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Nano-tendril bundles behavior under plasma-relevant electric fields

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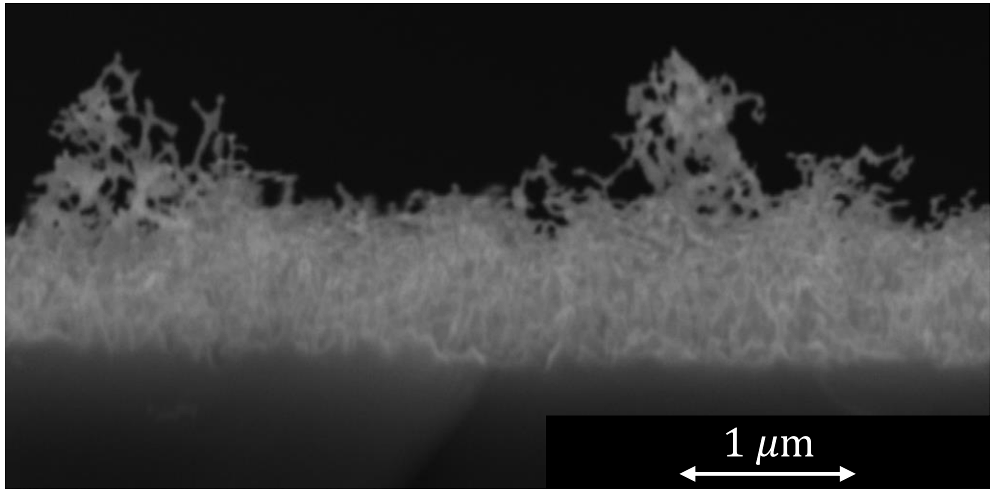
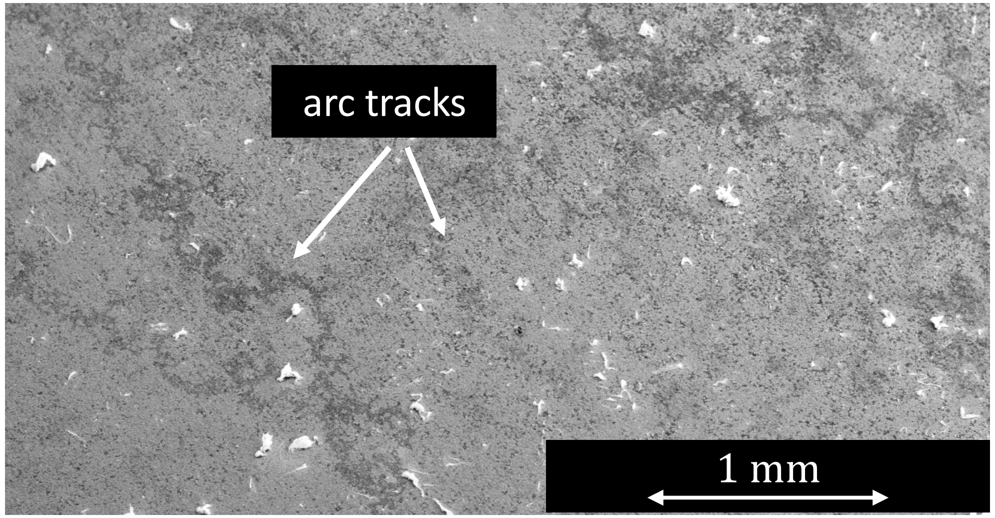
1. Introduction

- Plasma-wall interaction is one of the most critical factors determining plasma parameters in fusion devices
- Material properties and morphology of plasma-facing components (PFCs) determine this interaction
- In the case of tungsten (W) PFC, its surface morphology may change under helium plasma impact, which results in the formation of helium bubbles, tungsten fuzz growth, or the formation of nano-tendril bundles (NTBs)
- Electric field near the PFC [1]: $F = \sqrt{\frac{en_e}{\epsilon_0}}(8UT_e)^{1/4}$
- Arcing events were detected on fuzzy tungsten after experiments in NAGDIS-II
- Appearance of nanostructures on PFC leads to an increase of PFC material erosion



