The effects of solenoids and dipole magnets of LHC experiments

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Abstract

The LHC experiments are equipped with solenoids or spectrometer magnets. Both types affect the beam dynamics or constrain the choice of the optical configurations. The implications are estimated and possible limitations are discussed. The present working scenario is presented and its flexibility is subjected to a critical assessment.

EXPERIMENTAL AREAS AND MAGNETS

The layout of the LHC features 4 experimental areas where beams collide (Fig. 1) [1]. In all four areas the beams exchange between the inner and outer vacuum chambers and cross at a finite angle to avoid unwanted collisions. The main features of the four experiments are:

- Two high luminosity experiments (IP1 and IP5) with low $\beta^*$.  
- B-physics with lower luminosity and asymmetric IP (LHCb, IP8).  
- Heavy ion experiment (ALICE, IP2), offset beams with p-p collisions.  
- Vertical beam crossing in IP1 and IP2.  
- Horizontal beam crossing in IP5 and IP8.

The interaction point 5 (CMS) also houses the TOTEM experiment, which is designed to measure small angle scattering and requires dedicated running conditions, such as large $\beta^*$ and no crossing angle. This implies operating with a much smaller number of bunches, i.e. maximum 156 bunches [2].

In all four experiments magnets are installed:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>barrel and encap toroids and central solenoid</td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>solenoid</td>
<td></td>
</tr>
<tr>
<td>ALICE</td>
<td>solenoid (L3) and dipole spectrometer</td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>dipole spectrometer</td>
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</table>

Only magnets which provide a significant magnetic field near the beam axis can influence the circulating beams, therefore the ATLAS toroids and the ALICE solenoid (too weak) can be omitted in the further studies. The main purpose of this study is to estimate the expected effects and to evaluate whether a correction is necessary. Possible corrections are proposed. Since some of the magnets are required to be operated at full field at all times, special emphasis has to be on the operation during the injection when the beam energy is small.

EXPERIMENTAL SOLENOIDS

To evaluate the effects of solenoid magnets, it is useful to use cylindrical coordinates $(r, \phi, z = s)$. Solenoid magnets provide a magnetic field parallel to the beam axis ($B_z$). Where this longitudinal field varies (e.g. fringe fields) a radial field component ($B_r$) is present. This field component is responsible for the focusing properties of a solenoid magnet.

This radial field component can easily be derived and is proportional to the change of the longitudinal field times the radial distance:

$$
B_r = -\frac{1}{2} \frac{\partial B_z}{\partial s} \cdot r = -\frac{1}{2} B'_z \cdot r \quad (1)
$$

The azimuthal field component vanishes for a completely symmetric solenoid:

$$
B_\phi = 0 \quad (2)
$$

For the motion of charged particles in a solenoid it is therefore sufficient to consider the longitudinal field component $B_z$ and its derivative $B'_z$ with respect to the longitudinal coordinate $s$.

Solenoid properties

ALICE solenoid

The ALICE solenoid has been used in the L3 experiment at LEP. The maximum field is $\approx 0.5$ T and it can be neglected.

ATLAS solenoid

The ATLAS solenoid magnet has a magnetic length of $\approx 5.3$ m and a maximum field of 2 T. The integrated field $\int B_z \, ds$ is $\approx 12$ Tm. The maximum radial field is about $B_{r,\text{max}} \approx 5 \times 10^{-4}$ T.
at 1 mm from the axis. The field components along the beam axis are shown in Fig. 2 [3].

Figure 2: ATLAS solenoid field properties.

CMS solenoid

The CMS solenoid magnet has a magnetic length of \( \approx 13.2 \) m and a maximum field of \( 4 \) T. It is therefore significantly stronger than the ATLAS solenoid. The integrated field \( \int B_s \, ds \approx 52 \) Tm.

The maximum radial field is about \( B_r^{\text{max}} \approx 20 \times 10^{-4} \) T at 1 mm from the axis.

The field components as a function of \( s \) are shown in Fig. 3 [4]. Due to the long ramping time of the CMS solenoid, it will be at full field at all times.

