How do we have to operate the LHCb spectrometer magnet?

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Summary

The standard operational machine conditions at IP8 are first summarised. The crossing scheme angles and the corresponding terminology are explained. A strategy for the powering of the LHCb spectrometer magnet is analysed with respect to the aperture restrictions and beam-beam effects. The possible operational scenarios are proposed, in accordance with the beam dynamics constraints.

1 Standard operational machine conditions at IP8

1.1 Crossing scheme in IP8

During the 450 GeV beam injection, the energy ramping to 7 GeV and the $\beta^*$ squeeze, the beams are separated in both planes in order to avoid unwanted collisions [1, 2, 3]. The beam separation is provided by dipole correctors, acting in the desired planes. When collisions are requested, the beams are brought together at the interaction point by correct powering of the dedicated orbit correctors. In IP8, the beam crossing is performed in the horizontal plane, while during "non-collision" operation, the beams are, in addition, separated vertically.

There are constraints on the operational scenarios which are linked to the beam dynamics (e.g. beam-beam effects, beam stability...), the available physical aperture, the available magnet strengths (e.g. corrector magnets dedicated to the beam crossing scheme) [4, 5]. These constraints reduce the flexibility in terms of crossing angle sign and amplitude. The overall schematic LHC beam crossing is shown in Fig. 1. The beams cross in 1, 2, 5 and 8. Looking at IP8 from the inside of the LHC ring, it is seen that beam 1 crosses from the outside of the ring to the inside of the ring. In other words, the beam is transported towards a smaller ring radius. We adopt the convention to define the corresponding horizontal beam

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crossing angle as being *negative*. With the same assumptions, looking to the right side of IP8, the beam trajectories at IP8 are sketched in Fig. 2. The two strong trajectory kicks observed on each trajectory are provided respectively by the D1 and D2 dipole magnets. These are the separation trajectories which the two beams must follow to cross into the other beam pipe. This crossing over always happens in the horizontal plane for all interaction regions.

With nominal beam operation, 2808 bunches per beam will be injected in the LHC, separated by 25 ns (about 7.5 m). In the common vacuum chambers, if no beam separation is applied, this beam configuration will lead to beam crossings every 12.5 ns (about 3.75 m). This is illustrated in Fig. 3. In order to avoid this large number of parasitic interaction (of the order of 120 in total), it is required to separate the beam outside the central interaction point. Dipole correctors will be powered to provide the additional beam separation where required. This additional crossing scheme provides an angle which we shall call external crossing angle. At IP8, its nominal sign is *negative* for beam 1. The resulting orbits on the
right side of IP8 are shown in Fig. 4. Using the sign convention defined above, the external crossing angle shown in Fig. 4 is negative for beam 1. It is assumed that the minimum beam separation in the IP8 region should be larger than 10 \( \sigma \) in order to reduce the long-range beam-beam effects. At this stage, it is worth pointing out that changing the sign of the external crossing angle will create additional crossing points, as illustrated in Fig. 5. The reason is that such a crossing angle would imply a wrong sign for the crossover between the two beams. Therefore, the sign of the external crossing angle is fixed to negative for beam 1. This conflict can however only appear when the external angle is in the horizontal plane, i.e. the plane of the crossover. A similar constraint is imposed in the high luminosity region in interaction point 5, where the external crossing angle must be positive. However, such restrictions do not exist in interaction points 1 and 2 where the crossing plane is vertical.

Figure 3: Beam trajectories with parasitic encounters at IP8 (right side).

Figure 4: Beam orbits with negative external crossing angle.
Figure 5: Beam orbits with *positive* external crossing angle.
1.2 Spectrometer (and compensators) bump at IP8

When switched on, the LHCb spectrometer field is compensated by 3 dedicated dipole magnets [6]. The resulting effect is an antisymmetric bump, producing another crossing angle which we call internal crossing angle. The orbit bump created by the nominal negative powering of the LHCb spectrometer (and powering of the compensators) is represented in Fig. 6. The LHCb bump is horizontal. The sign convention implies that the nominal negative field powering leads to a downward field in the spectrometer [6, 7].

![Orbit from spectrometer](image)

Figure 6: Orbit bump from nominal negative powering of the LHCb spectrometer (and powering of the compensators). The longitudinal position is counted from IP1.

