Laser induced fluorescence measurements on W- and Ba atoms eroded from fluorescent lamp electrodes

J Ehlbeck\textsuperscript{1}, K Rackow\textsuperscript{1}, F Sigeneger\textsuperscript{1}, D Uhrlandt\textsuperscript{1}, K-D Weltmann\textsuperscript{1}, S Hadrath\textsuperscript{2} and G Lieder\textsuperscript{2}

\textsuperscript{1} Leibniz Institute for Plasma Science and Technology, Felix-Hausdorff Str. 2, 17489 Greifswald, Germany

\textsuperscript{2} RLS-M, OSRAM GmbH, Munich, Germany

ehlbeck@inp-greifswald.de

Abstract. The method of laser induced fluorescence (LIF) is applied to fluorescent lamps (FL) in order to investigate processes of electrode erosion in the vicinity of the electrodes. The life time of FLs which are ignited by instant start is mainly limited by sputtering of the coil electrodes and in final breaking. This sputtering of tungsten mainly occurs during the ignition in the glow discharge phase. Therefore, the density of W atoms is measured in the electrode region during ignition. Temporal and spatial resolved profiles were measured by LIF which has been combined with fast imaging. The life time of FLs which are started with preheated coils is also caused mainly by electrode failures. But the reason differs from the instant start case because here the loss is caused mainly by evaporation. End-of-lamp life is reached if the emitter material which is deposited at the coil to reduce the work function of the coil is lost completely. LIF is used to measure the density of the eroded emitter material, namely Barium atoms. First result of phase resolved absolute Ba atoms densities are presented.

1. Introduction

Today, the lifetime of fluorescent lamps (FL) is mainly limited by the electrode durability. The electrode is the junction between plasma and solid and is therefore responsible for driving the lamp current. In general it consists of a tungsten coil coated with a work function reducing emitter mix of alkali oxides, such as BaO, SrO and CaO. During lamp life such an electrode is damaged by two essential processes. In case of an instant start ballast the electrode is heated up by ion bombardment before transitioning into the arc-mode (glow-to-arc-transition) where the so called hot-spot builds up. During this time electrode material such as emitter material and also tungsten is eroded by sputtering. This process limits the number of switching cycles. After transition into the arc-mode, during steady state operation, the emitter material (primary Barium) erodes from the hot-spot. In case of a good adaption of the electrode to the discharge conditions, this erosion is in general evaporation.

For a detailed investigation of these processes a local and very sensitive diagnostic is needed. To quantify the erosion this method should be able to measure absolute densities. The laser induced fluorescence (LIF) fulfils all this requirements [1-2]. The good temporal resolution (the temporal resolution is limited by the lifetime of the excited level and the laser pulse length) also enables the investigation of the dynamic of such processes.
2. Laser induced fluorescence

The LIF technique allows the detection of ground state or long-lived, excited-state atoms, molecules or radicals. The LIF process can be described as a two-step process [3]. First, a specific species in its ground state \( |1\rangle \) (energy \( E_1 \)) is excited by resonant absorption of laser photons (\( h\nu_{\text{laser}} \)) to a higher electronic energy level \( |2\rangle \) of energy \( E_2 \) with

\[
\Delta\nu_{12} = E_2 - E_1.
\]

After laser excitation, this excited state relaxes by spontaneous emission to a lower state \( |3\rangle \) of energy \( E_3 \) by emitting fluorescence photons with the energy \( h\nu_{\text{LIF}} = E_2 - E_3 \). This fluorescence radiation is emitted nearly isotropic [4]. For a spectral width of the laser \( \Delta\nu_{\text{laser}} \) that is much broader than the line width of the exited transition \( \Delta\nu_{12} \), a rate equations model could be used to describe the excitation and relaxation processes [5-8].

In the first approximation the time integrated fluorescent signal \( S_{\text{LIF}} \) is proportional to the ground state density \( n_1 \):

\[
S_{\text{LIF}} = \int I_{\text{LIF}}(t) dt \propto S(\lambda) \frac{\Delta\Omega}{4\pi} \frac{A_{23}}{A_2} \sigma_{\text{LIF}} \frac{E_{\text{laser}}}{F_{\text{laser}} h\nu_{\text{laser}}} \cdot V \cdot n_1,
\]

where \( S(\lambda) \) is the sensitivity of the detection system at the fluorescent wavelength, \( \Delta\Omega \) is the detection angle, the ratio \( A_{23}/A_2 \) of the Einstein transition probabilities is the relation between the detected and all possible transitions to lower energy levels, \( \sigma_{\text{LIF}} \) is the corresponding fluorescence cross section, \( F_{\text{laser}} \) is the cross sectional area of the laser beam and \( V \) is the observation volume.

2.1. Absolute density measurements

For measurements of absolute densities the specific atomic data (such as Einstein coefficients), the laser energy and its spectral profile, the exact observed volume and angle, as well as the sensitivity of the detection system is needed. The main difficulties are the determination of the geometry and the spectral response of the optical imaging and detection. We therefore use the Rayleigh scattering calibration technique to overcome the determination of sensitivity, detection angle and observation volume. This commonly used method is described in text books and literature e.g. by Hadrath [4] in the case of tungsten atoms.

