Impact of experimental solenoids on LHC optics

- See J.P. Koutchouk, “Correction of the systematic and random betatron coupling in LHC with an application to LHC version 2”, (SL-Note-94-101-AP; LHC-Note-306), 1 Jan 1994.
  - ↳ *Conclusion: Solenoid effects negligible, no local compensation scheme (skew quadrupoles) foreseen.*
- See A. Koschik, “On the implementation of experimental solenoids in MADX and their effect on coupling in the LHC”, Proc. of EPAC 2006.
  - ↳ *Conclusion: Solenoid effects small, global coupling compensation scheme will do the job.*

Effect of the experimental solenoids is small, why look at it?

- Numbers have changed since 1994.
- Once big effects (a2, dipole errors) corrected, “smaller” effects might become visible.
- Experimental solenoids might be ramped up/down, good idea to have a knob to follow the changes?

What effects of the solenoids on the optics do we expect?

- Coupling in transverse planes (tunes Q_x/Q_y couple)
- Orbit changes when using separation bumps and crossing scheme
- Roll of the crossing plane (rotation of the beam)

Numbers for ATLAS (IP1) and CMS (IP5)

Magnetic properties of experimental solenoids, ATLAS (IP1) and CMS (IP5)

Property/Experiment		ATLAS	CMS
Magnetic induction at IP	[T]	2.0	4.0
Coil length	[m]	5.3	12.5

Rotation angle at 450 GeV

$$\Theta = \frac{B_s l}{2B\rho}$$

$$\Theta_{ATLAS} = 3.5\,mrad = 0.2^\circ \qquad \Theta_{CMS} = 17\,mrad = 0.95^\circ$$

This rotation corresponds to a roll of the crossing plane.
The beam cross sections stay congruent!

Complex coupling coefficient

$$c_{sol}^{\mp} = -\frac{i}{4\pi}\frac{B_s l}{B\rho}\left(\sqrt{\frac{\beta_y^*}{\beta_x^*}} \pm \sqrt{\frac{\beta_x^*}{\beta_y^*}}\right)$$

Round beams at 450 GeV:

$$c_{ATLAS}^{-} = -\,0.0011\,i \qquad c_{ATLAS}^{+} = 0.0$$
$$c_{CMS}^{-} = -\,0.0053\,i \qquad c_{CMS}^{+} = 0.0$$

Flat beams at 450 GeV:
β_x/β_y = 6/3.7 m at IP1 (ATLAS)
β_x/β_y = 3.7/6 m at IP5 (CMS)

$$c_{ATLAS}^{-} = -\,0.0012\,i \qquad c_{ATLAS}^{+} = 0.0003\,i$$
$$c_{CMS}^{-} = -\,0.0055\,i \qquad c_{CMS}^{+} = -\,0.0013\,i$$

Impact of experimental solenoids on LHC optics
Adding solenoids to the sequence

```
// Define single solenoid ATLAS and CMS
on_sol1 := 0; // to switch solenoid on and off for nominal energy (7TeV)
on_sol5 := 0; // to switch solenoid on and off for nominal energy (7TeV)
              // for injection energy set this switch to 7/.45
l.xsol.ip1     = 5.3;
a.xsol.ip1     = 2.;
l.xsol.ip5     = 12.5;
a.xsol.ip5     = 4.;

msol.ip1: solenoid, l:= l.xsol.ip1/2, ks:= a.xsol.ip1*clight/(7e12) * on_sol1;
msol.ip5: solenoid, l:= l.xsol.ip5/2, ks:= a.xsol.ip1*clight/(7e12) * on_sol5;

XSOL.L1 : msol.ip1;
XSOL.R1 : msol.ip1;
XSOL.L5 : msol.ip5;
XSOL.R5 : msol.ip5;

seqedit, sequence= lhcb1;
  install, element= XSOL.L1, at= -l.xsol.ip1/4, from= IP1;
  install, element= XSOL.R1, at= +l.xsol.ip1/4, from= IP1;
  install, element= XSOL.L5, at= -l.xsol.ip5/4, from= IP5;
  install, element= XSOL.R5, at= +l.xsol.ip5/4, from= IP5;
  flatten;
endedit;

seqedit, sequence= lhcb2;
  install, element= XSOL.L1, at= -l.xsol.ip1/4, from= IP1;
  install, element= XSOL.R1, at= +l.xsol.ip1/4, from= IP1;
  install, element= XSOL.L5, at= -l.xsol.ip5/4, from= IP5;
  install, element= XSOL.R5, at= +l.xsol.ip5/4, from= IP5;
  flatten;
endedit;
```