Quantitatively, the spectrometer adds an additional horizontal angle of $\mp 135 \ \mu\text{rad}$\textsuperscript{1} when powered with negative full field at 7 TeV (at 450 GeV, $\mp 135 \ \mu\text{rad}$ corresponds to 6.4 % of the LHCb nominal powering).

If the spectrometer is powered positively, the corresponding internal angle is represented in Fig. 7. The polarity change of the spectrometer induces a change of sign of the internal crossing angle which, in turns, will have to be overcompensated by the external crossing [7].

\textsuperscript{1} In our convention $\mp$ means negative for beam 1 and positive for beam2, $\pm$ means positive for beam 1 and negative for beam2, respectively.
Figure 7: Orbit bump from nominal positive powering of the LHCb spectrometer (and compensators).
1.3 Effective beam separation

In total, 3 angles have to be combined: angles from the orbit separation in the dipoles D1 and D2, from the external crossing scheme (created by the orbit correctors) and from the internal angle (created by the field of the spectrometer and compensators). In Fig. 8, the three angles are applied, for the negative internal angle from the spectrometer and the negative external angle. A zoom of the 20 m right of IP8 is shown in Fig. 9. The separation between the two beams is sufficient.

Figure 8: Orbits with negative internal and external crossing angles.

Figure 9: Zoom of the first 20m right of IP8 of Fig. 8.

If the spectrometer is switched on with the positive polarity and the external crossing scheme kept at nominal value, the beam orbits are represented in Fig. 10. A zoom of the beam orbits in the first 20m right of the IP8 is drawn in Fig. 11 and shows the reduced separation and the additional beam encounter, as compared to the negative nominal spectrometer powering. By increasing the external crossing angle, the effect of the positive spectrometer
bump may be compensated as seen in Fig. 12 and Fig. 13. However the required external angle is ± 210 µrad. At 7 TeV a significantly larger external angle is not possible due to the limited strength of the orbit correctors.

In Fig. 14, the beam orbits resulting from the negative and positive powering of the LHCb spectrometer are compared. Even with a much larger external angle used to compensate the positive spectrometer field, the beam separation is reduced in the range of ± 8 m around the interaction point.
Figure 12: Compensation of positive powering of the LHCb spectrometer with large negative external crossing angle.

Figure 13: Zoom of the first 20 m right of the IP8 of Fig. 12.
Figure 14: Orbits right of IP8 for a positive (dashed line) and negative (continuous line) powering of the LHCb spectrometer, with negative external angle. Note that the external angle values if different for the two LHCb powering signs.
In Tab. 1 the different crossing angle values are summarised: The effective crossing angle combines the external and internal bumps and is the angle relevant for the machine performance, i.e. the luminosity when the beams are colliding. Furthermore, in this case the effective crossing angle also determines the separation of bunch encounters within the spectrometer bump, i.e. the first few encounters from the interaction point. For separated beams, the size of the effective crossing angle is less important and a small angle can be tolerated. However, a zero angle or an angle with the opposite sign must be avoided.

<table>
<thead>
<tr>
<th></th>
<th>External crossing angle</th>
<th>Internal crossing angle (LHCb)</th>
<th>Effective angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 GeV</td>
<td>± 170 µrad</td>
<td>± 135 µrad</td>
<td>± 305 µrad</td>
</tr>
<tr>
<td></td>
<td>± 170 µrad</td>
<td>± 135 µrad</td>
<td>± 35 µrad</td>
</tr>
<tr>
<td>7 TeV</td>
<td>± 65 µrad</td>
<td>± 135 µrad</td>
<td>± 200 µrad</td>
</tr>
<tr>
<td></td>
<td>± 210 µrad</td>
<td>± 135 µrad</td>
<td>± 75 µrad</td>
</tr>
</tbody>
</table>

Table 1: Crossing angle values. Usual convention, i.e. ± means negative for beam 1 and positive for beam2, ± means positive for beam 1 and negative for beam2, respectively. Negative internal crossing angle corresponds to downward field in the spectrometer.
1.4 Commissioning machine conditions at IP8

For the purpose of machine commissioning, a reduced number of bunches per beam will be used[8]. For less than 156 bunches per beam, there will not be any parasitic encounters, and therefore no external crossing angle is required.

