MODELLING OF PLASMA-SURFACE INTERACTIONS IN A SMALL-SCALE LABORATORY SETUP

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Development of fusion devices is strongly related to accumulation of data on interaction of high particle and heat fluxes with plasma facing components. FALCON ion source is suggested as affordable and compact complement solution for existing plasma devices. It can cover significant range of experimental conditions relevant for fusion oriented material research. Present work describes the properties of the source and discusses its niche in the overall data accumulation.

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INTRODUCTION

The development of fusion reactor slowly progresses from scientific problem towards the engineering task [1]. The economic efficiency of the fusion power plant is mostly defined by the stability and the lifetime of the first wall and divertor components, which are subject to erosion by high heat and particle fluxes from the edge plasma [2]. The erosion of the plasma-facing components (PFCs) is the key process, which should be taken into account when developing the ITER and the future commercial fusion power plants. Other processes related to plasma-surface interactions, like fuel retention and recycling, material migration and re-deposition are also for paramount importance.

The development of the fusion device relies strongly on preliminary modeling. It uses data obtained either from the experimental results or directly from simulations. ITER and future fusion devices will produce high particle fluxes ($10^{21}...10^{24}$ $m^{-2}s^{-1}$ and above) toward the PFCs. Some of the plasma-surface processes like sputtering and chemical erosion may significantly change its character with increasing flux. However, experimental data and ability of its acquisition are limited for the high-flux region. This delays the accumulation of data on plasma-surface interactions, which directly impacts the modeling and, as the consequence, optimization and improvement of the fusion devices.

Present work analyses weak points of the existing strategy of data accumulation for fusion oriented material research and suggest their respective strengthening.

1. ESTABLISHED RESEARCH CYCLE

Plasma-surface interactions were under great attention of fusion community for many decades. Intensive research has allowed forming intensive database due to experimental work and modeling. Through decades, typical research cycle had also been established as optimal for the sequential progress in the research. For example, similar cycle has been observed in study of sputtering by ion bombardment, numerous experiments have contributed to understanding of this process [3].

The typical research cycle is shown in Fig. 1. It starts from planning of the experimental work and preparation of the setup (see stage I in Fig. 1). Once setup is prepared, the bombardment of the sample (or samples) is following at stage II. The sample could be exposed to certain particle fluence before its surface should be analyzed (stage III). Here the surface analysis can range from trivial microscopy and weight measurements to advanced analysis techniques, like μm depth profiling of isotopes. Depending on experimental campaign, stages II and III can be repeated several times, while surface analysis may be performed either *in-situ* or *ex-situ* after each exposure step. Once the exposure had reached its target fluence and the surface has been analyzed, the results are discussed and experimental data could be used for comparison with existing numerical or analytical models (stage IV). Discussion and comparison lead to new ideas for further experimental campaigns and the repeat of stage I follows.

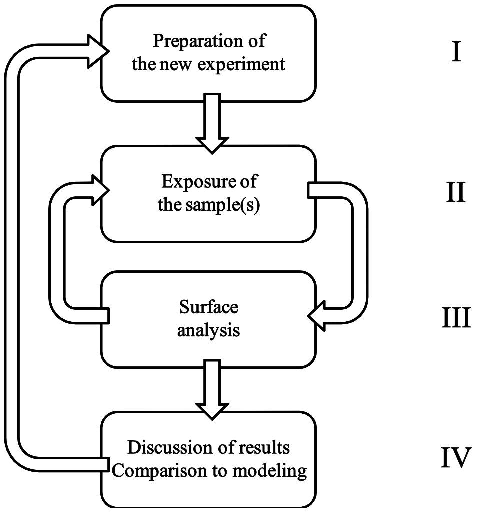

Fig. 1. The typical research cycle in the field of fusion oriented material research. Number of the stage is shown by roman numerals on the right

Regular repeating of the research cycle will lead to accumulation of data and decreasing the cycle time allows speeding up the growth of the respective database. Therefore, one can examine present pattern of the research and optimize it considering the investigations in high-flux region.

Experimental facilities (stage I) could be clearly separated in two types: tokamaks and laboratory high-flux devices. Currently, tokamaks are used primarily for investigation of particle transport and re-deposition, rarely they are used for investigation of the high-flux ion-surface interactions due to large uncertainties in flux composition. The experimental cycle lasts about half a year and it produces typically a bunch of samples and the following surface analysis may take years. Experimental campaigns may be disrupted by unpredictable events, like occasional melting of components. All of this significantly complicates the optimization of the research cycle.

