FEASIBILITY OF 2 GeV INJECTION INTO THE CERN PS

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Abstract

The increase of the extraction energy of the CERN PSB to 2 GeV has been suggested as a method to increase the intensity of the LHC beam which can be obtained from the present injector complex. Such a change would require a redesign of the present PS proton injection system, which is already operating at close to its limits. The feasibility of a 2 GeV proton injection is discussed and a potential solution outlined. The implications on the injection equipment and on the performance in terms of beam parameters and losses are discussed.

INTRODUCTION

An increase in the extraction energy of the CERN PSB has been mooted [1] as a possible route to removing the space charge limit at injection into the CERN PS for the LHC beam. This could open a path to significantly increase the brightness of the beam for future LHC luminosity upgrades [2], and might be a cost-effective alternative to the SPL-PS2 injector complex upgrade route [3]. Many PSB systems would be affected by the increase from 1.4 GeV to 2 GeV; in addition, the beam transfer to the PS and in particular the PS fast injection system for p+ would need to be redesigned. The present injection scheme is outlined, and the constraints for a 2 GeV injection are presented. Two possible upgrade concepts are compared: injection into the same straight section SD42 as present, and injecting into the upstream straight section SD41 which has longer available drift space. The reasons for preferring an injection into the present straight section are presented. The feasibility of this solution is examined in terms of the required injection equipment performance, the available aperture, the impact on the injection of other beams and the requirements for modifications to associated beam instrumentation, vacuum and the injection line. Experimental studies on emittance blow up made with the present injection kicker are reported, which have implications for the choice of kicker operating mode (short-circuit or terminated) and on the necessity for an additional injection kicker system.

EXISTING 1.4 GeV INJECTION

The present injection into the PS is a classical horizontal plane fast bunch-to-bucket scheme to transfer protons only, using a closed orbit bump to approach the septum. The septum is located in a straight section with low horizontal β, which minimises the beam size but increases the effective septum width and hence required kick strength. The injection bump makes use of a bumper magnet located just upstream of the septum, to allow injection with a large angle, required to fit the beam inside the aperture of the main lattice magnet downstream of the septum. The injection bump and trajectory are shown in Figures 1 and 2 for the LHC beam and high intensity beam, respectively, together with the physical aperture model of the PS in this region. It should be noted that the injected beam is not fully optically matched to the circulating beam.

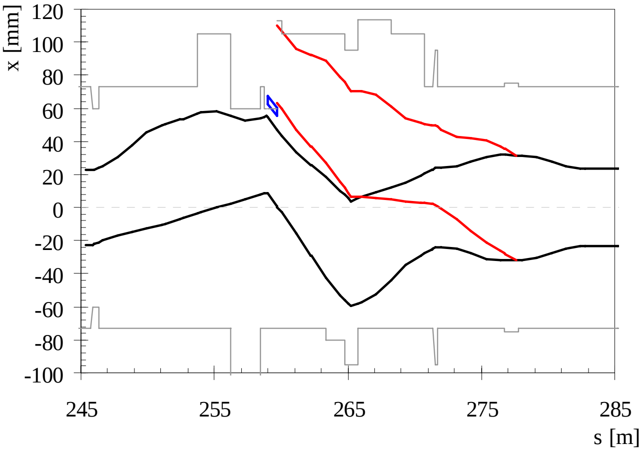

Figure 1: Existing injection bump and injected trajectory envelopes for 12.0 μm high intensity beam at 1.4 GeV.

CONSTRAINTS

The new injection should be at a rigidity 30% higher than at present, Table 1. The kicker rise time should not increase beyond 56 ns, to avoid losses from the 220 ns long bunches injected with 276 ns spacing. The injection should accept LHC beams at 2.0 GeV with a maximum emittance of 3.0 μm, and should also conserve the emittance of the 1 μm pilot beam. Ideally it should be possible to inject the large emittance high intensity beam at 2.0 GeV; it is essential that it be possible to continue to inject this beam at 1.4 GeV.

