BEAM LOSS CONTROL FOR THE UNSTRIPPED IONS FROM THE PS2 CHARGE EXCHANGE INJECTION

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Abstract

Control of beam losses is an important aspect of the H- injection system for the PS2, a proposed replacement of the CPS in the CERN injector complex. H- ions may pass the foil unstripped or be partially stripped to excited H0 states which may be stripped in the subsequent strong-field chicane magnet. Depending on the choice of the magnetic field, atoms in the ground and first excited states can be extracted and dumped. The conceptual design of the waste beam handling is presented, including local collimation and the dump line, both of which must take into account the divergence of the beam from stripping in fringe fields. Beam load estimates and activation related requirements of the local collimators and dump are briefly discussed.

INTRODUCTION

The H^- injection for PS2 is required to achieve the high brightness and intensity beams [1], and is planned to accommodate both foil- and laser-stripping systems, placed in the 22 m drift between the triplets of the long straight section, Fig. 1. A long D2 dipole with a magnetic field below 0.13 T merges the H^- and circulating p^+ beams, Fig. 1, with a stripping foil located in the fringe field at the exit. The low field is chosen in order to avoid Lorentz stripping in the magnet.

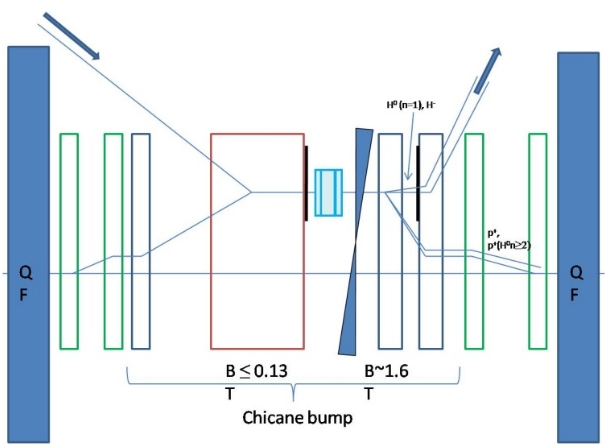

Figure 1: H^- Injection. The first chicane dipole (red) has low field B ≤ 0.13 T to avoid Lorentz stripping the incoming H^-. Kickers (green) make the painting bump.

PS2 is designed in the framework of the foreseen LHC injector upgrade and thereby the requirements are mainly set by the LHC beam type. The injected beam power of ~40kW does not present foil damage issues in particular; however, losses due to scattering processes in the foil and by deflection of particles with different charge number or state in the chicane dipoles need to be investigated carefully. In this paper we focus on the emittance growth and losses expected for the foil stripping system, in particular at the specific locations shown in Fig. 2. It should be mentioned that laser assisted stripping [2] may offer an attractive alternative with lower beam loss and without the need for a delicate and radioactive stripping foil system.

The following sections will address the different scattering processes with their resulting loss rates and/or emittance growths and the emittance growth and losses due to stripping of different excited states in the fringe fields of the chicane magnets.

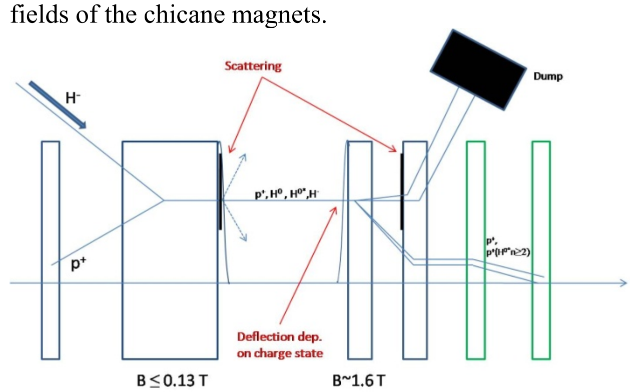

Figure 2: Critical points where emittance growth is caused due to scattering or fringe field deflection.