In contrast, advantages of laboratory facilities are accurate characterization of the particle flux and precise measure of the surface conditions. Simple replacement of the sample is often accompanied by *in-situ* analysis of its surface. Typically, laboratory setups use linear plasma devices with strong magnetic field in the range from several to tens of kGs. They could generate high particle fluxes with lower energy approaching the fusion conditions. For example, DIONISOS plasma device could generate particle fluxes up to 10^{22} $m^{-2}s^{-1}$ with an average ion energy of 10…500 eV (this corresponds to heat fluxes <0.8 $MW{\cdot}m^{-2}$) [4]. Similar parameters could be obtained in other plasma devises, like PISCES [5]. NAGDIS device could operate at higher particle flux of 10^{23} $m^{-2}s^{-1}$ [6]. Pilot-PSI plasma device is capable to reach particle flux of $\approx 10^{24}$ $m^{-2}s^{-1}$ and heat flux of 10 $MW{\cdot}m^{-2}$; however, due to technical reasons, the time of single exposure is limited by 100…160 s.

Still, currently existing plasma devices are relatively expensive, their price varies in the range of $\$10^6…10^7$, respective maintenance and support requires annual funding as well. Their linear sizes vary also from about several to tens of meters. All this limits the availability of high-flux laboratory setups down to research institutes, which are aimed only on material investigations. Therefore, growth of the database (i.e. progress on stages II and III see in Fig. 1) is significantly limited by number of devices.

One of the solutions is development of small-scale laboratory setup suitable for generation of fusion-relevant particle and heat fluxes. Such a setup should afford compact size in order to be installed in a small university lab or used as an addition for existing equipment in the material research lab. Large number of relatively inexpensive setups can be installed in universities and/or institutes and operated by small groups of researchers and even students. These groups would be able to produce bulk data and significantly increase data accumulation. Range of parameters unreachable by the small-scale laboratory setups could still be investigated with plasma devices.

Obviously, compact plasma devices would produce less particle flux and cannot be the considered for the small-scale lab research. Alternatively, one could suggest ion sources for this task. However, most of the available ion sources, like duoplasmatrons or RF ion sources, have been already involved in material research and are unable to produce fusion relevant fluxes maintaining compact sizes. Therefore, fusion oriented material research requires the type of ion sources, which have been left until now beyond the attention of the community.

2. FALCON ION SOURCE

The unique combination of high ion beam current, simplicity and extremely compact size are typical for electric space propulsions. Existing propulsions are based on the physical principles of the closed drift thrusters [7]. They are used for the space missions and strongly optimized for minimum size and maximum ion current. The reason they have not been used for generation of the high-flux irradiation of the surface is the shape of the ion beam, which is not optimized for highest ion beam current density. Upgrading the closed drift thruster with the focusing system would produce unique experimental tool for the fusion oriented material research.

These ideas have been implemented in FALCON ion source [8, 9]. This ion source is based on anode layer thruster. This particular type of thrusters is characterized by thin electron layer drifting in the crossed E×B fields, where all the processes of ionization and ion acceleration take place. Schematic drawing of the FALCON ion source is shown in Fig. 2. The biased anode (1) and cathode at the ground potential (2) form the discharge gap of few millimeters. Tilted shape of the electrodes coupled with the magnetic focusing system (3) provides the convergence of the ion beam into a small spot, which increases the ion flux.

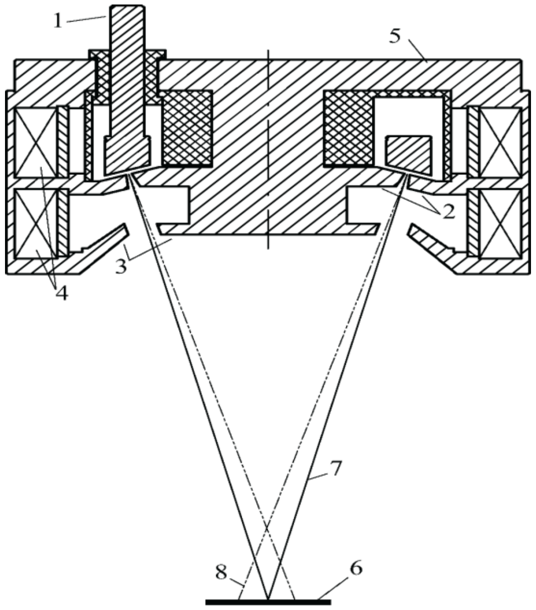

Fig. 2. Schematic drawing of the FALCON ion source: 1 – anode; 2 – cathodes; 3 – magnetic focusing lens; 4 – magnetic field coils; 5 – magnetic circuit; 6 – the target placed in the H+ crossover plane; 7 – Hydrogen ions beam trajectory; 8 – impurities trajectory

