A FAST ROTATING WIRE SCANNER FOR USE IN HIGH CURRENT ACCELERATORS*

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Abstract

We have developed a cost-effective, fast rotating wire scanner for use in accelerators where high beam currents would otherwise melt even carbon wires. This new design uses a simple planetary gear setup to rotate a carbon wire, fixed at one end, through the beam at speeds in excess of 20 m/s. We present results from bench tests, as well as transverse beam profile measurements taken at Cornells high-brightness ERL photoinjector, for a beam energy of 4 MeV and beam currents up to 35 mA.

INTRODUCTION

Recently, a new regime of beam parameters has become accessible with the advent of very intense photoinjectors, such as the Cornell ERL photoinjector, which feature very high average beam currents (up to 100 mA) and low transverse beam emittances (<1 mm-mrad rms normalized) [1, 2]. The beam energy out of the photoinjectors is near or below 10 MeV, with very large beam powers (on the order of MW) contained inside a small beam cross-section (diameter of 1 mm or less).

This parameter range poses special challenges for diagnostics at full beam current operation, particuarly due to the beam's high charge density. First, the beam power density is high enough that any material intercepting the beam will melt on the order of 10's of microseconds or less. Second, the beam energy is low enough that synchrotron or diffraction radiation, which are often the method of choice for beam profile measurements at higher energies, are generally not available without introducing strong magnetic fields or placing apertures undesirably close to the beam for diffraction radiation.

One obvious candidate for a beam profile diagnostic capable of measuring MW type electron beams is a wire scanner that can sample the beam profile at a suitable transverse resolution (on the order of microns or even better) [3]. However, particle beams with small transverse dimensions and high intensities require a wire scanner with a very fast scanning speed, as these beams can melt even carbon wires - one of the best materials for withstanding extremely high temperature rises[4]. For example, a beam current of 100 mA and both an electron beam diameter and a wire diameter of $34\mu m$, like those found in the Cornell photoinjector, require a minimal scanning speed of 20 m/s. In this paper, we describe the design and show tests of a simplified wire scanner capable of reaching this speed and optimized for a large quantity reproduction, resulting in significant cost reduction.

WIRE SCANNER CONSTRUCTION

The principle of operation of the new wire scanner is illustrated in Fig. 1. It consists of a stationary gear G_1 and a smaller gear G_2 rotating around the gear G_1. The blade attached to the gear G_2 holds the carbon fiber cemented on its end. If the center of the small gear moves with the linear velocity v_g then the fiber scanning speed is

$$v_s = v_g\left(\frac{R}{R_2}+1\right), \quad (1)$$

where R_2 is the radius of the gear G_2 and R is the distance from the center of the gear G_2 to the electron beam. Uncertainty of the beam position along the fiber results in the scanning speed variation

$$\frac{\delta v_s}{v_s} = \frac{\frac{\delta R}{R_2}+1}{\frac{R}{R_2}+1} \approx \frac{\delta R}{R}, \quad (2)$$

where it is assumed that $\delta R \ll R, R_2$. In the current prototype $R = 82.4$ mm, so for $\delta R = 5$ mm the relative scanning speed variation is $\delta v_s/v_s = 0.061$. This value sets the absolute precision of the transverse bunch profile measurement.

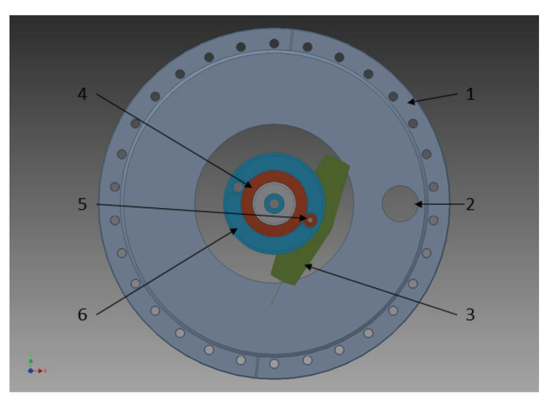

Figure 1: A 3D rendering of the gears setup. (1) - vacuum flange; (2) - beam pipe; (3) - blade with attached carbon wire; (4) - stationary gear G_1; (5) - rotating gear G_2; (6) - rotating gear box.

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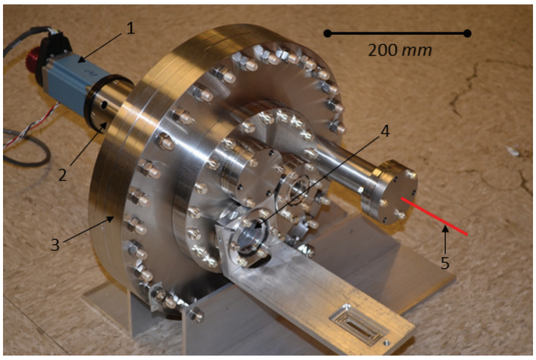

Figure 2: A photograph of the wire scanner. (1) - stepper motor; (2) - ferrofluidic rotary feadthrough; (3) - vacuum flanges; (4) - vacuum flange with viewports; (5) - beam direction.

