OPTIMAL CHARACTERISTICS OF E-BEAM EXCITED XE EXCILAMPS

* General Physics Institute of Russian Academy of Science Moscow, Russia;
** High Current Electronics Institute Siberian Brunch of Russian Academy of Science,
Tomsk, Russia,

Abstract
Calculations of optimal parameters for the e-beam excited Xe spontaneous radiation source (excilamp) at \( \lambda \sim 172 \) nm have been done. The optimal values of gas density and specific excitation power have been calculated. Gas temperature dependence of radiation conversion efficiency related to the injected into media energy has been also computed. It has been shown that there is an optimum in excitation pulse duration at frequency operation mode.

1. Introduction
Recently considerable attention has been focussed on excilamp development and utilization, e.g. to the sources of spontaneous radiation at exciplex or excimer molecule transitions [1-5]. In particular, of a great interest are excilamps on Xe dimers (\( \lambda \sim 172 \) nm) [3-5]. The barrier discharge is most widely used for excilamp excitation. It allows to achieve, as it has been recently shown in [5], radiation efficiency values of more than 50 % at \( \lambda \sim 172 \) nm. Previously, high efficiencies of radiation were obtained at conventional e-beam or e-beam controlled discharge excitation with elevated Xe pressure values [6-8]. Nevertheless, in some well-known papers, where use of e-beam excitation is mentioned, investigation of Xe dimers were conducted at rather high pressures, and efficiency of radiation was estimated for particular experimental conditions, and in practice the use of such installations was limited due to their complexity and necessity in protection from X-ray. It is of more direct interest to have a possibility to gain high efficiency of excilamps at comparatively low pressures.In present paper, optimal excitation parameters and operating pressure value required to maximal radiation efficiencies at 172 nm of Xe-dimer were theoretically obtained, and also influence of He additions to Xe was simulated. This research is interesting in connection with projection of excilamps, pumped by a discharge with a hard component of electron distribution function. Such type investigations can stimulate also the development of low
energy (10-20 keV) electron beam accelerators that use ceramic foils for e-beam input to the gas volume [9].

2. The model

The action of beam was characterized [10-12] by the ionization frequency of \( \nu = 2\sigma j/e \), where \( \sigma \) – ionization cross-section, \( j \) - current beam density, \( e \) - electron charge. In a similar manner frequencies of excitation atoms from the ground state entered. Then pumping power into corresponding gas component is given by

\[ W = E_p \nu N, \]

where \( E_p \) is the energy, spent for formation of one electron-ion pair (\( E_p = 22 \text{ eV for Xe and 46 eV – for He} \)); \( N \) – density of the atoms being ionized. For simplicity the temporal dependence of the ionization frequency \( \nu \) was assumed close to rectangular with time duration \( \Delta t \).

In kinetic particle balance equations there were taken into account 17 components: ions and excited states of atoms and molecules of Xe and He. Besides, thermal balance equations for electron temperature \( T_e \) and gas temperature \( T_g \) were considered. Two states for Xe dimer were taken into account: (resonance \( \text{Xe}_2(\Sigma_u^+) \), and metastable one \( \text{Xe}_2(\Pi_u^+) \)), giving contribution to the discussed radiation band. Thus, the following expressions were used in order to perform calculations for spontaneous radiation power:

\[ Q_i = A_i [\text{Xe}_2(i)], \quad Q = Q_1 + Q_2, \]

where \( A_1 = 1.82 \times 10^8 \text{ s}^{-1} \), \( A_2 = 1 \times 10^7 \text{ s}^{-1} \) – spontaneous decay rates, \([\text{Xe}_2(\Pi)]\) is the \([\text{Xe}_2(\Sigma_u^+)]\), and \([\text{Xe}_2(\Pi)]\) is the \([\text{Xe}_2(\Sigma_u^+)]\) - corresponding dimer state population. Efficiency of conversion of the pumping energy (energy injected into medium) to spontaneous radiation \( \eta \) was defined as the ratio of total radiated energy to the input energy:

\[ \eta = \frac{\int Q dt}{\int W dt} \]

The plasma-chemical reactions rates were used, which were earlier used in modeling XeCl- and XeF- lasers [13, 14], radiation in binary mixture Kr-Xe [15], and also with modeling of the third continuums of Xe [16, 17]. The kinetic model of Xe-He – mixture included 132 reactions. Fig. 1 presents the most important reaction rates for pure Xe. The dependencies of reaction rates from gas temperature were chosen in a next way. According to the Thomson theory the gas temperature dependence of rate of conversion should be \( T_g^{3/4} \), for rates of association dependence should be \( T_g^{-1/3} \). Simulation was made by PLASER code [18].

1656
3. Simulation results

Temporal dependencies. Plasma parameters temporary relaxation has a character usual for the case of hard ionizer excitation of dense gases (see fig. 2). At the excitation front, electron temperature sharply grows up to several eV, further with increase of number of electrons it becomes lower 1 eV, and keeps its rather high level in afterglow phase due to recombination heating of electrons.

