Microwave discharge with multiply charged ions in expanding gas jet as a point source of UV radiation

A. G. Shalashov, S. V. Golubev, E. D. Gospodchikov, I. S. Abramov

Institute of Applied Physics of Russian Academy of Sciences, Nizhny Novgorod, Russia

Introduction

Now the only practical source of extreme ultra-violet (XUV) radiation for high resolution projection lithography is line radiation of multiply charged ions of certain elements such as stannum or xenon [1]. Encouraging experiments on a development of a point-like UV radiation source have been performed at IAP RAS [2]. These experiments demonstrate localized rf discharge sustained by submillimeter waves in the expanding gas jet. The peculiar feature of such a discharge is formation of a strongly non-equilibrium plasma with multiply charged ions and the electron temperature being much greater than the temperature of ions and neutral atoms, $T_e \sim 100$ eV and $T_i \sim 1$ eV. Despite the resonant nature of the power deposition, a high electron thermal conductivity results in acts against localization of a discharge in space. In these conditions, a size of XUV source is more likely governed by the fly-time of an ion in a particular ionization/excitation state rather than electrodynamics of resonant absorption of microwaves.

To support the experiments, we consider a fluid model of the stationary highly-localized plasma discharge formed under resonant microwave heating in a gas jet freely expanding after a high-pressure nozzle. A regime is found that provides a smooth transition from subsonic to supersonic velocities in the expanding flow of plasma with multiply charged ions. This allows conjugating the slow movement of initially neutral dense gas and the supersonic flow of accelerated plasma while providing spatial localisation of the discharge. In these regimes, being of particular interest for applications, an average ion charge is consistently increased along the plasma flow, simultaneously the fraction of power losses due to line emission of highly charged ions is growing, and the emission spectrum is shifted to the extreme ultraviolet in case of a proper gas composition (e.g., Xe).

Basic model

We consider stationary fluid equations [3] for multi-component plasma that takes into account step-by-step electron-impact ionization. The particle balance and quasi-neutrality condition would result in

$$\partial_r(\sigma u n_i) = \sigma n_e(k_{i-1}n_{i-1} - k_i n_i)\,, \quad n_e = \sum_{i=1}^{Z_{\max}} i n_i\,, \tag{1}$$

here n_i is a density of a plasma fraction with charge $Z=i$, $i=0,1,\ldots Z_{\max}$, n_e is the electron density, u is the flow velocity assumed equal for all fractions, k_i is the ionization constant for the i-th fraction assumed to be known function of the electron temperature, $k_{-1} = k_{Z\max} = 0$. The geometrical factor $\sigma(r)$ defines the jet expansion along the coordinate r and assumed to be known. In the one-fluid approximation momentum balance reads:

$$\partial_r(\sigma m_i n u^2) + \sigma\,\partial_x(n_0 T_0 + n_e T_e) = 0\,, \; n = \sum_{0}^{Z_{\max}} n_i\,. \tag{2}$$

The ion pressure is neglected. The fluid equations are closed assuming the constant electron temperature justified by high electron thermal conductivity typical for XUV sources.

Equations (1)-(2) become singular at the critical point where the flow velocity approaches a local ion-acoustic velocity. This point may be found from

$$\partial_r(n_e/\sigma) = 0, \quad u = c\,. \tag{3}$$

The position of the ion-acoustic singularity depends on the dynamics of the preceding flow. However, the critical point may be isolated in explicit way. By introducing a new variable τ such that $n_e\,dx = u\,d\tau$, the particle balance (1) is transformed to the universal form

$$\partial_\tau \gamma_i = k_{i-1}\gamma_{i-1} - k_i\gamma_i\,, \quad \gamma_i = \sigma u n_i/\Gamma\,, \tag{4}$$

where γ_i represents the specific flux of i-th component normalized over the total flux $\Gamma = \sigma n u = \text{const}$. Solution of these equations with constant k_i is trivial and may be expressed even in analytical form. Note that the solution is completely independent of the momentum balance. Once this solution is found, one can define the average charge and the local acoustic velocity as functions of τ:

$$\overline{Z}(\tau) = \sum_{1}^{Z_{\max}} i\,\gamma_i\,, \quad c^2(\tau) = \gamma_0 T_0/m_i + \overline{Z}\,T_e/m_i\,. \tag{5}$$

With these definitions, the momentum balance equation (2) is transformed to

$$\begin{cases} (1 - c^2(\tau)/u^2)\,\partial_r u = -(\sigma/u)\,\partial_r(c^2(\tau)/\sigma) \\ \partial_r\tau = \Gamma\,\overline{Z}(\tau)/(\sigma u^2) \end{cases}. \tag{6}$$

Thus, the fluid velocity $u(r)$ is reconstructed simultaneously with $\tau(r)$; then all other parameters, such as $n_e(r)\,, \overline{Z}(r)$ etc., are recovered.

In particular, combining Eqs. (3) and (6), one finds for the critical gradient for the ion-acoustic transition,

$$\partial_r \sigma = (\Gamma m_i / T_e)\, \partial_\tau \ln \overline{Z} \,. \qquad (7)$$

This equality allows to link the coordinate r_c of the critical point with the average ion charge $Z_c = \overline{Z}(\tau_c)$ at that point. Expansion of Eqs. (6) in the vicinity of the critical gradient results in linear equations for variations of Mach number $\delta M = u/c - 1$ and $\delta r = r - r_c$:

$$\partial_\xi \, \delta M = \alpha\, \delta r + \beta\, \delta M , \quad \partial_\xi \, \delta r = \delta M \,, \qquad (8)$$

where constant coefficients $2\alpha = \partial_r^2 \sigma / \sigma + (\partial_r \sigma / \sigma)^2$ and $2\beta = \partial_r \sigma / \sigma$ are calculated at the point $r = r_c$, and ξ is an effective time. Fig. 1 shows the eigenvalues and typical solutions of this system for different expanding laws of the flux.

