STUDY OF ELECTRON SWARM IN HIGH PRESSURE HYDROGEN GAS FILLED RF CAVITIES*

K. Yonehara#, M. Chung, A. Jansson, A. Moretti, M. Popovic, A. Tollestrup, Fermilab, Batavia, IL 60510, U.S.A.
M. Alsharo'a, R.P. Johnson, M. Notani, Muons, Inc., Batavia, IL 60510, U.S.A.
D. Huang, Illinois Institute of Technology, Chicago, IL 60616, U.S.A.
T. Oka, H. Wang, University of Chicago, Chicago, IL 60637, U.S.A.
D. V. Rose, Voss Scientific, Albuquerque, NM 87108, U.S.A.
Z. Insepov, Argonne National Lab, Argonne, IL 60439, U.S.A.

Abstract

A high pressure hydrogen gas filled RF cavity has been proposed for use in the muon collection system for a muon collider. It allows for high electric field gradients in RF cavities located in strong magnetic fields, a condition frequently encountered in a muon cooling channel. In addition, an intense muon beam will generate an electron swarm via the ionization process in the cavity. A large amount of RF power will be consumed into the swarm. We show the results from our studies of the HV RF breakdown in a cavity without a beam and present some results on the resulting electron swarm dynamics. This is preliminary to actual beam tests which will take place late in 2010.

INTRODUCTION

The operation of High Pressure hydrogen gas filled RF (HPRF) cavity has been successfully tested under various conditions [1, 2]. A description of the physics processes in a HPRF cavity with beam is described at length in [3]. Beam tests are necessary to verify the theory and are planned in the near future.

A high intensity beam passing through dense hydrogen gas forms a beam-induced electron swarm via the ionization process. These electrons are shaken by the RF field, and thus their inelastic collisions with the hydrogen molecules will consume a large amount of RF power from the cavity. Consequently, the cavity Q value is degraded as a function of the amount of beam passing through the cavity. The degradation will be an issue since the beam in the later part of bunch train will see less electric acceleration amplitude than that in the earlier part of bunch train. In case of muon collider, 10^{11} muons per bunch at kinetic energy 100 ~ 400 MeV may pass through a 200 atm HPRF cavity during 60 ns and generate up to 10^{14} cm^{-3} electron swarm in the cavity [3]. In the worst case, a half of RF acceleration field will be dissipated into this amount of electrons if all ionized electrons survive in 60 ns. However, the recombination rate in such a dense hydrogen gas has never been investigated.

A HPRF cavity beam test is scheduled to investigate beam-induced electron swarm [4]. A 400 MeV H^- beam line has been built from the Linac to the MTA (Mucool Test Area) experimental hall at Fermilab. Up to 10^{13} protons per 20 μs bunch train will be sent to the MTA hall. The density of built-up beam-induced electron swarm can be large enough to perturb the RF resonance field. Therefore, the recombination rate can be observed precisely by measuring the time domain amplitude of RF field with a well-known intensity beam [5]. The first beam test will be carried out in summer of 2010.

Meanwhile, we have studied the electron swarm which was generated in an RF breakdown without beam. In this analysis, we used a RF field pickup and the optical spectroscopic signals. The experimental result and analysis are discussed in this document.

EXPERIMENT

Breakdown probability

The RF breakdown probability in the HPRF cavity was measured systematically. Fig. 1 shows the observed external electric field with Cu electrodes as a function of the hydrogen gas pressure. The color codes correspond to the probability of breakdown. The lowest probability reproduces the breakdown curve in the past measurements. The maximum electric field was 50 MV/m with the breakdown probability less than 10^{-4} at higher gas pressure than 1000 psi.

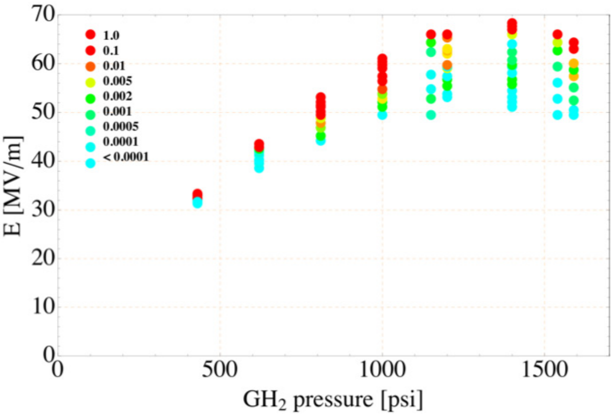

Fig. 1: The breakdown probability plot in the HPRF cavity.

