Compensation of detector solenoid for any beam energy in NLC

Andrei Seryi

LCD meeting, March 18, 2004

With thanks to

John Hodgson, Yuri Nosochkov,
Tor Raubenheimer, Peter Tenenbaum
(SLAC)

and

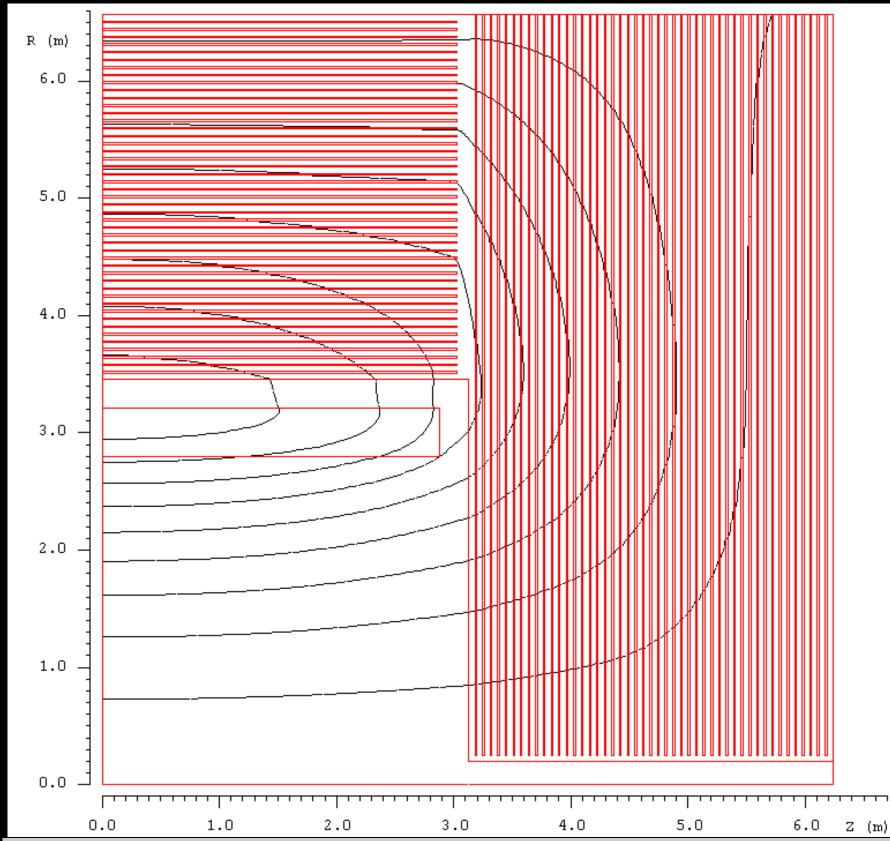
Brett Parker
(BNL)

Request from particle physicists

- NLC should be able to work at any beam energy without changing the Detector solenoid field
  - “Any energy” means from 50 GeV/beam and up

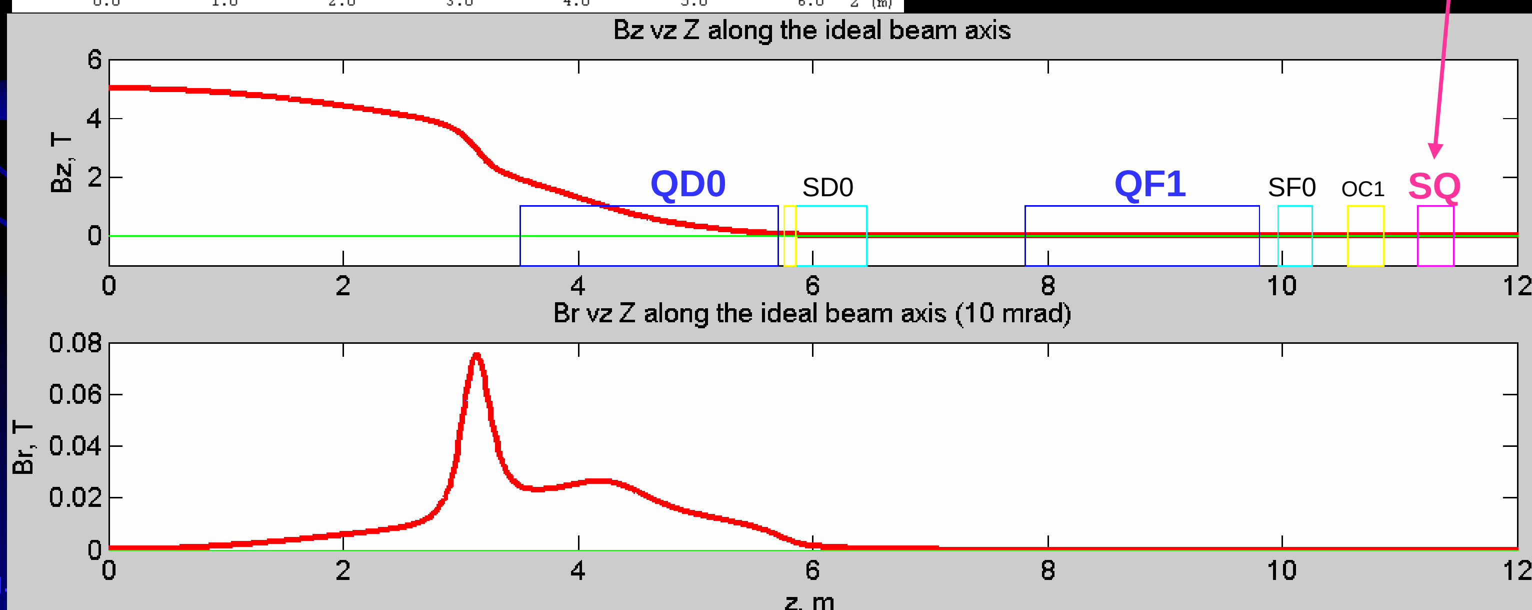
SiD solenoid model

[J.Hodgson]

