Crab waist interaction region for FCC-ee and the arc (one quarter of the ring IR: v. 6-14-3, arc: v16)

A. Bogomyagkov

Budker Institute of Nuclear Physics
Novosibirsk

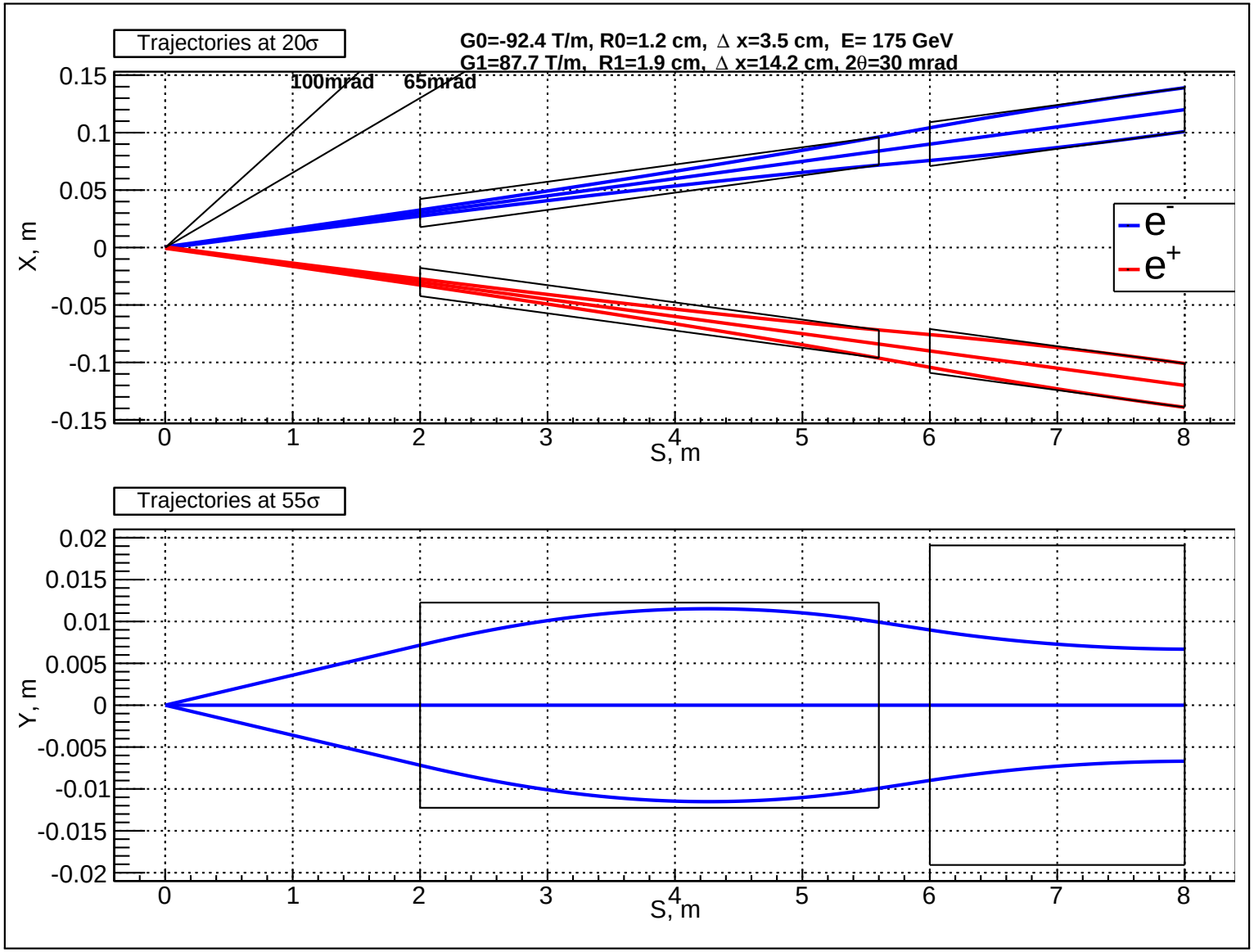
12 June, 2015

Parameters for crab waist

	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

PHYS. REV. S.T. - AB 17, 041004 (2014)

Final Focus layout



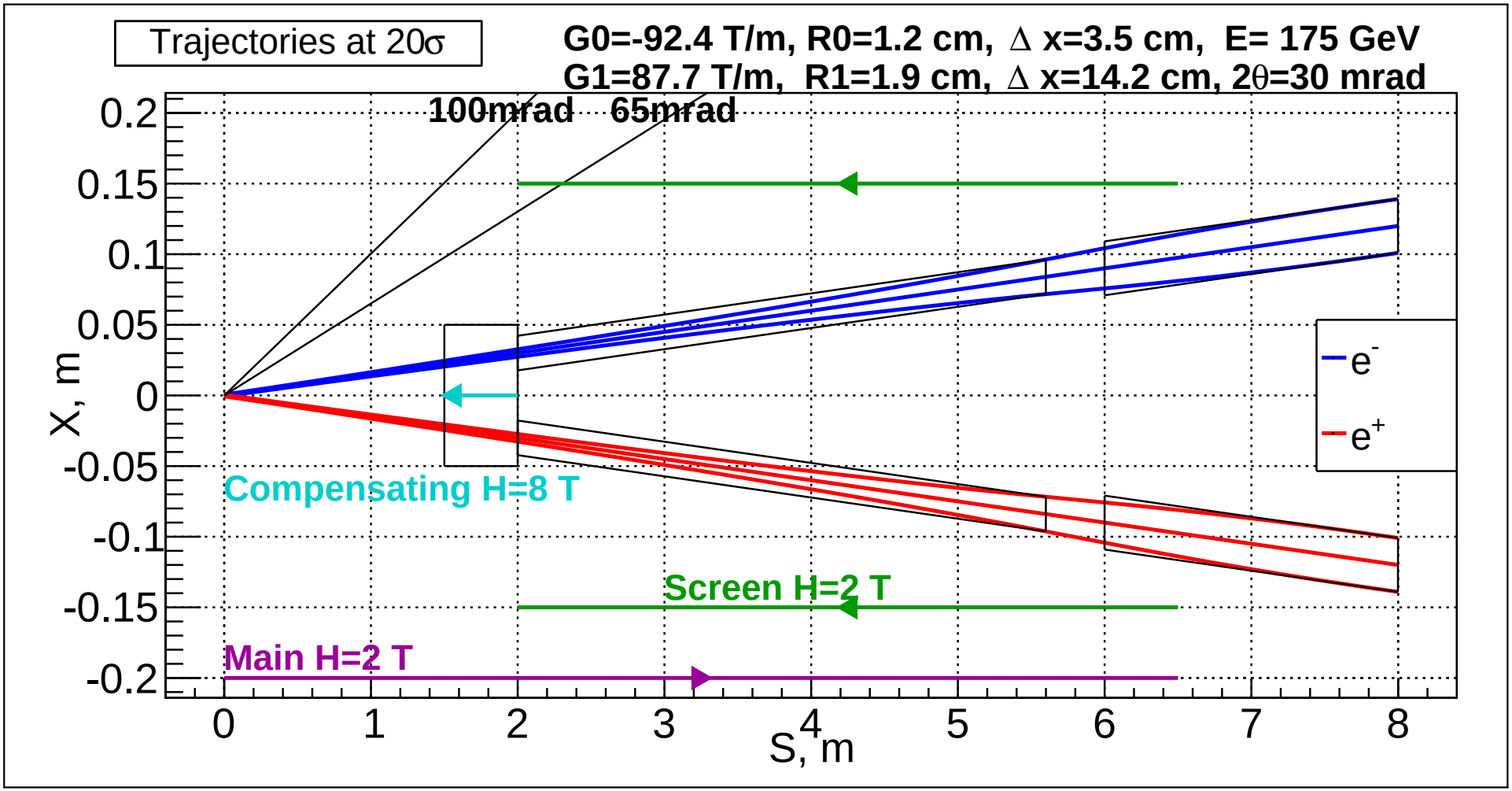
Rectangles are bare apertures.

