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A simple kinetic model of a Ne–H_2 Penning-plasma laser

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Abstract. A simple kinetic model of the Ne–H_2 Penning-Plasma Laser (PPL) (NeI 585.3 nm) is proposed. The negative glow of a hollow cathode discharge at intermediate pressures is considered as the active medium. The balance equations for the upper and lower laser levels, electrons, ions and electron energy are solved. The dependences of the laser gain on the discharge conditions (Ne and H_2 partial pressures, discharge current) are calculated and measured. The calculated values are in a good agreement with the experimental data.

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The Penning-Plasma Laser (PPL) whose main principles of operation have been reported in [1, 2], is based on recombination population of the Upper Laser Level (ULL) and depopulation of the Lower Laser Level (LLL) through Penning reactions with buffer-gas atoms or molecules. The active medium is a non-equilibrium recombinating plasma. To create high recombination, it is necessary to achieve strong ionization (usually produced by electron beams from electron guns or gas discharges) followed by effective cooling of the electrons (reached by elastic scattering, excitation of vibrational and rotational levels of the buffer gas or in the afterglow).

In the Ne–H_2 and He–H_2 PPL, the H_2 molecules play the role of the Penning component. At the same time, H_2 is a very convinient buffer gas for electron cooling.

Lasing on the HeI 706.5 nm line in He–H_2 mixture has been obtained for the first time by Pixton and Fowles [3] and on the NeI 585.3 nm line in Ne–H_2 mixture by Schmieder et al [4]. During the last ten years, investigations on the PPL have been carried out by many researchers using e-beam pumping [5, 6] and different kinds of discharges: Blümlein [7, 8], hollow cathode [9, 10], mesh anode [11, 12], discharges with pre-ionization [13, 14] etc. It has been shown that lasing may not only be pulsed but quasi-CW as well. In our previous works [15, 16], investigations on Ne–H_2 PPL operating on the NeI 585.3 nm line have been carried out using high-voltage hollow cathode discharges with a helical configuration of the electrodes.

According to the conventional model of the hollow cathode discharges, 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. Then, they penetrate the negative-glow region losing their energy mainly by ionization and excitation.

In a previous paper by Fetzer and Rocca [17], a kinetic model of a He–Hg hollow cathode laser (HgII 615 nm) has been proposed. It describes self-consistently the dynamics of the negative-glow and the cathode regions of the discharge and calculates the electron-energy distribution and the population of the excited states considered in the negative glow with the charged particle fluxes and electric field distribution in the cathode sheath.

Kinetic models of a He–Zn a and He–Kr hollow cathode laser have been proposed in our earlier works [18, 19]. A review on the kinetic models created for high-pressure recombination lasers (about several atm) pumped by high-energetic electron beams is given in [20].

The aim of this paper is to develop a simple kinetic model of the Ne–H_2 PPL operating on the NeI 585.3 nm line ($2p_1$–$1s_2$ transition) in the negative glow of a high-voltage hollow cathode discharge at intermediate pressures (5–30 Torr). The model allows to estimate the basic plasma parameters (ULL and LLL population, electron and ion densities and electron temperature) and inversion population conditions depending on the macroscopic plasma parameters: Ne and H_2 pressures and peak current. The dependences of the laser gain on the Ne and H_2 partial pressures and peak current are measured as well. The theoretically calculated curves are compared with the experimental data.

1 Brief description of the model

1.1 Physical assumptions

The following physical assumptions are made:
– Intensive ionization is produced by an e-beam of primary electrons entering the negative glow with energies up to the cathode-fall potential, while the slow electrons have a Maxwellian distribution. This approach is convenient for the Ne–H_2 recombinating plasma because only two groups of electrons play important role: the slow electrons of about 0.2 eV temperature (responsible for the recombination processes) and the beam electrons producing ions. Thus, such an approach is good as a first approximation. Such an assumption for the EEDF has been used earlier to study high-pressure recombination lasers pumped by high-energetic electron beams [20] and in our earlier studies on He–Zn and He–Kr hollow cathode lasers [18, 19], where good agreement between the model and experiment was observed.
– Steady-state conditions are considered at the peak of the excitation pulse.
– Uniform plasma-parameter distribution in the active volume.

