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A model to evaluate the lifetime of stripping foils with high energy H^- beams

Masamitsu Aiba*, Luca Bruno, Brennan Goddard and Malika Meddahi

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BE department (*Present address PSI)
Ref. PS2

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, Date

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An analytical model to evaluate the lifetime of a carbon foil used to strip a high energy H^- beam is proposed and discussed in this paper. The existing model based on elastic scattering is not applicable when the H^- beam energy is in excess of several hundred MeV, since the inelastic radiation damage then dominates. Based on the proposed model, carbon stripping foil lifetimes for the CERN PS2 and SPL-based proton driver accumulator are evaluated.

* Present address:Paul Scherrer Institut,
CH-5232 Villigen PSI, Switzerland

INTRODUCTION

The energy of H^- beams accelerated with drive linacs is steadily increasing for upgrades and proposed machines, to facilitate high intensity and high brightness proton beams by mitigating space charge effects. Several projects are based on a high energy H^- linac: the SNS linac was designed to accelerate H^- beam up to 1 GeV [1] and became operational in 2006. The CERN SPL (Superconducting Proton Linac) project [2] is aiming to accelerate an H^- beam up to 4 GeV for the beam injection into the PS2 [3] and to 5 GeV for a proton driver for a Neutrino Factory [4] and other applications. The Project-X in US aims to build 8 GeV drive linac [5]. For all of these projects, charge exchange injection with a stripper foil is used to inject the H^- beam into a ring for storage, further acceleration and/or beam manipulation. It is of great interest to evaluate the lifetime of the stripper foil at the design stage for operation and maintanance aspects, since this can have a major impact on the design of the injection region.

To date, the foil lifetime has generally been evaluated by taking into account the radiation damage due to elastic scattering by the incoming H^- and circulating proton beams during the injection process, if the foil temperature is low enough such that evaporation remains negligible. This method has been well established [6–9] and is reasonable when the beam energy is low enough that the dominant cross section for proton to foil atom interaction is elastic scattering. However, inelastic scattering starts to dominate when the beam energy is several hundred MeV or more, and the existing model is therefore not applicable. Thus a new analytical model is proposed for the GeV regime which takes inelastic scattering into account. In the following the discussion is limited to carbon stripping foils, since these are used (or proposed) for all of the facilities considered.

MODEL

The fundamental difference between the radiation damage due to inelastic scattering and that due to elastic scattering is the fact that with inelastic scattering the nuclei are spalled into fragments such as protons, neutrons and alphas etc. which can escape the foil. In contrast, elastically scattered atoms are displaced from their lattice locations but remain in the foil and have a temperature-dependent probability to migrate and combine with a lattice vacancy, resulting in "self-restoring" to prolong the lifetime. This fact is indeed taken into account in evaluating the lifetime for elastic scattering damage, where the lifetime depends on the foil temperature [7, 9].

The permanent damage due to inelastic scattering allows rather simple modeling. The inelastic reaction rate is given by

$$R = \sigma_{in}\phi N \tag{1}$$

where σ_{in} is the inelastic cross section, ϕ is the particle flux of H^- plus circulating protons and N is the density of foil atoms. Normally the circulating protons will hit the foil several times by design, to allow the accumulation of high intensity beams with reasonable transverse emittance.

The integration of Eq. 1 over time gives

$$\int_0^t R\left(t'\right) dt' = \int_0^t \sigma_{in}\phi N\left(t'\right) dt'. \tag{2}$$

Since the integral of the reaction rate corresponds to the density of lattice vacancies,

$$\int_0^t R\left(t'\right) dt' = N_0 - N\left(t\right), \tag{3}$$

where N_0 is the initial atom density. Finally the atom density N is expressed as the exponential function of time

$$N = N_0 \exp\left(-\sigma_{in}\phi t\right). \tag{4}$$

To estimate the foil lifetime, it could be assumed, as an analogy of the elastic scattering case [7], that the foil fails mechanically when a certain fraction (for example one half) of the foil atoms are scattered. For instance,

$$T_{life} = -\frac{\ln 0.5}{\sigma_{in}\phi}. \tag{5}$$

It is worth mentioning that the foil thickness is not relevant to the lifetime in this definition, because both the reaction rate and the initial number of atoms are proportional to the foil thickness - a thicker foil has proportionally more atoms removed per unit time.

