Optics, crossing angle and aperture in p-Pb physics conditions in the LHC

R. Versteegen, J. M. Jowett / BE-ABP

Keywords: p-Pb operation, aperture, beam-beam, separation, crossing angle

Summary

The first p-Pb run at the LHC is planned for November 2012. As this is a very new way of operating the machine, several uncertainties remain and many aspects have to be studied carefully. This note concentrates on the beam-beam separation and the machine aperture in the interaction regions (IRs). These are two major concerns for determining the bunch spacing and the betatron amplitude function $\beta^*$ at the interaction points (IPs). Various schemes of collisions in terms of $\beta^*$-values and crossing angle in the ALICE experiment are considered and compared, in view of the coming choice of these essential parameters for operation and luminosity production.

1. Introduction

A p-Pb run is foreseen for November 2012 at the LHC at 4 $\mathrm{Z\,TeV}$ per beam [1]. The asymmetric collisions at such energies will require operation off-momentum, so that the RF frequencies of both beams can be locked together for physics. For an equivalent and opposite orbit shift for p and Pb beams, the relative rigidity offsets will be $\delta = \pm 2.3 \times 10^{-4}$ respectively. One of the consequences is a reduction of available aperture in the IRs. Global effects, including chromatic beta-beating and tune-dependences will be treated separately.

Key optics parameters in the interaction regions are still to be determined: the $\beta$-functions at IP1 (ATLAS), IP2 (ALICE), IP5 (CMS) are of course crucial for luminosity performance; the crossing angle at IP2 should be minimized so as not to shadow the zero-degree calorimeters (ZDCs) of ALICE detectors [2]. Present policy is to have the same $\beta$-function at IP1, IP2, and IP5. This parameter has to be chosen considering the separation of the two beams in the IRs in order to avoid parasitic crossings, and considering the aperture limitations, mainly those close to the triplets. The beam-beam separation at the long range encounters will also have an impact on the choice of the bunch spacing, another choice that is to be made.
The separation \( r_{12} \) is defined as the distance between the centres of the two beams, divided by the beam size of Beam 1 or Beam 2. As the influence of Beam 1 (proton beam) is more likely to be stronger on Beam 2 (lead beam) than the other way around, we consider for the separation estimates \( \sigma_{x1} \) and \( \sigma_{y1} \), the Beam 1 horizontal and vertical beam sizes:

\[
r_{12} = \frac{\sqrt{(x_{c1} - x_{c2})^2 + (y_{c1} - y_{c2})^2}}{\max(\sigma_{x1}, \sigma_{y1})}
\]

where \( x_{c1}, y_{c1}, x_{c2}, y_{c2} \) stand for the central orbit coordinates of Beam 1 and Beam 2 respectively.

The aperture has to be checked carefully especially in IR2, as an unexpected bottleneck was found there during the measurements campaign in 2011 [3]. This is the driving parameter that determines the crossing angle at IP2, as the aperture limitation prevents the net crossing angle, \( p_{yc}(IP2) \) as defined below, from being set to zero, the ideal choice for the experiment. \( p_{yc}(IP2) \) is the sum of ALICE spectrometer’s bump half angle and the external half crossing angle \( p_{yext}(IP2) \) at IP2, defined conventionally for Beam 1, for an on-momentum beam:

\[
p_{yc}(IP2) = \pm \frac{490 \mu\text{rad}}{E/(Z \text{TeV})} + p_{yext}(IP2)
\]

This note presents calculations in all the envisaged configurations of the beam-beam separation and of the parameter \( n_i \), closely related to the aperture [4], [5]. Calculations are done depending on the IR, on \( \beta^*(IP1, IP2, IP5) \), and on the crossing angle at IP2. \( n_i \) is used to compare these configurations one to the other, but also to compare the results to previous situations such as during the Pb-Pb run in 2011 or during the p-p run in 2012, using one single parameter. The study assumes that the collimators are correctly positioned, starting from a working configuration for protons, and adjusted to cope for the offset of the central trajectory. The work presented hereafter focuses on the effect of off-momentum beams in the quadrupole triplets near the IPs. Moreover the requirements for tertiary collimators closure in IR2 in the presence of both a proton beam and a Pb beam are not discussed. The first section of the note presents plots of the beam-beam separation in IR2. The influence of the energy offset on \( n_i \), and consequently on the aperture, is shown in the second section. Its variations depending on \( \beta^*(IP1, IP2, IP5) \) and on the net crossing angle at IP2 are given in the third section.

