SPECTROMETER OPERATION IN IR2 & IR8

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ABSTRACT

It is well known that the spectrometer dipoles of ALICE and LHCb have a considerably larger and more challenging impact on the LHC beams than the magnets in the high luminosity regions. The presentation summarises the basic layout of these devices, including the compensation of their fields and shows the theoretically expected beam orbits, envelopes and aperture needs. In addition the experience on beam will be presented for standard operation, but mainly in case of polarity flips. Possible scenarios for future operation in the context of faster and more transparent operation will be discussed. The special problem of 25ns operation together with the so-called negative LHCb polarity will be addressed as well as the latest results from aperture measurements performed during the machine development block MD#4 to decide on possible vertical crossing angle operation in IP8 at injection energy.

ALICE - IP2

The layout of the lattice of LHC in IR2 is shown in Fig.1. Ignoring for a moment the fact that the injection for beam 1 is included in the design, the layout of the straight section and the machine geometry is the same as in the other interaction regions where beam collisions take place - IR1, 5, 8 - [1]. A major difference however arises from the fact that the main magnet of the ALICE experiment is a spectrometer dipole, acting in the vertical plane and being operated during the complete LHC procedures from injection to collisions at full field. Compensator magnets, located within the drift space in front of the triplet magnets are used to counter balance the effect on the two counter rotating beams. Still the overall effect is an energy-dependent vertical crossing angle between the two beams.

At injection energy, 450 GeV, the spectrometer field creates a half crossing angle of y' = ±1089 µrad, at 4TeV (the maximum energy in the run year 2012), y'=±122.5µrad are obtained with the signs referring to the two counter rotating beams. Under usual conditions the ALICE operation requires a change of the dipole polarity once per run-mode, i.e. for standard p-p collisions in LHC once per year. Fig 2 shows the ALICE dipole before its installation into the experiment.

Fig 2: ALICE spectrometer dipole

For the operation of the machine the effect of the ALICE dipole has a number of implications that has to be taken into account. At injection and during the ramp, beam collisions have to be avoided at the interaction point (IP) and at any possible parasitic encounter. Therefore in addition to the crossing angle bump that is created by the ALICE magnets (the so-called *internal* bump) a horizontal symmetric bump is applied to separate the beams in the horizontal plane and an external vertical angle bump to guarantee sufficient separation at the parasitic encounters. Both external bumps are created by the LHC standard orbit corrector coils, located near the quadrupoles Q4...Q6.

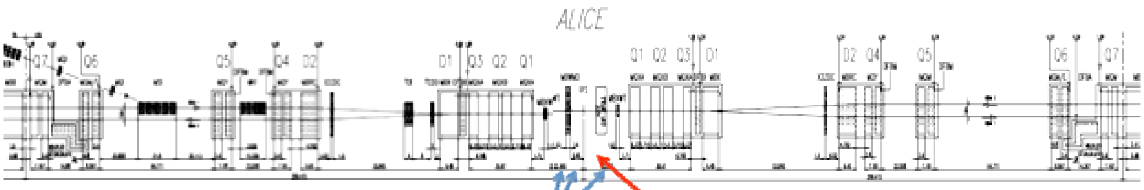


Fig.1 LHC lattice in IR2

compensators, spectrometer dipole

Proton-Proton Operation

Table 1 summarises the effect of the different bumps that are applied at injection energy during the typical 2012 run. Clear enough, for any beam energy and the corresponding beam emittance a compromise has to be found between maximum possible beam separation and available aperture. The beam orbits that are created by these combined effects are plotted in Fig. 3. They refer to the standard injection optics, i.e. β*=10m and a typical value of ε_n=2.5µmrad for the normalised emittance in both transverse planes.

Table 1: Effect of internal and external bumps in IR2 at 450 GeV injection energy

E=450 GeV		
spectr. dipole	y'	±1089µrad
ext. vert. crossing angle	y'	±170µrad
ext. hor. separation	Δx	±2mm

The vertical dotted lines in the plot show the position of the parasitic encounters for 50ns bunch spacing [2].

