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NEW HADRON MONITOR BY USING A GAS-FILLED RF RESONATOR *

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Abstract

A novel pressurized gas-filled RF-resonator beam monitor is proposed that will be simple and robust in high-radiation environments for intense neutrino beam facilities and neutron spallation sources. Charged particles passing through the resonator produce ionized plasma, which changes permittivity of the gas. Radiation sensitivity is adjustable using gas pressure and RF amplitude. The beam profile will be reconstructed by X, Y, and U hodoscopes using strip-shaped gas resonators.

INTRODUCTION

The Long Baseline Neutrino Facility (LBNF) is the flagship experiment at Fermilab. Hadron monitors play an important role to measure quality of the secondary charged particles and to precisely direct the beam to the neutrino detector located hundreds of kilometers away. An ionization chamber is a standard device to use as the hadron monitor in the NuMI beam line at Fermilab. Operational failure of the hadron monitor due to high radiation is the present issue. A custom hardline cable is used to bring the electrical connections across the body of the hadron monitor to each of its feedthroughs. Since these cables lie in the beam they are subject to radiation damage and possible signal pickup. To guard against both, the cables are designed with both polyimide and ceramic insulators around the conductor and enclosed in aluminum tubing [1]. These materials significantly improved the lifetime. However, the conventional hadron monitor still has a limited lifetime and the cabling structure is complicated. Especially, future hadron monitors must operate in even higher radiation environments. The LBNF beam line design beam power for the primary protons is > 2 MW, which is three times higher than the NuMI facility. There is no particle detector device currently working in such an extremely high radiation environment.

A gas-filled RF-resonator hadron monitor will be simple and radiation-robust in this environment. The gas-filled RF resonator has been originally developed for muon beam ionization cooling channels [2]. A conceptual drawing is shown in fig. 1. When the charged beam passes throughout the gas-filled resonator it produces a large amount of electron-ion pairs by interacting with gas. The permittivity in the resonator is changed proportional to the number of incident charged particles. The beam profile will be reconstructed by X, Y, and U hodoscopes using strip-shaped gas resonators.

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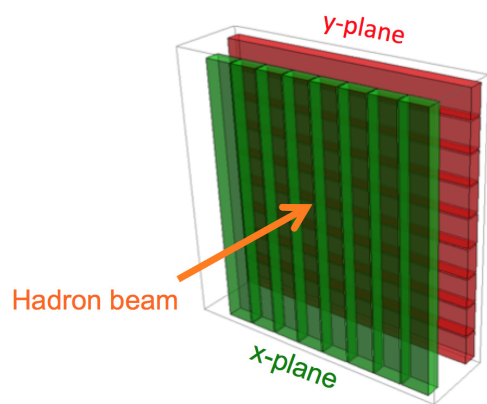

Figure 1: Schematic of the gas-filled RF hadron monitor.

PERMITTIVITY IN GAS-FILLED RF RESONATOR WITH PLASMA

The characteristic of permittivity is determined by electrons rather than ions since the ion mass is three orders of magnitude heavier than electron mass. We start our discussion from the equation of motion for a single electron in an RF field in gas,

$$m\ddot{\vec{r}} = -e\vec{E}e^{-i\omega_{RF}t} - m\nu\dot{\vec{r}}, \tag{1}$$

where ν is the collision frequency of the electron with gas molecules. The first term is acceleration of the electron by the external RF field while the second one is the frictional force caused by interactions with the gas. The electron motion is expected to be $r = r_0 e^{-i\omega t}$ where the position vector is assumed to be parallel to the electric field ($\vec{r} \| \vec{E}$). Putting this into eq. (1) results in

$$r_0 = -\frac{eE_0 e^{-i(\omega_{RF}-\omega)t}}{m(\omega^2+\nu^2)}\left(1 + i\frac{\nu}{\omega}\right). \tag{2}$$

