Ionization cloud formation in rotary cathode plasma confinement

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Abstract

Visually static ionization clouds have been observed forming within the plasma confinement for rotary cathodes. The magnitudes and frequency of occurrence for these ionization clouds are explored as a function of the process variables through observations and plasma simulations. A governing theory for the creation of the ionization clouds is also presented.

Introduction:

Ionization clouds, originally called "Spokes" when initially reported on by Janes and Lower in 1966 [1] and described as "local ionization zones" by Andre Anders [2], have been studied for many years in DC magnetrons and hall thrusters for propulsion in space [3]. Existing research on ionization clouds has primarily focused on DC magnetrons with small flat circular targets. Ionization cloud formation in the plasma for large area planar and rotary magnetrons has not been extensively studied. The industry-driven trend of using stronger magnetic fields for confining the plasma on large area magnetrons has spurred this research as the ionization clouds become visible to the naked eye.

Advances in simulation capabilities and computing power have enabled 3D-charged-particle-tracing-based simulations to become capable of simulating low-density DC plasma [4]. COMSOL Multiphysics can be used to generate static magnetic and electric fields that charged particles can be introduced into to simulate the production of DC plasma.

Large Area Rotary Cathode Plasma Observation:

The primary difference in the ionization clouds produced in large area rotary cathodes compared to the smaller circular cathodes that have been extensively studied is that the ionization clouds are not visibly moving around the racetrack [5]. Much of the recent literature has focused on images produced by high speed cameras to capture the individual ionization clouds. A consumer grade DSLR can easily capture the ionization clouds produced on a large area rotary cathode as shown in figure 1:

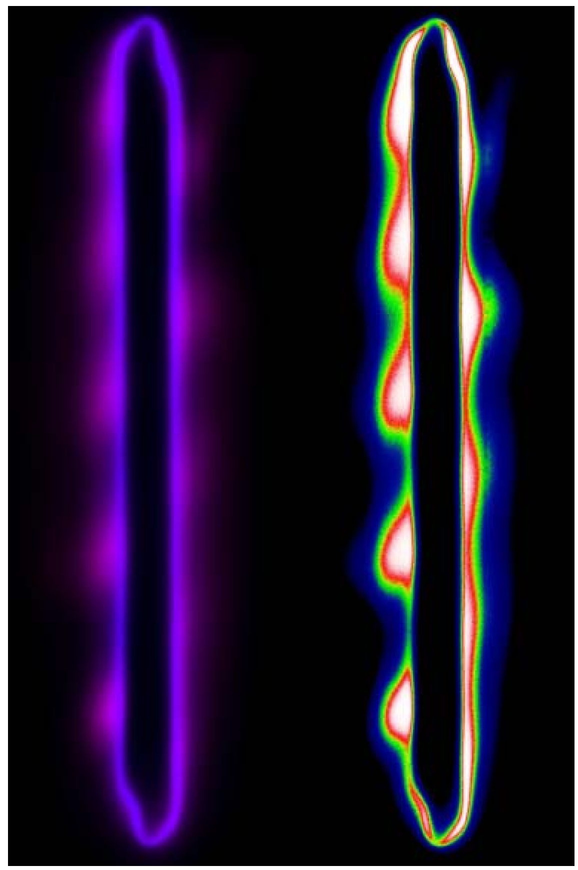

Figure 1: True color ionization cloud image (left) and a corresponding false color intensity gradient (right) of an 1110 mm long aluminum target running in DC metal mode.

The intensity images were created by running the original pictures through the Adobe Photoshop gradient tool. All images are of a 152 mm OD aluminum target that is 1110 mm long. The target was viewed from a viewport on a large and empty box-shaped vacuum chamber. The argon gas for the sputtering process is provided by a binary gas manifold located along the right-hand side of the cathode as viewed from the orientation of the plasma pictures. The closest grounded surface to the plasma is the gas manifold.

When running the plasma at a fixed power of 1 kW and increasing the process pressure using the argon gas flow rate, the number of visible ionization clouds in the plasma changes. At lower pressures, there are many static ionization clouds that all have a broad head and taper down to a narrower tail in the direction of the hall current. The hall current direction for all images is clockwise around the racetrack. When increasing the process pressure the number of ionization clouds decreases until each side of the racetrack appears to have a single ionization cloud that stretches between the turnaround regions as shown in figure 2.

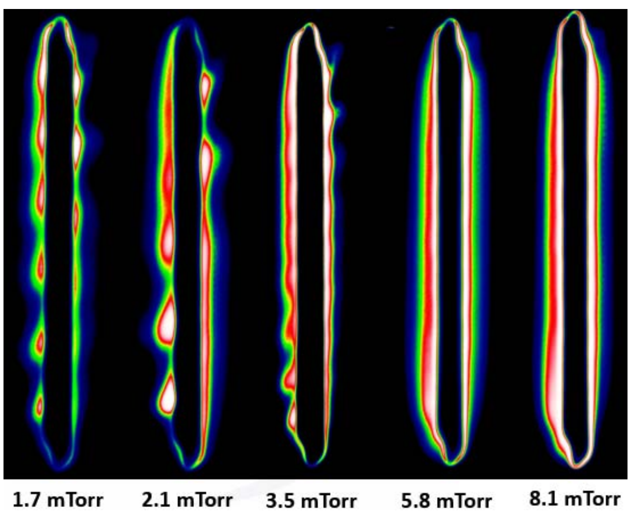

Figure 2: Ionization cloud formation as a function of process pressure for a 1 kW plasma

If the pressure is kept constant and the power is increased, the opposite trend takes place. At 5 mTorr and 1 kW the ionization clouds stretch from turnaround to turnaround, but as the plasma discharge power is increased the number and intensity of the ionization clouds increases, figure 3.

