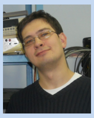
Pre-breakdown currents from tungsten nanofuzz – the surface with a high unipolar arc ignition probability



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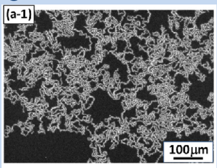
Unipolar arcing

Unipolar arcs in thermonuclear devices are negative phenomenon in plasma-surface interaction. The arcs significantly modify the wall surface, change local potential of plasma, contaminate plasma by microscopic particle injection in a solid and liquid state. This phenomenon was observed in several modern tokamaks, which simulate ITER exploitation: JET, JT-60U, DIII-D and ASDEX Upgrade. Moreover, there are propositions that the unipolar arcs limit plasma confinement with high parameters with increasing incoming power per square unit.



Traces from unipolar arc on tungsten

Mechanism of the unipolar arc initiation

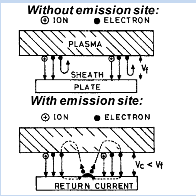
Plasma is positively charged due to hot electrons escape up to potential:

$$V_f = 0{,}5kT_e \ln\left[\left(2\pi\frac{m_e}{m_i}\right)\left(1+\frac{T_i}{T_e}\right)(1-\delta)^{-2}\right]$$

This potential forms on several Debye radii: $\lambda_d = \sqrt{\frac{kT_e}{4\pi ne^2}}$

but in the dense plasma it can be rather small (~µm) => significant for autoemission electric field to accrue:

$$E = \sqrt{\pi kT_e ne^2}\ \ln\left[\left(2\pi\frac{m_e}{m_i}\right)\left(1+\frac{T_i}{T_e}\right)(1-\delta)^{-1}\right]$$

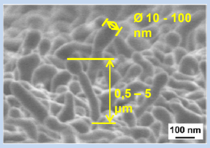


Field emission leads to the intensive heating of the emission site and results in its exploding which can be the initiator of unipolar arc.

Tungsten "fuzz" structure

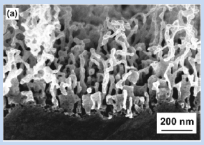
W fuzz forms on a plasma-facing surface under the following conditions:

- Tungsten surface temperature T in the range of 1000 - 2000 K
- Irradiation by He^+ ions with energies 20-50 eV
- Ion fluence > 10^{25} m^{-2} and flux > 10^{21} m^{-2}s^{-1}



This structure contains a lot of helium bubbles with a diameter ~10 nm.

Conditions for W fuzz formation are expected to be met in the divertor zone of ITER.

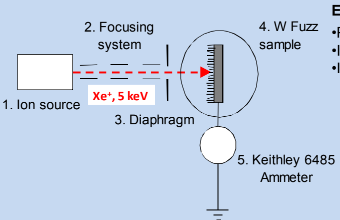


W fuzz facilitates unipolar arcing, which could result in significant **surface erosion** and plasma contamination during ELMs in ITER.

Low erosion method of fuzzy surface modification is needed to reduce the emission current!

Experimental procedure

Surface modification on the "Large MEPhI Mass-Monochromator"



Experimental parameters:
- Pressure under irradiation P=10^{-5} Torr
- Ion beam Xe^+ 5 keV
- Ion current density j=3 µA/cm^2

Fuzzy sample after irradiation

Field emission measurement

- The design of vacuum diode allows the cathode-sample ejection for a SEM observation and an ion beam irradiation **without changing of the vacuum gap**.
- The vacuum gaps were in the range from 0.1 to 0.5 mm.
- A spherical shape of the anode (d=10mm) was used for reducing field enhancement on the sample edges.
- Working pressure 10^{-7} Torr

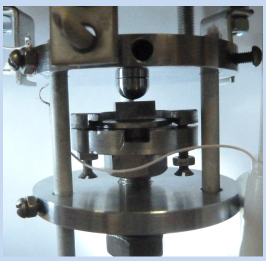
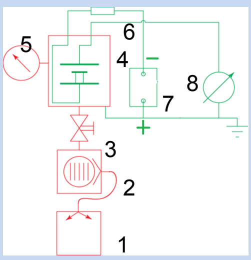
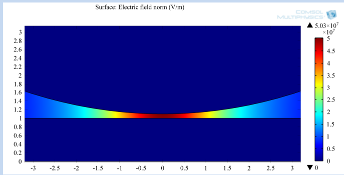


