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Wright, G.M., Brunner, D., Baldwin, M.J. *, Doerner R.P. *,
Labombard, B., Lipschultz, B., Terry, J.L., Whyte, D.G.

* Center for Energy Research, University of California-San Diego

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**Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA**

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Tungsten nano-tendrils growth in the Alcator C-Mod divertor

G M Wright¹, D Brunner¹, M J Baldwin², R P Doerner², B Labombard¹, B Lipschultz¹, J L Terry¹, and D G Whyte¹

¹ MIT Plasma Science and Fusion Center, 77 Massachusetts Ave, Cambridge, MA, USA, 02139

² Center for Energy Research, University of California in San Diego, 9500 Gilman Dr, La Jolla, CA, 92093-0417, USA

*Main author email: wright@psfc.mit.edu

Growth of tungsten nano-tendrils (“fuzz”) has been observed for the first time in the divertor region of a high-power density tokamak experiment. After 14 consecutive helium L-mode discharges in Alcator C-Mod, the tip of a tungsten Langmuir probe at the outer strike point was fully covered with a layer of nano-tendrils. The thickness of the individual nano-tendrils (50-100 nm) and the depth of the layer (600 ± 150 nm) are consistent with observations from experiments on linear plasma devices. The observation of tungsten fuzz in a tokamak may have important implications for material erosion, dust formation, divertor lifetime, and tokamak operations in next-step devices.

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1. Introduction

The growth of tungsten (W) nano-tendrils (or “fuzz”) has been well documented in a wide range of linear plasma devices [1-3]. The growth conditions used for W fuzz in these devices are elevated surface temperatures ($T_s = 1000\text{-}2000\text{ K}$) implanted with helium ions at low incident energies ($20\text{ eV} < E_{\text{He}^+} < 150\text{ eV}$) for a sufficient exposure time ($t_{\text{exp}} \geq 100\text{ s}$). It is possible to grow similar structures at much higher ion energies ($\sim 10\text{s of KeV}$) [4,5]. In future devices, there will be sections of the divertor that reach surface temperatures $>1000\text{ K}$ and He ions will always be present in D-T burning devices, thus the growth of W fuzz in future devices is a possibility. The impact of W fuzz on plasma-surface interactions and tokamak operations is still largely unknown but is expected to be significant given that fuzz layers have been grown to large depths ($>5\text{ }\mu\text{m}$)[1] and therefore dramatically alter the plasma-surface interaction region. For example, W fuzz layers have been shown to lower effective physical sputtering yield as compared to bulk tungsten [6] and to be susceptible to unipolar arcing [7]. A major concern is that the growth of W fuzz will result in a large increase in the effective erosion in a W divertor, via the mechanical failure of the individual nano-tendrils and, in turn, significant production of W dust; perhaps compromising the viability of a W divertor. However, to date, W fuzz growth has not been observed in tokamak experiments. This is because the necessary formation conditions of high surface temperature and long exposure time are typically not met simultaneously in current devices, and so the potential existence and impact of W fuzz in future devices, such as ITER, is uncertain.

There are also significant differences between the plasmas of a tokamak divertor and linear plasma devices, such that it was uncertain if the W fuzz growth process would be different, or suppressed altogether in a tokamak divertor. For instance, ions are typically much “colder” than electrons in linear devices and accelerated via target biasing resulting in normal incidence to the surface where as ions are closer to grazing incidence in tokamak divertors. Parallel heat flux is much larger in a tokamak, while the sheath distances are much smaller (due to high B field and/or high local density). Also, in a tokamak

divertor, the ionization mean free-path of fuel and sputtered species is much smaller than the divertor characteristic size leading to high local recycling and prompt re-deposition of sputtered atoms, whereas linear plasma devices tend to have weak recycling.

Despite these differences we will show, for the first time, that W fuzz growth can occur in a tokamak under plasma–material exposure conditions similar to those conducive to fuzz formation in linear plasma devices.

2. Experiment

This experiment was performed in the compact, high field Alcator C-Mod tokamak ($R=0.67$ m, $a=0.22$ m, $B<8$ T)[8]. Alcator C-Mod has high-Z refractory metals (molybdenum and tungsten) as plasma-facing surfaces in the divertor and first-wall. While there are no low-Z plasma-facing components, thin layers (<1 μm) of boron are applied periodically to the walls for impurity control. The redeposition of thick boron layers would likely inhibit W fuzz growth [9]. This necessitated carrying out the experiment at the strike point in the outer lower divertor, where the thick boron layer is rapidly eroded away [10]. While the boron layer is removed in the outer lower divertor, there remains a boron impurity concentration in the plasma of typically 0.5-1 %. Alcator C-Mod has a reactor-level global-power density resulting in high parallel heat fluxes in the divertor ($q_{\parallel} \leq 0.5$ GW/m^2), and operates at ITER-like divertor densities.

