OPERATIONAL CONSIDERATIONS FOR THE PSB H^- INJECTION SYSTEM

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Abstract

For the LINAC4 project the PS Booster (PSB) injection system will be upgraded. The 160 MeV H^- beam will be distributed to the 4 superimposed PSB synchrotron rings and horizontally injected by means of an H^- charge-exchange system. Operational considerations for the injection system are presented, including expected beam losses from unwanted field stripping of H^- and excited H^0 and foil scattering, possible injection failure cases and expected stripping foil lifetimes. Loading assumptions for the internal beam dumps are discussed together with estimates of doses on various components.

INTRODUCTION

The 160 MeV H^- beam from the future LINAC4 linear accelerator [1,2], which will replace the present 50 MeV LINAC2, needs to be distributed over the 4 superimposed synchrotron rings of the PSB [3]. Downstream of a vertical distribution system the LINAC4 beams will be injected horizontally into each of the 4 PSB rings by means of an H^- charge-exchange injection system using a graphite stripping foil. The local orbit of the PSB circulating beam is horizontally displaced by a set of four pulsed dipole magnets (BS) in order to merge with the injected beam. The first BS magnet (BS1) must act as a septum, only deflecting the circulating beam, providing a field-free region for the injected H^- beam.

A series of four horizontal kickers outside the injection region (KSW) produce a closed orbit bump with falling amplitude, which will paint the beam into the required horizontal emittance. An internal beam dump will be installed downstream of the stripping foil to intercept the partially stripped H^0 and unstripped H^- particles.

The main machine parameters [4] for LINAC4 PSB injection are shown in Table 1.

Table 1: Main LINAC4 PSB Machine Parameters

Ion species		H^-/H^+
Beam energy (kinetic)	MeV	160
Max. repetition rate	Hz	1.11
Max injection turns (per PSB ring)		100
Peak LINAC current	mA	65
Average LINAC current	mA	40
Nom. beam power	kW	2.84
Peak beam power (chopper off)	kW	4.6
Number of particles per beam pulse		1.0×10^{14}

INJECTION OPTIMISATION AND MATCHING

The LINAC beam is round with a normalised emittance (1 σ RMS) of $\varepsilon_{nx/y}$~0.4 µm. For the LHC beam, the target emittance is $\varepsilon_{nx/y} = 2$ µm in the PSB. The high intensity CNGS, fixed targets, etc., beam should reach $\varepsilon_{nx/y}$~8/4 µm. Injection will take place over 20 × 1 µs PSB-turns for the LHC beam and 80 PSB-turns for the high intensity beam. The design of the vertical distribution system allows for up to 100 injected turns per ring.

In the current design, no vertical painting is foreseen. Injection with ~2 mm fixed offset and some deliberate betatron mismatch will give ~2 µm emittance for the LHC beam. For the high intensity beam the 3-4 µm vertical emittance can be obtained by a more pronounced betatron mismatch, implying different line optics for different beams, or an increase of the fixed offset, which would start to give a hollow beam distribution. One could also rely on natural blow-up from space-charge effects, but this is difficult to control.

Optimisations and detailed evaluations made with linear tracking codes have shown that painting bump fall times of between 80-120 turns are needed for the LHC and high intensity beams.

Another important issue is longitudinal painting. It is planned to vary the dp/p of the incoming beam by ±0.4%, to produce a uniformly filled RF bucket [5]. The PSB dispersion at the injection point is -1.4 m, and studies of D_x/Dp_x injection mismatch, using ORBIT, have shown no strong effects on emittance growth but an offset in horizontal emittance (Fig. 1). Presently a zero D_x/Dp_x is assumed at the delivery point, which minimises the foil hits and foil size but results in a horizontal emittance blow-up of about 0.5 µm.

In the previous design [2], an asymmetric injection chicane region was chosen to maximise the clearance between the H^0/H^- dump and the circulating beam.