Photo of the vacuum diode

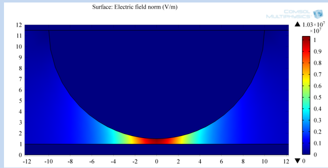


Experimental scheme :
1. Membrane pump
2. Turbomolecular pump
3. Gate
4. Vacuum chamber
5. Pressure gauge
6. Ballast resistance
7. High voltage source
8. Nano ammeter

Simulation of the electric field strength distribution in the vacuum gap



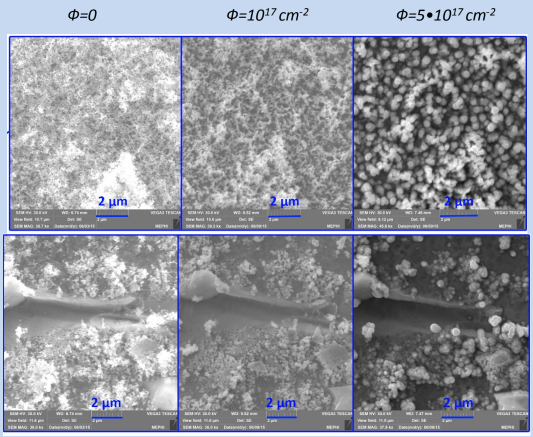
Vacuum gap 0.1 mm – emission area ~0,8 cm^2



Vacuum gap 0.5 mm – emission area ~1,8 cm^2

Experimental results

Dynamic of fuzz modification under the influence of the ion beam



N_f, µm^{-2}	100±30
d_f, µm	0.04±0.01
h_f, µm	±0.2
v_f, µm	**0.13±0.08**
N_b, µm^{-2}	6±1
d_b, µm	0.35±0,07
v_b, µm	**0.17±0.11**
Φ, µm^{-2}	4.4±0.5·10^9
v_s, µm	**0.021±0.002**

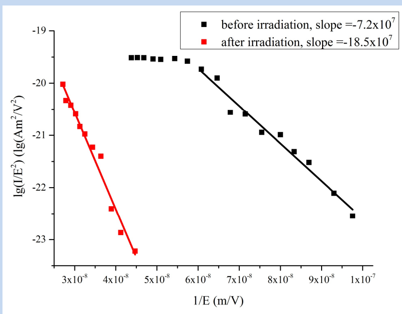
Where v_f is a nanofibre volume, v_b is a ball volume and v_s is sputtered volume per 1 µm^2 of the smooth surface area. N_f is the number of fuzz fibres per unit area, N_b is the number of balls per unit area, d_f is the fibre diameter, d_b is the ball diameter, h_f is the height above the smooth surface.

$$v_f \approx v_b \text{ and } v_s \ll v_b$$

This means that the balls are the result of nanofibre merging, however, **redeposition due to sputtering** is **not** the key process in the formation of balls.

It is assumed that irradiation-induced **He release** from the bubbles is a major factor in the formation of ball-like structures.

Fowler-Nordheim plots of the fuzzy surfaces

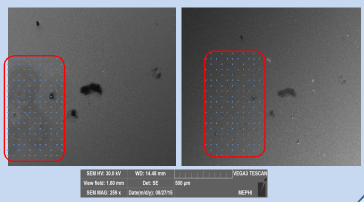


Fowler-Nordheim formula:

$$\lg\left(\frac{I}{E^2}\right) = \underbrace{\frac{2.818\cdot10^9\cdot\phi^{3/2}}{\beta}}_{\text{Slope}}\frac{1}{E} + \frac{4.406}{\phi^{1/2}} + \lg\left(\frac{S\cdot\beta^2}{\phi}\right) - 5.854$$

- **Emission currents significantly decreased after the irradiation.**
- **Amplification of the electric field factors β** were calculated for both surfaces: 370 (before irradiation) and 140 (after irradiation) using Fowler-Nordheim formula. They seem **to be rather high** for the observed surface relief.
- Thermo-field emission could be the reason of such a high emission intensity.

Irradiation can vanish emission sites on the surface formatted after field emission measurement:



Conclusion

- Ball-like structures were observed on a W fuzzy surface as a result of irradiation with the 5 keV Xe^+ beam.
- The threshold fluence for ball formation was estimated at ~10^{17} cm^{-2} and redeposition due to sputtering can only account for **10%** of the ball volume.
- Irradiation of the W fuzz structure by 5keV Xe^+ beam significantly decreases field emission currents and could reduce unipolar arc ignition probability.