CONVENTIONAL SOLENOID COMPENSATION SCHEME

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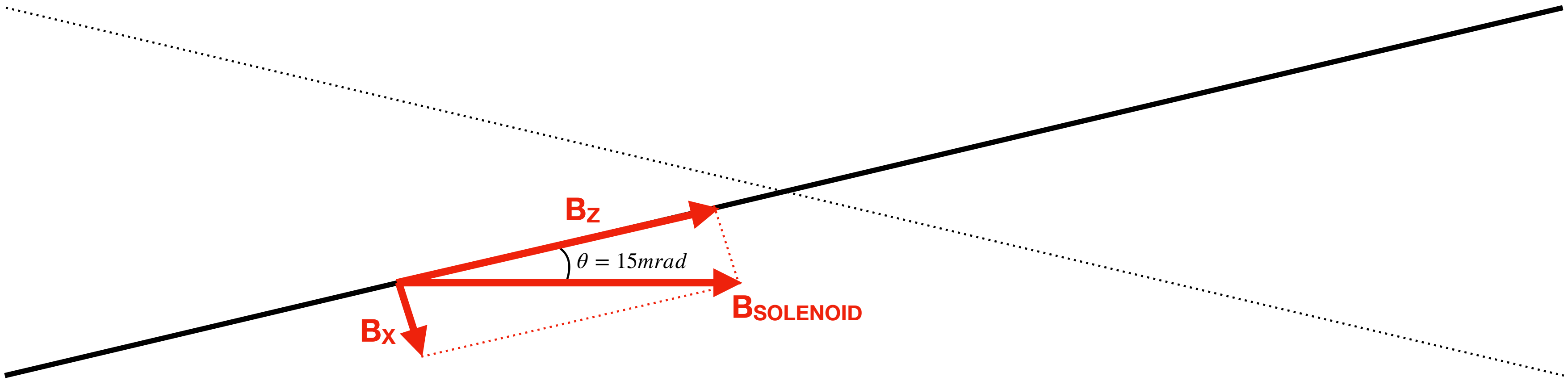
Intro

Large detector solenoids are strong coupling elements.

At FCC-ee the beams cross the 2T detector solenoid with a **15mrad angle**, experiencing B-field component along both the **Z-axis** and the **X-axis.** This generates vertical emittance blow-up and orbit oscillation.

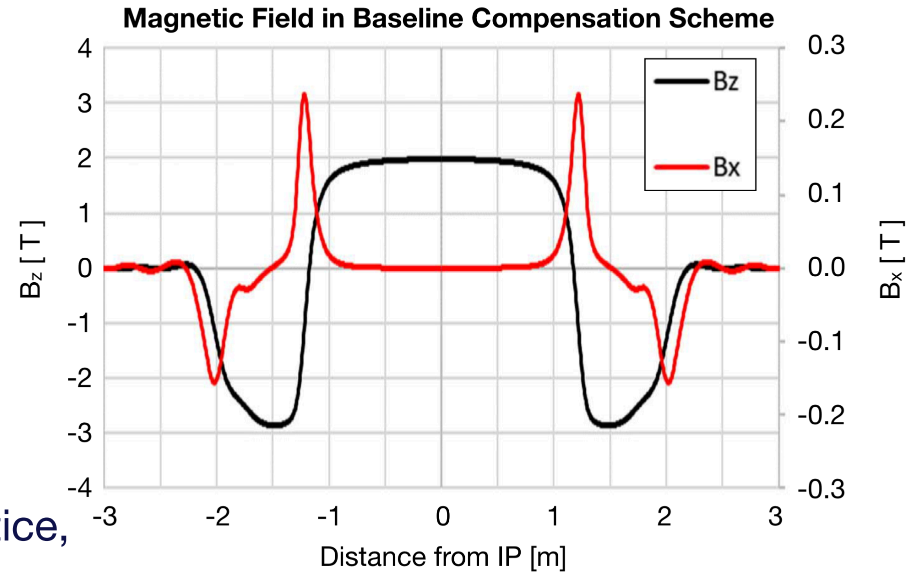


Baseline Solenoid Compensation at FCC-ee

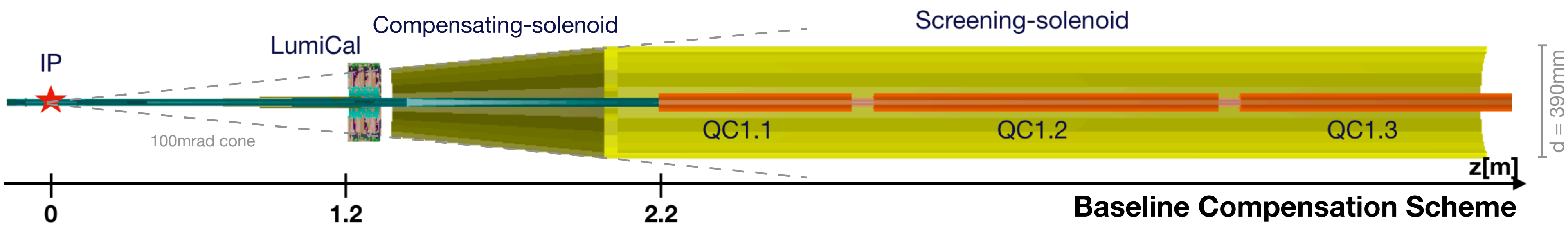
- Compensating solenoids cancel the $\int B_z ds$ **before the FD**.
- Screening solenoids nullify the detector field in the quadrupole region

These elements are **common to both beam pipes**.

They are located **inside the detector** (start at ±1.23m) and require dedicated cryostat.



ϵ_y blowup at Z was calculated to be **0.24pm** for the **2IP CDR** lattice, and twice this value for the baseline 4IP lattice (nominal $\epsilon_y = 1pm$).



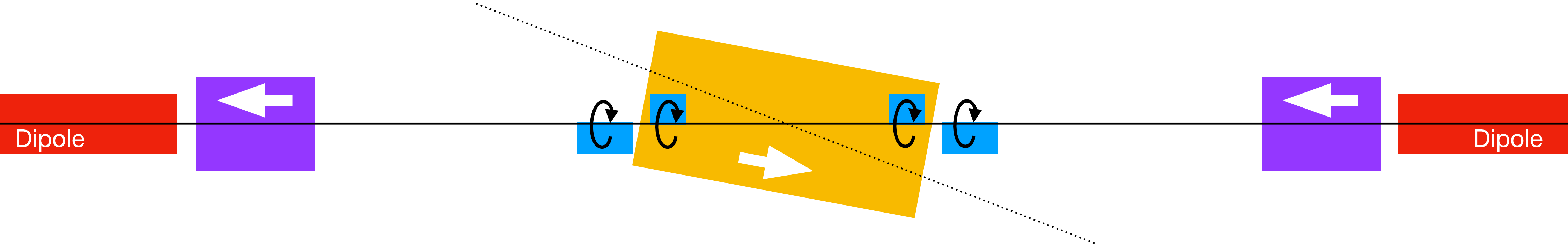
Baseline Compensation Scheme

Conventional Solenoid Compensation Scheme

A compensation scheme similar to that used in DAΦNE would allow for the **removal of the IR anti-solenoids**, resulting in benefits such as **increased available space** in the MDI area.

The beam reference frame rotates because of the **solenoid**, so the **Final Focus Quadrupoles** are rotated to follow the beam rotation.

