Prototype Flying-Wire Beam-Profile Monitor*

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Abstract

A prototype flying-wire beam-profile monitor has been designed, fabricated, and tested to measure profiles of high-current high-duty electron beams. The device measures the beam's horizontal and vertical profiles with a pair of thin carbon filaments mounted on a wheel. The beam that intercepts the filaments, or wires, produces electrons by secondary emission in proportion to the incident beam current. The secondary electron signal is detected either by measuring the charge depletion current on the wires or by measuring the current collected on a pair of positively biased charge collectors. A servo motor is used to accelerate the wheel from rest to a speed of 25 RPS in less than half a revolution passing the wires through the path of the beam at a speed of ~10 m/s. The wheel is then decelerated back to rest before completing one full revolution. The precise timing requirements of this application led to the development of an indexer capable of controlling the servo motor position with less than 20 μs of timing jitter.

I. INTRODUCTION

A prototype flying-wire beam-profile monitor, shown schematically in Figure 1, has been developed to measure profiles of high-current high-duty electron beams where the use of view screens or fixed-wire scanners is not practical. The system was designed for use on the Average Power Laser Experiment and High Powered Oscillator (APLE/HPO) electron accelerator under construction at Boeing Aerospace Corporation. The nominal APLE/HPO beam has an energy of ~18 MeV and current of about 0.2 A averaged over an 8 ms long macropulse. The width of the beam varies from 1 mm to 5 mm. The profile monitor measures the beam's horizontal and vertical profiles using a pair of 35 μm diameter carbon filaments mounted perpendicular to one another on a wheel that sweeps them through the beam. The wheel diameter is 17 cm and the distance from the wheel's axis of rotation to the axis of the beam is 6.6 cm. The design minimizes the length of beam line occupied by the setup. The discontinuity in the beam pipe is kept to a gap of ~2 cm which helps reduce the deleterious effects caused by wake fields. Due to the high power density of the beam, is it is not desirable to place any material, other than the wires, in the path of the beam. The single spoke design of the wheel allows the maximum angular range to accelerate the wheel from rest to the operating velocity and back to rest before the spoke can pass through the path of the beam. The profile is determined by measuring either the charge depletion current of the wires or the charge collection current from a pair positively biased charge collectors mounted concentric with the beam axis on either side of the wheel. The current signal from either the wires or collectors is converted to a proportional voltage signal which can be displayed on an oscilloscope or recorded by a transient digitizer.

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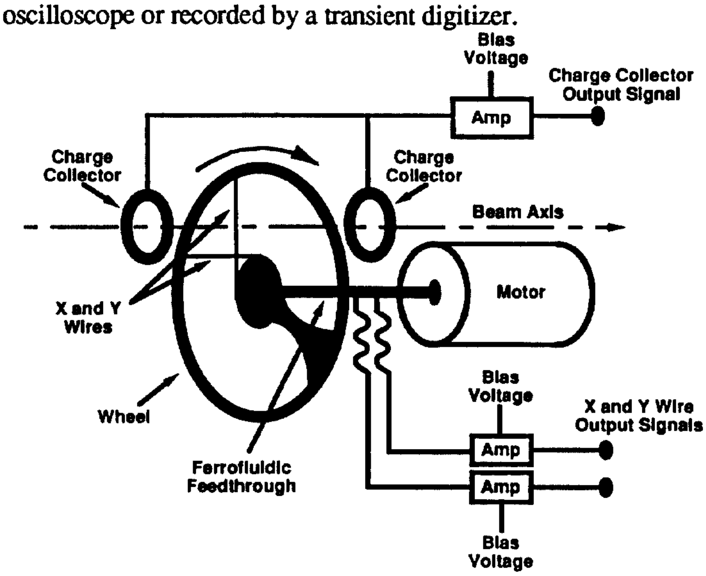

Figure 1 Schematic view of the prototype flying-wire beam-profile monitor.

II. SECONDARY EMISSION ELECTRONS

The beam profile is determined by measuring the secondary emission electron signal from the interaction of the beam with the wire. The secondary electron production rate for 30 MeV electrons on carbon has been measured to be about 3%.[1] Assuming this rate, the secondary electron current is calculated to be on the order of 200 μA for a 35 μm wire in the center of a 1 mm diameter 0.2 A beam. Because the distribution of the secondary electrons falls off rapidly with energy, nearly all the secondaries can be attracted to a nearby collector biased at a few hundred volts.

