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Layout considerations for the PSB H- injection system

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Summary

The layout of the PSB H- injection system is described, including the arguments for the geometry and the required equipment performance parameters. The longitudinal positions of the main elements are specified, together with the injected and circulating beam axes. The assumptions used in determining the geometry are listed.

1. Introduction

Linac4 [1] is an H- linear accelerator, intended to replace Linac2 as injector to the PS Booster (PSB) and as first stage of an envisaged new injector chain for the LHC. The 160 MeV beam from Linac4 will be distributed to the four levels of the PSB by a system of five pulsed magnets, the proton distributor (BI.DIS) and 3 vertical septum magnets (BI.SMV).

A new injection system is required for the PSB [2]. The beam will be injected horizontally into each PSB ring with a chicane using four dipole magnets (BS), and a painting bump using four kicker magnets (KSW). A stripping foil will strip the H- to p+. Any remaining unstripped H^0 and H^- will be intercepted by an internal dump.

During the injection process the BS chicane stays constant, since the BS2 magnet is used to merge the incoming H^- beam and the circulating p+ beam. The KSW painting bump decays in a controlled manner during the injection to accomplish transverse phase space painting to the required emittance. A schematic layout of the injection system is shown in Fig. 1.

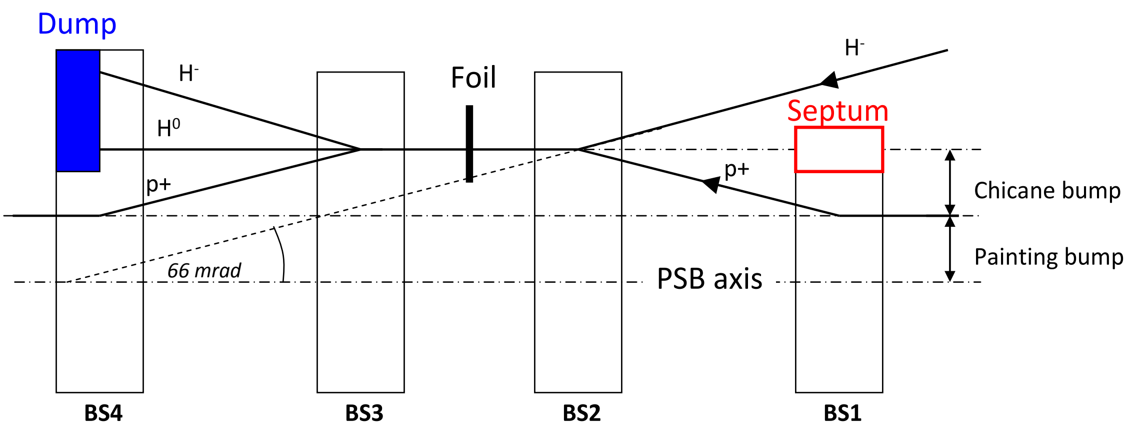

Figure 1. Schematic of PSB H- injection system.

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The 160 MeV injection into the PSB will require longitudinal painting of about ±0.4% in dp/p [3], which is planned to be accomplished by a modulation of the injected beam momentum.

2. Assumptions for determining the layout

The injected beam axis intercepts the PSB circulating beam axis, Fig. 2, with an angle of 66 mrad, at a distance of 2410 mm from the start of the 2564 mm long straight section in Period 1 (the injection straight). The injected beam axis is therefore 159.06 mm from the circulating beam axis at the start of the injection straight.