The goal of the experiment is to achieve the required nano-tendrils growth conditions ($T_s = 1000\text{-}2000$ K, $E_{\text{He}^+} > 20$ eV) in the Alcator C-Mod lower divertor. Such a high value of He ion flux is readily obtained by fuelling with helium and given the high-density plasmas achievable on Alcator C-Mod. The greatest operational challenge was to achieve high divertor power density to quickly elevate the surface temperature, while keeping the local electron temperature (T_e) low enough that sputtering from the He ions does not dominate over the fuzz growth rate [11].

In order to maximize power to the divertor surfaces, plasmas were run in L-mode with 0.9 MA of

plasma current and 3.25 MW of ICRF power. To prevent transition to H-mode at these high levels of injected power and to keep the local electron temperature low to prevent sputtering, the line-averaged electron density (\bar{n}_e) was kept high ($\bar{n}_e \sim 1.4 \times 10^{20} \text{ m}^{-3}$) resulting in a divertor $T_e \sim 25 \text{ eV}$. A full time trace of plasma parameters for a typical plasma discharge for this experiment can be seen in figure 1a. Exposure time for fuzz growth was accumulated over 11 repeated plasma discharges performed at these conditions. It should be noted that the 3 discharges immediately prior to this 11-discharge sequence are included in the total growth time accumulated on the W Langmuir probe (14 discharges in total) since the appropriate growth conditions (for the W Langmuir probe, not for the Mo tiles) were met for these discharges as well (see section 3). These 3 discharges were similar to conditions found in figure 1a except with ICRF power of 2, 2.25, and 3 MW respectively, and corresponding divertor T_e of $\sim 15 \text{ eV}$ during ICRF injection for all 3 discharges. Thus, 14 discharges in total are considered in this experiment. While these conditions were selected to re-create the plasma-material interaction conditions conducive to fuzz growth in linear plasma devices, they do not fully re-create the conditions expected in future fusion devices (active cooling with constant surface temperature, ELMs, impurity seeding, D-T-He mixture, etc.).

Even with these optimized operating conditions, a typical surface in the Alcator C-Mod divertor will not reach the required surface temperature of $T_s > 1000 \text{ K}$ within a 2 second discharge. Fortunately, there is a section of the C-Mod divertor that is specifically designed to measure and analyze heat loads to the divertor surfaces. This section of Mo tiles is ramped $\sim 2^\circ$ into the toroidal magnetic field lines allowing them to intercept more of the parallel heat flux, thus resulting in higher surface temperatures and higher infrared emission. There is infrared thermography imaging (calibrated for Mo) on this section of the divertor as well as embedded thermocouples, calorimeters and tungsten Langmuir probes. The W Langmuir probes are made from 99.95 at% polycrystalline W purchased from Ed Fagan Inc. The Langmuir probe dimensions are 3 mm diameter and 60 mm total length. The Langmuir probe surfaces are angled $\sim 11^\circ$ into the magnetic field lines and were scanned from -150 V to + 50 V in a triangle wave at

100 Hz. The outer strike point was placed at the top of the vertical section of the outer divertor (“nose” tile) rather than the vertical face (see figure 1b). This reduces flux expansion, and thus increases local heat flux at the strike point such that more time was spent with the surface temperature in the optimal growth range.

The experiment was run on the final day of an Alcator C-Mod run campaign. This helped ensure that the surfaces were not further modified by additional experiments before they were removed and examined. Upon manned-access, a shield was installed to protect the tile and probe surfaces during the removal of the divertor modules.

3. Results

Surface temperatures are determined through two methods: (1) The surface temperature for the Mo surfaces are measured by infrared thermography. This is done through a grey-body fit with the bulk temperature of the molybdenum (measured by implanted thermocouple) used as a reference [12]. (2) Although the tungsten Langmuir probes are in view of the IR camera, they do not contain thermocouples and thus are not calibrated. Their surface temperature is found through use of a 1-D finite-element heat flux model and Langmuir probe measurements of heat flux based on the local plasma conditions [13-14]. Heat fluxes mapped parallel to the magnetic field are found to agree well between these two methods.

