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INTENSE NEUTRINO SOURCE FRONT END BEAM DIAGNOSTICS SYSTEM R&D*

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Abstract

We present the R&D of radiation-hard beam profile monitor at Fermilab for future intense neutrino beam experiments. We evaluate the existing monitor which is based on an ionization chamber operating at 700 kW primary proton beams and show a possible issue to apply it for Mega Watt-class beam facilities. Then, we report the R&D of new radiation-hard beam detector which is based on a gas-filled RF cavity.

INTRODUCTION

Intense neutrino beam is a unique probe to research elementary particle physics beyond the standard model. Fermilab is the host institution to provide world's most powerful and wide-spectrum neutrino beam. Fermilab recently achieved consistent 700 kW proton beam delivery to the secondary-particle production target by using the Main Injector ring (NuMI) [1]. Currently, the Long Baseline Neutrino Facility (LBNF) project is on-going, i.e. a multi-MW beam facility will be build for intensity frontier neutrino beam experiments [2]. It requires a radiation-hard beam detector to maintain the high beam quality to obtain a rare and precise neutrino physics event with a high confident level. We present the R&D of radiation-hard beam profile monitor at Ferimilab.

NuMI IONIZATION CHAMBER

The NuMI beam is characterized by using a beam profile monitor which is based on an ionization chamber. The first monitor is located downstream of a pion decay pipe. Because a great amount of hadronic charged particles passes through the chamber, this chamber is called a hadron monitor. It is primary used to align beam elements including with the target and two magnetic focusing horns with respect to the near and far neutrino detectors. Typically, the beam alignment takes place during the beam commissioning after a long shutdown [3]. We also measure the beam position on the target by using a Beryllium wire with thermocouple which is stretched on the front size of target in vertical and horizontal directions to cross-check the monitor measurement. Once the beam operates for the neutrino experiment, the monitor measures a beam position of the primary beam and a deterioration of the target.

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Three additional ion chamber based beam profile monitors are lined up on the beam axis downstream of an absorber. Most charged particles are ranged out in the absorber except for muons. Each time muons pass the monitor they meet more material. Thus, each monitor measures muons with a specific energy band. It is called a muon monitor. Because the muon monitor is located behind a thick material, it does not have an intensity issue up to a 1 MW beam power. We have developed a new muon monitor with a new technique for multi-MW operation [2]. We do not discuss the muon monitor in this article.

Possible Issue on Ionization Chamber

Because the hadron monitor is directly exposed with intense hadronic showers, a dose at the monitor is extremely high, that is more than 10 Grad per year. As a result, some pixels in the existing monitor lost the signal gain due to a radiation damage. Figure 1 shows an example of the observed beam profile on the monitor. A contour plot on left hand side in fig. 1 is a snapshot when the monitor started functioning in 2013. The beam profile was reconstructed properly. On the other hand, the other plot on right hand side shows the recent measurement which shows some pixel has been malfunctioned. We significantly lost the accuracy of monitor signal to reconstruct the beam profile.

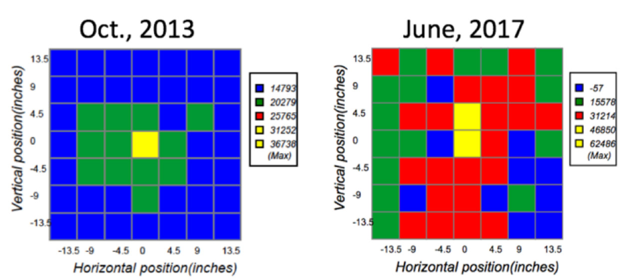

Figure 1: The observed beam profile on the NuMI hadron monitor.

Figure 2 shows the vertical and horizontal beam profile crossing at the beam center. Luckily, the central pixel still provides a beam signal. However, adjacent pixels do not provide any signal. We investigated a lifetime of a dead pixel. Some pixel has a very short lifetime within a couple of months after the monitor functioned and it suddenly stopped signal. Other pixel gradually lost a signal gain within a couple of years. From the observation, there can be various

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signal-gain lost mechanisms. We plan to take a part the existing monitor to investigate the mechanism.

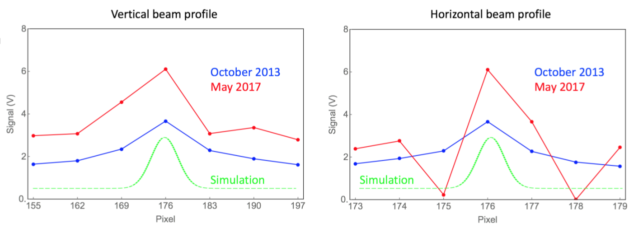

Figure 2: Observed beam signal on the monitor. The signal is taken from only one array of column (vertical) and raw (horizontal) across the beam center pixel in the monitor. Some pixel has a low signal gain or lost a gain at all.