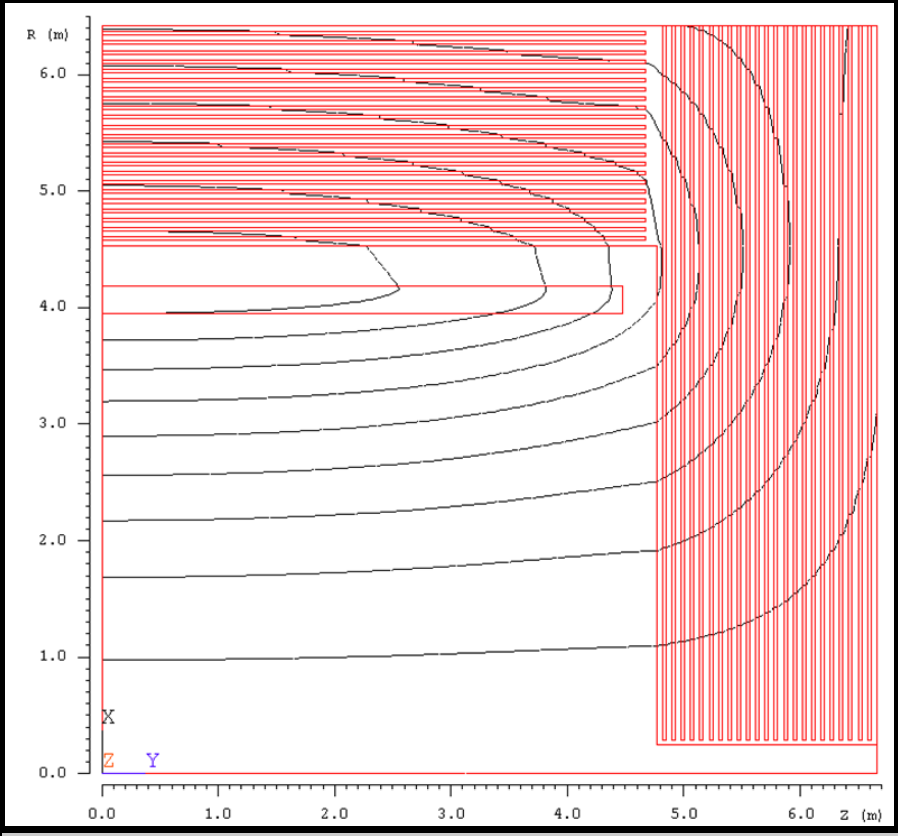


Max field = 5T

Skew quad

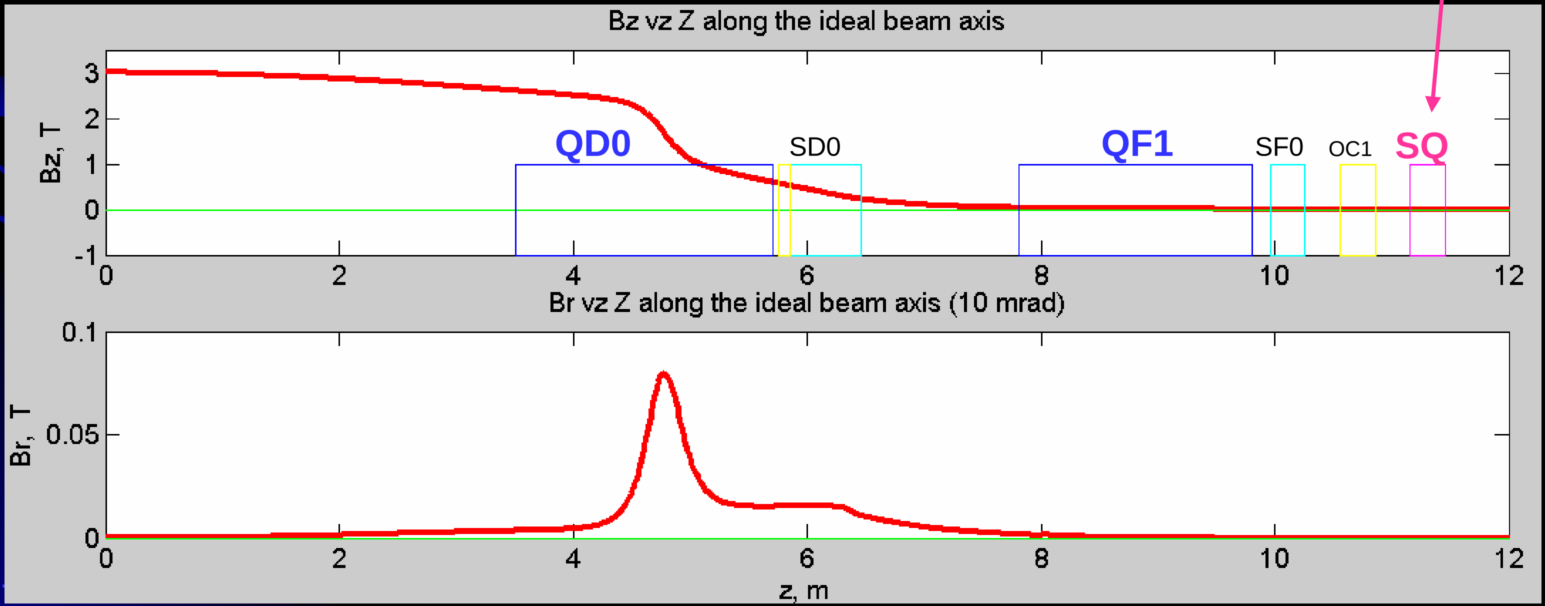


LD solenoid model



Max field = 3T

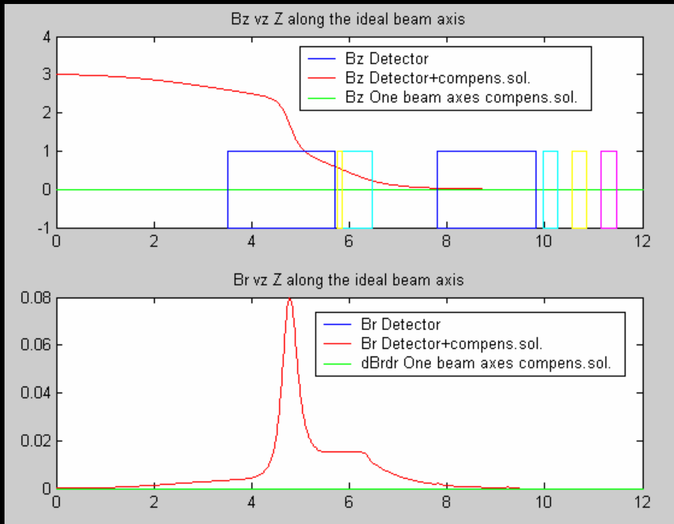
Skew quad

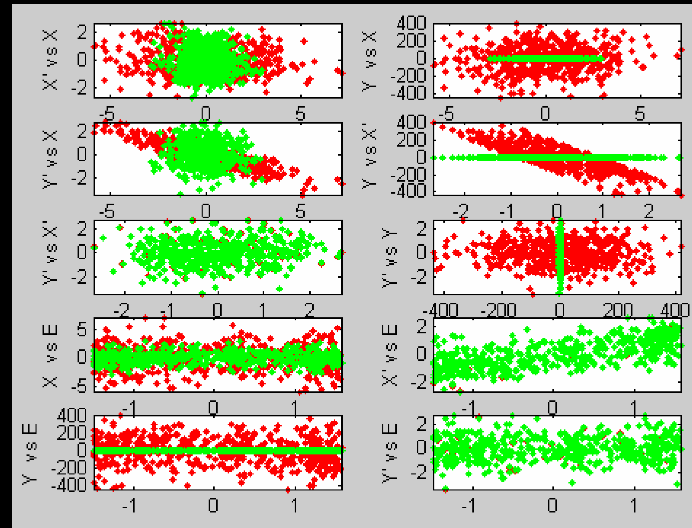


Effects of detector solenoid and "standard" compensation

- Dominant effect of detector solenoid is coupling of the flat beam
- Crossing the solenoid field also introduces vertical dispersion and bump in the Y orbit
  - In terms of detector solenoid compensation, the crossing angle does not make much of a difference, as we will see
- Compensation is usually done with a skew quad located near the Final Doublet and additional knobs to correct remaining terms
  - Below we will see that "standard" compensation can be used, but…
  - There is much better and more natural way to compensate the detector solenoid…

LD

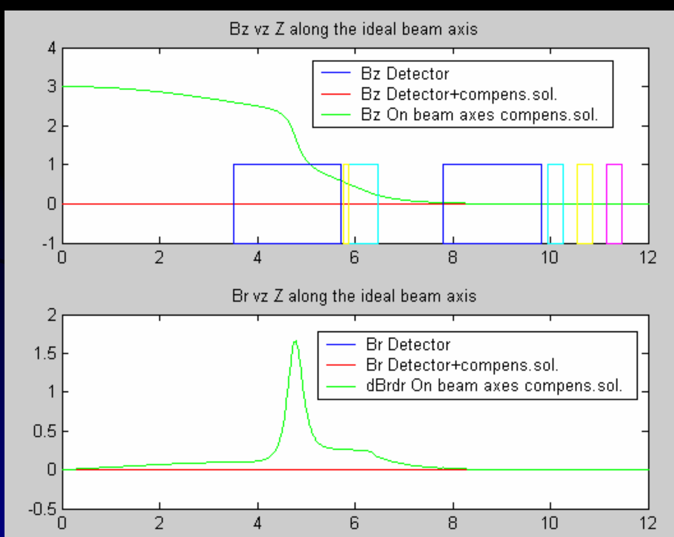


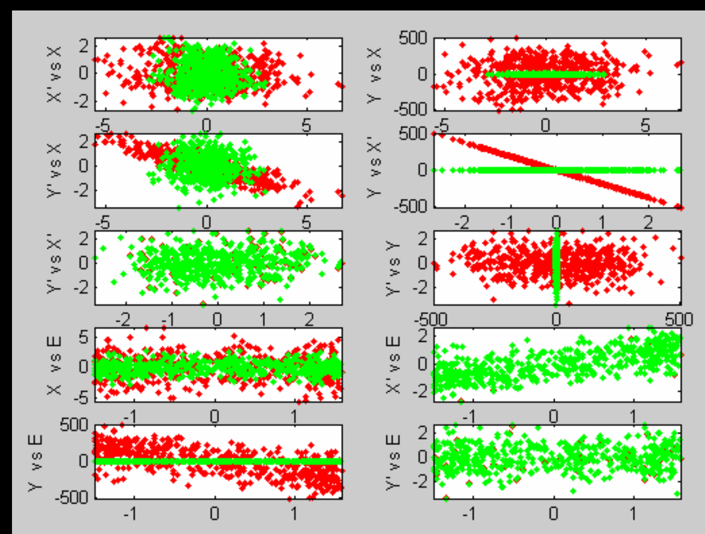


Dominant terms:
R32 coupling (x' => y)
and the next one is
R36 dispersion (δE => y)

Green – ideal beam,
red – current beam.
All beam σ of ideal beam normalized to 1

LD, x-ing angle 20mrad. Without compensation the beam is ~600nm*500nm





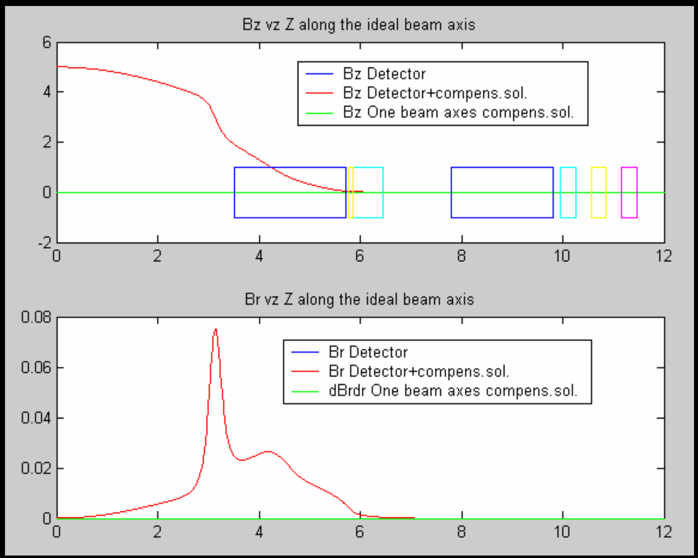
Dominant terms:
R32 coupling (x' => y)

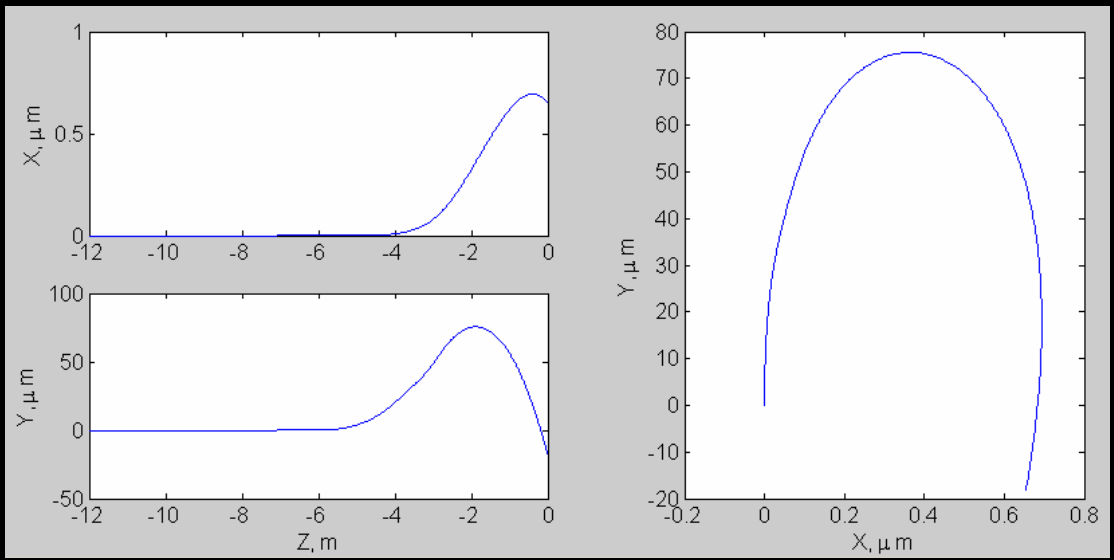
LD, zero x-ing angle for comparison.   The beam is ~550nm*650nm

NLC nominal beam parameters were used in this study: 250 GeV/beam, σ_{x0}=243nm, σ_{y0}=3nm, β_x*=8mm, β_y*=0.11mm, σ_z=0.11mm. Energy spread: Batman distribution with 0.8% full width.

Br and Bz of the solenoid create a bump in vertical orbit

Y orbit goes up and down and at IP almost come to 0





SiD without compensation : the IP Y beam position is -18µm

As we will see below, the fact that the Y at IP is not exactly zero is very important for compensation of solenoid effect on the beam size

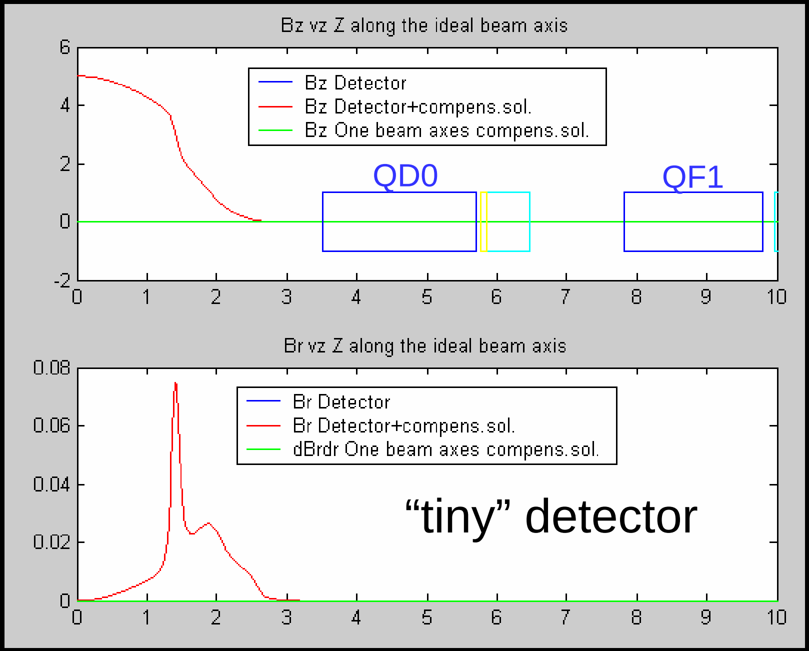
For luminosity, the Y angle at IP does not matter, the e+ and e- trajectories are antisymmetrical and they collide without vertical crossing angle, like this

