MOMENTUM ACCEPTANCE OPTIMIZATION IN FCC-ee LATTICE (CERN)[*]

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Abstract

The part of the ongoing study of the future circular collider (FCC) [1] is an electron positron machine with center of mass energy from 90 to 350 GeV. Crab waist collision scheme [2, 3] and small (1 mm) vertical beta function at the interaction point (IP) provide superior luminosity. At the top energy, radiation in the field of the opposite bunch (beamstrahlung) [3–5] limits the beam lifetime and therefore achievable luminosity. Beamstrahlung influence depends on momentum acceptance of the lattice, and acceptance of 2% provides acceptable lifetime. The small value of vertical beta function enhances effects of nonlinear chromaticity. The present work describes principles used in design and optimization of FCC-ee momentum acceptance optimization.

INTRODUCTION

The beam lifetime of the future circular collider (FCC) [1] at beam energy of 175 Gev is limited by beamstralung [3–5]. To attain feasible beam lifetime lattice of the collider should provide momentum acceptance of 2%. This is only possible with local chromaticity correction sections. Geometrical constraints of the interaction region (IR), optical requirements of chromaticity correction sections and a need for low synchrotron radiation (SR) background in the detector limit the maximum dispersion function in the sextupoles hence raising the sextupoles strength. The sextupoles, final focus quadrupoles fringes and kinematic term in the IP with extremely small vertical beta function increase effects of nonlinear dynamics. The obvious remedy of moving the final quadrupole closer to interaction point (IP) is not possible because of detector equipment. Crossing angle is a necessary condition of the crab waist collision; small decrease of the angle relaxes geometrical constraints of the IR tunnel therefore we changed the crossing angle from 30 mrad to 26 mrad. IR lattice should satisfy several requirements:

1. must fit hadron collider tunnel 100 km long,
2. two interaction points (defined by FCC-hh and price),
3. vertical emittance is less or equal than 1 pm at 45 GeV,
4. horizontal emittance is 1-2 nm at 175 GeV,
5. energy acceptance ±2%,
6. SR from the dipoles within 250 m from IP should have critical energy $E_{\gamma,c} \leq 100$ keV.

Table 1 presents parameters relevant for the present work.

Table 1: Relevant Parameters for Crab Waist IR [3]

	Z	W	H	tt
Energy [GeV]	45	80	120	175
Perimeter [km]	100			
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_{0x}/β_{0y} [m]	0.5 / 0.001			
Crossing angle [mrad]	30			
Luminosity / IP $[10^{34}\ cm^{-2}s^{-1}]$	212	36	9	1.3
Crossing angle [mrad]	26			
Luminosity / IP $[10^{34}\ cm^{-2}s^{-1}]$	255	43	10	1.4

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 [7] 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. Quadrupole parameters length, gradient and radius of aperture at $E = 175$ Gev are presented in Table 2. The distance between the bare apertures for the first quadrupoles is 2.6 cm, for the second pair the distance is 11.6 cm.

Table 2: Parameters of FF Quadrupoles at 175 GeV

	L [m]	G [T/m]	R [m]
Q0	3.6	-90.6	0.013
Q1	2	84.3	0.02

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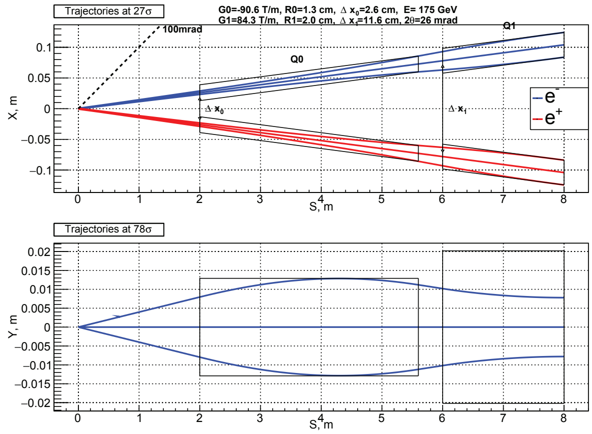

Figure 1: Trajectories of e^- and e^+ bunches from IP through FF quadrupoles. Black rectangles over trajectories depict bare quadrupole apertures.

