The effects of solenoids and dipole magnets of LHC experiments

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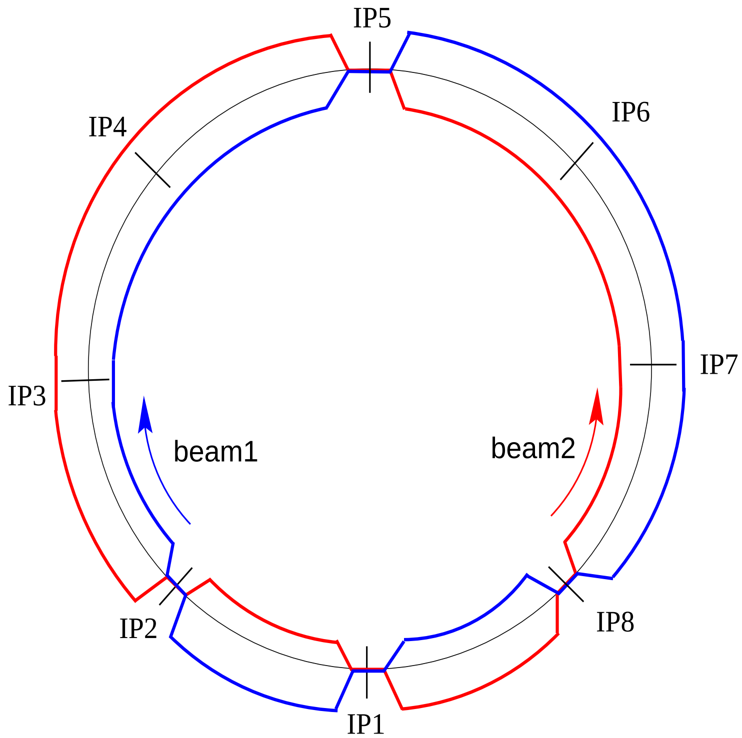
AB/ABP

Layout of experiments at LHC



IP1: ATLAS

IP2: ALICE

IP5: CMS / TOTEM

IP8: LHCb

Standard running conditions

- Two high luminosity experiments (ATLAS, IP1) and (CMS, IP5)
- B-physics with lower luminosity and asymmetric IP (LHCb, IP8)
- Heavy ions (ALICE, IP2), offset beams with p-p collisions
- Vertical crossings in IP1 and IP2
- Horizontal crossings in IP5 and IP8

Experimental Magnets

ATLAS: toroids plus solenoid

CMS: solenoid

ALICE: L3 solenoid plus dipole

LHCb: dipole

Relevant: *significant* fields near beam axis

Experimental Magnets

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Effects on Beam Dynamics

- **Solenoids:**
  - → Coupling
  - → Focusing
  - → Orbit effects (crossing angle)
- **Dipoles:**
  - → Orbit distortion
  - → Separation at collision point

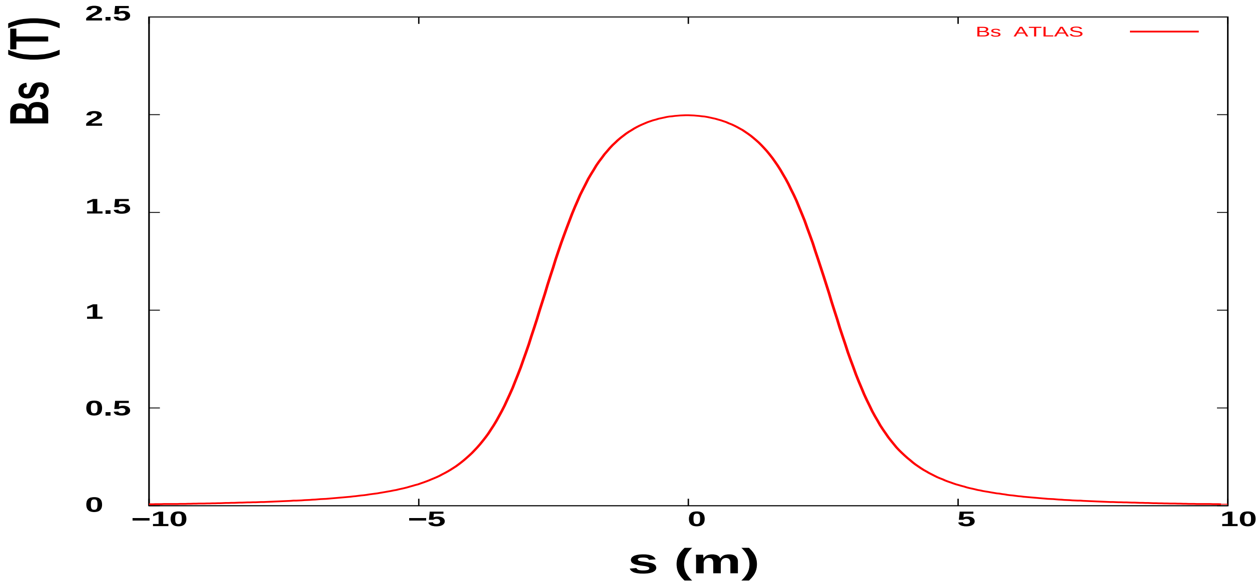
Solenoid fields:

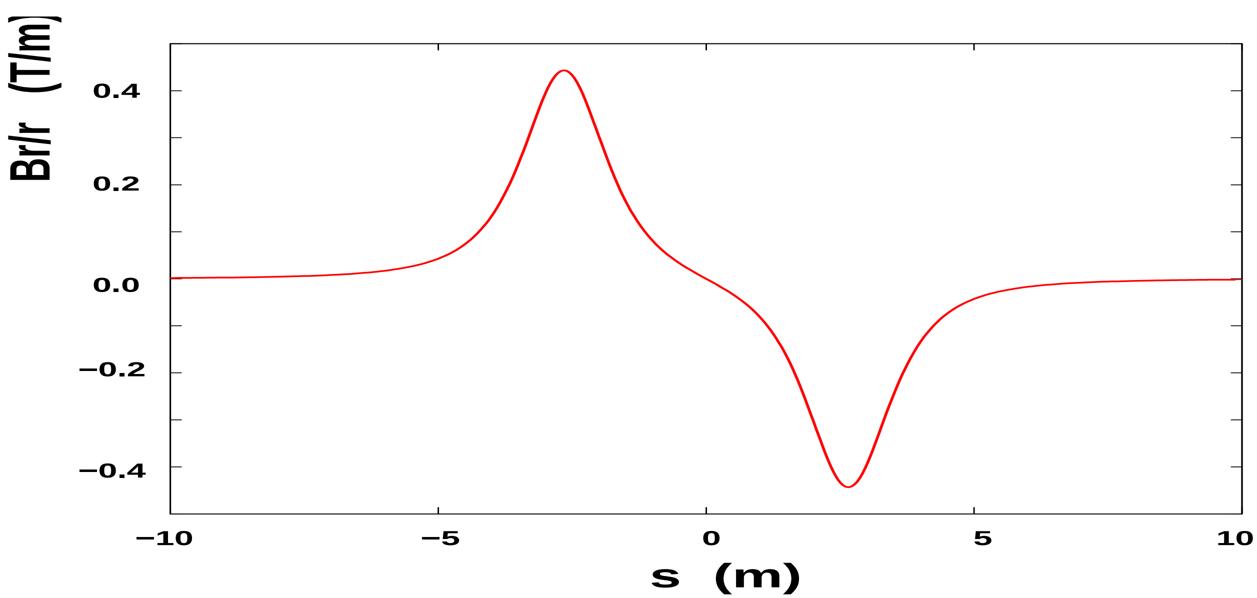
- Cylindrical coordinates (r, ϕ, $s = z$)
- Longitudinal (B_s) and radial (B_r) fields

- B_s parallel to beam axis
- $B_r = -\frac{1}{2}B'_s \cdot r$ important for focusing
- $B_\phi = 0$

Parameters Solenoids (ATLAS)