Three values of \( p_{yc}(IP2) \) are considered: \(-60 \mu\text{rad}, 0 \mu\text{rad and } +60 \mu\text{rad} \) as \( \pm 60 \mu\text{rad} \) was defined as the maximum tolerance for efficient ZDCs detection of spectator neutrons. The minimum \( \beta^* \)-value is 0.6 m at IP1, IP2, IP5 since this value has already been achieved during the proton run in 2012 at IP1 and IP5; and the maximum under consideration corresponds to the value used in all three experiments during the 2011-ion run, i.e., 1.0 m.

The \( \beta^* \) at IP8 (LHCb) will remain the same as for proton operation, \( \beta^*(IP8) = 3.0 \text{ m} \).

The assumed normalised emittances are \( \gamma \varepsilon(p) = 2.5 \mu\text{m.rad} \) for the proton beam, and \( \gamma \varepsilon(Pb) = 1.5 \mu\text{m.rad} \) for the ion beam. The polarity of ALICE spectrometer is taken to be negative (in MAD-X convention [6]).
2. Beam-beam separation in IR2 as a function of $\beta^*$, and total crossing angle at IP2

The beam-beam separation in IR2 has been calculated for all the possible configurations depending on $\beta^*$ and on $p_{yc}(IP2)$. The resulting plots are presented in this section. For comparison, Figure 1 shows the separation $r_{12}$ obtained with 2011 Pb-Pb run parameters:

- an energy of 3.5 $Z$ TeV,
- 1.0 m-$\beta^*$,
- $-60$ μrad crossing angle.

The bunch spacing was 200 ns, consequently the minimum separation in 2011 was about $4\sigma$ in IR2.

![Figure 1](image1.png)

Figure 1  Beam-beam separation in terms of Pb-beam size at 3.5 $Z$ TeV, for 2011 Pb-Pb run parameters: $\beta^*(IP2) = 1.0$ m, and $p_{yc}(IP2) = -60$ μrad. Dashed lines represent the 100 ns encounter points.

Figure 2 shows $r_{12}$ for $\beta^*(IP1, IP2, IP5)$ successively equal to 1.0 m, 0.9 m, 0.8 m, 0.7 m, and 0.6 m, for a net crossing angle $p_{yc}(IP2) = -60$ μrad. As this is the crossing angle adopted in 2011, the situation is similar to last year’s run in terms of beam-beam separation. But at 4 $Z$ TeV, getting to $\beta^* < 0.8$ m leads to less than $4\sigma$ beam-beam separation at the 200 ns encounters. From these plots we can say that 200 ns would be preferable compared to 100 ns bunch spacing as the separation gets very small at the first 100 ns encounter near IP2.

Figure 3 shows $r_{12}$ for $\beta^*(IP1, IP2, IP5)$ successively equal to 1.0 m, 0.9 m, 0.8 m, 0.7 m, and 0.6 m, for a net crossing angle $p_{yc}(IP2) = 0$ μrad. This corresponds to the optimum crossing scheme from the experiment point of view. Regarding the beam-beam separation we obtain more than $4\sigma$ beam-beam separation at the 100 ns encounters and more than $6\sigma$ beam-beam separation at the 200 ns encounters. But an aperture limitation is to be expected taking into account 2011 experience. This will be discussed in the next section.

Finally Figure 4 shows $r_{12}$ for $\beta^*(IP1, IP2, IP5)$ successively equal to 1.0 m, 0.9 m, 0.8 m, 0.7 m, and 0.6 m, for a net crossing angle $p_{yc}(IP2) = +60$ μrad. Using the opposite maximum crossing angle could suppress all the potential parasitic long range interactions since the minimum separation is about $7.5\sigma$ at the first long range 100 ns encounter. But, as mentioned in the previous case, the aperture will become the main concern, and a compromise has to be found.
To illustrate this compromise, beam envelopes are given in Figure 5 and Figure 6 for \( \beta^*(IP1, IP2, IP5) = 0.6 \) m, and for \( p_{yc}(IP2) = -60 \) μrad and \( p_{yc}(IP2) = 0 \) μrad respectively. It is clear that the separation is better in the second case, but the 10-σ envelope reaches \( y = -0.026 \) m for Beam 2 whereas it stays below \( y = 0.022 \) m for \( p_{yc}(IP2) = -60 \) μrad.

As can be seen on Figures 2 to 6 the separation at the IPs is not strictly zero, and the net angle for Beam 1 not strictly \(-60, 0, \) or \(+60 \) μrad. This effect results from the off-momentum trajectories. These deviations are small and could be corrected by steering during the adjusting phase as in a normal physics fill.