A photograph of the wire scanner is shown in Fig. 2. The only custom made parts are the aluminum gear box and the fiber holding blade. These are installed between a pair of standard high vacuum flanges with a 337 mm outer diameter and an inner hole with a 152 mm diameter. Another set of two vacuum flanges of diameter 203.2 mm enclose the setup. One of the flanges is equipped with three optical view ports for monitoring the carbon fibers condition between scans. The rotation is provided by a ferrofluidic rotary feedthrough (Thermionics FRMRE-275-38CL) driven by a stepper motor. The maximum scanning speed is determined by the moment of inertia of the rotating parts (motor rotor, rotary feedthrough, gear box, and the blade), the friction in the gears and ball bearings, and the maximum torque rating of the rotary feedthrough. The gears and ball bearings were lubricated with Dicronite - a high vacuum compatible lubricant. Bench tests confirmed that mechanical friction is sufficiently small, and, with the existing moment of inertia of the system and torque limit of the feedthrough (1.06 Nm) scanning speeds can reach up to 30 m/s.

The starting position at the beginning of the scan is chosen so that the fiber is located slightly outside of the beam pipe. During the acceleration stage, the gear G_2 makes an almost complete revolution around the gear G_1 and the carbon fiber reaches its maximum velocity when it crosses the center of the beam pipe. Afterwards, the mechanism is decelerated and the fiber is stopped just outside the beam pipe, opposite its starting position. In order to avoid abrupt changes in the wire's acceleration, which lead to excessive vibrations, the velocity profile is programmed to follow a smooth sinusoidal curve for a nominal scanning speed of 20 m/s.

BENCH TESTS

In contrast to other wire scanners described in the literature [3, 5], the carbon fiber is attached to the rotating blade only by one end, so that a large amplitude vibration – up to 1 mm or more – can be easily excited. This should be compared to typical wire vibration amplitudes not exceeding $10\mu m$ in instruments with stretched wires fixed at both ends [6]. The oscillation speed will add to the wire scanning speed and, as a result can, affect the beam profile measurement. In the prototype instrument the oscillation frequency of the wire, $\omega = 75 \pm 2$ Hz, was determined experimentally by shining a laser onto the vibrating wire and tuning the laser pulse frequency until the image of the wire, obtained using a standard CCD camera, became stationary. Given the maximum amplitude of the oscillation $A_0 = 5mm$ (as determined by direct observation with the video camera), the wire scanning speed can be modulated by up to $\omega A_0 = 0.4m/s$.

In order to verify these estimates, a bench test designed to measure speed variations along the wire due to oscillations was performed. Specifically, a modulated laser was used to capture multiple images of the moving wire in a single CCD frame. The wire scanner was evacuated to a pressure of approximately 10^{-7} torr during these tests, and the laser beam was sent through the beam pipe using two flanges with optical windows. Figure 3 shows a frame obtained for a wire moving at 20 m/s using a laser pulse duration of 7 μs and a pulse frequency of 8 kHz. The laser pulse frequency of 8 kHz causes the wire oscillations to manifest as a slight broadening of the image. The laser light scattered by optical imperfections is removed by subtracting the frame without the wire.

The wire speed was calculated by measuring the distance between adjacent wire images in the scanning direction, and the results are shown in Fig. 4. Wire speed variations are observed both along the wire and in the scanning direction, pointing to the presence of the higher order vibrations. The average speeds determined at two wire scanning positions -2.0 mm and 0.4 mm are 20.2 ± 0.2 m/s and 20.0 ± 0.3 m/s respectively. The uncertainty is well within the estimate of 0.4 m/s based on the assumption that the amplitude of the fundamental wire vibration is less than 5 mm. The conclusion is that the wire scanning speed uncertainty is approximately (0.3 m/s)/(20 m/s) = 0.015, or 1.5%.

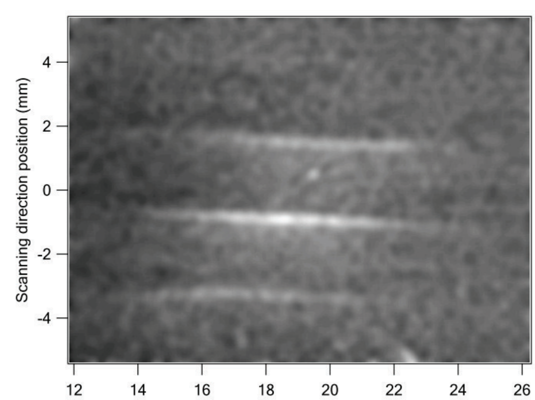

Figure 3: Three images of a wire captured on a single camera frame during a scan. The wire is moving at 20 m/s in the upward direction.

