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Temporal evolution of electron beam generated Argon plasma in pasotron device

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Abstract. The plasma- assisted slow wave oscillator (PASOTRON) is a high power microwave source in which the electron beam in the interaction region is confined by the background plasma. The plasma is generated by impact ionization of background gas with the electron beam. A model has been developed for temporal evolution of Argon plasma in pasotron device. In this model, we consider electron beam of energy E interacting with Argon gas. The resulting ionization creates quasi neutral argon plasma composed of argon Ar atoms, singly ionized ions Ar^+ and electrons having energy from 0 to E . Electron impact excitation, ionization, radiative decay, radiative recombination and three body recombination processes are considered in this model. Population of ground and excited states of argon atom, ground state of argon ion as well as the population of electron energy groups is calculated by solving time dependent rate equations. Temporal evolution of electron beam generated plasma is given.

1. Introduction

The plasma assisted slow wave oscillator (PASOTRON) [1,2], is a unique high power microwave source that operates in the absence of external magnetic fields that makes these device light in weight and therefore is attractive for airborne applications. The transport of an intense electron beam in the pasotron is based on the focusing effect of beam generated plasma which neutralizes the beam space charge. Initially the interaction region is filled with a neutral argon gas, so there is no plasma and beam diverges due to its own self fields [3]. The plasma neutralizes the space charge field of the electron beam and consequently an external magnetic field to guide the beam is not needed.

The paper is organized as follows. In section 2, kinetics and rate equations of electron beam generated plasma for pasotron is described. Section 3 contains the simulation results and in the final section we summarize our results.

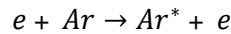
2. Kinetics of electron beam generated argon plasma

In our model, we consider impact ionization of argon gas with an electron beam of energy E . The resulting ionization creates quasi neutral argon plasma composed of argon Ar atoms, argon singly ionized ions Ar^+ and electrons having energy from 0 to E . We ignore higher ionization states of Ar. When an energetic electron interacts with gas, it loses its energy through excitation, ionization and secondary electron production. The important processes are spontaneous radiative transition and collisional transitions induced by electron impact. The processes included in the model are:

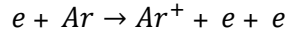
- (i) Electron impact excitation: Ar atom can be excited from one energy level to a higher energy



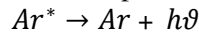
level due to inelastic collision with incident electrons.



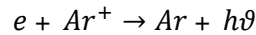
- (ii) Electron impact ionization: Electrons with sufficient energy can remove an electron from an atom and produce one extra electron and ion.



- (iii) Spontaneous emission: Once an atom is excited, it will de-excite to the ground state without any external influence. This process is called spontaneous emission.



- (iv) Radiative Recombination: Ar^+ can recombine with secondary electrons creating Ar atom and a photon.



- (v) Three body recombination: Ar^+ can recombine with secondary electrons in the presence of Ar atom.



During these processes primary electrons loose energy while the secondary electrons gain energy. The secondary electrons will then generate tertiary electrons and the avalanche process will follow. To obtain the energy distribution, the energy range 0-E is discretized into N subgroups, i.e., energy bins, denoted by index g, of different energies [4]. The flow of electrons in energy bins for secondary electrons due to collision with atoms, ions and electron is calculated in a top to down order. An appropriate rate equation system is needed to describe the energy distribution of argon plasma. These equations involve the process of excitation, spontaneous emission, ionization, radiative recombination and three body recombination processes of populating and depopulating the levels. Beam induced field effect is not considered in this model.

2.1 Rate Equations

The rate equation for the population density $N(n)$ of the n discrete state can be expressed in the general form [4]:

$$\frac{dN(n)}{dt} = G - L, \quad (1)$$

where G is the gain term and L is the loss term.

The rate equation begins with the ground state of argon atom:

$$\begin{aligned} \frac{dN_1}{dt} = & \sum_{k>1} A_{k,1} N_k(t) - \sum_{g_i=1}^{N_g} \sum_{g_j=g_i+1}^{N_g} \alpha(g_i, g_j) N_e(g_i, t) - \sum_{k \leq 6} \sum_{g_i}^{N_g-1} R_{1k}(g_i) N_1(t) + \\ & [\sum_{g_i=1}^{N_g} \beta_r(g_i) N_e(g_i, t) + \sum_{g_i=1}^{N_g} \beta_3(g_i) N_e(g_i, t) N_1(t)] N_7(t) \end{aligned} \quad (2)$$

In Eq. (2), the first term is the spontaneous radiative decay rate from excited energy state of argon atom k to ground state of argon atom, by which ground state are populated. The second term is product of the ionization coefficient and the electron number density at time t. Third term is the product of the excitation rate for generating excitation from ground state to energy state k in argon atom due to electron impact excitations by the beam electrons. Last two terms are due to recombination processes.

