INTERACTION REGION FOR CRAB WAIST SCHEME OF THE FUTURE ELECTRON-POSITRON COLLIDER (CERN)*

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Abstract

Design study in CERN of the accelerator that would fit 80-100 km tunnel called Future Circular Colliders (FCC) includes high-luminosity e^+e^- collider (FCC-ee) with center-of-mass energy from 90 to 350 GeV to study Higgs boson properties and perform precise measurements at the electroweak scale [1–3]. Crab waist interaction region provides collisions with luminosity higher than $2 \times 10^{36}\ cm^{-2} sec^{-1}$ at beam energy of 45 GeV. The small values of the beta functions at the interaction point and distant final focus lenses are the reasons for high nonlinear chromaticity limiting energy acceptance of the whole ring. The paper describes interaction region for crab waist collision scheme in the FCC-ee, principles of tuning the chromaticity correction section in order to provide large energy acceptance.

INTRODUCTION

One of the limiting factors of high energy e^+e^- collider (FCC-ee) is beamstrahlung [4–6], which limits the beam life time. Consideration of this effect by different authors gave several sets of parameters to achieve high luminosity and feasible beam lifetime. The first one is based on head-on collisions [7], the second is relying on crab waist collision scheme [6, 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 and require energy acceptance of the ring more than ±2% to provide feasible beam life time. Advantages of the crab waist set are higher luminosity (7.5 times at 45 GeV) and crossing angle that provides natural separation of the bunches. The list of parameters relevant to present work is in Table1.

Table 1: Relevant Parameters for Crab Waist IR [6]

	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

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

1. since successor to FCC-ee is proton accelerator, the IR tunnel should be straight;
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 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.

FINAL FOCUS QUADRUPOLES

The minimum distance from IP to the face of the first quadrupole is chosen to be $L^* = 2$ m which at the present moment looks like a good compromise between beam dynamics [9] and detector constraints. 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. Particles trajectories from IP through the FF doublet are on Figure 1 together with lines at several angles representing detector blind spot and rectangles for bare apertures of the quadrupoles. Quadrupole parameters length, gradient and radius of aperture at $E = 175$ Gev are presented in Table 2. The distance between bare apertures for the first quadrupoles is 3.5 cm, for the second pair the distance is 14.2 cm.

LATTICE

The IR lattice should provide desired values of optical functions at IP and compensate geometrical and chromatic aberrations which define dynamic aperture (DA) and energy acceptance of the ring. The optics of IR consists of sev-

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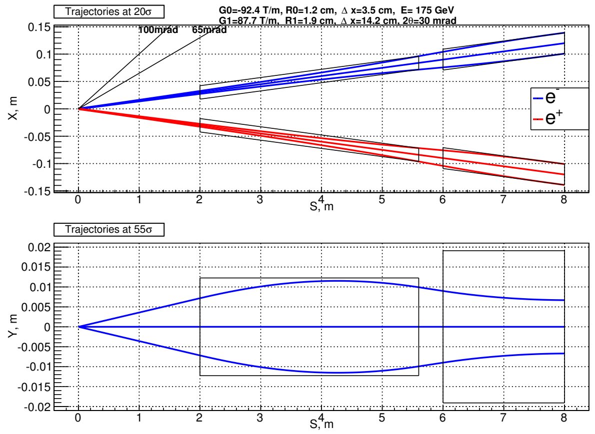

Figure 1: Trajectories of e^- and e^+ bunches from IP through FF quadrupoles. Several lines are drawn at 10°, 15°, 20° to represent blind solid angle of the detector. Black rectangles over trajectories depict bare quadrupole apertures.

Table 2: Parameters of FF Quadrupoles at 175 GeV

	L [m]	G [T/m]	R [m]
Q0	3.6	-94.5	0.012
Q1	2	93.3	0.019

eral blocks each having an intrinsic property of telescopic transformation: FFT — final focus telescope, CCSY and CCSX — chromaticity corrections section in vertical (Y) and horizontal (X) planes, CRAB — section that provides necessary phase advances and optical functions for crab waist sextupole [8]. The first dipole from IP is split in two, one closer to IP having a smaller field than the the other. Redistribution of the field between the dipoles gives a useful knob to minimize synchrotron radiation background in the detector. The elements and optical functions are on Figure 2. The overall geometry of the beam lines is on Figure 3.

