TRANSVERSE BEAM HALO MEASUREMENTS AT HIGH INTENSITY NEUTRINO SOURCE (HINS) USING VIBRATING WIRE METHOD*

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Abstract

The measurement and control of beam halos will be critical for the applications of future high-intensity hadron linacs. In particular, beam profile monitors require a very high dynamic range when used for the transverse beam halo measurements. In this study, the Vibrating Wire Monitor (VWM) with aperture 60 mm was installed at the High Intensity Neutrino Source (HINS) front-end to measure the transverse beam halo. A vibrating wire is excited at its resonance frequency with the help of a magnetic feedback loop, and the vibrating and sensitive wires are connected through a balanced arm. The sensitive wire is moved into the beam halo region by a stepper motor controlled translational stage. We study the feasibility of the vibrating wire for the transverse beam halo measurements in the low-energy front-end of the proton linac.

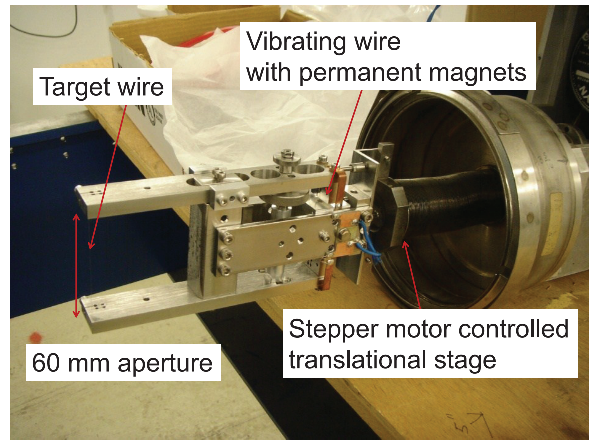

Figure 1: Picture of the large aperture vibrating wire monitor assembly.

INTRODUCTION

The measurement and control of transverse (as well as longitudinal) beam halos will be critical for the applications of future high-intensity hadron linacs, such as Project-X at Fermilab for intensity-frontier particle physics experiments and Accelerator Driven System (ADS) for nuclear energy applications [1]. The beam halo is often defined as the low-flux region far from the beam center with intensity less than per mil of the core [2]. The range of the halo reaches around $4\sigma - 6\sigma$ in many cases (σ is the rms beam size). Sources of the beam halo formation are space-charge forces, beam-mismatch, scattering processes, RF noise, instabilities, and resonances, to mention a few examples. The beam halo is one of the causes of uncontrolled beam losses, radioactivation of beam pipe, damage of sensitive equipments, and quenching of superconducting magnets. The diagnostic capability for the beam halo measurement is typically limited in both dynamic range and resolution. A nice overview was given by Wittenburg [2] about recent beam profile measurements and halo monitoring with focuses on the dynamic range.

There are plans to investigate the beam halos at the Project-X Injector Experiment (PXIE), which is an R&D program to address accelerator physics and technology issues for the multi-MW superconducting proton accelerator facility, Project-X. Various methods can be considered to characterize the transverse beam halo, for example, wire scanners, wire scanner with scraper, scrapping with collimators, and vibrating wire monitors (VWM) [3, 4, 5]. Also, optical methods such as laser wire beam monitors and beam core subtraction of screen images utilizing micro-mirrors have the potential to meet the required dynamic range goal. Recently, a new type of vibrating wire monitor (LA-VWM) that has a large aperture size and two mechanically coupled wires was proposed to facilitate the transverse halo measurements [5] (see Fig. 1).

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LARGE APERTURE VIBRATING WIRE MONITOR

Conventional wire scanners (usually made of tungsten or carbon wires) are based on the signals generated by the secondary electron emission (SEM) for low energy protons and heavy ions, and by the scatted secondary particles for ions with $>$ 10 MeV/u and electrons with $>$ 10 MeV [6]. The former uses current-to-voltage converters while the latter uses scintillators and photomultipliers which are located outside the vacuum chamber. In linac front-ends with low beam energy and low average beam current (or low repetition rate), neither of the above mentioned methods are adequate for the beam halo measurements. The wire diameter can be increased to get higher SEM currents, or to capture protons or electrons directly. Even a scrapper of a few mm-thick (made of aluminum surface) is often used [2].

On the other hand, the operating principle of the VWM

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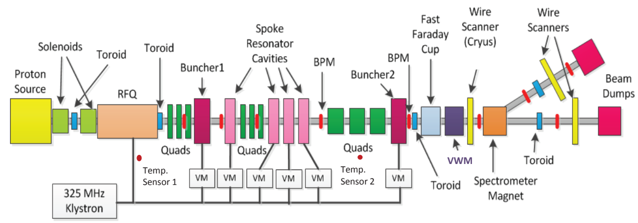

Figure 2: Block diagram of the HINS beamline configuration used for the beam test of the LA-VWM. The ambient temperature is monitored by the two temperature sensors shown in red circles.