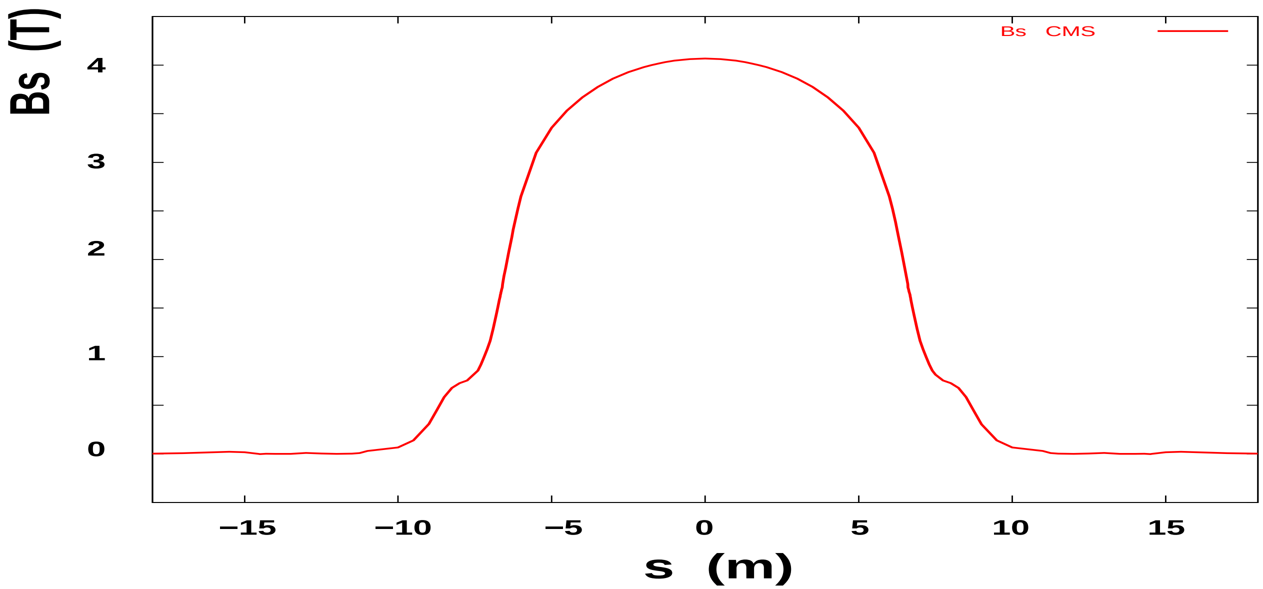
- **Length: $\approx$ 5.3 m**
- **Maximum field: 2 T**
- $\int \mathbf{B}_s\ \mathbf{dl} \approx \mathbf{11.5\ Tm}$
- $\mathbf{B}_r \leq \mathbf{5} \times \mathbf{10}^{-4}$ **T at 1 mm from axis**

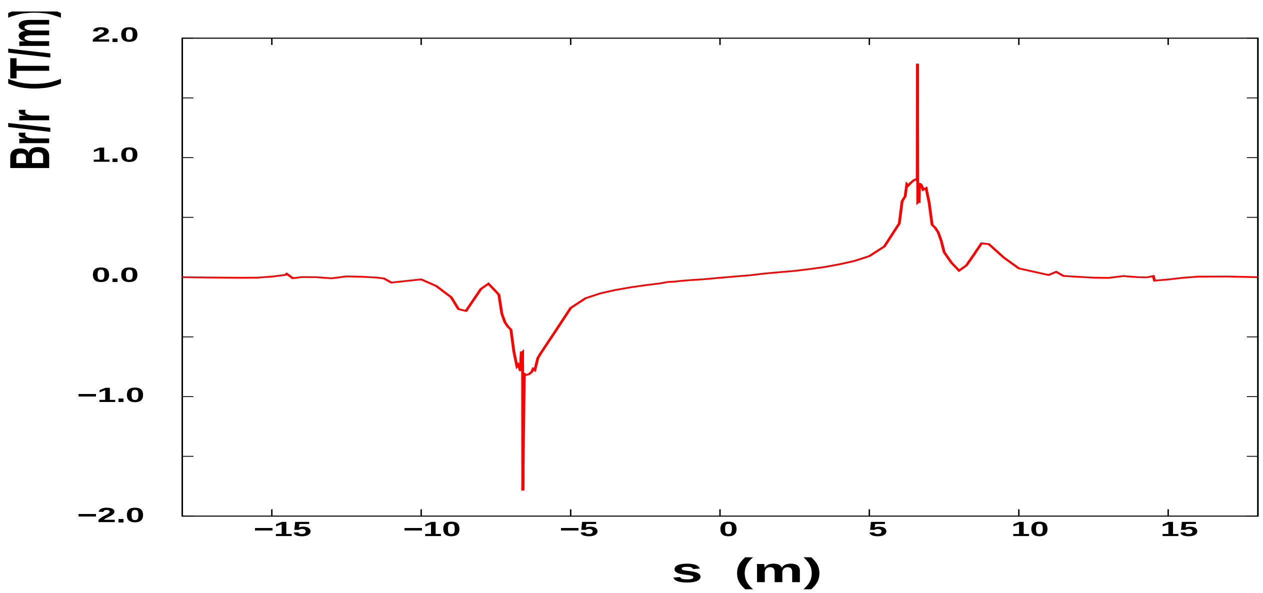

Bs (T)
Bs ATLAS
2.5
2
1.5
1
0.5
0
−10
−5
0
5
10
s (m)

