Plasma dynamics in hollow cathode triggered discharge with influence of fast electrons on ionization phenomena and EUV emission

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The 2-D computational code Z* is used to simulate physical phenomena in hollow cathode triggered low-pressure capillary discharge at different phases of the process: electron beam generation, formation of a channel by ionization wave, and discharge dynamics together with ionization kinetics and plasma emission, particularly in EUV band interesting for applications. Run-away electrons in gas-filled capillary discharge with hollow cathode play an important role both in ionization wave propagation, and in ionization of multicharged ions in discharge plasma. The electron beam prepares a tight ionized channel. The fast electrons shift the ionization equilibrium in discharge plasma increasing the EUV emission from relatively low-temperature plasma of argon or xenon. At ionization wave stage, the electron flow is simulated in electron-hydrodynamic model. At discharge stage, the plasma is described by the radiative magnetohydrodynamics with ionization kinetics and radiation transfer.

1. Introduction

Discharge produced plasmas (DPP), like hollow cathode triggered Z-pinch, capillary discharge, laser induced pseudo-spark, and laser produced plasma (LPP) are considered as possible candidates for the creation of a compact high power EUV radiation source in 2% bandwidth around 13.5nm spectral wavelength for next generation of lithography application [1]. To achieve a suitable ionization degree to emit at 92eV the high Z plasma should be heated up to tens of electron-volts. To produce the radiation in a narrow spectral band effectively the plasma should be almost transparent. Fast electrons, which are often present in discharge or laser produced plasma, affect the ionization degree. Therefore most experimental plasmas of EUV sources under conditions of interest exist in the non-LTE regime. Knowledge of the behaviour of plasma containing multiply-charged ions (further 'multicharged ion plasma') is critical for the study of DPP or LPP EUV source. Accurate numerical modelling of transient plasmas together with ionization phenomena and radiation transfer with at least 2-D effects has been recognized as an essential part in the continuing development of plasma radiation sources.

Z* is a 2-D computational code [2] designed at EPPRA, in collaboration with the RRC Kurchatov Institute, Keldysh Institute of Applied Mathematics RAS, and Troitsk Institute of Innovation and Fusion Research (TRINITI), to focus specifically in the modelling of a multicharged ion plasma in experimental and industrial facilities. It uses either a radiative magnetohydrodynamic (RMHD) approach to simulate dynamics of quasi-neutral plasma or electron-hydrodynamic approach to simulate flows of fast electrons in a weakly ionized gas. The code Z* is a further development from the well-proven code ZETA [3,4].

EPPRA is currently developing a system tool based on the adaptation of the RMHD code Z*, to facilitate numerical modelling by non-numerical specialists. This tool, called a Z* Black-box Modelling Engine (Z*BME) [5,14], is integrated into a specific computation environment to provide a turn-key simulation instrument, which does not require knowledge of numerical computation. It has been adapted, in particular, to simulate DPP and LPP radiation sources.

2. Computation code Z*

The RMHD code Z* is designed on the basis of the magnetohydrodynamic formalism of multicharged ion plasma in a 2-D axially symmetric geometry with full radiation transport. Plasma radiation properties, ionization and equation of state, as well as excitation and ionization rates, and plasma kinetic coefficients are calculated by means of interpolations from a set of tables prepared in pre-processing with the Hartree-Fock-Slater model [6] in both the optically thick LTE, and the transparent non-LTE limits. The actual non-LTE condition at any instant is modelled by analytical interpolation between these two limits [4]. The influence of fast electrons on ionization degree is taken into account [7]. The databases are calculated in steady-state approximations, and, to be able to take into account non-stationary effects on plasma state, the rates of atomic processes are also calculated in distorted wave approximation [2,8]. Another set of tables prepared by the pre-processor is used for the post-processing treatment of data obtained by the RMHD processor, to calculate detailed spectra of the plasma emission with high resolution in specific spectral bands, like EUV or other regions as desired. Interpolations of preliminary prepared databases allow the code to avoid on-line calculations of absolutely different processes like the plasma dynamics, the atomic physics and ion kinetics. As a result, the robustness of the code and accuracy of calculations of the main processes is enhanced considerably.

