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FIRST CONSIDERATIONS ON BEAM OPTICS AND LATTICE DESIGN FOR THE FUTURE ELECTRON-POSITRON COLLIDER FCC-ee

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Abstract

Following the recommendations of the European Strategy Group for High Energy Physics, CERN launched the Future Circular Collider Study (FCC) to investigate the feasibility of a new large circular collider for high energy physics research. This paper presents the constraints on the design of the lattice and optics of the lepton collider version of FCC, that has to be optimised for four different beam energies and parameter sets. Special emphasis is put on the need for a highly flexible magnet lattice in order to achieve the required beam emittances for the four energies and on the layout of the interaction region that will have to combine an advanced mini-beta concept, an effective beam separation scheme and a local chromaticity control to optimise the momentum acceptance and dynamic aperture of the ring.

INTRODUCTION

The lepton collider part of the FCC study is based on racetrack geometry with a circumference of about 100 km and foresees the design of an electron-positron collider, running at four different centre-of-mass energies to allow precision measurements at the Z resonance, at the energy with maximum Higgs production rate, as well as above the WW and t-tbar thresholds [1]. For each energy the beam parameters depend crucially on the synchrotron light emission and the lattice has to be optimised to provide the emittance target values that are summarised together with the general beam parameters in the parameter list of Table 1. The general layout of the machine is shown in Figure 1.

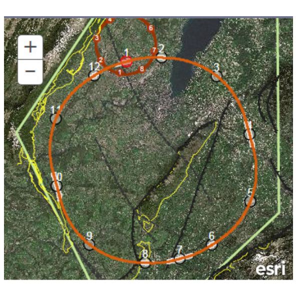

Figure 1: Geometry of the FCC storage ring.

MAIN PARAMETRES

The general parameters [2] have been optimised for each beam energy and are determined by the overall synchrotron radiation load that can be accepted in the design. In general, for all operation energies the same global synchrotron radiation limit of P_γ =50 MW has been assumed, leading e.g. to a considerable higher number of stored bunches at the lowest operation energy and to a large variation of beam emittances over the complete energy range of the machine.

Table 1: FCC-ee Parameters at Four Different Beam Energies

	Z	W	H	t
Beam Energy (GeV)	45.5	80	120	175
Current (mA)	1450	152	30	6.6
Bunch population 10^{11}	1.8	0.7	0.46	1.4
Bunch number	16700	4490	1360	98
Hor. Emittance (nm)	29	3.3	0.94	2
Vert. Emittance (pm)	60	7	1.9	2
β_x function at IP(m)	0.5	0.5	0.5	1
β_y function at IP(mm)	1	1	1	1

General Layout of the Lattice Cells

The design of the basic cell follows the usual rules for particle beams that are determined by synchrotron radiation aspects. The basic cell that has been chosen for 175 GeV operation is shown in Figure 2. It combines four dipole magnets and two main quadrupoles in a 50 m long FODO cell.

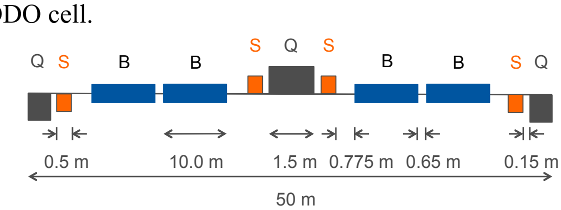

Figure 2: FODO cell chosen for the arc design. The cell parameters are optimised for maximum dipole fill factor and design emittance.

Applying the usual scaling laws for the beam emittance of lepton rings, the dispersion and the arc beta function,

$$\varepsilon = \left(\frac{\delta p}{p}\right)^2 \left(\gamma D^2 + 2\alpha D D' + \beta D'^2\right) \qquad (1)$$

$$\hat{D} = \frac{\ell^2}{\rho} * \frac{\left(1 + \frac{1}{2}\sin\frac{\psi_{cell}}{2}\right)}{\sin^2\frac{\psi_{cell}}{2}}$$

