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PLASMA CHEMISTRY IN A HIGH PRESSURE GAS FILLED RF TEST CELL FOR USE IN A MUON COOLING CHANNEL

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INTRODUCTION

Current muon collider schemes call for significant six dimensional (6D) cooling of the muon beam before it is accelerated [1]. One cooling scheme, the Helical Cooling Channel (HCC), employs RF cavities filled with high pressure hydrogen gas [2]. The gas acts both as an energy loss mechanism to allow for ionization cooling [3, 4], and as a buffer in order to prevent RF breakdown [5].

When a beam of particles passes through a HPRF cavity, it will ionize the gas. The amount of plasma generated is dependent on the beam energy, the stopping power of the gas, and the density of the gas. The resulting plasma will gain energy from the RF electric field and transfer it through collisions to the gas. This effect is called plasma loading. An experiment performed at the MuCool Test Area at Fermilab studied the formation of plasma created by a proton beam and its evolution over the course of many 805 MHz RF cycles [6].

PLASMA PROCESSES

In a pure gas, electrons may only recombine with ions. For the range of pressures in this experiment (20 - 100 atm), it is in most cases a three-body reaction in which the third body can be an electron, an ion, or a neutral molecule. Large clusters of positive ions, for example hydrogen, can form through the processes:

$$H_n^+ + 2H_2 \leftrightharpoons H_{n+2}^+ + H_2 \quad (1)$$

An equilibrium in the population of each cluster is reached based on the gas pressure and temperature.

When an electronegative dopant is added, electrons may become captured by the dopant, forming a negative ion. For the case of O_2 this is a ternary process.

Positively and negatively charged ions may "recombine", or become neutral, and this is also a ternary process for the pressure range of this experiment.

It is important to note that for the three-body processes listed above, the identity of the third body plays a significant role. For example, oxygen captures an electron and forms an excited state with a certain lifetime. If the excited oxygen molecule experiences a collision within that lifetime, one of two things can happen: the oxygen ion may become ionized, or the collision may de-excite the oxygen ion, with the third-body carrying off the excess energy. How frequently de-excitation occurs is largely dependent on the identity of the third body.

Rate equations for each of the charged particles can be written:

$$\frac{dn_e}{dt} = \dot{N}_e - \sum_k \beta_k n_e n_{H_k^+} - \frac{n_e}{\tau} \quad (2)$$

$$\frac{dn_{H^+}}{dt} = \dot{N}_{H^+} - \sum_k \beta_k n_e n_{H_k^+} - \sum_{k,l} \eta_{k,l} n_{H_k^+} n_{O_l^-} \quad (3)$$

$$\frac{dn_{O^-}}{dt} = \frac{n_e}{\tau} - \sum_{k,l} \eta_{k,l} n_{H_k^+} n_{O_l^-} \quad (4)$$

where $\dot{N}$ is the production term, β is the electron-ion recombination rate, τ is the electron attachment time, η is the ion-ion recombination rate, and the sums are taken over the existing ion species. For the case of a pure gas, the final terms of the electron and positive ion equations are dropped (and the negative ion equation isn't applicable).

RESULTS

Hydrogen

The results for electron-hydrogen recombination are shown in Figure 1. There was some beam intensity dependence observed over the three beam intensities used during the experiment. This is most likely due to varying cluster populations. It can be seen that the general trends are for the recombination rate to increase with gas pressure and decrease with X_0 (electric field amplitude normalized by the gas pressure).

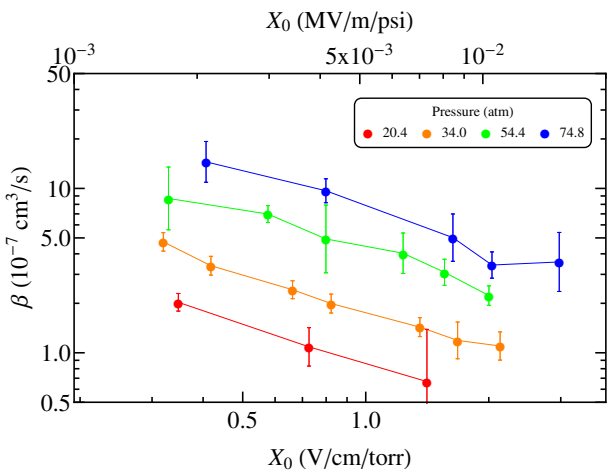

Figure 1: Electron-hydrogen recombination rates at the lowest beam intensity for various gas pressures.

