EXTRACTION OF FUSION RELEVANT ION SPECIES FROM DISCHARGE OF FOCUSED ANODE LAYER THRUSTER

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The modification of anode layer thruster, which utilizes the focusing with reversed magnetic field (FALCON ion source), has been investigated for operation with H, He and Ar working gases. Current efficiency was measured to be in the range of 30…40% for H and Ar ion beam, while for He gas it varies from 10 to 20%.

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INTRODUCTION

The progress and success of International Thermonuclear Experimental Reactor (ITER) is tightly related to problem of the plasma-facing materials (PFMs). Interacting with high particle and heat fluxes from edge plasma, PFMs experience erosion and degradation, fuel accumulation, etc [1, 2]. Therefore, the behavior of plasma-facing materials under extreme conditions needs to be investigated preliminary in order to provide the database for development and design of plasma-facing components (PFCs).

While few of the erosion mechanisms are well known and could be predicted by existing theoretical models [1, 3], many degradation and erosion effects related to high heat and particle loads are under investigations [4]. The main method of investigation of the plasma-surface interaction effects is experimental modeling. It requires the source of intense particle fluxes: plasma devices, like Magnum-PSI [5], PISCES [6] or NAGDIS [7]; ion sources, like HiFiT [8], FALCON [9] or neutral beam sources [5].

Since plasma devices and most ion sources are expensive in operation and maintenance, the development of compact device for small-scale labs is essential. FALCON ion source has been developed to provide fusion relevant heat and particle fluxes [9 - 12]. It is based on design of closed drift thrusters (also known as Hall thrusters), which are typically used as space propulsions [13], which should be simple in operation, compact and provide high ion currents. However, primary working gas for space propulsions is xenon (Xe) due to its high atomic mass and, consequently, the momentum, which can be provided to the satellite. Application of FALCON ion source for fusion oriented material research [14 - 17] requires its operation with fusion relevant gases, like hydrogen (H), deuterium (D), helium (He), argon (Ar).

The special feature of the FALCON ion source is thin anode layer, which typical thickness is few millimeters. It consists of electrons drifting in the crossed electric and magnetic field (this layer essentially gives the name to the thrusters family), where all processes of gas ionization and ion acceleration take place. The confinement of anode layer requires relatively strong magnetic field of several kilo Gauss. While Xe ions are heavy and their trajectories are weakly bent by magnetic field, the trajectories of light ions might be affected stronger [11, 17], directing them to the cathodes of discharge gap and focusing system. Even more, the magnetic field in FALCON ion source is responsible for the focusing of the ion beam as well. As the result, significant part of the ion beam current is lost inside the ion source, which decreases the ion beam current delivered to the target. Present work studies the operation of FALCON ion source with fusion relevant species, like H, He and Ar. Particular attention is paid to the operation conditions optimal for experimental modeling of plasma-surface interactions.

1. EXPERIMENTAL

The principal design of the FALCON ion source is presented in Fig. 1. The biased anode (1) and cathode at the ground potential (2) form the discharge gap designed to provide the drift of electron layer in crossed E×B fields. Main ionizing processes and acceleration of the ions occur within this electron drift layer.

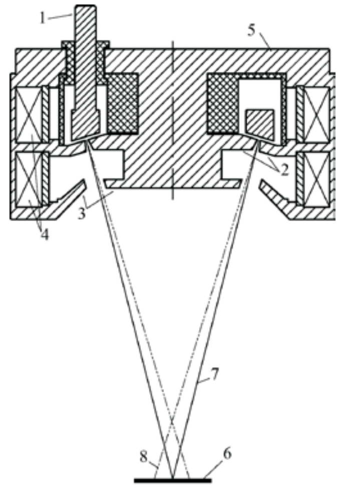

Fig. 1. Schematic drawing of the FALCON ion source. 1 – anode; 2 – cathodes; 3 – magnetic focusing lens; 4 – magnetic field coils; 5 – magnetic circuit; 6 – the target placed in the H+ crossover plane; 7 – Hydrogen ions beam trajectory; 8 – impurities trajectory

The ion source has an ion focusing system consisting of two parts. The first part is the ballistic focusing system, consisting of tilted anode (1) and cathode (2); it forms ion beam of the conical shape. The magnetic focusing system (3) focuses the ion beam further by cancelling a momentum, which ions gain in the magnetic field of the discharge gap. The reversed magnetic field configuration is powered by two magnetic coils (4); the magnetic circuit delivers the generated magnetic fluxes to the respective gaps.

