INTERACTION REGION LATTICE FOR FCC-EE (TLEP)*

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Abstract

FCC-ee (TLEP) project is high-luminosity e^+e^- collider and is an essential part of the Future Circular Collider (FCC) design study at CERN [1–3]. FCC-ee is being designed to reach center-of-mass energy from 90 to 350 GeV with circumference of 80-100 km to study Higgs boson properties and perform precise measurements at the electroweak scale. It is also an intermediate step towards 100 TeV proton-proton collider built in the same tunnel. Some of the limiting factors of the new collider are total energy loss due to synchrotron radiation, beam lifetime degradation owing to beamstrahlung, geometry of the tunnel required to accommodate the successor. The present paper describes linear lattice of interaction region and results of nonlinear beam dynamics study.

INTRODUCTION

One of the limiting factors of the new collider is beamstrahlung [4, 5]. Considering this effect there were several sets of parameters to achieve high luminosity and feasible beam lifetime. The first one is based on head-on collisions [6], the second is relying on crab waist collision scheme [7, 8] with crossing angle $2\theta = 30$ mrad. Both sets implement the same values of beta functions at the interaction point (IP): $\beta_x^* = 0.5$ m, $\beta_y^* = 0.001$ m. Advantages of the crab waist set are higher luminosity and crossing angle that provides natural separation of the bunches. The list of parameters relevant to present work is given in Table 1.

Lattice of the interaction region (IR) should satisfy several requirements:

1. since successor to FCC-ee is proton accelerator, the IR tunnel should be as straight as possible;
2. small values of IP beta functions produce large chromaticity, which should be compensated as locally as possible in order to minimize excitation of nonlinear chromaticity;
3. synchrotron radiation power loss should be significantly smaller than in the arcs;
4. synchrotron radiation at high energy will produce flux of high energy gamma quanta, therefore the lattice should minimize the detector background;
5. small beta functions at IP enhance effects of nonlinear dynamics, decreasing dynamic aperture and energy acceptance of the ring, therefore the lattice should be optimized to provide large dynamic aperture and energy acceptance.

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Table 1: Relevant Parameters for Crab Waist IR [7]

	Z	W	H	tt
Energy [GeV]	45	80	120	175
Perimeter [km]	100			
Crossing angle [mrad]	30			
Particles per bunch [10^{11}]	1	4	4.7	4
Number of bunches	29791	739	127	33
Energy spread [10^{-3}]	1.1	2.1	2.4	2.6
Emittance hor. [nm]	0.14	0.44	1	2.1
Emittance ver. [pm]	1	2	2	4.3
β_x^*/β_y^* [m]	0.5 / 0.001			
Luminosity / IP [$10^{34}\ cm^{-2}s^{-1}$]	212	36	9	1.3
Energy loss / turn [GeV]	0.03	0.3	1.7	7.7

FINAL FOCUS QUADRUPOLES

The first final focus (FF) quadrupole strength scales with distance from interaction point as $K_1L = -2/L^*$, chromaticity produced by the same quadrupole is $\mu' = -L^*/\beta^*$. Thus, in order to reduce chromaticity it is better to have smaller L^*, but minimum distance is defined by minimizing the solid angle taken from the detector by quadrupoles, cryogenic equipment, anti-solenoids etc. Having the minimum distance the maximum reliably achievable gradient defines the quadrupole length. In the present study we demanded the quadrupole strength to be lower than 100 T/m, which is a very relaxed condition. We also chose $L^* = 2$ m which at the present moment looks like a good compromise between beam dynamics [9] and detector constraints. Particles trajectories from IP through the FF doublet are shown on Figure 1 together with lines at several angles representing detector blind spot and bare apertures of the quadrupoles. Quadrupole parameters at $E = 175$ Gev are presented in Table 2.

Table 2: Parameters of FF Quadrupoles at 175 GeV

	L [m]	G [T/m]
Q0	3.6	-94.5
Q1	2	93.3

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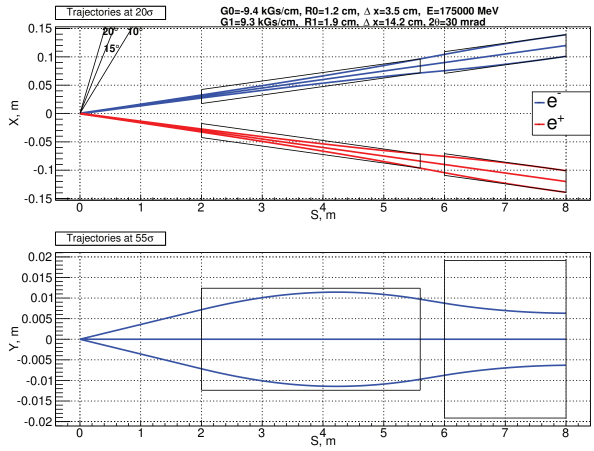