2.2. Experimental setup

For the generation of the laser beam a Nd:YAG pumped dye laser operating at 10 Hz is used to pumped the dye laser at 532 nm (figure 1). In case of Barium atoms, the dye laser provides radiation at 700.22 nm and is frequency doubled by a KDP crystal to the desired 350.11 nm. In case of tungsten, the radiation of 575.98 nm is frequency doubled to 287.94 nm. The resulting beam is directed through a 1 mm aperture to get a defined beam diameter.

Figure 1. Experimental setup for measurement of Barium ground state densities.

A spatial filter (consist of two lenses (\( f = 100 \) mm each) in a distance of 200 mm with a 20 \( \mu \)m pinhole located at the common focal point) is used to reshape the resulting degraded beam profile to a nearly Gaussian shape. This beam is directed through the lamp (perpendicular through the glass surface) directly in front of the electrode. The fluorescent radiation at 582.63 nm is observed
perpendicular to the beam. The region of interest is imaged (1 : 3) to the entrance slit of a 0.5 m monochromator (Acton Research SpectraPRO-500I) with a 1800 grooves mm\(^{-1}\) grating. The observed volume has a dimension of approximately 0.7 x 0.7 x 1.0 mm\(^3\). For measuring the fluorescent radiation a photomultiplier (Hamamatsu Photonics, R-1477) is used, whereas the laser intensity is measured by a photodiode.

3. Results

3.1. Tungsten erosion

For investigation of tungsten erosion processes during instant start a commercial FL is driven by an electronic control gear with a frequency of around 44 kHz. A few milliseconds after power on (t = 0), the lamp ignites in the glow-mode. After a certain time which is typical in the range between 15 and 25 ms and has a stochastic nature the discharge changes into the arc-mode which is called the glow-to-arc transition. Due to the low laser repetition rate of 10 Hz there is only one laser pulse per ignition available to excite eroded tungsten atoms. Therefore the temporal evolution of the sputtered tungsten density is reconstructed on the base of subsequent lamp starts.

In figure 2 the investigated section of the coil is presented and the location where the discharge attaches is marked. In contrast to the modeling results of Haverlag et al [9] the discharge attaches not only at the bare tungsten ends of the coil but also at the emitter covered part. One possible reason could be that the electrode is covered inhomogeneous by the emitter. LIF-measurements were performed at five equidistant positions 2 mm in front of the coil and with distances of 0.5 mm between them.

![Figure 2. Diagram of the location of the hot spot (discharge attachment point) and the LIF measurements Laser beam (black cycles) at a distance of 2 mm.](image)

![Figure 3. Two reconstructions of the same tungsten population density measurements, according to the time after ignition (a) and the time related to the glow-to-arc-transition (b) at different positions near the coil. Due to the neglect of the transmission of the bulb the density will be about four times higher.](image)

By measurement of the lamp voltage and the discharge current we could determine the moment when the ignition starts and the moment when the glow-to-arc-transition takes place. The reconstructed tungsten density profiles are presented in figure 3. In figure 3(a) one can see the temporal evolution of the tungsten population density in relation to the moment of the ignition of the lamp (\(\Delta t_2\)) and in (b) the same densities in relation to the moment of the glow-to-arc-transition (\(\Delta t_3\)).

Due to the large scatter of the time interval between the ignition and the glow-to-arc-transition for different instant starts the left figure better describes the tungsten densities directly after the ignition, and the right one better describes the behaviour during the glow-to-arc-transition.

The eroded tungsten density starts immediately with the ignition, reaches a maximum where the discharge contracts at the end of the glow mode and decreases some milliseconds before the glow-to-arc-transition takes place.
3.2. Barium Erosion
For investigation of Barium erosion in steady state operation a current controlled electronic ballast working at 25 kHz is used. The commercial FL is driven with its nominal rms-current of 320 mA. As the laser has a low repetition rate of 10 Hz the measured time dependence results from the reconstruction of several periods, where each point is the average of 600 laser pulses. As the Barium densities are very low, they are measured at a distance of 0.5 mm from the hot-spot (of the coil).
During the anode phase the lamp voltage as well as the current are defined to be positive (figure (4b)). The Barium density strongly depends on the electrode and plasma processes (figure (4a)). During the cathode phase the electrode needs to sustain the lamp current. To emit the electrons a very thin plasma sheet with a strong potential drop builds up at the electrode surface, the so called cathode fall. The emitted electrons pass this sheet and are accelerate by the field to a kinetic energy in the range of the cathode fall (approx. 15 eV). These high energetic electrons ionize and excite the rare gas as well as the Barium atoms in the electrode region. At the beginning of the cathode phase the lamp current is very low and therefore the Barium atom ground state density decreases with a short delay (related to the beginning of the cathode phase). With the end of the cathode phase this excitation and ionisation processes are reduced. During the anode phase these processes are more or less insignificant and therefore the Barium density builds up again.

Figure 4. The time dependent Barium density 0.5 mm in front of the hot-spot (a) and the regarding lamp current and voltage (b).

4. Conclusion
The durability of electrodes mainly influences the lifetime of FL. In the case of instant start the electrodes will be destroyed due to coil fracture at the emitter-free ends, whereas in the case of preheating the Barium erosion during steady state operation is the lifetime limiting factor.

We concentrated on a commercial FL and presented our reconstructions of the temporal evolution of the absolute tungsten and barium population density of the ground state. The temporal behaviour of tungsten erosion during instant start was presented, where constant tungsten erosion during the whole glow-phase was found.

We also presented the temporal Barium densities during steady state operation. Here a strong decay of the density during the cathode phase was found. An evidence for sputtering of barium could not be found.

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