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Angelica Ottaviano , Sankha Banerjee , and Yevgeny Raitses 

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Angelica Ottaviano,<sup>a)</sup> Sankha Banerjee,<sup>b)</sup> and Yevgeny Raitses<sup>c)</sup>

## AFFILIATIONS

Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA

<sup>a)</sup>**Current address:** Mechanical and Aerospace Engineering Department, University of California, Los Angeles, California 90095, USA.

<sup>b)</sup>**Current address:** Mechanical Engineering Department, California State University, Fresno, California 93740, USA.

<sup>c)</sup>**Author to whom correspondence should be addressed:** [yraitses@pppl.gov](mailto:yraitses@pppl.gov)

## ABSTRACT

Plasma-wall interaction in the presence of secondary electron emission (SEE) can lead to a degradation and reduction in the performance of plasma devices. Materials with complex surface architectures such as velvet, fuzz, and feathered surfaces have a lower SEE yield than the same materials with a flat surface and can, therefore, be useful for plasma applications. This reduction in the SEE is due to the trapping of secondary electrons in the microcavities formed by complex surfaces. In this paper, we present a rapid method for a simultaneous comparison of the SEE yield and surface properties of materials with different surface architectures. The method uses Scanning Electron Microscopy to simultaneously evaluate the surface morphologies and SEE yield properties for a microarchitected surface. This technique was applied to carbon velvets, and results show agreement with recent theoretical models and with the direct determination of the SEE yield from measurements of the currents of the primary electrons impinging the surface and of the secondary electrons emitted from the surface.

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## I. INTRODUCTION

In plasma applications such as electric propulsion<sup>1,2</sup> and magnetic fusion devices,<sup>3,4</sup> the secondary electron emission (SEE) from plasma bounding walls can be an undesired phenomenon, causing an enhancement of plasma-wall interactions and increasing power losses in plasma devices.<sup>5–7</sup> Texturing the surface of secondary electron emitting materials with nano-, micro-, and even millimeter sized features allows one to significantly reduce SEE by trapping and reabsorption of emitted electrons in cavities formed between these features.<sup>8–17</sup> Secondary electrons can either be *true secondary electrons* or backscattered electrons. True secondary electrons originate from the surface atoms of the target material and have energies of up to 50 eV. Backscattered secondary electrons are primary electrons, which are either elastically or inelastically backscattered, and they have energies between 50 eV and the primary electron (PE) energy. In general, the total SEE of a surface is dominated by true secondary electrons.<sup>12</sup> Recent studies have shown that the SEE yield of these complex materials, which is defined as the ratio of

true secondary electrons to the primary electrons impinging the wall, depends on the geometries of their surface structures. For example, in Ref. 14, the net SEE yield of a microporous Ag surface was reduced by 45% as compared with that of the SEE yield from a flat surface made from the same material. This was achieved by controlling the depth and relative placement of the pores with respect to each other. In another case, shown in Ref. 15, the reduction of the SEE yield of a grooved TiN surface is both theoretically simulated and experimentally characterized with respect to the aspect ratio ( $A_R$ ), which is defined as the ratio of the height to the radius of the groove. In the above examples, the aspect ratio of these materials was typically low ( $<10^2$ ). In recent studies of higher aspect ratio ( $>10^2$ ) carbon velvet materials, the SEE yield was reduced up to 65% as compared to a flat graphite surface.<sup>1</sup> In Ref. 9, it is predicted that a fractal repeating fibrous structure of a velvet surface may suppress SEE even more than the high aspect ratio velvet due to the loss of the characteristic angular dependence of the SEE yield on the incident angle of primary electrons.

Indeed, for the tungsten fuzz surface, a weaker sensitivity of the SEE yield to the incidence angle of primary electrons was measured as compared to a flat tungsten surface.<sup>12</sup> A strong dependence of the SEE yield on the surface morphology and possible variations and deviations of the actual surface morphology from the designed morphology implies the importance of *in situ* characterization of the surface structure during the measurements of the SEE properties. In Refs. 10 and 12, a large spread in the local misalignment of fibers from carbon velvets and tungsten fuzz compared with the manufacturing design of the material is observed.

