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ALTERNATIVE SOLENOID COMPENSATION SCHEME FOR THE FCC-EE INTERACTION REGION *

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Abstract

We present the optics design of the solenoid compensation scheme at the FCC-ee. The 2 T solenoids of the experiments can generate many kW of synchrotron radiation power and induce coupling on the beams resulting in an increase of the vertical emittance. We propose a modified compensation scheme to minimize these effects. A Screening Solenoid is placed around the Final Focus Quadrupoles (FFQ) to shield them from the experiment's field. A skew quadrupolar component is added to the Final Doublet (FD), aligning the magnet axis to the rotated reference frame of the beam. Two Compensating Solenoids are placed at approximately ±20 m from the Interaction Point (IP) to cancel the longitudinal field integral. The orbit distortion generated by the horizontal crossing angle in the detector field is compensated by correctors placed right after the beam pipe separation and around the final focus quadrupoles. We describe the Interaction Region (IR) optics in this scheme, including the detector solenoid and the magnetic elements used for compensation.

INTRODUCTION

The Future Circular Collider electron-positron (FCC-ee) [1] will reach a luminosity of about $2 \times 10^{36}\,\mathrm{cm^{-2}s^{-1}}$ per IP. This result is achieved thanks to the crab-waist collision scheme [2], which is based on small vertical beam size at the IP and large horizontal crossing angle. At FCC-ee the layout of the IR is common for all working points. The crossing angle is set to $\theta_c = 30$ mrad, the distance between the IP and the first quadrupole is $l^* = 2.2$ m and the detectors' solenoid magnetic field is $B = 2$ T. Progress on the FCC-ee MDI region design are described in [3].

To reach high luminosity it is important to correct any effects that can degrade the vertical emittance (of the order of $\epsilon_y \sim 1$ pm rad), in particular compensating the coupling and other distortions introduced by the detector solenoid. The baseline compensation scheme [4] acts locally with −5 T Compensating Solenoids, used to cancel the $\int B_z dz$ between the IP and the first of the FFQs. These elements pose mechanical constraints in the design of the Machine Detector Interface (MDI) region and produce about 80 kW in Synchrotron Radiation (SR) per beam due to the strong fringe fields.

We propose an alternative solution similar to that used in DAΦNE [5] based on [6], that we will refer to as "standard" solenoid compensation scheme. It would allow for the removal of the −5 T Compensating Solenoids, resulting in benefits such as reduced SR, increased available space in the MDI area and an overall simplification of the hardware requirements. This scheme uses skew quadrupolar components winded around the FFQs to minimize the vertical emittance increase, and weak correctors in the IR to close the orbit bumps generated by the beams passing with an angle through the detector's field.

DESCRIPTION OF THE STANDARD SCHEME AND COMPARISON WITH THE BASELINE

Field Profile

The main difference between the two schemes is the location of the Compensating Solenoids, used to cancel the field integral coming from the detector's solenoid.

In the baseline scheme this is achieved by two 0.77 m long −5 T Compensating Solenoids starting at ±1.23 m from the IP. Right after these magnets, −2 T Screening Solenoids are used to nullify the detector's field in the region of the first quadrupoles of the final focus, located inside the experiments at ±2.2 m from the IP.

Coupling compensation in the standard scheme proposed here is mainly achieved by weak correctors in the IR and skew components winded around the Final Focus quadrupoles. The Screening Solenoids are preserved and start as close as possible to the IP (according to mechanical constraints like bellows, flanges, acceptance, …). Based on our present knowledge, we use a value of ±1.5 m from the IP. The shape of the Screening Solenoids can be tapered to match the angular acceptance of the detectors. The integral of the magnetic field from the IR $\int B_z dz = 6.25$ Tm is canceled by two Compensating Solenoids placed further away from the IP, before the first dipoles. Here there is sufficient space available to achieve the compensation with fields reduced to −2 T over 1.5 m.

Figure 1 shows the longitudinal and radial component of the magnetic field along the 15 mrad axis (corresponding to the trajectory of one beam) for the standard (top) and the baseline (bottom) schemes, calculated from analytical equations.