Figure 1: Trajectories of e^- and e^+ bunches from IP through FF quadrupoles. Several lines are drawn at 10°, 15°, 20° to represent blind solid angle of the detector. Black rectangles over trajectories depict bare quadrupole apertures.

LATTICE

The IR lattice should provide desired values of optical functions at IP and compensate geometrical and chromatic aberrations defining dynamic aperture (DA) and energy acceptance of the ring. The optics of IR consist of several blocks each having an intrinsic property of telescopic transformation: FFT — final focus telescope, CCSY and CCSX — chromaticity corrections section in horizontal (X) and vertical (Y) planes, CRAB — section that provides necessary phase advances and optical functions for sextupole from crab waist scheme [8]. The first dipole from IP is split in two, one closer to IP having a smaller field than the the further. Tuning of these dipoles allows to minimize synchrotron radiation background in the detector. The elements and optical functions are shown on Figure 2, optical blocks are also marked.

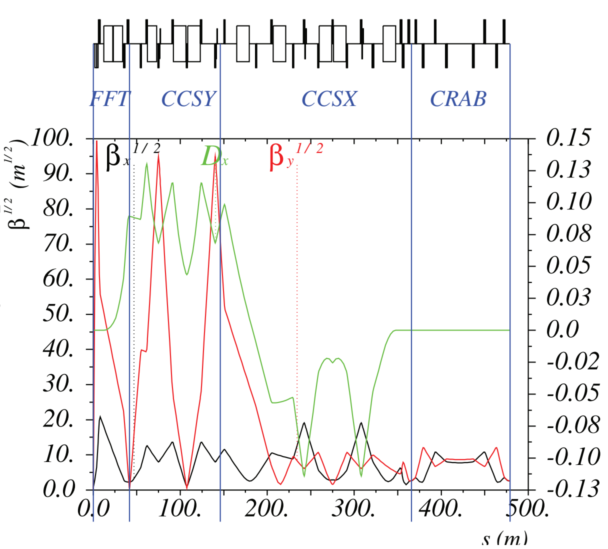

Figure 2: Optical functions of IR. IP is at the origin. Divergence of the beam lines is 7.3 mrad.

The overall geometry of the beam lines is shown on Figure 3. The divergence angle between beam lines is 7.3 mrad and will be intercepted by matching section to bring the beams into the arc.

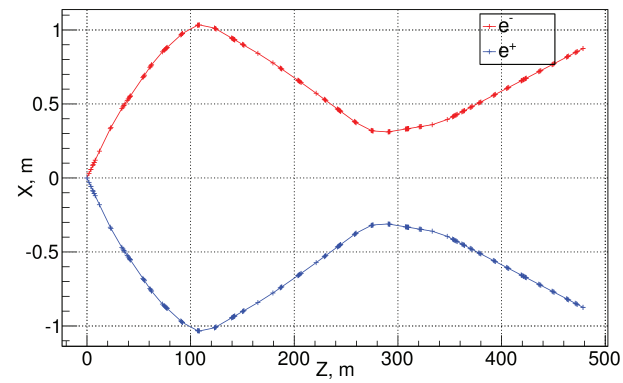

Figure 3: Layout of the electron and positron beam lines. IP is at the origin.

Synchrotron radiation energy loss for the whole IR from one arc to the other is $2 \cdot 0.11 = 0.22$ GeV at beam energy of 175 GeV. The relative power loss of four IPs with respect to the arcs is then $4 \cdot 0.22/7.7 = 0.11$.

CHROMATICITY

The measure of chromaticity correction is Montague functions [10], which are shown on Figure 4.

