29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. ***26B****, P-2.023 (2002)*

INVESTIGATION OF THE IR RADIATION LOSSES IN MICROWAVE OPERATED SULFUR LAMPS

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Introduction

The High Intensity Sulfur (S_2) Discharge is of special interest for lighting applications as it shows the highest known plasma efficacy (~170 lm/W) for the generation of white light. The main reason for this striking efficacy is the small amount of (loss) radiation emitted in the IR. In this paper we present investigations on the IR losses of a microwave driven Sulfur discharge in dependence on important lamp parameters (power density, filling amount, vessel geometry, buffer gas). Furthermore we find indication that besides the well known electronic $B^3\Sigma_u^- - X^3\Sigma_g^-$ transition visible radiation is also emitted via the $B''\Pi^3_u - X^3\Sigma_g^-$ transition, especially in the red part of the visible spectrum.

Experimental Set-up

Microwave radiation at 2.45 GHz fixed frequency is generated by a magnetron and directed by waveguides via a matching / power detection system into a half ellipsoidal resonator (TM_{010} mode, see also Ref. [1]) in which the Sulfur lamps are placed in the region of maximum electric field strength. The lamp vessels are spherical quartz bulbs (wall thickness 2 mm) which are fused to thin (∅ = 4 mm, length = 10 cm) cylindrical quartz rods. With the help of these rods the lamps can be mounted through a hole in the back wall of the resonator to a drill which is used to rotate the operating lamps in order to homogenize the plasma and to avoid damage of the vessels by local overheating and sputtering. The inner resonator wall is covered with diffusive paint for performing spatially integrating measurements of the visible light flux. This light flux is recorded by a monolithic multichannel spectrometer (Zeiss) which is connected to the resonator via an optical fiber and which provides wavelength and intensity calibrated spectra between 250 nm and 1020 nm (spectral resolution ~2 nm). The IR radiation is monitored side-on through a small hole in the resonator wall and imaged into the entrance slit of a f = 0.25 m triple grating spectrometer (Yobin Ivon) which covers the wavelength range between 500 nm and 6 µm. Absolute calibration of the IR intensity is achieved by taking the optical thin part of the Sulfur radiation above 750 nm as a reference. Additionally the surface temperature of the quartz bulbs is monitored by a thermo-optical camera (AGEMA).

Results and Discussion

Fig. 1 shows typical emission spectra of a microwave operated Sulfur high intensity discharge (Lamp volume: 17.2 cm^3, Sulfur amount: 30.7 mg ⇒ calculated S_2 operating pressure: ~6 bar, Ar gas fill pressure: 200 mbar) for different microwave input powers.

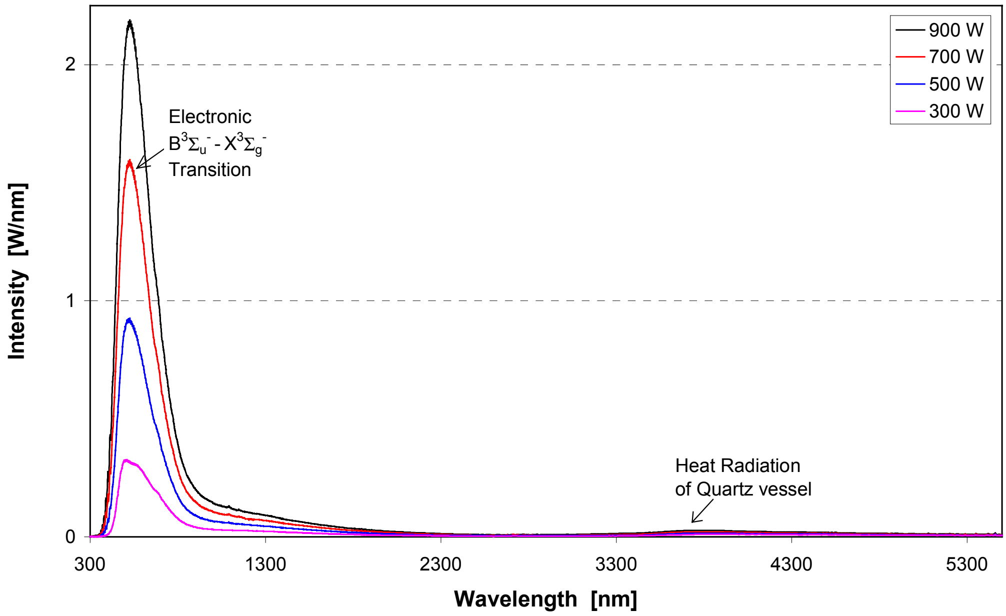

Fig. 1: Typical emission spectra of Microwave Sulfur Lamp

The radiation in the visible range mainly originates from the electronic $B^3\Sigma_u^-$ - $X^3\Sigma_g^-$ transition in the S_2 molecules which are the dominant particle species in the discharge. This part of the spectrum can be quantitatively described in a simple way by using a classical Franck-Condon radiation model (Ref. [2]) which allows the calculation of the temperature and frequency dependent absorption coefficient from the molecular potential curves. With the assumption of local thermal equilibrium (LTE) and of a cubic temperature profile with a wall temperature of T_{wall} = 1200 K and a temperature of T_{center} = 4800 K in the center of the discharge a radiation transport calculation can be carried out providing the total emitted light flux. The result of this model calculation for the above described lamp is shown in Fig. 2 for a microwave power of 900 W.