III. BEAM HEATING

Heating of the wire during a single pass through the beam is a major concern when attempting to measure the profile of high average power electron beams. For this reason it is imperative that the wire pass through the beam quickly enough to prevent thermonic emission or breakage. The rise in temperature of the wire as it traverses the beam is proportional to;

$$\Delta T_{wire} \propto (I_{beam}\, dE/dx)/(C_s\, V_{wire}\, W_{beam}),$$

where, I_{beam} is the beam current, dE/dx is the energy loss of the electrons in the wire, C_s is the specific heat of the wire, V_{wire} is the velocity of the wire, and W_{beam} is the width of the beam. This does not take into account any heat loss due to thermal radiation or conductance. Of the many possible wire materials, carbon filament has the lowest ratio of dE/dx over C_s. Combined with its high tensile strength this material is well suited for use in flying-wire scanners. For a 1 mm diameter, 0.2 A beam, the carbon wire must be moved through the beam at a speed of at least 10 m/s to keep the calculated ΔT in the carbon wire below 2000 K. For wire temperatures above 2000 K thermonic emission and breakage become a concern.

IV. MECHANICAL DESIGN

The primary challenge of the mechanical design was to accelerate the motor and wheel from rest to the required velocity and back to rest in less then one revolution. The acceleration must be smooth and reproducible, with minimal timing jitter when the wire passed through the beam. A Compumotor model KS-230 servo motor with indexer position control was chosen for this system. The motor was selected to provide sufficient torque to accelerate the motor and wheel to a velocity of 25 RPS in less then half a revolution. The ideal velocity profile would have a trapezoid shape, i.e., constant acceleration from rest up to the desired operating speed, followed by a period of constant velocity as the wires pass through the beam, and finally constant deceleration back to rest. However the inertia of the motor and wheel combined with the rapid change in velocity makes it difficult to achieve the ideal velocity profile. Figure 2 shows a plot of an ideal velocity profile specified by the indexer and an actual profile measured by a tachometer mounted on the back of the motor. There is considerable overshoot in the measured velocity due to the inability of the servo motor's closed loop control system to react fast enough to keep the motor on the specified velocity profile. However the traversal time of the wire through the beam is less then 1 ms. Therefore the velocity can be considered constant during the measurement. The motor speed is recorded along with the signal data in order to determine the wire's velocity at the time of the measurement.

For the best performance the wheel must be both stiff and light weight. Of the several materials; aluminum, G-10 fiberglass epoxy, and VESPEL (a polyimide) that were tried, 1.6 mm-thick G-10 was found to best. Because the one-spoke wheel tends to distort a small amount during acceleration and deceleration, it is not possible to rigidly attach the wires to the wheel. Instead one end of each wire is attached to the wheel with a small spring which helps maintain a constant wire tension. Using the spring attachment the wires are able to survive over 10,000 cycles at a peak wheel speed of 25 RPS. The electrical contacts to the wires were routed through a hole in the shaft of the ferrofluidic feedthrough between the wheel in vacuum and the motor in air, and potted to maintain the vacuum seal. A short length of wire was left on the motor end of the ferrofluidic feedthrough to take up the slack as the motor rotated back and forth. Two small rings were mounted on either side of the wire-beam intersection point to act as the charge collectors. The collector rings were connected in series to a vacuum feedthrough to an external connector.

