IR solenoids in FCC-ee

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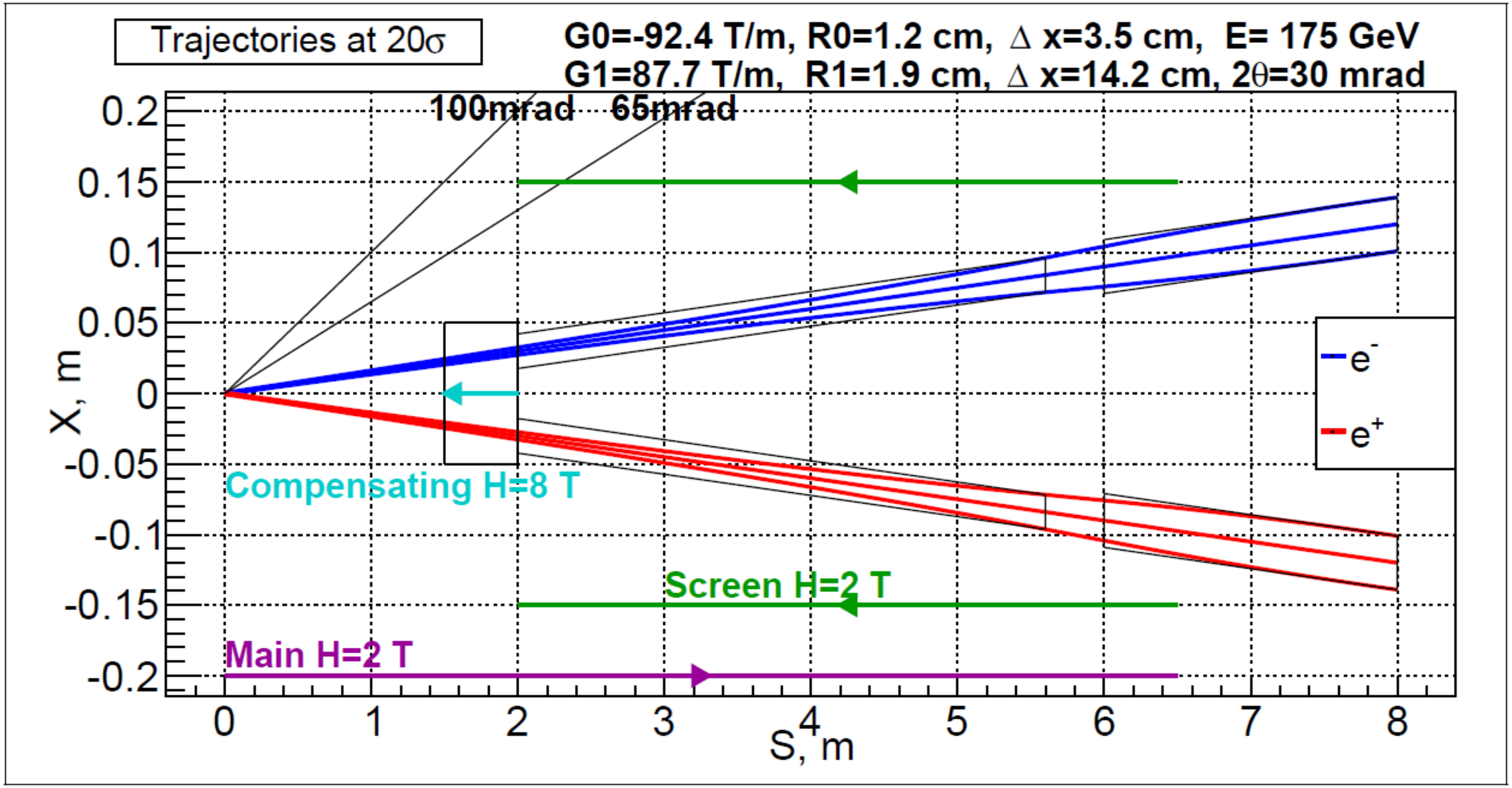
Task

- Detector solenoid and compensating solenoids influence beam parameters dependently on the anti-solenoids location, parameters and field model.
- We have studied effect of the solenoids to the ring optics and beam emittance for two versions: (1) the anti-solenoids are placed close to the IP inside the FF quad doublet and (2) they are placed outside the doublet.
- Different schemes of betatron coupling correction are considered.
- Solenoid fringe field effect is estimated.
- We have used MAD8, quarter of the ring, IR v. 6-14-3, arc v. 14.

Final Focus layout: sketch of solenoids

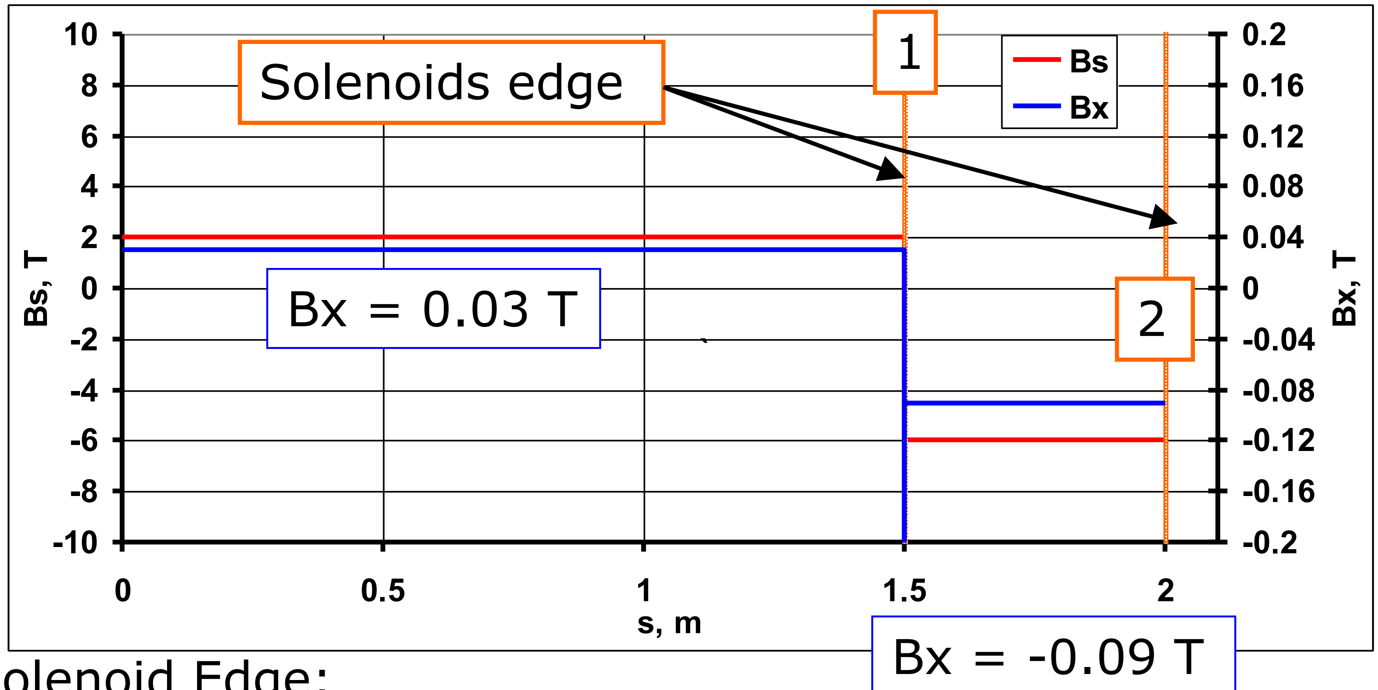


Version 1 – compensating solenoid is located between the IP and QD0

Version 1

- Main solenoid field area before the compensating solenoid: L = 3 m, B = 2 T
- 2 compensating solenoids, each of L = 0.5 m, B = - 6 T (B max = - 8 T)
- Screening solenoid covers the FF quadrupoles
- Angle between the beams reference trajectory and axis of solenoid ±15 mrad
- Beams at the compensating solenoid entry (from IP) are displaced horizontally for $1500 \cdot \sin(\pm 0.015) \approx \pm 22.5$ mm