It is also possible to evaluate numerically the degradation of the foil in terms of stripping efficiency, as a function of time. This may also be of use in estimating the foil lifetime, since the stripping efficiency is an important figure of merit for all injection systems, since unstripped H^0 in highly excited quantum states can contribute directly to uncontrolled beam loss.

When the H^- ions traverse a stripping foil, charge exchange processes happen on a femtosecond time scale, which easily remove the loosely bound outer electron and can either excite the remaining electron into a higher energy level or strip it completely. The stripping efficiency in terms of the yield of unstripped H^- and H^0, together with the yield of different H^0 excited states depend on the foil thickness and incident H^- ion energy. Semi-empirical treatments exist for estimating the relative yields of the different charge states over a range of incident energies, see e.g. [14, 15]. These can be adjusted to give reasonable agreement with data measured at 200 and 800 MeV, and which are then scaled to the energy of interest.

The probability $y_-(x)$ that the H^- ions remain intact after passage through a foil of density N is given by:

$$y_-(x) = \exp(-N\sigma_- x) \tag{6}$$

where $\sigma_- = \sigma_{-0} + \sigma_{-+}$ is the sum of the cross-sections for one- and two-electron stripping of the H^- ion, and x is the length for particles to pass over the foil. The probability of the ion being stripped to H^0 is given by:

$$y_0(x) = \frac{\sigma_{-0}}{\sigma_- - \sigma_{0+}} \left[\exp(-N\sigma_{0+}x) - \exp(-N(\sigma_{-0} + \sigma_{-+})x)\right] \tag{7}$$

where σ_{0+} is the cross section for stripping of the neutral H^0 atom. The probability of the ion being fully stripped to p^+ is then simply

$$y_+(x) = 1 - y_-(x) - y_0(x). \tag{8}$$

The cross sections have been measured at 200 MeV from FNAL [16] and at 800 MeV from PSR at LANL [15]. The values can be scaled reasonably well according to β^{-2} [17], although there is some question about the validity for energies above a few GeV [18]. Table I summarises the measured and scaled cross-sections at some energies of interest.

Combining the expressions for the charge state yield and the foil density reduction through inelastic scattering gives the thickness- and time-dependent charge stripping yields:

Energy GeV	β	σ_{-0} $\times 10^{-19} cm^2$	σ_{-+} $\times 10^{-19} cm^2$	σ_{0+} $\times 10^{-19} cm^2$	comment
0.16	0.520	17.73	0.31	6.92	scaled (PSB)
0.2	0.566	15.33±1.3	0.27±0.03	6.0±0.1	measured [16]
0.4	0.713	9.42	0.17	3.68	scaled (JPARC)
0.8	0.842	6.76±0.09	0.12±0.09	2.64±0.05	measured [15]
1.0	0.875	6.26	0.111	2.44	scaled (SNS)
4.0	0.982	4.97	0.088	1.94	scaled (PS2)
5.0	0.987	4.91	0.087	1.92	scaled (proton driver)
8.0	0.994	4.85	0.086	1.89	scaled (Project-X)

TABLE I: Measured and scaled cross sections for charge exchange processes for carbon foils, for different H^- injection systems.

