R&D OF A GAS-FILLED RF BEAM PROFILE MONITOR FOR INTENSE NEUTRINO BEAM EXPERIMENTS*

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Abstract

We report the R&D of a novel radiation-robust hadron beam profile monitor based on a gas-filled RF cavity for intense neutrino beam experiments. A time-domain RF power equation was simulated with an intense beam source to optimize the sensitivity of monitor. As a result, the maximum acceptable beam intensity is significantly increased by using a low-quality factor RF cavity. The demonstration test is planned to prepare for future neutrino beam experiments.

INTRODUCTION

Intense neutrino beam is a unique probe to research physics beyond the standard model. Fermilab is the center institution to create the most powerful and wide-spectrum neutrino beam. Fermilab recently achieved consistent 700 kW proton beam delivery by using the Main Injector ring (NuMI) [1], but will need to almost triple this power to achieve the goals of future neutrino experiments. Two major R&D activities have been going on to realize a multi-MW power proton driver [2] and target [3]. On the other hand, the radiation robust beam diagnostic system is critical to maintain the quality of neutrino beam required for future physics experiments. To this end, a novel beam profile monitor based on a gas-filled RF cavity is proposed.

Gas in the cavity serves an ionization media by interacting with incident charged particles. The amount of beam-induced plasma is proportional to the number of incident particles. The plasma consumes a RF power, so called plasma loading [4,5]. It is interpreted as an imaginary part of the permittivity in the cavity [6] or a plasma resistance which is an ohmic RF power dissipation in plasma [7]. The beam profile is reconstructed by observing the amount of plasma loading from an individual cell of a multi-RF cavity assembly which forms a hodoscope structure.

The gas-filled RF monitor is potentially radiation robust and reliable by comparing to the present hadron monitor based on an ion chamber [8] for following reasons.

- A main component of the RF cavity is a simple metal chamber. A low power RF (~mW) and near atmospheric pressurized gas are applied in the cavity, hence, a simple RF window is used. On contrary, the structure of present ion chamber is complicated, especially an electric feedthrough, which limits lifetime of the detector.
- The RF signal can be remotely calibrated by measuring the quality (Q) factor of multi-RF cavity array when the beam is turned off. Impedance shifts due to radiation damage are involved in the calibration. Remote calibration is not possible for the present ion chamber.
- The quality of RF monitor signal is independent from the gas pressure and gas impurity while the ion chamber is very sensitive to the fraction of those parameters. It is one of the sources of measurement error.

The main goal of the R&D is validating the concept and developing the technology to apply the monitor for intense neutrino experiments.

BEAM LOADING RF MODEL

A complete model of plasma production and plasma loading mechanisms in a gas-filled RF cavity is given in ref. [4,5]. Here, simplified formulae are recalled from the model to demonstrate how to tune the beam sensitivity in the RF monitor. The plasma loading takes place when ionized particles (electrons and ions) in the cavity gain a kinetic energy from the RF field and lost the energy via the Coulomb interactions with the gas. Especially, electrons are a good energy transfer media because of their light mass. Therefore, controlling the number of electrons in the plasma is the key to tune the plasma loading.

The number of ion pairs, N_e produced by crossing incident charged particles in the cavity is given,

$$N_e = \overline{\frac{dE}{dx}} \frac{\rho N l_c}{W} P_g, \qquad (1)$$

where $\overline{\frac{dE}{dx}}$ is a mean energy loss, ρ is a gas density at the STP, N is the number of incident charged particles, l_c is a mean path length of incident charged particles, W is an ion pair production energy, and P_g is a gas pressure. On the other hand, the simplified plasma loading formula is,

$$P_{plasma} = eN_e \frac{\tilde{\mu} E^2}{P_g} \equiv \frac{V^2}{2R_g}, \qquad (2)$$

where e is a unit charge, $\tilde{\mu}$ is a net reduced mobility of an ion pair, and E is the RF gradient. V and R_g are a RF voltage and a plasma resistance in an equivalent circuit model,

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respectively. The reduced mobility in eq. (2) is a constant in a low E/P_g condition. Thus, eq. (2) suggests that P_{plasma} and R_g are independent from the gas pressure.

An equivalent circuit diagram including with a RF source is shown in Fig. 1. The time-domain RF power equation based on the equivalent circuit is given,

$$\frac{(V_0 - V)}{2R}V = \frac{V^2}{2R_g} + \frac{V^2}{2R_c} + CV\frac{dV}{dt}, \tag{3}$$

where V_0 is the initial RF voltage. The shunt impedance of the cavity, R_c is given by the observed Q factor, $R_c = QZ_0$, where Z_0 is an intrinsic impedance, $Z_0 = \sqrt{L/C}$; That is constant and determined by the geometry of cavity.