Because of marker at IP, we split solenoid in left/right part.

Impact of experimental solenoids on LHC optics
LHC optics sequence file (V6.501)

➔ V6.501.inj.str

```
abas                    := 2.0*clight/(7E12)*on_atlas;
abcs                    := 4.0*clight/(7E12)*on_cms;
```

To be defined by the user!

➔ V6.501.seq

```
REAL CONST l.MBAS = 5.3;
REAL CONST l.MBCS = 12.5;

//---------------------- SOLENOID      --------------------------------------------
mbas: solenoid, l:= l.mbas/2, ks:= abas;
mbcs: solenoid, l:= l.mbcs/2, ks:= abcs;

//------------------------- LHC SEQUENCE              -------------------------
LHCB1 : SEQUENCE, refer = CENTRE, L = LHCLENGTH;
IP1:OMK,              AT= pIP1+IP1OFS.B1*DS;
  mbas.r1:mbas,         at=  1.325+(0-IP1OFS.B1)*DS,        from= IP1;
  .
  .
  .
```

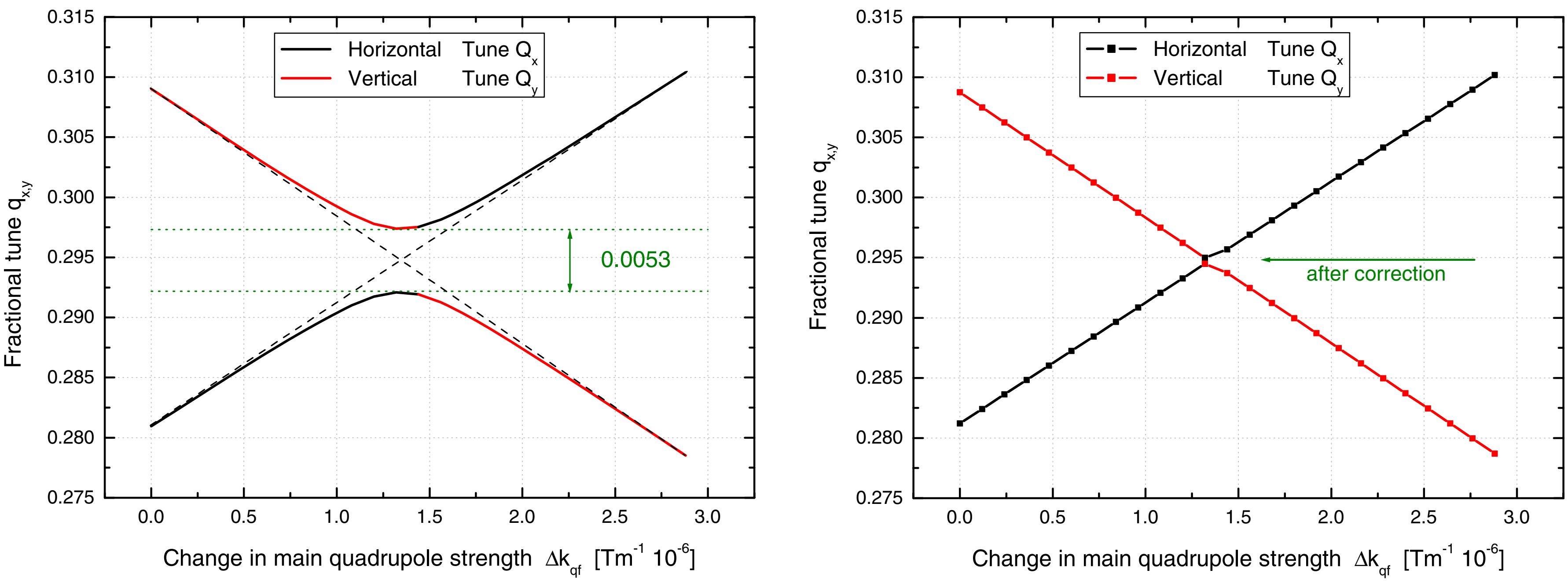
The current proposal is to put the solenoids directly into the sequence, as done by Thys for optics version V6.501.

