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Ion extraction from a flowing plasma using electrostatic field: Simulation and experiment

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ABSTRACT

The mechanism of ion extraction from flowing plasma using an external electrostatic field is investigated experimentally and computationally. The plasma is generated by electron impact ionization of a copper atomic beam. The plasma, along with the atomic beam vapor, flows upward and ions from the plasma are extracted using an external electrostatic field set up by a pair of parallel-plate electrodes. The extraction mechanism is studied using in-house developed hybrid 2D Particle-In-Cell (2D-PIC) code. The experimental results are found to be in good agreement with the computationally obtained values.

1. Introduction

Electron beam evaporation is a widely used technique in areas ranging from metal vapor deposition to isotope purification [1,2]. The atomic vapor produced by this technique contains a weakly ionized plasma originating from the thermal ionization, the electron impact ionization of the vapor due to the primary as well as the secondary electrons, and the electron impact ionization caused by the thermionic electrons [3,4]. This background plasma propagates upward along with the atomic vapor. In many applications such as atomic collision experiments and laser isotope purification, it is crucial to remove this plasma from the atomic vapor beam as, for instance, it would populate the collision region with undesired charged particles in the case of atomic collision experiments or hinder selectivity in the case of laser isotope purification [3].

Electrostatic removal of such plasma has been reported earlier [5,6], where either a positive or negative potential is applied to a pair of parallel plate electrodes kept along the flow of the plasma. It was reported that at high evaporation rates, applying a positive potential to the pair of parallel plates could not remove ions from the plasma completely, whereas applying a negative potential to the plates showed complete removal of the plasma even at high evaporation rates. In the present article, ion removal is accomplished by applying a negative potential to one of the two plates keeping the other grounded with the experimental chamber. This configuration offers the advantage of readily collecting the electrons from the plasma, too, which would otherwise be available for impact ionization of the atomic vapor. The ion extraction mechanism has been investigated experimentally and computationally using a in-house developed 2D PIC code.

2. Experimental setup

The experiments were carried out in a 100-kW electron beam evaporator system having a linear electron gun details of which are reported elsewhere [7,8]. The evaporator consists of a double-walled water-cooled SS chamber maintained at a pressure of $\approx 1 \times 10^{-5}$ mbar using a combination of a rotary and a diffusion pump. The evaporator, as shown in Fig. 1, has various ports for diagnostic studies (with periscope, microbalance etc.) as well as for electrical connections. Metal vapor is generated by the electron beam evaporation technique using a linear electron gun. The 100-kW (50 kV, 2 A) electron gun primarily consists of a segmented filament of tantalum (total length = 130 mm, width = 3.7 mm, thickness = 0.75 mm) in a Pierce-type configuration producing a parallel electron beam in the post-anode region. A uniform magnetic field ($\approx$50 gauss, ±2%) generated by a pair of Helmholtz coils deflects the electron beam with a radius of curvature $R \approx 140$ mm focusing it onto the target kept at an angle of 270°.

The evaporator is divided into two compartments using a separator plate. The lower compartment consists of the electron gun, a water-cooled crucible and a dump plate, whereas the upper compartment consists of the ion suppression setup. The separator

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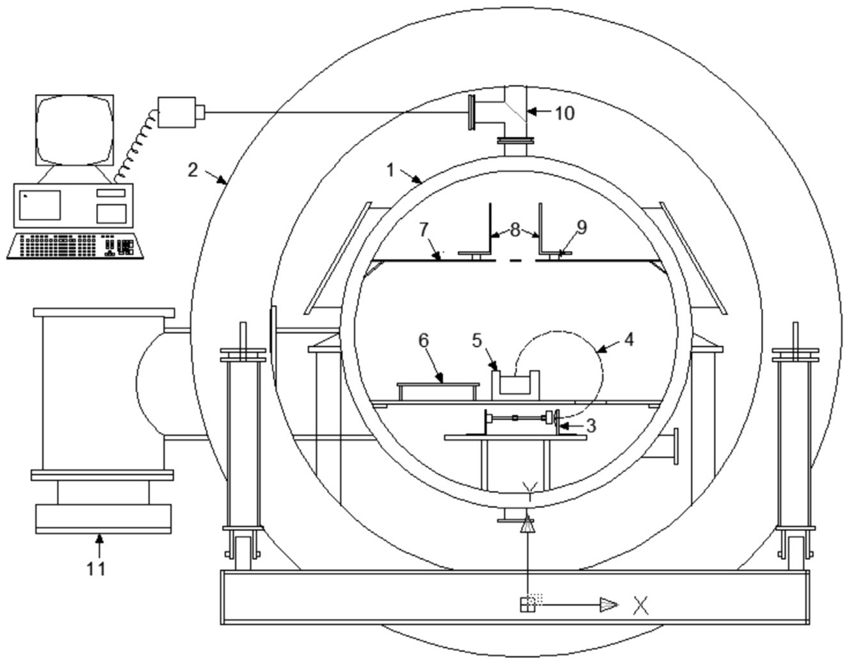