Outside the Final Focus **two anti-solenoid** are used to cancel the $\int B_z ds$ from the detector. These elements are far from the IR and are on-axis with the beam.



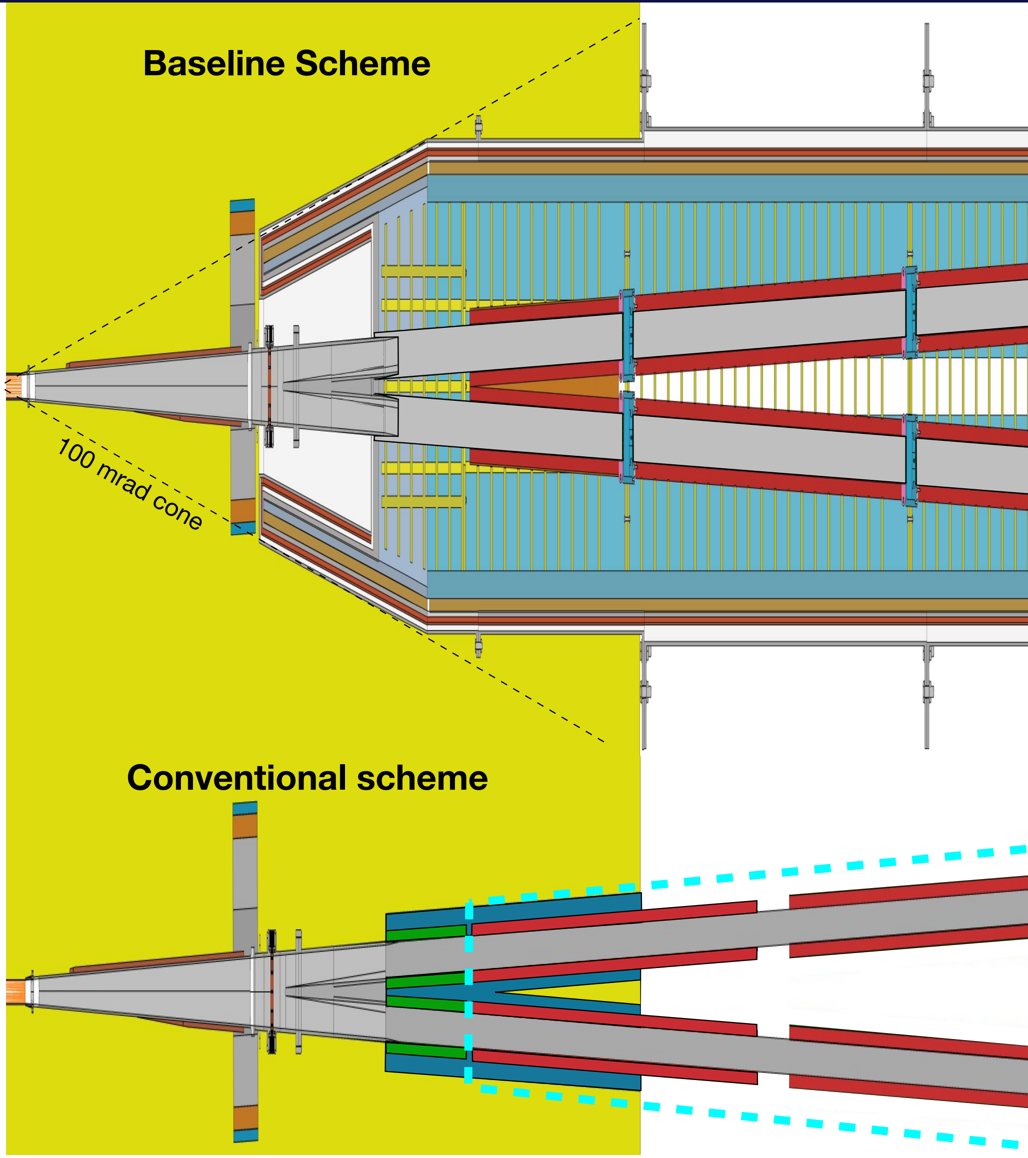
Volume taken in the IR

The compensating solenoid and its cryostat are designed within a **100mrad cone.**

The dimension of these elements currently poses strong mechanical **constraints on the MDI design**.

Removing the anti-solenoids in the IR could allow the design of a **much smaller cryostat** suited for the SC quadrupoles only.

Compensation of the Bx component requires **dedicated correctors** before and around the first quadrupole.



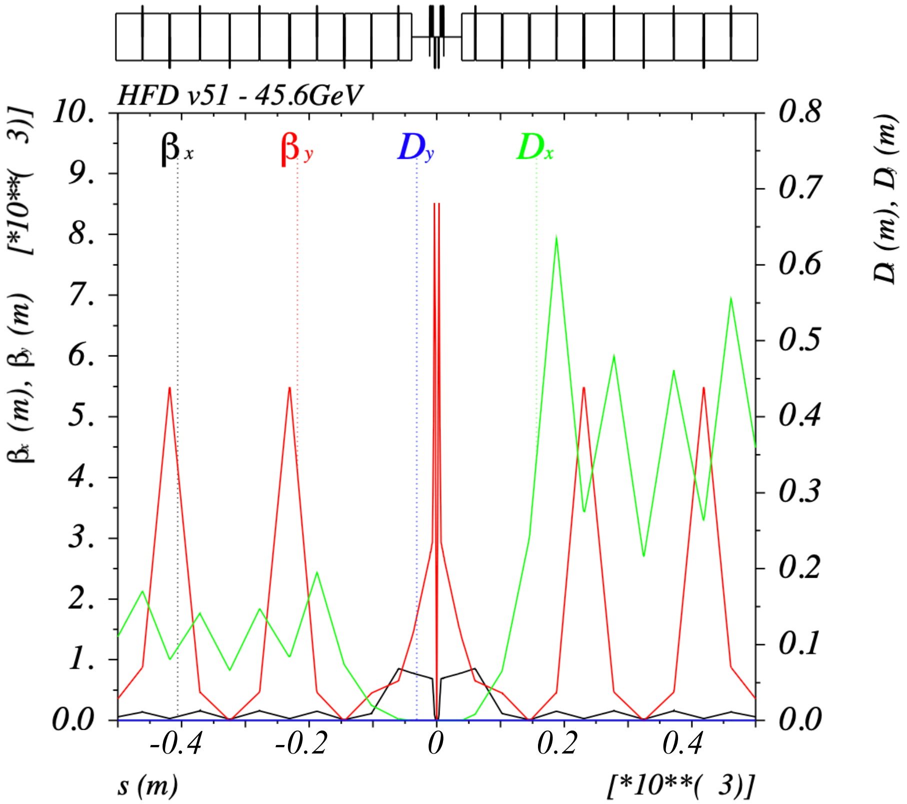
The starting point

This scheme was tested on the Hybrid-FODO alternative lattice (v51) at the Z working point, but in principle can be applied also to other energies and to the baseline optics.

β_x	0.20 m
β_y	0.8 mm
ϵ_x	500 nm rad
ϵ_y	1 pm rad

A 6m-long 2T solenoid placed at each IP will cause a **vertical emittance blow-up** of

$$\left(\frac{\epsilon_y}{\epsilon_x}\right)_{sol} = \frac{0.048[\pi\, nm\, rad]}{0.481[\pi\, nm\, rad]} = 10\,\%$$



Reduced Coupling by Alternating Solenoid Signs

Without any correctors, coupling is reduced of a factor 4 simply by alternating the sign of the detector's magnetic field.