Default: SWITCHED OFF!

Impact of experimental solenoids on LHC optics
Coupling effects, closest tune, global decoupling

- Induced peak β-beating is $(\Delta\beta/\beta)_{peak}$= 0.1%. Dispersion beating below 1%. Orbit can change up to 100 μm (to be checked further???).
- Coupling effects from CMS solenoid and global decoupling with SF’s algorithm (all skew quadrupoles around the machine are used)
- Local compensation is not possible (only 1 skew quadrupole on each side of the solenoid. Next skews are in the arcs.)

Closest Tune Scan with CMS solenoid ON
and after decoupling using global scheme by SF



Quasi-local decoupling (analytical approach)

- Coupling introduced by solenoids can be compensated using skew quadrupoles.
- In general 4 skew quadrupoles on each side of the solenoid are needed for the compensation to work.

Complex coupling coefficient

$$c_{skew}^{\pm} = \frac{1}{2\pi}\sqrt{\beta_x \beta_y}\cdot k_s \cdot e^{i\left[\mu_x \pm \mu_y\right]}$$

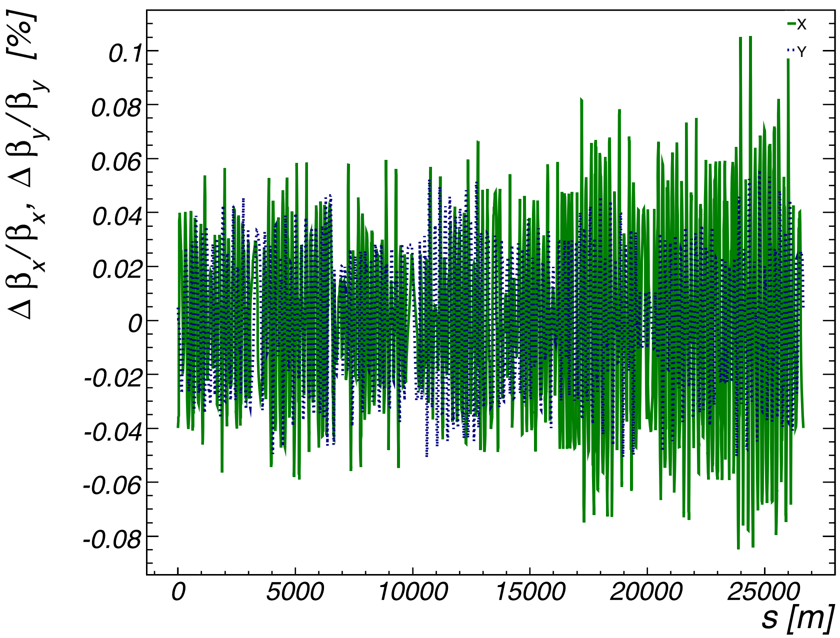
- 4 linear equations have to be satisfied in order to decouple the machine:

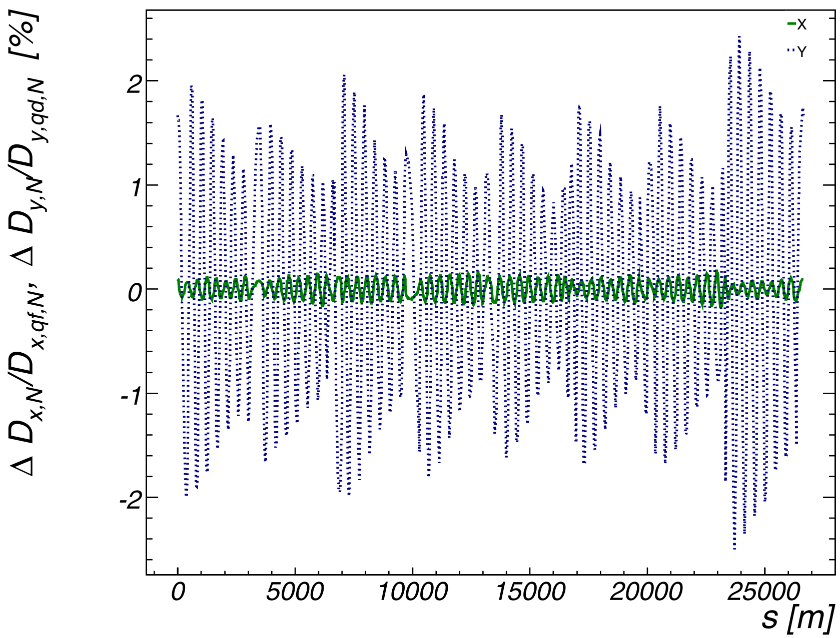
$$\sum_m c_{skew}^{+} = \sum_m \frac{1}{2\pi}\sqrt{\beta_x^m \beta_y^m}\cdot k_s^m \cdot e^{i\left[\mu_x^m + \mu_y^m\right]} = c_{sol}^{+}$$

$$m = 1, \ldots, 4$$

$$\sum_m c_{skew}^{-} = \sum_m \frac{1}{2\pi}\sqrt{\beta_x^m \beta_y^m}\cdot k_s^m \cdot e^{i\left[\mu_x^m - \mu_y^m\right]} = c_{sol}^{-}$$

- Standard optics
  - β-beating smaller 0.1%
  - Dispersion beating smaller than 1%

