PROGRESS OF GAS-FILLED MULTI-RF-CAVITY BEAM PROFILE MONITOR FOR INTENSE NEUTRINO BEAMS*

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Abstract

We develop a concept of a novel pressurized gas-filled multi-RF-cavity beam profile monitor that is simple and robust in high-radiation environments. Charged particles passing through each RF-cavity in the monitor produce intensity-dependent ionized plasma, which changes the gas permittivity. The sensitivity to beam intensity is adjustable using gas pressure, concentration of electronegative dopant, and RF gradient. The performance of the RF gas monitor has been numerically simulated to evaluate the sensitivity of permittivity measurements. The range will cover the expected beam intensities in NuMI and LBNF. The critical plasma parameters to design the RF gas monitor and the proposed demonstration test to validate the concept of RF gas monitor are discussed in this presentation.

INTRODUCTION

The Long Baseline Neutrino Facility (LBNF) is the future flagship experiment at Fermilab. Beam profile monitors play an important role to check healthiness of a target which generates the beta-decaying secondary charged particles for neutrino experiments and to diagnose the quality of primary and secondary beams. One of the challenges to realize a multi-MW beam complex such as LBNF is monitoring of the beam profile under extreme radiation environments. Potential radiation damages were found in the present beam profile monitor based on an ionization chamber at NuMI (Neutrinos at the Main Injector) even though the present operating beam power is sub-MW [1].

We propose a radiation-tolerant gas-filled RF cavity beam profile monitor that provides precise measurements of the beam profile downstream of the target. The RF monitor is based on microwave cavity resonators that are a simple metallic box filled with gas. Incident particles interact with the gas to form plasma via the ionization process. As a result, the gas permittivity is changed proportional to the number of ion pairs. The beam profile is reconstructed by measuring the permittivity change in the individual RF cavity of the monitor. The change is measured by observing the modulation of RF signal, e.g. the time domain resonant frequency and quality factor changes in the RF cavity.

Beam-induced plasmas in a high-pressure gas-filled high-gradient RF cavity were studied in experiments at the Mucool Test Area (MTA) for muon ionization cooling applications [2, 3]. The multi-RF-cavity beam profile monitor has been evaluated in analytical and numerical simulations by using the experimental result [4]. However, the observed plasma parameters at MTA were taken at quite high RF gradients and gas pressures, i.e. the design RF gradient and gas pressure are 20 MV/m and 160 atm at room temperature, respectively, and a gaseous hydrogen is considered as an ionization material. The RF frequency in the muon ionization cooling channel is 0.2-1 GHz. On the other hand, a present interesting plasma parameter in the RF gas monitor occurs at lower RF gradient and gas pressure than the muon application, i.e. the designed RF gradient and gas pressure are 0.1 MV/m and 10 atm, respectively, and a gaseous nitrogen is considered as an ionization material. The RF frequency for the beam profile monitor is 1-10 GHz. A new beam test is required to study the plasma parameter for the RF monitor.

Current design of the RF gas monitor is optimized for the LBNF application [5]. The primary proton beam power and energy at LBNF are 2.4 MW and 120 GeV, respectively. The beam pulse length is 10 μs, and the cycle time is 1.2 sec. The number of protons per beam pulse (cycle) is $1.5{\cdot}10^{14}$ protons per pulse. The target will be made of either a 1-meter-long or a 2-meter-long graphite, or using different material, like Be. There are three toroidal magnet horns near the target to focus one-sign of charge pions and other beta decaying particles. The RF gas monitor will be located 200 m downstream from the target. Figure 1 shows the simulated fraction of secondary protons incident into a 3×3 cm^2 bin, which is the size of single RF cavity in the monitor, per POT (protons on target) at 200 m downstream of a 1-m-long and 2-m-long graphite targets in G4Beamline [6]. It shows that the RF gas monitor should respond to the maximum beam intensity per unit area, that is $5{\cdot}10^{10}$ ppp/cm^2, without losing a linearity. Ionized plasma due to other charged particles, like pions, kaons, and muons, etc, is two orders of magnitudes lower density than protons. Hence, it is omitted in this analysis.

