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# DEVELOPMENT OF WIRE SCANNER PROFILE MONITOR IN FETS-FFA TEST RING

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*Abstract*

A wire Scanner profile Monitor (WSM) has been developed for the demonstration ring of Fixed Field Alternating gradient (FFA) accelerator, called FETS-FFA. From previous studies, Carbon Nano Tube (CNT) wire is selected for the FETS-FFA WSM, durable for the heat damage of low-energy proton beams on the FETS-FFA test ring (3–12 MeV). A bias voltage, applied to the measuring wires, is required to prevent secondary electrons from returning to the wire due to the stray magnetic fields of the FFA main magnets. The endurance tests of bias voltages on different sizes of CNTs were performed prior to the beam tests on the Front-End Test-Stand (FETS) beam line and the FFA ring at KURNS. The beam tests with bias voltages on FETS and numerical simulations revealed secondary electrons from adjacent wires degraded the reading sensitivity, hence profile accuracy, explaining why the peak of the beam profile was not proportional to the wire size in previous studies. This paper will focus on the endurance test of bias voltages on CNTs as well as beam profile measurements with bias voltages on the FETS beam line. The mechanical design of the rig to install a thin CNT wire (diameter of 10 µm) on the frame head of FETS-FFA WSM will also be presented.

## INTRODUCTION

A wire Scanner profile Monitor (WSM) has been developed to identify the transverse beam profile and position of proton beam for the FETS-FFA [1]. A WSM can also provide a horizontal beam profile of accelerating beams through the interception of the beam with the wire. The challenge is to select an appropriate material of signal wire, durable for heat damage due to interception of low-energy proton beams and its energy depositions on the wire. In previous studies [2], profile measurements of accelerating beams in the FFA ring using carbon nanotube wire (CNT) were successfully performed at KURNS [3] with a 13.5 MeV proton beam. This energy was chosen as it was the minimum required to mitigate the influences of secondary electrons generated at the charge stripping foil during the injection process at KURNS. Additionally, the measurements conducted with 3 MeV H- beam on Front End Test Stand (FETS) [4] at RAL evaluated the durability of wires against the impact of low-energy beams as well as evaluating beam profiles. However, the tests revealed the peak signals of measured profile were not proportional to the cross-section of the wires. To investigate the reason behind, additional experiments with bias voltages applied to the wires in the FETS will be presented. The development of a mounting frame designed for the installation of a thin CNT wire in the frame head of the FETS-FFA WSM will be also discussed.

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## BIAS VOLTAGES ON WIRES

The wire signal for the FETS-FFA WSM will be a positive charge as secondary electrons impinged by the proton beam will escape from the wire. To maintain optimal monitor sensitivity, it is crucial the secondary electrons generated from the wire do not return to the wire. When low-energy secondary electrons (~25 eV) are experienced stray magnetic fields from the FETS-FFA magnets, expected to be within 40 Gauss on the median plane, their trajectories will spiral around the magnetic field lines, returning to the wire. This can be avoided by applying negative bias voltages to the wire. The model simulations were performed using CST electromagnetic solver with bias voltages along with the static magnetic fields of 40 Gauss. The simulations revealed that applying negative bias voltages to the wire increased the Larmor radius of electrons, reducing the number of returning electrons to the wire. The ideal bias voltage will be established once the geometry of the FFA vacuum chamber has been determined. Contrary to the FETS-FFA WSM, the wire signals for the FETS H- beam will be a negative charge generated by stopped electrons (~2 keV) of H- ion at the wires. The profile measurements previously made [2] without bias voltages indicated additional electrons were entering the wire from the surrounding space. A likely source of these incoming electrons is the secondary electrons emitted from adjacent wires when the FETS beam strikes the wires. A Monte Carlo simulation using PHITS [5], based on the configuration of the ISIS Single Wire Injector Profile Monitor (SWIPM) [6] (Fig. 1), indicates that low-energy electrons, within a few tenths of eV generated at the wire by the protons, can entre the adjacent wires as shown in Fig. 2. The secondary electron interference can potentially be minimised by applying positive bias voltages on the wires.

