

Measurement of the energy and mass-charge composition of the ion flux of the vacuum spark on a tungsten cathode coated with fuzz nanostructures

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Abstract. The spark discharge was burned by applying a pulse of 20 kV, 50 ns to the anode. Distance cathode-anode was 30–20 microns. Measurements were taken in several series of 100 pulses. For each position of the cathode, three series of 100 pulses were performed. This design of the spectrometer differs from the previously used one by the presence of a plasma disruption system with additional acceleration of the ion component by 200 eV. As a result of the measurements performed, it can be unambiguously indicated that during the first few tens of discharges on the FUZZ surface, the flow contains mainly hydrogen ions and impurities. Subsequently, the proportion of tungsten ions increases, while the proportion of hydrogen ions decreases to a few percent.

1. Introduction

The process of discharge ignition on the nanostructured surfaces on a tungsten wall of the fusion reactor is of a great importance. It is well known that the vacuum discharge ignites when the power of electron emission current and ion current from ambient plasma exceed the power consumption by thermal conduction of cathode material. The vacuum breakdown criterion usually stated as follows [1]

$$j^2 t = h, \quad (1)$$

where j is a current density, t – delay time. The h can be described as specific action (s.a.). The s.a. defines the energy necessary to explode a volume of cathode material. If a cathode is made of pure smooth material the delay time and s.a. have significant values. This is because the current must explode a significant volume of material. The bigger volume to explode the longer delay time t and higher current density j should be.

If cathode surface contains small sized structures the cathode spot operation needs to explode small volumes of the structures to sustain the cathode spot operation. The small exploding volumes need much less delay time and current to keep the cathode spot operation. Thus, the nanostructured coating of the cathode surface should provide breakdown facilitation and a low threshold current of the cathode spot.

The FUZZ nanostructures are believed to coat the walls of fusion reactors [2]. So, the presence of these nanostructures should lead to increase probability of arcing between fusion plasma and reactor walls.

The present work is devoted to examination of breakdown and spark process occurred on the FUZZ surface. The use of Thomson spectrometer should show the difference between breakdown on the clean tungsten surface and FUZZ coated surface.

2. Experimental setup

2.1. Thomson spectrometer

Measurements of the mass-charge and energy composition of the ion flux of a vacuum spark with a tungsten cathode coated with the FUZZ nanostructure were carried out in vacuum at a residual pressure of 10^{-5} mm Hg. The experimental equipment had a coaxial design and was placed

in an evacuated tube 80 mm in diameter and 300 mm long. An image of the general view of the installation is shown in Fig.1

All components of the experimental setup are arranged coaxially, which makes it easier to find the optimal relative position of the spectrometer source and detector to obtain a spectrogram. The

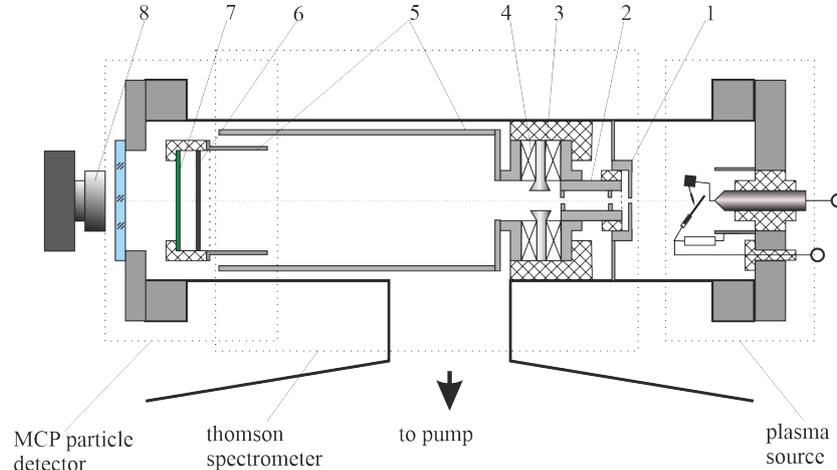


Fig.1. The spectrometer setup: 1 – spectrometer input node with 300 μm aperture; 2 – ion collimator with two 150 μm apertures; 3 – block of field tips for creating parallel magnetic and electric fields; 4 – Insulating insert; 5 – flight pipe; 6 – microchannel plate (MCP); 7 – phosphor screen; 8 – CCD camera.