The baseline scheme presents (on each side of the IP) two regions with radial magnetic field B_r bumps, due to the fringe fields in the two transitions between different magnetic

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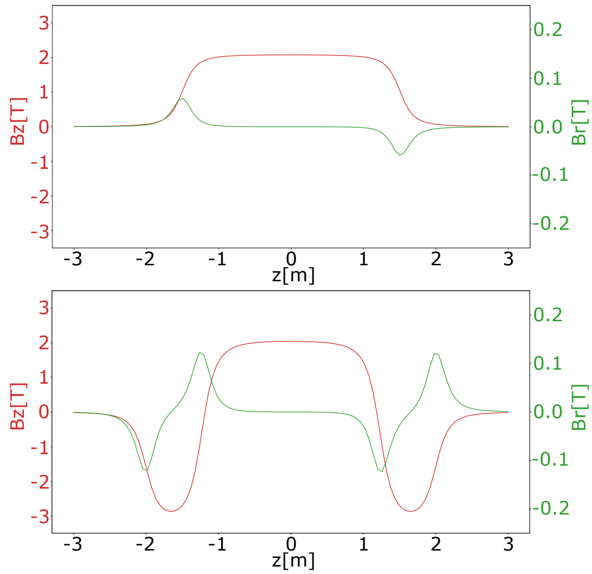

Figure 1: Longitudinal (red) and radial (green) magnetic fields along the 15 mrad axis in the two compensation schemes (standard proposed here on the top, baseline on the bottom).

field areas. These fringe fields induce dispersion resulting in an emittance blowup. In the standard scheme there is only a weaker transition, between the detector and the Screening Solenoids.

The synchrotron radiation power radiated in the interaction region was determined using tracking methods. For FCC-ee Z the scheme proposed here the power gets reduced from 80 kW to 12 kW per interaction region.

Coupling Compensation

In the standard scheme the beam is rotated by a small amount in the transverse space under the detector solenoidal field until it enters the Screening Solenoid.

The transport matrix of a solenoid can be written as:

$$M_{solenoid} = \begin{pmatrix} C^2 & \frac{SC}{K} & SC & \frac{S^2}{K} \\ -KSC & C^2 & -KS^2 & SC \\ -SC & -\frac{S^2}{K} & C^2 & \frac{SC}{K} \\ KS^2 & -SC & -KSC & C^2 \end{pmatrix}, \quad (1)$$

where $K = B_0/2B\rho$, $C = \cos(KL)$ and $S = \sin(KL)$. The rotation induced by a solenoid with strength $K_s = B_0/B\rho$ and length L is:

$$p_y' = -SCp_x \simeq -p_x KL = -p_x \frac{K_s}{2} L \;\rightarrow\; \theta = \frac{K_s}{2} L \quad (2)$$

A 45.6 GeV electron beam in a 1.5 m long 2 T solenoidal field rotates of $\theta = 0.009\,86$ rad (from the IP to the Screening Solenoid).

The flat beam arrives at the first quadrupole tilted, which for the beam is equivalent to an additional skew component due to the feed-down effect. This induces coupling and resulting in an increase of the vertical emittance. To correct this effect, we add an opposing skew component to the final focus quadrupoles. This is conceptually identical to rotating the magnets on the beam tilted reference frame, successfully cancelling the vertical emittance growth due to this effect. For our scenario the corresponding skew component is: $K_{1s} = K_1 \sin(2\theta) \sim 0.02 K_1$.

Due to the crossing angle, the beam also experiences a field component transverse to its direction, which acts as a vertical kick. This kick coupled with the rotating motion induced by the solenoid causes both horizontal and vertical orbit. The bumps are closed before reaching the compensating solenoid using the horizontal and vertical correctors already present in the IR and weak dipole components winded around the FFQs. Skew quadrupoles families can be used to match the IR optical functions to the arcs.

APPLICATION TO LCCO LATTICE

The performances of both standard and baseline solenoid compensation schemes have been tested using MAD-X [7–9]. The lattice considered for this study is v92 of the Local Chromatic Correction Optic (LCCO) proposed by P. Raimondi [10], but in principle can be adapted to every lattice. Preliminary studies on a previous LCCO lattice version are shown in [11]. We perform the study at the lowest proposed beam energy 45.6 GeV where the coupling and emittance increase effects are most significant.