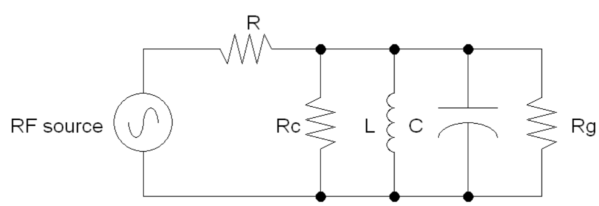

Figure 1: Equivalent RF circuit diagram.

Control Plasma Population by Electronegatives

$N_e\tilde{\mu}$ in eq. (2) is broken down to an electron and ion components,

$$N_e\tilde{\mu} = n_e\mu_e + n_+\mu_+ + n_-\mu_-, \tag{4}$$

where $n_e, n_+, n_-, \mu_e, \mu_+$, and μ_- are a population and reduced mobility of electron, positive ions, and negative ions, respectively. Contributions of multi-charge state ions to the plasma loading is negligible, which is found from past measurements. This permits us to set $n_+ \approx n_e + n_-$. By doping electronegative gas in the cavity, a great amount of electrons are captured by the dopant. n_e is a time-domain function as $\exp(-t/\tau)$ where τ is an electron capture time. Figure 2 shows the estimated electron capture time in a O_2 doped N_2. The RF power simulation suggests that the required τ for LBNF application is shorter than 10 ns while τ in an atmospheric dry air is ~ 6 ns. Because the electron capture is the three-body process τ reaches sub-ns in 3 atm dry air. Other electron attachment processes, e.g. a charge recombination or escape fast electrons from the cavity are negligible.

Figure 3 shows the simulated 2.45 GHz RF envelope by solving eq. (3). The beam parameters are taken from the LBNF application. A sawtooth RF envelope (blue line) is the timing of injected bunched beam into the cavity. Because electrons are quickly captured by the dopant the RF voltage is partially recovered in a ~20 ns bunch-gap.

An averaged RF envelope reaches equilibrium after 4~5 bunches due to balancing between the plasma loading and the feeding RF power. The equilibrium RF voltage is given from eq. (2),

$$\frac{V}{V_0} = \frac{\frac{R_g}{R}R_c}{R_g + \frac{R+R_g}{R}R_c}. \tag{5}$$

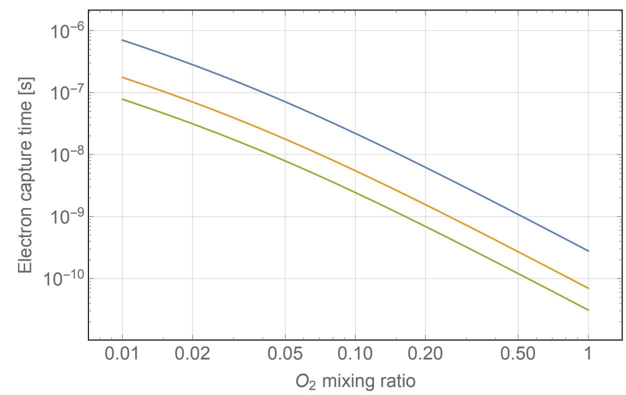

Figure 2: Electron capture time in O_2 doped N_2 gas (blue: P_g = 1 atm, orange: P_g = 2 atm, and green: P_g = 3 atm).

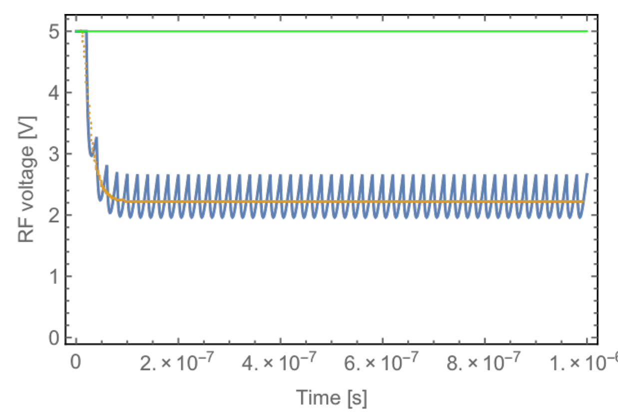

Figure 3: Blue line is a beam loaded RF envelope in atmospheric dry air filled RF cavity. The Q factor is 500. Green and orange correspond to the RF envelope with no-beam and a moving averaged of beam-loaded signal, respectively.

Because R and R_c are a constant the equilibrium voltage is the function of R_g which represents the intensity of incident charged particles in the cavity. Figure 4 shows the simulated equilibrium voltage as a function of R_g by solving eq. (5). A half of RF current goes to R_c so that the voltage ratio V/V_0 is a half without plasma ($R_g = \infty$). The lowest acceptable designed value V/V_0 is set 0.05 to hold the reasonable signal-to-noise ratio. In case of LBNF, the range of R_g is 1,800-18,000 Ω so that the designed Q factor 500 will be optimum.

