Status and challenges of Crab waist interaction region for FCC-ee (one quarter of the ring)

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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

Optics challengers for FCC-ee with crab waist

- Very small β^* leads to high beta in quadrupoles.
- Therefore high nonlinear chromaticity.
- Energy acceptance is limited.
- Strong sextupoles to correct chromaticity limit DA.
- Effect of sextupole length limits DA.
- Kinematic term limits DA.
- Quadrupole fringes with high beta limit DA.
- Strong crab sextupoles limit DA.

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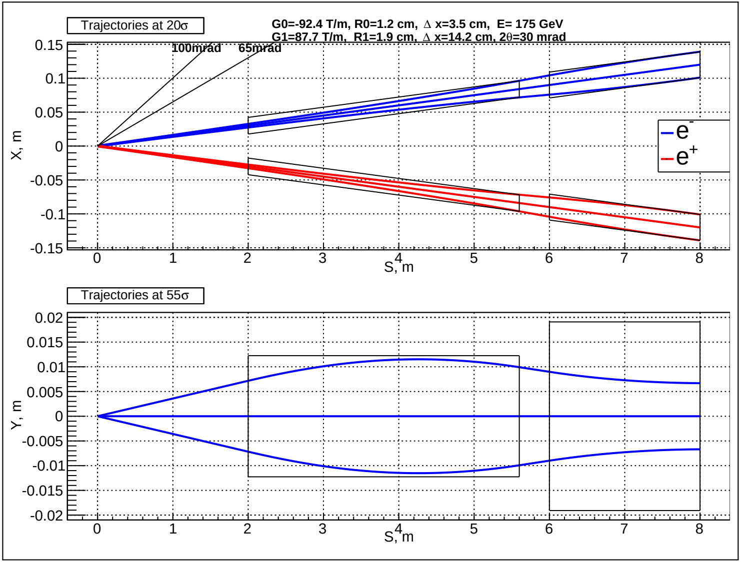
Final Focus layout

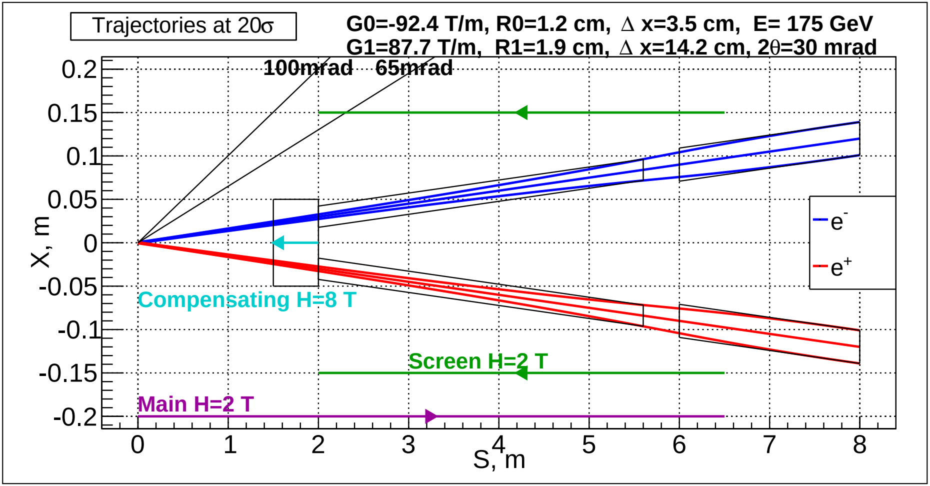


Rectangles represent bare apertures.

