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Stripping foils for the PSB H^- injection system

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Summary

Beam physics considerations for the stripping foil of the 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 required movement ranges and tolerances are detailed, together with the assumptions used.

1. Introduction

Linac4 [1] is an H^- linear accelerator which will replace Linac2 as injector to the PS Booster (PSB). The 160 MeV beam from Linac4 will be distributed to the four levels of the PSB by a system of five pulsed magnets, the proton distributor (BI.DIS) and 3 vertical septum magnets (BI.SMV). 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. Details of the injection geometry can be found in [3].

The momentum range for the injected beam is large, due to the need for longitudinal painting [4]. 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 proton hits is about 22, and with zero dispersion the average number of proton hits is about 8, for both the CNGS and LHC beams. Since the emittance growth and uncontrolled beam loss both increase with increasing foil hits, the zero dispersion arrangement is presently the baseline.

2. Stripping foil material

For thermal stability, high sublimation temperature, radiation and mechanical resistance the foil material will be carbon, either amorphous or possibly diamond [5], with an assumed density in the range 1.7-2.0 g/cm^3.

3. Foil thickness, stripping efficiency and scattering effects

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.

3.1 Stripping efficiency

The stripping efficiency of a carbon foil depends on the energy of the H^- ion and the foil thickness. The yield of H^-, H^0, and p^+ can be calculated from the rate equations [6] as:

$$y_-(x) = \exp\left(-n\left(\sigma_{-0} + \sigma_{-+}\right)x\right), \tag{1}$$

$$y_0(x) = \frac{\sigma_{-0}}{\sigma_{-0} + \sigma_{-+} - \sigma_{0+}}\left[\exp\left(-n\sigma_{0+}x\right) - \exp\left(-n(\sigma_{-0} + \sigma_{-+})x\right)\right], \tag{2}$$

$$y_+(x) = 1 - y_-(x) - y_0(x), \tag{3}$$

where x is the foil thickness, σ_{-0} and σ_{-+} the cross sections for one- and two-electron stripping of H^- respectively, σ_{0+} is the cross section of one-electron stripping for H^0 and $n = \rho N_0 / A$ is the foil density in atoms per unit volume, N_0 being Avogadro's number and A the atomic mass number of the foil atoms.

The 160 MeV cross-sections for the charge-exchange processes can be extrapolated from data measured at 200 MeV [7], since the cross-sections scale well with β^{-2} [8]. Table 1 shows the measured and scaled cross-sections of interest. The stripping yields at 160 MeV as a function of foil thickness are shown in Figure 1. For a theoretical stripping efficiency of >99 %, the foil thickness should be greater than 150 μg/cm^2. The unstripped H^- and H^0 will be dumped on a block inside the BS4 magnet and the minimization of the beam load on this block is a major design issue [9]. The stripping foil should therefore be as thick as possible.

Table 1. Measured and fitted charge exchange cross-sections for a carbon stripping foil

Kinetic energy [MeV]	β	σ_{-0} [$\times 10^{-19}$ cm^2]	σ_{-+} [$\times 10^{-19}$ cm^2]	σ_{0+} [$\times 10^{-19}$ cm^2]
160 (scaled)	0.520	17.72	0.31	6.92
200 (measured, [7])	0.566	15.33 ±1.3	0.27±0.03	6.0±0.10