DEMONSTRATION TEST

The concept will be verified in the demonstration test. The plasma loading will be measured as functions of beam intensity and the concentration of electronegative dopant. One of the technical challenges is measuring a low power RF signal in a low Q factor RF cavity. Two step demonstrations are considered to establish the RF monitor technology.

Table-top Test

A main goal of the table-top test is developing the low power RF signal measurement in a low Q factor RF cavity. Figure 5 shows the conceptual design of a tunable Q-factor

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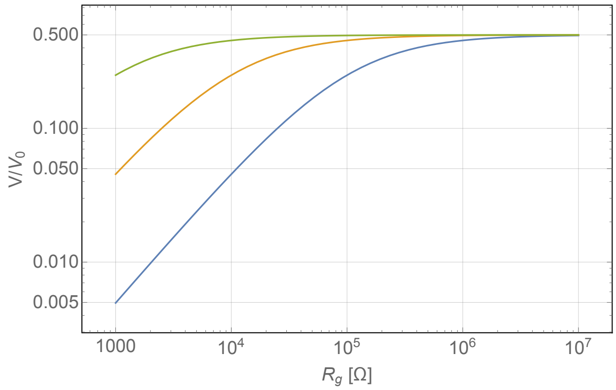

Figure 4: Calibration of the beam loaded RF signal with various Q factors (green: Q = 50, orange: Q = 500, and blue: Q = 5,000). Assume that the input impedance is matched to the cavity ($R = R_c$).

pillbox RF cavity. Two coupling loops load the cavity. By changing the coupling strength of loops, the Q factor will be tuned 100-1,000. A dummy dielectric material will be loaded in the cavity to check the sensitivity of the RF data acquisition system.

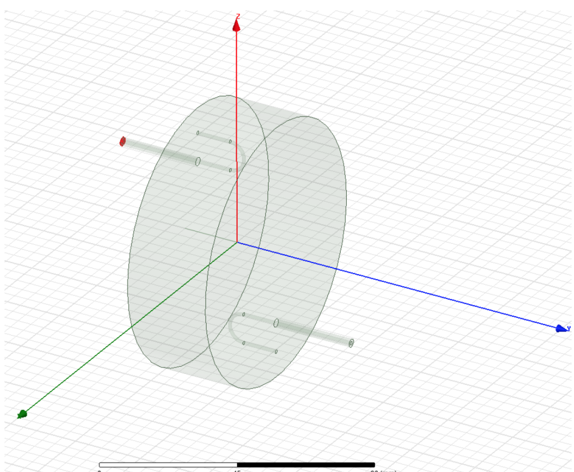

Figure 5: Conceptual design of a Q-factor variable pillbox RF cavity.

Beam Test

The tunable Q-factor pillbox RF cavity will be used for the first beam test. The response function of the gas-filled RF cavity will be measured by using a known-intensity and known-size beam. The electron capture rate will be measured by tuning the Q factor. Then, the optimum Q-factor and ideal electronegative gas concentration are identified in this test. A fast RF peak power detector will be used to measure the beam loading RF envelope.

A re-entrant shape RF cavity is designed for practical neutrino beam applications. Figure 6 shows a superfish simulation of the first designed re-entrant RF cavity. The size of coupling loop in the re-entrant cavity can be smaller than the tunable Q cavity. Therefore, the re-entrant cavity has a small perturbation on the RF signal due to a local plasma which is created near the loop. Electric field in the re-entrant cavity is concentrated and radially flat in a gap of two electrodes. The plasma loading is localized in the gap. It increases a sensitivity and hence reduces an uncertainty of the RF measurement.

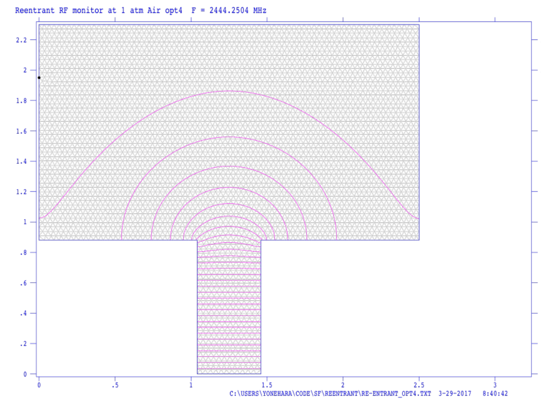

Figure 6: The result of superfish simulation for a re-entrant RF cavity.

Timeline

The table-top test will be finished by Summer 2017 and the first beam test will be taken place in Fall 2017. SY120 beam dump [9] will be used for the beam test. Meantime, a prototype RF monitor will be built and installed in the MI beam dump for the radiation endurance test. Ultimately, if all tests will be passed a prototype monitor will be built and applied in the NuMI beam line.

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