Scanning electron microscopy (SEM) is a widely used tool for the evaluation of the surface structure of materials. Its basic principle of operation is based on the generation of SEE, which is registered by an Everhart-Thornley detector.<sup>18</sup> The Everhart-Thornley detector has a scintillator inside a Faraday cage, which is biased to different voltages for attracting secondary electrons. A bias of 50 eV is applied to the Faraday cage so as to attract true secondary electrons, and backscattered secondary electrons will reach the detector if their direction of travel leads them to it. Therefore, the image signal is generated by mostly true secondary electrons and a fraction of high energy backscattered electrons proportional to the solid angle subtended by the detector.<sup>19</sup> The SEM used in these experiments has a collection angle of 30°. Based on the angular distribution of backscattered electrons described by Lambert's cosine law in Ref. 20, the fraction of collected backscattered electrons should be approximately 12%. In addition, the surface composition of the evaluated material can be characterized using energy-dispersive X-ray spectroscopy (EDS), which is an integrated part of many modern SEMs. In the operation of a conventional SEM, a focused electron beam scans the surface of a sample, which in turn emits true and backscattered secondary electrons collected by a detector. The signal generated by the interaction between the primary electrons and the material surface results in a two-dimensional gray scale image of the scanned surface area of the sample.<sup>18,21</sup> The main advantage of using SEM rather than optical microscopy to image the surface of a material is that its depth of field is very long due to the narrow electron beam, which can penetrate far into a sample. These characteristics of SEM are ideally suited for simultaneous characterization of surface morphology and SEE yield from complex surfaces. SEM images were used in a recent study to measure the actual fiber packing density of velvet samples and were compared to measurements of the SEE yield of the sample surfaces.<sup>10</sup> These SEE yield measurements are normally made using the current-sample method,<sup>10,12,13,22</sup> but it should also be possible to use SEM to qualitatively analyze the SEE yield properties of an imaged surface.<sup>18</sup> Methods for measuring the SEE yield and backscattered electron coefficients in an SEM have been reported in the literature by Reimer *et al.*<sup>23</sup> where a small, modified instrument was mounted on the specimen support of an SEM. The apparatus consisted of a spherical grid connected to ground and a spherical collector, which is positively biased to +50 eV so that the grid-collector combination prevents secondary electrons generated by backscattered electrons from leaving the collector. By applying a positive or negative bias on the sample under consideration, the backscattered coefficient and SEE yield coefficients were calculated by measuring current at the collector. Previous work, however, does not make use of SEM imaging of the sample surface, while in this research, we present

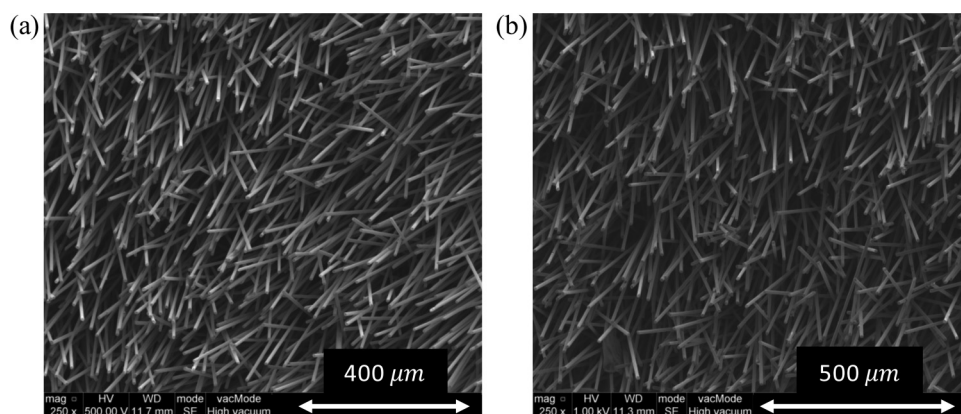
simultaneous SEE and complex surface morphology property evaluations by producing SEM images.

In this paper, we demonstrate the use of SEM for the evaluation of surface morphology and SEE properties from carbon velvet. Rather than directly measuring collector current, the pixel intensity of an SEM image is calibrated with planar graphite to estimate the SEE yield and directly compared with geometrical properties of the sample surface, which are also determined by the SEM image itself. The dependence of the SEE yield on the length of the carbon velvet fiber, fiber packing density, and fiber orientation is compared with recent theoretical results<sup>9</sup> and experimental results obtained using a conventional method for characterization of SEE properties with an electron gun and a collector of secondary electrons.<sup>10</sup> This method of SEE determination by measuring primary and secondary electron currents will be referred to as the direct SEE method. The details of this method are reported in Ref. 24: the solid angle of the first grid is 120° and the collector efficiency was measured to be between 85% and 87%. The accepted energies for secondary electrons were between 0 eV and 50 eV, and for primary electrons these were between 50 eV and 2 keV. In the SEM, the efficiency of the Everhart-Thornley detector based on the subtended solid angle is 80%–82%, and the collector grid is also biased to 50 eV while the primary electron beam can be modulated between 500 eV and 40 keV for an optimal SEM image quality. In both cases, a cosine distribution is assumed for emitted electrons. The main differences between the proposed and conventional methods are that the former can provide information on local morphology and chemical composition of the surface irradiated by the electron beam, while the conventional method can provide a direct measurement of the SEE yield for a lower range of electron energies. These energies can be between 50 eV and 2 keV, while the SEM method typically should be kept at >500 eV electron energies. The SEM method, however, has the advantage of a precise stage for translating and tilting samples, which can be used for measurements of the yield dependence on the incident electron beam angle. Both techniques can be complementary for the characterization of SEE properties from complex surfaces.

## II. SEM ANALYSIS OF VELVET SAMPLES

### A. Measurement procedure

Surface morphology and SEE properties of five carbon velvet samples with different fiber lengths and fiber packing densities were characterized using a conventional Environmental Scanning Electron Microscope at the Princeton Research Institute for the Science and Technology of Materials (PRISM). The carbon velvet samples used in this research were the same as those described in Table 1 of Ref. 10. In particular, the samples have fiber lengths varying between 0.5 mm and 3.0 mm, and a fixed fiber diameter of  $\sim 3.5 \mu\text{m}$ . In each sample, the fibers are attached to a 25.4 mm diameter graphite substrate. The packing density of a sample is normally defined as the ratio of fiber area to the total sample area. For the samples under this investigation, the packing densities are indicated by the manufacturer to be between 0.8% and 4.0%. These values, however, refer to the case when the fibers are normal with respect to their substrate, and the fiber area is comprised of fiber tips only. The actual packing densities of the samples range



**FIG. 1.** (a) SEM image of carbon velvet with 0.5 mm fiber length and a manufacturer specified packing density of 4.0%. The primary electron beam energy is 0.5 keV, and the actual packing density of the imaged region is 86%. (b) SEM image of the same sample using a primary electron beam energy of 1.0 keV. The actual packing density of this region is 92%.

from 60% to 90%. This is because the fibers are mostly misaligned, and the fiber side surfaces contribute to the total fiber area. The method for calculating the true packing density of the carbon velvets using SEM is described in Ref. 10.