The polarization of the gas plasma is given as

$$P = \frac{n_e e^2 E_0 e^{-i(\omega_{RF}-\omega)t}}{m(\omega^2+\nu^2)}\left(1 + i\frac{\nu}{\omega}\right) \equiv \varepsilon_0 \chi_e E(t), \tag{3}$$

where n_e is the total number of electrons in the resonator and χ_e is the susceptibility of the gas plasma. Assuming that ionization electrons are oscillating in phase with the RF electric field, i.e. $\omega = \omega_{RF}$, eq. (3) can be simplified, and the relative permittivity of gas plasma is derived as

$$\frac{\varepsilon}{\varepsilon_0} = 1 + \chi_e \simeq 1 + \frac{n_e e^2}{\varepsilon_0 m(\omega^2+\nu^2)}\left(1 + i\frac{\nu}{\omega_{RF}}\right). \tag{4}$$

This assumption is valid if the gas pressure is sufficient to cool electrons down to an equilibrium condition within one

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RF cycle. Eq. (4) is separated into the real and imaginary parts,

$$\hat{\varepsilon}' = 1 + \frac{n_e e^2}{\varepsilon_0 m(\omega^2 + \nu^2)}, \tag{5}$$

$$\hat{\varepsilon}'' = \frac{n_e e^2}{\varepsilon_0 m(\omega^2 + \nu^2)} \frac{\nu}{\omega_{RF}}. \tag{6}$$

The real part $\hat{\varepsilon}'$ represents the inductance of the plasma; it contributes the resonant frequency shift. On the other hand, the imaginary part $\hat{\varepsilon}''$ is the resistance of plasma; it gives the amount of RF power dissipation in the plasma.

The collision frequency ν is derived by the RF gradient, $E(t)$ and the gas pressure, P_{gas} via the electron temperature, T_e. The collision frequency must be larger than the RF driving frequency ($\nu > \omega_{RF} = 2\pi\nu_{RF}$) for the electrons to achieve to an equilibrium condition within one RF cycle. Especially, in case of $\nu >> \omega_{RF}$, the gas plasma becomes a lossy material, i.e. a significant amount of RF power is dissipated in the plasma via momentum transfer collisions between electrons and gas molecules. The lossy plasma model has been validated in experiments at Fermilab [3].

The electron collision frequency has been measured for various materials. We are particularly interested in using nitrogen gas, whose collision frequency is given as a function of electron temperature [4],

$$\nu = 2.33 \times 10^{-11} n_{N_2} [1 - 1.21 \times 10^{-4} T_e] T_e. \tag{7}$$

Now we need to find the electron temperature in the gas. Note that the electron temperature can be different from the gas temperature because free electrons gain energy from the external RF electric field. The electron velocity distribution should be Maxwellian in an equilibrium condition. In this case, the Einstein relation can be applied to determine the electron temperature, i.e. $D/\mu = kT_e$. D/μ has been measured as a function of E/P_{gas} for nitrogen gas [5]. We assume that the lowest limit of electron temperature should be equal to the gas temperature, e.g. 300 K. In this case, D/μ is 0.03 eV and it should be constant at E/P_{gas} to be less than 0.01 V/cm/Torr from ref. [5].

The number of ionization electrons, n_e is proportional to the gas pressure and the intensity of the incident beam. The formula is given by

$$n_e = N_b \times h \sum_k w_k \left(\rho_m \frac{dE/dx}{W_i} \right)_k, \tag{8}$$

where N_b is the number of incident charged particles, h is the path length of particles in the resonator, and w_k, ρ_m, dE/dx, and W_i inside the parentheses are the statistical weight, density, average energy loss, and required ion pair production energy of material k, respectively. The ionization process takes place in the gas-filled RF resonator when a fast charged particle passes throughout the gas-filled resonator, $p^\pm + M \rightarrow p^\pm + M^{*/+} + e^-$, where $p^\pm$ is an incident charged particle, M is the gas molecule, and $M^{*/+}$ represents that M is excited and/or positively ionized. The ionization loss rate, dE/dx can be calculated by using the Bethe-Bloch formula. W_i can be found in past measurements, which is 33.6 eV for nitrogen gas [6]. Note that it is a measured quantity and is higher than the ionization energy of molecules since W_i includes all final states via the various interaction processes.

