

Large Hadron Collider Project

LHC Project Report 1174

LHCb Injected Beam Accidents

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Abstract

The LHCb (point 8) interaction region is sensitive to beam orbit errors arising from magnet setting errors on injection. In this report, beam accident scenarios under injection for LHCb are described, focusing on ultra- fast error injection scenarios for the interaction straight correctors and dipoles. Beam 1 and beam 2 accident scenarios are considered, where the errors can lead to beam orbits striking the LHCb vacuum chamber or elements of the machine. The required thresholds for magnet current interlocks are calculated to avoid machine and detector risk.

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1 Introduction, simulation procedure and scenarios

The high beam intensities of the LHC require control of beam losses, and a detailed consideration of possible beam accident scenarios. In particular beam losses in the experimental insertion could result in significant damage to the detector systems. Of particular concern are ultra-fast losses, which arise in less than 1 turn of the machine, and should be contrasted to circulating beam failures, which generally occur on a longer timescale. These injection turn scenarios can arise from incorrectly set magnets on injection or from faulty hardware, and require controlled injection procedures and magnet current interlocks. In this report, beam accident scenarios are considered for the LHCb interaction region on injection, with a retracted VELO [1]. The accident scenarios are ultra-fast, and correspond to the potential loss of a pilot bunch of 5×10^9 protons on the turn of injection due to an error in the setting of a magnet. Magnet failures will be considered in future work. The techniques used and conclusions drawn for point 8 are also applicable to point 2 and the machine protection of ALICE, which will be contained in a separate report.

The LHCb accident scenarios are dependent on the geometrical aperture in the interaction region, which is composed of the vacuum chamber and the machine element apertures. The LHCb interaction region contains an 18m conical beam pipe [2], consisting of three cone-shaped segments, and running through the detector. This beam pipe provides the principle aperture restriction in this region. The VELO sets the aperture restriction at the interaction point [1], and provides an asymmetrical structure about the IP, with the 1st station of the VELO is located at -17.5cm, and the final station is located at +75cm. The distance of approach to the beam at injection is 30mm (the VELO is wound into 5mm for collisions). The VELO has a secondary vacuum, which connects to the primary machine vacuum, and the 18m LHCb vacuum chamber, through a 2mm thick window. The next significant aperture restriction begins 2.25m from the IP, where the beam pipe becomes 50mm in diameter for 0.25m, and then around 20m from the IP, where the apertures of MBXWS and Q1 begin. The aperture model used for this work is shown in figure 1, where the solid line shows the vacuum chamber and the stars show the aperture restrictions from magnetic elements (both are plotted as a cross-check of the aperture model). The aperture model is automatically generated from the LHCb beam pipe engineering data table at [3], and the beam line element apertures are taken from the LHC optics [4]. Figure 2 shows the magnets in the interaction region relevant to this study. The final triplet quadrupoles Q1 around IP8, MQXA.1L8 and MQXA.1R8, provide an aperture restriction dependent on the orientation of the beam screen. These magnets have a beam screen in the V orientation, with a circular aperture of 48mm in the horizontal plane and a flat aperture of 38mm in the vertical plane [5]. This smaller flat aperture will impact the computation of vertical orbit distortion and beam loss.

The LHCb spectrometer dipole (MBLW) is located about 5m to the right of IP8, and is designed to give a deflection of $181 \mu\text{rad}$ at the top energy of 7 TeV. The field is located in the vertical plane, and hence the magnet gives a horizontal deflection. MBLW is 1.92m long [6] and is normal conducting with a peak field of 1.24 T. The integrated field is 4.2 T·m, which would give a deflection of 2.82 mrad at injection; hence the magnet is ramped. The spectrometer is also required to work with the opposite polarity to reduction of LHCb analysis of systematic errors. The strong effect on (both) beams is compensated by three additional horizontal corrector magnets which, when acting with the experimental dipole magnet, give a closed asymmetrical bump across the IP. This bump is independent of the optics, as there are no magnetic elements between the magnets. The bump magnets are MBXWH, located at -5m, (with a bend angle of $181 \mu\text{rad}$, positive and opposite MBLW),

and two much weaker magnets at $\pm 20\text{m}$, called MBXWS with a bend strength of $\pm 46\text{ }\mu\text{rad}$. The bump gives a residual IP crossing angle of $135\text{ }\mu\text{rad}$. Note there is an additional crossing angle bump imposed on LHCb in the horizontal plane, to reduce parasitic bunch collisions [6], and a vertical plane parallel separation bump for injection. The injection optics horizontal and vertical orbit bumps across LHCb for beam 1 are shown in figure 3. Note that horizontal spectrometer compensation bump is superimposed on a horizontal crossing angle bump, which gives a set of operation constraints [6]. The study in this report of compensator dipole errors shall focus on wrong settings at injection of the strongest compensator magnet, MBXWH, due to the high field strength of this magnet. This magnet, nominally set to $181\text{ }\mu\text{rad}$ in the horizontal plane at injection, and could be set to any strength up to the maximum of $4.2\text{ T}\cdot\text{m}$, and/or with reversed polarity. Hence the orbit error about the closed orbit will be in the horizontal plane. Further errors can occur when the corrector coils attached to the low- β quadrupole Q1, MCBXH and MCBXV, are incorrectly set on injection. These orbit correctors play a role in setting the beam crossing angle and parallel separation on injection, with MCBXH involved in creating the beam crossing angle at the IP, and MCBXV part of creating the vertical parallel separation of 2mm between the beam at the IP for injection. The hardware parameters and angles on injection are shown in table 1. The possible orbit excursions when these coils are set up to their maximum field on injection will occur in the horizontal plane (MCBXH) and in the vertical plane (MCBXV).

The incorrect settings of the D1 (MBX.4L8) and D2 (MBRC.4L8) horizontal separation dipole magnets can also cause beam accident scenarios to hit elements of the interaction region. These magnets are used to separate and re-combine the beams, and cause the transition from separate beam pipes to a shared beam pipe. They are both 9.45m long and are superconducting, with a single set of coils in the cryostat (in contrast to the magnets in points 1 and 5, where D1 is normal conducting). The bend angles are -0.001533 rad for D1 and $+0.001533\text{ rad}$ for D2, for beam 1, and the opposite for beam 2. The role of D2 is to send the beam towards the centre of the ring, and D1 provides an opposite kick towards the outside of the ring. The maximum bend angle is 0.02383896 rad for the injected beam at maximum magnet current.

Coil name	Length [m]	Angle [μrad]
MCBXH	0.45	1011
MCBXV	0.48	1042

Table 1: The lengths and maximum bend angles at 450 GeV for the H and V corrector coils in MCBX in Q1 [8].

The simulations are made for LHC injection optics version 6.5, with MADX [7], and are made for both beam 1 and beam 2. The method of orbit analysis follows [8], where the orbit error from the incorrectly set magnet is modelled by the addition to the lattice of a virtual corrector close to the wrongly set magnet. The wrongly set magnet is then kept at the nominal strength. This method requires the addition of two further virtual corrections, downstream of the error location, which correct the orbit distortion back to the nominal orbit. This ensures the optics for the rest of the machine are undisturbed, and the orbit distortion from the error is confined to the region close to the error. The justification is that the machine orbit correction will correct the orbit deviation, and only local deviations are relevant to interaction region accident scenarios. In this work, the

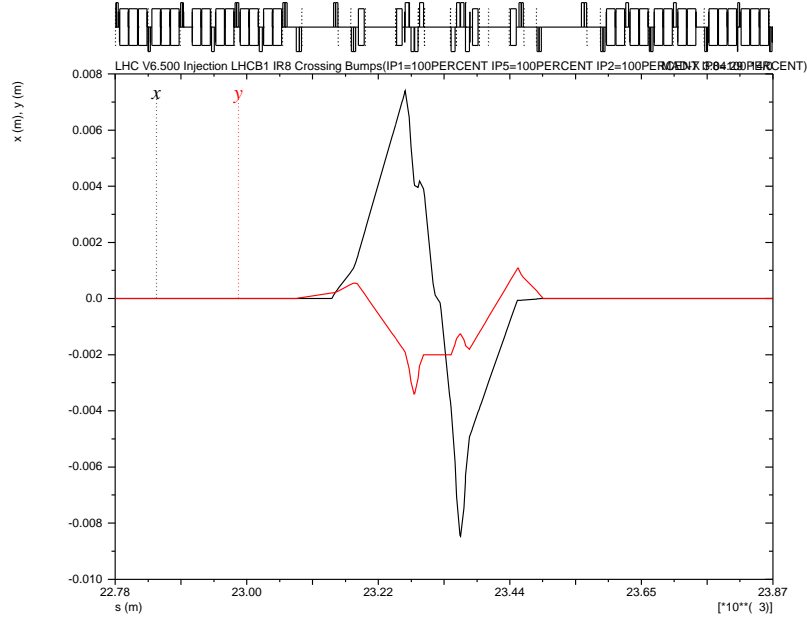


Figure 3: The injection optics horizontal and vertical orbit bumps across LHCb for beam 1 and v6.5 optics. Note the crossing angle for LHCb is in the horizontal plane.

MBXWH is a wrong setting of nominal to injection, up to the maximum strength of the magnet, on the nominal polarity side. This corresponds to an angle of $+181 \mu\text{rad}$ (6.4% of maximum), to an angle of $+2.82 \text{ mrad}$ (100% of maximum) for MBXWH. Note the maximum angle at 450 GeV corresponds to an angle of $181 \mu\text{rad}$ at the top energy. Scenario 2 is similar to scenario 1, with the polarity of the magnet reversed. Hence the dipole angle ranges from $-181 \mu\text{rad}$, to the maximum angle of -2.82 mrad for MBXWH. Scenario 3 considers the case of a zero current into the magnet (the most probable scenario for machine startup), and scenario 4 presents the situation of an inverted power supply (opposite polarity). These scenarios can be applied to all the wrongly set magnets considered in this work. For example, scenario 3 for MCBXH corresponds to zero current in this particular corrector.

