BEAM INDUCED PLASMA DYNAMICS IN A HIGH PRESSURE GAS-FILLED RF TEST CELL FOR USE IN A MUON COOLING CHANNEL

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Abstract

Filling an RF cavity with a high pressure gas prevents breakdown when the cavity is place in a multi-Tesla external magnetic field. The choice of hydrogen gas provides the additional benefit of cooling a beam of muons. A beam of particles traversing the cavity, be it muons or protons, ionize the gas, creating an electron-ion plasma which absorbs energy from the cavity. The ionization rate can be calculated from a beam intensity measurement. Energy loss measurements indicate the loading per RF cycle per electron-ion pair range from 10^{-18} to 10^{-16} J in pure hydrogen, and 10^{-20} to 10^{-18} J when hydrogen is doped with dry air. The addition of an electronegative gas (oxygen) has been observed to reduce the lifetime of ionization electrons in the cavity to below 1 nanosecond. Additionally, the recombination rate of electrons and hydrogen ions has been measured to be on the order of 10^{-6} cm^3/s. The recombination mechanism and hydrogen ion species, along with the three-body attachment process of electrons to oxygen, will be discussed.

INTRODUCTION

Operating RF cavities in multi-Tesla magnetic fields is a requirement in a muon cooling channel. Vacuum cavities break down under such conditions, however a high pressure gas-filled RF (HPRF) cavity does not [1, 2]. The effects of the beam-induced plasma (plasma loading) created in an HPRF cavity must be studied. A beam test at the MuCool Test Area (MTA) at Fermilab [3], utilizing the 400 MeV linac proton beam, was performed to characterize the plasma loading [4].

PLASMA FORMATION

The beam (in this case protons, but muons as well) ionizes the gas (hydrogen) in the HPRF cavity. The dominant process is single ionization:

$$p + \mathrm{H}_2 \to p + \mathrm{H}_2^+ + e^- \tag{1}$$

The ionization electrons can also have enough energy to ionize hydrogen:

$$e + \mathrm{H}_2 \to \mathrm{H}_2^+ + 2\,e^- \tag{2}$$

At the pressure range under investigation (20.4 to 103 atm), the H_2^+ ions quickly form clusters of hydrogen:

$$\mathrm{H}_2^+ + \mathrm{H}_2 \;\to\; \mathrm{H}_3^+ + \mathrm{H} \tag{3}$$

$$\mathrm{H}_{n-2}^+ + \mathrm{H}_2 + \mathrm{H}_2 \;\leftrightharpoons\; \mathrm{H}_n^+ + \mathrm{H}_2,\ (n = 5, 7, 9, ...) \tag{4}$$

An equilibrium in hydrogen species is reached based on pressure and temperature (the gas is at 293 K).

The electrons gain energy from the RF electric field and transfer it to the surrounding gas through collisions. Because the electrons thermalize with the surrounding gas in much less than a half RF period, and they are assumed to be in constant equilibrium, and drift with the RF field.

The number of electron-ion pairs produced can be estimated based on the stopping power of protons in hydrogen gas (dE/dx), gas density (ρ), accelerating gap length (h), average energy required to ionize hydrogen (W_i), and number of incident protons (N_p):

$$N_{pairs} = \frac{dE/dx\,\rho\,h}{W_i}\,N_p \tag{5}$$

ENERGY LOSS

The energy loss in cavity due to plasma loading can be estimated based on the electron or ion drift velocity (v) or mobility (μ) and applied electric field ($E_0\ \sin(\omega\,t)$):

$$\begin{aligned} dw &= q\int (v_e + v_+ + v_-)\,E_0\ \sin(\omega\,t)\,dt \\ &= q\int (\mu_e + \mu_+ + \mu_-)E_0^2\ \sin^2(\omega\,t)\,dt \end{aligned} \tag{6}$$

where the "+" and "-" subscripts indicate the contribution from positive and negative ions. Eq. 6 can be integrated over one RF cycle and compared to the measured energy loss in the cavity normalized to a single electron-ion pair-RF cycle.

For the case of pure hydrogen, the energy loss measurement will consiste entirely of electrons and positive hydrogen ions. When hydrogen is doped with an electronegative gas (in this case oxygen, in the form of dry air), the electrons become attached to the electronegative gas and form negative ions. In this case, the energy loss measurement will consist of electrons, hydrogen ions, and oxygen ions.

Figures 1–3 show the energy loss measurements and predictions based on Eq. 6.

Our measurements match the predicted values well for low pressures. A pressure and X (X = electric

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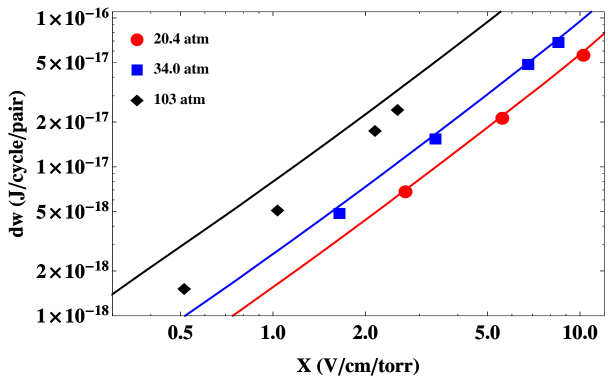

Figure 1: Energy loss of electrons and hydrogen ions in pure hydrogen. The lines correspond to the prediction based on Eq. 6.