Figure 3 shows the signal gain of the central pixel as a function of the primary proton beam intensity on target. Approximately 20% of protons survive from the target, so that less than 10% of POT protons pass through the central pixel. It has lower gain at higher beam intensity. It is known as a space charge effect, i.e. the electric field on a free electron is screened by plasma. The space charge effect can be mitigated by reducing a bias voltage. However, the gain cannot be calibrated during the neutrino measurement mode.

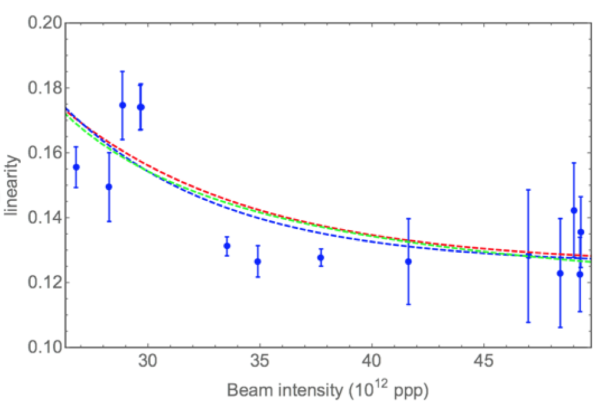

Figure 3: The observed signal gain on the central pixel of the NuMI hadron monitor as a function of POT.

RF BEAM DETECTOR

We propose a conceptually new beam detector which is based on a gas-filled RF resonator. A plasma in the cavity is formed by interacting an incident beam with gas and shifts the gas permittivity. The shift is proportional to the beam intensity and measurable by observing the loading of RF power into the gas plasma, which is called a plasma loading [4–6]. The RF detector mitigates several issues related with high radioactive environments. A cable configuration of the RF detector will be simple to mitigate a radiation damage problem. A gain of the output signal of RF detector can be calibrated by measuring RF parameter when the beam is turned off. It permits to measure the absolute beam intensity.

In order to verify the proof-of-principle of the RF detector, we carried out the first beam test at the Switch Yard (SY) beam line at Fermilab. A prototype 2.4-GHz RF detector was fabricated and mounted in front of a SEM near the SY beam dump (Figure 4). The RF cavity is a pillbox shape and made of stainless steel. It has a beam window at the axial center on upstream and downstream RF plates, which is a 1 mm-thick SS. There are three RF interface ports on the cavity; one is for tuning the cavity quality (Q) factor (a loading loop), other is to pick-up RF signal in the cavity (a pickup loop), and the last is to feed RF power to the cavity (an input loop) [7]. There are two gas lines accessing from a sidewall; one is a gas inlet and other is a spare. The ambient air was used for the first beam test.

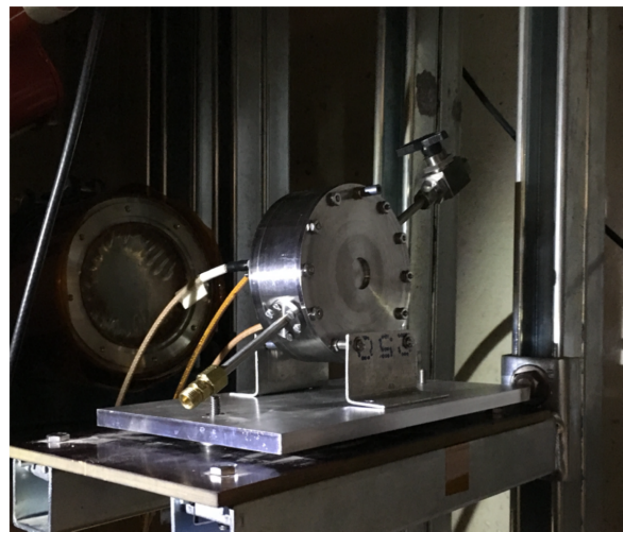

Figure 4: The fabricated RF test cavity on the SY beam line. The SEM behind the cavity is used to measure the beam intensity.

Figure 5 shows the observed recovery signal and an exponential curve. For convenience, we define the recovery time from the time at the lowest voltage point after the beam is turned off to the other time at the output signal reaching to 99% of the baseline. The definition will be changed in future when we study a specific plasma process. Because the time resolution of data acquisition is 6 ns in this measurement, the observed recovery time has a ±3-ns error.