Experiments are (supposedly) symmetrical w.r.t. the x-y plane, so changing the sign of the 2T solenoidal field should not be a problem.

$$\left(\frac{\epsilon_y}{\epsilon_x}\right)_{sol} = \frac{0.048[\pi\, nm\, rad]}{0.481[\pi\, nm\, rad]} = 10\,\%$$

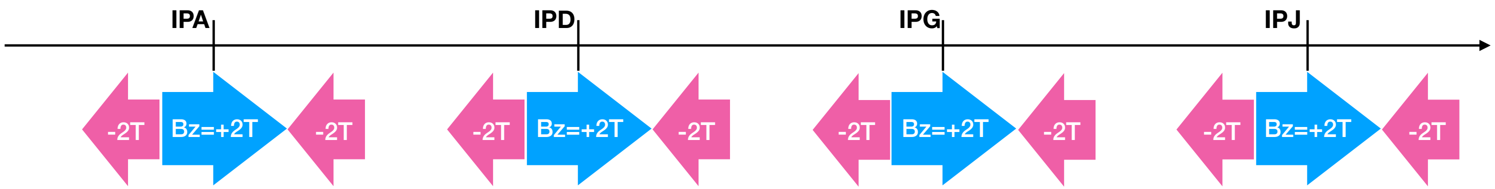
$$\left(\frac{\epsilon_y}{\epsilon_x}\right)_{alt.\,sol} = \frac{0.012[\pi\, nm\, rad]}{0.512[\pi\, nm\, rad]} = 2.3\,\%$$

Reduced Coupling by Alternating Solenoid Signs

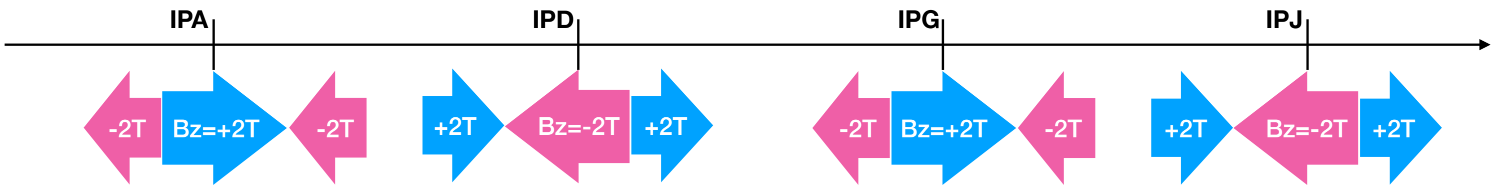
Without any correctors, coupling is reduced of a factor 4 simply by alternating the sign of the detector's magnetic field.

Experiments are (supposedly) symmetrical w.r.t. the x-y plane, so changing the sign of the 2T solenoidal field should not be a problem.

Also the antisolenoids should have alternated sign.



$$\left(\frac{\epsilon_y}{\epsilon_x}\right)_{sol} = \frac{0.038[\pi\, nm\, rad]}{0.500[\pi\, nm\, rad]} = 7.6\,\%$$



$$\left(\frac{\epsilon_y}{\epsilon_x}\right)_{alt.\,sol} = \frac{0.011[\pi\, nm\, rad]}{0.519[\pi\, nm\, rad]} = 2.1\,\%$$

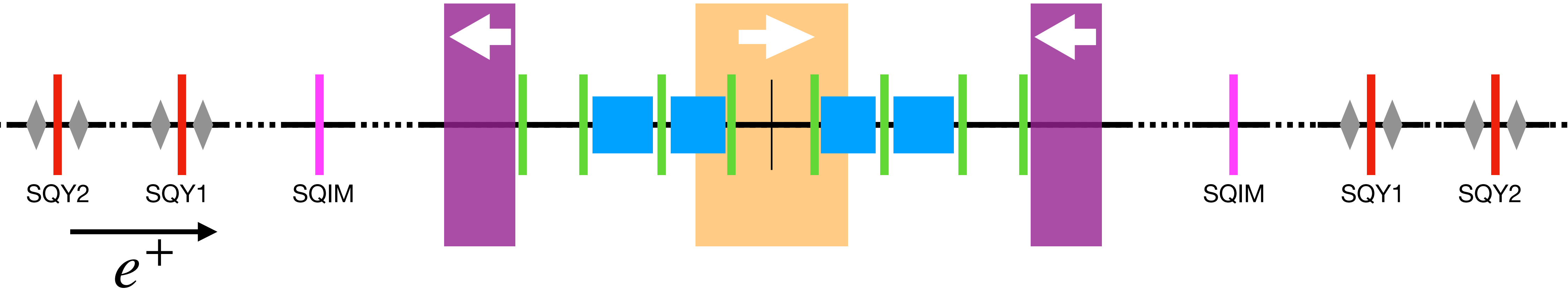
Decoupling the Coupling Sources

Due to the crossing angle, the beam will see a longitudinal and a transverse component of the B field.

The effects on the two components are studied and compensated independently

z-axis : **tilt of the Final Focus Quadrupoles**, two **skew quadrupoles** (SQY1/SQY2) at the **sextupole pairs** location.

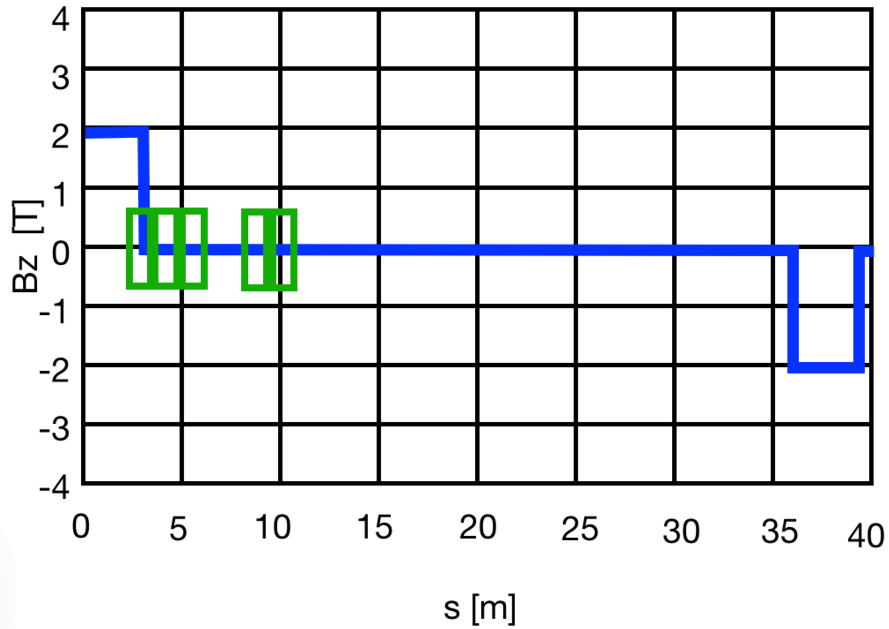
x-axis : **vertical correctors**, a **skew quadrupole** (SQIM) at the first image point, and the two **skew quadrupoles** SQY1/SQY2.