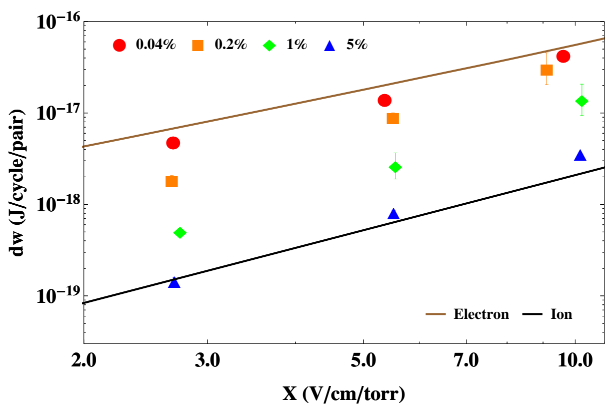

Figure 2: Energy loss of electrons, hydrogen ions, and oxygen ions in 300 psi dry air doped hydrogen. The lines correspond to the energy loss prediction for only electrons and only hydrogen ions. Various dry air concentrations are shown.

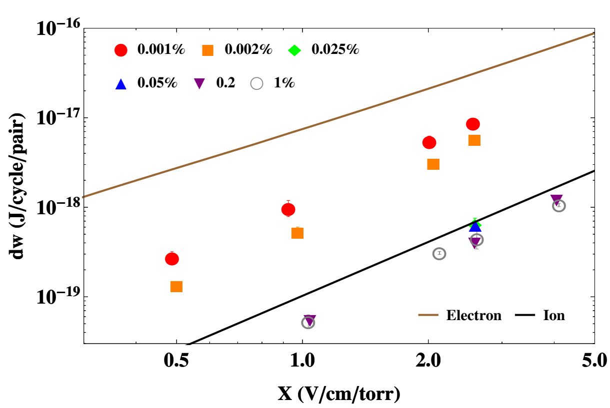

Figure 3: Energy loss of electrons, hydrogen ions, and oxygen ions in 1470 psi dry air doped hydrogen. The lines correspond to the energy loss prediction for only electrons and only hydrogen ions. Various dry air concentrations are shown.

field/pressure) effect is observed at high pressures, at which point the energy loss begins to saturate and is much lower than the predicted value. This effect is even greater at small X. There are a number of explanations for this effect. One is that at the high densities present in this experiment, electrons may briefly form bound states with molecular hydrogen, thereby decreasing the electrons' effective mobility [5]. Another predicts that multiple scattering will lower the mobility due to the mean free path of the electrons becoming equal to or less than the wavelength of a thermal electron [6]. Predictions based on these models fit data from the literature taken at high pressure of thermal electrons (at 77 or 300 K) reasonably well. However in the experiment reported here, the electron temperature is much greater than 300 K, and while the electrons are in thermal equilibrium with the surrounding gas, they are not in equilibrium with the entire volume of gas in the cavity.

Overall, this energy loss saturation, or reduced mobility, is a positive effect with respect to a muon cooling channel in that higher pressures of hydrogen gas do not correspond to larger energy losses.

Ions have a much smaller mobility than electrons (due to their larger mass), and so produce less energy loss. This can be seen in Figs. 2 and 3. At lower pressure more electrons remain in the cavity and so dw is larger. At higher pressure all of the electrons have become attached to oxygen and so dw corresponds to that of the ions.

ELECTRON-HYDROGEN RECOMBINATION

Electrons my recombine with hydrogen ions through two processes. The first is binary dissociative recombination:

$$e^- + \mathrm{H}_n^+ \rightarrow \frac{n-1}{2}\,\mathrm{H}_2 + H, \quad (n = 3, 5, ...) \tag{7}$$

The second is ternary neutral-stabilized recombination:

$$e^- + \mathrm{H}_n^+ + \mathrm{H}_2 \rightarrow \frac{n+1}{2}\,\mathrm{H}_2 + \mathrm{H}, \quad (n = 3, 5, ...) \tag{8}$$

Rate equations for the time evolution of the number of electrons and hydrogen ions are:

$$\frac{dn_e}{dt} = \dot{n}_e - \beta\, n_e\, n_H \tag{9}$$

$$\frac{dn_H}{dt} = \dot{n}_H - \beta\, n_e\, n_H \tag{10}$$

where $\dot{n}_i$ is the prodiction rate of electrons or hydrogen ions, and n_i is the number density. We assume that an electron is produced for every hydrogen ion ($\dot{n}_e = \dot{n}_H$ and $n_e = n_H$) and that β is the effective recombination rate of the hydrogen ions in the cavity:

$$\beta\, n_e\, n_H = \Sigma_i \beta_i\, n_e\, n_i, \quad (i = \mathrm{H}_3^+, \mathrm{H}_5^+, ...) \tag{11}$$

β is electric field, and therefore time, depedent. When the production reaches an equilibrium, $dn_e/dt = 0$, and a measurement of the recombination rate can be made directly:

$$\beta = \frac{\dot{n}}{n^2} \tag{12}$$

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where the assumption that the number of electrons and hydrogen ions are the same has been used. When the system is not in equilibrium, a functional form of β, dependent on the voltage in the cavity (the electric field on axis multiplied by the accelerating gap) can be found. Using the rate equation to model the number of particles in the cavity and the measured energy loss per pair as described in the previous section, the total energy loss can be calculated and compared to the measured value.