A clear Paschen curve was observed at GH2 pressure below 1000 psi. In this pressure region, the derivative of

---

*Work supported by DOE STTR grant DE-FG02-08ER86350 & FRA under DOE contract DE-AC02-07CH11359

#yonehara@fnal.gov

breakdown probability with respect to the electric field strength was very steep, and the reproducibility was quite good, i.e. the maximum electric field strength was reproduced immediately after many breakdowns. On the other hand, we observed large fluctuations in the breakdown probability at gas pressure range above 1000 psi. The RF cavity conditioning was needed during a long time (although it was ~30 mins. with 15 Hz RF rep rate) to recover the maximum RF amplitude after many breakdowns. This is likely due to heavy surface damage by multiple breakdown.

Analysis of electron swarm by resonance frequency measurement

The RF cavity electrically forms the high-Q LC resonance circuit. Therefore, the RF resonance field is very sensitive to the electron swarm. Such a destructive process of resonance field was measured by the RF pickup probe. An electrical model of the cavity has been used to extract information about the discharge channel. Initially, field emission starts a streamer propagating across the cavity which changes into an arc upon reaching across the cavity. Initially the current grows exponentially, but when it reaches a current of several hundred amps a pinch occurs and the current can increase to more than 1000 amps near the end of the discharge. The period before the pinch has been analyzed by the reduction of the cavity voltage versus time. The using the known mobility of the electrons in the gas allows an estimation to be made of the total number of electrons participating in the initial stages of the discharge. A plot of the growth of the number of electrons per half cycle is shown in Figure 2.

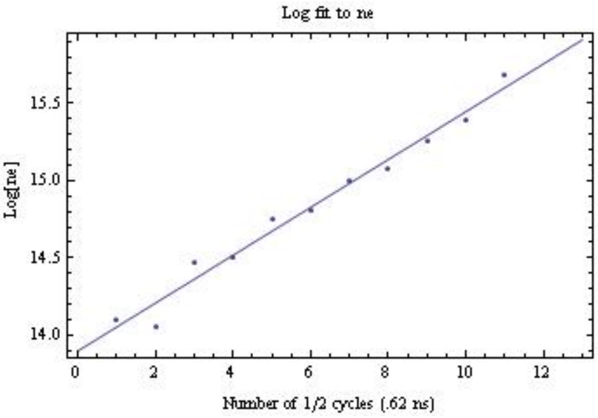

Fig. 2: Growth of electron swarm as a function of a half of RF cycles.

Electron swarm in spectroscopic measurement

A spectroscopic measurement with various hydrogen gas pressures (540, 740, 930, 1120, and 1310 psi) was done. Strong light was observed during the RF breakdown. The spectrometer system consists of a pressure tight 1-mm diameter optical feed-through that is connected to an optical spectrometer (Horiba iHR320 + Hamamatsu H5783-20). The resolution of the spectrometer was set to ± 2.5 nm. In order to obtain a clear light signal, the light was accumulated over 100 RF breakdowns. The applied electric field strength was carefully adjusted to make the breakdown probability of less than 1 % to avoid sequential breakdowns. To obtain a stable trigger signal, an additional PMT (Hammamatsu H5783) and an optical fiber was connected to another optical port. The trigger level was high enough to remove any background signal, e.g. cosmic ray. Figure 2 shows the observed non-corrected 503 and 656 nm time domain spectroscopic lights from 740 psi HPRF cavity. The "zero" timing is at the peak of spectroscopic light signal. Since only one PMT was assembled on the spectrometer only one wavelength light was taken for one data acquisition.