Solenoid field at reference trajectory

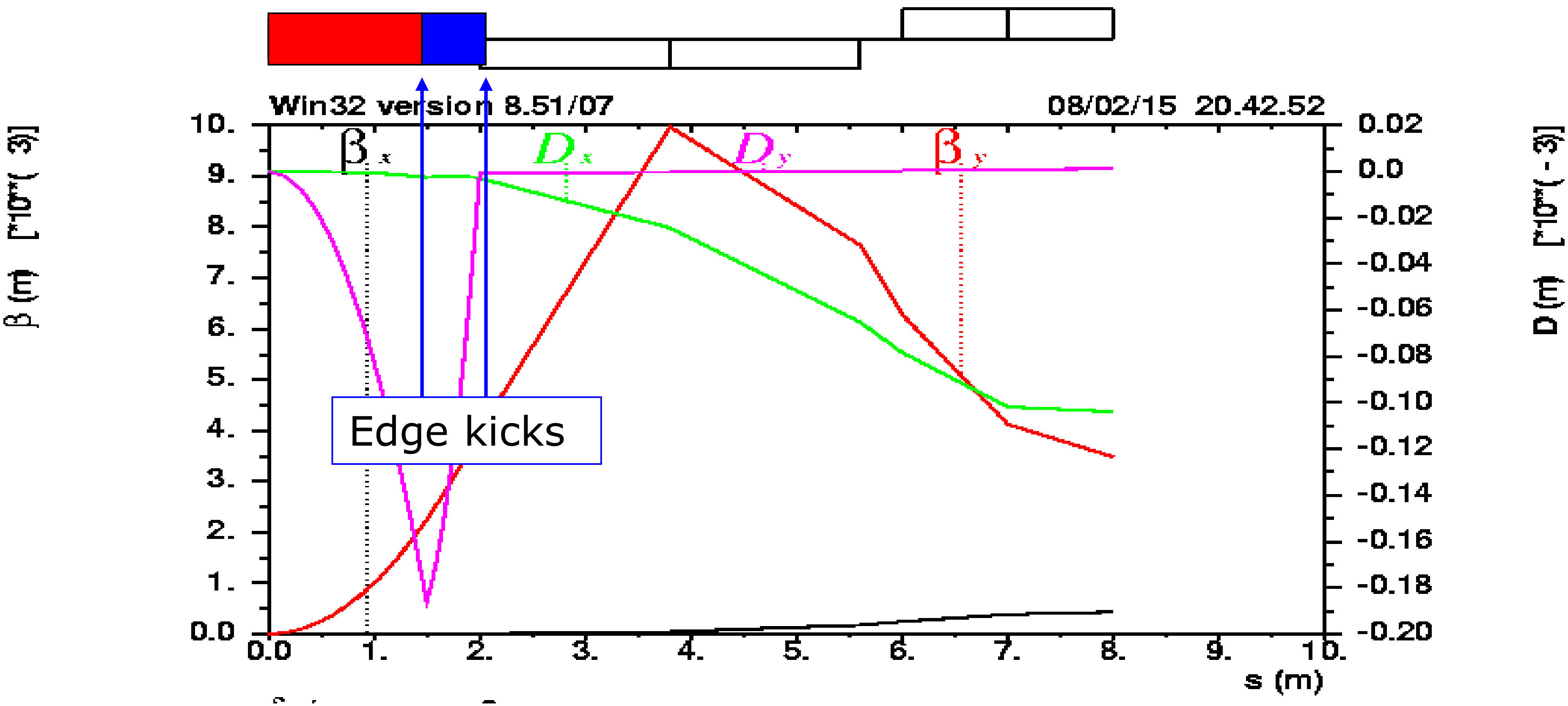


Solenoid Edge:

1 Vert. Kick $\Delta y' \approx (B_{com\_sol} - B_{sol}) \cdot \Delta x / (2 \cdot BR) = (-6-2) \cdot 0.0225/(2 \cdot 45/0.3) = -6 \cdot 10^{-4}\ rad$

2 Vert. Kick $\Delta y' \approx (0 - B_{comp\_sol}) \cdot \Delta x / (2 \cdot BR) = (0 - -6) \cdot 0.03/(2 \cdot 45/0.3) = 6 \cdot 10^{-4}\ rad$

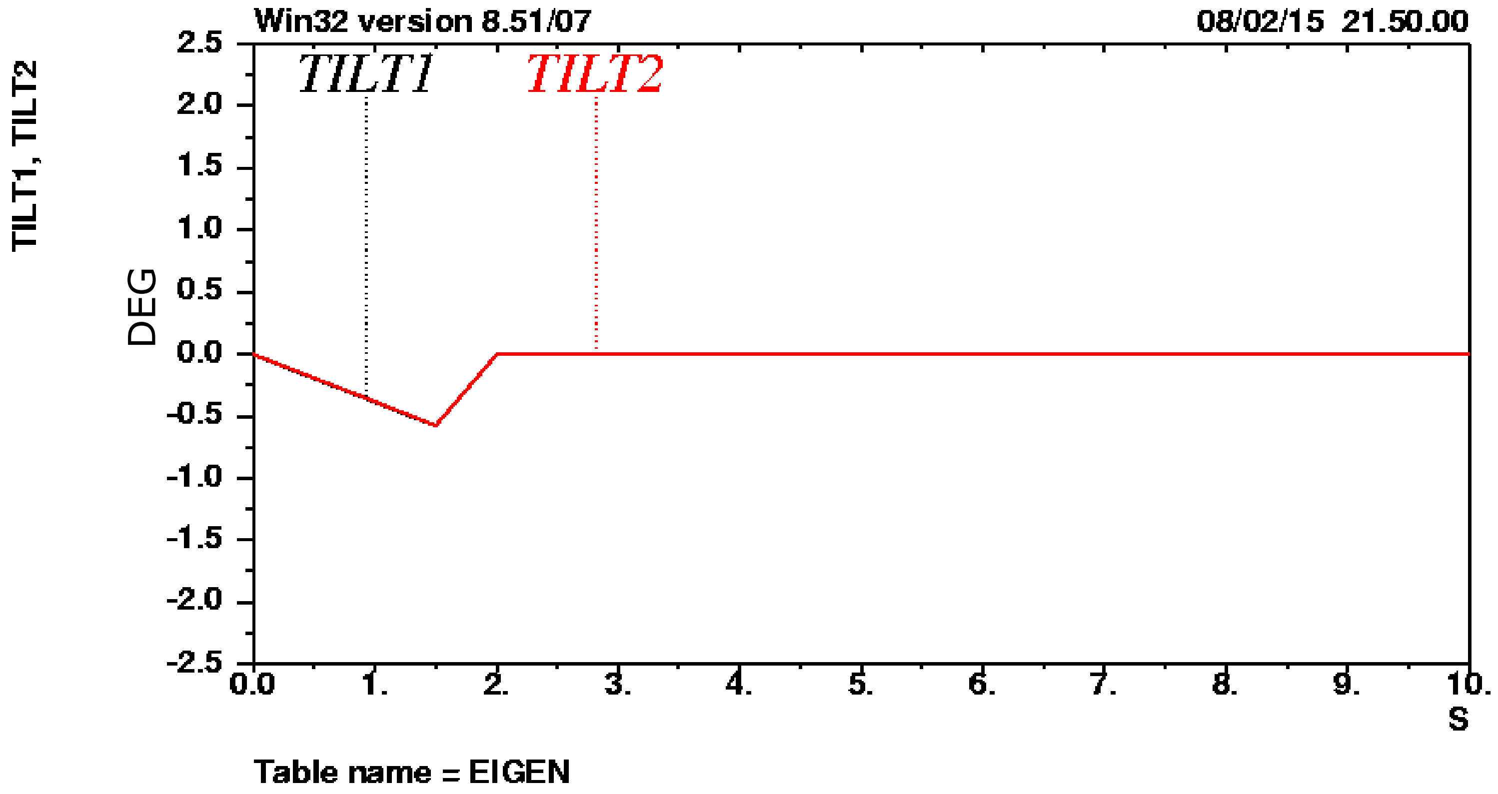
IR optical functions at E= 45 GeV



Main solenoid

Compensating solenoid

Betatron coupling modes



With anti-solenoid before the FF quads

- There is no coupling outside it.
- Skew quads are not used to compensate of betatron coupling.

Beam parameters with solenoid fields*

Energy, GeV	45	45	175	175
Solenoids	off	on	off	on
Betatron tunes:				
qx	124.540	124.540	124.540	124.540
qy	84.570	84.643	84.570	84.577
Betafunction IP:				
Betx, m	0.50	0.50	0.50	0.50
Bety, mm	1.00	1.84	1.00	1.09
Emittance, nm*rad:				
horizontal	0.084	0.084	1.26	1.26
vertical	**0**	**3.71E-05**	**0**	**3.13E-05**
Betatron coupling	0.00E+00	4.45E-04	0.00E+00	2.48E-05

* Excitation of vertical emittance by solenoids edges is not taken into account!