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$$\hat{\beta} = \frac{\left(1+\sin\frac{\psi_{cell}}{2}\right)L_{cell}}{\sin\psi_{cell}}$$

the optimum cell parameters can be calculated. Accordingly the basic cell structure follows a 50 m long FODO design whose length has been chosen according to the above equations to get the design equilibrium (horizontal) beam emittance and a maximum achievable dipole fill factor of η_{fill} =80 %. It is schematically shown in Figure 2. While for the given maximum energy the single cell layout is pre-defined by the emittance requirements and the synchrotron light integrals, in the case of FCC-ee, the beam emittance will change in a wide range due to the large range of operation energies. In order to counteract the natural scaling with the square of the beam energy, it is foreseen to change the layout of the arc lattice, by re-arranging the quadrupole structure. Figure 3 schematically shows the idea. As a consequence in case of the lowest energy, i.e. on the Z pole, the effective cell is increased by a factor of 6 compared with the top-quark running and the intermediate steps are optimised by a proper choice of the single cell phase advance.

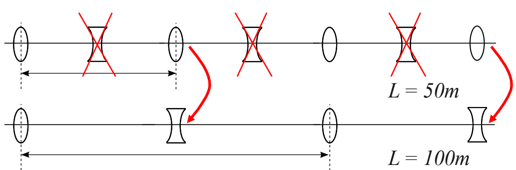

Figure 3: Optimising the cell length to achieve the desired beam emittance at different energies.

BEAM OPTICS

The layout of the beam optics follows the typical pattern used for modern collider rings and is divided in four parts:

- A standard FODO cell in the arcs to define the beam emittance for the 4 energies
- Matching sections to provide smooth modification of the optics towards the straight sections
- Dispersion suppressors to establish dispersion free straight sections for installation of the 4 experiments and the RF stations.
- Four interaction regions to achieve the mini-beta values including a feasible beam separation scheme as well as a local chromaticity correction.

For the case of the 175 GeV set up the beam optics, based on a phase advance per cell of 90/60 degrees is shown in Figure 4. The plot includes in addition to the periodic arc structure the dispersion suppressor that is based on a half bend scheme and, as visible in Figure 5, allows a smooth transition between the arc optics and the cells of the straight section. It has to be emphasised however that for the lower energies the dispersion suppressor has to be equipped with additional quadrupoles, as the effective cell length and phase advance vary with the operation energy. This is part of the required lattice flexibility of the design.

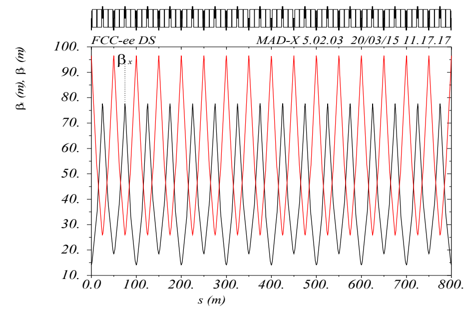

Figure 4: Optics in the periodic structure of the arc, including the dispersion suppressor scheme.

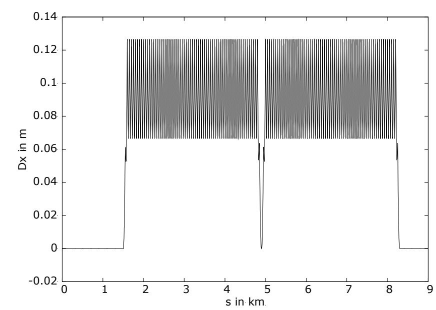

Figure 5: Dispersion function for the high energy case. Dispersion free sections are foreseen in the long straight sections and in the middle of the arc for RF installation.

Cell Design for the Low Energy Case

In order to counter act the natural shrinkage of the beam emittance at low energy, the design of the arc cell had to be chosen properly. Following the scaling law of Eq. 1, the effective cell length is increased by re-arranging the quadrupole focusing scheme. The amplitude function and the dispersion of the lattice are increased correspondingly, and the emittance can be optimised so as to obtain the values of Table 1.

The new optics, with larger beta values and higher dispersion however has to fulfil the same requirements as before, namely a smooth match to the dispersion free RF sections, where empty FODO cells are used to provide space for the RF installation. Figure 6 shows as example the optics that has been established for 45 GeV operation.

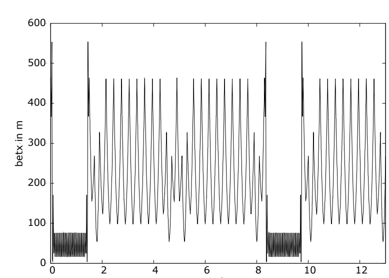

Figure 6: Beam optics for the 45 GeV low energy case. A longer cell design has been chosen to achieve higher values of β. In the straight sections the optics remains unchanged.