KEY PARAMETER TO DESIGN RF GAS MONITOR

The essential plasma dynamics in a gas-filled RF cavity is presented in references [2–4]. The critical plasma parame-

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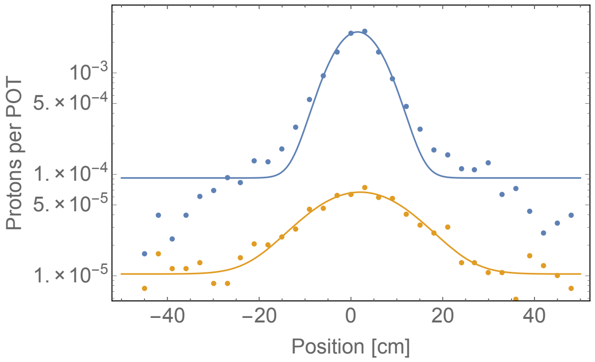

Figure 1: Simulated protons per POT at the beam profile monitor location. A blue and orange curves are the simulated beam profile with a 1-meter-long and 2-meter-long graphite targets, respectively. Each bin size is 3×3 cm^2.

ters to design the RF monitor are presented in the document. We start from considering the time domain electron and ion populations in the gas-filled RF cavity. The simplified rate equation is given,

$$\frac{dn_e}{dt} = \dot{n} - \beta n_e n_+ - \frac{n_e}{\tau}, \quad (1)$$

$$\frac{dn_+}{dt} = \dot{n} - \beta n_e n_+ - \eta n_+ n_-, \quad (2)$$

$$\frac{dn_-}{dt} = \frac{n_e}{\tau} - \eta n_+ n_-, \quad (3)$$

where $\dot{n}$ is the production rate of ion pairs by incident high-energy charged particles, β is the electron-ion recombination rate, τ is the electron capture time, η is the ion-ion recombination rate, and n_e, n_+, and n_- are the population of electrons, positive ions, and negative ions in the cavity, respectively. Any dissociative processes and secondary chemical reactions are omitted because their probabilities are negligible.

Ion Pair Production

The number of ion pairs production rate per unit length is calculated by

$$\dot{n} = h\frac{dE/dx}{W_i}\rho \dot{N}_b, \quad (4)$$

where dE/dx is the average energy loss rate, W_i is the ion pair production energy, and ρ is the density of gas, h and $\dot{N}_b$ are the average path length and the instantaneous number of incident particles, respectively. Table 1 shows the summary of the estimated average number of ion pairs per single incident particle ($\dot{N}_b$=1). Eq. (4) is essential to establish the concept of RF gas monitor. The validity of eq. (4) has been tested in experiment.

Plasma Loading in Pure Gas

Beam induced electrons and ions gain their kinetic energies from RF fields and convert the gained energy into thermal energy of gas via the Coulomb scattering. Phenomenologically, the RF quality factor is reduced due to such a RF power consumption. The new RF power consumption is called the plasma loading.

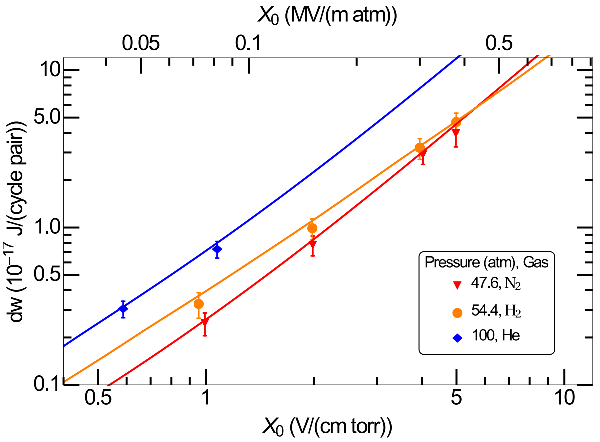

Figure 2: Observed plasma loading in various pure gases as a function of $X = E/p$, where E is the peak RF gradient and p is the gas pressure. A solid line is the prediction based on the Drude model in AC fields [2, 3].