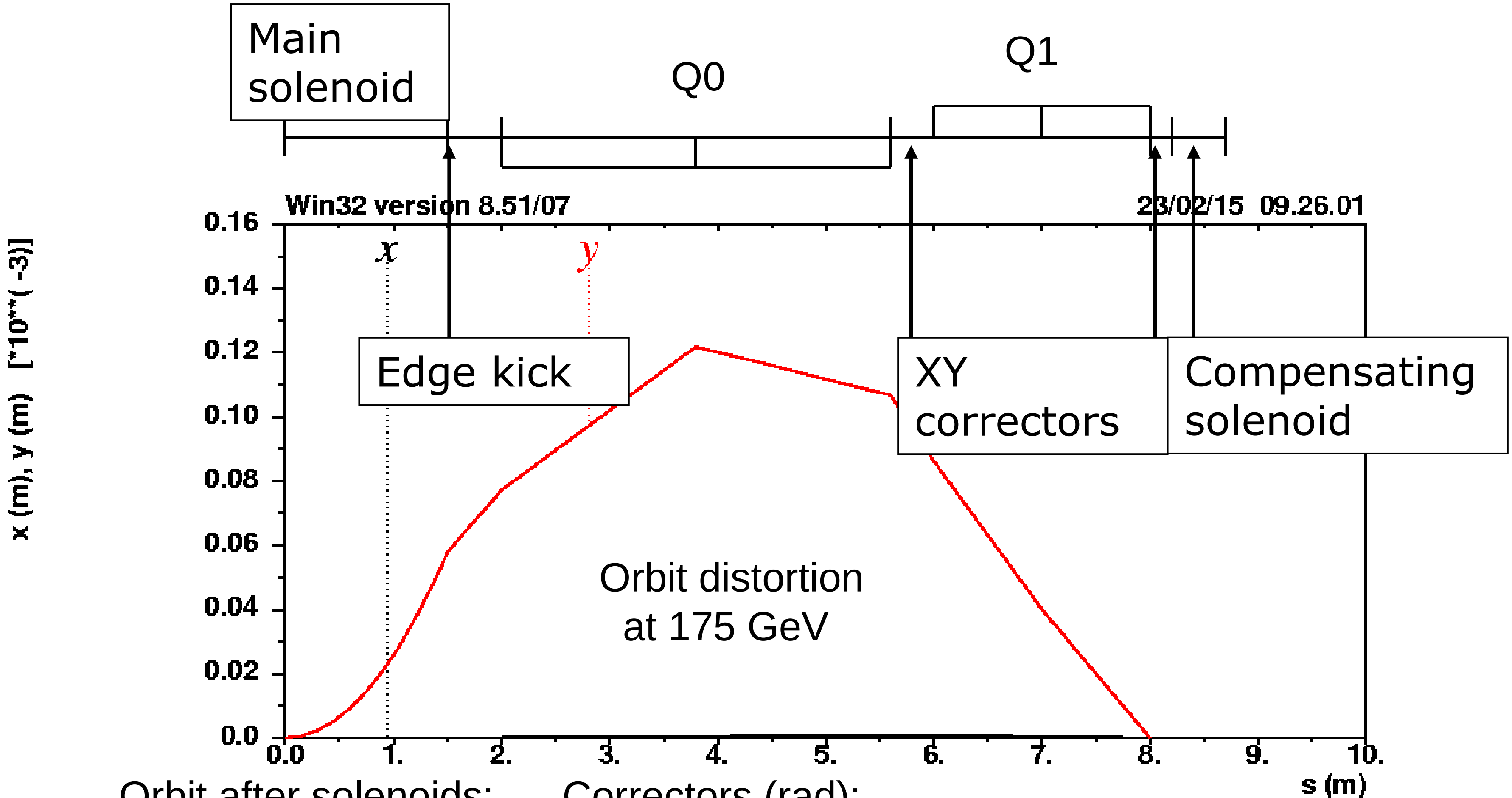
Version 2

Compensating solenoids are moved downstream the FF quadrupole doublet

There are two separate anti-solenoids on the each beam axis without the transverse fringe kicks

The detector solenoid field is projected to the beam axis and sliced (only linear longitudinal and transverse field components). The sliced field model is used by MAD.

Orbit distortion for V2



Orbit after solenoids:

X= 0 mkm

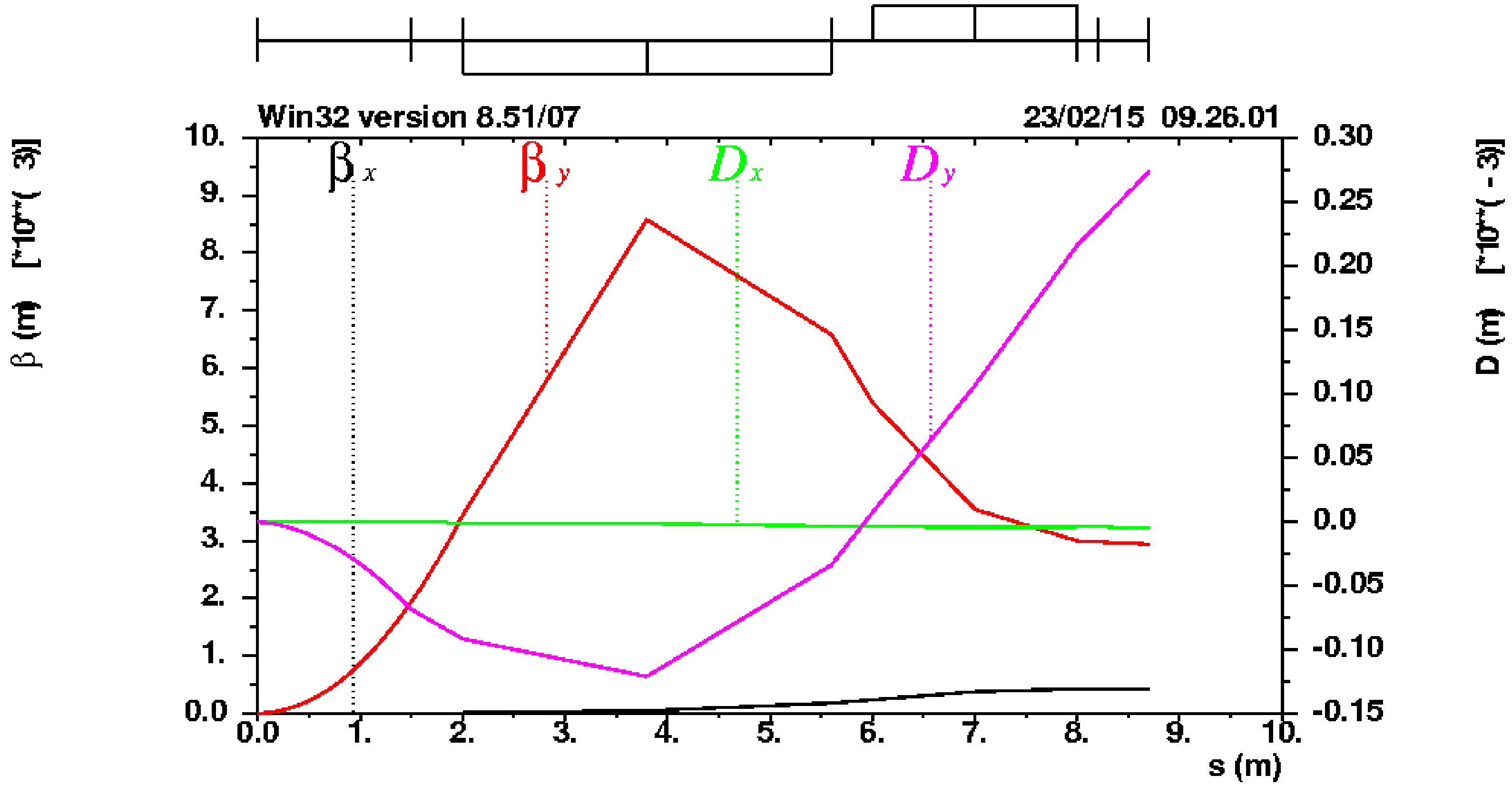
Y= 0 mkm

Correctors (rad):