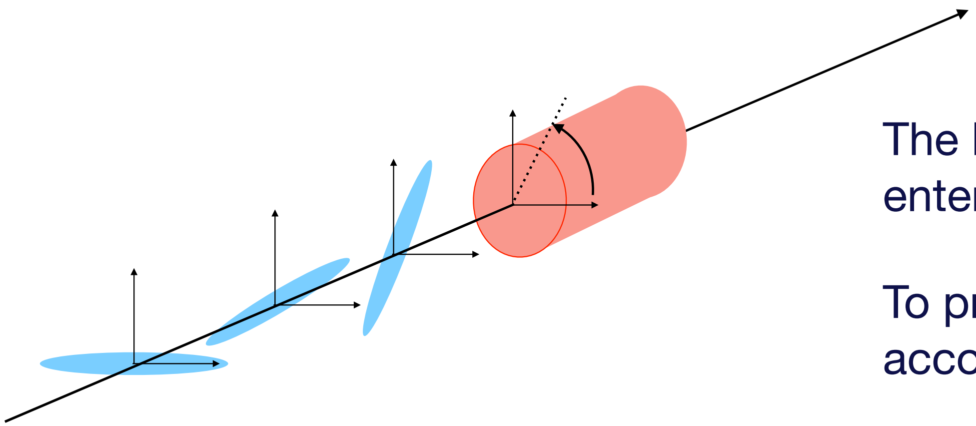


Longitudinal component Bz

The **anti-solenoid** required to cancel the field integral is placed **far from the IR**, just before the first dipole.

$$\int_{-40m}^{+40m} B_z ds = 0$$





The beam therefore is on a **rotated reference frame** when entering the Final Focus Quadrupoles.

To prevent beam blowup due to this, **FFQs are rotated** accordingly to the beam.

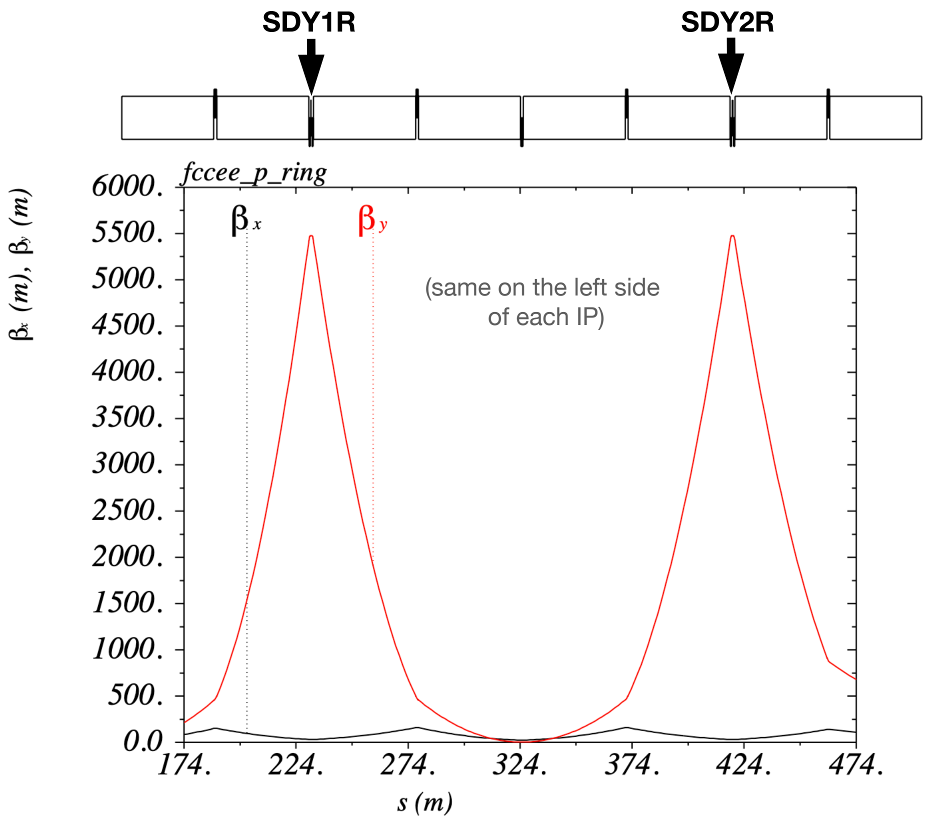
The quadrupole rotation is **asymmetrical**: $\theta_{QD0A,L} = -\theta_{QD0A,R}$

To better correct coupling and ease the matching, **skew quadrupole pairs** have been placed in correspondence of the SDY1 and SDY2 sextupoles.

The absolute value of the gradient is the same, but the sign is asymmetric w.r.t. IP: $K_{SQY} = K_{SQY1/2,L} = -K_{SQY1/2,R}$

Tuning this value to minimize ϵ_y and rematching one obtains:

$$\epsilon_{y,Bz} = 0.0187\ [\pi\ pm\ rad]$$

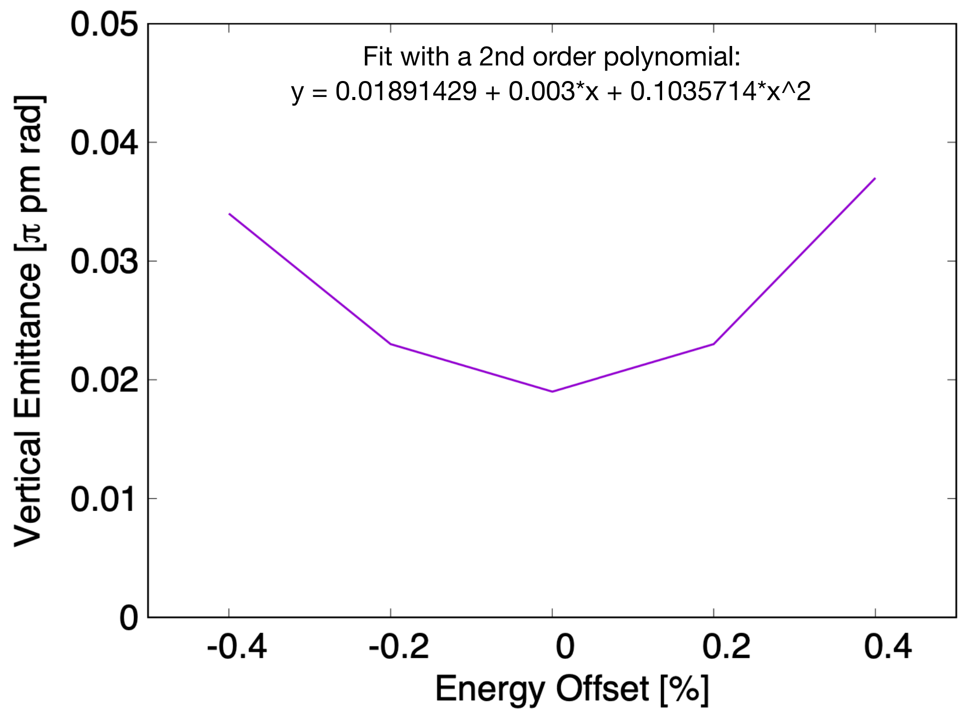


The final contribution to vertical emittance value is **few percents of the nominal one** $\epsilon_y = 1\ [\pi\ pm\ rad]$.