Figure 6 is the measured RF recovery time as a function of the beam intensity. The recovery time is proportional to the beam intensity. The measurement validates the plasma loading theory. The theory also predicts that the cavity Q factor changes the beam sensitivity: Higher Q makes higher beam sensitivity. The measurement validates the prediction. When the cavity is operated near resonance (red point), it is high sensitive to the beam. On the other hand, the cavity is operated at 3 dB off from the resonance (blue point) it is low sensitive to the beam. A low-Q cavity is more effective when the RF detector measures higher beam intensity. The signal gain is changed by adjusting the driving frequency. The primary beam intensity measured upstream of the cavity by a toroid pickup is ~20% lower than the observed beam intensity in the SEM because the SEM counts secondary

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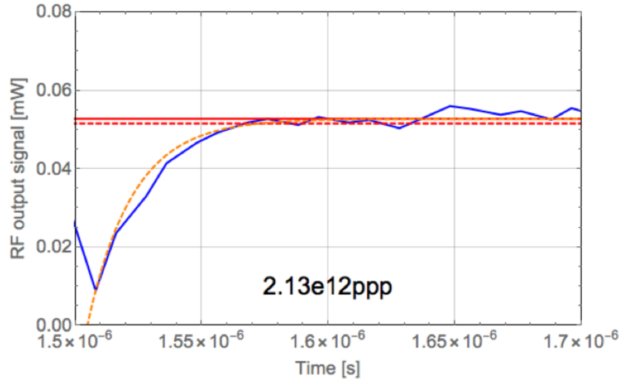

Figure 5: The observed RF recovery signal. A blue line is a raw data, a red solid line is a baseline which no plasma loading takes place, a dashed red line is a 99 % of the baseline, a dashed orange line is an exponential fitting.

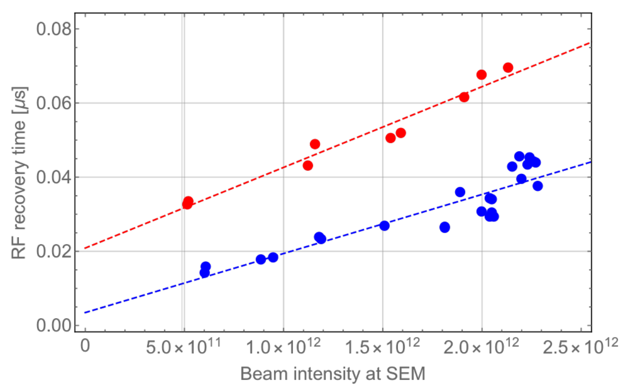

Figure 6: The observed RF recovery time as a function of incident beam intensity.

particles created in the cavity. Nevertheless, the range of beam intensity at the SY beam line is comparable with the present NuMI beam intensity.

FUTURE PROSPECT

Figure 7 shows a conceptual design of a new prototype RF detector. As we originally designed, the cavity is powered by a waveguide instead of using a coaxial cable. We verified that the cavity Q factor can be changed by tuning the driving frequency. So that the cavity does not have a loading loop. Ionization gas will serve through the waveguide. It is worth to note that the amplitude of excitation field in the waveguide is extremely small. Thus, the plasma loading in the waveguide is negligible. This will be demonstrated in the next beam test.

We found an unexpected background beam noise when the beam is turned on. One of the reasons is because the incident RF power into the cavity is lower than the designed power. In order to eliminate the noise signal, we plan to

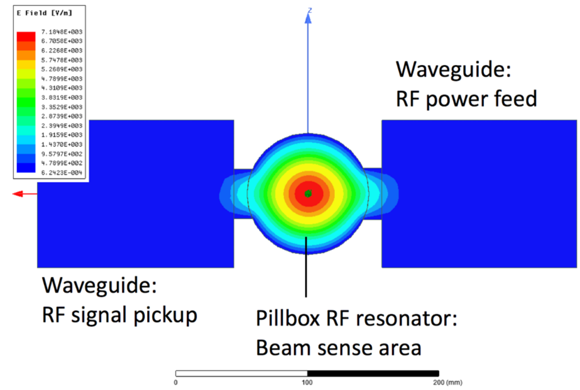

Figure 7: Conceptual design of a new prototype RF detector.

add an RF amplifier to increase an input RF power. We also add a narrow band pass filter to cut an unwanted frequency signal. If everything works, we can measure the transit plasma loading during the beam is turned on. The cavity provide us an opportunity to precisely measure the plasma loading in various conditions. It is an important source to calibrate the RF signal.

A fast extraction kicker was removed from the MI ring because an outgas from the kicker was an issue to significantly drop the machine time. It means that the single-turn extraction beam is not available in the SY beam line. Now, we plan to have the second beam test by using the MI beam abort line. The new prototype cavity will be made and installed in the beam line the summer shutdown 2018 and start taking data in Fall 2018. If success, we consider to demonstrate the RF detector in the NuMI beam line. It will happen in 2019.

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