1.2 Two-level model

The two-level model describes the simplest kinetic mechanism for obtaining population inversion. A simplified kinetic scheme for the processes is considered, including two levels only — the ULL and the LLL — under the following assumptions.

- The ULL Ne($2p_1$) is populated through two-electron recombination of the Ne^+ ion. The dissociative recombination of the Ne_2^+ and NeH^+ molecular ions is neglected. It is depopulated through spontaneous emission, Penning ionization with H_2 molecules electron deexcitation.
- The LLL Ne($1s_2$) is populated by spontaneous emission and electron deexcitation from both the ULL and the block of levels Ne($2p_2$–$2p_{10}$). It is depopulated through Penning ionization with H_2 molecules.

The balance equations for the ULL and LLL are as follows:

$$\frac{\mathrm{d}}{\mathrm{d}t}[\mathrm{Ne}(2p_1)] = k_{\mathrm{rec}}(2p_1)n_e^2[\mathrm{Ne}^+] - \{\nu_{\mathrm{sp}}(2p_1) + k_{\mathrm{pen}}(2p_1)[\mathrm{H}_2] + k_{\mathrm{deexc}}(2p_1)n_e\} \times [\mathrm{Ne}(2p_1)] \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}[\mathrm{Ne}(1s_2)] = [\nu_{\mathrm{sp}}(2p_1) + k_{\mathrm{deexc}}(2p_1)n_e][\mathrm{Ne}(2p_1)] + \nu_{\mathrm{exc}}[\mathrm{Ne}] + [\nu_{\mathrm{sp}}(2p) + k_{\mathrm{deexc}}(2p)n_e] \times [\mathrm{Ne(2p)}] - k_{\mathrm{pen}}(1s_2)[H_2][\mathrm{Ne}(1s_2)], \tag{2}$$

where k_{rec} is the two-electron recombination rate constant of Ne^+ ion, ν_{sp} are the spontaneous emission probabilities, k_{pen} are the rate constants for Penning ionization, k_{deexc} are the electron deexcitation rate constants, n_e is the electron density, [H_2] is the hydrogen-molecule density, [Ne($2p_1$)] and [Ne($1s_2$)] are the ULL and LLL population, respectively, and [Ne($2p$)] is the total population of the $2p_2$–$2p_{10}$ block of levels.

1.3 Charged-particle balance

An important step in the PPL description is the determination of the electron density n_e. It is calculated by solving the balance equations for charged particles. Since the ULL is populated through the recombination flux of two-electron recombination, the dependence on n_e is strong.

If it is assumed that creation of Ne^+ and H_2^+ ions is due to the ionizations by fast electrons and that these ions are destroyed by two-electron recombination and dissociative recombination, respectively, the balance equations have the form:

$$\frac{\mathrm{d}}{\mathrm{d}t}[\mathrm{Ne}^+] = \nu_{\mathrm{ion}}(\mathrm{Ne})[\mathrm{Ne}] - k_{\mathrm{rec}}n_e^2[\mathrm{Ne}^+],$$

$$\frac{\mathrm{d}}{\mathrm{d}t}[H_2^+] = \nu_{\mathrm{ion}}(\mathrm{H}_2)[\mathrm{H}_2] - k_{\mathrm{diss}}n_e[\mathrm{H}_2^+], \tag{3}$$

where [Ne^+] and [H_2^+] are the Ne^+ ion and H_2^+ molecular-ion densities, respectively, ν_{ion} is the ionization frequencies of Ne and H_2 by fast electrons, k_{diss} is the dissociative-recombination-rate constant for the H_2^+ molecular ion. Assuming that $n_e \cong [\mathrm{Ne}^+] + [\mathrm{H}_2^+]$ (estimations show that the number of H^+, Ne_2^+ and NeH^+ ions is about two orders of magnitude lower than the number of Ne^+ ions), it follows for the Ne^+ density:

$$[\mathrm{Ne}^+] = \frac{[\mathrm{Ne}]}{[\mathrm{Ne}] + \dfrac{\nu_{\mathrm{ion}}(\mathrm{H}_2)k_{\mathrm{rec}}n_e}{\nu_{\mathrm{ion}}(\mathrm{Ne})k_{\mathrm{diss}}}[\mathrm{H}_2]}\, n_e. \tag{4}$$