For these plasma conditions a calculated heat flux of $35 \pm 5 \text{ MW/m}^2$ is obtained on the W Langmuir probe surface. The ramped Mo tiles received $9 \pm 1 \text{ MW/m}^2$ since they are angled considerably less into the parallel heat flux (see figure 2). Given these different heat fluxes and the electrical/thermal isolation of the W Langmuir probe, the W surface has a much different thermal evolution and reaches temperatures much higher than the surrounding Mo surfaces.

Figure 2 shows that over the course of a plasma discharge, the W Langmuir probe reaches a surface temperature of 1000 K (the minimum temperature required for fuzz growth) earlier in the shot than the Mo surfaces. In some discharges, the W surface can exceed 2000 K (maximum temperature for fuzz growth), reaching as high as $\sim 2700 \text{ K}$ in the hottest case. While the Mo surfaces are slower to reach 1000

K, they never exceed 2000 K. For the three plasma discharges immediately prior to the set of 11 repeated discharges with slightly lower ICRF power (2.0 MW, 2.25 MW, and 3.0 MW respectively), the W Langmuir probe reached surface temperatures of >1000 K but the Mo surfaces did not. Integrating the plasma exposure time of the surfaces for $1000 \text{ K} < T_{\text{surf}} < 2000 \text{ K}$ for these three discharges plus the eleven repeated discharges (14 total discharges) we have a total integrated growth time of ~ 13 s for the W Langmuir probe and ~ 7 s for the Mo surfaces. Total He ion fluence to the W probe and Mo surfaces in these exposure times is $\sim 9 \times 10^{25} \text{ He/m}^2$ and $\sim 2 \times 10^{25} \text{ He/m}^2$ respectively.

The potential drop from the plasma to the grounded Mo tiles can be approximated as $\sim 3T_e$ for a He plasma where $T_e = T_i$. The W Langmuir probe was scanning with a bias voltage from -150 V to $+50$ V (with respect to the grounded walls) at 100 Hz during the exposures. Therefore the potential drop from the plasma to the W Langmuir probe is $3T_e - V_{\text{bias}}$. In determining the energy of incident He ions, one must account for charge state and inherent energy of the ion ($T_i = T_e$). For a typical divertor T_e during the current flat-top (see Fig. 1a), the He^+ ion energy will be between 50-250 eV on the W Langmuir probe.

Upon the removal of the ramped tiles from Alcator C-Mod, visual inspection revealed that the W Langmuir probe at the outer strike point was optically black (figure 3a). Inspection of the same W probe tip with a JEOL-6320FV SEM shows fully developed nano-tendrils with almost complete coverage of the surface (figure 3b). A higher magnification image shows the individual W nano-tendrils are typically ~ 100 nm thick (figure 3c). The C-Mod nano-tendrils are thicker than most nano-tendrils grown in linear plasma devices, which tend to be closer to 20-30 nm in diameter [15] for surface temperatures of 1000-1400 K. However, the W Langmuir probe surface was at very high temperatures and it has been shown that the diameter of the nano-tendrils increases with surface temperature, likely due to the diameter of the He bubbles precipitated in the W lattice increasing at higher temperatures [15].

The depth of the fuzz layer cannot be determined from figure 3, but it is known that fuzz surfaces have a near-zero reflectivity (i.e. optically black) at depths of 400-500 nm [16]. Thus we can assume the fuzz layer on the W Langmuir probe has a depth of >400 nm. Using the $t^{1/2}$ -dependent growth rate formula from Baldwin et al [1] we can calculate the predicted layer depth. This growth rate formula is

