4 GEV H- CHARGE EXCHANGE INJECTION INTO THE PS2

B.Goddard, W.Bartmann, M.Benedikt, T.Kramer, A.Koschik, CERN, Geneva, Switzerland

Abstract

The proposed PS2 will accelerate protons from 4 to 50 GeV. The required beam intensity and brightness can only be achieved with a multi-turn H- charge exchange injection system, where the small emittance injected beam is used to paint the transverse phase space of the PS2 machine. This paper describes the constraints and conceptual design of the H- injection system and its incorporation into the present PS2 lattice. The requirements for the special injection system elements are described, in particular the injection chicane and painting magnet systems and the change exchange foil. Some key performance aspects are investigated, including the stripping efficiency, expected emittance growth and beam loss arising from the simulated number of multiple foil traversals, together with estimates of foil heating.

THE PS2 ACCELERATOR

The existing CERN PS is a combined function synchrotron with an injection energy of 1.4 GeV and a top energy of 25 GeV. It forms the core of the CERN complex, presently providing many proton beams for the different users. The replacement of the existing PS with a modern, reliable, flexible and robust synchrotron has been identified as an important part of the future CERN programme. A separated-function PS2 is assumed, with a circumference of 1346 m (twice that of the existing PS) and an initial parameter set as given in Table 1. The injection energy is 4.0 GeV for p+, and 135 MeV/u (1.3 GeV p+ equivalent) to accept heavy ions from LEIR.

Table 1: Main Parameters of the Proposed PS2 Accelerator

Parameter	Unit	Value
p+ injection energy (kinetic)	GeV	4.0
Extraction energy (kinetic)	GeV	20-50
Circumference	m	1346.4
Beam intensity	p+	1.4×10^{14}
Beam power	kW	400

The basic design of the PS2 depends on the approach to transition. The present choice is between a regular FODO lattice, which would have a real γ_{tr} of around 10, or an imaginary γ_{tr} lattice based on a negative momentum compaction cell, which would avoid transition crossing. In both cases, the long straight section for injection and extraction [2] can be a regular FODO insertion with β-functions in the range of 7-40 m, a cell length of about 21-23 m giving ~10 m free drift per half-cell and a phase advance per cell of ~90° in the horizontal plane. Table 2 shows the parameters of different beam types in the PS2.

Table 2: Parameters for different PS2 beam types.

Beam	ε_n [μm·rad] h/v	N_B 10/40 MHz	S_B [ns] 10/40 MHz
LHC 25ns	3/3	$1.7\cdot10^{12}/4.2\cdot10^{11}$	100/25
LHC 50ns	3/3	$---/3.1\cdot10^{11}$	---/50
FT	15/8	$3.2\cdot10^{12}/7.9\cdot10^{11}$	100/25
nTOF	15/8	$9.5\cdot10^{12}/---$	300/---

PS2 TUNE SHIFTS

The tune shift at injection has been calculated according to the formula [1]:

$$\Delta Q = \frac{-r_p \cdot N_B \cdot C}{4\pi \cdot \varepsilon_n \cdot \gamma^2 \cdot \beta \cdot S_B} \cdot \frac{FGH}{B}$$

where r_p is the proton radius (1.535×10^{-18} m), N_B the number of particles per bunch, C the circumference, ε_n the normalised r.m.s. emittance, S_B the bunch spacing and B the bunch ratio of bunch length to bunch spacing. F denotes to image forces, G to the transverse density distribution and H to the beam shape. Values have been chosen for a circular beam with parabolic density distribution and no image forces which gives F = 1, G = 2 and H = 0.5. Table 3 shows the resulting tune shifts at injection if a bunch-to-bucket ratio of 0.6 is assumed.