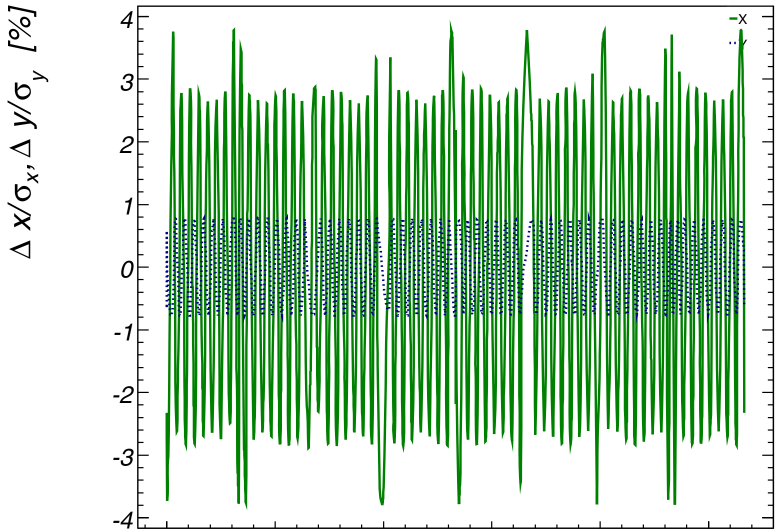


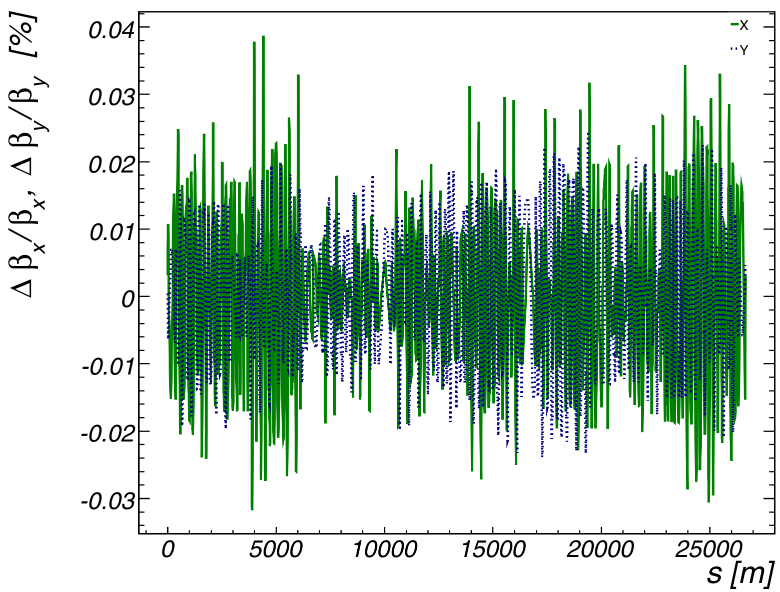


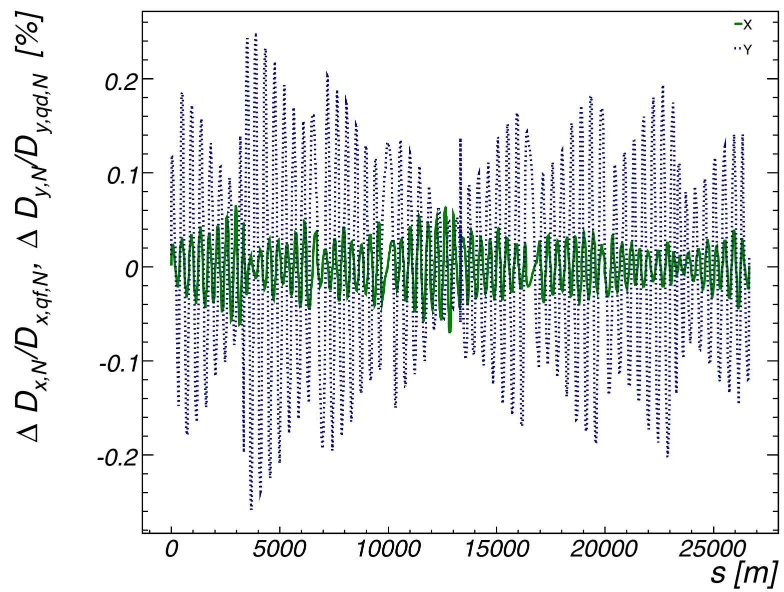
- *Results for 450 GeV collision optics under discussion*
  - Pre-squeezed injection optics (β* = 11m)
  - Squeezed (round beam) optics (β* = 6m)
  - Squeezed (flat beam) optics (β* = 6/3.7m)

Impact of experimental solenoids on LHC optics
Pre-squeezed injection optics ($\beta^* = 11m$)

- ➔ β-beating smaller than 0.1%
- ➔ Dispersion beating smaller 0.25%
- ➔ Orbit excursion changes smaller than 60μm, occurring in quadrupoles; this is less than 4% expressed in σ_{beam} (beam separation turned ON in all IPs)