Thomson spectrometer has a circuit modified with respect to those previously used [1]. In this scheme, all parts of the spectrometer, except for the input node (1), are under negative potential to break the plasma. The plasma break occurs between the aperture of the grounded input node (1) and the grid at the end of the ion collimator (2). The plasma burst potential was 200–300 V. The ion beam formed in the ion collimator enters the region of parallel magnetic and electric fields (3). In this region, the ions are separated according to the parameters E/Z M/Z , as a result an image of parabolas is formed on the particle detector. Next, the ion beam enters the flight tube (5), where the beam is separated into fractions. The block of field tips and the flight tube are isolated from the walls of the vacuum chamber by a dielectric insert (4). The ions hit the microchannel plate (5) where the signal of charged particles is amplified up to 10^3 times. The final image is formed on the phosphor screen (7).

This design of the spectrometer differs from the previously used one [2] by the presence of a plasma disruption system with additional acceleration of the ion component – by 200–400 eV.

2.2. The electrode system

The general scheme of the electrode system is shown in Fig.2. The discharge was ignited between a pointed spark anode and a cathode plate. A high voltage pulse was applied to the anode. The pulse amplitude was 20 kV with a duration of 50 ns. The anode tip was always on the optical axis of the spectrometer. This position determined the place where the discharge should occur. The cathode plate was connected to the body of the vacuum chamber through a shunt resistance of 0.25 Ω . The current to the cathode was recorded with an oscilloscope. The cathode assembly was a flat holder of two stainless steel plates, into which a tungsten plate 200 μm thick was inserted. For experiments, both the plate itself for control measurements on pure tungsten and the plate with a FUZZ-coated sample welded onto it (treatment period 1 hour) were used. The cathode plate could slide in the holder, which made it possible to change the place of the discharge on its surface. For a more complete disclosure of the cathode surface on which the discharge occurred, the cathode plate was located at an angle of 60 degrees to the optical axis of the spectrometer.

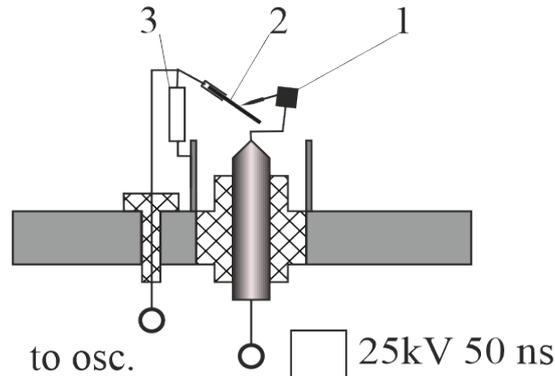


Fig.2. The electrode setup: 1 – point anode; 2 – cathode plate; 3 – current shunt.

3. The experimental results

3.1. The measurements on the clean tungsten cathode

Preliminary measurements were carried out on the cleaned surface of tungsten foil. After cleaning with discharges, oscillograms of the current pulse were obtained (Fig.3). After cleaning the tungsten surface with several tens of discharges, the discharge current has a noticeable delay time and a relatively slow increase.

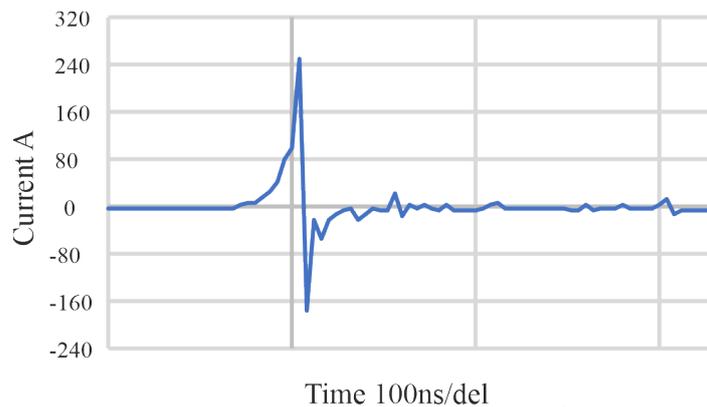


Fig.3. The spark current on the clean surface.

The energy and mass-charge compositions of the stream of accelerated ions of a vacuum spark accumulated over 10 pulses were also obtained (Fig.4 and Table 1).