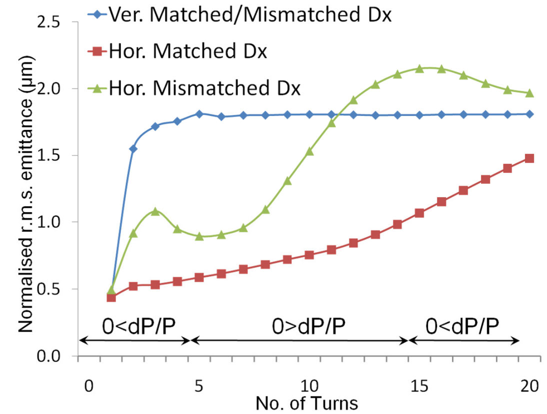

Figure 1: Transverse emittance evolution during painting.

Recent studies [4] have indentified that major perturbations of the lattice due to the edge- focusing of the injection chicane magnets will occur. In order to minimise this effect, the length of the BS chicane magnets was increased and the position of the magnets optimised in order to reduce the vertical focusing and beta-beating effects. A symmetric layout provides the least lattice perturbation and is the present baseline design. Both active and passive correction of the perturbation by additional quadrupole field components are being studied.

APERTURE CONSIDERATIONS

Studies have shown that the PSB machine aperture allows for a painting bump of up to 35 mm, with a chicane bump amplitude of 45 mm, having the stripping foil edge at about 74 mm, see Fig 2. The machine aperture limits being the main bending magnets and quadrupoles having similar values.

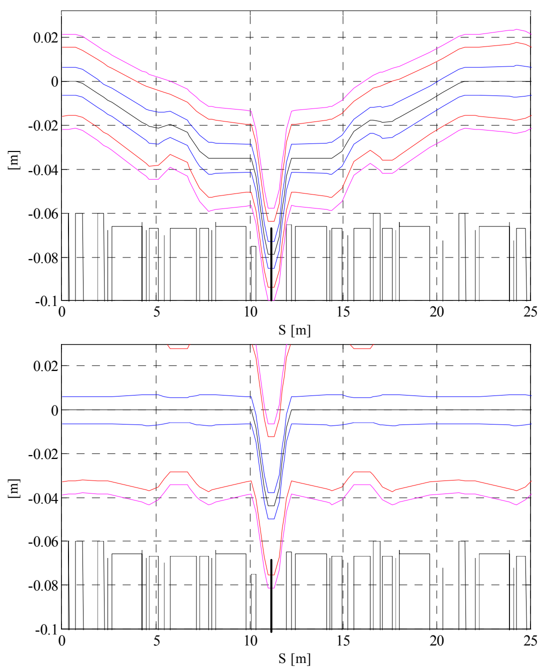

Figure 2: Horizontal physical PSB machine aperture at the injection chicane at the start (top) and end (bottom) of the painting process for a 35 mm painting bump.

The aperture limits in injection region are mainly at the BS1 septum and at the H^0/H^- dump inside BS4, which needs to be optimised in shape. All physical aperture limits are outside the 3 σ edge of the beam, with the offsets due to momentum painting, orbit and mechanical tolerances taken into account. The only remaining issue is the edge of the injection foil for the high intensity beam, which at the end of the painting bump fall is still at a transverse position of only ~2.6 σ. However, under these pessimistic assumptions any static orbit or mechanical error can be corrected during setting up of the injection, which will increase the clearance and, in addition, there is still some margin to increase the amplitude of the painting bump, which would move the beam off the foil completely at the end of the painting bump fall.

INJECTION FAILURE CASES

The worst case injection failure is associated with a painting bump (KSW) or chicane (BS) triggering failure, resulting in up to 100 turns injected in one ring without painting. The beam emittance would remain very small (~1 µm) and been blown up only by direct space charge; the foil would reach 2250 K within ~300 turns (0.30 ms) as shown in Fig. 3.

