STRIPPING FOIL ISSUES FOR H- INJECTION INTO THE CERN PSB AT 160 MEV

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Abstract

Beam physics considerations for the stripping foil of the 160 MeV PSB H^- injection system are described, including the arguments for the foil type, thickness, geometry and positioning. The foil performance considerations are described, including expected stripping efficiency, emittance growth, energy straggling, temperature and lifetime. The different beam loss mechanisms are quantified in the context of the aperture limits, operational considerations and collimation requirements.

INTRODUCTION

Linac4 [1] is an H^- linear accelerator which will replace Linac2 as injector to the PS Booster (PSB). A new charge-exchange H^- injection system is required for the PSB [2], which will allow transverse phase space painting to control the transverse emittances.

The momentum range for the injected beam is large, due to the need for longitudinal painting [3]. Injection can either be made with the incoming beam dispersion matched to the PSB ring, which will minimize the emittance growth from dispersion mismatch but will require a larger foil; or the dispersion for the injected beam can be zero, which produces some dispersion mismatch but minimizes the foil size and number of foil hits. For the matched dispersion case the average number of foil hits per proton is about 25, and with zero dispersion the average number of proton hits is about 10. Since the emittance growth and uncontrolled beam loss both increase with increasing foil hits, the zero dispersion arrangement is presently the baseline.

FOIL MATERIAL, THICKNESS AND SCATTERING EFFECTS

For thermal stability, high sublimation temperature, radiation and mechanical resistance the foil material will be carbon, either amorphous or possibly diamond [4], with an assumed density in the range 1.7-2.0 g/cm^3.

A thicker foil gives better stripping efficiency and is more stable mechanically, but will give higher beam loss and emittance growth through scattering. Inelastic scattering and large-angle elastic scattering are assumed to result directly in beam loss, while multiple Coulomb scattering will give a small angle increase and will blow up the circulating beam emittance. The optimum foil thickness is a compromise between these effects.

Stripping efficiency

From Figure 1, showing charge fraction as a function of foil thickness, one concludes that for a theoretical stripping efficiency of >99 %, the foil thickness should be greater than 150 μg/cm^2. The cross-sections for the relevant charge exchange processes, Table 1, have been extrapolated from data measured [8] at 200 MeV.

Table 1: Measured and scaled charge exchange cross-sections for a carbon stripping foil

Energy [MeV]	σ_{-0} [$\times 10^{-19}$ cm^2]	σ_{-+} [$\times 10^{-19}$ cm^2]	σ_{0+} [$\times 10^{-19}$ cm^2]
200 [8]	15.33 ±1.3	0.27 ±0.03	6.0 ±0.1
160 (scaled)	17.72	0.31	6.92

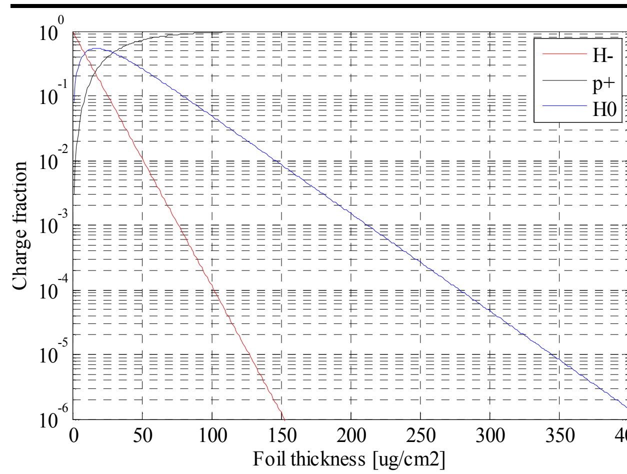

Figure 1: Charge fraction for carbon stripping foil with density of 1.7 g/cm^3.

The unstripped H^- and H^0 will be dumped on a block which will be located inside the finale chicane magnet BS4; since the minimization of the beam load on this block is a major design issue the stripping foil should be as thick as possible. The H^- yield is several orders of magnitude below the H^0 yield and can be neglected as regards transmission through the foil. The outgoing H^- beam is likely to be dominated by ions which miss the stripping foil, or which impact the foil in a damaged or much thinner than average region. Collimation of the incoming H^- beam is important to minimise this load.

Nuclear scattering

Both inelastic and elastic nuclear scattering processes will result in the uncontrolled loss of the impacting proton. The combined inelastic and elastic nuclear interaction length λ_n for carbon is taken to be 37 cm, corresponding to a total cross section of about 330 mb [9]. The resulting beam loss is below the 10^{-4} level for a foil thickness of about 200 μg/cm^2. The angular distribution of elastically scattered protons derived from simple scattering formulae [10] for 160 MeV protons on carbon gives an RMS angle which is very large, of the order of 100 mrad, which justifies the assumption that these protons are simply lost from the circulating beam.