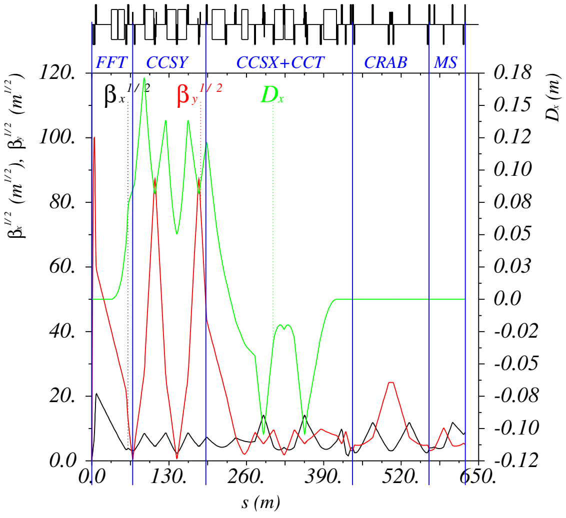

Figure 2: Optical functions of IR (version 6-14-3).

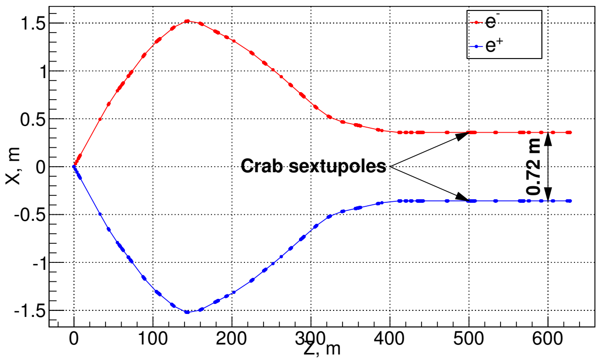

Figure 3: Layout of the electron and positron beam lines.

Synchrotron radiation energy loss for the whole IR from one arc to the other is $2 \cdot 0.1 = 0.2$ GeV at beam energy of 175 GeV. The relative power loss of four IPs with respect to the arcs is then $4 \cdot 0.2/7.7 = 0.1$.

CHROMATICITY

Chromaticity is corrected by pairs of sextupoles with -I map within the pair to minimize geometrical aberrations. There are two chromatical sections with sextupoles adjusted to be in corresponding betatron phase $(2n + 1)\pi$ away from the center of the appropriate FF quadrupole. The second order chromaticity is adjusted by shifting the sextupoles in phase slightly off the ideal $(2n + 1)\pi$ ($\Delta\mu_x = -0.01$, $\Delta\mu_y = -1 \cdot 10^{-5}$). The third order vertical chromaticity is corrected by additional sextupole installed at the end of FFT where the first order beta chromaticity is almost zero and second order is large (Figure 4). Chromatic functions [10] are on Figure 5. Obtained phase advance chromaticities are in Table 3. Tunes variation for one quarter of the ring are on Figure 6 providing stable optics for energy deviation of [-3.9%;+1.9%].

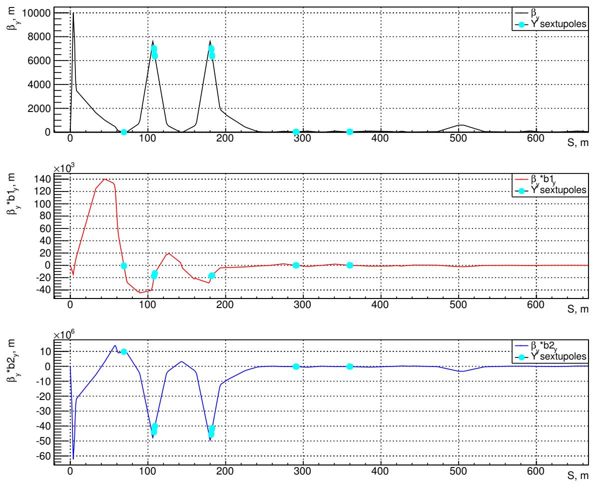

Figure 4: Vertical beta function (top), $\partial\beta_y/\partial\delta = \beta_y b_{1,y}$ (middle), $\partial^2\beta_y/\partial\delta^2 = \beta_y b_{2,y}$ (bottom).