SEM-image of tungsten fuzz

- If $U = 150$ V, $n_e = 4 \cdot 10^{18}\text{m}^{-3}$, $T_e = 6$ eV $\Rightarrow F \approx 2.5$ kV/mm – lower than field emission (FE) threshold
- Local field amplification near fiber tips leads to the reduction of FE threshold



Arc tracks on a sample with NTBs

Properties of tungsten fuzz in comparison with pure W

- Low thermal/electrical conductivity($\sim 1\% W$) [2, 3]
- Increased field emission current due to local field amplification [4]
- Increased probability of unipolar arc ignition [5]
- Lower sputtering yield [6]
- Lower light reflection value [7, 8]
- Lower secondary electronic emission [9]
- Reduced D retention [10]

2. Nano-tendril bundles (NTBs)

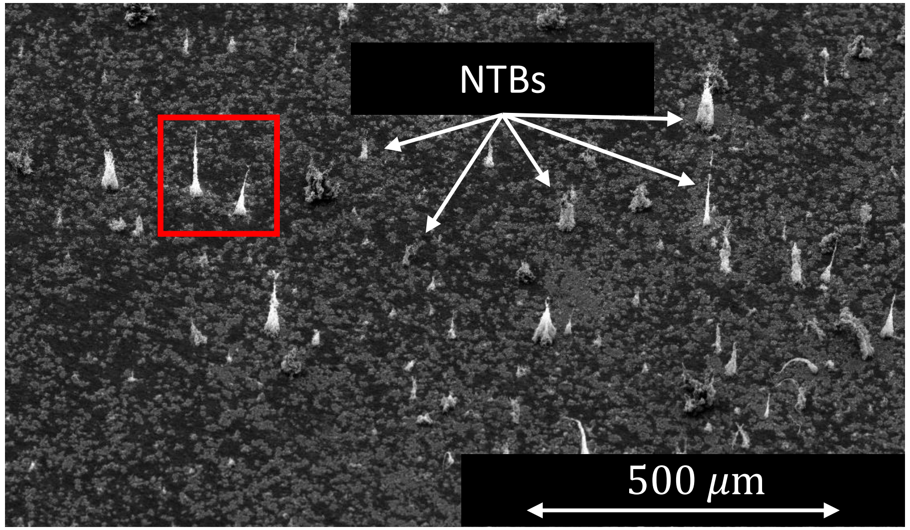
Growth conditions:

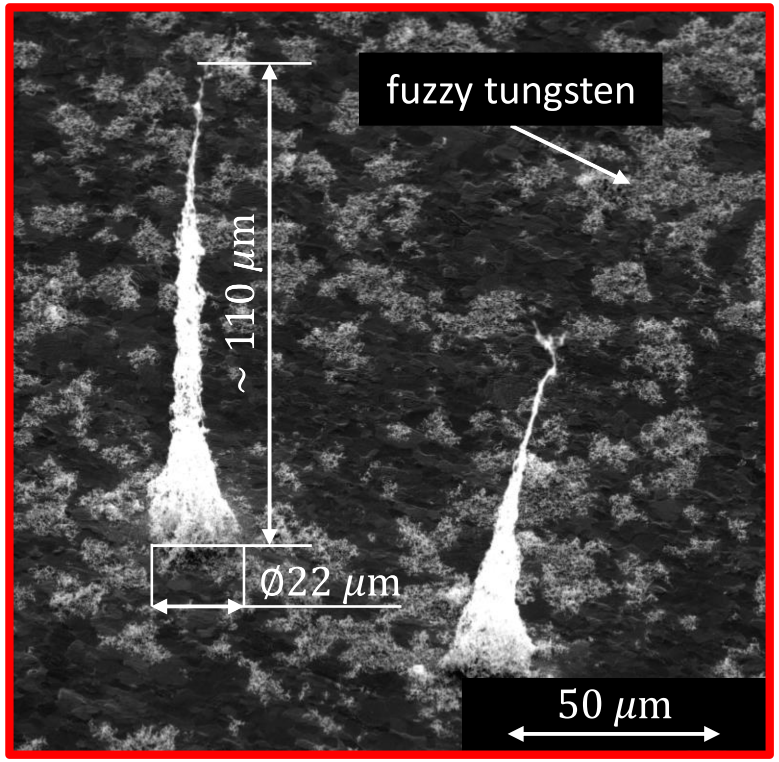
- Irradiation by helium plasma ions that contain a kind of impurity:
  - Ne (from 1% to 15%)
  - Ar (from 1% to 12%)
  - N_2 (from 1% to 10%)
- Ion energy: 70-350 eV
- Surface temperature: 870-1300 K
- Helium fluence: $\sim 10^{25}\ \mathrm{m}^{-2}$