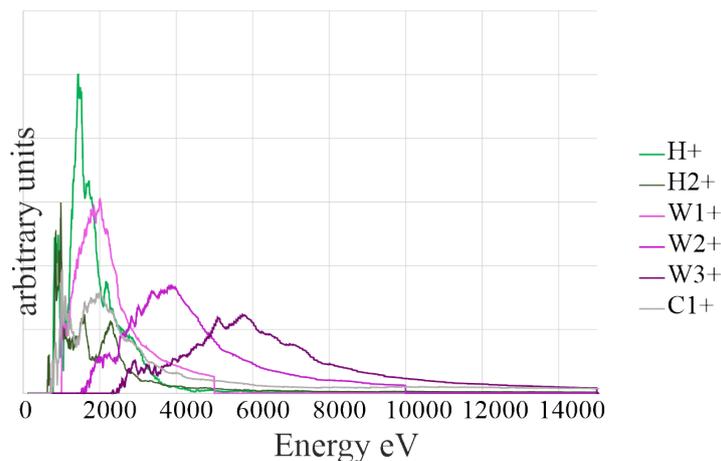


Fig.4. Energy spectra of ions on pure tungsten foil.

Table 1. Mass-charge composition of the ion flux for a clean tungsten surface

Ion fraction	H ⁺	H ₂ ⁺	C ¹⁺	W ¹⁺	W ²⁺	W ³⁺
Content %	17	9	20	17	18	19

3.2. The measurements on the FUZZ structures

The same pulse (20 kV, 50 ns) was used. Distance cathode-anode 30–20 microns. Measurements were taken in 10 series of 100 pulses. For each position of the cathode, three series of 100 pulses were performed. In the first series, the spectrograms shown in Fig.6 and 7 were obtained; in the third series, the spectrogram shown in Fig.8 was obtained. All series are characterized by the presence of single spectrograms with the presence of only a hydrogen ion signal. Such spectrograms were not included in the total accumulation.

Fresh FUZZ surface

Spectrograms for the first hundred pulses are shown in Fig.6 and 7. In this case, the discharge current is shown in Fig.5.

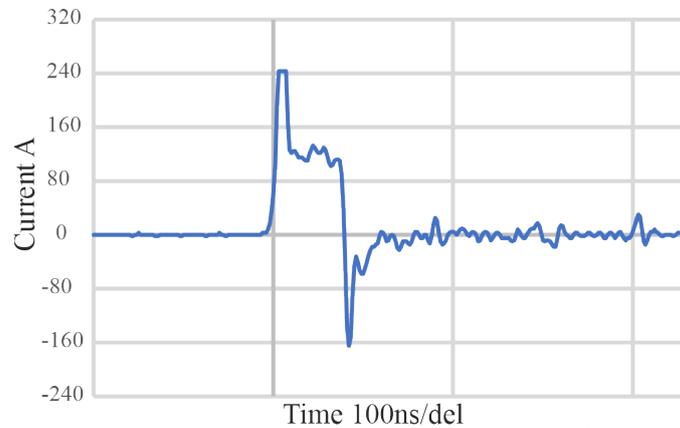


Fig.5. The spark current on the fresh FUZZ surface.

In contrast to the discharge on pure tungsten, the discharge on the surface of the FUZZ nanocoating has practically no delay time and the current begins to rise rapidly. This is most likely due to the presence of a large amount of fast fraction – hydrogen ions.

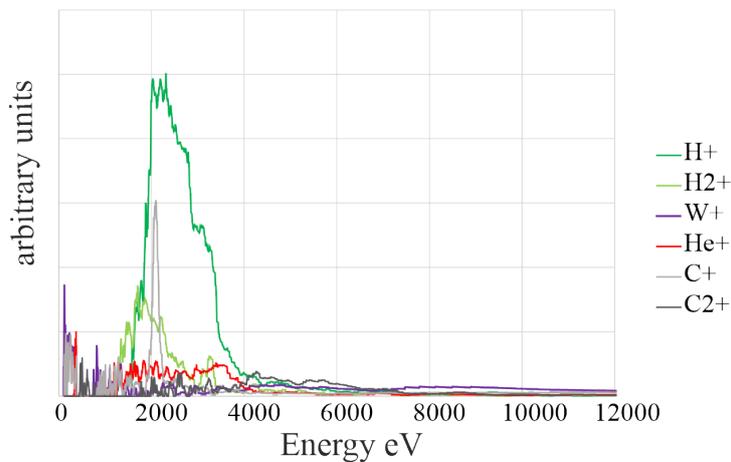


Fig.6. Energy spectra of ions for a fresh FUZZ surface.

