Application of a multi-pass absorption cell for measurement of sputtered tungsten atoms’ density

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Abstract. A dedicated gas discharge tube equipped with a hollow cathode made of tungsten is setup for sputtering of W atoms. A multi-pass White type absorption cell is designed to increase the sensitivity of the absorption method. The optical system consists of three externally mounted aluminium-coated spherical mirrors with 70 cm radius of curvature. Measurements of the cell relative transmittance in the UV and visible spectral regions are carried out. Time-resolved measurements of sputtered ground-state tungsten atoms’ density in 2-pass configuration, as well as assessment of the diffusion coefficient of these atoms in argon at 350 K temperature are made.

1. Introduction

Tungsten has been widely applied in various plasma devices, given its high thermal resistance, excellent mechanical properties and low rate of sputtering due to bombardment with ions and neutral atoms with high energy. These are various gas discharge lighting sources, plasma reactors for layer deposition, as well as fusion devices of type tokamak, stellarator, etc. Under certain conditions, however, tungsten components are still eroded and tungsten atoms enter the plasma. Typical example is the electrode destruction in gas discharge lamps at start-up [1]. This effect has an impact on the lifetime of the lighting sources, on their stability and parameter reproduction. A key problem, concerning controlled fusion research is the interaction of plasma with the reactor walls. The requirements for the materials that come into contact with the burning plasma are complex. In the scope of the international fusion reactor project ITER, the plasma–facing materials to be used are beryllium for the main chamber wall, and carbon and tungsten in the divertor. A lot of tests are made with tungsten on existing experimental devices (ASDEX-Upgrade, Garching, Germany, JET, Culham, UK) [2,3]. A program for gradual covering of the device’s walls with tungsten is carried out, and the obtained results are quite optimistic. A potential problem that has to be addressed is plasma pollution with high-Z impurity (Z = 74), which leads to radiation cooling. The maximum accepted tungsten concentrations in the tokamak core plasma, beyond which the normal operation of the device is restricted by radiation cooling, are very low (of the order of $10^{-3}$ % of plasma density). Whether relevant to low-temperature or high-temperature laboratory plasma, tungsten erosion makes it necessary to control the influx of sputtered atoms and their concentration in the near-wall plasma with
high enough sensitivity. Time resolved measurements help clarifying the processes in the plasma device and are needed for optimizing its operation regimes.

This work is a part of research, aimed at application of optical methods (absorption and laser induced fluorescence) for sensitive detection of low densities of sputtered tungsten atoms with time resolution. A dedicated experiment, based on multi-pass absorption measurement of sputtered ground- and excited-state tungsten atoms is described.

2. Experimental
The experimental setup (figure 1) is similar to one previously used [4], with the exception of the White type multi-pass cell [5]. It consists of a light source, absorption tube, optical system, monochromator, photomultiplier working in gated photon-counting mode, computerized experiment controller and a 2-channel high voltage pulsed source (last two not shown in the figure). The absorption tube, used for sputtering of the metal by pulsed gas discharge, is made of pyrex glass. It contains a 20 cm in length and 30 mm in inner diameter cylindrical hollow cathode, the inner surface of which is covered by a tungsten sheet. The anode is a small aluminium cylinder placed at one side of the tube, close to the edge of the cathode. The glass tube is sealed at both ends with quartz optical windows. The White optical system is mounted externally and consists of 3 concave spherical mirrors, which have 70 cm radius of curvature. The main mirror has 2 holes allowing the light from the external source to enter the system and to leave it after a number of passes, produced by successive reflections from the mirrors. An additional spherical mirror is used as a condenser, introducing into the cell a converging beam from the external light source. The latter is a commercial tungsten hollow cathode lamp (Hamamatsu, filling gas neon). Both the absorption tube and the lamp are operated in synchronized pulse-periodic mode. The typical periods of pulse repetition are chosen in the range 25–30 ms. The absorption tube pulses have widths in the range 2–3 ms with 300–400 mA average current. The lamp discharge current is 40–50 mA and its duration — 500–600 μs. Figure 2 shows typical emission spectra of both tubes.