Table 3: Tune Shifts at Injection for 10 and 40 MHz RF

Beam type	**10 MHz** h/v	**40 MHz** h/v
LHC 25ns	-0.19/-0.19	-0.19/-0.19
LHC 50ns	---/---	-0.07/-0.07
SPS/PS2 fixed target	-0.07/-0.14	-0.07/-0.14
nTOF	-0.07/-0.14	---/---

CHARGE EXCHANGE H- INJECTION

H- charge exchange injection is now the preferred injection method for high intensity machines. The constraints imposed by Liouville's Theorem on conventional multi-turn injection can be circumvented since the injected ion changes charge state within the machine acceptance. Phase space painting schemes are used in all three dimensions (X, Y and momentum) to fill the emittances as uniformly as possible and to minimise the space charge tune shift. The charge exchange is generally accomplished by means of a stripping foil, which is also traversed by circulating protons. During injection it is important to minimise the number of foil hits per proton, since this leads to foil heating, emittance growth and beam losses. A promising alternative [2] is to use a laser beam in conjunction with magnetic fields to strip the electrons, which obviates the need for a foil. Such a system is under consideration for PS2.

H- INJECTION INTO THE PS2

Injection of an H- beam into the PS2 presents several difficulties associated with the very high injection energy of 4.0 GeV. The injection system is assumed to be integrated into the regular FODO structure in the long straight section, and will occupy 3 half-cells. The present design assumes horizontal injection and comprises an injection septum, chicane dipoles, stripping foil, and fast orbit bumpers for phase-space painting. An extraction and transport system and dump will be required for unstripped H-. The LHC beam is injected over about 130 turns and the CNGS beam over about 270 turns.

Lorentz Stripping

Relativistic H- ions experience a Lorentz force when traversing a magnetic field, which leads to a lifetime τ of:

$$\tau = -a/E \exp(b/E)$$

where $E = p \times B$ is the Lorentz transform of the magnetic field, $a \approx 4\times10^{-14}$ MV·s/cm and $b \approx 44$ MV/cm. The relative losses per m of dipole are plotted for 4.0 GeV and (for illustration) 1.0 GeV in Fig. 1: to keep the losses below the 10^{-4} level the fields traversed by the injected beam must therefore remain below about 0.13 T.

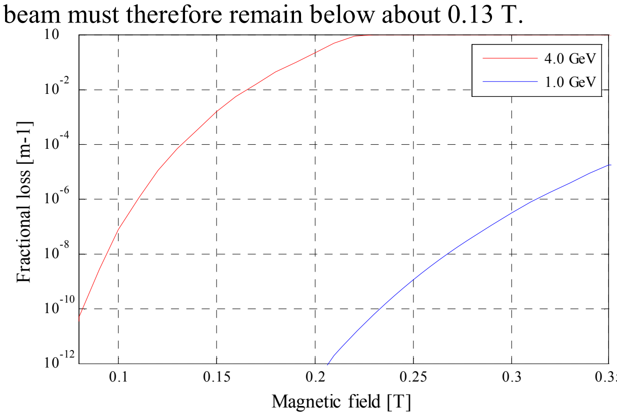

Figure 1: Fractional H- beam loss from Lorentz stripping.

Injection Chicane Half-Cell

The injection foil should be outside of the PS2 aperture (≈50 mm scaled to the local β). With the foil located in the centre of the injection half-cell, this implies a foil edge at least 35 mm from the axis. This is achieved in the injection geometry shown in Fig. 2.

The H- beam is injected through the aperture of the upstream QF, which must be a special enlarged-aperture magnet providing a good-field region extending to about ±80 mm. The injection chicane is made with 1 m long dipoles D1-D4 providing 7 mrad deflection, operating at about 0.11 T. The injected beam meets the circulating beam at a point about 47 mm from the beam axis, with a superposition of the 24 mm painting bump and the 23 mm chicane bump. Dispersion at the foil needs to be less than 10-20 cm to decouple transverse and longitudinal effects.

The unstripped H- and H0 ions traverse the D3-D4 dipoles and are stripped to p+ by a thick second foil. The downstream QD must also have a large aperture to accept the resulting p+ beams. The injection and extraction are essentially symmetric due to the difficulties of getting the H- beam into the PS2 aperture, and of extracting the residual H- and H0 beams. The field in the quadrupoles at the maximum excursion of about 80 mm is about 0.11 T, such that the losses from Lorentz stripping are below 10^{-6}.

