Solenoid Compensation Scheme for FCC-ee FF

S. Sinyatkin
Budker Institute of Nuclear Physics

20 January 2017, CERN

What was done

•The solenoid fringe field effect is estimated for various solenoid models:

- compensating and main solenoid lengths are varied, the sum is kept unchanged;

- compensating solenoid length is varied, the main solenoid length is kept unchanged.

- L_star vs. L_main_sol at ε_y = *const*

•Update of solenoid geometry for L^*= 3 m and 2.2 m.

•Checked MAD calculations (EMIT module) of emittance.

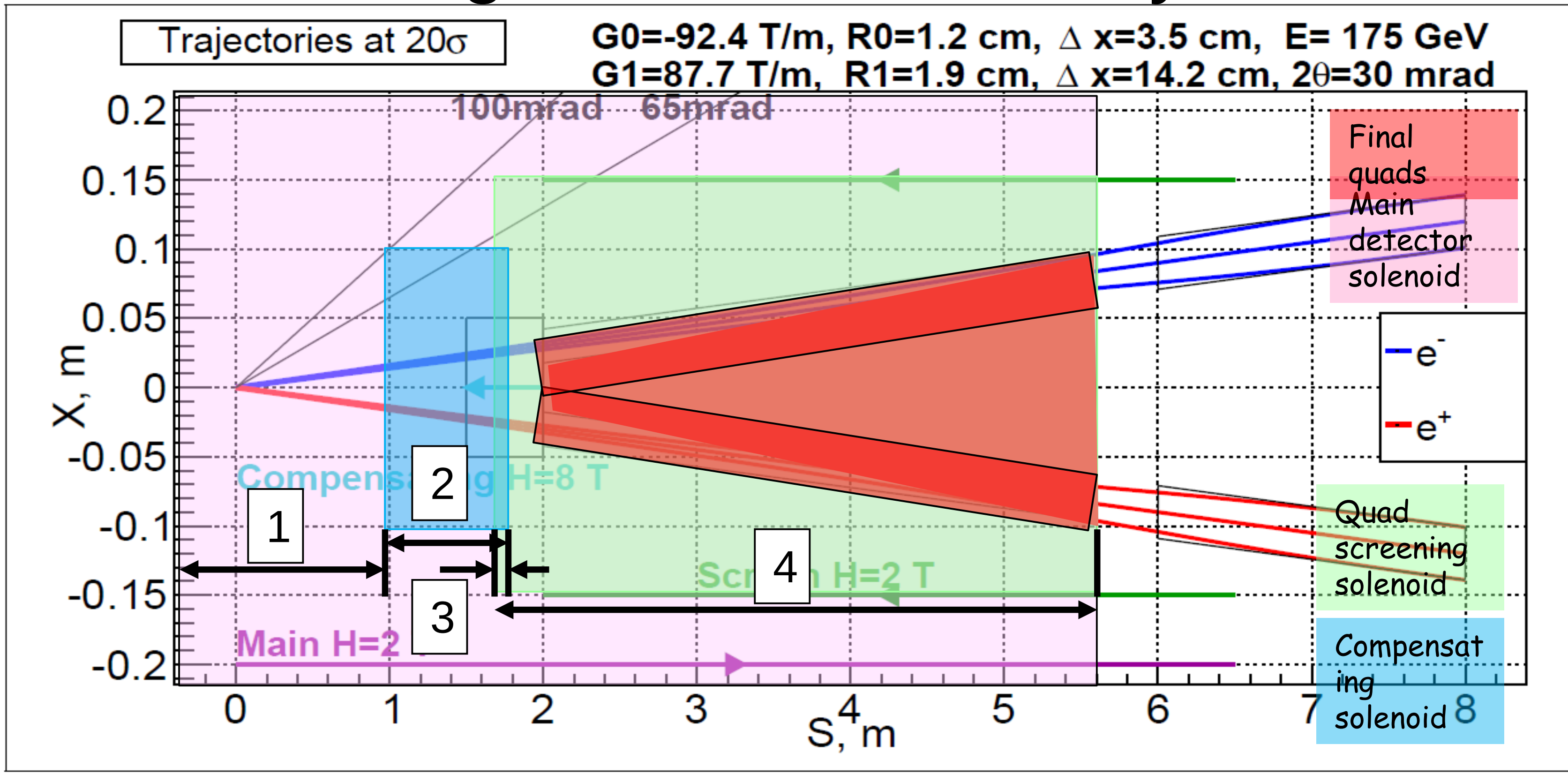
2016 Parameters

parameter	FCC-ee			
energy/beam [GeV]	**45**		**120**	**175**
bunches/beam	91500	30180	770	78
beam current [mA]	1450		30	6.6
energy loss/turn [GeV]	0.03		1.67	7.55
synchrotron power [MW]	100			
RF voltage [GV]	0.2	0.4	3.0	10
rms bunch length (SR,+BS) [mm]	1.6, 3.8	1.2, 6.7	2.0, 2.4	2.1, 2.5
rms emittance $\varepsilon_{x,y}$ [nm, pm]	0.1, 1	0.2, 1	0.6, 1	1.3, 2.5
$\beta^*_{x,y}$ [m, mm]	1, 2	0.5, 1	1, 2	1, 2
long. damping time [turns]	1320		72	23
crossing angle [mrad]	30			
beam lifetime [min]	185	94	67	57
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	**207**	**5.1**	**1.3**

Parameters

Circumference [km]	99.984	
Vending radius of arc dimple [km]	11.190	
Number of IPs / ring	2	
Crossing angle at IP [mrad]	30	
Solenoid field at the IP [T]	±2	
ℓ^* [m]	2.2	
Ebeam [GeV]	**45.6**	**175**
SR energy loss per turn [GeV]	0.0346	7.47
Current / beam [mA]	1450	6.6
Bunches / ring	30180 (91500)	81
$P_{SR,tot}$ [MW]	100.3	98.6
ε_x [nm]	0.86	1.26
β^*_x [m]	0.5 (1)	1 (0.5)
β^*_y [mm]	1 (2)	2 (1)

Original Final Focus layout



1 – Half of main solenoid length *L_main/2* (1 m, length of magnetic field area on reference trajectory)

2 – Length of compensating solenoid *L_comp* (0.7 m)

3 – Overlap of compensating and screening solenoids

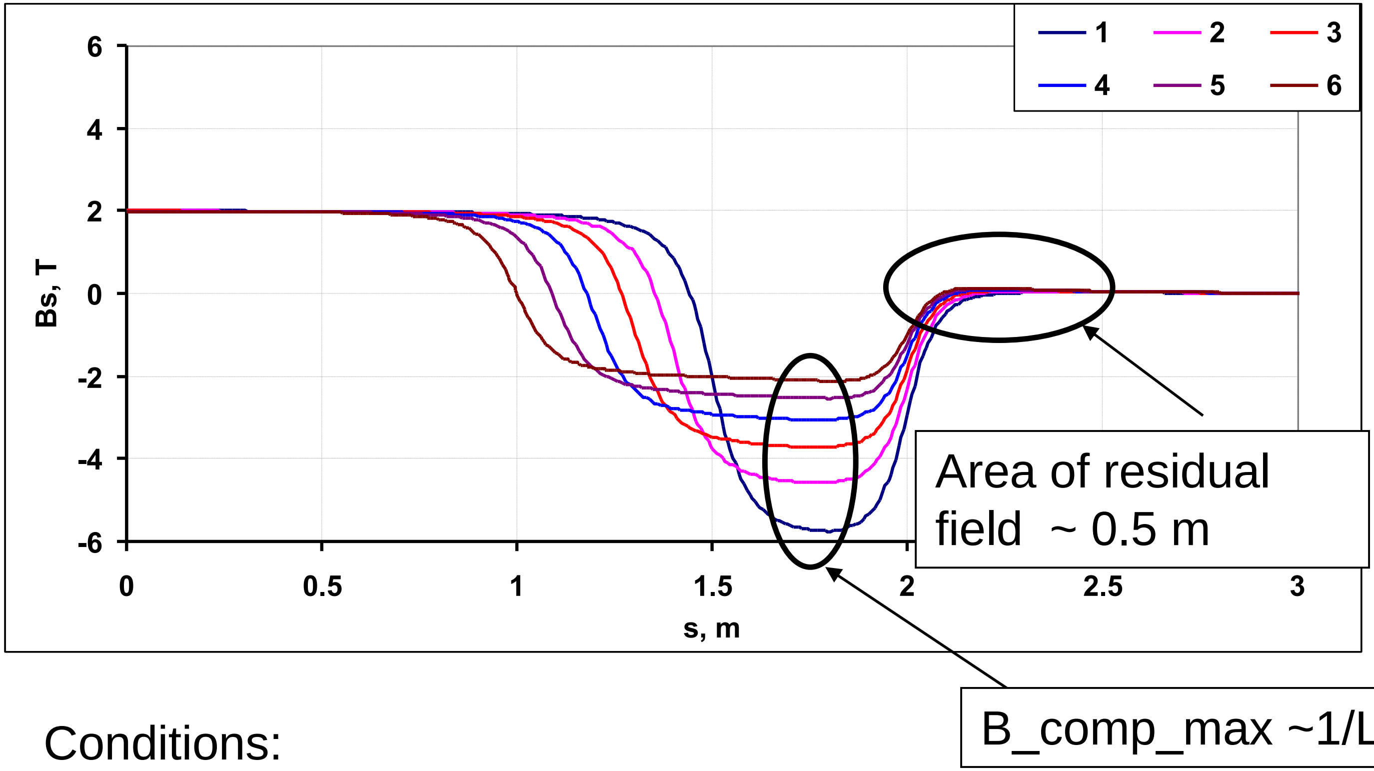
L_over (5 cm)

4 – Length of screening solenoid L_screen (3.95 m)

Transverse half size:

- compensating cylindrical solenoid R = 0.1 m
- screening solenoid R = 0.15 m

Variation of main and compensating solenoids lengths (1)



Geom. length:

1 – L_comp = 0.5 m

2 – L_comp = 0.6 m

3 – L_comp = 0.7 m

4 – L_comp = 0.8 m

5 – L_comp = 0.9 m

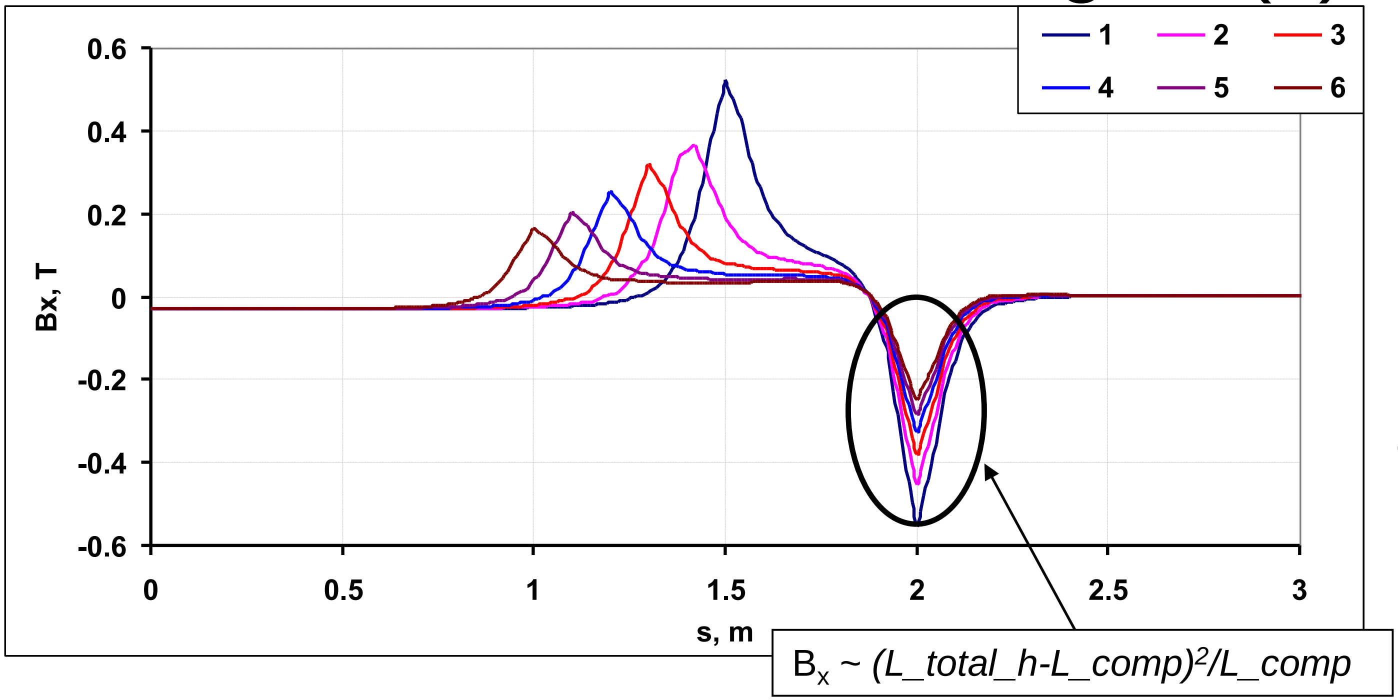
6 – L_comp = 1 m

Conditions:

*B_main*L_main+2*B_comp*L_comp=0*

*L_total=L_main+2*L_comp=const=4 m* (geometric length)

Variation of main and compensating solenoids lengths (1)



Geom. length:

1 – L_comp = 0.5 m

2 – L_comp = 0.6 m

3 – L_comp = 0.7 m

4 – L_comp = 0.8 m

5 – L_comp = 0.9 m

6 – L_comp = 1 m

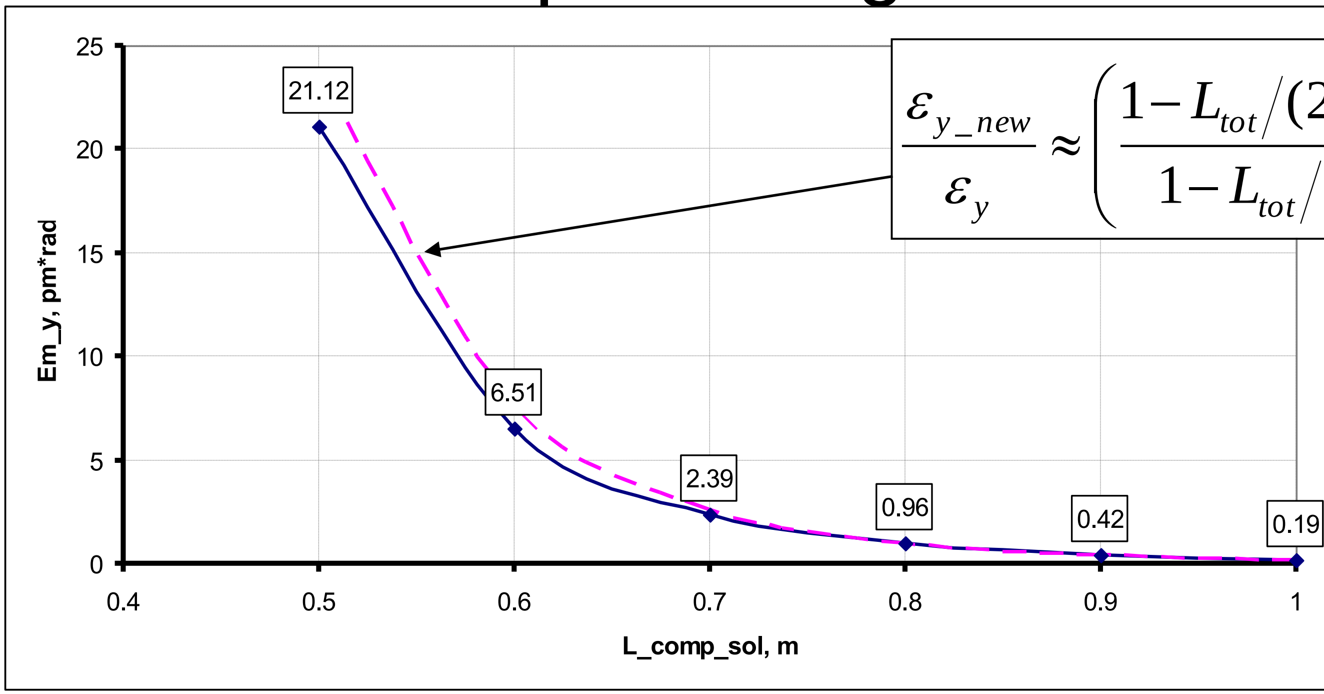
Conditions:

*B_sol*L_main+2*B_comp*L_comp=0*

L_main+L_comp=const=2 m (geometric length)

Bx~ (L_total_h-L_comp)^2/L_comp

Estimation of vertical emittance dependence on compensating solenoid length (1).



$$\frac{\varepsilon_{y\_new}}{\varepsilon_y} \approx \left(\frac{1 - L_{tot} / (2 \cdot L_{comp\_new})}{1 - L_{tot} / (2 \cdot L_{comp})} \right)^5$$

Conditions:

*B_sol*L_main+2*B_comp*L_comp=0*

L_tot=L_main+L_comp=const=2 m (geometric length)

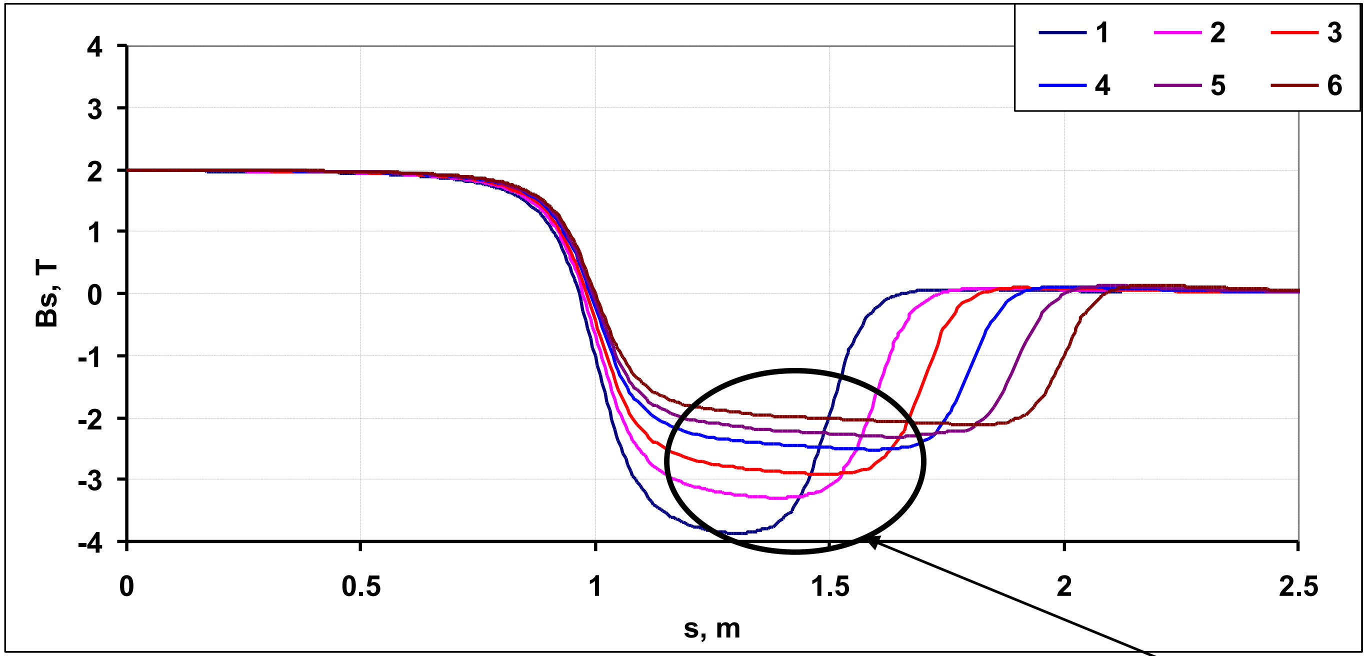
$I_{5,y} \sim h_y^5 \sim B_x^5$

Variation of main and compensating solenoids lengths*(1)

Main solenoid						
Half geometric length, m	1	1.1	1.2	1.3	1.4	1.5
Half magnetic length, m	0.912	1.001	1.089	1.176	1.257	1.342
Comp. solenoid						
Geometric length, m	1	0.9	0.8	0.7	0.6	0.5
Magnetic length, m	0.856	0.786	0.711	0.631	0.547	0.466
Energy E, GeV	45	45	45	45	45	45
Betatron tunes						
qx	0.100	0.100	0.100	0.100	0.100	0.100
qy	0.268	0.278	0.290	0.307	0.328	0.356
Emittance, pm*rad	87.78	87.7	87.6	87.3	87.0	86.4
Ver. Emittance, pm*rad	0.19	0.42	0.96	2.39	6.51	21.12
Emittance Ratio (v./h.)	0.0022	0.0048	0.0110	0.0274	0.0748	0.2444
Energy spread	3.82E-04	3.85E-04	3.90E-04	4.01E-04	4.20E-04	4.64E-04
Energy loss, MeV	35.06	35.10	35.15	35.24	35.37	35.61

**- for ordinary round solenoids*

Variation of compensating solenoids length (2)



Geom. length:

1 – L_comp = 0.5 m

2 – L_comp = 0.6 m

3 – L_comp = 0.7 m

4 – L_comp = 0.8 m

5 – L_comp = 0.9 m

6 – L_comp = 1 m

B_comp_max ~1/L_comp

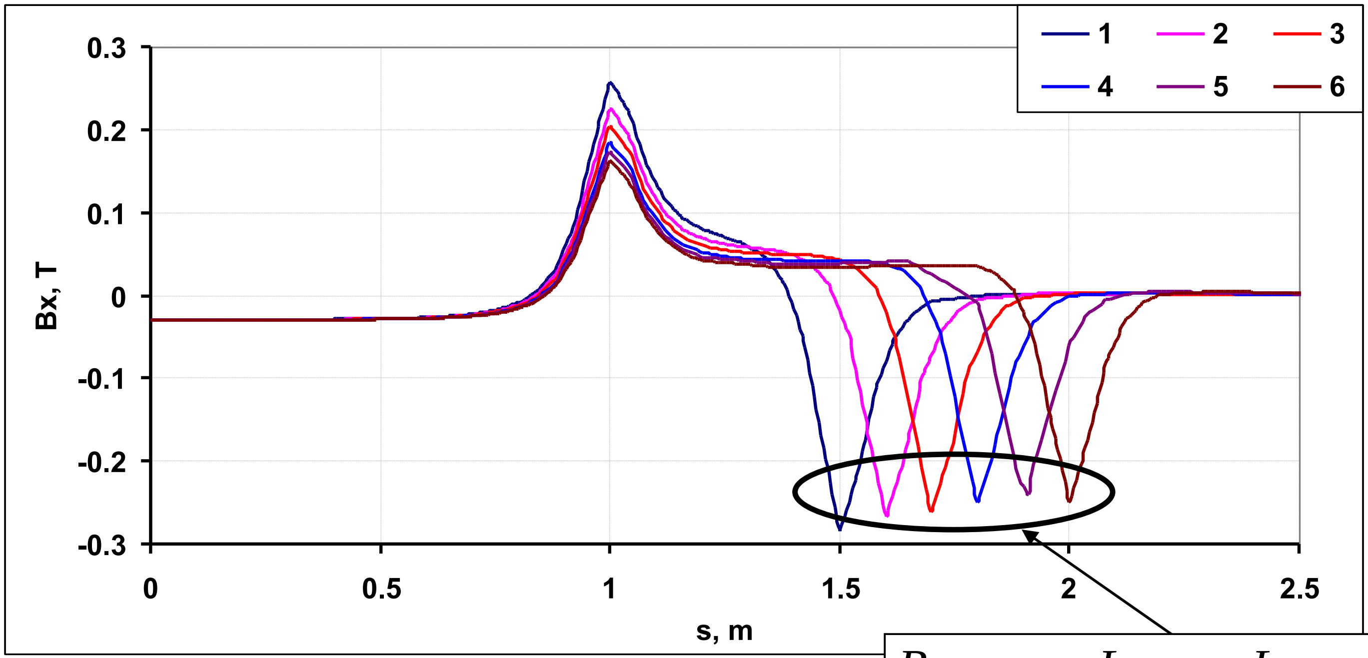
Conditions:

*B_sol*L_main+2*B_comp*L_comp=0*

L_main+L_comp is variable

L_main=±1 m (geometric length)

Variation of compensating solenoids length (2)



Geom. length:

1 – L_comp = 0.5 m

2 – L_comp = 0.6 m

3 – L_comp = 0.7 m

4 – L_comp = 0.8 m

5 – L_comp = 0.9 m

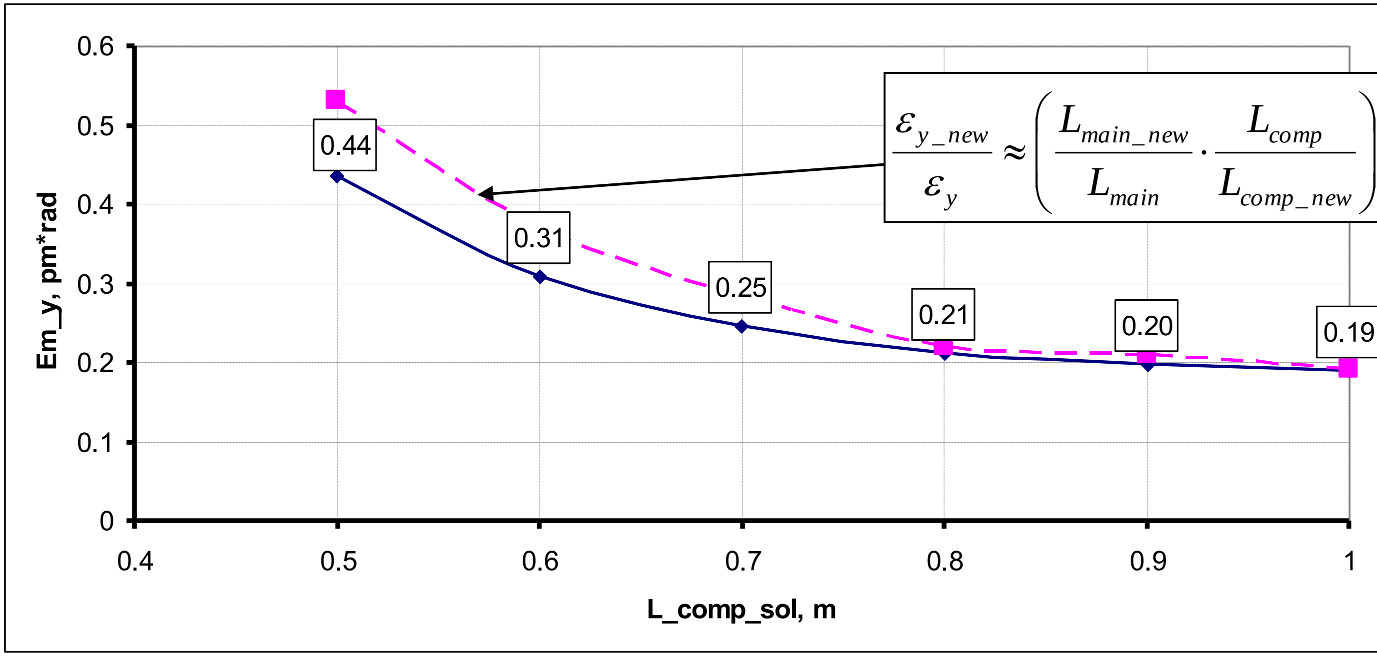
6 – L_comp = 1 m

$$\frac{B_{x\_new}}{B_x} \approx \frac{L_{comp}}{L_{comp\_new}} \cdot \frac{L_{main\_g}/2 + L_{comp\_new\_g}}{L_{main\_g}/2 + L_{comp\_g}}$$

Conditions:

*B_sol*L_main+2*B_comp*L_comp=0*
L_main+L_comp=var.
L_main=2 m (geometric length)

Variation of compensating solenoids length(2)*



$$\frac{\varepsilon_{y\_new}}{\varepsilon_y} \approx \left(\frac{L_{main\_new}}{L_{main}} \cdot \frac{L_{comp}}{L_{comp\_new}}\right)^5 \left(\frac{L_{main\_g}/2 + L_{comp\_new\_g}}{L_{main\_g}/2 + L_{comp\_g}}\right)^7$$

Conditions:

*B_sol*L_main+2*B_comp*L_comp=0*

L_main/2+L_comp=const=2 m

$I_{5,y} \sim h_y^5 \sim B_x^5$

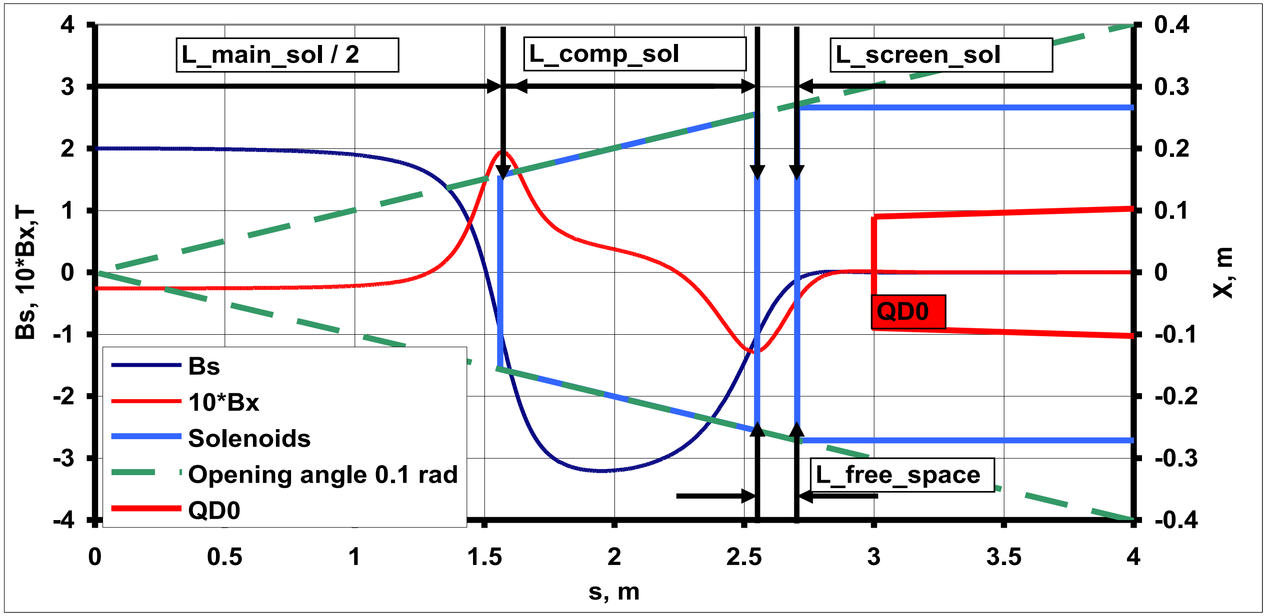
**-Equivalent model is used for MAD simulation*

Variation of compensating solenoid length(2)*

Main solenoid						
Half geometric length, m	1	1	1	1	1	1
Half magnetic length, m	0.912	0.906	0.902	0.893	0.885	0.874
Comp. solenoid						
Geometric length, m	1	0.9	0.8	0.7	0.6	0.5
Magnetic length, m	0.856	0.776	0.710	0.608	0.532	0.447
Energy E, GeV	45	45	45	45	45	45
Betatron tunes						
qx	0.100	0.100	0.100	0.100	0.100	0.100
qy	0.269	0.270	0.270	0.271	0.271	0.272
Emittance, pm*rad	87.78	87.8	87.7	87.7	87.7	87.6
Ver. Emittance, pm*rad	0.19	0.20	0.21	0.25	0.31	0.44
Emittance Ratio (v./h.)	0.0022	0.0023	0.0024	0.0028	0.0035	0.0050
Energy spread	3.82E-04	3.81E-04	3.82E-04	3.83E-04	3.85E-04	3.89E-04
Energy loss, MeV	35.0641	35.0619	35.0766	35.0880	35.1087	35.1385

**-Equivalent model is used for MAD simulation (old layout)*

Update of solenoid geometry (3)



E = 45 GeV

Main solenoid:

B_s = 2 T

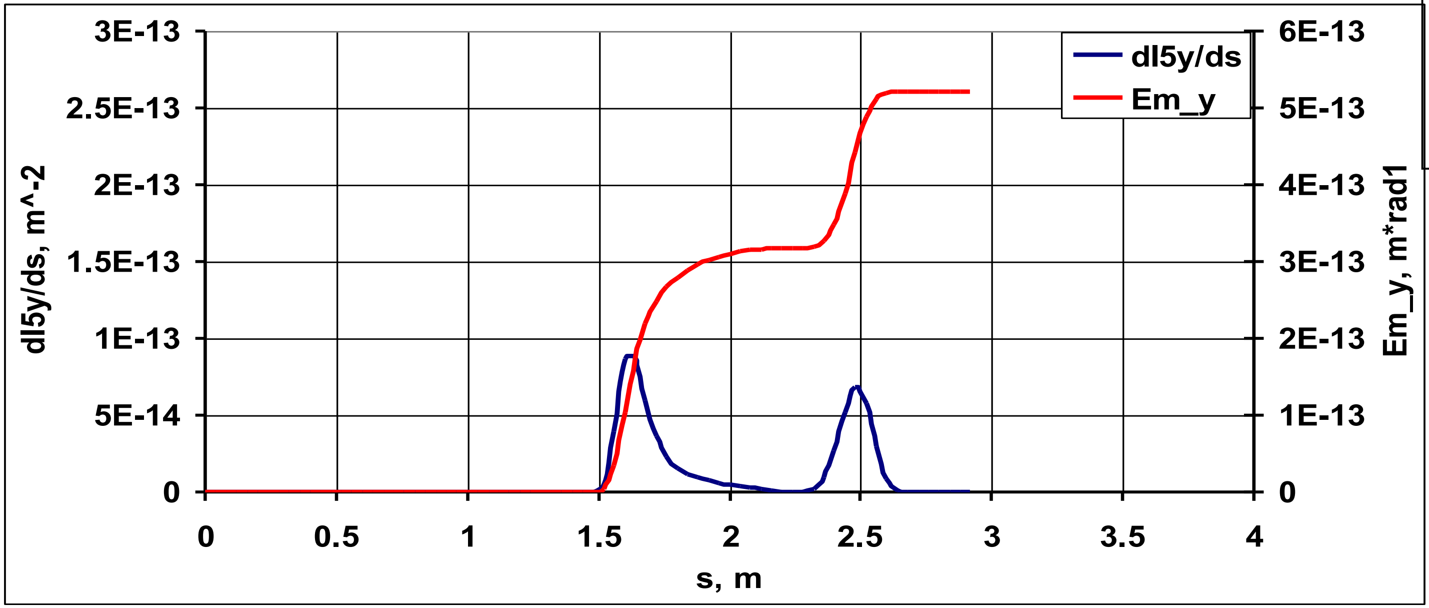
L_{eff_geom}=2*1.56 m

Compensating solenoid:

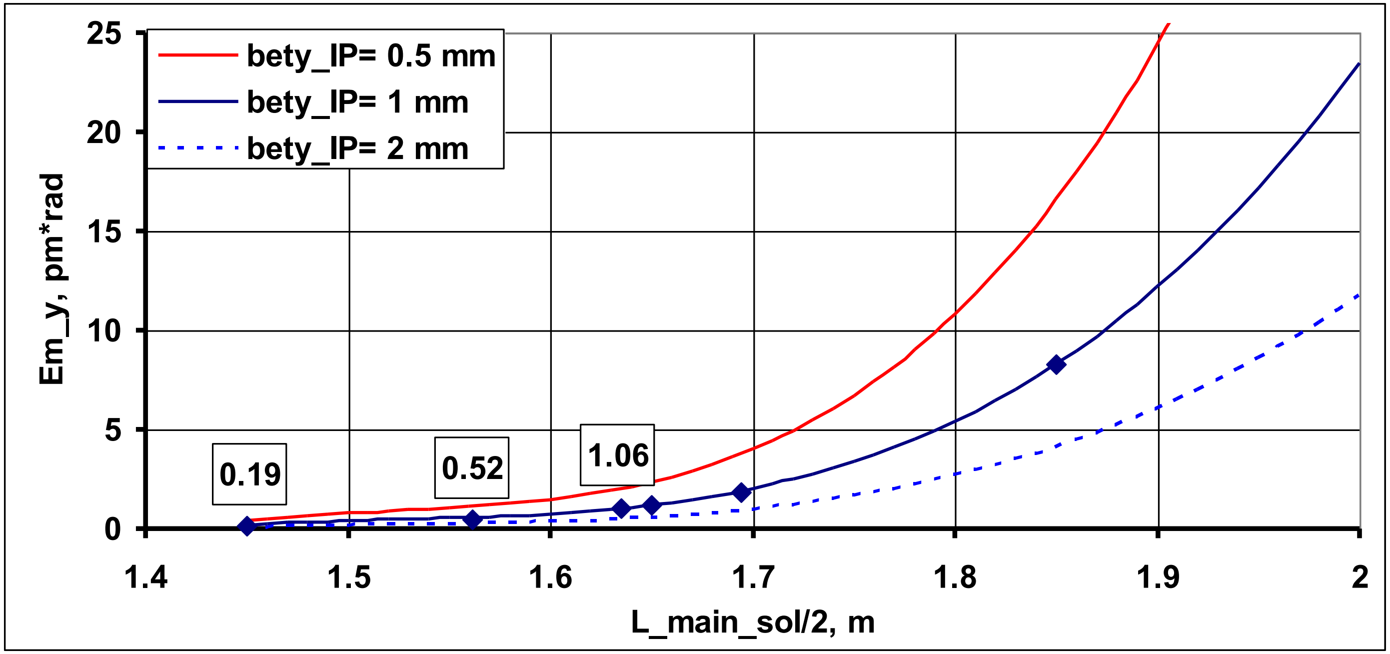
$|B|_{s\_max\_eff}$ = 3.2 T

L_{geom}= 1 m

e_y = 0.5 pm*rad



Vertical emittance vs. effective length of main solenoid (3)