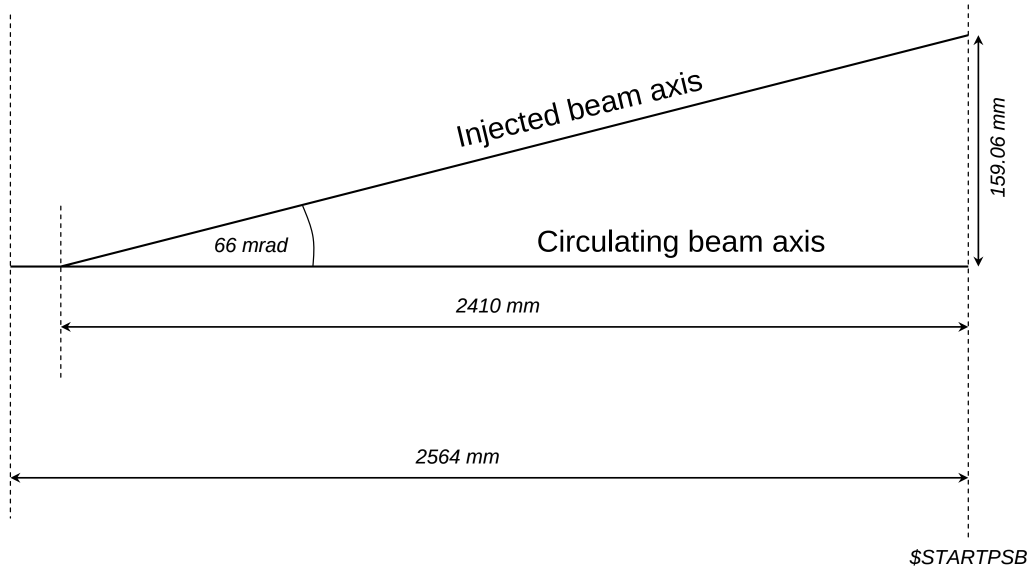


Figure 2. Geometry of the injected beam axis and PSB axis.

The chicane is assumed to be symmetric, with all BS magnets providing 66 mrad deflection. An asymmetric version would offer some advantages in the aperture at the internal dump, but would enhance the optics perturbations caused by the fringe fields of the strong chicane dipoles [4], since higher fields are required for some magnets.

The beam may be injected with a fixed offset with respect to the nominal injected beam axis, and the circulating beam may have a fixed offset with respect to the nominal PSB circulating beam axis. The locations of the BS magnets and the amplitude of the chicane bump are then determined by the length of the BS magnets and the height of the KSW painting bump, assuming that for the nominal injection layout there is no horizontal offset between the injected beam axis and the circulating beam axis at the start of the painting process.

At the start of the painting process, with the painting bump at full amplitude, the effective beam envelope is defined by the injected emittance, by any injection mismatch factors, and by the momentum offset (due to painting). At end of the injection process, the effective beam envelope is defined by the circulating beam emittance and by the momentum painting.

The assumptions for the different parameters used in estimating the emittances and the geometry are given in Table 1. It should be noted that the β_x value used for the injected beam is that of the PSB lattice at this location, although in reality a deliberate mismatch of the betatron parameters with lower β_x will help minimize foil hits and associated beam loss [5].

Table 1. Parameters used for determining the injection layout

Parameter	Unit	Value	Comment
Energy	MeV	160	Kinetic
Max Δp/p		±0.0044	PSB bucket height
Injected emittance	π.mm.mrad	0.5 / 0.5	H / V rms 1 sigma normalised
Circulating emittance	π.mm.mrad	8.0 / 6.0	H / V rms 1 sigma normalised (FTPRO)
Injection mismatch		2.4	Factor on injected emittance
Beta-beat		1.2	Factor on circulating emittance
Maximum trajectory	mm	5	
Beam envelope	sigma	3	
BS magnetic length	mm	370	Physical (vacuum) length 400 mm
BS magnet field	T	0.34	
Maximum trajectory	mm	5	

3. Layout

A KSW bump amplitude of 35 mm from the PSB machine axis has been chosen as the baseline, with a chicane bump height of 45.9 mm and a 10 mm offset of the injected beam. This defines the interception of the injected beam with the full amplitude chicane plus painting bump at 80.9 mm, which allows enough clearance at the injection elements at the start of the injection process, Fig. 3, and maximizes the height of the KSW bump such that the beam is moved as far as possible from the foil at the end of the injection process, Fig. 4.

This choice allows some flexibility in the configurations of the injection. The offset of the injected beam can be reduced from 10 to 0 mm, with the KSW bump increasing accordingly, and in addition the central orbit of the PSB could also be displaced away from the foil, again to be compensated by an increase in the KSW bump amplitude. The KSW system should therefore provide a bump of up to 55 mm amplitude to cover these eventualities.

