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FAST AND ROBUST WIRE SCANNERS WITH NOVEL MATERIALS FOR PROFILING HIGH INTENSITY BEAMS

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Abstract

Wire scanners are robust devices for beam characterization in accelerator facilities . However, prolonged usage with intense particle beams leads to wire damage, requiring replacement and beam diagnostic downtime. The fast, robust wire scanner was recently designed and engineered with swappable and modular wire cards, that can accommodate different wire materials under tension. Testing is currently underway at the Jefferson Laboratory (JLab) Low Energy Recirculating Facility. During the course of the diagnostic development and commissioning, we will test Tungsten, Carbon, and boron-nitride nanotube in wire form. The latter is particularly relevant as early results on the material show that it has very high thermal thresholds and may withstand the high-power of the beam during regular operations. This paper will report on the system design and engineering, and preliminary results with operation on the beamline.

INTRODUCTION

Transverse profile diagnostics for high intensity particle beams are critical for quality beam operations and incorporation into feedback controls [1]. Wire scanners allow for beam scanning at high powers by moving a rigid wire across the beam and measuring detector response downstream. However, the wires tend to degrade over prolonged exposure to the beam. In this wire-scanner project, the wires are mounted on a modular card-mount, and will be driven at very high speed, with precision control and readback on position. The modular card permits rapid swapping of the wires with minimal downtime. Additionally, the wire-scanner is mounted with boron nitride nanotubes (BNNT) in thread-form, which holds the promise for prolonged usage in high power beams, due to the higher thermal load handling of the material [2, 3].

General Considerations

The final design of the wire scanner that was developed is shown in Figure 1. The scanner consists of two linear motion stages mounted on a strongback. Direct-drive linear motors provide fast, smooth motion compared to ball screw systems. The wire-card is mounted axially in a large interaction chamber. Two in-vacuum bellows, on either side of the chamber, allow for full retraction of the wire-card for beam clear operation in both directions. The central chamber includes multiple feedtrhoughs and viewports for optical characterization of the wires, as well as for collection of light emitted from the wire during the interaction. The large upper port also serves as the access port, both for initial assembly and for the eventual exchange of wire cards.

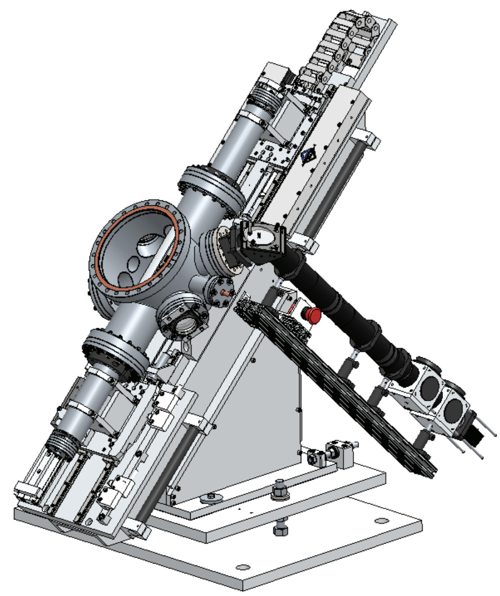

Figure 1: Scale model of wire-scanner. Central chamber incorporates wire mounting card that is precision controlled using linear stages. Optical transport provides imaging of the wires during the interaction and collection of spectral information.

Wire Card Mount

The main engineering directives for the wire-card design are modularity, accommodation of thin wires, and rapid, reproducible replacement. The card is designed to hold wires as small as 10 μm diameter, for high resolution operations [4]. Multiple wire card mounts are available and the modularity allows for use of different wire materials and sizes. The card also accommodates different wire materials, such as tungsten (W), carbon (C), and BNNT threads, with constant and controllable tensioning.

The wire-card holds coplanar wires, suspended across an open fixture, with one wire oriented horizontally, one oriented vertically, and the third at 45° (Fig. 2). The set of wires is sewpt through the beam diameter during operation of the wire scanner, and provides horizontal, vertical and

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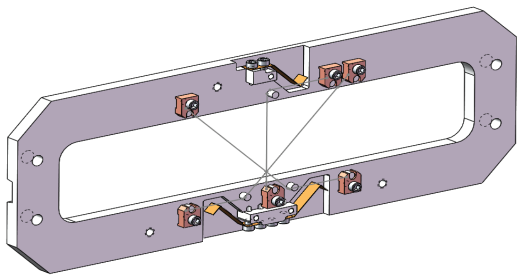

Figure 2: Model of Wire card mount that orients three individual wires: a horizontal, vertical, and 45 ° wire. .

correlation terms in a single scan. A primary constraint is the diameter of the beam since the wires need to be spaced wide enough to avoid any signal crosstalk. The design also places clearance on either side of the wire set, allowing the scanner to be parked in either position, with additional clearance to allow for overrun, for beam propagation without interaction.

The space needed for the wire routing, tensioning, and clamping sets additional width requirements for the mounting card. The card is a monolothic aluminum mount with integrated, individual leaf springs for each of the three wires to provide the appropriate tension. Each of the wires is looped around a set of three round bosses, with the active part of the wire located in the first gap and the tensioning spring in the second. Either end of the wire is located to within 25 µm, providing accurate and repeatable wire location. The wires are each clamped separately and are replaceable individually in case of failure.

Understanding the mechanical behavior of the BNNT threads, in their current form, is crucial to integration into the wire scanner. The threads must be properly tensioned, without sag, and maintain position throughout the duration of the beam scan. The BNNT threads exhibit a wide range of morphologies and it is likely that they have a similarly varied spread in tensile characteristics indicating a careful survey of the various threads is important.

