INFLUENCE OF INTENSE BEAM IN HIGH PRESSURE HYDROGEN GAS FILLED RF CAVITIES*

K. Yonehara#, M. Chung, M.G. Collura, M.R. Jana, M. Leonova, A. Moretti, M. Popovic, T. Schwarz, A. Tollestrup, Fermilab, Batavia, IL 60510, USA, R.P. Johnson, G. Flanagan, M. Notani, Muons, Inc., Batavia, IL 60510, USA, B. Freemire, Y. Torun, P. Hanlet, Illinois Institute of Technology, Chicago, IL 60616, USA

Abstract

The influence of an intense beam in a high-pressure gas filled RF cavity has been measured by using a 400 MeV proton beam in the Mucool Test Area at Fermilab. The ionization process generates dense plasma in the cavity and the resultant power loss to the plasma is determined by measuring the cavity voltage on a sampling oscilloscope. The energy loss has been observed with various peak RF field gradients (E), gas pressures (p), and beam intensities in nitrogen and hydrogen gases. Observed RF energy dissipation in single electron (dw) in N_2 and H_2 gases was 2 10^{-17} and 3 10^{-17} Joules/RF cycle at E/p = 8 V/cm/Torr, respectively. More detailed dw measurement have been done in H_2 gas at three different gas pressures. There is a clear discrepancy between the observed dw and analytical one. The discrepancy may be due to the gas density effect that has already been observed in various experiments.

INTRODUCTION

Operating a high accelerating gradient RF cavity in a magnetic field is an essential requirement for muon a muon cooling channel to confine a large beam phase space in the muon cooling structure. However, the available RF accelerating field gradient in a pillbox vacuum RF cavity is limited because the field strongly concentrates the dark current in the cavity. Consequently, the probability of RF breakdown that is ignited by the dark current is higher in stronger magnet. By putting a dense buffer gas in a RF cavity, the current flow can be diffused by a Coulomb scattering. Molecular hydrogen is the ideal buffer gas since it produces the lowest multiple scattering for the muon beam and beam phase space growth.

A high pressure hydrogen gas filled RF (HPRF) cavity has been made to experimentally validate the gas-filled cavity breakdown model under various conditions [1, 2]. From experimental results, a model for energy loss by beam-induced plasma in a HPRF cavity has been successfully generated [3]. The plasma is shaken by the RF field, and takes energy from the field and loses it by collision of its ions and electrons with the gas molecule. Consequently, the cavity Q factor is degraded as a function of the amount of density of beam-induced plasma. We call this process as the beam-plasma loading effect. It is worth noting that the plasma is very dilute being only 10^{-6} or less than the ambient hydrogen molecular density which is of the order of 10^{21} molecule/cm^3. The degradation can be an issue since the beam in the later part of bunch train will see less electric acceleration than that in the earlier part of bunch train. In case of a muon collider design, 3.5 10^{12} muons per bunch train with 12 bunches separated by 5 nsec at kinetic energy 100 ~ 400 MeV passes through a 180 atm HPRF cavity at E = 15 ~ 25 MV/m during 60 ns with a 15 Hz repetition rate. The muon beam will generate 5.6 10^{15} cm^{-3} electron-ion pairs per muon beam bunch in the cavity.

A HPRF cavity beam test has been carried by using a 400 MeV proton beam in the MTA (Mucool Test Area) at Fermilab in Summer 2011 and Spring 2012. We mainly report the former experimental result and analysis in this document. RF energy consumptions of single electron (dw) in pure hydrogen and nitrogen gases were investigated with various peak RF field gradients (E) and gas pressures (p). The observed dw is well agreed with the beam-plasma loading effect. It means that we have a way to estimate the RF Q factor reduction at different E/p, beam intensity, and time structure by the theory. The theory also suggests that a small amount of electronegative gas doping can remove the ionized electron in the cavity. The dopant gas test has been done and reported in Ref. [4]

EXPERIMENT

Details of the experiment are depicted in Refs. 5, 6 and 7. Here, we describe the experimental parameters that are needed for data analysis. A 400 MeV H^- beam was delivered from an extended Fermilab Linac beam line to a high pressure gas filled RF cavity in the MTA. The beam intensity in the cavity was tuned by changing the beam spot size at the input to a collimator with a 4 mm diameter hole located upstream of the cavity. Beam current in the cavity was measured by using a toroid beam current monitor. The total number of beam bunches was 1500 spaced by 5 ns and a total length of 7.5 µs.

An 800 MHz high pressure RF cavity was used for this test. The shunt impedance of the cavity (R) was 2.0 MΩ at 1 atm. The cavity was powered by a 13 MW Klystron. Since the time constant of beam-plasma loading effects were longer than the 200 MHz beam bunch spacing the phase of 800 MHz cavity was not locked to that of the beam. There was a pickup loop in the cavity to monitor RF field strength.