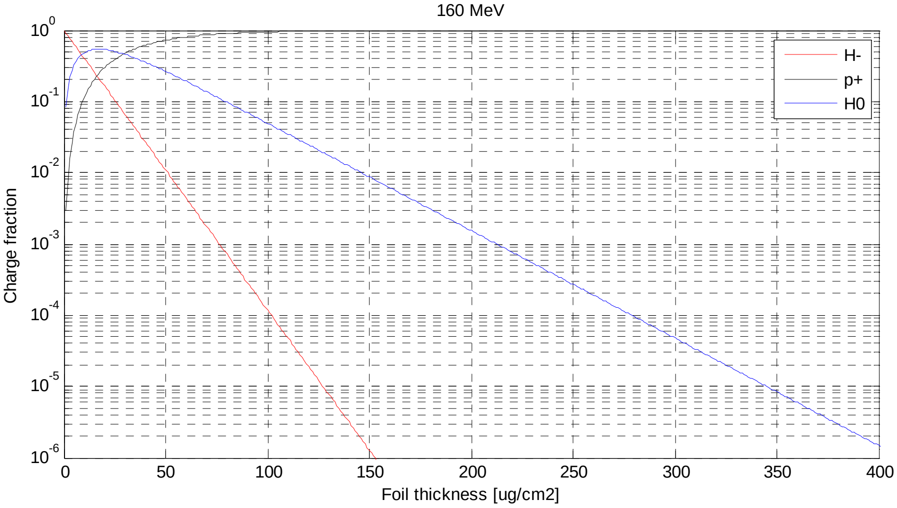

Figure 1. H^-, H^0 and p^+ yield as a function of stripping foil thickness.

The H^- yield is several orders of magnitude below the H^0 yield and can be neglected as regards transmission through the foil. However, this does not mean that the waste H^- beam can be neglected - 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 – a 50 μg/cm^2 thickness already transmits about 1% H^-, and about 25% H^0. To limit the load on the H^-/H^0 dump, the total transmission of H^- (including beam missing the foil) must be kept to a minimum, and has been assumed to be below 2% [9] in considering the dump design.

3.2 Beam loss through nuclear scattering

Both inelastic and elastic nuclear scattering processes are assumed to 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 [10]. With an average number of foil hits per proton of N_h, then provided that $N_h \cdot x << \lambda_n$ the total fraction of protons lost y_{loss} is then simply

$$y_{loss} = 1 - \exp\left(- N_h \cdot x / \lambda_n\right), \tag{4}$$

The resulting beam loss as a function of foil thickness is shown in Figure 2, for 10 or 25 hits per proton. The uncontrolled 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 can easily be derived from simple scattering formulae [11] – for 160 MeV protons on carbon the rms angle is very large, of the order of 100 mrad which justifies the assumption that these protons are simply lost from the circulating beam.

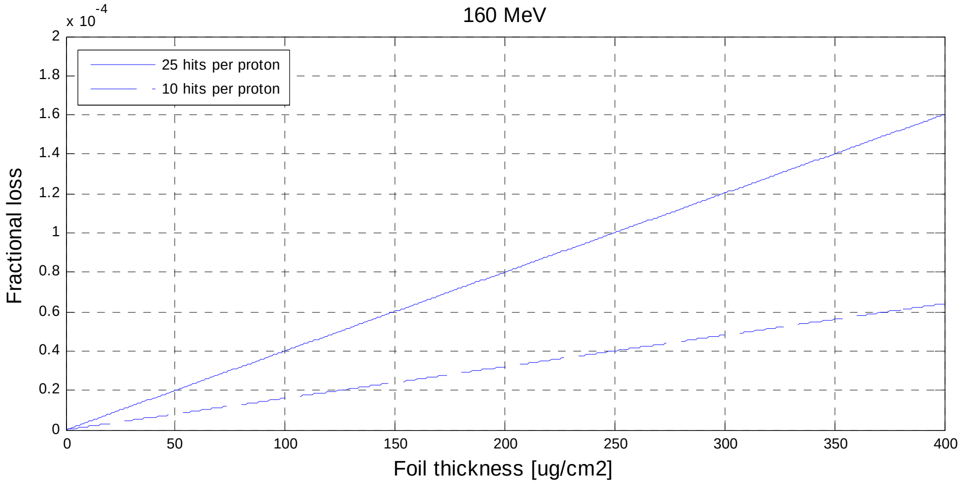

Figure 2. Beam loss through nuclear scattering as a function of stripping foil thickness, assuming 10 and 25 hits per proton on average, for zero and matched dispersion, respectively.

3.3 Emittance growth through multiple-Coulomb scattering

Multiple Coulomb scattering of the proton beam traversing the foil will result 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 as a worst-case by:

$$\theta_{MC} = \frac{0.0136}{\beta_r c \cdot p}\sqrt{\frac{N_h x}{L_{rad}}}\left(1 + 0.038 \cdot \ln\frac{N_h x}{L_{rad}}\right), \tag{5}$$

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:

$$\Delta\varepsilon_n = \frac{\beta}{2}\beta_r\gamma_r\langle\theta_{MC}\rangle^2 . \tag{6}$$

Calculated normalised emittance increases are shown in Figure 3, assuming the nominal beta functions at the injection point. 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 corresponding 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. Note that if the number of proton hits would reach 50, the emittance growth in the horizontal plane would be 0.55 π.μrad for this foil.