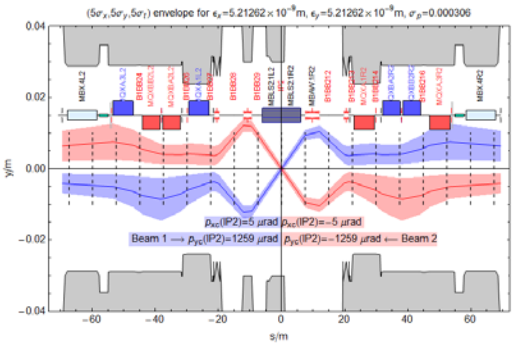


Fig 3: vertical orbit at LHC injection. under the influence of the ALICE spectrometer dipole and the external crossing angle bump.

The beam envelopes in the plot refer to 5 sigma beam size and show that a sufficient (i.e. more than 10 σ) separation is obtained at any bunch encounter.

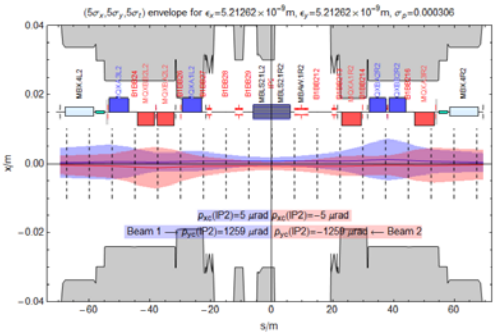


Fig 4: horizontal orbit in IR2 as result of the separation bump at LHC injection.

At 4 TeV luminosity operation the situation looks different: the hor. separation bump has to be collapsed to allow for collisions at the IP. In addition he ALICE internal bump scales down as 1/γ due to the constant magnet field and the external vertical crossing angle bump is optimised to obtain sufficient separation at the parasitic encounters, for the luminosity optics with β*=3m and an absolute emittance of ε_0=6.6*10^{-10} radm, given at that energy. It should be pointed out that in p-p operation mode, the external crossing angle bump is always chosen to support the crossing angle of the ALICE dipole.

E=4 TeV		
spectr. dipole	y'	±122.5µrad
ext. vert. crossing angle	y'	±145µrad
ext. hor. separation	Δx	0 mm

Table 2: Effect of internal and external bumps in IR2 at 4 TeV collision energy

For systematic reasons a polarity switch of the ALICE dipole is needed, to guarantee equal integrated luminosities in both spectrometer polarities. Therefore once per beam mode (p-p, Pb-Pb p-Pb or Pb-p) the polarity has to be changed and accordingly the external vertical bump. The impact on the LHCoperation is small as it leads to a quasi symmetric situation and no major impact is observed on the overall beam orbits - outside the bump regions. However - as indicated schematically by green dashed lines in Fig. 5 the tertiary collimators, TCT, have to be re-aligned for all LHC settings: injection, flat top and collision mode.

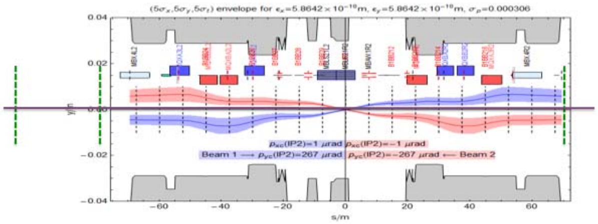


Fig 5: position of the TCT collimators: for operation with reverted ALICE polarity the beam orbits will be interchanged and the TCTs have to be re-aligned.

Proton-Pb Operation

In the run year 2013 a special operation mode using proton-lead collisions is foreseen. At injection the orbit situation is unchanged and the parameters of the separation and crossing angle bumps are the same as in table 1.

In collision however some modifications have to be taken into account: the beam optics will establish an optical function of β*=0.8m at the IP and for reasons of the detector acceptance the effective crossing angle has to be kept as small as possible [3]. The external vertical crossing angle bump therefore is used to counteract the internal spectrometer bump. The settings foreseen are summarised in table 3.