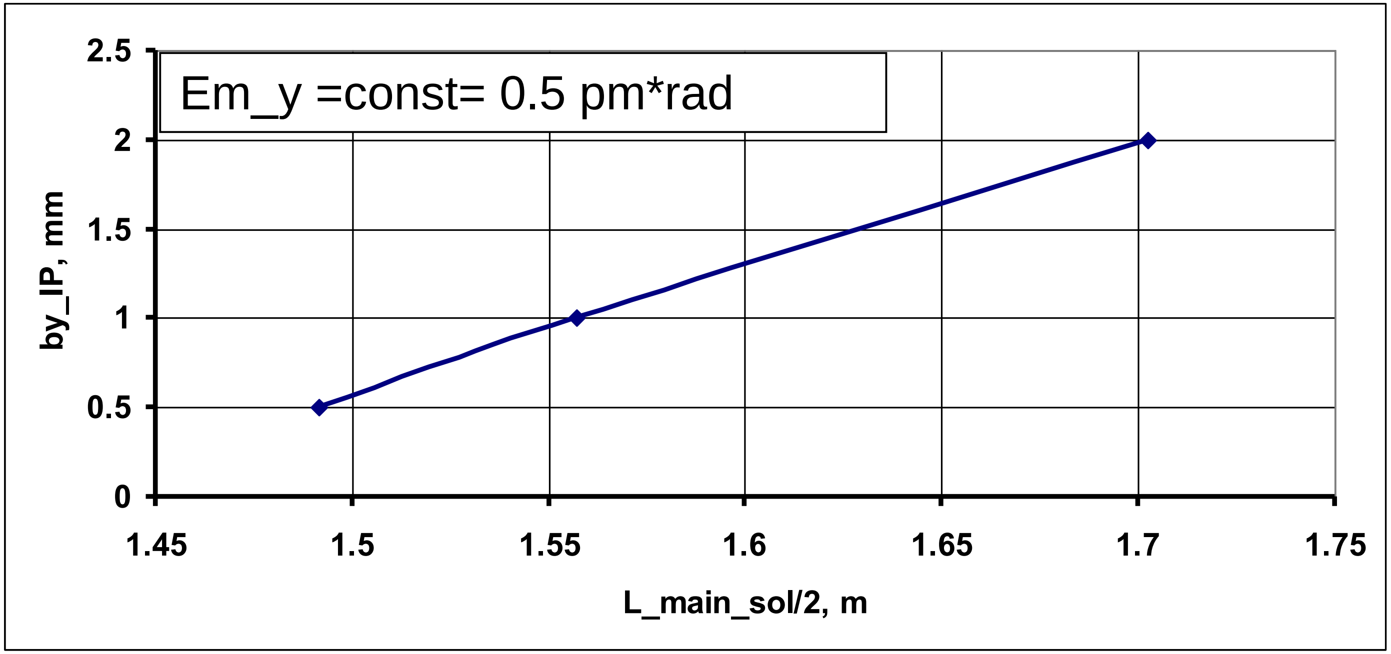
E = 45 GeV

L_star = 3 m

b_{x_IP}= 0.5 m

b_{y_IP} = 1 mm

β_{y_IP} vs. main solenoid length (3)



$$\varepsilon_{y\_new} = \varepsilon_y \cdot \frac{\beta_{y\_IP}}{\beta_{y\_IP\_new}}$$

E = 45 GeV

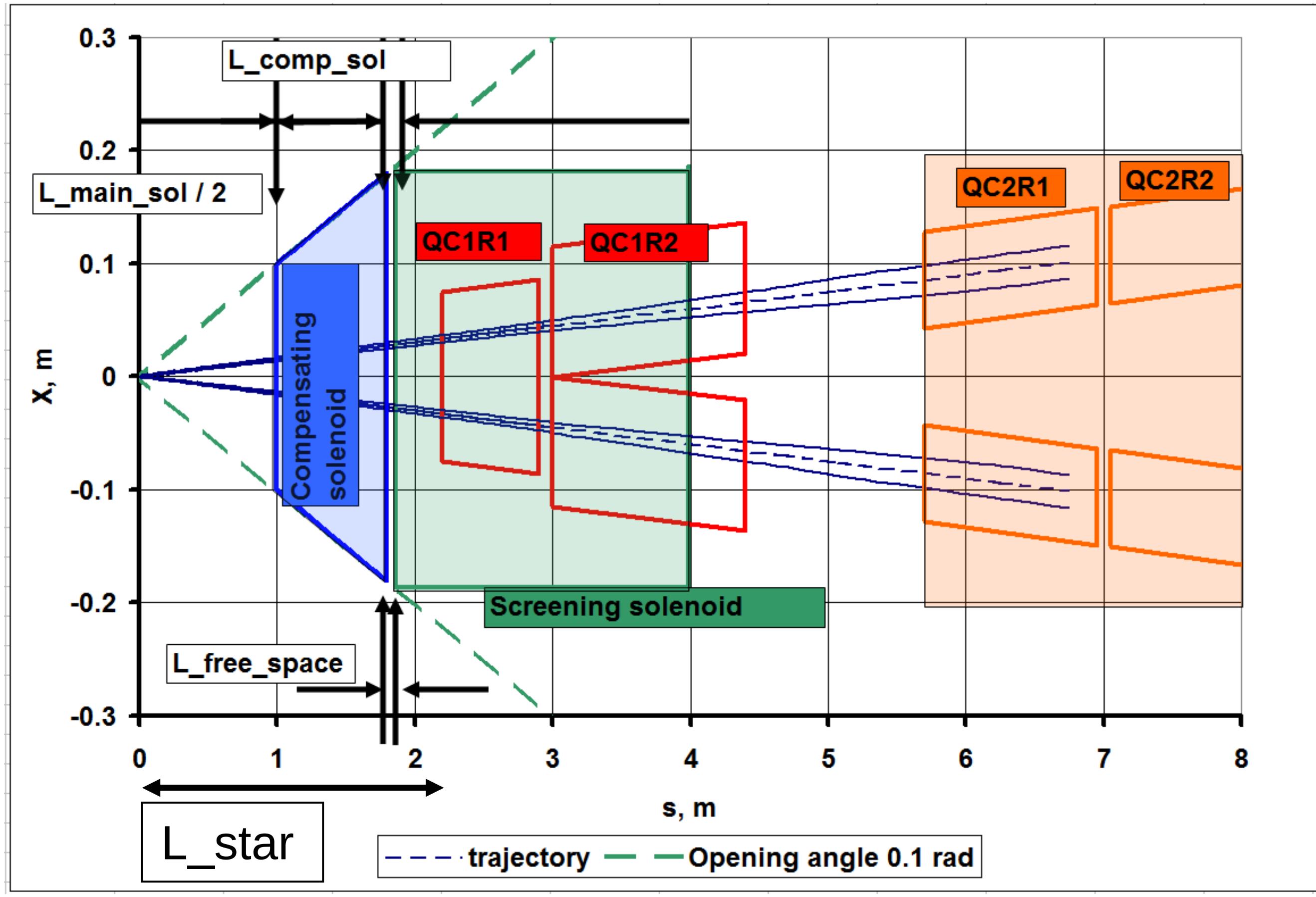
L_star = 3 m

Em_y = 0.5 pm*rad

Ver. Emittance & Change of free space for detector (3)

Parameters	Original*		Geometry Update				
E, GeV	45						
Cross angle (tot), rad	0.03	***0.026***					
Compensating solenoid							
R_in, m	0.100	0.100	0.145	***0.157***	0.164	0.170	0.186
R_end, m	0.100	0.171	0.256	***0.256***	0.256	0.256	0.256
L, m	0.7	0.7	1.1	***0.989***	0.915	0.856142	0.7
L_free_space, m	0.001	0.094	0.134	***0.155***	0.176	0.184	0.221
Screening solenoid							
R_sc_sol,m	0.171	0.180	0.269	***0.271***	0.274	0.274	0.278
Main solenoid							
B, T	2.01	2.01	2.00	***2.00***	2.00	2.00	2.00
L_main/2, m	***1.00***	***1.00***	***1.450***	***1.561***	***1.635***	***1.694***	***1.850***
Optics							
bx_IP, m	0.5	0.5	0.5	***0.5***	0.5	0.5	0.5
by_IP, m	0.001	0.001	0.001	***0.001***	0.001	0.001	0.001
I2_sol, m^-1	1.94E-06	1.19E-06	1.56E-06	***2.11E-06***	2.63E-06	3.09E-06	4.97E-06
I5y_sol, m^-1	3.42E-14	8.38E-15	3.82E-14	***1.05E-13***	2.15E-13	3.70E-13	1.68E-12
Emy_sol, m*rad	***1.69E-13***	***4.14E-14***	***1.88E-13***	***5.21E-13***	***1.06E-12***	***1.83E-12***	***8.29E-12***
Emy_sol/Emx	1.82E-03	4.48E-04	2.04E-03	***5.64E-03***	1.15E-02	1.98E-02	8.98E-02
Uo_sol, keV	111.8	69.0	89.9	***121.7***	151.8	178.6	287.0

Optimisation of edge field area (4)



Lattice (Oide)

FCCee_t_85_by2:

(R / L)

- QC1_1: L= 0.7 m K1=-75 / -75 T/m
- QC1_2: L= 1.4 m K1=-173 / -166 T/m
- QC2_1: L= 1.25 m K1= 72 / 46 T/m
- QC2R2: L= 1.25 m K1= 28 / 64 T/m

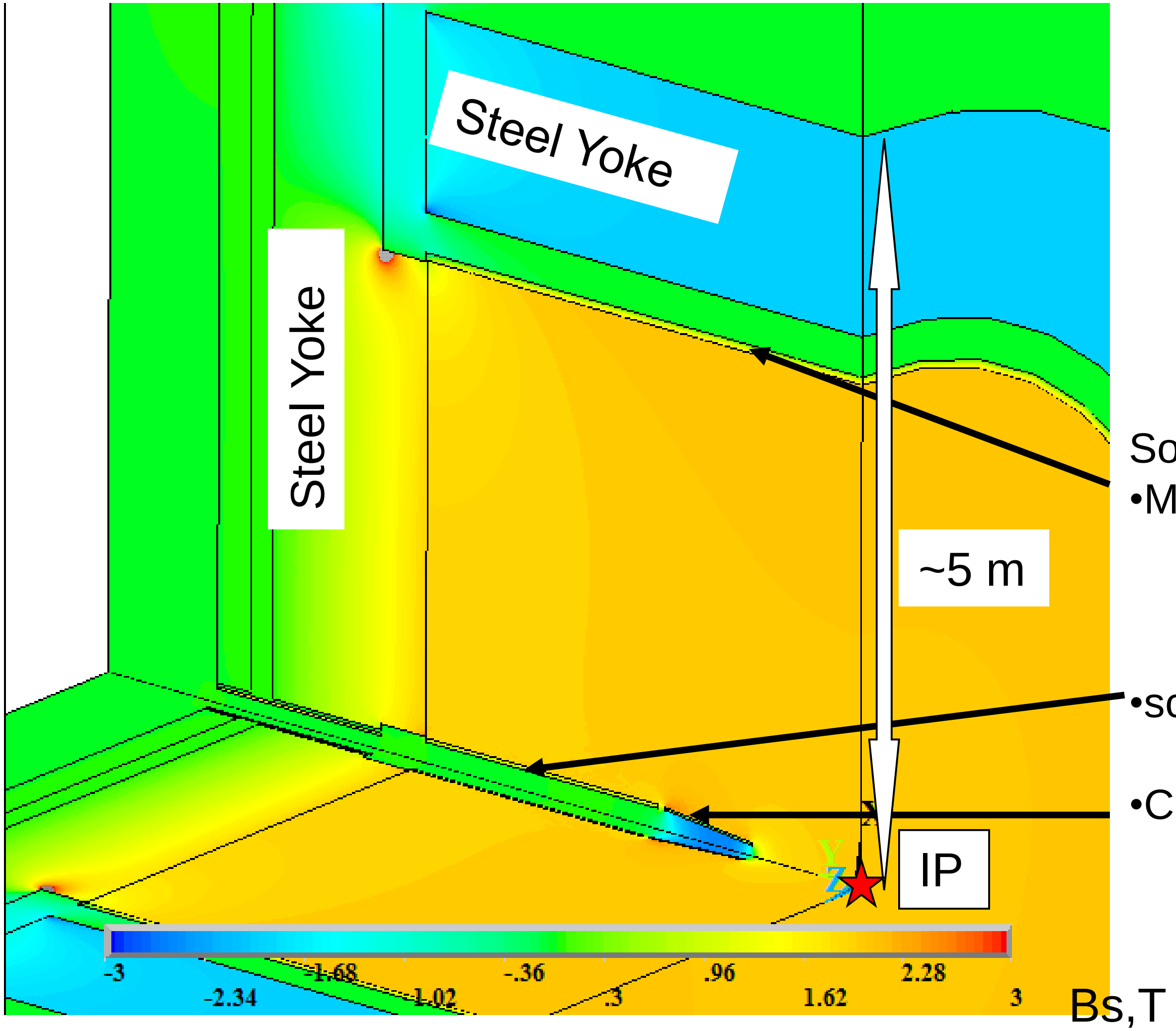
1 – Area (1/2) of main solenoid magnetic field on reference trajectory L_main_sol/2 = 1 m