PROTON FLUX MEASUREMENT

Two different E_0/P_{gas} are considered to measure the permittivity shift by the beam-induced plasma in the resonator.

$\nu > \omega_{RF}$ *(Low RF Power Mode)*

In order to achieve this condition, the resonator is turned on with a low electric field and filled with low pressure gas, but the electron collision frequency needs to be larger than the RF frequency. To this end, we use a 0.1 atm N_2 gas. The electron temperature is constant, 0.03 eV with $E(t)/P_{gas} <$ 0.01 V/cm/Torr. The electron collision frequency becomes constant, 1.64 10^{10} Hz from eq. (7). Therefore, there is no spatial correlation between plasma and RF field. The number of electrons produced by single proton is n_e=1.83$\cdot 10^6 \times$ 1.17$\cdot 10^{-4}$/33.6 N_b = 6.3 N_b electrons/cm from eq. (8). The resonant frequency is shifted by changing the real part of permittivity, i.e. $f \propto \varepsilon^{-1/2} \rightarrow \delta f/f = -1/2\delta\varepsilon/\varepsilon$. The quantity of imaginary permittivity is very small in this condition. Fig. 2 shows the estimated frequency shift in the one-layer hodoscope with the LBNF beam. The hodoscope consists of 10 strip gas-filled RF resonators where its width, i.e. the position resolution is 10 cm. Driving RF frequency, f is 1.5 GHz. The hadron flux is simulated in MARS [7]. For simplicity, we use only protons to estimate N_e whose momentum is at the minimum ionization.

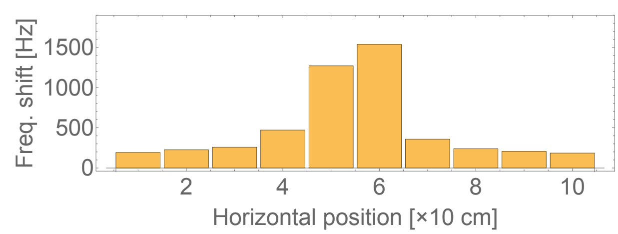

Figure 2: Estimated frequency shift in the one-layer hodoscope. The calculation has been made based on the LBNF beam line with the primary proton beam flux 1.2×10^{14} p/pulse.

This mode is quite simple and should be cost effective. The estimated frequency shift by plasma by using the LBNF beam seems to be sufficient to measure with the current RF technology. Note that the estimated value is under the conservative assumption. Secondary protons from the production target have a very wide energy spectrum and generates more electrons in the resonator via the ionization process. Other secondary particles, i.e. pion, muons, kaons, etc, which were omitted in this analysis should generate electrons. We should evaluate the background noise in this mode since the resonant frequency can also be shifted by the thermal expansion of the resonator. The instantaneous temperature

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increment due to energy deposition by the incident particles will be evaluated.

$\nu \gg \omega_{RF}$ *(High RF Power Mode)*

Eq. (1) is valid only when the friction force is proportional to the electron velocity, which occurs at low gas pressure and low RF gradient. In case of $\nu \gg \omega_{RF}$, the momentum transfer cross section becomes more complicated. The cross section is perturbed by the molecular force from adjacent molecules (pressure effect). To avoid such complicated microscopic effects, we introduce a macroscopic plasma parameter, that is the electron drift velocity. The RF power dissipation by a single electron (dw) is given in the formula,

$$dw = \int\int q\bar{v}E(r,t)drdt, \qquad (9)$$

where $\bar{v}$ is the drift velocity of electrons. Eq.(9) can be represented with the different formula with $\hat{\varepsilon}''$, $dw = 1/2n_e\varepsilon_0 \int\int \hat{\varepsilon}''(r,t)E(r,t)^2 drdt$. Fig.3 shows the observed dw in N_2 gas at Fermilab. A blue solid line is the prediction from eq.(9).