The rate equations for excited states for neutral argon atom are given as follow:

$$\frac{dN_l}{dt} = \sum_{l=2}^6 \sum_{g_i}^{N_g-1} R_{1l}(g_i) N_1(t) - \sum_{l=2}^6 A_{l1} N_l(t) \quad (3)$$

Excited states are populated by electrons of higher energy created from ionizing collisions that scatter down into the excited states and population density reduces by spontaneous emission and product of ionization coefficient and number density of that excited level. The rate equation for the ground level of singly ionized argon is

$$\frac{dN_7}{dt} = \sum_{g_i=1}^{N_g-1} \sum_{g_j=g_i+1}^{N_g-2} \alpha(g_i, g_j) N_e(g_i, t) - [\sum_{g_i=1}^{N_g-1} \beta_r(g_i) + \sum_{g_i=1}^{N_g} \beta_3(g_i) N_1(t)] N_e(g_i, t) N_7(t).$$

(4)

The rate equation for secondary electrons of energy bins g_j is given by following expression:

$$\frac{dN_e(g_j, t)}{dt} = \sum_{g_i=1}^{N_g-1} \alpha(g_i, g_j) N_e(g_i, t) - [\beta_r(g_j) + \beta_3(g_j) N_1(t)] N_e(g_j, t) N_7(t) - \sum_{g_p=g_j}^{N_g+7} \chi(g_j, g_p) N_e(g_j, t) + \sum_{g_p=g_{j-1}}^1 \chi(g_j, g_p) N_e(g_{j-1}, t) \quad (5)$$

The gain term in secondary electron rate equation is due to electrons of higher energy created from ionizing collisions that scatter down into the energy bin. The loss term is due to electrons which suffer scattering collisions which cause them to lose sufficient energy to drop down to a lower energy bin as well as electrons in the bin which experience recombination with argon ion.

2.2 Transition Rates

In the study of relativistic electron beam produced plasma, several methods of energy apportionment have been developed to calculate the production yields from degradation of the incident electron energy. We have used Peterson- Green integral equation, in which a continuous energy loss [5] is assumed. The energy spectrum of the secondaries is rather broad, it extends from 0 up to $(E_p - I_j)/2$, where is E_p incident kinetic energy and I_j the ionization potential of the j^{th} shell.

Excitation rates are calculated by product of loss function $L(g_i)$, velocity v , fractional energy loss μ_k and secondary electron number density N_e of that energy group is

$$R_{1k}(g_i) = \frac{L(g_i) v(g_i) \mu_k(g_i) N_e(g_i)}{E_{1k}}$$

Ionization rates for electrons in group g_i causing an ionization of Ar in ground state resulting in an emitted electron in energy group g_j can be expressed as

$$\alpha(g_i, g_j) = \frac{L(g_i) v(g_i) \mu_{gi}(g_i) N_1(t)}{\Delta E}$$

where ΔE is the difference of energy group g_i and group g_{i+1} .

Spontaneous radiative decay rates are taken from standard data table [6]. Recombination rate coefficient is calculated using formula [7]

$$\beta_r = 3.8 \times 10^{-9} T_e^{-4.5} N_e + 1.55 \times 10^{-10} T_e^{-0.63}$$

Three body recombination rate coefficients for electrons in group g recombining with argon ion to create argon atom is calculated using formula [8]

$$\beta_3 = 3.68 \times 10^{-32} \left(\left(\frac{135300}{T_e} \right) + 2 \right) \exp(47800/T_e)$$

3. Numerical Results

We have $N_g + 7$ set of coupled differential equations given by Eqs. (2) – (5) that are solved for number densities of different energy levels. The results are given for the following set of parameters: $N_g=8000$, electron beam energy $E=40$ keV, beam duration 100ns and beam current 50mA in presence argon gas at pressure 10 mtorr. The beam radius is 0.12mm.

The electron number density can be calculated by sum of number density of each energy groups. The result of are given in Fig.1. The numerical value $3.204 \times 10^{14} \text{cm}^{-3}$ of the electron density is nearly equal to the gas density $3.2126 \times 10^{14} \text{cm}^{-3}$ indicating that almost whole gas converted into plasma. Energy distribution of the secondary electrons for various times is given in Fig. 2.

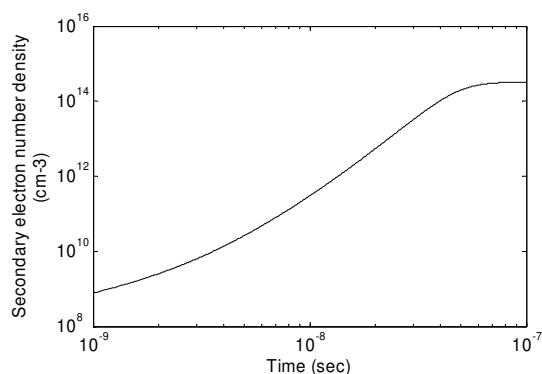


Fig.1 Variation of plasma density with time

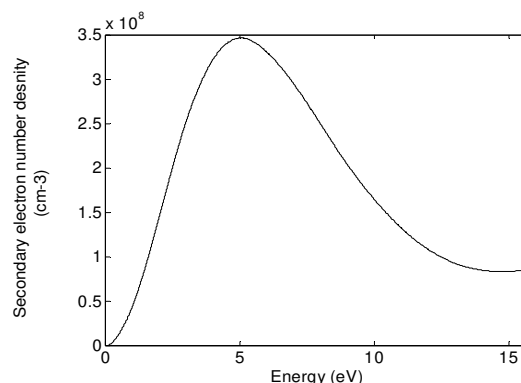


Fig 2. Distribution of plasma density in different energy bins at different time

The flow of electrons due to collision with atoms, ions and electron is calculated in a top-down order. An electron may collide with an electron, an atom or an ion and thus impart some of its energy to other particle in either elastic or inelastic manner. This causes a loss of an electron from the bin corresponding to initial energy and a production of an electron at some lower energy bin. Energy bin corresponding to energy 5.0 eV has maximum secondary electron number density. Similar results for different set of parameters and variation of plasma density at different beam radius has been presented elsewhere [9].

4. Conclusions and Discussions

Kinetics of relativistic electron beam interacting with neutral argon gas is developed. The results provide a general qualitative picture of the physical processes in a temporal evolution of electron beam generated argon plasma and electron energy distribution, which are consistent with general trend.

Acknowledgment

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