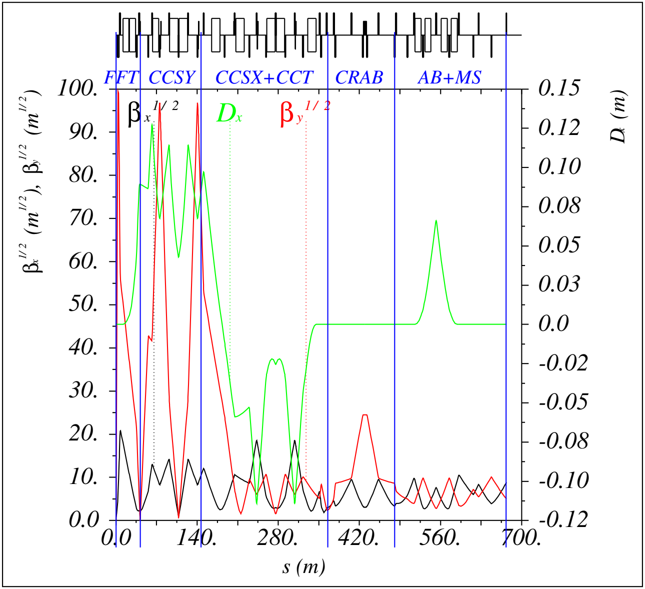
	L [m]
Q0	3.6
Q1	2

	R [m]
Q0	0.012
Q1	0.019

Final Focus layout: sketch of solenoids



Interaction Region optical functions: Old



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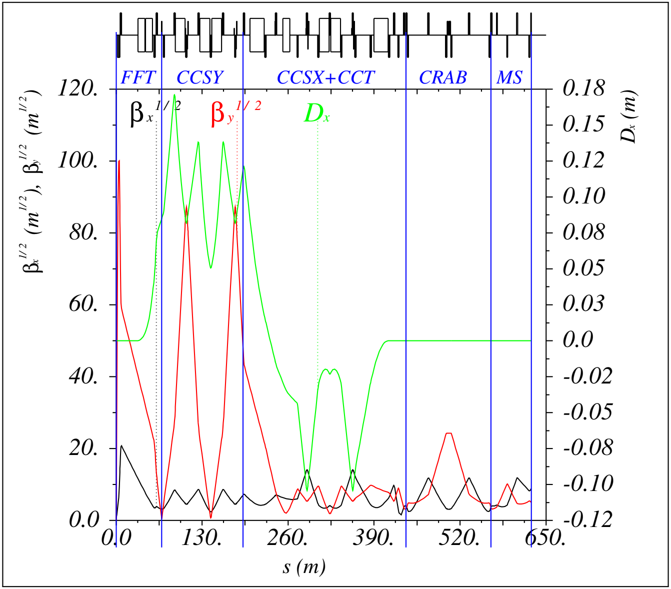
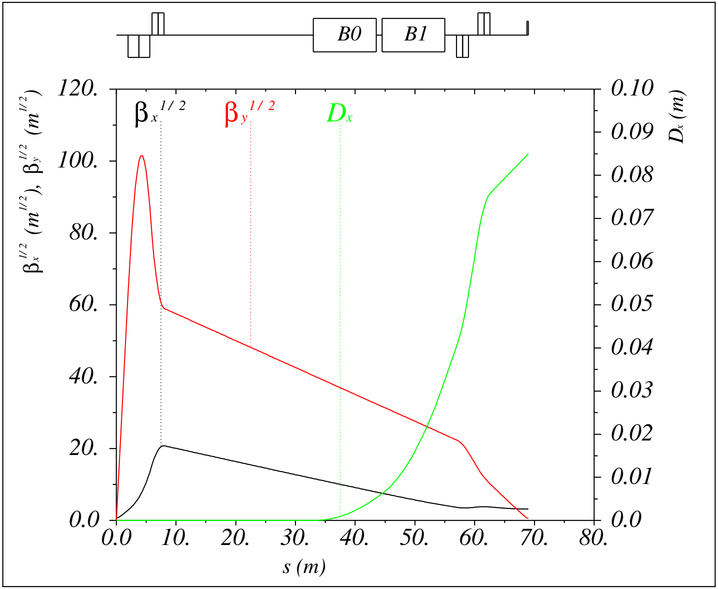
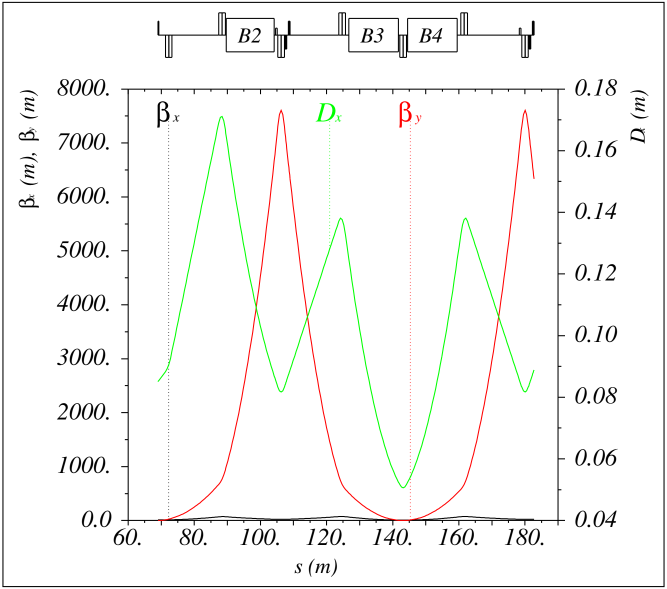


