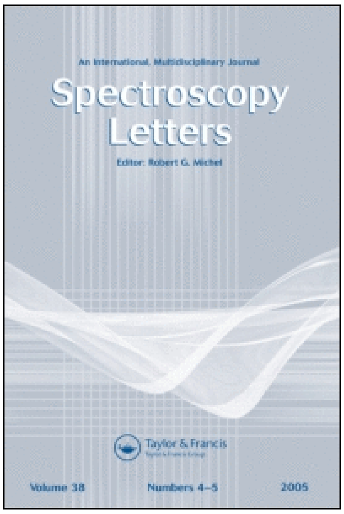

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Theoretical and Experimental Investigation of Neon-Hydrogen Penning Recombination Laser

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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF NEON-HYDROGEN PENNING RECOMBINATION LASER

KEY WORDS: Recombination laser, Hollow cathode glow discharge, Numerical simulation

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ABSTRACT

A theoretical and experimental study of $Ne-H_2$ Penning Recombination Laser operating on the *NeI 585.3 nm* line in the negative glow of a helical hollow cathode discharge is presented. A detailed kinetic model of the plasma-chemical reactions determining the inversion population on the *NeI* $(2p_1\text{-}1s_2)$ transition is developed. The time dependent behaviour of the main plasma and laser parameters is numerically calculated. The behaviour of the plasma and laser parameters as a function of the discharge conditions is investigated and compared with the experimental results.

INTRODUCTION

One of the most advanced schemes for obtaining inversion population operates in nonequilibrium, recombining low temperature plasma [1,2]. The recombination nonequilibrium of such a medium is thermodynamically opposite to the ionisation nonequilibrium typical for the conventional gas lasers. It requires an increased degree of ionisation and efficient cooling of the electrons. The lasers whose upper laser level is populated predominantly by a recombination flux are called Recombination Lasers. Further improvement of the Recombination Lasers is achieved by efficient depopulation of the lower laser level through collision processes. In the Penning Recombination Lasers the lower laser level is efficiently depopulated by Penning ionisation [1-2]. High degree of ionisation in the Recombination Lasers is achieved by using electron beams, neutron beams or gas discharges having an electron beam component. Effective cooling of the electrons is achieved by elastic scattering, vibrational and rotational level excitation of molecular buffer gases or in the afterglow. One of the most advanced schemes for laser generation is proposed in [3], where a high power Ne-H_2 laser, operating on *NeI 585.3 nm* line at atmospheric pressures has been reported.

It is of practical interest to realize a Penning Recombination Laser in gas discharges, having a beam of high energy primary electrons. Lasing has been obtained by using special types of discharges like fast transverse discharge, open discharge, discharges with pre-ionisation and microwave discharges. Various mixtures: *He-Ne-Ar (Kr)*, *Ne-Ar*, He-H_2, Ne-H_2 and Ne-NF_3 are used as an active medium.

Penning Recombination Lasers can be realized in the negative glow plasma of a high voltage pulsed hollow cathode discharge as well. High degree of ionisation (10^{-4} - 10^{-3}) followed by recombination is reached due to the high energy beam component of non-Maxwellian electrons in the tail of the electron energy distribution function. The Ne-H_2 Penning Recombination Laser operating in a Hollow Cathode Discharge shows a great promises for practical realization.

The aim of this paper is to develop a detailed non stationary kinetic model of the processes determining the inversion population between the *NeI* $2p_1$ and $1s_2$ levels (*NeI 585.3 nm* line). The negative glow plasma of a pulsed high voltage Ne-H_2 hollow cathode discharge is considered as an active medium. A program package for solving a system of 13 non-stationary differential equations for plasma and laser parameters is created. Numerical calculations are carried out and the time dependent behaviour of the plasma and laser parameters (electron and ion density, excited states population, electron and gas temperature, laser output power and laser gain) is obtained. The dependence of the laser parameters as a function on the discharge conditions is obtained as well. A comparison of the experimentally measured and theoretically calculated values is made.

