PARAMETER SPACE FOR THE MAGNETIC DESIGN OF NESTED MAGNETS IN THE FCC-ee ARC CELL

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Abstract

The Future Circular Collider (FCC-ee) is designed to explore the Z^0 and W± bosons, along with the Higgs boson and top quark, achieving exceptionally high luminosity. In order to minimize the energy lost per turn due to Synchrotron Radiation (SR) we explore the use of Nested Magnets (NMs) into the arcs cell. For this, it is necessary to explore the possible combinations of the different magnet types in the cell, namely: dipoles, quadrupoles and sextupoles. Specifications in terms of strength and alignment tolerances are reviewed in this paper.

INTRODUCTION TO FCC-ee

In circular synchrotron-type accelerators, the energy that can be achieved is limited by the size of the accelerator and the maximum available bending magnetic field. In synchrotrons of leptons, the limit is the synchrotron radiation power.

For the FCC-ee, the plan is to have a circumference of around 91 km and achieve 4 energies, namely, 45.6 GeV (Z^0), 80 GeV (WW), 120 GeV (H(ZH)) and 182.5 GeV (tt) for different experiments [1]. For the above configurations a bending field of less 1 T is required to keep the electrons and positrons on orbit along the circumference with a maximum synchrotron radiation power loss of 50 MW/beam at all energies. In this paper we will describe the magnet requirements for an alternative lattice configuration designed to reduce the synchrotron radiation power loss by around 17% that makes use of the NMs in High temperature Superconductor (HTS). The smallest unit necessary to transport a bunch of particles through a synchrotron-type accelerator is called a FODO cell, consisting in a pair of quadrupole magnets with alternating polarity (Focusing and Defocusing) with one or more dipole magnets in between. This alternating gradient sequence guarantees net focusing. The dipoles bend the particles on a reference circular orbit, the quadrupoles maintain particles trajectories confined around a reference orbit, and the sextupoles correct the natural chromaticity created by the quadrupoles.

For the baseline design of the FCC-ee [1], a structure made of 5 slightly different FODO cells that repeats itself in the arcs. In this super-FODO cell, we will have two pairs of non-interleaved sextupoles with a phase advance of π between the pairs [2]. For further detail, refer to Fig. 1 where the super FODO cell layout is sketched for the Z and tt scenarios.

THE FCC-ee SEEN FROM THE NESTED MAGNETS

In previous efforts, the use of magnets that have dipolar, quadrupolar and sextupolar components was explored as an alternative to the current baseline design of the FCC-ee [3]. An up-date of the alternative optics for the arcs can be found in [4]. The design using a dipolar field into the other magnets in the arcs increase the filling factor and reduces the energy loss per turn attributable to SR. Studies have shown a net reduction of 17% [3]. In Figure 2 the alternative layout is sketched assuming the use of High Temperature Superconducting nested magnets, where the electrical currents feeding the different functions in this magnet are independent. This provides greater freedom to change the strengths of the magnets between the different operating modes (and levels of energy).

Three solutions for the entire lattice with NMs were found in [4, 5], including a solution for the Z lattice that reacquires a mismatch between the geometric and magnetic layout, resulting in a non-zero orbit, which is obtained by adjusting the strength value for the dipolar component, see Fig. 2.

Dipoles

The final values for the magnetic fields and gradients are shown in detail in Table 1 and Table 2 . To achieve this, we transitioned from having 3 families of main dipoles (B1, B1S, and B1L) to just one (B1CF), thereby reducing the periodic solution for the arcs from a super-FODO cell of 5 units to just 2 for the compatibility between Z and tt lattices. The magnetic fields of the new dipole components in the NMs are at least 15% lower than in the baseline. This directly affects the electrical current required for their operation and reduce the SR power.

Quadrupoles

The gradient of the quadrupoles in both lattices is maintained compared to the nominal, while ensuring the preservation of the 90° phase advance of the FODO cells. In the case of tt, we have twice the number of FODOs because the length of each one is half that in Z. It is also for this reason that we have double the number of quadrupoles, which remain off when the low-energy lattice is used.

