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Journal of Nuclear Materials 290–293 (2001) 220–223

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

The porous vanadium as a plasma facing material for the fusion devices

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Abstract

The purpose of this work is to investigate a possibility to use porous vanadium as components for the first wall of a tokamak-reactor which can accept the halo-currents generated during a disruption in a tokamak. Samples of pure porous vanadium were tested in pulse high current discharges in lithium plasmas. A total electric charge up to 1000 C flowed through the sample in the series of the discharges. The measured erosion was about of 3×10^{-5} g/C when the sample was used as a cathode. Samples of pure porous vanadium were also tested in TEXTOR-94. This was inserted into a carbon test limiter. The test limiter was placed in the scrape-of-layer of the main toroidal ALT-II limiter. Vanadium, deuterium and carbon were measured spectroscopically. The estimated relative flux of the vanadium atoms to deuterium atoms drops from 3.8% to 0.4% with line average electron density increase from 2.5×10^{19} to 6×10^{19} m^{-3}.

Keywords: Plasma–material interaction; Vanadium; Lithium; Erosion; Limiter; TEXTOR

1. Introduction

It is well known that the halo-currents generated during a disruption in a tokamak keep at least 20% of the total plasma current. One of the problems in elaborating a fusion reactor construction is the localization of these halo-currents on special wall components which will accept a part of the evolved energy during disruptions. These wall components should be replaceable and protected against erosion. Vanadium as construction material for such wall components has evident advantages due to its radioactive safety. Unfortunately, it has a rather low melting temperature and, for this reason, it should be additionally cooled. Cooling of porous surfaces by liquids was already used for a long time in the different fields of modern thermophysics. We suggest that porous vanadium filled with liquid lithium can be used in such a special wall component. The liquid lithium film on the vanadium surface will reduce the heat flux to the porous vanadium due to lithium evaporation and protect it against erosion by energetic particles. The presence of lithium plasma near the surface can suppress the development of thermal contraction [1–3]. The phenomenon of thermal contraction is based on surface overheating instability due to replacement of cold emitted electrons by hot plasma electrons. Without this surface protection the flux of vanadium atoms from one

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0022-3115/01/$ - see front matter
PII: S0022-3115(00)00605-X

hot spot can be of 10^{20} atoms/s [2]. This value is by five order of magnitude larger than the one for hot spot formation on tungsten surface.

The present report continues the researches published earlier [4,5]. The purpose of this work is the investigation of a possibility to use porous vanadium as components of the first wall of tokamak-reactor. This report is a result of the following researches:

1. Tests of samples from porous vanadium as electrodes (both cathodes and anodes) in pulsed high current discharges in lithium plasmas. These experiments are important, since in earlier works the large erosion caused by droplets formation was found for the anode made of vanadium alloy 98% V 2% Nb [4].
2. The first testing of vanadium sample in TEXTOR as first step of the researches in tokamaks. All investigations were carried out with pure vanadium samples.

2. Experiments in a lithium plasma

Investigations were carried out in a setup 'Robotron' aiming for production of dense metal vapors plasmas. The experimental arrangement is shown schematically in Fig. 1. The plasma is initiated by a vacuum arc between electrodes **K** and **A**. Solid lithium is loaded in the cathode **K**. The diameter of the cathode is 7 mm. The vanadium anode of a diaphragm shape is located at a distance 10 mm from cathode. A voltage up to 2 kV is applied at electrode **I** for initiating an arc. A capacitor bank of 2600 μF charged up to 250 V is used as a power supply for the plasma injector. A load resistor restricts the arc current to 1 kA. The lithium plasma penetrates into the main discharge through a gap between electrodes **E1** and **E2**. The length of the gap is 140 mm. The electrodes are placed in a quartz tube with an inner diameter of 26 mm. A capacitor bank of 4000 μF charged up to 500 V is used as a power supply for this discharge. A load resistor restricts a discharge current to 1.2 kA.

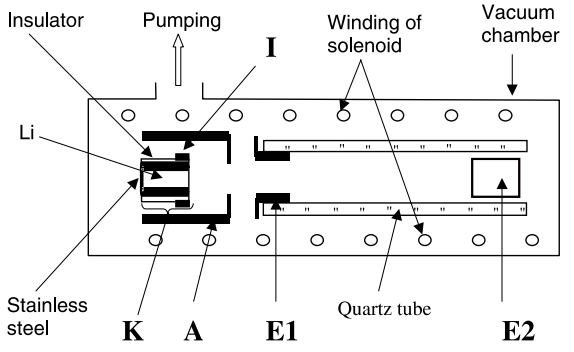

Fig. 1. Schema of the 'Robotron' experimental arrangement: **K** – cathode; **I** – ignited electrode; **A** – anode; **E1** – electrode; **E2** – porous vanadium electrode.

The porous vanadium sample (size of pores: 35–45 μm, volume of pores: total 45.2%, open 32.4%) is allocated on a place of electrode **E2**. The polarity of voltage applied between electrodes **E1** and **E2** can be changed and, consequently, **E2** is used either as a cathode or an anode of main discharge. We studied two kinds of samples. The first had a diameter of 10 mm and the second of 20 mm. So the mean current densities were, respectively, 1.5×10^7 and 0.4×10^7 A/m^2.

