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STRIPPING EXTRACTION AND LORENTZ DISSOCIATION

Hui Wen Koay, TRIUMF, Vancouver, B.C. Canada*

Abstract

Stripping extraction of hydrogen molecular ions has gained immense interest in the cyclotron industry due to its high extraction efficiency. However, the magnetic field could result in undesired Lorentz dissociation of the hydrogen anion/molecular ions during acceleration. This work summarizes and compares the Lorentz dissociation of several types of hydrogen ions, as well as other important aspects that are crucial when deciding the best candidate for stripping extraction in a cyclotron.

INTRODUCTION

This paper is a brief summary of a more extensive and in-depth discussion of Lorentz dissociation of hydrogen ions in [1]. Generally, stripping extraction involves the stripping of one or more electrons from the accelerated ions. Owing to the nature of the change in the charge-to-mass ratio, the stripped particles have different trajectories after stripping. This leads to the possibility of having a close to 100% extraction efficiency. This feature is appealing, as final turn separation is no longer mandatory for a clean extraction. However, there are other issues associated with this. Among all, one of the very critical one is the Lorentz dissociation of the accelerated ions under the effect of external magnetic field. The following will discuss briefly the effect of Lorentz dissociation on the potential candidates to produce a proton beam: H^-, H_2^+ and H_3^+.

LORENTZ DISSOCIATION OF HYDROGEN IONS

In general, Lorentz dissociation is a quantum mechanical effect where the bound electron or proton can tunnel out of its potential well because in its own reference frame, the magnetic field is an electric field that tilts the well. Dissociation occurs anywhere along ions' orbits and so they are lost, not extracted and eventually cause activation.

In the particle's rest frame, the electric field component perpendicular to the motion can be simplified as:

$$\mathcal{E} = \gamma\beta c B_z \cong (3\,\mathrm{MV/cm})\gamma\beta(B_z/1\,\mathrm{T})\,, \qquad (1)$$

where $\mathcal{E}$ and B_z are the equivalent electric field and the perpendicular magnetic field respectively; β is the ratio of the particle's speed, v, to the speed of light, c and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$.

H^-

The time constant, i.e. the probability of the ion to survive a time t is $e^{-t/\tau}$. It can be expressed by [2]:

$$\tau = \frac{A_1}{\mathcal{E}} \exp \frac{A_2}{\mathcal{E}}\,. \qquad (2)$$

The constants A_1 and A_2 are fitted constants from experimental results [3]. They are: $A_1 = 3.07 \times 10^{-6}$ V-s/m and $A_2 = 4.414 \times 10^9$ V/m respectively. Due to the popularity of stripping extraction of H^-, this effect is well studied and documented by many past researchers [3, 4]. Using Eq. (2) and assuming B is a constant, the integrated fractional loss F is shown in Fig. 1 (the energy gain per turn is taken as 0.48 MeV).

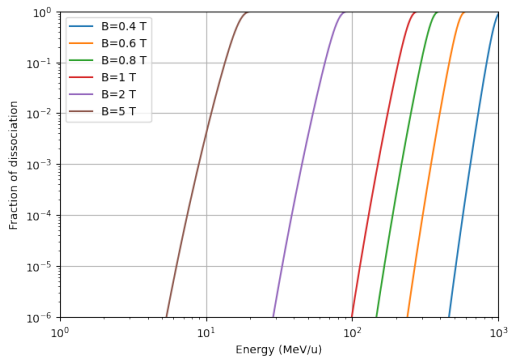

Figure 1: Integrated fractional dissociation of H^- as a function of energy for various B. Note that this calculation assumed a constant B and the energy gain per turn is 0.48 MeV. However since the loss as such a steep function of B, this can be taken as the peak B for cyclotrons with flutter.

From Fig. 1, F of H^- particles accelerated up to 1 GeV is 100% for any $B > 0.4$ T. Taking a maximum loss of 0.01%, the maximum permissible beam energy at a low B of 0.4 T is about 600 MeV; at a very large radius of $r = 10$ m. Hence, any acceleration at high energy is uneconomic, as the average magnetic field will be too low to achieve the desired beam loss, and the machine has to be extremely large to accommodate such a low magnetic field.