based on a limited data set and some work has shown it to overestimate growth rates for $T_{\text{surf}} > 1400 \text{ K}$ [3,17]. It has been suggested that a factor dependent on He ion energy might be missing from the formula [17] and that re-crystallization effects might be competing with the surface changes at higher temperatures [3]. However, it is the only explicit growth rate formula presented to date. It is not clear how the growth of these fuzz layers proceeds once the surface temperature is $>2000 \text{ K}$ since this is above the temperature that the nano-tendrils are formed. If it is assumed the layer growth stops completely at $T_{\text{surf}} = 2000 \text{ K}$, then we calculate a layer depth of $\sim 395 \text{ nm}$ ($t_{\text{growth}} = 12.7 \text{ s}$). If it is assumed that the layer growth continues for $T_{\text{surf}} > 2000 \text{ K}$ (although the morphology of the layer growth changes at these temperatures), we calculate a layer depth of $\sim 515 \text{ nm}$ ($t_{\text{growth}} = 15.6 \text{ s}$). The layer depth was directly measured by focused ion beam cross-section to be $600 \pm 150 \text{ nm}$, demonstrating that the layer depth is in-line with calculations for a layer continuing to grow for $T_{\text{surf}} > 2000 \text{ K}$ and consistent with the observation of an optically black surface. A significant layer has been formed in C-Mod despite growth times that are typically much shorter than in linear plasma devices demonstrating that growth of these fuzz layers in the beginning of development is very rapid. This is not unexpected given the layer depth is in good agreement with the growth formula from Baldwin et al (with data from linear devices) using a $t^{1/2}$ -dependence.

There is no evidence of the nano-tendrils melting in the SEM images, demonstrating that despite what is assumed to be a strongly reduced thermal conductivity across the tiles [18], these nano-tendrils can survive and even grow in steady thermal heat fluxes of up to $\sim 40 \text{ MW/m}^2$. During the 14-shot sequence there were three full current (900 kA) disruptions, which had no obvious effect on the fuzz. There is also no evidence of the uni-polar arcing that was seen on nano-tendril surfaces exposed in the LHD stellarator [19] and in NAGDIS-II [7].

There were no indications or obvious pre-cursors of fuzz formation on the Mo surfaces despite the minimum surface temperature requirements being met for $\sim 7 \text{ s}$ of total plasma exposure time. However, the Mo surface had a much different thermal evolution than the W Langmuir probe and less growth time accumulated. Using the growth rate formula of Baldwin et al. we calculate an expected layer depth of $\sim 71 \text{ nm}$ ($t_{\text{growth}} = 7.1 \text{ s}$). Another key difference between the W probe and Mo surfaces is the lower sputtering

threshold for the Mo surfaces. Exposure of a W fuzz surface in the TEXTOR tokamak demonstrated that if the local T_e was too high, the plasma, especially plasma impurities, can erode away the fuzz [16]. The Mo surfaces in Alcator C-Mod are susceptible to sputtering from the He ions as well as plasma impurities. Since the plasma flux is so high in these experiments ($\Gamma_{\text{He}^+} > 10^{24} \text{ m}^{-2}\text{s}^{-1}$), the erosion can be significant. Assuming a $\sim 3T_e$ potential drop from the plasma to the grounded walls and a 90:10 distribution between He^+ and He^{++} , the sputtering formula from Eckstein [20] leads to an estimate of ~ 272 nm of gross sputtering of bulk Mo via He ions during the series of shots where growth conditions were met. If a 1% population of B^{3+} in the plasma is assumed, then an additional ~ 21 nm of bulk Mo is sputtered via the B ions. This total depth of ~ 293 nm is significantly larger than the expected fuzz layer depth, and thus we do not expect Mo fuzz in a condition where local gross sputtering is comparable to the fuzz growth rate. For W, only ~ 28 nm of bulk W is expected to be sputtered by He ions and ~ 7 nm of bulk W via B impurities, so sputtering is not a hindrance for fuzz growth on the W Langmuir probe. The plasma impurities found in this experiment (B) are not indicative of impurity species in future fusion devices where impurity seeding (eg. Ne, N, or Ar) will certainly be used to mitigate heat loads to divertor surfaces. Impurity seeding could lead to more heavy ion sputtering but will also reduce the divertor T_e as well. Depending on the magnitude of the reduction of T_e , impurity seeding could either raise (due to increased plasma impurities) or lower (due to low T_e and therefore low sheath potentials) sputtering rates compared to experiment.

4. Conclusions

The defining result of this work is that W fuzz can be grown on surfaces in a tokamak divertor. These structures not only survive under the intense heat flux of up to $\sim 40 \text{ MW/m}^2$ and transient conditions of the Alcator C-Mod lower divertor, but grow in these conditions. The growth of fuzz on the W probe had no effect on the operation of the tokamak, but this is only a tiny fraction of the total divertor surface area and thus no conclusions can be made about the effects of this fuzz on tokamak operations if it were to grow on a significant portion of a divertor. If W fuzz grows in future devices with elevated wall temperatures

and long pulse or steady-state operation such as future reactors or ITER, fuzz layer depths could become large (e.g. $>10\ \mu\text{m}$) over the lifetime of the tokamak. The interaction between the plasma and the fuzz is likely to evolve as the layer becomes deeper and the thermal conduction between the tips of the nano-tendrils and the bulk W continues to decrease. With the proof that W fuzz can grow and survive in a tokamak divertor, there is a strong need to understand how other plasma conditions not re-created in this work, such as ELMs and impurity seeding, can affect growth, how these fuzz layers can impact plasma-material interactions on an atomic and more global scale, and what effect the existence of fuzz might have on tokamak operation.