LATTICE

Asymmetrical lattice (proposed by K. Oide) with weaker and longer dipoles for the incoming beam decreases SR critical energy towards IP, the stronger bending of the outgoing beam minimizes dimensions of the IR tunnel. The optics of IR consists of several blocks: 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 [2]. Figure 2 shows the elements and optical functions of the IR. The overall geometry of the beam lines is on Figure 3. Table 3 presents parameters and SR critical energy for the dipoles of the incoming beam line.

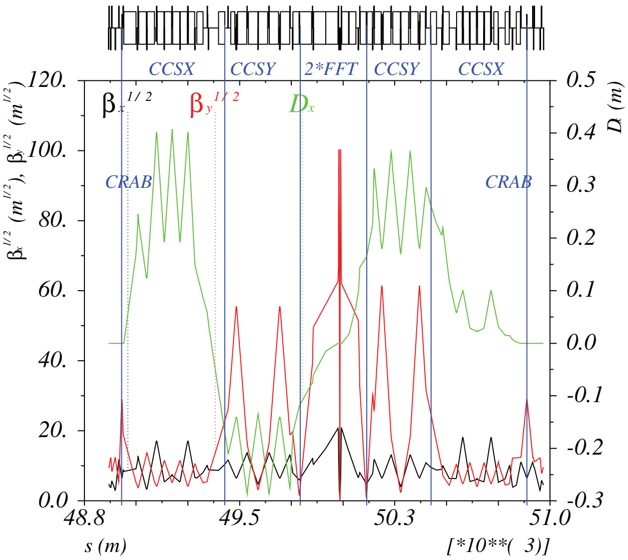

Figure 2: Optical functions of IR.

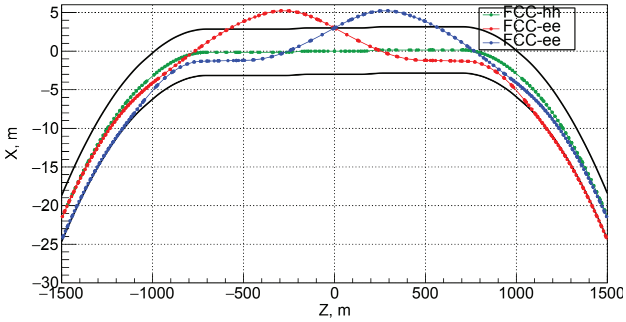

Figure 3: Layout of the electron and positron beam lines for 26 mrad crossing angle.

Table 3: The List of Names, Lengths and Position of the Furthest End from IP of the Dipoles and Critical Energy of the Synchrotron Radiation at 175 GeV.

	L [m]	S [m]	E_γ[keV]
B0	59	67.5	101
B1	59	127	101
B2	59	195	202
B3	30	226	311
B4	45	287	494

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 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). Obtained phase advance chromaticities are in Table 4. Tunes

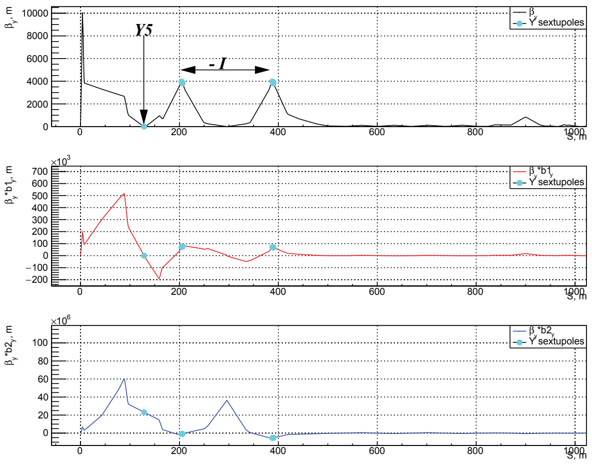

Figure 4: Vertical beta function (top), $\partial\beta_y/\partial\delta = \beta_y b_{1,y}$ (middle), $\partial^2\beta_y/\partial\delta^2 = \beta_y b_{2,y}$ (bottom).

variation of the ring are on Figure 5 providing stable optics for energy deviation of [-2.1%;+1.4%].