KINETIC MODEL

Kinetic models of hollow cathode lasers have been proposed by several authors. The main assumption in these models is that in the hollow cathode discharge the electrons emitted from the cathode by ion bombardment are accelerated in the cathode dark space up to energies, corresponding to the cathode fall potential *U* [4-5]. These electrons penetrate the negative glow region, losing their energy mainly by excitation and ionisation. Therefore the accelerating space and the discharge region for the electrons are spatially separated. The cathode dark space appears as an external ionizer related to the negative glow. After numerous inelastic processes the electron energy distribution function consists of three groups of electrons: slow (plasma) electrons having Maxwellian energy distribution with mean energy of about *0.2-0.4 eV*, electrons with energies below the first ionisation potential and fast electrons with energies from the first ionisation potential to the cathode fall potential. This approach is convenient for the Ne-H_2 recombining plasma because only two groups of electrons play an important role: the beam electrons producing electrons and ions and the slow electrons responsible for the recombination processes and the population of the upper laser level. Such an assumption for the electron energy distribution function has been used in our earlier study on a *Ne-*H_2 Penning Recombination Laser operating in a helical Hollow Cathode Discharge, where a two level steady state kinetic model have been developed [5]. A uniform distribution of plasma parameters in the active volume is considered.

In the $Ne-H_2$ plasma the following atoms, molecules, ions and excited states are considered: H_2, *Ne*, H_2^+, Ne^+, NeH^+, Ne_2^+, H^-, *e*, *Ne(2s)*, *Ne(*$2p_1$*)*, *Ne(2p)*, *Ne(*$1s_2$*)* and *Ne(1s)*, where *Ne(2s)*, *Ne(2p)* and *Ne(1s)* represent the $2s_2$ - $2s_5$, $2p_2$ -$2p_{10}$ and $1s_3$ - $1s_5$ blocks of levels, respectively. The scheme of the *NeI* energetic levels is given in Fig. 1.

About 60 plasma-chemical reactions are considered in the kinetic model. These include: *Ne* and H_2 direct ionisation by fast electrons, *Ne* excitation by fast electrons, *Ne* stepwise ionisation, two-electron recombination of Ne^+, dissociative recombination of Ne_2^+, NeH^+ and H_2^+, ion-ion recombination of Ne^+ and H^-, Penning ionisation, *Ne* stepwise excitation and deexcitation, electron mixing between *NeI* excited states, radiative transitions, H_2 rotational and vibrational levels excitation, creation and destruction of molecular ions, H_2 dissociation, ambipolar diffusion and electron elastic scattering. The cross sections and rate constants for the reactions are either taken from publications or calculated in this work.

A system of 13 non-stationary balance equations for all species considered is written. Solving the balance equations the time dependent behaviour of all ion densities, *Ne* excited states populations and both the electron and gas temperatures is obtained. The system is solved numerically using Euler method at properly chosen initial conditions and step.

EXPERIMENTAL SET-UP

The laser tube design is similar to that used in our previous work [5]. The cathode is made of molybdenum band *10 mm* wide, helically wound with a *15 mm* pitch to form a cylindrical hollow. The anode is a

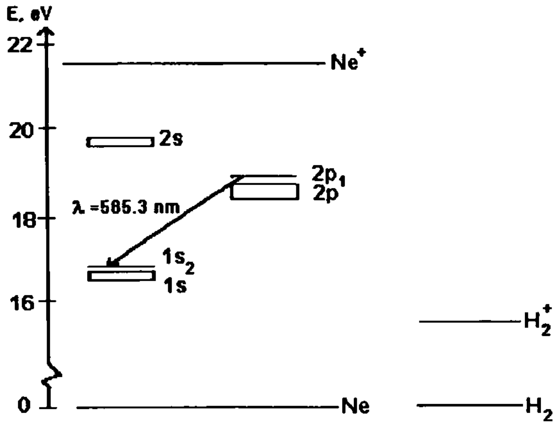

FIG.1. *NeI* and H_2 energy levels diagram.

molybdenum wire of *1 mm* diameter, placed parallel to the anode at *2 mm* distance. The laser tube investigated has a cathode with *5.5 mm* inner diameter, *26 cm* length, $5cm^3$ volume and $33cm^2$ cathode area.

The output power and gain are investigated at current pulses up to *350 A* peak value, *1-10* μs duration and up to *500 Hz* repetition rate. The duration of the pumping pulse is chosen to be *3* μs, measured on the basis, as the most efficient regime of operation of the laser. The output power is measured by means of a calibrated PIN photo-diode. The laser gain is measured by the method of calibrated loses inserted into the resonator.