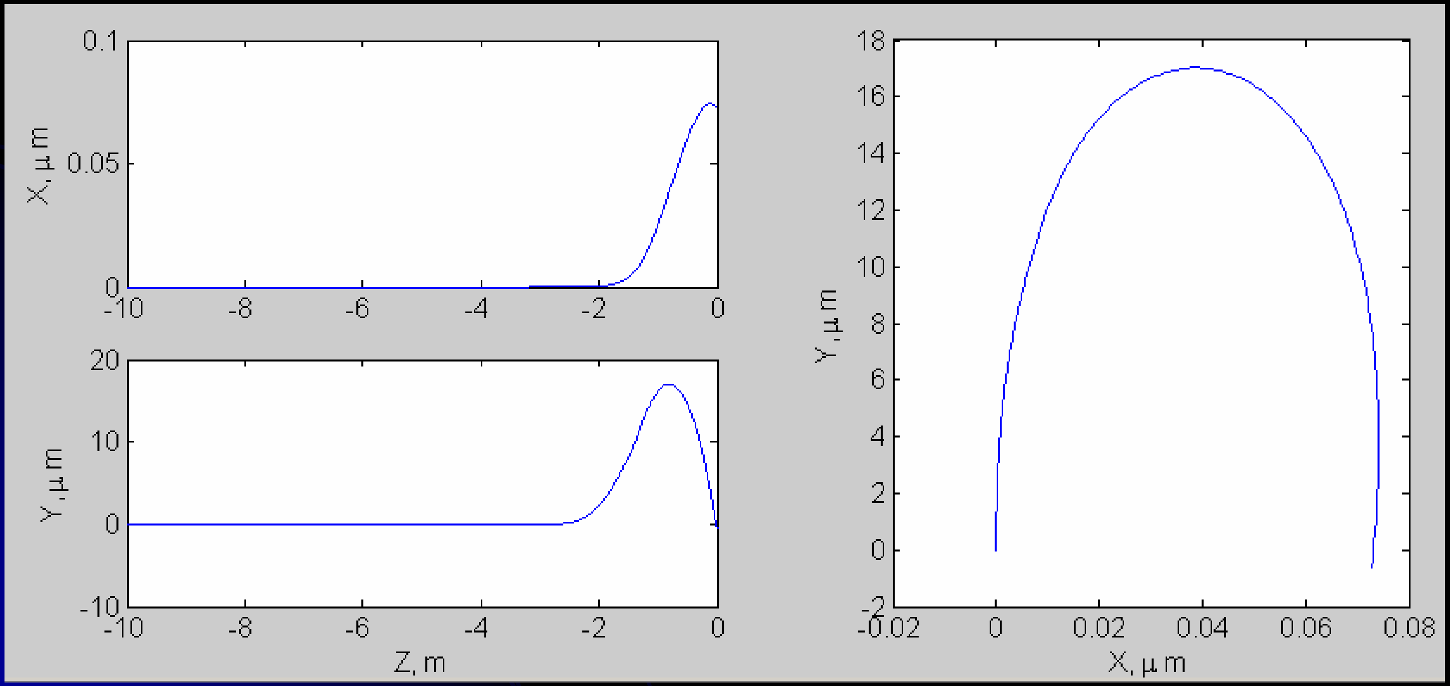
It is not the case for e- e- which naturally would collide like this with ~150µrad vertical crossing angle. The case of e- e- would require compensation of Y angle, which can be done.

Orbit properties

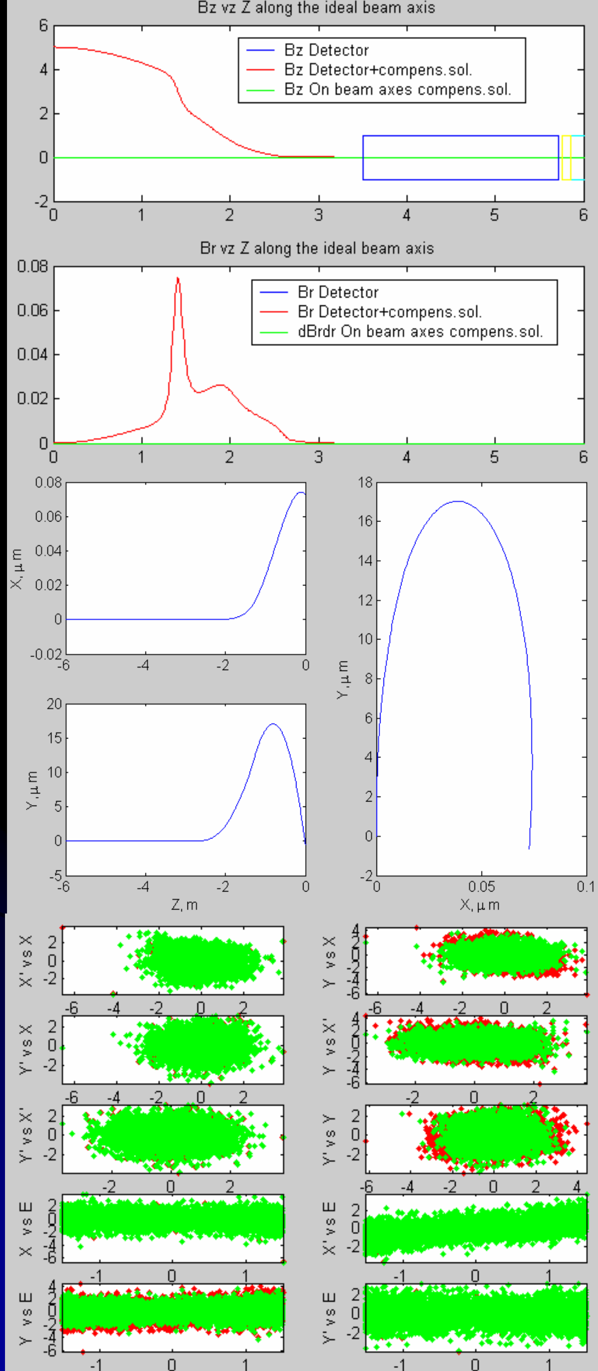
The theorem: If solenoid field does not overlap with quads, then vertical trajectory returns to Y=0 at the IP. Vertical dispersion also cancels.

[see e.g. R.Helm, SLAC-R-4, 1962, and P.Tenenbaum, J.Irwin, T.Raubenheimer, PRST-AB 6, 061001 (2003)]





In “tiny” detector, even without any compensation the beam size increased only by 16% in y. Compensation is trivial.



Tiny detector with 5T and 25T field

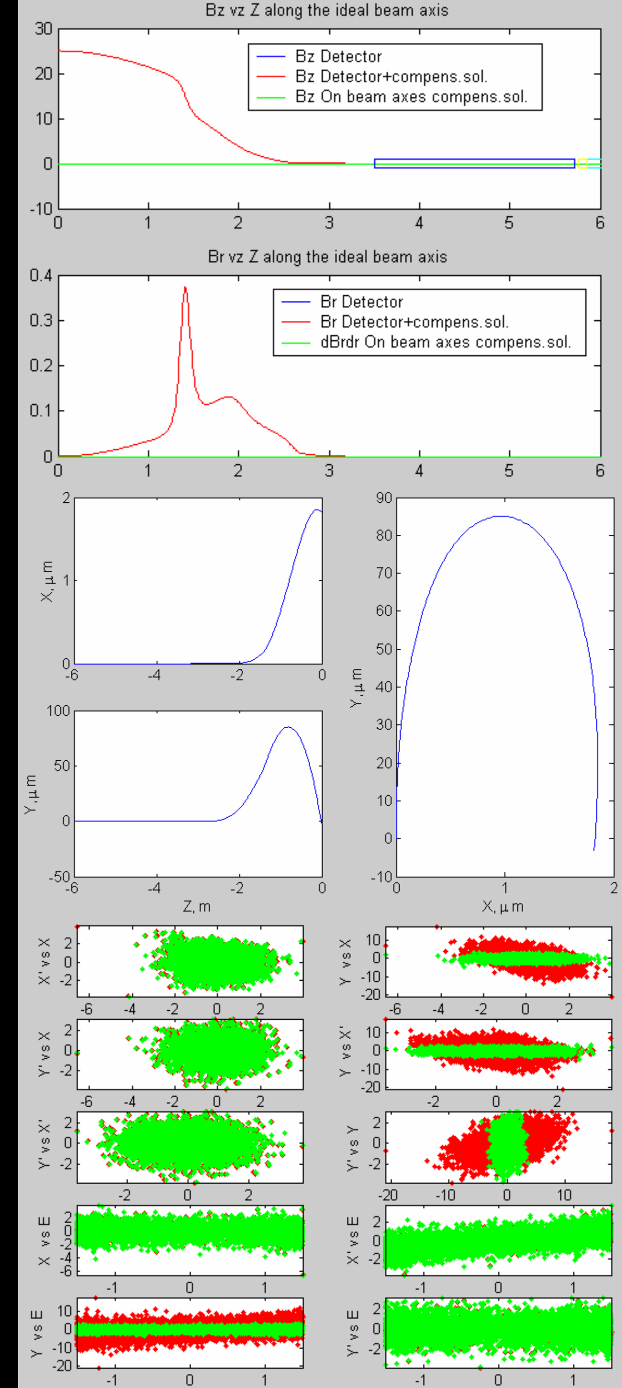
(~ equivalent to 250 GeV/beam and 50 GeV/beam)

5T :

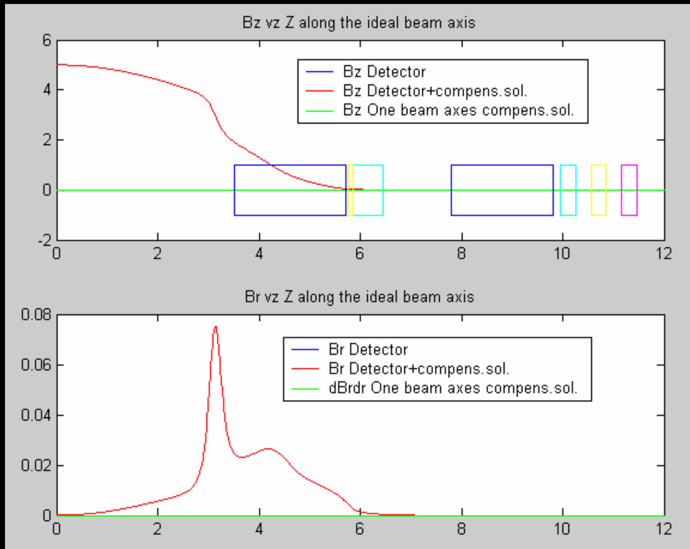
σ_X/σ_{X0} =1.00 , σ_Y/σ_{Y0}= 1.16

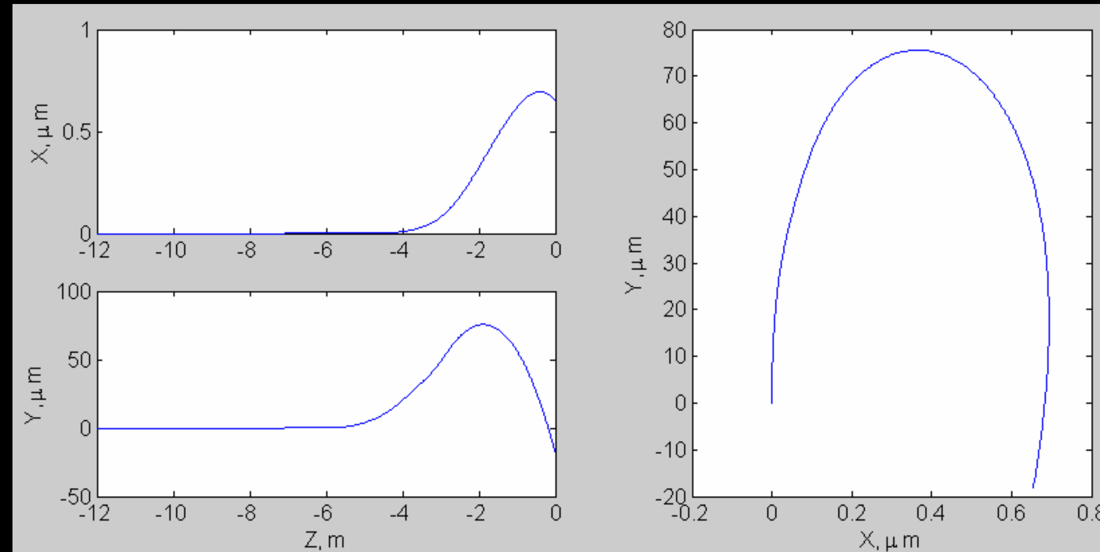
25 T:

σ_X/σ_{X0} =1.00 , σ_Y/σ_{Y0}= 3.66



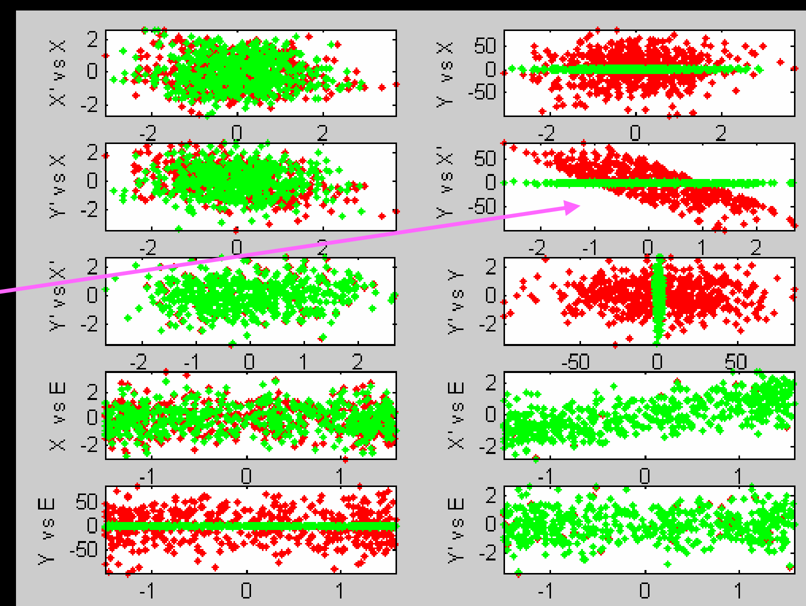
Green – ideal beam (no solenoid),
red – current beam.
Normalized. All σ of ideal beam = 1





SiD. Without compensation the beam is σ_X/σ_{X0} =1.07 , σ_Y/σ_{Y0}= 31.6 and the Y orbit is -18 µm

This is significantly different from the "tiny" detector. The reason is that solenoid overlaps with FD quad.

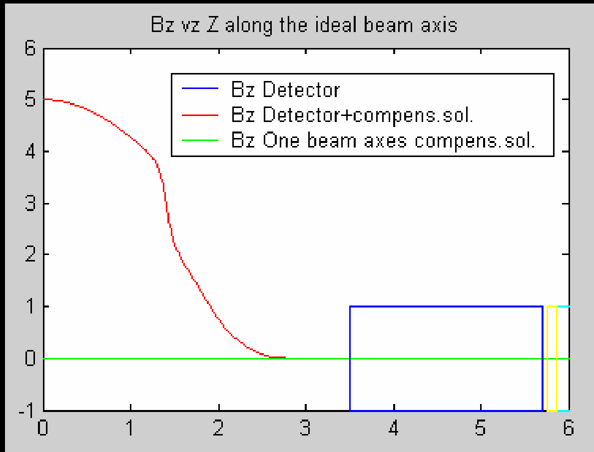


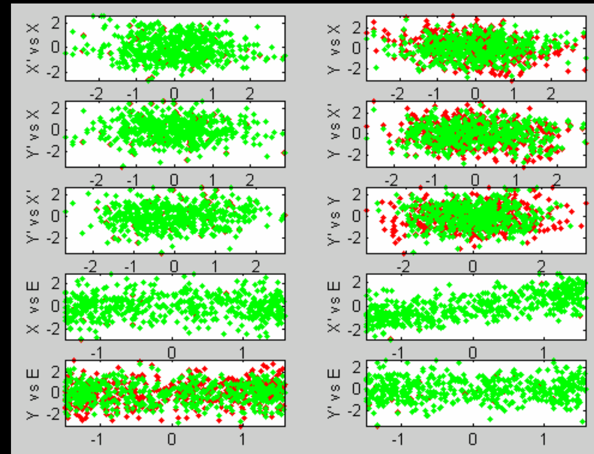
normalized M' (ideal IP beam => current IP beam) -1 =

-0.0001	0.0000	-0.7380	0.0000	0.0000	0.0000
0.0074	-0.0000	-43.5283	-0.0147	0.0000	0.0000
0.0001	0.0000	-0.0112	-0.0000	0.0000	0.0000
-0.3836	0.0067	1.0173	0.0000	-0.0000	0.0000
-0.0001	0.0000	-0.0161	0.0000	-0.0000	-0.0000
-0.0120	0.0000	28.2246	0.0101	-0.0000	0.0000

The dominant term that we see is R32 coupling (x' => y)

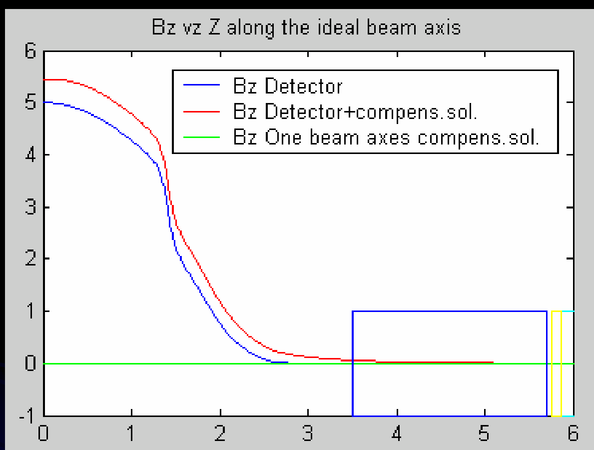
Tiny detector + additional field overlapping with QD0

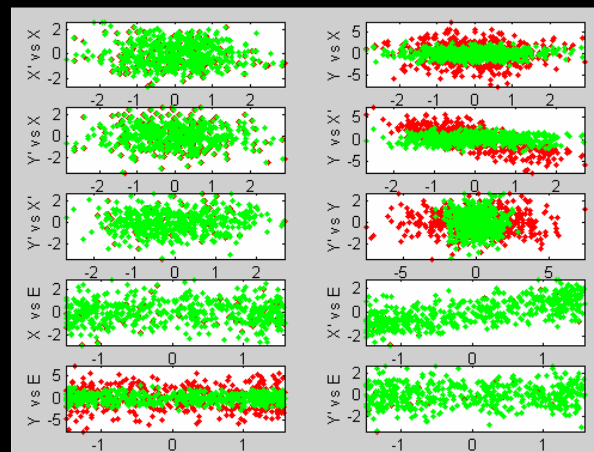




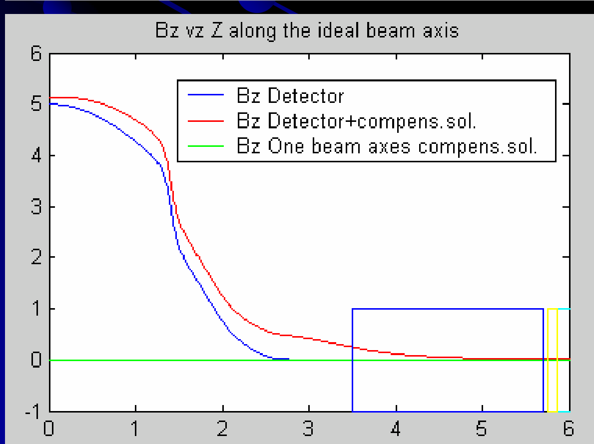
σ_X/σ_{X0} =1.00 , σ_Y/σ_{Y0}= 1.16

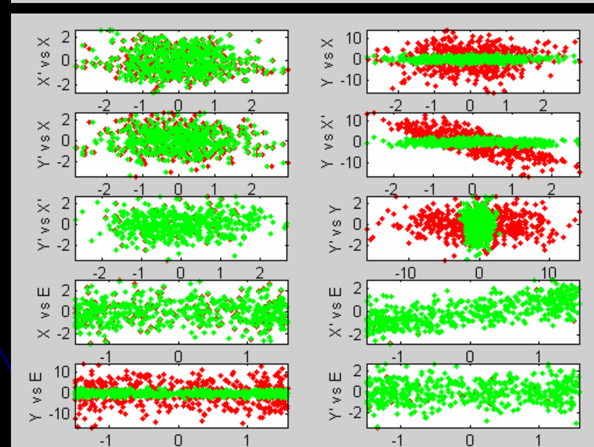
Increasing the overlap





σ_X/σ_{X0} =1.01 , σ_Y/σ_{Y0}= 2.3





σ_X/σ_{X0} =1.02 , σ_Y/σ_{Y0}= 5.2

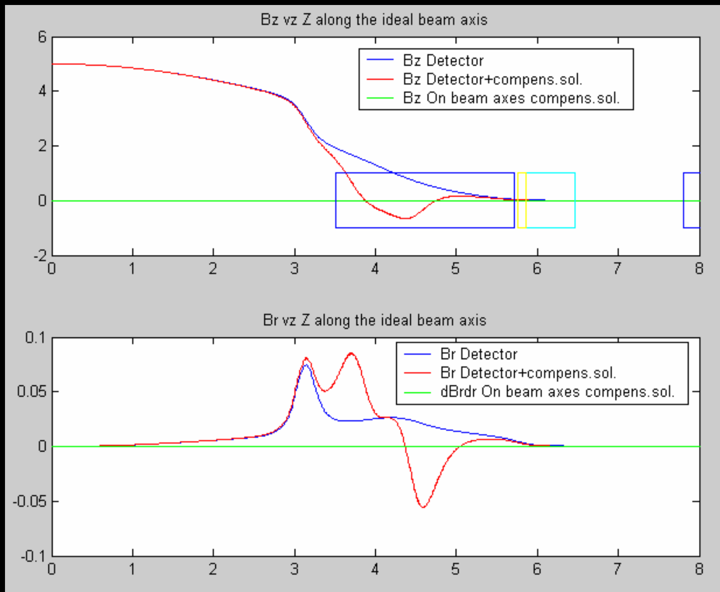
Thus we can conclude:

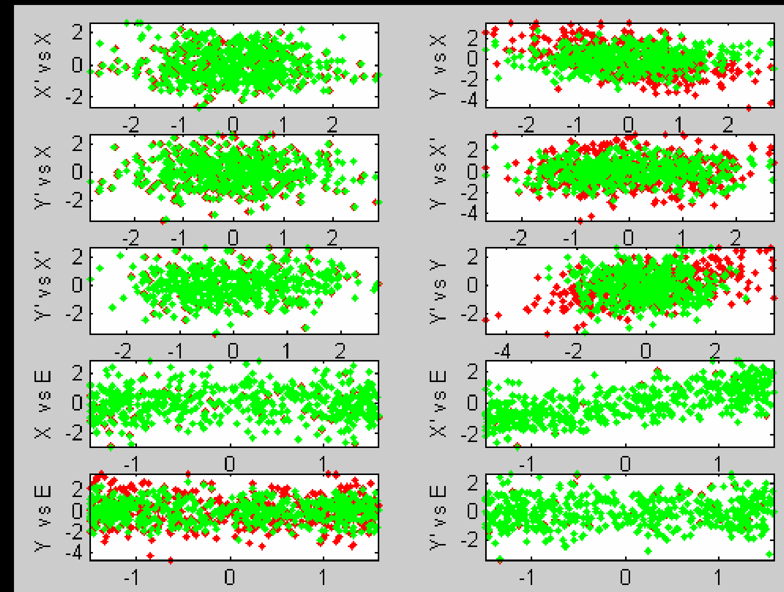
- Increase of the beam size due to solenoid is primarily due to overlap between solenoid and FD quadrupoles