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Hydrogen doped with Dry Air

The results dry air doped hydrogen are shown in Figures 2, 3, and 4. The timing resolution of the experiment was such that attachment time measurements below 1 ns could not be made accurately.

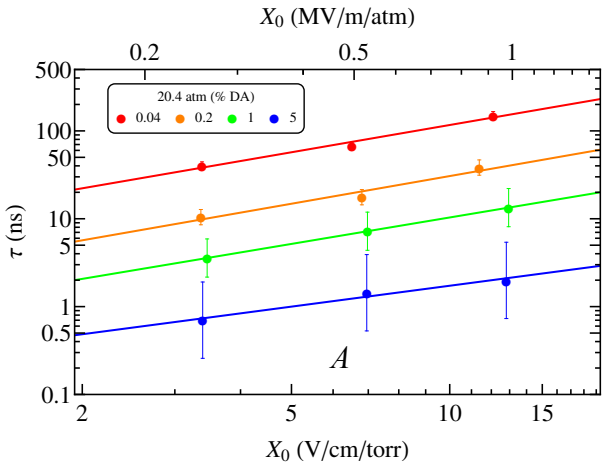

Figure 2: Measurements of electron attachment time to oxygen in hydrogen (points) and fits to the data (lines) at 20.4 atm for various dopant concentrations.

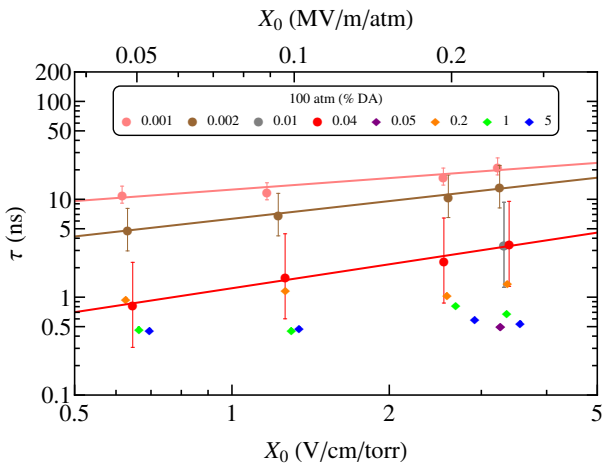

Figure 3: Measurements of electron attachment time to oxygen in hydrogen (points) and fits to the data (lines) at 100 atm for various dopant concentrations.

The attachment time gets smaller with increasing gas pressure and dopant concentration, and larger with increasing X_0

The ion-ion recombination rate is fairly independent of X_0 and tends to decrease with increasing dry air concentration.

Deuterium

Figure 5 shows the results for deuterium. As in the case of hydrogen, the electron-ion recombination rate increases with increasing gas pressure, and the values are roughly equivalent.

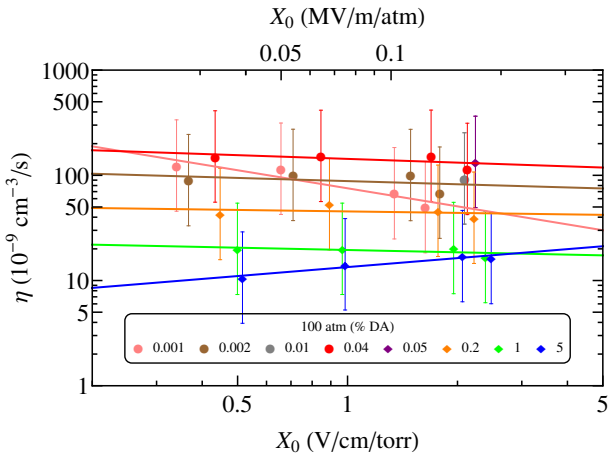

Figure 4: Measurements of ion-ion recombination rates for oxygen in hydrogen (points) and fits to the data (lines) at 100 atm for various dopant concentrations.

