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A FAST WIRE SCANNER FOR THE TRIUMF ELECTRON LINAC

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Abstract

The superconducting CW LINAC presently being commissioned at TRIUMF will accelerate up to 10mA of electrons to the energy of 30 – 50 MeV. Thus, beam powers up to 0.5 MW are eventually expected. To support high beam power operation modes, a Fast Wire Scanner (FWS) capable of velocities up to 3 m/s over a 70 mm range was developed. A stepper motor driven helical cam allows for a long stroke enabling two orthogonal wires to scan both axes in one scan. The radiation produced when the wires pass through the beam is detected by a BGO scintillator coupled to a photomultiplier (PMT), while wire position is measured with a precision linear potentiometer. A Struck SIS3302 VME transient recorder, synchronized to the beam pulses, simultaneously captures both signals to produce the beam profiles in the EPICS control system. The design of the FWS and initial beam measurements will be presented.

INTRODUCTION

As a part of the effort to substantially expand the Rare Radioactive Isotope Beam (RIB) program, TRIUMF is currently in a construction phase of a 50 MeV 10 mA CW superconducting electron LINAC, to act as a driver for production of neutron-rich isotopes via photo-fission reactions [1]. The electron accelerator comprises a gridded 10 mA 300 keV thermionic gun operated at 650 MHz, a 50 MeV superconducting CW LINAC and a 70 m long beam transport line to deliver the electron beam to RIB production targets. The LINAC presently consists of two cryomodules housing three 1.3 GHz 9-cell cavities of TESLA type. Two additional cavities in a separate cryomodule will be added to the setup in the future. The first beam was accelerated to 22 MeV in 2014 and presently various accelerator systems are still undergoing commissioning to prepare the machine for high beam power operation.

Although the beam tuning is typically done with beam currents of a few microamperes using diagnostic devices such as view screens and Faraday cups [2], the actual RIB production will require monitoring of beam parameters at the full beam current. To support production modes several diagnostic devices have been developed including the FWS.

Calculations show that a carbon wire needs to travel at speeds of about 3 m/s to survive the 10 mA and 50 MeV electron beam with the size of about 0.5 mm FWHM [3]. Wire scanners operated at even higher speeds exist [4] but employ a rotary motion of the wire. For the sake of compatibility with the standard diagnostics vacuum chamber, the TRIUMF design is based on a linear motion. The linear motion allows both X- and Y-plane scans in a single pass using two orthogonally mounted wires on the same frame. To our knowledge this is the fastest linear wire scanner presently in operation.

MECHANICAL DESIGN

The FWS design was inspired by the wire scanner developed for FLASH at DESY [5], which utilizes a slot winding cylinder that engages a follower to produce a 48 mm stroke with 24 mm working range at speeds of 1 m/s. The short travel range of the DESY design requires a dedicated device for measuring each plane. For the TRIUMF FWS (Fig. 1) we required a longer working range of 70 mm to allow one FWS to scan both planes, and a speed up to 3 m/s which resulted in an overall stroke of 170 mm. To achieve the longer stroke in a compact device, a multi-turn helical cam was developed.

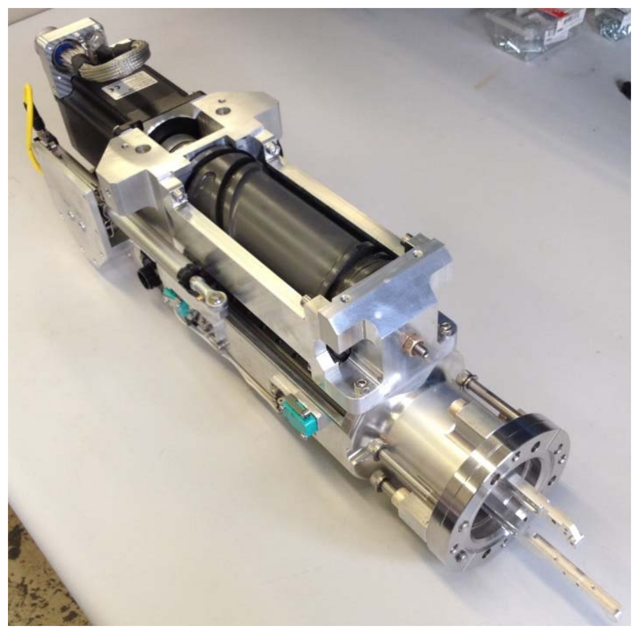

Figure 1: TRIUMF Fast Wire Scanner assembly.

The TRIUMF FWS mounts a wire fork assembly to a carriage which is supported on the main frame by linear bearings, and is driven in and out by the cam. To minimize the momentum generated at high accelerations, the mass of the moving parts is minimized where possible to a total of 816 grams.

Cam Design

The cam is a hollow 75 mm diameter cylinder constructed of aluminium and is hard anodized after machining. The 170 mm stroke includes two 70 mm ramps, and 30 mm of constant 168 mm/rev pitch in the middle. The motion of the FWS minimizes jerk by using a sinusoidal velocity ramp which is machined into the cam profile. The flat section at the end allows the cam to reach full speed before the carriage motion begins.