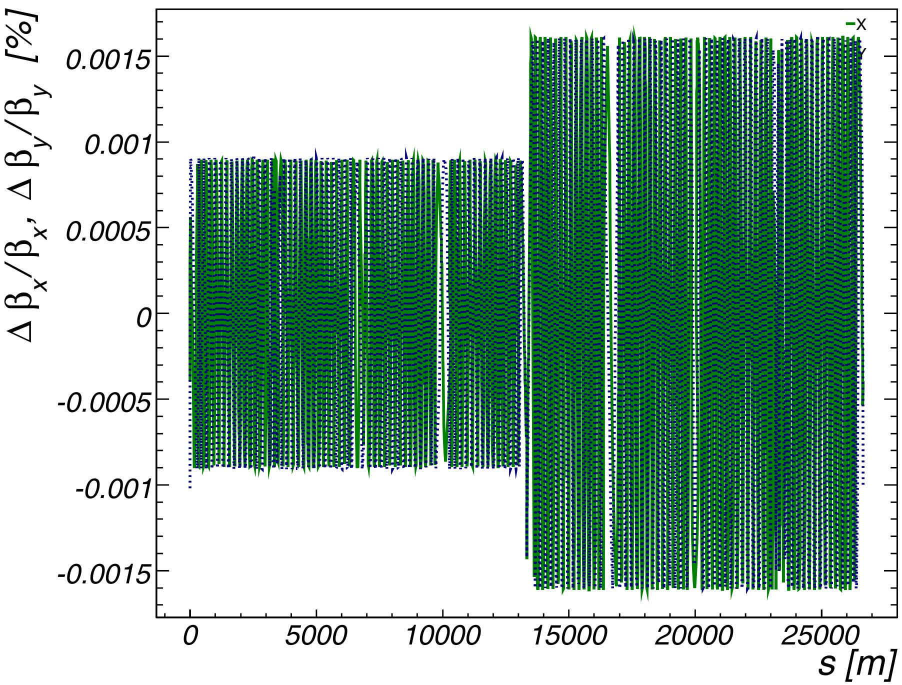


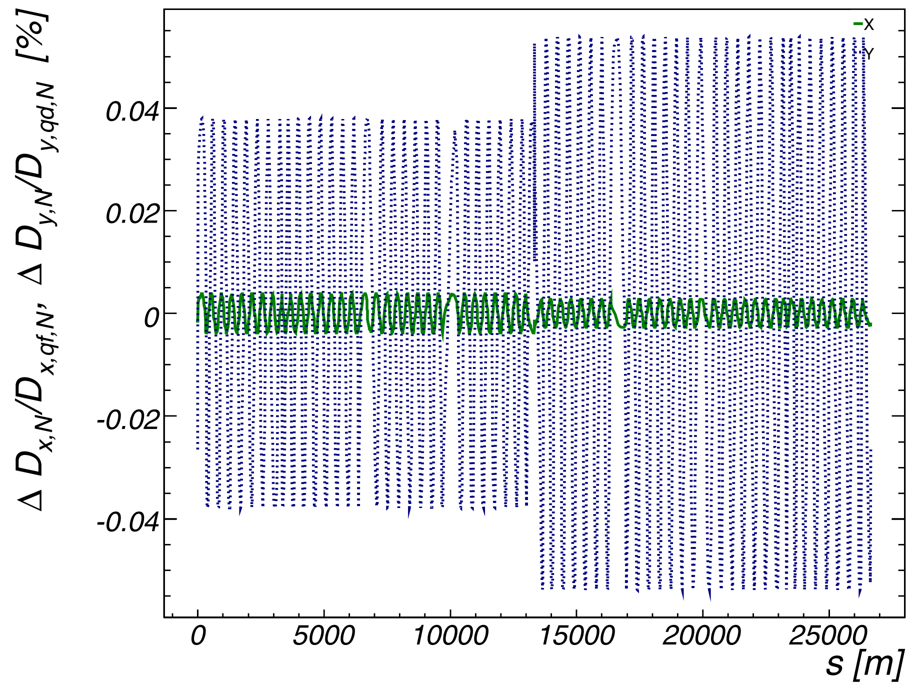


Additions as after the meeting.

Impact of experimental solenoids on LHC optics
Squeezed (round beam) optics (β = 6m)*

- β-beating negligible
- Dispersion beating negligible
- No orbit changes visible (separation bumps turned OFF)

