EXPERIMENTAL STUDIES OF ION EMISSION FROM RPI-IBIS FACILITY AND MODELING OF ION MOTIONS

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The paper presents the recent measurements of ion beams emitted from an RPI-IBIS plasma injector and some preliminary results of the theoretical modeling. The RPI-IBIS facility was equipped with coaxial electrodes made of thin molybdenum rods and a fast acting electromagnetic valve for the injection of a working gas. Plasma discharges were initiated with a variable time delay (τ) after the gas injection and they were powered from a condenser bank charged to 30 kV, 30 kJ. The first part describes measurements of spatial distributions and energies of intense ion beams, which were performed by means of ion-pinhole cameras equipped with nuclear track detectors. Detailed analysis of ion mass- and energy-spectra was performed by means of a Thomson analyzer. The second part presents numerical simulations of ion motions in the RPI-IBIS facility, which were performed on the basis of a single-particle model.
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1. INTRODUCTION

Research on characteristics of plasmas produced by multi-rod plasma injectors (RPI) has been carried out at IPJ in Swierk, Poland, for many years [1]. The RPI-type devices have been used for basic plasma investigation [2] as well as for different application-oriented studies, e.g. to study plasma-target interactions. The main aim of this paper was to compare some important experimental results with results of theoretical simulations.

2. EXPERIMENTAL SETUP

The RPI-IBIS device was equipped with two coaxial electrodes of 9 cm and 13 cm in diameter. Each electrode was transparent for particles, because it was composed of 32 thin molybdenum (Mo) rods oriented coaxially [1,2]. The injector was placed inside a vacuum chamber, which was pumped out to the background pressure equal to about 10^{-6} Pa. Before each discharge the inter-electrode gap was filled up with some amount of a working gas (usually H_2 or D_2) injected by a fast acting valve. Each plasma discharge was initiated (with a chosen delay time after the gas injection) by the application of a high-voltage pulse from a 30-kJ condenser bank charged to U_0 = 30 kV. The working gas, after its ionization, was accelerated in the injector and emitted along the z-axis in a form of an intense plasma-ion stream. The important parameter was the time delay (τ) which decided about the gas density distribution at the initiation of the plasma discharge. Experiments described in this paper were performed with the D_2 injection and at time delays τ = 160…170 μs (a so-called middle operational mode) and at τ = 130 μs (the fast mode).

3. ION EMISSION MEASUREMENTS

To investigate a spatial structure of the pulsed deuteron streams emitted in the RPI-IBIS device the use was made of an ion pinhole camera [2]. Ions (mostly deuterons), which penetrated through a pinhole of 0.2 mm in diameter, were recorded by means of exchangeable nuclear-track detectors (NTD) of the PM-355 type. The pinhole was placed at a distance of 22 cm from the electrode outlets. To perform a rough energy analysis of the investigated deuterons the NTD were shielded by absorption filters made of Al-foils. In particular the use was made of a 0.75-μm-thick foil (with the energy threshold E_D > 74 keV) and 1.5-μm-thick foil (with E_D > 170 keV) [3]. The irradiated detectors (after their removal from the camera) were etched under standard conditions [2] for 2 hours and the developed tracks (micro-craters) of several μm in diameter formed a visible image of the deuteron beams, as shown in Fig. 1.

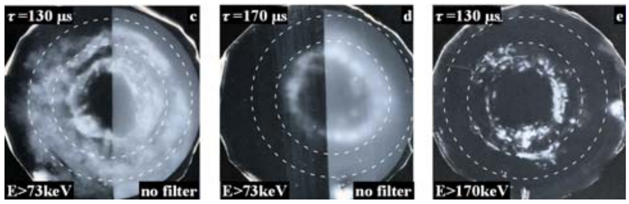

Fig. 1. Images of the deuteron beams recorded in the RPI-IBIS facility. Regions without tracks are shown as black, and the most intense (>10^7 cm^{-2}) deuteron beams are mark as white. The broken-line circles correspond to projections of the electrode ends