To estimate the SEE yield using SEM images of the velvet surfaces, all five samples were introduced into the SEM vacuum chamber simultaneously. The beam-sample parameters such as beam spot size, working distance, brightness, and contrast were kept fixed so that the acquired images could be compared in post-processing under the same conditions. The digital brightness and contrast were chosen by monitoring a live pixel intensity histogram of the image so that the dynamic range was always entirely included. The primary electron beam was scanned at a rate of  $8 \mu\text{s}$  per pixel and was focused to a  $\sim 2 \text{ nm}$  spot size. The beam current was  $\sim 10 \text{ pA}$ , therefore, the dosing was of  $8 \times 10^{-17} \text{ C}$  per location. A planar HOPG graphite sample smoothed by a lathe and with a square area of  $5 \times 5 \text{ mm}^2$  was also imaged together with the velvet samples. This is in order to establish the link between the image pixel intensity and the SEE yield for the reference flat surface with the known SEE yield obtained in previous direct measurements conducted using the current-sample method.<sup>24</sup>

In SEM measurements, the electron beam energy was set to 0.5 and 1 keV. A total of ten adjacent  $\sim 1 \times 1 \text{ mm}^2$  surface regions of each sample was imaged. Each velvet SEM image was then analyzed as an 8-bit gray scale array of pixel intensities. The average gray scale pixel intensity of each image was calculated using MATLAB. Because the SEM detector signal strength is proportional to the number of secondary electrons collected, pixels with black intensity indicate no SEE yield, and pixels with white intensity indicate the highest SEE yield for graphite, which should correspond to the SEE yield at very shallow angles of incidence. The average pixel intensity of the smooth graphite sample was set equal to the known SEE yield from a graphite sample at the normal incidence angle of primary electrons. For example, in Refs. 10 and 24, the SEE yield of 0.85 was measured for a smooth graphite surface at 0.5 keV primary electron beam energy and the SEE yield of 0.75 at 1.0 keV primary electron beam energy. Brighter pixel intensities and SEE yields larger than the planar values indicate an increased angle of incidence with the primary electron beam.<sup>25</sup> References 10 and 24 used the same HOPG graphite sample in their measurements.

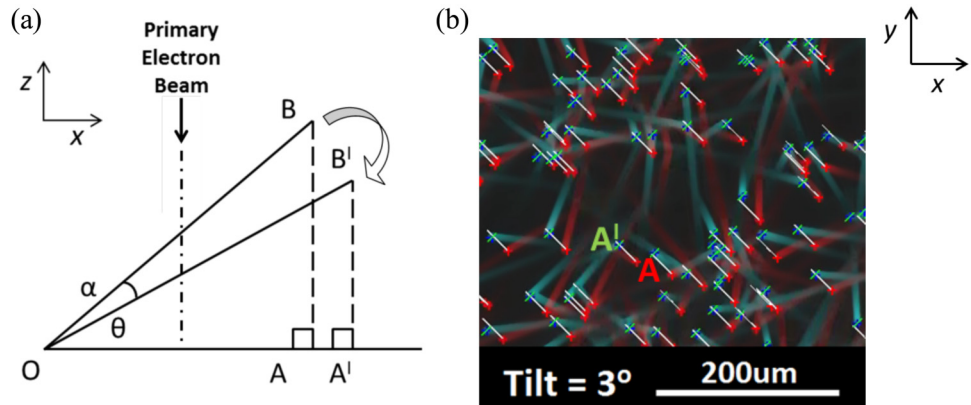
For our experiments, the conversion factors between an 8-bit gray scale pixel intensity value to the SEE yield at 0.5 keV and 1.0 keV primary energies were, respectively, 0.0058 and 0.0043. For each SEM image, this factor was used to determine a qualitative estimate of the SEE yield obtained in SEM measurements at the same beam energies. This process was repeated for each primary electron beam energy and, therefore, each primary energy measured produced a different conversion factor. Figure 1 shows an example of a velvet surface imaged with 0.5 keV and 1.0 keV primary electron beam energies.

## B. SEM evaluation of samples morphology

SEM images were postprocessed to estimate the average tilt angle of the fibers,  $\theta$ , from their graphite substrate and the actual packing density of the samples.<sup>10</sup> The tilt angles of the fibers were determined using SEM stereomicroscopy.<sup>26,27</sup> To apply this method, the same fiber surface was imaged twice: once with the sample stage at a normal angle to the primary electron beam, and once with a small eucentric tilt of  $\alpha = 3^\circ$ . These two images constitute a *stereopair*. During sample tilting, surface features with different heights will have different lateral displacements. Therefore, by tracking distinguishable features of the velvet fibers such as, for example, a fiber tip and its displacement with the known stage tilt angle and the fiber length, one can deduce the inclination angle of the tilted fiber to the surface (azimuthal or tilt angle),  $\theta$ . Figure 2(a) shows a diagram of a fiber represented by the segment  $\overline{OB}$ . When tilted, the same fiber is represented by the segment  $\overline{OB'}$ .  $A$  and  $A'$  are the fiber tip projections onto the plane imaged by SEM. The sum of angles  $\alpha$  and  $\theta$  is the total azimuthal fiber angle retrieved by the stereomicroscopy method. Figure 2(b) is an anaglyph made of the SEM stereopair, which shows the lateral displacement between fiber tips (segment  $\overline{AA'}$ ). The geometric calculations relating these quantities to solve for  $\theta$  using the known fiber length and diameter are described in the Appendix.