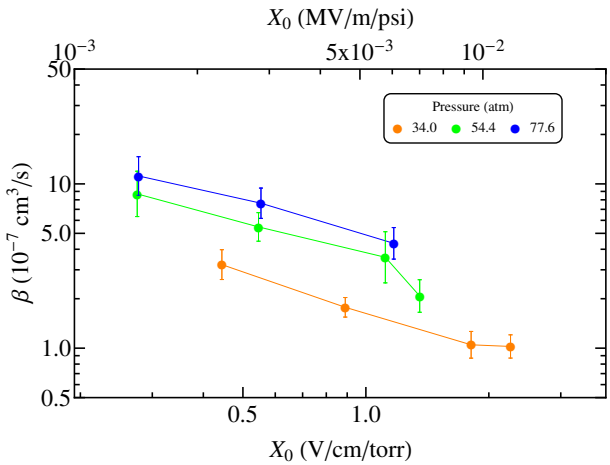

Figure 5: Electron-deuterium recombination rates at the lowest beam intensity for various gas pressures.

Deuterium Doped with Dry Air

Figures 6 and 7 show the results for dry air doped deuterium. As can be seen in the electron attachment time, there are residual electrons only for the smallest gas pressure. The ion-ion recombination rate tends to decrease slightly with gas pressure and is larger than that of hydrogen for 1% dry air at 100 atm.

Nitrogen and Helium

Figure 8 shows the results for nitrogen and helium. The highest beam intensity was used for these data, and only one pressure was recorded for each.

Nitrogen and Helium Doped with Dry Air

Figures 9 and 10 show the results for dry air doped nitrogen and helium. Residual electrons can be observed in the 0.1% and 1% nitrogen and for all cases in helium.

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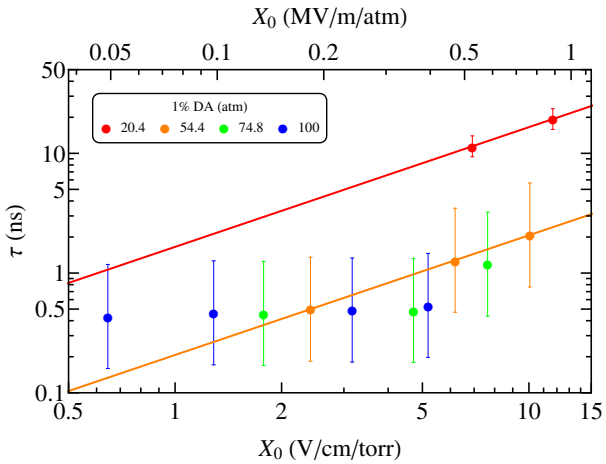

Figure 6: Measurements of electron attachment time to oxygen in deuterium with 1% dry air (points) and fits to the data (lines) for various gas pressures.

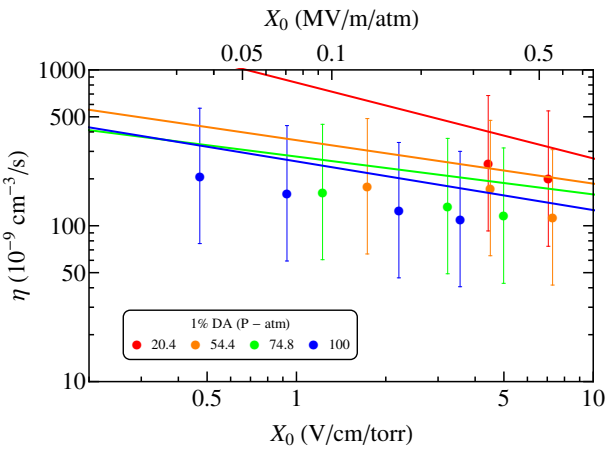

Figure 7: Measurements of ion-ion recombination rates for 1% dry air in deuterium (points) and fits to the data (lines) for various gas pressures.