Sextupoles

For sextupoles, the number of families (75 and 146) and their distribution is respected in both lattices compared with the baseline lattices, to avoid disturbing the Dynamic

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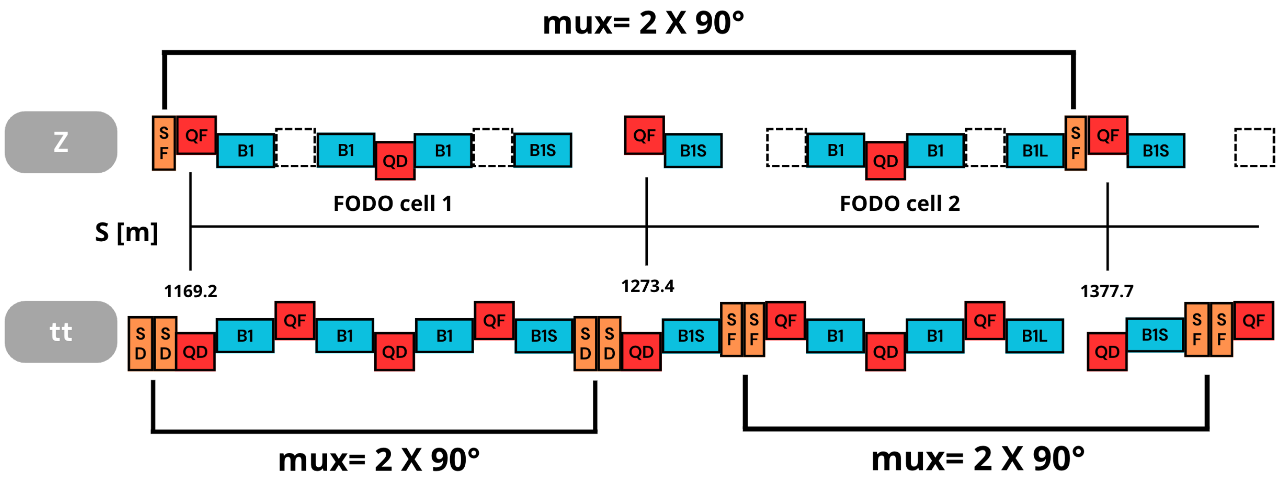

Figure 1: Part of the super-FODO cell showing the structure of the internal FODOs and the arrangement of the the magnets and in particular the pairs of sextupoles. The main dipoles are the same for both lattices, while the quadrupoles can alternate polarity due to the different design of the FODO cells (half length for the tt design). This diagram does not take into account the drift spaces present in the lattice.

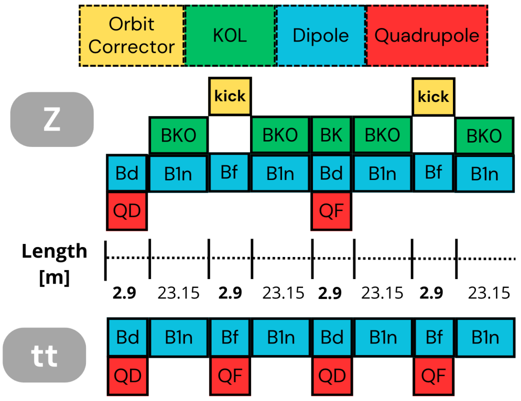

Figure 2: Adjustments in the Z and tt lattices were made to implement the NMs in the FCC-ee. This involved introducing a non-zero orbit in the Z mode with a different magnetic field called K0L in MADX. This prevents realignment of the magnets when transitioning between operating modes. Additionally, a 29% reduction in emittance for Z was achieved [4].

Aperture (DA) [5]. The only difference lies in their implementation into the NMs. With two options available, the first one nests the sextupolar component within the nearest quadrupole, see Fig. 3, which itself contains a dipolar component, or simply at the original position but adding a dipole to it. In the first case for Z the magnet's strength is renormalized since the length has changed from 1.5 m to 2.9 m, as the quadrupoles are longer. From the optics design perspective, both options adhere to the required parameters, and having two options allows greater freedom for optimizing the required DA. The bottom half of the Table 1 and 2 generally shows a decrease in the gradients of the sextupole families. This occurs because they become more effective, given that the peaks of the β-function (and the main chromatic aberrations) are located at the quadrupoles.

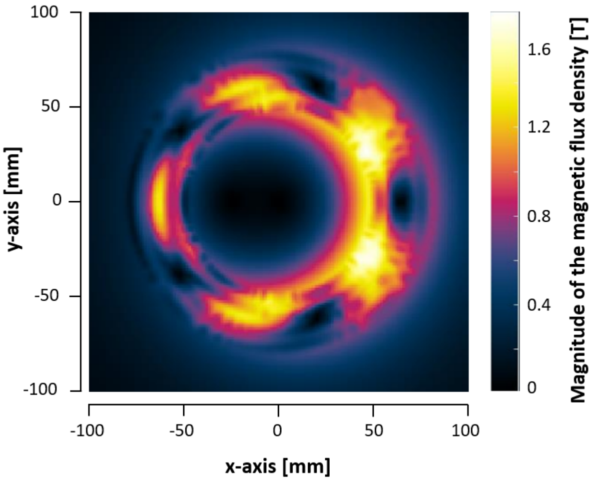

Figure 3: Example of the magnetic field across the beampipe aperture resulting from a nested quadrupole and sextupole at full power.