To reproduce the tilted solenoid in MAD-X we factorized the components of the magnetic field with respect to the beam trajectory. The parallel component has been simulated with several 1 cm thin solenoid slices. The transverse component has been calculated using the analytical model of the IR solenoidal fields following the beam trajectory with steps of 1 cm. Horizontal and vertical "virtual" correctors are used in the sequence to reproduce this path. Figure 2 shows the IR layout of the standard scheme. This scheme also includes two skew quadrupoles families located far from the IR.

The skew component of the FFQs is set as described in the previous section. The correctors and the skew quadrupoles are used in the matching routine to close and optimize the amplitude of both orbit and dispersion bumps, and to minimize the vertical emittance increase. Figures 3 and 4 show the orbit and dispersion bumps after the correction. Orbit bumps have been kept below the millimeter level and are closed before the Compensating Solenoids. The vertical dispersion bump generated in the insertion remains below 1 cm and is closed using the skew quadrupole families at -600/+400 m from the IP.

The vertical emittance increase calculated using the MAD-X model described above for the standard solenoid compensation scheme is 0.002 pm rad, to be compared with the nominal vertical emittance of 1 pm rad.

We used the same MAD-X algorithm (EMIT module) to predict the emittance increase for both schemes. Table 1 shows the vertical emittance increase for the two schemes calculated for different energy offsets.

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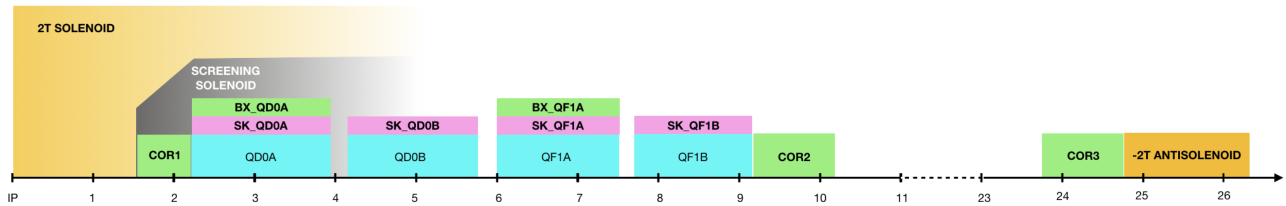

Figure 2: Layout of the standard solenoid compensation scheme for LCCO lattice v92.

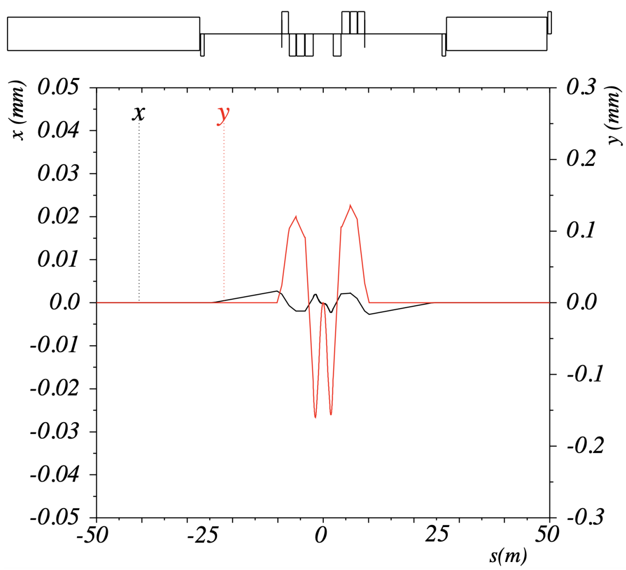

Figure 3: Horizontal and vertical orbit bumps.

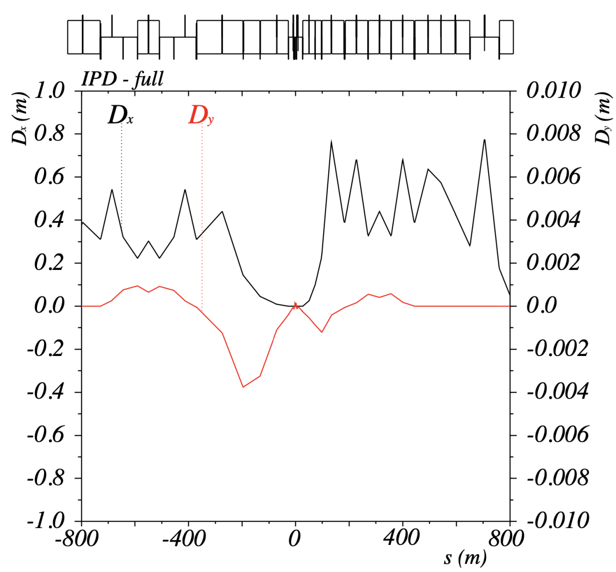

Figure 4: Horizontal and vertical dispersion.