2 Spectrometer powering at injection

In the nominal scenario, at 450 GeV, the LHCb spectrometer is powered at 6.4% of the full field (450 GeV/7 TeV). It is then ramped with energy to 100% at 7 TeV. In the following, it is investigated whether the spectrometer could already be powered at 100% at 450 GeV [9].

2.1 Full spectrometer field at injection

In Tab. 2 the different crossing angle values are presented for the 450 GeV injection energy with 6.4% and 100% of LHCb spectrometer field.

<table>
<thead>
<tr>
<th></th>
<th>External crossing angle</th>
<th>Internal crossing angle</th>
<th>Effective crossing angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 GeV and 6.4%</td>
<td>± 170 µrad</td>
<td>± 135 µrad</td>
<td>± 305 µrad</td>
</tr>
<tr>
<td>450 GeV and 100%</td>
<td>± 170 µrad</td>
<td>± 2100 µrad</td>
<td>± 2270 µrad</td>
</tr>
<tr>
<td>7 TeV and 100%</td>
<td>± 65 µrad</td>
<td>± 135 µrad</td>
<td>± 200 µrad</td>
</tr>
</tbody>
</table>

Table 2: Crossing angle values with different LHCb spectrometer powering signs and strength.

For the commissioning scenarios with non standard operation of 43 and 156 bunches, no external crossing angle is required. Therefore, these modes of operation can, in terms of aperture and beam-beam, be performed with the LHCb spectrometer powered at 100% of its field at 450 GeV injection energy, with both polarities. For 75 ns, 50 ns, and 25 ns bunch spacing, the beams require an external crossing angle to be superimposed. In Fig. 15, the orbit of beam 1 is represented at IP8 with the LHCb spectrometer negatively powered at 100% of the field, at 450 GeV. No external crossing angle has been yet applied. It should be noted that the represented orbit bump is the result of the 4 magnet bump, extended over ±20 m, in a region where no other magnets are present.

For more than 156 bunch operation, a negative external crossing angle must be applied, as shown in Fig. 16. With a value of ± 170 µrad for the external angle, the resulting beam separation is sufficient.

The corresponding aperture around IP8 is shown in Fig. 17.
Figure 15: Beam 1 orbit at IP8 with the LHCb spectrometer switched on at 100%, 450 GeV, negative polarity, without the addition of an external crossing angle. The longitudinal position is counted from IP3.

If the spectrometer is powered positive, at 100% of the field at 450 GeV and the external crossing angle is switched on at the nominal negative value of $\mp 170 \mu$rad, the orbit for beam 1 at IP8 is represented in Fig. 18. With a value of $\mp 170 \mu$rad for the external angle, the resulting beam separation is insufficient since additional crossings must be avoided.

The external crossing angle must be increased in order to overcompensate the less desirable (positive) polarity of the internal crossing angle. The resulting orbit bump for beam 1 is represented in Fig. 19. The orbit excursion is too large and the resulting aperture is shown in Fig. 20. Not surprisingly, the aperture is down to 0 in between the triplet magnets.
Figure 16: Beam 1 orbit at IP8 with the LHCb spectrometer switched on at 100 % at 450 GeV, negative polarity, with the addition of the nominal external crossing angle.

Figure 17: Beam 1 aperture with the LHCb spectrometer switched on at 100 % at 450 GeV, negative polarity, with the addition of the nominal external crossing angle. $n1$ in units of beam size.
Figure 18: Beam 1 orbit at IP8 with the LHCb spectrometer switched on at 100 % at 450 GeV, *positive* polarity, with the addition of the nominal external crossing angle.

Figure 19: Beam 1 orbit at IP8 with the LHCb spectrometer switched on at 100 % at 450 GeV, *positive* polarity, with the addition of the large external crossing angle.
Figure 20: Beam 1 aperture with the LHCb spectrometer switched on at 100% at 450 GeV, positive polarity, with the addition of the large external crossing angle.
2.2 What can be the possible positive spectrometer field at injection?

We have evaluated which possible positive field could be applied in the LHCb spectrometer, before reaching the physical aperture. The spectrometer is first switched on at 20 % of the nominal field. The orbit of beam 1 is shown in Fig. 21. The resulting aperture for beam 1 is still not acceptable, as demonstrated in Fig. 22.