The balance equation for the electrons is:

$$\frac{\mathrm{d}n_e}{\mathrm{d}t} = \nu_{\mathrm{ion}}(\mathrm{Ne})[\mathrm{Ne}] + \nu_{\mathrm{ion}}(\mathrm{H}_2)[\mathrm{H}_2] - k_{\mathrm{diss}}n_e[\mathrm{H}_2^+] - k_{\mathrm{rec}}n_e^2[\mathrm{Ne}^+]. \tag{5}$$

Taking into account that $k_{\mathrm{diss}} \cong 5\times10^{-9}T_e^{-1/2}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ [21] and $k_{\mathrm{rec}} \cong 5.4\times10^{-27}T_e^{-9/2}\,\mathrm{cm}^6\,\mathrm{s}^{-1}$ at an electron temperature of $T_e \cong 0.2$–0.3 eV and at an electron density $n_e \cong 10^{14}\,\mathrm{cm}^{-3}$ (see later), we can assume that $k_{\mathrm{diss}} \gg k_{\mathrm{rec}}n_e$. At H_2 and Ne pressures of 22 and 2.5 Torr, respectively, a gas temperature of 400 K and if $\nu_{\mathrm{ion}}(\mathrm{H}_2) \cong \nu_{\mathrm{ion}}(\mathrm{Ne})$ (see later), it follows from (4) that $[\mathrm{Ne}^+] \cong ne/2$. Hence, $[\mathrm{H}_2^+] \cong [\mathrm{Ne}^+]$.

Under steady-state conditions it follows for the electron density:

$$n_e \cong \sqrt{2\{\nu_{\mathrm{ion}}(\mathrm{Ne})[\mathrm{Ne}] + \nu_{\mathrm{ion}}(\mathrm{H}_2)[\mathrm{H}_2]\}/k_{\mathrm{diss}}}. \tag{6}$$

The Ne and H_2 ionization and excitation frequencies ν_{ion}, ν_{exc} by beam electrons are [2, 6]:

$$\nu_{\mathrm{ion}} \cong 2\frac{\overline{\sigma_{\mathrm{ion}}}}{e}j_e[\mathrm{s}^{-1}]; \quad \nu_{\mathrm{exc}} \cong 2\frac{\overline{\sigma_{\mathrm{exc}}}}{e}j_e[\mathrm{s}^{-1}], \tag{7}$$

where $\overline{\sigma_{\text{ion}}} = [(1/U)\int_0 \mathrm{d}\varepsilon/\sigma_{\text{ion}}(\varepsilon)]^{-1}$ is the averaged ionization cross section in cm^2, $\overline{\sigma_{\text{exc}}}$ is the averaged excitation cross section, ε is the electron energy, e is the electron charge and j_e is the density of primary electrons in $\mathrm{A/cm}^2$. j_e can be expressed by the measured current density j as follows: $j_e = \gamma j_i = (\gamma/\gamma + 1)j$ where γ is the secondary-electron-emission coefficient and j_i is the ion-current density on the cathode. According to [6], the ionizations and excitations by secondary electrons are taken into account by means of the factor 2 in (7).

Each fast electron makes $z_i = \varepsilon/E_c$ ionizations and loses its energy completely (E_c is the energy necessary for electron–ion pair creation) [2] because the geometry of the cathode confines it in the discharge volume.

Estimations show that, at 22 Torr H_2 pressure, 2.5 Torr Ne pressure, 5.5 mm cathode diameter, an electron with an initial energy of 1500 eV moving in radial direction creates up about 38 ionizations and loses its energy completely. Its reaching distance is about several times larger than the cathode diameter.