Table 1: Beam Characteristics and Constraints

	Present	**Upgrade**
Beam rigidity [Tm]	7.14	9.28
Kicker rise time [ns]	56	56
Normalised emittance LHC physics beam [μm] H / V	3.0 / 3.0	3.0 / 3.0
Normalised emittance LHC pilot beam [μm] H / V	1.0 / 1.0	1.0 / 1.0
Normalised emittance high intensity beam [μm] H, V	12 / 9	12 / 9

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Septum SMH42

The injection septum is already near the feedthrough limit in terms of current. The present magnets have a 5 mm thick septum with a 60.4 mm gap height, and 102 mm between conductors. A larger vertical aperture (e.g. 70 mm) can only be possible if the septum width is increased to 8-10 mm.

Kicker KFA45

The injection kicker would be very difficult to modify to gain more kick strength, as there is no space in the lattice in SD45, and the 80 kV gas filled cables are no longer manufactured. It is possible to run the present system in short-circuit mode to gain about 80% in kick strength: this increases the rise time by a similar amount.

BSM Bumper Magnets

The bumper magnets are limited in current to about 4,500 A for a linear kick. The present power convertor limit is 4,000 A.

Transfer Line BT/BTP

The injection line is presently not matched in dispersion to the PS lattice, unavoidably so in the case of the vertical optics, since the beams from the 4 different PSB rings have different dispersions at the injection point. The beam size at the injection point is presently too large, causing losses on the SMH42, which is a specific concern for the beam losses in the PS complex.

UPGRADE CONCEPTS

For PS injection no strength margin exists on the present septum or kicker system in terminated mode. A new injection scheme is therefore mandatory to provide the additional space for a longer septum, as well as to either allow the use of the injection kicker in short-circuit mode (with the associated degradation of rise, fall time and ripple at the flattop), or with the replacement or extension of the kicker system.

Two options were explored: injection into PS straight section SD42 (the present PS injection location, standard PS short straight section with 1 m length), or to displace the injection region to straight section SD41 (PS standard long straight section with 2.4 m length, in which little equipment is installed at present).

Injection into SD41

This solution has the largest impact on the PS and on the BTP line, which will have to be rebuilt. However, the advantage of SD41 is that it is a long straight section, presently almost empty of equipment. In addition, the required kicker strength decreases, as the phase advance to the KFA45 would then be more favourable, at very close to π/2, and the β function at the septum is larger. Finally, the rebuilding of the injection here could allow measures to be taken to reduce beam losses at injection.

In a preliminary version the injection bumpers presently installed in SD40 and SD42 would need to be moved to SD39 and SD41. The remaining bumpers and KFA45 stay in their present locations in SD43, SD44 and SD45, respectively. The present KFA45 could remain, but a total of 5 bumpers would be needed, together with a longer septum. The injection bump has as large an angle as possible at the septum to minimise the SMH strength needed. However, the beta functions are large at the septum location and the consequent larger beam size will not fit easily into the aperture, especially for the high intensity beam, Figure 2. Possibly a temporary perturbation of the injection optics would allow the beam sizes to be reduced enough to make such a scheme possible, or replacement of existing chambers with enlarged ones. No satisfactory solution for injecting into SD41 was found. It is possible that the affected main magnets could be fitted with new enlarged vacuum chambers, and also that the optics could be specially rematched at injection to reduce the beta function at this location; these options were not investigated.

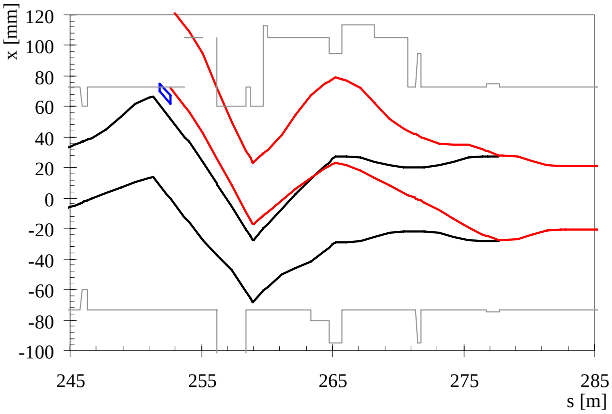

Figure 2: Injecting into SD41 with 12.0 μm high intensity beam at 2 GeV. The apertures are insufficient, especially at main magnet 41.

