STUDY AND OPERATIONAL IMPLEMENTATION OF A TILTED CROSSING ANGLE IN LHCb

R. Alemany-Fernandez, F. Follin, B. J. Holzer, D. Jacquet, R. Versteegen, J. Wenninger, CERN, Geneva, Switzerland

Abstract

The current crossing angle scheme at LHCb interaction point (horizontal crossing angle and vertical beam separation) prohibits the use of the LHCb dipole positive polarity for 25 ns bunch spacing operation since the beam separation at the first parasitic encounter is very small inducing unwanted beam encounters. To overcome this limitation a different crossing angle scheme was proposed in 2007 by W. Herr and Y. Papaphilippou. The new schema implies a vertical external crossing angle that together with the horizontal internal crossing angle, from the LHCb dipole and its three compensator magnets, defines a new tilted crossing and separation plane providing enough beam separation at the parasitic encounters. This paper summarizes the feasibility study of the new crossing scheme, the implementation in routine operation and analyzes the beam stability during the building up of the tilted crossing plane.

INTRODUCTION

The first motivation [1] for implementing a vertical crossing angle in LHCb (IP8) is to allow the operation of the LHCb dipole positive polarity# with 25 ns bunch spacing. For this polarity the external horizontal crossing angle and the internal horizontal crossing angle from the LHCb dipole field and its compensators cancel each other nearly (-16 μrad at 4 TeV and β*=3 m) creating unwanted parasitic beam encounters. For the negative dipole polarity both angles sum up (-456 μrad at 4 TeV and β*=3 m) and the beam-beam separation is always guaranteed. On top of that, the net crossing angle asymmetry introduces a systematic uncertainty in the LHCb vertex reconstruction. In the new schema this problem is overcome since, for both dipole polarities, the net crossing angle is the same in both planes. An extra advantage, which applies only to the 50 ns bunch spacing, is that the position of the tertiary collimators is the same regardless the polarity of the dipole, therefore, the polarity change procedure is simpler for machine operation.

The studies carried out for implementing a vertical crossing angle showed that the procedure depends on the bunch separation. The studies and implementation in operation are presented in the following.

Hereafter all angles and separations refer to one beam. The corresponding signs denote the clockwise rotating beam (beam 1) and the anticlockwise rotating beam (beam 2), respectively.

The LHCb dipole field is upwards and the clockwise rotating beam crosses from the inside of the ring to the outside.

50 NS BUNCH SPACING STUDY

The procedure to change from the parallel vertical beam separation at injection and flat top, to the final vertical crossing angle at luminosity operation, has been studied theoretically in detail, established on beam during machine commissioning and applied successfully during the 2012 LHC operation. The study is based on the LHC standard collision optics in IR8, β*=3 m, 4 TeV per beam collision energy and a normalized emittance of 3.5 μm. The following steps were required to build up the tilted plane without parasitic encounters during the complete procedure:

1. reduce the vertical separation from ∓0.65 mm to ∓0.1 mm (Fig. 1-1 and 1-2);
2. built up the vertical crossing angle to ±90 μrad (Fig. 1-3 and 1-4);
3. reduce the external horizontal crossing angle from ∓220 μrad to 0 μrad (Fig. 1-5);
4. separate horizontally each beam by 42 μm, the sign depends on the dipole polarity (Fig. 1-6).

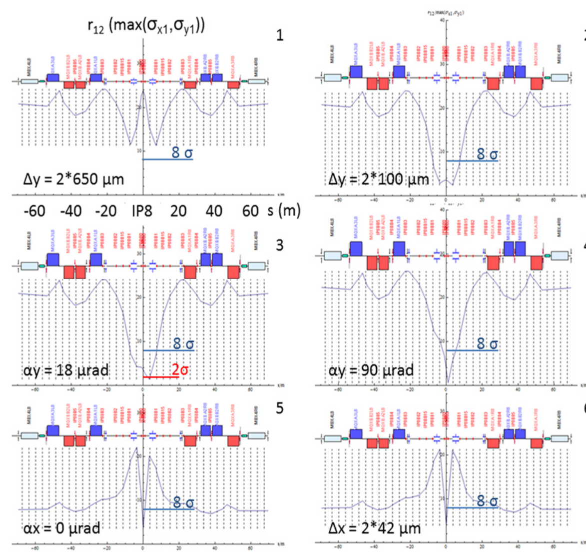

Figure 1: Evolution of the beam separation in beam 1 sigma (blue line) around the interaction point for some crucial steps of the 50 ns bunch spacing procedure.

