15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR10

# FIRST FCC-ee LATTICE DESIGNS WITH NESTED MAGNETS

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## *Abstract*

The Future Circular Electron-Positron Collider (FCC-ee) represents a cutting-edge particle physics facility designed to further investigate the $Z^0$, W± and Higgs boson in addition to the top quark. The implementation of Nested Magnets (NMs) in the FCC-ee arc cells would maintain high luminosity and reduce its energy consumption. The use of these special magnets induces changes in the damping partition numbers. To mitigate this the dipole fields in focusing and defocusing quadrupoles have to be different. This solution gives rise to incompatibility problems for the machine layout between the different energy configurations as the optics is also changed. This problem is tackled by defining different bending and geometric angles for the NMs. The beam dynamics and performance aspects of the new lattice are studied in this paper.

## INTRODUCTION

The FCC-ee project aims to achieve unprecedented challenges in a single design: four experiments with a large amount of energy for a lepton collider (ranging from 45.6 GeV for the so called Z-mode to 182.5 GeV for the so called ttbar-mode) and high luminosity. With its nearly 91 km circumference, it aims to reach the conditions for the search of new physical phenomena beyond the standard model elucidated by the discovery of the Higgs Boson.

Although there are four operational energies explored involved in this new project [1], only two lattices are required since the lower energies share an optical design and the higher energies share another one. Therefore, it boils down to just the so called Z and ttbar mode lattices.

In a first attempt the use of combined function magnets (CFMs) was explored for the FCC-ee [2]. Such solution could have been applied making use of normal or superconducting technologies. After more detailed studies, the current proposal is to make use of Nested Magnets (NMs) [3,4] based on high temperature superconductors. We have not fully excluded CFMs option with normal conductors, although it is clearly more challenging to tune. The idea of introducing CFM and/or NM comes from the opportunity to apply a dipolar component all along the available space in the arcs, thereby increasing the bending radius ($\rho$). Since the energy loss per turn ($U_0$) due to Synchrotron Radiation (SR) is proportional to the fourth power of the beam energy and inversely proportional to bending radius this alternative will result in a much reduced synchrotron radiation power loss as evaluated in [2].

One of the most important parameters for the design of the FCC-ee is the SR power limited to 50 MW per beam for each of the energy modes [1]. Therefore, as the energy increases in the different energies, the beam current decreases to maintain this loss constant. With the present proposal, the aim is to reduce the SR power, which results in two outcomes: either a saving in the operational consumption or an increase in the available beam current, leading to an increased in integrated luminosity. Table 1 shows this in detail.

Table 1: The different operation modes have varying energy loss per turn and, consequently, different beam currents to fix the SR power per beam at 50 MW at the four operational modes.

| | $Z^0$ | WW | H(ZH) | ttbar |
|---|---|---|---|---|
| Beam Energy [GeV] | 45.6 | 80 | 120 | 182.5 |
| Baseline beam current [mA] | 1280 | 135 | 26.7 | 5.00 |
| Improved beam current [mA] | 1488.41 | 156.98 | 31.08 | 5.82 |

## THE USE OF NESTED MAGNETS IN FCC-ee

To get the baseline equilibrium emittance through the use of NMs and similar partition numbers, it is necessary to set a different dipolar strengths in the two quadrupole magnets, Focusing Quadrupole (QF) and Defocusing Quadrupole (QD) [2]. This gives rise to an incompatibility problem for the layout between the Z and tt configurations.

The simplest way to address this issue is to take the tt lattice as a reference and apply a different distribution of the geometric angle in the main dipoles (B1) and the quadrupole QF in the Z lattice. Geometric angle is the chosen angle from the reference trajectory. This action will result in a horizontal displacement between the two lattices, which can be quantified as observed in Fig. 1. Finally, by realigning the QF quadrupoles (moving them by 1.5 mm), we could restore the ideal orbit as in the ttbar lattice. We will refer to this as the realigned lattice or mechanical solution, achieved through the mechanical movement of the magnets.

The actual bending from the magnetic field is called bending angle. Usually, the bending and geometric angle are the same, meaning it is an orbit centered on the magnets. Particles pass through the center, which eliminates the need for additional alignment of the magnets when switching between operation modes. However, in a scenario where the magnets corresponding to the QF and QD have different dipolar components, this implies that the trajectory will be slightly

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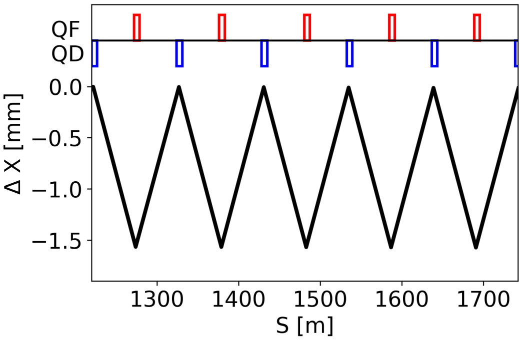