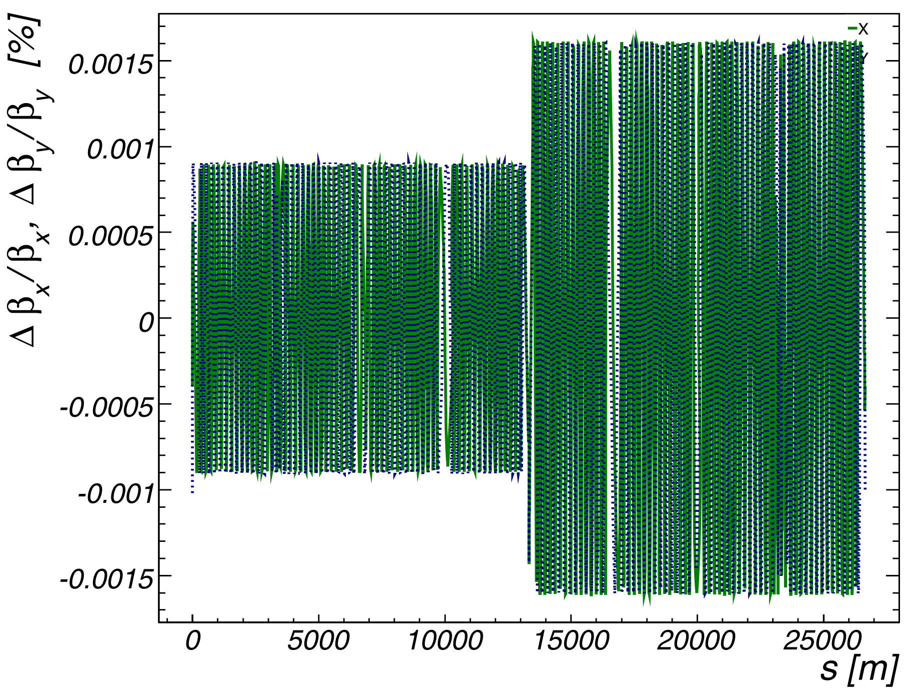


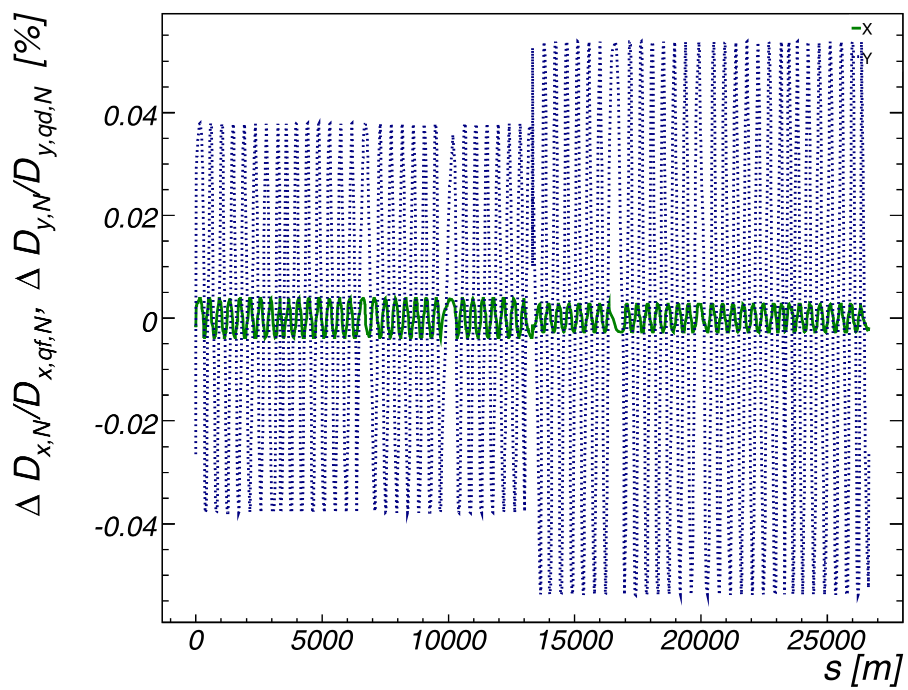


Additions as after the meeting.

Impact of experimental solenoids on LHC optics
Squeezed (flat beam) optics (β^* = 6/3.7m)

- ➔ β-beating negligible
- ➔ Dispersion beating negligible
- ➔ No orbit changes visible (separation bumps turned OFF)





Additions as after the meeting.

Conlusions

- Effect of solenoids small
- Transverse betatron coupling small
- β-beating negligible
- Dispersion beating negligible
- Orbit changes negligible

- Coupling compensation can be done globally if needed

Additions as after the meeting.