Table 3: Internal and external bump in IR2 at 4 TeV p-Pb operation

beam optics 4TeV	β*=80cm	
spectr. dipole	y'	+/-122.5μrad
ext. vert. crossing angle	y'	-/+ 62.5μrad

A new procedure is proposed for the polarity change of the ALICE dipole in this operation mode [4]: to save time and effort it is planned in case of a polarity switch to keep the external crossing angle at injection and during acceleration the same. The larger bunch distance of at least Δs=200ns will allow that kind of operation. Only at the end of the squeeze procedure the external vertical bump will be set to ±62.5 μrad, and as explained before counteract the spectrometer angle to keep the overall angle small. The advantage is that only in the collision mode the TCT collimators will have to be realigned, which saves time and effort. At injection and during acceleration the orbits outside the ALICE compensators will be untouched and the TCT settings are independent of the polarity. The drawback is that during the procedure of changing the external bump, a small beam separation of not more than 1σ cannot be avoided. It has been shown in machine studies with Pb-Pb in 2011 however that due to the limited bunch intensities foreseen in p-Pb mode the beam-beam effect is still small enough to be neglected.

In summary the foreseen procedure will be:

- injection: set external bump from y'=+170 to +145μrad at flat top independent of the spectrometer polarity
- collision: change external bump to ±62.5μrad with the sign chosen to counteract the spectrometer angle
- leading to an effective crossing angle of ±60μrad

LHC-B - IP8

While the accelerator lattice situation in IR8 is quite similar to the one in IR2 - a dipole spectrometer magnet and three compensator magnets that form a closed crossing angle bump (Fig 6) - there is an important qualitative difference between the two experiments: the LHCb dipole magnet deflects the LHC beams in the horizontal plane. And thus has a large impact on the beam crossing geometry, which is by the nature of the storage ring layout designed in the horizontal plane.

This in principle trivial statement has a large impact on the possible running scenarios for the LHCb experiment and therefore we dare to redraw the overall geometry of the LHC storage ring in Fig 7.

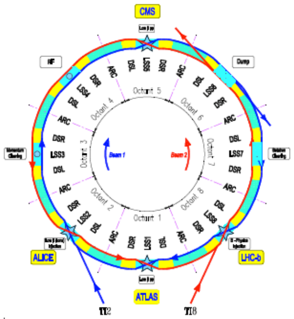


Fig. 7: LHC geometry

Under the influence of the separator / combiner dipoles D1 and D2 beam 1 is deflected in IR8 to the inner side of the ring, and accordingly will have an overall negative crossing angle. The layout of IR8, including the position of the LHCb dipole and its three compensators is shown in Fig. 6 and Fig 8 gives an impression of the LHCb spectrometer dipole magent.

As in the case of IR2, the LHCb dipole magnet is operated at constant field and so its influence is largest at LHC injection energy. However the field direction leads to a horizontal deflection of the LHC beams and the magnet strength is considerably stronger than in the case of ALICE.

Fig 8: LHCb spectrometer magnet

At injection energy and during acceleration, bunch collisions at the IP as well as at the parasitic encounters have to be avoided and thus the internal horizontal crossing angle provided by the experiment is supported by an external hor. crossing angle bump and a vertical parallel beam separation. Table 4 summarises the values.

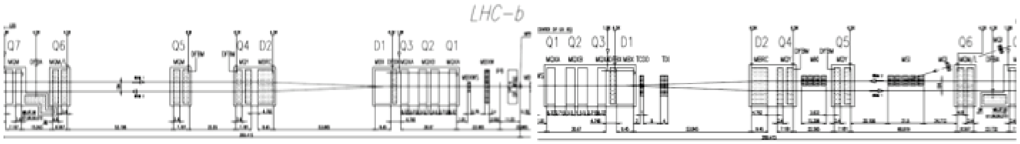


Fig 6 Lattice in IP8

Table 4: IR8 bumps at injection

E=450 GeV		
spectr. dipole	x'	±2100μrad
ext. hor. crossing angle	x'	±170μrad
ext. vert. separation	Δy	±2mm

As the LHCb dipole is powered at constant field, the deflecting effect on the beam scales down as 1/γ and at the flat top energy of 4TeV, used in 2012, we get a remaining crossing angle of x'=±235μrad.