If the values of $4.5\times 10^{-17}\,\mathrm{cm}^2$ [22] and $4.5\times 10^{-17}\,\mathrm{cm}^2$ [23] for the average ionization cross section of H_2 and Ne, respectively, a value of $4.5\times 10^{-18}\,\mathrm{cm}^2$ [24] for the LLL excitation cross section are used and if $\gamma = 0.15$ from (7), it follows:

$$\nu_{\text{ion}}(\mathrm{H_2}) \cong 73j\,\mathrm{s}^{-1};\ \nu_{\text{ion}}(\mathrm{Ne}) \cong 73j\mathrm{s}^{-1} \text{ and;}$$

$$\nu_{\text{exc}}(\mathrm{Ne}) \cong 7.3j\,\mathrm{s}^{-1}\,\mathrm{cm}^{-3}. \tag{8}$$

At H_2 and Ne pressures of 22 and 2.5 Torr, respectively, and a current density of $6\mathrm{A/cm}^2$ (discharge conditions near to those where the laser operates) and if we chose a value for the electron temperature $T_e = 0.25$ eV, it follows from (6) for the electron density:

$$n_e \cong 1\times 10^{14} j^{1/2}. \tag{9}$$

It is seen from (6) that the dependence of the electron density on the electron energy is weak: $n_e \propto k_{\text{diss}}^{-1/2} \propto T_e^{1/4}$. Hence, the value for T_e chosen when estimating the n_e value is of minor importance.

1.4 *Electron temperature*

An important part of the kinetic model consists of solving of the electron-energy balance equation. The recombination processes depend strongly on the electron temperature T_e. To obtain a correct value of T_e, it is necessary to know the mechanisms of electrons cooling and heating.

The plasma considered has some features that must be taken into account, namely: the presence of molecular gas, strong Penning ionization and the presence of an electron beam with an energy of about 1500 eV.

The estimations show that, in the presence of H_2 gas and at low electron temperature $T_e < 1$–2 eV, the major contribution to the electron-gas cooling comes from the H_2 vibrational-level excitation. The electron cooling by elastic collisions with H_2 molecules and Ne atoms is negligibly small. The electrons are heated by ionization with fast electrons. The Penning ionization has a small contribution in the electron-gas heating.

A good approximation for the electric energy imparted in the electron gas as a result of the ionizations with fast electrons is [25]:

$$\Delta E_{\text{ion}} \cong E_1/2, \tag{10}$$

where E_1 is the energy of the first excited electron level.

The balance equation for T_e is:

$$\frac{3}{2}\frac{\mathrm{d}}{\mathrm{d}t}[n_e(t)T_e(t)] = Q_{\text{ion}} - Q_{\text{vib}}, \tag{11}$$

where Q_{ion} and Q_{vib} are the energies imparted by or dissipated from the electrons per unit time and volume by ionizations with fast electrons and H_2 vibrational-level excitation, respectively. The H_2 rotational-level excitation is neglected:

$$Q_{\text{vib}} = k_{\text{vib}}(T_e)\Delta E_{\text{vib}} n_e[\mathrm{H_2}(v=0)],$$

$$Q_{\text{ion}} = \Delta E_{\text{ion}}(\mathrm{Ne})\nu_{\text{ion}}(\mathrm{Ne})[\mathrm{Ne}] + \Delta E_{\text{ion}}(\mathrm{H_2})\nu_{\text{ion}}(\mathrm{H_2})[\mathrm{H_2}],$$

where $\Delta E_{\text{vib}} = 0.515$ eV, $k_{\text{vib}} \cong 4\times 10^{-10} \times T_e^{1/2}\mathrm{e}^{-0.515/T_e}\,\mathrm{cm^3/s}$ [26, 27];

$\Delta E_{\text{ion}}(\mathrm{Ne}) \cong 8$ eV; $\Delta E_{\text{ion}}(\mathrm{H_2}) \cong 5$ eV.

At H_2 and Ne pressures of 22 and 2.5 Torr, respectively, and a current density of $j = 6\mathrm{A/cm}^2$, the electron temperature is calculated to be:

$$T_e \cong 0.23 \text{ eV}.$$

1.5 *Laser gain*

The condition for population inversion for the transition considered is:

$$\alpha = \sigma\{[\mathrm{Ne}(2p_1)] - (1/3)[\mathrm{Ne}(1s_2)]\} > 0, \tag{12}$$

where α is the laser gain, σ is the phototransition cross section and 1/3 is the g-factor ratio. Doppler-line broadening is considered.