NESTED MAGNET DESIGN

To realize the nested magnet configuration in practice, we propose to turn towards superconducting systems, instead of using normal-conducting superferric magnets. While superferric magnet are capable of generating combined function fields (e.g. a quadrupolar+dipolar component) [6], it is not possible to change the ratio of the generated component freely by changing the operating current. That instead requires the use of independent magnets. If these are to be nested, which is desired in order to have as high as possible dipole filling factor, the use of iron to shape the field has to be avoided to ensure that field quality targets are met

Table 1: The magnetic field strengths for the baseline and NMs cell in the Z mode are shown, at a reference radius of 10 mm. For the Z lattice we have 38 families for the sextupoles SF and 37 for the SD.

Magnetic field & gradient	**Baseline**	**Nested Magnets**	**length [m]**
B1	0.0152 T	- - -	22.654
B1S	0.0152 T	- - -	19.304
B1L	0.0152 T	- - -	20.954
B1CF	- - -	0.0129 T	23.155
BTT	- - -	0.0066 T	2.9
BD	- - -	0.0125 T	2.9
BF	- - -	0.0059 T	2.9
Orbit Corrector	- - -	0.0084 T	2.9
Quad F	1.450 T/m		2.9
Quad D	-1.450 T/m		2.9
Sextupoles SF option 1	A reduction of 8.81 %		2.9
Sextupoles SF option 2	A reduction of 2.51 %		1.5
Sextupoles SD option 1	A reduction of 17.90 %		2.9
Sextupoles SD option 2	A reduction of 15.86 %		1.5

Table 2: The magnetic field strengths for the baseline and NMs cell in the tt mode are shown.

Magnetic field & gradient	**Baseline**	**Nested Magnets**	**length [m]**
B1	0.0612 T	- - -	22.654
B1S	0.0612 T	- - -	19.304
B1L	0.0612 T	- - -	20.954
B1CF	- - -	0.0511 T	23.155
BD	- - -	0.0503 T	2.9
BF	- - -	0.0267 T	2.9
Quad F	11.842 T/m		2.9
Quad D	-11.842 T/m		2.9
Sextupoles SF option 1	A reduction of 17.98 %		2.9
Sextupoles SF option 2	An increase of 2.95 %		3.0
Sextupoles SD option 1	A reduction of 7.32 %		2.9
Sextupoles SD option 2	An increase of 5.43 %		3.0

for different scenarios. Without the aid of iron to boost the magnetic field, it is not practical to use copper-based coils. By using nested superconducting magnets, one of the main advantages that comes is the elimination of ohmic dissipation in the quadrupoles and sextupoles, and the second big advantage is a potential in reduced synchrotron radiation, due to the mentioned increased dipole filling factor.

The total FCC-ee energy consumption over the lifetime is around 20 TWh in the baseline design [7], and we believe we can reduce this by approximately 4 TWh by using nested superconducting magnets. This estimate includes initial considerations for the cooling circuit power consumption of the superconducting magnets [8].

DISCUSION

The introduction of NMs into the FCC-ee lattice represents a significant progress in minimizing energy loss due to SR and the decrease of the power consumption of the different magnets. This reduction is around 20%. Our investigation identified three NM solutions for the entire lattice, tailored to specific operational needs. Adjustments were made to the Z and tt lattices to accommodate NMs, including introducing a non-zero orbit in the Z mode. The values of the new fields and gradients are decreased in most cases.

CONCLUSION

This work has aimed to provide a summary of the fields and gradients required for the implementation of NMs in the various lattices of the FCC-ee. Significant reductions in magnetic field strengths were observed, with NMs showing at least a 15% decrease in magnetic fields compared to the baseline, leading to lower electrical current requirements and energy savings. The main advantages of using this type of magnets over normal conducting ones have also been discussed in this parameter space paper. The energy loss per turn in both lattices is reduced in 16%. Additional analysis is necessary to optimize the DA and these adjustments can be made to decrease the rises in the sextupoles.

ACKNOWLEDGEMENTS

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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ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR11

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