Table 4: Chromaticity of Phase Advances from IP to the End of IR

	No additional sextupole	**With additional sextupole**
Q_x	393.098	393.098
Q'_x	0	0
Q''_x	-441	-53
Q'''_x	$-1.1 \cdot 10^5$	$-14 \cdot 10^3$
Q''''_x	$24 \cdot 10^6$	$-13 \cdot 10^6$
Q_y	293.154	293.154
Q'_y	0	0
Q''_y	-386	-100
Q'''_y	$-26 \cdot 10^5$	$-8.4 \cdot 10^3$
Q''''_y	$-8 \cdot 10^8$	$-2 \cdot 10^7$
Energy acceptance[%]	[-2.2;+0.5]	[-2.1;+1.4]

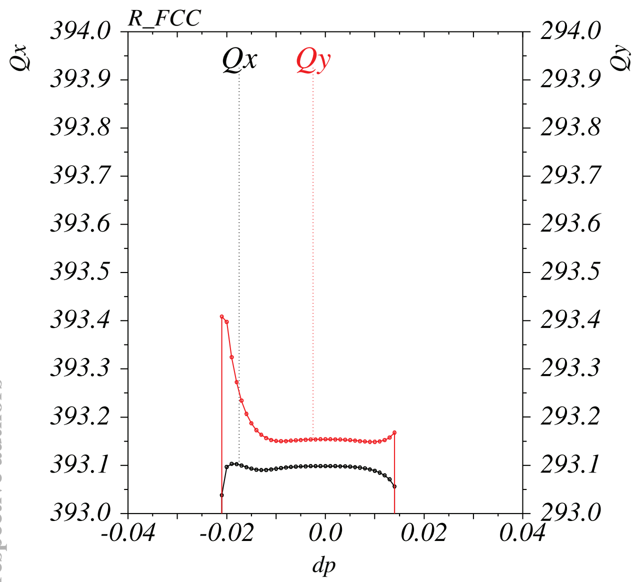

Figure 5: Phase advance variation with sextupoles shifted in phase and additional sextupole.

ESTIMATIONS OF DETUNING

Detuning coefficient of the vertical plane $\Delta\nu_y = \alpha_{yy} J_y + \alpha_{yx} Jx$ is a simplest characteristic to evaluate nonlinear properties of the lattice [6, 7]. Assuming that FF quadrupole changes sign of α_y we reckon its integrated strength $K_1 L_q \approx -2/\left(L^* + L_q/2\right)$ and chromaticity $\xi_y \approx -(1/2\pi)(L^* + L_q/2)/\beta_{0y}$, where L^* is a distance from IP to the face of the FF quadrupole and L_q is a length of the quadrupole. From the Hamiltonian of the kinematic term $\mathcal{H} = \left(P_x^2 + P_y^2\right)^2/8$ we figure out detuning coefficient for the drift between the FF quadrupoles $\alpha_{yy}^k \approx (3/16\pi)(L^* + L_q/2)/\beta_{0y}^2$. The Hamiltonian of the fringe field of FF quadrupole is $\mathcal{H} = K_1''\left(x^4 - y^4\right)^2/48$, and we derive $\alpha_{yy}^f \approx (1/2\pi)L^{*3}/\left(L_q(L^* + L_q/2)\beta_{0y}^2\right)$. The "$-\mathcal{I}$" pair [7, 8] of chromatic sextupoles gives $\alpha_{yy}^{sp} \approx -\frac{\pi}{4}\frac{L_s}{d_x^2}\xi_y^2$. The Table5 compares analytical estimations of detuning coefficients with ones calculated by MADX PTC.

Table 5: Comparison of Detuning Coefficients

	Kinematic	**Fringe**	**Sextupole pairs**
		Estimation	
$\alpha_{yy}[\mathrm{m}^{-1}]$	9.1×10^5	3.7×10^5	-2.4×10^7
		MADX PTC	
$\alpha_{yy}[\mathrm{m}^{-1}]$		3.9×10^5	-3.7×10^6
$\alpha_{yx}[\mathrm{m}^{-1}]$		2.2×10^4	-3.2×10^4
$\alpha_{xx}[\mathrm{m}^{-1}]$		7.8×10^2	-6.2×10^2

CONCLUSION

We developed interaction region lattice with 26 mrad crossing angle for crab waist collision scheme. Staging of the SR critical energy partially satisfies the requirement but gives the smaller IR tunnel. Introduction of additional sextupole weaker (≈ 15%) 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 the whole ring is [-2.1%;+1.4%].

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