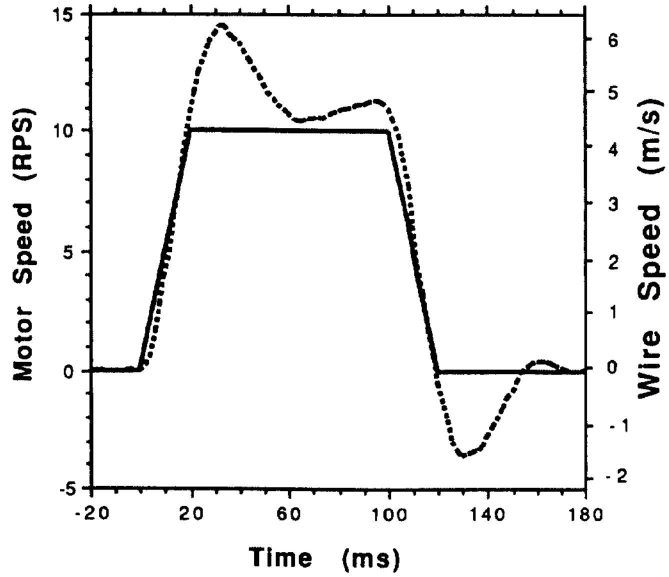

Figure 2. Specified and measured velocity profiles, (solid and dashed curves respectively).

V. ELECTRONICS

The servo motor is controlled by a prototype VME indexer, designed and built at LANL.[2] This indexer was designed to replace commercially available indexers that tend to have timing jitter of up to a few ms due to the cycle time of their onboard microprocessors which must be interrupted to begin the control sequence. The LANL indexer has no onboard microprocessor. Instead the indexer has only memory which is loaded ahead of time with a bit pattern corresponding to the motor step sequence. Upon receipt of a trigger the bit pattern is immediately read out at a constant rate determined by a clock frequency. Using this indexer, the jitter between the trigger and the time the wheel rotates half a revolution, passing one of the wires through the beam center at a wheel speed of 25 RPS, was measured to be 20 μs with respect to the external trigger.

A set of transimpedance amplifiers were designed and fabricated to convert the small secondary electron current to a voltage signal with a gain 20,000 volts per ampere. The transimpedance amplifiers could also isolate the input and apply either a positive or negative bias of up to 300 V.

VI. BEAM TESTS

The system was tested using the electron beam provided by the APLE Prototype Experiment (APEX) electron accelerator at LANL.[3] The APEX beam is a low-duty 20 to 40 MeV electron beam with a typical beam current of 10 to 50 mA over a 5 to 20 μs long macro pulse. The beam at the flying wire station was typically 2 to 4 mm in width. The short macro pulse length of the APEX electron beam ruled out the possibility of operating the system in the flying-wire mode. However the short macro pulse allowed the wires to be placed directly in the path of the beam without being overheated. The first goal of the APEX beam tests was to determine the best means of detecting the secondary electron signal from the beam and wire interaction. The secondary electron signal measured from the charge depletion current on the wires had a typical signal to noise ratio of less then 10. The poor signal to noise ratio of the wires is attributed to the ~1k Ω resistance of the carbon wires which makes them good antennas for picking up noise. Applying a negative bias potential of a few hundred volts did not have any measurable effect the wire's signal to noise ratio. The signal to noise ratio of the charge collector was found to be almost an order of magnitude better then the wire's. However the charge collectors had a background level of about 10%. The source of the background is not completely understood but is believed to be due to secondary electrons produced by the interaction of the beam halo with the walls of the beam pipe. The background subtracted signal from the collectors was comparable to the signal measured from the wires, indicating that the collection efficiency was near 100%. The signal measured from the wires and collectors was consistent with a secondary emission rate of about 1% per incident electron.

The second goal of the APEX beam tests was to see how well the secondary electron signal from the wires could determine the beam profile. Because the macro pulse was too short to operate the system in the flying-wire mode, the wires were slowly stepped through the beam between macro pulses to map out the beam profile averaged over a number of macro pulses. An optical transition radiation (OTR) screen and video camera system was mounted 28 cm upstream of the flying wire setup to allow comparison between the flying-wire and video profile measurements. Figures 3 and 4 show OTR screen vs flying-wire profile measurements made in the same plane of two different width beams. The flying-wire profile measurements were made using the charge collection rings with the background subtracted. The width of the OTR profile has been normalized to match the width of the flying-wire profile to account for the expansion of the beam over the drift