Chromatic Coupling

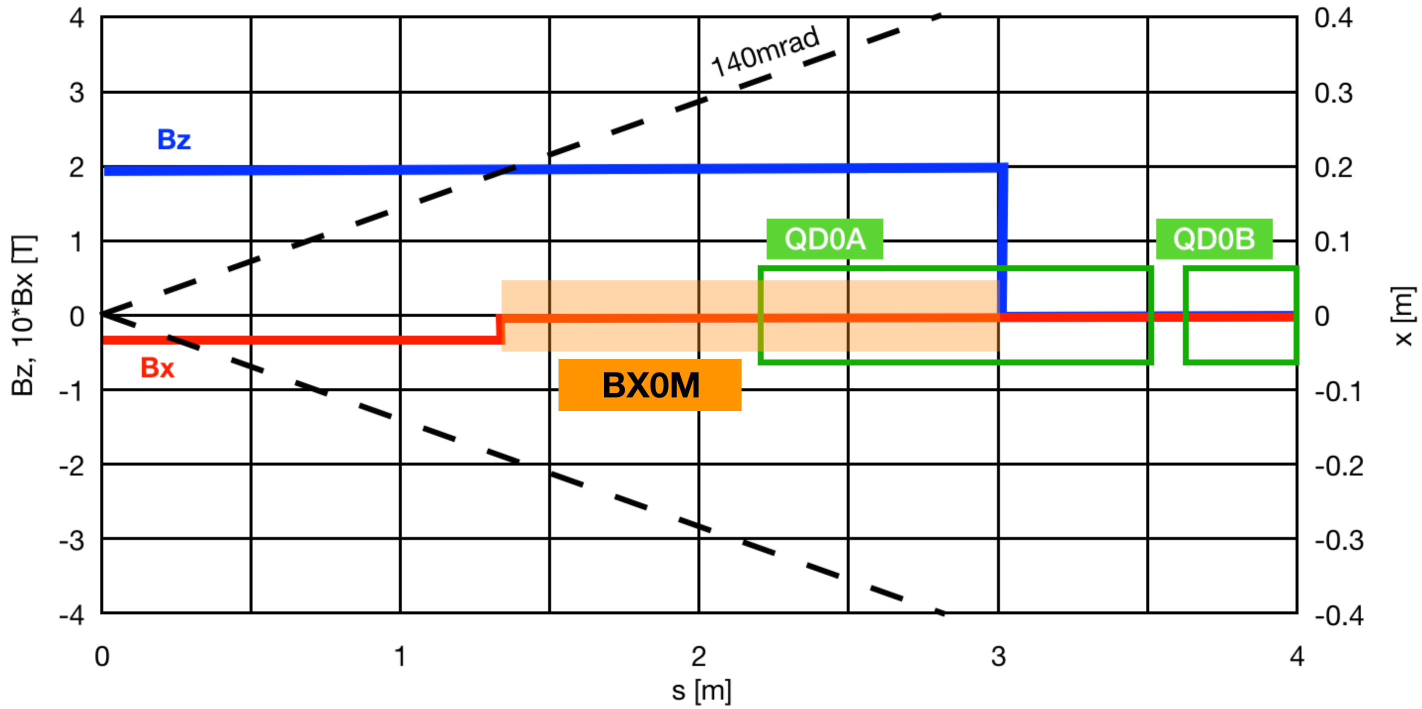
The effect of chromatic coupling has been estimated by performing a scan on the relative energy offset of the beam.

Without corrections this effect is small, still contributing with few percents to the nominal vertical emittance value.

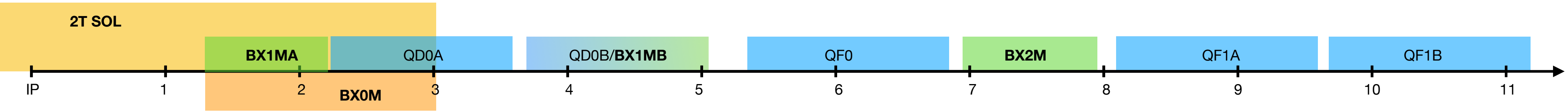


Horizontal component Bx

Due to the 15mrad crossing angle, the beam experiences a field component **transverse** to its direction.
This acts as a **vertical kick**, and induces orbit and emittance blowup.



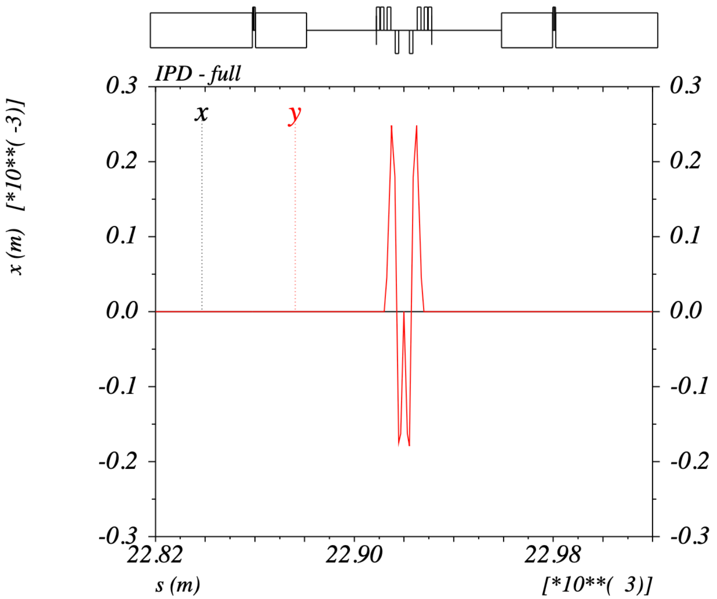
A **first corrector BX0M** is placed just after the beam pipe separation at ±1.285m, to cancel the solenoid Bx.

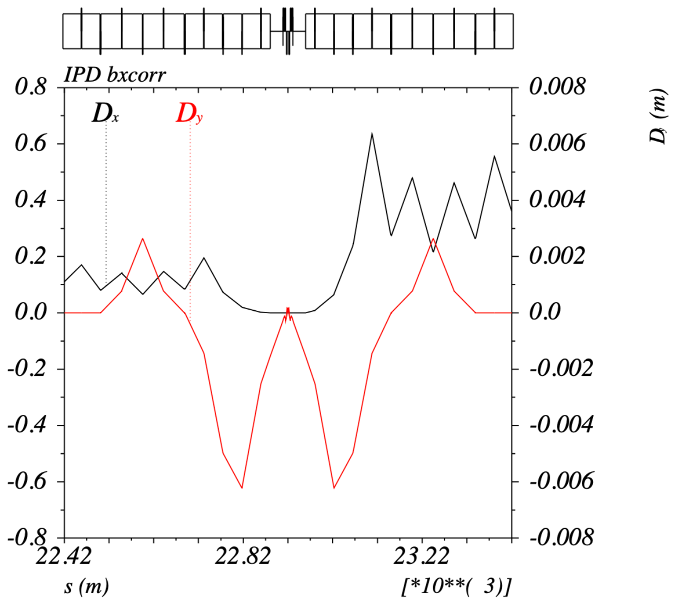


A **corrector (BX1MA)** placed before QD0A is used to correct beam offset w.r.t. the quadrupole, **mitigating generation of coupling**. Corrector **BX0M** (prev. slide) is winded around both **BX1MA** and **QD0A**.

Other **two correctors (BX1MB, BX2M)** are then used to close an **orbit bump** of about ±200μm

Coupling is corrected using pairs of **skew quadrupoles** at the sextupoles location and at the first image point.





