8 GEV H⁻ IONS: TRANSPORT AND INJECTION*

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Abstract

Fermilab is working on the design of an 8 GeV superconducting RF H^- linac called the Proton Driver. The energy of H^- beam will be an order of magnitude higher than the existing ones. This brings up a number of technical challenges to transport and injection of H^- ions. This paper will focus on the subjects of stripping losses (including stripping by blackbody radiation, field and residual gas) and carbon foil stripping efficiency, along with a brief discussion on other issues such as Stark states lifetime of hydrogen atoms, single and multiple Coulomb scattering, foil heating and stress, radiation activation, collimation and jitter correction, etc.

INTRODUCTION

H^- injection was invented decades ago and has been successfully employed in many accelerator laboratories. The highest H^- energy today is 800 MeV at the PSR at LANL. Soon the SNS will provide 1 GeV H^- beams. The proposed Fermilab Proton Driver, which is based on a superconducting RF H^- linac, would accelerate H^- particles to 8 GeV and inject them into the Main Injector via a charge exchange process. To transport and inject H^- at such a high energy is technically a big challenge.

H^- has two electrons, one tightly bound (binding energy 13.6 eV), another loosely bound (binding energy 0.75 eV). During transport, both electrons must stay with the proton, whereas at injection both must be stripped immediately. However, when H^- energy goes higher, these tasks become harder. On the one hand, the second electron becomes easier to be detached from the ion during transport because of blackbody radiation and magnetic field stripping. On the other hand, the foil stripping becomes more difficult because the electron loss cross-section decreases. It is imperative to make sure that 8 GeV H^- from the Proton Driver can indeed be transported and injected. This paper will give a brief discussion of the problems. For more details the readers are referred to Ref. [1].

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STRIPPING LOSS DURING TRANSPORT

Blackbody Radiation Stripping

When an H^- ion is moving at luminal velocity, the normally innocuous contribution of beam pipe ("black body") radiation to the photodetachment rate of electrons can be greatly increased. The large Doppler effect that one encounters in the situation shifts impotent lab frame infrared photons to energies in excess of the electron affinity of hydrogen where the photodetachment cross section is large. Figure 1 illustrates this effect.

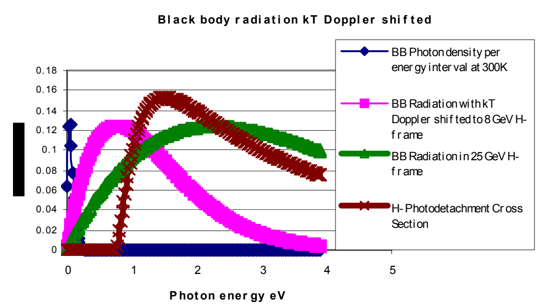

Figure 1: The brown curve is the photodetachment cross section. The Doppler effect shifts the 300 °K thermal photon distribution curve from blue (rest H^-) to pink (8 GeV H^-) and green (25 GeV H^-) respectively. The overlapping between the photon distribution and cross section curves gives rise to blackbody radiation stripping.

Ref. [2] gives an analysis of this effect. The results are shown in Figure 2. It is seen that both energy and temperature dependences of this effect are strong. The stripping rate is increased by 3 orders of magnitude when the H^- energy increases from 800 MeV to 8 GeV. At 8 GeV and 300 °K, the stripping rate is about 0.8×10^{-6} per meter and is the dominant loss mechanism in the H^- transport line. One effective way to mitigate it is to employ a cold beam screen inside the vacuum beam pipe, e.g., at gas nitrogen temperature of 150 °K. This would give more than a factor of 10 in loss reduction.

Although nobody has seen any blackbody stripping of H^-, it was observed on He^-, of which the extra electron has very low binding energy (0.077 eV) [3].