1) Hkick = -6.2e-7 Vkick = -2.6e-5

2) Hkick = 3.9e-7 Vkick = 3.9 e-5

IR optics at E= 175 GeV

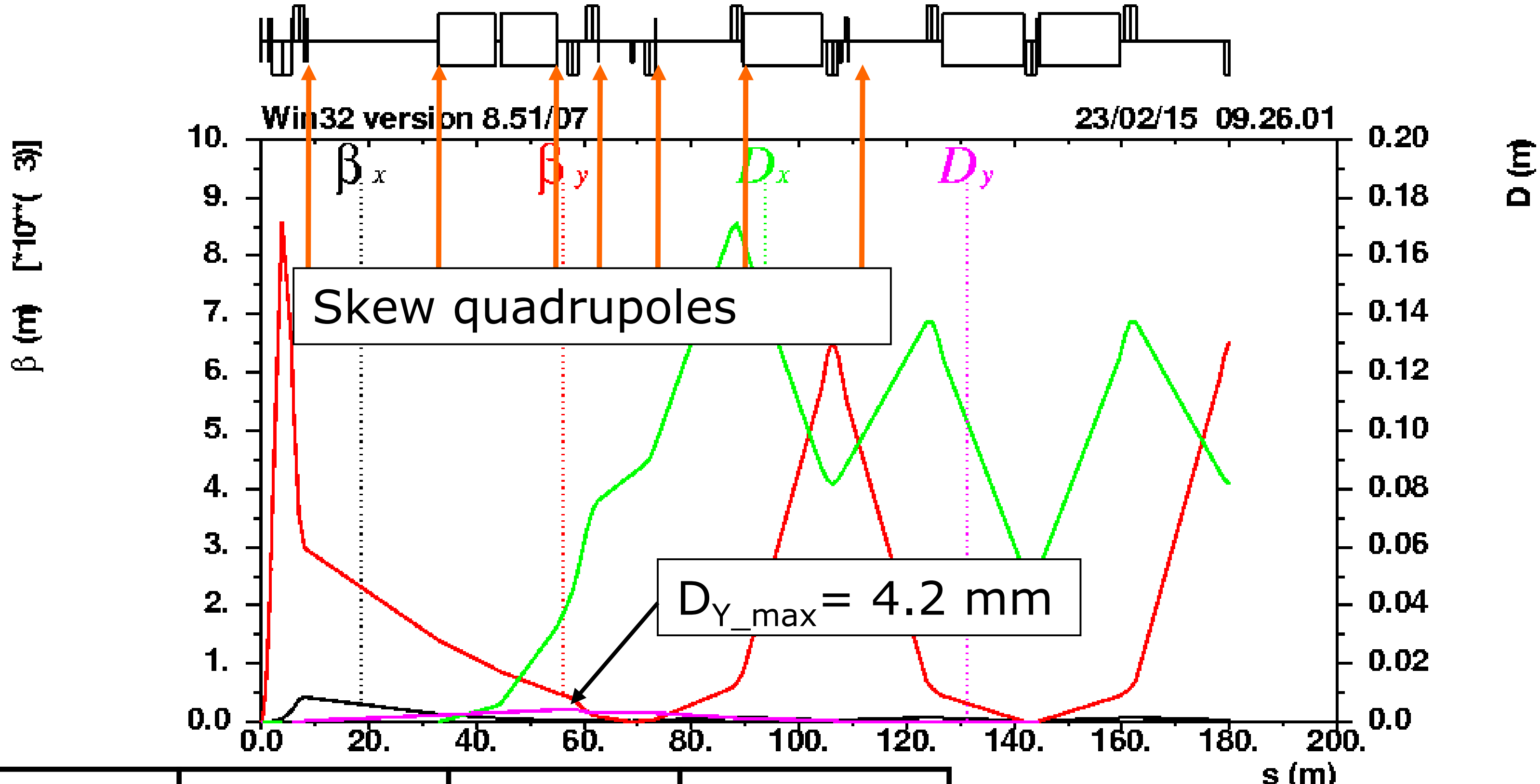


Dispersion after solenoids:

D_X= -0.02 mm

D_Y= 0.28 mm

Coupling correction V2-0

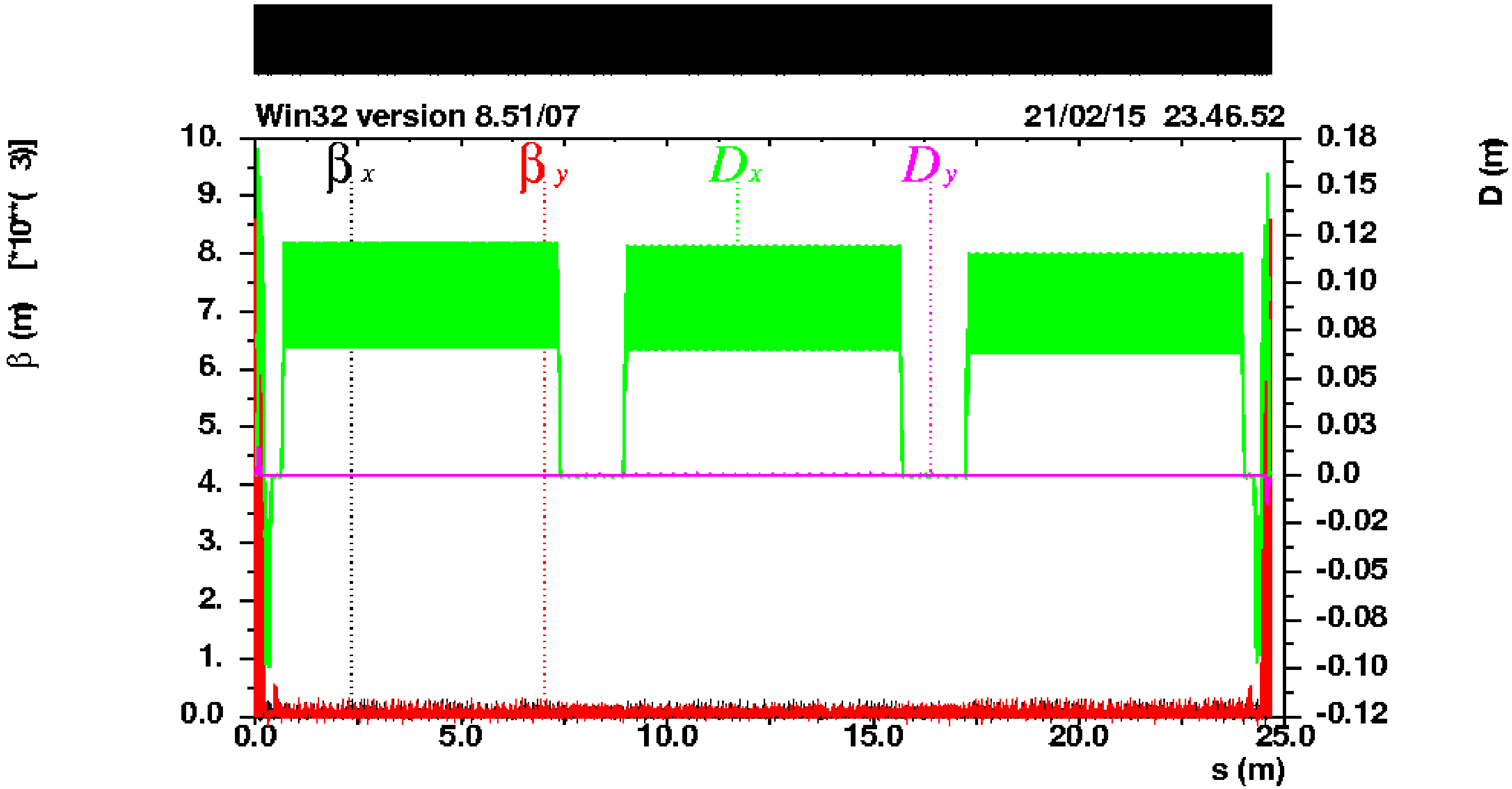


Name	K1L, m^-1	Name	K1L, m^-1
L.SQ01	-3.36E-04	R.SQ01	3.36E-04
L.SQ02	3.82E-04	R.SQ02	-3.82E-04
L.SQ03	-6.97E-04	R.SQ03	6.97E-04
L.SQ04	6.19E-04	R.SQ04	-6.19E-04
L.SQ05	-4.24E-05	R.SQ05	4.24E-05
L.SQ06	-2.18E-04	R.SQ06	2.18E-04
L.SQ07	8.66E-04	R.SQ07	-8.66E-04

