STUDY OF ELECTRONEGATIVE GAS EFFECT IN BEAM INDUCED PLASMA*

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Abstract

A large amount of stored RF energy dissipation in a beam-induced plasma can be an issue in a high-pressure hydrogen gas filled RF cavity. It is called beam-plasma loading effect. In order to mitigate the effect, a small amount of electronegative gas was doped in the cavity. As a result, an ionized electron was quickly removed from the cavity. However, a small amount of RF power dissipation still remained. More RF power dissipation measurement was carried out in various gas combinations, i.e. H_2 with SF_6, H_2 with dry air, N_2 with dry air, and He with dry air. We found that the small RF power dissipation can be induced by residual heavy ions. Based on the theory of beam-plasma loading effect, the RF power dissipation in the gas filled cavity is estimated with a realistic muon collider beam.

INTRODUCTION

Operating a high gradient RF cavity placed in a strong magnetic field is essential for realizing practical muon ionization cooling and acceleration. However, available accelerating gradient in a conventional vacuum pillbox cavity is limited by the strength of the magnetic field, because the dark current is confined by the magnetic field. Consequently, an RF breakdown is induced at lower accelerating gradient in a stronger magnetic field. A high pressure gas filled RF cavity has a great potential to solve the magnetic field problem since the dark current flow is diffused by the gas via Coulomb scattering [1,2]. A possible drawback of the cavity is that beam-induced plasma is generated by an intense beam and it consumes a huge amount of stored RF energy in the cavity [3]. It is called beam-plasma loading effect. According to the theory, ionized electron is the major candidate to consume the RF power. In order to remove the ionized electron from the cavity, a small amount of electronegative gas was doped in the dense hydrogen gas. As a result, the RF power dissipation was drastically improved, i.e. a power loss in an electronegative gas doped H_2 gas was 50 times lower than that in a pure H_2. However, a small amount of RF power loss was still observed. It could not be explained by the electron swarm dynamics in an RF field.

The small RF power dissipation was observed with different dopant electronegative gases, i.e. H_2 with SF_6, H_2 with dry air, N_2 with dry air, and He with dry air. We found that the power loss can be induced by the residual heavy ions. If this hypothesis is correct, the RF power dissipation in an electronegative gas doped H_2 gas filled RF cavity can be estimated with a realistic muon collider beam. Experiment descriptions can be found in Refs. 4, 5, and 6.

DISCUSSION

Beam tests of a high pressure gas filled RF cavity have been carried using a 400 MeV proton beam in the MTA (Mucool Test Area) at Fermilab in Summer 2011 and Spring 2012. First, we discuss the past, summer 2011, result. Figure 1 shows the beam-plasma loading in a 950 psi pure H_2 gas filled 800 MHz RF cavity. The beam-induced plasma dynamics in a high gradient RF field is well understood [7]. The ionized electron consumes a huge amount of RF power from the cavity. It can produce a large RF amplitude drop as shown in Figure 1.

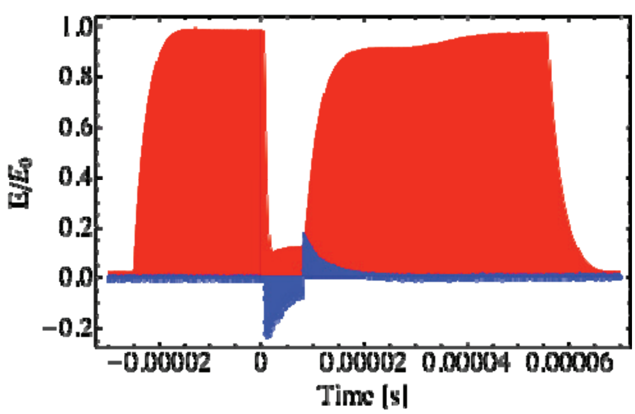

Figure 1: Observed RF envelope with the beam-plasma loading effect in a 950 psi pure H_2 gas (red) and toroid beam current monitor signal (blue).