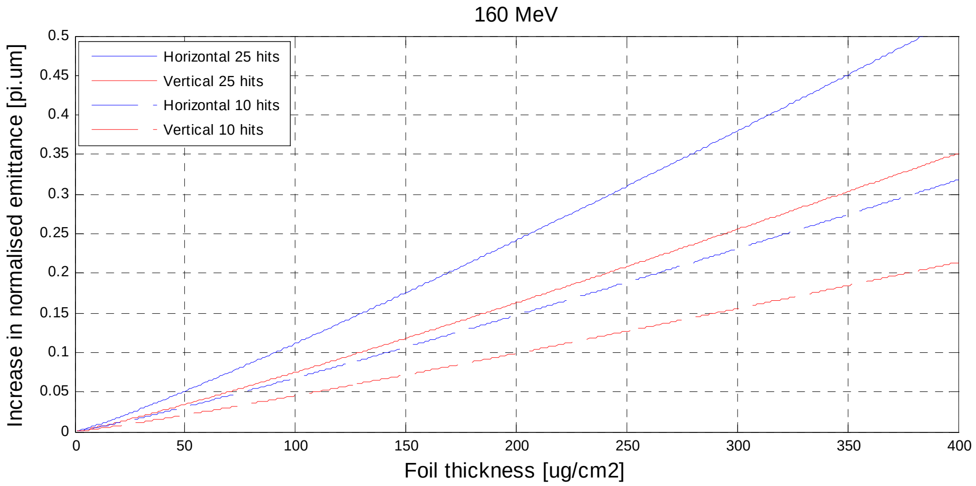

Figure 3. Emittance growth by multiple Coulomb scattering as a function of foil thickness, assuming 10 and 25 hits per proton on average, for zero and matched dispersion, respectively.

3.4 Beam loss through large angle single Coulomb scattering

The contribution to beam losses from large angle single Coulomb scattering in the foil is often overlooked in comparison to the emittance growth from standard multiple Coulomb scattering [12]. A thorough discussion of this effect and the derivations of the following relations can be found in [13]; for our purposes we quote the results. The probability P per proton of a single large angle scattering that leads to loss can be expressed as:

$$P = N_h \cdot n \cdot x \cdot \left(\frac{2Zm_e r_e}{\gamma M \beta^2} \right)^2 \left[\frac{1}{\theta_{xl}\theta_{yl}} + \frac{1}{\theta_{xl}^2} \tan^{-1}\left(\frac{\theta_{yl}}{\theta_{xl}} \right) + \frac{1}{\theta_{yl}^2} \tan^{-1}\left(\frac{\theta_{xl}}{\theta_{yl}} \right) \right], \tag{7}$$

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.:

$$\theta_{xl}^2 = \frac{X_A}{\beta_{fx}} \quad \text{and} \quad \theta_{yl}^2 = \frac{Y_A}{\beta_{fy}}, \tag{8}$$

where X_A and Y_A are the machine acceptance in horizontal and vertical plane, and β_{fx}, $\beta_{f,y}$. are the horizontal and vertical beta functions at the foil.

Equation (7) is valid for scattering angles in the range $\theta_{\min} \rightarrow \theta_{\max}$ given by:

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

Evaluating these limits gives a range of validity between about 8 μrad and 100 mrad. For the PSB the limiting machine acceptances are assumed to be $X_A = 191\ \pi$.mm.mrad and $Y_A = 74\ \pi$.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 of equation (7).

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

4. 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 BS3 magnet, 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.

Figure 4 indicates that states above $n=4$ may contribute to the uncontrolled beam loss. The population of excited states is assumed to vary with $n^{-1.3}$ [6], which indicates that about 40% of the H^0 beam will be in these states. In reality the number contributing to beam loss will be lower, since highly excited states with $n>10$ will strip immediately in the fringe field of the BS3 magnet. 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, which depends on the lifetime.

