GAS FILLED RF RESONATOR HADRON BEAM MONITOR FOR INTENSE NEUTRINO BEAM EXPERIMENTS*

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Abstract

A novel pressurized gas-filled multi-RF-cavity beam profile monitor has been studied 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. Standard RF techniques to measure the change in quality factor and frequency as a function of time are then used to determine the change in permittivity and corresponding beam intensity in each cavity in the profile monitor. The sensitivity to beam intensity is adjustable using gas pressure and RF gradient. The performance of the gas-filled beam profile monitor has been numerically simulated to evaluate the sensitivity of permittivity measurements.

INTRODUCTION

The Long Baseline Neutrino Facility (LBNF) is the flagship experiment at Fermilab. Beam profile 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. One of the challenges to realize a multi-MW beam complex is monitoring of the beam profile under extreme radiation environments. We propose a radiation-tolerant gas-filled RF cavity beam profile monitor that provides precise measurements of the beam downstream of the hadron production target for high beam intensities. The RF monitor is based on microwave cavity resonators that are simple metallic boxed filled with gas. Incident particles interact with the gas to form plasma via the ionization process. The permittivity shift is measured using a modulated RF signal. The beam profile is reconstructed from the signals from the individual RF cavities of the monitor.

Beam-induced plasmas in a high-pressure gas-filled high-gradient RF cavity were studied in experiments at the Mucool Test Area (MTA) in 2012 for muon cooling applications [1]. The proposed multi-RF-cavity beam profile monitor has been evaluated in analytical and numerical simulations based on these experimental studies. The results show that the RF monitor has a wide dynamic range of primary proton beam intensities, from 10^6 to 10^{13} protons/bunch. The range covers the expected beam intensities in NuMI (Neutrinos from the Main Injector) and LBNF.

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DESIGN HADRON MONITOR

Conceptual Design

An ionization chamber has been used for the NuMI beam line as a beam profile monitor. Because the 2.4 MW LBNF beam power is three times higher than that for NuMI, several major issues have to be addressed before the present hadron beam monitor will server LBNF. First, the ionization signal strength will not be proportional to beam intensity due to space charge of collecting electrons [2]. This non-linearity is seen even at the NuMI beam power. Second, radiation damage to the feedthrough is substantial, and the lifetime of the HV insulator becomes short. Third, contamination is an issue. Materials such as stainless steel used at the feedthrough become highly radioactive.

A schematic of the multi-RF-cavity beam profile monitor is shown in Fig. 1. Each monitor element consists of a metallic RF cavity and waveguide. The forward RF wave (incident RF wave into the resonator) and the reflected RF wave from the resonator are picked up with a directional coupler to measure the transmission RF wave in the resonator. An RF capacitive or inductive pick-up inside each cavity feeds a coaxial cable is optionally added to calibrate the signal from the directional coupler. These signals are fed into a signal analyzer located behind a radiation shield wall. Aluminum can be used to make the cavity wall and the coaxial cable since it is robust for radiation. Nitrogen or helium gas will be used for an ionization gas. As was learned in the MTA experiments in 2012, a small amount of electronegative gas will be added as a dopant in the gas to control the plasma dynamics. The RF monitor is so simple that it promises to be radiation robust in comparison with ionization chambers.

N_2 and He are considered as an ionization material. Varying the gas pressure is the primary tuning knob to control the plasma dynamics. The pressurized gas quickly thermalizes ionization electrons. The design pressure is 1 atm to simplify the present analysis. Gas is sent to the resonator through the waveguide.

The designed RF cavity width is 30 mm with 12 cavities to define the horizontal profile and 12 for the vertical profile. The structure is identical to make 12 × 12 RF pixels. The position resolution of the beam center is then better than 2 mm, which allows the angle of the primary proton beam to be corrected to within 10 μrad if the target center is the pivot point. This is the design goal of the hadron monitor. The resonator size determines the resonant frequency, i.e. it is 5 GHz. Since the plasma permittivity is given by the

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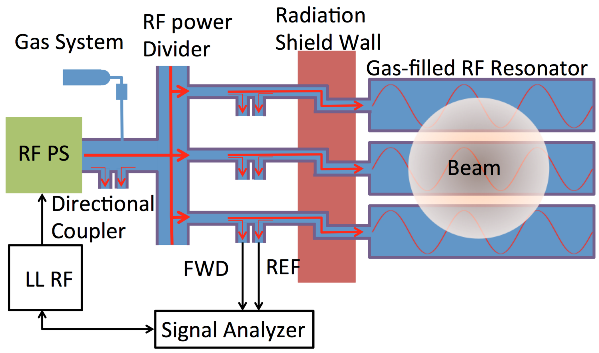

Figure 1: Schematic diagram of the profile monitor made with RF cavities. All parts inside the radiation enclosure can be made of radiation resistant materials such as aluminum for the cavity and waveguide and alumina to hold the central conductor of the coaxial line.

abundance of plasma particles in the neutral gas the gap in the beam direction is a free parameter. It is 1 cm in the present analysis. Varying the RF gradient is another tuning knob to control the plasma dynamics. The range of possible RF gradient is 0.001 to 1 MV/m. The maximum gradient in the gas-filled resonator is limited by the electric breakdown of the gas. The designed RF gradient in this calculation is 0.1 MV/m. The required peak RF power is 1 W for each RF pixel.