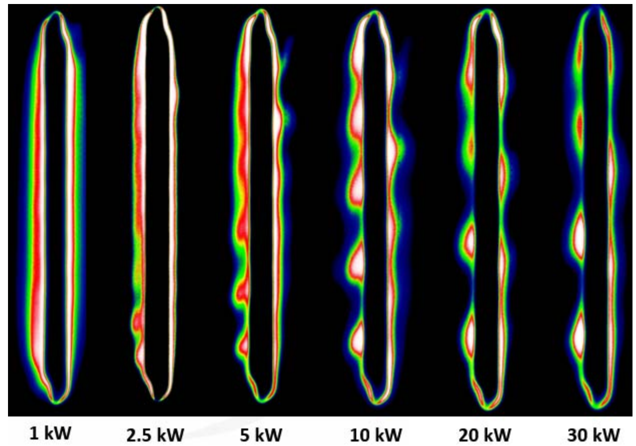

Figure 3: Increasing power density for a fixed process pressure of 5 mTorr.

Plasma Simulation:

To help understand how the ionization clouds form the magnetron was modeled in a simplified chamber using COMSOL Multiphysics. The chamber walls were set as floating potential surfaces as they are aluminum shields that have a layer of native aluminum oxide. The gas manifold was modeled as a grounded surface and the target surface was set to 400 V. The magnet pack inside the target is a 1110 mm QRM magnet bar and the magnetic field is solved for in an initial static simulation with the initial electric field. When solving for the plasma the charged particle tracing module was used insert electrons into the magnetic confinement and set an ionization probability as a function of the process pressure and argon atomic cross section.

The initial static solution results of the magnetic field and the electric field are shown in figure 4 as a cross product between the two values. The cross product of the static electric and magnetic fields produces a value analogous to the hall drift force that would cause the electrons to move along the hall current direction. The Lorentz force equation for an individual electron is [6]:

$$F = q(E + v \times B)$$

The Lorentz force equation requires a defined velocity of the electron to determine the force. If the velocity of the electrons is ignored for a static simulation then the equation can be rewritten as:

$$F_{ExB} = q\left(\frac{E \times B}{B}\right)$$

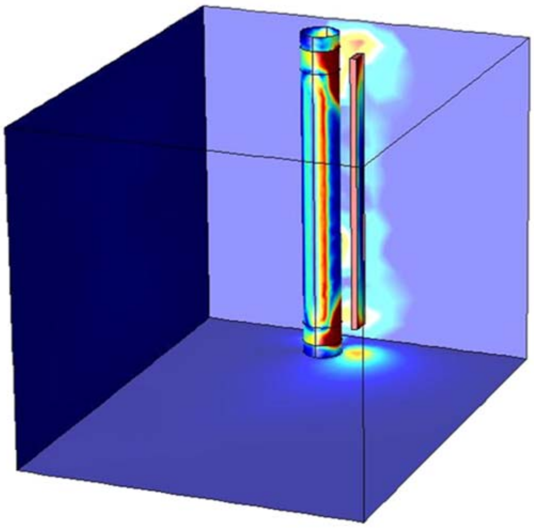

Figure 4: ExB Electrostatic forces

Once the static fields have been solved for, the electrons can be inserted into the magnetic confinement to start the plasma production as a dynamic time based study. The simulation software automatically computes the maximum timestep required to resolve the motion of the electrons, and at the end of each timestep the electric field is computed again with the addition of space charge terms produced by the charged species in the plasma. This process produces a plasma that is only bound by the magnetic and electric fields in the model. This is a different approach from the analytical simulation that defines the dark space between the plasma and the target surface for each timestep [4]. The dark space forms naturally since the electrons are reflected away from the target potential.

The ionization clouds form using this simulation technique as shown in figure 5. The shape of the ionization clouds is like the shape of the plasma observations with a high-density head and a tapered tail with a decreasing plasma density in the direction of the hall current drift.

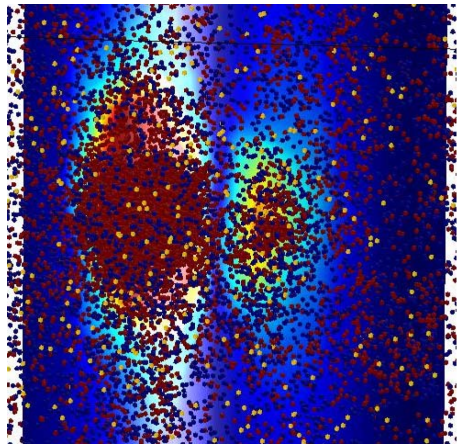

Figure 5: Close up of ionization cloud formation on target surface. Red dots are ions, blue dots are electrons, and yellow dots are sputtered aluminum. The background color on the target surface is the space charge.