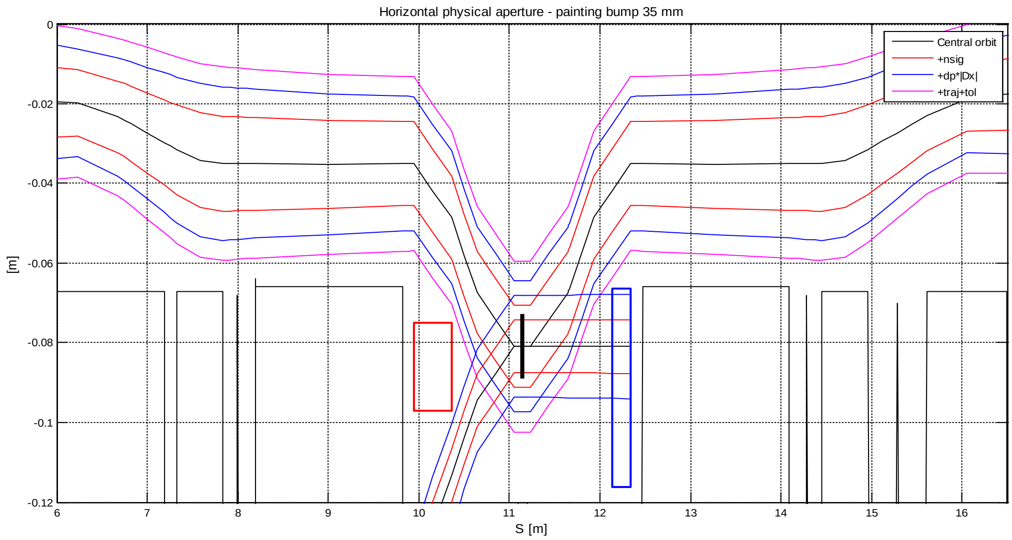


Figure 3. Beam envelopes at the start of the injection process, with KSW and chicane bumps at full amplitude.

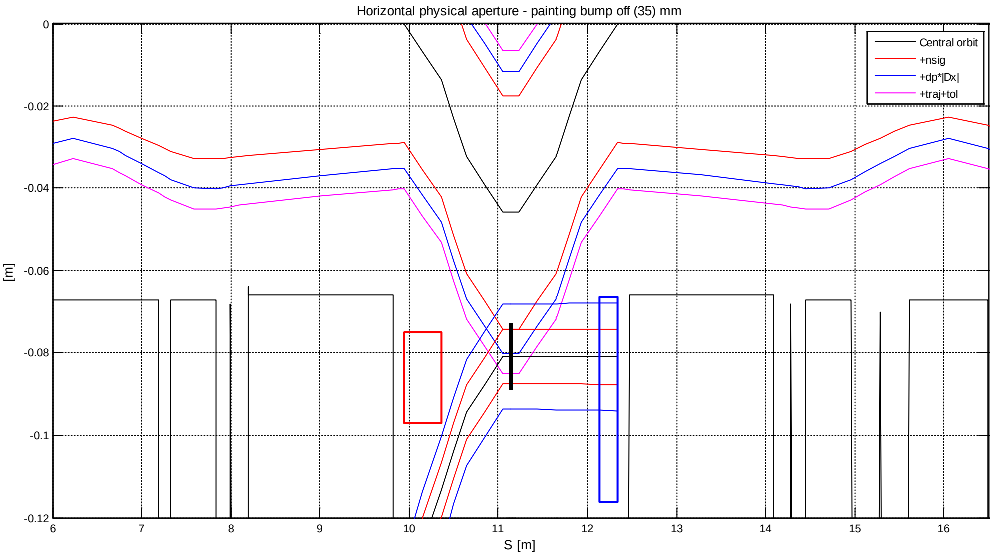


Figure 4. Beam envelopes at the end of the injection process, with KSW bump at zero amplitude.

The S-locations of the elements (centers) and the other main parameters for the injection layout are summarised in Table 2. The madx coordinate conventions are used, which means that x is negative towards the outside of the PWB ring (hence the BS and KSW bumps are negative while the injected beam and orbit offsets are positive).