	L [m]
Q0	3.6
Q1	2

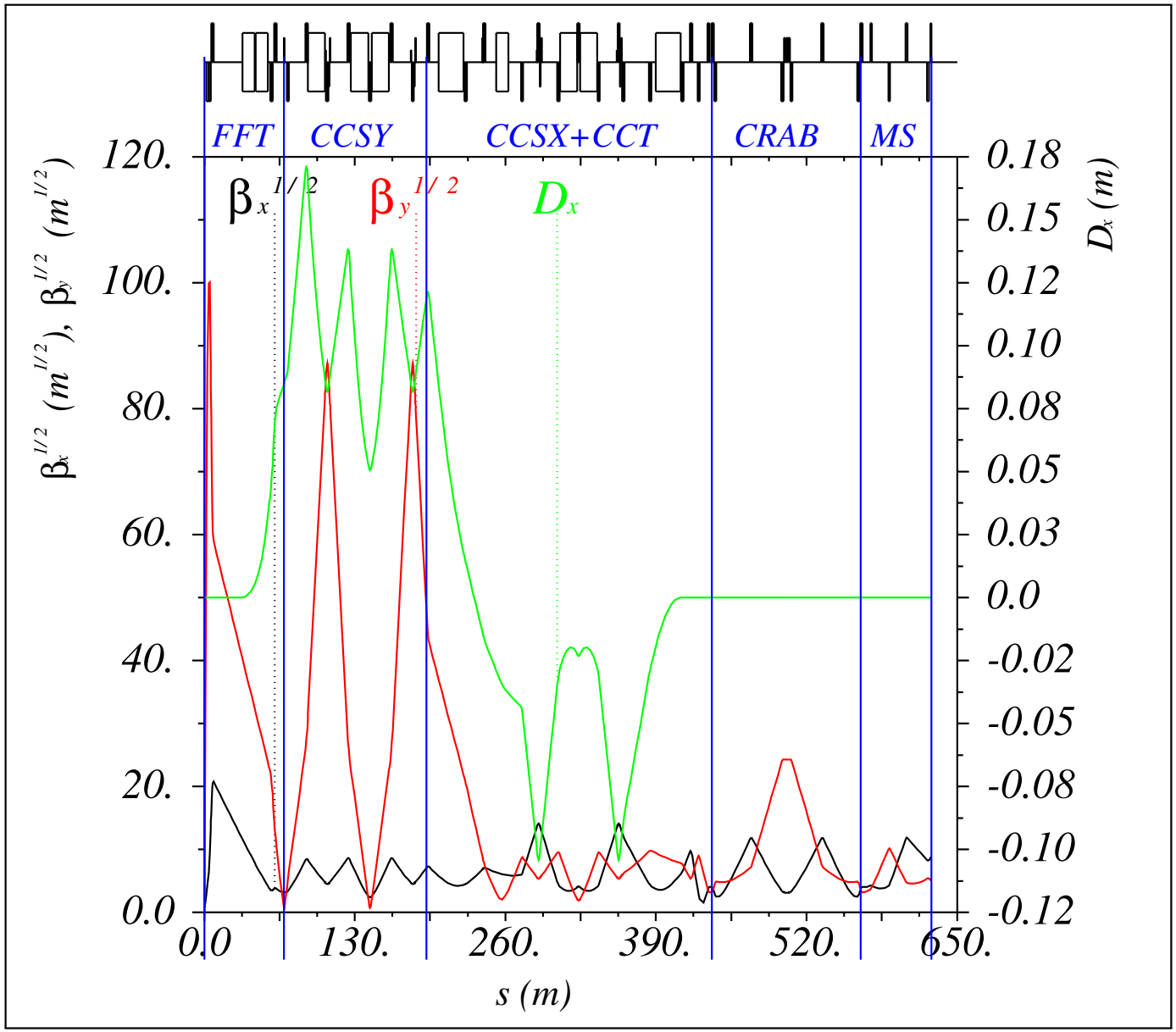
	R [m]
Q0	0.012
Q1	0.019

	B [T]
Q0	1.1
Q1	1.7

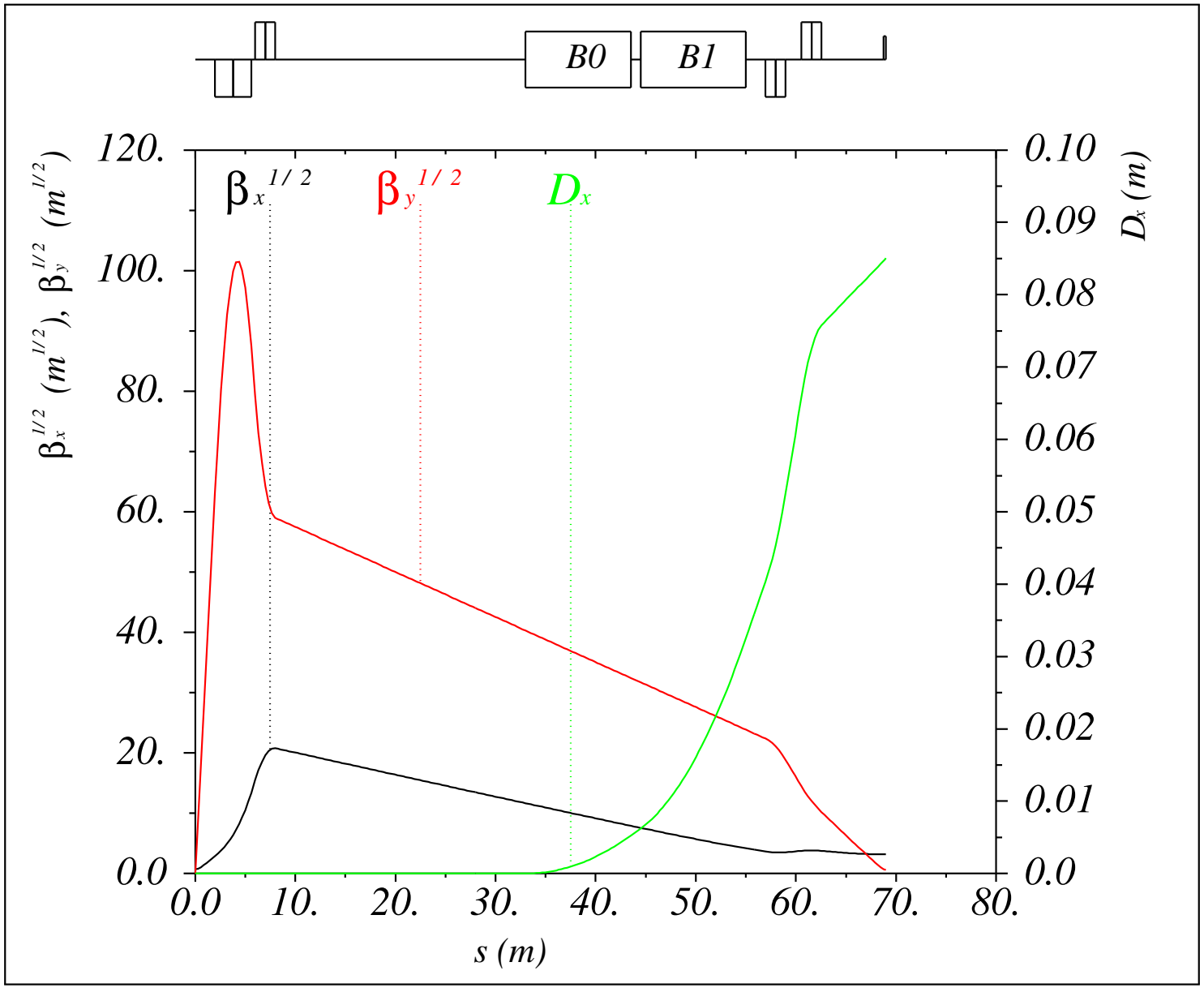
Final Focus layout: sketch of solenoids



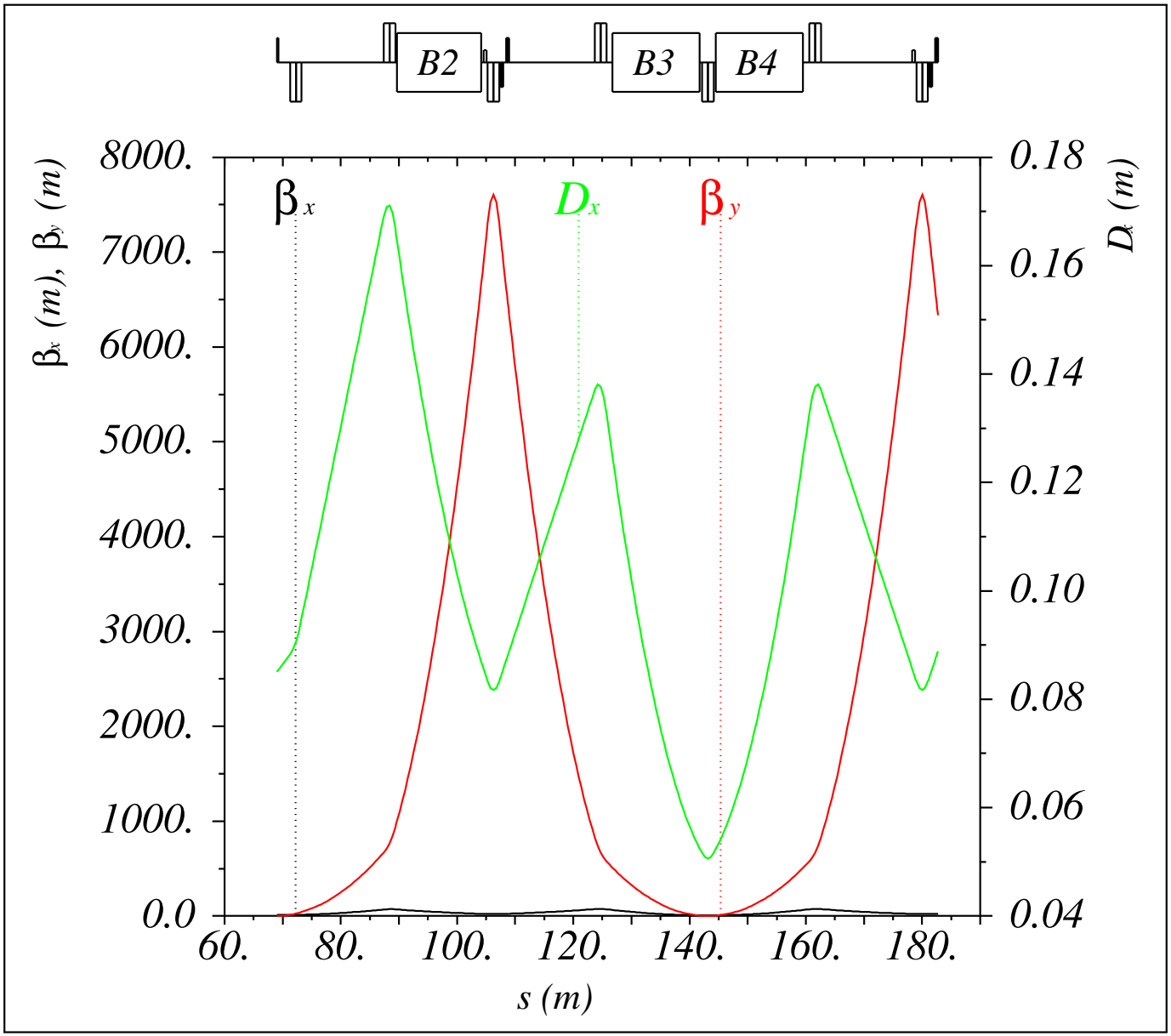
Interaction Region optical functions



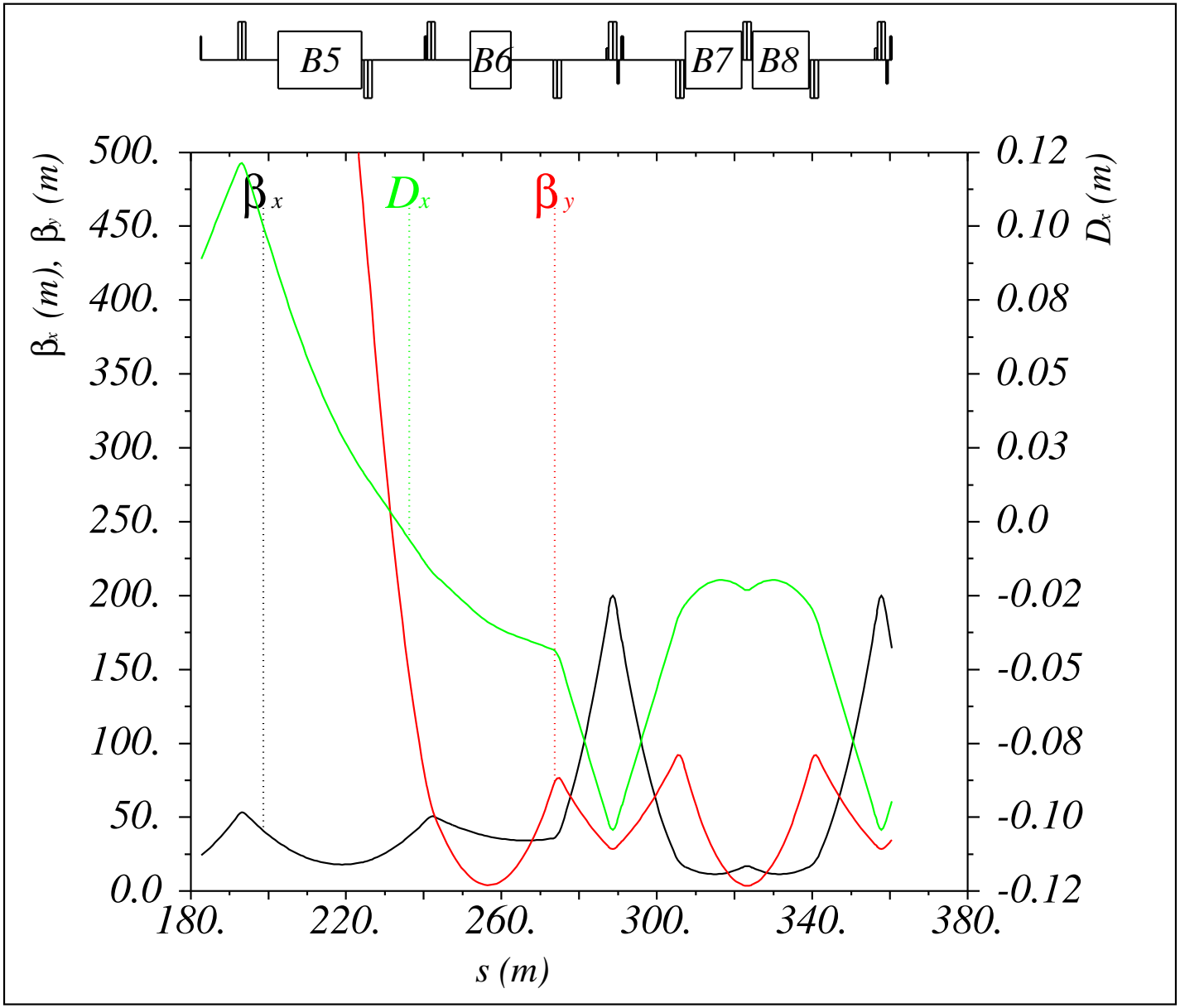