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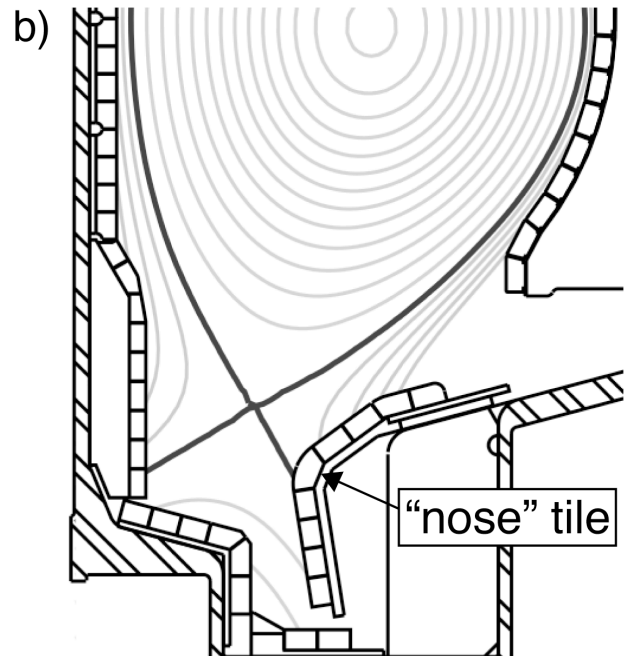
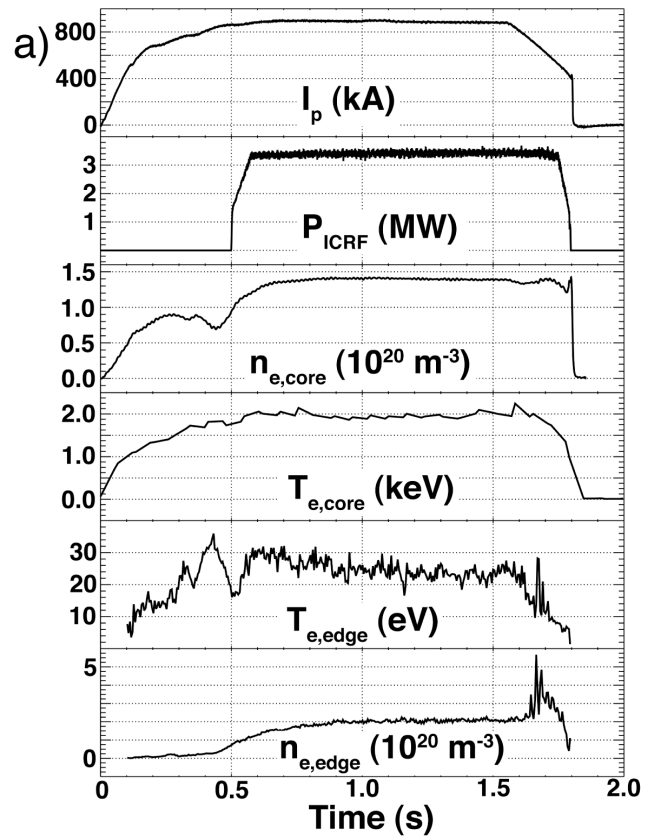


figure 1: a) Plasma parameters for the 11 repeated, sequential discharges conducive to nano-tendrils growth and b) magnetic geometry and plasma shape for those discharges.