Figure 1 shows, for some crucial steps of the procedure, the evolution of the beam separation r_{12} in beam 1 sigma (blue line) around IP8 at position zero. Each dotted line represents a parasitic encounter placed every 3.75 m from IP8, which corresponds to 25 ns bunch spacing. Every second encounter corresponds to 50 ns bunch spacing (space out by 7.5 m). At the top of each plot the lattice elements position is shown.

ISBN 978-3-95450-122-9

The first plot corresponds to the initial situation after squeeze: both beams separated vertically ∓0.65 mm and crossing horizontally with ∓220 μrad; the beam separation at all parasitic encounters is well beyond 8σ. In Fig. 1-2 the vertical separation has been reduced to ∓0.1 mm; during this process the beam separation at all parasitic encounters is ≥ 8σ. Figure 1-3 shows an intermediate step when building the vertical crossing angle (± 18 μrad). As it can be seen, at the first 25 ns parasitic encounter the beam separation is below 2σ and in the fourth plot (vertical crossing angle ± 90 μrad) the beams at IP8 are almost head on. From those pictures it can be deduced that this method is not adequate for 25 ns bunch spacing operation due to the small beam separation. Figure 1-5 shows the beam separation for a fully collapsed horizontal crossing angle. Only at the inner triplets (magnets in dark blue and red) the separation is slightly below 8σ. The last step applies the horizontal beam separation; from this moment on the beams lie on the new tilted separation plane.

As shown in Figure 3-top, the dipole polarity change does not affect the position of the tertiary collimators since the orbit difference at this location between both methods is ±0.13σ, small enough to be neglected. This simplifies considerably the machine operation at each polarity change as there is no need for intermediate fills for collimator position validation.

25 NS BUNCH SPACING STUDY

An alternative method was elaborated for 25 ns, a bit more complex than the one for 50 ns, but leading to the same results. The procedure described in the following is applied after squeeze with β*=3 m and 4 TeV per beam assuming that the beams can be injected and ramped with the originally designed horizontal crossing angle:

1. increase the horizontal separation of each beam from 0 to 0.350 mm (Fig. 2-1);
2. build up the vertical crossing angle to ∓90 μrad (Fig. 2-2);
3. reduce the vertical separation from ∓0.65 mm to 0 (Fig. 2-3);
4. reduce the external horizontal crossing angle from ∓220 μrad to 0 (Fig. 2-4 and 2-5);
5. reduce the horizontal separation of each beam from 350 μm to 42 μm (Fig. 2-6);
6. increase the vertical separation from 0 to ∓0.1 mm (Fig. 2-6).

Figure 2 shows the evolution of the beam separation as a function of the steps being applied during the method. The initial beam-beam separation was already shown in Fig. 1-1. The procedure guarantees a minimum separation at the first 25 ns beam encounter of ~ 5σ during the collapsing of the horizontal crossing angle, which is the most critical step (Fig. 2-4). It requires, though, different tertiary collimators settings as a function of the LHCb dipole polarity as can be seen in Fig. 3-bottom due to the non-negligible orbit difference, ±1σ, between both polarities during step 5. The method remains a theoretical study not yet validated with beam.