Final Focus Telescope



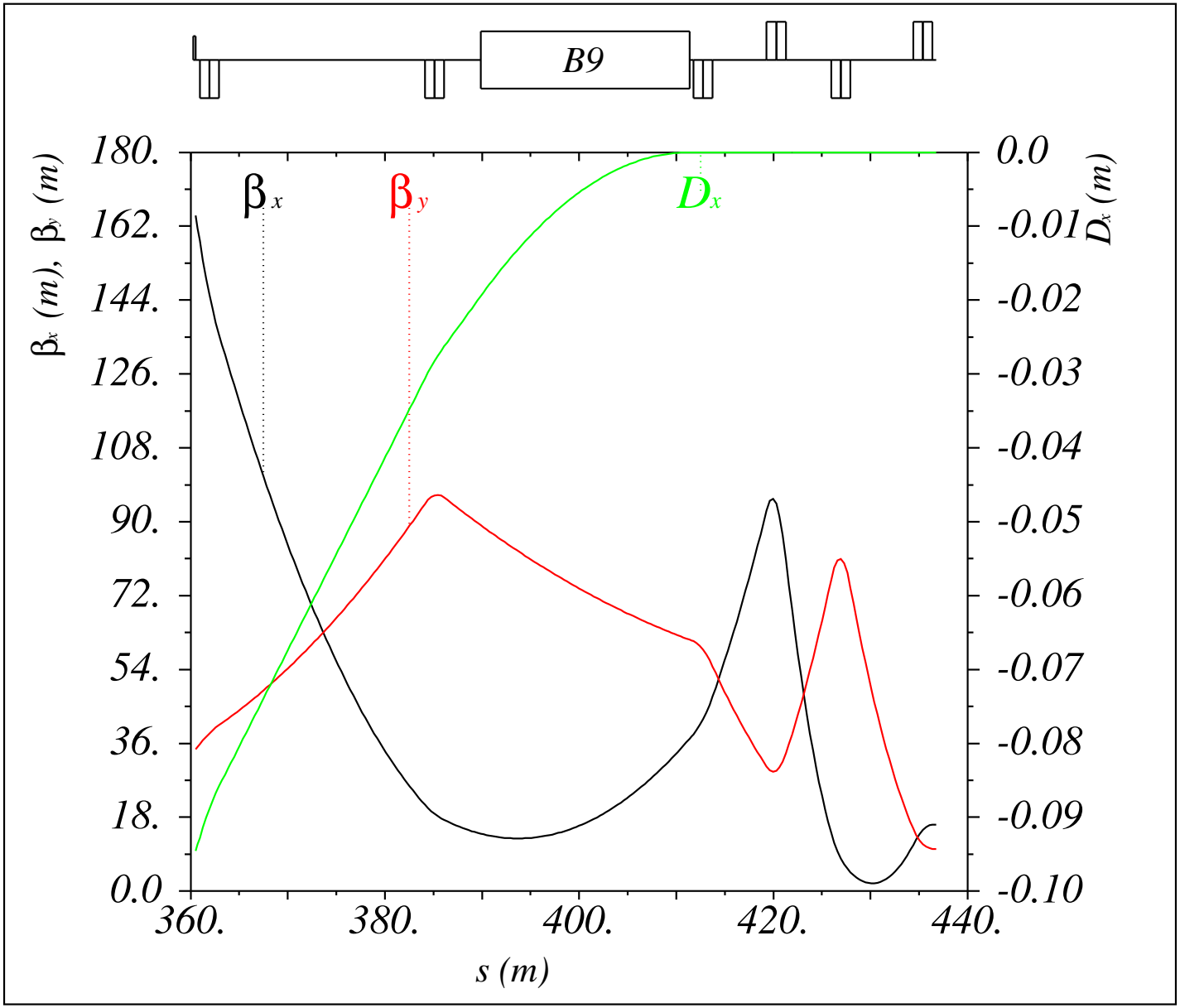
Y Chromaticity Correction Section



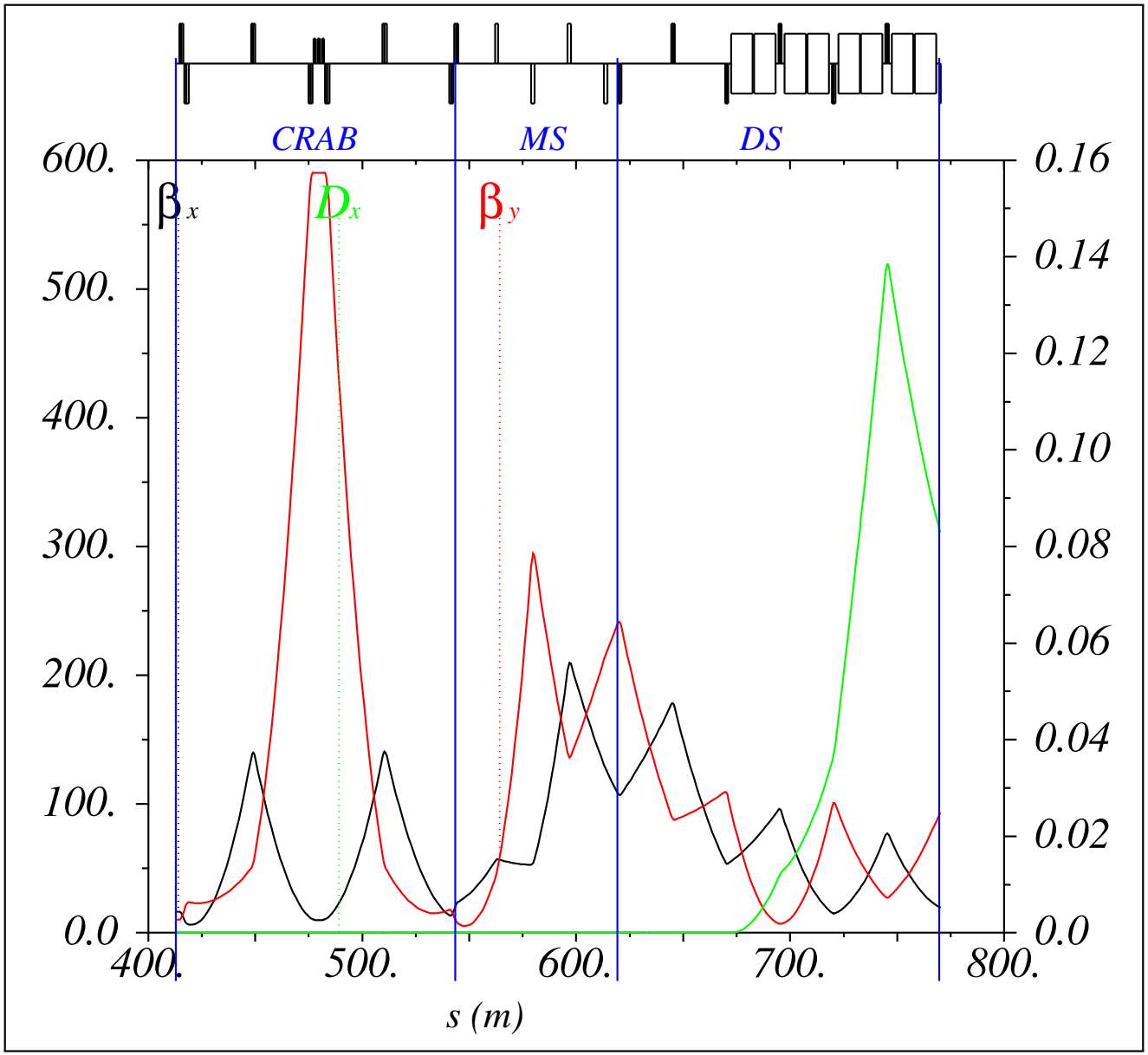
X Chromaticity Correction Section



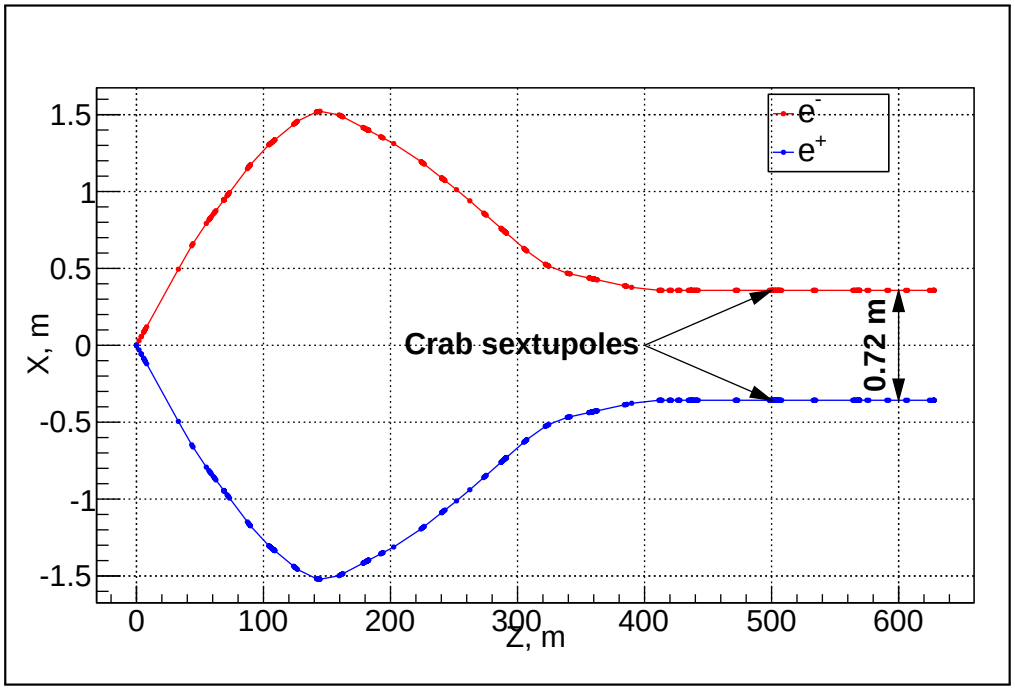
Chromaticity Correction Telescope



CRAB, MS, DS sections



Interaction Region layout



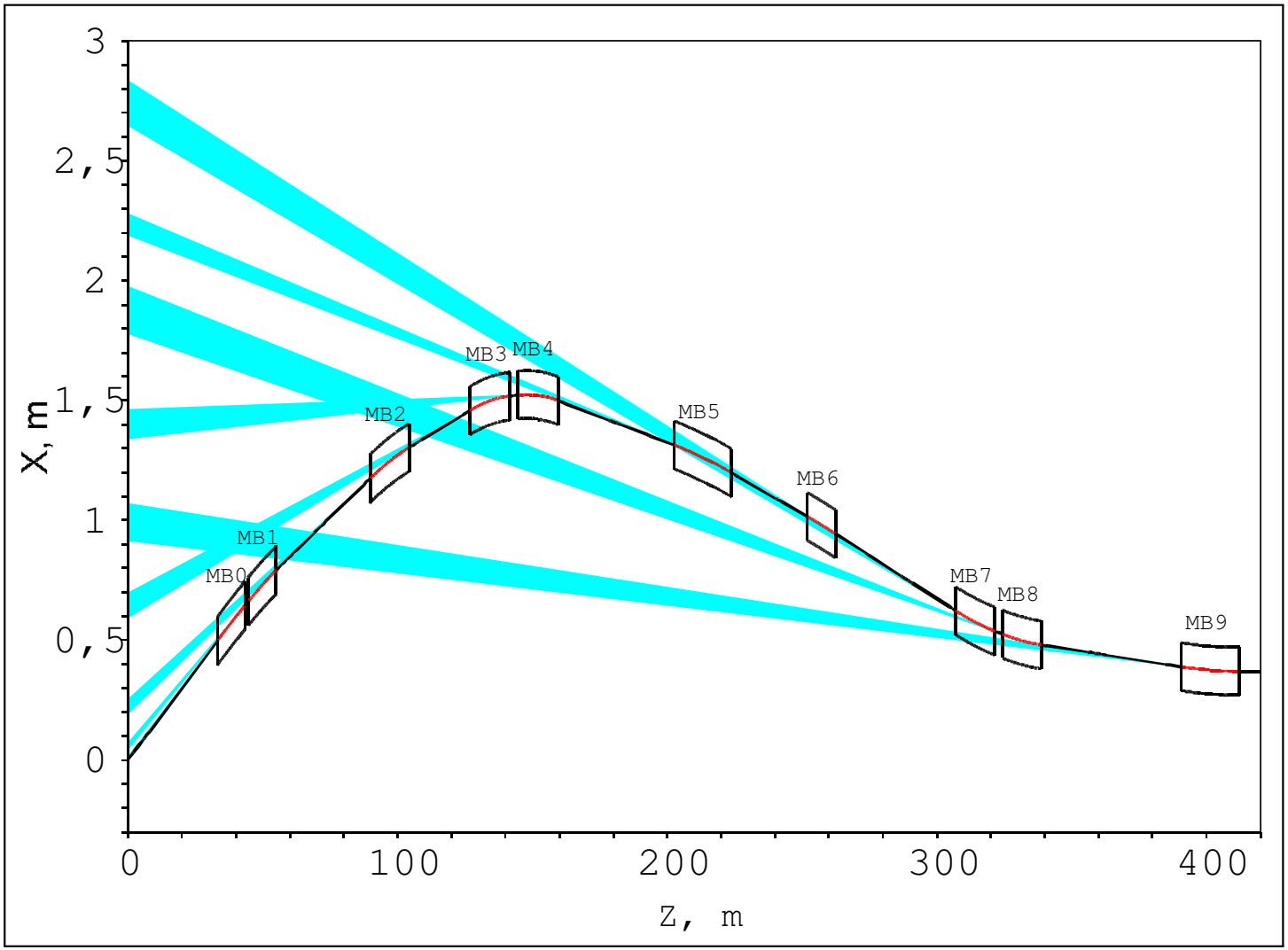
Energy loss $\Delta U = 0.1$ GeV

	L [m]	B [T]	ϕ [mrad]
B0	10.5	0.06	1
B1	10.5	0.17	3
B2	14.5	0.17	4.2
B3	15	0.22	5.6
B4	15	0.22	5.6
B5	21.5	0.06	2.2
B6	10.5	0.04	0.7
B7	14.5	-0.11	-2.7
B8	14.5	-0.11	-2.7
B9	21.5	-0.05	-1.8

Requirement

The tunnel should be straight in order to accommodate IR for FCC-pp!