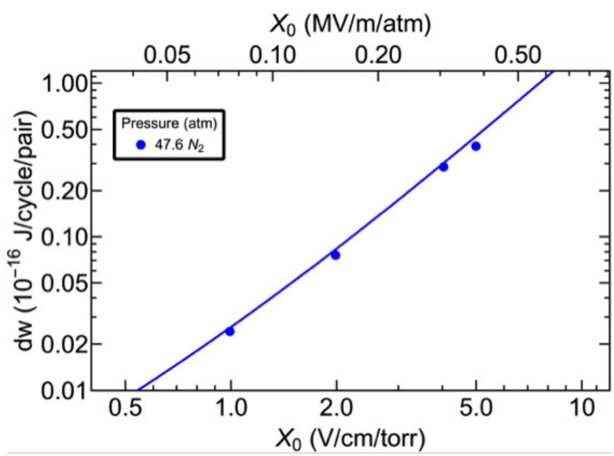

Figure 3: Observed dw in N_2 gas at various E. $X_0 = E_0/P_{gas}$.

To achieve the condition, for example, the applied peak RF gradient is 1 MV/m in 10 atm N_2 gas. The ratio of the peak electric field and the gas pressure, E_0/P_{gas} is 1.3 V/cm/Torr. Note that the estimation of dw is strongly dependent on the spatial correlation between plasma and RF fields. Evaluation of the RF power dissipation in the resonator with the LBNF beam will be done in the next step once the resonator geometry is fixed.

This method can be more practical and reliable than the first one since the RF power dissipation due to the beam-induced plasma has been measured at Fermilab. The sensitivity range of the beam intensity is very wide. Indeed, we demonstrated that the resonator has a good sensitivity with 10^8 to 10^{12} protons/bunch. Ionized electrons and ions are eventually recombined to the neutral state. Time constant of the recombination is typically order of μsec. Since population in plasma is predictable by solving the rate equation the beam profile can be reconstructed not only spatial distribution but also the time dependent.

One possible concern in this mode is the cost of a RF power source. The required peak RF power can be very small by comparing with the conventional RF accelerating cavity. Besides, the driving RF frequency is relatively high so that the high power RF source is available. We expect that the cost will be up to five times more than the conventional ionization chamber. The great benefit is that the gas-filled RF resonator will be a maintenance free device. Even we do not need to calibrate the system since all plasma processes are known including with the time constant of the plasma. The lifetime of the resonator will be much longer than the lifetime of an ionization chamber.

CONCLUSION

A new hadron monitor based on the gas-filled RF resonator has been proposed for future extremely intense beam facilities, like neutrino beam facilities and neutron spallation sources. The characteristic of the resonator has been analytically evaluated in two different modes. Ideally, the resonator has a function to operate both modes to cover very wide dynamic range and cross check the measurement. We move on the engineering concept as the next step.

REFERENCES

[1] R.M. Zwaska et al., "Operation of the NuMI Beam Monitor System", Fermilab-Conf-06-090-AD.

[2] "Pressurized RF Cavities for Muon Ionization Cooling", http://www.osti.gov/scitech/servlets/purl/886710.

[3] M. Chung et al., “Pressurized H2 rf Cavities in Ionizing Beams and Magnetic Fields”, PRL 111, 184802, (2013).

[4] Peter Banks, "Collision Frequencies and Energy Transfer Electrons", Planet. Space Sci., 1966, Vol.14, p. 1085.

[5] A. Peisert, "Drift and diffusion of electrons in gases", CERN 84-08, 1984.

[6] "Stopping power and Energy loss for Ion Pair Production for 340-MeV Protons", Phys. Rev. 81, 489, 1951.

[7] www-ap.fnal.gov/MARS/.