The background pressure in the system is about 10^{-5} Torr. The discharges were repeated with a frequency of 0.2 Hz. The discharge chamber is immersed in a longitudinal magnetic field with induction up to 600 G.

The porous vanadium has a high surface area and, consequently, is a strong getter. So it was heated up to 250–300°C, before the discharges were started.

The plasma density injected from the first stage into the main discharge can be estimated in the following way. Kimbling [6] studied the vacuum arcs of 16 materials (including easy-melting gallium, lead, zinc and tin) for current less than 1 kA and found that the coefficient of proportionality between an ion current and a total discharge current is in a range 0.06–0.1 for all investigated materials. Assuming a discharge current of 1.2 kA we get an ion current on a level of 100 A. It is also known that the energy of ions is usually in the range of 10–100 eV. Our measurements for lithium plasmas carried out with a multi-grid analyzer show an ion energy of 35–40 eV. Taking into account that the plasma is immersed into a strong longitudinal magnetic field and that a diameter of the cathode is 7 mm, it is easy to estimate a plasma density near the outer of the injector on a level $\sim 5 \times 10^{20}$ m^{-3}. If we assume that the initial plasma occupies the whole volume of the quartz tube in the central part of the main discharge we get a plasma density $\sim 3 \times 10^{19}$ m^{-3}. The estimates carried out with using the discharge current value [4] show that the plasma density in the main discharge should be order of 10^{21} m^{-3}.

The lithium vapor ionization degree was close to unity. This has been confirmed by spectroscopic measurements. If only the lithium injector works and the capacitor bank for the main discharge is switched off, the intensive LiI resonance line ($\lambda = 670.78$ nm) is observed in the central part of the quartz tube. The intensity of this line drops by more than in an order of magnitude when the main discharge is switched on. It can be attributed to an almost full burn-out of lithium atoms into lithium ions.

The magnitude of porous vanadium erosion is determined by the weight-loss method. A few experiments were carried out for each kind of samples. Each run of measurements contains at least 500 impulses. This corresponds to a total electric charge more than 1000 C. The erosion was estimated as ratio of the reduction of weight of sample to the total electric charge. This

erosion includes all types of erosion (evaporation, sputtering by lithium ions, etc.). The traces of melting are observed on porous vanadium surface when it is used as an anode; but a detectable erosion is not found. The area of melting increases when the current load grows. If the sample is used as a cathode, the erosion is about 3×10^{-5} g/C for samples of 10 mm diameter and 2.4×10^{-5} g/C for samples of 20 mm diameter.

3. Test limiter with porous vanadium sample in TEXTOR-94

The experiments have been performed in the tokamak TEXTOR-94 with a major radius $R = 1.75$ m and a minor radius $a = 0.46$ m. TEXTOR-94 was operated at a toroidal magnetic field of 2.25 T and plasma current of 350 kA. The line averaged central electron density was varied between 1.5×10^{19} and 6×10^{19} m^{-3}. Additional heating was provided by a neutral beam injector (NBI) injecting tangentially in the co-direction of the current with a power of 1.3 MW.

A porous vanadium sample of 20 mm diameter and 15 mm length was inserted into a carbon test limiter in the region of the expected highest thermal flux. (20 mm from the test limiter center at the ion drift side.) The dimensions of the test limiter are 120 mm × 80 mm and a spherical shape with a radius of 70 mm. This limiter was inserted from the top of the torus into the edge plasma through a limiter-lock [7] to the position $r = 0.48$ m.

The emission spectra of the plasma in front of the test limiter were measured in the range of 409–436 nm by an image intensified CCD-camera coupled test limiter has to a spectrometer (Ebert type, $f = 0.5$ m). The entrance slit of the spectrometer was oriented along the minor radius and centered at the position of the porous vanadium sample. Typical spectra of the plasma in front of the test limiter which includes the porous vanadium sample in the line of sight are shown in Fig. 2 for low and high electron densities. The relative intensity of neutral vanadium lines to deuterium line strongly decreases with rising electron density. For the flux measurement, most bright VI line ($\lambda = 411.8$ nm) in this wavelength range has been selected. The ionization events per photon S/XB for this line have been calculated with the help of excitation cross-sections from [8] and ionization cross-sections from [9]. Note that there is a substantial uncertainty for the ionization rate of neutral vanadium: a four times less value is predicted by the Lotz-formula and a two times less value by the Voronov-formula [10].