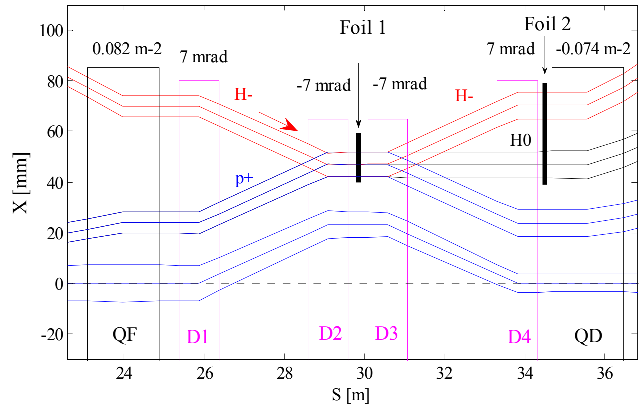

Figure 2. Injection chicane half-cell and apertures of chicane dipoles and quadrupoles (±4 sigma envelopes).

Painting Kickers

The painting bump, Fig. 3, can be made using fast kicker magnets in adjacent cells. The need to control both the angle and position imposes the use of four painting kickers – to keep the beam angle zero at the foil also means that the 2nd and 3rd kickers need to be adjacent to the injection and unstripped H- extraction septum, and will need large (~170 mm) horizontal aperture.

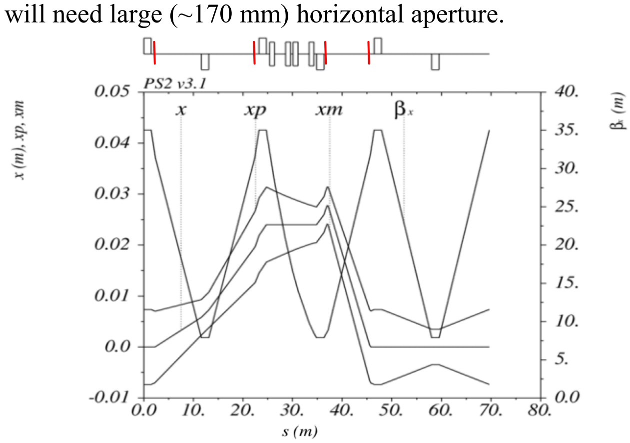

Figure 3: Horizontal painting bump in injection region.

The kick angles required are 1 to 6 mrad, which for a 1 m long kicker magnet implies a field of about 0.1 T, which is reasonable for ferrite yoke magnets. The main issue will be the integration of the 3rd kicker with the unstripped H- extraction septum.

Injection Septum System

The injection septum is limited in field to ~0.13 T, which constrains severely the geometry. The injected H- beam should be delivered with 77 mm offset and -

8.5 mrad angle at the entrance of the upstream QF. The septum could occupy 8.5 m of the 10 m free drift in the half cell, and would have a magnetic field length of 7.5 m, Fig. 4. The injected beam would therefore be displaced by ~420 mm at the edge of the upstream quadrupole. A septum width of 10 mm allows a comfortable design at this low field.

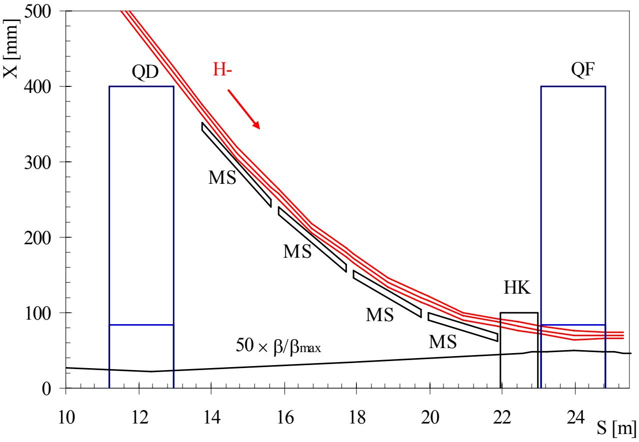

Figure 4: Injection septum half-cell, showing the 0.13 T, 13 mrad MS septa, and the painting magnet HK.

