Pushing the limits: crossing angles, aperture and β^*

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Abstract

First experiences with colliding beams have been collected during the 2010 LHC run. These will be critically examined and serve as input to define strategies for operation with more bunches and higher luminosities in 2011. The proposed strategies include running scenarios for proton operation in ALICE and LHCb.

INTRODUCTION - WHERE ARE THE LIMITS

Running the LHC at lower energy, the possible β^* and the crossing angles are limited by the available mechanical aperture. At the same time a minimum crossing angle is required to avoid a reduction of the dynamic aperture due to long range beam-beam effects. For a low-β insertion (i.e. not at injection), the normalized separation for a given crossing angle α is a function of β^* as well as the emittance and can be written as [1]:

$$d_{sep} = \sqrt{\frac{\alpha^2 \cdot \beta^* \cdot \gamma}{\epsilon_n}}$$

The corresponding long range beam-beam tune shift can be approximated by:

$$\Delta Q_{lr} \propto \frac{N}{d_{sep}^2} = \frac{N \cdot \epsilon_n}{\alpha^2 \cdot \beta^* \cdot \gamma}$$

Given the desired separation (12 σ, [2]), we can define the necessary crossing angle as:

$$\alpha = \sqrt{\frac{d_{sep}^2 \cdot \epsilon_n}{\beta^* \cdot \gamma}}$$

However, the mechanical aperture imposes a maximum crossing angle [3, 4].

CONFIGURATION IN IP1 AND IP5

To obtain maximum luminosity in IP1 and IP5, it is desirable to operate with the smallest possible β^*. Furthermore, the proposed scenario should work for any bunch spacing foreseen for running the LHC in 2011 and 2012. Both conditions defined above are summarized and superimposed in Fig.1. The required crossing angle as defined above is plotted for different emittances and the constraints from the mechanical aperture are superimposed [5]. The latter are slightly pessimistic since the nominal emittance is assumed for the calculation. The two curves represent different assumptions on the quality of the orbit control.

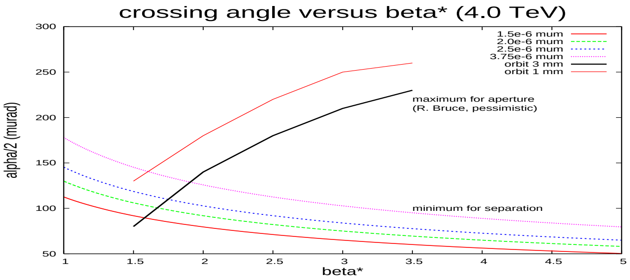

Figure 1: Required crossing angle versus β^* for different emittances. Also shown are limits from mechanical aperture [5].

Realistically, the curve for orbits of 1 mm should be used. The crossing points of the curves define the lower limit for β^* and give the required crossing angle.

The result of this is summarized in Tab.1 assuming different values for the normalized transverse emittance and the energy of the machine.

ϵ_n Energy	β^* 3.5 TeV	β^* 4.0 TeV	α (μrad) 3.5 TeV	α (μrad) 4.0 TeV
1.5 μm	1.4 m	1.4 m	$\pm$ 120	$\pm$ 120
2.0 μm	1.5 m	1.4 m	$\pm$ 120	$\pm$ 120
2.5 μm	1.6 m	1.5 m	$\pm$ 120	$\pm$ 120
3.75 μm	1.8 m	1.6 m	$\pm$ 140	$\pm$ 140

Table 1: Crossing angle versus β^* for different emittances.

Recommendations IP1 and IP5

Following the results from Tab.1, a scenario for interaction points 1 and 5 is proposed as (assuming an emittance of ϵ_n = 2.5 μm [7]):

- Operating with β^* = 1.5 m
- Half crossing angle of $\pm$ 120 μrad.
- Works for bunch spacings of 50 ns and 75 ns.

For emittances larger than ϵ_n = 2.5 μm the numbers must be modified (see Tab.1).

A question that may be raised is the minimum β^* in case of a substantial emittance growth during a physics fill. While the aperture at the beginning of a fill may be sufficient it may not be towards the end, leading to a limit for β^*. So far it was not yet attempted to optimize the machine working point for collision and it can be hoped that a possile emittance growth can be controlled. In particular for future running with more substantial long range encounters the search for a good working point becomes important and should be pursued as an operational procedure.

CONFIGURATION IN IP2

The operation in IP2 is complicated by two requirements:

- Moderate luminosity, levelled with adjustable transverse separation [8].
- Spectrometer magnet, producing an antisymmetric bump and a rather large crossing angle [8].