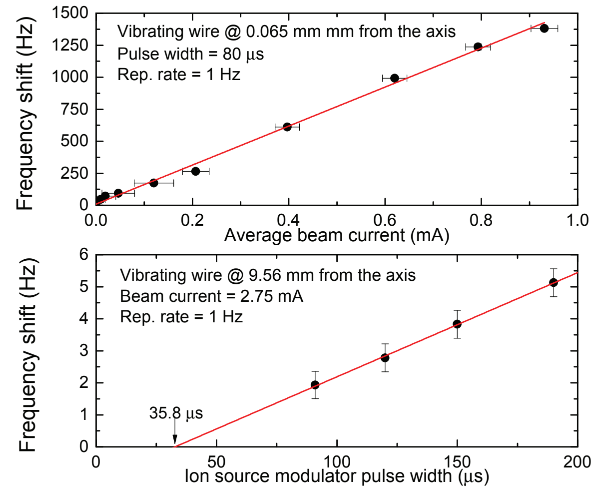

Figure 3: Linearity of the frequency shift of the LA-VWM with respect to the average beam current (top) and the ion source modulator pulse width (bottom).

is based on the measurement of the change in the natural oscillation frequency of vibrating wires [3, 4]. Note that the natural oscillations arise as a result of the interaction between the AC current through the wire and a permanent magnetic field. The wire should be conductive and be involved into a positive feedback loop. When the beam particles are intercepted by the wire, heat is generated. An equilibrium temperature is achieved by the balance between conduction, radiation, and heating. The frequency change Δf is proportional to the wire temperature change ΔT, in turn the wire temperature to the power deposition ΔQ, and finally the power deposition to the current deposition I_w. For a Gaussian beam profile,

$$\Delta f(x) \propto I_w(x) = I_0 \frac{d}{\sqrt{2\pi}\sigma_x} \exp\left(-\frac{x^2}{2\sigma_x^2}\right), \quad (1)$$

where x is the distance between the wire and the beam center, and d is the wire diameter. If the total beam current I_0 is measured by the beam toroids, the line current density I_w/d $[\mathrm{A/m^2}]$ can be estimated by fitting the beam profile (given in terms of the frequency change) with a Gaussian.

The aperture size of the original VWM was only 12 mm, so sometimes a lot of halo particles are deposited on the magnetic poles of the monitors, making the interpretation of the experimental results very difficult. The new idea is to increase the aperture size by using two separate wires. One is the target wire (sometimes called sensitive wire) and the other is the vibrating wire. Only the vibrating wire is covered by a permanent magnet system. Two wires are coupled through a balanced arm. The choice of the target wire material is arbitrary (i.e., does not need to be a conductor). So, an exotic material such as Graphen could be used to redice response time. Details of the LA-VWM will be described elsewhere [5].

BEAM TEST AT HINS FACILITY

The LA-VWM with aperture 60 mm was installed at Fermilab High Intensity Neutrino Source (HINS) facility [7] to test its performance for the actual transverse beam profile measurements. The HINS front-end is composed of a 50 keV proton source, a Low Energy Beam Transport (LEBT) line with solenoid focusing, and a 2.5 MeV Radio Frequency Quadrupole (RFQ). Figure 2 shows a block diagram of the HINS beamline with various beam instrumentation, which includes BPMs, toroids, and wire scanners. The spoke cavities and buncher cavities were not used for this test. Note that the RFQ was operated without water cooling; therefore the repetition rate of the beam pulse was limited to 1 Hz. The LA-VWM (shown in the purple box in Fig. 2) is installed next to the first wire scanner which is located in front of the spectrometer magnet. The LA-VWM is moved into the beam center by a stepper motor controlled translational stage (0.1266 mm step size). For the initial test, we used 0.1- mm-thick stainless steel for both the sensitive and vibrating wires.

In Fig. 3, we checked the linearity between Δf and I_w by changing the average beam current and the ion source modulator pulse width. The ion source modulator pulse width is supposed to determine the beam pulse width. However, from the fact that the linear fitting curve has a finite x-intercept, it seems that the actual beam pulse width is shorter than the modulator pulse width. Comparison between the measurements with the wire scanner and the vibrating wire in Fig. 4 also indicates that the LA-VWM works well for the beam profile characterization. The wire scanner has a 0.125-mm-thick Molybdenum wire, and the induced currents in the wire are converted into the voltage output via the I-V conversion circuit. For higher beam currents, however, the deposited power is too large at the beam core that the frequency shift in the LA-VWM becomes out of range.