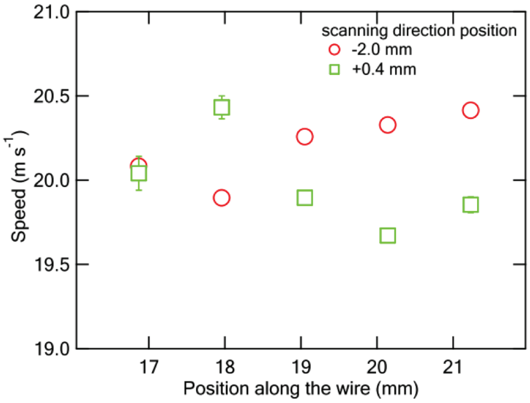

Figure 4: Wire speeds calculated at different locations along the adjacent wires shown in Fig. 3. The circles represent values calculated using the top and middle wires, while the squares use the middle and bottom wires. The error bars are smaller than the symbol size for some points.

BEAM TESTS

Beam tests of the new wire scanner were performed after installation in the chicane section of the Cornell ERL photoinjector [2]. X-rays produced when the wire crosses the electron beam were detected using a combination of a scintillator crystal and a silicon photomultiplier sensor (MicroSM-60035-X13 by SensL). The detector output was sampled at a rate 2 million samples per second with the aid of a digital acquisition device (Agilent U2500A USB DAQ). At a scanning speed of 20 m/s, this corresponds to a distance sampling interval of $10\mu m$, compared to the $34\pm1\mu m$ diameter of the carbon fiber used in these experiments. Data acquisition can be triggered either by the stepper motor controller (DMC-2183 by Galil Motion Control) at a preset wire position, or by the control software after a fixed time interval.

In order to test the dynamic range of the instrument, several sets of tests were performed for beam currents varying from $250\mu A$ to 35 mA, at a beam energy of 4 MeV and a bunch repetition rate of 1.3 GHz. The measured beam profiles were normalized by subtracting an offset and dividing the amplitude by the value of the current in mA. Results are shown in Fig. 5. The total area under the curve is preserved, confirming the good linearity of the detection system. As bunch charge is increased, a systematic broadening of the profile is observed that is the result of space charge repulsion.

At low beam currents the profiles can be obtained using a luminescent viewscreen. Figure 6 shows a comparison of the viewscreen and wire scanner profiles measured for the same beam current of $20\mu A$, which was obtained by decreasing bunch charge to 0.015 pC. A regular beam loss monitor photomultiplier was used for the wire scanner signal detection this time. Both curves are in very close agreement, confirming that both diagnostics are consistent for low bunch charge values.

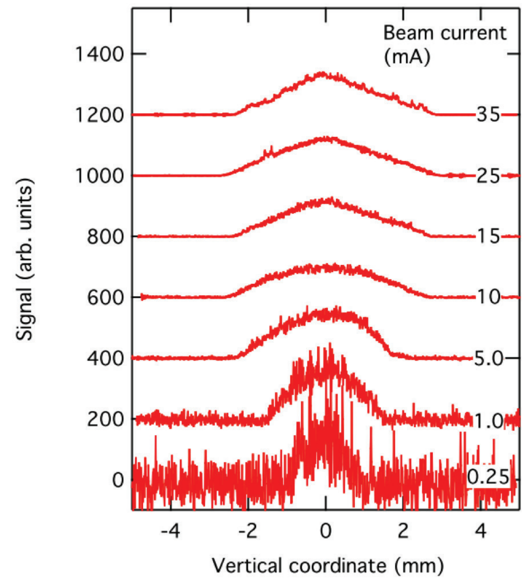

Figure 5: Wire scans at different beam currents, where the data is normalized to 1 mA current.

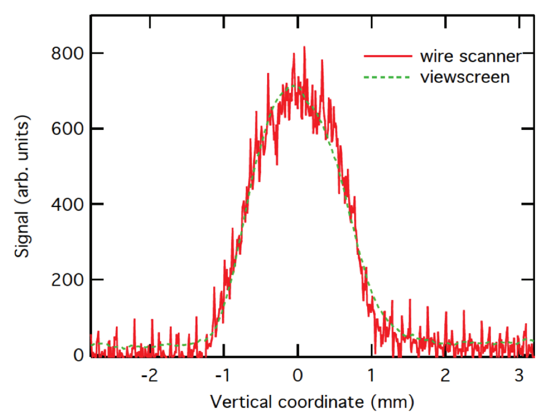

Figure 6: Comparison of the beam profile obtained with the wire scanner (solid line) and the luminescent viewscreen (broken line) for $20\mu A$ average beam current (0.015 pC bunch charge).

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