The obtained ion images showed the complex spatial structure of the investigated ion beams. Those images were analyzed quantitatively by means of an optical microscope, and it made possible to determine numbers of deuterons above the chosen energy thresholds. In order to determine the deuteron energy distribution more accurately, the use was made of a miniature Thomson-type spectrometer [4]. The input diaphragm of that spectrometer was placed on the z-axis, at a distance of 30 cm from the electrode outlets. Ions, after penetration through the input diaphragm and their deflections by the analyzing magnetic and electric fields in the spectrometer, formed characteristic Thomson parabolas, which were recorded upon the NTD placed in the detection plane. The analysis of the exposed and etched NTD enabled the track density on the obtained parabolas and corresponding energy spectra to be determined.

An example of the deuteron energy spectrum, as obtained in the RPI-IBIS experiments, is presented in Fig. 2.

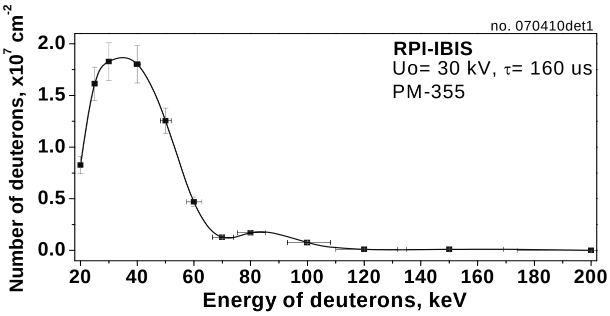

Fig. 2. Energy distributions of deuterons, as determined from the deuteron parabola recorded for the middle operational mode (τ = 160 μs)

4. MODELLING OF ION MOTIONS

In order to explain the experimental results the second part of this describes some theoretical simulations of deuteron trajectories and computations of their angular and energetic distributions. Those simulations were performed using a single-particle model applicable for RPI-type injectors [5] and a Monte Carlo method. In this analysis it was assumed that the ions are non-relativistic, and the equations of motion (for particles with a mass *m* and an electric charge *q*) can be written in the form:

$$\frac{d^2r}{dt^2} - r\dot{\varphi}^2 = \frac{q}{m}\left(\dot{z}\frac{\partial A}{\partial r} - \frac{\partial \Phi}{\partial r}\right)$$

$$\frac{d}{dt}(r^2\dot{\varphi}) = \frac{q}{m}\left(\dot{z}\frac{\partial A}{\partial \varphi} - \frac{\partial \Phi}{\partial \varphi}\right)$$

$$\frac{d}{dt}(m\dot{z} + qA) = 0$$

The numerical computations, as performed at appropriate boundary and initial conditions, made possible to determine positions and velocities of the analyzed particles (deuterons) in successive time instants (*t*). The computations were carried out under assumptions that the initial voltage between the coaxial electrodes was equal to 30 kV, and the total discharge current amounted to 200 kA (split symmetrically between 32 electrode rods). It was also assumed that the considered deuterons started from different points near the gas-valve outlet, and their initial velocity corresponded to the room temperature (0.03 eV) and was oriented stochastically. Examples of the computed trajectories, are presented in Fig. 3, and an energy spectrum, which was obtained from Monte Carlo computations for 34000 deuterons, is shown in Fig. 4.