### *Durability Tests of Bias Voltage*

Before profile measurements with bias voltages, durability tests of bias voltages were conducted in different sizes of CNT wires: $\phi$10 µm, $\phi$20 µm, $\phi$30 µm and $\phi$40 µm, all installed on the test frame (Fig. 3). The wires underwent various baking conditions prior to endurance tests, ranging from −300 V to 0 V applied on the wires twice. Other conditions were placing the wire in a baking chamber at 250 °C for three days or heating the wires by DC currents at 100 mA for six hours. The leakage currents from the CNT wires were monitored by ramping up the bias voltages as shown in Fig. 4. In the case of CNTs heated in a baking chamber at 250 °C, the increase in leakage currents was observed

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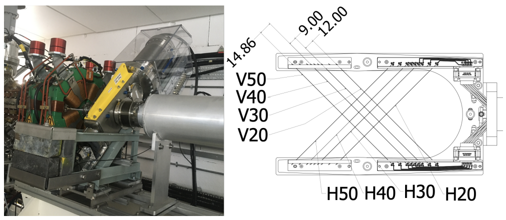


Figure 1: Left is the SWIPM on the FETS beam line. The linear stage of the SWIPM was inclined at 44.5 degrees and was capable of traveling about 150 mm from the park position. The wire head is illustrated in the right figure. The $\phi$20 µm (H20, V20) and $\phi$40 µm (H40, V40) wires were single-wall CNTs provided by DexMat [7]. In contrast, the $\phi$30 µm (H30, V30) and $\phi$50 µm (H50, V50) CNT wires were multi-wall CNTs manufactured by Hitachi Zosen [8].

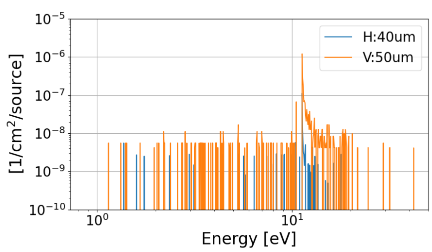


Figure 2: Energy distribution of secondary electrons generated at horizontal $\phi$50 µm wire that enters adjacent wires: horizontal $\phi$40 µm wire (represented by H:40 µm, about 10 mm apart from horizontal $\phi$50 µm) and vertical $\phi$50 µm wire (represented by V:50 µm, about 3 mm apart from the horizontal $\phi$50 µm in the beam direction), computed by PHITS. In the simulation model, a pencil beam of 3 MeV protons impacting the horizontal $\phi$50 µm wire without external electric fields. The statistical result was not sufficiently robust in this simulation.

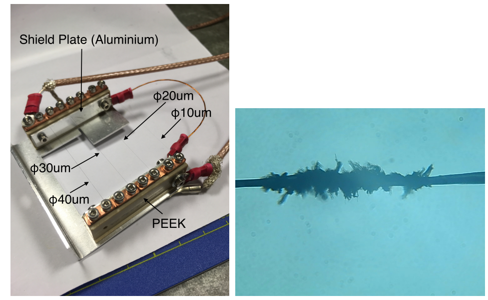


Figure 3: Left: Test monitor with several diameters of CNTs in the vacuum vessel. The wires are clamped by PEEK and copper plates by screws. Two BNC cables were attached on the copper plates where a voltage was applied. The aluminium frame was grounded to the vacuum vessel. Right: The microscope image of $\phi$10 µm CNT after the endurance test. In this case, the CNT were baked in baking chamber at 250 °C for three days.

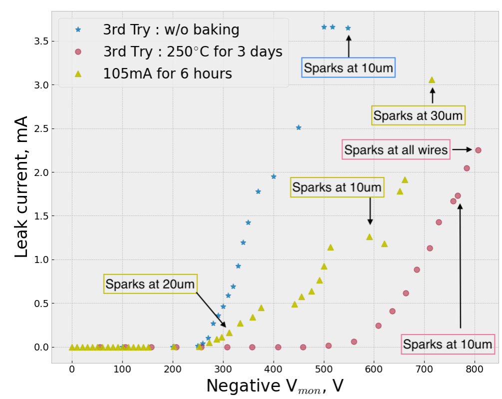


Figure 4: Leakage currents from the wires as a function of negative bias voltages on the wires across the various baking conditions on the wires.

to be slower than the other conditions, and the maximum bias voltage without electric sparking at the wires reached −800 V, lowest leakage currents. The surface of CNTs after the durability tests were observed using a microscope (right photo in Fig. 3). Whilst not the entire wire was affected, certain parts were damaged.