Scenario	Description	Angle of MBXWH
1	Nominal to + maximum	$+181 \mu\text{rad} \rightarrow 2.82 \text{ mrad}$
2	Reverse polarity to - maximum	$-181 \mu\text{rad} \rightarrow -2.82 \text{ mrad}$
3	Turned off	0mrad
4	Reversed polarity	$-181 \mu\text{rad}$

Table 2: The magnet scenarios, using the corrector MBXWH as an example. Note scenario 1 corresponds to a corrector strength with it's nominal polarity. The nominal setting for MBXWH corresponds to $+181 \mu\text{rad}$ on injection, and the maximum strength is 4.2 T·m.

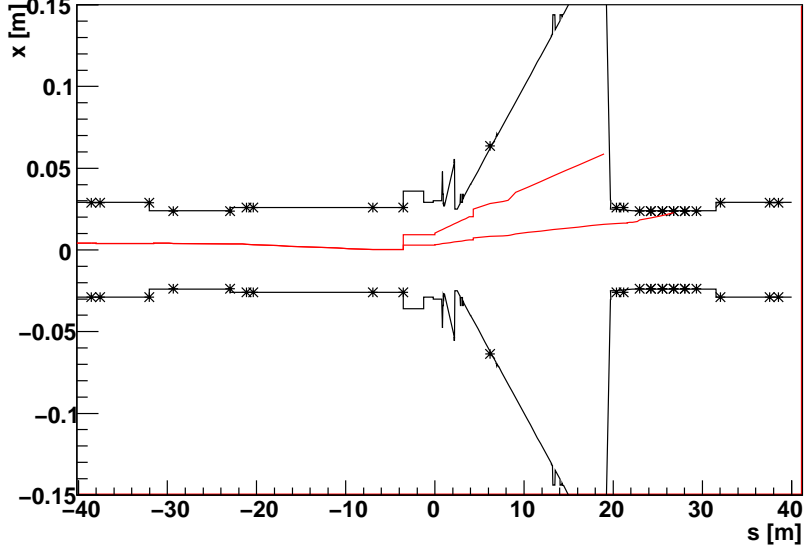


Figure 4: The range of MBXWH corrector settings which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 1 and beam 1.

2 Beam accident scenario results for beam 1

In this section, the wrong settings of the MBXWH, MCBXH, MCBXV, MBX and MBRC are considered on the injection turn for beam 1 and for accident scenarios 1 to 4.

2.1 MBXWH (beam 1)

The results for scenario 1 for MBXWH with beam 1 are shown in figure 4, where the corrector is set from the nominal injection strength (6.4% of maximum) to maximum strength. This corresponds to an angle of $+181 \mu\text{rad}$ to $+2.82 \text{ mrad}$. The range of magnet settings shown by the cone show those which could be dangerous to the interaction region beam pipe or elements. The calculations show this dangerous region is defined by MBXWH being set to an angle of $981 \mu\text{rad}$ to the maximum angle, which is equivalent to 34.8% to 100% of maximum strength (recall 6.4% is nominal at injection). The figure shows the beam can hit the LHCb conical beam pipe, the spectrometer corrector MBXWS or, for a few settings of the magnet, the beam pipe of Q1 (the beam trajectory can hit the element MQXA). The situation for LHCb can be contrasted to a similar study performed for ATLAS [8], where a similar range of beam accidents were considered for the main orbit correction magnet MCBX (attached to Q1). It was found the mis-setting of the magnet resulted in pilot beam loss in the ATLAS beam pipe or the TAS collimator. There is no TAS collimator in LHCb, and hence there is possible beam loss in MBXWS or MQXA.

The results for scenario 2 are shown in figure 5, where the corrector is set from the reversed polarity nominal injection strength (6.4% of maximum) to reversed polarity maximum strength. This corresponds to an angle of $-181 \mu\text{rad}$ to -2.82 mrad . The range of magnet settings in the cone show those which could be dangerous to the interaction region beam pipe or elements. The calculations show this dangerous region is defined by MBXWH being set to an angle of $-381 \mu\text{rad}$ to maximum, which is equivalent to -13.5% to -100% of maximum strength (recall 6.4% is nominal at injection). The difference to scenario 1 is that the beam centroid angle is negative immediately before the IP ($-35 \mu\text{rad}$). The figure shows the beam can potentially hit the LHCb conical beam pipe, or the beam

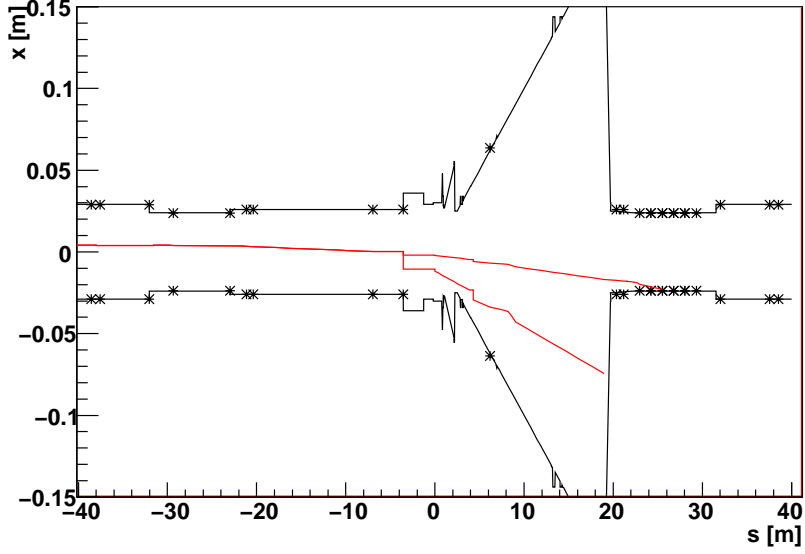


Figure 5: The range of MBXWH corrector settings which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 2 and beam 1.

pipe of Q1 (MQXA), for certain settings of the corrector.

Figure 6 show the resulting beam orbit distortion for scenario 3, when MBXWH is turned off for injection. The calculation shows there is no danger to the experiment from this scenario.

Finally, figure 7 show the resulting beam orbit distortion for scenario 4, when MBXWH has an inverted power supply. The calculation shows there is no danger to the experiment from this scenario.

In summary for MBXWH, the scenarios of zero current in the magnet or opposite nominal polarity have no risk for the experimental region. However, mis-setting the magnet on injection to higher magnet currents could pose a risk to the LHCb beam pipe or adjacent magnets. The results presented here can be used as a starting point to assess the potential impact of the loss of a pilot bunch under the magnet error scenarios presented, and should be used to guide the setting on software magnet current interlocks.

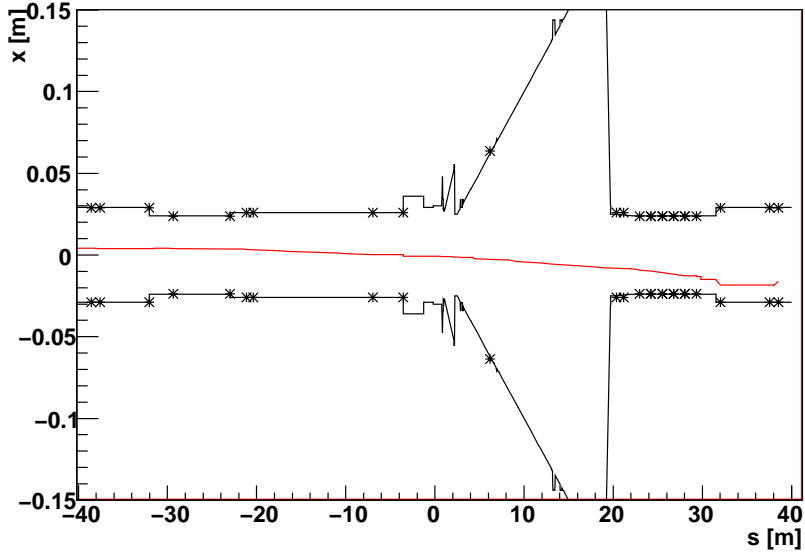


Figure 6: The range of MBXWH corrector settings, which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 3 and beam 1, corresponding to a zero magnet current. This scenario is not dangerous for the interaction region.

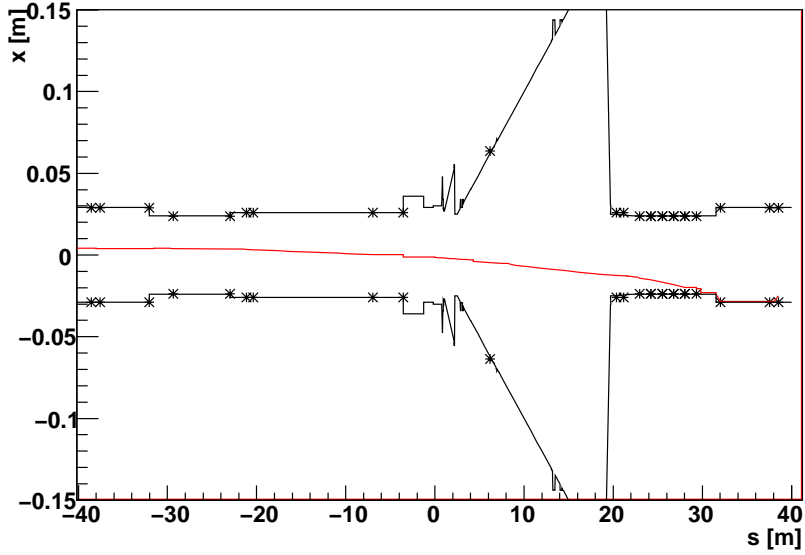


Figure 7: The range of MBXWH corrector settings, which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 4 and beam 1, corresponding to a reversed nominal polarity setting. This scenario is not dangerous for the interaction region.

