



Contents lists available at ScienceDirect

## Journal of Nuclear Materials

journal homepage: [www.elsevier.com/locate/jnucmat](http://www.elsevier.com/locate/jnucmat)

## The occurrence and damage of unipolar arcing on fuzzy tungsten

D.U.B. Aussems<sup>a,\*</sup>, D. Nishijima<sup>b</sup>, C. Brandt<sup>b</sup>, H.J. van der Meiden<sup>a</sup>, M. Vilémová<sup>c</sup>, J. Matějčíček<sup>c</sup>, G. De Temmerman<sup>a</sup>, R.P. Doerner<sup>b</sup>, N.J. Lopes Cardozo<sup>d</sup><sup>a</sup> FOM Institute DIFFER – Dutch Institute for Fundamental Energy Research, Nieuwegein, NL-3430 BE, The Netherlands<sup>b</sup> Center for Energy Research, University of California at San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0417, USA<sup>c</sup> Institute of Plasma Physics, Association EURATOM-IPP, 182 00 Prague 8, Czech Republic<sup>d</sup> Science and Technology of Nuclear Fusion, Eindhoven University of Technology, Den Dolech 2, Eindhoven, The Netherlands

## ARTICLE INFO

## Article history:

Available online xxx

## ABSTRACT

This research investigated whether unipolar arcing in the divertor of fusion reactors is a potential cause for enhanced wear of the divertor. It was found that 1  $\mu\text{m}$  of nano-fuzz growth is sufficient to initiate arcing, mainly depending on the sheath potential drop and electron density. The average mass loss rate induced by the arc was determined from mass loss measurements and found to be consistent with the value estimated from the arc current. The average arc track erosion depth was estimated by using the measured mass loss and damaged surface area and was found to be one tenth of the fuzzy layer thickness. Due to melting of the fuzzy structures the actual depth is larger and some arc tracks occasionally appeared to even reach the bulk beyond the fuzzy layer. The conclusion of this study is therefore that arcing in the divertor of future tokamaks (e.g. ITER) potentially is an important cause for surface damage and plasma pollution.

© 2014 Elsevier B.V. All rights reserved.

## 1. Introduction

Tungsten will be used as divertor material in ITER. Recent experiments show that helium plasma exposure on tungsten can lead to nano-scale structure formation referred to as ‘fuzz’, even when the incident ion energy is less than the threshold energy for physical sputtering [1]. In fact, the growth of fuzz has recently been observed in the divertor of the Alcator C-Mod tokamak [2]. Fuzz may significantly increase the occurrence of unipolar arcing due to transient heat loads (e.g. ELMs) on the divertor [3].

The existence of the unipolar arc has been confirmed phenomenologically by erosion craters found in numerous fusion devices [4–7]. Arcing on fuzzy tungsten has recently been investigated in special model experiments using amongst others a plasma gun [8] and a laser pulse [9].

Unipolar arc behavior has not been investigated sufficiently in an divertor relevant environment in which amongst others the sample temperature, sheath potential and electron density can be varied. This research aims to investigate the conditions for which arcing on fuzz tungsten may occur, and how the damage can be related to those conditions. Arcing is investigated in a fusion

relevant environment using the PISCES-A and MAGNUM-PSI linear plasma devices, which enable us to easily access the plasma and tungsten sample.

## 2. Experimental setup

Most of the work done in this research has been performed on PISCES-A, while some supporting experiments were done on MAGNUM-PSI.

## 2.1. PISCES-A

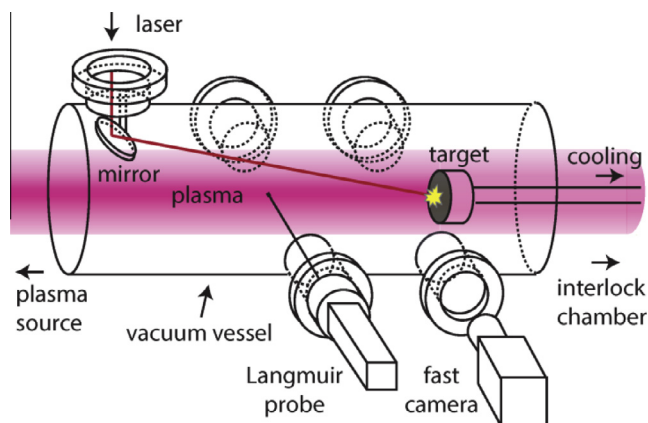
The linear plasma device PISCES-A is described in detail in Ref. [10]. The typical plasma is generated with a density of  $>10^{18} \text{ m}^{-3}$  and electron temperature of 5–7 eV (measured by a plunging Langmuir probe [11]). The plasma flows along the magnetic field to the target where the ions are accelerated by a sheath potential on an electrically biased target, producing an ion flux on the order of  $10^{22} \text{ m}^{-2} \text{ s}^{-1}$  with an ion energy that can be controlled between 50 and 250 eV. The target temperature was set to  $\sim 1200 \text{ K}$  by controlling the cooling air flow.