$N_e$, cm$^{-3}$
$Q/10 \text{ (W/cm}^3\text{)}, T_e \text{ (eV)}$

![Graph showing plasma parameters and radiation specific power temporary dependence of Xe-excitation with density $[\text{Xe}] = 5 \cdot 10^{18} \text{ cm}^{-3}$ by a beam at ionization frequency $\nu = 4 \text{ s}^{-1}$ (this corresponds to the specific pumping power $W = 80 \text{ W/cm}^3$) and ionization duration $\Delta t = 2 \mu\text{s.}$ $T_\text{g} = 300 \text{ K.}$

The figure is labeled as follows:

- **a)** The solid curve indicates the density of Xe-molecule metastables [$\text{Xe}_2(1\Sigma_u^+)$]; the primed line indicates the density of Xe resonance molecules [$\text{Xe}_2(1\Sigma_u^+)$]; the dashed line is the density of electrons $N_e$; dot(-and-)dash line indicates the density of molecular ions [$\text{Xe}_2^+$].

- **b)** The solid curve is the specific radiation power $Q_2$ at the transition metastable state of molecule $\text{Xe}_2(3\Sigma_u^+) \rightarrow \text{Xe} + \text{Xe}$; the dashed curve indicates the specific power $Q_1$ of radiation at the transition from the resonance state of the molecule $\text{Xe}_2(1\Sigma_u^+) \rightarrow \text{Xe} + \text{Xe}$; the primed curve is the electron temperature $T_e$. Temperature of electrons is in eV, specific power values $Q_1$ and $Q_2$ are in $10 \text{ W/cm}^3$.

At Xe density higher $10^{19} \text{ cm}^{-3}$ the main part of charged heavy particles make molecular ions. Though dimer metastables density is about one order higher than resonance state density, they give a comparable with resonance transition contribution into radiation (see Fig. 2b) since the probability of resonance dimer spontaneous decay is by an order of magnitude greater.

**Efficiency dependence on density and temperature.** Radiation efficiency grows sharply with Xe density increase up to $10^{19} \text{ cm}^{-3}$ (see Fig. 3a), when the channel of molecular ions and dimers begins to operate. With following growth of Xe density the efficiency changes negligibly. This fact is interesting from the point of view that one can use considerably lower gas densities in excilamps in distinction to excimer lasers.

$\eta$ (%)

1658
Fig. 3. Efficiency ($\eta$) dependence of conversion of input energy into radiation on Xe density [Xe] at [He] = 0 cm$^{-3}$ (a) and He density [He] at [Xe] = 5 $\times$ 10$^{19}$ cm$^{-3}$ (b). Ionization frequency is $\nu = 4$ s$^{-1}$ with ionization duration $\Delta t = 2$ $\mu$s. $T_e = 300$ K.

It should be mentioned that the highest efficiency reached the kinetic efficiency

$$\eta_{km} = \frac{\hbar \nu (1/E^+ + \beta/\alpha)}{(1 + \beta)} = 68\%$$

where $\nu$ - energy of radiation quant of Xe$_2^+$ molecule, $E^+$ - excitation energy and $I$ - ionization potential of Xe, $\beta = 0.5$ - is the ratio of the frequency of excitation to the frequency of ionization in Xe. He-additions makes Xe-excilamp efficiency somewhat lower (see Fig. 3b) at He density exceeding Xe density. With gas temperature growth, the efficiency becomes lower monotonically since dimer formation rate fall off and their decay rate increases.
Fig. 4. Efficiency dependence of conversion of input energy into radiation via the temperature of gas $T_g$. Xe density $[\text{Xe}] = 5 \cdot 10^{18} \text{ cm}^{-3}$, [He] = 0, ionization frequency is $\nu = 4 \text{ s}^{-1}$, ionization duration $\Delta t = 2 \text{ ms}$.

Efficiency dependence on ionization frequency and duration of excitation. Dependence on ionization frequency (and corresponding excitation power) has a maximum which position depends on duration of excitation $\Delta t$ (see Fig. 5).

$\eta (%)$

Fig. 5. Efficiency dependence of conversion of input energy into radiation via the excitation specific power $W$ (in W/cm$^3$) with different excitation pulse duration values $\Delta t$. Xe density $[\text{Xe}] = 5 \cdot 10^{18} \text{ cm}^{-3}$, [He] = 0, $W = 20 (\nu \cdot \text{ W/cm}^3$, $T_g = 300 \text{ K}$.

The solid curve - $\Delta t = 2 \text{ ms}$; the primed curve - $\Delta t = 500 \text{ ns}$; the dashed line - $\Delta t = 100 \text{ ns}$; dot-(and-)dash line - $\Delta t = 20 \text{ ns}$.

Also there is an optimum on excitation duration $\Delta t$. When using the data of Fig. 5 for frequent operation mode of excitation one ought to keep in mind that here the power during the excitation by rectangular pulse is given. Correspondingly, it is necessary to take into
account the porousness (relative pulse duration) when one convert the pulse power to power averaged by time.

4. Conclusion
From the presented mathematical modeling it follows that the efficiency of excilamp pumped by hard ionizer can be as high as 68% calculated as radiation output to energy input in gas media. Here one could use comparatively low Xe density $[\text{Xe}] = (5-20) \times 10^{18} \, \text{cm}^{-3}$ (pressure values of about 300 Torr) at excitation power density of $W \sim 100 \, \text{W/cm}^3$ and excitation pulse duration in a range from 2 $\mu$s to 100 ns.

As it was already mentioned, these results of simulation are more precise for the case of e-beam excitation that is in particular interest from the point of view of using thin ceramic foils and low-energy beams [9]. These simulations are also interesting for excitation by discharges with hard component of electron distribution function, for instance, mesh anode discharges, barrier discharges and discharges with cathodes of small radius of curvature (stick and spiral cathodes). Besides, these results can be applied for nuclear-pumped excilamps.

References