The geometry of the beam orbits during collisions however looks quite different. While the vertical beam separation is collapsed to provide collisions at the interaction point, the horizontal external crossing angle bump is replaced by an equivalent vertical one, leading finally to a diagonal crossing plane [5]. This scheme, including the so-called diagonal levelling had been established and used routinely during the 2012 run in both LHCb polarities without problems. Difficulties arise however at LHC injection energy if the LHCb dipole is powered with "negative" polarity. Standard settings foresee a vertical separation of the beams of Δy=2mm at the IP, an internal crossing angle of 2.1mrad created by the LHCb dipole and its compensators and an additional external horizontal crossing angle of 170μrad. This combination allows for LHCb in "positive" polarity sufficient separation of the two beams at the IP and any parasitic encounter. The vertical and horizontal orbit and the beam envelopes, calculated for a normalised emittance of ε=3.0μradm and referring to 5 σ, are shown in Fig 9 and 10. The crosses in the plots indicate the location of the possible parasitic encounters for a bunch distance of 25ns - as planned for the next LHC run after LS1.

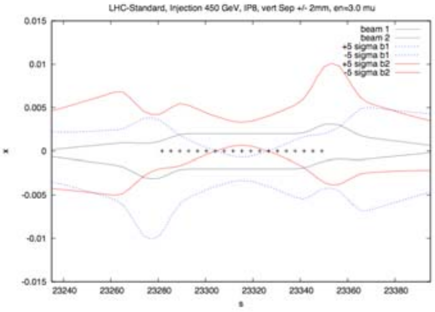


Fig 9: A parallel separation in the vert. plane delivers at injection 2mm beam separation at the IP and sufficient (more than 10σ) distance between the beams at the first three parasitic encounters

If on the contrary, LHCb is powered in "negative" polarity, the internal bump leads to a positive angle in beam 1 at IP8, deflecting the beam 1 to the outer side of the ring. This effect is balanced out by the LHCb compensator magnets, which bend the beam back to the inner side of the storage ring (Fig 11).

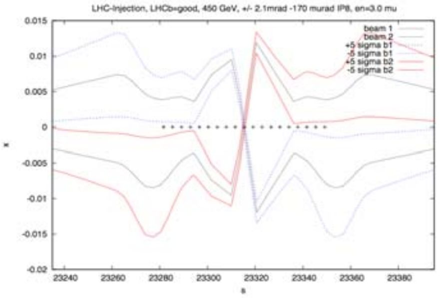


Fig 10: The horizontal beam orbits at injection are determined by the internal LHCb bump, x'=2.1mrad, and the external crossing angle bump. The net angle therefore depends on the LHCb polarity. The plot refers to the LHCb polarity that creates a negative angle of beam 1 in IP8, which corresponds to the "natural" geometry of the machine (see Fig 7).

However, due to the negative LHCb polarity, a second cross over, after the beam crossing at the IP cannot be avoided. For a bunch distance of Δs=50ns this cross over had been placed between two bunch locations.

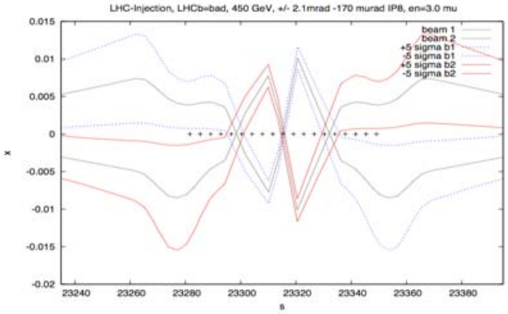


Fig 11: The horizontal beam orbits for the case of "negative" LHCb polarity. Beam 1 (blue) is deflected to the outer side of the ring, bent back by the LHCb compensators and crosses over with beam 2 before the separator dipoles D1 can take over. For 25ns operation this situation leads to detrimental collisions at injection and on the ramp.