3. Aperture in all four IRs for \( \beta^*(IP1, IP2, IP5) = 0.6 \) m on- and off-momentum

The APERTURE module of MADX has been used to compute the \( n_1 \) parameter, expressed in terms of number of \( \sigma \) of the beam considered [6]. The off-momentum central trajectory has been used for these calculations. For the aperture calculation of an off-momentum beam, we can either introduce the \( \delta \) offset in the TWISS module, and then calculate \( n_1 \) for the same bucket edge as for the on-momentum case, or we can do an on-momentum calculation in TWISS, and then the energy offset has to be added to the bucket edge to account for the orbit shift. These two methods are equivalent to first order but the first one was adopted so that the effects of energy deviation on the optical functions are taken into account. In terms of the maximum synchrotron oscillation amplitude, expressed as a fractional momentum deviation, the square of the bucket height can be estimated as:

\[
\left( \frac{\delta p}{p} \right)_{\text{max}}^2 \approx \frac{2 e V_{RF}}{\pi h |\eta| (\gamma - 1/\gamma)(m_p c^2) A} Q
\]

where \( e \) is the elementary charge, \( V_{RF} \) is the RF voltage, \( h \) the RF harmonic number, \( \eta \) the slip factor, \( \gamma \) the usual relativistic factor, \( (m_p c^2) \) the rest energy of the proton and \( Q/A \) is the charge over the mass number of the particle, being 1. for the proton beam and 0.39 for the Pb beam. At 4 \( Z \) TeV, with \( V_{RF} = 12 \) V (during physics operation) it leads to \( \left( \frac{\delta p}{p} \right)_{\text{max}} = 0.55 \times 10^{-3} \) for Beam 1, and \( \left( \frac{\delta p}{p} \right)_{\text{max}} = 0.22 \times 10^{-3} \) for Beam 2. The orbit tolerance is 3 mm and the β-beat tolerance (added to the effect of the energy offset) is 10% on beam size.

Plots given in Figures 7, 8, 9 and 10 show the variation of \( n_1 \) in each IR, for both beams. In the case of IR2 (Figure 8), the results are presented for the same three cases of crossings as before. The minimum values of \( n_1 \) given in Table 1, where the loss of aperture due to the energy offset, expressed as \( \frac{n_1(\delta \neq 0)}{n_1(\delta = 0)} \), has been added. As one can see the ratio \( \frac{n_1(\delta \neq 0)}{n_1(\delta = 0)} \) is about 5%, but is larger in IR1 for Beam 1 and can reach 15% for Beam 2 for a large crossing angle at IP2.
Figure 2  p-Pb beam-beam separation in terms of proton beam size at 4 Z TeV, as a function of $\beta^*(\text{IP}2)$ (equal to $\beta^*(\text{IP}1)$ and $\beta^*(\text{IP}5)$) for $-60 \mu\text{rad}$ net crossing angle at IP2. Dashed lines represent the 100 ns encounter points.
Figure 3  p-Pb beam-beam separation in terms of proton beam size at 4 Z TeV, as a function of β*(IP2) (equal to β*(IP1) and β*(IP5)) for 0 μrad net crossing angle at IP2. Dashed lines represent the 100 ns encounter points.
Figure 4  p-Pb beam-beam separation in terms of proton beam size at 4 Z TeV, as a function of $\beta^*(IP2)$ (equal to $\beta^*(IP1)$ and $\beta^*(IP5)$) for +60 $\mu$rad net crossing angle at IP2. Dashed lines represent the 100 ns encounter points.
Figure 5 Central trajectories and 10-σ vertical beam envelopes in IR2 at 4 Z TeV for −60 μrad net crossing angle at IP2 and β*(IP1, IP2, IP5) = 0.6 m. Beam 1 is in blue, Beam 2 in red. The gray areas figure the physical aperture, and dashed lines represent the 100 ns encounter points. IP2 is at \( s = 0 \).

Figure 6 Central trajectories and 10-σ vertical beam envelopes in IR2 at 4 Z TeV for 0 μrad net crossing angle at IP2 and β*(IP1, IP2, IP5) = 0.6 m. Beam 1 is in blue, Beam 2 in red. The gray areas figure the physical aperture, and dashed lines represent the 100 ns encounter points. IP2 is at \( s = 0 \).
Figure 7  Calculated aperture function, \( n_1 \), in IR1 on- and off-momentum for Beam 1 (left) and Beam 2 (right). The lower reference limit of \( n_1 = 7 \) is indicated.