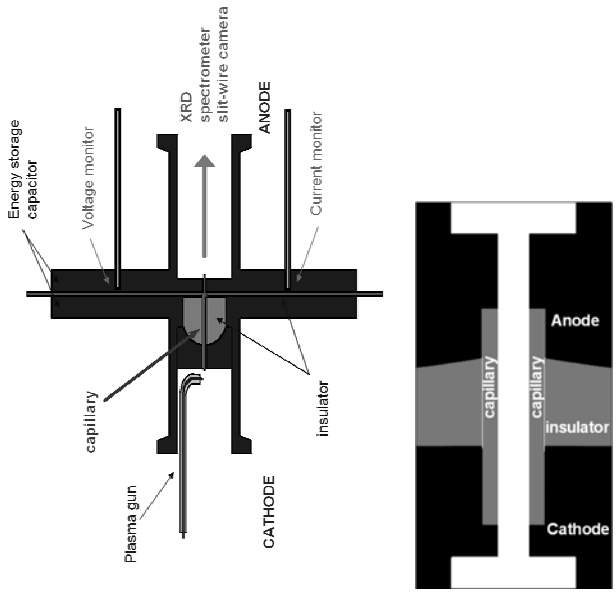
Weakly ionized plasma may be described by equations analogous to MHD equations only if the quasi-neutrality condition is satisfied and the electron inertia is negligible, i.e., at sufficient degree of ionization. Those conditions are not fulfilled at the beginning of the ionization process, especially in the pre-ionization stage or triggering of a discharge. That pre-ionization stage is described by the code using electron-hydrodynamic approach [9]. In this model, the electrons are considered flowing in self-consistent 2D electromagnetic field [2]. The atoms and ions once ionized are supposed to be motionless. The specific friction rates in the equation of motion are defined by inelastic and elastic collisions of electrons with atoms and ions. The ionisation kinetics is defined by the respective cross-sections of impact ionization, photo- and 3-body recombination interpolated from a set of tables prepared in pre-processing described above.

3. Hollow cathode triggered capillary discharge

The capillary discharge is of interest due to an opportunity to develop a directed source with high intensity of EUV radiation in a beam [10] for the metrology, and also as a high volume-manufacturing (HVM) source for EUV lithography by means of multiplexing a large number of such emitters [11].

In a capillary discharge system, a high current is made to pass rapidly through a small diameter (less han the skin-depth) insulating tube. The operation of a gas filled capillary discharge with small dimension requires the proper preparation of the initial current conduction path in order to avoid a wall initiated sliding spark discharge. By mating a suitable hollow cathode structure to a capillary discharge, a self-generated on axis electron beam is produced as a process of the transient hollow cathode effect [12]. The hollow cathode effect is used in low-density discharges working at the left hand side of the Pachen curve to produce a tight (of the order of 100μm) pre-ionized conducting channel on axis, where the main current begins to develop and effective energy deposition from the power supply to the discharge realized. The hollow cathode system is widely used in EUV plasma sources.

A set of simulations was performed for fast capillary discharges in geometry close to the experimental micro plasma pulse (MPP) discharge device established in EPPRA [10,11]. The MPP radiation source is unique among the DPP sources in operating at a stored electrical energy < 1J. It relies on very low inductance discharge geometry to allow current of several kA to be delivered to a pre-ionized discharge channel in several ns, despite the small energy used. The structure is shown schematically in Fig. 1a. Various capillary diameters, from 0.8mm to 3.2mm, and lengths 6mm-12mm, with various gas and gas compositions, including pure Ar, Kr, Xe, or their admixtures with He, at a range of pressures from 1mTorr to 1Torr, were examined.



a b

Figure 1: a) Geometry of the EPPRA MPP capillary discharge; b) – zoomed view of the capillary region adopted for simulation.