Under steady-state conditions, we can write for the ULL and LLL population:

$$[\mathrm{Ne}(2p_1)] = \frac{k_{\text{rec}}(2p_1)n_e^2[\mathrm{Ne}^+]}{\nu_{\text{sp}}(2p_1) + k_{\text{pen}}(2p_1)[\mathrm{H_2}] + k_{\text{deexc}}(2p_1)n_e}, \tag{13}$$

$$[\mathrm{Ne}(1s_2)] = \frac{[\nu_{\text{sp}}(2p_1) + k_{\text{deexc}}(2p_1)n_e][\mathrm{Ne}(2p_1)] + \nu_{\text{exc}}[\mathrm{Ne}]}{k_{\text{pen}}(1s_2)[\mathrm{H_2}]} + \frac{[\nu_{\text{sp}}(2p) + k_{\text{deexc}}(2p)n_e][\mathrm{Ne}(2p)]}{k_{\text{pen}}(1s_2)[\mathrm{H_2}]}. \tag{14}$$

Substituting (13), (14) and (4) in (12), we get:

$$\alpha = \sigma\frac{k_{\text{rec}}(2p_1)n_e^3[\mathrm{Ne}]/\{[\mathrm{Ne}] + (k_{\text{rec}}n_e/k_{\text{diss}})[\mathrm{H_2}]\}}{\nu_{\text{sp}}(2p_1) + k_{\text{pen}}(2p_1)[\mathrm{H_2}] + k_{\text{deexc}}(2p_1)n_e} \times\left(1 - \frac{\nu_{\text{sp}}(2p_1) + k_{\text{deexc}}(2p_1)n_e + \nu_{\text{exc}}[\mathrm{Ne}]/[\mathrm{Ne}(2p_1)]}{3k_{\text{pen}}(1s_2)[\mathrm{H_2}]} - \frac{[\nu_{\text{sp}}(2p) + k_{\text{deexc}}(2p)n_e][\mathrm{Ne}(2p)]/[\mathrm{Ne}(2p_1)]}{3k_{\text{pen}}(1s_2)[\mathrm{H_2}]}\right) - \alpha_{\text{thr}}. \tag{15}$$

It is seen that the laser gain depends on the Ne and H_2 pressures and on the electron density (discharge current) in a complex manner.

The two-electron recombination flux, populating the block of levels $Ne(2p_2–2p_{10})$ is two times larger than the flux populating the ULL [6]. So, we can assume that $[Ne(2p)]/[Ne(2p_1)] \cong 2$. If the following values are substituted in 13–15:

$$\nu_{sp}(2p) \cong 1.1 \times 10^7\,s^{-1}\,[6];$$
$$k_{deexc}(2p) \cong 3.5 \times 10^{-8}\,cm^3s^{-1}\ [26,28];$$
$$\nu_{sp}(2p_1) \cong 7.2 \times 10^7\,s^{-1}\,[6];$$
$$k_{deexc}(2p_1) \cong 1 \times 10^{-7}\,cm^3s^{-1}\ [26,28];$$
$$k_{pen}(2p_1) \cong 1 \times 10^{-10}\,cm^3s^{-1};$$
$$k_{pen}(1s_2) \cong 2.5 \times 10^{-10}\,cm^3s^{-1}\ [29];$$
$$\sigma \cong 5.6 \times 10^{-12}\,cm^2;$$
$$P_{H_2} \cong 22\ \text{Torr},$$
$$P_{Ne} \cong 2.5\ \text{Torr},\ \alpha_{thr} = 10^{-3}cm^{-1};$$
$$j \cong 6A/cm^2;$$

for the ULL and LLL population, and for the gain, the following values are calculated:

$$[Ne(2p_1)] \cong 1.8 \times 10^{10}\,cm^{-3},$$
$$[Ne(1s_2)] \cong 3.4 \times 10^{10}\,cm^{-3},$$
$$\alpha \cong 385\%/m.$$

2 Results

2.1 Threshold and optimal Penning-component pressures

From the population inversion condition (15), the threshold value of H_2 pressure for laser action can be obtained:

$$[H_{2,thr}] = \frac{\nu_{sp}(2p_1) + k_{deexc}(2p_1)n_e + \nu_{exc}[Ne]/[Ne(2p_1)]}{3k_{pen}(1s_2)} + \frac{[\nu_{sp}(2p) + k_{deexc}(2p)n_e][Ne(2p)]/[Ne(2p_1)]}{3k_{pen}(1s_2)} \cong (18 + 4.4j) \times 10^{16}\,cm^{-3}. \tag{16}$$