In order to accurately implement this method, all SEM parameters including the magnification, the beam spot size, the electron beam energy, and working distance were kept fixed for all acquired SEM stereopair images. A feature-matching algorithm was applied to the stereopairs in postprocessing using MATLAB to measure the





**FIG. 2.** (a) Diagram of a single fiber represented by segments  $OB$  before tilting and  $OB'$  after tilting. The distance  $AA'$  is found with an anaglyph as shown in (b), and it is proportional to the fiber height from the graphite base, segment  $BA$ . (b) A carbon velvet anaglyph composed of a nontilted image (red) and an image tilted by  $3^\circ$  (blue) with respect to the PE beam in the direction toward the SEE detector. This sample has a fiber length of 1.5 mm and an actual packing density of 68%.

displacements  $AA'$  from Fig. 2(b) and to subsequently retrieve the individual azimuthal fiber tilt angles,  $\theta$ . The average azimuthal angles of three velvets each with a fiber length of 1.5 mm were calculated (Table I). Four stereopairs per sample were used to make these estimates. The uncertainty indicated in the table is due to the large spread in the individual fiber misalignment.

### III. RESULTS AND DISCUSSIONS

#### A. Effect of local actual packing density on the SEE yield

The SEE yield and actual packing densities of five carbon velvet samples were measured via SEM imaging. The average SEE yield was calculated using the pixel intensity calibration method with planar graphite as described in Sec. II A. Figure 3 shows the dependence of the average SEE yield on the fiber packing density for multiple regions across each sample surface. Results show that the local SEE yield across a velvet surface is linearly related to the local actual packing density. This suggests that for velvet samples with actual packing densities in the range of 55%–97% and fiber lengths of 0.5–1.5 mm, there is an increasing dependence of the SEE yield on the total amount of fiber surface area exposed to the incoming electron beam. At a primary electron beam energy of 0.5 keV, the percent increase in the SEE yield with actual packing density for samples of 1.5 mm fiber length are 33%, 19%, and 23% corresponding to data in Figs. 3(b), 3(c), and 3(d), respectively, and at 1.0 keV, the percent increase in the SEE yield with actual packing density for the same samples is 56%, 47%, and 14%. Other samples demonstrate a similar trend at both primary electron beam energies. The errorbars in Fig. 3(a) are much smaller than the errorbars in the rest of Fig. 3 due to a small variation in fiber orientation for

that sample. Figure 3(a) corresponds to the velvet sample with the shortest fibers (0.5 mm). SEM imaging revealed that taller fibers tend to be more misaligned and, therefore, more susceptible to bunching and bending, causing more variation in actual packing density across the sample surface. The sample with 0.5 mm length fibers has a more uniform arrangement of fibers than other samples and the smallest variations in the actual packing density and SEE yield.

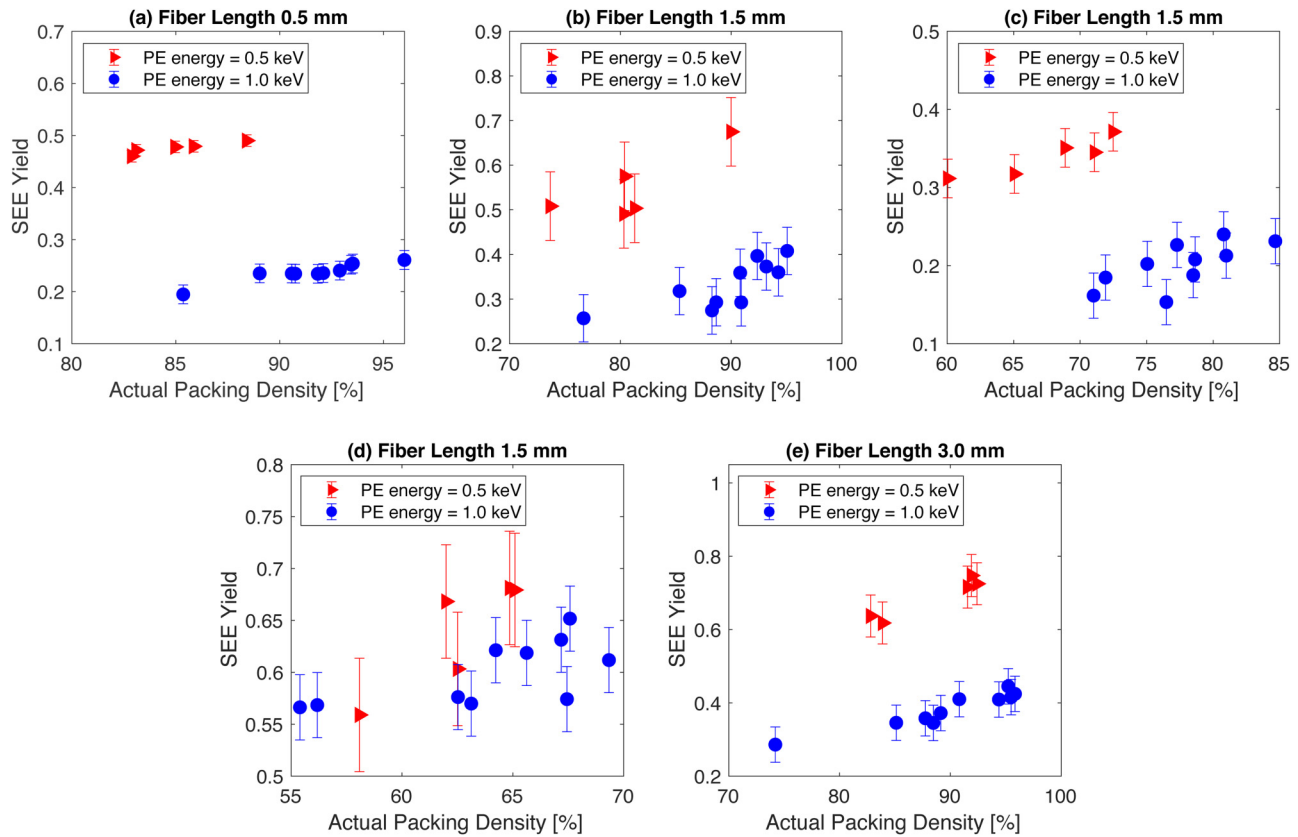
#### B. Effect of actual packing density on the SEE yield