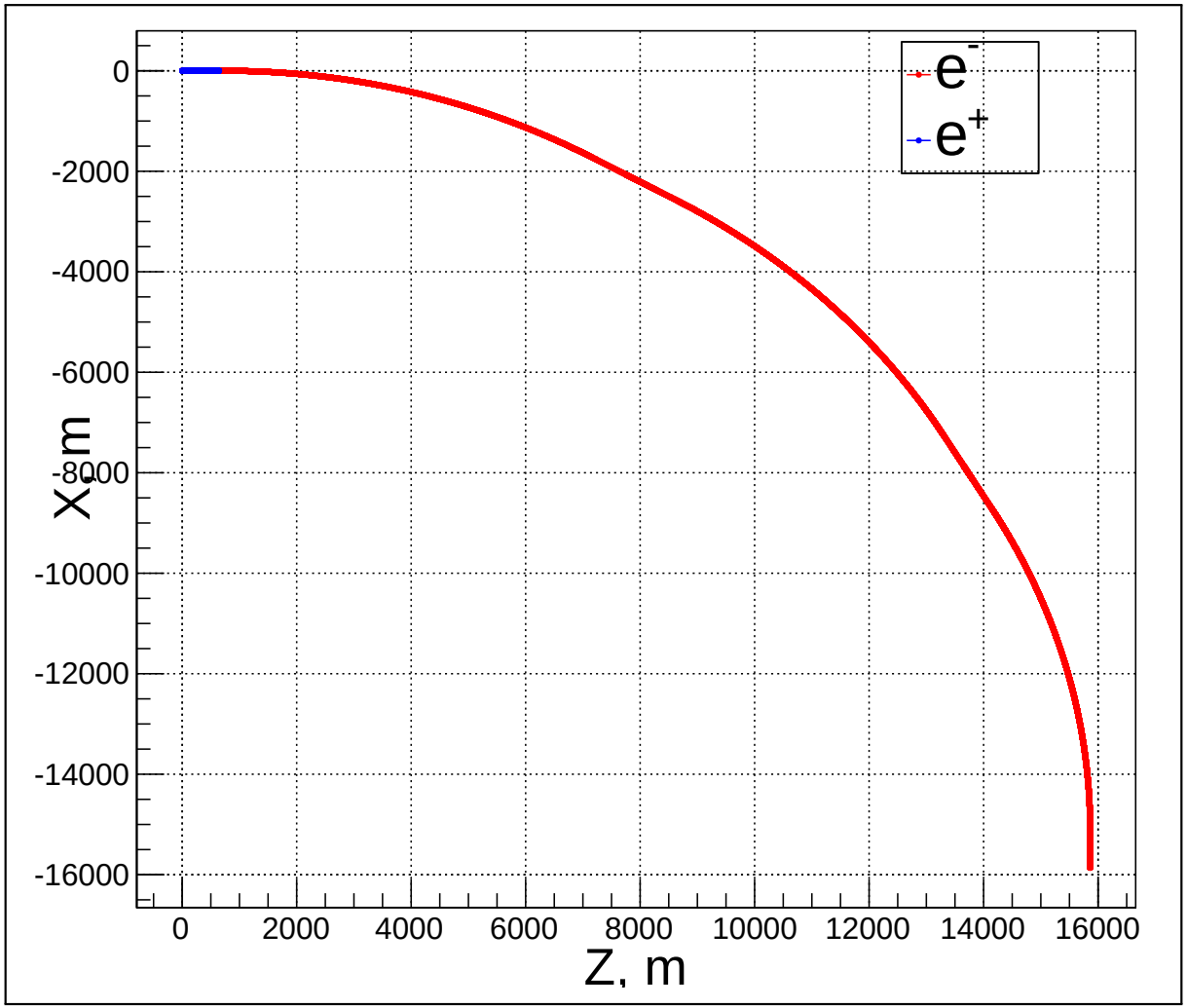
Synchrotron radiation fans from S. Glukhov



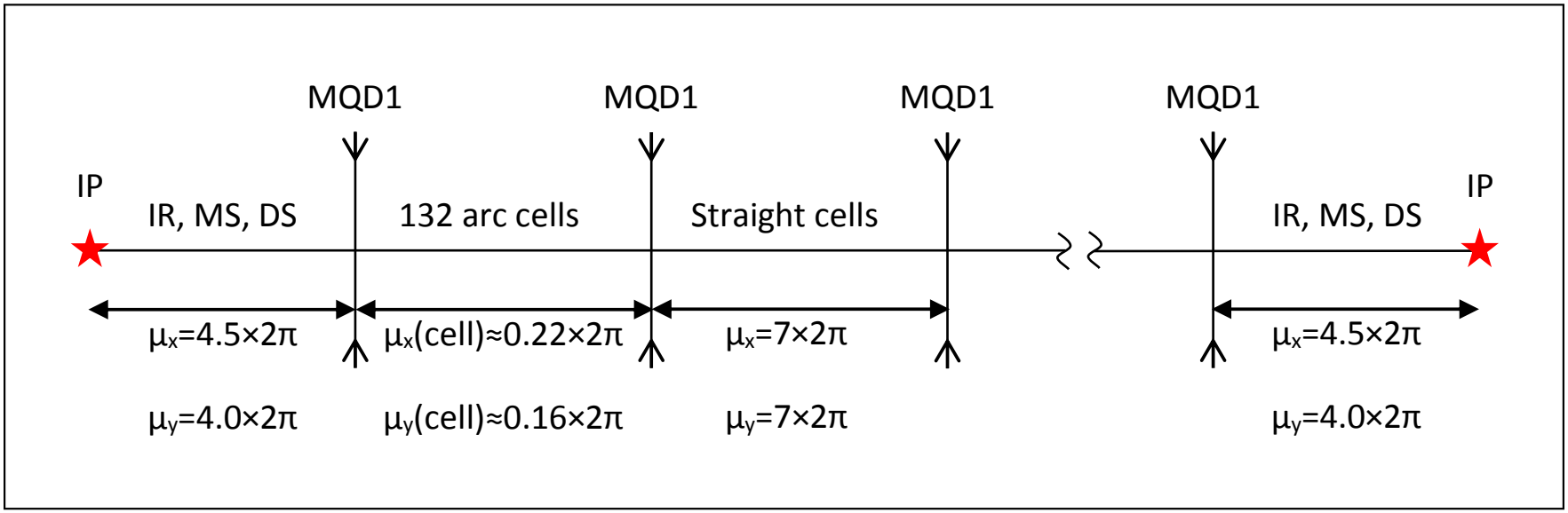
$E_b = 175$ GeV

	E_γ, keV
B0	1132
B1	3397
B2	3416
B3	4428
B4	4428
B5	1218
B6	827.1
B7	2238
B8	2238
B9	1002