Plasma Dynamics in Gas-Filled RF Resonators

The present plasma dynamic model is based on the Drude model. It is valid when ionization electrons are thermalized by momentum transfer collisions with gas within one RF cycle. This condition is satisfied in the present cavity design. The plasma permittivity is given [3],

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

where m, ν, n_e, and ω_{RF} are electron mass, the collision frequency with gas, the total number of electrons in the resonator, and the driving frequency of the RF, respectively. Eq. (1) consists of the real and imaginary components, which are proportional to the number of ionization electrons. The real component changes the resonant frequency as $f \propto (\varepsilon)^{-1/2}$. The following relation is derived,

$$\frac{df}{f} = -\frac{1}{2}\frac{d\varepsilon}{\varepsilon}. \tag{2}$$

The simulation result shows that the frequency shift is order of 10 kHz when the entire LBNF beam passes through the RF monitor.

The imaginary component gives the resistivity of the plasma motion, corresponding to electrons oscillating in the RF field in a resistive medium. Consequently, the electron kinetic energy transfers into the ohmic energy like $I^2R/2$. The imaginary component is measurable as the energy consumption rate in the resonator. The energy consumption rate by the plasma, ΔP is inserted into the equivalent LC circuit equation,

$$\Delta P = \frac{V(t)\left[V_0 - V(t)\right]}{R} - CV(t)\frac{dV(t)}{dt}, \tag{3}$$

where C and R are the capacitance and the shunt impedance of the resonator. $V(t)$ is the time domain electric potential in the resonator, and $V_0 = V(0)$. Once ΔP is obtained from a measurement, the number of ion pairs in the resonator can be obtained,

$$n = \frac{1}{g_c}\frac{\Delta P}{dw f_{RF}}, \tag{4}$$

where $f_{RF} = \omega_{RF}/2\pi$ and g_c is the geometry calibration factor, that calibrates the electric field distribution in the resonator [4]. The time differential of eq. (4) is proportional to the energy consumption rate,

$$\frac{dn}{dt} \simeq n f_{RF} = \frac{1}{g_c}\frac{\Delta P}{dw}. \tag{5}$$

dw is the RF energy consumption by a single ion pair per one RF cycle which has been measured in the experiment. It is represented by the following formulae,

$$dw(X)_{N_2} = 2.10 \cdot 10^{-16} X^{1.71}, \tag{6}$$

$$dw(X)_{He} = 2.71 \cdot 10^{-16} X^{1.44}, \tag{7}$$

where X is a ratio of the RF gradient and the gas pressure, $X = E/P$.

Eq. (5) is substituted into the plasma population equation to extract the gross ion production rate in the resonator $\dot{n}$ by the incident particles,

$$\dot{n} = \frac{dn}{dt} + \beta n^2 + \gamma n, \tag{8}$$

where β is the recombination rate and γ is other ion pair loss rate due to diffusion and absorption at the conductor wall. The electron capture is a critical time domain plasma process when an electronegative gas is doped. This quantity is represented as a time constant τ. β and τ have been measured in the experiment [5]. γ is $\sim 10^{-3}$ sec in the experiment, therefore it is neglected in the present analysis.

Electrons dominantly contribute to the RF energy consumption because of their light mass. A small amount of electronegative dopant in the ionization gas causes electrons to be immediately captured by the electronegative atoms or molecules. Consequently, each captured electron effectively gains the mass of the electronegative atom or molecule, and its mobility becomes significantly lower. The mobility of heavy ions are typically 50 times lower than that of electrons. The blue points in Figure 2 show the calculated evolution of ionization electrons in the pure N_2 gas filled resonator with the LBNF beam as a function of time by solving eq. (8). Since the primary beam is a bunched structure, the number of electrons grows as a step function. A red line is when the recombination is turned off ($\beta = 0$). These indicate that the recombination process is too small to remove electrons in the resonator. In case of dopant, a new tern, τn is added in the right-hand size of eq. (8) and the recombination term is modified $\beta n^2 \rightarrow \beta n n_i$ where n_i is the number of positive ions. $\tau = 10^{-9}$ s is used in this calculation. Orange points in Figure 2 show that the number of electrons is decayed exponentially in the bunch gap and there is no electron accumulation.