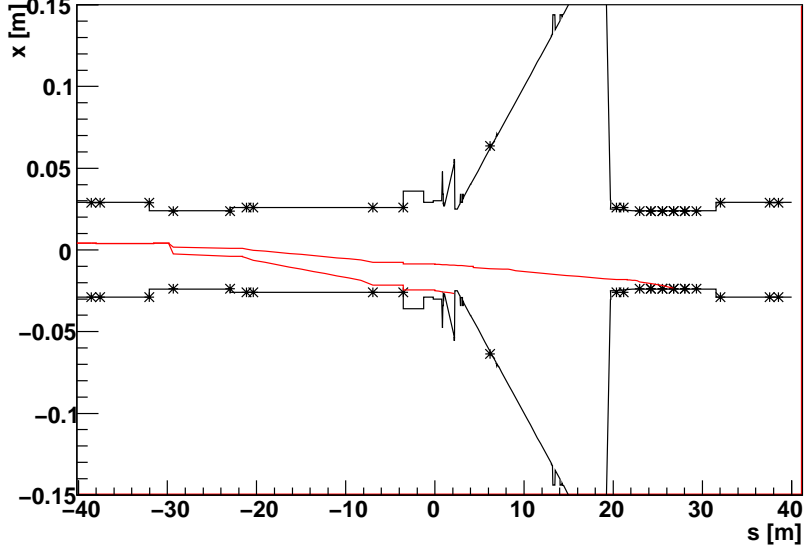


Figure 8: The range of MCBXH corrector settings, which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 1 and beam 1. Note the horizontal plot range is -30m to 40m, in contrast to MBXWH.

2.2 MCBXH (beam 1)

The results for scenario 1 with beam 1 for MCBXH are shown in figure 8, where the corrector is set from the nominal injection strength to maximum strength. This corresponds to an angle of $-5\mu\text{rad}$ to $-1011\mu\text{rad}$. The range of magnet settings in the cone show those which could be dangerous to the interaction region beam pipe or elements. The calculations show this dangerous region is defined by MCBXH being set to 35.3% to 100% of maximum strength, with negative (nominal) polarity. The figure shows the beam can hit the LHCb conical beam pipe, the spectrometer corrector MBXWS or, for a few settings of the magnet, the beam pipe of Q1 (the beam trajectory can hit the element MQXA).

The scenario 2 results for MCBXH are shown in figure 9. The range of dangerous currents is -54.5% to -100% (recall the magnet is nominally set at $-5\mu\text{rad}$, so these currents correspond to a positive bending angle), which causes a vacuum chamber hit at positive x . The nominal beam horizontal centroid angle at this magnet is $-170\mu\text{rad}$, and hence the scenario 2 threshold magnitude is much larger than scenario 1 (i.e. the beam needs to be bent to a positive angle by the reversed polarity magnet much more than the normal polarity magnet, bending it down).

In common with MBXWH, there is no danger to the experimental areas for scenarios 3 and 4 for MCBXH, as shown in figure 10 for scenario 3.

2.3 MCBXV (beam 1)

The results for scenario 1 with beam 1 for MCBXV are shown in figure 11, where the corrector is set from the nominal injection strength to maximum strength. This corresponds to a vertical bend angle of $-48\mu\text{rad}$ to $-1042\mu\text{rad}$. The range of magnet settings in the cone show those which could be dangerous to the interaction region beam pipe or elements. The calculations show this dangerous region is defined by MCBXV being set to 30.1% to 100% of maximum strength, with negative (nominal) polarity. The figure shows

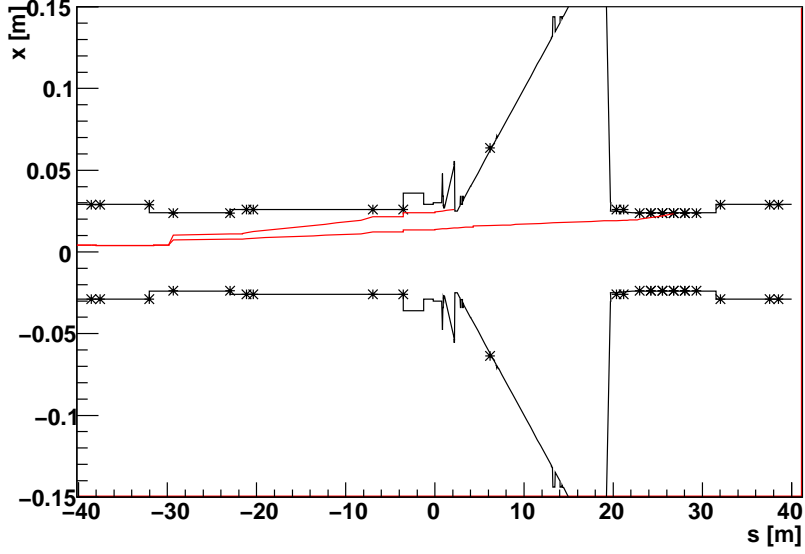


Figure 9: The range of MCBXH corrector settings, which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 2 and beam 1.

the beam can hit the LHCb conical beam pipe, the spectrometer corrector MBXWS or, for a few settings of the magnet, the beam screen of Q1 (the beam trajectory can hit the element MQXA). Note the aperture of Q1 is reduced to 38mm in the vertical direction by the beam screens.

The scenario 2 results for MCBXV are shown in figure 12. The range of dangerous currents is -27.9% to -100% (recall the magnet is nominally set at $-48\mu\text{rad}$, so these currents correspond to a positive bending angle), which causes a vacuum chamber hit at positive y.

In common with MBXWH, there is no danger to the experimental areas for scenarios 3 and 4 for MCBXV.

2.4 MBX.4L8 [D1] (beam 1)

The high field strength of MBX.4L8 means the incorrect settings can pose considerable danger of machine vacuum chamber around LHCb. It is nominally set to -1.533 mrad on injection (equal to 6.4% of maximum current), and a scenario 1 mis-settings of at least -2.0 mrad on injection would send the beam into Q1 on the near side of the experiment, MQXA.1L8, at large positive x. This corresponds to 8.5% of maximum current, and arises because a larger negative bend sends the beam to the outside of the vacuum chamber i.e. to larger positive x. Larger mis-setting would cause beam loss in elements close to MBX.4L8. The MBX.4L8 mis-setting which causes beam loss in MQXA.1L8 is shown in figure 13. It should be noted that D1 is a very strong magnet, and a small change in current can cause a beam accident. The studies for D1 and D2, which are errors on dipole magnets, need to take care of the MADX and LHC coordinate system. The MADX coordinate system coincides with beam 1, where moving out of the ring (away from the centre) corresponds to positive x and a positive dipole bend angle bends to the right, or negative x. Conversely positive angle corrector magnet increases p_x and hence the spatial coordinate x after a drift. Therefore an increased current in a positive bend dipole is modelled with a negative angle corrector for beam 1, and vice versa.

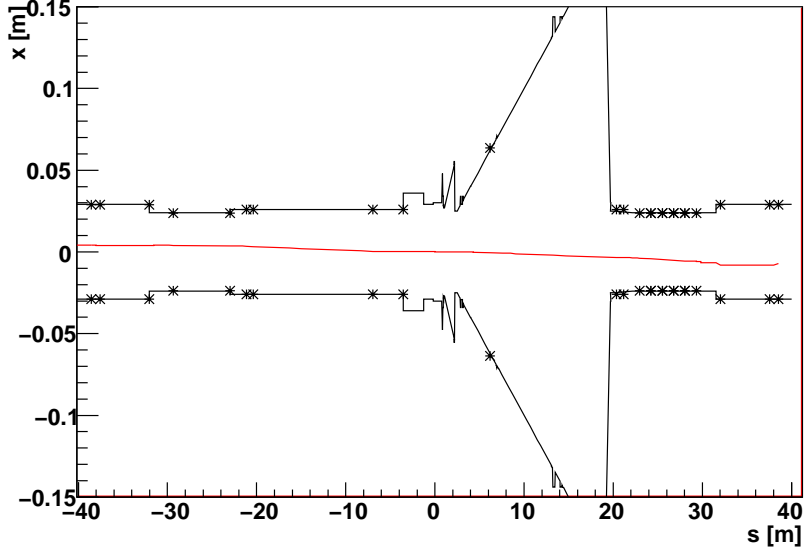


Figure 10: The range of MCBXH corrector settings for corrector setting scenario 3 and beam 1, corresponding to a zero magnet current. This scenario is not dangerous for the interaction region.

For scenarios 2, 3 and 4, the beam will impact in the first aperture restriction on the far side of the IR, MQXA.1R8, where the diameter is 48mm, if the bending field of MBX.4L8 drops below -1.18mrad, which corresponds to 4.9% of maximum current. Therefore scenarios 2, 3 and 4 (magnet turned off and any reverse polarity) will cause beam loss in the machine or detector vacuum chamber. The beam orbit arising from a magnet current of just below 4.9% of maximum (just below -1.18mrad) is shown in figure 14, showing a beam impact in MQXA.1R8. This arises because a reduced field negative bend will move the beam to the inside of the ring i.e. to smaller x . Note the beam will miss MQXA.1L8 in this scenario.