RESULTS AND DISCUSSION

Lasing on the *NeI 585.3 nm* line is obtained and its dependence on the discharge parameters is investigated. An experimental study of the laser output power and gain and their dependencies on the partial gas mixture pressure, current density and pulse duration is performed. A similar study on *NeI 585.3 nm* and *NeI 1.15* μ*m* line is reported in [6].

The typical shapes of the voltage, current and laser pulses are shown in Fig. 2. The laser pulse starts approximately at the peak of the

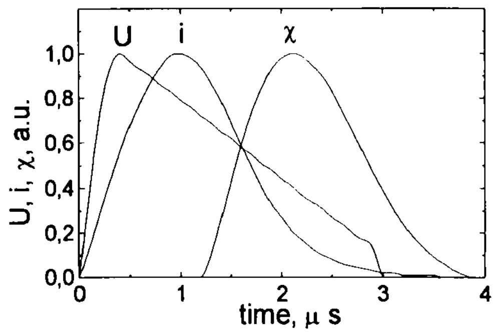

FIG.2. Shapes of the current pulse *i*, voltage pulse *U and* laser gain χ

current pulse, reaches a maximum after *1* μs and lasts about *1* μs in the afterglow. The voltage peak is shifted with respect to the current pulse so that it has its maximum 0.5 μs earlier. The voltage and current peak values, shown in Fig. 2 are *1.5 kV* and *200 A*, respectively.

The dependence of the laser gain on the Penning component pressure (Fig. 3) is strongly expressed. If the H_2 pressure is lower than a certain threshold value the lower laser level deexcitation is insufficient for the inversion population creation. When the Penning component pressure increases above the threshold value, the lower laser level depopulation rises as a result of the Penning ionisation. The gain coefficient increases as well. But when the Penning component pressure is higher than a certain optimal value, the upper laser level depopulation through Penning ionisation become considerable and the gain coefficient decreases, which can be clearly seen in Fig. 3. The experimental data are compared with the theoretical values for three different discharge currents. A good agreement between the theoretical model and the experimental results is observed.

The dependence of the output power on the *Ne* pressure is shown in Fig. 4. The optimal *Ne* pressure is *3 Torr*, but in the region of pressures from 1 to 6 *Torr* the output power and gain vary only by 30 %.

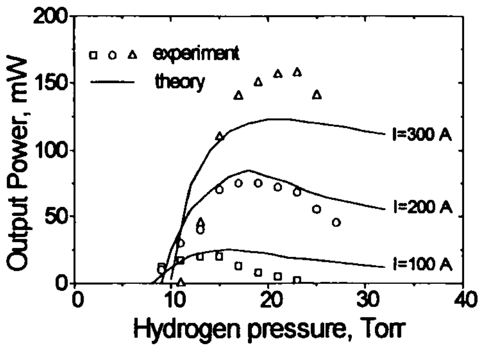

FIG.3. Dependence of the laser gain on the H_2 pressure at *3 Torr Ne* pressure and peak discharge currents of *100*, *200*, and *300 A*.

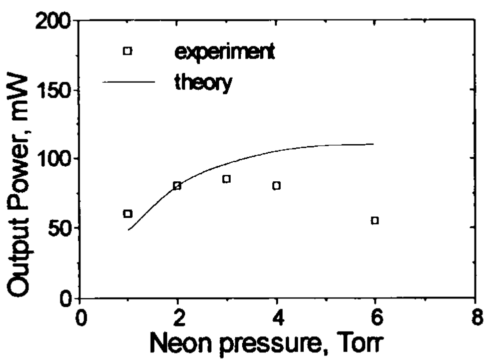

FIG.4. Dependence of the laser gain on the *Ne* pressure at H_2 pressure of 20 *Torr* and peak discharge current of 200 *A*.

The dependence of the output power on the discharge current (Fig. 5) is characterised by the existence of a threshold peak current value $i_{thr} \cong 50 - 60\,A$. By increasing the peak current value the electron density and hence the recombination flux to the upper laser level increases too. Further increase in the electron density causes the depopulation of the upper laser level by electron impact deexcitation. Hence, at very high currents a saturation of the output power and laser gain could be expected.