Table 2. Mass-charge composition of the ion flux for a fresh FUZZ surface

Ion fraction	H ⁺¹	H ₂ ⁺	He ⁺¹	C ⁺¹	C ⁺²	O ⁺¹	W ⁺¹	W ⁺²	W ⁺³
Content %	39	13	11	14	9	0	14	0	0

In this measurement, the main component of the ion flux turned out to be atomic hydrogen, while there were signals from molecular hydrogen, carbon, helium, and tungsten. In this measurement, the ion flow contains mainly ions of dissolved gases (H, He). The presence of base material ions (W) is negligible.

Fig.7 also shows the spectrogram for the first series of 100 pulses. This measurement was made for a new position on the cathode surface.

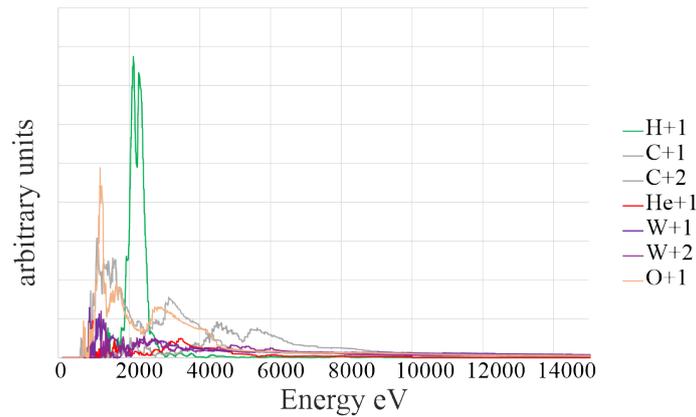


Fig.7. Energy spectra of ions for a fresh FUZZ surface.

Table 3. Mass-charge composition of the ion flux for a fresh FUZZ surface

Ion fraction	H ⁺¹	H ₂ ⁺	He ⁺¹	C ⁺¹	C ⁺²	O ⁺¹	W ⁺¹	W ⁺²	W ⁺³
Content %	16	0	5	21	13	23	12	10	0

In this case, the composition of the ion flux is very different. The flow is also based on ions of various inclusions (H, He, O) and impurities (C). But at this point, the ion flow contains more contaminants (carbon),

The FUZZ surface after 100 discharges

The spectrogram obtained in the third series of experiments is shown in (Fig.8). This spectrogram was obtained at a new point on the cathode.

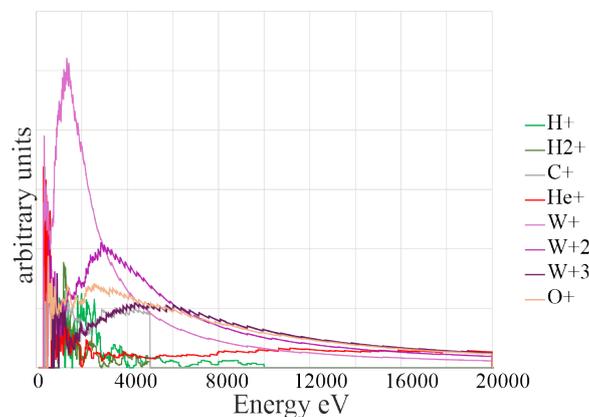


Fig.8. Energy spectra of ions for a fresh FUZZ surface after 100 discharges.

Table 4. Mass-charge composition of the ion flux for a FUZZ surface after 100 discharges

Ion fraction	H ⁺¹	H ₂ ⁺	He ⁺¹	C+1	C+2	O ⁺¹	W ⁺¹	W ⁺²	W ⁺³
Content %	3	1	8	8	0	19	24	20	17

At this point, after the third series of experiments, an erosion spot 0.5 mm in diameter and 50 μm deep remained. There are no traces of the FUZZ nanocoating in the center of the spot. In this series of measurements, there were several pulses with a weak signal and one with a clear ion flux signal. This measurement shows a low content of dissolved hydrogen (3%). Such a hydrogen content is characteristic of spark plasma in a cleaned section of the cathode [4].

4. Conclusion

As a result of the measurements performed, it can be unambiguously indicated that during the first few tens of discharges on the FUZZ surface, the flow contains mainly hydrogen ions and impurities. Subsequently, the proportion of tungsten ions increases, while the proportion of hydrogen ions decreases to a few percent. The helium ion signal is present in almost all frames with a good ion signal. The energy spectra of the ions contain several local maxima in the range of 1000–6000 eV, which is several times less than the pulse amplitude at the anode, and, consequently, the energy of explosive electrons. When the cathode surface is cleaned from the coating, the proportion of fast hydrogen ions decreases, therefore, the velocity of the plasma boundary should drop by an order of magnitude from 10^8 cm/s to 10^7 cm/s

Acknowledgement

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5. References

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