2.5 MBRC.4L8.B1 [D2] (beam 1)

In a similar way to MBX.4L8, the high field strength of MBRC.4L8.B1 means the incorrect settings can pose considerable danger of the experimental region and machine beam pipe of LHCb. It is nominally set to +1.533 mrad on injection (equal to 6.4% of maximum current), and a scenario 1 mis-settings of at least 2.10 mrad on injection would send the beam into Q1 on the near side of the experiment, MQXA.1L8, which forms the first aperture restriction after MBRC.4L8 and effectively screens the IR region from errors in this magnet. The beam strikes at negative x , and D2 is a positive bend magnet and an excess current will bend the beam to the right i.e. to negative x . This corresponds to 8.8% of maximum current. This accident scenario is shown in figure 15.

For scenarios 2, 3 and 4, the beam will impact in the first aperture restriction after the magnet, MQXA.1L8, where the diameter is 48mm, if the bending field of MBRC.4L8 drops below +1.12 mrad, which corresponds to 4.7% of maximum current. Therefore scenarios 2, 3 and 4 (magnet turned off and any reverse polarity) will cause beam loss in the machine or detector vacuum chamber. This is shown in figure 16, where the beam loss occurs on MQXA.1L8, which effectively screens the interaction region elements from beam loss in these scenarios.

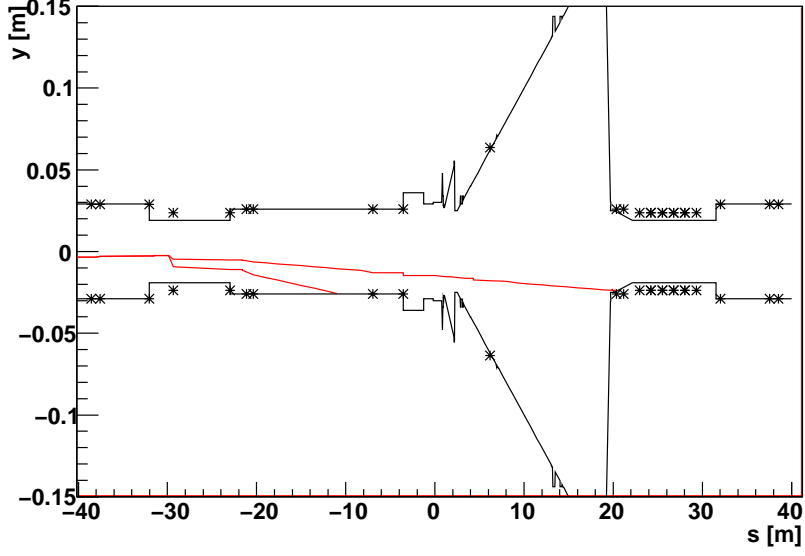


Figure 11: The range of MCBXV corrector settings, which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 1 and beam 1. Note the horizontal plot range is -30m to 40m, in contrast to MBXWH.

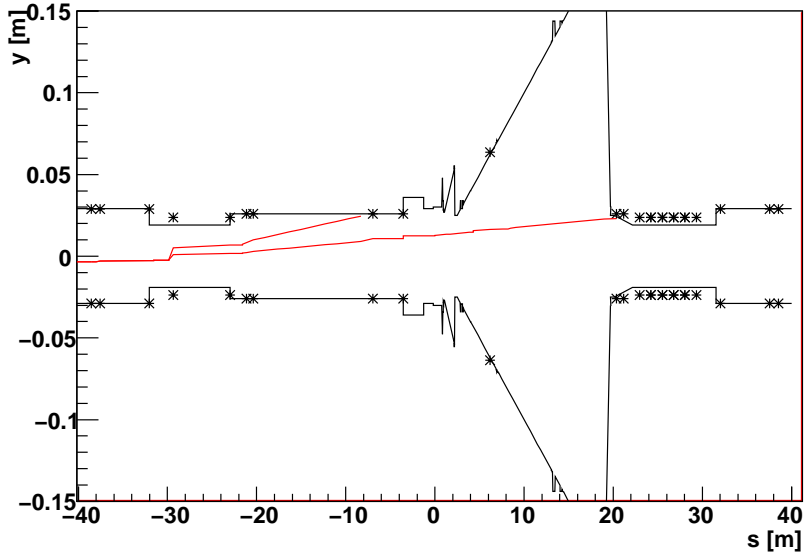


Figure 12: The range of MCBXV corrector settings, which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 2 and beam 1. Note the horizontal plot range is -30m to 40m, in contrast to MBXWH.

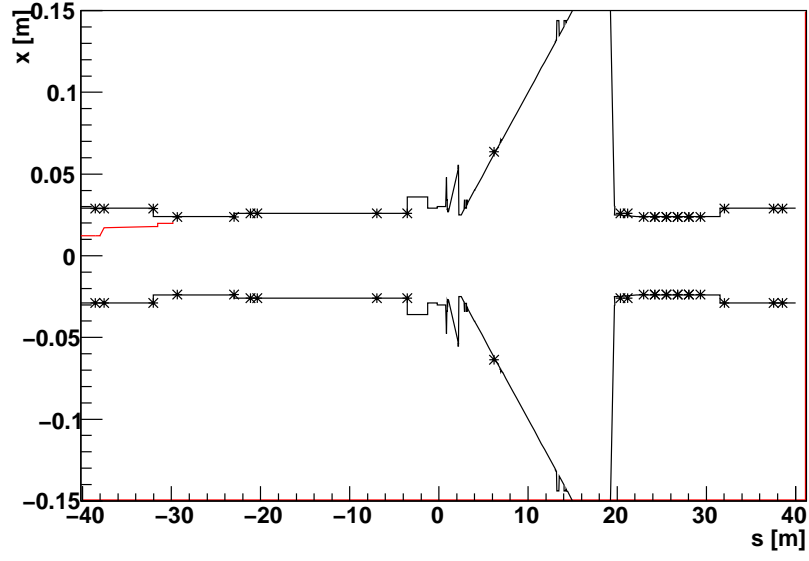


Figure 13: A possible MBX.4L8 dipole settings which is dangerous for the LHCb beam pipe and interaction region magnets, for magnet setting scenario 1 and beam 1.

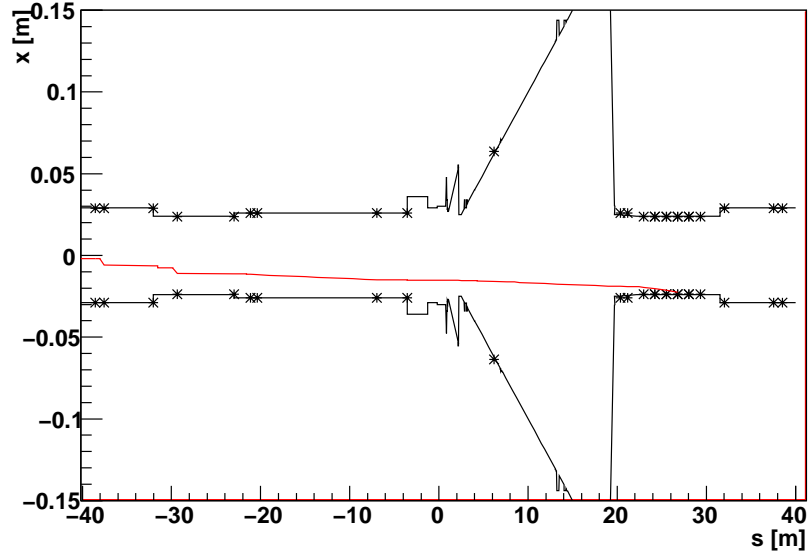


Figure 14: A possible MBX.4L8 dipole settings which is dangerous for the LHCb beam pipe and interaction region magnets, for magnet setting scenario 2 and beam 1.

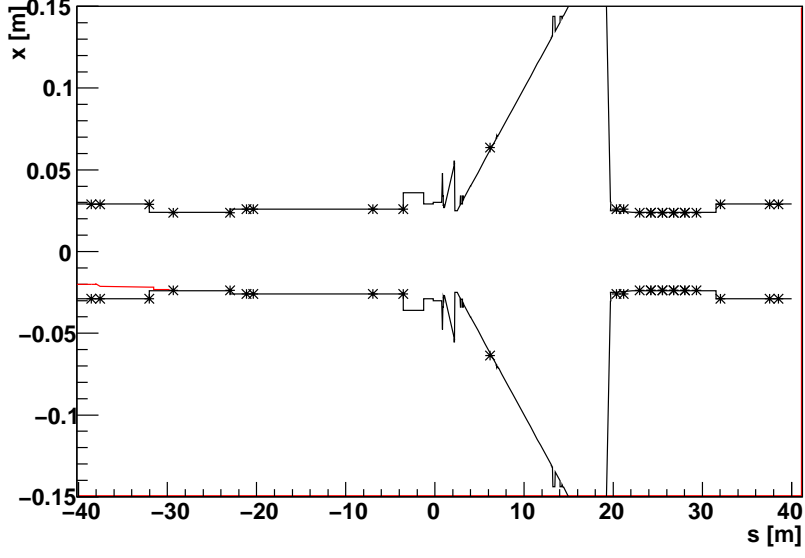


Figure 15: A possible MBRC.4L8 dipole settings which is dangerous for the LHCb beam pipe and interaction region magnets, for magnet setting scenario 1 and beam 1. The beam strike is on the left side of the figure.