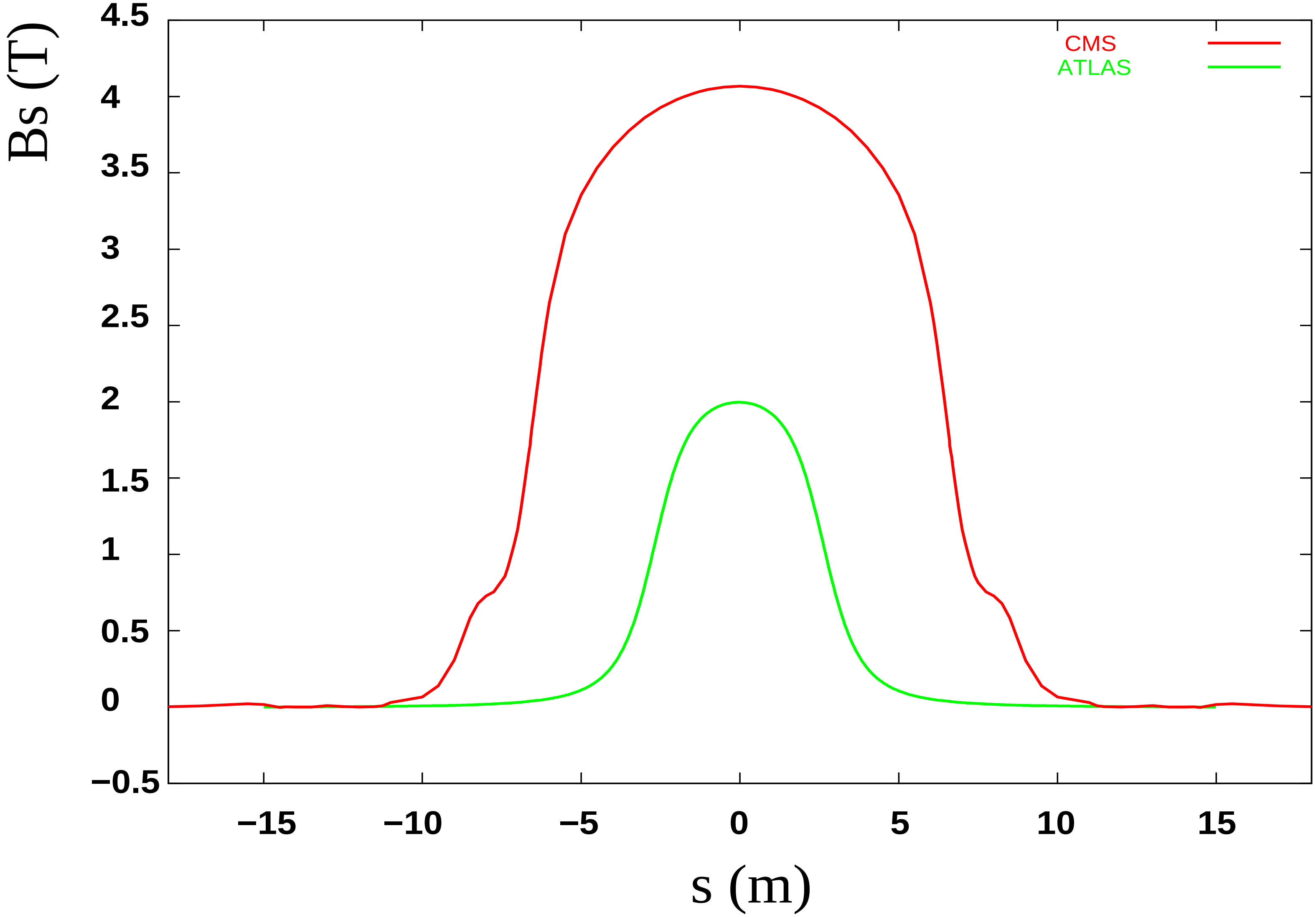

Br/r (T/m)
0.4
0.2
0.0
−0.2
−0.4
−10
−5
0
5
10
s (m)

Parameter Solenoids (CMS)