Geometric properties:

- Height H: 10-200 μm
- Tip radius r: ~10 nm (several fuzz fibers form the tip)
- Bottom radius:
  - 5-10 μm for a single NTB
  - might be greater if several close NTBs form one protrusion

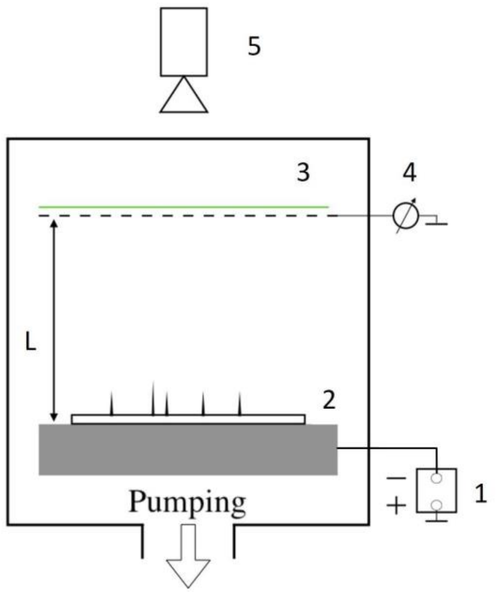
- NTBs grow on already formed tungsten fuzz and consist of its interviewed fibers
- Geometry of structures varies, depending on irradiation parameters (impurity type, impurity to helium ratio, etc)
- Probably, NTBs grow due to re-deposition of tungsten, sputtered by the gas impurity
- Aspect ratio ($A \approx H/r$) can be up to several thousands ⇒ high field enhancement near the tip of protrusions ⇒ reduced threshold for field emission initiation
- High porosity and low thermal conductivity of structures can lead to overheating due to Joule heat source and heat accumulation
- Reaching the melting point in few tens of ns can initiate an explosive emission or even trigger unipolar arc leading to NTBs destruction ⇒ increased erosion