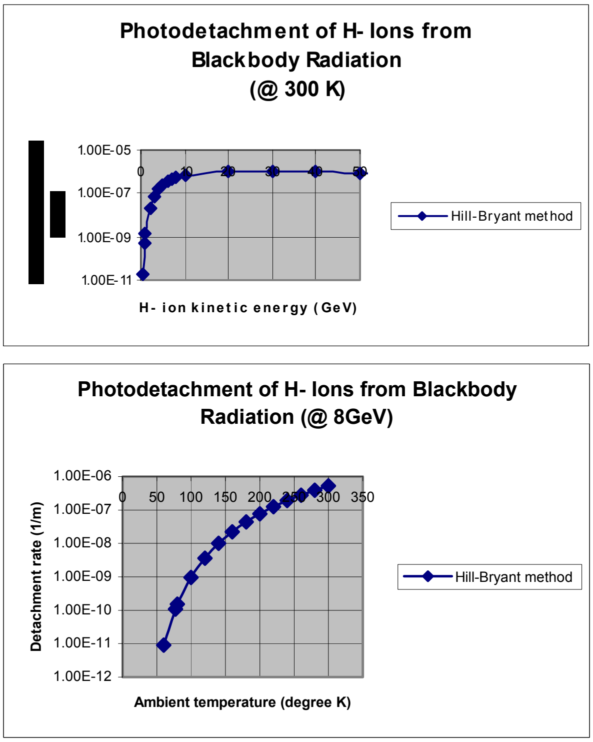

Figure 2: Top – energy dependence of blackbody radiation stripping; bottom – temperature dependence.

Field Stripping

When an H⁻ ion traverses in an electric field F, the electrons and proton tend to go to opposite directions. If the field were strong enough, electrons would be stripped. This field can be the Lorentz transformation of a magnetic field B:

$$F\,(\text{MV/cm}) = 3.197\, p\,(\text{GeV/c})\, B\,(\text{Tesla})$$

For the same F field, higher momentum p of H⁻ implies lower B field. This is why field stripping is a concern for high energy H⁻. A seminal theoretical paper on H⁻ lifetime τ in a field is by Scherk [4], in which he gives a simple yet commonly used 2-parameter formula:

$$\tau = \frac{a}{F}\exp\left(\frac{b}{F}\right)$$

in which a and b are two constants to be fitted to experimental data. Table 1 lists three measurements of H⁻ lifetime [5-7].

Table 1: H⁻ ion lifetime measurement

Experiment	Energy (MeV)	a (10^{-14} s-MV/cm)	b (MV/cm)
Stinson et al.	50	7.96	42.56
Jason et al.	800	2.47	44.94
Keating et al.	800	3.073	44.14

Although the fitted parameters look different, the results are remarkably similar when they are used to calculate H⁻ lifetime at 8 GeV, as shown in Figure 3. This gives us reason to believe that this energy extrapolation to 8 GeV is valid. The design field in the 8 GeV H⁻ transport line is 500 Gauss. Based on the curves in Figure 3, the stripping loss would be negligibly low at 10^{-9} per meter.

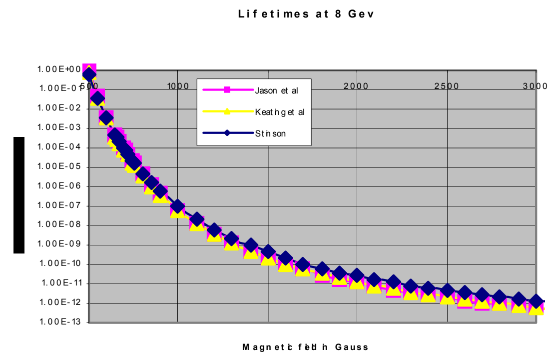

Figure 3: Prediction of H⁻ lifetime at 8 GeV using three different sets of parameters in Table 1.

Residual Gas Stripping

When H⁻ energy increases, the electron loss cross section for H⁻ incident on residual gas atoms decreases, as shown in Figure 4 [8]. Based on Born approximation, the energy scaling goes essentially as $1/\beta^2$, where β is the relativistic factor [8-10]. Table 2 lists the cross section scaled to 8 GeV from the measurement data at lower energies.

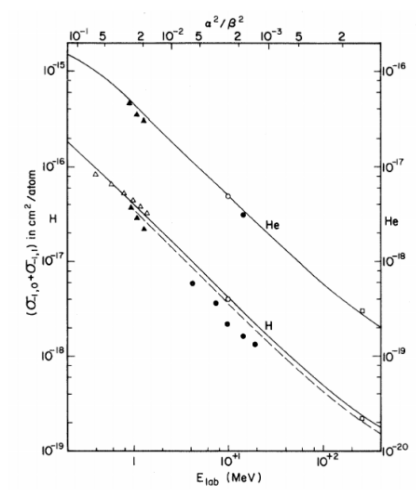

Figure 4: Energy dependence of electron loss cross section for H⁻ incident on H and He atoms [8].