The following analytical approximation can be used:

$$P_{H_{2,thr}} \cong 5.6 + 1.3j\ \text{Torr}. \tag{17}$$

Therefore, the threshold H_2 pressure increases with increasing current density. At current densities $j = (2–10)A/cm^2$, the threshold pressure is:

$$P_{H_{2,thr}} \cong (8–18)\ \text{Torr}.$$

When the Penning-component pressure is increased above the threshold value, the LLL depopulation increases due to Penning ionization. The gain α increases as well. From the expression (15), it is seen that if the Penning component is higher than a certain optimal value, the ULL depopulation through Penning reactions becomes also considerable. To estimate the optimal value of the Penning component, it is necessary to obtain the H_2 pressure for which the ULL depopulation through Penning reactions is comparable to the other processes depopulating the ULL, namely:

$$\frac{k_{pen}(2p)[H_2]}{\nu_{sp}(2p_1) + k_{deexc}(2p_1)n_e} = c. \tag{18}$$

The ULL depopulation through Penning ionization for values of $c = 0.2–0.4$ is weak, and for values of $c = 0.6–0.8$ is strong enough. If we choose a value of $c = 0.7$ as a criterion for the optimal H_2 pressure we have:

$$P_{H_{2,opt}} \cong (14 + 2j^{1/2})\ \text{Torr}. \tag{19}$$

Hence, the optimal H_2 pressure depends on the current density, and at the current density of $j = (2–10)A/cm^2$ it is:

$$P_{H_{2,opt}} \cong (17–21)\ \text{Torr}.$$

When the H_2 pressure is higher than the optimal one, the ULL is strongly depopulated by Penning ionization and the population inversion decreases.

Therefore, there exists a region of H_2 pressures within which the laser can operate. The laser action is due to the specific features of the Penning-ionization cross section, namely, its different values for different energy levels of the active gas. In the particular case of $Ne(1s_2)$ and $Ne(2p_1)$ levels, the Penning-rate-constant ratio is:

$$k_{pen}(1s_2)/k_{pen}(2p_1) \cong 2–3. \tag{20}$$

In Fig. 1, the calculated dependence of the laser gain on the Penning component pressure is shown. The experimental data are given for comparison.

2.2 Experiment

Experiments were carried out using a laser tube with a helical hollow cathode [16]. The helical hollow cathode has a 5.5 mm inner diameter and is 260 mm long. It is made of a 10 mm wide molybdenum band. The anode is a tungsten wire of 1 mm diameter, placed at 3 mm distance from the cathode, parallel to the optical axis. The

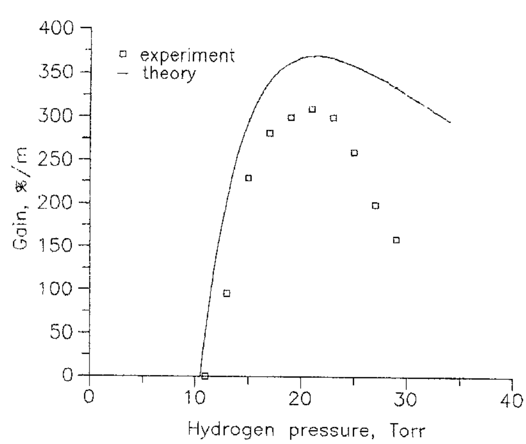

Fig. 1. Dependence of the gain α on H_2 pressure at a Ne pressure of 2.5 Torr and a peak current of 200 A