Skew Quads

$K1s_{R.SQ} = -K1s_{L.SQ}$

Ring optical functions



IP:

$\beta_x = 0.51$ m

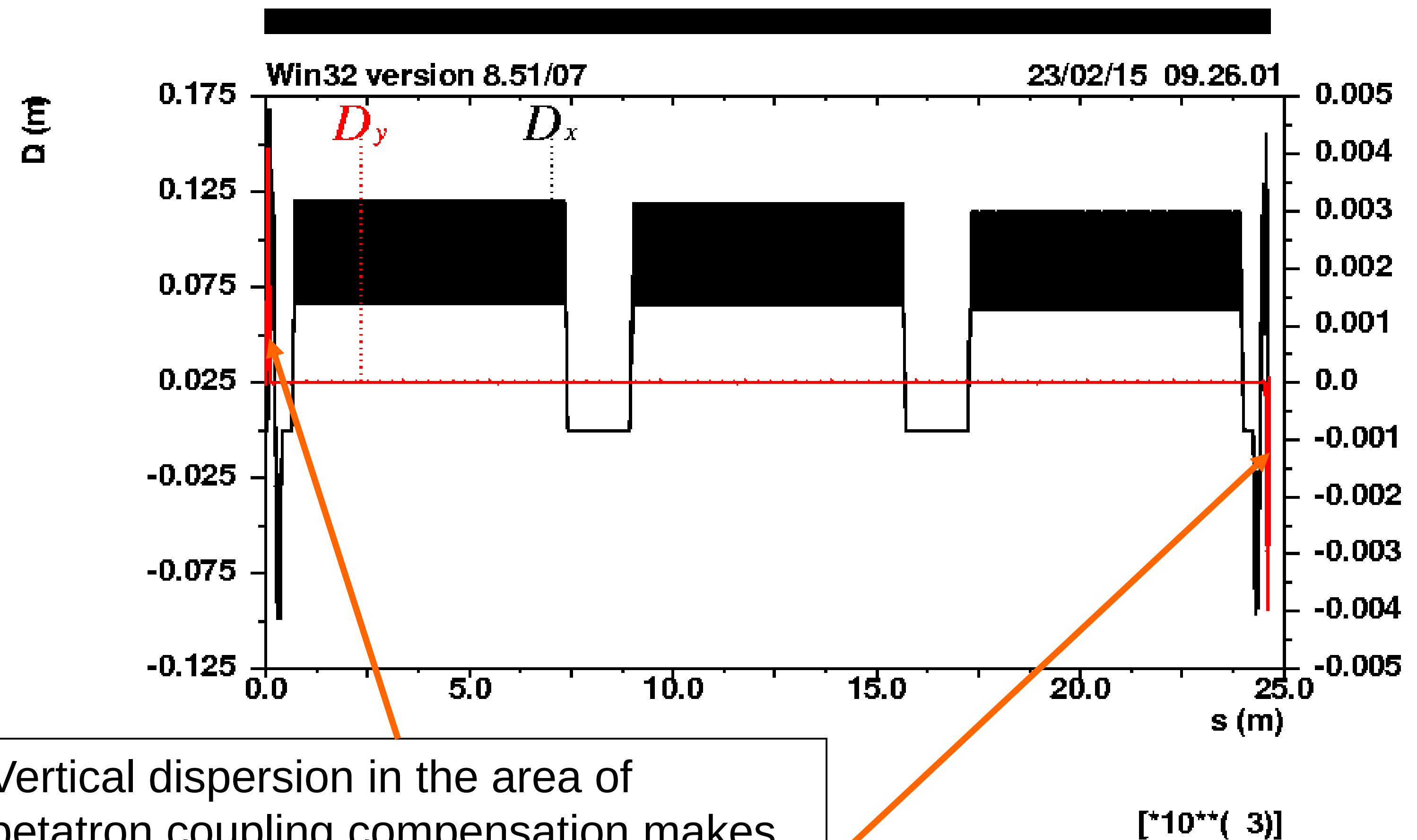
$\beta_y = 1.16$ mm

Maximum value :

$\beta_x = 426$ m

$\beta_y = 8578$ m

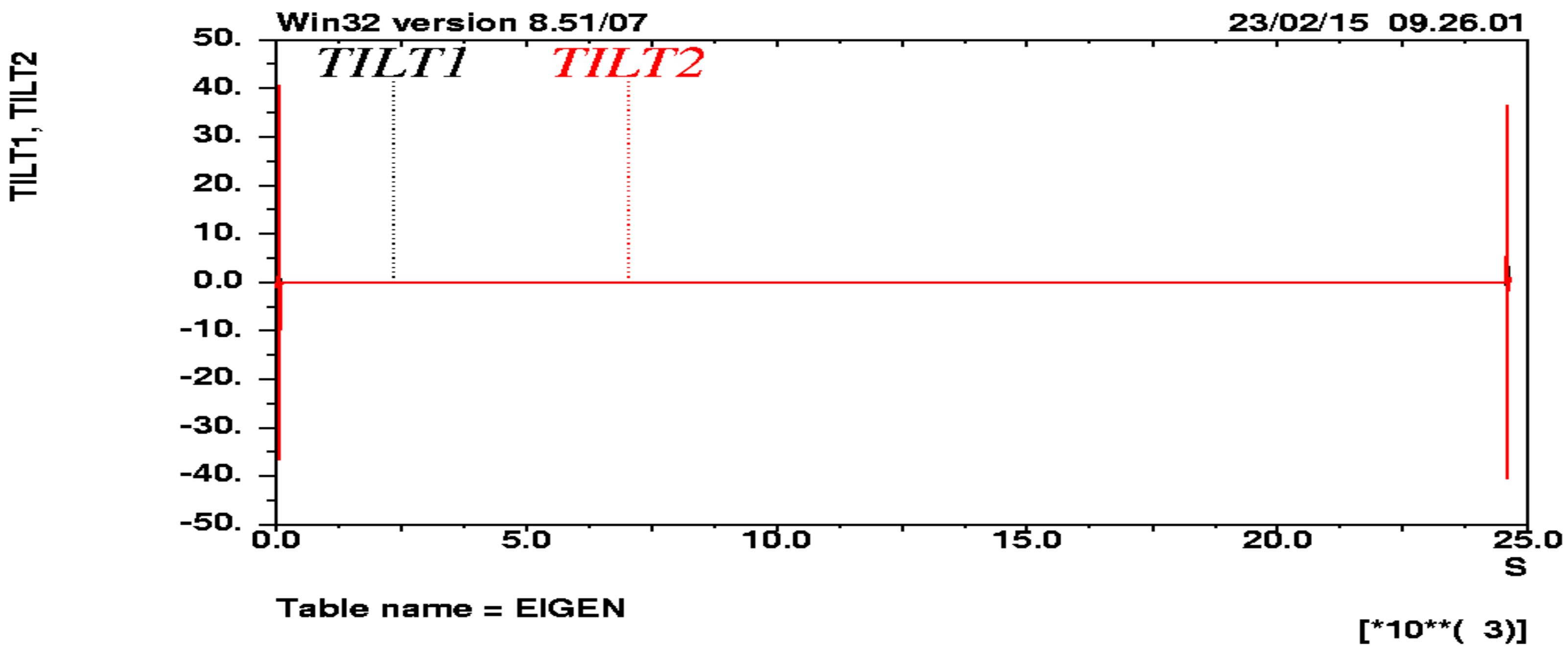
Dispersion functions



Vertical dispersion in the area of betatron coupling compensation makes main contribution to vertical emittance.