The emittance increase for each state was obtained, which is below 0.1 π.μrad for the *n=11* level, Figure 5. The total contribution to the uncontrolled beam loss is therefore assumed to 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.

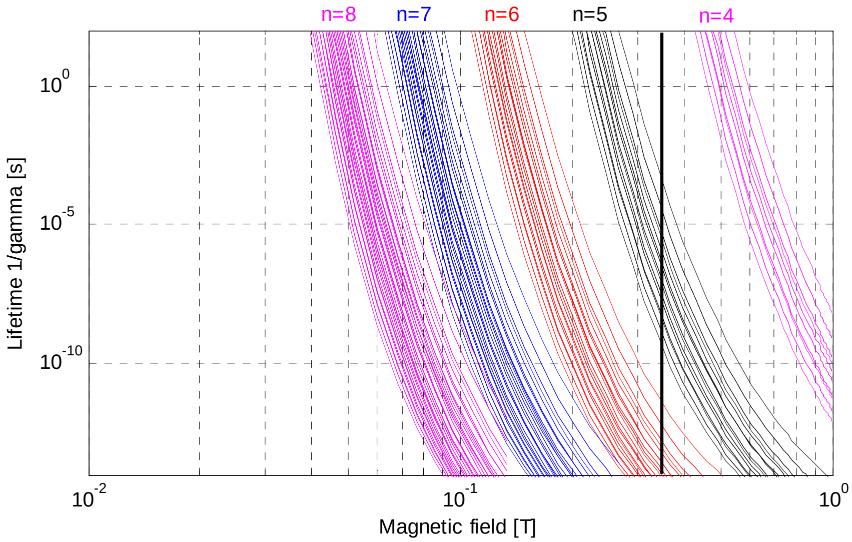

Figure 4. Lifetime of 160 MeV H^{0*} in magnetic field. Excited states above n=4 will contribute to uncontrolled beam loss.

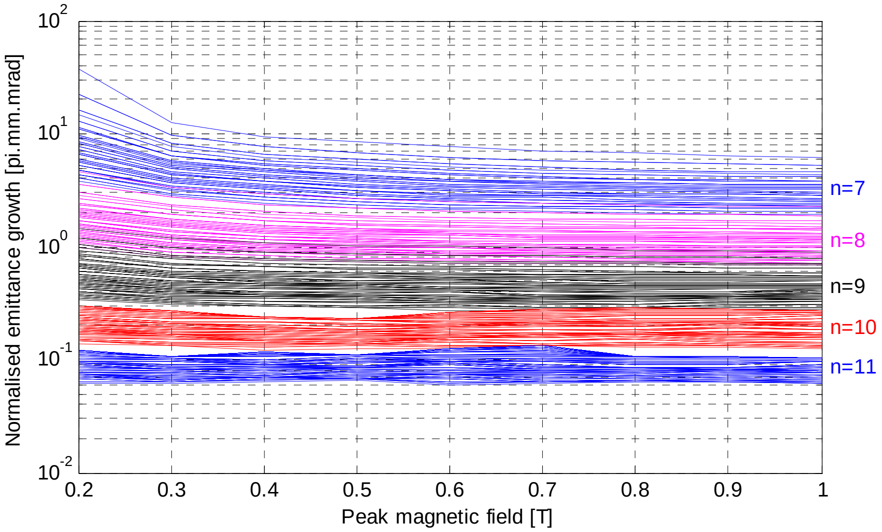

Figure 5. The rms emittance growth per excited state for protons stripped in the BS3 fringe field, as a function of peak BS3 field. Above *n=10* the emittance increase is below 0.1 π.mm.mrad and all particles are assumed to remain in the circulating beam.

5. 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 – for our calculation we assume that the energy lost is all deposited in the foil, and that the each electron deposits as much energy as a proton.

The maximum expected temperature rise has been simulated for the LHC beam and the high intensity CNGS beams by recording the H- beam and proton density traversing the foil, for the different painting schemes, and calculating the energy deposition dE/dx. The temperature is then obtained by integrating the temperature-dependant heat-capacity curve. Note that this is somewhat pessimistic as the heat loss from radiation is not taken into account here. The foil cooling is then calculated numerically from the Stefan-Boltzmann radiation law, with an emissivity of 0.7 assumed – note that the cooling will be slowed for a thicker foil. More detailed calculations were made using ANSYS, to check the effects of a supporting edge, but the effects are negligible at these low temperatures.

