ELECTRON RECOMBINATION IN A DENSE HYDROGEN PLASMA*

B. Freemire[†], P.M. Hanlet, Y. Torun, Illinois Institute of Technology, Chicago, IL 06016, USA
M. Chung, M.R. Jana, C.J. Johnstone, T. Kobilarcik, G. Koizumi, M. Leonova, A. Moretti,
M. Popovic, T. Schwartz, A.V. Tollestrup, K. Yonehara, FNAL, Batavia, IL 60510, USA
R.P. Johnson, Muons, Inc., Batavia, IL 60510, USA
M.G. Collura, Politecnico di Torino, Torino, Italy

Abstract

A high pressure hydrogen gas filled RF cavity was subjected to an intense proton beam to study the evolution of the beam induced plasma inside the cavity. Varying beam intensities, gas pressures and electric fields were tested. Beam induced ionized electrons load the cavity, thereby decreasing the accelerating gradient. The extent and duration of this degradation has been measured. A model of the recombination between ionized electrons and ions is presented, with the intent of producing a baseline for the physics inside such a cavity used in a muon accelerator.

INTRODUCTION

One of the main technological challenges in building a muon accelerator is operating high gradient RF cavities in strong magnetic fields. A compelling solution is to fill the cavities with high pressure gas (or HPRF cavity) in order to mitigate breakdown. Field emitted electrons from the surface of the cavity wall can form an avalanche which is strongly focused and traverse the cavity, shorting it. With a suitable buffer gas, these electrons lose their energy through Coulomb scattering before forming an arc. This principle has been demonstrated using various surface materials and gas species [1, 2].

The problem with this technology is that the beam ionizes whatever gas is present when it traverses the cavity. These ionized electrons and ions gain energy from the electric field and load the cavity. Each incident beam particle can produce thousands of electron-ion pairs, and while this plasma density is typically six orders of magnitude less than the parent gas density, significant field degradation is possible. This becomes an issue because the subsequent bunches in the beam would see a smaller accelerating gradient. The question becomes how much the field gets reduced over the duration of the bunch length and how fast it recovers.

In the current muon collider design, the beam pulse consists of 3.5 10^{12} muons per bunch, with 12 bunches separated by 5 ns at a kinetic energy of 100 - 400 MeV. The baseline cavity design calls for an accelerating gradient of 15 - 25 MV/m at a repetition rate of 15 Hz, filled with 180 atm of gas. Hydrogen gas seems to be an ideal candidate because it provides an ideal energy loss and radiation length for this energy range of muons and has been shown to mitigate breakdown in the cavity.

EXPERIMENTAL SETUP

The HPRF program is carried out at the MuCool Test Area, located at the end of an extension to the Fermilab linac. The linac provides a 400 MeV proton beam (H^- is accelerated and the electrons are stripped just before the experimental apparatus) 7.5 - 9.5 μs long, bunched at 200 MHz, with variable intensity set by a quadrupole triplet and collimators. The maximum intensity achieved in the cavity was 2 10^8 protons per bunch. This is roughly four orders of magnitude less intense than the muon collider design. Thirteen megawatts of RF power is provided at 805 MHz.

Electric and magnetic pickup probes are installed in the cavity to measure the electric field, and optical fiber feedthroughs allow PMTs and SiPMs to measure the light signal. There are also beam intensity monitors before and after the collimator system to measure the number of protons incident on the cavity, and a phosphorescent screen to assist in beam steering and focusing.

Various gas species and pressures have been used, including pure hydrogen, nitrogen, helium and dry air, as well as dry air, sulfur hexafluoride and nitrogen doped hydrogen. Additionally, variable electric fields and beam intensities were recorded.

HYDROGEN PLASMA DYNAMICS

For the case of a hydrogen filled RF cavity, the incident beam will produce electrons and H_2^+. The cross section for H_3^+ production is quite high and usually takes place within 1 ps [3].

$$H_2^+ + H_2 \rightarrow H_3^+ + H \tag{1}$$

Larger hydrogen clusters can form through three body collisions of the form

$$H_{n-2}^+ + H_2 + H_2 \rightleftharpoons H_n^+ + H_2 \tag{2}$$

The energy needed to produce an ion pair (W) in gaseous hydrogen has been measured to be 35.3 eV/pair [4]. Together with the $\frac{dE}{dx}$ curve from the Bethe-Bloch formula and the density of hydrogen (ρ), one can calculate the number of electrons produced in the cavity from a single incident particle.

$$n_e = \langle \frac{dE}{dx} \rangle \frac{\rho}{W} \tag{3}$$

These ions recombine with the ionized electrons and this process must be relatively fast for an HPRF cavity to be re-

---

[*] Work supported by DOE contract DE-AC02-07CH11359

[†] freeben@iit.edu

alistic in a muon collider design. The cross sections of electrons with H_2 and H_3^+ are shown in Fig. 1 and 2. Plasma electron energies are typically 0.1 - 1 eV, and over this range the cross section of $H_3^+ +$ recombination is roughly an order of magnitude larger.