H_2^+

H_2^+ is a diatomic ion with an equilibrium bond distance of about 1.06 Å. The binding energy of H_2^+ is about 2.7 eV, which is 3.6 times larger than the binding energy of H^-. Unlike the H^- ion that has a well-studied time constant, there is a lack of experimental work to study Lorentz dissociation of H_2^+. To fill in the missing piece of information, some theoretical models are used here as the preliminary tools to estimate the Lorentz dissociation of H_2^+.

The ionic lifetime of each vibrational v state (rotational state $J = 0$) at different electric fields can be obtained from Hiskes' calculation [5]. The lifetimes of high v states are generally comparable to the revolution period of H_2^+ in a cyclotron ($\sim 10^{-8}$ s), i.e. the ions at high v states will dissociate completely within a turn of revolution. Therefore, instead of the lifetime, it is the state population that limits the fraction of dissociation. Unlike H^- that has only one bound state,

* hkoay@triumf.ca

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H_2^+ has many populated bound states that highly depend on the initial conditions of the source. Many studies had shown consistently that more than 90% of the population lie at $\nu < 12$ [6–9]. Among them, the most important work was done by Busch, as a comparison between calculation and experiment was made [7]. If we assume the state populations p_ν are distributed as Busch and the lifetime prediction is as given by Hiskes, the integrated fractional loss F of H_2^+ at different B fields can be estimated. Similar to the calculation done for H^-, flutter is omitted and the energy gain per turn is taken as 0.48 MeV. This result is summarized in Fig. 2.

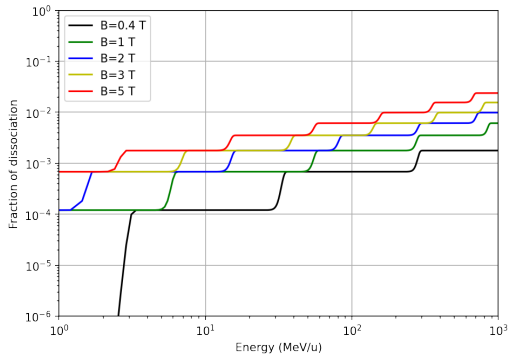

Figure 2: The total dissociated fraction of H_2^+ from all ν states when $B = 0.4, 1, 2, 3$ and 5 T respectively. Each plateau indicates the maximum dissociated fraction at each ν state. This corresponds to the population of states in [7]. For instance, the blue line is the summation of all vibrational states at $B = 2$ T. As B increases from 1 to 5 T, the total dissociated fraction also increases up to $\sim 2\%$.

At $B = 2$ T, the equivalent electric field for 100 MeV/u of H_2^+ is 2.8 MV/cm. At this $\mathcal{E}$, 0.35% of ions lying at $\nu \geq 15$ will dissociate. As the energy or magnetic field increases, $\mathcal{E}$ increases, and so does the number of populated ν states that are prone to dissociation. For example, at energy of 1 GeV/u, ions lying at $\nu \geq 13$ and at $\nu \geq 11$ will dissociate when $B = 2$ T and 5 T respectively. This amounts to a total dissociated fraction of about 1% and 2% respectively. If we take the maximum permissible power loss of 1 W/m for hands-on-maintenance, the maximum current allowed at $B = 2$ T and 5 T for acceleration up to 1 GeV/u are merely 1.8 and 0.7 µA. If acceleration at a higher current (say 1 mA) is desired, the H_2^+ beam has to be cooled or state-selected so that more than 99.9% lie at $\nu \leq 11$ [10, 11].

H_3^+

The binding energy (dissociation energy) of H_3^+ is about 4.5 eV [12], which is about 2 times larger than H_2^+, and is thus the most stable among the hydrogen ions discussed in this work.