The highest foil temperatures of about 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 1.3×10^{13} p^+ of is about 280 K, Figure 6. 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, Figure 7, and is about 650 K. These temperatures are very comfortable in comparison to the values in excess of 1500 K which are required at other machines. Thermal damage to the foil is therefore not expected to be an issue for the foil lifetime or performance.

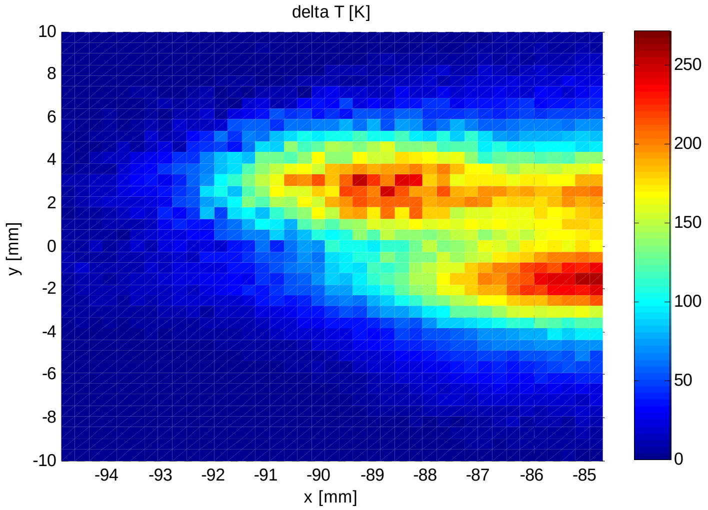

Figure 6. Temperature rise in carbon foil for CNGS beam. The peak is about 280 K – the edge of the foil is to the right.

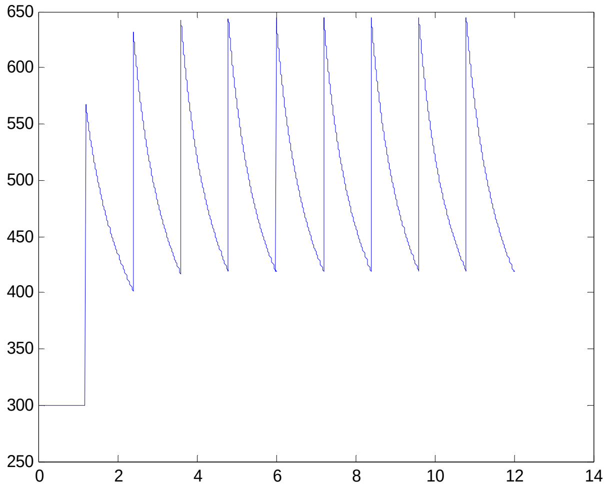

Figure 7. Evolution of maximum temperature in carbon foil for 1.3 × 10^{13} p+ CNGS beam injected at 1.2 s intervals. The equilibrium peak temperature is about 650 K.

6. Energy loss straggling

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.

Simulations for the transverse painting have showed that the average number of hits per proton is expected to be about n = 8 for the zero dispersion case, and about 22 for the matched dispersion case. With a dE/dx of 4.8×10^6 $\mathrm{eVg^{-1}cm^2}$ [11], the energy loss per hit for a 200 μg/cm^2 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, Figure 8, for the zero dispersion and matched dispersion cases using a 200 μg/cm^2 thick foil. It can be seen that the particles with higher initial dp/p are those which undergo more foil hits and have the largest change in dp/p – overall the effect on the momentum distribution is small, Figure 9, and from the longitudinal phase space distributions the additional beam loss from this source is expected to be below the 10^{-4} level.