Injection into SD42

The simplest solution is to inject into SD42 as at present, which requires a longer injection septum, and a ~13 mrad bumper integrated into the septum tank. The KFA45 kicker can be operated in short-circuit mode for LHC beam if the blow-up due to the increased ripple is acceptable – if not, a new supplementary kicker can be built in SD53, with about -1 mrad.

The integration of the bumper and septum in SD42 is a particular mechanical challenge, the feasibility of which is crucial to the overall concept.

The orbit increases by about 10 mm in main magnet 41, and the trajectory of the injected beam is about 3 mm further out, in main magnet 42, Figure 3. This means that this injection will probably not work for the large emittance high intensity beam at 2.0 GeV; however, the layout is such that the high intensity beam can be injected in almost exactly the same way as present at 1.4 GeV, with a reduction of the orbit bump.

The ripple from KFA45 blows up the beam emittance. In case the ripple is too large from the existing KFA45 operated in short-circuit mode, an additional kicker module could be built and located in SD53, which has exactly π phase advance from the existing kicker. The new unit would provide about -1 mrad, while the existing kicker would work at its present voltage in terminated mode, and deliver 3.4 mrad. The resulting beam envelopes look reasonable, Figure 4, especially since the excursions are for a single turn only.

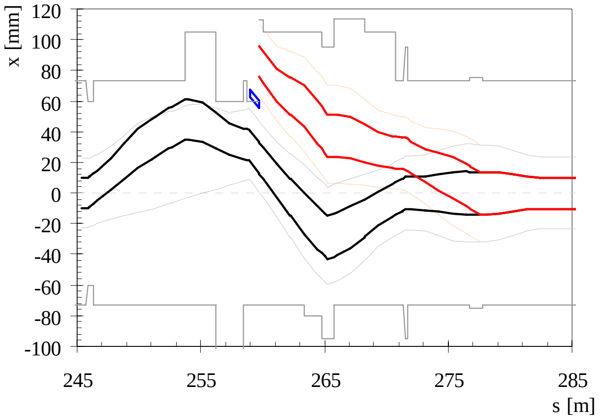

Figure 3: New injection bump and injected trajectory envelopes (bold) for 3.0 µm LHC beam at 2.0 GeV.

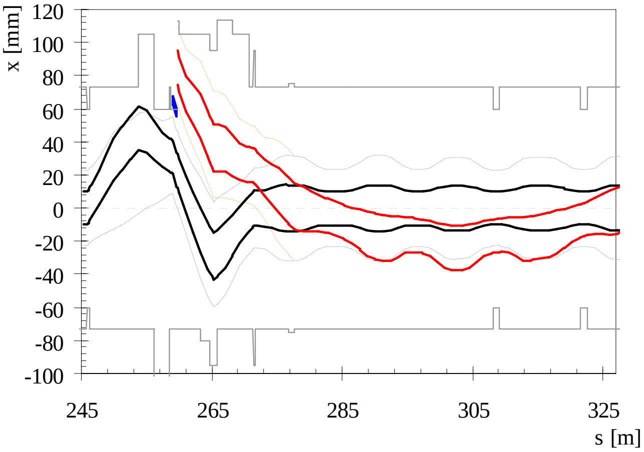

Figure 4: Use of auxiliary kicker π downstream of KFA45, to supplement the existing kicker if this can only be operated in terminated mode.

EQUIPMENT REQUIREMENTS FOR 2 GeV INJECTION IN SD42

The deflection angles and nominal operating voltages/currents of the injection elements are shown in Table 2 for the 2.0 GeV LHC beam injection, and also for comparison for the 1.4 GeV high intensity beam injection with the new layout. The detailed implications for the systems are discussed below.