Optimal value of emittance blowup due to this contribution is:

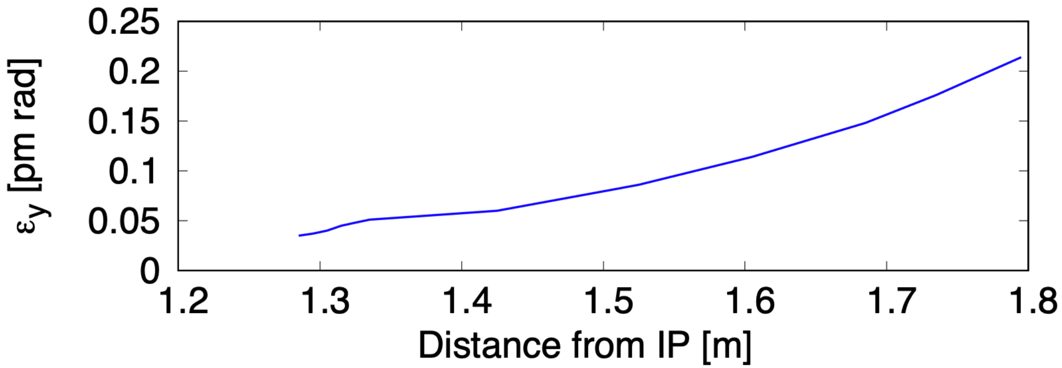
$$\epsilon_{y,Bx} = 0.035 \ [\pi \ pm \ rad]$$

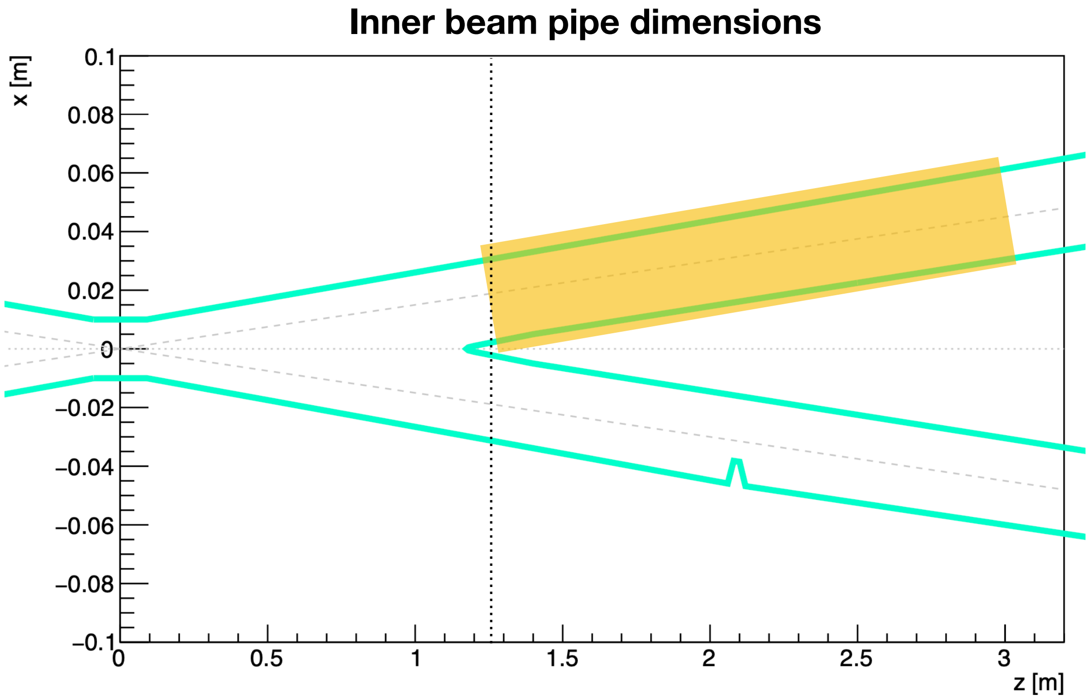
Dependance on the first corrector position

For this study the first Bx corrector is assumed to start **right after the beam pipe separation** s=1.285m, and ends at the end of the detector solenoid at 3m.

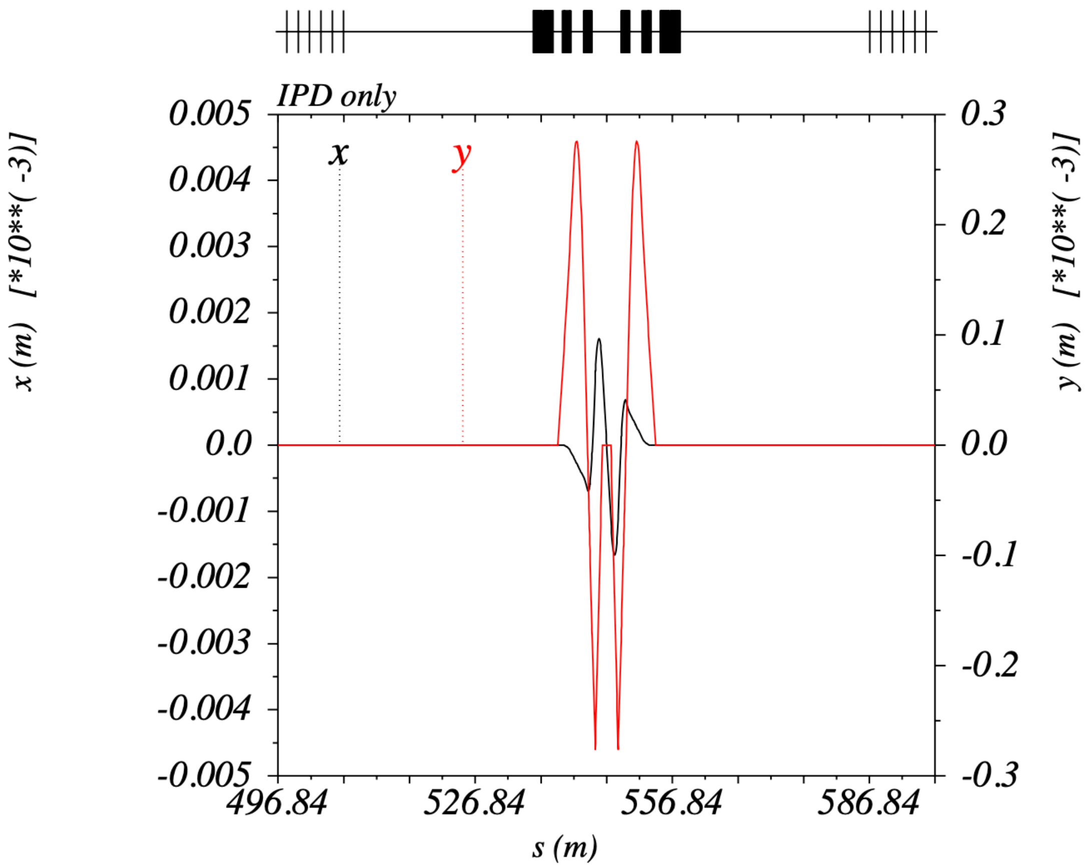
Due to **mechanical constraints** this may change.

Moving the start point reduces the lenght of the corrector and its effectiveness.





Cumulative effect of the two components



The two effects have succesfully been **independently corrected** and emittance contribution minimized.

The vertical bump due to the Bx induces **horizontal orbit** once the Bz is accounted.

This is corrected using a single **horizontal corrector** before QD0A.

The total contribution to vertical emittance using this scheme is:

$$\epsilon_y = 0.040 \ [\pi \ pm \ rad]$$

D_y^* for monochromatization

Vertical dispersion at the IP of ±0.5 mm is introduced for monochromatization runs.