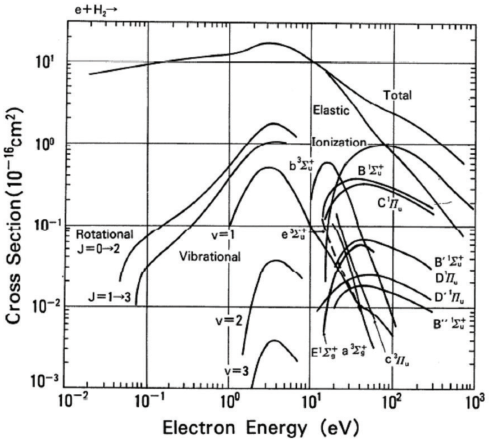

Figure 1: Cross section of electrons on H_2 [5].

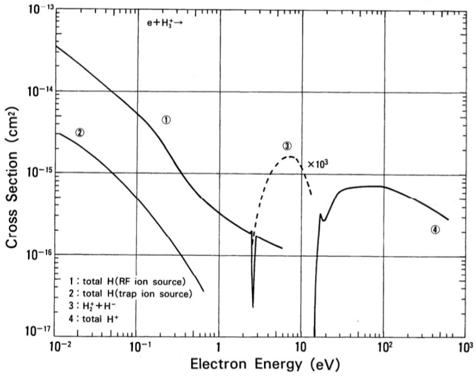

Figure 2: Cross section of electrons on H_3^+ [5] .

PHYSICS MODEL

The rate equation can be used to model the number of electrons in the cavity as a function of time and position.

$$\frac{dn_e}{dt} = \dot{N} - \alpha n_e n_\gamma - \beta n_e n_\delta - ... \tag{4}$$

Where α and β are the recombination rates of electrons with particles γ and δ. For the case of pure hydrogen, the number of electrons is equal to the number of hydrogen molecules ionized, so

$$\frac{dn_e}{dt} = \dot{N} - \beta n_e^2 \tag{5}$$

This formula can be applied during various segments of the RF pulse. Fig. 3 shows the envelope of the RF signal in the cavity during beam. There are five distinct regions. The recombination rate can be calculated when the beam first turns on, when the cavity is in equilibrium, and when the beam turns off with RF on.

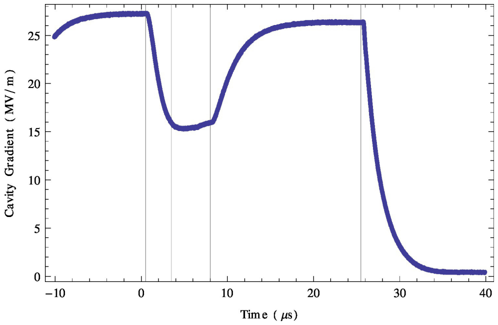

Figure 3: RF envelope during a beam pulse. There are five distinct regions. They are (sequentially): before the beam turns on and the voltage in the cavity fills; when the beam first turns on; when beam is on and the cavity has reached equilibrium; when the beam turns off; and when the RF turns off and the voltage in the cavity decays.

The main region of interest is the second, just after the beam turns on. The experimental beam pulse length is 9.5 μs, while that of a muon collider is 60 ns, so only the first 60 ns of the RF pulse with beam is of interest. It is important to note that the cavity recovers in time for the next beam pulse.

The number of electrons in the cavity is given by

$$\begin{aligned} n_e &= \frac{Energy\,loss\,in\,the\,cavity}{Energy\,loss\,per\,electron} \\ &= \frac{\frac{V(V_0-V)}{R_c} - \frac{d(1/2CV^2)}{dt}}{dw} \end{aligned} \tag{6}$$

Here, V is the cavity voltage at any given time, V_0 is the voltage just before the beam turns on, R_c is the cavity resistance, C is the cavity capacitance, and dw is the energy lost in the cavity per electron (and is presure dependent - see Ref. [6] for more details). Fig. 4 shows an example of the electron evolution in the cavity over time.

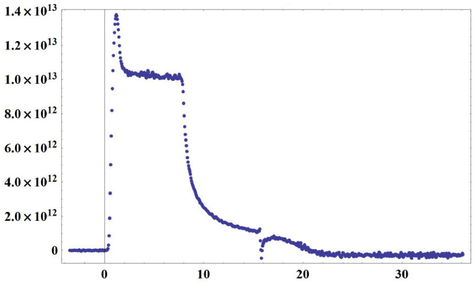

Figure 4: The number of electrons in the cavity during one RF pulse (μs) averaged over 10 beam pulses.