Table 2: Assumed deflections and strengths of injection elements in new layout, compared to present

	2.0 GeV LHC	**1.4 GeV high intensity**
Kicker deflection [mrad]	4.3	4.3
Septum deflection [mrad]	55	55
BSM1.40 angle [mrad]	6.7	3.7
BSM1.41 angle [mrad]	-5.2	n/a
BSM1.42 angle [mrad]	-9.0	-13.3
BSM1.43 angle [mrad]	11.3	11.1
BSM1.44 angle [mrad]	-4.6	-4.4

Injection Septum SMH.42

The injection septum would need to be completely rebuilt, to deliver 55 mrad at 2.0 GeV, which requires a magnetic length of 0.8 m and a field of 0.64 T. The septum tank would need to incorporate the new BSM42 bumper, which would also be under vacuum. Preliminary mechanical studies have shown that such a combined septum-bumper tank is feasible, Figure 5. The septum alignment is horizontally adjustable, and the BSM bumper coil would be aligned with the septum coil, such that the aperture for the circulating beam is not reduced for any septum position. The peak current for the septum would be 31 kA, which is possible with the present feedthroughs. The parameters for the septum are shown in Table 3.

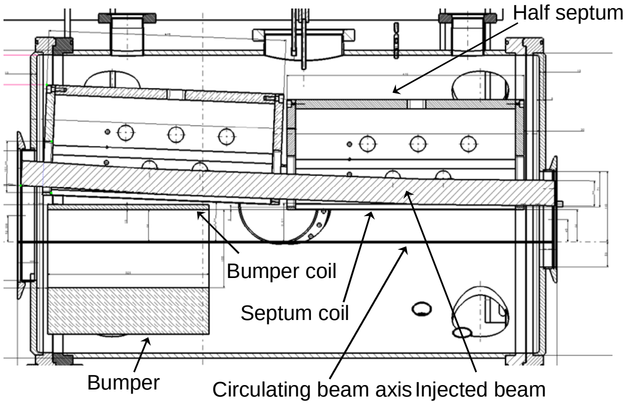

Figure 5: New SMH.42 tank containing the two half septum SMH.42 magnets aligned to the injected beam, and the BSM.42 bumper.

Table 3: Parameters for New SMH42 Half Septum

Parameter	**Value**	**Unit**
Lphysical	470	mm
Lmagnetic	400	mm
Deflection angle	27.5	mrad
Gap height	60	mm
Gap width	100	mm
Ipeak	31	kA
Current density	4.1	A/mm2
Inductance	0.9	µH
Coil resistance	0.1	mOhms
Power rating	100	W
Water cooling	3	l/min.

Injection Bumpers

In addition to the BSM42 which needs to be incorporated into the SMH42 tank, another 4 injection bumpers are needed. The existing magnets can remain in

SD40, SD43 and SD44. A new magnet needs to be located in SD41. This could be the existing BSM42 unit and its power supply, since the BSM42 will be rebuilt inside the septum tank, with a new power supply. The deflections required at 2.0 GeV for the existing 4 magnets (including BSM.42 displaced to SD41) are within the acceptable limits for the present power supplies (maximum 3000 A).

The field quality of the new BSM.42 magnet has been evaluated with a 3D finite element model, Figure 6, and shows an acceptable homogeneity of +/−1% can be achieved over the required aperture, Figure 7. The parameters for the new bumper are shown in Table 4.

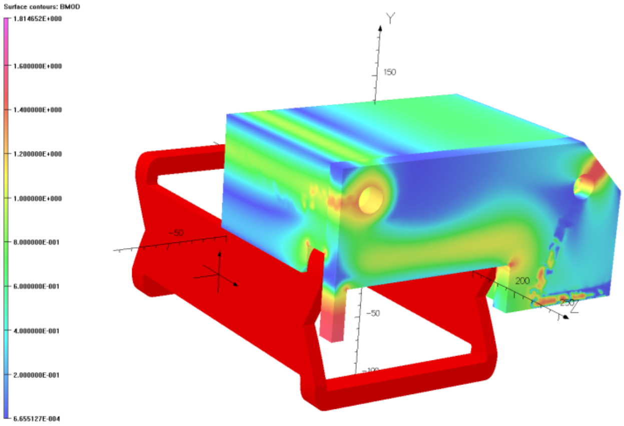

Figure 6: 3D Opera model of the new BSM.42 bumper.