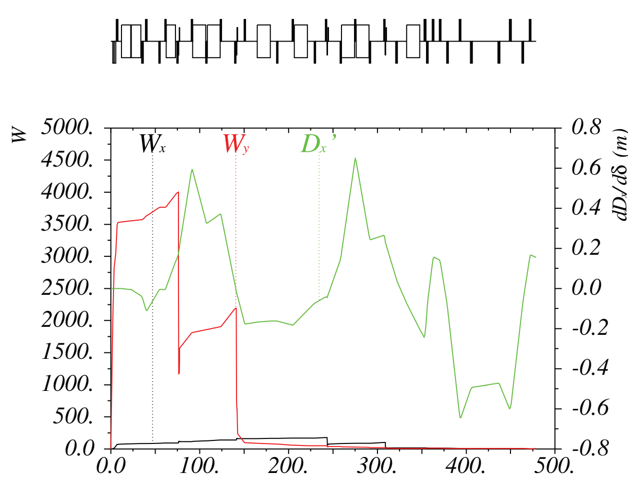

Figure 4: Chromatic (Montague) functions and nonlinear dispersion.

It is also possible to estimate second and third order derivatives of phase advances with respect to relative energy deviation δ. Expanding tune dependence with respect to energy deviation we obtain

$$Q(\delta) = Q_0 + Q_0'\delta + Q_0''\frac{\delta^2}{2} + Q_0'''\frac{\delta^3}{6} + \ldots ,$$
$$Q'(\delta) = Q_0' + Q_0''\delta + Q_0'''\frac{\delta^2}{2} + \ldots , \quad (1)$$

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where "′" denotes $d/d\delta$. Assuming that $Q_0' = 2$ and each higher order term contribution should be less than one for energy deviation equal the relative beam energy spread $\sigma_\delta = \sigma_E/E = 2.5 \cdot 10^{-3}$ (at $E = 175$ GeV) we obtain

$$|Q_0''| < \frac{1}{\sigma_\delta} \approx 400\,,$$
$$|Q_0'''| < \frac{2}{\sigma_\delta^2} \approx 3.2 \cdot 10^5\,. \qquad (2)$$

Not having a closed ring with realistic arcs makes our estimations rough, but still they give a number to look for. Obtained chromaticities of tune from IP to the end of IR are given in Table 3. Shifting the sextupoles pairs in phase relative to corresponding FF quadrupole we minimized the second order chromaticities and satisfied our rough estimation in (2), results are shown in Table 3.

Table 3: Chromaticity of Phase Advances from IP to the End of IR

	Sextupoles in phase	Sextupoles shifted in phase
Q_x	4	
Q_x'	-3.62	-3.94
Q_x''	-278	-169
Q_x'''	$-2.4 \cdot 10^3$	$-3.1 \cdot 10^3$
Q_y	3	
Q_y'	-2.5	-2.4
Q_y''	$1.5 \cdot 10^3$	300
Q_y'''	$-3.9 \cdot 10^4$	$-3.9 \cdot 10^4$

DYNAMIC APERTURE

We closed both shoulders of IR with the linear map providing the fractional tunes $\nu_x = 0.54$ $\nu_y = 0.57$ in order to track particles through such a structure ind study dynamic aperture. Optimization of sextupole's strengths gave the aperture of $R_x > 100 \cdot \sigma_x$ and $R_y > 200 \cdot \sigma_y$ (Figure 5).

CONCLUSION

We developed interaction region lattice with crossing angle for crab waist collision scheme. Geometrical layout, synchrotron radiation energy loss requirements are satisfied. Chromatic aberrations are compensated and satisfy estimations. Estimation of dynamic aperture is done and found sufficient. Since, IP parameters are the same as in head-on collision scheme the lattice could be used without crab sextupole section in head-on collision scenario.

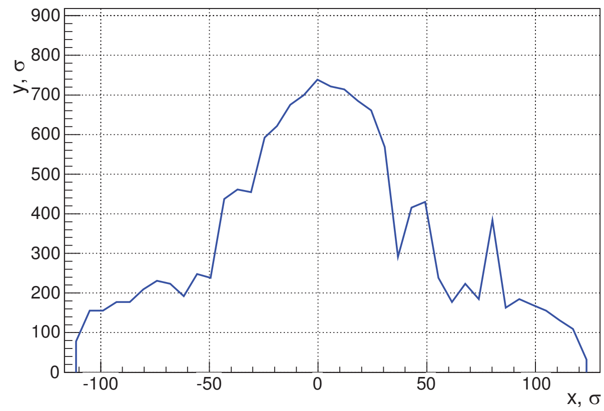

Figure 5: Dynamic aperture of the interaction region closed by the linear map $\sigma_x = 3.26 \cdot 10^{-5}$ m, $\sigma_y = 6.52 \cdot 10^{-8}$ m.

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