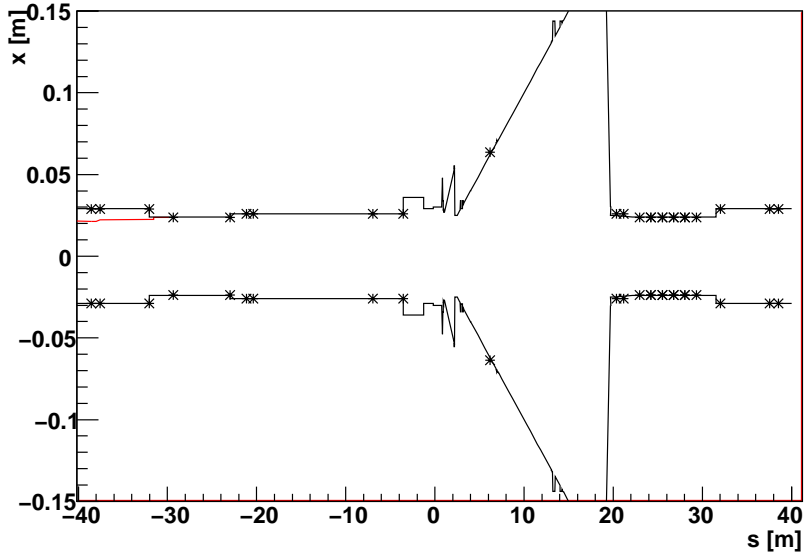


Figure 16: A possible MBRC.4L8 dipole settings which is dangerous for the LHCb beam pipe and interaction region magnets, for magnet setting scenario 2 and beam 1. The beam strike is on the left side of the figure.

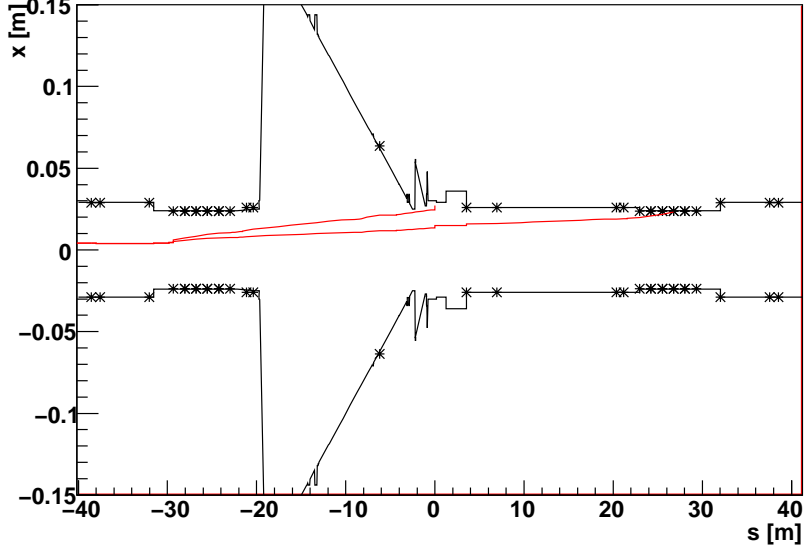


Figure 17: The range of MBXWH corrector settings which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 1 and beam 2.

3 Beam accident scenario results for beam 2

In this section, the wrong settings of the magnets MCBXH, MCBXV, MBX and MBRC are considered on the injection turn for beam 2 and for accident scenarios 1 to 4. These scenarios are particularly interesting for beam 2 as this beam is injected immediately upstream of point 8.

3.1 MCBXH (beam 2)

The results for scenario 1 with beam 2 for MCBXH are shown in figure 17, where the corrector is set from the nominal injection strength to maximum strength. This corresponds to an angle of $+5\mu\text{rad}$ to $+1011\mu\text{rad}$. The range of magnet settings in the cone show those which could be dangerous to the interaction region beam pipe or elements. The calculations show this dangerous region is defined by MCBXH being set to 54.5% to 100% of maximum strength, with positive (nominal) polarity. The figure shows the beam can hit the final triplet magnet MQXA.1L8 or parts of the LHCb conical beam pipe.

The scenario 2 results for MCBXH are shown in figure 18. The range of dangerous currents is -32.8% to -100% (recall the magnet is nominally set at $+5\mu\text{rad}$, so these currents correspond to a negative bending angle). Note the current limits are broadly equivalent to beam 1 for MCBXH, with an inversion between scenarios 1 and 2 due to the nominal angle being the opposite sign for beams 1 and 2.

Scenarios 3 and 4 for MCBXH beam 2 are shown in figures 19 and 20. There is no danger to the experimental regions from these accident scenarios.

3.2 MCBXV (beam 2)

The results for scenario 1 with beam 2 for MCBXV are shown in figure 21, where the corrector is set from the nominal injection strength to maximum strength. This corresponds to a vertical bend angle of $48\mu\text{rad}$ to $1042\mu\text{rad}$. The range of magnet settings in the cone show those which could be dangerous to the interaction region beam pipe or elements. The calculations show this dangerous region is defined by MCBXV being set to

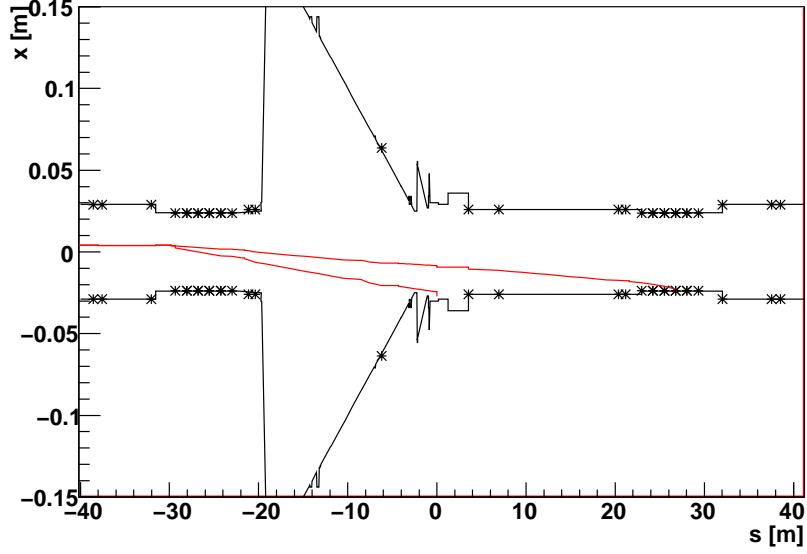


Figure 18: The range of MBXWH corrector settings which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 2 and beam 2.

33.2% to 100% of maximum strength, with positive (nominal) polarity. The figure shows the beam can hit the LHCb conical beam pipe, the spectrometer corrector MBXWS or, for a few settings of the magnet, the beam screen of Q1. Note the aperture of Q1 is reduced to 38mm in the vertical direction by the beam screens.

The scenario 2 results for MCBXV are shown in figure 22. The range of dangerous currents is -28.4% to -100% (recall the magnet is nominally set at $48\mu\text{rad}$, so these currents correspond to a negative bending angle). The current limits are set the narrow aperture of the beam screen in Q1 (38mm), where the first beam strike occurs as current increases. The beam can also strike the LHCb vacuum chamber.

Scenarios 3 and 4 for MCBXV beam 2 are shown in figures 23 and 24. There is no danger to the experimental regions from these accident scenarios.

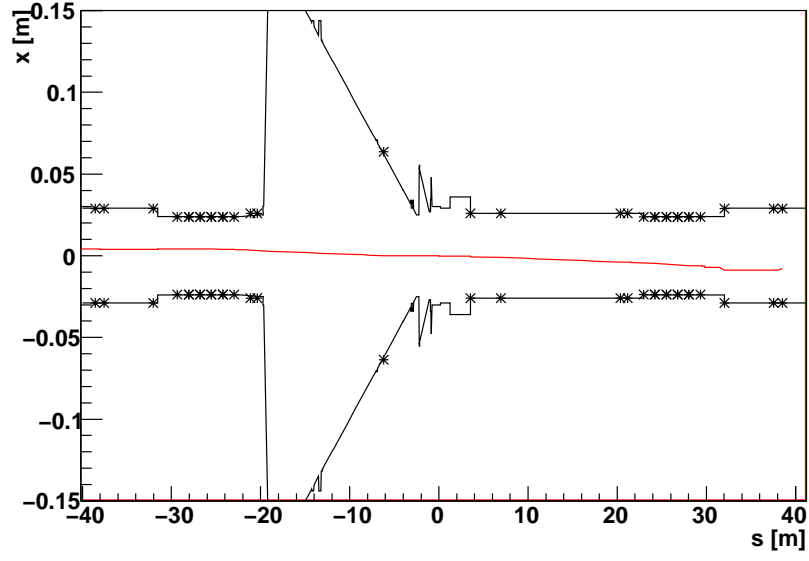


Figure 19: The range of MBXWH corrector settings which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 3 and beam 2.

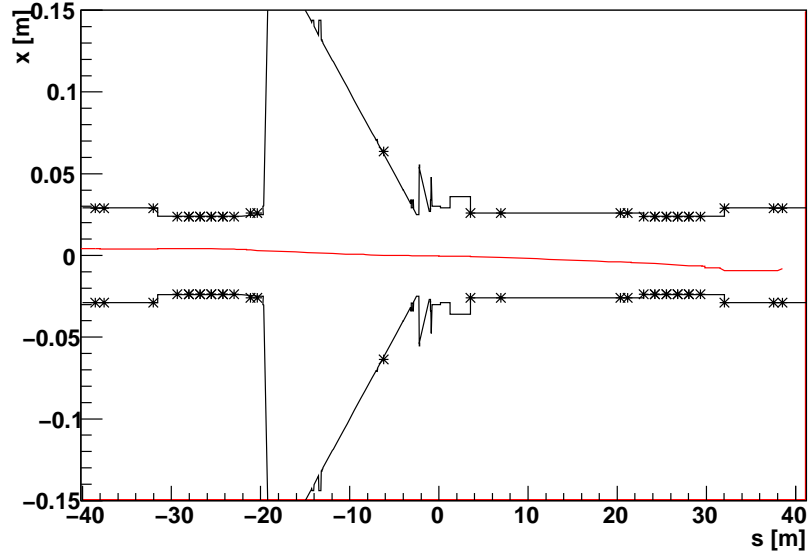


Figure 20: The range of MBXWH corrector settings which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 4 and beam 2.