SEM-image of a sample with NTBs

3.1. Field emission study in vacuum diode



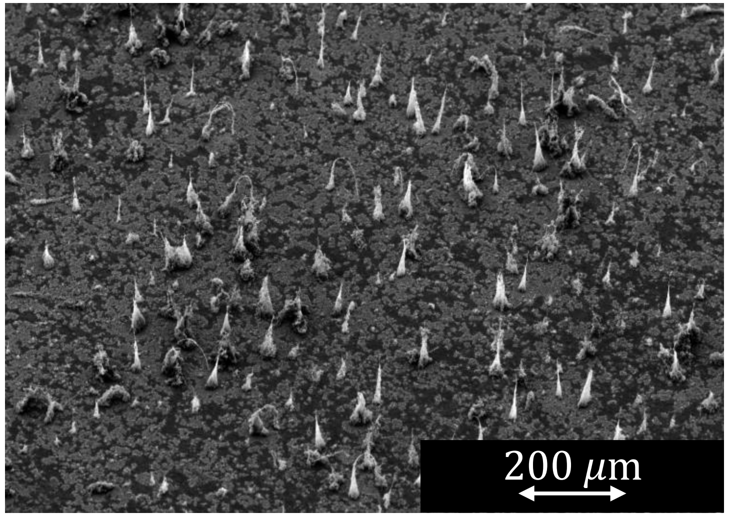
Experimental setup

1. DC source (0-20 kV)
2. Cathode
3. Mesh anode with luminophore
4. Nanoampermeter
5. Camera

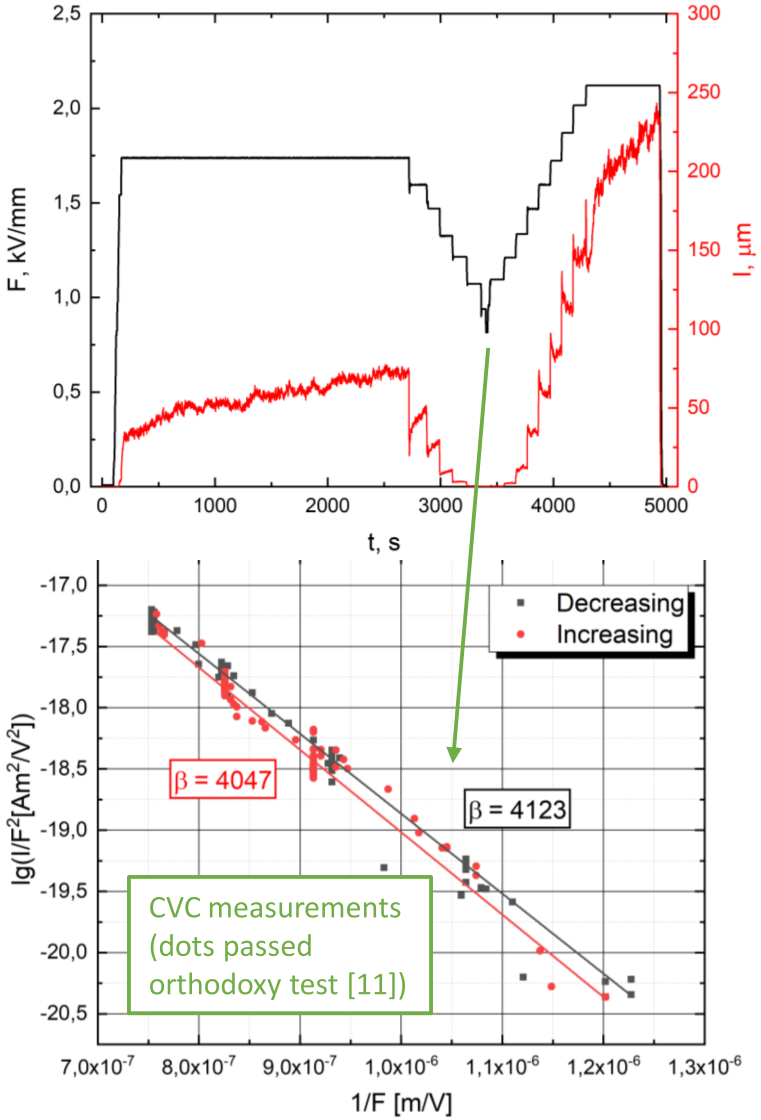
$L = 1$ mm

Samples with NTBs (Ø21mm) were produced in NAGDIS-II device during He+Ne($\sim$ 1%) irradiation

