EXPLORING FCC-ee OPTICS DESIGNS WITH COMBINED FUNCTION MAGNETS

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Abstract. The FCC-ee project takes a step forward towards the discovery of new physical phenomena beyond the frontier of the standard model, by aiming at unprecedented center of mass energies and luminosities in a double-ring lepton collider. In order to explore potential improvements to the current lattice design, this paper examines the use of combined function magnets within the short straight sections of the arc cells. The use of High Temperature Superconductors (HTS) with an operating temperature of 12 K and maximum field of 18.2 T for the combined function magnets allows increasing the bending radius and decreasing the synchrotron radiation. A first design is presented with comparisons to the current baseline.

1. INTRODUCTION

The FCC-ee project considers a double-ring lepton collider with a circumference of 91 km to achieve the right conditions for the discovery of new physical phenomena beyond the current frontier established by the standard model. To achieve this, different concepts and designs for the construction and operation of the machine are being explored. The FCC-ee will have 4 modes of operation: Z pole, WW, (Z)H and tt threshold [1, 2]. The energy range will go from 45.6 GeV for Z-mode to 182.5 GeV in tt-mode.

2. COMBINED FUNCTION MAGNETS

This paper explores the use of Combined Function Magnets (CFMs) for lattice design [3] to reduce Synchrotron Radiation (SR). SR is the electromagnetic radiation emitted by a charged particle beam when bent. The total energy loss per turn per particle is given by [4]:

$$U_0 = \frac{e^2}{3\epsilon_0}\frac{\beta^3\gamma^4}{\rho}\,, \tag{1}$$

$$U_0[eV] = 2.65\times 10^4 E^3[GeV]B[T], \tag{2}$$

where e is the charge of the electron, ϵ_0 is the permittivity of vacuum, ρ is the bending radius of the circular collider, β and γ are the relativistic factors, E is the beam energy and B is the magnetic field in dipoles. Therefore the SR power loss per beam in MW is proportional to γ^4/ρ.

The main motivation for using CFMs in an optics design for FCC-ee is the increase in filling factor (FF), defined as the percentage of the accelerator filled by dipole magnets. This will result in an increase of the bending radius with a consequent reduction of the synchrotron radiation power loss. Finally, this would result in a net power savings during FCC-ee operation.

When using CFMs, a quadrupolar magnetic component is superimposed on a dipolar one. CFMs have been previously used in many particle accelerators such as the Proton Synchrotron (PS) at CERN, the ALBA in Spain, the Alternating Gradient Synchrotron (AGS) at the Brookhaven National Laboratory in USA [5] and FCC-hh at CERN [6]. Typically, arc dipoles have a quadrupolar field to minimize the length needed for quadrupole magnets. However, in the FCC-ee a novel proposal that utilizes High Temperature Superconductors (HTS) has been put forward [7, 8] to replace the lattice quadrupoles with CFMs, while employing normal conducting magnets for the arc dipoles with only dipolar field. Nevertheless, it is possible to explore the optical solution suggested later in this paper for normal conducting CFMs as well. The FCC-ee collider is designed using elementary FODO cells made by a focusing quadrupole (QF), one or two main dipole magnets (B1), depending on the operational mode (Z-mode or tt-mode), a defocusing quadrupole magnet (QD) and again one or two dipole magnets (B1) as illustrated in Figure 1. In a first study on the Z-mode optics, the total bending angle of the baseline FODO cell, corresponding to the sum of the four dipoles (B1), was distributed among four dipoles and two new CFMs containing quadrupolar components with bending angle (θ_{QF} and θ_{QD}). Figure 1 illustrates the new FODO structures for the Z and tt runs of FCC-ee compared to the baseline design. In the CFMs solutions, Bf and Bd correspond to the field of the dipolar components in the quadrupole magnets.