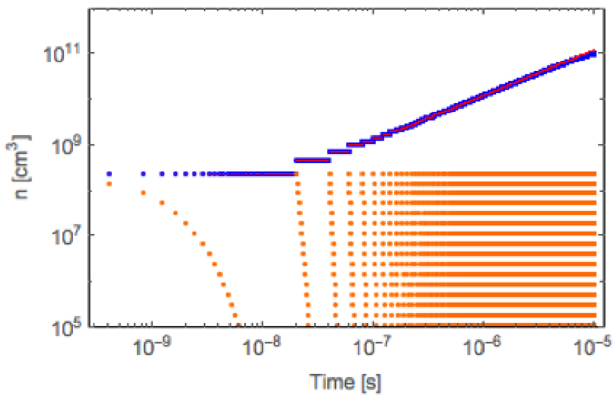

Figure 2: Electron accumulation in various gas filled resonators. Blue, red, and orange points correspond to pure N_2, pure N_2 without recombination, and Oxygen doped resonator, respectively.

Figure 3 shows the estimated RF energy consumption in a pure N_2 and a doped resonators as a function of time. The stored RF energy disappears with several beam bunches in a pure N_2 resonator while the energy still remains even the whole bunch train traverse through the dopant resonator. This indicates possible time domain measurement in the doped resonator.

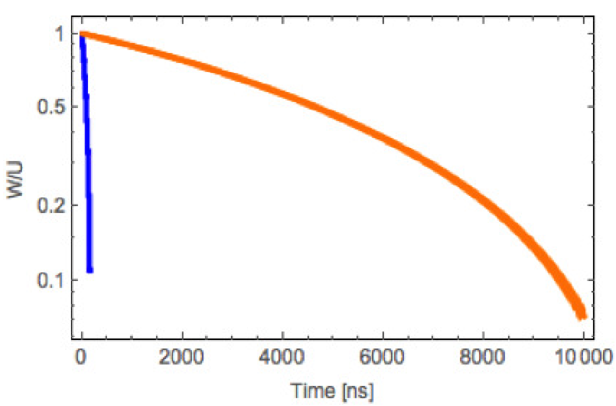

Figure 3: Time domain residual RF energy in a pure N_2 (blue) and an Oxygen doped (orange) resonator.

Evaluate Gas-Filled RF Resonator for LBNF beam in G4Beamline Simulation

G4Beamline [6] was used as the event generator in the present simulation study. The plasma distribution is constructed from the recorded charged particles in the simulation [1, 4]. The horn lens was eliminated in this analysis because the kinematics of high-energy protons, which is the major particle to detect in the RF monitor, is not significantly affected by the horn. The pure N_2 gas filled RF monitor is evaluated by measuring the instantaneous RF energy consumption that is induced by the first bunched beam. Figure 4 shows the expected RF energy consumption in the RF monitor. The orange line is a fit. A position sensitivity test in the RF monitor has been made and found that the absolute error is within 0.5 mm. This is better than the design value.

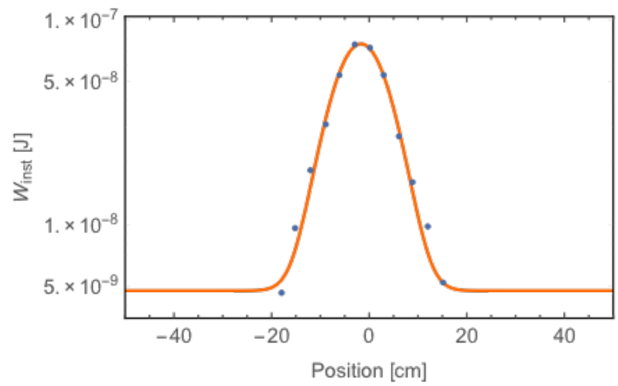

Figure 4: RF energy consumption in the pure N_2 gas filled RF monitor. The plot is made by the 12×12 RF cavity profile monitor to demonstrate the second normal distribution. The RMS size is 7.5 cm.

CONCLUSION

A novel gas-filled RF resonator is evaluated in numerical simulations. The result indicates that the RF resonator will be useful to measure the beam profile with a charged beam intensity range from 10^6 to 10^{13} particles, which covers NuMI and LBNF beam intensity. The parts of system including with RF resonators, RF waveguides, RF power sources, and a data acquisition system have been designed. The demonstration experiment is proposed as the next step. The time line is matched to the LBNF project.

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