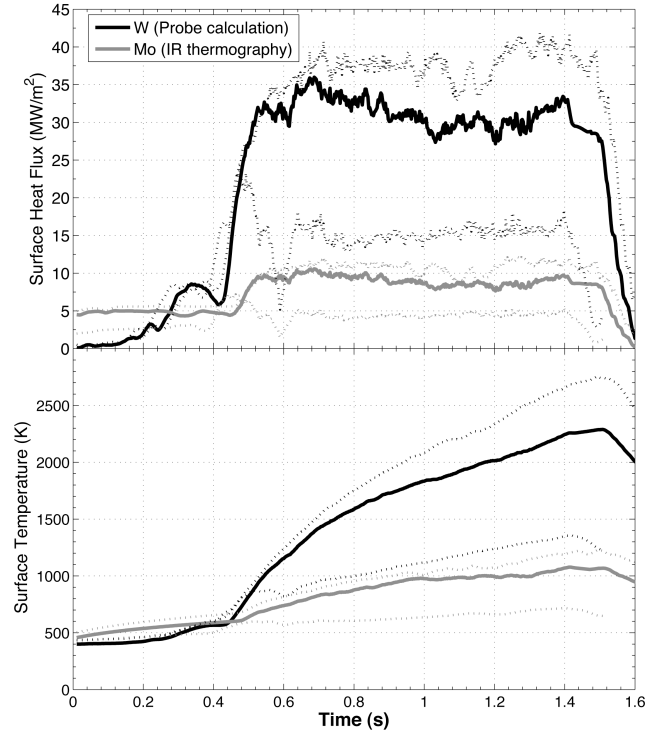


figure 2: a) Surface heat flux and b) surface temperature for the W probe and surrounding Mo surfaces during a plasma discharge. The solid lines represent the shot with the median heat flux/temperature for the 14-shot sequence. The dashed lines represent the shots with the maximum and minimum heat flux/temperature for the 14-shot sequence.

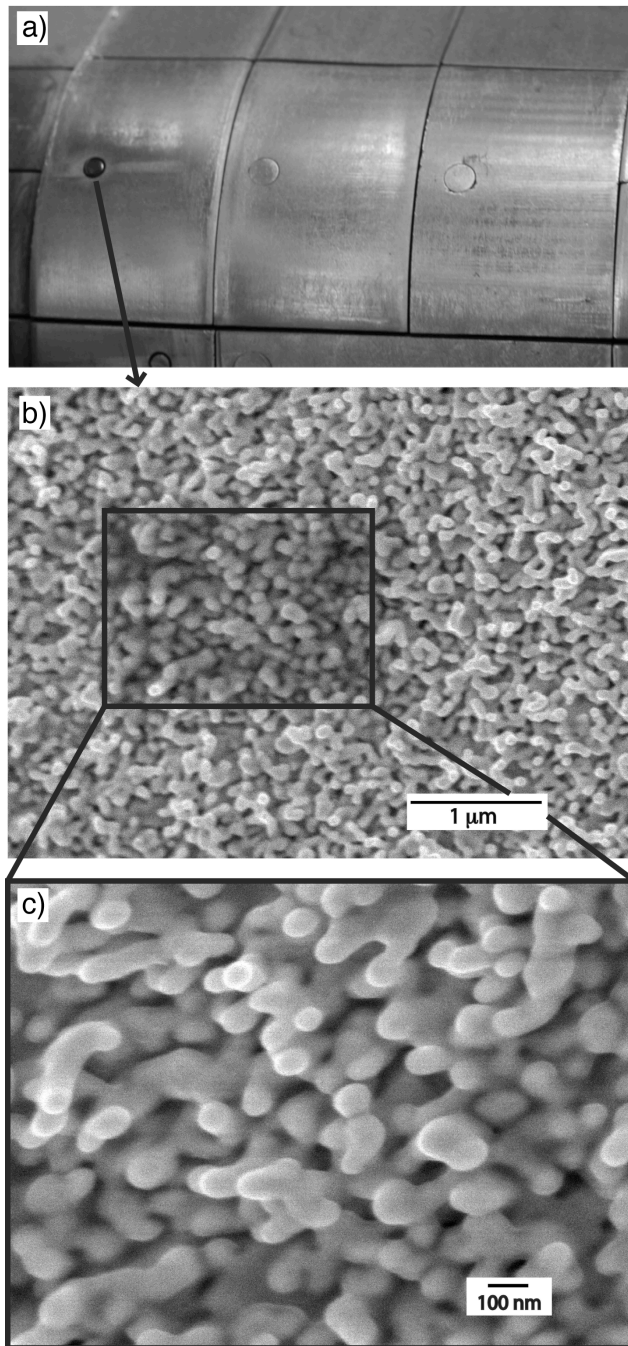


figure 3: a) The ramped Mo tiles and W probe upon removal from Alcator C-Mod, b) SEM image of the W probe surface showing nano-tendrils on the surface, and c) high magnification SEM image showing the average thickness of the individual nano-tendrils to be ~100 nm.