Figure 3: CMS solenoid field properties.

Solenoid focusing

From (1) we know that \( B_r \propto r \), therefore the focusing of a solenoid is the same in both planes. The effect in the LHC is small and can easily be corrected, if required.

Solenoid coupling

From the equations (3) and (4) the strong coupling from a solenoid becomes obvious: the variation of a coordinate in one plane depends only on the coordinates of the other plane. The contribution of a solenoid to the coupling can be computed in terms of the coupling coefficients \( c^{\pm} \) [5]. The contributions \( \Delta c^{\pm}_s \) of the solenoid to the coefficients are then:

\[
\Delta c^{\pm}_s = -i \frac{B_s L}{4 \pi B \rho} \left( \sqrt{\frac{\beta_y^{\pm}}{\beta_x}} \pm \sqrt{\frac{\beta_x^{\pm}}{\beta_y}} \right) \tag{5}
\]

For round beams we have \( \beta_x^{\pm} = \beta_y^{\pm} \) and therefore:

\[
\Delta c^{+}_s = 0 \quad \text{and} \quad \Delta c^{-}_s = -i \frac{B_s L}{2 \pi B \rho} \tag{6}
\]

For the CMS solenoid at full field at 450 GeV/c we get \( \Delta c^{-}_s \approx -5i \times 10^{-3} \). This should be compared to the tolerances of \( |e^{-}| \ll 0.03 \) (at 450 GeV/c) and \( |e^{-}| \ll 0.01 \) (at 7 TeV/c) [1]. The contribution is therefore relevant when the solenoid is at full field at injection. The contribution to the global coupling will be corrected at injection energy. Whether a local compensation is possible and useful is under study [6].
Solenoid orbit distortions

From the equations (3) and (4) one can easily derive the orbit distortions produced by a solenoid. Particles traveling parallel to the solenoidal fields experience no force, however traversing a solenoid with a finite angle \( x' \) or \( y' \) produces an orbit deflection into the other plane (equations (3) and (4)). Since in the experimental regions of ATLAS and CMS the beams cross at an angle to avoid parasitic beam-beam interactions, a small orbit distortion is produced by the solenoids.

At injection the crossing angles are ± 160 \( \mu \)rad in both, CMS and ATLAS. The CMS solenoid gives a vertical deflection of \( \approx 5 \) \( \mu \)rad to the beam which produces a closed orbit distortion of about 0.1 mm r.m.s. around the ring. This distortion should be corrected at injection while at top energy the effect can be ignored. A local correction with a small number of correctors around the interaction region is possible and recommended. Assuming the optics squeeze of the \( \beta^* \) is performed at top energy, this correction can be static and computed for the injection optics.

The effect of the ATLAS solenoid on the closed orbit can be neglected. During the early commissioning and for dedicated running conditions (e.g. TOTEM) the crossing angles will be zero and no orbit distortion is produced by the solenoids.

EXPERIMENTAL DIPOLES

In the interaction regions 2 (ALICE) and 8 (LHCb) strong dipole magnets are installed as spectrometers. These dipoles are close to the interaction region and act on both beams simultaneously.

Dipole properties

ALICE:
The ALICE spectrometer dipole is positioned approximately 10 m to the right of the interaction point 8 and the integrated field is \( \int B \, dl = 3 \) m which produces a deflection of \( \approx 130 \) \( \mu \)rad deflection at top energy of 7 TeV. The field direction is in the horizontal plane and the deflection therefore in the vertical plane.

LHCb:
The LHCb spectrometer dipole is positioned approximately 5 m to the right of the interaction point 2 and the integrated field is \( \int B \, dl = 4.2 \) Tm which produces a deflection of \( \approx 180 \) \( \mu \)rad deflection at top energy of 7 TeV. The field direction is in the vertical plane and the deflection therefore in the horizontal plane.

DIPOLAR EFFECTS

Since the dipoles act on both beams simultaneously, they would create a strong orbit distortion around the machine for both beams. Their effects must therefore be compensated exactly to avoid loss of aperture or beam offsets at any of the collision points. This compensation is provided by 3 dedicated magnets which, together with the spectrometer magnets, produce a closed, antisymmetric bump. Since no other active elements are inside these bumps, the compensation is independent of the optics.