SEM-image of NTBS on the studied sample



Current/Field time dependencies

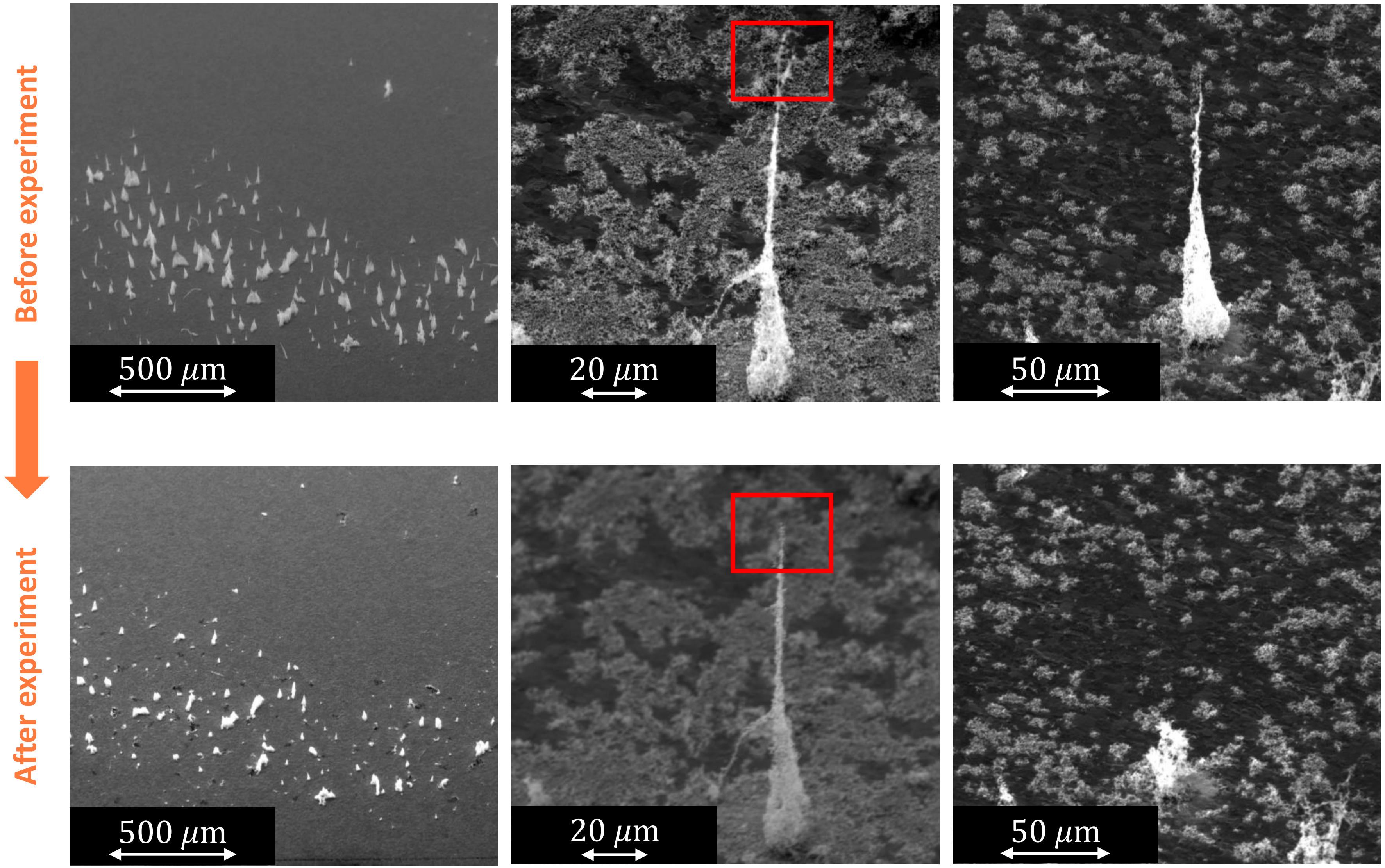


- Applied voltage was manually varied during experiments
- Electron emission from samples with NTBs can be stable for a long period of time
- Emission current can reach the value up to 100 μA under kV/mm applied field
- Estimations of field enhancement in FN-coordinates show that $\beta \sim 1000$
- **Samples with NTBS can be used as FE-cathodes?**