FOIL STRIPPING EFFICIENCY

The stripping efficiency, the absolute yield of H^0 and unstripped H^- and the yield of the different H^0 excited states depend on the foil thickness and the incident ion energy. Some semi-empirical treatments exist, e.g. [3] which have been adjusted to give reasonable agreement with measured cross-sections at 200 and 800 MeV which can be scaled to the energies of interest here. The different charge state yields can be written as:

$$y_-(x) = e^{-\rho(\sigma_{-0}+\sigma_{-+})x}$$

$$y_0(x) = \frac{\sigma_{-0}}{\sigma_{-0}+\sigma_{-+}-\sigma_{0+}} x \cdot e^{-\rho\sigma_{0+}x} + e^{-\rho(\sigma_{0+}+\sigma_{-+})x}$$

$$y_+(x) = 1 - y_-(x) - y_0(x)$$

where x is the foil thickness (μg/cm^2), ρ is the material density in atoms per μg, i.e. $\rho = 1\cdot10^{-6} N_A / Z$, and σ_{-0}, σ_{-+} and σ_{0+} are the cross sections in cm^2 for the different stripping processes. The cross-sections used were [$\cdot10^{-19}$ cm^2] σ_{-0}= 4.97, σ_{-+} = 0.09 and σ_{0+} = 1.94.

For a carbon foil with 400 μg/cm^2 a stripping efficiency of 97% percent is expected. 3% of the beam escapes from the foil as H^0 of which ~46% occupy the ground state and with decreasing probabilities also higher energy level states as illustrated in Fig. 3.

The field of the D3 chicane magnet is chosen to assure the stripping of excited states with n > 1within the first mm of the fringe field. Fig. 4 shows the lifetime of the excited states with indicated B field of D2 and D3. Between D3 and D4 a second, thicker, stripping foil is placed. Here, any remaining H- and the H^0 in ground state will be stripped to protons and deflected outwards by the D4 chicane magnet into a dump line.

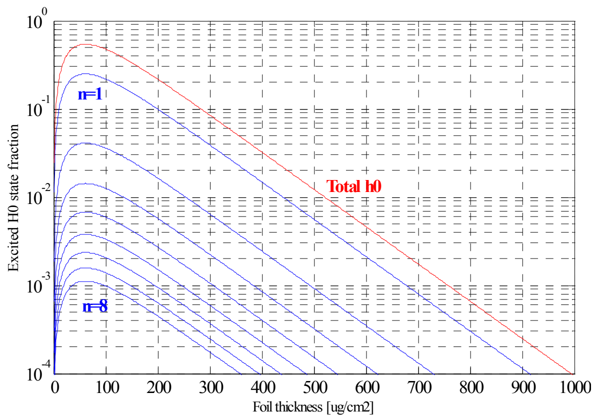

Figure 3: Fraction of excited H^0 states of total beam.

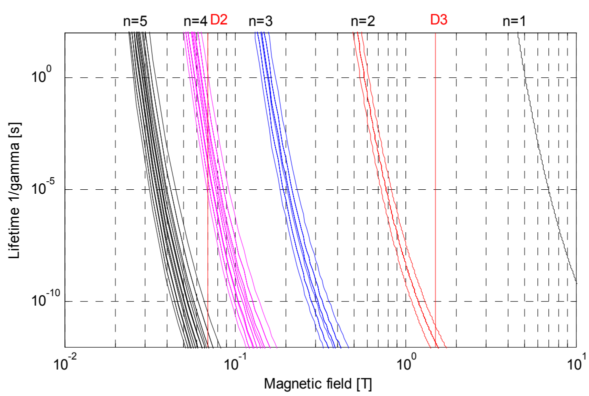

Figure 4: Lifetime in D2, D3 fringe fields.

FOIL SCATTERING

Three scattering processes have been investigated for a carbon foil.