Steady-state magnetic coils (4) are connected inversely and deliver the magnetic fluxes through the magnetic circuit (5) to the respective gaps. As a result, the magnetic fields are directed oppositely in the discharge gap and in the magnetic focusing system providing the reversed magnetic field configuration. Therefore, the transversal pulse obtained by the ion in the gap is compensated by the transversal pulse of the opposite direction magnetic field of the lens. Varying the electric current through the coils one can manipulate the magnetic field fluxes and, as consequence, the size of the beam spot in the crossover plane, where exposed target (6) should be placed.

Direct consequence of the magnetic nature of the focusing system is its intrinsic ability for separation of ions of different masses. Fig. 2 schematically shows the trajectories of hydrogen ions (7) focused in the crossover plane and trajectories of heavier ions, like oxygen, which are located further from the central point.

The source could be fed with virtually any gas or the mixture because of a filament absence. This allows producing fluxes of light ions like hydrogen, deuterium or helium as well as molecular ions like CD_3 and other.

The source can be run steady-state for 200 hours without interruptions allow reaching very high fluence. Long term stability of operation is based on stability of the power supplies for anode and magnetic coils, respective cooling systems and gas inlet. All these components can run stable for hundreds of hours, however, one may expect the shifts of parameters due to heating of the sample with consequent change of the pressure in the vacuum chamber.

3. CHARACTERISTICS OF THE ION BEAM

The ion beam parameters are the most important characteristics of the FALCON ion source. They define the energy of the ions, particle and heat flux, and other parameters of the bombardment [9].

The beam profile shown in Fig. 3 has been obtained by sputtering the SiO_2 layer with hydrogen ion beam. The beam current profile is bell-shaped with the half width on half height with a diameter of ≈3 mm. This size of the spot is used further for calculation of particle and heat fluxes.

The hydrogen ions energy distribution function is shown in Fig. 4. The broad distribution is explained by origin of the ion accelerating zone which is thin electron layer drifting in crossed E×B fields. It shields all the electric potential applied to anode, therefore, the energy of the particular ion depends on location of ionization. The strong magnetic field in the discharge gap affects the trajectories of the slow hydrogen ions, bending them towards the cathodes; therefore, low-energy part (0...650 eV) of distribution function is cut off.

This measurement does exclude the neutralized ions, which has been recharged due to collision with the molecules of the residual gas. The calculations show that about <10 % of accelerating ions passing through the vacuum chamber will be neutralized.

The ion beam current is strongly dependent on the gas flow which could be pumped through the discharge gap maintaining residual gas pressure in the bombardment region within 10^{-4} Torr range. Experiments show that at the pumping speed of 1200 l/s the total current of the hydrogen ion beam may reach up to 17 mA. Fig. 5 shows the dependence of the particle and heat fluxes as a function of accelerating voltage. In general, both fluxes do have trend to rise up with increasing voltage.

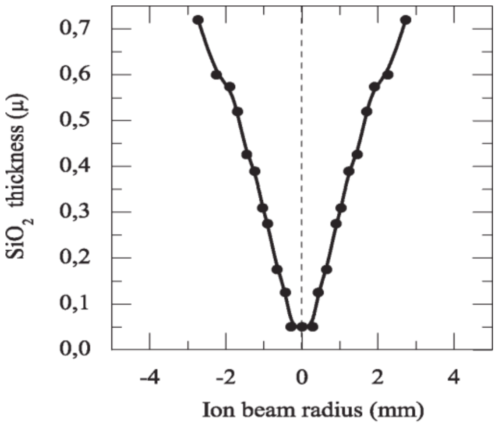

Fig. 3. The current density profile of the ion beam was obtained by sputtering of the SiO_2 layer with hydrogen ions