It is requested to change the polarity of the spectrometer on a regular basis, i.e. the sign of the crossing angle changes. To avoid parasitic encounters, an additional, external crossing angle must be applied and it is assumed that this angle has the same sign as the internal angle, i.e. it must be inverted when the polarity of the spectrometer is changed. Both angles are in the vertical plane and can be chosen freely since no interference with the exchange of aperture between the separate vacuum chambers is expected.

Choosing the external and internal angles with opposite sign allows a small effective crossing angle, but at the expense of additional crossings, depending on the bunch spacing [8]. When the bunch spacing is large enough, such a scenario, including to reduce the effective angle to zero, is possible.

Recommendations IP2

The proposed parameter set for the operation in IP2 is:

- Internal crossing angle at 3.5 TeV is $\pm$ 140 μrad.
- External crossing angle at 3.5 TeV is $\pm$ 80 μrad, leading to a net crossing angle of $\pm$ 220 μrad.
- Operation with β^* = 10 m.

To avoid additional crossings and the implied complications it is highly recommended to choose the external and internal crossing angles with the same sign.

CONFIGURATION IN IP8

Like IP2, in IP8 a moderate luminosity is wanted and can be provided with a small separation. The full feasibility of this separation in the presence of long range beam-beam encounters remains to be verified [1].

Unlike IP2, the crossing plane in IP8 is horizontal and in order to avoid multiple crossings, the sign of the external angle is fixed [8], i.e. beam 1 crosses the interaction point with a negative angle. This is shown in Fig.2 where the orbits of the two beams are shown for the external crossing angle only. Shown are also the positions of beam-beam

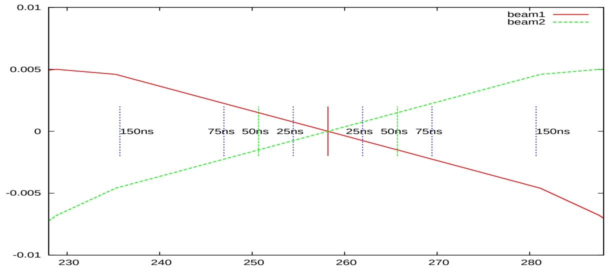

Figure 2: Geometry of external crossing angle in IP8. Shown are also the positions of beam-beam encounters for different bunch spacing.

encounters for different bunch spacings. This configuration (sign) is the only one allowed for IP8.

The Figs.3 and 4 show the orbits of the two beams produced by the spectrometer magnets together with its compensators [8]. It is assumed [6, 9] that the spectrometer is always operated with full field during physics data taking, independent of the machine energy. At the energy of 3.5 TeV this produces a half crossing angle of $\pm$ 270 μrad (Figs.3 and 4). It is clearly visible that the orbits of the

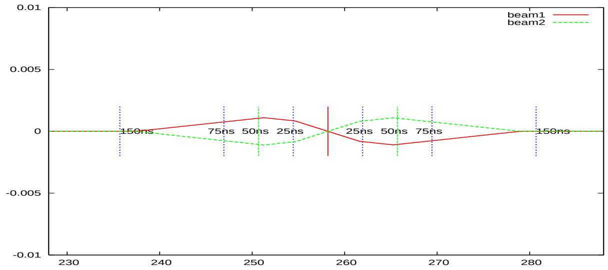

Figure 3: Geometry of internal crossing angle in IP8. Picture shows the preferred polarity. Shown are also the positions of beam-beam encounters for different bunch spacing.

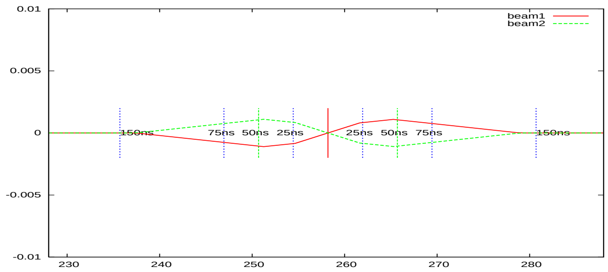

Figure 4: Geometry of internal crossing angle in IP8. Picture shows the less preferred polarity. Shown are also the positions of beam-beam encounters for different bunch spacing.

two beams change signs when the polarity of the spectrometer is inverted. The bunch spacing used during 2010, i.e. 150 ns, has the advantage that the first parasitic encounter is outside this bump and a change of the polarity does not affect the separation. This spacing was chosen considering this feature.