In the case of the planned 25ns operation, this cross over will lead to beam collisions, that have to be avoided at injection and during the complete acceleration procedure. Therefore it is proposed here for injection and ramp to apply a different scheme: the unavoidable internal crossing angle bump will be combined with a horizontal separation of 2mm and a vertical external crossing angle bump. In a first step the situation had been studied with a vertical angle of y'=±170μrad, corresponding to the present horizontal situation (see table 5).

Table 5: new proposed crossing / separation scheme, the values correspond to the first test and are not applicable for the real machine.

E=450 GeV		
spcctr. dipole	x'	±2100µrad
ext. hor. separation	Δx	±2mm
ext. vert. crossing angle	y'	±170µrad

The orbits and beam envelopes are plotted in Fig. 12 - 14. As before the combination of separation and internal / external crossing angles avoid successfully bunch crossings at any encounter.

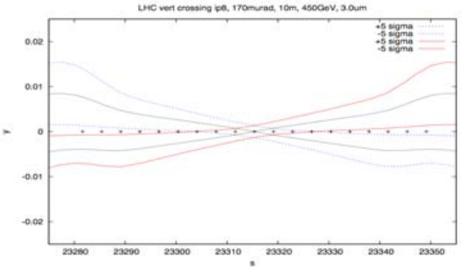


Fig 12: Beam orbits and 5σ envelopes in the vertical plane for the new proposed scheme. The applied vertical crossing angle avoids collisions already after the second parasitic encounter.

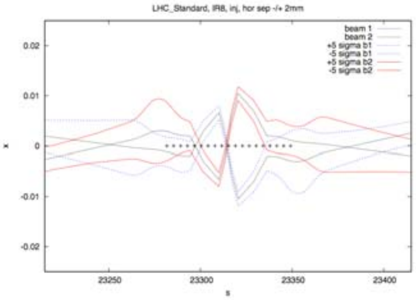


Fig 13: Beam orbits and 5σ envelopes in the horizontal plane for the new proposed scheme: the internal LHCb bump is powered in "positive" polarity. Beam separation is guaranteed by the crossing angle between parasitic encounters #2...#5. In addition the parallel horizontal separation of 2mm avoids collisions at the IP.

The plots of Figs 12-14 should directly be compared to the ones of the present scheme, Fig 8, 9. To complete the analysis of the new proposed crossing scheme for 25ns iteration, the LHC aperture model has been used to study the effect of the new bumps. Knowing, that in IP8 the beam screen in the mini beta triplets is oriented in the horizontal plane, and concluding that considerably more aperture is available in this plane compared to the vertical one, it is no surprise that the large vertical crossing angle that has been studied here as a first step, leads to considerable reduction in free aperture.

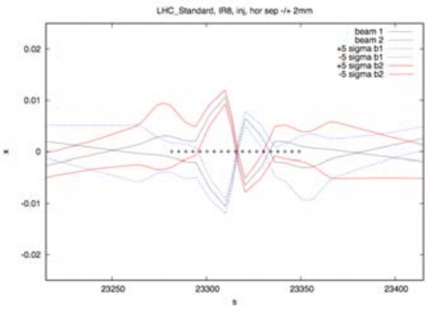


Fig 14: Beam orbits and 5σ envelopes in the horizontal plane for the new proposed scheme: the internal LHCb bump is powered in "negative" polarity, leading as before to a cross over. However due to the vertical crossing angle applied at the same time sufficient beam separation is guaranteed at that position in the vertical plane and the problem of unwanted collisions has been overcome.