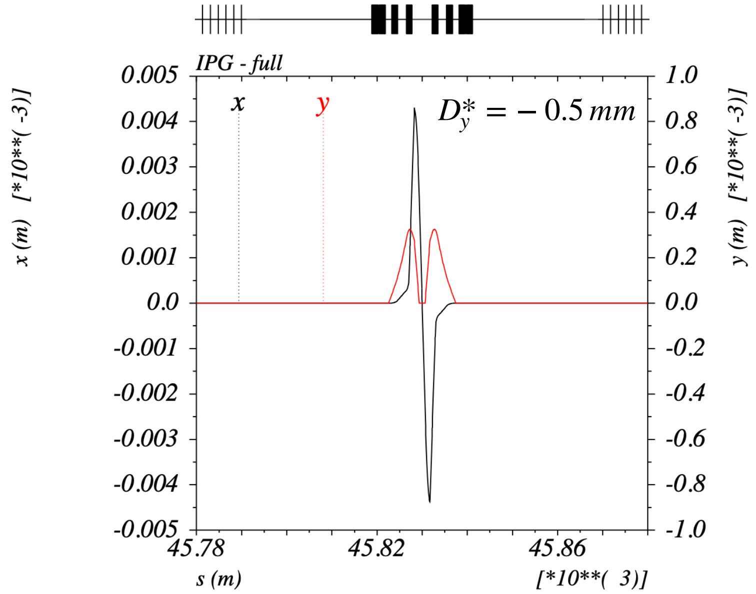
Emittance blowup is controlled by optimization of the **BX1MA vertical corrector** (before QD0A) and further rematch of other correctors and skew quadrupoles.

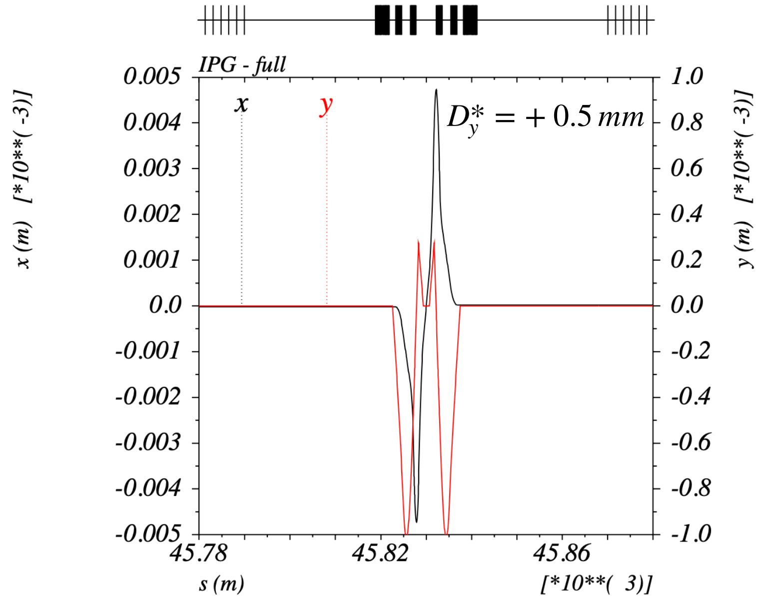
In both scenarios vertical blowup is minimized to:

$$\epsilon_{y,D_y} = 0.054\ [\pi\ pm\ rad]$$

For $D_y^* = -0.5\,mm$ the intensity of the first corrector is reduced and the vertical bump is ~0.3mm.

With the other sign both corrector strenght and bump increase.





Summary and open points

- Conventional solenoid compensation scheme has been presented
- Longitudinal and Transverse components are corrected independently
  - Bz: IR quadrupoles rotation and skew quadrupole pairs
  - Bx: vertical correctors in the IR and skew quadrupole pairs
- Emittance blowup corrected down to $\epsilon_y = 0.040\ [\pi\ pm\ \ rad]$ (4% of the nominal emittance)
- Small emittance increase also for $D_y^* = -0.5\,mm$

- In the baseline solution, beam pipe and IR quadrupoles are sustained by the cryostat (cantilever). <u>How will the support look like if we remove the current cryostat?</u>
- The start of the innermost Bx corrector will depend on the <u>available space at the crotch location</u>
- Next step: apply the same scheme to <u>baseline optics</u>
- Possibility to <u>keep screening solenoid</u> around FD can be explored