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Cam Endless Slot

The cam follower is 8 mm in diameter, made of phosphor bronze, and supported by two ball bearings. During bench testing, it was found that a stepper motor stall causes the cam to freewheel until the follower collides with the end of the cam slot. To prevent this, a continuous slot with a decreasing depth was made at both ends. This allows a spring loaded follower pin to skip around when the cam is rotated in one direction, and drive the carriage when rotated in the opposite direction. Monitoring the height of the follower is also used to index the cam position.

Cam Equations

The cam slot is machined by a multi-axis CNC machine which uses 3D coordinates generated in MATLAB to ensure the slot conforms to the motion equation. Each section of the cam, illustrated by the colours in Fig. 2, uses a different set of equations which are stitched together to create the full curve.

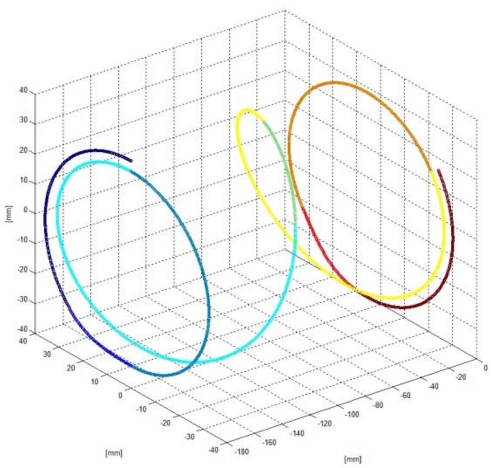

Figure 2: MATLAB 3D cam curve.

The equations used to generate the sinusoidal velocity ramp shown in yellow are as follows:

$$x = r\cos(\theta) \quad (1)$$

$$y = r\sin(\theta) \quad (2)$$

$$z = \frac{(\theta - 2\theta_i + \theta_f)p}{4\pi} - \left(\frac{l}{\pi}\right)\sin\left(\frac{(\theta - 2\theta_i + \theta_f)p}{4l}\right) - l + z_i \quad (3)$$

For:

$$\theta_i \le \theta \le \theta_f \quad (4)$$

Where:

$$\theta_f = \theta_i + \frac{4\pi l}{p} \quad (5)$$

Here *x, y, z* are the curve coordinates in mm, *r* is the radius in mm of the bottom of the cam slot, *l* is the length of the ramp in the *z* direction in mm, *p* is the maximum cam pitch in mm/rev, θ_i is the start angle of the ramp in radians, θ_f is the ending angle of the ramp in radians, and z_i is the starting *z* coordinate in mm.

Vacuum Sealing

The motion of the FWS is transferred to the vacuum using an edge welded bellows, constructed of AM350 stainless steel. During testing, it was found that the high rates of acceleration caused the initial bellows to oscillate excessively. This was eliminated by selecting a different bellows with a higher spring rate. An external spring helps shift the combined force of the vacuum and bellows spring such that the net force is near zero at the middle of travel and close to opposite at each end.

Motion Parameters

Several theoretical parameters for a peak speed of 3.25 m/s, shown in Table 1, were calculated using the cam equations, moving mass, vacuum force and spring properties. Stress calculations were then performed for the follower pin, which showed a safety factor of over 6 times for yield strength.

Table 1: Theoretical Motion Parameters

Parameter	**Value**
Max acceleration	118 m/s^2
Max jerk	8640 m/s^3
Max follower pin force	360 N
Max cam torque	7.5 Nm

Scanning Wire

The scanning wires are mounted to an aluminium fork with stainless steel springs to maintain tension. Machined features on the fork set the wires at the correct angles. Initial beam tests have been done using a 50 µm diameter titanium wire. A carbon wire may be tested in the future when measuring higher beam currents is required.

MOTOR CONTROL AND DAQ

The FWS cam is driven by a NEMA 34 stepper motor and powered by a 10 Amp peak, 160 VDC bus, 64 micro-stepping driver. The driver is controlled by a Galil DMC4040 motion controller. To ensure a minimum 3.0 m/s velocity over the 70 mm scanning range, a peak velocity of 3.25 m/s is required. With a 168 mm/rev pitch, this equates to 19.3 rev/s or a 247.6 kHz pulse rate which is within the driver limit of 400 kHz.

The radiation produced when the wires pass through the beam is detected by a BGO scintillator coupled to a PMT. The PMT location was optimized with a FLUKA simulation and in the low energy section is mounted directly in line with the FWS to a stainless steel flange machined to 500 µm thick in the centre.

The wire position is measured with a precision linear potentiometer. The PMT and linear potentiometer signals pass through a signal conditioning module before going to the Struck SIS3302 VME transient recorder.

The EPICS control system is used to set the PMT high voltage level, send motion commands to the Galil motion controller, and capture and process the data from the transient recorder.

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BENCH TESTS

To evaluate the FWS performance, several bench tests were performed at various stages of development.