Emittance growth from Multiple Coulomb scattering

Multiple Coulomb scattering of the proton beam traversing the foil results in an accumulation of small angle deflections. For N_h proton hits of a foil thickness x, the overall RMS scattering angle can be approximated by:

$$\theta_{MC} = \frac{0.0136}{\beta_r c \cdot p}\sqrt{\frac{N_h x}{L_{rad}}}\left(1 + 0.038 \cdot \ln \frac{N_h x}{L_{rad}}\right)$$

where p in GeV is the momentum, $\beta_r c$ the velocity and L_{rad} is the radiation length of carbon (~19 cm). For the beta-function value β at the foil, the normalised emittance blow-up is then:

$$\Delta\varepsilon_n = \frac{\beta}{2}\beta_r\gamma_r\langle\theta_{MC}\rangle^2$$

For 25 hits per proton, the emittance increases in the vertical and horizontal planes are about 0.15-0.25 π.μm, respectively, for a foil of about 200 μg/cm^2 in thickness. For 10 hits per proton, the emittance increase is 0.1 - 0.15 π.μrad. These numbers should be compared to the ≈2 π.μrad required emittance for the LHC beam, and the <1 π.μrad required for the LHC probe beam. Note that if the number of proton hits would reach 50, the emittance growth in the horizontal plane would be 0.55 π.μrad.

Beam loss through large angle single Coulomb scattering

The contribution to beam losses from large angle single Coulomb scattering in the foil [11] is often overlooked in comparison to the emittance growth from standard multiple Coulomb scattering. The probability P per proton of a single large angle scattering that leads to loss can be expressed [12] as:

$$P = N_h \cdot n \cdot x \cdot \left(\frac{2Zm_e r_e}{\gamma M\beta^2}\right)^2\left[\frac{1}{\theta_{xl}\theta_{yl}} + \frac{1}{\theta_{xl}^2}\tan^{-1}\left(\frac{\theta_{yl}}{\theta_{xl}}\right) + \frac{1}{\theta_{yl}^2}\tan^{-1}\left(\frac{\theta_{xl}}{\theta_{yl}}\right)\right]$$

where N_h is the number of foil hits per proton, n the foil density in atoms per unit volume, x the foil thickness, Z the target atomic number, A the target mass number, m_e and r_e the electron mass and classical radius, respectively, M the incident particle rest mass. The angles θ_{xl}, θ_{yl} are the limiting angles above which a scattered particle will be lost, i.e.:

$$\theta_{xl}^2 = \frac{X_A}{\beta_{fx}} \text{ and } \theta_{yl}^2 = \frac{Y_A}{\beta_{fy}}$$

where X_A and Y_A are the machine acceptance in horizontal and vertical plane, and $\beta_{fx}\beta_{f,y}$ are the horizontal and vertical beta functions at the foil. This is valid for scattering angles in the range $\theta_{min} \rightarrow \theta_{max}$ given by:

$$\theta_{min} = \frac{Z^{1/3}}{192}\left(\frac{m_e}{M\beta\gamma}\right),\ \theta_{max} = \frac{274}{A^{1/3}}\left(\frac{m_e}{M\beta\gamma}\right)$$

For the PSB the limiting machine acceptances are assumed to be X_A = 191 π.mm.mrad and Y_A = 74 π.mm.mrad. The limiting scattering angles θ_{xl}, θ_{yl} are therefore 5.8 and 5.4 mrad, respectively, which are well inside the range of validity.

The numerical value of P for the PSB injection is found to be 7.0 × 10^{-4} for a foil of 200 μg/cm^2 thickness with 25 hits, or 2.8 × 10^{-5} per foil hit, which indicates that this loss mechanism is a significant one.

BEAM LOSSES FROM MAGNETIC FIELD STRIPPING OF EXCITED H^0

The neutral hydrogen atoms emerging from the foil are in a distribution of exited principle quantum states. The high-lying states can be field-stripped by the downstream chicane magnet BS3, contributing to the uncontrolled beam loss, since the resulting proton will be outside the acceptance of the ring. The lifetime of each state in a magnetic field was computed analytically from the Stark broadened line width which depends on the quantum state, the magnetic field and the particle relativistic βγ. States above n=4 may contribute to the uncontrolled beam loss. The population of excited states is assumed to vary with $n^{-1.3}$ [5]. Highly excited states with n>10 will strip immediately in the fringe field of the BS3 magnet, and these protons will join the circulating beam, resulting in a small emittance growth. This was evaluated by taking a representative end-field distribution and calculating the RMS angle increase for each excited level.

The emittance increase is below 0.1 π.μrad for the n=11 level, Figure 2, for the nominal BS3 field of 0.34 T. The total contribution to the uncontrolled beam loss will come from the n=5 to n=10 levels, which is some 15% of the H^0, or about 1.5×10^{-4} of the incoming H- beam.