However, since they act on both beams, they produce crossing angles of ± 70 \( \mu \)rad in ALICE and ± 135 \( \mu \)rad in LHCb. This is shown for one case in Fig. 4. All numbers and Fig. 4 correspond to top energy.

The bump produced by the dipole and its compensators is short and to minimize unwanted long range beam-beam interactions, an additional (external) crossing angle is superimposed [2, 7]. In the base-line design [1] these external angles are vertical (ALICE) and horizontal (LHCb), i.e. they follow the crossing planes given by the dipole magnets. The effective crossing angles are therefore different from the values quoted above and depend on the running conditions [2].

Operational issues in ALICE

The ALICE experiment is designed for ion collisions and cannot take to full interaction rate of proton-proton collisions. In order to reduce the luminosity, the beams collide with a small offset. Decreasing the luminosity by increasing the \( \beta^* \) function at the interaction point is limited, since for \( \beta^* \leq 35 \) m a sufficient separation of the beam-beam encounters is not possible for the regular bunch spacing of 25 ns.

The intensity for operation with ions is much lower and the bunch spacing is larger, therefore long range beam-beam interactions can be neglected. It is possible to reduce the effective crossing angle or set it to zero by superimposing an external angle with the opposite sign of the crossing angle caused by the dipole magnet.

Polarity changes

It is foreseen to change the polarity of the spectrometer dipole on a regular basis. Since the crossing in IP2 is in the vertical plane, this can be achieved by changing the sign of the external angle together with...
the polarity. The effective crossing angle between the two beams changes sign but its absolute value does not change. The base-line running conditions for interaction point 2 are summarized in Tab. 1 [1, 2].

<table>
<thead>
<tr>
<th>Spectrometer</th>
<th>$\beta_{x,y}$ (m)</th>
<th>$\alpha_x$ (µrad)</th>
<th>$\alpha_x$ (µrad)</th>
<th>$\alpha_{eff}$ (µrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>10.0</td>
<td>±70.0</td>
<td>±80.0</td>
<td>±150</td>
</tr>
<tr>
<td>+</td>
<td>10.0</td>
<td>±70.0</td>
<td>±80.0</td>
<td>±150</td>
</tr>
</tbody>
</table>

Table 1: Required crossing angle scheme for interaction point 2 for different spectrometer polarities. The angles $\alpha_x$, $\alpha_x$ and $\alpha_{eff}$ denote the angle from the dipole, the external angle and the effective crossing angle. The convention is upward deflection for positive angle and $\mp$ denotes negative angle for beam 1 and positive angle for beam 2.

**Operational issues in LHCb**

The design luminosity for interaction point 8 (LHCb) is lower than for ATLAS and CMS ($\mathcal{L} \approx 2.0 \times 10^{32}$ cm$^{-2}$s$^{-1}$) but it is required to keep it above $\mathcal{L} \geq 1.0 \times 10^{32}$ cm$^{-2}$s$^{-1}$ during data taking or in case of low intensity beams by an adjustment of $\beta^*$. Furthermore, it is required to regularly change the polarity of the dipole.

**Polarity changes** The conditions in interaction point 8 show one important difference to point 2: the crossing is in the horizontal plane. In interaction point 8 the beams exchange from the outer to the inner vacuum chamber (beam 1) and vice versa in the horizontal plane. In order to avoid additional crossings [2] the sign of the effective crossing angle cannot change. When the crossing angle of the dipole $\alpha_x$ has the 'wrong' sign, this requires an overcompensation with the external angle and: $\alpha_x \gg \alpha_s$. As a result the change of polarity of the dipole magnet is not transparent for the operation and results in a different absolute value for the effective crossing angle, depending on the polarity of the spectrometer dipole.

The present base-line configuration is given in Tab. 2 [1, 7]. Using the standard convention, it shows in Tab. 2 that the sign of the crossing angle does not change the sign for changed dipole polarity, contrary to the situation in ALICE (Tab. 1).