Figure 4 shows the effect of the actual packing density on the SEE yield measured for samples each with a fiber length of 1.5 mm. The average SEE yield value was obtained by taking the mean average of multiple adjacent SEM measurements for each of the samples under analysis. While each data point in Fig. 3 represents one SEM image at one location across the sample surface, the data points in Fig. 4 are the average of all images for three different samples. These SEM results are also compared with recent SEE yield measurements of the same samples<sup>10</sup> and with values found by using recent models of the SEE yield from velvet surfaces.<sup>9</sup> The theoretical values were calculated using Eq. (25) from the model of Swanson *et al.* in Ref. 9. The model uses the velvet aspect ratio, fiber density, and angle from normal,  $\theta$ , to compute a SEE yield of a carbon velvet surface from a 0.5 keV primary electron energy beam. The fiber angles found via stereomicroscopy (Table I) were used for  $\theta$  in the model, and the resulting SEE yields are shown in Fig. 4.

The SEM results suggest that there is an optimal actual packing density at  $\sim 68\%$  for a 1.5 mm long velvet surface. The trend of SEE reduction between a 63% ( $\theta = 30.9^\circ$ ) and a 68% ( $\theta = 25.2^\circ$ ) velvet surface is consistent in the SEM data and the modeled results. This optimal configuration suggests that the SEE yield depends not only on the fiber packing density but also on the orientation of the fibers with respect to the graphite substrate. At the same time, the orientation depends also on the packing density as neighboring fibers may support each other. Thus, for the same fiber length, there is a nonlinear effect of the packing density of the SEE yield. This explains the optimum packing density and fiber length found in Fig. 4.

**TABLE I.** Average azimuthal fiber angle properties for samples with 1.5 mm fiber length.

Manufacturing packing density (%)	Actual packing density (%)	Average azimuthal fiber angle, $\theta$ (deg)
3.5	$81 \pm 6$	$20.0 \pm 2$
1.8	$68 \pm 5$	$25.2 \pm 2$
0.8	$63 \pm 3$	$30.9 \pm 2$



**FIG. 3.** SEE yield measured from SEM shown as a function of actual packing density for five carbon velvet samples using a primary electron beam energy of 0.5 keV (red markers) and 1.0 keV (blue markers). Each data point represents one SEM image analyzed for its actual packing density and SEE yield.

Note that the above results are not in agreement with all direct electron gun measurements for the same samples. In particular, the SEE from the sample with a 68% packing density is the largest with an average SEE yield of 0.39, while in SEM, it is the smallest with an average SEE yield of 0.64. This may be due to the fact that the spot size of the SEM beam is focused to  $\sim 10$  nm in diameter, while the spot size of the electron beam in the direct SEE experiments is 2–3 mm in diameter. Thus, in these SEM experiments, the results are given for different actual packing densities rather than for one averaged density value across an entire sample surface. With respect to Ref. 10, the SEM measurements are much more localized because with SEM it is possible to observe exactly where the electron beam is pointing at on the sample. Good agreement between the SEM image data and the direct SEE current measurement is found for the actual SEE yield values of the velvet sample with 63% fiber density and the velvet with 81% fiber density. For these cases, the direct measurements and the SEM measurements are, respectively, within 8.2% and 10.9% of each other.