Figure 2 shows the beam-plasma loading effect in a 0.01 % SF_6 doped 950 psi H_2 gas. It is clear that the beam-plasma loading effect is significantly mitigated by a small amount of SF_6 gas. However, the cavity still lost a small amount of RF power. Moreover, the time of the amplitude drop is very slow. If a doped electronegative gas could not capture all ionized electrons and hence the residual electrons responsible for the RF power consumption, the RF amplitude drop must be very steep and reach the equilibrium RF amplitude. The observed RF amplitude drop rate cannot be explained by the residual ionized electrons.

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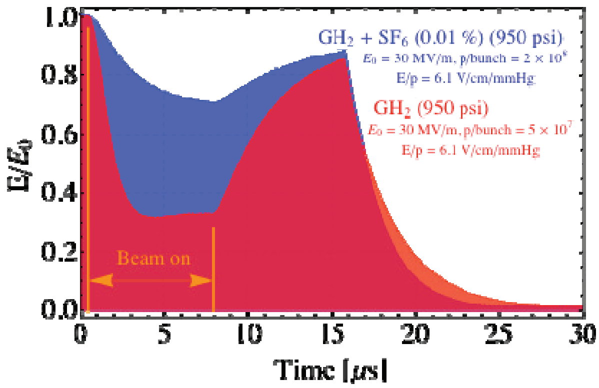

Figure 2: Observed RF pickup signals in 0.01 % SF_6 doped H_2 gas (blue) and a pure H_2 gas (red).

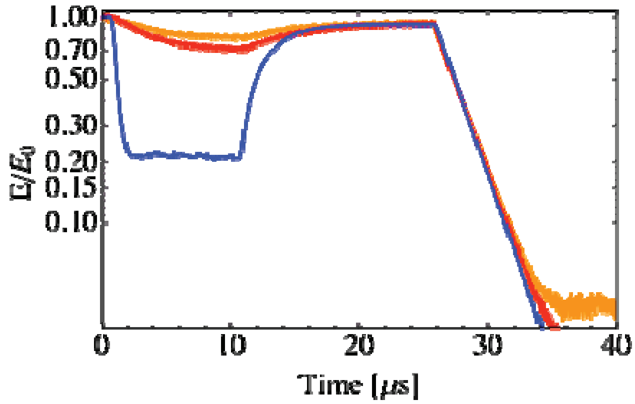

Figure 3: Observed beam-plasma loading effect in 1 % DA doped H2 (red), 0.01 % SF6 doped H2 (orange), and pure H2 gases. Gas pressure was 1470 psi in all cases.

We also notice that SF_6 will not be a great solution to capture the ionized electron in the real muon accelerator application since SF_6 causes drift of the resonant frequency. If SF_6 is dissolved in H_2 gas, it may form HF which is a very strong acid and is erosive for a metal surface. Besides, the SF_6 doped cavity cannot be operated at cryogenic temperature. This could limit design of the practical high-pressure gas filled RF cavity. Therefore, the aim of the electronegative run was 1) to understand the physics in the doped gas and 2) to find the practical electronegative gas for muon acceleration applications.

Molecular oxygen is a good candidate since it has a large electron capture cross section via the three body reaction ($A + B + e^- \rightarrow A^- + B$). But, we should take care that the concentration of O_2 does not exceed the LFL (Lowest Flammable Level). Therefore, we use DA (Dry Air), in which O_2 abundance is 20 %. From past experiment, we knew that N_2 doped H_2 gas does not remove the ionized electron from the cavity even though NH_3 would be made from ½ N_2 + 3/2 H_2 reaction.

Figure 3 shows the beam-plasma loading effects in 1 % DA doped H_2 (red), 0.01 % SF_6 doped H_2 (orange), and a pure H_2 (blue) gases, respectively. Gas pressure is 1470 psi for all cases. Although the final RF amplitude at t = 10.5 μs in the SF_6 doped gas is 10 % higher than the DA doped one, the DA doped gas works as well as the SF_6 one. We also noticed that the initial RF amplitude drop in both gas combinations were very similar.