In order to find which maximum positive spectrometer field can be used, the field was scanned and the corresponding aperture was calculated. In this process the external crossing angle value was optimised to maximise the aperture. This was done mainly by using different settings for the common correctors of the type MCBX. The results are shown in Fig. 23 for two MCBX settings. We scale the external angle and compute the available aperture in units of n1. It can be seen that at an external angle scaling of 1.2 (corresponding to 8.2 % of the maximum spectrometer field), the aperture is already below 6.1. If the external crossing angle is further increased to the corrector magnet strength, the aperture of beam 1 shows a very marginal increase, as shown in Fig. 24. It is concluded that the maximum positive spectrometer field at injection is 7.5 % (vs. 6.4 % in the nominal scenario).

Figure 21: Beam 1 orbit at IP8 with the LHCb spectrometer switched on at 20 % at 450 GeV, positive polarity, with the addition of the external crossing angle.
Figure 22: Beam 1 aperture in IP8 with the LHCb spectrometer switched on at 20% at 450 GeV, positive polarity, with the addition of the external crossing angle. $n1$ in units of beam size.

Figure 23: Aperture of beam 1 as a function of the external crossing angle value for different spectrometer field. Upper curve (blue diamonds) correspond to MCBX strength of -5 $\mu$rad, lower curve (red dots) correspond to a strength of 0 $\mu$rad.
Figure 24: Aperture of beam 1 as a function of the external crossing angle value for different spectrometer field. The additional curve corresponds to the corrector magnet strength for the MCBX of -30μrad.
3 Collisions at lower energy

It has been discussed recently to have collisions at lower energies (i.e. 5 TeV) during part of the LHC commissioning period. It has been evaluated at which collision energy the full positive spectrometer field is possible. It should be remembered that without the need of external crossing angle (with less than 156 bunches), the full powering of the spectrometer magnet with both polarities is always possible in terms of beam-beam and aperture considerations.

For the evaluation of the beam-beam effects and the aperture we restrict ourselves to the positive spectrometer polarity. The reasons are mainly:

- While for small $\beta^*$ ($\leq 2$ m) the beam separation is about constant for all encounters in the drift space and scales with $\sqrt{\beta^*}$, for larger $\beta^*$ ($\geq 3$ m) mainly the few encounters closest to the central interaction point are important [10].

- As a consequence a simple scaling does not exist and the separation at each encounters must be computed explicitly.

- For the positive spectrometer polarity the separation at the encounters within the spectrometer bump is reduced.

To allow sufficient margin for the beam-beam effects, we require a minimum separation above $8 \sigma$. This is more than in the nominal case with $\beta^* = 10$ m at 7 TeV, but ensures that long range beam-beam effects from this interaction point are entirely in the shadow of the high luminosity interaction regions. We rather find the maximum crossing angle compatible with the aperture requirements.
3.1 \( \beta^* \) of 4 m, 5 TeV beams

Taking the collision energy at 5 TeV, the \( \beta^* \) was then reduced to 4 m, with full positive spectrometer field. To get sufficient separation at the first encounter an external angle of \( \mp 310 \mu \text{rad} \) can be accommodated within the aperture. The beam orbit with this new crossing angle value is shown in Fig. 25. The beam aperture was checked for collisions at 5 TeV and the results are shown for beam 1 in Fig. 26. The resulting effective crossing angle is 121 \( \mu \text{rad} \), the aperture is 7.1 \( \sigma \) and the resulting minimum beam separation is around 12 \( \sigma \). It can be concluded that under these conditions (5 TeV, 100 \% spectrometer field, both polarities), the resulting beam aperture and beam-beam effects are within requirements.

Figure 25: Beam orbit at 5 TeV, 100 \% positive spectrometer field, with \( \beta^* \) of 4 m and crossing angle of \( \mp 310 \mu \text{rad} \).

3.2 \( \beta^* \) of 3 m, 5 TeV beams

For collisions at 5 TeV, with full positive spectrometer field, the \( \beta^* \) was then reduced to 3 m. The corresponding beam orbits are shown in Fig. 27. The beam aperture was checked for collisions and the result is shown in Fig. 28. This scenario is acceptable in terms of beam-beam effects and aperture constraints.