Collisions in IP8

When beams are colliding, both, internal and external crossing angles must be present to avoid parasitic encounters. Since the sign of the external angle is fixed, the combined orbits in the two cases are rather different. The Fig.5

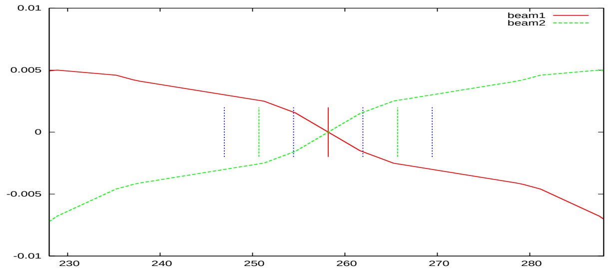

Figure 5: Geometry of external and spectrometer crossing angle in IP8 for the preferred polarity. Shown are also the positions of beam-beam encounters for different bunch spacing.

shows the external angle superimposed on the internal angle for the preferred polarity. Both angles add and provide sufficient separation for all possible encounter. This configuration is operational for all β^* allowed by the mechanical aperture [3, 4] and the foreseen bunch spacings. The situ-

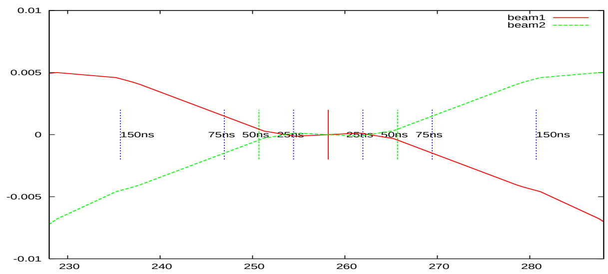

Figure 6: Geometry of external and spectrometer crossing angle in IP8 for the less preferred polarity. Shown are also the positions of beam-beam encounters for different bunch spacing.

ation is very different for the case depicted in Fig.6 where the polarity of the spectrometer is switched, while the external angle is the same as in Fig.5. Since the two signs are opposite, the separation for the encounters inside the antisymmetric bump are very small and insufficient for operation. The situation depends on the bunch spacing and the situation is more critical for 50 ns than for the 75 ns case. The crossing angle must therefore be increased to separate the beams sufficiently. Due to aperture considerations and the requirement of a minimum beam separation the available β^* is limited. To find the required set of parameters, an optimization similar to the one for IP1 and IP5 was done for IP8. This is shown in Fig.7. In this case the minimum required angle is shown as a function of β^* for

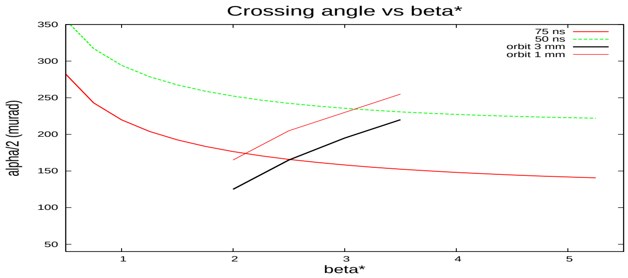

Figure 7: Required crossing angle versus β^* in IP8 for 50 ns and 75 ns spacing. Superimposed constraints from mechanical aperture.

the two options for the bunch spacing, i.e. 50 ns and 75 ns. The emittance in this figure is assumed to be 2.0 μm, but the evaluation was done also for other values.

Recommendations IP8

The results of this procedure are summarized in Tab.2 where the recommended β^* together with the proposed crossing angles are shown. As expected, the required configuration depends on the bunch spacing. It appears, that a

spacing	ϵ_n	β^*	α
50 ns	2.0 μm	3.0 m	$\mp$ 235 μrad
50 ns	2.5 μm	3.2 m	$\mp$ 250 μrad
50 ns	3.75 μm	3.6 m	$\mp$ 270 μrad
75 ns	2.0 μm	2.0 m	$\mp$ 160 μrad
75 ns	2.5 μm	2.2 m	$\mp$ 170 μrad
75 ns	3.75 μm	2.5 m	$\mp$ 210 μrad

Table 2: Possible operational parameters for IP8, less preferred polarity of spectrometer.

scenario with:

- ϵ_n = 2.5 μm
- $\beta^* \geq$ 3.0 m
- $\alpha \approx \mp$ 250 μrad

is possible for both bunch spacings. This reduces the possible β^* reach for 75 ns, but allows a common setup for all considered bunch spacings, simplifying the operation of the machine, inparticular if it can be adopted also for the preferred polarity.

However, it should be noted that an operation with a bunch spacing of 25 ns is excluded unless a different configuration is used [10].