$$y_- (x,t) = \exp\left(-N_0 \exp\left(-\sigma_{in}\phi t\right) \sigma_- x\right) \tag{9}$$

$$y_0 (x) = \frac{\sigma_{-0}}{\sigma_- - \sigma_{0+}} \left[\exp\left(-N_0 \exp\left(-\sigma_{in}\phi t\right) \sigma_{0+} x\right) - \exp\left(-N_0 \exp\left(-\sigma_{in}\phi t\right) \left(\sigma_{-0} + \sigma_{-+}\right) x\right)\right] \tag{10}$$

LIFETIME EVALUATION

Based on the proposed model, the foil lifetime of the PS2 and the neutrino factory accumulator [4, 10] are evaluated, assuming that the foil material is carbon. The inelastic cross section is essential input and is computed based on the systematic equations derived in Ref. [11, 12]; the cross section is shown in Fig. 1. The total cross section is also computed based on Ref. [12], and the elastic cross section is then given as the difference of total and inelastic cross sections. From Fig. 1 the inelastic cross section is taken as 250 mb for both 4 and 5 GeV.

Table II summarizes the results assuming the foil fails when half of the carbon atoms are removed, comparing the values with the elastic scattering-based model.

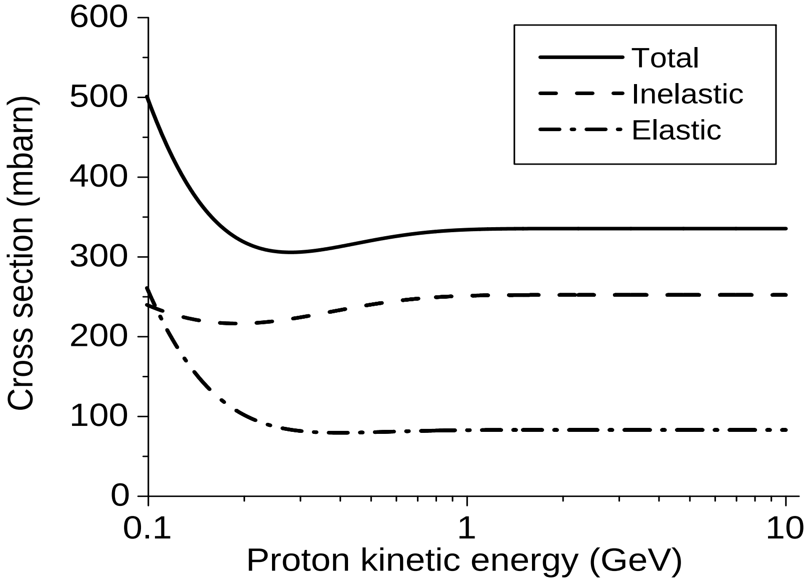

FIG. 1: Proton-carbon cross section.

Parameters	PS2	Accumulator	Units
Injection energy	4	5	GeV
Particle flux per cycle	8×10^{15}	6.4×10^{15}	/cm^2/cycle
Repetition rate	0.4	50	Hz
Particle flux	3.3×10^{15}	3.2×10^{17}	/cm^2/s
Lifetime inelastic based	26.6	0.27	year
Lifetime elastic based	160.7	2.0	year

TABLE II: Lifetime evaluation for the PS2 and SPL proton driver accumulator. Particle flux includes circulating proton and H^-. The presently assumed input parameters are quoted. The lifetime based on elastic scattering are computed using the equations in Ref [13]

In Figure 2 the evolution of the H^- and H^0 stripping yield for the 4 GeV PS2 are plotted as a function of time, using the cross relations derived above and assuming a foil thickness of 400μgcm^{-2} [19]. It can be seen that there is only a very slow degradation of the stripping efficiency - after 100 months of operation the H^- fraction has increased from 3.9×10^{-5} to 2.8×10^{-4} and the H^0 fraction from 3.2% to 6.8%. For the proton driver the situation is