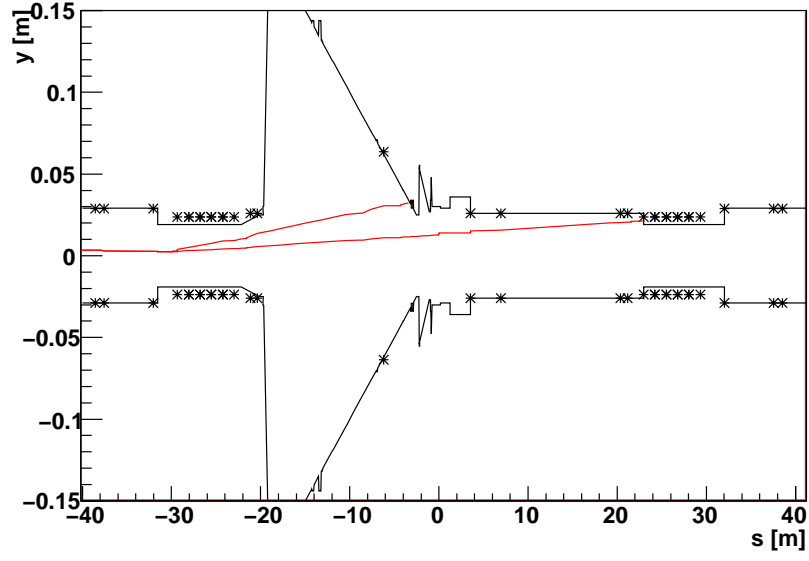


Figure 21: The range of MCBXV corrector settings which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 1 and beam 2.

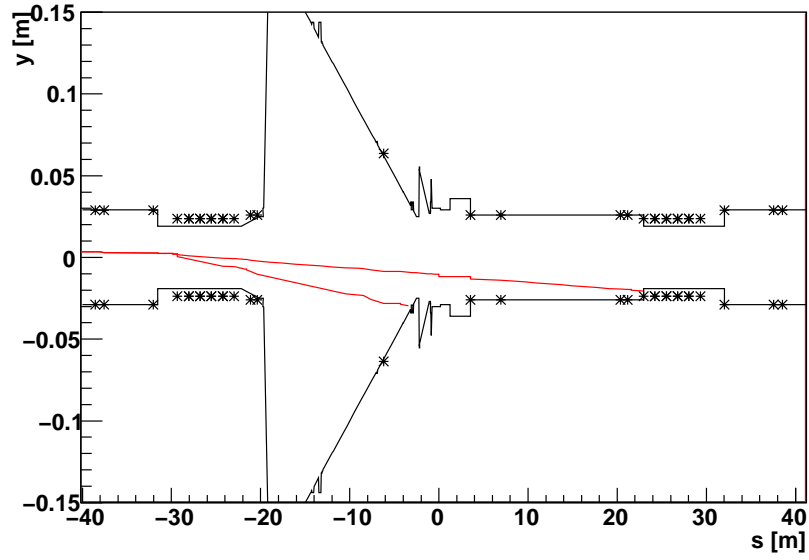


Figure 22: The range of MCBXV corrector settings which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 2 and beam 2.

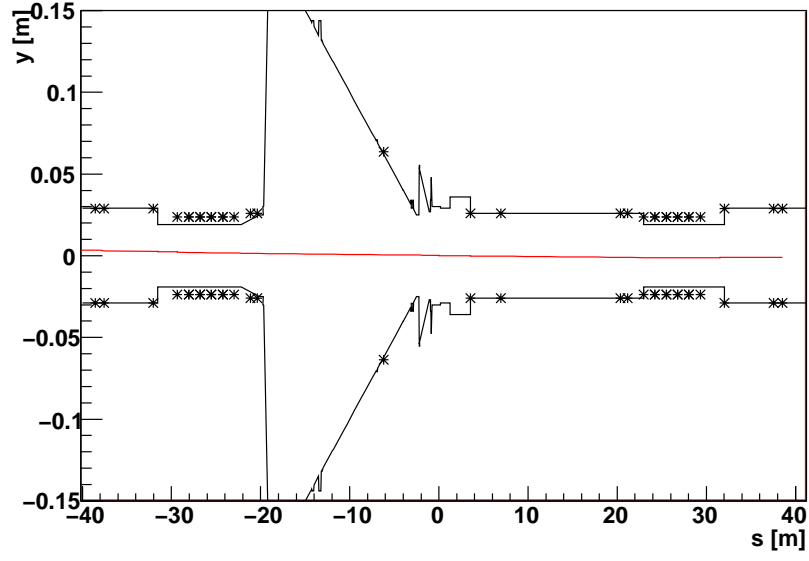


Figure 23: The range of MCBXV corrector settings which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 3 and beam 2.

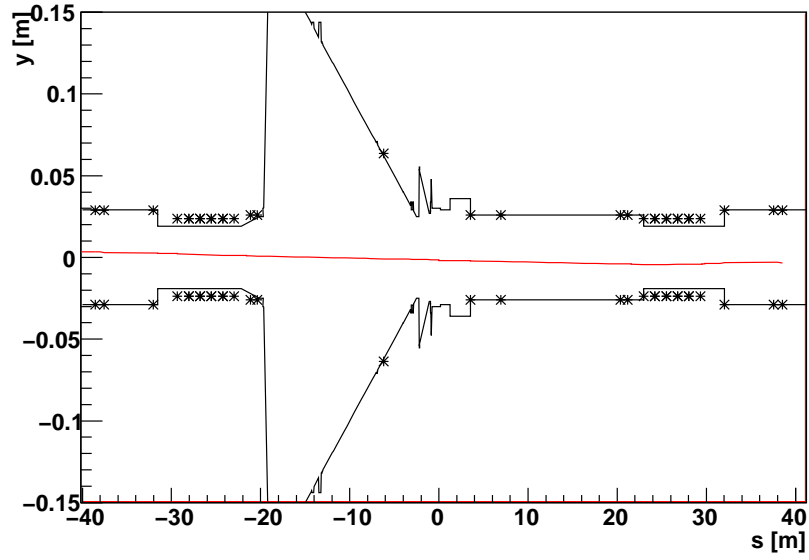


Figure 24: The range of MCBXV corrector settings which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 4 and beam 2.

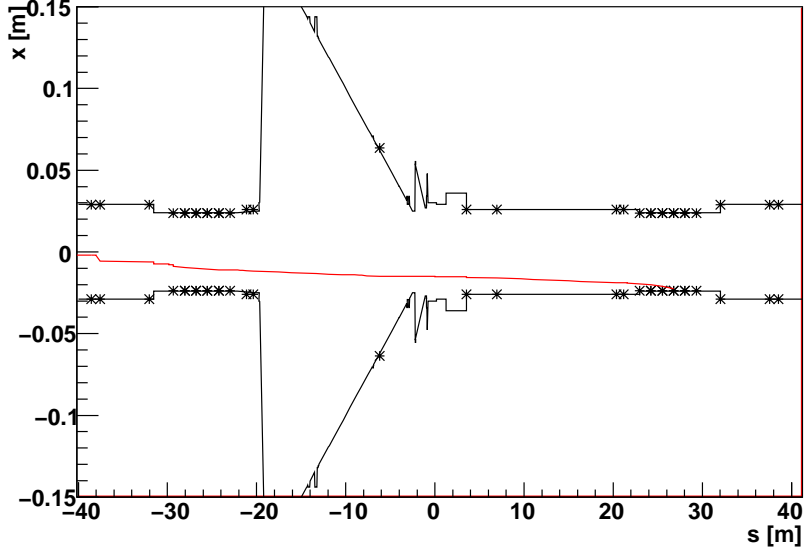


Figure 25: A possible MBX.4R8 dipole settings which is dangerous for the LHCb beam pipe and interaction region magnets, for magnet setting scenario 1 and beam 2.

3.3 MBX.4R8 [D1] (beam 2)

The high field strength of MBX.4R8 means the incorrect settings can pose considerable danger of machine vacuum chamber around LHCb. It is nominally set to +1.533 mrad on injection (equal to 6.4% of maximum current), and a scenario 1 mis-settings of at least +1.89mrad on injection would send the beam into Q1 on the far side of the experiment, MQXA.1L8, on the outside of the vacuum chamber. This corresponds to 7.9% of maximum current, and arises because a larger positive bend sends the beam to the outside of the machine i.e. to larger negative x (for beam 2). Larger mis-setting would cause beam loss in elements closer to the IP. The MBX.4R8 mis-setting which causes beam loss in MQXA.1L8 is shown in figure 25. The studies for D1 and D2, which are errors on dipole magnets, need to take care of the MADX and LHC coordinate system. For beam 2, moving out of the ring (away from the centre) corresponds to negative x . Note the sign change between dipole and corrector angles is still needed for beam 2 in MADX.

For scenarios 2, 3 and 4, the beam will impact in the first aperture restriction on the near side of the IR, MQXA.1R8, where the diameter is 48mm, if the bending field of MBX.4L8 drops below -1.05mrad, which corresponds to 4.4% of maximum current. Therefore scenarios 2, 3 and 4 (magnet turned off and any reverse polarity) will cause beam loss in the machine or detector vacuum chamber. The beam orbit arising from a magnet current of just below 4.4% of maximum (just below -1.05mrad) is shown in figure 26, showing a beam impact in MQXA.1R8. This arises because a reduced field negative bend will move the beam to the inside of the ring i.e. to positive x in the coordinate system of beam 2.