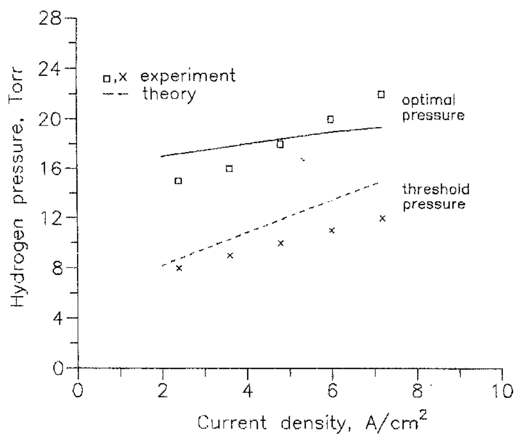

Fig. 2. Dependence of the optimal and threshold H_2 pressures on the peak current density at a Ne pressure of 2.5 Torr

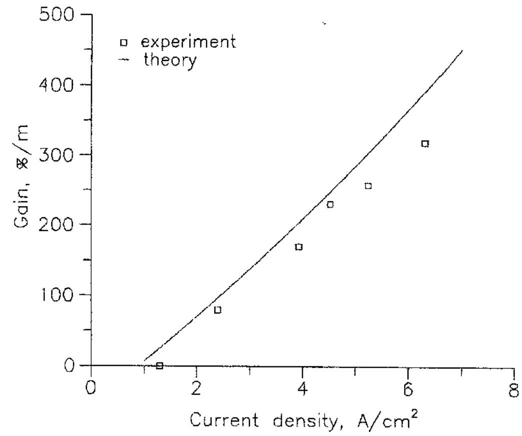

Fig. 3. Dependence of the gain α on peak current density at a H_2 pressure of 22 Torr and a Ne pressure of 2.5 Torr

discharge is excited by a thyratron power supply, providing pulses up to 300 A peak current, up to 5 kV peak voltage, 2μs pulse duration, and 30 Hz pulse-repetition rate. The operating voltage changes from 500 to 2000 V which correspond to peak-current variations from 0 to 300 A. The laser cavity consists of dielectrically coated mirrors of 99% and 99.9% reflectivity for the investigated line. The laser gain is measured using the method of calibrated losses.

In Fig. 2, calculated (using (17) and (19)) and measured threshold and optimal H_2 pressures at different discharge currents are given. Good agreement between the calculated and measured values is observed.

2.3 Dependence of the laser gain on the discharge current

The threshold current for lasing can be estimated from the condition for population inversion. Let us make some modifications in the balance equations (1) and (2). At the threshold current for lasing, the ILL is populated mainly by fast electrons from the Ne ground state. The LLL population from the ULL and other $2p$ levels is negligibly small since they are not strongly populated. Under threshold conditions, the balance equations have the form:

$$\frac{\mathrm{d}}{\mathrm{d}t}[\mathrm{Ne}(2p_1)] = k_{\mathrm{rec}}(2p_1)n_e^2[\mathrm{Ne}^+] - \{\nu_{\mathrm{sp}}(2p_1) + k_{\mathrm{pen}}(2p_1)[\mathrm{H}_2]\}[\mathrm{Ne}(2p_1)], \quad (21)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}[\mathrm{Ne}(1s_2)] = \nu_{\mathrm{exc}}[\mathrm{Ne}] - k_{\mathrm{pen}}(1s_2)[\mathrm{H}_2][\mathrm{Ne}(1s_2)]. \quad (22)$$

Under steady-state conditions, the following values for the ULL and LLL population are obtained:

$$[\mathrm{Ne}(2p_1)] = k_{\mathrm{rec}}n_e^2[\mathrm{Ne}^+]/\{\nu_{\mathrm{sp}}(2p_1) + k_{\mathrm{pen}}(2p_1)[\mathrm{H}_2]\} \cong 1.4\times 10^9 j^{3/2}\ \mathrm{cm}^{-3}, \quad (23)$$

$$[\mathrm{Ne}(1s_2)] = \nu_{\mathrm{exc}}[\mathrm{Ne}]/\{k_{\mathrm{pen}}(1s_2)[\mathrm{H}_2]\} \cong 4.1\times 10^9 j^{1/2}\ \mathrm{cm}^{-3}. \quad (24)$$

The condition for population inversion gives the threshold current density for oscillation: $j_{\mathrm{thr}} \cong 1.1\ \mathrm{A/cm}^2$. If we consider a cathode area of 33 cm^2, we get: $i_{\mathrm{thr}} \cong 36$ A.

The calculations show that the threshold current is rather high.