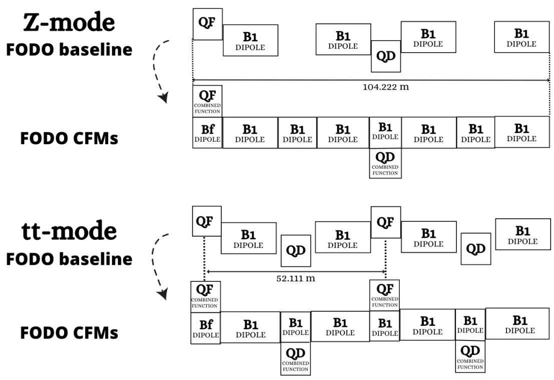

Figure 1. The diagrams show a comparison between the CFMs-based FODO cells for the Z and tt operation modes and the baseline design. Bf reresent the dipolar component in the CF focusing quadrupole, B1 is the dipolar component in the CF defocusing quadrupole and main dipoles.

However, implementing an equal dipolar magnetic field in the quadrupoles with CFMs leads to an unstable lattice due to increased synchrotron radiation in these quadrupoles and the change in the Damping Partition Numbers (DPNs). Therefore, alternative schemes involving unbalanced dipolar strengths in the two quadrupole magnets had to be investigated. In more detail, it can be observed the relationship between the Radiation Integrals I_2, I_4, and I_5 with the equilibrium emitance, ϵ_u, the DPNs, J_u, and the damping time, τ_u [9]:

$$I_2 = \oint \frac{1}{\rho^2} ds, \quad I_4 = \oint \frac{D_x}{\rho}\left(2\,k_1 + \frac{1}{\rho^2}\right) ds, \quad I_5 = \oint \frac{\mathcal{H}(s)}{\rho^3} ds, \quad J_u = 1 - \frac{I_4}{I_2}, \quad \epsilon_u = C_q \frac{\gamma^2}{J_u}\frac{I_{5u}}{I_2}, \quad \tau_u = \frac{2E}{J_u U_0} T_0$$

where D_x is the Dispersion function, k_1 is the quadrupole gradient, E is the beam energy, U_0 is the energy loss per turn, T_0 is one revolution time and C_q is a constant equal to 3.832×10^{-13} m.

When CFMs are introduced into the lattice, the DPNs change due to the introduction of a dipolar component in the quadrupoles, with a direct impact on I_4, that depends on the sign of k_1. As I_2 is positive and depends only on ρ, it is necessary to obtain a negative or very small I_4 such that J_u remains positive. With this in mind, the impact on the equilibrium beam emittance for the Z lattice was scanned versus the ratio $\frac{\theta_{QF}}{\theta_{QD}}$. In Figure 2 the equilibrium emittance normalized to the baseline lattice value is shown as a function of the ratio between the bending angle in the quadrupoles with CFMs. For larger ratios, calculations have shown that there is no stable solution. To maintain the baseline equilibrium emittance for the lattice and similar partition numbers (red dashed line), it is necessary to set the ratio between $\frac{\theta_{QF}}{\theta_{QD}}$ at 0.537. Table 1 displays the necessary magnetic field strengths for both the baseline and CFMs lattices to obtain same equilibrium emittances.

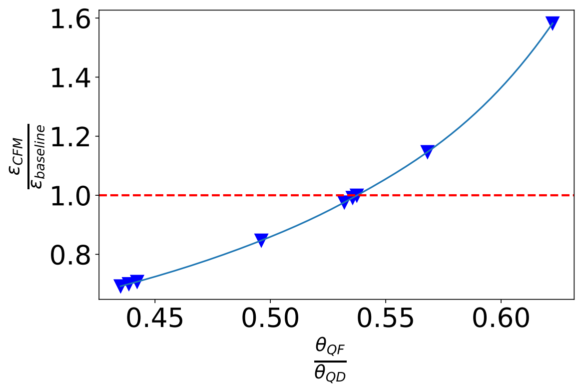

Figure 2. The ratio between CFMs and baseline equilibrium emittances calculated using MAD-X [10] versus the ratio of the bending angles in QF and QD.