Inelastic nuclear scattering:

The attenuation $N(L)/ N_0=\exp(-L/\lambda_i)$ for protons in the carbon foil is characterised by the ratio foil thickness (L) to inelastic interaction length (λ_i) for protons at 4 GeV. Since the foil thickness is of the order of μm and the interaction length ~50cm, the inelastic nuclear scattering process is negligible.

Elastic nuclear scattering:

The interaction length for nuclear elastic scattering (λ_e) is of the order of ~1.4 m. The angle from a single scattering process can be described by:

$$1/\theta_{el}^2 = \frac{1}{3} A^{\frac{2}{3}} \left(\frac{p}{0.135}\right)^2$$

where A denotes the atomic number and p the momentum of the scattering particles in GeV/c. This results in an rms angle of 21 mrad.

The probability of observing N interactions in a length L with the interaction length λ_e is given by:

$$P\left(\frac{L}{\lambda_e}, n\right) = e^{-\frac{L}{\lambda_e}} \left(\frac{L}{\lambda_e}\right)^n 1/n!$$

The total angle after n scattering events is distributed about $(n)^{1/2}\,\theta_{el}$.

The probability for one scattering event is $\sim 1\cdot 10^{-6}$, for two events $\sim 1\cdot 10^{-13}$ and strongly decreasing for higher numbers of events. Considering the single scattering angle to be Gaussian distributed, the superposition of the angle distributions for higher numbers of scattering processes does not deviate the initial Gaussian. So the rms value is taken to calculate the resulting emittance growth for the elastic scattered particles.

Multiple Coulomb scattering:

The angle for multiple scattering is given by:

$$\theta_{MC} = \frac{0.0136}{\beta c p} z \sqrt{\frac{x}{X_0}}\left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

with p in GeV the momentum, βc the velocity and z the charge state of the incoming particles. x/X_0 denotes the thickness of the foil in radiation length.

For a foil of 1.7 um thickness the rms scattering angle results in 0.007 mrad. The second foil creates an angle of 0.025 mrad.

The absolut normalised emittance growth is calculated as:

$$\Delta\varepsilon = (\beta\gamma)_{rel} \frac{1}{2} \beta \theta_{rms}^2$$

The corresponding emittance growth for the thin foil amounts to 0.0012 π·mm·mrad and 0.0031for the second foil.

FRINGE FIELD DEFLECTION

The yield for H- emerging the first stripping foil with 400 μg/cm2 is about 1e-4. However, it is assumed that the total H- fraction can be as high as 2%, to take into account for possible local foil damage and beam missing the foil. Entering the D3 magnet the H- ions are deflected in the opposite direction to the fully stripped protons until they are Lorentz stripped to H0.

The rest frame lifetime for H^- in a magnetic field is expressed as [5]:

$$\tau = \frac{A_1}{E} e^{\frac{A_2}{E}}$$

where E=βcγB the transverse electric field. The coefficients are $A1=2.47\cdot 10^{-6}$ Vs/m and $A2=4.49\cdot 10^{9}$ V/m. The RMS angular spread for the H- stripped in a 1.6 T D3 field was numerically calculated at 0.065 mrad using a simulated fringe field and the field-dependant lifetime. The emittance growth amounts to 0.25 π·mm·mrad for the waste $H^- \rightarrow H^0$ beam.

THICKNESS OF SECOND FOIL

The second foil placed between D3 and D4 aims at stripping all the H^0 originating from H^- that might have missed the first foil, and the H^0 in the ground state which pass the D3 field without stripping. The thickness of this foil needs to be optimised to minimise the beam loss while controlling emittance increase from scattering. Any H^0 after the foil have to be regarded as uncontrolled losses. An emittance increase determines the acceptance of the dump line and might give rise to uncontrolled losses from large angle scattering.

The total beam loss from stripping inefficiency and nuclear scattering was calculated for 4 GeV ions and carbon foil, Fig. 5. The optimum foil thickness is at about 1500 μg/cm^2, where the emittance growth from multiple Coulomb scattering is calculated to be about 0.003.