Table 2. Layout details, with element locations (centres) and main parameters

		Inj. beam dispersion		
Parameter/location	**Unit**	**0 m**	**Matched**	**Comment**
Start PSB period 1 S location	mm	0		
BS1 S location	mm	336		
BS2 S location	mm	1032		
Foil S location	mm	1327		
BS3 S location	mm	1622		
BS4 S location	mm	2318		
H0-H- dump S location	mm	2318		At centre of BS4 magnet
Chicane bump height	mm	-45.9		
Injected beam H offset	mm	-80.9	-80.9	From nominal PSB axis
Nominal injected beam offset	mm	10	4	
Nominal KSW bump height	mm	-35	-41	
Maximum KSW bump height	mm	-55		
Maximum PSB orbit offset	mm	10		

4. Magnet strengths

Due to the limited space in the injection straight it is proposed to move KSWP1L1 to a new location in P16L1, which means that a much more efficient KSW bump can be constructed. For 55 mm bump the kicks required are given in Table 3, assuming a PSB working point of 4.28/ 5.45 in the H/V planes respectively.

The BS magnets must provide 66 mrad deflection with 0.37 m magnetic length, which requires a peak field of about 0.34 T.

Table 3. KSW kicks and fields required for a 55 mm KSW bump

Parameter	Unit	Value	Comment
KSWP16L1 kick	mrad	8.74	
KSWP16L4 kick	mrad	2.04	
KSWP1L4 kick	mrad	2.75	
KSWP2L1 kick	mrad	7.65	
KSWP16L1 field	T	0.045	Limit 0.06 (magnet ferrite saturation)
KSWP16L4 field	T	0.011	
KSWP1L4 field	T	0.014	
KSWP2L1 field	T	0.039	

6. Consequences on Injection Steering

Steering of the incoming beam at the injection on the stripping foil is required to set up and optimize the injection process. Similar to present operations with Linac2 and a conventional multiturn injection, the position and the angle of the injected beam have to be adjusted with respect to the closed orbit of the PSB. The present tuning range is shown in Fig. 5. A betatron function of β = 5 m has been assumed for normalization. The outer contour circumscribes all possible settings, the points denote corrections programmed at present for typical machine cycles, and the circle with a radius of 0.25 $mm^{1/2}$ is assumed to be the nominal (required) tuning range. The dashed circle with radius 0.15 $mm^{1/2}$ is sufficient in the present situation.

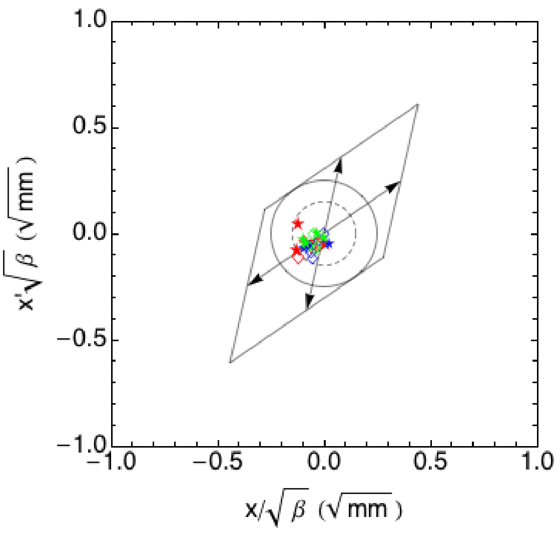
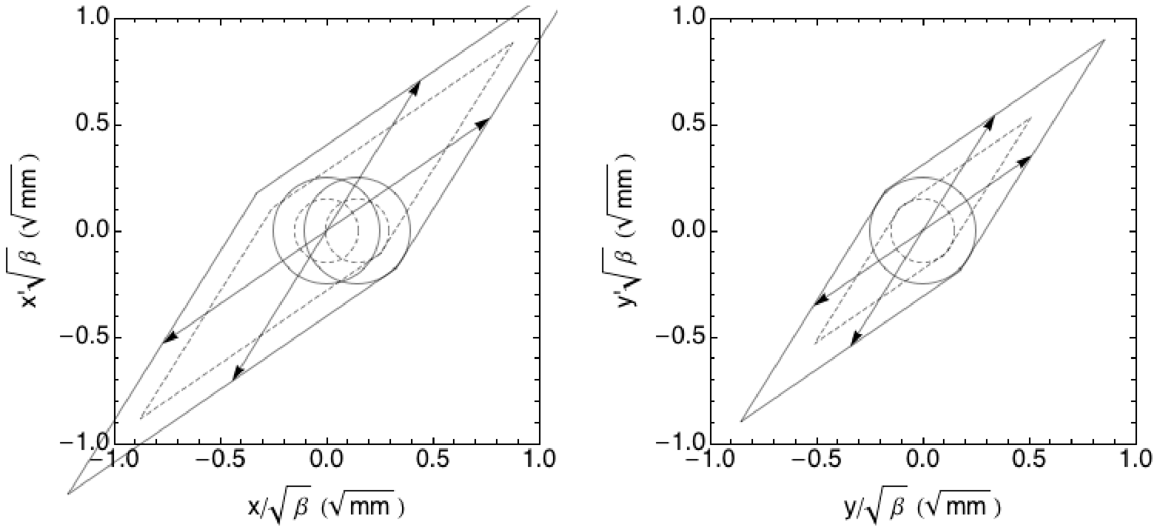


