Source of extreme ultraviolet light based on expanding jet of dense plasma supported by microwaves: theory and modelling

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Transition to exposure by the means of extreme ultraviolet (EUV) light is vital for development of modern projection lithography [1–4]. The only practical source of this radiation is line radiation of multiply charged ions as ionization causes shift of the ion spectrum towards UV region. Radiation of such short wavelengths is efficiently absorbed in atmosphere and elements of refractive optics. Thus focusing of EUV radiation should take place in vacuum and the optics used for it should be reflective. To focus EUV radiation multilayer mirrors (MLM) are used. These mirrors have narrow wavelength band where their reflection coefficients are high enough for efficient collecting of EUV radiation.

Nowadays, most of existing EUV radiation sources operate at 13.5 nm ±1% wavelengths corresponding to peak reflection coefficients of Mo/Si MLMs. With this kind of mirrors, tin plasmas are used due to significant number of corresponding lines in spectra of Sn^{7+} – Sn^{12+}. The most successful projects use evaporation of tin droplets in focused beam of CO_2 laser: 200 W EUV-light sources are available for industry, while 250 W source is demonstrated in the lab. But a significant decrease in integral circuit scales requires much higher EUV-light power up to 1 kW that hardly can be achieved by laser-based sources [4].

In this paper, we discuss an alternative for laser plasma in EUV-light generation based on microwave discharge in a stream of a heavy noble gas. The schematic of the EUV radiation source is proposed in Ref. 5 and illustrated in Fig. 1. The concept involves generation of plasma with multiply charged ions in expanding jet of neutral or pre-ionized heavy noble gases (Ar, Xe) by the means of high-power radiation from modern gyrotrons. The jet expands into vacuum and provides a good

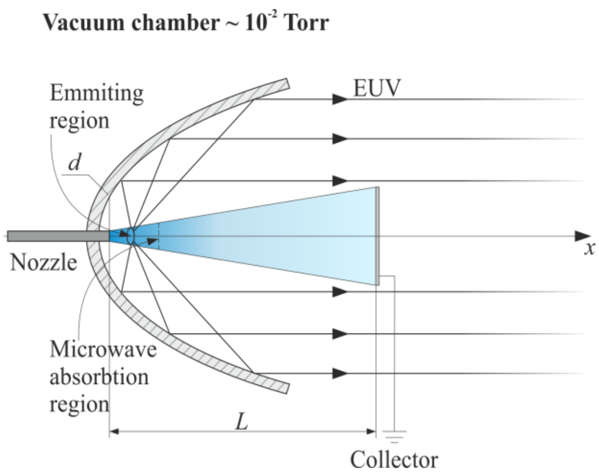

Fig. 1: Schematic of the EUV-light source

spatial localization of the discharge that is important for EUV radiation focusing with available optic systems. Duration of the gyrotron pulses is much longer (from 50 μs up to CW) and its power is much higher (up to 1 MW) than the corresponding characteristics of lasers. It allows us to expect stationary EUV-light generation instead of 10 ns pulsed mode realized in the laser produced plasma. Moreover, the microwave heating leads to a strongly non-equilibrium plasma with high energy electrons and cold ions. Such conditions provide high rates of electron impact ionization and excitation with no channels for essential ion acceleration. Usage of the directed flow helps to save MLM optics from damaging by jet particles. The mirrors for EUV-light generated by noble gases are now available and may be used in a collecting system. In particular there are Ru/Be mirrors for efficient focusing of line radiation of Xe^{10+} at 11.2 nm ±1% [6].

In our model we assume a stationary discharge which is strongly inhomogeneous along the flow direction x and strongly non-equilibrium: the electron temperature essentially exceeds the ion temperature $T_e >> T_i$. We use fluid equations taking into consideration the variation of all fluid characteristics along the flow direction and averaging them over the transverse plane. We neglect the electron momentum flux due to difference in the ion and electron masses and the ion pressure in comparison to electron one due to difference in the temperatures. High electron temperature also causes high electron thermal conductivity that allows us to assume electron temperature to be constant along the flow (T_e enters the model as a parameter). Under these assumptions the fluid equations are expressed as follows [7, 8]:

$$\tfrac{d}{dx}(n_j S u) = n_e S (k_{j-1} n_{j-1} - k_j n_j), \tag{1}$$

$$\tfrac{d}{dx}\left(SMnu^2\right) + S\tfrac{d}{dx}(n_e T_e) = 0,\ n = \sum_{j=1}^{Z_{\max}} n_j, \tag{2}$$

where n_j are the densities of ions with charge-state $Z_j=j$ (i.e. with charge je), u is the flow velocity, n_e is the electron density followed from the quasi-neutrality of the plasma, k_j is j-th ionization constant, $S(x)$ is the flow cross section, M is ion mass. Non-trivial boundary conditions for (1) and (2) follow from the presence of ion acoustic transition in the flow expanding into vacuum as described in [9].