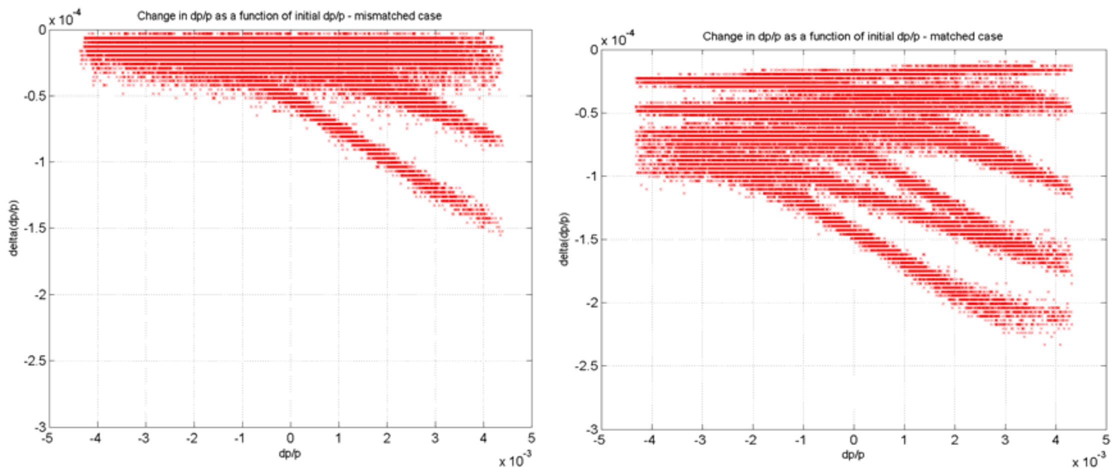

Figure 8. Change in dp/p as a function of initial dp/p for the zero dispersion (left) and matched dispersion (right) cases, for the CNGS beam.

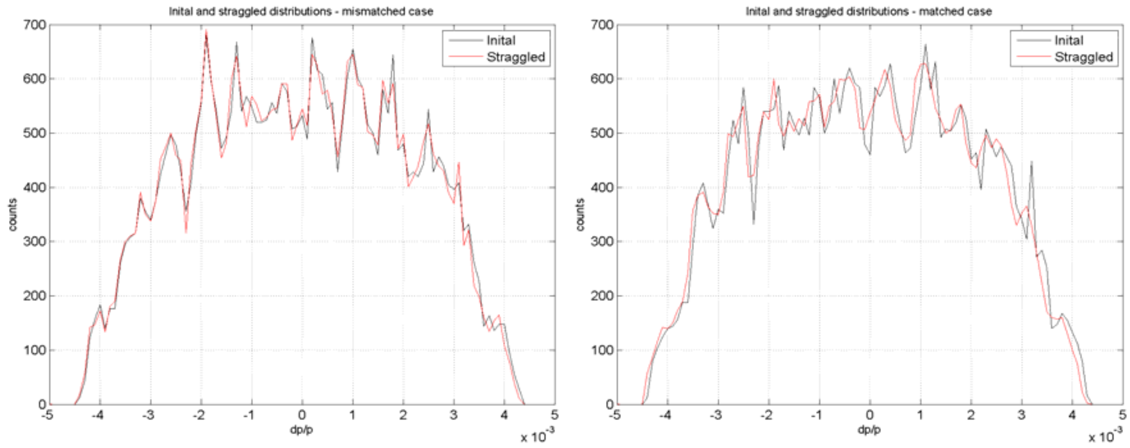

Figure 9. Modification due to straggling of the distribution of dp/p for the zero dispersion (left) and matched dispersion (right) cases, for the CNGS beam.

7. 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’.

8. Foil lifetime and handling considerations

A number of factors affect the lifetime of carbon stripping foils. The main ones are the instantaneous temperature rise, mechanical stress, fatigue due to thermal cycling, buckling, sublimation and displacement or removal of lattice carbon atoms by elastic or inelastic scattering. Analytical estimates or numerical simulations can be used to evaluate all of these effects individually, but the actual foil lifetime also depends strongly on the manufacturing and handling processes, and is a complicated interaction between many different factors. For the moderate operating regimes planned for the PSB injection, none of the effects caused by exposure to beam are expected to limit the foil lifetimes. The maximum foil operating temperature is expected to be 650 K, compared to the sublimation temperature of about 1900 K and melting point of about 3800 K, and the total H^- and p^+ flux is relatively low, since the repetition period is only 1.2 s, which means that damage or thinning from nuclear scattering [13] is not expected to be an issue.