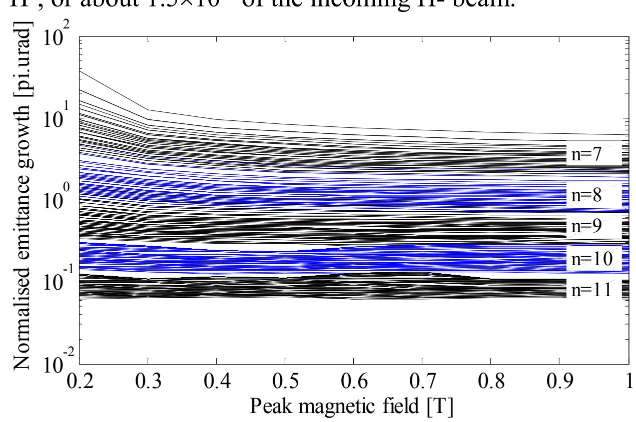

Figure 2: RMS emittance growth per excited state for protons stripped in the BS3 fringe field, as a function of peak BS3 field. Above n=10 the emittance increase is below 0.1 π.mm.mrad and all particles are assumed to remain in the circulating beam.

EXPECTED FOIL TEMPERATURE

The expected foil temperature depends on the injected intensity, the painting process and the injection repetition rate. At low repetition rates the foil thickness has only a small influence, since the energy deposited and the heat capacity per unit both scale linearly with thickness for very thin foils. The foil is heated by ionization and electron excitation energy loss of the impacting proton and stripped electrons. The highest foil temperatures of about 550 K were obtained for the high intensity CNGS type beam, where emittances of around 8 and 6 π.μrad were assumed in the horizontal and vertical planes, respectively. The temperature rise for a single injection of 1.3×10^{13} p+ of is about 280 K. The effect of multiple injections every 1.2 s was investigated assuming black-body radiation as the only cooling mechanism – the equilibrium peak temperature is reached after a few cycles, and is about 650 K. These temperatures are very comfortable in comparison to the values in excess of 1500 K which are experienced at other machines. Thermal damage to the foil is therefore not expected to be an issue for the foil lifetime or performance.

ENERGY LOSS

The energy lost in the foil by the proton on each passage will modify the beam momentum distribution, and the total energy lost depends on the number of foil hits. With a dE/dx of 4.8×10^6 $eVg^{-1}cm^2$ [10], the energy loss per hit for a 200 μg/cm2 foil is then dE = 0.96 keV. Since $dp/p = 1/\beta^2\ dE/E$, this gives dp/p of 3.24×10^{-6} per hit, or averages of 2.6×10^{-5} and 7.1×10^{-5} in dp/p for the zero dispersion and matched cases, respectively. This is to be compared with the full bucket height of $dp/p = \pm 4 \times 10^{-3}$. The distribution of energy loss for the full beam depends on the painting parameters and space change effects – an estimate in the absence of space charge was made for the high-intensity CNGS beam. Overall the effect on the momentum distribution is small, Figure 3, and from the longitudinal phase space distributions the beam loss from this source should be below the 10^{-4} level.

STRIPPED ELECTRON HANDLING

The electrons stripped from the incoming H^- beam have a momentum of 0.31 MeV/c and a magnetic rigidity of 0.001 T.m. The electrons will be strongly deflected in the fringe field of the BS chicane dipole magnets and will impact the vacuum chamber in this region. The total electron power for the highest intensity CNGS beam is about 0.3 W, which is considered negligible. No special precautions (fringe field shaping, collectors, cooling) are therefore foreseen for the disposal of the stripped electrons – this small power load will be absorbed by the vacuum chamber.

One concern could be multiple foil passages of the stripped electrons, which could result in excessive foil heating. The fringe field at the stripping foil location should either be oriented such as to direct the electrons away from the foil onto the adjacent aperture, or should be lower than around 0.005 T, to have a bending radius larger than (say) 20 cm, such that the electrons will be lost 'naturally'.

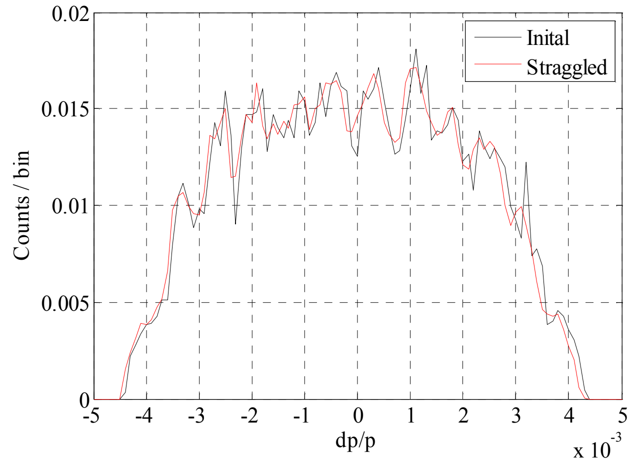

Figure 3: Modification due to straggling of the distribution of dp/p for the CNGS beam with matched dispersion.

CONCLUSIONS

The beam physics considerations for the foil for the 160 MeV H^- charge exchange injection for the PSB lead to the choice of a carbon foil of between 150 and 200 μg/cm2 thickness, with the upper figure preferred to minimize the load on the H^-/H^0 dump. The foil lifetime is expected to be dominated by purely mechanical effects or by accidents such as being moved into the circulating beam. The losses, emittance growth and energy straggling from scattering processes in the foil are acceptable. Beam losses from magnetic field stripping of excited H^0 are expected to be at the 10^{-4} level.

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