Steady-state magnetic coils (4) are connected inversely and deliver the magnetic fluxes through the magnetic circuit (5) to the respective gaps. Varying the electric current through the coils one can manipulate the magnetic field fluxes and the size of the beam spot in the crossover plane, where exposed target (6) should be placed. While the trajectories of light ion species (7) can be focused in the crossover plane, trajectories of heavier ions, like oxygen, which are located further from the central point (8).

In experiments three working gases were fed to the gas inlet system of the source: H, He and Ar. The ion beam current and the discharge current have been measured while range of voltage applied to the discharge gap varied from 1 to 6 keV.

2. RESULTS AND DISCUSSION

Fig. 2 shows the measurements of ion beam currents for H, He and Ar working gases fed to the source. The pressure range of (2…4)·10^{-4} Torr has been maintained as optimal for the operation of the source. The system has been evacuated with turbomolecular pump with the pumping speed of 1200 l/s. Higher pressure typically results in higher ion beam current, however, the anode layer thruster has upper limit for the pressure in the vacuum chamber. Exceeding the limit, discharge experience significant drop of the voltage with corresponding increase of the ion beam and discharge current. These parameters are typical for the magnetron regime with the disruption of the focusing properties of the system.

Typically, ion beam current growth with the voltage increasing, different types of working gas show different dynamics. Hydrogen and argon ion beam currents increase monotonically with increasing voltage and pressure, while helium shows another dynamics (see Fig. 2,b). In the voltage range from 1 to 2.5 keV, ion beam current for lower pressure of 2·10^{-4} Torr exceeds one for higher pressure of 4·10^{-4} Torr. This might be related to the pumping efficiency of the helium or processes inside the discharge gap.

Generally, the FALCON ion source generates singly charged ions. Once ion is created, it is immediately accelerated and removed from the ionization zone. However, there is no data on the number of atoms in the single ion. Since it typical for noble gases, He and Ar ions are monoatomic, while H ions may contain one, two or three atoms per ion.

The current of the ion beam depends strongly on species. For H and He ions, the current growth from 1 mA up to 6…12 mA depending on acceleration voltage and the pressure in the vacuum chamber. Current for the beam of Ar ions shows much higher peak values and broader range of variations: it starts from about 5 mA and increases up to 25…65 mA.

Present set of measurement does not take into account the errors originating from secondary electrons and the electrons confined in the potential well of the ion beam [12]. Ion-electron emission increases the measured ion beam current. The electrons confined by the potential of the ion beam decrease the measured ion beam current, when collected by the target. Previous studies [9] have shown that the deviation of the ion beam current does not exceed 10…15%, if the bombarded target remains unbiased.

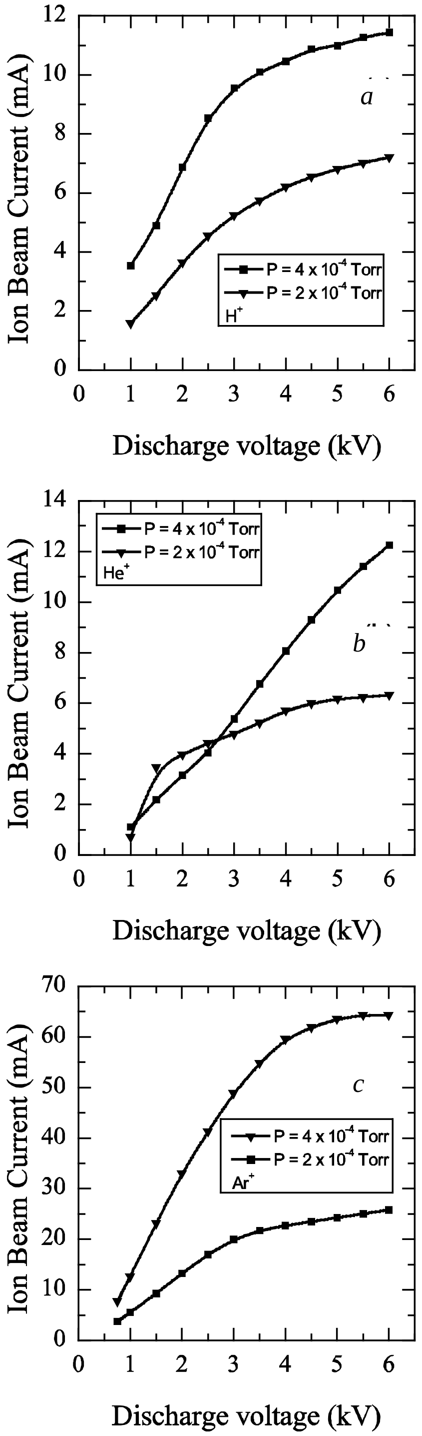

Fig. 2. Ion beam current as a function of voltage applied to the discharge gap: hydrogen (a); helium (b); argon (c)