Figure 5: Present tuning range with Linac2 for adjusting the trajectory of the injected beam at the injection point.



BI.DHZ70/DVT70 shifted upstream by 2 m

Figure 6: Tuning range for adjusting the trajectory of the injected beam with Linac4.

With Linac4, the last two steerers will be required for optimization and fine tuning of the trajectory of the injected beam, and also to generate the nominal offset of 10 mm, as given in Tab. 2, of the injected beam. The existing layout with a first steerer BI.DHZ/DVT50 far upstream from the injection and the second one BI.DHZ70/DVT70 very close to the injection point allows for efficient steering. However, with the proposed injection chicane layout given above, Table 2, there is no longer any space near the injection point to accommodate the downstream BI.DHZ70/DVT70 steerer. The nearest possible location is about 2 m upstream.

The situation with BI.DHZ70/DVT70 shifted upstream by 2 m, sketched in Fig. 6 and summarized in Table 4, is as follows:

- The required horizontal tuning as indicated as solid lines in the lower right image of Fig. 6, can be covered with maximum deflections of 7.5 mrad and 10 mrad for the steering magnets EI.DHZ50 and EI.DHZ70. The reduced tuning range allows for a small reduction of the deflections to 5.5 mrad and 7 mrad;

- The full vertical tuning range requires maximum deflections of 5.0 mrad and 7.7 mrad for the magnets EI.DVT50 and EI.DVT70. The reduced tuning range could be covered with deflections of 3.0 mrad and 4.5 mrad.

Table 4. Required deflections and magnet strength for tuning of the trajectory at the injection point with BI.DHZ70/DVT70 shifted upstream by 2 m.

Magnet	**Defl. (mrad)**	**Required strength (Gm)**	**Present max strength(Gm)**
EI.DHZ50	7.5	143	36
EI.DHZ70	10	190	53
EI.DVT50	5.0	95	36
EI.DVT70	7.7	147	53

7. Considerations on machine acceptance and apertures

The Linac4 project aims at keeping the transverse emittances of beams delivered by the PSB similar to the ones available now with Linac2, but to allow increasing the beam brightness by increasing the intensities. Thus, beams with normalized emittances larger than the ones of present high intensity beams delivered with Linac2 would lead to increased losses in the Booster ejection channel and at PS injection and have to be avoided. With the increased injection energy and keeping normalized emittances similar to the present ones, one expects maximum physical emittances after injection almost a factor two smaller than at present.

A reduction of the PSB acceptance for Linac4 is proposed for the following reasons:

- Particles with too large betatron oscillation amplitudes already close to injection are lost at low energy where they induce less activation of the machine than if they would be lost after acceleration in the ejection channel.
- In case large amplitude protons are injected due to imperfections and could hit the foil during the chicane fall (after complete fall of the painting bump); some of them would be intercepted by the reduced machine aperture. If the reduction of the acceptance is accompanied by a displacement of the reference trajectory by displacing this aperture transversely towards the inside of the ring, the injection foil could even be placed at a position safe from proton impacts after the complete fall of the painting bump.
- The acceptance margin gained by preparing the PSB for Linac4 may render a (simple) two-stage collimation system feasible. A first feasibility study of such a system is underway.