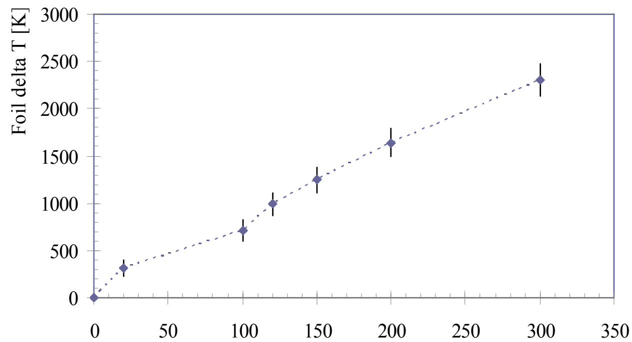

Figure 3: Foil temperature rise as a function of injection turns, in the absence of horizontal painting.

This is clearly not acceptable and triggering of the vertical distributor (BI.DIS) needs to be linked to the painting bump triggering. Another injection failure is associated with a BI.DIS kicker failure, in which case 4 x 100 turns could be injected into one ring. If one assumes that the painting bump decay is triggered correctly, foil temperatures up to ~1700 K can be reached.

Another failure scenario is foil failure resulting in full beam (100 µs) on the H^0/H^- dump, in which case the thermal load on the dump per injection would be relatively low with $2.5{\cdot}10^{13}p^+$@160 MeV (~500J). It could be, although unlikely, a factor 4 worse for combined BI.DIS and foil failure, where the instantaneous temperature rise could result in thermal shock in local cooling channels.

INJECTION DUMP BEAM LOAD

During nominal operation and, assuming a stripping efficiency of 98% [6], including beam missing the foil, the continuous load at 1.11 Hz on the H^0/H^- beam dump will be 14.2 W resulting in an activation load on the dump, for 200 days of operation, of $9.61{\cdot}10^{18}$ p^+/y. If the foil is degrading, a pessimistic stripping efficiency of 90% can be assumed for a limited period of ~8 hours resulting in a continuous load on the H^0/H^- dump of 71 W. Assuming this happens ~10 times a year, the activation load would be $7.99{\cdot}10^{18}$ p^+/y.

The H^0/H^- beam dump is expected to be the most activated item and preliminary simulations [7], on a Boron Nitride dump, have shown that the equivalent dose could reach 70 mSv/hr after 200 days of operation with a reduction by a factor 10 after 1 week of cooldown. Since the dumps need to be integrated inside the BS4 magnets this is a major concern and an optimisation study of the dump is required. Furthermore, the design of the 4 superimposed H^0/H^- dumps, foil module and chicane dipoles needs to facilitate rapid exchange and careful application of ALARA* principles to minimise the radiation dose taken by personnel.

FOIL ISSUES AND LOSSES

The stripping efficiency of the carbon foil can be calculated from extrapolated cross-section data [8] (see Fig. 4) and a 200 μg/cm^2 (~1 μm) would be a sufficient thickness, having a H^0 yield of about 0.1%.

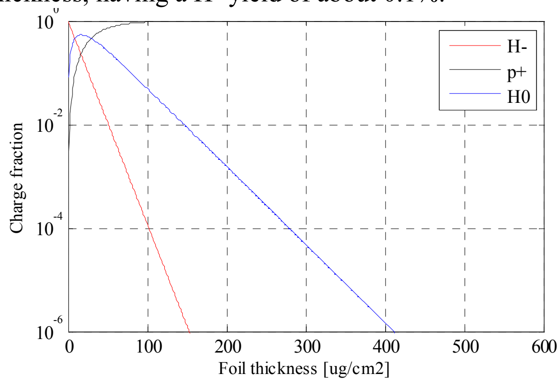

Figure 4: Stripping efficiency of carbon foil at 160 MeV.