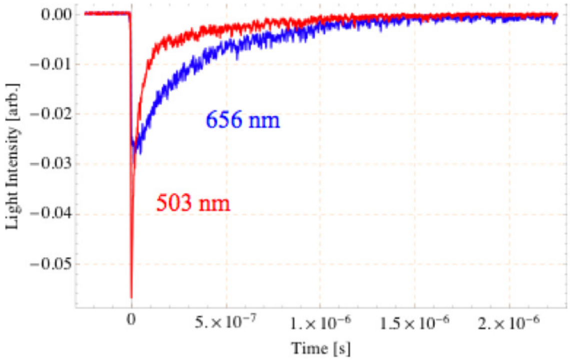

Fig. 3: 503 and 656 nm spectroscopic lights from 740 psi HPRF cavity. The signal was accumulated over 100 RF breakdowns.

The spectroscopic light intensity (integrated within Δt = 1 ns) was corrected by the sensitivity of PMT and the transmission efficiency of optical system as a function of wavelength and was normalized by the integrated intensity of trigger PMT signal. We observed a very broad spectrum and an Hα resonance peak (Fig. 3). The broad spectrum is well fitted with a blackbody radiation formula. In the blackbody radiation analysis, the non-resonant data points are chosen (red point). The obtained plasma temperature is 15,000 K at t = 0 ns. This value is quite independent from pressure of gaseous hydrogen.

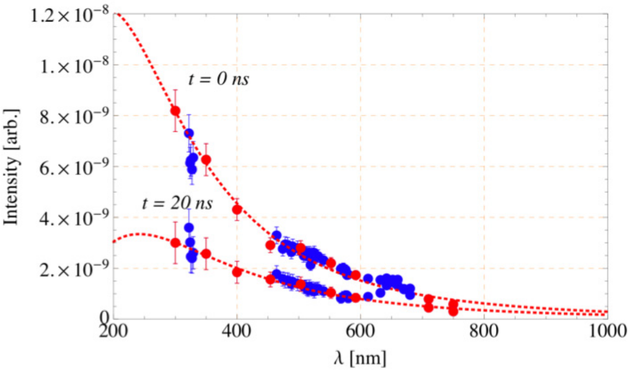

Fig. 4: Spectra from 740 psi HPRF cavity with various timing. Red points are chosen for the blackbody radiation analysis.

The Hα line shape is extracted by fitting a Lorentz distribution curve. Figure 4 shows the enlarged spectra from Figure 3 and the fitted Lorenz curve on Hα resonance. First, we noticed that the intensity of Hα resonance at t = 0 ns was much smaller than the Hα at t = 20 ns. In this time duration, the plasma temperature goes down from 15,000 to 12,000 K. The time delay can be due to the pumping and spontaneous emission rates of hydrogen molecule/atom.

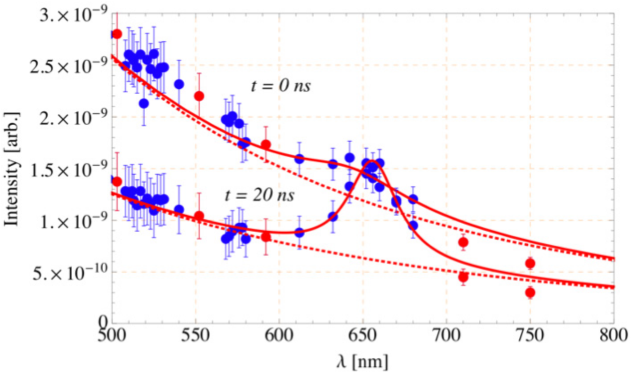

Fig. 5: Enlargement around Hα resonance from Figure 3. The dotted line is the blackbody curve and the solid line includes the Lorentz curve.

Fig. 5 shows the width of Hα line as a function of time. A similar broadening of resonant light in dense hydrogen plasma conditions has been reported by several groups. They proved that the Stark effect can well explain the broadening [7, 8] where the hydrogen energy level is perturbed by a local electric field. Therefore, the line width strongly depends on the plasma density and the plasma temperature. We are working on further analysis.