DY_max= 4.2 mm

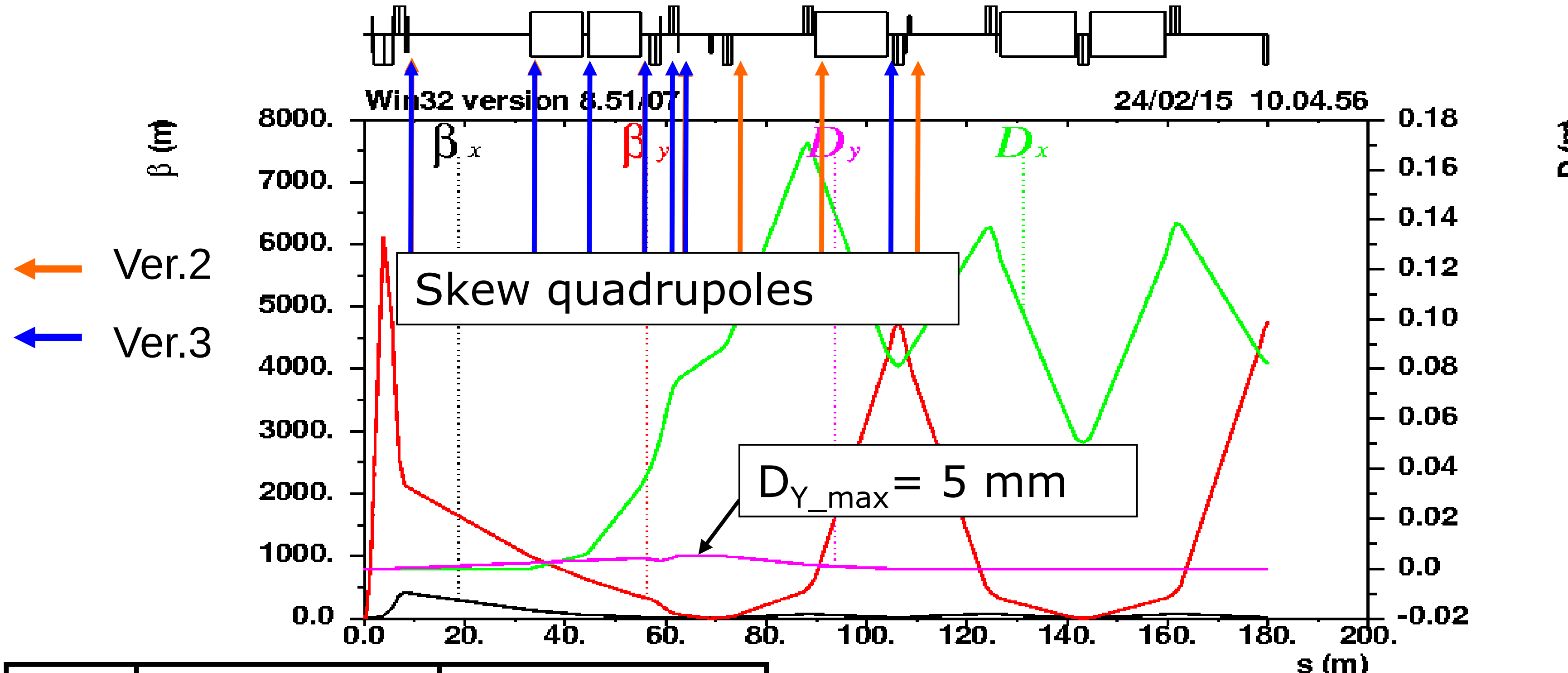
Normal mode angles



Full compensation of betatron coupling is performed, but the tilt is quite large (~40 deg) in the IR chromatic sections. The tilt influence to the DA and MA should be studied carefully (skew-sextupoles?) .

$$M_{ring} = \begin{pmatrix} 0.03 & 3.13 & 0.00 \\ -0.31 & 1.15 & 0.00 \\ 0.00 & 0.00 & -3.1e-5 \\ 0.00 & 0.00 & -0.36 \end{pmatrix}$$

Different set of skew-quads, V2-1 (175 GeV)



	Ver.2		Ver.2-1	
Name	s, m	K1L, m^-1	s, m	K1L, m^-1
IP	0		0	
L.SQ01	8.00	-3.36E-04	8.70	-4.11E-04
L.SQ02	33.00	3.82E-04	33.00	-3.19E-04
L.SQ03	55.00	-6.97E-04	43.50	1.52E-03
L.SQ04	62.54	6.19E-04	55.00	-9.93E-03
L.SQ05	73.27	-4.24E-05	58.96	1.98E-02
L.SQ06	89.37	-2.18E-04	62.54	-1.20E-02
L.SQ07	108.97	8.66E-04	104.17	1.13E-03

- Skew Quads K1s$_{R.SQ}$= -K1s$_{L.SQ}$
- Emittance ratio (ver.2-0) = 0.26 %
- Emittance ratio (ver.2-1) = 0.12 %
- Skew quads of Ver.2-1 are stronger.

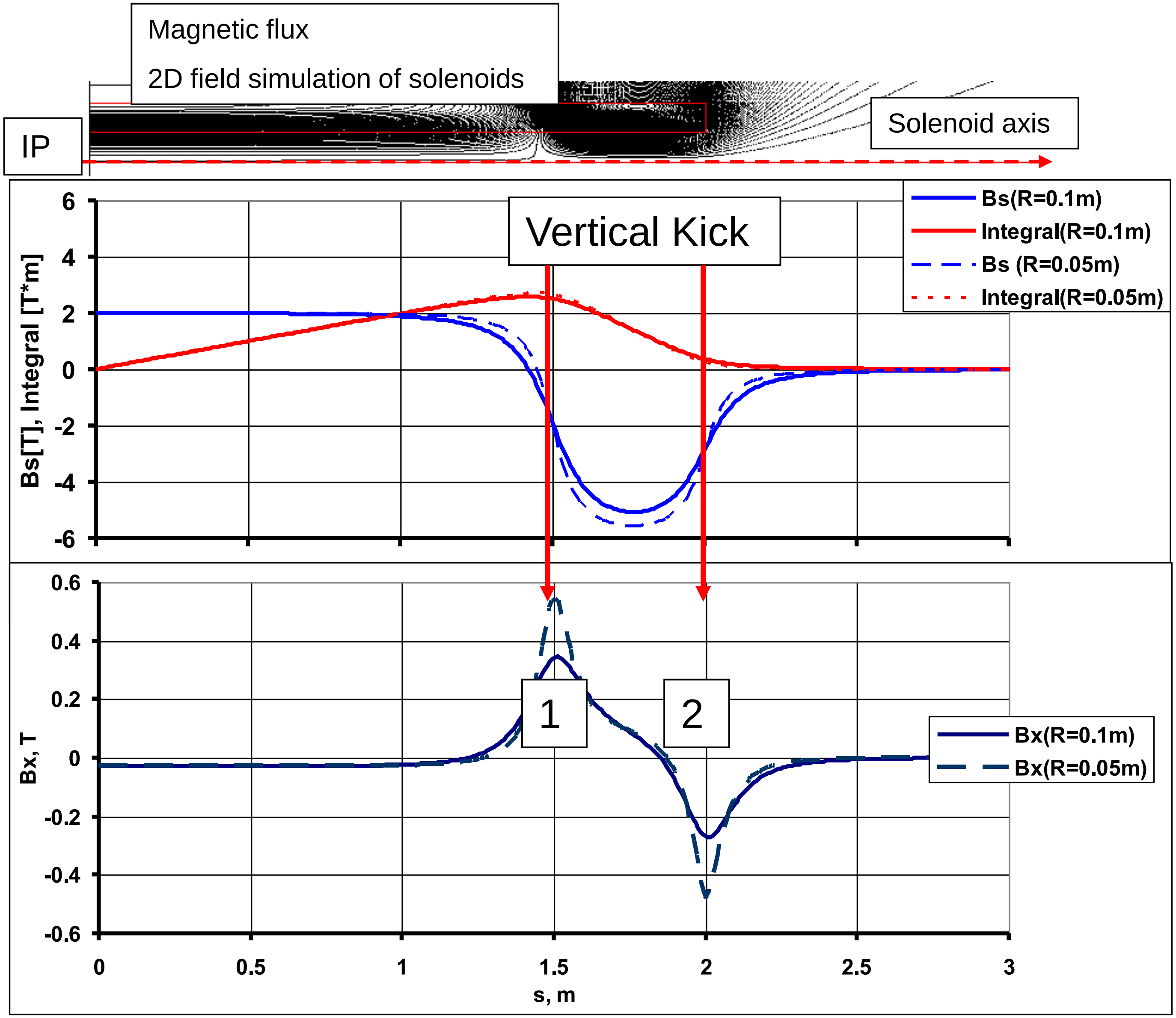
Beam parameters with solenoids

Energy, GeV	175	175	175	175	45
Version	Original	Ver.1**	Ver.2-0	Ver.2-1	Ver.2-0
Solenoids	off	on	on	on	on
Betatron tunes:					
qx	124.540	124.540	124.540	124.543	124.552
qy	84.570	84.577	84.582	84.619	84.693
Betafunction IP:					
Betx, m	0.50	0.50	0.51	0.52	0.62
Bety, mm	1.00	1.09	1.16	1.63	2.20
Emittance, nm*rad:					
horizontal	1.26	1.26	1.26	1.26	8.40E-02
vertical	0	3.13E-05	3.23E-03	1.47E-03	1.70E-03
Emittance ratio	0.00E+00	2.48E-05	2.56E-03	1.17E-03	2.02E-02

