CHALLENGES AND STATUS OF THE FCC-*ee* LATTICE DESIGN

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Abstract

Following the recommendations of the European Strategy Group for High Energy Physics, CERN started the Future Circular Collider Study (FCC), a design study for possible future circular collider projects to investigate their feasibility for high energy physics research. One part of this study is FCC-ee, an e+e- collider with a circumference of 100 km. Challenges for the lattice design result from operation at four different beam energies ranging from 45.5 GeV to 175 GeV. Very high beamstrahlung effects at high energies and the beam-beam limit at low energies request emittance parameters that rise with decreasing beam energy. This paper will present the status of the lattice design and the lattice modifications needed to achieve the requested emittance parameters.

INTRODUCTION

The Large Electron Positron Collider (LEP) was the most powerful lepton machine that was ever build. Its maximum beam energy was limited by the available power of the RF cavities that fed back the high amount of energy lost by synchrotron radiation. When LEP finished operations in 1995 investigations of lepton machines with even higher beam energy moved to linear accelerators (e.g. CLIC, ILC). After nearly 20 years CERN launched a design study for the feasibility of circular colliders for future high energy physics research, called FCC. One part of the study, FCC-hh, is a possible proton discovery machine with 100 TeV center of mass energy. The circumference would be about 80 km-100 km based on Nb_3Sn technology with magnetic fields of 16 T-20 T [1]. Given the technical infrastructure and the large bending radius of 10.6 km a future circular lepton collider for precision studies in the energy range of 90 GeV to 350 GeV could still be operated with an acceptable amount of synchrotron radiation loss. This part of the study, which could bring the come back of circular high energy lepton colliders, is called FCC-ee. As a third part, a proton electron option called FCC-he is considered. Deep inelastic scattering could basically be studied in two options: a LHeC like linac-ring option and a ring-ring option. In this paper the status of the FCC-ee lattice design and its modifications in order to achieve the requested emittance parameters are discussed in detail.

Physics Goals

FCC-ee is designed to provide highest possible luminosity for precision studies of a wide physics program. This covers four different center of mass energies: 91 GeV for measurements of the Z pole, 160 , which is the W pair production threshold, 240 GeV for H production and the $t\bar{t}$ threshold at 350 GeV. To reach the goal of highest possible luminosity, for each of the physics programs a set of baseline parameters was assembled shown in Table 1.

CHALLENGES

The limit of luminosity performance in a lepton storage ring strongly depends on the energy of the colliding beams. Thus the machine has to be designed and optimized for each of the four energies separately while using the same hardware. At high energies the luminosity lifetime is limited to 15-20 min by beamstrahlung [2]. This requires on the one hand top up injection from a full energy booster and on the other hand a very high momentum acceptance of 1-2 %. At low energies the luminosity is limited by the beam-beam effect, which creates a tuneshift of the working point. Assuming two equal beams sizes the beam-beam parameter is given by [3]

$$\xi_q = \frac{N r_e}{\gamma} \frac{\beta_q^*}{2\pi\sigma_q(\sigma_x + \sigma_y)}, \qquad (1)$$

where q stands for x or y and N is the bunch population. To keep the tuneshift small, the beam size σ must be increased by a larger emittance. However in electron storage rings the horizontal equilibrium emittance is proportional to γ^2 [4], so the emittance is decreasing with lower energy. Consequently the lattice needs to be modified between operation at different energies. At the same time a very small ration of vertical and horizontal emittance of 0.1 % must be achieved for highest luminosity. The vertical emittance of 1 pm corresponds to performances of synchrotron light sources and sets serious constraints on the alignment requirements of the machine.

At 175 GeV beam energy very high synchrotron radiation losses of 7.5 GeV per turn will require a sophisticated absorber design to protect the vacuum chamber. Furthermore equally distributed RF sections will be needed to keep the energy sawtooth effect on a reasonable level. At 45.5 GeV beam energy the high beam current and the large number of bunches make it mandatory to use two separated vacuum chambers instead of a common one and a crossing angle in the interaction region to avoid multiple bunch crossings inside the detector. A further challenge for the interaction region design is the very small vertical beta function at the interaction point $\beta^* = 1$ mm. Very strong focusing is required, which creates high chromaticity. Therefore a local chromaticity correction scheme is foreseen before entering the arcs [5]. Still the strong sextupoles must provide sufficient dynamic aperture for momentum deviations of up to 2 % created by the beamstrahlung.