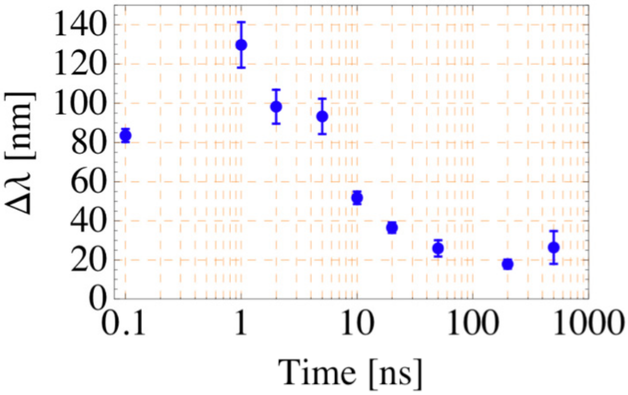

Fig. 6: Full Width Half Maximum of Hα line as a function of time where t = 0.1 ns corresponds to t = 0 ns

HPRF BEAM TEST

Polyatomic hydrogen

Ionized hydrogen ions quickly form polyatomic hydrogen cluster ions which recombine with ionized electrons faster than H_2^+ and H^+. This process has been well known in molecular physics in dilute hydrogen gas conditions, i.e. in stellar hydrogen, for a long time. Polyatomic hydrogen is produced in a chain process in a very short time. The molecular hydrogen ion H_2^+ forms H_3^+ via the reaction $H_2^+ + H_2 \rightarrow H_3^+ + H$ which forms cluster ions very quickly via chain of reaction. Additional three body interaction is taken place and generates larger hydrogen cluster ions, i.e., $H_3^+ + 2H_2 \rightarrow H_5^+ + H_2$, $H_5^+ + 2H_2 \rightarrow H_7^+ + H_2$ etc [3, 6]. Two crucial questions remain to be answered by actual beam tests. The first is how quickly the electrons are neutralized and thus their loading effect on the cavity reduced to tolerable values. And second how long it takes the plasma in the cavity to dissipate so it doesn't induce a break down on subsequent RF pulses.

Electronegative dopant gas

Adding an electronegative dopant gas in hydrogen plasmas is another important topics in the beam test if the beam induced RF Q reduction is significant. SF_6 and c-C_4F_8, which are candidate gasses, have a different attachment cross-section as a function of electron kinetic energy (Fig. 6). The ionized electron kinetic energy is widely distributed. Thus, c-C_4F_8 may be more effective for electron density reduction than SF_6 if the electron kinetic energy is high.

Admixtures of SF_6 in H_2 have been studied in the HPRF cavity without beam [1]. The maximum RF amplitude (in the Paschen limit) is increased ~20 % with 0.2% levels of SF_6. However, SF_6 may be dissociated during RF breakdown, forming F^- and HF. These elements are very active and interact with metals. In fact, cavity surface damage was observed after the tests. Non-fluorine dopant gasses exists will be more useful from practical point view although their attachment cross-sections are orders of magnitude lower than SF_6 and c-C_4F_8.

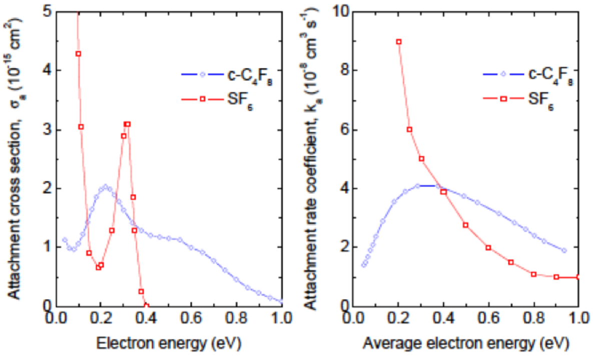

Fig. 7: (Left) Attachment cross-sections and (Right) attachment coefficients of SF_6 and c-C_4F_8

REFERENCES

[1] K. Yonehara et al., PAC09, TU5PFP020.
[2] P. Hanlet et al., EPAC06, TUPCH147.
[3] A. Tollestrup et al., FERMILAB-TM-2430-APC.
[4] M. Chung et al., IPAC'10, WEPE066.
[5] M. Chung et al., NFMCC-doc-532-v2.
[6] K. Hiraoka, J. Chem. Phys. **87**, 4048-4055 (1987).
[7] St. Boddeker et al., Phys. Rev. **E47**, 2785 (1993).
[8] H.R. Griem, Phys. Rev. **A28**, 1596 (1983).