It is estimated that particles which are undergoing elastic or inelastic scattering are lost, while MC scattering increases the emittance. By using the nuclear interaction length λ_I to estimate the fraction of p^+ lost, at λ_I~0.3 m a single 1 μm foil passage gives 7x10^{-6}. Losses at the 10^{-4} level for 5-15 hits/p^+ are expected. The emittance increase from foil scattering has been calculated analytically from the RMS angle increase. Up to ~20 foil hits/p^+ are acceptable for the LHC beam.

The excited quantum state yields have been estimated analytically and the lifetimes in the magnetic fringe fields estimated. The state n=5 and above are stripped in the BS3 fringe field (see Fig. 5). The population fraction in these states is estimated at 0.17, pessimistically assuming that all these particles are lost, the total relative loss from this source is 1.7×10^{-4} for a 200 μg/cm^2 foil.

Foil temperatures can be estimates using p^+ density maps tracking and non-linear heat capacity of carbon giving moderate ΔT for normal operation. Fig. 6 shows the foil temperature distribution, of a pessimistic 2 μm

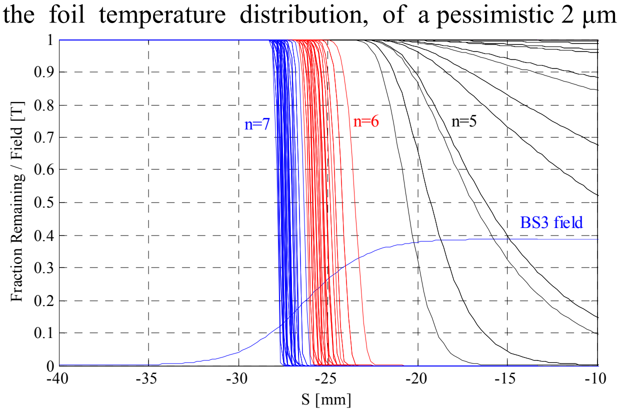

Figure 5: BS3 fringe field stripping loss with n>5.

thick foil, after 7 injections of 70 turns per ring with each turn consisting of 1.14 × 10^9 particles. Peak temperatures are ~680 K at the end of an injection pulse, with cooldown primarily due to radiation to ~320 K between injections.

The expected foil temperatures at nominal operation are relatively low, and foil lifetimes are not expected to be an issue. Lifetime will depend mainly on the quality of the foil and an exchange system with ~5 foils per ring seems reasonable to ensure 1 year of uninterrupted operation.

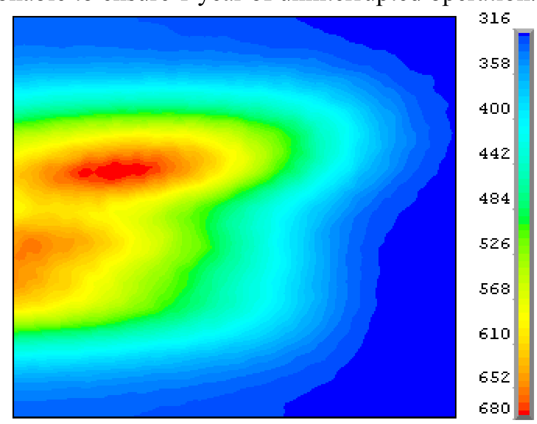

Figure 6: Temperature [K] of a 2 μm thick, 400 μg/cm^2 graphite foil at the end of the injection of 7 CNGS pulses.

Uncontrolled losses at injection are estimated to be in the range of few 10^{-4} (~10 W) for the different processes considered. In the present design transfer line collimation has not been considered but is under study in order to localise losses on dedicated devices, to avoid activation of kickers and septa in the injection line and to reduce the number of halo particles missing the foil.

CONCLUSION

A 160 MeV H^- charge-exchange injection system will use a >200 μg/cm^2 graphite foil. This provides sufficient stripping efficiency while the losses remain acceptable. Activation, however, due to failure and load on the H^0/H^- dump is an issue and needs further study. The injection optimisation and effects on emittance growth have been discussed and the machine aperture has been described.

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* As Low As Reasonably Achievable