_2},$$

  - Large I4 integral due to quadrupole field overlapping with dipole

$$J_u = 1 - \frac{I_4}{I_2}$$

$$I_4 = \oint \frac{D}{\rho} \left(2k + \frac{1}{\rho^2} \right) ds$$

- Need to develop strategies improve partition number
  - E.g by changing bending radius in CF magnets
    - First iteration performed

Conclusions and Outlook

- First look at lattice with b2 errors
  - Showed that if we allow for 1% beta-beating, we can tolerate 1.6 units of b2
    - Arc/IR optics rematching can absorb the b2 errors with very similar properties to baseline
- Next step to explore b2 systematic errors of 4 units in dipoles
  - Predicted by magnet design team
  - Generates above 2% beta-beating
  - Validate if this can be absorbed by lattice

- First steps in lattice design using HTS combined function magnets
  - One option explored
    - Further options in the close future
  - 6% decrease in synchrotron radiation
    - Perhaps further with other option or if tt-bar quadrupole slots used for Z
  - Minor perturbation of most optical functions
- Observe negative horizontal partition number
  - Unacceptable emittance
  - Studies for solutions under way
    - e.g. adjust bending radius in quadrupoles

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Many thanks!