3.4 MBRC.4R8.B2 [D2] (beam 2)

In a similar way to MBX.4R8, the high field strength of MBRC.4R8.B2 means the incorrect setting can pose considerable danger of the experimental region and machine beam pipe of LHCb. It is nominally set to -1.533 mrad on injection (equal to 6.4% of

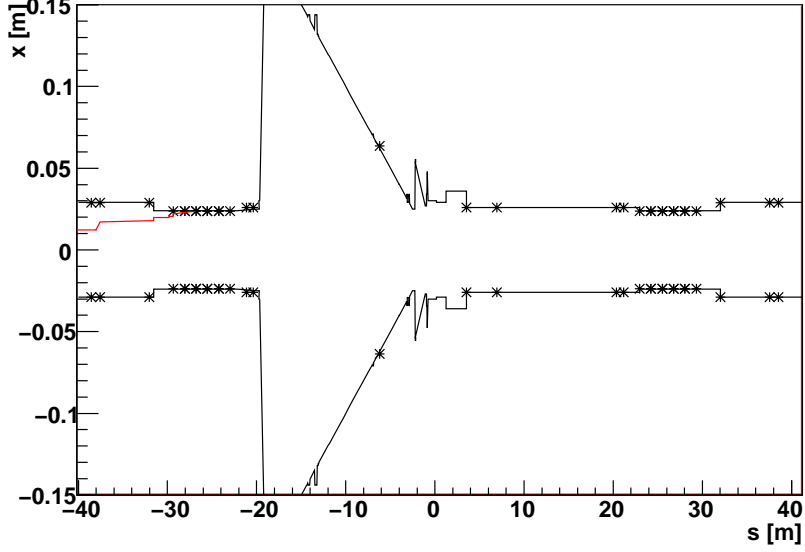


Figure 26: A possible MBX.4R8 dipole settings which is dangerous for the LHCb beam pipe and interaction region magnets, for magnet setting scenario 2 and beam 2.

maximum current), and a scenario 1 mis-settings of at least -1.92 mrad on injection would send the beam into Q1 on the near side of the experiment, MQXA.1R8, which forms the first aperture restriction after MBRC.4R8 and effectively screens the IR region from errors in this magnet. The beam strikes at positive x , and D2 is a negative bend magnet and an excess current will bend the beam into the inner side of the vacuum pipe (positive x for beam 2). This corresponds to 8.0% of maximum current. This accident scenario is shown in figure 27.

For scenarios 2, 3 and 4, the beam will impact in the first aperture restriction after the magnet, MQXA.1R8, where the diameter is 48mm, if the bending field of MBRC.4R8 drops below -0.981 mrad, which corresponds to 4.1% of maximum current. Therefore scenarios 2, 3 and 4 (magnet turned off and any reverse polarity) will cause beam loss in the machine or detector vacuum chamber. This is shown in figure 28, where the beam loss occurs on the outer side of the vacuum chamber of MQXA.1R8, which effectively screens the interaction region elements from beam loss in these scenarios.

4 Summary of current thresholds and software interlocks

The resulting magnet current thresholds for beam 1 to avoid beam orbits striking the vacuum chamber are shown in table 3, as a fraction of the maximum field and expressed as integer percentiles. In this table, the trends in the current thresholds are understandable from consideration of the optics and apertures. The MBCXW reversed polarity threshold is much lower than the nominal polarity threshold as the beam centroid angle is negative at this magnet, and hence the beam needs less bend to hit some machine element. Therefore reverse polarity errors are more dangerous. Similarly, the horizontal beam centroid angle is negative at MCBX, so the nominal polarity magnet errors are the most dangerous (lower threshold). The vertical beam centroid angle at this point is zero. The MBX.4L8 current must be confined between 4.9% and 8.5% of maximum to avoid beam loss, with very similar limits for MBRC.4L8 (the slight difference in limits arises from the differing linear optics at the two error locations). These current thresholds should

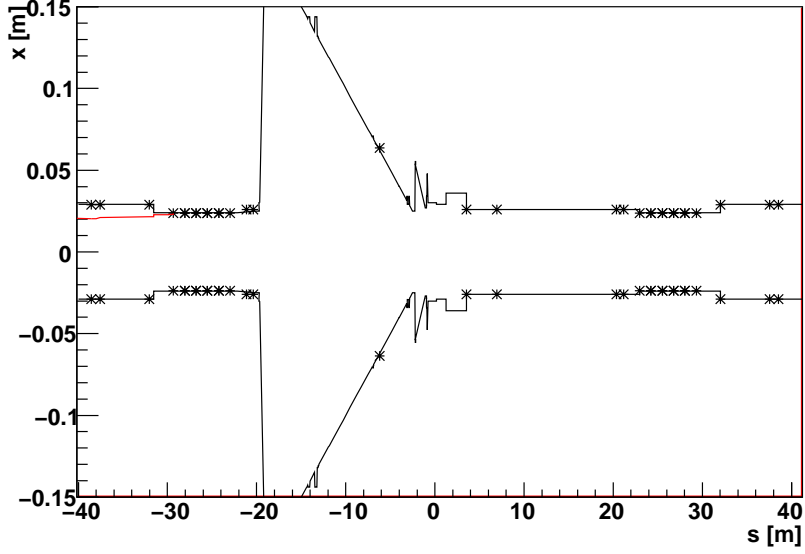


Figure 27: A possible MBRC.4R8 dipole settings which is dangerous for the LHCb beam pipe and interaction region magnets, for magnet setting scenario 1 and beam 2.

be considered as maximum permissible currents to avoid injection turn beam accidents, and should be considered as part of the current software interlocks to avoid beam strikes on the aperture restrictions of MQXA.1R8, MQXA.1L8 or the conical vacuum chamber of LHCb.

Magnet	Nom. angle [μrad]	Max angle [μrad]	Threshold (nom. pol.)	Threshold (rev. pol.)
MBXWH	+181	+2820	35% (987 μrad)	-14% (-395 μrad)
MCBXH	-5	-1011	35% (-354 μrad)	-55% (556 μrad)
MCBXV	-48	-1042	30% (-313 μrad)	-28% (292 μrad)
MBX.4L8	-1533	-23,837	8.5% (-2026 μrad)	4.9% (-1168 μrad)
MBRC.4L8	+1533	+23,837	8.8% (2098 μrad)	4.7% (1120 μrad)

Table 3: The required thresholds of the magnets to avoid beam accident scenarios on injection, rounded to a integer percentile, for beam 1.

The resulting magnet current thresholds for beam 2 to avoid beam orbits striking the vacuum chamber are shown in table 4, as a fraction of the maximum field and expressed as integer percentiles. Similar comments apply to this table, as to the table for beam 1.

The current thresholds to avoid beam loss calculated for the various accident scenarios can be used to set the magnet current interlocks on injection. These interlocks are done in software and controlled by the Software Interlock System (SIS). The interlocks can be bypassed by all engineers-in-charge (EIC), and are protected by the role-based access system. At the present settings [10], the orbit correctors are interlocked to a tolerance of approximately 100 μrad around the nominal current, until the injected beams have been steered. This is equivalent to about 10% of nominal current. The separation dipoles (D1 and D2) have an injection current tolerance of 3% of the nominal injection current.

For the beam separation dipoles for beam 1 and beam 2, a current interlock of 3% of nominal injection current would corresponds to a bend angle change of 46 μrad , or

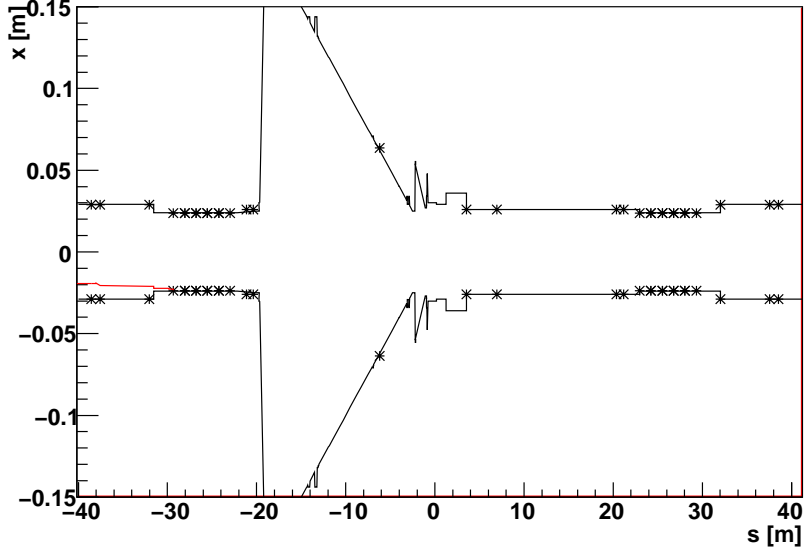


Figure 28: A possible MBRC.4R8 dipole settings which is dangerous for the LHCb beam pipe and interaction region magnets, for magnet setting scenario 2 and beam 2.

Magnet	Nom. angle [μrad]	Max angle [μrad]	Threshold (nom. pol.)	Threshold (rev. pol.)
MCBXH	+5	+1011	55% (556 μrad)	-33% (-334 μrad)
MCBXV	+48	+1042	33% (344 μrad)	-28% (-292 μrad)
MBX.4R8	+1533	+23,837	7.9% (1883 μrad)	4.4% (1049 μrad)
MBRC.4R8	-1533	-23,837	8.0% (-1907 μrad)	4.1% (-977 μrad)

Table 4: The required thresholds of the magnets to avoid beam accident scenarios on injection, rounded to a integer percentile, for beam 2.

0.19% of maximum current. Consideration of tables 3 and 4 show there is no danger to the experimental region if this software interlock is maintained. For the corrector magnets, a tolerance of 100 μrad corresponds to approximately 10% of maximum current. Again, consideration of tables 3 and 4 show there is no danger to the experimental region if this software interlock is maintained. These conclusions are correct for the scenarios considered in this report, and for the case of single magnet incorrect setting.