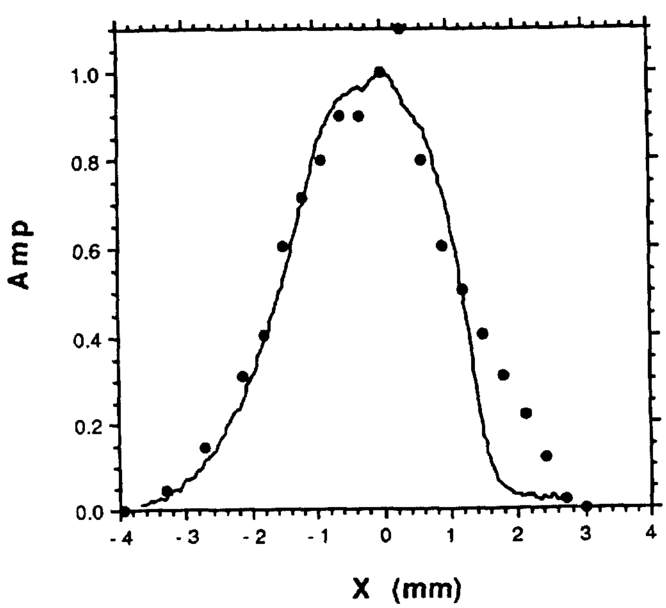

Figure 3. Wide beam profile measured by the flying wire (dots) compared to the profile measured by the OTR screen (solid curve).

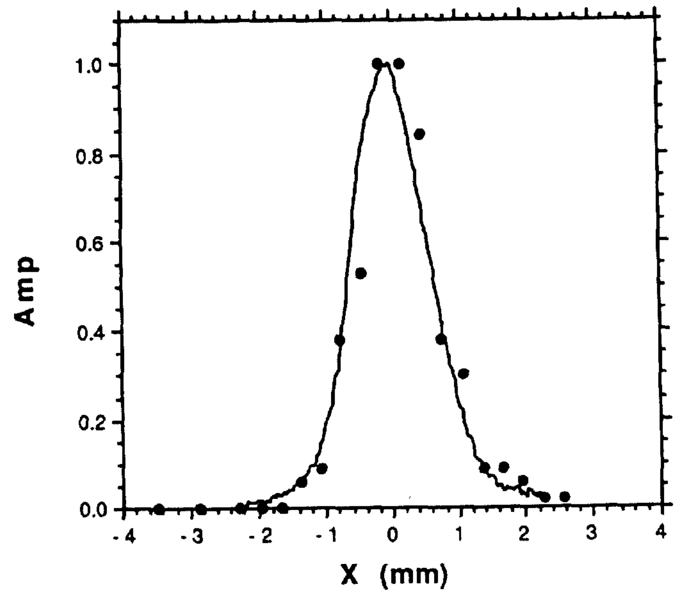

Figure 4. Narrow beam profile measured by the flying wire (dots) compared to the profile measured by the OTR screen (solid curve).

between the OTR screen and the flying-wire. The amplitude of both profiles has also been normalized to one, and both peaks have been centered at the origin. The flying-wire profile measurements show agreement with the normalized OTR profiles.

VII. CONCLUSIONS

The prototype flying-wire system performed well during bench tests of the mechanical assembly. The system was found to be capable of accelerating the wheel up to the required speed with very little timing jitter. The prototype flying-wire also performed well during beam tests. The beam tests indicated that the charge collectors had a significantly higher signal to noise ratio and were therefore the best method of detecting the secondary electron current signal from the beam and wire interaction. The use of charge collectors greatly simplify the setup by eliminating the electrical connections to the wires mounted on the rapidly moving wheel. Measurement of a beam profile, using the charge collectors, was in agreement with beam profiles observed on a near by OTR screen. Further refinements are being incorporated into the second generation system that will be put into service on the APLE/HPO beam line for a fully integrated test of the mechanical assembly, electronics, and control system. This system can be readily adapted to measure the profile of almost any charge particle beam providing its macro pulse length is sufficiently long for the wires to scan it, and its current density is low enough to not overheat the wires.

VIII. REFERENCES

[1] R. Chehab et al., IEEE Transactions on Nuclear Science, Vol NS-32 No. 5, p 1953 (1985).

[2] C. M. Fortgang, Los Alamos National Laboratory, LA-CP-90-466 (1990).

[3] P. G. O'Shea et al., NIM A318, 52 (1992).