Recombination rates measured with electrons in thermal equilibrium at room temperature are, for H_3^+, on the order of 10^{-7} cm^3/s, and for H_5^+, on the order of 10^{-6} cm^3/s [7]. The calculated recombination rates for the HPRF beam test are on the order of 10^{-6} cm^3/s, which indicate that H_5^+ is the dominant hydrogen ion present in the cavity. Note that the electron temperature reported here is much larger than the temperature of the parent gas, however H_5^+ is still believed to be the recombining ion.

ELECTRON ATTACHMENT TIME

When hydrogen is doped with dry air, electrons may become attached to oxygen molecules through a two-step, three-body process:

$$\begin{aligned} e^- + O_2 &\rightarrow O_2^{-*} &(13)\\ O_2^{-*} + M &\rightarrow O_2^- + M &(14)\\ &\rightarrow e^- + O_2 + M \end{aligned}$$

in which M is, in this experiment, hydrogen, oxygen, or nitrogen, and a collision between O_2^{-*} and one of these molecules may cause de-excitation or ionization.

The rate equations governing the number of charged particles (which we assume to be e^-, H_5^+, and O_2^-) are:

$$\begin{aligned} \frac{dn_e}{dt} &= \dot{n}_e - \beta\, n_e\, n_H - \frac{n_e}{\tau} &(15)\\ \frac{dn_H}{dt} &= \dot{n}_e - \beta\, n_e\, n_H - \eta\, n_H\, n_O &(16)\\ \frac{dn_O}{dt} &= \frac{n_e}{\tau} - \eta\, n_H\, n_O &(17) \end{aligned}$$

where n_H and n_O are the number densities of hydrogen and oxygen ions, respectively, and we have assumed one electron is produced for every hydrogen ion. β is the electron-hydrogen ion recombination rate reported in the previous section, and η is the ion-ion recombination rate. The electron lifetime, τ, that is measured is an effective lifetime that is the result of the three-body reactions described above and their corresponding attachment coefficients, k_M:

$$\frac{n_e}{\tau} = \Sigma_M\, k_M\, n_e\, n_O\, n_M \qquad (18)$$

As for the case of electron-hydrogen ion recombination, functional forms of τ and η dependent on cavity voltage were used to predict the number of charged particles in the cavity. This, combined with the energy loss per particle, was used to predict the total energy loss and compare it to the measured value.

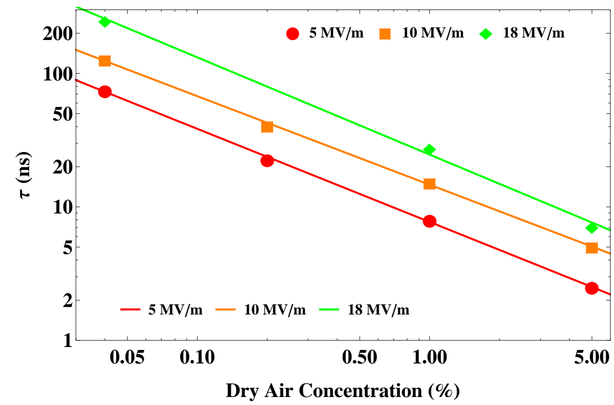

Figure 4: Attachment time of electrons in dry air doped hydrogen vs. dry air concentration at 20.4 atm. The lines are fits to the data. Various electric fields are shown.

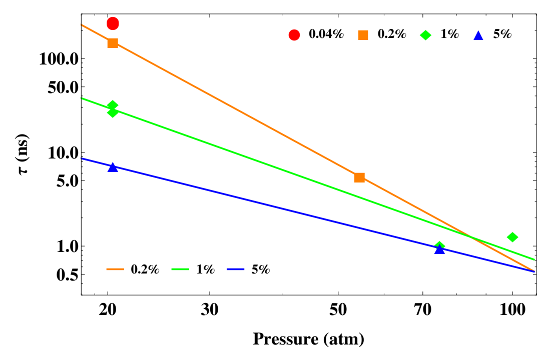

Figure 5: Attachment time of electrons in dry air doped hydrogen vs. gas pressure at 20 MV/m. The lines are fits to the data. Various dry air concentrations are shown.

Figure 4 shows the effect of dry air concentration on the attachment time at 20.4 atm. Figure 5 shows the effect of gas pressure on the attachment time at 20 MV/m.

Note that with both increasing dry air concentration and gas pressure, the attachment time decreases. At the highest pressure and concentration our calculation resolution was limited, which places an upper limit of ≈1 ns on the attachment time.

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