The experimental setup is depicted in Fig. 1. In each campaign, a fuzz layer ( $\sim 1 \mu\text{m}$ ) was created by exposing the target to a He-plasma for 1 h at a fixed sample temperature between 1170 and 1220 K, and bias voltage of  $-100 \text{ V}$  and  $-60 \text{ V}$  in campaign 1 and 2, respectively. Quickly before the onset of the arcing, the

\* Corresponding author at: FOM Institute DIFFER, P.O. Box 1207, Nieuwegein NL-3430 BE, The Netherlands.

E-mail address: [d.aussems@diffier.nl](mailto:d.aussems@diffier.nl) (D.U.B. Aussems).

<sup>1</sup> Presenting author.



**Fig. 1.** Illustration of the arcing experiment in PISCES-A. A tungsten target is exposed to helium plasma and a fuzz layer is grown. The laser hits the fuzzy tungsten target and arcing is initiated if the conditions are within the parameter space for arcing.

relevant experimental parameters are varied. To initiate arcing, a 1064 nm Nd–YAG laser pulse is focused on the target (max. laser power density  $1.1 \times 10^{14} \text{ W m}^{-2}$ , 6 ns pulse, spot size 1 mm).

A fast camera (Phantom I) is installed at the right side view port to observe the arcs on the target. To calculate the transient current during arcing, a Pearson current monitor is installed between the target and the ground. After each experiment the tungsten sample is removed from PISCES-A, and photographed by a handheld camera. An image analysis program is used to determine the damaged surface area. The mass of the sample is measured in threefold (for statistics) before and after each experiment using a high precision scale (10  $\mu\text{g}$  min scale).

## 2.2. MAGNUM-PSI

The experimental setup of MAGNUM-PSI plasma device is described in [12]. In MAGNUM-PSI a plasma is generated with a typical high plasma density ( $>10^{19} \text{ m}^{-3}$ ) and electron temperature of 1–2 eV (measured by a Thomson Scattering system [13]). The plasma is radially confined by the magnetic field of 0.8 T and flows to a water-cooled, electrically biased target, achieving a particle flux of  $1.5\text{--}3 \times 10^{23} \text{ m}^{-2} \text{ s}^{-1}$ , ion energy of 25–65 eV, and surface temperature of 500–720 K. For the arc experiments, fuzzy W samples were first made in PISCES-A (the plasma diameter is larger in PISCES and allows for a more uniform fuzz surface), and then installed in MAGNUM-PSI.

Initiation of arcing was achieved in a similar fashion as in PISCES-A, this time using two different lasers systems (for pulse width comparison). The first is a 1064 nm fiber-coupled Nd:YAG laser (pulse width 1 ms, power density  $1.0 \times 10^8 \text{ W m}^{-2}$ , spot size 1 mm). The other laser system is a 1064 nm Nd:YAG laser with a conventional beam line (pulse width 8 ns, power density  $4.8 \times 10^{12} \text{ W m}^{-2}$ , spot size 1 mm).

The surface temperature of the target during the experiment is determined by an IR-camera (FLIR SC7500 MB). The fuzz emissivity was measured *ex-situ* in the wavelength range 3.97–4.01  $\mu\text{m}$  and equals approximately 2.2 times the emissivity of pristine tungsten.

## 3. Arc observation

The fast camera emission images (side view) of a typical arc in PISCES-A are shown in Fig. 2 for different delay times (exposure time is 7.8  $\mu\text{s}$ ). The unipolar arc is ignited by a laser pulse which induces a dense tungsten plasma. After  $\sim 40 \mu\text{s}$  this plasma has been significantly expanded and the unipolar arc plasma becomes

dominant. The arc splits into two emission spots, which start to randomly move around the surface. At 2.56 ms droplets are emitted from the surface and finally the arc spot extinguishes after 2.67 ms.