Table 2: Energy scaling of electron loss cross section

Energy of H⁻ ion	H	He	N	O	Ar
400 MeV	0.2	0.2	–	–	–
800 MeV	–	–	1	1	3
8 GeV (scaled)	0.1	0.1	0.7	0.7	2.2

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Using the residual gas spectrum measured on a beam line with similar vacuum system, the estimated stripping rate from residual gas is about 0.1×10^{-6} per meter.

Combine the three loss mechanisms together, the total predicted loss is about 0.9×10^{-6} per meter. The design beam intensity is 1×10^{14} per second. At 8 GeV, the loss corresponds to about 0.13 W/m. Because this is a continuous loss along the whole beam line, the so-called 1 W/m allowable loss criterion cannot be applied. As a matter of fact, MARS calculation shows that at such a loss rate the bare beam pipe would have hot spots at 1000 mR/hr after 30 days of irradiation. We are working on a mitigation plan including the option of using a cold beam screen as described above.

CARBON FOIL STRIPPING EFFICIENCY

Because the new technology of laser stripping has a long way to go, our design uses the conventional carbon foil for stripping H^- to H^+ at injection. However, there is a serious concern about the stripping efficiency of H^- at 8 GeV, because the cross section would be small. There are two earlier measurements that serve as valuable references [11,12]. When a 200 μg/cm^2 foil was used, the reduction of stripping efficiency of H^- from 200 MeV to 800 MeV was dramatic: the unstripped H^0 increased from 0.4% to 11.2%. In order to estimate the efficiency at 8 GeV, we use the cross section method and the same Born approximation as in the residual gas stripping case. Figure 5 shows the results.

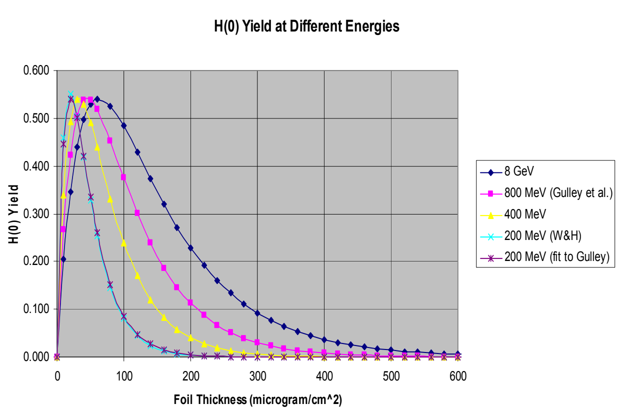

Figure 5: Unstripped H^0 *vs.* foil thickness at different energy of H^- ions.

The pink curve is a reproduction of the measured upstripped H^0 at 800 MeV as published in Ref. [12]. The light blue and dark pink curves, which almost overlap each other, demonstrate the agreement between the measured data at 200 MeV in Ref. [11] (light blue) and the calculation based on energy scaling from the 800 MeV data (dark pink). Such a good agreement shows the energy scaling indeed works. Therefore, we use the same 800 MeV data to calculate the unstrpped H^0 at 400 MeV (yellow curve, which will be measured at the Fermilab Booster) and 8 GeV (blue curve). The 8 GeV design will use 600 μg/cm^2 foil (actually two 300 μg/cm^2 foils in series). The predicted unstripped H^0 is 0.5%.

OTHER TECHNICAL ISSUES

The unstripped H^0 carries considerable beam power (in the order of kW) and must be dumped. Because these atoms are at different excited states (Rydberg and Stark states), their lifetime has strong dependence on magnetic field. Hence, one may place the stripping foil in a field so that the H^0 would either be stripped immediately to become H^+ and get into the ring or stay as H^0 long enough to be dumped. This would leave the injection area clear.

When thick foils are used, the foil lifetime is a serious issue. It is not well understood when foil damage occurs whether it is caused by radiation or heating or mechanical stress or a combination of them, albeit all these effects can be analyzed and calculated. Based on some preliminary measurements of foil lifetime carried out for the SNS, it is believed that for long pulse operation (3 ms) of the Proton Driver, diamond foil would be needed [12]. We are collaborating with ORNL on this R&D.

Thick foils also have impact on beam quality (e.g., emittance dilution and energy straggling from single and multiple Coulomb scatterings) and will cause radiation activation of nearby accelerator components. A trade off between stripping efficiency and the various adverse effects of using thick foils can be found in [1].

Beam collimation (both betatron and momentum) is necessary in the transport line in order to keep the injection loss low. Linac beam jitter correction using passive debunching cavity (as in the SNS design) and active feedback is another important part of the transport design. These will be discussed later in another paper.

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