The LHC beam screen that limits - inside the triplet - the free aperture to 29mm*24mm radius is shown in Fig. 15 and the result of the aperture calculations for the new proposed crossing scheme at 450 GeV injection and expressed in "n1" units is plotted in Fig 16. For comparison the LHC standard situation for the same energy and beam optics is shown in Fig 17.

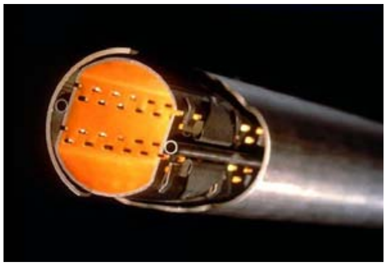


Fig 15: LHC beam screen, which is oriented in IR8 along the horizontal plane, leading to some aperture restrictions if a large vertical crossing angle is applied.

The considerable vertical angle of y'=±170µrad in IP8 leads to an aperture reduction from n1=7 to n1≈4.5, which is considered as not a marginal effect.

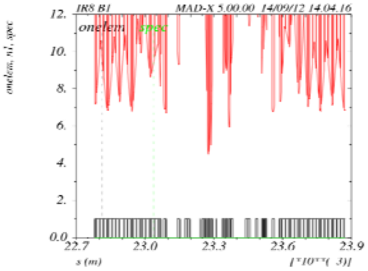


Fig 16: Aperture calculation - in units of "n1" for the new vertical crossing bump configuration

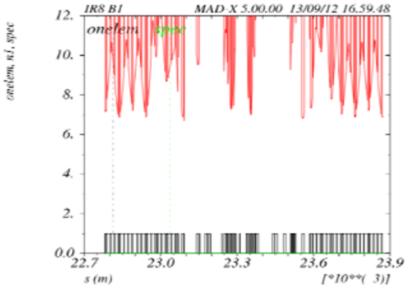


Fig 17: For comparison the figure shows - under the same conditions - the n1 aperture for the present horizontal crossing angle bump

To optimise the situation and regain free aperture, several issues have been studied:

- the use of the orbit correctors "mcbx" in the triplet magnets to flatten the crossing angle bump
- the reduction of the vertical crossing angle bump to the real needed beam separation
- a calculation of the aperture using more realistic values in the aperture model for the orbit fluctuations and beam emittances.

The effect of the first step mentioned, namely the use of the triple correctors to optimise the shape of the vertical crossing angle bump, is visualised in Fig 18. It is proposed to power the mcbx correctors in the first triplet quadrupole "Q1" in a way that - after reaching sufficient separation at the entrance of the triplet quadrupoles the beam envelopes follow a quasi parallel line, leading to nearly constant separation of $5+5\ \sigma$ and avoiding too high aperture need inside the triplets. The position of the additional coils and the direction of the kick are indicated by arrows in the plot. The required normalised strength of the correctors is well within the allowed range of the magnets.

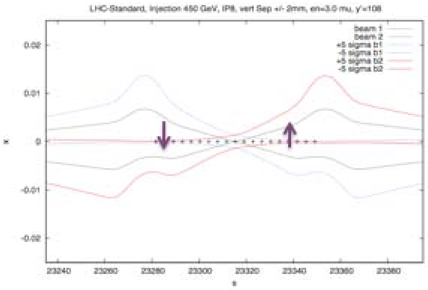


Fig 18: Optimised vertical crossing angle bump, using in addition the first orbit corrector in the triplet.

A realistic optimisation of the vertical crossing angle needed for sufficient beam separation has to be based on the actual position of the cross over. Following the results shown in Fig 14, the beams have to be separated from parasitic encounter #4 onwards.

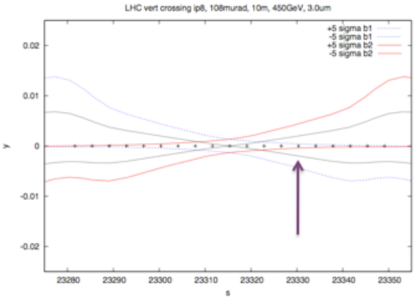


Fig 19: Optimisation of the vertical crossing angle to obtain maximum aperture and still sufficient beam separation at encounter #4.