Removing the plasma and sputtered species and looking at just the space charge with an overlay of the electrostatic electron drift velocity, the velocity inside the ionization clouds is much higher than outside the ionization clouds as shown in figure 6.

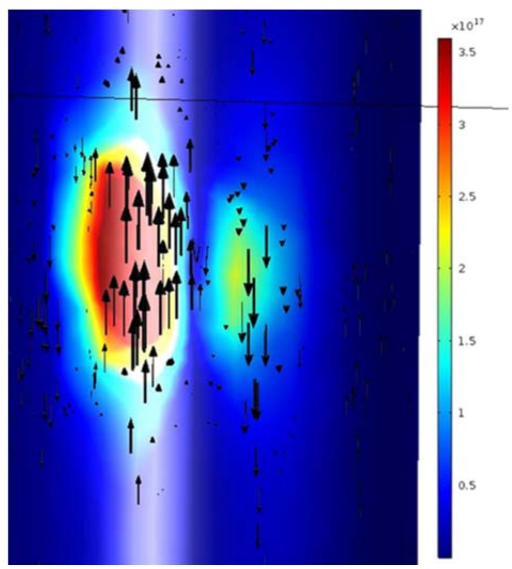

Figure 6: Electrostatic electron drift velocity in an ionization cloud. Color represents drift velocity, and arrows are a log-scale-based representation of the drift force vectors on the electrons.

The asymmetrical production on ionization clouds visible in the plasma observations is also visible in the simulation data. The increased ExB electrostatic forces on the right hand side of the racetrack shown in figure 4 reduce the intensity of the ionization clouds.

Ionization Cloud Governing Theory:

The intensity of an ionization cloud is a function of the ionization efficiency of the electron in the magnetic confinement and traveling in the hall current drift direction. When the ionization efficiency reaches a threshold in the magnetic confinement, an ionization cloud forms. The ionization process cascades until it is limited, either by the energy in the system or by the increasing plasma impedance, as the plasma is forced to expand into weaker magnetic fields as the volume of plasma increases. The maximum intensity of the ionization cloud determines the space charge produced within as the drift force on the electrons increases and the electrons are forced away from the ions created, resulting in a positive space charge. In addition to the increased hall current drift forces, $F_{E\times B}$, the expanding plasma will increase the electron loss from the magnetic confinement, Φ_e.

The base hall current density, J_e, anywhere in the magnetic confinement is a function of the plasma discharge power, P, the local process gas pressure, n, the magnetic field, B, the electric field, E, the hall current drift force, $F_{E\times B}$, the sputter yield of the target material, γ, the secondary electron yield of the target material, γ_{SE}, and the electron loss density, Φ_e.

$$J_e \cong \frac{PnB}{EF_{E\times B}}\gamma(1+\gamma_{SE})-\Phi_e$$

The above equation produces the hall current density in units of electrons per cubic meter within the magnetic confinement. The equation can be broken up into three terms. The first term $\frac{PnB}{EF_{E\times B}}$ is the ionization efficiency, which is process and magnetic field dependent. The second term, $\gamma(1+\gamma_{SE})$, is the secondary electron emission term and is a function of the target material properties and the discharge voltage. The last term, Φ_e, is a function of the magnetic field strength that the plasma is expanding into, the weaker the magnetic field strength the higher this value will become.

The runaway ionization process that forms the ionization clouds starts as soon as J_e reaches a threshold. The runaway ionization process triggers a Townsend avalanche multiplication factor that is integrated over any two points in the magnetic confinement, dx:

$$M(\alpha)=\frac{1}{1-\int \alpha\, dx}$$

The Townsend factor, α, is a ratio of the hall current density, J_e, and the electron loss density, Φ_e.

$$\alpha \propto \frac{J_e}{\Phi_e}$$

When α is large the ionization cloud will readily expand and if at any point in the ionization cloud α becomes much smaller the ionization cloud will reduce in intensity. If α becomes small enough, the ionization cloud will completely end, leaving the hall current density at a local minimum. The hall current after an ionization zone will build back up in the magnetic confinement—as a function of distance in the hall current direction according to the equation for J_e—until the ionization cloud formation threshold is reached again.

The ionization clouds formed in the large area rotary cathode plasma confinement are not moving according to the previous literature, [2] [5], because the turnaround sections of the magnetic field have a high rate of electron losses that create a choke in the hall current. Thus, the hall current must build up after exiting each of the turnarounds until the ionization cloud threshold is reached. If the hall current losses in the turnaround region were minimized, the ionization clouds should travel in the direction opposite of the hall current drift at a velocity that is proportional to the ionization efficiency.

Conclusions:

A governing theory to produce ionization clouds as a function of the hall current density anywhere in the magnetic confinement has shown how they are a function of the magnetic field, electric field, process pressure, and target material properties. This theory can be used to develop solutions to reduce or eliminate side effects from the ionization clouds.

References

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