7.1 Analysis of the Booster Acceptance

At present, the acceptance of the PSB is limited by the so-called "BeamScope" window. Investigations during the shutdown 2008/2009 showed that at present this window is installed in section 8L2, a short straight section between the exit of the first bend in period 8 and a focusing quadrupole, and has an approximately rectangular shape with openings ±50 mm and ±28.6 mm in horizontal and vertical direction, respectively. The lattice functions at this location are about $\beta_{H,BS}$ = 7.2 m, $\beta_{V,BS}$ = 6.0 m for the injection working point with high intensities. Reducing the available opening by 3 mm to take closed orbit perturbations into account yields acceptances of $A_{H,L2}$ = 307 mm (for protons without momentum offset) and $A_{V,L2}$ = 109 mm translating into normalized acceptances at injection of $A^*_{H,L2} = (\beta\gamma)_{50MeV}\, A_{H,L2}$ = 100 mm and $A^*_{V,L2}$ = 36 mm.

To keep the normalized acceptances similar to the present situation to avoid additional losses in the ejection channel and/or the PS injection, an appropriate acceptance defining window has to be defined. To allow for a possible installation of a simple collimation section removing lost particles in a controlled way, we assume that this window will be installed in a straight section (preferably in 5L1, about a horizontal betatron phase advance of 2 π from the injection to ensure a similar closed orbit). The appropriate opening can be estimated scaling the size of the present window with the square root of the ratio of the betatron functions and the square root of the ratio of the beam rigidities with Linac2 and Linac4. One obtains:

- a horizontal full opening of:
  $(5.7\text{ m}/7.2\text{ m})^{1/2} \times (1.03\text{ Tm}/1.90\text{ Tm})^{1/2} \times \pm 50\text{ mm} \approx \pm 33\text{ mm}$ and,
- a vertical opening of:
  $(4.1\text{ m}/6.3\text{ m})^{1/2} \times (1.03\text{ Tm}/1.90\text{ Tm})^{1/2} \times \pm 28.6\text{ mm} \approx \pm 17.4\text{ mm}$

where "±" refers to the opening around the reference orbit, which could be displaced horizontally from the geometric chamber axis.

7.2 Estimates for the maximum space required for the beam

Estimates of the space needed for the beam are plotted in Figs. 7 and 8 for an injected beam arriving at the injection point with zero dispersion and for a dispersion matched to the PSB. Required spaces by the beam at different stages of the injection processes have been plotted for relative momentum offsets of -4 10^{-3}, 0 and +4 10^{-3} (the full bucket height is ±4 10^{-3}):

- Incoming beam plotted as solid lines: transverse emittances 2x0.4 mm = 0.8 mm of two times the ones from Linac4 to take betatron mismatch of up to a factor 2 into account. Transverse offsets of 10 mm and 4 mm are taken into account.
- Unstripped and partially stripped beam as dotted lines.
- Circulating beam at the beginning of the injection as solid lines: For every momentum, the maximum betatron oscillation amplitude is determined. Then the maximum space required for this betatron amplitude around the closed orbit is plotted.
- Pessimistic estimate of the space required at the end of the injection as dashed lines. For every momentum considered, the maximum betatron oscillation amplitude at the acceptance defining window is determined. Then the height of the painting bump, where this amplitude coincides with the maximum position of the incoming beam is determined. Finally the beam size around the corresponding closed orbit is plotted.
- Maximum space after fall of painting bump (with full chicane bump) as black solid line.