The calculated ionization events per photon S/XB for VI (411.8 nm) versus electron temperature is shown in Fig. 3. The first curve on this figure was calculated with data from [9]. The second curve was calculated with

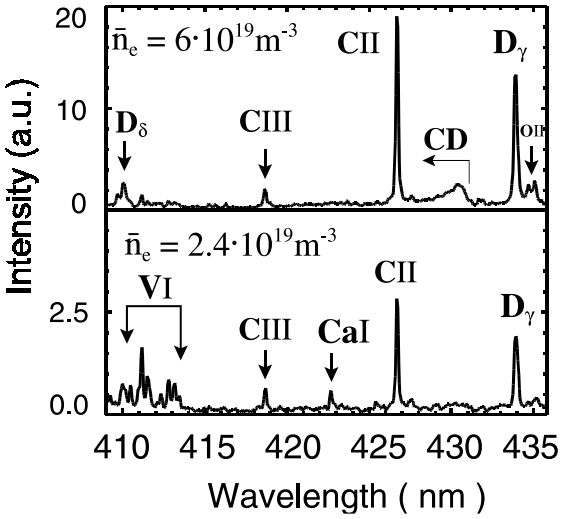

Fig. 2. Typical spectra of plasma in front of carbon limiter with porous vanadium sample for two different electron densities.

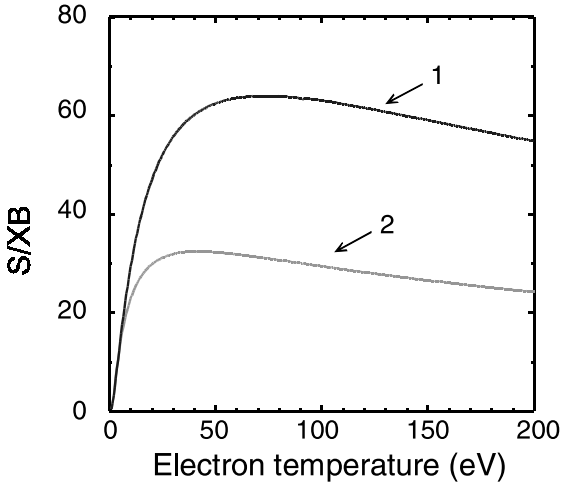

Fig. 3. Ionization events per photon for VI ($\lambda = 411.18$ nm): (1) ionization rate from [9]; (2) ionization rate from [10].

using data from [10] and shown for comparison. We have chosen S/XB = 60 as conversion factor for the vanadium flux measurement, because S/XB is a constant within ±10% for the electron temperature range of 30–200 eV which is expected for the plasma in front of the test limiter.

Fig. 4 shows the measured relative vanadium and carbon fluxes emitted from the test limiter as a function of line averaged central electron density. This measurement was made during a density ramp. The C/D flux ratio is obtained from a CII line ($\lambda = 426.7$ nm) and D_γ using a ratio for the ionization to photon rates S/XB(CII):S/XB(D_γ) of 0.035. For the V/D flux ratio, a

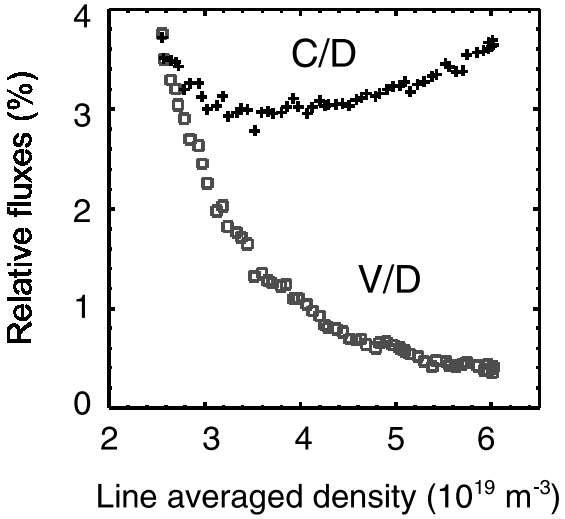

Fig. 4. Density dependence of the relative V/D and C/D fluxes emitted from the carbon limiter.

ratio of S/XB(VI $\lambda = 411.8$ nm):S/XB(D_γ) of 0.06 has been used. As it can be seen, the vanadium yield decreases with increasing electron densities from 3.8% to 0.4%. The C/D flux shows different behaviours. At the lowest (2.5×10^{19} m^{-3}) and highest (6×10^{19} m^{-3}) electron densities it is 3.6% and shows a minimum of 3% at 3.4×10^{19} m^{-3}. The increase of the carbon flux can be attributed to an enhanced hydrocarbon production because also the **CD**-band emission remarkably grows with electron density as seen in Fig. 2.

4. Summary

Thus, the investigation of the electrodes from porous vanadium in a lithium plasma is carried out. An erosion in each experiment is determined after 1000 C is fluxed through a sample. In contrast with solid electrode [1] the erosion of porous vanadium is not considerable when it is used as an anode. When the samples under investigation are employed as a cathode, the erosion $(2.7 \pm 0.3) \times 10^{-5}$ g/C has been detected.

A sample of porous vanadium as a part of a test limiter was inserted into the boundary layer of TEXTOR-94. The relative erosion V/D of vanadium decreases from 3.8% to 0.4% when line averaged central electron density grows from 2.5×10^{19} to 6×10^{19} m^{-3}. It was demonstrated that porous vanadium components can be operated in the scrape-of-layer of the main toroidal ALT-II limiter.

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