Table 1. The magnetic field strengths for the baseline and CFM cell in the Z mode are shown. It is worth noting that the B1 field in the default configuration is associated with the longer arc dipole in the FCC-ee lattice.

Magnetic field & gradient	**Baseline**	**CFM**	**length [m]**
B1	0.0137 T	0.0113 T	22.65
Bf	0	0.0060 T	2.9
Quad F	1.306 T/m		2.9
Quad D	-1.306 T/m		2.9

With the values obtained for the magnetic field and bending angle for the CFMs, the new lattice was implemented. The reduction achieved in U_0 is around 17.22%, as shown in Table 2.

Table 2. The changes in the DPNs and damping times can be observed as a consequence of the implementation of CFMs to the Z-mode lattice. A reduction of 17.22% in the U_0 is also observed.

	Baseline	**CFM**
Length [m]	91174.117	91174.117
$D_{x_{\max}}$ [m]	0.634	0.679
U_0 [MeV/turn]	39.06	32.33
ϵ_x [nm]	0.705	0.705
Damping times[s]	0.709 0.709 0.354	1.041 0.857 0.394
J_x	1.000	0.823
J_y	1.000	0.999
J_z	1.999	2.176

To ensure an appropriate behaviour of the optical functions in the lattice, it is neccesary to match the k_1 for the quadrupoles QG, QH, QU, QRDR, QI, QL, QB, QF4, QF2, QD3, and QD1 located in the IRs, Intermediate Straight Sections (ISS) and the arcs. This can be achieved using the matching function on MAD-X. The deviation between this new lattice and the baseline can be quantified through the β-beating function, defined as

$$\frac{\Delta\beta}{\beta} = \frac{\beta_{\text{CFMs}} - \beta_{\text{baseline}}}{\beta_{\text{baseline}}} , \tag{3}$$

where β_{CFMs} is the β-function for the CFMs lattice and β_{baseline} is the original one. A maximum β-beating of about 20% is observed in the intermediate straight sections and therefore will not affect the machine performance, see Fig 3. In the arcs the β-beating is below 1%.

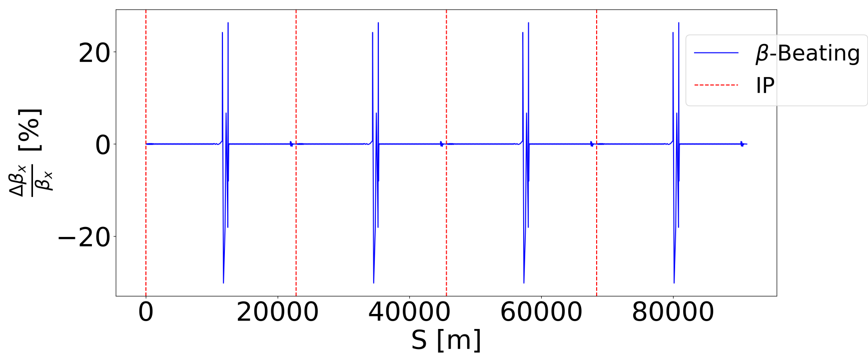

Figure 3. β-beating along the collider lenght for the CFMs lattice versus the baseline.

2.1. Layout of the CFMs lattice

The FCC-ee twin quadrupole magnets for the e^+ and e^- apertures have opposite polarity. In the CFM cell this implies a different bending angle for the two counter-rotating beams at the location of the quadrupoles (QF and QD), resulting in slight differences in the layouts. This should be carefully evaluated and taken into account for the final ring and magnet designs. In a first approach, the super-FODO cell structure consisting of 5 FODOs was taken into account to analyze the behavior of the separation between the two beams. The maximum change (peak-to-peak) is found to be 3 mm between the $e+$ and $e-$ layouts for the Z-mode using CFMs, see Fig. 4.