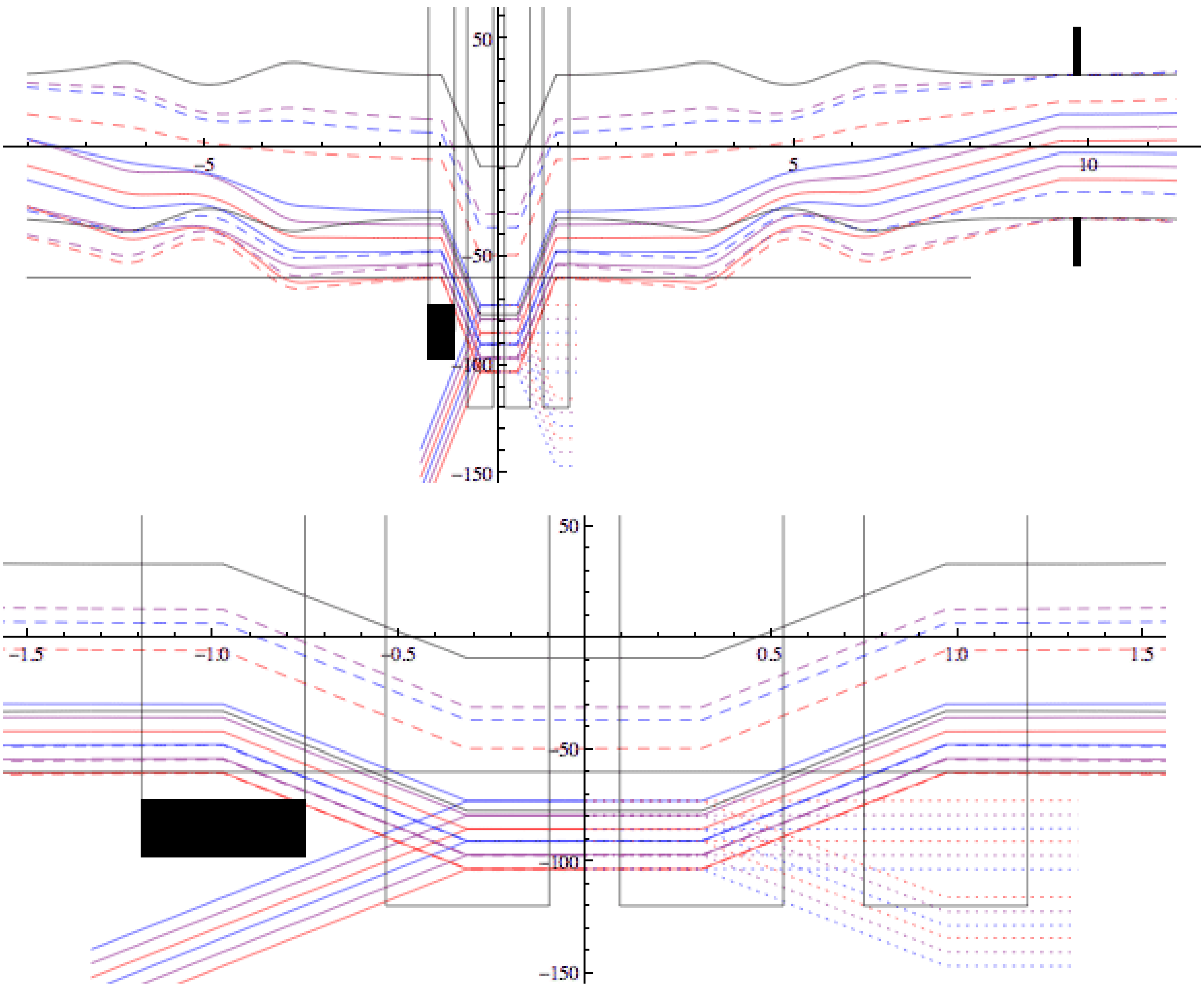


Figure 7: Space requirements for the beam for an injection with matched dispersion (injection line ending with the dispersion of the Booster).