3.2. Field emission study in vacuum diode

Part of the sample with NTBs

SEM-images of NTBs showing partial and complete destruction



Destruction of NTBs

- Some of NTBs were destroyed after appliance of ~kV/mm field
- The tallest and sharpest structures were dominantly destroyed (highest aspect ratio and lower bottom radius)
- There is a critical value for the electric field when destruction occurs
- The critical value for the electric field depends on geometry of NTBs and their relative to each other position
- Some microprutrusions had only tips destroyed. Probably, due to local overheating of the thinnest part of the tip
- After destruction of the tip the field enhancement decreases leading to a reduction of field emission current

4.1. Numerical study of power balance for a single structure

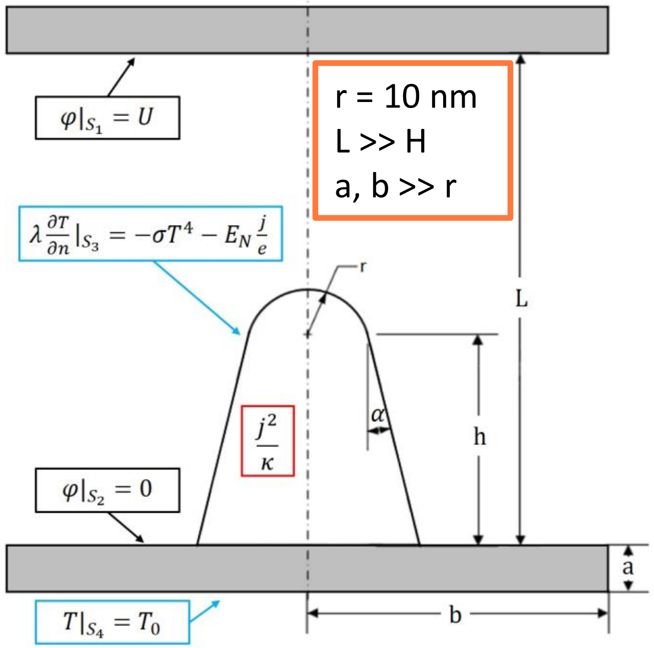
Laplace equation

- $\Delta\varphi = 0$
- $\varphi|_{s_1} = U$
- $\varphi|_{s_2}=0$

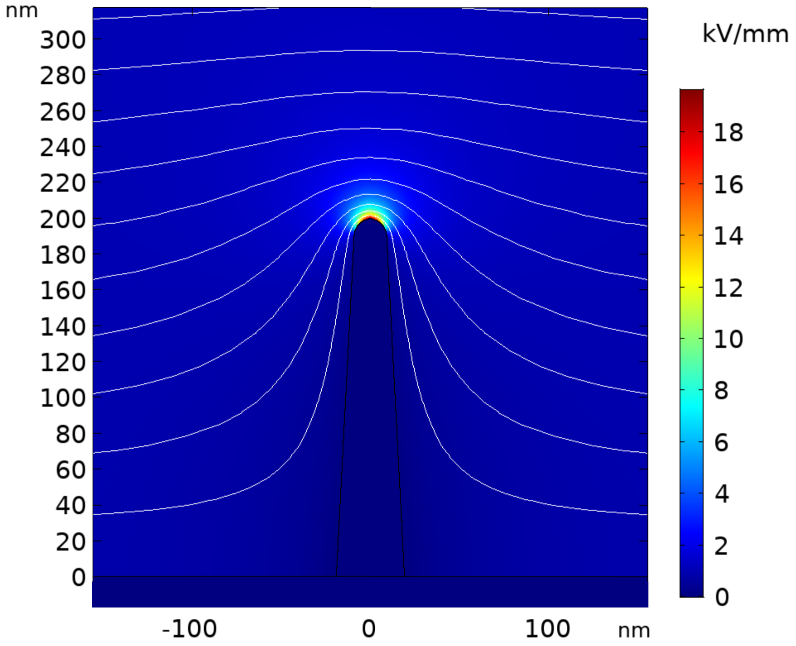
Heat transfer equation

- $c\rho\frac{\partial T}{\partial t} = \nabla\lambda\nabla T + \frac{j^2}{\kappa}$ Joule heat source
- $\lambda\frac{\partial T}{\partial n}|_{S_3} = -\sigma T^4 - \frac{j}{e}E_N$ Nottingham effect $E_N < 0$ (pure FE) $E_N > 0$ (pure TE)