When the LA-VWM is moving toward the beam center where the current density is high, the vibrating wire frequency goes down. On the other hand, when the LA-VWM is moving from the beam center to the low-density region,

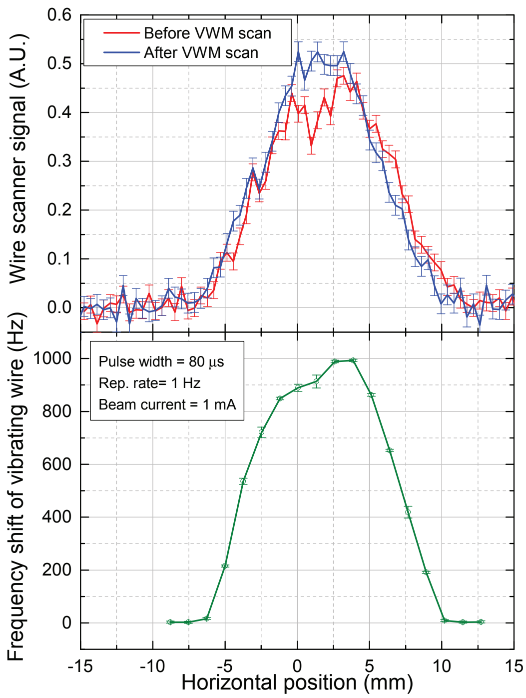

Figure 4: Comparison between the beam profile measurements with the wire scanner (top) and the LA-VWM (bottom). To obtain overall beam profile quickly, we use a coarse step size for the vibrating wire scanning. Also, a low beam current of $I_0 = 1$ mA is used to enable frequency measurements at the beam core.

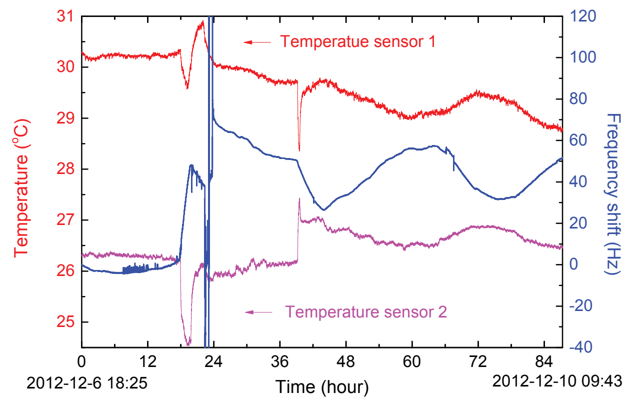

Figure 5: Effects of the ambient temperatures on the frequency change. A spike in the frequency at $\sim$ 24 hours after the start of the experiment occurred because we broke the vacuum of the beamline.

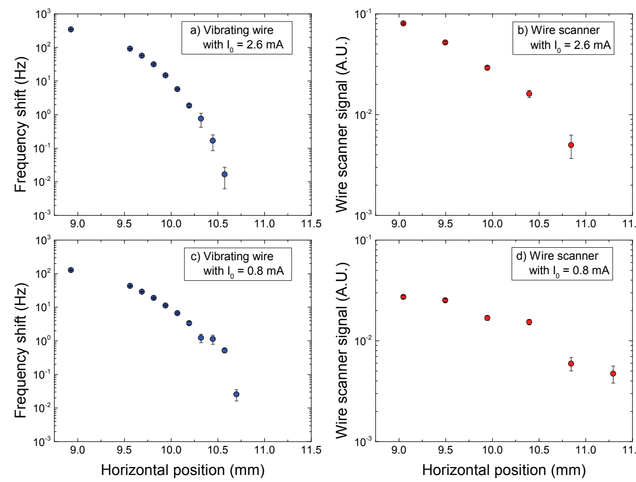

Figure 6: Comparison between the beam profile measurements in the tail region (i.e., around the horizontal position of 10 mm in Fig. 4): (a) LA-VWM for I_0 = 2.6 mA, (b) wire scanner for I_0 = 2.6 mA, (c) LA-VWM for I_0 = 0.8 mA, and (b) wire scanner for I_0 = 0.8 mA. The beam pulse width and repetition rate are 80 μs and 1 Hz for all cases.

the wire frequency goes up. In this paper, we plot the absolute value of the frequency change in most cases. Since we use stainless steel for the sensitive wire, the response time is rather long ($\sim$ 2 min). During the experiments, we found that the frequencies were slowly decreasing before and after the wire positions were changed. The cause of this slow frequency drift turned out to be due to the ambient temperature changes of the HINS facility (see Fig. 5).

For both high (I_0 = 2.6 mA) and low (I_0 = 0.8 mA) beam current operations, the LA-VWM demonstrates much higher dynamic range ($\sim 10^4 - 10^5$) than the conventional wire scanner for the characterization of the low density tail regions (see Fig. 6).

FUTURE PLAN

We plan to test various target wire materials to optimize the performance of the LA-VWM possibly in the PXIE LEBT beamline. Also, we'll investigate the solutions to minimize the effects of the mechanical vibration and ambient temperature. When a conducting material is used for the target wire, we may actually measure the induced currents at the same time, which would make the LA-VWM a more versatile beam instrumentation.

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