## BEAM TESTS ON FETS

Whilst profile measurements utilised bias voltages on the CNT wire were not conducted at KURNS due to scheduling conflicts, the experiments on FETS were performed with positive bias voltages applied to the wires. The SWIPM was used with several diameters of CNT wires: $\phi$20, $\phi$30 , $\phi$40 and $\phi$50 µm. The top two plots in Fig. 5 presents the signal outputs from both horizontal and vertical wires of $\phi$20 µm at positive bias voltages ranging from 0 V to 30 V. Whilst a few volts of positive bias voltages were effective in maintaining the escape of electrons, small signal bumps were observed in between −50 ms and −10 ms before the beam reached the wires in time when the bias voltages exceeded 10 V. These bumps disappeared when negative bias voltages were applied to all wires as shown in the bottom two plots of Fig. 5. The results confirmed that the secondary electrons generated at adjacent wires affected the beam profile.

Figure 6 plots the peak signals in relation to the wire diameters for various positive bias voltages. Despite the utilise of positive bias voltages, the peak amplitude of the beam profile was yet proportional to the wire sizes. The measured root mean squared (RMS) beam size approached the design value (5 µm) by application of positive bias voltages on the wires as listed in Table 1. The signal from the vertical $\phi$50 µm wire was not readable as it was not connected to the data acquisition system properly.

## SETTING JIG FOR FETS-FFA WSM

Challenges remained in consistently and stably mounting the thin wire to the frame head of the monitor for the FETS-FFA WSM (Fig. 7). The crimped copper beads were not securely fixed on the loop of the tensioning spring wires, leading to the wire dropping from the frame head. Addition-

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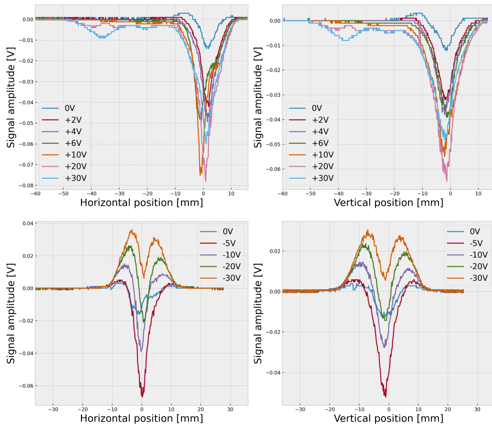


Figure 5: Horizontal (left) and vertical (right) beam profile measured by the $\phi 20\,\mu m$ CNT wire for different positive (tops) and negative (bottoms) bias voltages.

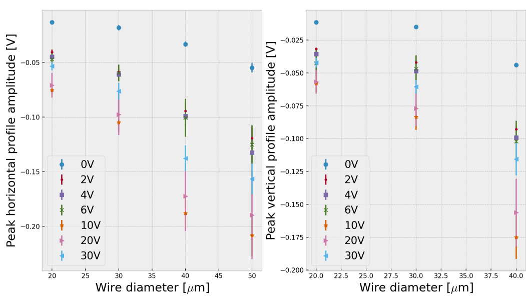


Figure 6: Peak amplitudes of measured profile in horizontal (left) and vertical (right) for different wire thicknesses with positive bias voltages. Peak amplitudes were estimated using second polynomial fit on three data points near the peak.