Injection in IP8

At injection, the operation of the spectrometers can impose additional complications. If it is desired to have the fields at full strength already at injection energy, the amplitude of the antisymmetric bump and the associated crossing angle are very large (approximately $\pm$ 2.1 mrad in the case of IP8). It is therefore excluded that the external angle can be chosen large enough to compensate for such an angle in case the signs are opposite. The two cases with full field

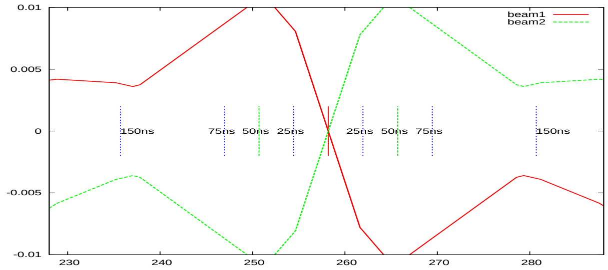

Figure 8: Crossing scheme at injection energy for IP8, full field of the spectrometer with preferred polarity of spectrometer.

of the spectrometer in the case of IP8 are shown in Figs.8 and 9. The additional crossing points in Fig.9 cannot be

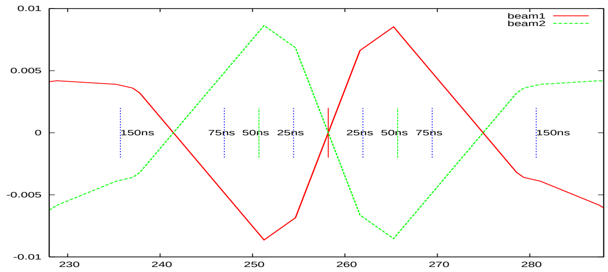

Figure 9: Crossing scheme at injection energy for IP8, full field of the spectrometer with less preferred polarity of spectrometer.

avoided. During the energy ramp the bump amplitude decreases and the unwanted crossing points move longitudinally, thus always sampling the potential encounters for any bunch spacing.

To solve this problem, two possible solutions are proposed:

- Run the spectrometer at a lower field at injection and ramp up with energy.
- Try to separate all encounters with the parallel separation bump.

It can be shown that setting the magnetic field of the IP8 spectrometer to about 10% or less provides sufficient separation.

The second option relies on the separation in the other plane. Originally [8], the parallel separation is designed to separate the central collision point only, while all parasitic encounters are separated by the crossing angle bump. To test whether the parallel bump is sufficient to also separate the first few parasitic encounters, the normalized separation

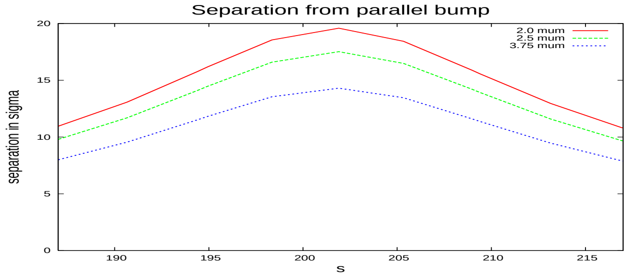

Figure 10: Normalized beam separation provided by parallel separation bump around IP8. Numbers given for 3 different emittances.

provided by this bump is shown in Fig.10. Three curves are shown computed with different normalized transverse emittances between 2.0 μm and the nominal emittance.

Using the criterion for a sufficient separation one comes to the conclusion that the separation provided is sufficient under the condition that the emittance is not larger than 2.5 μm. In that case the IP8 spectrometer can be operated at full field at injection energy for both polarities and all bunch spacings.

Finally, it is desired to keep the luminosity in IP8 approximately constant at a moderate value. To this purpose the beams are separated transversely and this was tested in 2010. It remains to be demonstrated that such a separation (of the order of 1 σ) can be used also in the presence of many additional long range encounters, a configuration not yet used.

SUMMARY

The main results of this study can be summarized as:

- Given the boundary conditions from mechanical aperture and required beam-beam separation, the collision points in IP1 and IP5 can be operated with a β^* = 1.5 m and a crossing angle around $\pm$ 120 μrad.
- The external angle in IP2 proposed is $\pm$ 80 μrad.
- The minimum β^* in IP8 depends on the bunch spacing and the spectrometer polarity and will be between 2 m and 3.5 m. The corresponding crossing angles are specified.
- For emittances smaller than 2.5 μm at injection, the separation provided by the parallel bump is sufficient for both polarities and bunch spacings when the spectrometer is at full field.

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