The arcs have a duration of 2–6 ms and sustain a current of 20–70 A. The maximum emission intensity is caused by the laser-induced plasma, and occurs during the first 100  $\mu\text{s}$ , and is at least a factor 10 higher than the average intensity during the arc. A typical arc propagation speed was found of  $\sim 50 \text{ ms}^{-1}$ . The light emission area (side view as in Fig. 2) was  $50 \pm 30 \text{ mm}^2$  on average.

For some shots we were able to observe droplets. The droplets mainly originated from the edges of the target and moved with a speed  $\sim 10 \text{ ms}^{-1}$  from the arc emission center, one order of magnitude lower than the literature value  $100 \text{ ms}^{-1}$  [14].

## 4. Arc occurrence

Several parameters influencing the arc ignition threshold have been investigated, and have found to be mutually related. For example in some cases the bias voltage can be smaller, if the electron density is higher. For this reason the threshold value has to be viewed considering the other parameters.

### 4.1. Bias voltage/sample temperature

Table 1 shows the occurrence of arcing as function of the bias voltage and sample temperature in PISCES-A ( $P_{\text{laser}} = 7.5 \times 10^{13} \text{ W m}^{-2}$ ,  $n_e = 2.5 \times 10^{18} \text{ m}^{-3}$ ).

First of all, the occurrence of arcing highly depends on the bias voltage. During our experiments in PISCES-A arcing never occurred at  $|V_{\text{bias}}| < -80 \text{ V}$ . In the temperature range 970–1220 K the occurrence of arcing depends on the bias voltage only. The lower  $|V_{\text{bias}}|$  threshold for arcing at  $T_s = 1270 \text{ K}$  can be either explained by the shot-to-shot variation or a more intense primary erosion plasma due to a higher base temperature. The lower threshold at  $T_s = 870 \text{ K}$  was unexpected and needs to be confirmed.

### 4.2. Pressure/electron density

In an experiment in PISCES-A ( $P_{\text{laser}} = 7.5 \times 10^{13} \text{ W m}^{-2}$ ,  $V_{\text{bias}} = -100 \text{ V}$ ,  $T_s = 1120 \text{ K}$ ) the neutral gas pressure was decreased from 1.0 to 0.3 Pa, corresponding to an electron density drop from  $2.5 \times 10^{18} \text{ m}^{-3}$  to  $9.0 \times 10^{17} \text{ m}^{-3}$ , and arcing no longer occurred.

In an experiment in MAGNUM-PSI the electron density was  $3.4 \times 10^{19} \text{ m}^{-3}$  and arcing already occurred at a bias voltage of  $-65 \text{ V}$  ( $T_s = 710 \text{ K}$ ), using a similar laser with pulse width 8 ns and power density  $9.2 \times 10^{12} \text{ W m}^{-2}$  (one order of magnitude lower than PISCES-A).

The 35 V smaller bias voltage at which arcing occurs in MAGNUM-PSI can be related to the fact that the electron density is one order of magnitude higher. A higher density decreases the (Child) sheath thickness  $s_{\text{Child}} = \sqrt{2} \lambda_{\text{De}} / 3 \times (2e|\Delta V| / (kT_e))^{3/4}$ , in which  $\lambda_{\text{De}} = \sqrt{\epsilon_0 kT_e / (n_e e^2)}$  [14]. To reach the same electron emission, and thus local electric field (roughly approximated as  $E_{\text{surf}} = 4V_c / (3s_{\text{Child}})$ , in which  $V_c$  is the cathode fall), the bias voltage can be less negative. This can also explain the electron density dependence which we observed in our experiments.

Remarkably, this electron density dependence was not observed under the conditions of previous work on NAGDIS-II [9]. A possible explanation is that the fuzz thickness is larger than in PISCES-A, because the surface temperature during exposure was significantly higher (1630 K vs  $\sim 1200 \text{ K}$ ). This can ease the triggering of arcing and thus, under the experimental conditions used in Ref. [9], the influence of the electron density may be negligible.

Download English Version:

<https://daneshyari.com/en/article/7965725>

Download Persian Version:

<https://daneshyari.com/article/7965725>

[Daneshyari.com](https://daneshyari.com)