2 – Length of compensating solenoid L_comp_sol = 0.8 m

3 – Free space between compensating and screening solenoids L_free_space = 6 cm

- compensating solenoid R = 0.1 / 0.18 m
- screening solenoid R = 0.19 m

Optimisation of edge field area (4)



Magnetic field distribution:

L_main_sol/2 = 1 m

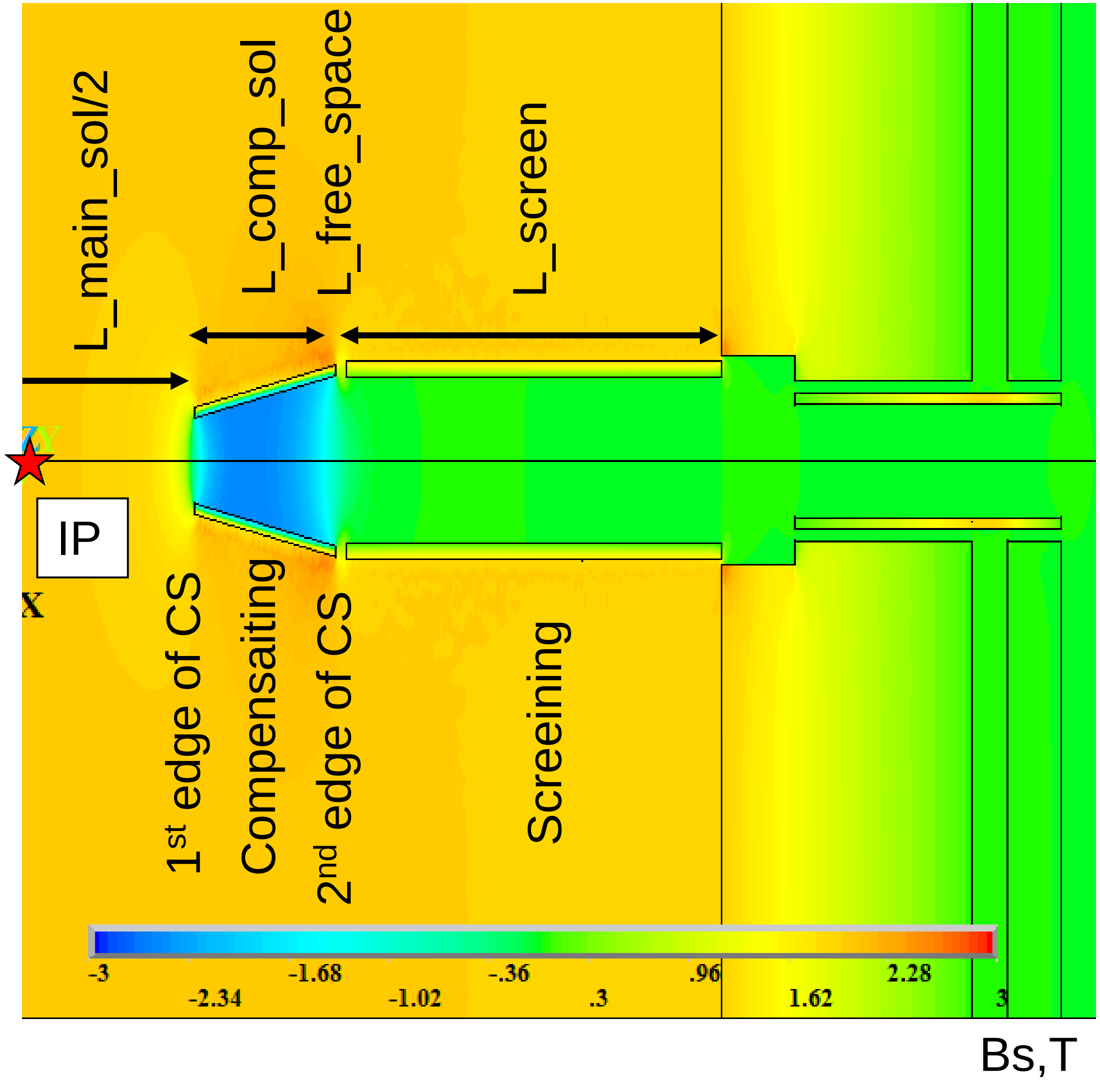
L_comp_sol = 0.8 m

L_free_space = 6 cm

Solenoid:

- Main Rin = 3.76 m
  Rout = 3.82 m
  L = 4 m
- screening R = 0.19 m
- Compensating R = 0.1 / 0.18 m

Optimisation of edge field area (4)



Magnetic field distribution:

L_main_sol/2 = 1 m

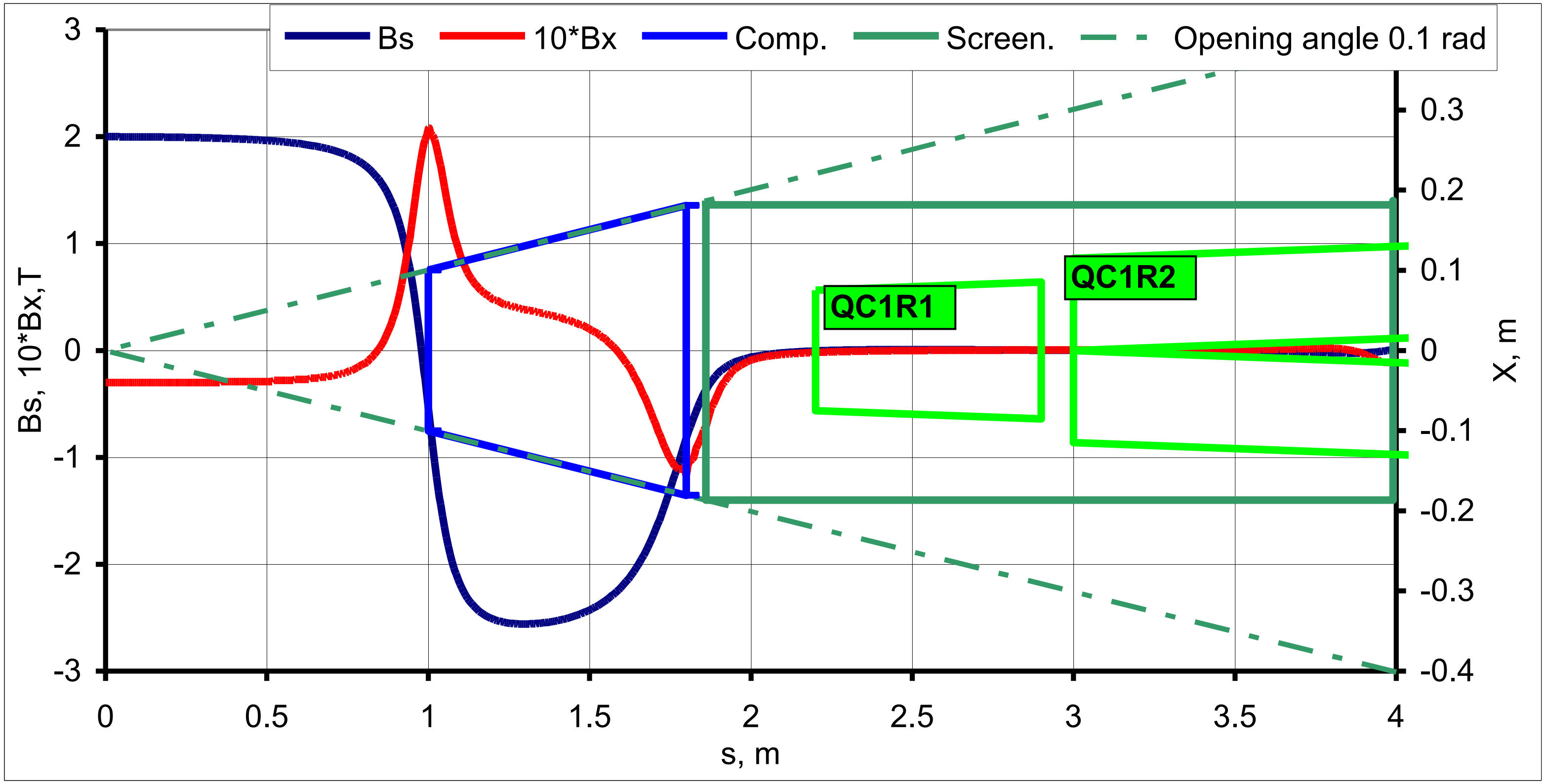
L_comp_sol = 0.8 m

L_free_space = 6 cm

Solenoid:

- Main: Rin = 3.76 m, Rout = 3.82 m, L = 4 m
- screening: R = 0.19 m, L= 2.13 m
- Compensating: R = 0.1 / 0.18 m, L = 0.8 m

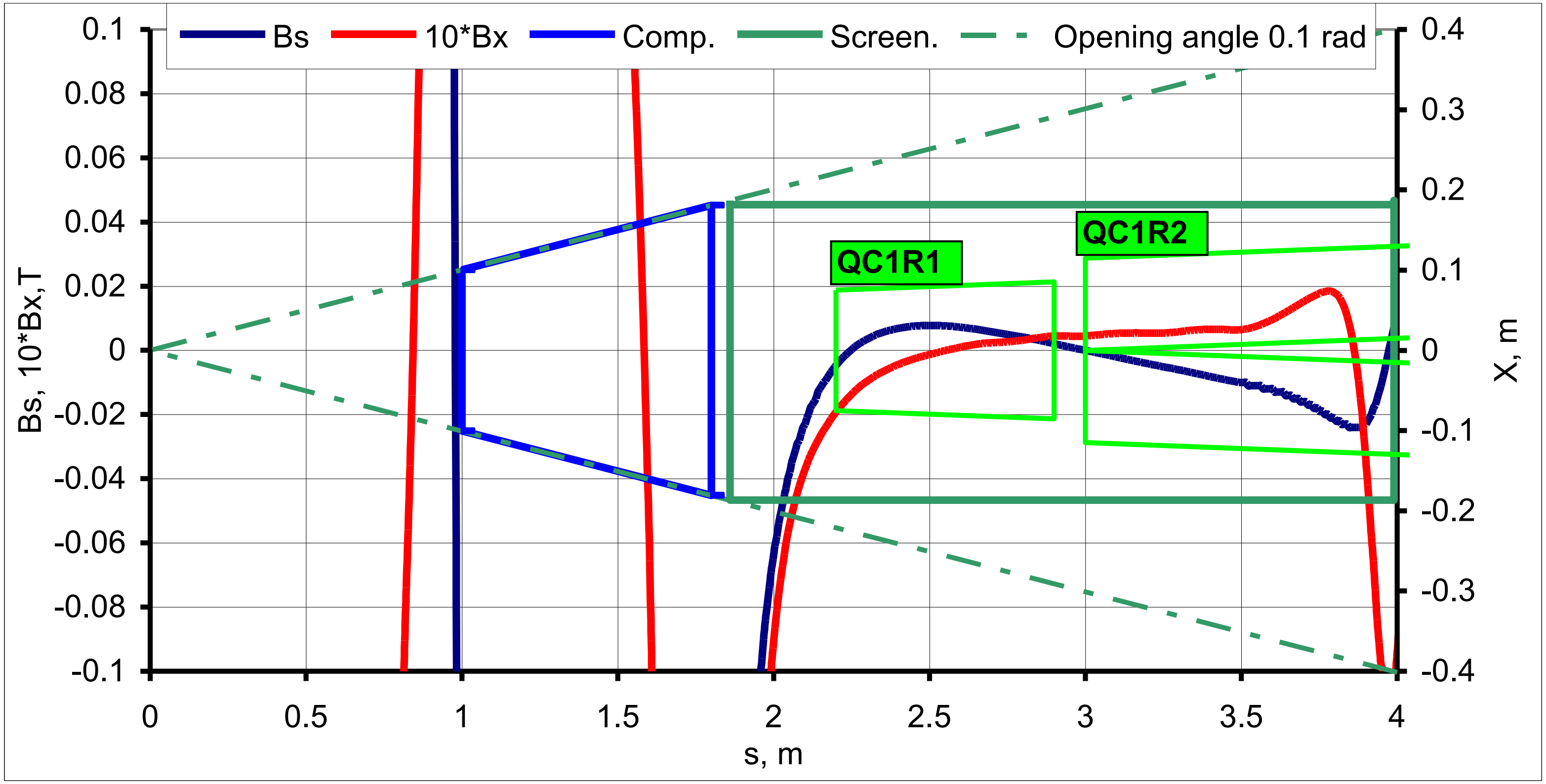
Field distribution (4)



Transverse half size:

- main solenoid field - L_{geom} = 1 m, B_s = 2 T
- compensating solenoid - R = 0.1 / 0.18 m, L_{geom} = 0.8 m, B_s ~ 2.6 T
- screening solenoid - R = 0.19 m , L_{geom} = 2.15 m

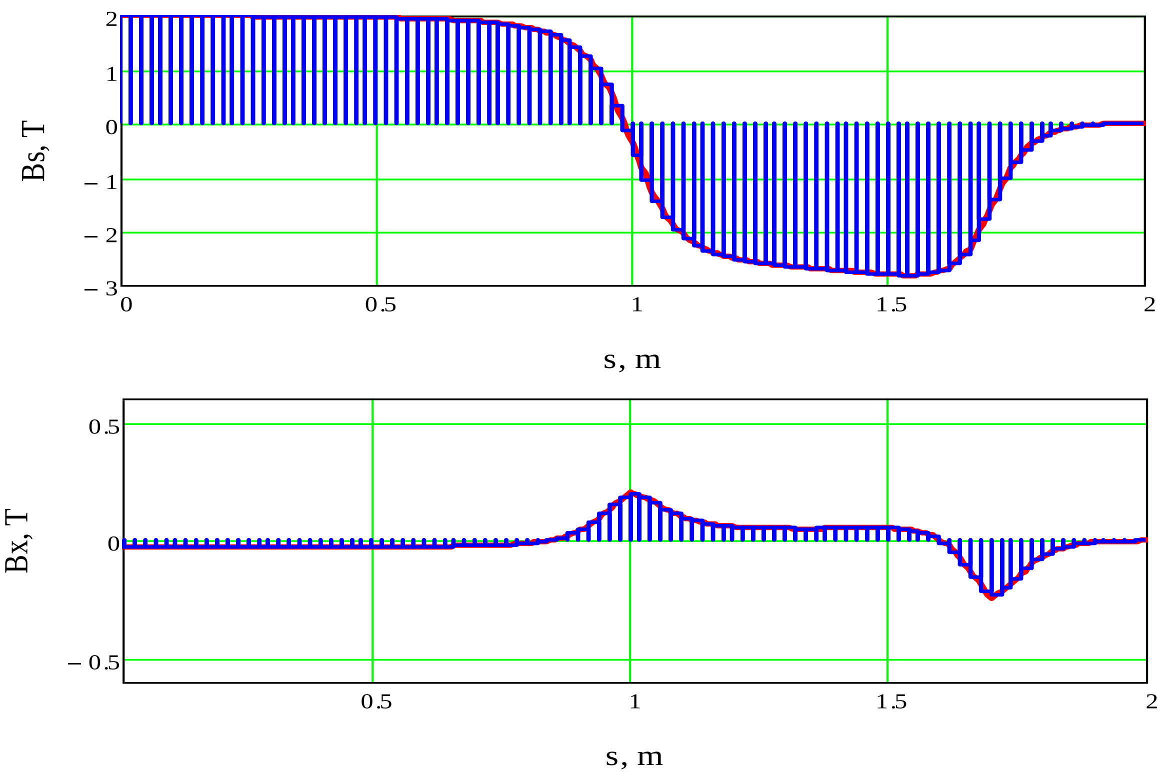
Field distribution (4)



Edge field in quad area: B_s<0.02 T B_x<0.002 T

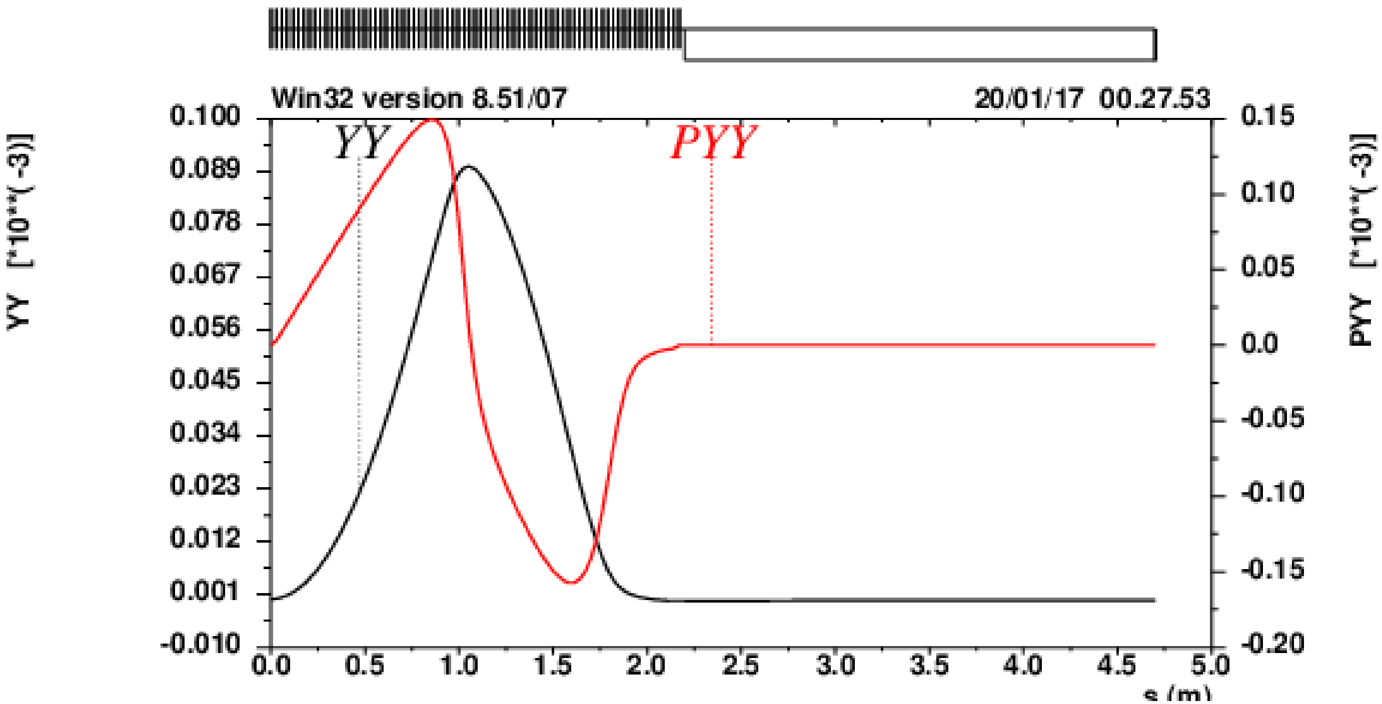
It is necessary additional corrections of screening area and steel yoke area.

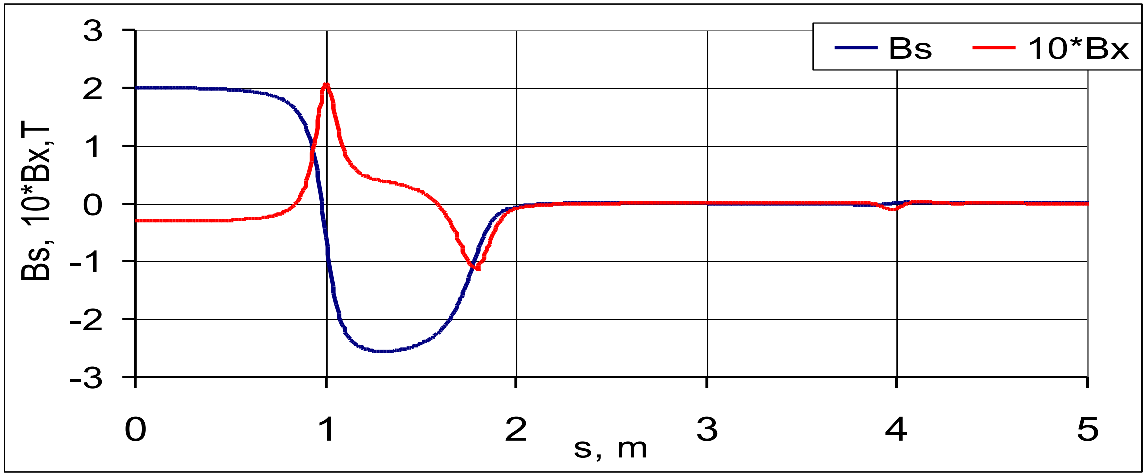
MADX optic model of solenoids (4)



- Piecewise elements have been inserted into 2.2 m (distance from IP to QC1_1)
- Solenoids are presented by thick elements.
- Skew components are thin elements.
- Radial and vertical fields are presented by thin elements with nonzero length to carry out emittance calculation by EMIT module (Lrad = 2.2/N, N – slices number).

Beam Orbit at IR (4)





Critical photon energy (E=175 GeV):

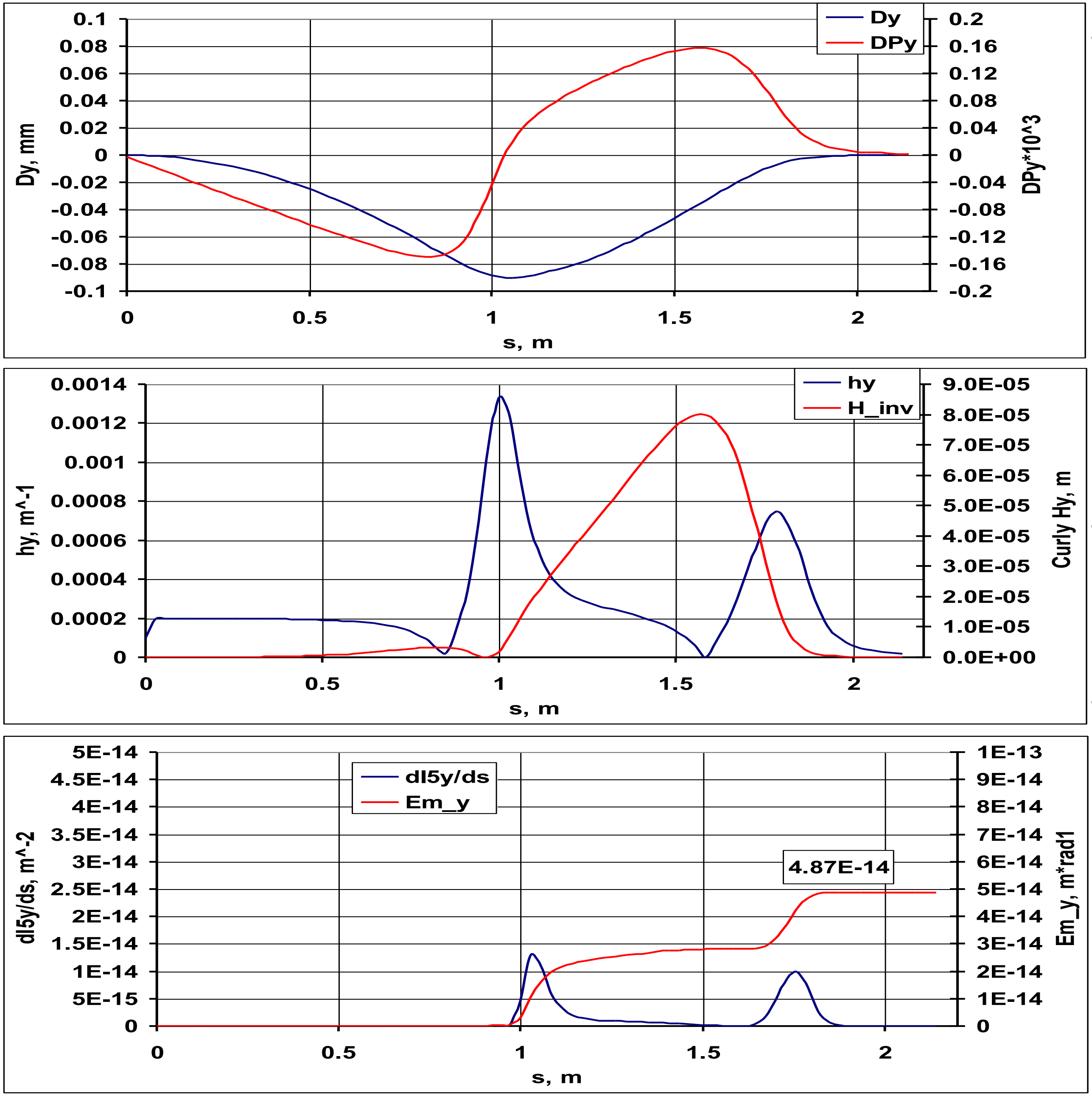
ε_c up to 4.9 MeV

Radiation angle

~ ± 0.15 mrad

B_{x_max} = 0.21 T

Check of emittance calculation (4)