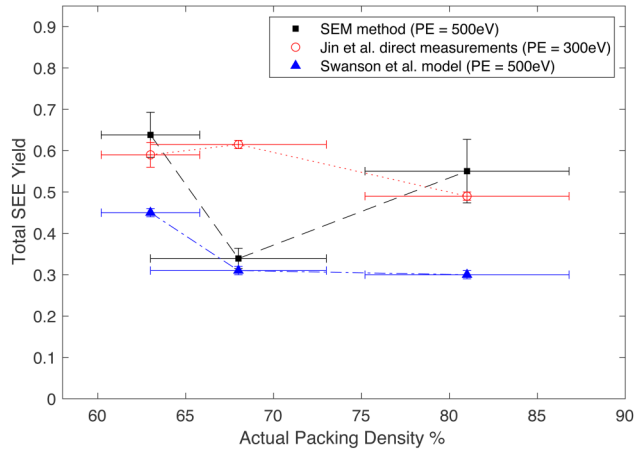
### C. Effect of fiber length on the SEE yield

To investigate the effect of fiber length on the total SEE yield, three samples of varying fiber length and of similar actual fiber

densities between 85% and 89% were compared [Fig. 5(a)]. It is found that fiber length increases the total SEE yield of these samples. Swanson *et al.* recently developed an analytical model to describe the SEE yield of a velvet surface as a function of fiber length and of packing density [Eq. (25) in Ref. 10]. An approximation of this model was used to describe the SEE yield of a velvet surface and then compared with the SEM measurements.

The approximation uses an outgoing particle flux equation to calculate the SEE yield ( $\gamma$ ) of a velvet surface. The flux of secondary electrons outgoing from the graphite base of a velvet is attenuated due to the loss of these electrons to the fiber sides. The total rate of this attenuation is scaled by the packing density,  $D$ , and is expressed as  $\frac{d\gamma(z)}{dz} \frac{1}{D}$ . The corresponding flux term is defined as  $-\gamma L$ , where  $L$  is the fiber length. SEE generated from the fiber tips are not trapped and, therefore, they add to the total outgoing flux. This flux term is defined as  $D\gamma_{flat}$ , where  $\gamma_{flat}$  is the SEE yield from a fiber tip that is the same as the SEE yield from a flat graphite surface. The sum of these two terms defines the change of the SEE yield as a function of depth from the graphite base,  $z$ ,

$$\frac{d\gamma(z)}{dz} \frac{1}{D} = -\gamma(z)L + D\gamma_{flat}. \quad (1)$$



**FIG. 4.** SEE yield shown for three samples of 1.5 mm fiber length. The primary electron (PE) beam energy is 0.5 keV for the SEM method results (red circles), 0.3 keV for the experimental results (blue triangles), and 0.5 keV for the modeling results (black squares). The data points representing the SEM data are mean averages of 10 surface regions per sample.

The solution to this differential flux equation is the exponential decay function

$$\gamma(z) = c_1 e^{-Dz/L} + D\gamma_{flat}. \quad (2)$$

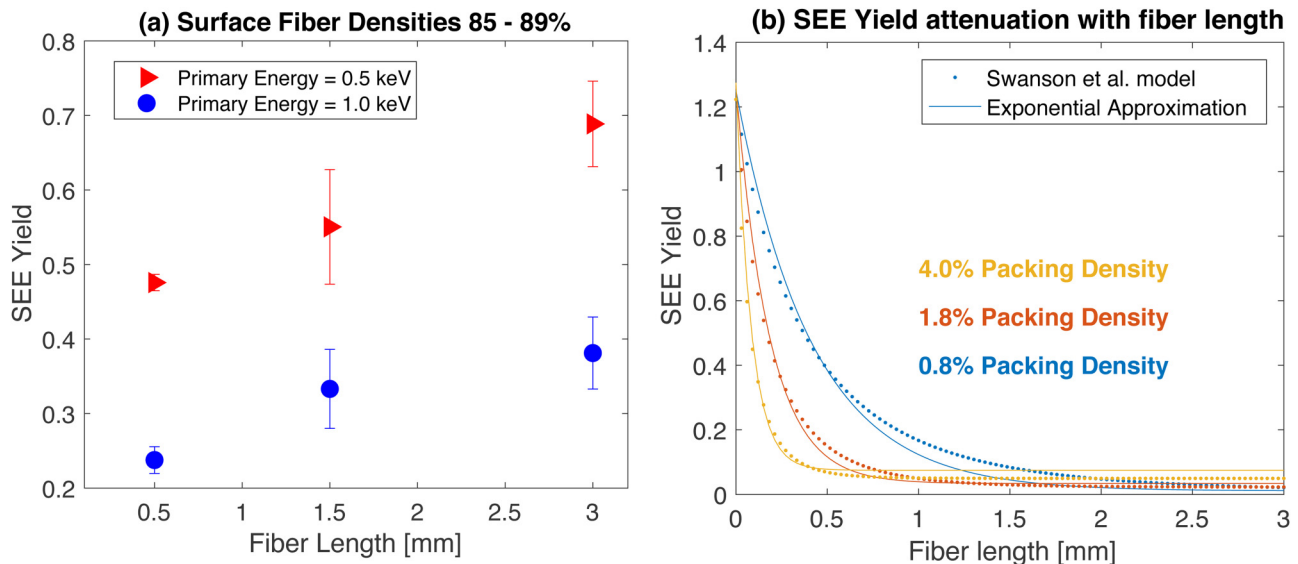
By applying the appropriate boundary conditions to Eq. (2), the quantity  $c_1$  can be determined. At  $z = 0$ , the total SEE yield of the