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Table 1: Compendium of Baseline Parameters for the Different Physics Programs of FCC-ee [2]

	FCC-ee Z	**FCC-ee W**	**FCC-ee H**	**FCC-ee tt**
Beam energy (GeV)	45.5	80	120	175
Beam current (mA)	1450	152	30	6.6
Bunches/beam	16700	4490	1330	160
Transverse emittance ϵ (nm)				
- Horizontal	29.2	3.3	0.94	2
- Vertical	0.06	0.007	0.0019	0.002
Betatron function at IP β^* (m)				
- Horizontal	0.5	0.5	0.5	1
- Vertical	0.001	0.001	0.001	0.001
Energy loss/turn (GeV)	0.03	0.33	1.67	7.55
Total RF voltage (GV)	2.5	4	5.5	11
Peak luminosity (10^{34} cm^{-2}s^{-1})	28.0	12.0	5.9	1.2

THE FCC-EE LAYOUT

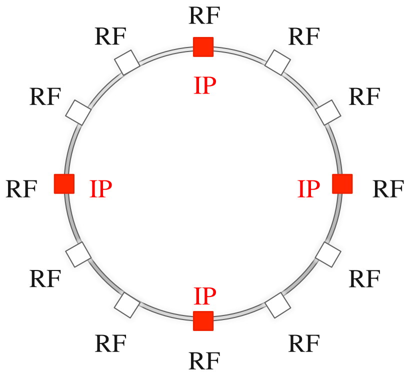

Figure 1: The layout of the FCC-ee lattice. Twelve dispersion free straight sections are equally distributed around the ring. The ones housing RF are marked in white, the ones that also include an interaction point (IP) in red.

The FCC-ee layout illustrated in figure 1 has a circular shape with the circumference of 100 km. Twelve dispersion free straight sections with the length of 1.5 km each are equally distributed to house RF installation. Four of them additionally contain mini-beta insertions for the experiments in a 4-fold symmetry. The final length of the straight sections for injection, beam dump, collimation and RF is determined by the requirements of the FCC hadron machine. The straight sections including experiments need to provide enough space for the interaction region of FCC-ee, which probably will be broader and longer than the one of FCC-hh due to the chromaticity correction scheme [1]. The twelve arcs in-between the straight sections have a length of 6.8 km including half-bend dispersion suppressors at the beginning and at the end. Currently they still consist of two sub-arcs, divided by a dispersion suppressor. To store a high number of bunches, two separate beam pipes are foreseen, which are placed side-by-side to conserve polarization and avoid vertical dispersion. However in this early design stage one single ring is implemented. For the calculations presented in this paper, the straight sections including mini-beta insertions were replaced by regular straight sections. This has no influence on the equilibrium emittance as the emittance is defined by the parts of the lattice with non-zero dispersion.

THE FCC-EE FODO CELL

The regular FCC-ee arc FODO cell is designed for 175 GeV beam energy and is the basis for the High Energy Lattice. A non-scale sketch is provided in figure 2. The cell is 50 m long and contains four bending magnets with the length of 10.5 m each. According to calculations of the CERN vacuum group after this length an absorber must be installed to protect the vacuum chamber from the synchrotron light fan. In addition lumped absorbers will be placed inside the vacuum chamber in the middle of each bending magnet [6]. Both focusing and defocussing quadrupoles have the length of 1.5 m and divide the cell into two parts with equal length. After each quadrupole a sextupole, a beam position monitor and a corrector magnet for the respective plane are placed. The current FCC-ee FODO cell layout already considers drift spaces for absorbers, flanges and bellows. In the straight sections the bending magnets are replaced by RF cavities.

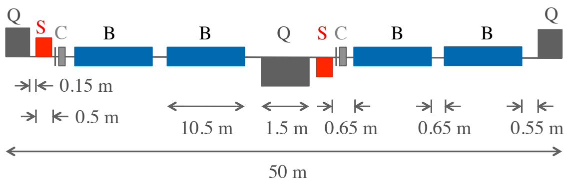

Figure 2: Non-scale sketch of the FCC-ee FODO cell. Bending magnets are labeled with B, quadrupoles with Q and sextupoles with S. C stands for a collective of beam position monitor and a corrector.