The observed plasma loading in various pure gases is shown in Figure 2. A solid line is the prediction, which is given in eq. (6) in reference [2]. It is noted that the electron capture time τ is infinite in a pure gas condition. It suggests that the plasma population n_e and n_+ (indeed, $n_e = n_+$ and $n_- = 0$) can be evaluated by measuring the plasma loading. However, the plasma chemistry becomes crucial to precisely estimate the population.

Plasma Chemistry

Electron-ion recombination: The effective electron-ion recombination rate β has been measured in the same set of gases as measured the plasma loading, which is shown in Figure 3. It is noted that the electron recombination time with positive ions is determined by the positive ion density. Since β is ~10^{-7} cm^3/s the time constant of the recombination becomes the order of 1-10 μs when the density reaches 10^{12-13} ions/cm^3, that is the expected range in the RF gas monitor at the LBNF application. The time constant is comparable with the pulse length of the LBNF beam. Thus the recombination process makes a big uncertainty to estimate the number of ion pairs in the cavity for MW-beam applications. In addition, the RF power consumption by ionized

Table 1: Estimated $\dot{n}$ in Various Gases with $\dot{N}_b$ =1

Gas	dE/dx at 100 GeV/c	ρ at STP	W_i	$\dot{n}$
	MeV· cm^2/g	mg/cm^3	eV	ions/cm
H$_2$	6.47	0.084	36.2	15
He	3.30	0.166	46.3	12
N$_2$	3.24	1.17	34.3	111
Dry air	3.24	1.21	31.7	124

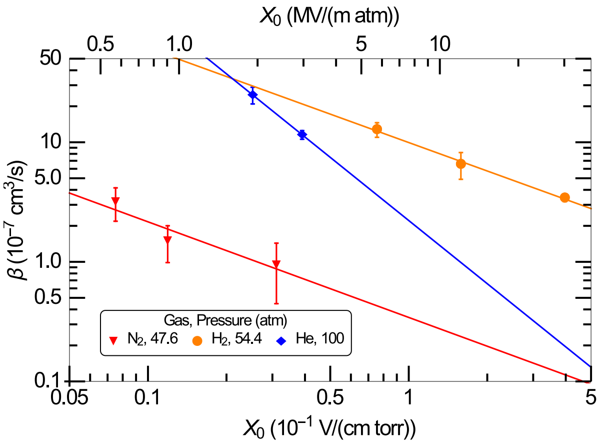

Figure 3: Observed electron-ion recombination rate in various gases as a function of $X = E/p$. A solid line is a fitting of data.

electrons is often too large to save a residual RF energy stored in the cavity.

Electron capture by electronegative: Any uncertainties caused by ionized electrons will be mitigated by doping an electronegative in the cavity. Shorter τ makes more accurate beam profile measurement by counting the number of ion-ion pairs in the cavity. O_2 is a good dopant since it is relatively stable in radiation environments by comparing other electronegative, like F and SF_6. O_2 captures electrons via the three body reaction, whose rate is k_O ~10^{-30} cm^6/s for thermal electrons [7]. τ in a few atm dry air can be $[10^{-30} \cdot (3\ 10^{19})^2]^{-1}$ ~10^{-9} s. Doping CO_2 in dry air will speed up the electron capture process. Dry air and SF_6 dopants were tested in various base gases [2, 3]. The observed τ was shorter than 1 ns. Unfortunately, the measurement reached to the limit of time resolution in the 800 MHz RF system. It is hard to measure τ in sub-nano seconds. Figure 4 shows the observed plasma loading in the dry air doped RF test cell. A dashed line presents the prediction under assumption that only n_+ and n_- take into account the plasma loading. The measured plasma loading for H_2 and N_2 is lower than the prediction while He + 1 % dry air shows opposite. It is agree with the prediction: τ for H_2 and N_2 should be shorter than a half RF cycle so that the plasma loading in H_2 and N_2 are dominated by heavy ions while τ in He is longer than the RF cycle so that the dw in He is the mixing of ionized electrons and heavy ions. This suggests that the plasma loading measurement indirectly presents τ with respect to the RF cycle. Measuring the plasma loading in higher frequency RF cavity should be done in experiment.