Figure 3: Tension testing apparatus to evaluate the tensile properties of BNNT thread using the wire-scanner leaf spring clamps.

For the preliminary testing a simulacrum of the scanner wire card for holding a single wire was fabricated (Fig. 3). This device clamps one end of the thread, then passes the thread across a small opening to a terminal clamp. The tension is variable and controlled with brass leaf springs. Successful hand assembly of threads in this setup provides preliminary evidence that application in a wire scanner is feasible.

Once a thread has been mounted, the tension can be quantitatively measured using a vibrating wire system. In the vibrating wire setup, the metal wire is replaced with the mounted BNNT thread (or other) and a low-power, tightly focused laser beam shines on the thread. The resulting signal from the downstream photodetector will allow to measure the vibration of the thread as variations in the transmitted laser intensity. Assuming a constant linear mass density, the tension on the thread can be deconvolved from the Fourier transform of the photodetector signal data.

Detector

The wire scanner design encompasses the ability to test many basic features of the beam-wire interaction. The scanner detector includes many options including the measurement of generated secondary electrons, and the current induced in the wires when using conducting wires. BNNT wires, which are naturally insulators, can be doped with metal in this case. In addition, beam loss monitors with photomultipler (PMT) tubes can be incorporated (for W, C, BNNT wires). Finally, an imaging monitor for the BNNT threads provides a quasi-2D image of the wires during the interaction. The monitor includes a photodiode for optical energy measurements and can provide signals similar to conventional scanners however at much simpler and cost-effective means to institute than a PMT that operates in a radiation-noisy environment. The optical camera also provides real time information on the health of the wires during operation.

Boron Nitride Nanotube Threads

Boron nitride nanotubes are similar in structure to carbon nanotubes, yet have demonstrated some superior material properties [2, 3]. Individual multi-walled boron nitride nanotubes are mechanically robust, with axial Young's modulus greater than measured for other existing nanostructures and resist oxidation above 1,100° in air . A thread comprised of BNNT material has the potential to better resist damage, by sustaining higher beam induced heating, than either tungsten or carbon-based wires, which have shown limited performance in high repetition rate operations [5]. The production of BNNT in composite thread forms has been demonstrated and procured for the wire-scanner applications (see Fig. 4). The consistency of quality thread fabrication is currently a major effort of study.

The original discovery that BNNT material could be used as a beam wire scanner was determined during proof-of-concept testing of BNNT fibers at JLab. This test, summarized in Fig. 5, was performed at the Low-Energy Recirculator Facility at a reduced duty cycle yielding 300 µA in a 350 µs pulse (200 nA average current). The image formation was overlaid over many shots of the wire position, and a beam profile image was reconstructed. This preliminary result with a single fiber presents the opportunity for the use of BNNT threads as a suitable replacement for Tungsten

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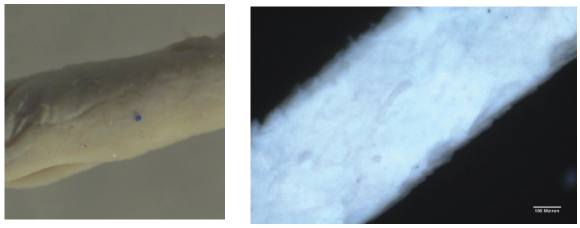

Figure 4: BNNT threads under optical microscope (left) and scanning electron microscope (right).

(or other) wires in wire scanner applications for high current beams. The first results, with larger diameter threads, showed that the BNNT fibers are robust and can handle high intensity without noticeable damage or deterioration.

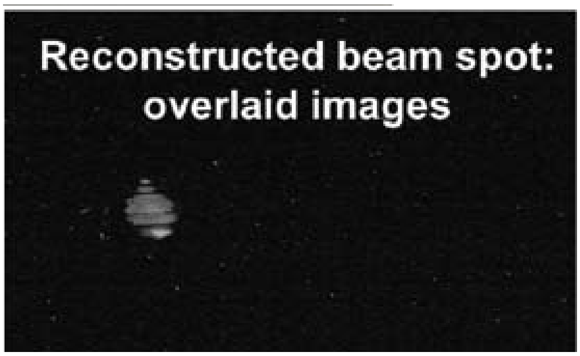

Figure 5: Overlay of images of BNNT wire scanned over beam spot at multiple vertical positions (courtesy B. Jacobson).

In wire scanners with conventional materials, the condition of the individual wire is typically monitored by measuring its conductivity across the mounting structure. Reduced conductivity would indicate significant heating. Wire breakage would be observed if the circuit through the wire was open [6]. However, BNNT is electrically insulating and therefore requires optical characterization of the wires in-situ to determine integrity. The incorporation of a viewport with an optical transport line, including beamsplitters to direct light to a spectrometer and secondary camera, is implemented in the prototype.

CONCLUSION

The wire-scanner designed and developed for testing at the LERF and CEBAF facilities at JLab incorporates design modifications for fast sweeping of the wires through the beam trajectory, and the incorporation of an optical port for direct viewing of emitted light at the interaction point. The relay optics also allow for emission characterization of the spectral and temporal properties of the light. The light properties yield an additional method to characterize the beam profile, complementary to downstream loss-monitor detectors. The BNNT wire development shows the potential to produce thin (sub-25 µm) wires), with tensile strength sufficient for rapid scanning. Currently, the device is installed at the LERF line for preliminary characterization and controls testing with beam delivery. A natural future application of the BNNT-based wire scanner includes the investigation and characterization of beam halo properties at high intensity accelerator facilities [7].

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