- $T|_{S_4} = T_0$
- $T|_{t=0} = T_0$
- $T_0 = 300\ K$

Δ – Laplace operator, φ – electric potential, U – applied voltage, $c = c(T)$ – heat capacity, ρ – tungsten fuzz density, T – surface temperature, ∇ – nabla operator, $\lambda = \lambda(T)$ – coefficient of thermal conductivity, $j = j(T, F)$ – density of emission current, F – local electric filed strength,$\kappa = \kappa(T)$ – electrical conductivity, σ – Stefan's constant, $\partial/\partial n$ – directional derivative along a surface normal vector



The studied geometry. Left part - boundary conditions, right part - variable parameters

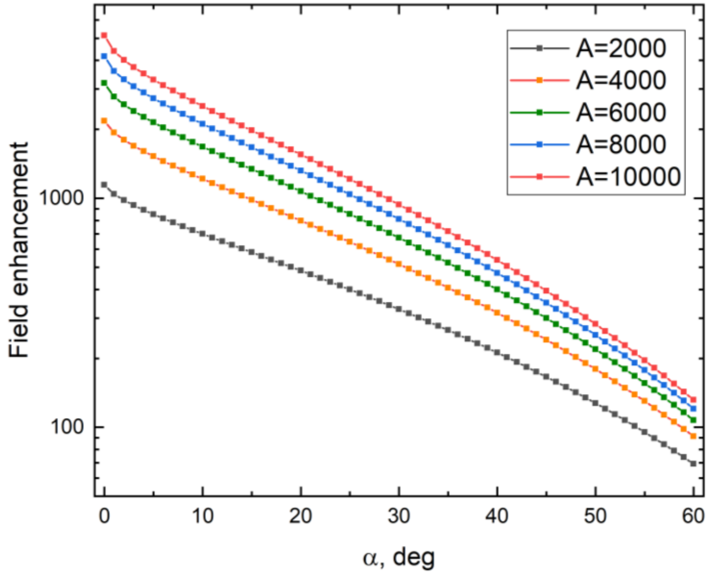


Electric field enhancement near the top of a structure. Lines - equipotentials

- Laplace's equation was solved to get the potential distribution between electrodes
- Time-dependent heat transfer equation was solved to study the evolution of structures' temperature
- The generalized equation for density of thermo-field emission current $j(T, F)$ was used [12]
- The problem was numerically solved in COMSOL Multiphysics
- NTBs were simulated as tungsten cones with density: $\rho = \rho_W/94$ [13]