When the discharge current is increased, the recombination flux to the ULL increases also. At considerably high currents, the role of ULL depopulation by electron collisions also increases. Therefore, the gain increases with increasing current and saturation can be expected.

The calculated and experimentally obtained dependences of the gain on the discharge current using (15) is given in Fig. 3. Good agreement between the calculated and measured data is obtained, and for the threshold current for oscillation, a maximal gain of about 400%/m is reached.

2.4 Optimal Ne pressure

To determine the optimal Ne pressure, we use a similar approach to that employed for H_2 optimal pressure determination, i.e., we look for the Ne pressure for which the ULL-excitation flux by fast electrons from the ground state is comparable to the flux populating the LLL from the ULL and the $2p$ block of levels:

$$\nu_{\mathrm{exc}}[\mathrm{Ne_{opt}}] \cong \{\nu_{\mathrm{sp}}(2p_1) + k_{\mathrm{deexc}}(2p_1)n_e\}[\mathrm{Ne}(2p_1)] + [\nu_{\mathrm{sp}}(2p) + k_{\mathrm{deexc}}(2p)n_e][\mathrm{Ne}(2p)]. \quad (25)$$

For the Ne optimal pressure, it follows:

$$P_{\mathrm{Ne_{opt}}} \cong 2.0\ \mathrm{Torr}. \quad (26)$$

At Ne pressures $P_{\mathrm{Ne}} \geq P_{\mathrm{Ne,opt}}$, the parasitic population of the LLL from the Ne ground state is higher than the ULL population, while at Ne pressures $P_{\mathrm{Ne}} \leq P_{\mathrm{Ne,opt}}$ it practically does not influence the LLL population.

In Fig. 4 the calculated [using (15)] and measured dependences of the gain coefficient on the Ne pressure are shown. There exists good agreement between the calculated and measured curves.

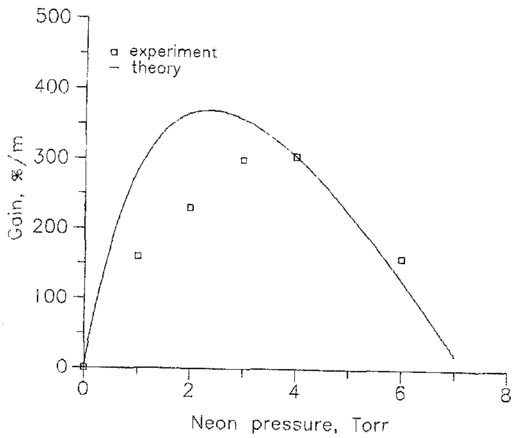

Fig. 4. Dependence of the gain α on the Ne pressure at a H_2 pressure of 22 Torr and a peak current of 200 A

3 Conclusions

A simple kinetic model of Ne–H_2 PPL operating on the NeI 585.3 nm line is proposed. The negative-glow plasma of a hollow cathode discharge at intermediate pressures is considered as an active medium.

The balance equations for the upper and lower laser levels, charged particles and electron temperature are solved. The dependences of the laser gain on the H_2 and Ne pressures and discharge current are calculated. The threshold and the optimal H_2 pressures as well as the optimal Ne pressure for lasing are established:

$$P_{H_{2,\text{thr}}} \cong 8\text{–}18 \text{ Torr}, \quad P_{H_{2,\text{opt}}} \cong 19\text{–}24 \text{ Torr},$$

$$P_{\text{Ne}_{\text{opt}}} \cong 2.5 \text{ Torr}.$$

As a result of the calculations at the optimal pressures the following values for the ULL and the LLL are obtained: $[\text{Ne}(2p_1)] \cong 1.8 \times 10^{10}\,\text{cm}^{-3}$, $[\text{Ne}(1s_2)] \cong 3.4 \times 10^{10}\,\text{cm}^{-3}$. The electron density and temperature under optimal conditions are: $n_e \cong 1 \times 10^{14} j^{1/2}\,\text{cm}^{-3}$ and $T_e \cong 0.23$ eV.

In the range of the peak current densities considered (2–10 A/cm^2) and under optimal pressures, a gain of about 400%/m is reached. The agreement between the calculated and experimental data is very satisfactory.

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