Figure 1: Displacement between lattices Z and tt ($X_Z - X_{tt}$) in the arcs. This difference could be addressed by realignment of the quadrupoles for the tt mode operation. This realignment should be around 1.5 mm for the QF.

different. Since the Z and tt modes do not share the same layout for the FODO cells due to the different length, we have defined that the magnets will have the same geometric angle (according to our solution for the nominal emittance, see Fig. 2), to correct this discrepancy. Additionally, Z will have a design off-center orbit through the definition of the bending angle (K0 in MAD-X [5]). In this case, the offset is within the range of 2mm, see Fig. 3, which can be tolerated by defining the appropriate physical aperture (PA).

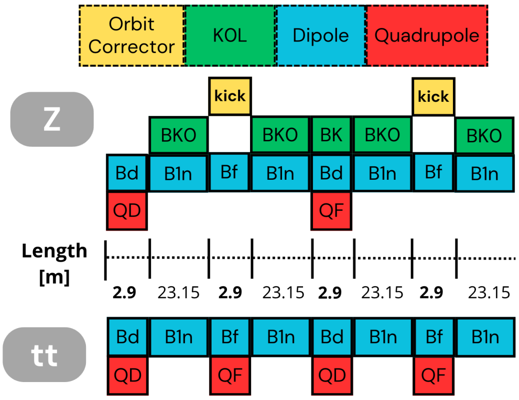

Figure 2: Taking the tt lattice as a reference, we observe that the dipolar component (represented by the geometric angle in blue) will be the same for both. However, the bending angle (K0L in MAD-X and depicted in green in the sketch) will be different to adjust the orbit and achieve a closed orbit solution. Additionally, two kickers in the Z lattice located at the position where the tt quadrupoles go will be used. The values (in mrad) for the different dipolar components are: B1n=1.94 for the main dipoles, Bd=0.24 & Bf=0.12 for quadrupoles, BK0=1.97 & BK=0.11 for the bending angle and the orbit corrector of Kick=0.16.

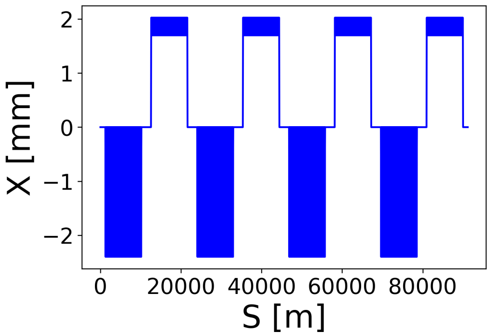

Figure 3: The non-centered orbit in the Z lattice due to the definition of a bending angle different from the geometric one. This orbit excursion is periodic, so the lattice performance is stable.

### *Performance of the Lattices with NMs and Non-centered Orbit*

We are considering 3 lattices with NMs, the first one called tt NMs, is obtained from the baseline by uniformly distributing the bending angles over the arc cells and it is used as a reference for the Z lattices with NMs. For Z with NMs, two options are being explored: the first one involves a mechanical realignment of the magnets following the layout change from the optimization of bending angles in the quadrupoles (Z NMs realignment), and the second one, which avoids the magnet realignment by allowing a non-zero closed orbit (Z NMs K0). This is achieved by defining different bending (K0) and geometric ($\theta$) angles in MAD-X.

To analyze the performance of these lattices compared to the baseline, the $\beta$-beating function was employed, defined as (1):

$$\frac{\Delta\beta}{\beta} = \frac{\beta_{\text{NMs}} - \beta_{\text{baseline}}}{\beta_{\text{baseline}}}, \qquad (1)$$

where $\beta_{\text{NMs}}$ is the new $\beta$-function for the NMs lattice and $\beta_{\text{baseline}}$ is the nominal one.

Within the arcs, the beta-beating for the $X$ and $Y$ planes is less than 1%, see Fig. 4, indicating that a behavior very similar to the original has been achieved. In addition, the horizontal and vertical phases for Z NMs realignment show an offset from zero that should be revised in more detail. The horizontal dispersion exhibits small variances with respect to the baseline, around 6%.