Speed Tests

The linear potentiometer used for the position signal was connected to an oscilloscope to verify the actual speed matched the target speed. The highest reliable peak speed was 3.25 m/s, while speeds higher than this were possible, they would occasionally stall the stepper motor. During testing it was found that a mechanical resonance occurs in the range of speeds from approximately 0.2 m/s to 0.4 m/s. This range will be avoided during operation.

Wire Tests

High acceleration rates may cause distortion of the wire straightness. A short exposure camera triggered by the motion controller was used to capture images of the wire at 3.25 m/s. In fact, wire distortions were observed as shown in Fig. 3, and these were later eliminated by implementing changes to the wire mounting and tensioning.

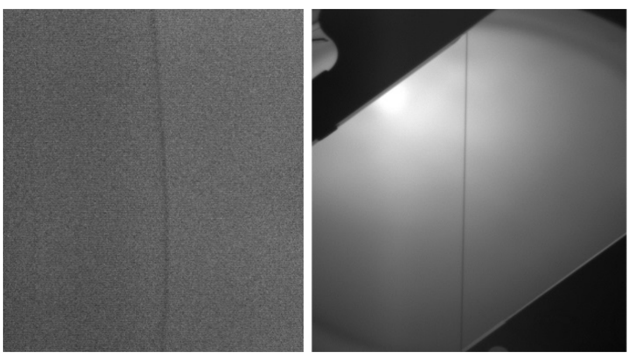

Figure 3: Wire at 3.25 m/s: distorted (left), straight (right).

To verify the linearity of motion, a long exposure capture at 3 m/s of the target shown in Fig. 4 was performed. The multiple holes of the target follow a linear path and overlap with no visible non-linear deviations though the entire motion.

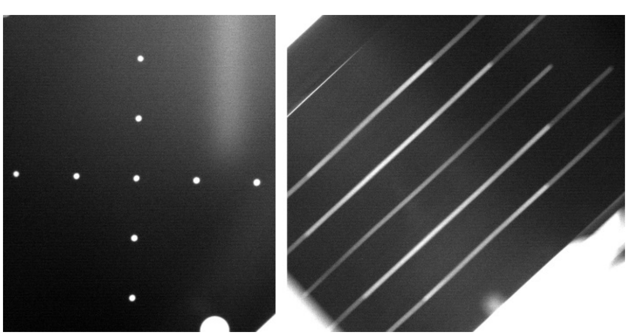

Figure 4: Target at rest (left), and at 3 m/s (right).

BEAM TESTS

Initial beam tests were performed on a FWS installed in the low energy section of the electron LINAC. During the test, 10 μs electron beam pulses at 300 keV were available at a 1 kHz rate with a peak current of ~100 μA; therefore the FWS was run in slow mode at 0.075 m/s with the acquisition system synchronized to the beam pulses.

To check the FWS response, the beam was steered around its nominal trajectory (Fig. 5) and the beam size was varied using the upstream solenoid (Fig. 6).

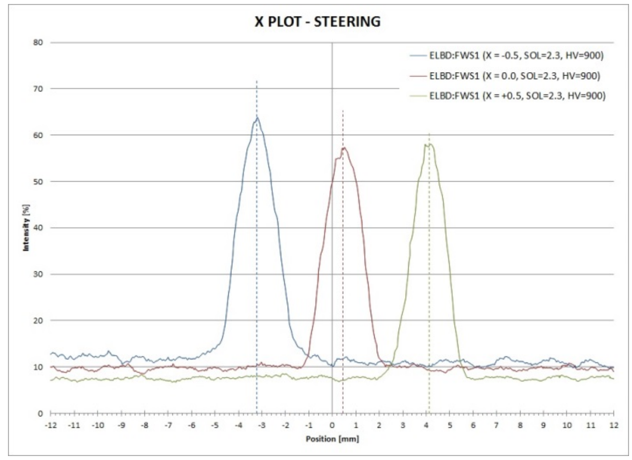

Figure 5: X axis steering changes.

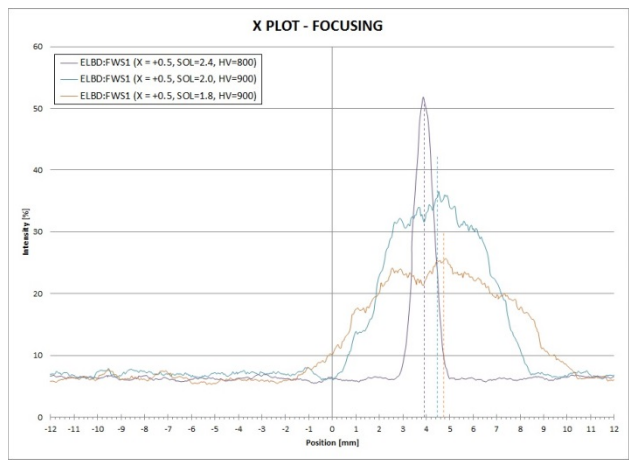

Figure 6: X axis intensity changes.

CONCLUSION

A FWS for the TRIUMF electron LINAC which met the goal of 3 m/s over a 70 mm scan was successfully designed and tested.

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