Despite of its better stability and higher abundance, only very few works studied directly the effect of external field on the dissociation of H_3^+ so far. This is mainly due to the complex dynamical structure of the non-linear tri-atomic molecule [13–15]. Reckzügel et al. are among the few who had looked into this for the case of a linear and triangular H_3^+ [14]. Figure 5 in [14] shows the change of the potential energy surface of a triangular H_3^+ as the external electric field increases. A higher electric field lowers the dissociation energy barrier, causing the ions to disintegrate more easily into a proton and a hydrogen molecule. The relationship between the dissociation energy (E_d) and $\mathcal{E}$ field (in MV/cm) is extracted from [14] with a fitted function given as follows:

$$E_d = (4.5\,\text{eV}) \exp\left[-\frac{\mathcal{E}}{128\,\text{MV/cm}}\right] \quad (3)$$

As with the H_2^+ case, it is excited states and their population that set the limit. In fact, there are over hundreds of bound excited states with non-zero quantum numbers [16]. The full population of all these states with transition time is not easy to determine. V.G. Anichich had computed a simpler estimation of the state populations of only the symmetric mode with a quantum number ν forming from the ground-state H_2^+ and H_2 [17]. As there is no work done so far to determine the lifetime of ν states at various $\mathcal{E}$, here we assume that it is short as compared to the acceleration period (as in the case of H_2^+). The maximum dissociation at a particular $\mathcal{E}$ can then be estimated by utilizing the state populations and Eq. (3). Figure 3 shows the state population as distributed in the one-harmonic model from [17].

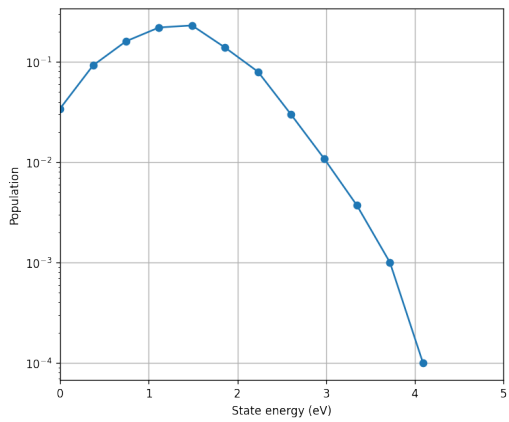

Figure 3: The population of state from the one-harmonic model in [17]. Each point corresponds to a bound ν state from $\nu = 0$ at the left to $\nu = 11$ at the right.

Taking H_3^+ of energy 1 GeV/u under a constant B field of 3 T, the equivalent $\mathcal{E}$ is about 16.3 MV/cm. This corresponds to a dissociation energy of about 4.0 eV and a dissociation of only the highest state with a population of about 0.01% from Fig. 3. The result is similar even if the population of the more detailed two-anharmonic model from [17] were used. If we assume a maximum beam loss of 1 W/m, acceleration of 1 mA of H_3^+ at a high energy of 1 GeV/u is possible at low $B = 1.7$ T. Note that this is about two times the maximum energy per nucleon attainable by H^- at the same radius of 10 m and the same beam current of 1 mA. Therefore, if the state population of an actual H_3^+ beam can be controlled or cooled [18, 19] so that it is similar to the one adopted here

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(> 99.9% lying at states with dissociation energy >4.0 eV), we can infer that the effect of external Lorentz field on the beam loss of H_3^+ is very minimal at high-energy (>500 MeV) extraction.

CONCLUSIONS

To summarize, the order of stability goes from $H_3^+ > H_2^+ > H^-$ at energy greater than 100 MeV. Nevertheless, the estimations given in this work, especially for H_2^+ and H_3^+ are based on the information that we have gathered so far from the literature, i.e. many factors such as the higher excited states with $J \neq 0$ have been omitted. In real practice, the Lorentz dissociation of H_2^+ and H_3^+ are more complex and it could vary by more than a factor 10, as it highly depends on the initial beam condition [20, 21]. Therefore, experimental verification of Lorentz dissociation using real hydrogen ions shall be the next to be done before H_2^+ and H_3^+ ions can be fully implemented at a higher beam power.

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