Optical Functions

Following LEP experience a phase advance of 90 ° per cell in the horizontal plane and 60 ° in the vertical plane

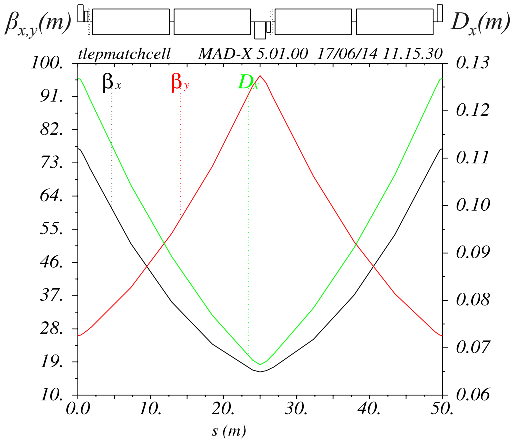

Figure 3: Beta functions and horizontal dispersion of the FCC-ee FODO cell.

were chosen. The beta functions and the dispersion function calculated with MAD-X are shown in figure 3. With a maximum of 12.7 cm the dispersion function is by one order of magnitude smaller compared to LEP (2.2 m) [7].

Horizontal Emittances of the High Energy Lattice

The horizontal equilibrium emittance of a beam in an electron storage ring can approximately be written as [4]

$$\epsilon_x = \frac{C_g}{J_x}\gamma^2\theta^3 F. \qquad (2)$$

$C_g = 3.832 \times 10^{-13}$ is a constant, J_x is the horizontal damping partition number, γ is the Lorentz factor and θ is the bending angle of the dipole magnets in a half cell. F is a numerical factor, that depends on the lattice design. In case of a FODO cell lattice it is given by

$$F = \frac{1}{2\sin\psi}\,\frac{5 + 3\cos\psi}{1 - \cos\psi}\,\frac{L}{l_b}, \qquad (3)$$

where L is the cell length, ψ is the phase advance per cell and l_b the total length of the bending magnets. According to equation (2) the equilibrium emittance ϵ_x of an 175 GeV electron beam in the FCC-ee lattice should be in the order of 1.04 nm rad. The emittance calculation with MAD-X had the result ϵ = 1.00 nm rad, which agrees nicely with the analytical result and is exactly the half of the baseline parameter. As the emittance probably will increase as soon as coupling, misalignments and non-linear effects like the beam-beam effect are considered, this factor of two for now will be kept to leave a margin.

Changing the beam energy while not modifying the lattice will have an impact on the emittance proportional to γ^2. For 120 GeV beam energy the analytically calculated emittance is 0.49 nm rad, which was confirmed by calculation with MAD-X. Also taking the margin of factor two into account, this is a deviation from the baseline parameter 0.47 nm rad of just 3.8 %. Fine tuning with wigglers will be applied using the same lattice. For 80 GeV beam energy the emittance however would shrink to 0.218 nm rad, for 45.5 GeV even to 0.071 nm rad. To disarm the beam-beam effect the emittance must be increased by one order of magnitude in case of 80 GeV beam energy and three in case of 45.5 GeV. With wigglers this is not possible both from technical and economical point of view. As a consequence the lattice itself must be modified.

POSSIBILITIES TO INCREASE THE EMITTANCE

The equilibrium emittance is generally given by [8]

$$\epsilon = \left(\frac{\delta p}{p}\right)^2 \left(\gamma D^2 + 2\alpha D D' + \beta D'^2\right), \qquad (4)$$

so the key to increase the emittance is a larger dispersion. The maximum dispersion in a FODO lattice can be derived as [9]

$$\hat{D} = \frac{L^2}{\rho} \cdot \left(1 + \frac{1}{2}\sin\left(\frac{\psi}{2}\right)\right) / \sin^2\left(\frac{\psi}{2}\right), \qquad (5)$$

which allows two possibilities to modify the emittance: changing the cell length and changing the phase advance.

Changing of the Cell Length

According to equation (5) the dispersion function depends on the cell length squared. Thus to obtain a larger dispersion the FODO cell must be increased. However changing the cell length is not possible in any arbitrary way because of the fixed the position of the quadrupole magnets. Thus it is just possible to increase the cell length by multiples of the High Energy FODO cell length, which is 50 m. An example of a possible scenario is illustrated in figure 4: by switching off all the defocussing quadrupoles and inverting the polarity of every second focusing quadrupole the cell length is doubled. Even longer cells can be achieved, when more quadrupoles are switched off. To guarantee smooth operation the relevant quadrupoles need to be equipped with switches, that should be included in the technical design from the beginning. This was already done for the sextupoles at HERA.

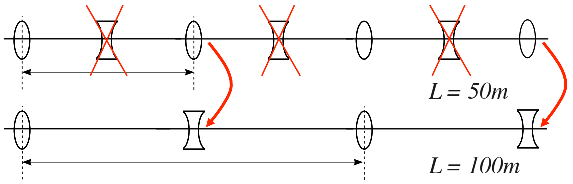

Figure 4: Approach of changing the cell length with fixed element positions. To double the cell length every defocussing quadrupole is switched off and the polarity of every second focusing is inverted.