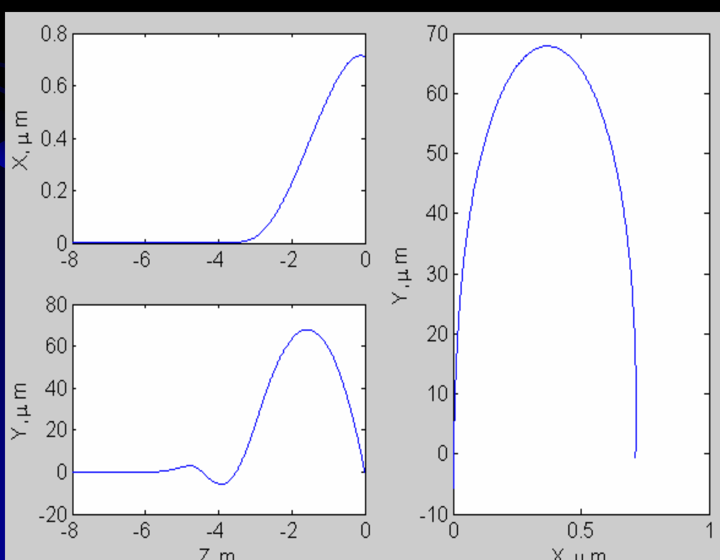
And can guess that:

- Most effective compensation can be achieved locally, with antisolenoid(s) overlapping with FD
  - Such compensation is almost perfect
  - Strength of the antisolenoid is proportional only to the overlap of detector solenoid with QD0, not to full solenoid strength
  - Such compensation is in major extend independent on the beam energy

SiD compensation by a single antisolenoid







σ_X/σ_{X0} =1.00 , σ_Y/σ_{Y0}= 1.29

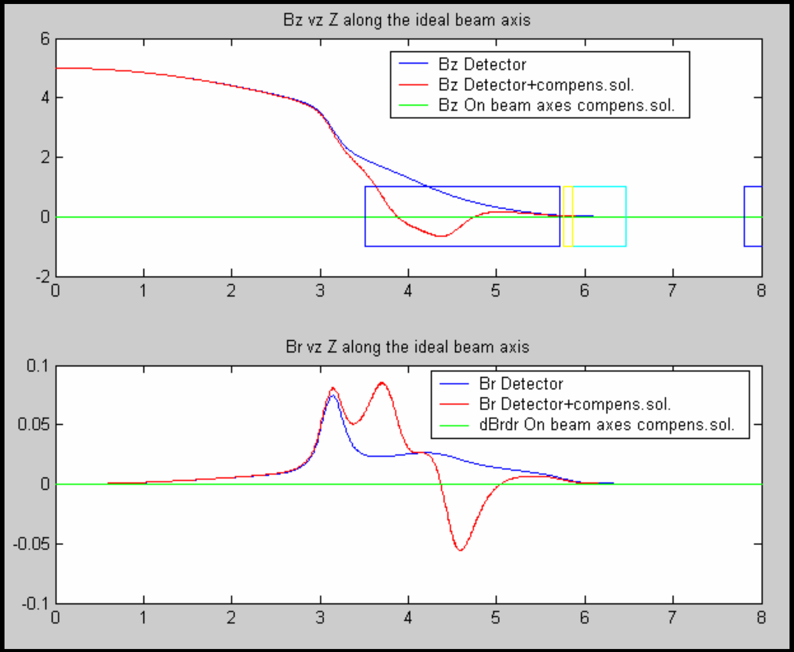
X_{IP}=0.71 µm, Y_{IP}= -0.76 µm

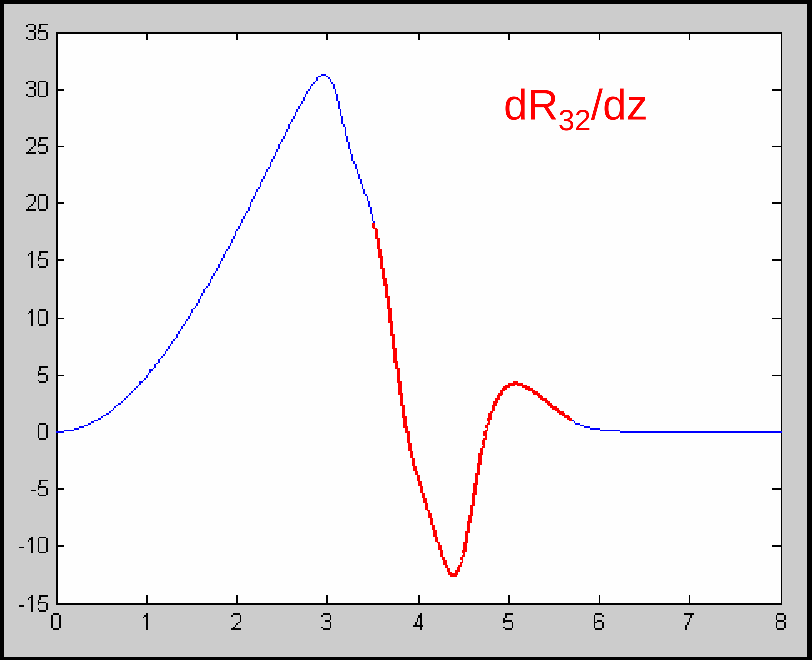
-0.0001	-0.0000	-0.7128	-0.0000	0.0000	0.0000
0.0107	-0.0000	0.0032	-0.0121	0.0000	0.0000
0.0001	0.0000	0.0002	-0.0000	0.0000	0.0000
0.0196	0.0067	0.6095	-0.0000	0.0000	0.0000
0.0000	0.0000	0.0003	-0.0000	0.0000	-0.0000
-0.0146	0.0000	-0.0102	0.0083	-0.0000	0.0000

Used ONLY one antisolenoid. Major terms R32 and R36 canceled. Remaining terms are easy to remove with tuning knobs. Note that the IP Y orbit is now also compensated.

Almost perfect (99%) compensation

Choice of the antisolenoid





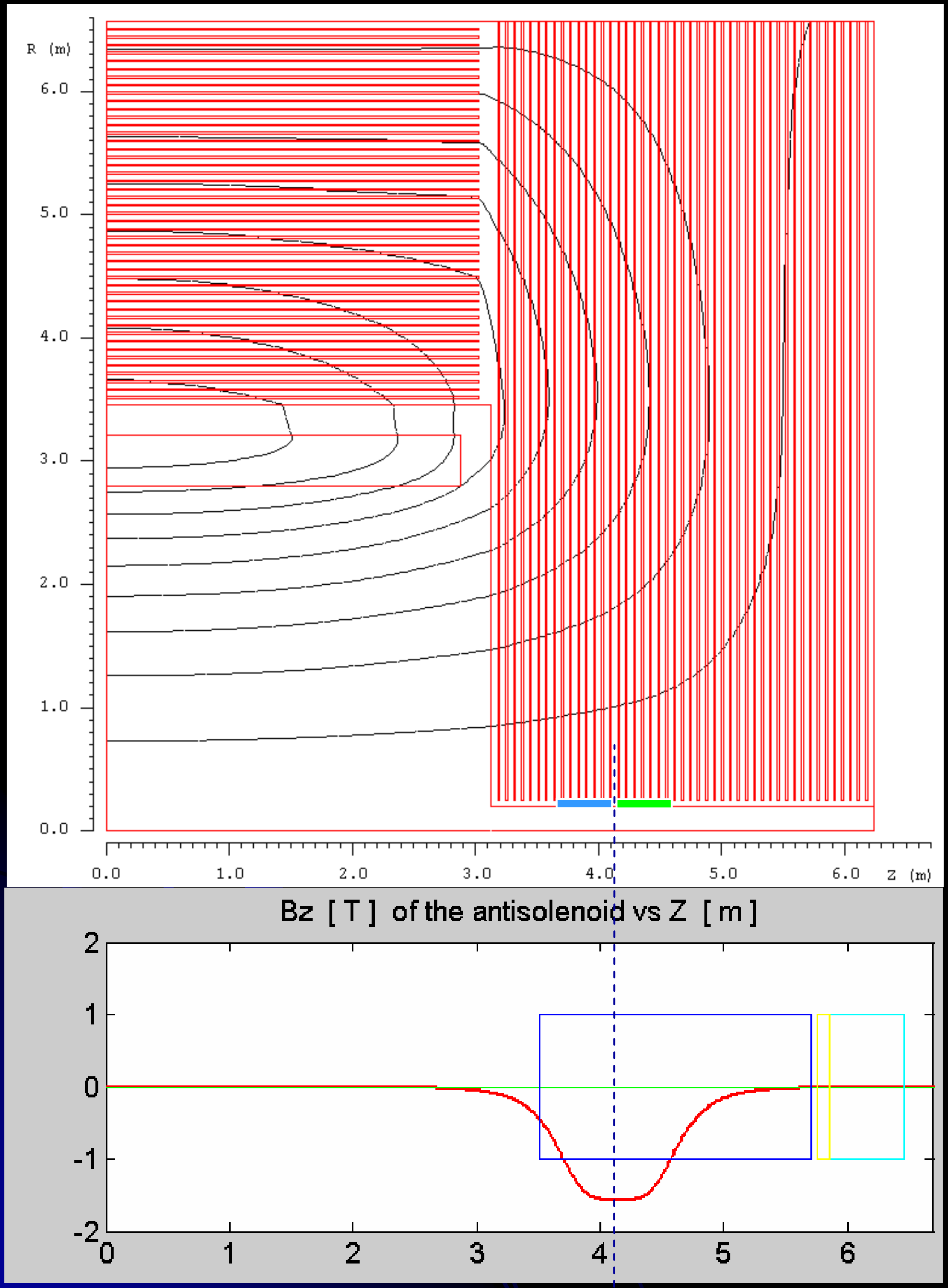
Strength and location of the antisolenoid is chosen in such a way that two major terms R32 and R36 are canceled simultaneously

$$R_{32} \propto \int B_z \sin(\mu_x)\ \sin(\mu_y) \sqrt{\beta_x \beta_y}\ dz \quad \Rightarrow \quad 0$$

$$R_{36} \propto \int B_z\ \eta_x\ \sin(\mu_y) \sqrt{\beta_y}\ dz \quad \Rightarrow \quad 0$$

integral is taken over QD0

Technical realization of antisolenoid



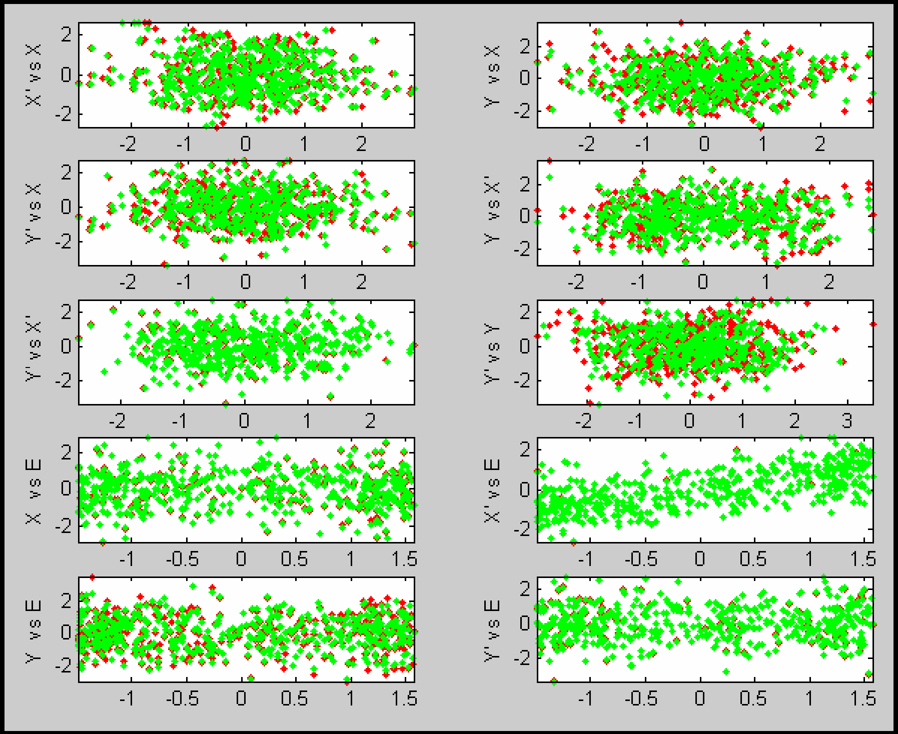
Antisolenoid overlapping with QD0 must be part of the detector