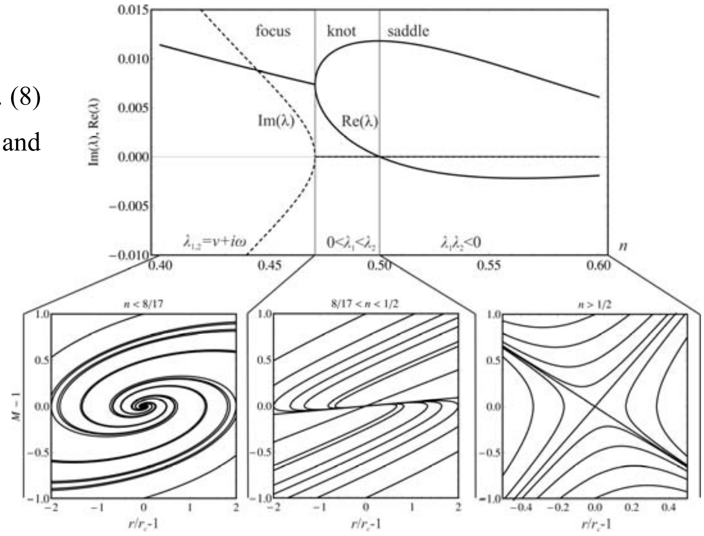

Fig. 1. The eigenvalues and solutions of Eqs. (8) for different flow expanding indexes *n*, and $\sigma(r) \propto (r / r_c)^n$.

Application to XUV source

The most relevant to practical applications case corresponds to a saddle structures shown in the right bottom panel in Fig.1. For fast enough flow expansion ($n > 1/2$) there are subsonic and supersonic regimes, separated by separatrix along which the smooth transition from sub- to supersonic movement is only possible. Detailed analysis of such regimes is done in [4]. In particular, it is possible to determine the initial conditions for the flow such that non-linear evolution of Eqs.(6) would match a particular trajectory of Eqs.(8) in the vicinity of the ion-acoustic singularity. Thus, the linearized equations may be used to classify all possible solutions of the non-linear problem far from the critical point.

As was already mentioned, in applications to experiments on XUV radiation source, one should inevitably consider the ion-acoustic transition inside a discharge. Then, the only possible stationary solution within our model is the saddle separatrix. We assume that once the physical system shows the stationary behaviour, it self-organizes such that the solution follows the separatrix. Although physics of such self-organization lies outside the scope of the studied model, we are able to construct the resultant steady-state just continuing the solution of Eqs. (6) in both sides from the saddle point. This technique is developed in [5].

An example of calculations for parameters close to the experiment [2] is shown in Fig. 2. Important feature of such modelling is that after fitting Eqs. (6) to the experimental data there is still one free parameter. Namely, the position r_c of the ion-acoustic transition remains uncertain. However it may be defined using the energy minimum principle. Total power losses $P(T_e, r_c)$ from the discharge may be calculated as a sum of the volumetric power losses due to ionization and line excitation and convective losses. The convective losses are growing with the electron temperature T_e, and the volumetric losses are decreasing, both resulting in a minimum of total power over T_e. As shown in [4], the increasing and decreasing brunches are both unstable, so the only possible stable solution correspond for the minimum of $P(T_e, r_c)$ over T_e. This allows us to determine the remaining free parameter r_c for a given power deposited into the discharge.

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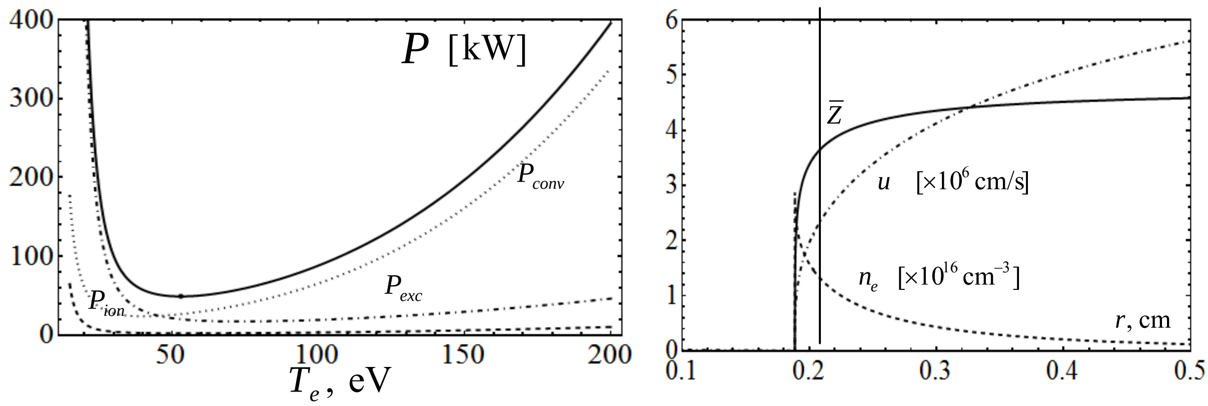

Fig. 2. Modelling of discharge in Argon. Left: power losses v.s. electron temperature. Bottom: average charge, fluid velocity and electron density v.s. coordinate along flux. Total power is 50 kW, neutral gas pressure is 2.5 atm, and gas nozzle radius is 75 μm, flux expansion is approximated by $\sigma(r) = \sigma_0 + \Omega r^2$.

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