Table 1: Horizontal and Vertical Beam Size Measured by Different Diameter of CNT Wires

| **Bias Voltage: 0 V** | **Horizontal** | **Vertical** |
|---|---|---|
| **Wire [µm]** | **Beam Size [mm]** | **Beam Size [mm]** |
| 20 | 2.37±0.021 | 4.08±0.14 |
| 30 | 2.82±0.231 | 2.72±0.19 |
| 40 | 2.87±0.043 | 4.21±0.19 |
| 50 | 4.84±0.69 | N.A |
| **Bias Voltage: 5 V** | | |
| 20 | 4.27±0.60 | 4.98±0.85 |
| 30 | 4.73±0.39 | 5.29±0.67 |
| 40 | 4.81±0.26 | 6.37±0.22 |
| 50 | 5.52±0.11 | N.A |

ally, it was difficult to provide a consistent wire length to fit the distance between the top and bottom tensioning spring wires on the frame. Therefore, the design of setting jig was developed to improve the installation procedure as shown in Fig. 8. In the new system, the wire is crimped with a copper ball at each end. The copper balls are modified using with a wire cutting machine to produce a 100 µm slit. The size of copper ball is sufficiently large compared to the loops of the tensioning spring wires. A setting jig consists of two small indents set at the correct pitch to house the copper balls and the 10 µm CNT placed in-situ. Once crimped, the wire assembly is attached and supported to the frame head which is suspended on the tensioning springs producing adequate tension, preventing the wire from falling off the frame head.

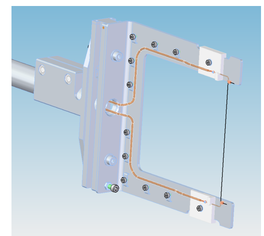

Figure 7: Mechanical view of the frame head of the FETS-FFA WSM. The wire (black line in the centre) is electrically isolated from the aluminium frame by the PEEK insulator (white plates). The signal cables are connected to the spring wires, allowing for the resistance of the wire to be measured from outside the vacuum vessel.

Figure 8: Left: the mounting frame of thin CNT wires for the FETS-FFA WSM. Right: a 2 mm diameter of copper ball on the mounting frame with 50 µm CNT wire in this figure.

## SUMMARY

The feasibility study of WSM has been performed under varying bias voltages applied to the CNTs. Durability tests revealed baking CNTs at high temperatures resulted in optimal performance, allowing for the application of bias voltages without causing critical damages on the wires. Beam profile measurements under the bias voltages in FETS have indicated that secondary electrons generated from the adjacent wires influenced the profile measurements, cross checked by PHITS simulations. Whilst positive bias voltages have been applied to the wires, the peak of beam profiles were not proportional to the wire sizes. To remove the effects of secondary electrons to the profile measurements, a single wire will be installed in future experiments. A new setting jig has been developed to install thin CNTs on the frame head of the FETS-FFA WSM, enabling consistent mounting procedure.

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## REFERENCES

[1] S. Machida, “FFA design study for a high intensity proton driver”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 1437–1439. doi:10.18429/JACoW-IPAC2023-TUPA044

[2] E. Yamakawa *et al.*, “Study of Single Wire Scanner Monitor for FETS-FFA Test Ring”, in *Proc. IBIC’23*, Saskatoon, Canada, May 2023, WEP019. doi:10.18429/JACoW-IBIC2023-WEP019

[3] Y. Mori *et al.*, “Present Status of FFAG Proton Accelerator at KURRI”, in *Proc. IPAC’11*, San Sebastian, Spain, Sep. 2011, paper WEPS077, pp. 2685–2687.

[4] A. P. Letchford, “Upgrades and Developments at the ISIS Linac”, in *Proc. LINAC’22*, Liverpool, UK, Aug.-Sep. 2022, pp. 1–6. doi:10.18429/JACoW-LINAC2022-MO1AA01

[5] T. Sato *et al.*, “Features of Particle and Heavy Ion Transport code System (PHITS), version 3.35”, *J. Nucl. Sci. Technol.*, vol. 55, no. 6, pp. 684–690, 2018. doi:10.1080/00223131.2017.1419890.

[6] D. M. Harryman and C. C. Wilcox, “An Upgraded Scanning Wire Beam Profile Monitoring System for the ISIS High Energy Drift Space”, in *Proc. IBIC’17*, Grand Rapids, MI, USA, Aug. 2017, pp. 396–400. doi:10.18429/JACoW-IBIC2017-WEPCC18

[7] DexMat, https://store.dexmat.com/

[8] HiTaCabyHitachiZosenLtd., https://www.hitachizosen.co.jp/