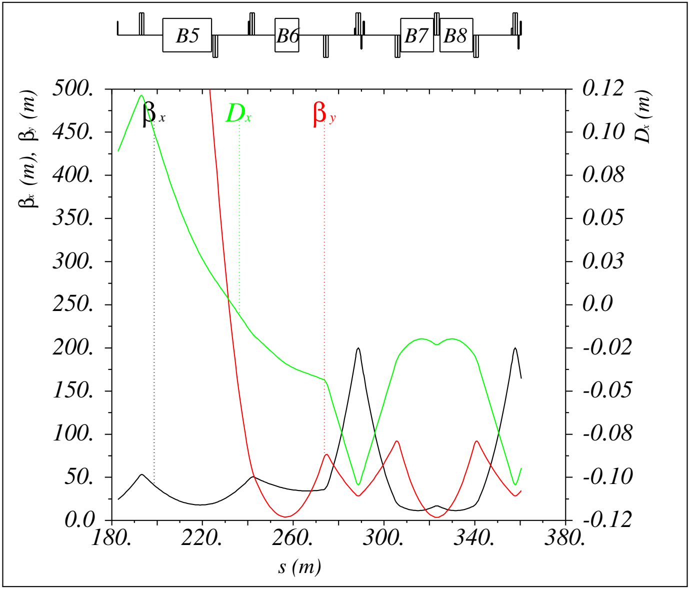
Final Focus Telescope: New



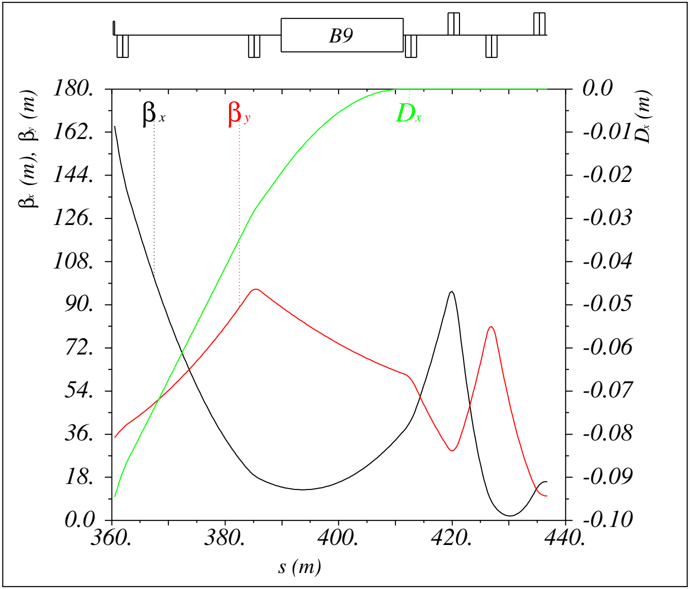
Y Chromaticity Correction Section



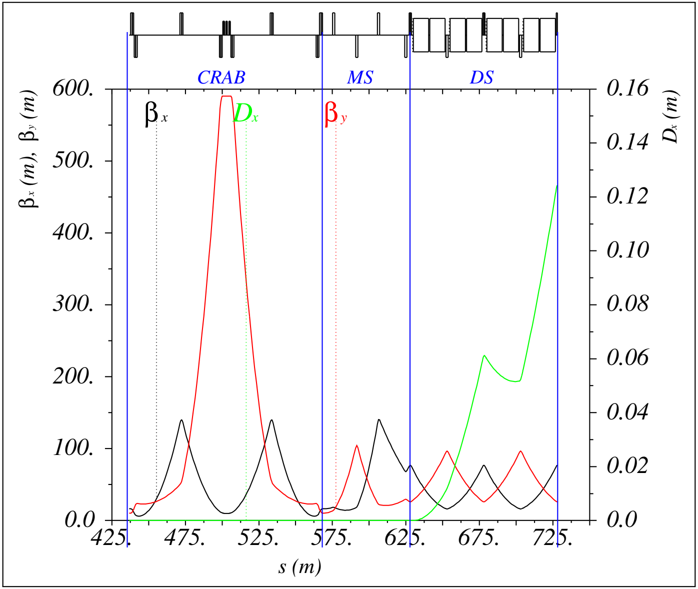
X Chromaticity Correction Section



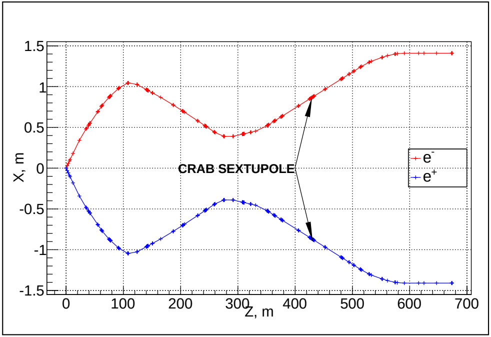
Chromaticity Correction Telescope



CRAB, MS, DS sections



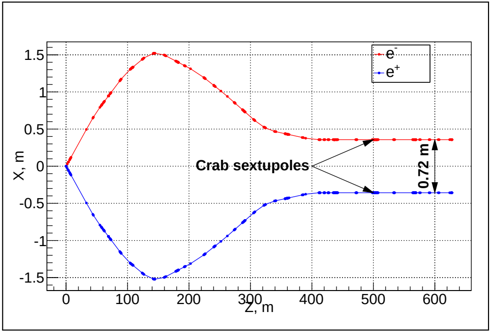
Interaction Region layout: Old



Before the achromatic bend at the crab sextupole each beam is diverging at ± 4.4 mrad.
Energy loss $\Delta U = 0.11$ GeV

	L [m]	B [T]	ϕ [mrad]
B0	10.5	0.06	1
B1	10.5	0.21	3.7
B2	10.5	0.21	3.8
B3	14.5	0.21	5.2
B4	14.5	0.21	5.2
B5	14.5	0.03	0.6
B6	14.5	0.01	0.2
B7	14.5	-0.13	-3.2
B8	14.5	-0.13	-3.2
B9	14.5	-0.11	-2.8
B10	10.5	0.06	1