The RF amplitude drop has been observed with other parent gases, i.e. He and N_2. Figure 4 shows the initial RF amplitude drop in various buffer gases. The RF amplitude drops in 1 % DA doped H_2 and 0.01 % SF6 doped H_2 are very similar, while that in 1 % DA doped He gas is steeper and that in 1 % DA doped N_2 gas is shallower than the H_2 based dopant gas. From these evidences, we brought up the model that the residual ions, i.e. positive hydrogen and negative ions, must contribute to the RF power dissipation from the cavity since there are no electrons in the cavity. If the motilities of ions are known, the RF power dissipation can be estimated by using the analysis technique we used in Ref. 7.

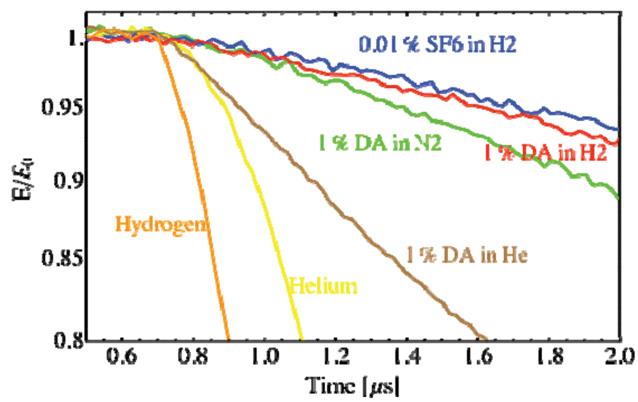

Figure 4: Initial RF amplitude drops in various gas conditions. (Blue) 0.01 % SF_6 in H_2 gas, (red) 1 % DA in H_2 gas, (green) 1 % DA in N_2 gas, (brown) 1 % DA in He gas, (yellow) pure He gas, and (orange) pure H_2 gas. Gas pressure was 1470 psi in all cases except for N_2 gas.

Figure 5 shows the summary of estimated power loss *dw* in various gases as a function of E/p. We can clearly see the tendency of *dw* for different gases. As we expected, the highest RF power dissipation takes place in He parent gas and the lowest one is in N_2 one.

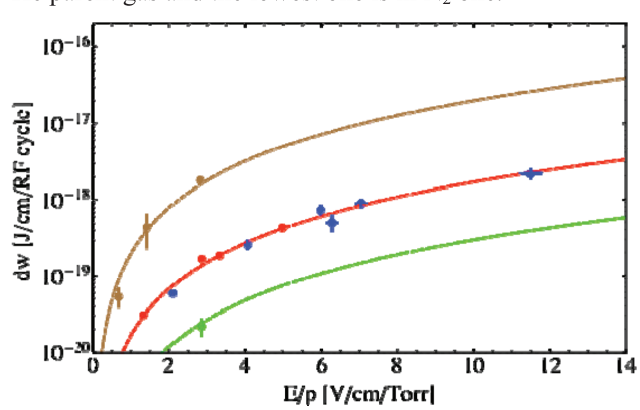

Figure 5: Observed *dw* in various gases. (Brown) 1 % DA in 1470 psi He, (red) 1 % DA in 1470 psi H2, (blue) 0.01 % SF_6 in 500, 800, and 950 psi H2, and (green) 700 psi N2 gases, respectively.

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An orange line in Fig.6 is the estimated *dw* if it is dominated by H_5^+ (reduced μ = 9.6 $cm^2/V/s$). The experimental data seems to be reproduced by the model. It should be noted that the discrepancy between experiment and model is larger for higher gas pressure. We do not fully understand the physics yet.