Ion-ion recombination: The ion-ion recombination rate η is the last piece of the plasma chemistry. η seems to be ~10^{-8} cm^3/s that is one order of magnitude smaller than the electron-ion recombination. The time constant is 10-100 μs when the ion density reaches 10^{12-13} ions/cm^3. Thus, the ion-ion recombination will be no issue in the RF gas monitor. This should be confirmed in experiment.

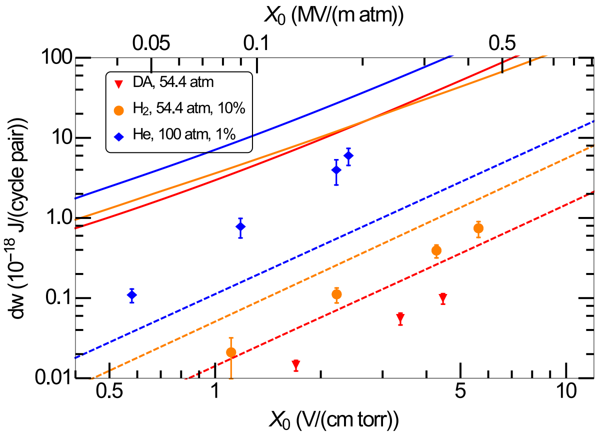

Figure 4: Observed plasma loading in a dry air doped RF cavity. A dashed line is the prediction under assumption that all ionized electrons are capture within a half RF cycle while a solid one is the dw with ionized electrons.

Table 2: Characteristics of Beam in each Facility

	M01	SY dump
Proton energy	120 GeV	120 GeV
Pulse length	4 sec	11 μsec
Int. beam intensity	10^{13}	$4{\cdot}10^{12}$

POSSIBLE TEST FACILITY

There are two possible beam facilities to test the RF gas monitor at Fermilab. Characteristics of beam for each facility is shown in Table 2. M01 is located upstream of the FTBF (Fermilab Test Beam Facility). The beam is extracted by the slow extraction method so that the beam pulse length is quite long and the stability of beam intensity in each bunch is poor. However, this facility has a great advantage because of good accessibility into the beam enclosure and a space available for infrastructures. So that, the facility will be mainly used to pretest the RF gas monitor. The capability of RF gas monitor for low beam intensity application will be demonstrated in this facility.

On the other hand, SY dump is located downstream of the switchyard. Since the beam is extracted by a fast kicker the time structure of beam is similar as the NuMI and LBNF applications. Indeed, the beam density can exceed the beam density at the LBNF application. Therefore, the facility is ideal to study the plasma loading and the plasma chemistry. Accessibility to the facility is poor when the beam for other experiments is turned on. The beam time should be shared with other experimental group.

REFERENCES

[1] R. Zwaska and J. Hylen, private communication.

[2] M. Chung *et al.*, “Pressurized H2 rf Cavities in Ionizing Beams and Magnetic Fields”, *Phy. Rev. Lett.*, vol 111, p. 184802, 2013.

[3] B. Freemire *et al.*, “Pressurized rf Cavities in Ionizing Beams”, *Phy. Rev. Acc. Beams*, vol. 19, p. 062004, 2016.

[4] K. Yonehara *et al.*, “Gas Filled RF Resonator Hadron Beam Monitor for Intense Neutrino Beam Experiments”, in *Proc. IPAC16*, 2016, p. 2733.

[5] "The Long-Baseline Neutrino Facility for DUNE", *CDR* vol. 3, `https://web.fnal.gov/project/LBNF/ReviewsAndAssessments/LBNF_DUNE%20DOE%20CD-1%20Refresh%20Review/SitePages/Conceptual%20Design%20Report.aspx`

[6] G4Beamline, `http://www.muonsinternal.com/muons3/G4beamline`

[7] I.A. Kossyi *et al.*, “Kinetic scheme of the non-equilibrium discharge in nitrogen-oxygen mixtures”, *Plasma Source. Sci. Tech.*, vol. 1, p. 207, 1992.