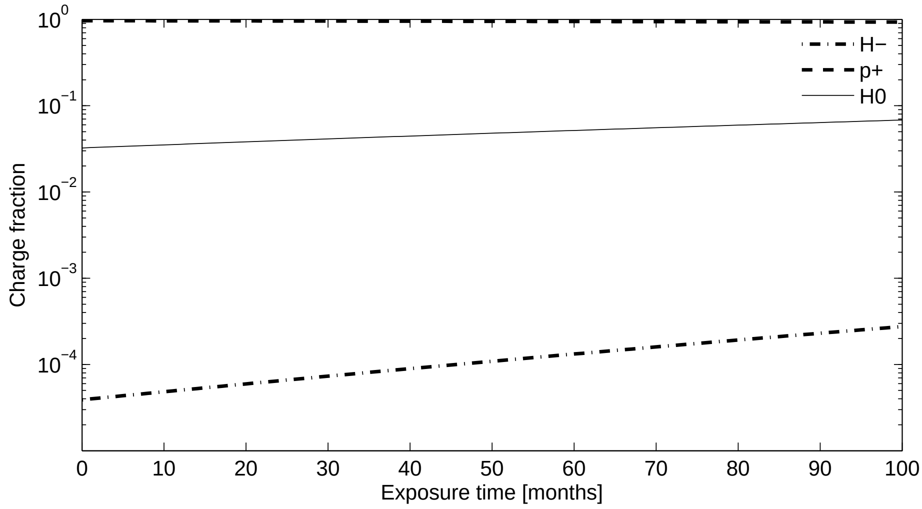

FIG. 2: Evolution of H$^-$ and H^0 stripping yield as a function of time for the 4 GeV PS2 with 400μgcm^{-2} carbon foil initial density.

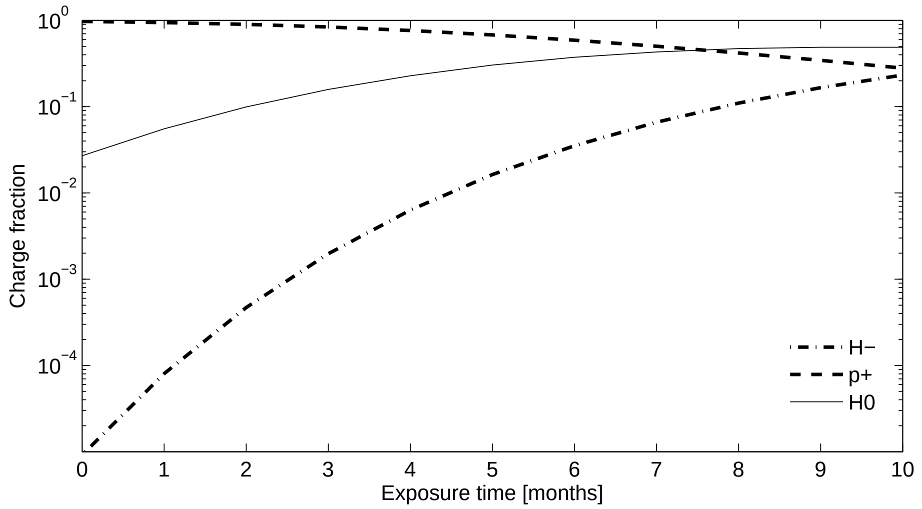

FIG. 3: Evolution of H$^-$ and H^0 stripping yield as a function of time for the 5 GeV proton driver with 400μgcm^{-2} carbon foil initial density.

very different. The proton flux on the foil is a factor of 100 higher and within 1 month of operation the H$^-$ fraction has increased from 9.1×10^{-6} to 8×10^{-5} and the H^0 fraction from 2.7% to 5.5%. After 10 months the fractions are 23% H$^-$ and 49% H^0.

If the foil lifetime is determined by the stripping efficiency, one could assume that the lifetime is reached when the H^0 yield is a certain factor above the design H^0 yield. At this stage, the beam position on the foil will either need to be adjusted to impact a new foil region, or the foil will need to be exchanged. For the PS2 and proton driver, these times are expected to be in the order of 100 months and 1 month respectively. For different machines and foil thicknesses, Eq. 10 allows an estimation of this time to be made, based on the expected particle flux and the inelastic scattering and charge exchange cross sections.