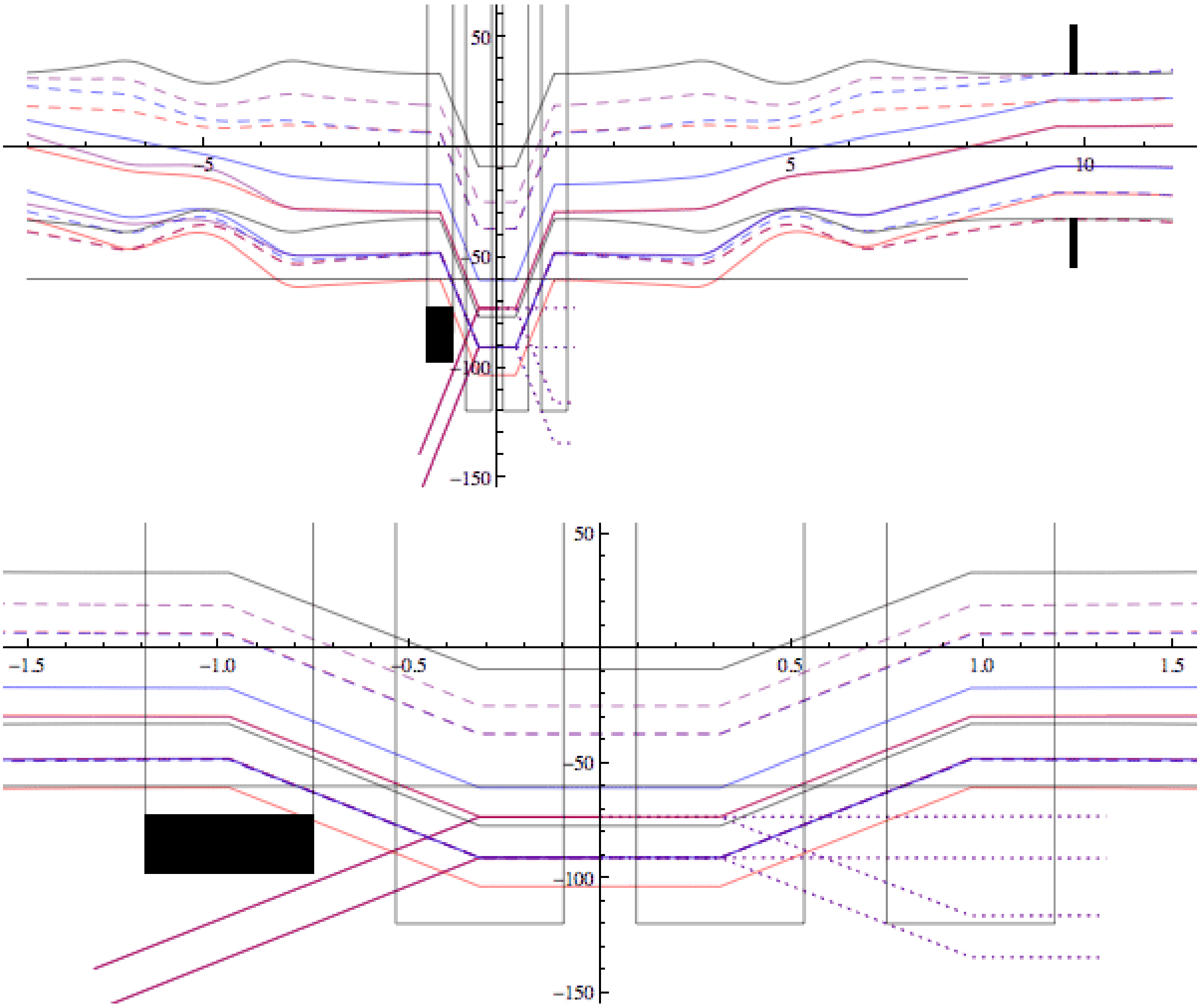


Figure 8: Space requirements for the beam for an injection with dispersion mismatch (injection line ending with zero dispersion at the injection point).

Plots in Figs. 7 and 8 of space requirements, for an injection line ending with zero dispersion and for matched dispersion, show that the chosen geometry is suitable for both cases. The main difference is that slightly more space and, thus as well a larger injection foil, is required for matched dispersion.

Both plots are for an acceptance window centered on the reference trajectory. In consequence, there is an overlap between of the injection foil (which must be located such that all incoming particles hit) and beam after the fall of the painting bump. If required the separation could be improved by displacing the acceptance window and the reference trajectory.

8. Conclusions

The magnet positions and lengths have been fixed from aperture considerations. The main remaining issue concerning the injection design is the fall time of the BS chicane, which can either be fast to remove the circulating beam from the foil edge, but with no possibility to actively compensate the changing optics perturbation, or which can be slow enough to allow an active compensation, but with a perturbation which lasts for many more turns.

The aperture requirements in the injection region can be met with the proposed layout – the addition of an aperture limiting collimator in the PSB is proposed to localize losses on a dedicated element.

The basic layout choice described above allows some flexibility in the configuration of the injection, which will allow some adjustments to be made, if required, once operational experience is gained with the system. The options for the configurations allow some interplay between the injected beam offset, the height of the KSW bump and the offset of the circulating beam.

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