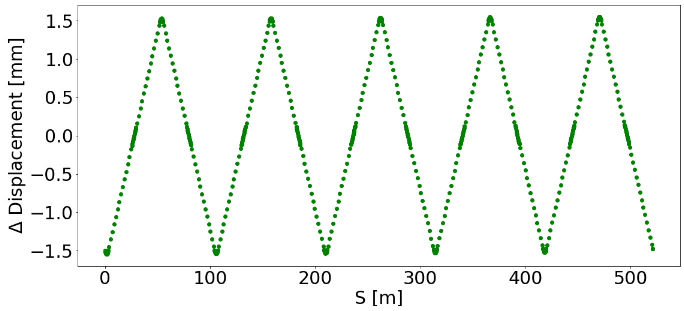

Figure 4. Fluctuation of the beam separation between the e^+ & e^- layouts for the Z-mode (the length of one FODO cell is 104.22 m).

In the same way, the use of CFMs for the tt lattice was scanned, obtaining a similar bending angle ratio (0.547) to match the baseline equilibrium emittance, despite the fact that the length of the FODO cell for this layout is half (52.11 m), see Fig. 5.

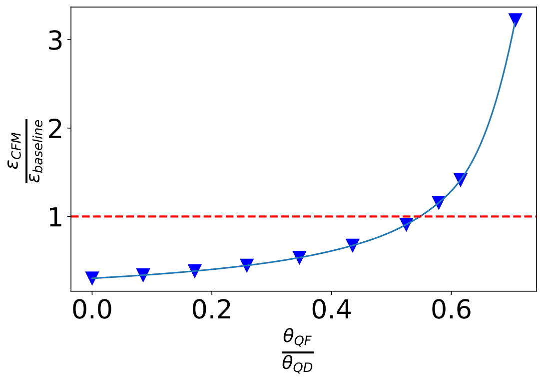

Figure 5. Emittance ratio for tt lattice with similar results than for the Z lattice in Fig. 2.

The e^+ and e^- beams separation in the tt-mode is shown inFig. 6. The peak-to-peak deviation is found to be 1.5 mm, half that for the Z-mode.

These layout differences between the different lattices represent a significant challenge for the magnet design or for the collider operation. Mitigations as including quadrupolar components in the the main dipoles, as proposed in [1, 11], or increasing the arc quadrupole length should be explored.

3. CONCLUSIONS

We have demonstrated that it is conceptually possible to use CFMs in the FCC-ee arc quadrupoles to increase the dipole bending radius and hence decrease the SR power. Yet, the dipole fields in the quadrupoles affect the partition numbers and must be introduced with a ratio of about 0.5 between the focusing and the defocusing CFMs. This yields a reduction in the SR power of about 17.22% for the Z-mode and 16.79% for the tt-mode. This bending angle

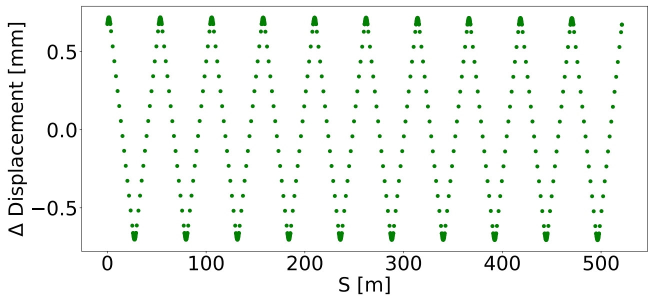

Figure 6. Fluctuation of the beam separation between the e^+ & e^- layouts for the tt-mode (the length of one FODO cell is 52.11 m).

ratio introduces a variation in the e^+ and e^- beams separation in the order of few mm that represents a significant challenge in the magnet design or in the collider operation. Mitigations as including quadrupolar components in the the main dipoles or increasing the arc quadrupole length should be explored.

Once practical solutions are found to implement the CFMs in the FCC-ee both superconducting and normal conducting designs should be explored and compared in terms of power consumption and operational efficiency. The impact on optics tuning performance will also need to be studied [12, 13].

4. ACKNOWLEDGMENTS

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