velvet surface should exclude SEE contributions from the fibers and should be equal to  $(1 - D)\gamma_{flat}$ . This condition is satisfied when  $c_1 = \gamma_{flat}(1 - 2D)$ . When  $z$  instead approaches infinity, the SEE yield of the velvet surface should only be due to the fiber tips and be equal to  $D\gamma_{flat}$ . Equation (2) satisfies this condition as well. The exponential decay equation for the SEE yield of a fiber surface varying with fiber length in terms of the fiber packing density and SEE yield of flat graphite is then,

$$\gamma(z) = (1 - 2D)\gamma_{flat}e^{-Dz/L} + D\gamma_{flat}. \quad (3)$$

In Fig. 5(a), the SEE yield of velvets measured with SEM with similar actual fiber densities is shown as a function of fiber length. The fiber length increases the SEE yield for velvets with actual fiber densities of 85%–89%. In Fig. 5(b), the exponential decay approximation [Eq. (3)] to the model of Swanson *et al.* shows the opposite trend: SEE yield is reduced for increasing fiber lengths. The SEE yield attenuation, however, is shown for packing densities, which are much smaller than the actual densities found with SEM measurements (0.8%–4.0%). For very large values of  $D$ , the expression approaches the value of  $\gamma_{flat}$ . The SEM measurements show that for actual fiber densities >75%, increasing the fiber length may not attenuate the SEE yield.

The increased SEE yield with increasing fiber length shown in Fig. 5(a) could be due to the realistic and nonuniform fiber arrangements revealed by SEM imaging of the velvet surfaces. For example, longer fibers in velvets with large packing density may tend to bend over and bunch more so than short fibers. The bent over fibers will then create regions where the primary electrons have shallow angles of incidence. Shallow incidence angles increase the SEE by an amount proportional to the inverse cosine law.<sup>28</sup>



**FIG. 5.** (a) Average SEE plotted against fiber length for three samples of fiber densities between 85% and 89%. (b) Exponential approximation function and the Swanson *et al.* for SEE yield as a function of fiber length shown for fiber packing densities between 0.8% and 4.0%.

## IV. CONCLUSIONS

To characterize SEE from complex surfaces, it is important to know the local morphology of the surface especially in the case where the surface is spatially nonuniform. This is difficult to achieve using conventional direct SEE measurements. To this end, a method of using SEM imaging on carbon velvet surfaces has been proposed, demonstrated, and validated for the simultaneous evaluation of the morphological features and SEE yield properties a velvet surface. It is shown that the method allows one to correctly identify the key trends of SEE as a function of the actual packing density, fiber orientation, and fiber length. In addition to using SEM for the SEE and morphological evaluation of a surface, the use of EDS incorporated with SEM can allow for the *in situ* characterization of chemical compositions of spatial locations across a sample surface.

With respect to conventional SEE measurement methods, the SEM technique is rapid and highly localized. This is particularly useful for surfaces where the manufacturing specifications of the material are different than the actual material configurations. For example, in the case of carbon velvets, SEM allows one to identify that the actual packing densities are up to 91% larger than the packing densities specified by the manufacturer. This is due to fiber bending and to nonuniform fiber alignment. By using SEM on the same velvet samples measured in Ref. 10, it was also shown that a single velvet surface may have local SEE variation of up to 43%. A weak increasing trend was found for all velvet samples between the local actual packing density and local SEE yield. These realistic surface configurations have also been shown to affect the SEE trends with respect to theoretical predictions.

The method of using SEM for a surface geometry and SEE evaluation on carbon velvets may be applied in the future to other conducting surfaces of high aspect ratio (>100), such as fractal feathered carbon velvets,<sup>11</sup> surfaces with deep grooves, or micro-foam structures.

## ACKNOWLEDGMENTS

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## APPENDIX: GEOMETRIC DERIVATION OF FIBER ORIENTATION USING STEREOIMMAGERY

The geometric representation shown in Fig. 2(a) is for a velvet fiber before tilting the SEM stage ( $\overline{OA}$ ) and after tilting the SEM stage ( $\overline{OB'}$ ) by an angle  $\alpha$ . The distance  $\overline{AA'}$  can be found by stereomicroscopy image processing techniques using the two-dimensional SEM micrographs where the fibers are viewed in the x-y plane and  $\overline{BA}$  is measureable as shown in Fig. 2(b). Then,  $\overline{B'A'}$  can be derived as<sup>26</sup>

$$A'B' = \frac{OA' \cos(\alpha) - OA}{\sin(\alpha)} \quad (\text{A1})$$

and for small angles  $\alpha$ ,

$$A'B' = \frac{AA'}{2 \sin(\alpha/2)}. \quad (\text{A2})$$

Then,

$$\theta = \arcsin\left(\frac{AA'}{L 2 \sin(\frac{\alpha}{2})}\right) \quad (\text{A3})$$

and the original fiber angle is  $\theta + \alpha$  (from the substrate).