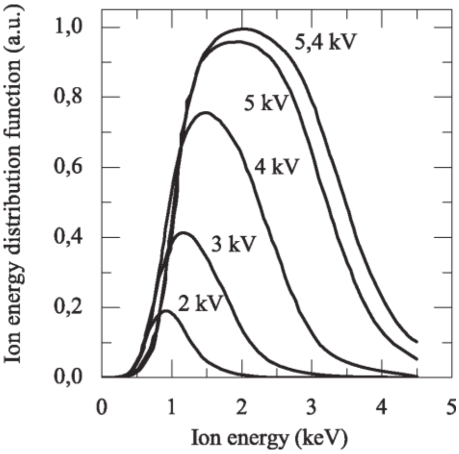

Fig. 4. The ion energy distribution function for various accelerating voltages

For the fixed pumping speed of 1200 l/s, the fluxes are in the range of 10^{22} $m^{-2}s^{-1}$ and 6 $MW \cdot m^{-2}$. The anode layer thruster typically converts up to 95 % of the gas introduced in the discharge gap into ions. The increase the ion beam current could be primarily done by increasing of the gas flow through the discharge gap. Therefore, pumping speed is the main parameter, which defines the overall performance of the system. Increasing the pumping speed one could increase the particle fluxes up to 10^{23} $m^{-2}s^{-1}$ and above.

4. MASS-SEPARATION PROPERTIES

As it has been mentioned above in Chapter 3, FALCON ion source is capable for mass-separation of ions due to the properties of the magnetic focusing system [10, 11]. Fig. 6 shows the calculated distribution of the magnetic field on the discharge gap and the magnetic focusing system (3). The ions created in the discharge pass through the cathodes and then through the magnetic focusing system experiencing the Lorenz force. The resulting shift depends on the mass and energy of the ion.

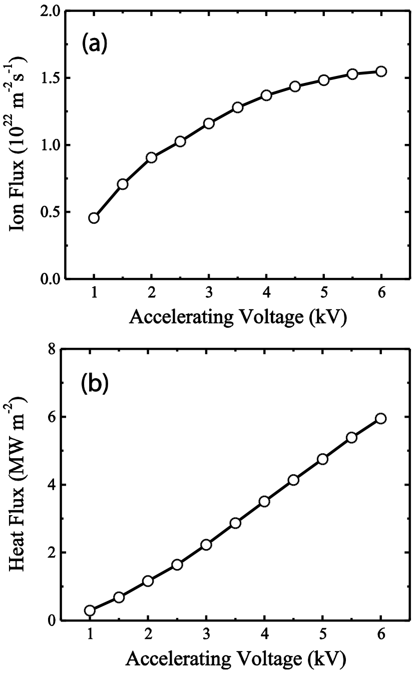

Fig. 5. Fluxes of the ion beam as obtained through current measurement. (a) – ion flux; (b) – heat flux

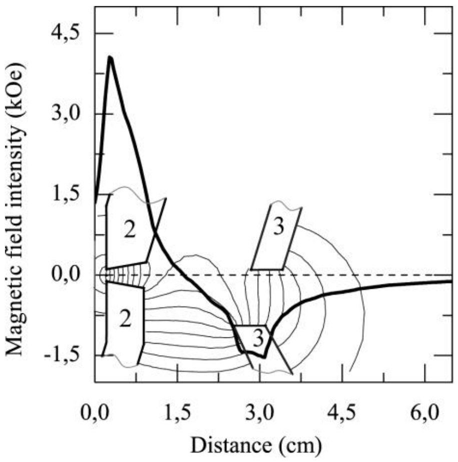

Fig. 6. The distribution of the B (perpendicular) of the magnetic intensity (bold solid line) that is perpendicular to the ion flux direction. Dashed line shows the ion flux. Thin lines show the lines of equal magnetic intensity. Numbers denote cathode (2) and focusing system (3) to be in line with designations in Fig. 2. Zero distance corresponds to the anode plane

Assuming the application of the source in the fusion oriented material research, the working gases should be primarily hydrogen, deuterium and helium. However, the presence of impurities in the working gas or residual gas may lead to undesired distortion of the elemental composition of the surface. In order to avoid respective effects, the magnetic focusing system can be used for mass-separation of the heavier ions.

For example, the presence of 5 % oxygen in the hydrogen working gas would lead to a ring-shaped component of the ion beam in the cross-over plane. The respective distribution of the ion beam is shown in Fig. 7. It has been calculated for the accelerating voltage of 5 keV and the crossover plane for hydrogen ions with energy of 2 keV. One can see that oxygen ions are separated away to form the circle with a diameter of ≈6 mm.