For these reasons the foil lifetime is expected to be dominated by mechanical rather than thermal effects – for instance stresses induced during a venting of the foil assembly, stresses induced by vibrations during transport or during manipulation of the foil changer. A relatively small number of operational foils per changer is therefore proposed, for instance 4 or 5, which should safely allow a year's uninterrupted operation. Clearly attention must be paid to avoiding vibration or stresses during any handling or venting of the foil or its assembly.

Issues which have been considered in other labs [12] should also be investigated for potential problems. These include indirect beam-induced heating, eddy-current heating, breakdown (arcing) caused by charge build up on the stripper foils from caused by SEM or thermionic electron emission, and the need for a good electrical contact between foil and support mechanism.

9. Foil size

It is presently planned to use a foil supported on the top edge only; a foil slightly larger than the minimum can be used, since there will not be any beam intercepted towards the outer side of the vacuum chamber and the horizontal and vertical position of the foil relative to the beam anyway needs to be adjustable.

The foil size needs to be large enough to cover the incoming H^- beam fully, to minimize the losses occurring from beam missing the foil, which argues for a larger foil. However, extending the foil too far horizontally into the circulating beam will result in larger numbers of foil hits per proton, with an attendant increase in beam loss, emittance growth and foil temperature. A maximum of ~1 % of H^- beam missing the foil has been assumed. Distributions from tracking through the Linac and the BI beam transfer line [15] show that the beam has significant non-Gaussian tails, and that the 98% emittances are at about 3.2 and 3.8 π.mm.mrad in the H and V planes, respectively. These are slightly more that the figure of around 2.6 π.mm.mrad that one would expect from a Gaussian distribution (corresponding to ~2.5^2 times the rms emittance of 0.42 π.mm.mrad). The 98 % emittance was therefore used to determine the betatron beam size, since the beam is missing the foil mainly on one side.

The foil width should also cover the offset due to momentum spread and any momentum painting, plus mechanical, alignment tolerances and delivery jitter. The parameters which contribute to the foil size are the injected beam emittance, the optical parameters at the end of the transfer line, the momentum offset and spread in the beam, the delivery jitter in position for the injected beam and the mechanical tolerance / reproducibility of the positioning system. The upper edge of the foil holder should at least be kept out of the acceptance of the PSB and, in addition to the other parameters, the vertical foil size will depend on this acceptance plus any tolerance added for orbit, alignment, movement range and mechanical precision etc. The acceptance of the PSB will be reduced for the 160 MeV injected beam [3], and the assumed values are 191 and 74 π.mm.mrad in H and V, respectively. To minimize the vertical height of the foil it is assumed that any fixed offset for injection painting in the vertical plane will be made towards the top of the vacuum chamber.

The values of the different parameters assumed are shown in Table 2, for an injection with zero dispersion at the end of the transfer line (baseline) and for the alternative with a matched dispersion, with which the overall design should remain compatible. The required foil sizes and clearances are shown schematically in Figures 10 and 11.

Table 2. Parameters used for determining foil size for zero and matched dispersion cases

Parameter	**Unit**	**Value**	
		Zero dispersion	**Matched dispersion**
Energy	MeV	160	
Max $\Delta p/p$		±0.004	
Injected rms emittance (h/v)	π.mm.mrad	0.5 / 0.5	
Injected 98% emittance (h/v)	π.mm.mrad	3.2 / 3.7	
Circulating emittance LHC (h/v)	π.mm.mrad	2.0 / 2.0	
Circulating emittance CNGS (h/v)	π.mm.mrad	8.0 / 6.0	
PSB acceptance (h/v)	π.mm.mrad	191 / 74	
Tolerance for orbit etc.	mm	10	
PSB β at injection (h/v)	m	5.6 / 2.5	
Max β at injection (h/v)	m	10.0 / 25.0	
Max offset at injection (h/v)	mm	5.0 / 5.0	
PSB β beat at injection (h/v)		1.2	
Delivery jitter (h/v)	mm	±1.0	
Movement range (h/v)	mm	±10 / ±5	
Mechanical tolerance	mm	±0.5	
Required number of sigma		2.8	3.0
Dx at injection	m	±0.2	|-1.4 | ±0.2
Minimum foil size (h/v)	mm	15.9 / 49.2	27.1 / 49.2
Suggested foil size (h/v)	mm	21.0 / 50.0	32.0 / 50.0
Minimum horizontal clearance	mm	43	43