- Length: $\approx$ 13.2 m
- Maximum field: 4 T
- $\int B_s\, dl \approx 52$ Tm
- $B_r \leq 20 \times 10^{-4}$ T at 1 mm from axis


Bs (T)
Bs CMS
4
3
2
1
0
−15
−10
−5
0
5
10
15
s (m)


Br/r (T/m)
2.0
1.0
0.0
−1.0
−2.0
−15
−10
−5
0
5
10
15
s (m)


Bs (T)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
CMS
ATLAS
−15
−10
−5
0
5
10
15
s (m)

Solenoid Beam Dynamics

Equations of motion (linear part):

$$x'' = +\frac{e}{cp} B_s \cdot y' + \frac{1}{2} \cdot \frac{e}{cp} B_s' \cdot y$$

$$y'' = -\frac{e}{cp} B_s \cdot x' - \frac{1}{2} \cdot \frac{e}{cp} B_s' \cdot x$$

Solenoid coupling:

→ **Change of coordinate depends only on coordinates in other plane**

Solenoid Coupling (1)

Solenoid contribution to coupling:

$$\Delta c^{\pm} \;=\; -\,i\,\frac{B_s L}{4\pi B\rho}\left(\sqrt{\frac{\beta_y^*}{\beta_x^*}} \;\mp\; \sqrt{\frac{\beta_x^*}{\beta_y^*}}\right)$$

Round beams: $\beta_x^* \;=\; \beta_y^* \quad \rightarrow$

$$\Delta c^{+} \;=\; 0 \quad \text{and} \quad \Delta c^{-} \;=\; -\,i\,\frac{B_s L}{2\pi B\rho}$$

Solenoid Coupling (2)

ALICE $\rightarrow$ negligible

ATLAS $\rightarrow$ negligible

CMS $\rightarrow \Delta c^{-} \approx$ -5.5i $\times$ 10^{-3} (full field at 450 GeV/c)

Total allowed $\rightarrow |c^{-}| \ll$ 0.03 (450 GeV/c)

- **Relevant at injection energy**
- **Global coupling will be compensated**
- **Round beams: local coupling should not be a problem (→)**

Solenoid orbit effects

Equations of motion (linear part):

$$x'' = +\frac{e}{cp}B_s \cdot y' + \frac{1}{2} \cdot \frac{e}{cp}B_s' \cdot y$$

$$y'' = -\frac{e}{cp}B_s \cdot x' - \frac{1}{2} \cdot \frac{e}{cp}B_s' \cdot x$$

Solenoid orbit effects:

- **deflection due to crossing angle**
- **orbit distortion in other plane**

Solenoid orbit effects

- **At injection: peak $\leq$ 0.20 mm (CMS)**
- **At top energy very small: peak $\ll$ 20 μm**
- **The same for all bunches:**
  - → **No orbit spread introduced**
  - → **Can be corrected locally, with few correctors, should be no problem**
- **For small number of bunches and TOTEM, no issue (zero crossing angle)**

Operational Parameters Dipoles

ALICE:

$\approx$ 10 m right of interaction point 2

B_y =0, $\int B_x$ dl = 3 Tm

$\rightarrow$ $\approx$ 130 μrad vertical deflection

LHCb:

$\approx$ 5 m right of interaction point 8

B_x =0, $\int B_y$ dl = 4.2 Tm

$\rightarrow$ $\approx$ 180 μrad horizontal deflection

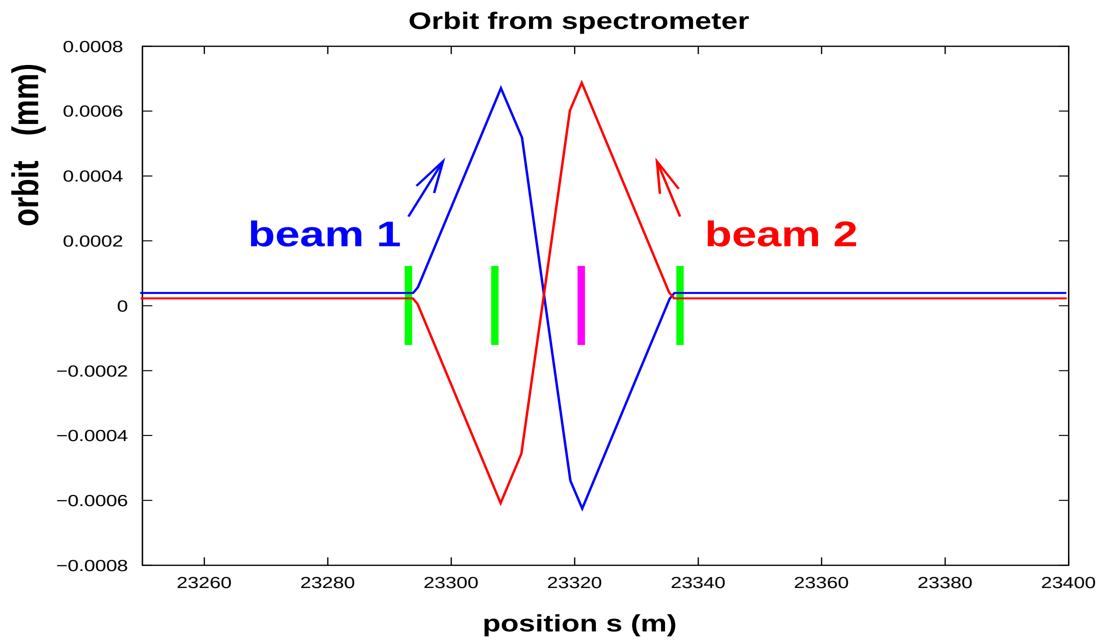
ALICE spectrometer dipole ....

LHCb dipole ....

Orbit and Compensation in ALICE

- Dipole compensated using 3 magnets around IP

→ Crossing angle of $\mp$ 70 μrad in vertical plane



Orbit and Compensation in ALICE

- Dipole compensated using 3 magnets around IP
- Crossing angle of $\mp$ 70 μrad in vertical plane

➞ Additional beam separation (crossing angle) added in vertical plane, makes the effective crossing angle $\mp$ 150 μrad

➞ Change of polarity: additional angle changes sign, no problem, effective crossing angle $\pm$ 150 μrad

Operational issues ALICE

- **Proton operation:**
  - **Offset beams to reduce interaction rate**
  - **Maximum β^* limited to: 35 m $\geq$ β^***
- **Ion operation:**
  - **Larger bunch spacing and low intensity**
  - **Effective crossing angle can be zero**
- **Magnet should be ramped with beam energy and controlled by machine operation**

Orbit and Compensation in LHCb

- Dipole compensated using 3 magnets around IP

→ Crossing angle of $\mp$ 135 μrad in horizontal plane

- Additional beam separation (crossing angle) added in horizontal plane
- Complication: inside and outside beams also cross horizontally

Orbit and Compensation in LHCb

- **Polarity change NOT transparent:**
  - → **Additional angle cannot change sign: wrong sign causes 2 additional crossings**
  - → **Only one sign of (effective) crossing angle possible ($\mp$)**
  - → **Full (effective) crossing angle depends on polarity ($\mp$ 75 μrad versus $\mp$ 200 μrad)**

Alternatives ?

- Crossing in both planes would make it transparent (vertical crossing added)
- Dipole polarity change would require no change to machine settings
- Absolute value of effective crossing angle independent of dipole polarity

→ Not possible due to hardware constraints

→ Not for minimal LHC

Other issues LHCb (1)

- β^* tuning to maintain $\mathcal{L} \geq 10^{32}$ cm^{-2}s^{-1}
- Constraints:
  - Required beam separation and crossing
  - Magnetic strength
  - Aperture

$\Longrightarrow$ possible for the range: 2 m $\leq \beta^* \leq$ 10 m (both polarities)

$\Longrightarrow$ present scenario fulfills the requirements

Other issues LHCb (2)

- Full spectrometer field at injection ?
- Only feasible for one of the polarities
- But: malfunction at injection could become dangerous

→ For crossing in both planes not (yet) excluded

→ Strongly recommended to ramp with beam energy and controlled by machine operation

Experimental magnets in computations

A: dipoles

- Dipoles in IP2 and IP8 included in model
- Compensation dipoles in IP2 and IP8
- Always considered in matching and simulations
- Optics for all polarities and β^* available

Experimental magnets in computations

B: solenoids

- Presently being implemented into MAD-X for computations and tracking (H. Burkhardt, A. Koschik)
- Effects included in matching
- Can/should we correct coupling locally ?

SUMMARY

- Effects of solenoids and dipoles are known (Maxwell was right)
- Effects included in machine model
- They present no conceptual problem
- Mostly important at injection energy

→ Procedures for their operation need to be established (on/off, ramping, interlocks, ...)

→ Present scenario compatible with requirements