![Figure 1. Experimental setup.](image)

The experimental arrangement provides time-resolved measurements of the relative absorption of a given spectral line in the absorption tube volume with extended effective absorption path. The number of passes through the volume can be varied by proper alignment of the cell mirrors.

Several tungsten atomic states are of primary interest for absorption measurements, since they are expected to be the most populated in the plasma: $^{1}\text{D}_0$ (ground state); metastable $^{3}\text{D}_1$ (0.207 eV), $^{7}\text{S}_3$ (0.363 eV), $^{5}\text{D}_4$ (0.412 eV), $^{5}\text{D}_3$ (0.599 eV), $^{5}\text{D}_4$ (0.771 eV). There are a number of spectral lines in the UV region between 240 and 260 nm, connected with transitions involving these states, which have
considerable strengths. However, higher loses in the UV, compared with the visible region are observed. This can be seen in figure 3, where continuum spectrum of a deuterium lamp has been recorded. The poorer transmittance is connected with losses in the monochromator and the multi-pass cell. The losses in the White cell accumulate with increasing the pass count, due to the multiple reflections at mirror surfaces and passes through the optical windows. Enhancement of the cell transmission will be obtained by multi-layer coating of the optical surfaces and in-tube arrangement of the multi-pass system.

Figure 2. Spectra in the UV region emitted by the tungsten hollow cathode lamp (a) and the absorption tube in the active phase of a pulsed discharge in krypton (b).

Figure 3. Deuterium lamp spectrum recorded in two arrangements for assessment of the multi-pass system throughput.

Illustration of the work of the system in two-pass arrangement can be seen in figure 4. Time resolved measurements of the density of ground-state tungsten atoms, sputtered in pulsed discharge in argon are shown. The absorption of the resonance line W I 2551 is used for the purpose. The curve is obtained by conversion of the recorded time dependency of the absorption signal (maximum value between 5 and 10 %), based on literature data for the line strength (0.52) [5] and modeled Doppler broadened line profiles. The line profiles are assessed by a model, considering the isotopic abundance
of tungsten [6] and isotopic splitting of the $^5D_0$ level, using available data from [7]. Further considerations or profile measurements might be necessary.

![Graph showing decay of ground-state $^5D_0$ sputtered tungsten atoms' density in the afterglow of pulsed discharge in argon. Two-pass arrangement of the optical cell. Gas pressure: 77 Pa; gas temperature: 350 K discharge period: 29 ms; discharge duration: 3 ms; pulse current: 400 mA.](image)

Figure 4. Decay of ground-state ($^5D_0$) sputtered tungsten atoms’ density in the afterglow of pulsed discharge in argon. Two-pass arrangement of the optical cell. Gas pressure: 77 Pa; gas temperature: 350 K discharge period: 29 ms; discharge duration: 3 ms; pulse current: 400 mA.

The decay curve from figure 4 exhibits mono-exponential behaviour. It is consistent with a mechanism of diffusion controlled losses in the afterglow period, where the decay rate is dependent on two parameters: the diffusion coefficient and the wall reflection coefficient [8]. Both parameters cannot be derived from a single curve. If however, the reflection of the tungsten ground-state atoms at the cathode wall is negligible (< 30 %), then their diffusion coefficient can be estimated to $D_0 = 210 \pm 30$ cm$^2$s$^{-1}$ at 133 Pa argon pressure, 350 K temperature. Further measurements at various gas pressures are needed to derive more definite values.

3. Conclusion
A multi-pass setup for absorption measurements of sputtered tungsten atoms’ density has been put in operation and tested. The relative transmission of the optical system has been measured with impact on future enhancement of the optical system. Based on measured densities, preliminary assessment of the diffusion coefficient of ground-state tungsten atoms in argon has been made.

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