Application of the Faraday cup may lead to strong re-deposition of the material from its edges to the exposed target. This is strongly undesired, because such deposition would contribute to unnecessary increase of the target weight, surface composition and other target properties relevant for the fusion oriented investigations.

The extraction of the ion beam is characterized by current efficiency defined as the ratio of the ion beam current to the discharge current. It shows which part of the discharge current is converted to the ion beam current. This parameter is naturally very important for space propulsions due to limited availability of the fuel gas. This parameter is also important for the material research, because it imposes upper limit on achievable ion flux for the given pumping system and gas type. In cases, when expensive gases like tritium are used, this parameter would define the economic efficiency of the experimental setup. Fig. 3 shows the current efficiency for H, He and Ar working gases.

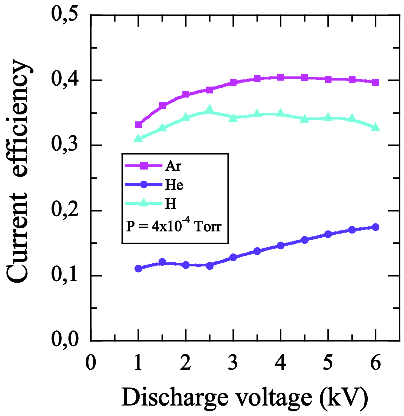

Fig. 3. Current efficiency measured for hydrogen, helium and argon working gas

One can see that the efficiency for H and Ar species is generally high and varies between 30 and 40%, while for He working gas only 10…20% of the discharge current is converted into the current of the ion beam.

CONCLUSIONS

The operation of the FALCON ion source has been investigated with fusion relevant species: hydrogen, helium and argon. The optimal pressure range has been maintained, while pumping speed of the system was 1200 l/s. It has been obtained that the beam current for H and He ions was in the range from 1 to 12 mA, while the current of the Ar ion beam can be as high as 65 mA. Generally, the ion beam current increases with the discharge voltage. The current efficiency of the source operating with H and Ar working gases varies from 30 to 40%, while for He it remains in the range 10…20%.

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ГЕНЕРАЦИЯ ПОТОКОВ ИОНОВ ДЛЯ МОДЕЛИРОВАНИЯ ВЗАИМОДЕЙСТВИЯ ПЛАЗМЫ СО СТЕНКОЙ В ТЕРМОЯДЕРНЫХ УСТАНОВКАХ УСКОРИТЕЛЕМ С АНОДНЫМ СЛОЕМ

А. Гирка, А. Бизюков, Ю. Коляда, К. Середа, И. Бизюков

Исследовалась модификация ускорителя с анодным слоем с использованием фокусировки реверсивным магнитным полем (ионный источник FALCON) для применения с рабочими газами водородом, гелием и аргоном. Ток легких ионов не превышал 12 мА, в то время как ток ионного пучка аргона достигал 25…65 мА. Измеренная токовая эффективность находилась в диапазоне 30...40% для водорода и аргона, 10…20% для гелия.

ГЕНЕРАЦІЯ ПОТОКІВ ІОНІВ ДЛЯ МОДЕЛЮВАННЯ ВЗАЄМОДІЇ ПЛАЗМИ ЗІ СТІНКОЮ В ТЕРМОЯДЕРНИХ УСТАНОВКАХ ПРИСКОРЮВАЧЕМ З АНОДНИМ ШАРОМ

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Досліджувалася модифікація прискорювача з анодним шаром з використанням фокусування реверсивним магнітним полем (іонне джерело FALCON) для застосування з воднем, гелієм та аргоном в якості робочих газів. Струм легких іонів не перевищував 12 мА, в той час як струм іонного пучка аргону сягав 25…65 мА. Виміряна струмова ефективність була в діапазоні 30...40% для водню та аргону, 10…20% для гелію.