(It should NOT be part of QD0 – forces on QD0 would be too large)

At least two independent coils are needed – this will allow controlling the strength and effective position of the antisolenoid

Part of the calorimeter iron near the antisolenoid may need to be replaced with nonmagnetic steel

If antisolenoid is superconducting, the cryostat needs to be compact



SiD: antisolenoid, plus standard knobs

σ_X/σ_{X0} =1.00 , σ_Y/σ_{Y0}= 1.02

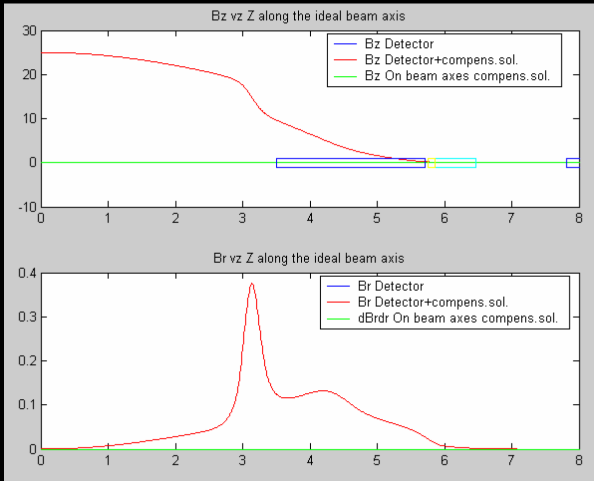
-0.0037	-0.0014	-0.0526	0.0000	-0.0000	0.0000
0.0157	0.0000	-0.0254	-0.0121	0.0000	0.0000
-0.0017	-0.0000	0.0050	0.0011	-0.0000	0.0000
0.0228	0.0004	0.0349	-0.0004	0.0000	0.0000
-0.0027	0.0000	-0.0012	0.0006	-0.0000	-0.0000
-0.0165	-0.0001	0.0112	0.0059	-0.0000	0.0000

Perfect compensation within resolution
(use only 500rays in tracking, resolution ~4%)

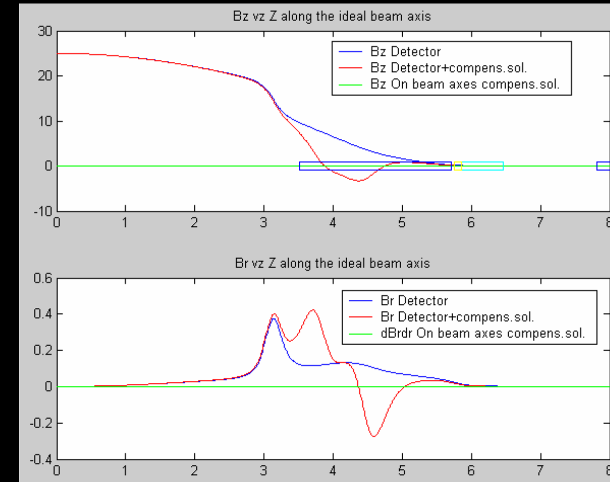
Standard orthogonal knobs use transverse offset of sextupoles to correct coupling, waist shift or dispersion.

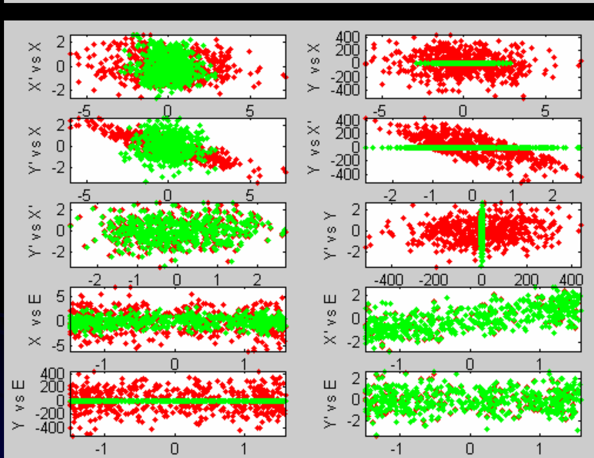
E.g. in this case, R34 was compensated with the following displacement of sextupoles:

sd0x	sd0y	sf1x	sf1y	sf6x	sf6y	sf5x	sf5y	sd4x	sd4y	
-1.28	0.05	-0.80	0.20	-0.07	0.48	0.35	-1.29	0.18	-0.32	μm



Increase SiD field 5 times (equivalent to going to 50 GeV/beam)

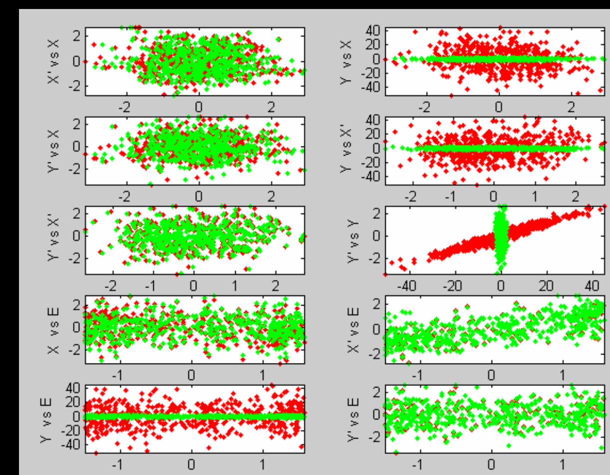




without knobs

No antisolenoid

With antisolenoid



$\sigma_X/\sigma_{X0} = 2.24$, $\sigma_Y/\sigma_{Y0} = 160$

$X_{IP} = 16.3\ \mu m$, $Y_{IP} = -93.3\ \mu m$

-0.0023	-0.0000	-3.6797	-0.0001	-0.0000	0.0000
0.1781	-0.0008	-218.4982	-0.0737	0.0000	0.0000
0.0005	0.0000	-0.0448	-0.0000	0.0000	0.0000
-1.9043	0.0338	25.0467	0.0002	-0.0000	0.0000
-0.0003	0.0000	-0.0583	-0.0000	-0.0000	-0.0000
-0.2960	0.0009	143.1210	0.0506	-0.0000	0.0000

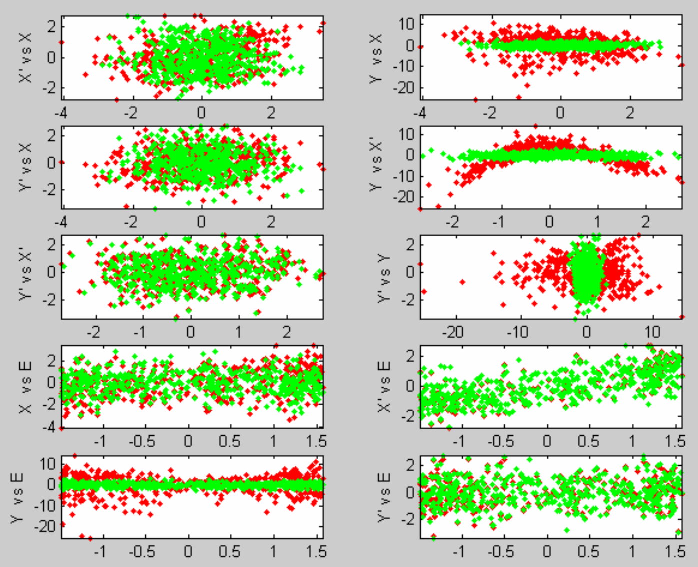
$\sigma_X/\sigma_{X0} = 1.04$, $\sigma_Y/\sigma_{Y0} = 15.6$

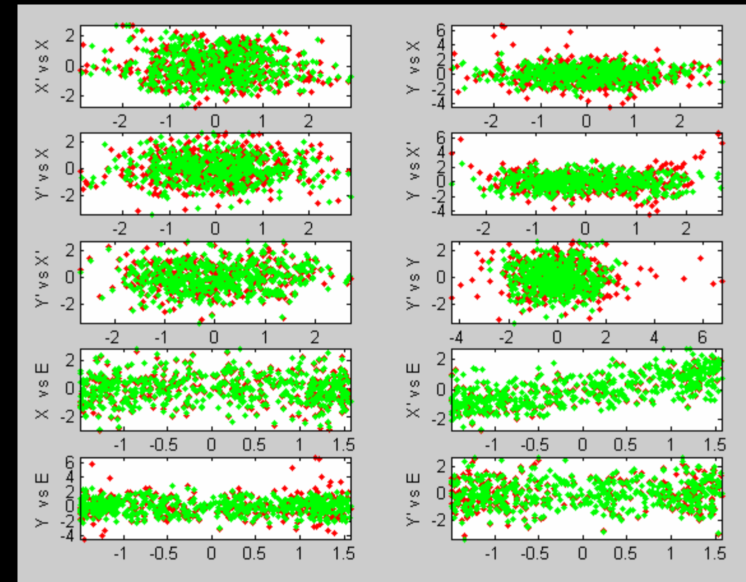
$X_{IP} = 17.8\ \mu m$, $Y_{IP} = -4.6\ \mu m$

-0.0019	-0.0000	-3.5585	-0.0001	-0.0000	0.0000
0.2670	-0.0001	-0.8987	-0.0605	0.0000	0.0000
0.0006	0.0000	0.0004	-0.0000	-0.0000	0.0000
0.1062	0.0333	15.2223	-0.0001	-0.0000	0.0000
0.0001	0.0000	0.0040	-0.0000	-0.0000	-0.0000
-0.3652	0.0002	1.8141	0.0417	-0.0000	0.0000

SiD field *5

with knobs





No antisolenoid

σ_X/σ_{X0} =1.25 , σ_Y/σ_{Y0}= 1.33

X_{IP}=70.7 μm, Y_{IP}= -91.5 μm

-0.0623	-0.0384	-0.0690	-0.0043	-0.0000	0.0000
0.3735	0.0101	0.1525	-0.0805	0.0000	0.0000
-0.0219	-0.0001	0.1584	0.0048	0.0000	0.0000
0.1676	0.0013	0.0357	-0.0121	0.0000	0.0000
-0.0318	0.0005	0.3042	0.0020	-0.0000	-0.0000
0.0945	0.0199	0.0854	0.0886	0.0003	0.0000