These calculations do not take into account the scattering of the accelerated ions on the molecules of the residual gas. At residual gas pressure in the 10^{-4} Torr range one could expect about 10 % of the ions experiencing the scattering. These ions may bombard the target at different radii allowing some impurity ions to bombard the target in the central region.

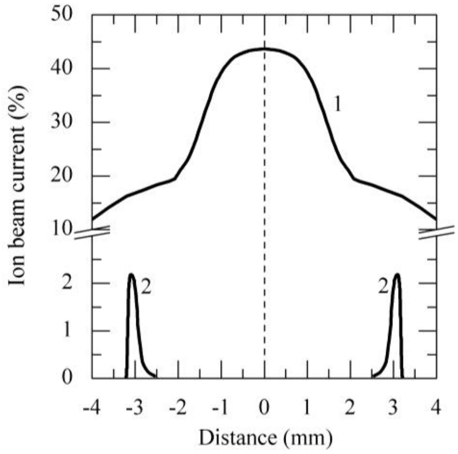

Fig. 7. The distribution of 95% H+ (“1”) and 5% O+ (“2”) ions species in the 2 keV H^+ crossover plane

Further calculations have been performed to evaluate the factor of ion mass and energy influencing the shift in the crossover plane. They assume the Lorenz force as the only factor influencing the ion trajectories. The calculation has been performed for ions with the masses in the range from 12 to 86 a.m.u. The results are shown in Fig. 8. One can see that displacement of ions varies from 3.4 to 16 mm.

Therefore, the central part of the spot could be set to be free of impurities due to magnetic separation. This provides the exposed area which is enough for many types of surface analysis like ion beam analysis, scanning electron microscopy, etc.

5. APPLICATIONS FOR FUSION ORIENTED MATERIAL RESEARCH

The characteristics of the ion beam allow using the FALCON ion source in the fusion oriented material research. Fig. 9 shows the range of the particle and the heat fluxes for each of the plasma facing components installed in ITER [2] overlapped with the range of fluxes provided by the source. One can see that only the low range of fluxes irradiating the beryllium first wall is not covered by FALCON ion source. Actually, it can easily be covered with conventional sources and no particular effects here are expected.

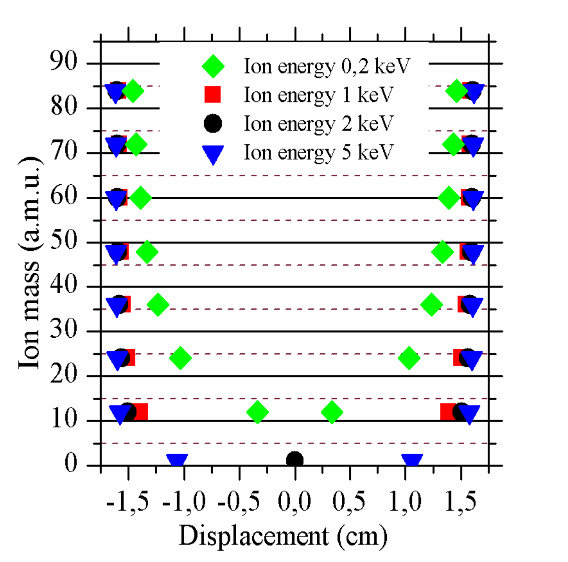

Fig. 8. Displacement of the ions in the crossover plane as a function of ion mass. Several calculations were performed for variety of ion energies

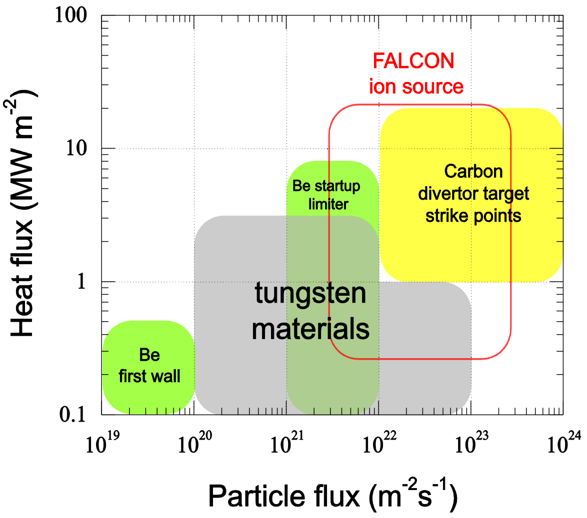

Fig. 9. Range of heat and particle fluxes irradiating the respective ITER plasma facing components and the range covered with the FALCON ion source