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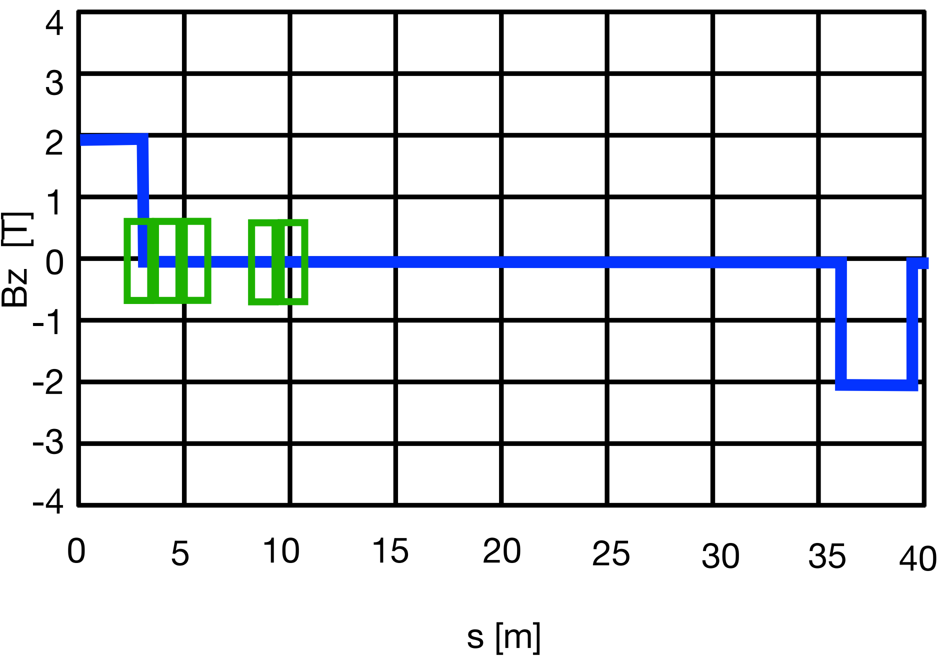
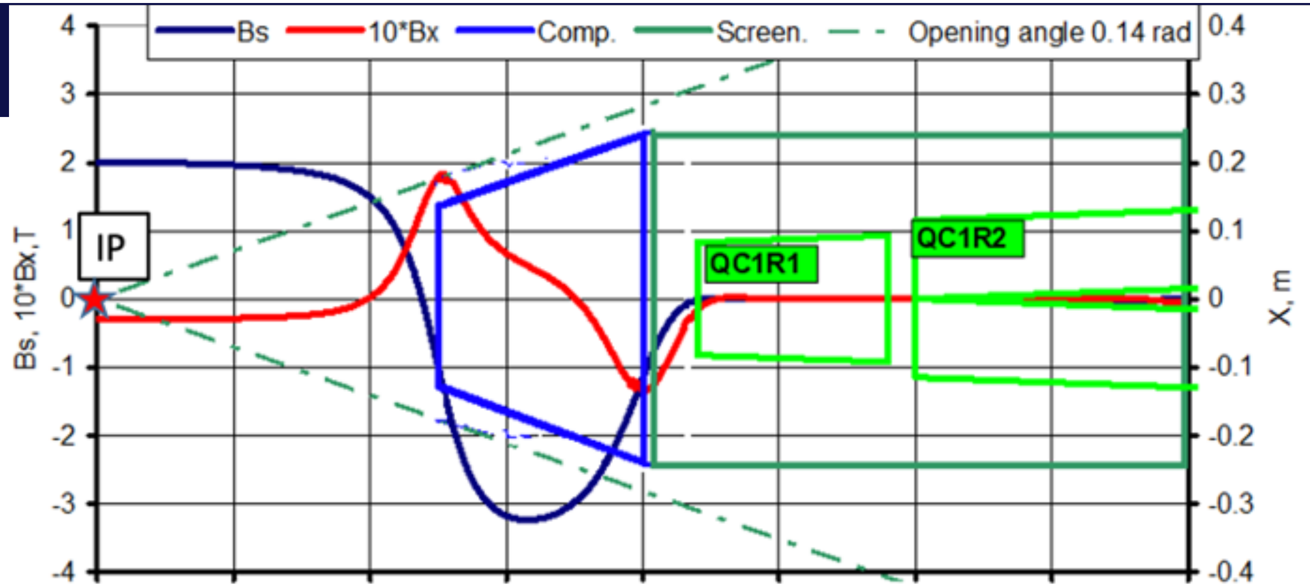
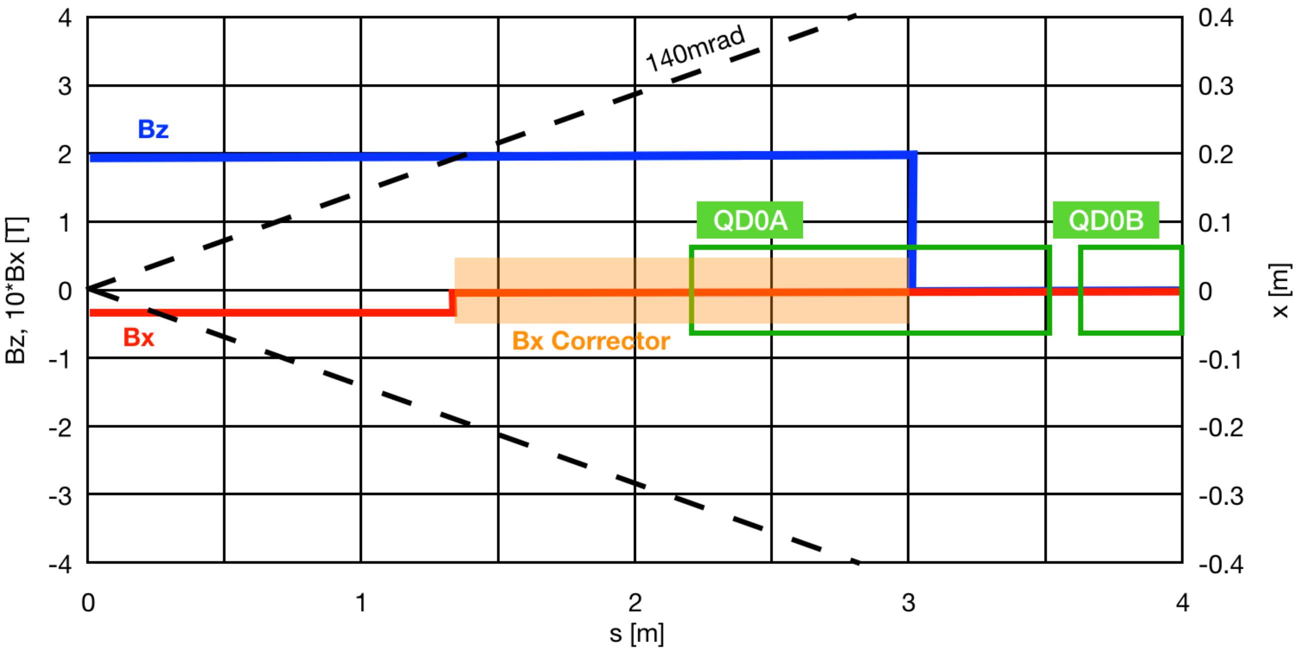
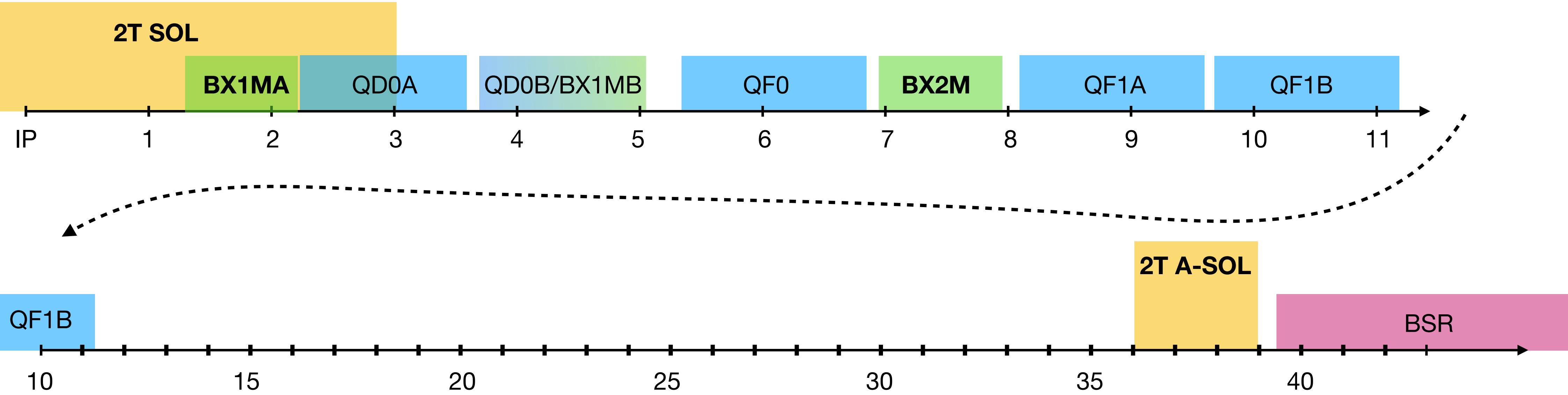

Bz [T]
s [m]


Bs
10*Bx
Comp.
Screen.
Opening angle 0.14 rad
IP
QC1R1
QC1R2
Bs, 10*Bx,T
X, m


140mrad
Bz
Bx
QD0A
QD0B
Bx Corrector
Bz, 10*Bx [T]
x [m]
s [m]


2T SOL
BX1MA
QD0A
QD0B/BX1MB
QF0
BX2M
QF1A
QF1B
IP
1
2
3
4
5
6
7
8
9
10
11
2T A-SOL
QF1B
BSR
10
15
20
25
30
35
40

Conventional Solenoid Compensation Scheme

A compensation scheme similar to that used in DAΦNE would allow for the **removal of the IR anti-solenoids**, resulting in benefits such as **increased available space** in the MDI area.

- Rotation of FFQs to fit beam orientation
- Skew quadrupoles
- Vertical correctors in the IR

Antisolenoids far from the IP to cancel $\int B_z ds$

Vertical emittance blowup with this scheme:

$$\epsilon_y = 0.040\ [\pi\ pm\ rad]$$