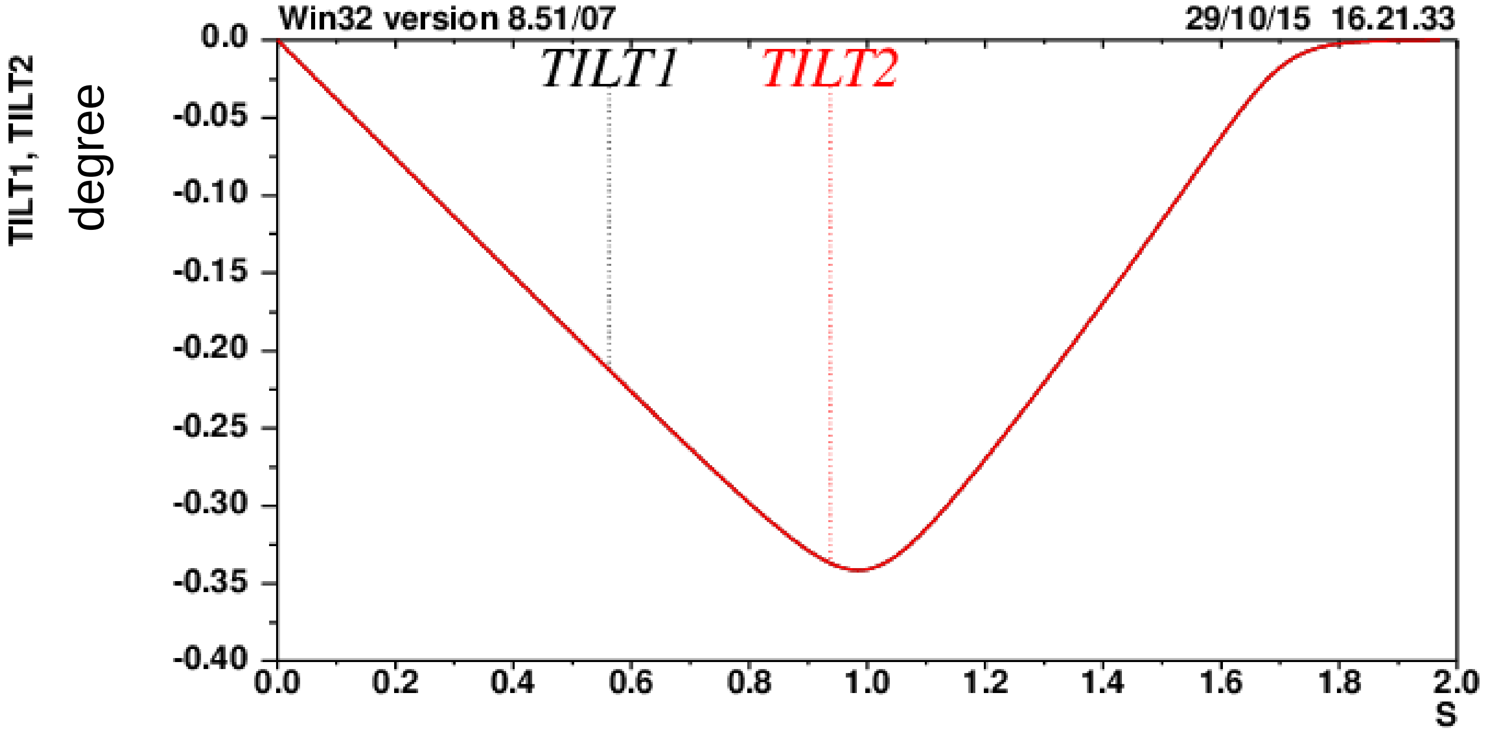
- Formula
  $I_2 = 6.07{*}10^{-4}\ m^{-1}$

$$I_{5y} = h_y^3 \oint \mathrm{H}_y(s)ds =$$
$$= 5.13\cdot 10^{-14}\ m^{-1}$$
$$\varepsilon_y = 3.83\cdot 10^{-13}\cdot \frac{\gamma^2}{J_y}\cdot \frac{I_{5y}}{I_2} =$$
$$= 0.48\ pm*rad$$

- MAD calculation (EMIT module)
  E_y = 0.46 pm*rad

- Deviation between MAD calculation and formulas increases at short comp. solenoid (strong comp. field)

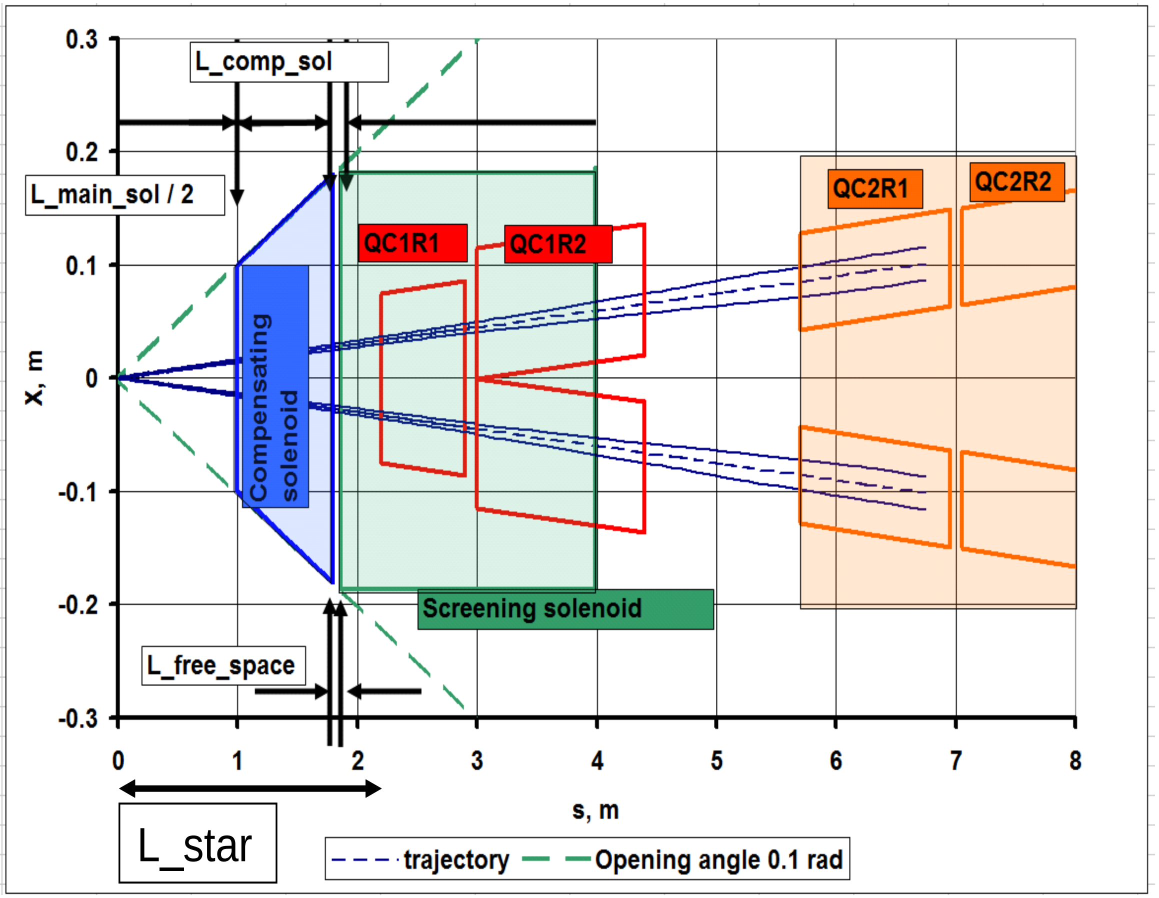
Tilt of eigen oscillation modes (4)



Beam parameters (E = 45 GeV) (4)

Cross angle (tot), rad	0.03
Free space, cm	6
Main solenoid	
Half geometric length, m	1
Half magnetic length, m	0.898
Comp. solenoid	
Geometric length, m	0.8
Magnetic length, m	0.697
Radius, m	0.1 / 0.18
Screening solenoid	
Geometric length, m	2.13
Inscribed radius, m	0.19
Betatron tunes	
Qx	0.08
qy	0.14
Emittance, pm*rad	82.7
Ver. Emittance, pm*rad	0.049
Emittance Ratio (v./h.)	0.00059
Energy spread	2.4E-04
Energy loss of particle per turn, MeV	32.64
Energy loss of particle (in solenoids), keV	76.5

L_star vs. L_main_sol (5)



Conditions:

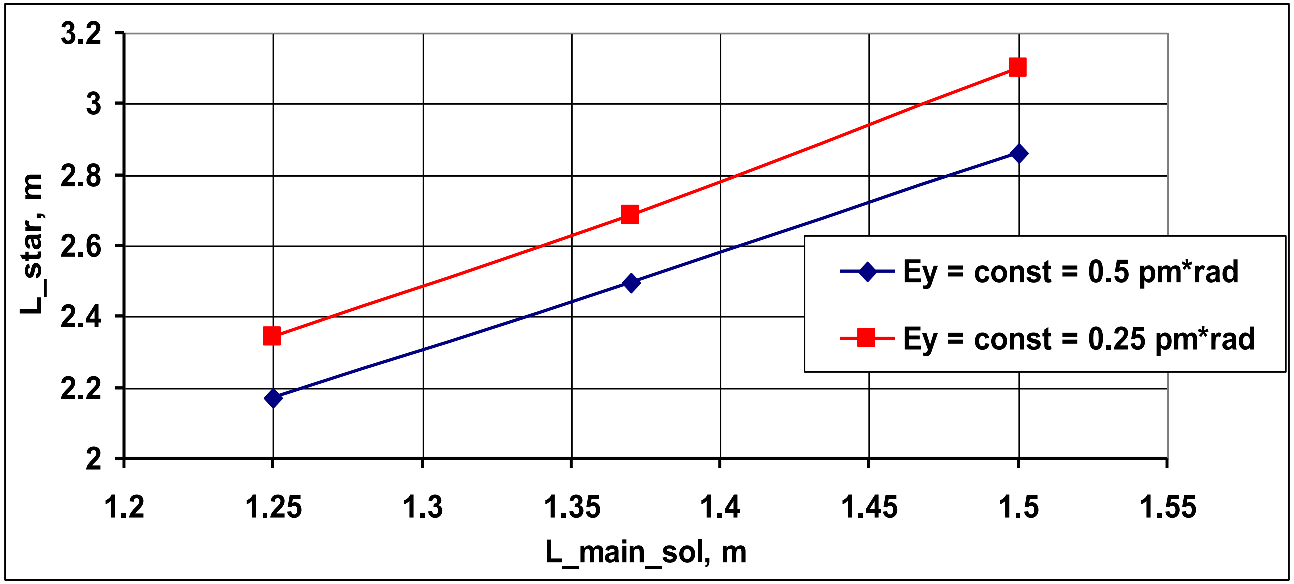
- B_{s_center} = 2 T
- $\int B_s(s)ds = 0$
- Magnetic field in Quads area B_{s_QUAD} < 0.01 T (parameter optimization: $L_{\_free\_space}$, $R_{2\_comp\_sol}$, $R_{\_screen}$ = max)
- Detector opening angle θ <0.1 rad
- ε_y = const

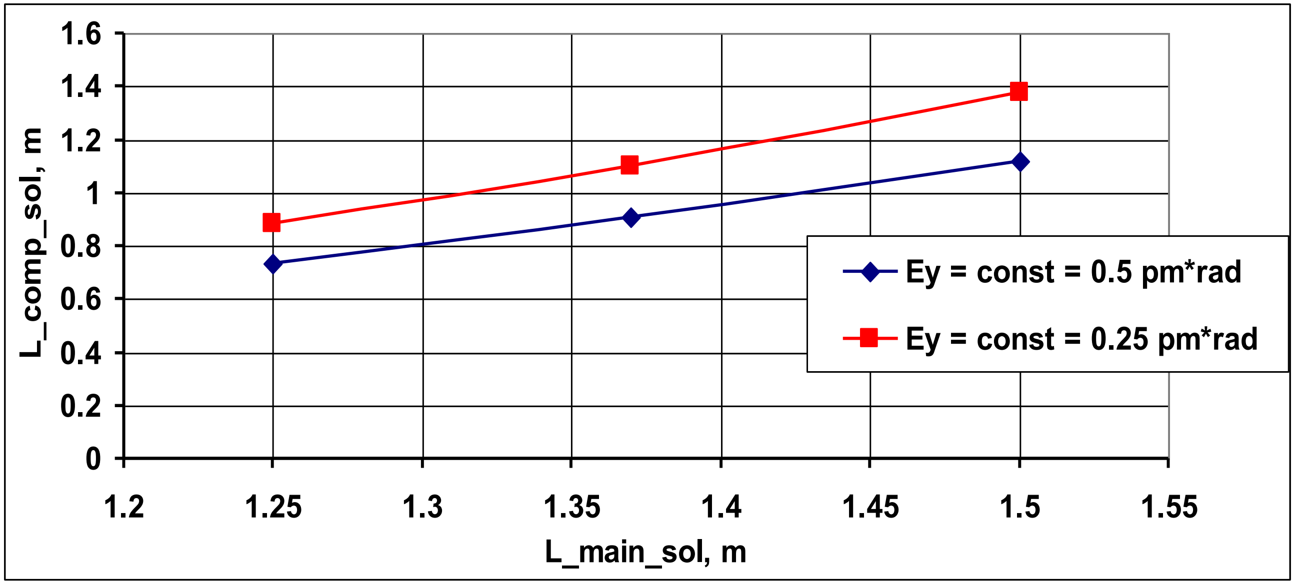
1 – Area (1/2) of main solenoid magnetic field on reference trajectory L_main_sol/2