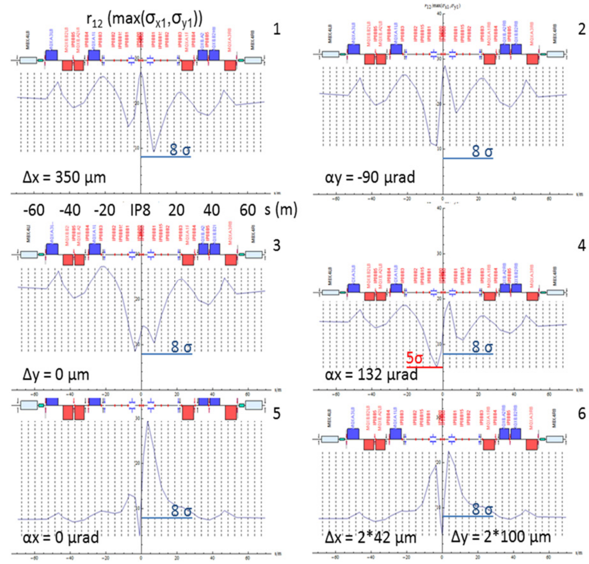

Figure 2: Evolution of the beam separation in beam 1 sigma (blue line) around the interaction point for some crucial steps of the 25 ns bunch spacing procedure.

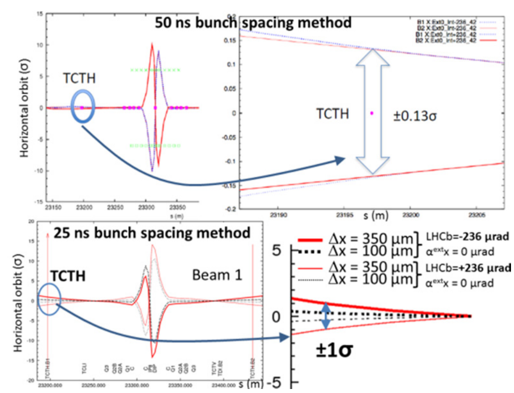

Figure 3: Horizontal orbit for the different dipole polarities. At the location of the tertiary collimators (TCTH) the orbit difference is negligible for the 50 ns bunch spacing procedure (top), but it is not for the 25 ns bunch spacing procedure (bottom).

OPERATIONAL IMPLEMENTATION

The vertical external crossing angle, α_y, together with the horizontal internal crossing angle from the LHCb dipole and its compensator magnets, α_{LHCb}, define a new tilted crossing and separation plane as indicated in Figure 4. The unitary vector orthogonal to this plane, $\hat{u}$, is a function of α_{LHCb} and α_y and is given by the expression:

$$\hat{u} = -\frac{\sin\alpha_y \vec{i} - \sin\alpha_{LHCb}\vec{j}}{\sqrt{\sin^2\alpha_{LHCb} + \sin^2\alpha_y}} \quad (1)$$

The vertical angle has always the same sign and value regardless the LHCb dipole polarity; therefore, the unitary vector direction depends on the dipole polarity. For negative (positive) polarity the crossing and separation planes are shown in Figure 4 left (right) respectively. The beams will be separated along the $\hat{u}$ direction during luminosity production to level the instantaneous luminosity to the value requested by the experiment [2].

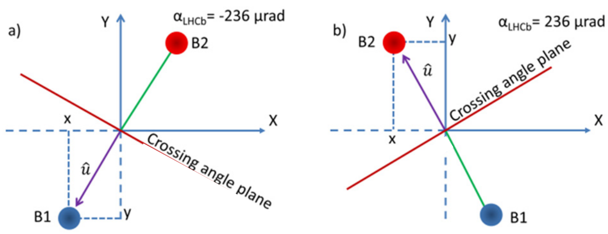

Figure 4: Schematic representation of the new tilted crossing angle and separation plane for negative (a) and positive (b) LHCb dipole polarity.