Spectroscopic study of the excited *Ne* $1s_{2\text{-}5}$ and *NeI* $2p_{1\text{-}10}$ levels is carried out. The re-absorption method is used to measure the population of the excited states. The upper laser level and lower laser level populations are measured at different discharge conditions. All measurements are carried out at the maximum of the laser pulse, i.e. at *2 μs* after the onset of the current pulse. The dependencies of the calculated and measured populations of the upper and lower laser level with the hydrogen pressure are shown in Fig. 6 at *150 A* peak current and *3 Torr Ne* pressure. As it can be seen according to the idea of Penning depopulation of the lower laser level the population of the $1s_2$ level decreases faster than the population of the upper laser level $2p_1$ with the hydrogen pressure increasing. At a certain threshold H_2 pressure (8 - 10 Torr) the population inversion occurs.

The electron density has been obtained using probe measurements. The increased ionisation and recombination in the probe region has been taken into account. As it can be seen in Fig. 7, at optimal for laser generation conditions the electron density has a value of $3 \cdot 10^{14}\ cm^{-3}$ and the degree of ionisation is relatively high: $4 \cdot 10^{-4}$. The comparison with the theoretical results shows a good agreement.

CONCLUSION

A theoretical study of a $Ne - H_2$ Penning Recombination Laser operating in the negative glow of a pulsed high voltage hollow cathode discharge is presented. A detailed kinetic model of the processes determining the inversion population on the $NeI(2p_1 - 1s_2)$ transition

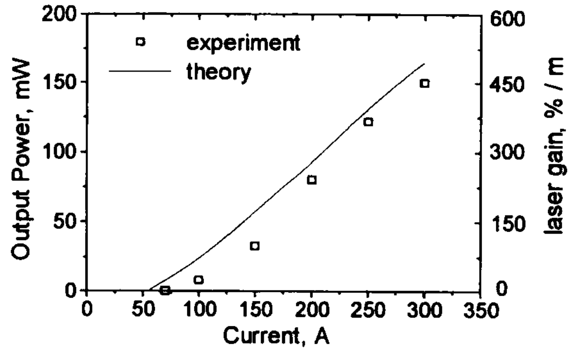

FIG.5. Dependence of the output power on the peak current value at H_2 pressure of *20 Torr* and *Ne* pressure of *3 Torr*.

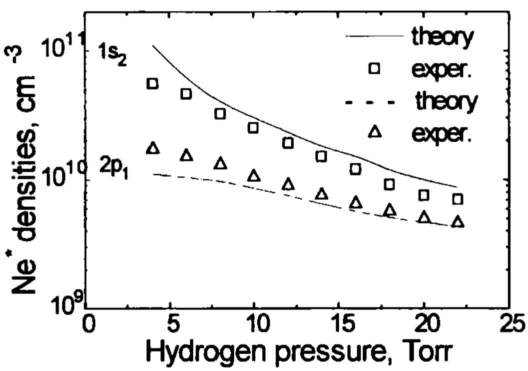

FIG.6. Dependence of the population of upper and lower laser level on output power at H_2 pressures at peak discharge current of *150 A* and *Ne* pressure of *3Torr*.

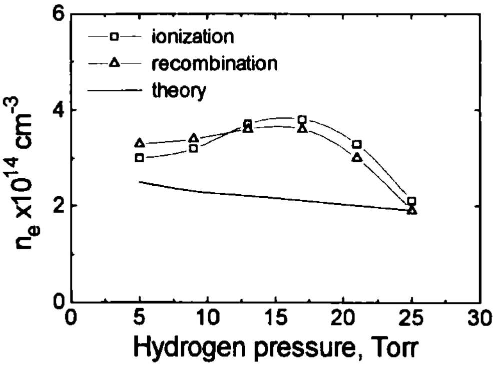

FIG.7. Dependence of the electron density n_e on the H_2 pressures at peak discharge current of 150 *A* and *Ne* pressure of *3Torr*.

(*NeI 585.3 nm* line) is developed. The time dependent behaviour of the electron and ion densities, the *Ne* excited states populations and the electron and gas temperatures is obtained.

The dependence of the laser gain and output power on the *Ne* and H_2 pressures and discharge current is investigated. The experimental data are in a good agreement with the values predicted by the non-stationary kinetic model.

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