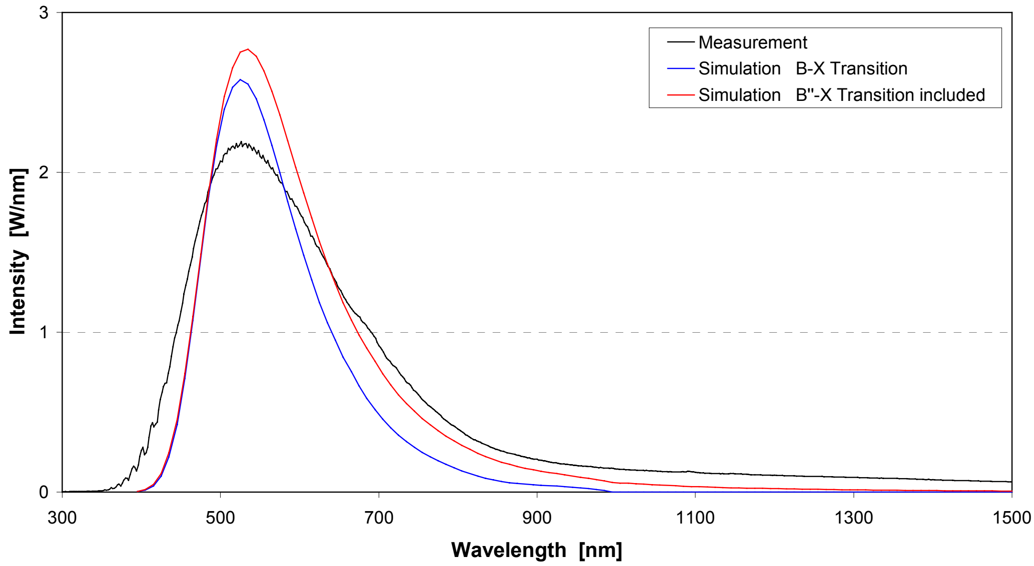

Fig. 2: Measured and calculated emission spectra.

With respect to the position of the emission maximum and the total visible power the model calculation gives satisfying results. There are however deviations in the UV and in the red part of the spectrum. The result for the emission in the red part can be significantly improved by including the electronic B’’Π^3_u - $X^3\Sigma_g^-$ transition into the model which indicates that this transition plays a non negligible role in the emission process. The lower simulated intensity in the UV may be caused by an overestimation of the overlap of ro-vibronic transitions which belong to adjacent bands leading to a too strong self absorption in the modelled UV spectrum. The origin of the long wavelength shoulder above ~900 nm is not yet clear up to now. We investigated theoretically the following continuous mechanisms: electron-ion recombination radiation, electron-ion Bremsstrahlung, electron-neutral particle Bremsstrahlung and radiative attachment. All these processes can be excluded as the source for the NIR radiation due to a too small radiation intensity. As possible other mechanisms we suggest the involvement of an unknown electronic state, of dissociative electronic states or the influence of non-LTE effects.

We also investigated the total energy balance of microwave Sulfur lamps in dependence on power density (range: 5-50 W/cm^3), Sulfur amount (2-10 bar S_2 operating pressure), buffer gas (fill pressure 50-400 mbar Ar/Ne/Xe) and lamp volume (9-42 cm^3). We distinguished between UV (λ < 400 nm), visible (VIS, 400 nm $\le \lambda \le$ 780 nm) and NIR (780 nm < λ < 3 µm) radiation, heat radiation of the quartz vessel and heat conduction between quartz vessel and air which can both be calculated from the simultaneously measured lamp surface temperature.

The amount of Sulfur in the lamp mostly influences the energy balance. As the absorption in the UV/blue increases with increasing Sulfur pressure the emission maximum shifts to longer wavelengths while the absolute intensity of the emission maximum decreases. This leads to an increasing emission in the NIR at the expense of visible radiation. Heat radiation and conduction losses remain unchanged however.

An increase of power density leads to an increase of visible radiation with respect to the total lamp power while the contributions of heat radiation and heat conduction decrease.

A variation of the noble gas – both kind of gas and pressure – around typical values (100-200 mbar Ar) was found to have no influence on the energy balance and on lamp efficacy.

The following typical ranges can be given for microwave driven Sulfur lamps (in quartz vessels) which are optimized for lighting applications, the data for the lamp with the optimum luminous efficacy of 170 lm/W (~6 bar S_2 operating pressure, 200 mbar Ar, volume 17.2 cm^3) are given in brackets:

- < 1% (0.5%) UV radiation
- 50-60% (60%) of input power emitted in the visible spectral region
- only 10-15% (15%) loss radiation in the NIR
- 20-30% (20%) of input power emitted as heat radiation
- Heat conduction losses are with 3-6% (3.5%) of input power of minor importance.

The uniquely high contribution of the (continuous) VIS radiation and the low NIR losses compared to other HID lamps result in the unique value of 170 lm/W plasma efficacy for white light.

References

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