Stripping Foil

The stripping foil is assumed to be carbon with a thickness of about 500 μg/cm^2. The stripping efficiency will be about 95 %, which gives about ~2 kW of unstripped H0/H- to be extracted and dumped. The small emittances result in high p+ densities on the stripping foil and high temperature rise of over 1200 K, shown in Fig. 5 for anti-correlated painting (calculated without space charge). The average number of foil traversals per proton is ~20; this produces emittance growth from multiple Coulomb scattering of <0.1 π.mm.mrad, and a beam loss of <0.02% from inelastic nuclear interactions. The foil cools to ambient temperature in the 2.4 s between injections. The β functions at the end of the H- injection line are assumed to be ~10 m, to avoid a too small beam spot on the foil. The details of the painting scheme and the particle distribution, Fig. 6, will need further optimisation to reduce the peak density.

Unstripped H- Beam Extraction and Dump

The unstripped H- and H0 will be stripped to p+ in the second (thick) stripping foil. The p+ beams will then be extracted by a strong septum into a large-acceptance beam line and transported to a beam dump. The septum needs to provide about 100 mrad, which can easily be achieved with a 2 m long magnet operating at around 1 T. The acceptance of the beam transport line is likely to be problematic, and requires detailed study.

Electron Dump

The stripping foil should be located in the fringe-field of one of the chicane dipoles, to allow the stripped 2 MeV electrons to follow spiral trajectories which avoid repeated foil traversals. Electrons should be collected on a dedicated dump to absorb the ~30 W of power dissipated.

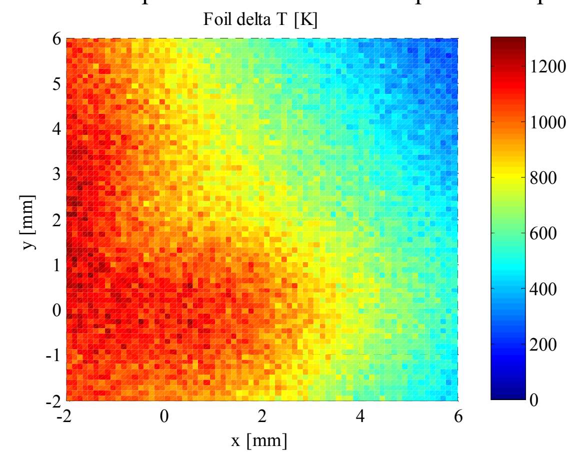

Figure 5: Foil ΔT (K): 270 turn injection of 1.4×10^{14} p+.

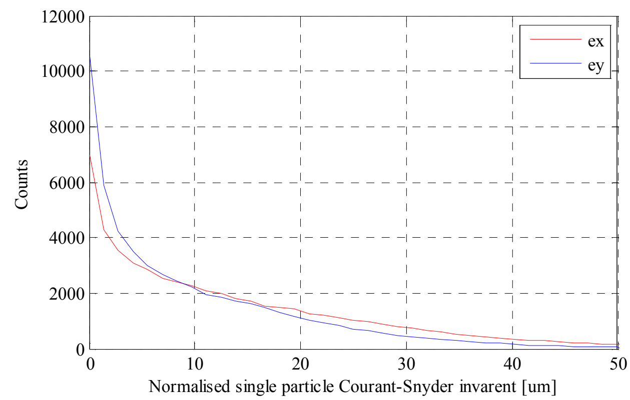

Figure 6: Single particle emittances after painting for fixed-target beam (ε_{xn} / ε_{yn} = 15/8 π.mm.mrad).

CONCLUSION

The 4 GeV H- injection system for PS2 presents several challenges associated with the high beam energy and small beam size – a concept for the integration of the injection into the FODO lattice has been investigated in terms of the geometry and performance requirements for the injection elements. Work is ongoing to demonstrate the overall feasibility of such a scheme. The possibility of laser stripping is being investigated, and numerical simulations of the injection process are being set up to start an optimisation of the scheme and to better quantify the effects described above.

REFERENCES

[1] M.Benedikt, PS2: basic considerations and optics, CARE-HHH-APD LHC-LUMI-06 workshop, 2006.
[2] W. Chou, H- injection mini-workshop, December 9-10, Fermilab, 2004.
[3] L.J.Laslett, On Intensity Limitations Imposed by Transverse Space-Charge Effects in Circular Particle Accelerators, BNL-7534, p. 325, 1963.
[4] M.Benedikt, S.Hancock, Analysis of RF Scenarios for the PS2, CERN-AB-Note-2008-028 OP.