At the encounters #1...#3, the beams are separated in the horizontal plane via the LHCb spectrometer effect. Accordingly a scan of the crossing angle bump had been performed to minimise the aperture need but still achieve this goal. The result is shown in Fig. 19, which shows a zoomed view of the beam envelopes at the first parasitic encounter locations. As before the beam envelopes refer to the standard injection optics and a normalised emittance of ε=3.0 μradm. The arrow in the picture indicates the location of the critical encounter point #4.

The third step in optimising the situation deals with realistic assumptions of the aperture model used. Mainly the maximum radial closed orbit uncertainty ("*cor*" parameter in the model) that is assumed for the simulations has a strong influence on the aperture result. For the optimised parameters explained above, Fig 20 shows the results of the aperture n1 assuming different values for the *cor* parameter. While the default value for *cor* is 4mm we compare the n1 results for a range of *cor* = 3.0mm ... 1.5mm. As expected the obtained n1 is increasing if the maximum orbit fluctuation is reduced. The dashed horizontal marker in the plots has been set to n1=8. For orbit fluctuation values of about *cor* = 2.0mm a value of $n1 \approx 7$ is obtained, considered as sufficient for the machine.

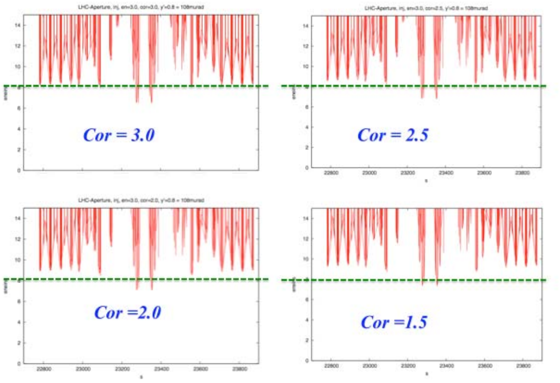


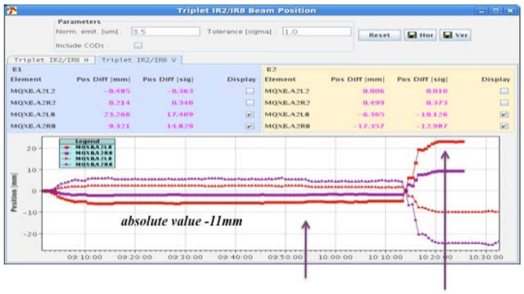
Fig 20: Aperture calculations for LHC injection optics, assuming a normalised emittance of ε_n=3.0 μradm.

Following the results summarised in Fig 20, an orbit fluctuation in the order of 2.0mm brings us back to an aperture value of n1 ≈7.

It might be worth to mention that for the real machine orbit fluctuations from fill to fill in the order of some tenth of a millimeter are observed and *cor* =2.0mm is still considered as a safe approach.

APERTURE MEASUREMENTS

During the last machine studies in the run year 2012 the actual vertical aperture in IR8 had been measured on beam and compared to the theoretically expected values. The main collimators were put to 4σ (referring the usual worst case emittance of ε=3.5μradm) and local bumps were steered until beam losses were observed in the IR8 triplet region. Fig 21 shows the measured difference orbit during the aperture scan. The difference between the two extreme values plus the beam size of 4σ (referring to ε=3.5μradm) gives the overall available aperture.