These simulations were carried out under different driving parameters, including different cell capacity, cell voltage, and different types of generator circuits. Many of these simulation results have been reported at the various EUVL meetings organized by SEMATECH.

3.1 Pre-ionization processes

Processes at hollow cathode effect are considered in the electron-hydrodynamic approach [9].

The geometry of the MPP capillary shown in Fig. 1b was simulated. An alumina capillary with internal diameter 1.6mm and length 12mm is placed between the electrodes. The capillary is filled with argon with an initial pressure 1Torr. The local energy store is a 0.8nF capacitor initially charged to 13kV. The ionization dynamics obtained is shown in Fig. 2.

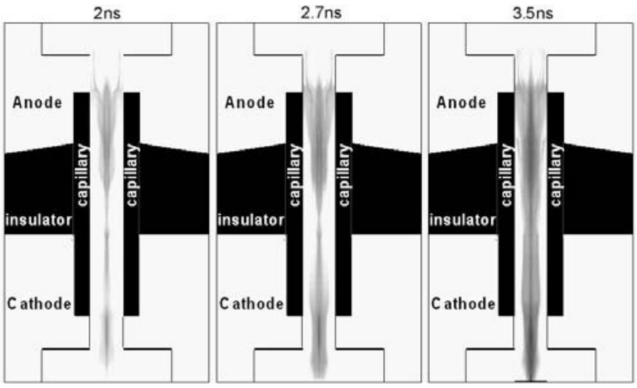


Figure 2: Preionization dynamics of a capillary discharge with iso-contours of ion density n_i shown at different times.

During almost 2ns an electron beam of several keV energy, initiated near the cathode, passes mainly along the axis of the capillary. The beam is tight, about 70µm in diameter, due to an action of combination of the self magnetic field and radial component of the external electric field refracted at the boundary gas-dielectric due to the high dielectric constant of the capillary material (it is about 8.5 at such frequencies). The beam and mainly secondary electrons produce ionization in time. At the same time electrons are exposed to the electrostatic turbulence and the dynamics is rather complicated. Near the cathode, the electrons have lower energy and ionise more effectively. While near the anode, where all electrons come together, the ionization also rises more quickly. Due to the increased plasma conductivity, the electric field become localized between these clouds of plasma, and ionization waves are observed to move respectively from the anode and from the cathode (from cathode it is much faster), and meet each other after 3ns. At 4ns the conductive channel occupies half of the diameter of the capillary, but the high-density region is localized on axis. This preionized channel is similar to the initial condition chosen for simulation of the main discharge.

3.2 Discharge dynamics

Discharge dynamics is examined in RMHD approach, where the initial conditions with pre-ionized channel are taken from corresponding preliminary electron-hydrodynamic calculations. The capillary is filled with argon with an initial pressure gradient from anode to cathode (35mTorr to 420mTorr). The local energy store is 300mJ.

The operating gas is pre-ionized due to the hollow cathode effect and generated electron beam in a tight axial channel. A presence of ~0.1% of fast electrons is taken into account in ionization rate. A peak current of 5kA is obtained with an oscillation half period of 19ns. The discharge dynamics is presented in Fig. 3, showing the mass density distribution at different times. Due to the high radiation-cooling rate of the heavy ion plasma, the plasma temperature is relatively low, so that the thermal pressure is less than the magnetic one and the plasma conductivity is low enough to permit penetration of the magnetic field into the plasma column. The capillary discharge plasma compresses volumetrically. Due to the initial gas density gradient along the capillary the lower density plasma is compressed faster and the cumulation in the low-density region generates a compression wave [13] in direction of the density gradient. The axial wave together with radial magnetic pressure produce a 3D plasma compression The EUV emission peaks is at 7.2ns. It is produced mainly by relatively dense plasma formed in the initially low-density region near the anode. In the brightest point, the plasma density reaches $5\cdot10^{-7}$g/cm^3 and an electron temperature of T_e=18eV. The average ionization degree is Z=8.8. This is higher than it corresponds to T_e=18eV equilibrium value (without fast electrons), which is 7.3. The associated EUV emission in the 13.5nm 2% bandwidth is 30µJ/shot, that corresponds to experimental measurements and 5 times higher than the value calculated without fast electrons.