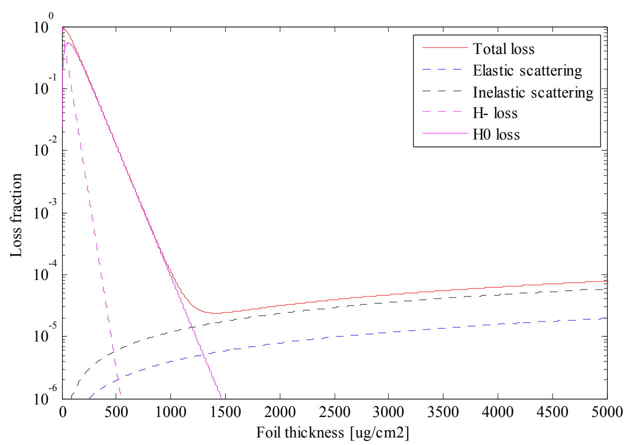

Figure 5: Total beam loss from stripping inefficiency and scattering. The optimum foil thickness is 1500 μg/cm2.

SUMMARY OF LOSSES AND EMITTANCE GROWTHS

Table 1: Values for loss levels and emittance growths at the critical points. (I)ES stands for (in)elastic nuclear scattering and MCS for multiple Coulomb scattering.

	Uncontrolled losses	Δε of waste beam [μm]	Δε of circulat. beam [μm]
D2	0.05% H^- stripped	-	-
1st foil	$6 \cdot 10^{-6}$% IES+ES	0.001 MCS	0.001 MCS
D2 fringe field	-	-	1.3 $H^{0*}_{(n>4)}$ to p^+
D3 fringe field	-	0.25 H^- to H^0	523 H^{0*} to p^+
2nd foil	$3 \cdot 10^{-9}$% H^0+IES+ES	0.003 MCS	-

The expected loss levels and emittance growth, for the circulating and different waste beams, is given in Tab. 1.

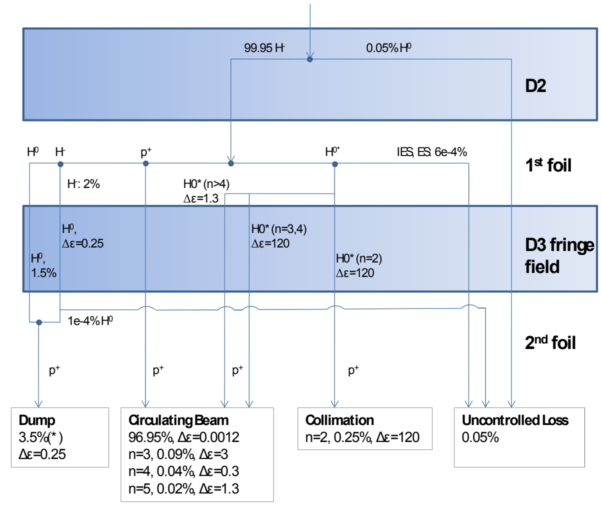

Figure 6: Particle flow through the H⁻ injection line.

In Fig. 6 the flow of the particle types through the elements in the H^- injection line is illustrated. The respective loss levels and emittance growth are drawn within the location area where they are caused. There are 3.5% of the total injected particles considered for the dump in case H^- are missing the foil due to e.g. foil damage.

CONCLUSION

Different scattering processes in the stripping foils and fringe field deflection contribute to emittance growth and uncontrolled losses, and have been quantified for PS2.

Due to the emittance growth the different lost particle types will require local collimation, transport in the dump line or will be uncontrolled losses. Minimisation of the total beamloss from the stripping inefficiency and scattering were used to optimise the length of the second foil. The main uncontrolled loss comes from stripping in D2; the layout will be revised to reduce this contribution.

These first estimates indicate the feasibility of this waste beam concept, however, the implementation of the H- injection line into a tracking code including scattering processes is necessary for a detailed loss analysis.

REFERENCES

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