At the same time, low intensity ion beam of the FALCON ion source allows to reproduce the conditions for the beryllium startup limiter. The fluxes produced by the source correspond to the most intensive fluxes irradiating the tungsten based components. Therefore, the source is suitable for experiments on erosion which may include sputtering and cracking. For beryllium surface the source might also be used for investigation of erosion in the temperature range approximating the melting point. Other opportunities involve the investigations on fuel retention and permeation.

The fluxes irradiating the divertor target strike point could also be reproduced with the source at least in the lower part of the particle fluxes. This indicates the opportunity for the experiments on high-flux sputtering, radiation enhanced sublimation and flux depended chemical erosion.

Another experimental aspect is related to the long time of continuous operation of the source and its stability. Combination of high-flux irradiation with long-term exposure allows reaching the very high fluence ranging from 10^{27} m^{-2} and above during reasonable time. This opens the opportunity for the experimental modeling of the long-term effects, which might not be expected basing on the currently existing data.

The ion energy of the beam is spread over the broad range from 0.6 keV to the energy corresponding to the accelerating voltage. The energy distribution function corresponds to the Maxwellian one approximately. Therefore, the source is not suitable for experiments which are demanding for low energy particle bombardment. In this respect the source complements the plasma devices which are particularly well suited for electron volt range. One may expect that many effects are pronounced in both eV and keV energy ranges. Since the cost and maintenance of FALCON ion source are significantly less than those for plasma devices, FALCON ion sources may be used for preliminary identification of new effects in the high-flux range. The irradiation campaigns with FALCON ion source may be arranged in a short time which provides significant advantage. The detailed investigations in the lower energy ranges may later be performed in plasma devices and tokamaks.

CONCLUSIONS

The accumulation of database on plasma-material interactions is of crucial importance for development of ITER and future commercial fusion power plants. The influences of the high fluxes as well as long-term (high fluence) effects on plasma facing components are under research still. Slow progress in this direction is conditioned by low availability of existing laboratory experiments as well as their high cost and expensive maintenance. FALCON ion source is suggested as affordable and compact complement solution for existing plasma devices which can cover significant range of experimental conditions relevant for fusion oriented material research. Relatively low cost, inexpensive maintenance and simple operation are all favorable for its wide spread use in small-scale laboratories either in universities or research institutes. Implication of the sources into the research will accelerate the data accumulation and, consequently, the development of respective fusion devices with magnetic plasma confinement.

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МОДЕЛИРОВАНИЕ ВЗАИМОДЕЙСТВИЯ ПЛАЗМЫ С ПОВЕРХНОСТЬЮ В ЛАБОРАТОРНЫХ МАЛОГАБАРИТНЫХ УСТАНОВКАХ

И. Бизюков

Разработка термоядерных устройств в значительной мере связана со сбором и накоплением данных по взаимодействию больших потоков частиц и тепла с компонентами, контактирующими с плазмой. Ионный источник FALCON предлагается в качестве доступного и компактного решения, которое дополняет существующие плазменные устройства. Он позволяет охватить значительный диапазон экспериментальных условий, важных для исследований материалов, перспективных для применения в термоядерных устройствах. Описаны основные свойства источника, а также показана его ниша в общем сборе и накоплении данных.

МОДЕЛЮВАННЯ ВЗАЄМОДІЇ ПЛАЗМИ З ПОВЕРХНЕЮ В ЛАБОРАТОРНИХ ПРИСТРОЯХ МАЛОГО РОЗМІРУ

І. Бізюков

Розробка термоядерних пристроїв значною мірою пов'язана зі отриманням та накопиченням даних зі взаємодії потоків частинок і тепла високої густини з компонентами, які контактують з плазмою. Іонне джерело FALCON запропоноване в якості доступного та компактного рішення, яке доповнює існуючі плазмові пристрої. Воно дозволяє охопити значний діапазон експериментальних умов, які є важливими для досліджень перспективних матеріалів термоядерних пристроїв. Описано властивості джерела та обговорено його нішу в загальному зборі та накопиченні даних.