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Tuning the Phase Advance

A second way to modify the dispersion without changing the lattice itself is tuning the horizontal phase advance by modifying gradient of the quadrupoles. Figure 5 shows the dispersion of the FCC-ee FODO cell as a function of the phase advance. To obtain a larger dispersion, the phase advance must be decreased. However the singularity for $\psi \rightarrow 0$ in equation (5) causes a very fast increase of the dispersion. At operation with phase advances smaller than 40 ° the beam emittance will be very sensitive tune shifts and optics tolerances. For stability reasons it is therefore recommended to choose a larger phase advance.

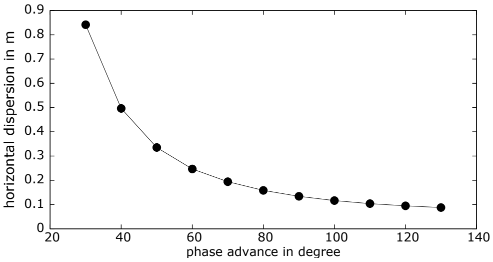


Figure 5: The maximum horizontal dispersion of an FCC-ee FODO cell as a function of the phase advance.

The strongest constraint on the choice of the phase advance is given by the necessity of a sophisticated sextupole scheme. For higher order chromaticity correction the phase advance between two sextupoles must be an integer divider of 360 ° like for example 60 °, 72 ° or 90 °.

OBJECTIVES FOR LATTICE CHANGES

The key to increase the emittance is the modification of the arc FODO cells. Feasible changes feature two characteristics: the cell length is a multiple of 50 m and the ratio of 360 ° and the phase advance is an integer value. Combinations of cell length and phase advance that approximately result in the desired emittance values are listed in Table 2. For 80 GeV there are two alternatives: $L = 100\,\mathrm{m}$ with $\psi = 90^\circ$ and $L = 50\,\mathrm{m}$ with $\psi = 45^\circ$, while for 45.5 GeV three options are possible: $L = 200\,\mathrm{m}$, $\psi = 60^\circ$, $L = 250\,\mathrm{m}$, $\psi = 72^\circ$ and $L = 300\,\mathrm{m}$, $\psi = 90^\circ$.

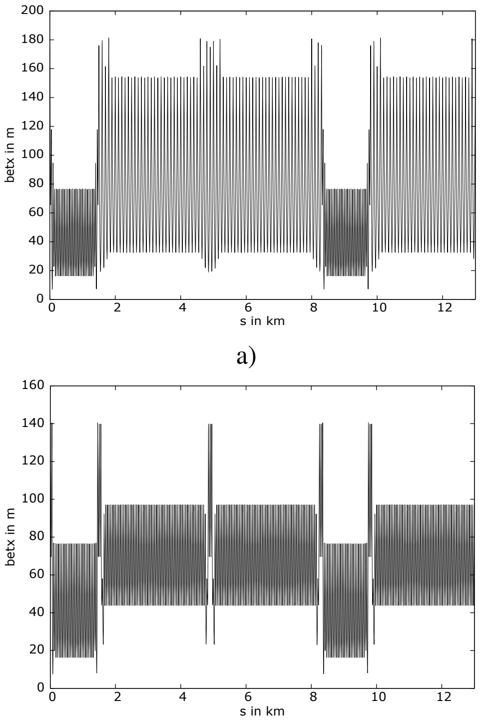
Table 2: Feasible FODO Cell Layouts for 80 GeV and 45.5 GeV Beam Energy and Their Design Emittances according to Equation (2)

E (GeV)	L (m)	ψ (°)	ϵ_x (nm rad)
80	100	90	1.74
	50	45	1.50
45.5	200	60	13.56
	250	72	15.91
	300	90	15.24

However both changing the cell length and tuning the phase advance result in a dysfunction of the dispersion suppressors. In order to keep the same geometry the strength of the bending magnets must not be changed. Instead quadrupoles of the arc are needed to re-establish the correct function of the dispersion suppressors. The lattice in the straight sections will not be changed, to keep the same optics conditions for the injection scheme, interaction regions etc.