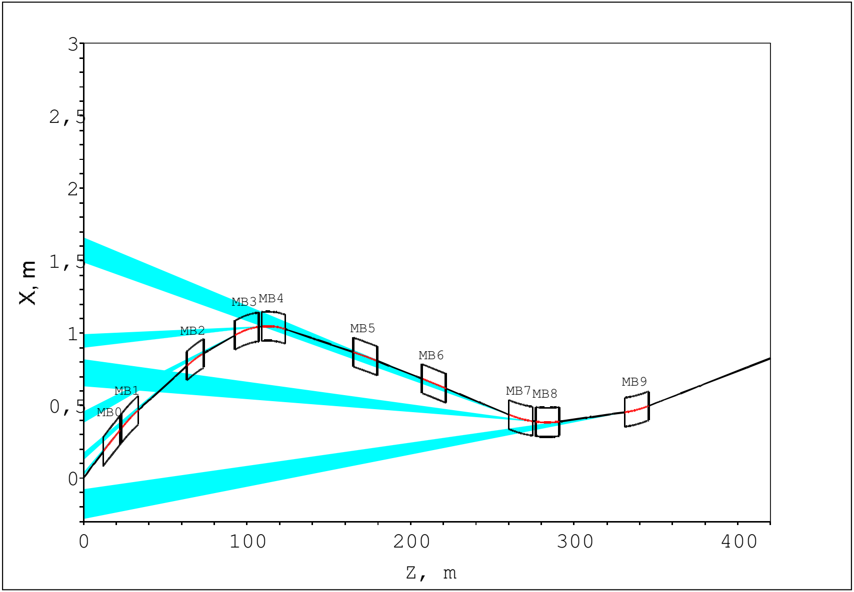
Interaction Region layout: New



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

Old synchrotron radiation fans from S. Glukhov



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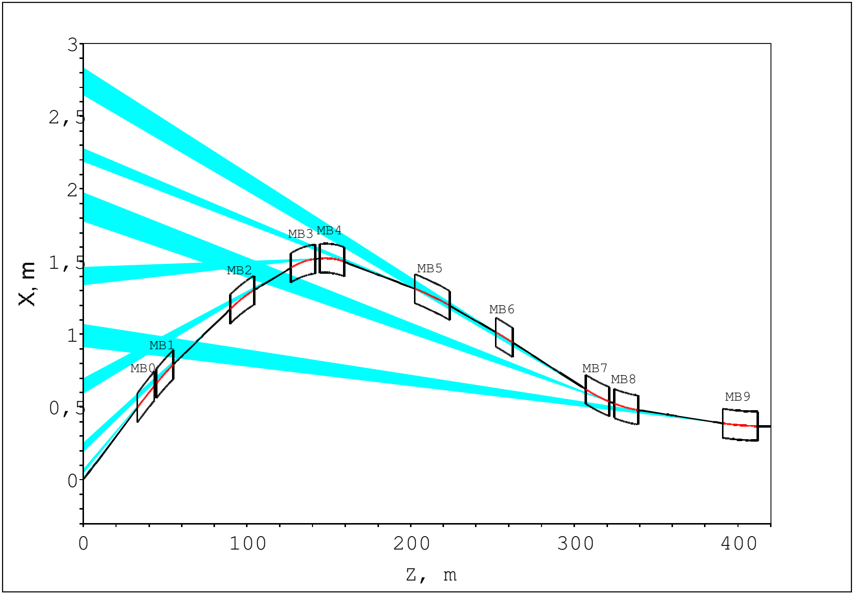
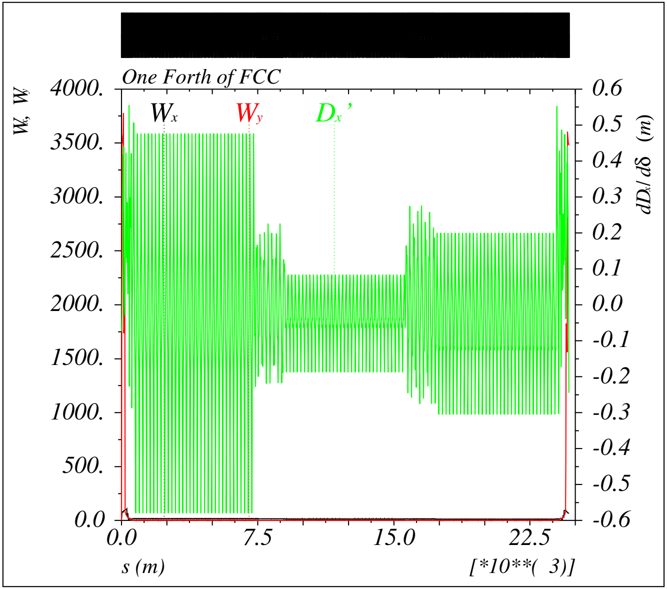
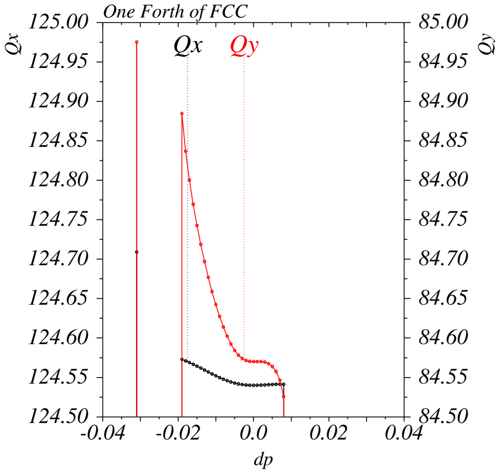