To study the influence of the pre- ionization channel size on the EUV emission yield from the MPP discharge, simulations with different pre-ionization conditions were carried out for a Kr:He gas mixture with Z*. The results are represented in Fig. 4a, which shows the radiation pulse recalculated with transmission function of a Zr filter in two cases; tight on-axis pre-ionization and broad volume pre-ionization. A large first radiation peak is observed for the tight pre-ionization case. In Fig. 4b, a series of experimental measurements with a fast diode behind Zr filter is shown. The measurements were made in discharges with a fixed He pressure of 20 mtorr, measured at the anode side, but with different percentage of Kr admixture. Experimentally, it was shown that a high percentage of Kr leads to a large pre-ionization channel. Qualitative agreement with the simulation results can be seen in the emission. Simulations with xenon filled capillary discharge show that EUV emission in 2% spectral band around 13.5nm spectral wavelength (the corresponding transition is 5p-4d of XeXI ion) in the optimum may be in 5-7 times higher than that from argon [14] with the help of extra ionization of xenon by fast electrons.

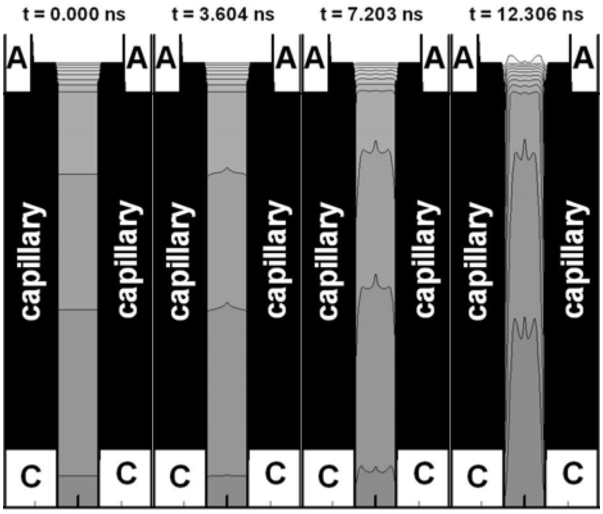
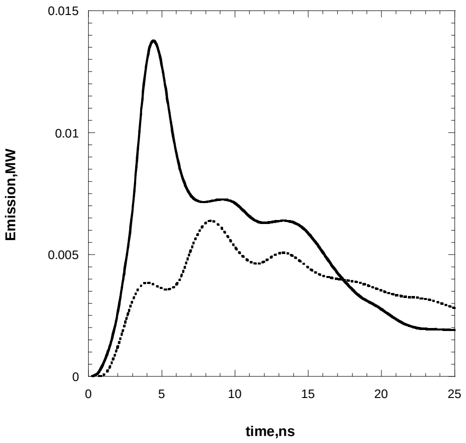


Figure 3: Capillary discharge dynamics in argon with a pressure gradient filled capillary; iso-density contours shown at different time moments.



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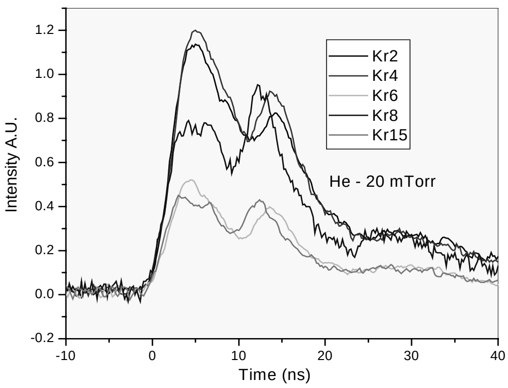

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Figure 4: a) Influence of the pre-ionization channel on EUV emission in the MPP capillary discharge with Kr:He admixture for axial (solid line) and broad (dashed line) pre-ionization obtained in simulations, and b) experimental measurements behind a Zr with different percentage content of Kr in 20mTorr of He.

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