The negative sign of the spectrometer dipole in Tab. 2 refers to the sign of the crossing angle for beam 1 and implies a dipole field that deflects the beam 1 to the outside (see Fig. 4).

**Luminosity adjustment** To maintain a luminosity $\mathcal{L} \geq 10^{32}$ cm$^{-2}$s$^{-1}$ requires the tuning of $\beta^*$. Limits to the available tuning range come from:

- Required beam separation and crossing
- Available magnetic strength (corretors for crossing angle)
- Mechanical aperture

It was found [2, 7] that $\beta^*$ can be adjusted in the range: $2 \text{ m} \leq \beta^* \leq 10 \text{ m}$ for both polarities of the dipole magnet. The effective crossing angles will be different when $\beta^*$ is changed [2].

For the assumed intensities, including the LHC commissioning parameters, these options ensure a luminosity $\mathcal{L} \geq 10^{32}$ cm$^{-2}$s$^{-1}$. The present base-line scenario is therefore compatible with the requirements.

**Injection field** The full field of the dipole (and its compensators) at injection energy produces a rather large angle ($\mp 2.1$ mrad !). While it can be considered for one of the polarities ($-$), such an angle cannot be overcompensated by an external crossing angle due to the limited aperture for the other polarity ($+$) since it would require $\alpha_x \gg \alpha_s = \mp 2.1$ mrad. This polarity is therefore excluded. It is recommended that the dipole is always (for both polarities) ramped with the energy, together with its compensator magnets.

**Crossing in two planes**

The limitation for the polarity change in IP8 is mainly due to the external angle which is in the horizontal plane. Its sign is fixed to avoid additional crossings between the two beams. Since in IP8 the beam 1 crosses from outside to the inside vacuum chamber, (see Fig. 1) its crossing angle must always be negative (Tab. 2). A positive crossing angle from the spectrometer must therefore be overcompensated by a large negative external angle [2]. This restriction does not exist when the external crossing angle is in the vertical plane [7] like in IP2 (ALICE) or IP1 (ATLAS). The consequence of a vertical external crossing
angle would be that the effective crossing plane is tilted where the beams collide. Crossing in the two planes simultaneously was already considered previously [8] for the high luminosity interaction regions to reduce the long range beam-beam effects. Horizontal and vertical external angles would reduce the long range tune spread, but cause transverse coupling and this option was discarded. However, this proposed type of crossing scheme in interaction point 8 is rather different from these earlier deliberations because:

- External crossing angle only in one plane.
- Tilted crossing plane produced locally by spectrometer arrangement.
- Only very few long range interactions occur in the tilted crossing plane.
- These few long range interactions near the interaction point occur at very large normalized separation and can be ignored.

The option to cross at a finite angle in the $x - y$ plane has advantages for the experiment as well as for the accelerator operation [7]:

- External crossing angle decoupled from dipole polarity.
- Dipole polarity change does not require change of external crossing angle.
- Absolute value of effective crossing angle independent of dipole polarity.
- Simplified operation and setting up of injection.

What needs to be clarified is whether or not it is acceptable for the experiment to have an effective crossing plane different from the x-y plane. To allow for a vertical external crossing angle, the orientation of the beams screen needs to be modified which for the start of the LHC is excluded.

It is further necessary to study possible side effects and implications for injection, protection etc. Should it be found that this option is superior to the present scenario, it should be considered for the future.

**SUMMARY**

It can be summarized that the experimental magnets do have noticeable effects on the beam. Corrections are required for some modes of operation. The basic results are:

- Only solenoids in IP1 and IP5 and the dipoles in IP2 and IP8 have to be considered.
- The coupling and orbit effects of the solenoids are significant for IP5 and at injection energy, a correction is suggested.
- The spectrometer dipole in IP2 and IP8 need local compensation.
- Polarity changes are without problems in IP2.
- Polarity changes in IP8 require modification of the machine parameters.
- The present scenario can fulfill all the requirements, i.e. required modes of operation and luminosity.
- Possible improvements need to be studied.

**REFERENCES**