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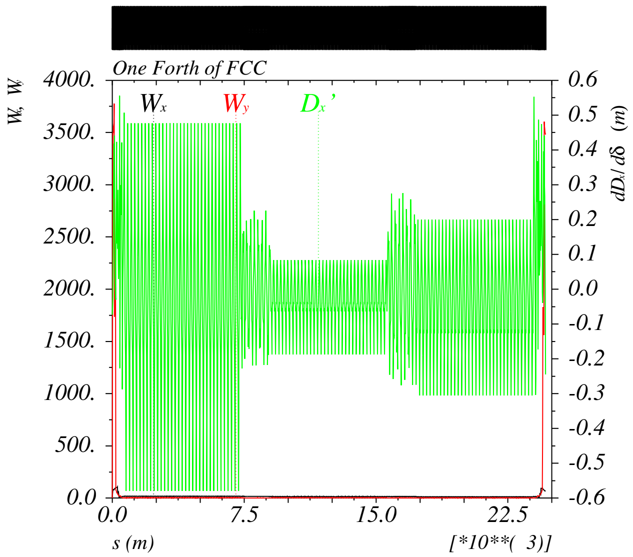
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Figure 5: Chromatic (Montague) functions and nonlinear dispersion for $\nu_x = 124.54$, $\nu_y = 84.57$.

Table 3: Chromaticity of phase advances from IP to the end of IR

	No additional sextupole	With additional sextupole
Q_x	124.54	124.54
Q'_x	0	0
Q''_x	170	170
Q'''_x	$-4.5 \cdot 10^4$	$-5.1 \cdot 10^4$
Q''''_x	$-5.3 \cdot 10^6$	$-4.8 \cdot 10^6$
Q_y	84.57	84.57
Q'_y	0	0
Q''_y	387	387
Q'''_y	$-5.3 \cdot 10^5$	$-1.4 \cdot 10^5$
Q''''_y	$-4.3 \cdot 10^6$	$1.9 \cdot 10^6$
Energy acceptance[%]	[-1.9;+0.8]	[-3.1;+1.9]

CONCLUSION

We developed interaction region lattice with 30 mrad crossing angle for crab waist collision scheme. Geometrical layout, synchrotron radiation energy loss requirements are satisfied. Shifting sextupoles in phase with respect to final focus quadrupoles proves to be efficient method to control second order chromaticity of the betatron phase advances. Introduction of additional sextupole four times weaker than the main sextupoles in the place with small value of beta function gives useful knob to control third order chromaticity. The energy acceptance for stable optics of one quarter of the ring is [-3.9%;+1.9%].

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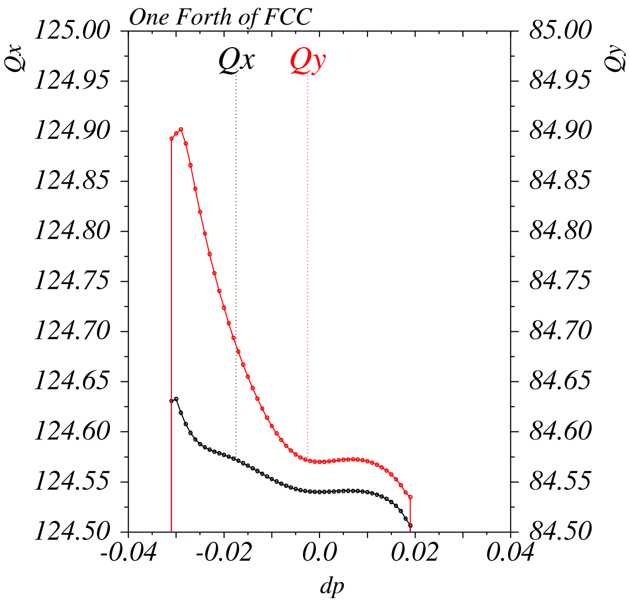

Figure 6: Phase advance variation with sextupoles shifted in phase and additional sextupole.

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