With antisolenoid

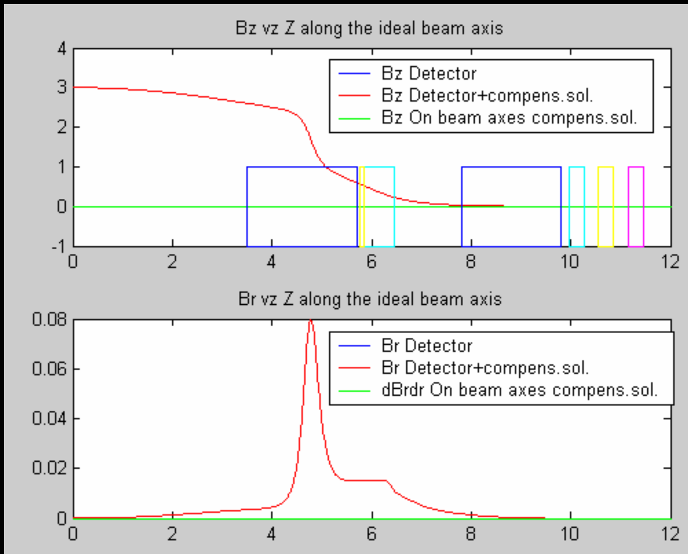
σ_X/σ_{X0} =1.00 , σ_Y/σ_{Y0}= 1.05

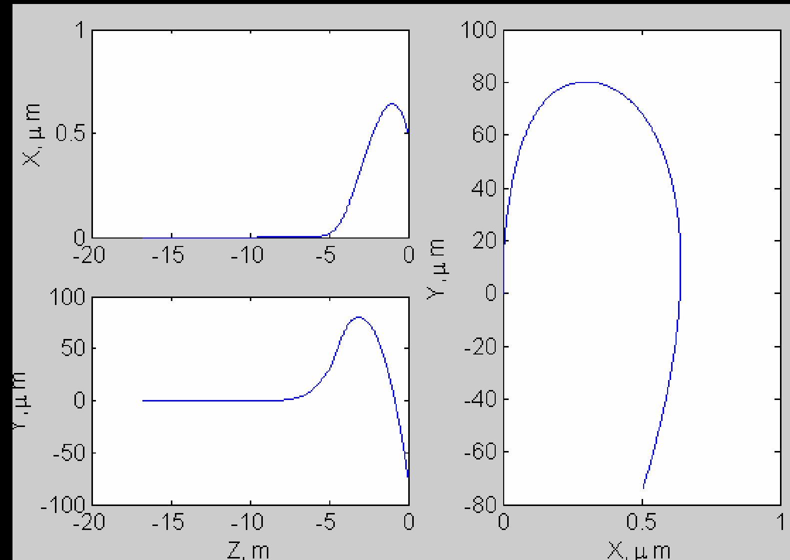
X_{IP}=17.9 μm, Y_{IP}= -4.6 μm

-0.0010	-0.0409	-0.0835	-0.0062	-0.0000	0.0000
0.0173	-0.0007	0.0559	-0.0593	0.0000	0.0000
-0.0003	-0.0000	0.0239	0.0057	-0.0000	0.0000
0.0984	-0.0012	-0.0443	-0.0071	0.0000	0.0000
-0.0021	0.0008	-0.0488	0.0032	-0.0000	-0.0000
-0.0050	-0.0015	-0.0352	0.0254	-0.0000	0.0000

Poor compensation.
Higher order aberration 322, 366...
Needed displacement of sextupoles reach 200 μm

Almost perfect compensation





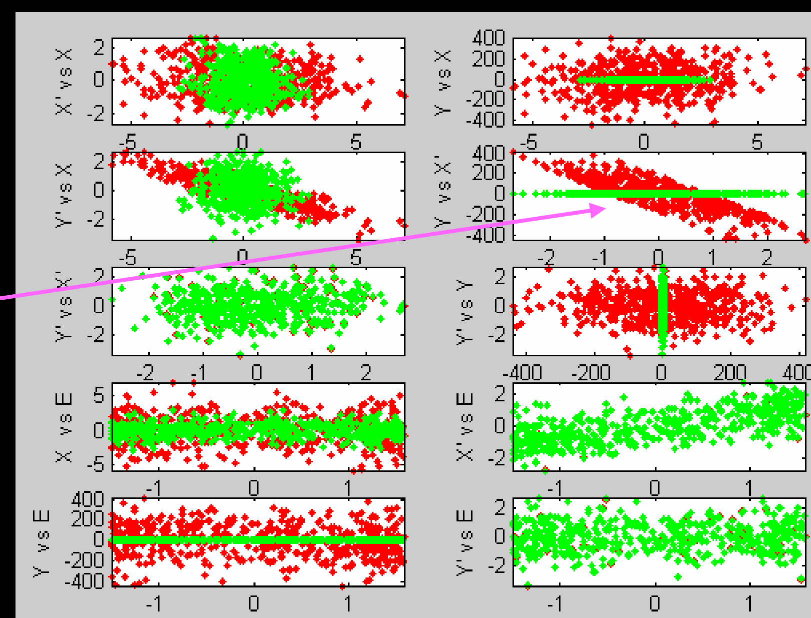
LD

LD. Without compensation the beam is σ_X/σ_{X0} =2.2 , σ_Y/σ_{Y0}= 150 and the IP Y orbit is -75 µm

In the Large Detector the solenoid overlaps with FD quads even more. => effect on the beam size is larger

M' -1 =

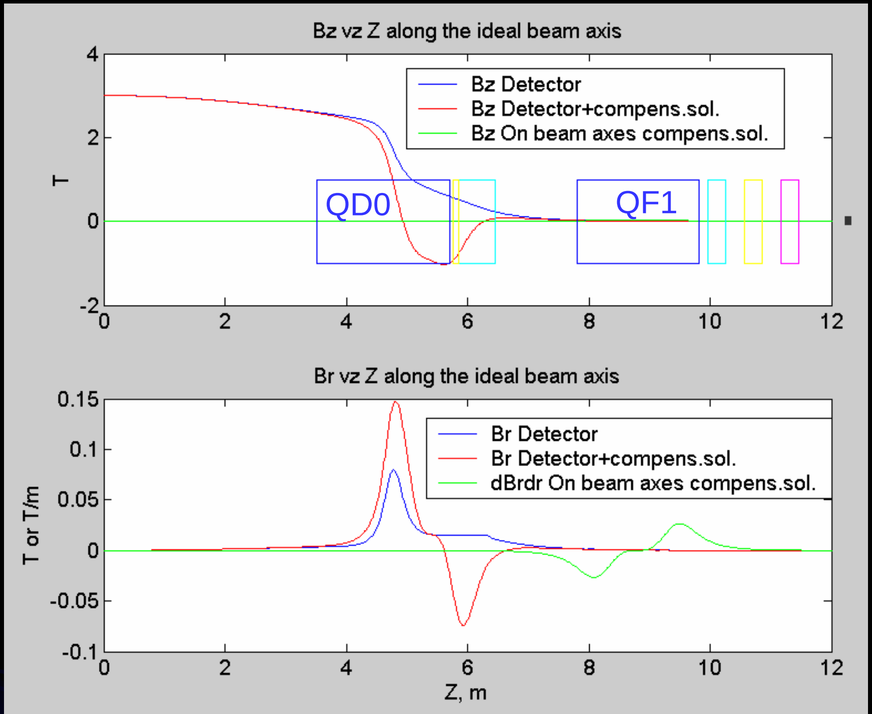
-0.00	-0.00	-0.42	-0.00	0.00	-0.00
-0.00	-0.00	-203.6	-0.02	0.00	-0.00
-0.00	0.00	-0.03	-0.00	0.00	0.00
-1.88	0.00	1.90	0.00	-0.00	0.00
-0.00	0.00	-0.05	-0.00	-0.00	-0.00
-0.01	0.00	115.6	0.01	-0.00	0.00

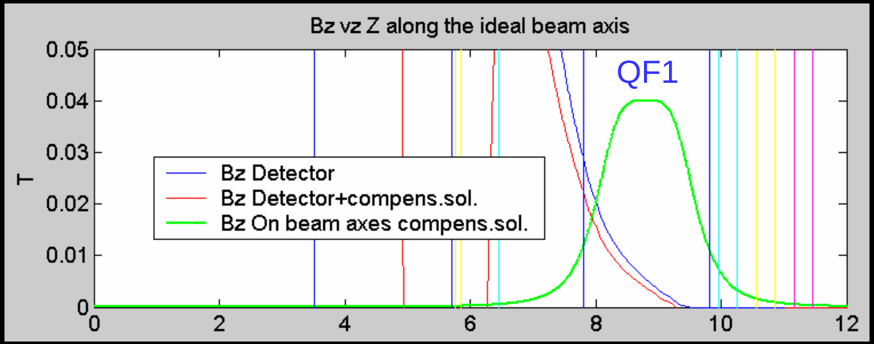


If we would increase the **LD** field 5 times, the uncompensated beam would be σ_X/σ_{X0} =9.6 , σ_Y/σ_{Y0}= 756 and the Y orbit is -370 µm

The dominant term is R32 coupling (x' => y) and the next one is R36 dispersion (δE => y)

LD compensation by two antisolenoids



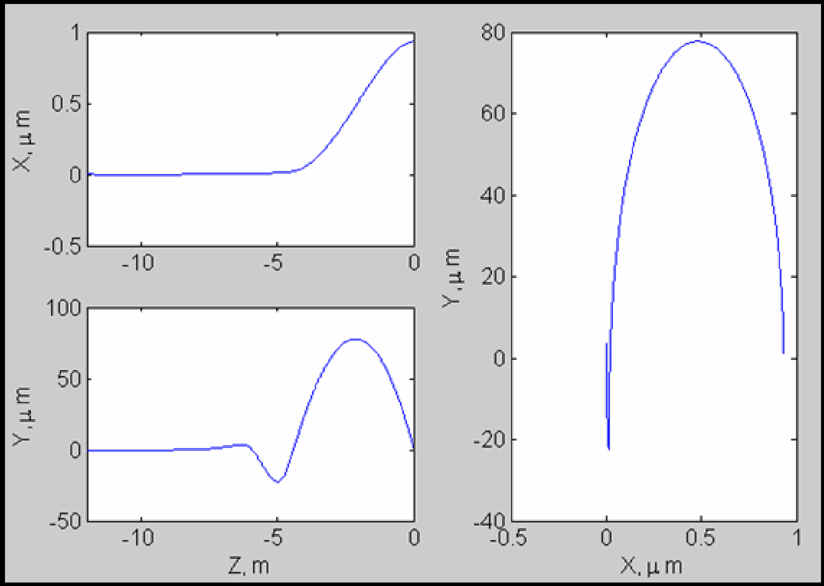


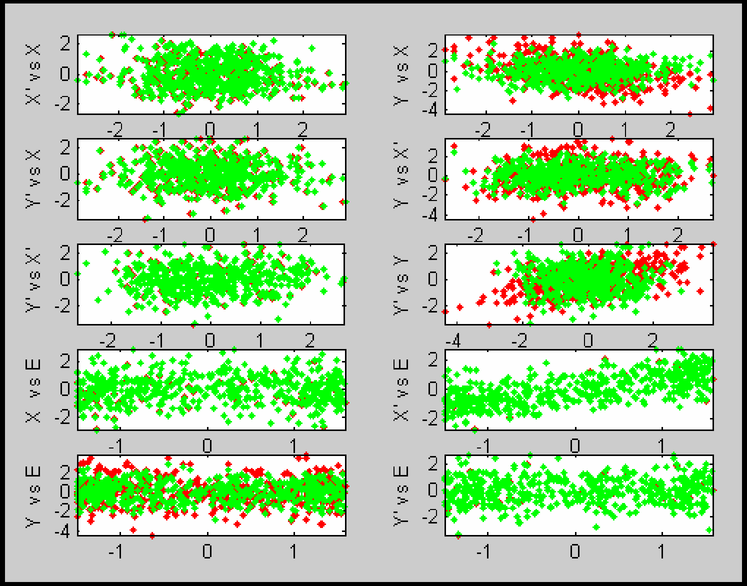
In this case, for better flexibility, we have chosen to use two antisolenoids:

1st antisolenoid is overlapping with QD0, it is part of the detector and is placed on the detector axis. Max field 1.7T. It affects R32 and R36

2nd antisolenoid is overlapping with QF1, it is wound on QF1 and thus placed on the beam axis. It is far from detector, so the forces on QF1 are already small. Max field 0.04T. It affects R32 only.