3.3 \( \beta^* \) of 2 m, 5 TeV beams

For collisions at 5 TeV, with full positive spectrometer field, the \( \beta^* \) was then reduced to 2 m. The crossing angle has been computed (Fig. 29) and the beam aperture checked (Fig. 30). The beam separation drops at one location to 6.4 \( \sigma \), well below the requirement of 8 \( \sigma \). Therefore, the positive powering of the full spectrometer is marginal at 5 TeV for a \( \beta^* \) of 2 m. With low beam commissioning intensity, the case may be tolerable.
Figure 26: Aperture of beam 1 at 5 TeV, 100 % positive spectrometer field, with $\beta^*$ of 4 m.

### 3.4 Summary of the results for reduced collision energy and $\beta^*$ and for positive full LHCb powering

In Tab. 3, the different cases are summarised. At 5 TeV, the internal positive crossing angle (LHCb) is $\pm 189$ $\mu$rad. In the last but one column the beam separation in units of $\sigma$ is given. It assumes a bunch spacing of 25 ns, i.e. the closest encounter at 12.5 ns distance from the collision point. The last column indicates if the scheme is operational or not.

<table>
<thead>
<tr>
<th>Energy [TeV]</th>
<th>$\beta^*$ [m]</th>
<th>External crossing angle [(\mu)rad]</th>
<th>Effective angle [(\mu)rad]</th>
<th>$\sigma^*$ [(\mu)m]</th>
<th>sep ($\sigma$)</th>
<th>Y/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2</td>
<td>$\mp 250$</td>
<td>$\mp 61$</td>
<td>37.5</td>
<td>5.7</td>
<td>N</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>$\mp 280$</td>
<td>$\mp 91$</td>
<td>46.0</td>
<td>9.2</td>
<td>Y</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>$\mp 310$</td>
<td>$\mp 121$</td>
<td>53.0</td>
<td>12.5</td>
<td>Y</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>$\mp 310$</td>
<td>$\mp 121$</td>
<td>65.0</td>
<td>11.4</td>
<td>Y</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>$\mp 310$</td>
<td>$\mp 121$</td>
<td>84.0</td>
<td>9.6</td>
<td>Y</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>$\pm 210$</td>
<td>$\mp 75$</td>
<td>32.0</td>
<td>8.2</td>
<td>Y</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>$\mp 210$</td>
<td>$\mp 75$</td>
<td>39.0</td>
<td>8.8</td>
<td>Y</td>
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<tr>
<td>7</td>
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</tr>
<tr>
<td>7</td>
<td>6</td>
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<td>55.0</td>
<td>8.3</td>
<td>Y</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>$\mp 210$</td>
<td>$\mp 75$</td>
<td>71.0</td>
<td>7.0</td>
<td>Y</td>
</tr>
</tbody>
</table>

Table 3: Feasibility of various operating scenarios for full positive powering of the LHCb spectrometer.
Figure 27: Beam orbits at 5 TeV, 100 % positive spectrometer field, with $\beta^*$ of 3 m.

4 Summary

After explaining the issues relevant for the beam crossing scheme in interaction point 8, we have investigated the possible configurations compatible with the constraints from beam dynamics and operation of the machine.

The working operational scenarios at injection are:

- If no external crossing angle is required (less than 156 bunches), the LHCb spectrometer can be powered at full field for both spectrometer polarities at 450 GeV.
- In case an external crossing angle is required (more than 156 bunches), the LHCb spectrometer can be powered at full field for negative polarity. For positive polarity it must be ramped with the energy.

The working operational scenarios at collisions are:

- For $\beta^*$ 3 m or larger, collisions at 5 TeV (or more) with full spectrometer field is possible for BOTH polarities.
- For $\beta^*$ of 2 m, one beam encounter shows a beam separation much below the specified value. The case can possibly be run with reduced intensity.

It has been stated recently [13] that due to a delayed installation of collimators for the triplet magnets in IP2 and IP8 the protection of the triplet requires $\beta^* \geq 6$ m. We have shown that such a scenario is possible (Tab.3).
Figure 28: Aperture of beam 1 at 5 TeV, 100 % positive spectrometer field, with $\beta^*$ of 3 m.

Figure 29: Beam orbits at 5 TeV, 100 % positive spectrometer field, with $\beta^*$ of 2 m.
Figure 30: Aperture of beam 1 at 5 TeV, 100% positive spectrometer field, with $\beta^*$ of 2 m.
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