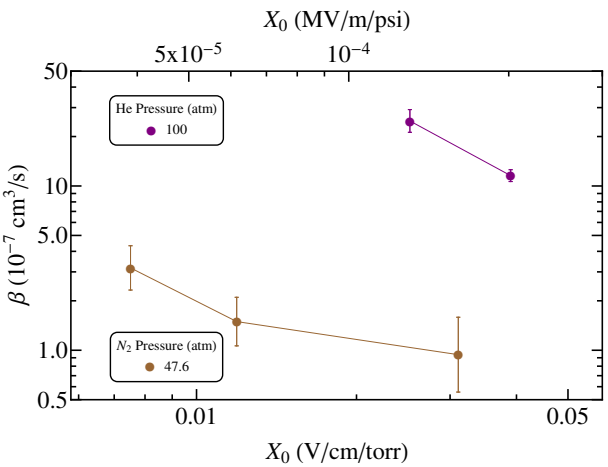

Figure 8: Electron-nitrogen and electron-helium recombination rates at the highest beam intensity.

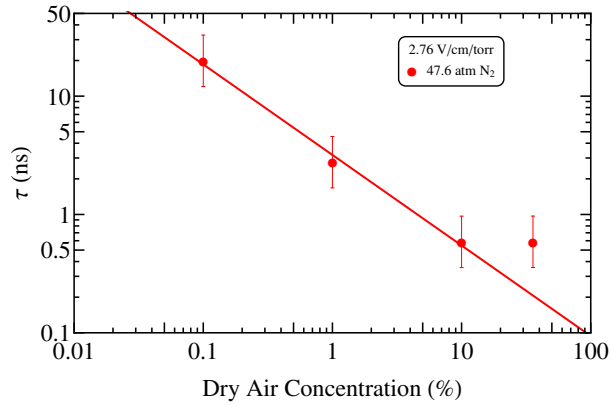

Figure 9: Measurements of electron attachment time to oxygen in nitrogen (points) and a fit to the data (line, excluding the largest concentration) at 10 MV/m.

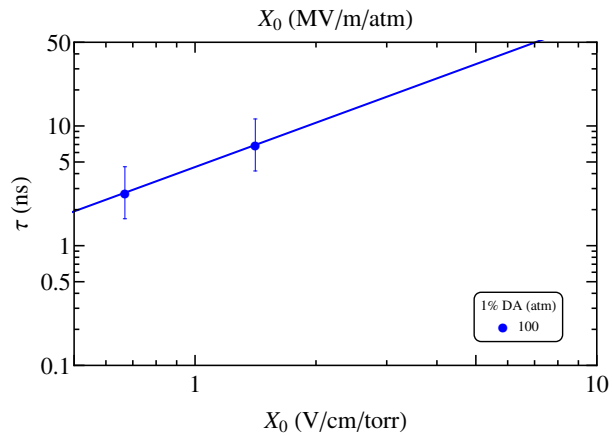

Figure 10: Measurements of electron attachment time to oxygen in helium at 1% dry air (points) and a fit to the data (line).

REMARKS

Measurements of electron-ion recombination rates are difficult to interpret because the exact ion cluster is not known. The general trends of increasing rate with gas pressure and decreasing electric field are consistent with past measurements. The magnitude of values of 10^{-7} to 10^{-6} cm^3/s are reasonable.

Very few results of electron attachment time to oxygen in hydrogen and deuterium have previously been made. Increasing gas pressure and dopant concentration decrease the electron lifetime, and the limit should be dependent on the collision frequency.

Ion-ion recombination results are also difficult to interpret, for the same reason as electron-ion recombination results. Very few measurements of ionic oxygen recombination have been made, however the order of magnitude and trend of decreasing with increasing gas pressure are consistent with previously measured non-oxygen results.

It should be noted that these measurements were taken at room temperature. Decreasing the temperature at which the cavity operates would decrease the plasma loading and electron attachment time, and increase the electron-ion recombination rate.

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