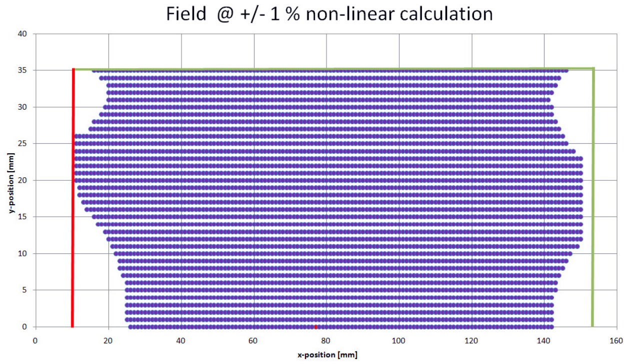

Figure 7: Integrated field homogeneity for the new BSM.42 bumper magnet, the top half of the magnet gap is shown, and the coloured region indicates a field within ±1% of nominal.

Table 4: Parameters for new BSM.42 bumper integrated in the septum tank, there is no active cooling foreseen

Parameter	Value	Unit
Lphysical	320	mm
Lmagnetic	260	mm
Deflection angle	13	mrad
Gap height	76	mm
Vertical beam acceptance	70	mm
Gap width	145	mm
Ipeak	27.9	kA
Current density	1.5	A/mm2
Inductance	0.7	µH
Coil resistance	0.05	µOhms
Power rating rms	44	W

AVAILABLE APERTURE

Injecting the 2 GeV LHC beam into SD42 implies changing the bump for the circulating beam, Figure 3. The aperture bottlenecks are the injection septum SMH42 on the outer side and the bumper magnet BSM.43 on the inner side of the ring. Assuming 3 mm orbit oscillation and $5 \cdot 10^{-4}$ momentum spread the 1.4 GeV high-intensity beam with the present injection bump is limited to 3σ. The 2 GeV LHC beam type with the modified bump allows for 6.5σ aperture for the circulating beam.

MODIFICATIONS TO OTHER SYSTEMS

In addition to the injection elements, several other systems will need modification.

Beam Instrumentation

The currently upstream of the injection septum placed BTV does not fit into the SD42 design and has to be moved upstream in the injection line.

Also the downstream placed SEM grids are suppressed in the proposed SD42 concept. Integrating the wires between the pole pieces of the downstream bending magnet has to be investigated as a possible solution.

BT-BTP Injection Line

The lattice of the injection line to SD42 needs to be re-designed due to a change of the injection point and the replacement of magnets and power converters to provide PPM powering. This gain in flexibility should allow to design the line optics such as to minimise the dispersion mismatch coming from different PS Booster beams and thereby reduce losses at the septum in particular for the high-intensity beam [4].

EMITTANCE GROWTH FROM KICKER RIPPLE

Expectations

The emittance growth due to kicker flat top ripple was calculated by the formula:

$$\varepsilon/\varepsilon_0 = 1 + 0.5\ (\Delta x^2 + (\beta\Delta x' + \alpha\Delta x)^2 / (\beta\varepsilon_0)$$

with α and β denoting the Twiss parameters and Δx and $\Delta x'$ the error in displacement and angle at the injection point. The kicker flat top uniformity is given as ±2% in terminated and ±3% in short-circuit (SC) mode [5]. The respective growth in emittance is shown in Table 5.