Table 1: Vertical emittance increase calculated for the baseline and standard solenoid compensation schemes in an energy offset range of $dE/E = \pm 4\%$. LCCO lattice at Z-pole.

Energy Offset	Baseline ϵ_y[pm rad]	Standard ϵ_y[pm rad]
-0.04	0.199	0.009
-0.02	0.196	0.003
0.00	0.195	0.002
+0.02	0.197	0.003
+0.04	0.204	0.004

CONCLUSION

The standard solenoid compensation scheme for FCC-ee has been presented. Compensation can be achieved mainly using weak correctors and skew components in the final focus quadrupoles, removing the need for strong compact Compensating Solenoids very close to the IR. This solution significantly reduces the SR produced at the IR and relaxes the tight space requirements in the IR region and the maximum fields required for the field compensation. The vertical emittance increase calculated with MAD-X is about 0.2% of the nominal value. The chromatic behavior of the vertical emittance increase was evaluated and found to be small in the energy range $dE/E = \pm 4\%$.

This study shows that to lower the SR and the vertical emittance growth is not necessary to cancel the vertical orbit before the first quadrupole after the IP. Such requirement indeed generates no vertical dispersion leakage from the orbit bump, but needs very strong fields to correct the orbit in the short space available. The proposed solution compensates the dispersion leakage in the IR insertion and finds the optimal compromise for emittance growth and SR power.

REFERENCES

[1] A. Abada *et al.* [FCC Collaboration], "FCC-ee: The Lepton Collider : Future Circular Collider Conceptual Design Report Volume 2." Eur. Phys. J. ST 228 no. 2, 261 (2019). doi:10.1140/epjst/e2019-900045-4

[2] M. Zobov *et al.*, "Test of Crab-Waist Collisions at the DAΦNE Φ Factory", Phys. Rev. Lett. 104 no. 17 p. 174801 (2010)., doi:10.1103/PhysRevLett.104.174801

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[3] M. Boscolo *et al.*, "Progress in the design of the Interaction region of the FCC-ee", presented at IPAC'24, paper TUPC67, this conference.

[4] M. Koratzinos and K. Oide, "The Magnetic Compensation Scheme of the FCC-ee Detectors", arXiv physics.acc-ph:2101.05704 (2021). doi:10.48550/arXiv.2101.05704

[5] C. Milardi, M. Preger, and P. Raimondi, "The DAΦNE Interaction Region for the KLOE-2 Run" DAΦNE Technical Note, Note: IR-14, Frascati, March 29, 2010.

[6] M. Bassetti, M. E. Biagini, and C. Biscari, "Solenoidal field compensation" in Proc. ICFA'97 Beam dynamics issues for e+ e- factories, Frascati, Italy, October 20–25, 1997.

[7] MAD-X, Methodical Accelerator Design: http://mad.web.cern.ch/mad

[8] A. Koschik, H. Burkhardt, T. Risselada, and F. Schmidt, "On the implementation of experimental solenoids In MAD-X and their effect on coupling in the LHC" Conf. Proc. C 060626 2011–2013 (EPAC 2006).

[9] M. Aslaninejad, C. Bontoiu, J. Pasternak, J. Pozimski, and S. A. Bogacz, "Solenoid Fringe Field Effects for the Neutrino Factory Linac - MAD-X Investigation", Conf. Proc. C 100523 pp. 3693–3695 (2010).

[10] P. Raimondi, "Alternative Optics and Variants" presented at FCCIS'23 WP2 Workshop (Rome). https://indico.cern.ch/event/1326738/timetable/\#45-alternative-optics-and-vari

[11] A. Ciarma, "Status and Perspectives for FCC-ee Detector Background Studies" in Proc. EPS-HEP'23, p. 614, DESY, Germany, Aug. 2023. doi:10.22323/1.449.0614