For the case of a double magnet setting error on injection, figure 29 shows the beam 2 injection orbit when the MBRC.4R8 current is reduced by 3% and the MBX.4R8 current is increased by 3%. These errors are at the limit of the software interlock tolerance and both act to move the orbit to the outside of the vacuum chamber i.e. the errors act coherently. The figure shows there is no danger to the experimental area for such double magnet errors, when the currents stay within the interlock thresholds. For the corrector errors, the calculated tolerances to avoid beam loss are several times greater than the 100 μrad of software interlock threshold. Hence no danger is expected to the experimental areas while the interlocks are maintained.

5 Conclusion

In this report, the beam accident scenarios for machine elements around LHCb are discussed for beams 1 and 2, focusing on MBCWH, MCBXH, MCBXV, D1 and D2 for

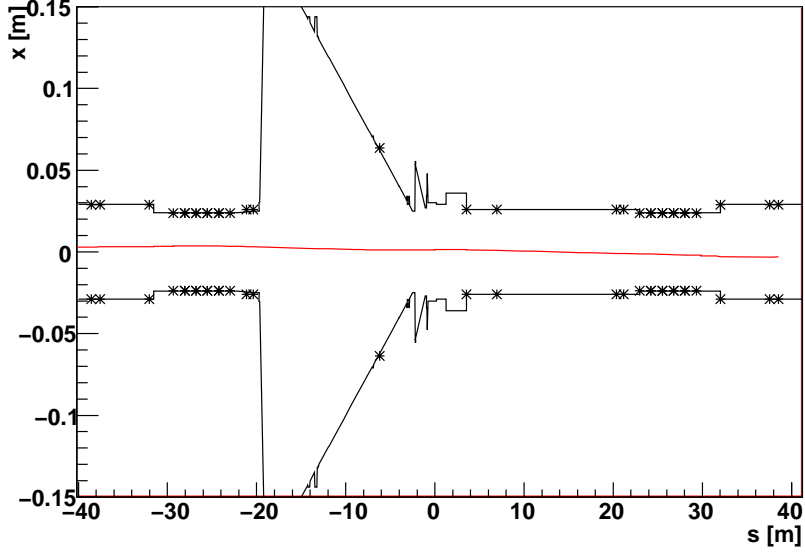


Figure 29: The beam 2 injection error obtained when the MBRC.4R8 current is reduced by 3% and the MBX.4R8 current is increased by 3%. There is no danger to the experimental area for such a double magnet error.

beam 1 and MCBXH, MCBXV, D1 and D2 for beam 2. For each magnet four magnet setting scenarios were considered, covering all possible magnet current settings. It was found it is possible for beam accidents on injection to strike elements of the LHCb conical beam pipe or elements of the machine, due to incorrect settings of magnets. Magnet current thresholds were calculated to avoid beam strikes under injection conditions. Finally, the software current interlocks were discussed, and it was shown these interlocks are adequate for single magnet setting errors and for double magnet separation dipole errors.

A extension to this work is a detailed consideration of the spot of beam impact, to understand the potential impact. For example, beam loss in the conical vacuum chamber would lead to showers which could impact the detector systems, or even cause physical damage to the LHCb vacuum chamber under repeated strikes by a pilot beam. Also, specific elements like vacuum chamber bellows or the VELO vacuum window may be particularly vulnerable to beam loss. The beam strikes will cause showers in the vacuum chamber and machine elements, and the results presented here can be used at the starting point for such shower calculations. The simulations can then be used to understand the potential fluxes in the beam condition monitors and the VELO, understand which detectors see the beam loss first and calibrate the beam loss monitor threshold and response.

Finally, the method of calculation and general results presented here for LHCb also apply to ALICE, although the detailed geometry of point 2 will determine the precise level of magnet current thresholds required. The calculations for ALICE have been presented in a separate report.

Acknowledgement

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A The impact of injection jitter and 3σ beam envelope scraping

Since this report was submitted, an extension has been performed to include the effects of injection jitter and scraping of the beam envelope. The work will be reported in this addendum. The calculations were performed, and the conclusion drawn, for LHCb but the similar geometry of ALICE means the conclusions are valid for this experiment too.

The injected beam arrives from the transfer line with an amount of centroid jitter in 4D phase space (horizontal and vertical position and angle), with the amount of jitter expected to be 1.5σ . Experimentally, closer to 1σ was seen during the LHC initial injection testing [11] but in this work the more conservative value of 1.5σ will be used. The jitter is included using a Monte Carlo simulation, with initial beam conditions being chosen randomly with a seed, and the potential beam loss in the experiment region calculated and integrated over many seeds. The calculation was also extended to include the impact of beam scraping, with the beam envelope impact on the LHCb beam pipe or detector considered as a scraping accident event. The beam envelope is defined to extend to 3σ of the betatron beam size, which is conservative given the pilot bunch population at injection. Taken together, the inclusion of jitter and the 3σ beam envelope constitute a pessimistic scenario for the likelihood of injected beam accidents. The 3σ beam envelope is shown as green in figure 30, and is plotted for a representative sample of 10 seeds for beam 1 in this figure.

The impact on the injected beam accident scenarios and the resulting magnet current thresholds and interlocks has been done for beam 1 and scenario 1 for MCBXH (where the corrector is set from the nominal injection strength to maximum strength). The beam envelope plot for this scenario is shown in figure 31, which is an development of figure 8. The calculations show the dangerous region for beam scraping is defined by MCBXH being set to 23% to 100% of maximum strength, where the 3σ beam scrapes part of the machine aperture when set to 23% of maximum strength. This should be compared to the 35% of maximum strength required for a direct beam hit, as calculated in section 2.2. Therefore a tighter magnet current threshold is required to avoid a beam accident.

Following the analysis in section 4, the updated tighter magnet threshold is still consistent with the $100\text{ }\mu\text{rad}$ magnet interlock on this corrector. Therefore, no danger to the experimental region is anticipated if this interlock is maintained, with the calculation now including injection jitter and 3σ beam envelope scraping. Similar conclusion can be drawn for other correctors with identical interlock thresholds to MCBXH (e.g. MCBXV),

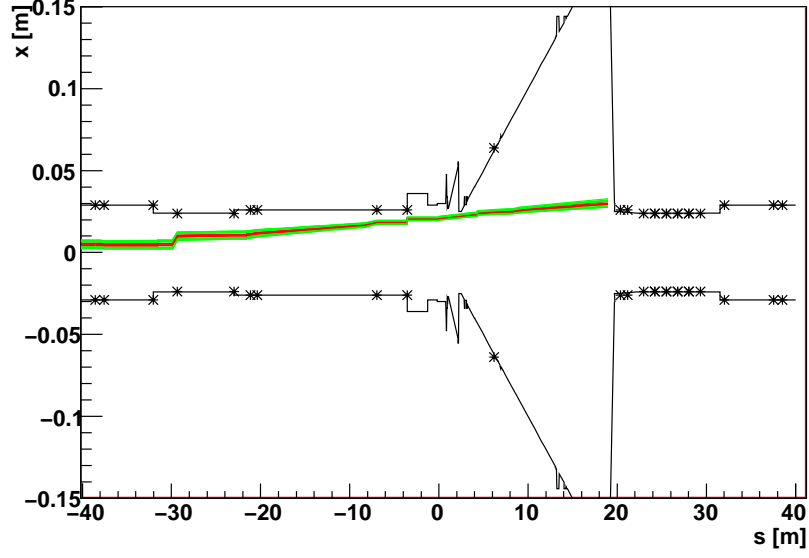


Figure 30: The 3σ beam envelope (green) around the beam centroid (red) for a beam 1 accident scenario. This plot shows a representative sample of 10 injection jitter seeds.

and for the corresponding calculations for beam 2. For the case of the separation dipoles, the interlocks are set to 3% of nominal injection current, and so the inclusion of beam jitter and scraping mean the interlocks are still valid. Therefore, the conclusions drawn in this report for all magnets, scenarios and beams are valid with the inclusion of beam jitter and scraping.

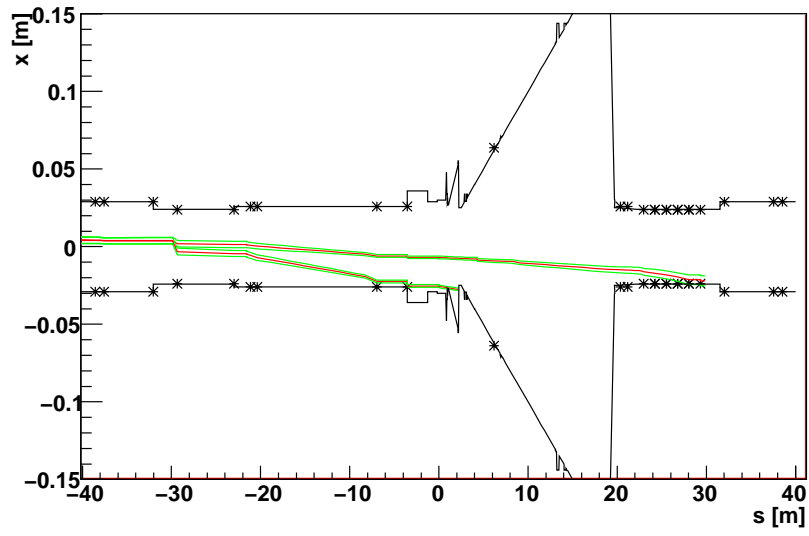


Figure 31: The range of MCBXH corrector settings, which are dangerous for the LHCb beam pipe and interaction region magnets, for corrector setting scenario 1 and beam 1. The effects of injection jitter and 3σ beam envelope scraping have been included. In this plot, the beam centroid is shown in red and the beam envelope is shown in green.