Norm. emit. [um]: 3.5

Tolerance [sigma]: 1.0

Include CODs: ☐

B1 Element	Pos Diff [mm]	Pos Diff [sig]	Display	B2 Element	Pos Diff [mm]	Pos Diff [sig]	Display
MQXB.A2L2	-0.485	-0.363	☐	MQXB.A2L2	0.006	0.010	☐
MQXB.A2R2	0.214	0.348	☐	MQXB.A2R2	0.499	0.373	☐
MQXB.A2L8	23.266	17.409	☑	MQXB.A2L8	-6.365	-10.126	☑
MQXB.A2R8	9.321	14.829	☑	MQXB.A2R8	-17.357	-12.987	☑

reaching the aperture limit in 1st direction -5.4mm

reaching the aperture limit in 2nd direction +23.3mm

Fig 21: Orbit reading inside Q2 of the LHC triplet during the aperture scan

$$a = \Delta y + 2 \cdot 4\sigma = \Delta y + 8\sqrt{\varepsilon\beta}$$

$$a = 28.7\,mm + 8 * \sqrt{270m * 3.5\mu m} = 40.8mm$$

$$r_a = 20.4\,mm$$

The result obtained above is based on the orbit readings of the beam position monitors and suffers from their considerable non-linearities.

A cross check therefore has been performed based on the theoretical bump amplitudes as calculated by MADX. The aperture limits have been observed for a bump amplitude of ±11mm at IP8. Following the MADX calculation this corresponds to an amplitude of Δy=±17.8mm in Q2, which is, according to the theoretical bump shape in Fig 22, the bump maximum.

Referring to these calculations, an overall vertical aperture of

$$r_a = 17.8mm + 4\sigma = 23.8mm$$

is obtained, a little bit larger than the measurements based on the BPM readings, and in astonishingly good agreement with the beam screen dimensions (r_y= 24mm).

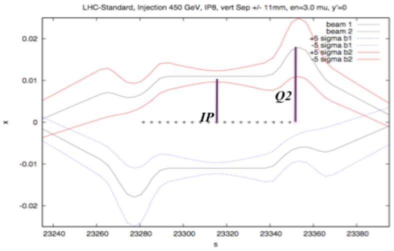


Fig 22: Bump amplitude and beam amplitudes for the bump used to measure the available aperture in IR8.

The external vertical crossing angle bump (Fig 19) needed to obtain sufficient separation at the parasitic encounters leads to an amplitude of Δy=6.8mm at the location of Q2. In other words, the remaining margin between beam orbit and the measured aperture limit corresponds to roughly 17mm or 12σ (ε=3.0μradm) at that position, which looks reasonably comfortable.

SUMMARY AND CONCLUSIONS

Spectrometer operation in IR2 does not have a big influence on the LHC operation and polarity switches are foreseen once per run mode, so in relatively rare occasions. Still a faster procedure is foreseen in p-Pb or Pb/Pb operation mode for the ALICE dipole polarity switch: the external bump will be kept constant for both spectrometer polarities, at injection and on the ramp until flat top. Only for the beta squeeze operation, i.e. going into luminosity conditions the external bump will be put to its final value and counteract the internal ALICE bump. As a consequence only in this very last file the TCT collimators have to be re-aligned. For so-called "negative" ALICE polarity this means however that during this process the bump will pass through zero crossing angle leading to very small beam separation for a moment Δy≈1σ). For the low bunch intensities foreseen during p-Pb runs it has been shown during the Pb-Pb run 2011 not to be a harmful procedure.

The spectrometer operation in IR8 is more problematic as the LHCb dipole field has a horizontal effect on the LHC beams. For the so-called "negative" polarity the deflecting effect is opposite to the natural beam geometry and leads to a second bunch cross over after the IP. Especially at 450 GeV injection energy due to the large beam emittance, this cross over cannot be avoided. In 50ns operation it is placed between two bunch positions, in 25ns however a harmful bunch collision will occur. To overcome this problem a new beam crossing and separation scheme is proposed: The internal spectrometer bump is combined with a horizontal beam separation to avoid collisions at the IP and a vertical crossing angle bump to establish sufficient separation at the parasitic encounters. As the beam screen in IR8 is oriented for horizontal crossing angles a simple swapping of the horizontal and vertical settings leads to small aperture values and the whole beam separation scheme had to be re-optimised. Assuming not too pessimistic orbit fluctuations and using the triplet correctors to optimise the vertical bump a scenario is proposed that will give sufficient beam separation and comfortable aperture at the same time.

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