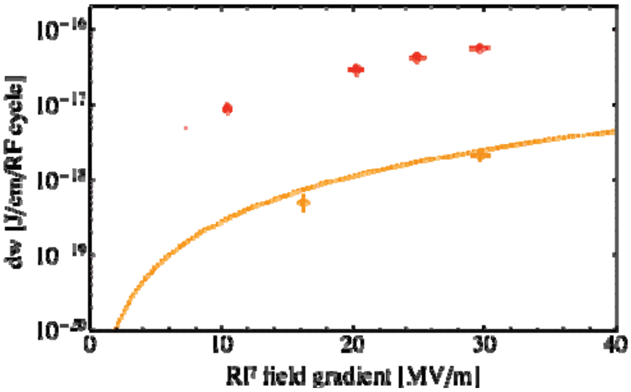

Figure 6: Comparison of *dw* in pure H_2 (red) and *dw* in 0.01 % SF_6 doped H_2 (orange) at 500 psi.

ESTIMATE BEAM-PLASMA LOADING EFFECT WITH REALISTIC MUON COLLIDER BEAM PARAMETERS

The beam-plasma loading effect in a realistic high pressure gas filled RF pillbox cavity is estimated. A 4 MW 8 GeV proton beam is generated in a proton driver [8,9,10]. In order to maximize pion/muon capture rate in a muon beam frontend channel, proton beam is accumulated and compressed in 2 ± 1 ns in a bunch compressor ring. The protons would be formed into 2ns-long bunches that hit the target at 15 Hz (2.1 10^{14} /pulse). The pion's from that collision would be captured by the front end transport and RF into a series of μ^+ and μ^- bunches that will propagate through the cooling channel. 12 μ^- bunches are obtained in 200 MHz spacing of varying intensity (with fewer muons toward later bunches), and one will also have a similar train of μ^+ bunches. For a first estimate of the resulting secondary beam, we estimate that each proton would produce ~0.2 $\mu^\pm$ and that these are split into 12 bunches spaced by 5ns; in this model there would then be 3.5 10^{12} $\mu^\pm$ charges per bunch. Therefore, 4.2 10^{13} μs go through the cavity in 60 ns.

The stored energy of RF pillbox cavity can be calculated from

$$U_{store} = \frac{\varepsilon}{2} E_0^2 \langle J_1 \langle 2.405 \rangle \rangle^2 \pi R_c^2 ,$$

where ε is a dielectric constant, E_0 is a peak RF amplitude, J_1 is a modified Bessel function, and R_c is a radius of a pillbox cavity. R_c is determined from the resonant frequency, i.e. $R_c = J_0(1)\, c/2\pi v$. For example, the stored energy of 200 and 800 MHz pillbox cavity are 313 and 20 Joules/m.

4.2 10^{13} muons will generate about 1900 electron-ion pairs/cm in a 200 atm H_2 gas filled RF cavity. The nominal RF peak acceleration field in the RF energy recovery cavity is 15 ~ 20 MV/m. Thus, the *E/p* is 1.3 V/cm/Torr. From Fig. 5, the expected *dw* in *E/p* = 1.3 is 2 10^{-20} Joules/cm/RF cycle. Therefore, the total RF power dissipation is *dw* × 1900 nμ × 100 cm = 0.16 Joules. On the other hand, a pure 200 atm H2 gas filled RF cavity, if there is no recombination rate although it is not true, *dw* is 2 10^{-17} Joules/cm/RF cycle. Then the RF power dissipation is 160 Joules. Figure 7 shows the estimate RF amplitude drop with 12 bunched muon beam with real muon collider beam parameter. The RF amplitude drops 5 and 8 % in 200 and 800 MHz cavities, respectively.

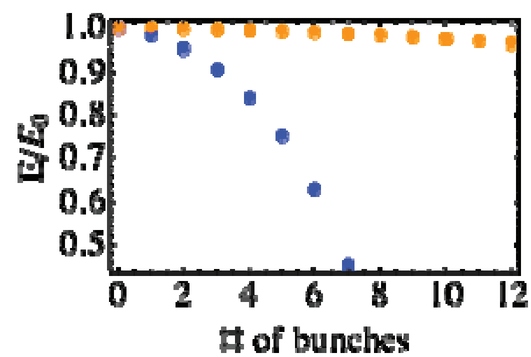

Figure 7: Estimated RF amplitude drop in a pure H_2 gas (blue) and an electronegative doped H_2 gas (orange) at gas pressure 200 atm.

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