2 – Length of compensating solenoid L_comp_sol

3 – Free space between compensating and screening solenoids L_free_space

L_star vs. L_main_sol (5)





$L_{\_main\_sol}/2$ – Length (1/2) of main solenoid magnetic field area on reference trajectory

$L_{\_comp\_sol}$ – Length of compensating solenoid

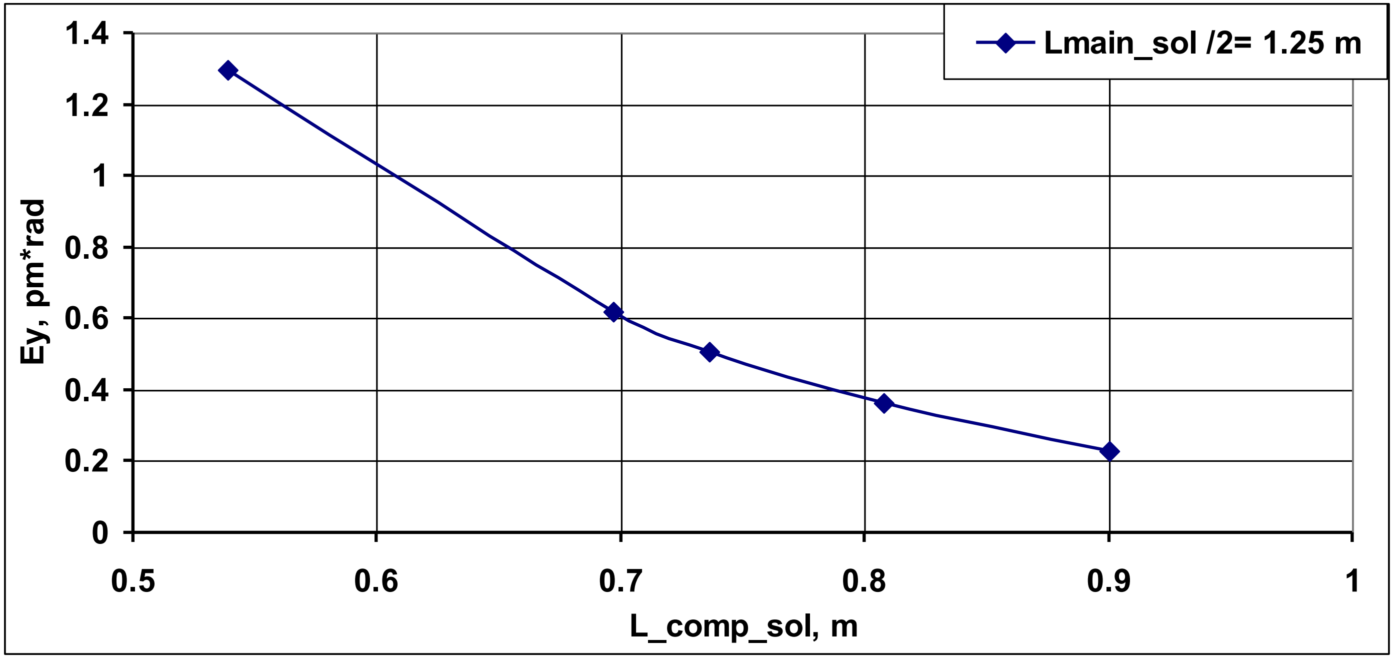
$L_{\_star}$ – distance between IP and first edge of QD0

- $B_{s\_center} = 2$ T
- $\int B_s(s)ds = 0$
- $B_{s\_QUAD} < 0.01$ T
- ε_y = const
- For 2 IPs

L_star vs. L_main_sol (5)

Parameters	Unit					
E, GeV	45					
L_star, m	2.171	2.497	2.860	2.342	2.686	3.103
Compensating solenoid						
R_in, m	0.125	0.137	0.151	0.125	0.137	0.151
R_end, m	0.199	0.228	0.263	0.214	0.248	0.289
L, m	0.736	0.906	1.119	0.884	1.103	1.376
L_free_spaice, m	0.120	0.125	0.132	0.110	0.118	0.126
Screening solenoid						
R_sc_sol,m	0.211	0.241	0.276	0.225	0.260	0.301
L_sr_sol, m	1.884	1.589	1.239	1.746	1.399	0.988
Main solenoid						
B, T	2.00					
R_main, m	3.82					
L_main_sol /2, m	1.25	1.37	1.50	1.25	1.37	1.50
Lattice						
bx_IP, m	0.5					
by_IP, m	0.001					
I2_sol, m^-1	2.58E-06	2.40E-06	2.23E-06	2.01E-06	1.88E-06	1.74E-06
I5y_sol, m^-1	1.03E-13	1.02E-13	1.02E-13	5.12E-14	5.04E-14	5.03E-14
Emy_sol, pm*rad	0.51	0.50	0.51	0.25	0.25	0.25
Emx, m*rad	9.24E-11	9.24E-11	9.24E-11	9.24E-11	9.24E-11	9.24E-11
Emy_sol/Emx	5.49E-03	5.46E-03	5.47E-03	2.74E-03	2.69E-03	2.69E-03
Uo_sol, keV	148.8	138.6	129.0	116.3	108.3	100.8

ε_y vs. L_{comp_sol} (6)



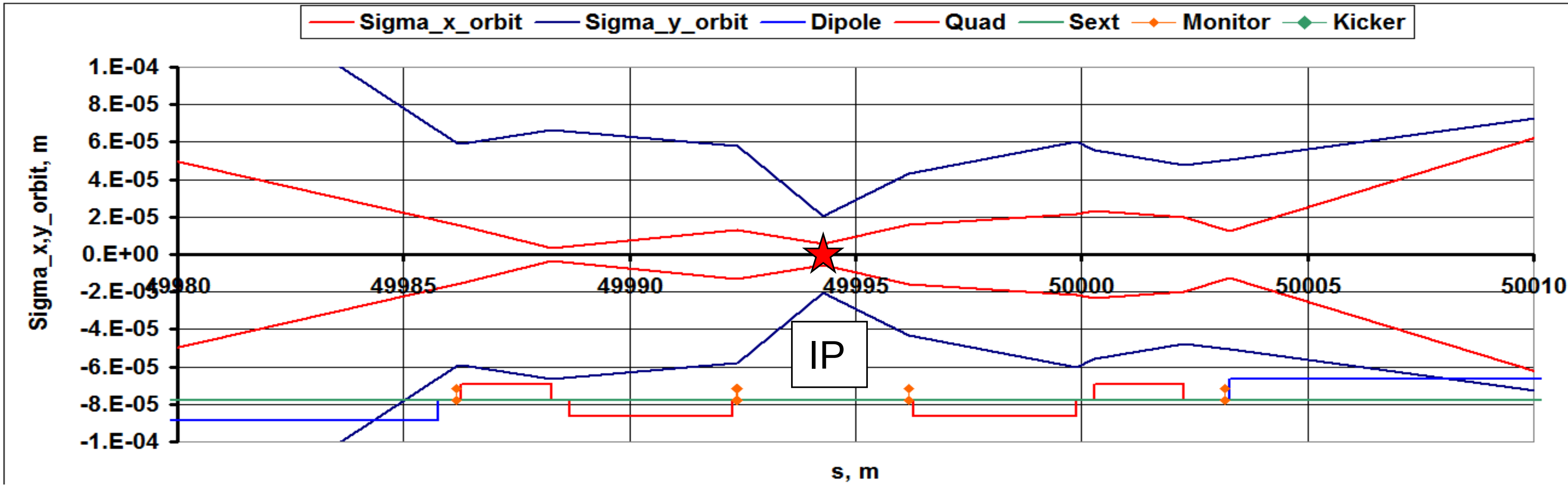
- $L_{\_main\_sol}$ / 2 – Length (1/2) of main solenoid magnetic field area on reference trajectory
- $L_{\_comp\_sol}$ – Length of compensating solenoid
- $L_{\_star}$ – distance between IP and first edge of QD0
- B_{s_center} = 2 T; $\int B_s(s)ds = 0$; B_{s_QUAD} < 0.01 T; For 2 IPs;

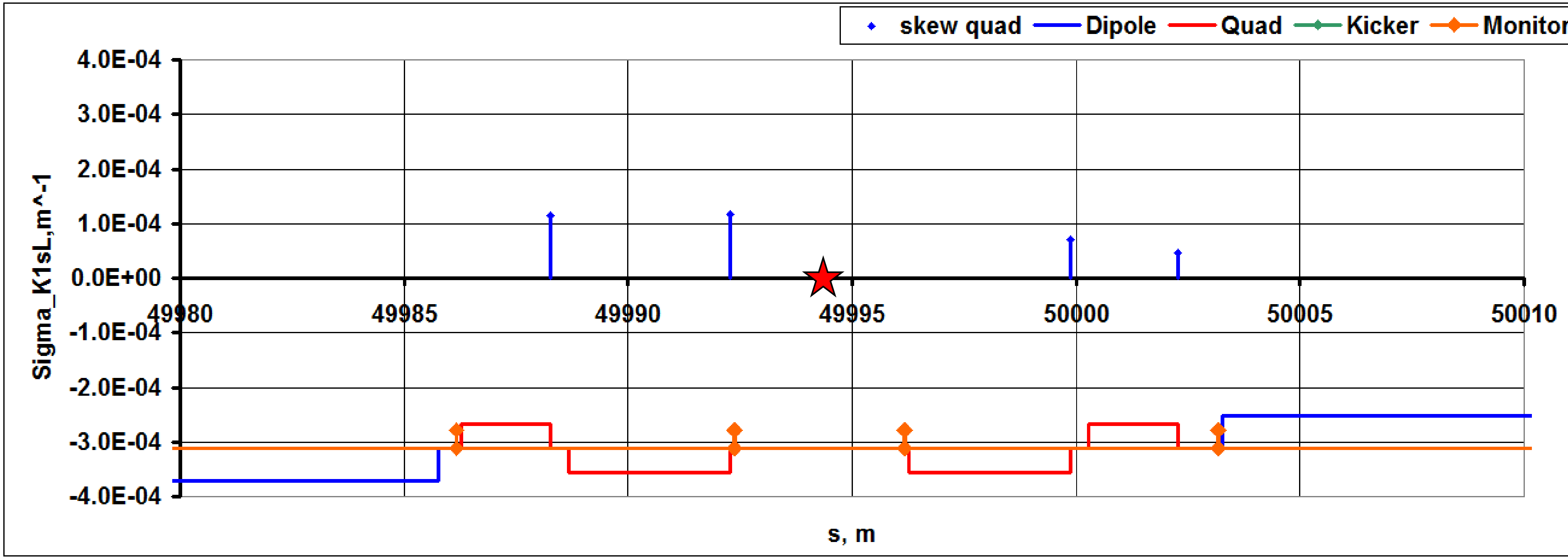
Misalignments of elements
(E =175 GeV; After CO & SQ correction)

Element	dx,y,um	Tilt, mrad	CO before corr.	D_y, mm	Qx	Qy	ε_x, nm*rad	$\varepsilon_y / \varepsilon_x$, %
ARC BPM	100	0	+	5.5	0.003	0.041	1.40	0.66
FF BPM	25	0	+	3.2	0.000	0.002	1.39	0.20
CCS_XY BPM	50	0	+	7.8	0.002	0.043	1.40	0.72
Dipole	-	0.2	+	2.6	0.000	0.000	1.39	0.14
Quads	100	0	-	3.3	0.003	0.063	1.46	0.12
FF Quads	25	0	-	4.0	0.000	0.000	1.40	0.38
CCS_XY Quad	100	0	-	1.8	0.002	0.024	1.40	0.07
Sextupole	100	0	+	3.1	0.005	0.009	1.42	0.26
CCS_XY Sext	100	0	+	1.8	0.004	0.082	1.40	0.28
Total	*	*	-	7.0	0.011	0.048	1.46	1.44

* - all misalignments included.

Preliminary misalignments results for IP





Summary

- Vertical emittance lightly increases when compensating solenoid length decreases with unchanged main solenoid length.
- Vertical emittance strongly increases when main solenoid length decreases with unchanged compensating solenoid length.
- The screening solenoid should be matched with the compensating solenoid to reduce magnetic field in area of FF quads.
- The distance between the compensating solenoid end and QD0 quadrupole should be more than 30 cm ~ compensating solenoid diameter of second edge.
- Slicing for MADX allows to take into account fringe fields of the solenoids more precisely.
- Vertical emittance blow up estimation at the solenoid fringe field corresponds to that calculated by Mike Koratzinos.