Quarter layout



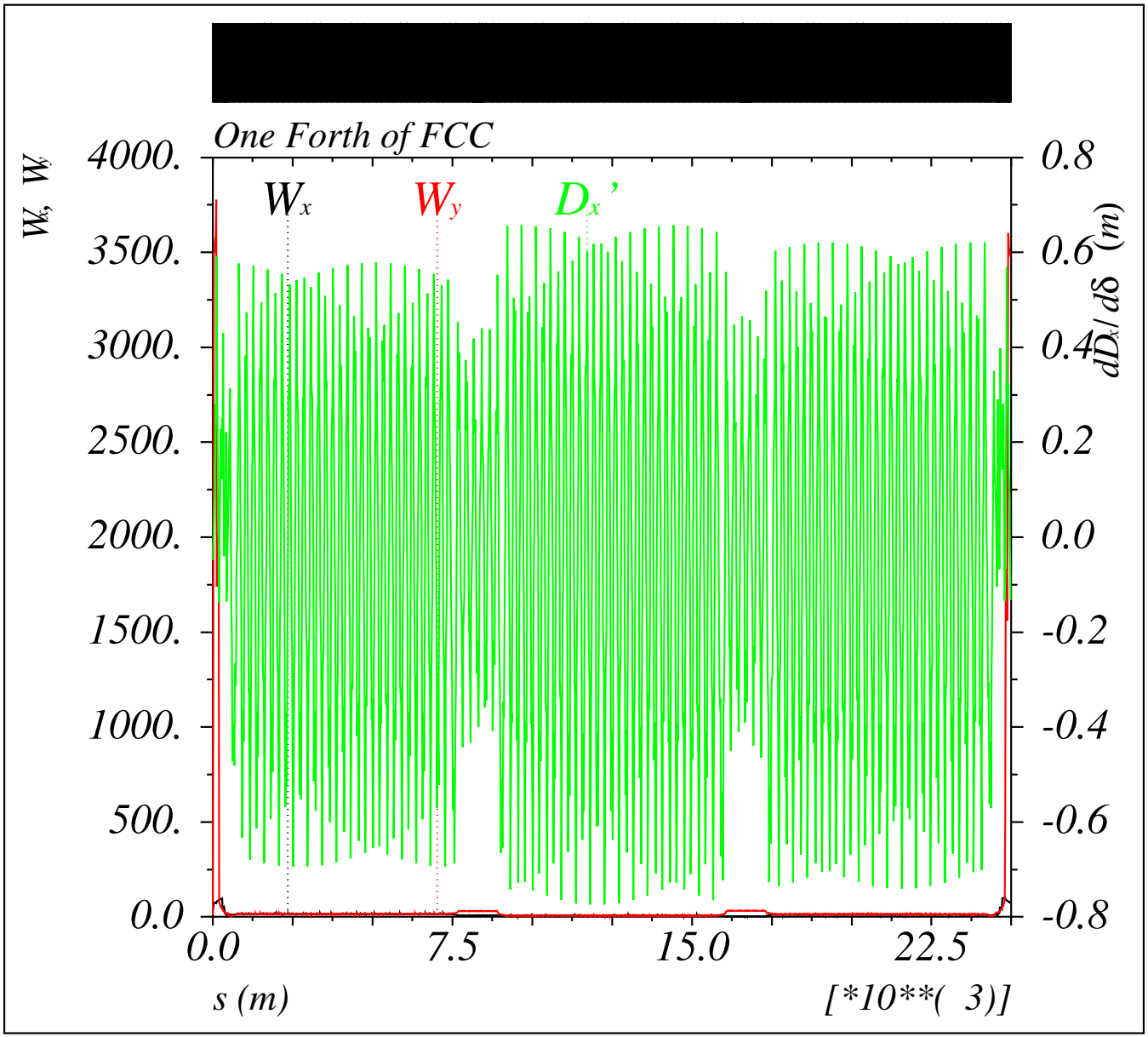
One quarter rematched



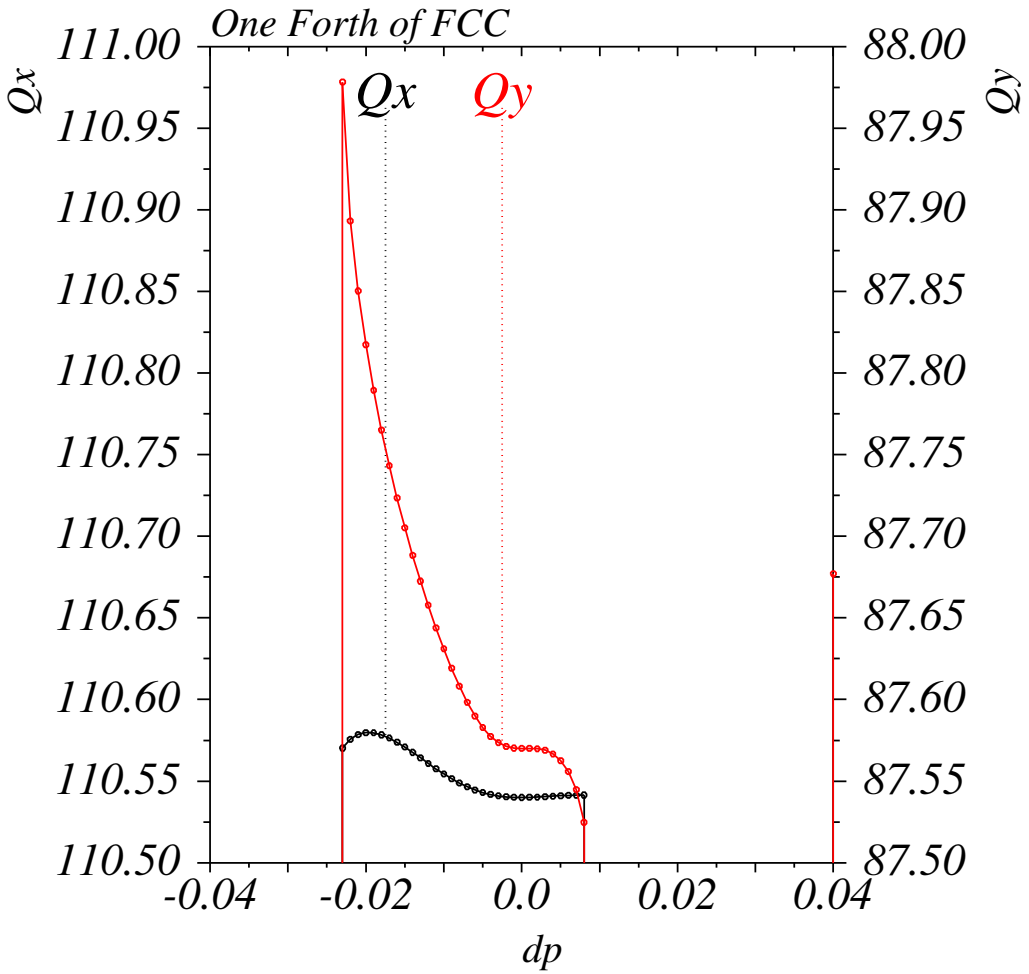
Global tune of one quarter

$$
\begin{aligned}
q_x &= 2 \cdot \mu_x(SC) + 3 \cdot 132 \cdot \mu_x(cell) + \mu_x(IR) \\
q_y &= 2 \cdot \mu_y(SC) + 3 \cdot 132 \cdot \mu_y(cell) + \mu_y(IR)
\end{aligned}
$$

Chromaticity: Montague functions, {110.54; 87.57}

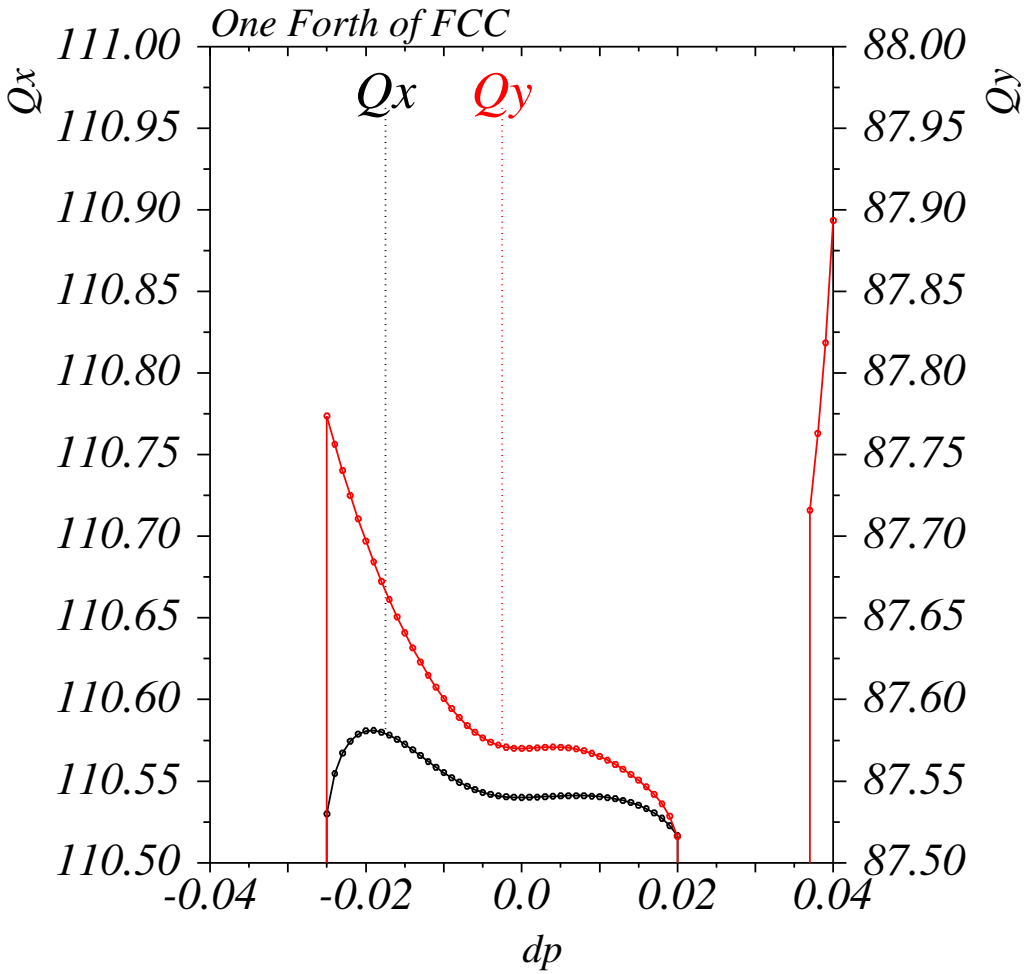


Energy acceptance I: [-2.3%;+0.8%]



	Value	$\Delta Q(2\%)$
Q_x	110.54	
Q'_x	0	0
Q''_x	160	0.032
Q'''_x	$-5.1 \cdot 10^4$	-0.068
Q''''_x	$2.2 \cdot 10^6$	0.014
Q_y	87.57	
Q'_y	0	0
Q''_y	300	0.06
Q'''_y	$-5.4 \cdot 10^5$	-0.71
Q''''_y	$-20 \cdot 10^6$	-0.13

Energy acceptance II: [-2.5%;+2%]



	Value	$\Delta Q(2\%)$
Q_x	110.54	
Q'_x	0	0
Q''_x	156	0.031
Q'''_x	$-5.7 \cdot 10^4$	-0.076
Q''''_x	$3.4 \cdot 10^6$	-0.023
Q_y	87.57	
Q'_y	0	0
Q''_y	300	0.06
Q'''_y	$-1.5 \cdot 10^5$	-0.202
Q''''_y	$-3.8 \cdot 10^6$	-0.026

Parameters of one quarter of the ring

	tt
Energy [GeV]	175
Perimeter [m]	24987.2
Momentum compaction	$6.96 \cdot 10^{-6}$
Emittance hor. [nm]	1.66
Energy spread [10^{-3}]	1.6
β_x^*/β_y^* [m]	0.5 / 0.001
Energy loss / turn [GeV]	2.22

Summary

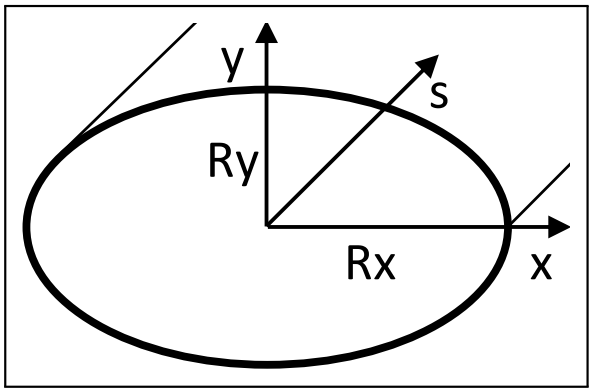
What is done?

1. Interaction region matched to arc v-16.
2. Phase advances over IR and Straight sections is fixed to integer of 2π.
3. Global tune is defined by arc cell.
4. At the end of IR the distance between the beams is 0.72 m.
5. Energy acceptance [-2.5%;+2%].
6. Geometry of the IR provides straight tunnel 3 m wide.

Plans

1. Decrease the fields of the dipoles in order to minimize SR critical energy.
2. Obtain reasonable geometry of the IR.
3. Is it possible to get rid of horizontal chromaticity correction section.