LATTICES FOR 80 GEV AND 45.5 GEV BEAM ENERGY

For each FODO cell option listed in Table 2 a lattice was set up and evaluated with MAD-X. An overview of the optics parameters is given in Table 3. The emittance values calculated by MAD-X are in nice agreement with the analytical calculation. Figure 6 shows the horizontal beta functions of the two lattices for 80 GeV beam energy. The FODO cell modifications have different impact on the betafunctions. In both lattices four additional quadrupoles from the arcs are supporting the dispersion suppressors. This of course has an impact on the beta functions and creates the peaks, that can be seen in both plots. The horizontal beta function for the 300 m FODO cell lattice intended for 45.5 GeV beam energy is displayed in figure 7. The beta function in the dispersion suppressors reaches up to 550 m. As the closed orbit depends on the absolute value of the beta function alignment becomes an issue. Independent of the lattice at 45.5 GeV beam energy the energy loss per



a)

b)

Figure 6: The horizontal beta functions for the lattices for 80 GeV beam energy. Plot a) shows the first 13 km of the lattice with 100 m, $\psi = 90^\circ$ FODO cells, b) the one with 50 m, $\psi = 45^\circ$ FODO cells beginning with a straight section.

Table 3: Comparison of the parameters of the lattices based on different FODO cell layouts and the design parameters. The listed parameters are the cell length L, the phase advance ψ_x, the equilibrium emittance ϵ_x, the energy loss per turn U_0, the momentum compaction factor α_p, the maximum values of horizontal and vertical beta functions $\hat{\beta}_x$ and $\hat{\beta}_x$ as well as the maximum horizontal dispersion $\hat{D}_x$.

	80 GeV		Design parameter	45.5 GeV			Design parameter
L (m)	100	50	-	200	250	300	-
ψ_x (°)	90	45	-	60	72	90	-
ϵ_x (nm rad)	1.70	1.47	2×1.65	12.5	14.5	14.2	2×14.6
U_0 (MeV/turn)	337.03	337.03	330	35.3	35.3	35.3	30
α_p (10^{-5})	2.22	1.99	2	1.69	1.86	1.81	1.8
$\hat{\beta}_x$ (m)	181.54	141.47	-	366.5	465.71	554.0	-
$\hat{\beta}_y$ (m)	211.05	141.68	-	407.92	477.70	626.43	-
$\hat{D}_x$ (m)	0.58	0.41	-	4.02	4.87	4.56	-

turn is 15 % higher than estimated in the baseline parameter list. This will have an influence on the maximum bunch number and bunch population, which are compatible with the maximum power consumption of 50 MW.

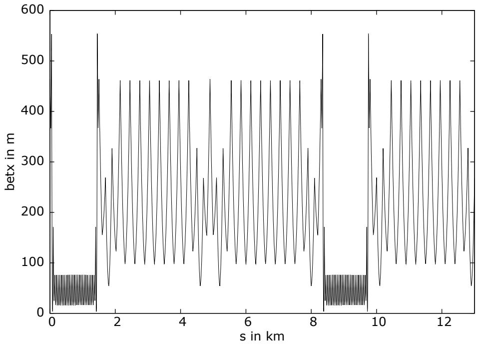


Figure 7: Horizontal beta function for a FODO cell with a 300 m length and a phase advance 90 ° at the first 13 km of the lattice beginning with a straight section.

NEXT STEPS

In following calculations misalignments will be introduced in order to analyze the vertical emittance and closed orbit corrections. To finalize the lattice design an advanced sextupole scheme including higher order chromaticity corrections will be added before investigating the impact of the beam-beam effect.

CONCLUSION

The design of the future FCC high energy electron positron collider has to face a variety of challenges: the lattice has to be designed and optimized for the requirements of four different center of mass energies in the range of 90-350 GeV. At high energies the luminosity is limited by beamstrahlung creating momentum deviations up to 2 %. At low energies the beam-beam effect demands an emittance increase of three orders of magnitude to avoid large tune shifts. The very strong focusing in the final focus system required to achieve a vertical β^* of 1 mm creates very high chromaticity, that has to be corrected in a local correction scheme while still providing sufficient dynamic aperture.

Starting at the highest beam energy of 175 GeV with a lattice consisting of 50 m FODO cells with 90/60 ° phase advance, first lattice layouts that achieve the emittance parameters for the low energy beams were developed. For 120 GeV beam energy the same lattice can be used, but for 80 GeV and 45.5 GeV the lattice has to be changed by increasing the cell length up to 300 m and tuning the phase advance. Still some fine tuning with wigglers is required, but the baseline parameters could approximately be achieved leaving a margin of a factor two for emittance increase caused by coupling, misalignments and non-linear effects like the beam-beam effect. The lattices described in this paper provide the basis for further development like a state-of-the-art chromaticity correction scheme. The final choice of the lattice will also depend on the results of those investigations.

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