Chromaticity: Montague functions, {124.54; 84.57}

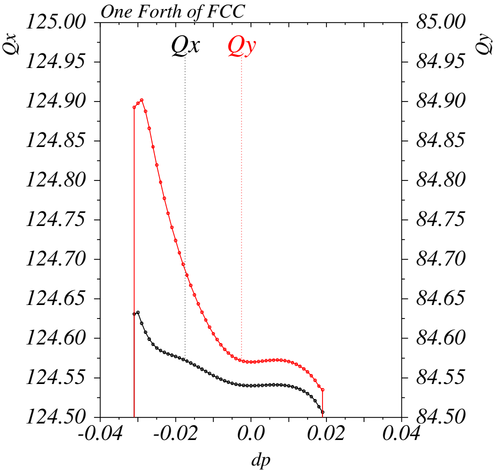


Energy acceptance I: [-1.9%;+0.8%]



	Value	$\Delta Q(2\%)$
Q_x	124.54	
Q'_x	0	0
Q''_x	170	0.034
Q'''_x	$-4.5 \cdot 10^4$	-0.059
Q''''_x	$-5.3 \cdot 10^6$	-0.035
Q_y	84.57	
Q'_y	0	0
Q''_y	387	0.077
Q'''_y	$-5.3 \cdot 10^5$	-0.7
Q''''_y	$-4.3 \cdot 10^6$	-0.029

Energy acceptance II: [-3.1%;+1.9%]



	Value	$\Delta Q(2\%)$
Q_x	124.54	
Q'_x	0	0
Q''_x	170	0.034
Q'''_x	$-5.1 \cdot 10^4$	-0.068
Q''''_x	$-4.8 \cdot 10^6$	-0.032
Q_y	84.57	
Q'_y	0	0
Q''_y	387	0.077
Q'''_y	$-1.4 \cdot 10^5$	-0.182
Q''''_y	$1.9 \cdot 10^6$	-0.013

How does it work (chromaticity estimations)?