Elliptical solenoid: field expansion



$$B_x = -x\frac{B_0' R_y^2}{R_x^2+R_y^2} - xs\frac{B_0'' R_y^2}{R_x^2+R_y^2} - \frac{xs^2}{2}\frac{B_0''' R_y^2}{R_x^2+R_y^2} + \left(x^3\frac{R_y^4}{(R_x^2+R_y^2)^2} + 3xy^2\frac{R_x^2 R_y^2}{(R_x^2+R_y^2)^2}\right)\frac{B_0'''}{6}$$

$$B_y = -y\frac{B_0' R_x^2}{R_x^2+R_y^2} - ys\frac{B_0'' R_x^2}{R_x^2+R_y^2} - \frac{ys^2}{2}\frac{B_0''' R_x^2}{R_x^2+R_y^2} + \left(y^3\frac{R_x^4}{(R_x^2+R_y^2)^2} + 3yx^2\frac{R_x^2 R_y^2}{(R_x^2+R_y^2)^2}\right)\frac{B_0'''}{6}$$

$$B_s = B_0 + sB_0' + s^2\frac{B_0''}{2} + s^3\frac{B_0'''}{6} - \left(x^2\frac{R_y^2}{R_x^2+R_y^2} + y^2\frac{R_x^2}{R_x^2+R_y^2}\right)\frac{B_0''}{2} - \left(x^2 s\frac{R_y^2}{R_x^2+R_y^2} + y^2 s\frac{R_x^2}{R_x^2+R_y^2}\right)\frac{B_0'''}{2}$$

Vertical emittance estimation

$$B_x = -x\frac{B_0' R_y^2}{R_x^2 + R_y^2}\,, \quad B_0' \approx \frac{B_0}{L}\,, \quad L \approx 2R_x\,, \quad x = \theta s\,,$$

$$I5_y = \left(\frac{B_x L}{B\rho}\right)^5 \frac{1}{60L^2}(-15L\alpha_y + 20\beta_y + 3L^2\gamma_y)\,, \quad \varepsilon_y = C_q\gamma^2\frac{I5_y}{I2}\,,$$

L – length of the fringe, $C_q = 3.84 \cdot 10^{-13}$ m, $B0 = 8$ T, $s = 2$ m,
$I2 = 1.68 \cdot 10^{-4}$ m^{-1}, $\alpha_y = s/\beta_{0,y}$, $\beta_y = \beta_{0,y} + s^2/\beta_{0,y}$, $\gamma_y = 1/\beta_{0,y}$.

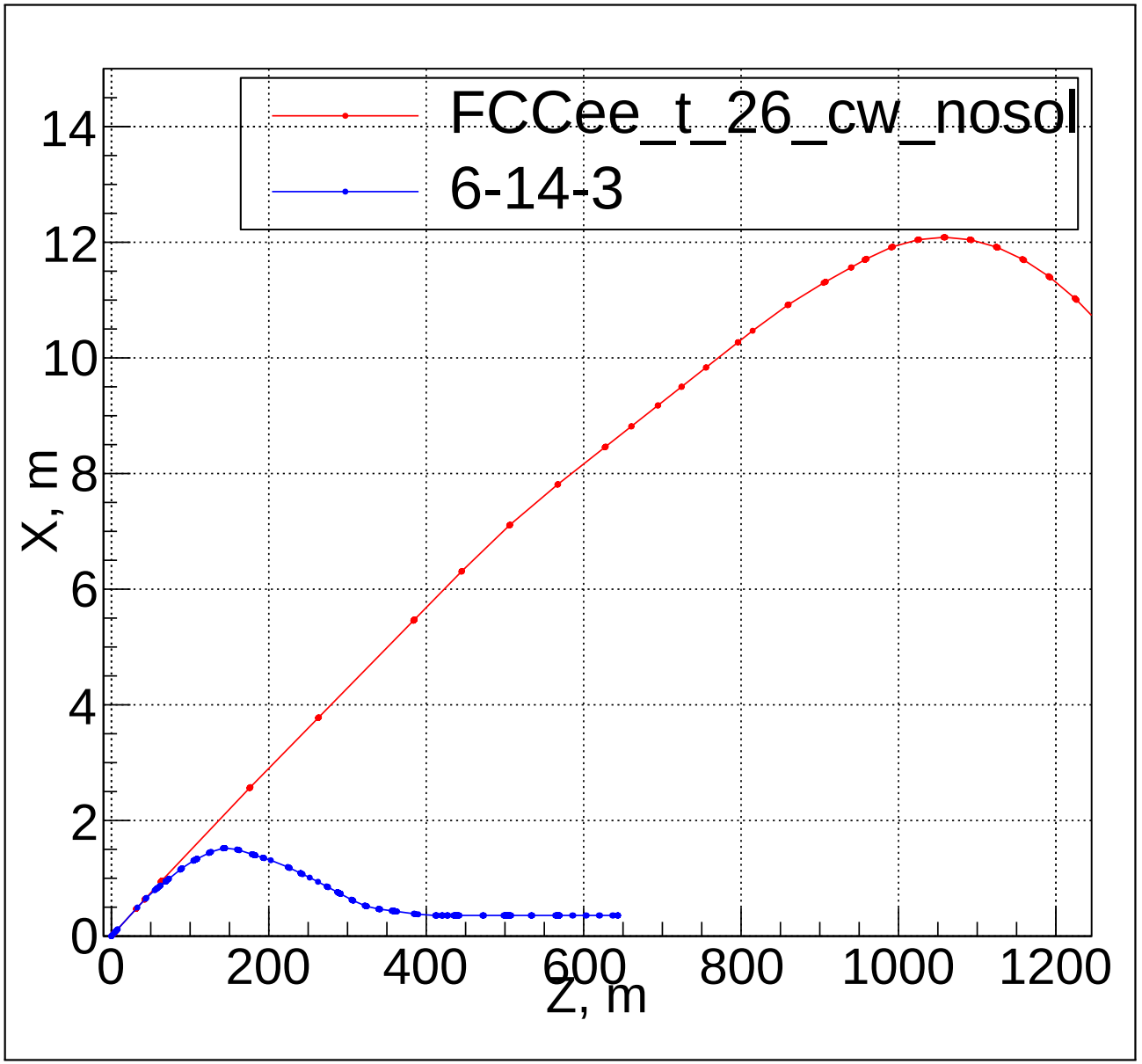
Round at E=45 GeV

Rx/Ry	15 cm/15 cm
B_x	0.4 T
ε_y	76 pm

Elliptical at E=45 GeV

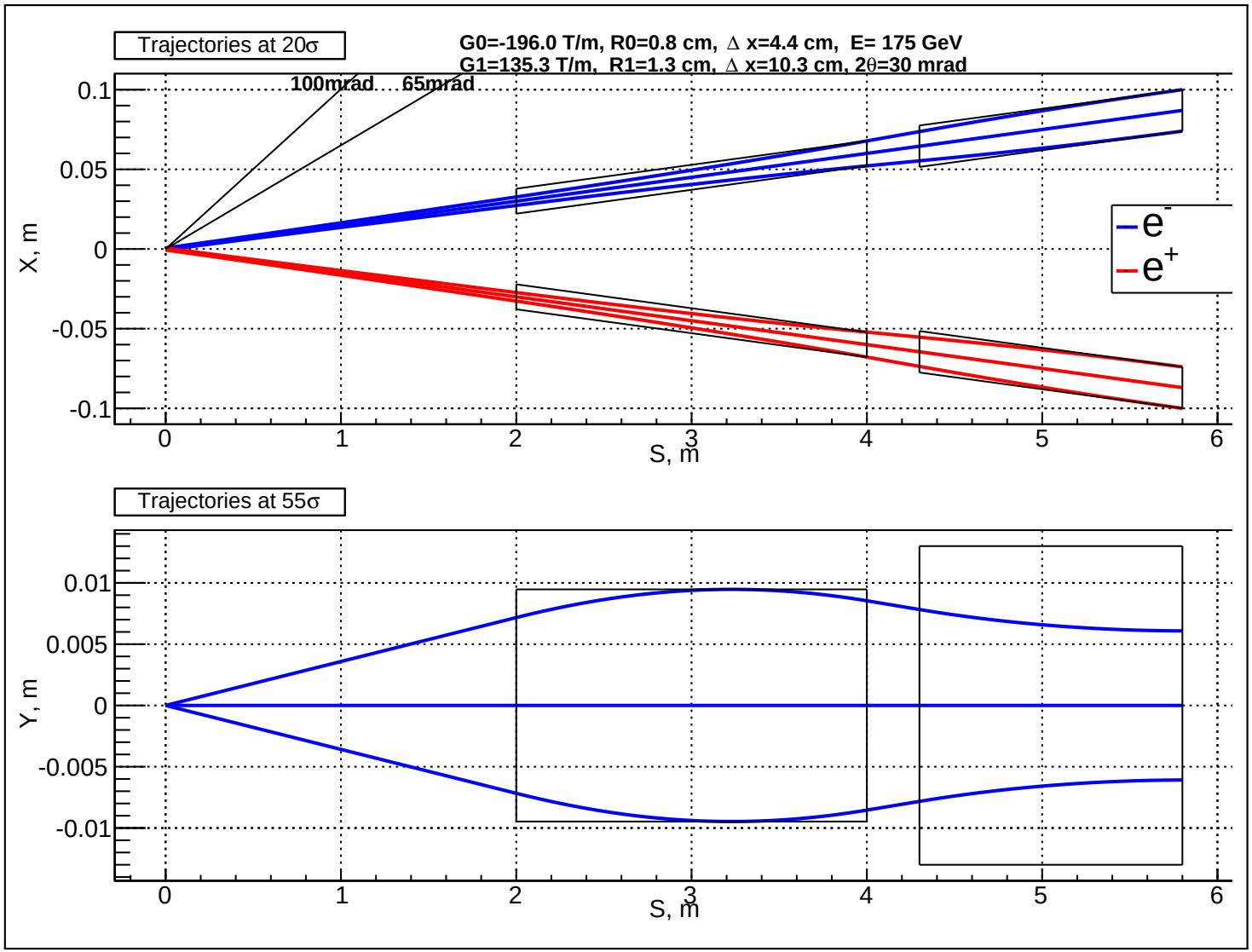
Rx/Ry	15 cm/2.4 cm
B_x	0.02 T
ε_y	$2.4 \cdot 10^{-5}$ pm

Comparison of Interaction Region layouts



The tunnel should be straight in order to accommodate IR for FCC-pp!