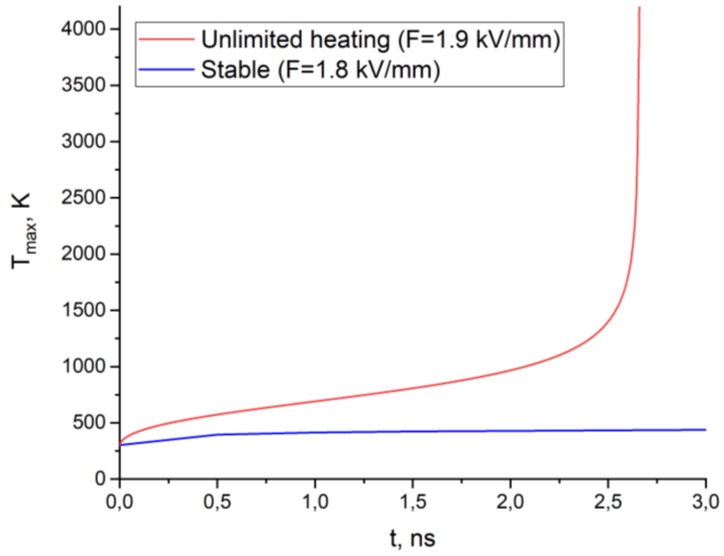
4.2. Results of numerical estimations

Field enhancement at the apex for different geometries



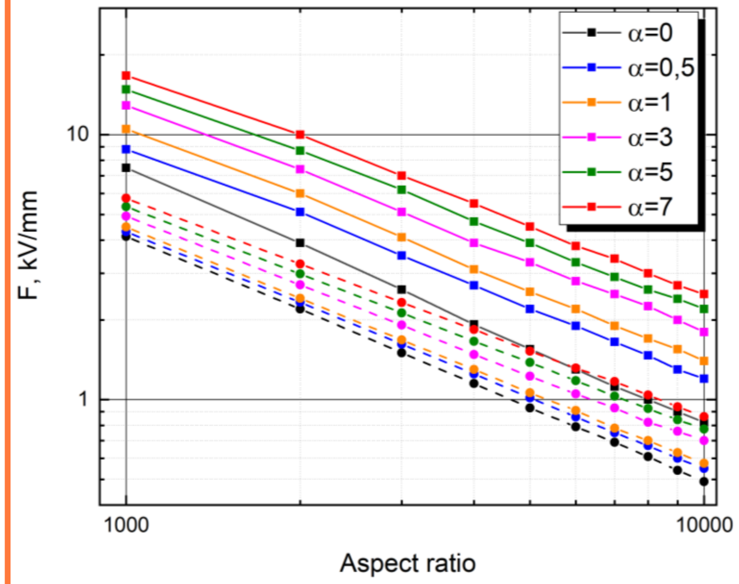
- Field enhancement factor is higher for smaller angles and taller structures
- Field enhancement can reach the value of several thousands
- Typical single NTBs have $\alpha = 1° - 10°$

Stable and unstable regimes



- Stable emission occurs under subcritical applied field when power sinks and sources compensate each other
- Unstable emission occurs when Joule heating unlimitedly increases structures' temperature, initiating thermo-field emission
- Critical values for the electric field depend on structures' geometry

Critical value of electric field corresponding to an instable regime



Solid lines – critical field value

Dashed lines – electric field value for 1 nA current

- There is a possibility of structures' destructions under field lower 10 kV/mm
- $F^{\alpha}_{crit}[kV/mm] \approx 472.2 \cdot (7.4 + \alpha[deg])A^{-0.86}$
- $F^{0}_{crit}[kV/mm] \approx 6668.2 \cdot A^{-0.98}$

5. Conclusions

Emission properties of samples with NTBs

- Simulations in COMSOL and analysis of experimental CVCs have shown that field enhancement is high ($\beta > 1000$) for tall and sharp NTBs
- Field emission current from tungsten samples with NTBs can reach the value up to several hundred μA under electric field of kV/mm magnitude
- Emission current depends on geometry of structures, their relative position to each other, number of NTBs on the sample
- Emission current can be stable for several hours
- Samples with NTBs, probably, can be used as flat FE-cathodes

Increased erosion under plasma-relevant electric fields

- Experimental results and modelling have shown the electric field threshold exceeding which leads to the destruction of main emitters
- Modelling has shown the probability of stable regime for single structures under applied field with magnitude lower than critical value
- Structures with $A > 1000$ can be destroyed under electric field of several kV/mm
- Increased erosion may occur under plasma-relevant electric fields (even without arcing)

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