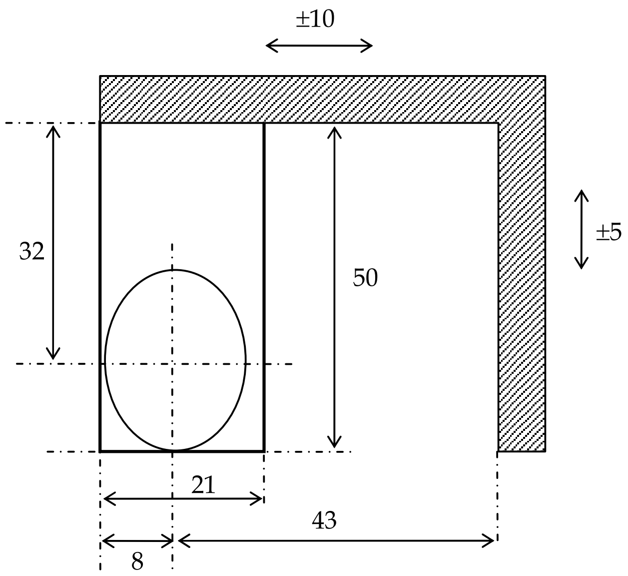

Figure 10. Foil size, movement and clearances required for zero dispersion at injection point.

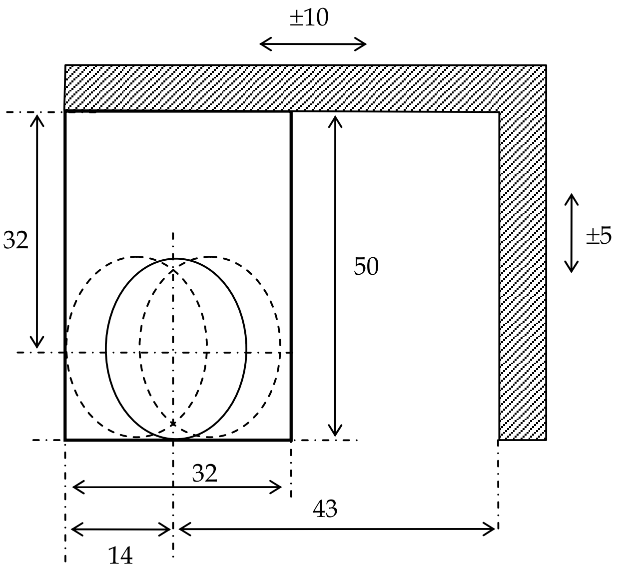

Figure 11. Foil size, movement and clearances required for matched (-1.4 m) dispersion at injection point.

The foil movement in the horizontal plane will be needed to adjust the injection – from SNS experience [12] the injection is set up by ensuring that the injected H^- beam is properly adjusted onto the H^-/H^0 dump, and then moving the foil horizontally and vertically to cover the injected beam. This means that the horizontal movement for the setting up of the injection should be from a retracted position to the nominal position, plus a margin for the expected variation in injected beam position and mechanical tolerances. This is set at ±10 mm. For the vertical plane, a small adjustment range will be necessary just to make sure that the lower edge of the foil covers the injected beam. A ±5 mm movement range should cover the variation in injected beam position plus the mechanical tolerance – note that this value needs to be added to the foil size above the axis, to keep the support out of the acceptance.

10. 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/cm^2 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 being moved into the circulating beam. The losses, emittance growth and energy straggling from scattering processes in the foil are acceptable. Beam loss from nuclear and Coulomb scattering in the foil is calculated to be at the 10^{-3} level overall, with beam losses from magnetic field stripping of excited H^0 expected to be at the 10^{-4} level. The dimension of the foil should ideally be about 21×50 mm for the zero-dispersion injection, and about 32×50 mm for the matched dispersion case. The losses from beam missing the foil should be kept at the 1 % level; the possibility of collimating the H^- beam late in the BI line should still be investigated to reduce the load on the H^-/H^0 dump.

Acknowledgement

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