LD compensation by antisolenoids only





LD

σ_X/σ_{X0} =1.00 , σ_Y/σ_{Y0}= 1.23

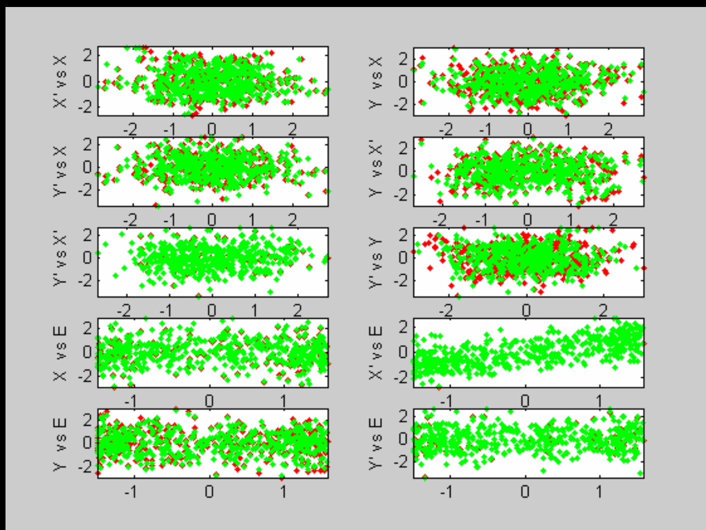
If the LD field (and field of antisolenoids) would be increased 5 times:

LD*5

σ_X/σ_{X0} =1.06 , σ_Y/σ_{Y0}= 16.1

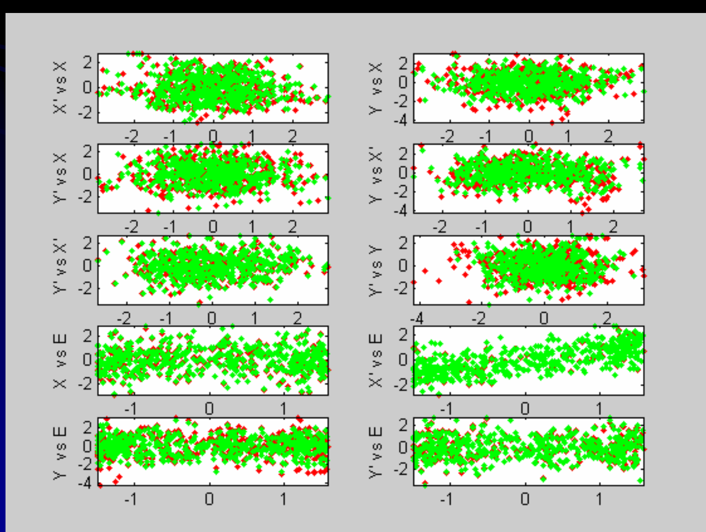
Antisolenoids compensate 99.8 % or 98 % of the beam size increase

LD compensation by antisolenoids and tuning knobs



LD

σ_X/σ_{X0} =1.00 , σ_Y/σ_{Y0}= 1.02



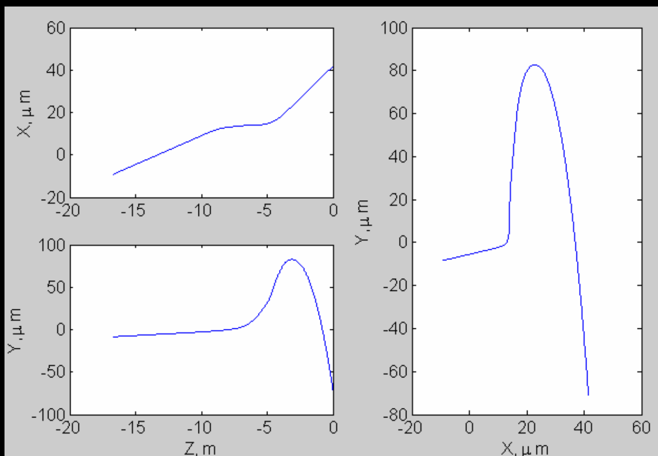
LD*5

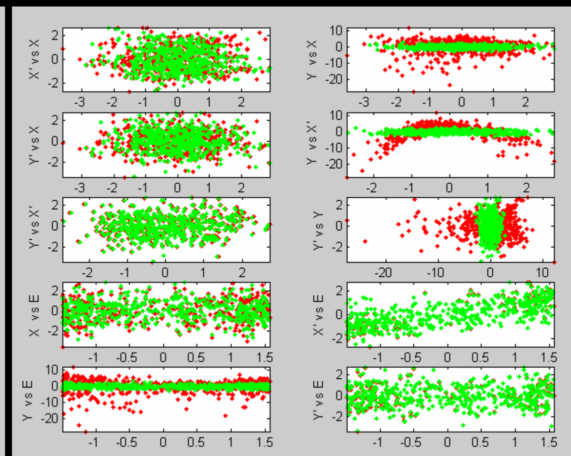
σ_X/σ_{X0} =1.01 , σ_Y/σ_{Y0}= 1.07

Again almost perfect compensation

LD compensation without antisolenoid

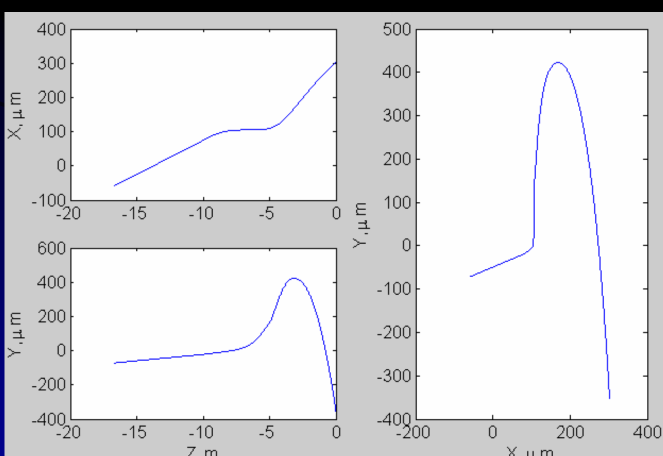
(only by skew in FD and tuning knobs)

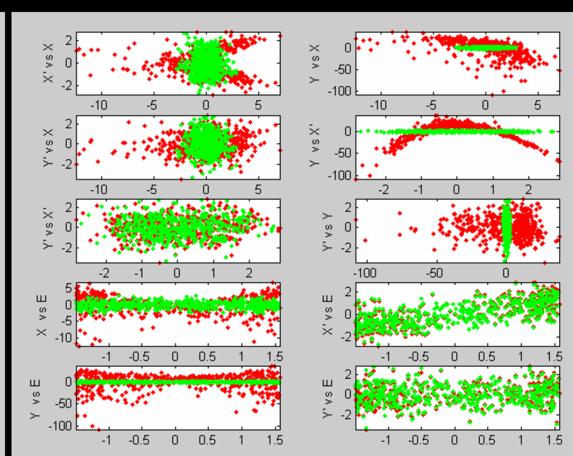




LD

σ_X/σ_{X0} =1.13 , σ_Y/σ_{Y0}= 1.27





LD*5

σ_X/σ_{X0} =2.51 , σ_Y/σ_{Y0}= 5.52

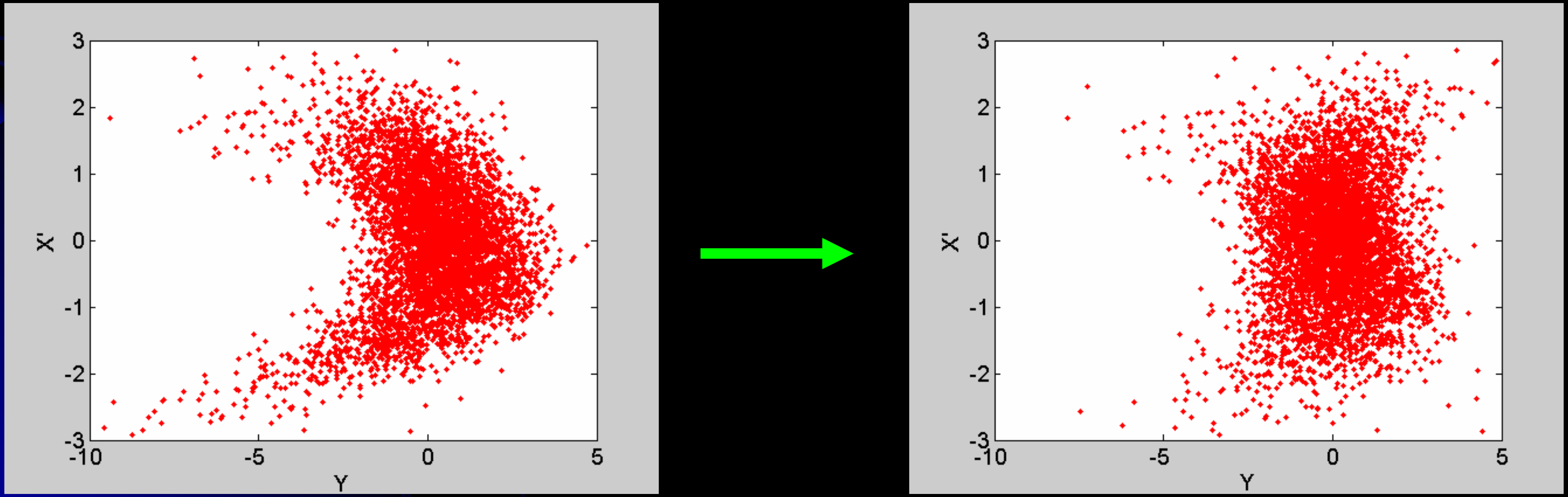
Limited by 2nd order aberrations T322, T366, etc. and require higher order knobs for further improvement.

Higher order knobs

If we do not use antisolenoids, the remaining beam size increase is due to second and higher order effects

They can be removed with higher order knobs

Example of T322 knob which involve rotation of sextupoles:



Summary of SiD and LD compensation

All numbers with compensation can be improved with more optimization (including higher order knobs). But with the same efforts, it is much easier to find an optimum if we use antisolenoid (would be true in real machine too)

SiD	bare	No antisolenoid, with knobs	Only antisolenoid, no knobs	With antisolenoid, with knobs
250 GeV/beam σ_X/σ_{X0}	1.07	1.01	1.00	1.00
σ_Y/σ_{Y0}	31.6	1.28	1.29	1.02
50 GeV/beam σ_X/σ_{X0}	2.24	1.25	1.04	1.00
σ_Y/σ_{Y0}	160	1.33	15.6	1.05

LD	bare	No antisolenoid, with knobs	Only antisolenoids, no knobs	With antisolenoids, with knobs
250 GeV/beam σ_X/σ_{X0}	2.2	1.13	1.00	1.00
σ_Y/σ_{Y0}	150	1.27	1.23	1.02
50 GeV/beam σ_X/σ_{X0}	9.6	2.51	1.06	1.01
σ_Y/σ_{Y0}	756	5.52	16.1	1.07

↑ These numbers can be brought to ~1 with higher order knobs.

Conclusion

- Effect of the detector solenoid on the beam size can be compensated for entire NLC energy range from 50 GeV/beam to TeV

- Compensation is done most effectively with antisolenoids overlapping with FD quads
  - Advantages of using antisolenoids:
    - natural almost perfect compensation of the detector solenoid
    - compensation does not depend on the beam energy

If ? is asked: "Is it easier to make compensation with 0 crossing angle?"

For comparison, consider LD *5 with much smaller crossing angle

If we use skew in FD and knobs, compensation is equally difficult

If we use antisolenoids, compensation is equally easy

LD	bare	No antisolenoid, with knobs	Only antisolenoid, no knobs	With antisolenoid, with knobs
250 GeV/beam σ_X/σ_{X0}	2.2	1.13	1.00	1.00
σ_Y/σ_{Y0}	150	1.27	1.23	1.02
50 GeV/beam σ_X/σ_{X0}	9.6 8.9	2.51 1.01	1.06 1.07	1.01 1.00
σ_Y/σ_{Y0}	756 945	5.52 8.48	16.1 16.4	1.07 1.07

Half crossing angle is 0.1mrad