DISCUSSION

The lifetime based on inelastic scattering is about 6∼7 times shorter than that of the elastic scattering model, if the simple criterion is applied that the foil lifetime is reached when half of the carbon atoms have been scattered. This ratio is reasonable given the ratio of inelastic cross section to elastic at this energy range (∼3 times) together with the self-restoring effect which is present for elastic scattering damage. The assumption of the lifetime being reached when half of the carbon atoms are scattered also seems reasonable since even if the foil does not fail mechanically, the yield of unstripped H^0 will increase rapidy as the foil density is reduced.

One could evaluate the lifetime as taking into account both elastic and inelastic radiation damage, i. e.,

$$\frac{1}{T_{life}} = \frac{1}{T_{el}} + \frac{1}{T_{in}}, \tag{11}$$

where T_{el} is the lifetime based on the elastic scattering model and T_{in} is from the inelastic scattering model. However, it is not clear whether this rather simplistic approach is applicable or not, especially for the energy range where the elastic and inelastic cross sections are comparable (∼100 MeV) since an elastically scattered atom staying in the foil could be removed due to inelastic scattering. For higher incident energy where most of the elastically scttered atoms would escape the foil, the cross section would be replaced by the sum of elastic and inelastic. This would further reduce the lifetime about 30%.

Another possible damage mechanism could come from the stripped electrons, since an H^- particle is composed of a proton and two electrons. However the radiation damage due to the electrons is on a few percent level for the case considered because the electron momentum is fairly low as these particles have comparable Lorentz factor. Heating from stripped electrons is another issue beyond the scope of this paper.

Inelastic scattering generates fragments within the foil, which could result in secondary damage and reduce the lifetime still further. However, the damage due to fragments is also considered to be negligible since the probability of secondary scattering after the primary scattering is very low for a thin foil.

Foil failure due to heat-shock or heat-cycle may happen before the lifetimes quoted above are reached, depending on the operating temperature, mechanical structure and foil material. Even if the mechanical lifetime is not reached, the stripping efficiency will be reduced with increasing dose due to inelastic scattering, and the model described above gives a method of quantitatively estimating the time between foil changes or adjustments required to maintain a given stripping efficiency, for a given particle flux and foil thickness.

Foil thickening may help to compensate the reduction of stripping efficiency but may not be so significant because 1) the initial foil thickness for high energy incident should be thick enough to achieve an adequate stripping efficiency and consequently the sputtering and spallation process would be dominant [20], 2) the vacuum pressure is rather low in modern accelerator to minimize influences to the beam as well as high voltage in-vacuum devices and 3) the carbon build-up is partly suppressed depending on the foil temperature [21].

The cross-sections for the different charge exchange processes are extrapolated from data taken at 200 and 800 MeV; more accurate data based on measurements at higher energies would increase the accuracy of the model.

CONCLUSION

An analytical model to evaluate the lifetime of a carbon charge exchange foil exposed to a high energy H^- beam is proposed, allowing a quantitative estimate of useful foil lifetime. The fact that the inelastic scattering results in permanent damage allows rather simple estimation of the dependence of the stripping efficiency on explosure time. The model applies to the case where the inelastic radiation damage is dominant, and can be used to predict when the stripping efficiency of a foil will drop below an acceptable value. More empirical information about foil failures through inelastic scattering dominated interactions will allow the model to be improved by a better estimate of the figure of merit for mechanical foil failure, presently assumed rather arbitrarily to be when 50% of the foil atoms are scattered.

Using the proposed model, the foil lifetimes for the CERN PS2 and SPL proton driver accumulator are evaluated, and the results show much shorter lifetime compared to the values from the existing model.

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