Fig. 1. Schematic diagram of the 100-kW evaporator: (1) water-cooled double-walled SS chamber, (2) Helmholtz coil, (3) strip electron gun, (4) strip electron beam, (5) water-cooled copper crucible, (6) water-cooled dump plate, (7) separating plate, (8) parallel plate suppression setup, (9) alumina insulator, (10) periscope, (11) vacuum system.

plate, located at a height of 300 mm above the evaporating source, has two rectangular apertures (20 mm × 200 mm each) separated by a distance of 20 mm for passage of the atomic vapor generated in the lower compartment. A shutter located at 240 mm above the evaporating source was used for time-dependant measurements and to avoid excessive deposition of metal vapors on insulators. The ion suppression setup was installed on the separator plate with electrical insulation using alumina. The suppression setup consists of a pair of parallel plates made of SS (160 mm × 300 mm) with a separation of 160 mm located at a height of 310 mm from the evaporating source.

Measurements of plasma parameters were carried out using Langmuir probes. The disc-type Langmuir probes were made of tantalum with a diameter 12 mm and thickness 0.5 mm. They were located above and below the suppressor plates at a height of 475 mm and 290 mm, respectively, from the evaporating source.

3. Experimental procedure

The ion suppression measurements were carried out by evaporation of copper using the linear electron gun operating at 80 kW (40 kV × 2 A). The evaporating source temperature was measured to be 1900 K using a 2-color pyrometer. The evaporating source dimensions (130 mm × 5 mm) were obtained from a digital image of the source along with an internal calibration. The number density of the atomic vapor beam close to the source was estimated [8] to be 6×10^{15} atoms/cc.

Characterization of atomic vapor for the setup was earlier studied with experiments as well as simulations using 3-D Direct Simulation Monte Carlo (DSMC) technique [8,9]. The flow velocity of the atomic beam has been taken to be 1150 m/s from experiments reported earlier [10] under similar experimental conditions, where the velocity and the flux of the atomic beam were measured using the microbalance technique [11]. The microbalance data were cross-checked with data obtained from a quartz crystal thickness monitor. From the microbalance data, the Knudsen number, K_n, of the atomic vapor beam was estimated to be 0.14. The atomic vapor density at a height of 300 mm above the evaporating source was measured to be 4×10^{12} atoms/cc.

For suppression of ions, a negative potential was applied to one of the two suppressor plates keeping the other at ground with the chamber. The net current collected by each of the suppressor plates was recorded in terms of voltage-drop across a resistor of 1 kΩ. The ion fluxes at the entry and exit of the suppressor setup were monitored with respective Langmuir probes biased at −30 V. For determination of plasma parameters, *I*–*V* characteristics were recorded by applying potentials to the lower Langmuir probe in the range of −30 V to 10 V. The Langmuir probe currents were recorded in terms of voltage-drop across a resistor of 100 kΩ. From the Langmuir probe measurements, the density and electron temperature of the plasma were estimated to be 3×10^8 cm^{-3} and 0.2 eV, respectively. The degree of ionization estimated from the ion and atom densities is ≈0.01%.

The background contributions to the currents recorded by the suppressor plates and the Langmuir probes were measured by blocking the vapor flow to the suppressor setup with the help of a shutter. The background contributions were subtracted from the respective measured currents for each setting of the suppressor plate voltage.

4. Simulation

A 2D hybrid Particle-In-Cell (PIC) code was developed for studying ion suppression from continuous plasma with an external electric field. As the ion time-scale of the simulation was up to several microseconds, electrons were incorporated with the Boltzmann relation as modeled by Cartwright et al. [12] and the ions were modeled with the standard PIC methodology. The electrons come to equilibrium with the ions at every time step, and hence the method can address systems with dynamic density and ambipolar diffusion. Following Cartwright et al. [12], the method is briefly described below.