* - Excitation of vertical emittance by solenoids fringes is not taken into account

** - Ver.1. Compensating solenoids are between IP and QD0 quadrupoles.

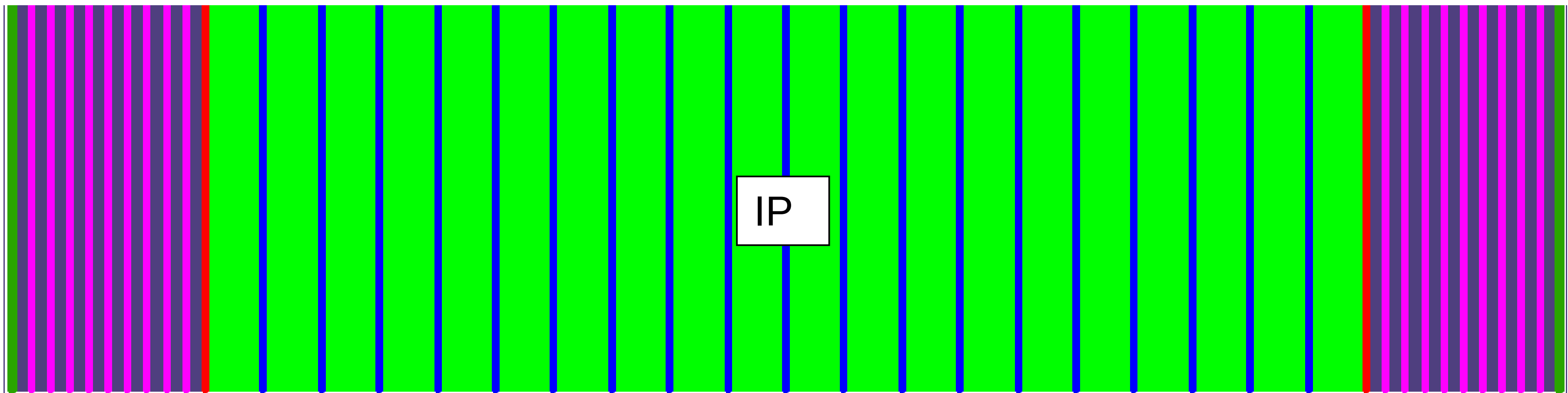
Solenoid fringes



- Inner radius of ante-solenoids R=0.1 m
- Geometric length of main solenoids ±3 m
- Magnetic length of main solenoids ±2.58 m
- Geometric length of compensating solenoids 0.5 m
- Magnetic length of compensating solenoids 0.51 m
- Vertical kicks for R=0.1 m

1. Bx=0.35 T L=0.27 m
2. Bx=-0.27 T L=0.22 m

Solenoids MAD model with fringes



$KICK_{edge\_2}$ – kicks by outer edge of compensating solenoid

$KICK_{edge\_1}$ – kicks by edge between solenoids

Compensating solenoid

Main solenoid

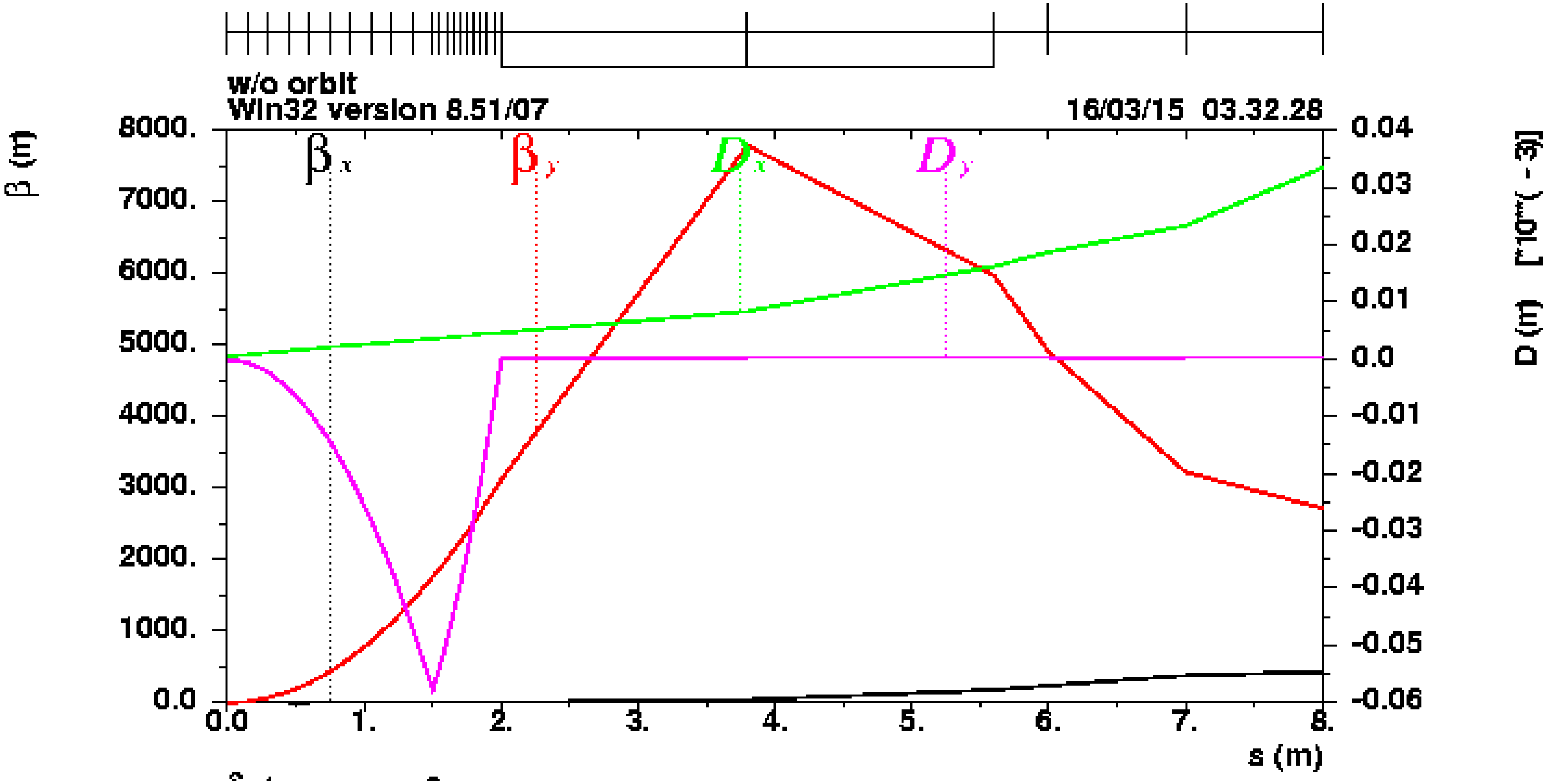
$KICK_i = B_{comp\_sol} L_i / (BR) \cdot \sin(\alpha)$