To use fluid model for EUV-light source simulation, it is necessary to analyze the power balance. Total power absorbed by the discharge is

$$P = AF\frac{Mu^2}{2}\bigg|_{x\to L} + \int\left(\sum_j E_j k_j n_e n_j\right)Sdx + \int\left(\sum_j\sum_l\sum_h E_{jhl} k^*_{jlh} n_e n_j\right)Sdx. \tag{3}$$

The first term represents the kinetic energy flux to a collector located at $x = L$ (convective losses). Numerical factor $A \approx 3+\ln(Mn/m_e n_e)$ depends on the collector properties (m_e is the electron mass) [9]. $F = Snu$ is the total ion flux that is conserved. The second term represents the power spent on ionization: E_j is the ionization energy of j-th ion, $k_j\, n_e$ is the effective rate of electron impact ionization. The third term stands for the line radiation losses: E_{jhl} are the transition energies and inner sums are taken over all possible ground and excited levels in an ion spectrum. Effective excitation coefficient k^*_{jlh} is defined taking into account reabsorption of the emitted photons with the possibility of nonradiative de-excitation of ions by electron impact (the radiation trapping effect). It may influence the performance significantly for plasma densities about 10^{16} cm^{-3} typical of our discharge. The radiation trapping effect is accounted as it is proposed in [10]

To explore the prospects of EUV-light sources we performed modelling of a conversion efficiency in wide range of practical parameters: total ion flux F, the electron temperature T_e and initial plasma diameter d (see Fig. 1).

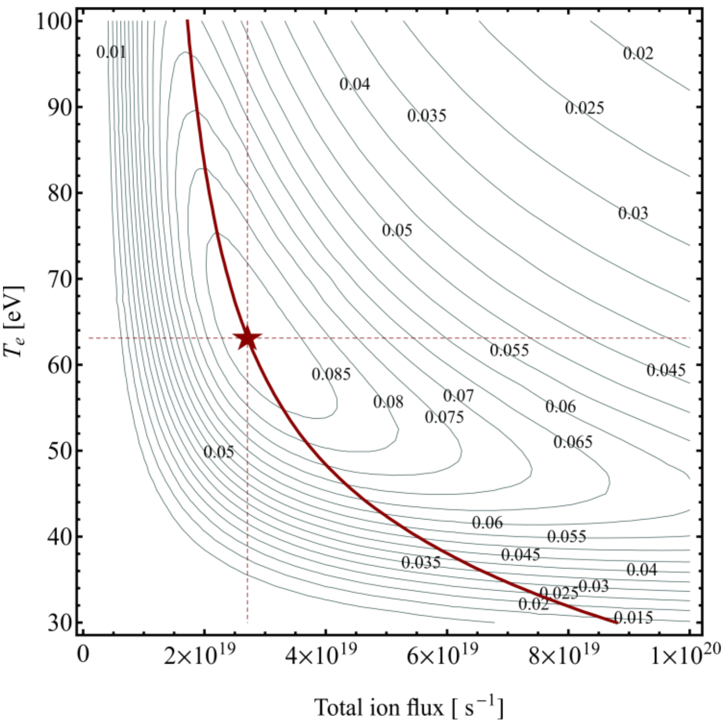

Fig. 2: EUV conversion efficiency for 11.2 nm ±1% band as a function of electron temperature T_e and total ion flux F for initial plasma diameter $d = 30$ μm; ★ indicates the maximum of the conversion at $F = 2.7\times10^{19}$ s^{-1}, T_e = 63 eV; the thick red curve corresponds to constant total power load $P = 100$ kW.

The results of modelling are shown in Fig. 2. There is an absolute maximum of conversion efficiency over the temperature and the total flux value (see "★" in Fig. 2).

The decrase of conversion efficiency at high T_e correspond to decrase of density as a result of increase in the ion acoustic velocity and increased percentage of the covective losses. The decrease of conversion efficiency at high F values is the result of the radiation trapping effect in dense plasmas. Considering further optimization, increase of the initial plasma diameter d may be beneficial as the volumetric losses grow faster than convective loss. However such a discharge would require more power to support. The best result for estimated absorbed power of 100 kW corresponds to diameter of about 30 μm.

Proof-of-principle experiments aimed at demonstration of the proposed concept are just initiated at IAP RAS, Nizhny Novgorod. Unique 200 kW / 250 GHz / 50 μs gyrotron is used to support plasma of Ar, Xe and Kr. The interpretation of preliminary experimental results evidences in favor of the possibility of EUV-light generation. In particular, registered with Al/Si filter radiation from a xenon jet corresponds to about 4 W of radiation with wavelengths smaller than 50 nm (according to the presented modelling).

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