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yonehara@fnal.gov

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Table 1 shows the variables for H_2 run in this experiment. The cavity shunt impedance changed at different gas pressure for unknown reasons. It was measured separately by taking data without beam.

Table 1: Variables in this Experiment

	Unit			
Beam intensity	10^8 p/bunch	2	0.4	0.2
Gas pressure	psi	500	800	950
RF amplitude	MV/m	10	20	30

Figure 1 shows a typical RF pickup signal and a toroid signal. It should be emphasized that the cavity did not breakdown under an intense beam although the beam-plasma loading effect was seen, i.e. a rapid RF amplitude drop when the beam was on. After the beam was turned off, the RF power was restored.

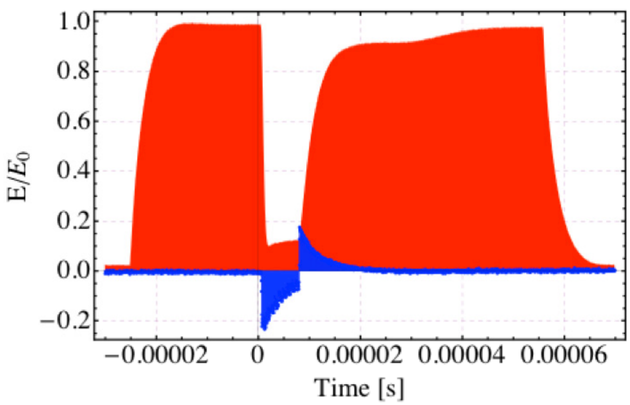

Figure 1: Observed RF pickup signal (red) and toroid current monitor signal (blue).

ANALYZE DATA

Solve Equivalent Resonant Electric Circuit Model

An RF system can be represented as an *LCR* resonant circuit diagram as shown in Figure 2. Thevenin's Theorem has been used to combine the cavity load and the generator resistance, i.e. $V_0 = V_g/2$ and if the cavity is matched $Z = R$ without beam loading. When a beam appears in the cavity, a new resistance, R_p is added in the equivalent circuit. It represents the conductance of beam-induced hydrogen plasma in the cavity.

The power balance equation is given by:

$$p_{plasma} = \frac{1}{2}\frac{(V_0 - V)V}{R/2} - \frac{d}{dt}\left(\frac{CV^2}{2}\right) \quad (1)$$

where p_{plasma} is the RF dissipated power in a plasma and V_0 is the peak initial field potential in the cavity without beam and V is the measured RF amplitude. The first term in the right hand side equation is the RF power gain from the Klystron and the second one power lost or gained from the cavity when its peak voltage changes.

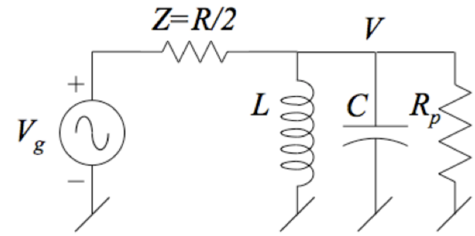

Figure 2: RF resonance circuit diagram with beam-plasma loading.

The ionization energy loss of a proton in a matter is well reproduced by the Bethe-Bloch formula. Since the ion-electron pair production energy (*W*) in hydrogen and nitrogen are known 35 and 35.5 eV, respectively [7], the number of electrons in the cavity produced by single proton can be estimated by

$$n_e = \langle\frac{dE}{dx}\rangle\frac{\rho}{W}, \quad (2)$$

where $\langle dE/dx\rangle$ is the Bethe-Bloch formula, ρ is the density of gaseous hydrogen.

The time-domain rate equation of the number of electrons in a pure hydrogen gas is

$$\frac{dn_e}{dt} = \dot{N} - \beta n_e n_{ion}, \quad (3)$$

where $\dot{N}$ is a production rate of electrons due to the ionization process, β is the hydrogen recombination rate. The electron diffusion rate is small and is omitted from Eq. (3). Because the hydrogen recombination process goes as n^2 it is zero at the beginning of beam-on, hence the dn_e/dt is simply represented as the electron production rate $\dot{N}$. Then, the RF dissipation energy of single electron, *dw* can be estimated from Eqs. (1) and (2),

$$dw = \frac{p_{plasma}}{dn_e/dt} \quad (4)$$

The *dw* is extracted in N_2 and H_2 gases, which are 2 10^{-17} and 3 10^{-17} Joules/RF cycle at E/p = 8 V/cm/Torr, respectively (shown in Figure 3). The *dw* in H_2 was taken with wider variables range. Figure 4 shows the *dw* as a function *E* in *p* = 500, 800, 950 psi. There is a strong correlation between *dw* and *E*. A line in each plot shows the best chi-square fit of the data by using an equation aE^b. We found that the fitting also depends on the gas pressure. On the other hand, we do not see any beam intensity dependence on the *dw*. In fact, a point at the same *E* in the plot is taken with different beam intensity.