Table 5: Emittance growth for kicker operated in terminated (2% ripple) and SC mode (3% ripple)

Beam type	ε_0 [µm]	Emittance growth [%]	
		2% ripple	3% ripple
LHCPROBE	1	9	20
LHC	2.5	4	8

Measurements

The emittance of the LHCPROBE beam has been measured for the two kicker modes with and without correcting injection oscillations, Figure 8. Measurements were only taken into account for bunch intensities between $0.45 \cdot 10^{10}$ and $0.55 \cdot 10^{10}$ protons.

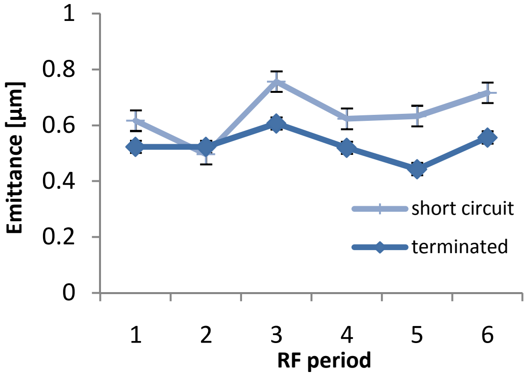

Figure 8: Emittance measurement with injection kicker in terminated and short-circuit mode, respectively.

The ripple pattern is visible in particular for the SC mode which is consistent with the expectations of less ripple in terminated mode. The correction of injection oscillations hardly changes the kick strength, the bigger part is corrected already by the transfer line dipole and the septum. From terminated to SC mode there is an emittance increase of ~10% which agrees well with the theoretical expectation of 9% and 20% blow-up for terminated and SC mode, respectively.

Implications

Assuming the presently extracted emittance of ~2.5 µm for the LHC physics beam with respect to the nominal emittance of 3 µm, an increase of 10% is acceptable and the injection kicker can be used in SC mode. Also, there is a handle to control the emittance increase by the installed but not yet commissioned PS damper system.

POTENTIAL SYNERGY WITH OTHER UPGRADES

The need to provide PPM powering for the BT/BTP line means that the magnets, power supplies and controls will need to be rebuilt. This should then be combined with an improvement of the injection line optics [4], to better match the beam to the PS optical functions, in particular the horizontal dispersion and the vertical beta function at the septum. This latter should be reduced to minimise the losses at the septum, which are presently a major source of irradiation in the PS ring [4]. Rematching the optics with a new line design seems easier than increasing the vertical gap of the SMH.42 septum to something like 70 mm, since this will increase both the magnet current (which is already very high) and require an increase in the septum thickness, from 5 to 8 mm. The extra strength available for the injection elements may allow some more optimisation of the injection at 1.4 GeV for the high intensity beam to reduce the losses, although this possibility has not yet been investigated.

CONCLUSION

The simplest solution is to inject into SD42 as at present, which requires a longer SMH septum, and a new ~13 mrad BSM bumper integrated into the septum tank. The bumper presently located in SD42 will need to be displaced to SD41. The KFA45 kicker can be operated in short-circuit mode for LHC beam if the blow-up from the ripple is acceptable – preliminary MD results show that this should be possible, with the extra normalised emittance increase about 0.1 µm, in agreement with analytical estimates. If this emittance increase is too large, a new supplementary kicker can be built in SD53, to provide about -1 mrad, or the PS injection damper could be commissioned, which would possibly result in gains with respect to the present emittances obtained.

Injecting into SD41 has been looked at but seems problematic. There is ample space for the septum and an adjacent bumper, and the kicker strength required is lower, as the phase advance and beta function are favourable. However, the beta functions are large at the septum location and the consequent larger beam size for the high intensity beam will not fit into the aperture. No feasible solution has been identified – possibly a temporary perturbation of the injection optics would allow the beam sizes to be reduced enough to make such a scheme possible.

The upgrade of the PS injection system is feasible on paper for the LHC beams at 2.0 GeV; the larger emittance high intensity beams can continue to be injected at 1.4 GeV. Since this will require anyway an upgrade of the BT/BTP line to PPM capability, it is strongly recommended that the upgrade of the PS injection system be combined with a new BTP line design which improves beam losses at injection of the high intensity beam, through better optical matching.

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