The currents of the magnet correctors providing with the different bumps are programmed in a series of functions and played during the beam mode called "ADJUST". The theoretical procedure explained before was adapted to the machine operation during beam commissioning before being routinely used. The evolution of some of those corrector magnets currents can be seen in Figure 5. The first part of the procedure, step 1 in Fig. 5-a, reduces the IP8 vertical beam separation from $\mp$0.65 mm to $\mp$0.1 mm (vertical corrector: dotted-dash red line). At the same time the beam separation in ATLAS (IP1) and CMS (IP5) is reduced to zero (horizontal corrector: dotted blue line for ATLAS). Then the external vertical crossing angle is build up to ±90 µrad (step 2 in Fig. 5-a). Finally, the external horizontal crossing angle in IP8 is reduced to 0 (horizontal corrector: dashed red line) and the beams are separated horizontally 42 µm each. At the end of step 3 in Fig. 5-a, head-on collisions are taking place in IP1 and IP5, while the luminosity in IP8 is leveled to a value required by the experiment, as indicated by the smooth growth of the LHCb instantaneous luminosity.

BEAM DYNAMICS OBSERVATIONS

As can be seen in Fig. 5-a (b), during the time the procedure is being applied in IP8, the relative beam losses (bunch intensity normalized to the intensity at the start of the ADJUST mode) are negligible regardless the dipole polarity. It is only at the end of step 3 (indicated in the top picture) that the beam losses start to increase due to the luminosity burn-off from the head on collisions in IR1 and IR5. The same behaviour is found for beam 2 and other analysed fills.

Beams instabilities were observed during the application of the procedure for some fills. Although the source was not the procedure itself, the process was divided in two phases, first the beams collided head on in IP1 and IP5, and only after, the tilted crossing and separation planes were built in LHCb before declaring stable beams.

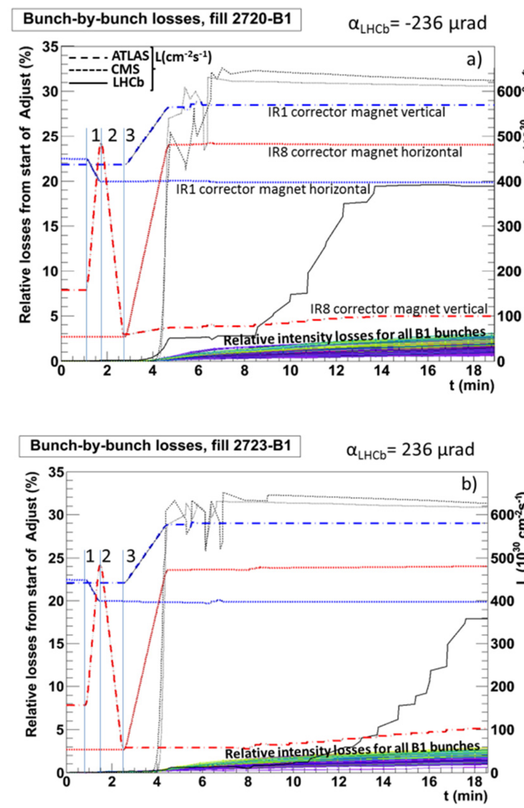

Figure 5: Relative beam losses from beginning of ADJUST for each of the 1380 bunches of beam 1, for negative (a) and positive (b) LHCb dipole polarity.

CONCLUSIONS

A new method for crossing and separating the beams at LHCb for 50 ns bunch spacing has been studied and implemented successfully in LHC operations during 2012. The new method provides the same net crossing angle regardless the LHCb dipole polarity removing the systematic uncertainty in the LHCb vertex reconstruction. It also simplified considerably the machine operation at each polarity change as the horizontal orbit difference between both polarities is very small and hence the same tertiary collimator settings could be used. An alternative method was found to allow the operation of the LHCb dipole positive polarity for 25 ns bunch spacing operation.

REFERENCES

[1] W. Herr, W. Papaphilippou, "Alternative running scenarios for the LHCb experiment" CERN-LHC-PROJECT-Report-1009 (2007).
[2] R. Alemany Fernandez, F. Follin, R. Jacobsson, "The LHCb Online Luminosity Control and Monitoring", TUPFI010, these proceedings.

ISBN 978-3-95450-122-9