Table 1  Minimum aperture for on- and off-momentum reference particle for Beam 1 (left) and for Beam 2 (right) in all IRs.

<table>
<thead>
<tr>
<th>( n_{1\text{min}} ), B1, (-60 \mu\text{rad at IP2})</th>
<th>( n_{1\text{min}} ), B2, (-60 \mu\text{rad at IP2})</th>
<th>( n_{1\text{min}} ), B1, (0 \mu\text{rad at IP2})</th>
<th>( n_{1\text{min}} ), B2, (0 \mu\text{rad at IP2})</th>
<th>( n_{1\text{min}} ), B1, (+60 \mu\text{rad at IP2})</th>
<th>( n_{1\text{min}} ), B2, (+60 \mu\text{rad at IP2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta = 0 )</td>
<td>( \delta = 2.3\times10^{-4} )</td>
<td>loss</td>
<td>( \delta = 0 )</td>
<td>( \delta = -2.3\times10^{-4} )</td>
<td>loss</td>
</tr>
<tr>
<td>IR1</td>
<td>7.27067</td>
<td>6.48422</td>
<td>-0.1212868</td>
<td>IR1</td>
<td>6.44584</td>
</tr>
<tr>
<td>IR2</td>
<td>8.35387</td>
<td>8.0021</td>
<td>-0.0439597</td>
<td>IR2</td>
<td>7.39766</td>
</tr>
<tr>
<td>IR5</td>
<td>7.29338</td>
<td>6.84394</td>
<td>-0.0656698</td>
<td>IR5</td>
<td>6.47798</td>
</tr>
<tr>
<td>IR8</td>
<td>14.8686</td>
<td>13.9881</td>
<td>-0.0629464</td>
<td>IR8</td>
<td>13.1182</td>
</tr>
<tr>
<td>( \delta = 0 )</td>
<td>( \delta = 2.3\times10^{-4} )</td>
<td>loss</td>
<td>( \delta = 0 )</td>
<td>( \delta = -2.3\times10^{-4} )</td>
<td>loss</td>
</tr>
<tr>
<td>IR1</td>
<td>7.12602</td>
<td>6.2606</td>
<td>-0.1382328</td>
<td>IR1</td>
<td>6.43963</td>
</tr>
<tr>
<td>IR2</td>
<td>7.53695</td>
<td>6.82788</td>
<td>-0.1038492</td>
<td>IR2</td>
<td>6.4852</td>
</tr>
<tr>
<td>IR5</td>
<td>7.28095</td>
<td>6.81821</td>
<td>-0.0678683</td>
<td>IR5</td>
<td>6.47961</td>
</tr>
<tr>
<td>IR8</td>
<td>14.7155</td>
<td>13.8723</td>
<td>-0.060783</td>
<td>IR8</td>
<td>13.1703</td>
</tr>
<tr>
<td>( \delta = 0 )</td>
<td>( \delta = 2.3\times10^{-4} )</td>
<td>loss</td>
<td>( \delta = 0 )</td>
<td>( \delta = -2.3\times10^{-4} )</td>
<td>loss</td>
</tr>
<tr>
<td>IR1</td>
<td>6.98137</td>
<td>6.03697</td>
<td>-0.1564361</td>
<td>IR1</td>
<td>6.43342</td>
</tr>
<tr>
<td>IR2</td>
<td>6.12291</td>
<td>5.36945</td>
<td>-0.1403235</td>
<td>IR2</td>
<td>5.29088</td>
</tr>
<tr>
<td>IR5</td>
<td>7.26662</td>
<td>6.79251</td>
<td>-0.0697989</td>
<td>IR5</td>
<td>6.48125</td>
</tr>
<tr>
<td>IR8</td>
<td>14.5625</td>
<td>13.7564</td>
<td>-0.0585982</td>
<td>IR8</td>
<td>13.1309</td>
</tr>
</tbody>
</table>
Figure 8  Calculated aperture function, $n_1$, in IR2 on- and off-momentum for Beam 1 (left) and Beam 2 (right); and for $-60 \mu \text{rad}$, $0 \mu \text{rad}$ and $+60 \mu \text{rad}$ crossing angle at IP2. The lower reference limit of $n_1 = 7$ is indicated.
Figure 9  Calculated aperture function, $n_1$, in IR5 on- and off-momentum for Beam 1 (left) and Beam 2 (right). The lower reference limit of $n_1 = 7$ is indicated.

Figure 10  Calculated aperture function, $n_1$, in IR8 on- and off-momentum for Beam 1 (left) and Beam 2 (right). The lower reference limit of $n_1 = 7$ is indicated.