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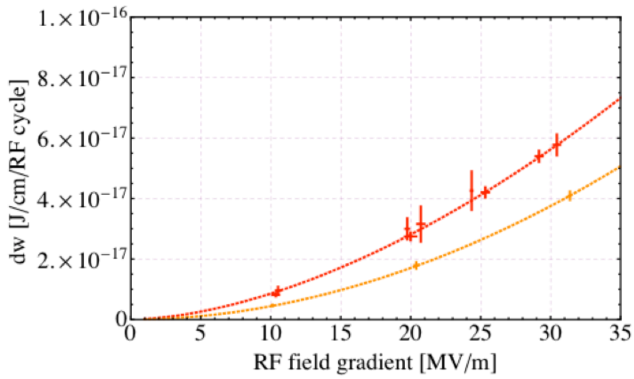

Figure 3: dw in N_2 and H_2 at 500 psi as a function of E. Error bars show the statistic error.

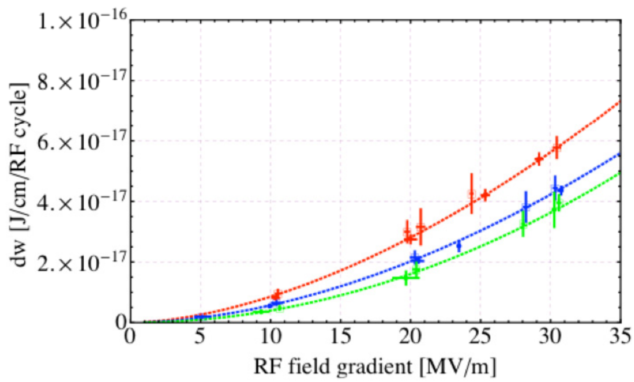

Figure 4: Observed dw as a function of E. Red, blue, and green marks are dw in 500, 800, 950 psi, respectively. Error bars show the statistic error.

Table 2: Fitting Parameter of dw in 500, 800, and 950 psi Pure H_2 and 500 psi Pure N_2. Fitting Factor is aE^b where E is MV/m.

	a	b
500 psi pure H_2	$1.67\ 10^{-19}$	1.71
800 psi pure H_2	$8.67\ 10^{-20}$	1.82
950 psi pure H_2	$3.89\ 10^{-20}$	2.01
500 psi pure N_2	$5.00\ 10^{-20}$	1.95

Estimate RF Energy Dissipation Per Single Electron

The RF energy dissipation per single electron, dw can be estimated by using a simple electron transport analysis. Since the electron drift velocity in H2 gas is known [8], the total RF power dissipation can be given by

$$p_{model} = jE = qn_e u_e E \tag{5}$$

where j and E are a current and an electric field gradient, respectively, and u_e is the drift velocity of electron in a matter. u_e is a function of E/p. Therefore, in order to estimate dw, eq. (5) must be integrated as a function of time,

$$dw = 2\int_{T/2} qn_e u_e(E_0 \sin(2\pi\nu t), p) E_0 \sin(2\pi\nu t) \tag{6}$$

where E_0 is a peak RF gradient, ν is an RF resonant frequency, T is an RF period, and p is a gas pressure.

The observed dw in this experiment is smaller than the estimated dw that is given from eq. (6). Figure 5 shows the correction factor of dw. The correction factor becomes larger in higher gas pressure. It indicates that the correction factor has gas density dependence. Table 3 shows the fitting parameter of correction factor where we use a linear fitting, $aE + b$. Interestingly, correction factor is met at the same electric field gradient, i.e. it is 40 MV/m in three different gas pressures.

Table 3: Fitting Parameter of Correction Factor. Fitting factor is $aE + b$ where E is MV/m

	a	b
500 psi pure H_2	$5.89\ 10^{-3}$	0.516
800 psi pure H_2	$7.50\ 10^{-3}$	0.449
950 psi pure H_2	$11.2\ 10^{-3}$	0.302

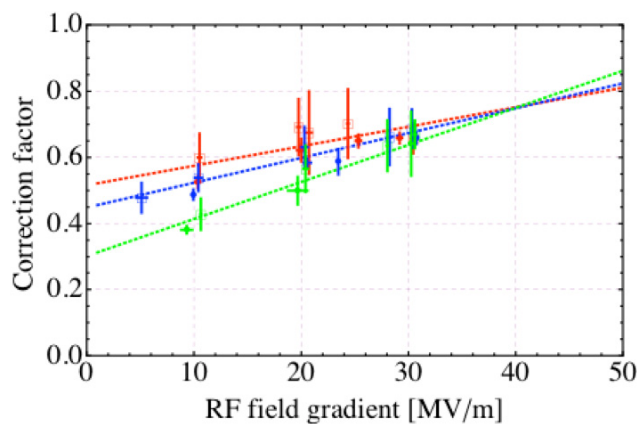

Figure 5: Correction factor of dw. Red, blue, and green marks are 500, 800, and 950 psi pure H_2 gases, respectively. Error bars show the statistic error.

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