When the beam turns off, the electrons in the cavity recombine with time, and Eq. 5 can be integrated to give

$$n(t) = \int \frac{n(\vec{x},0)d\vec{x}}{1+\beta t n(\vec{x},0)} \tag{7}$$

This produces an inverse dependence with respect to time on the number of electrons in the cavity. Should any impurities be present that provide some attachment process for the electrons, Eq. 4 would have to be integrated and would produce an exponential dependence with respect to time. The initial distribution of electrons in the cavity should be Gaussian, and the shape determined by the diameter of the collimator hole immediately upstream of the cavity. Eq. 7 can be integrated with a particular value of β and fit to the data, which is shown in Fig. 5.

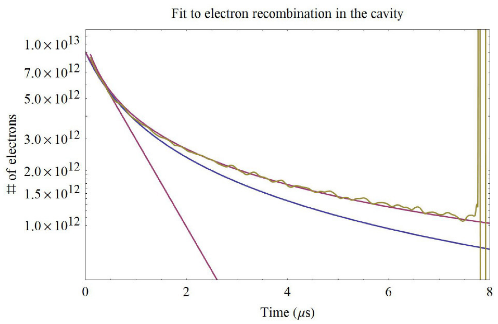

Figure 5: The number of electrons in the cavity after the beam turns off. The fitted curve is a Gaussian fit, the blue curve is a fit assuming a homogeneous distribution of electrons, and the purple curve is an exponential fit.

The value of β used in Fig. 5 was $1.2 \times 10^{-8} \frac{cm^3}{s}$ and as can be seen, the 1/t dependence closely matches the data. This indicates that pure hydrogen recombination is taking place.

During equilibrium, Eq. 5 can be simplified and a direct measurement of β can be made.

$$\beta = \frac{\dot{N}(\vec{x},t)}{n_e^2(\vec{x},t)} \tag{8}$$

Based on the existing data, recombination rates on the order of $10^{-6} \frac{cm^3}{s}$ have been measured during equilibrium of the RF pulse. Analytic forms of the recombination rates of electrons in H_3^+ and H_5^+ have been fit to data found in Ref. [7] and [8]. These are shown in Fig. 6.

CONCLUSIONS

Analysis of the data taken during the summer of 2011 shows that self recombination takes place in pure hydrogen gas. The decay of the number of electrons in the cavity once the beam is turned off indicates self recombination rather than attachment to electronegative dopants or impurities.

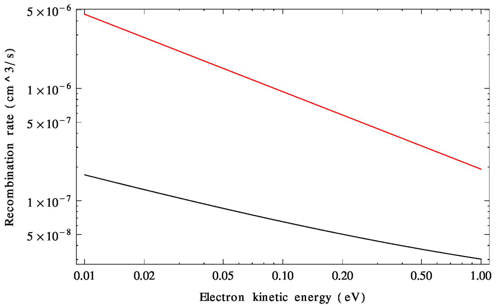

Figure 6: Analytic fits to hydrogen recombination data. H_3^+ is in black and H_5^+ is in red.

The cross section of electron recombination grows for larger clusters of hydrogen and so at the equilibrium of electron production and recombination in the cavity, processes involving H_5^+ or larger clusters must be taking place. The measured recombination rates during this time match or exceed the analytic predicted values.

The accelerating gradient in the cavity recovers fully in time for the next beam pulse of a muon collider. Exactly what the recombination rate is and how much the gradient degrades during the 60 ns muon collider beam pulse will be extrapolated from data taken during the spring of 2012.

REFERENCES

[1] K. Yonehara et al., PAC09, TU5PFP020.

[2] P. Hanlet et al., EPAC06, TUPCH147.

[3] A.V. Phelps, J. Phys. Chem. Ref. Data. 19 (1990) 653.

[4] C.J. Bakker and E. Segre, Phys. Rev. 81 (1951) 4.

[5] H. Tawara et al., J. Phys. Chem. Ref. Data. 19 (1990) 3.

[6] K. Yonehara et al., "Influence of Intense Beam in High Pressure Hydrogen Gas Filled RF Cavities," MOPPC036, these proceedings.

[7] R. Johnsen and S.L. Guberman, *Advances in Atomic, Molecular, and Optical Physics*. Vol. 57. Academic Press. London. 2010.

[8] J. Macdonald, M.A. Biondi, and R. Johnsen, Planet. Space Sci. 32 (1984) 651.