4. Aperture in all four IRs as a function of $\beta^*$

The aperture is the decisive factor that determines the minimum achievable $\beta^*$. Figures 11, 12, 13 show the evolution of $n_1$ in IR1, IR5, and IR8 as $\beta^*$(IP1, IP2, IP5) is increased from 0.6 m to 1.0 m for off-momentum beams.

Regarding IR2, an unexpected bottleneck was found for Beam 2 in 2011 during the aperture measurements. Because of this limitation, a zero crossing angle at IP2 could not be adopted at 3.5 $\mathrm{Z TeV}$. That is why the aperture has been calculated and compared to the result obtained using 2011 parameters. A criterion to determine $\beta^*$ could be to try to get similar results for $n_1$ in IR2 in 2012 compared to 2011. Figures 14 and 15 present the situation for Beam 1 and Beam 2 respectively. Each plot corresponds to a value of $\beta^*$(IP1, IP2, IP5), and shows the three crossing cases.
As the aperture gets very poor for $+60 \, \mu\text{rad}$, this case has been removed from the plots in Figure 16, where the comparison with 2011 situation is given for Beam 2 ($3.5 \, \text{Z TeV, } -60 \, \mu\text{rad}$). One can see on Figures 15 and 16 the bottleneck on the left hand side of the IP, at $s \approx 3260 \, \text{m}$.

**Figure 11** Calculated aperture function $n_1$ in IR1 for off-momentum Beam 1 (left) and Beam 2 (right) as a function of $\beta^\ast(\text{IP1, IP2, IP5})$.

**Figure 12** Calculated aperture function $n_1$ in IR5 for off-momentum Beam 1 (left) and Beam 2 (right) as a function of $\beta^\ast(\text{IP1,IP2,IP5})$.

**Figure 13** Calculated aperture function $n_1$ in IR8 for off-momentum Beam 1 (left) and Beam 2 (right) as a function of $\beta^\ast(\text{IP1, IP2, IP5})$. 

- 12 -
Figure 14  Calculated aperture function $n_1$ in IR2 for off-momentum Beam 1 as a function of $\beta^*(\text{IP1, IP2, IP5})$ and the net crossing angle at IP2. The lower reference limit of $n_1 = 7$ is indicated.
Figure 15 Calculated aperture function $n_1$ in IR2 for off-momentum Beam 2 as a function of $\beta^*(IP1, IP2, IP5)$ and the net crossing angle at IP2. The lower reference limit of $n_1 = 7$ is indicated.
Figure 16  Calculated aperture function, $n_1$, in IR2 for off-momentum Beam 2 as a function of $\beta^*$(IP1, IP2, IP5) and the net crossing angle at IP2, compared to the aperture calculated for 2011. The lower reference limit of $n_1 = 7$ is indicated.
5. Conclusion

According to the aperture calculation presented in this note, one should keep $\beta^* \gtrsim 0.8 \text{ m}$ and maintain the same non-zero crossing angle at IP2 as in 2011 ($-60 \mu\text{rad}$ for a negative spectrometer polarity) to get a similar $n_1$ function in IR2 as in 2011. This would lead to a minimum aperture in IR1 and IR5 greater than $7\sigma$. But this choice would not allow the operation using 100 ns bunch spacing, because of the small separation at the first beam-beam encounter. Increasing $\beta^*$ at IP1 and IP5 may enable to decrease the crossing angle at these points if the resulting impact on luminosity is high enough and if it does not lengthen the commissioning time too much.

One could think of using a crossing angle a bit larger if the ALICE experiment allows it, in order to gain a bit more aperture. The beam-beam separation is plotted for $-80 \mu\text{rad}$ on Figure 17 (left) and the resulting gain is compared to $-60 \mu\text{rad}$ case (right). $\beta^* = 1.0 \text{ m}$, so that the separation and the aperture are the biggest. The change of $n_1$ is very small while more than one $\sigma$-separation at the first 200 ns encounters is lost. Consequently if the $4\sigma$-separation is taken as a reference limit for beam-beam instabilities, this could not be adopted.

Figure 17  Beam-beam separation in IR2 (left), and calculated aperture in IR2 for $\beta^*(\text{IP2}) = 1.0 \text{ m}$ for $-80 \mu\text{rad}$ net crossing angle at IP2.

Detailed aperture measurements in IR2 and a final choice of $\beta^*$ will probably not be possibly until the set-up phase just before the p-Pb run. Meanwhile, the present calculations exploit the best available information.

References


Note 66, 1996.