Montague functions first order

$$
\begin{aligned}
b_{y,1} &= \frac{1}{\beta_y}\frac{\partial \beta_y}{\partial \delta}\,, \\
a_{y,1} &= \frac{\partial \alpha_y}{\partial \delta} - \frac{\alpha_y}{\beta_y}\frac{\partial \beta_y}{\partial \delta}\,.
\end{aligned}
$$

Montague functions second order

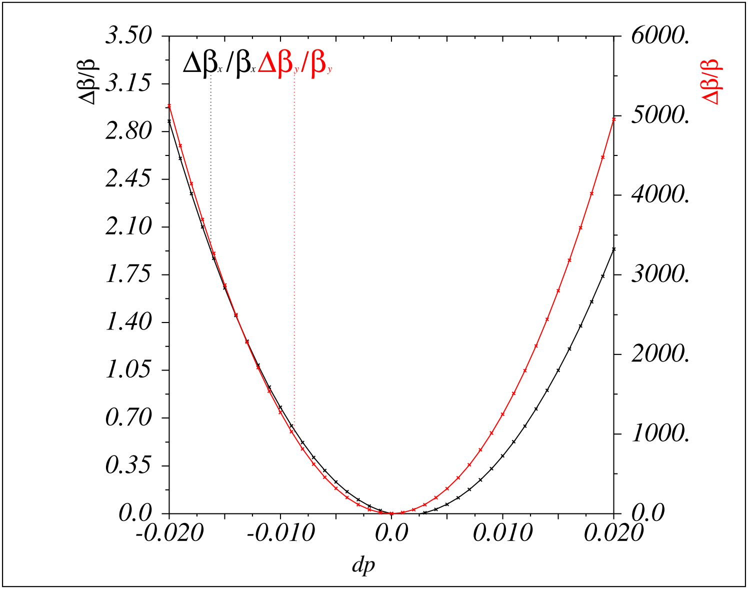
$$
\begin{aligned}
b_{y,2} &= \frac{1}{\beta_y}\frac{\partial^2 \beta_y}{\partial \delta^2}\,, \\
a_{y,2} &= \frac{\partial^2 \alpha_y}{\partial \delta^2} - \frac{\alpha_y}{\beta_y}\frac{\partial^2 \beta_y}{\partial \delta^2}\,.
\end{aligned}
$$

How does it work (chromaticity estimations)?

Chromaticity

$$
\begin{aligned}
\frac{\partial\varphi_y}{\partial\delta} &= \frac{1}{2}\int_0^{\Pi}\beta_y(K_1 - K_2\eta_0)ds\,,\\
\frac{\partial^2\varphi_y}{\partial\delta^2} &= -2\frac{\partial\varphi_y}{\partial\delta} - \int_0^{\Pi}\beta_y K_2\eta_1\,ds + \frac{1}{2}\int_0^{\Pi}\beta_y b_{y,1}(K_1 - K_2\eta_0)ds\,,\\
\frac{\partial^3\varphi_y}{\partial\delta^3} &= 6\frac{\partial\varphi_y}{\partial\delta} - \int_0^{\Pi}\beta_y(K_1 - K_2\eta_0)(a_{y,1}^2 + b_{y,1}^2)ds +\\
&+ 3\int_0^{\Pi}\beta_y(K_2\eta_1 - K_2\eta_2)ds + \frac{3}{2}\int_0^{\Pi}\beta_y b_{y,2}(K_1 - K_2\eta_0)ds\,.
\end{aligned}
$$

Final Focus Telescope: beta chromaticity



Parameters of one quarter of the ring

	tt
Energy [GeV]	175
Perimeter [m]	24655.9
Momentum compaction	$5.7 \cdot 10^{-6}$
Emittance hor. [nm]	1.3
Energy spread [10^{-3}]	1.6
β_x^* / β_y^* [m]	0.5 / 0.001
Energy loss / turn [GeV]	2.12

Summary

1. Closed ring is ready.
2. At the end of IR the distance between the beams is 0.72 m.
3. Synchrotron radiation fans are shifted away from IP.
4. A knob is created to control third order chromaticity in vertical plane.
5. Energy acceptance [-3.1%;+1.9%].
6. Further optimization of energy acceptance should be done numerically together with DA optimization.