kicks by radial field of compensating solenoid

$KICK_i = B_{main\_sol} L_i / (BR) \cdot \sin(\alpha)$

kicks by radial field of main solenoid

IR optics with fringes at E= 175 GeV



Dispersion after solenoids:
DX= 0.01 mm
DY=0 mm

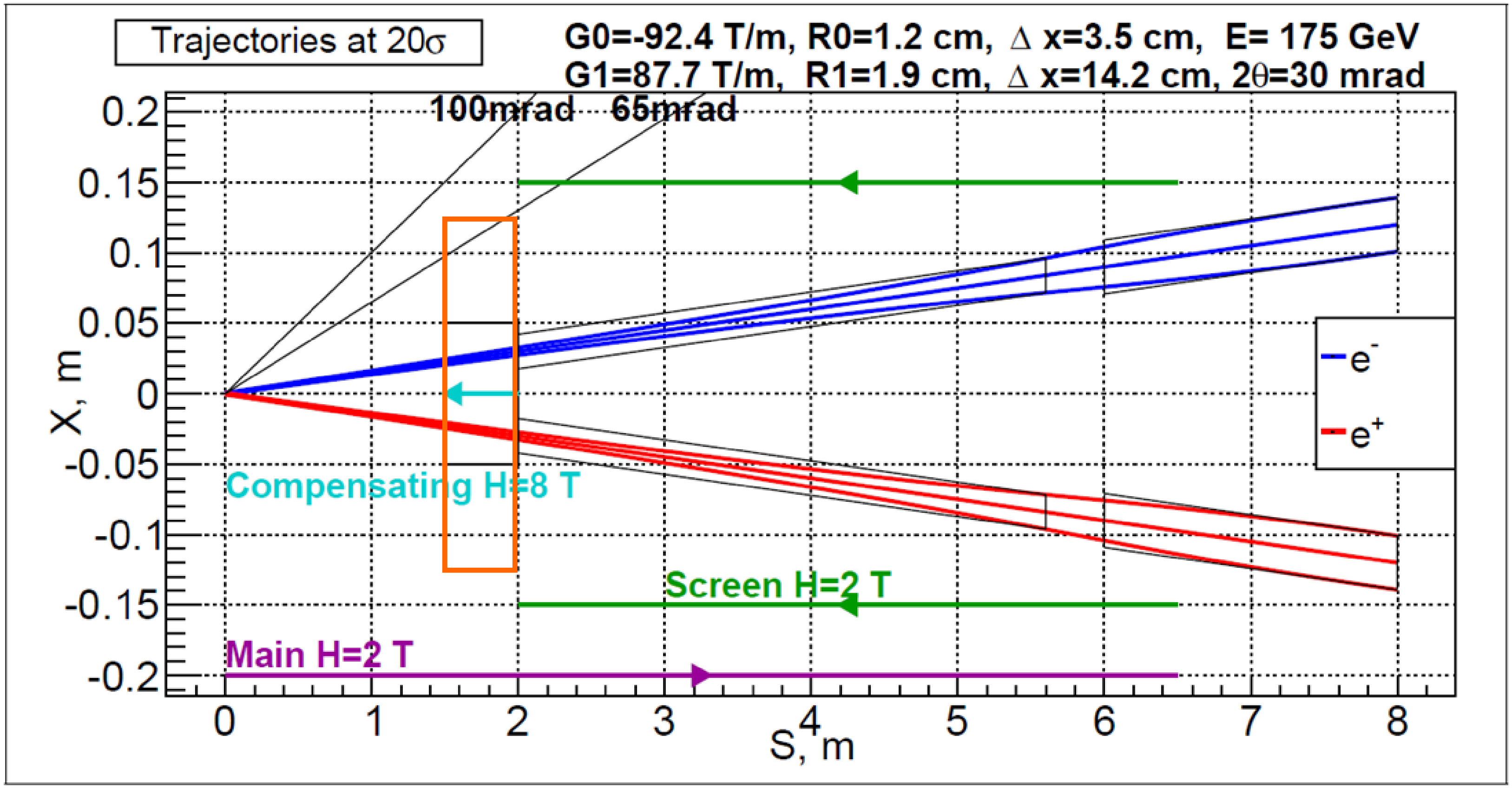
Beam parameters with solenoid fringes V1

Energy, GeV	45*	45**	175*	175**
Solenoids fringes	off	on	off	on
Main solenoid field, T	2	2	2	2
Ante-solenoid field, T	6	6	6	6
Emittance, nm*rad:				
horizontal	0.084	0.080	1.26	1.26
vertical	**3.71E-05**	**0.059**	**3.13E-05**	**1.58E-03**
Ver./Hor. Emittance	4.45E-04	0.74	2.48E-05	1.25E-03

The compensating solenoid is between the IP and QD0.

$L_{edge\_1,2}$ = 0.25 m, $B_{x\_edge\_1}$ = -0.36 T, $B_{x\_edge\_2}$ = 0.35 T

Rectangular anti-solenoid



Δy = 10 cm

Δx = 24 cm

For the “rectangular” solenoid the horizontal field is suppressed and the vertical emittance excitation is 4×10^{-2} pm instead of 60 pm.

Main solenoid fringes V2

Energy, GeV	175	175	175	45
Version	Original	Ver.2-0	Ver.2-1	Ver.2-0
Solenoids	off	on	on	on
Betatron tunes:				
qx	124.540	124.540	124.543	124.552
qy	84.570	84.582	84.619	84.693
Betafunction IP:				
Betx, m	0.50	0.51	0.52	0.62
Bety, mm	1.00	1.16	1.63	2.20
Emittance, nm*rad:				
horizontal	1.26	1.26	1.26	8.40E-02
vertical	0	3.68E-03	1.92E-03	3.62E-03
Ver./Hor. Emittance	0.00E+00	2.92E-03	1.52E-03	4.31E-02

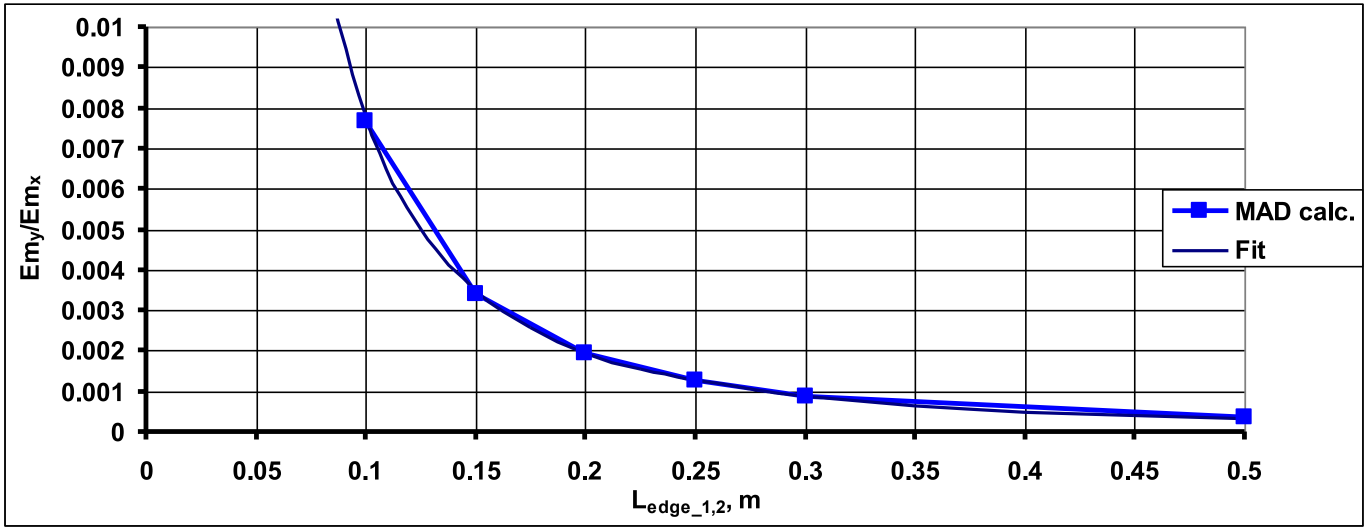
In Version 2 the compensating solenoids are placed on the beam axis and only main solenoid field affects the beam

Summary

Version 1 seems the simplest to compensate the main detector solenoid field. A disadvantage is the vertical emittance excitation by the fringe fields (especially at 45 GeV for our model Ey/Ex = 75%, Ey=60 pm). Possible cures: (1) rectangular anti-solenoid (horizontally wide but vertically narrow), horizontal field at the edges is suppressed, (2) more precise optimization of the fringe transition region.

Version 2 does not contain strong anti-solenoid fringe fields but requires complicated coupling correction with skew-quads in the area of chromatic sextupoles and bending magnets. Now the highest value of the vertical emittance is Ey = 1.7 pm at 45 GeV (w/o main solenoid fringes) and 3.7 pm (with). Influence on the dynamic aperture and momentum acceptance is expected and careful study is necessary.

Vertical emittance vs. fringe length



KICK $_{edge\_1,2}$ = $B_x \cdot L_{edge}$ = ±0.15 mrad = const

B_x ~ const / L_{edge}

$L_{edge\_1,2}$ – effective length of edge solenoid kick 1, 2

$Em_y \sim 1/(L_{edge})^2$