Table 2 shows the maximum dispersion values as well as the radiation integrals along with the emittance and damping times for the alternative options and the baselines. For the energy-dependent functions ($U_0$, $\epsilon$, and Damping Times), the values obtained from the MAD-X Emit module were scaled according to the Equation (2).

$$\frac{\gamma_2^2}{\gamma_1^2}\epsilon_1 = \epsilon_2, \quad \frac{\gamma_2^4}{\gamma_1^4}U_{0_1} = U_{0_2}, \quad \frac{\frac{2\gamma_2}{U_{0_2}}}{\frac{2\gamma_1}{U_{0_1}}}\tau_{u_1} = \tau_{u_2} \qquad (2)$$

Table 2: Overview of the different solutions for the Z and tt lattices with NMs, including optical and synchrotron radiation properties. The values for the tt lattice were scaled according to the gamma factor using the equations in (2). For the $\epsilon_y$ are considered the values found in [6].

| | **Z Baseline** | **Z NMs Realignment** | **Z NMs K0** | **tt Baseline** | **tt NMs** |
|---|---|---|---|---|---|
| $D_{x_{\max}}$ [m] | 0.634 | 0.638 | 0.722 | 0.559 | 0.559 |
| $I_2$ [$10^{-4}$] | 6.417 | 5.372 | 5.367 | 6.40 | 5.35 |
| $I_5$ [$10^{-10}$] | 1.484 | 1.027 | 1.101 | 0.194 | 0.138 |
| $U_0$ [MeV/turn] | 39.06 | 32.70 | 32.69 | 9994.85 | 8353.07 |
| $\epsilon_x$ [nm] | 0.705 | 0.605 | 0.500 | 1.478 | 1.388 |
| $\epsilon_y$ [pm] | 1.42 | 1.42 | 1.42 | 2.98 | 2.98 |
| Damping times[s] | 0.709 | 0.880 | 0.675 | 0.0110 | 0.0146 |
| | 0.709 | 0.848 | 0.847 | 0.0110 | 0.0132 |
| | 0.354 | 0.416 | 0.486 | 0.0055 | 0.0063 |
| $J_x$ | 1.000 | 0.963 | 1.255 | 0.999 | 0.903 |
| $J_y$ | 1.000 | 1.000 | 1.001 | 1.000 | 1.000 |
| $J_z$ | 1.999 | 2.036 | 1.745 | 2.000 | 2.096 |

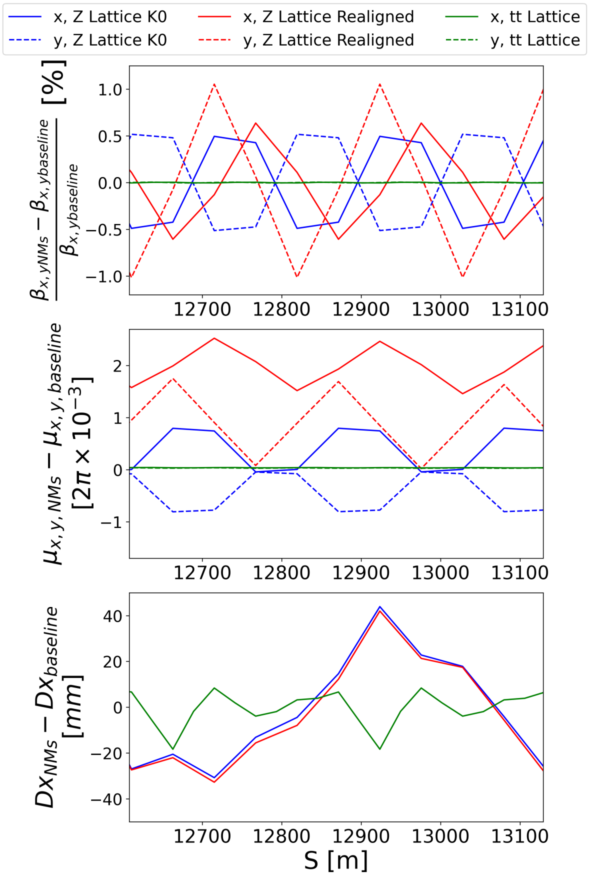

Figure 4: $\beta$-beating in percentage, phase advance ($\mu$) for both planes in $2\pi \times 10^{-3}$ and horizontal Dispersion ($Dx$) in mm along 5-FODO cells in FCC-ee for the various lattice configurations.

## CONCLUSION

We have demonstrated that a complete and stable design using NMs in the arcs of the FCC-ee is feasible, providing three solutions for the two required lattices of the project. These solutions show a decrease in SR power and equilibrium beam emittance. In all lattices, we achieve a 16% reduction in energy loss per turn. For $\epsilon_x$ in Z, reductions of 14% and 29% are achieved, while for tt, we have a decrease of 6%.

The possibility of increasing the beam current while maintaining the same limit of SR power allows for an enhancement of the integrated luminosity. The decrease in equilibrium emittance can allow a reduction of intensities relaxing collective effects while keeping luminosity constant.

The effect on the performance of optics tuning will require examination [7].

## ACKNOWLEDGEMENTS

The authors would like to thank Katsunobu Oide for his endless and insightful comments. This study is supported by the Swiss Accelerator Research and Technology (CHART). This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 945363, EPFLglobaLeaders.

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