Final Focus layout



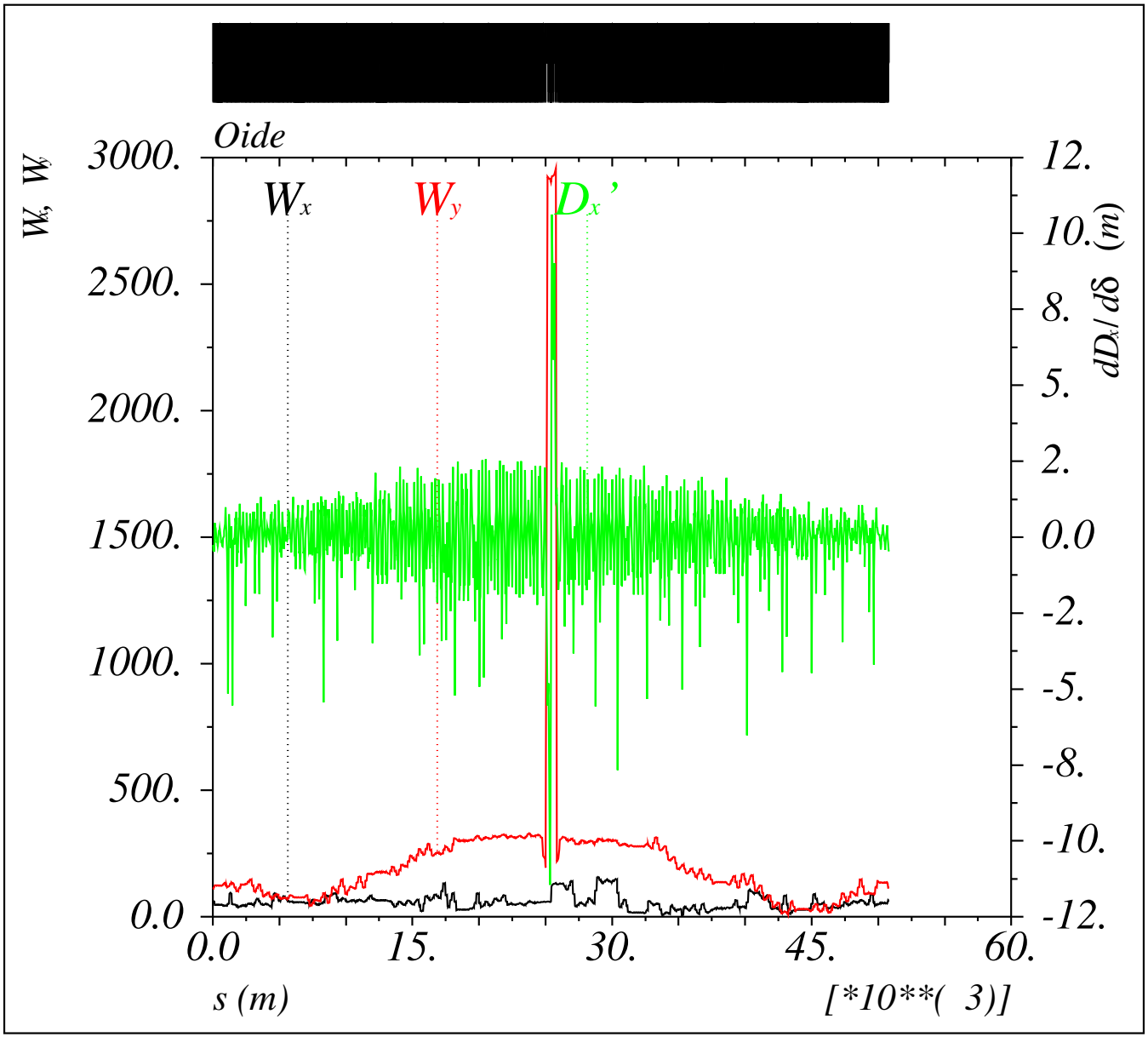
Rectangles are bare apertures.

	L [m]
QC1	2
QC2	1.5

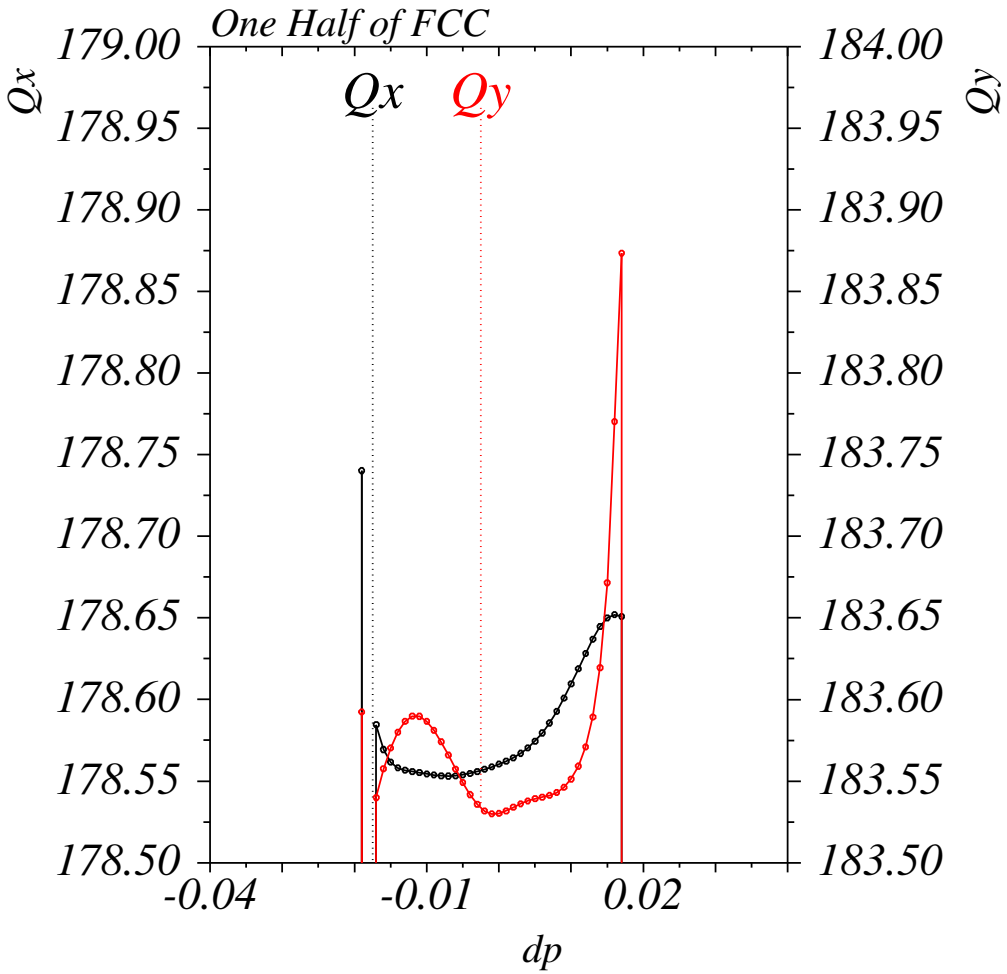
	R [m]
QC1	0.008
QC2	0.013

	B [T]
QC1	1.5
QC2	1.75

Chromaticity: Montague functions, {178.56; 183.53}



Energy acceptance: [-1.7%;+1.7%]



	Value	$\Delta Q(2\%)$
Q_x	178.56	
Q'_x	1.72	0.034
Q''_x	205	0.041
Q'''_x	$8.7 \cdot 10^4$	0.116
Q''''_x	$55 \cdot 10^6$	0.367
Q_y	183.53	
Q'_y	1	0.02
Q''_y	1377	0.276
Q'''_y	$-8.4 \cdot 10^5$	-1.115
Q''''_y	$-84 \cdot 10^6$	-0.56

What is β chromaticity we need?

Beam size

$$\sigma = \sqrt{\varepsilon\beta(\delta)} = \sigma_0 + \frac{\beta'}{\beta}\frac{\sigma_0}{2}\delta + \frac{\delta^2}{2}\left(-\frac{1}{4}\sigma_0\left(\frac{\beta'}{\beta}\right)^2 + \frac{1}{2}\frac{\beta''}{\beta}\sigma_0\right)$$

Average Luminosity

$$\left\langle\frac{\Delta L}{L}\right\rangle_\delta = -\left\langle\frac{\Delta\sigma}{\sigma}\right\rangle_\delta = -\frac{\sigma_\delta^2}{2}\left(-\frac{1}{4}\left(\frac{\beta'}{\beta}\right)^2 + \frac{1}{2}\frac{\beta''}{\beta}\right) \approx -\frac{\sigma_\delta^2}{4}\frac{\beta''}{\beta}$$

Numerical estimations for $E = 175$ GeV

$$-\frac{\beta''}{\beta} \le \left\langle\frac{\Delta L}{L}\right\rangle_\delta \frac{4}{\sigma_\delta^2} \approx 1\cdot 10^4\,, \left[\sigma_\delta = 2\cdot 10^{-3}, \left\langle\frac{\Delta L}{L}\right\rangle_\delta = 0.01\right]$$

Comparision of β chromaticity at IP

BINP, IR: 6-14-3, arc: V.16

	X	Y
$\frac{1}{\beta}\frac{d\beta}{d\delta}$	32	-6
$\frac{1}{\beta}\frac{d^2\beta}{d\delta^2}$	4561	9678
$\left\langle \frac{\Delta L}{L} \right\rangle_\delta$	-0.5%	-1%

FCCee_t_26_cw_nosol

	X	Y
$\frac{1}{\beta}\frac{d\beta}{d\delta}$	-49	33
$\frac{1}{\beta}\frac{d^2\beta}{d\delta^2}$	12234	51426
$\left\langle \frac{\Delta L}{L} \right\rangle_\delta$	-1.2%	-5%