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The arc structure and a part of the dispersion free RF section is shown and is to be compared to the high energy version of Figure 4.

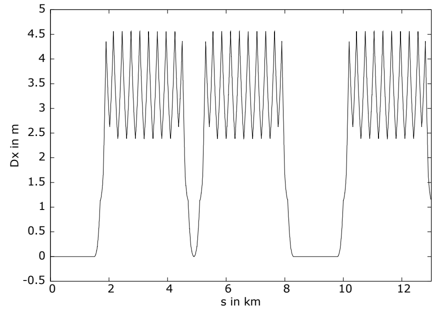

Figure 7: Dispersion for the low energy case.

The considerable increase on the arc amplitude function and dispersion is evident. A scaling is applied to the arc cells only, while the conditions in the straight sections are kept constant.

Mini-Beta-Insertion

In order to achieve the required luminosity of

$$L = 1.8 \cdot 10^{34}\, cm^{-2} s^{-1}$$

at 175 GeV beam energy the vertical beta function at the IP has to be as small as β_y=1mm. This unprecedentedly small value for a collider ring has a considerable impact on the layout of the interaction region and, especially, implications for the mini-beta concept.

A considerable crossing angle is needed to avoid parasitic bunch crossings on either side of the IP, and at the same time the synchrotron radiation emitted next to the high energy physics detector has to be kept low enough to allow successful data taking. The large excursions of the amplitude function combined with the small β^* values impose serious tolerances for magnet alignment and coupling compensation schemes. Last but not least, the chromaticity compensation scheme needed has to combine an optimised arc sextupole distribution scheme with a local correction in order to guarantee a sufficiently large off-momentum dynamic aperture of the machine extending up to $\Delta p/p \approx \pm 2\%$. Figure 8 shows a possible interaction region layout [3].

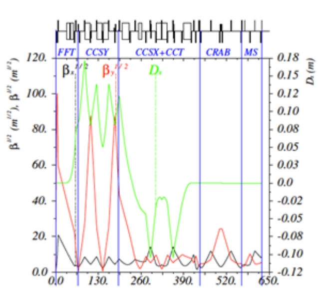

Figure 8: Proposed layout of the interaction region: the mini-beta insertion is combined with a local chromaticity compensation scheme.

Between the final mini-beta telescope, which is based on a doublet focusing and a matching section to obtain a smooth transition to the arc optics, a sequence is embedded which provides locally sufficient dispersion and sextupole strength to compensate a large fraction of the IR chromaticity [3]. Figure 9 shows as a first promising result, the momentum acceptance, expressed as the change in tune as a function of momentum deviation, for the present full lattice design consisting of arcs and straight sections. The combination of the local sextupole scheme in the IR and an optimised sextupole distribution in the arc design, yields a momentum acceptance sufficiently large to fulfil the requirements arising from the beamstrahlung lifetime [4].

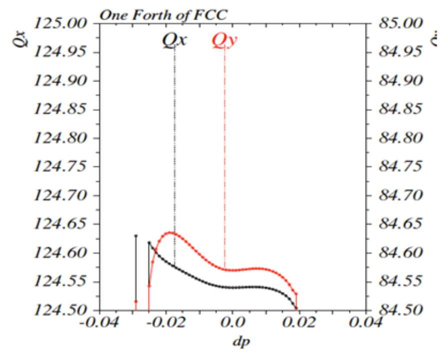

Figure 9: Tune variation as a function of the expected momentum spread on the beam. A value of $\Delta p/p \approx \pm 2\%$ is considered as sufficient.

CONCLUSION AND NEXT STEPS

The present design of the FCC-ee provides a highly flexible lattice, enabling the optimization of the machine optics for the large spectrum of desired operation energies. The layout of the single cell structure in the arc provides the foreseen beam emittances and the local sextupole arrangement in the straight sections of the mini-beta insertions allows for efficient correction of the chromaticity. The machine detector interface, especially the synchrotron radiation background created during the beam separation process are still under investigation, and so is the optimisation of a possible sextupole correction scheme for the longer cell designs at the low energy operation. The most critical requirements of momentum acceptance in a window of ±2% however are already within reach.

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