## REFERENCES

- Y. Raitses and I. D. Kaganovich, in *Electron Emission from Nano- and Micro-Engineered Materials Relevant to Electric Propulsion 33rd International Electric Propulsion Conference 390* (The George Washington University, DC, USA, 2013).
- S. Mazouffre, S. Tsikata, and J. Vaudolon, *J. Appl. Phys.* **116**, 243302 (2014).
- S. I. Krashennnikov, A. Y. Pigarov, and W. Lee, *Plasma Phys. Control. Fusion* **57**, 044009 (2015).
- F. Subba, D. Tskhakaya, H. Bürbaumer, U. Holzmüller-Steinacker, N. Schupfer, M. Stanojevic, and S. Kuhn, "Including the effect of secondary-electron emission at the divertor targets in code modelling," *Plasma Phys. Control. Fusion* **44**, 1 (2001).
- G. D. Hobbs and J. A. Wesson, "Heat flow through a Langmuir sheath in the presence of electron emission," *Plasma Phys.* **9**, 85–87 (1967).
- D. Sydorenko, A. Smolyakov, I. Kaganovich, and Y. Raitses, "Kinetic simulation of secondary electron emission effects in Hall thrusters," *Phys. Plasmas* **13**, 014501 (2006).
- J. R. M. Vaughan, "Multipactor," *IEEE Trans. Electron Devices* **35**, 1172–1180 (1988).
- S. Kato, M. Nishiwaki *et al.*, "Secondary electron emission from metals and graphites," in *Accelerator Tech. Design Report for J-PARC*, edited by Y. Yamazaki (Japan Atomic Energy Research Institute and High Energy Accelerator Research Organization, 2003).
- C. Swanson and I. Kaganovich, "Modeling of reduced effective secondary electron emission yield from a velvet surface," *J. Appl. Phys.* **120**, 213302 (2016).
- C. Jin, A. Ottaviano, and Y. Raitses, "Secondary electron emission from high aspect ratio carbon velvet surfaces," *J. Appl. Phys.* **122**, 173301 (2017).
- C. Swanson and I. Kaganovich, "'Feathered' fractal surfaces to minimize secondary electron emission for a wide range of incident angles," *J. Appl. Phys.* **122** (2017).
- M. Patino, Y. Raitses, and R. Wirz, "Secondary electron emission from plasma-generated nanostructured tungsten fuzz," *Appl. Phys. Lett.* **109**, 201602 (2016).
- Patino MI, Raitses Y, Koel BE, and Wirz RE, "Application of Auger spectroscopy for measurement of secondary electron emission from conducting material for electric propulsion devices," in *Proceedings of 33rd International Electric Propulsion Conference, Washington, DC, USA, 6–10 October 2013* (The George Washington University, DC, USA, 2013), pp. 1–8.
- A. Ottaviano, C. Jin, S. Banerjee, and Y. Raitses, "Characterization of secondary electron emission yield from velvet-type surface," in *35th International Electric Propulsion Conference—IEPC-2017-195, Atlanta, GA* (Georgia Institute of Technology, GA, 2017).
- J. M. Millet and J.-P. J. Lafon, "Secondary-electron emission from porous solids," *Phys. Rev. Lett.* **52**, 433–438 (1995).
- M. Ye, Y. N. He, S. G. Hu, and R. Wang, "Suppression of secondary electron yield by microporous array structure," *J. Appl. Phys.* **113**, 074904 (2013).
- M. T. F. Pivi and R. E. Kirby, "Sharp reduction of the secondary electron emission yield from grooved surfaces," *J. Appl. Phys.* **104**, 104904 (2008).



- <sup>18</sup>J. Goldstein, D. E. Newbury, D. C. Joy, C. E. Lyman, P. Echlin, E. Lifshin, L. Sawyer, and J. R. Michael, *Scanning Electron Microscopy and X-ray Microanalysis* (Springer, 1998).
- <sup>19</sup>L. Reimer, *Image Formation in Low-Voltage Scanning Electron Microscopy* (Springer, Berlin, 1985).
- <sup>20</sup>H. Drescher, L. Reimer, and H. Seidel, "Rückstreuoeffizient und Sekundärelektronenausbeute von 10–100 keV Elektronen und Beziehungen zur Raster-Elektronenmikroskopie," *Z. Angew. Phys.* **29**, 331–336 (1970).
- <sup>21</sup>K. S. Sim and J. D. White, "New technique for in-situ measurement of back-scattered and secondary electron yield for the calculation of signal-to-noise ratio in a SEM," *J. Microsc.* **217**, 235–240 (2005).
- <sup>22</sup>A. Dennison *et al.*, "Absolute electron emission calibration: Round Robin tests of Au and polyimide," in *Proceedings of 14th Spacecraft Charging Technology Conference, Noordwijk, Netherlands, April 4–8 2016* [Space Research and Technology Centre of the European Space Agency (ESA/ESTEC), 2016].
- <sup>23</sup>L. Reimer and C. Tollkamp, "Measuring the backscattering coefficient and secondary electron yield inside a scanning electron microscope," *Scanning* **3**, 35–39 (1980).
- <sup>24</sup>M. I. Patino, Y. Raites, and B. E. Koel, "Analysis of secondary electron emission for conducting materials using 4-grid LEED/AES optics," *J. Appl. Phys.* **48**, 195204 (2015).
- <sup>25</sup>D. C. Joy and D. E. Newbury, "Advanced SEM imaging," *AIP Conf. Proc.* **449**, 653 (1998).
- <sup>26</sup>J. Xie, *Stereomicroscopy: 3D Imaging of the Third Dimension Measurement* (Agilent Technologies, 2011).
- <sup>27</sup>D. Samak *et al.*, "3D reconstruction and visualization of microstructure surfaces from 2D images," *Ann. CIRP* **56**, 149 (2007).
- <sup>28</sup>H. Bruining, *Physics and Applications of Secondary Electron Emission* (Pergamon, London, 1954).