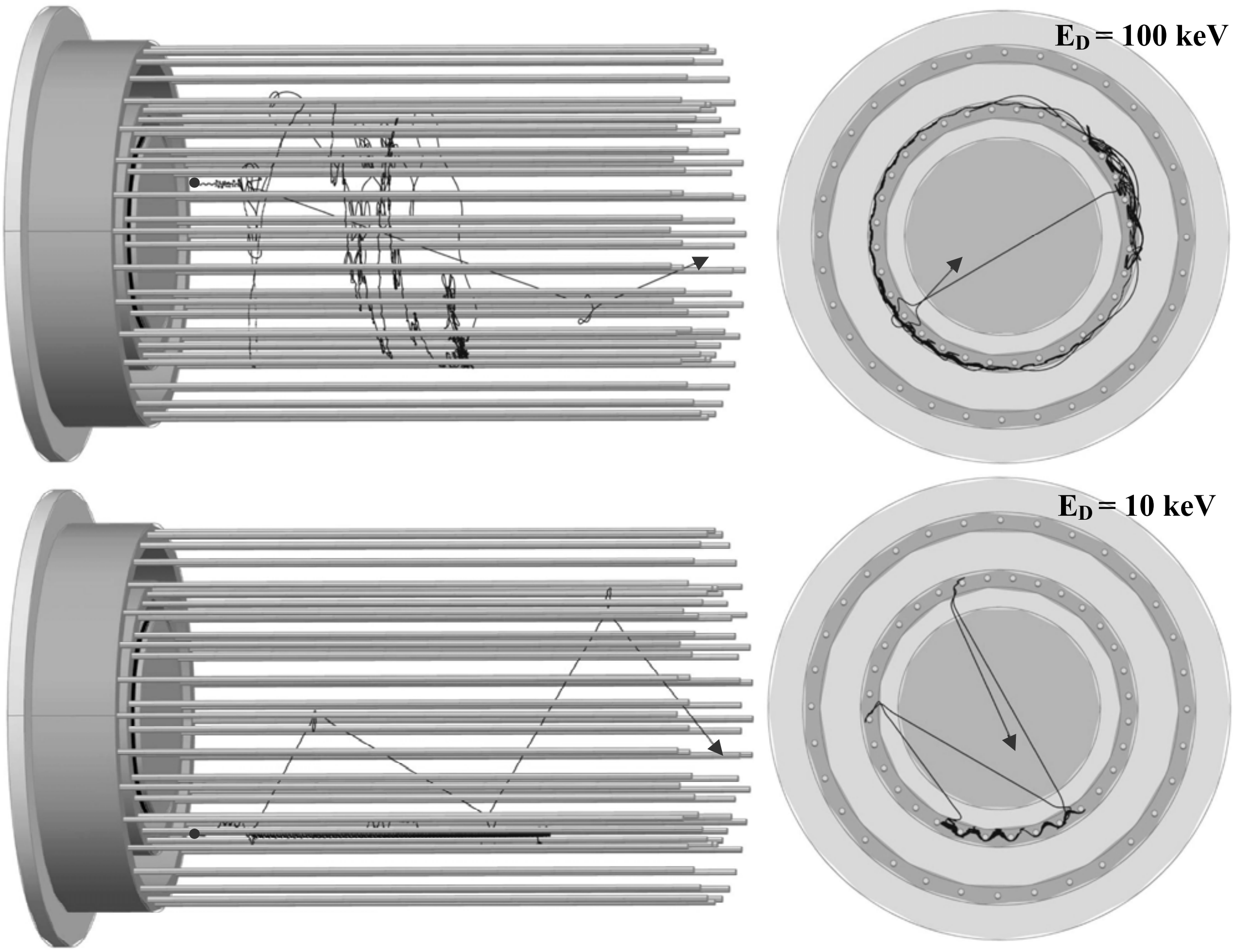

Fig. 3. Exemplary trajectories, as computed for deuterons accelerated in the RPI-IBIS system to the outlet energy value of 100 keV (upper picture) and 10 keV (lower picture)

To explain ion images, which were recorded on the z-axis by means of NTD, there were computed points of interactions of deuterons with a plane z = 22 cm without any pinhole. The computed images are shown in Fig. 5.

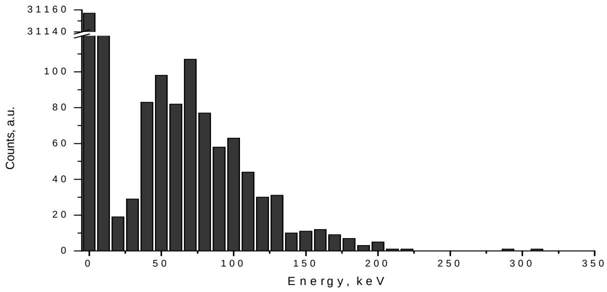

Fig. 4. Energy spectrum of deuterons emitted from RPI-IBIS, which was obtained from the computations

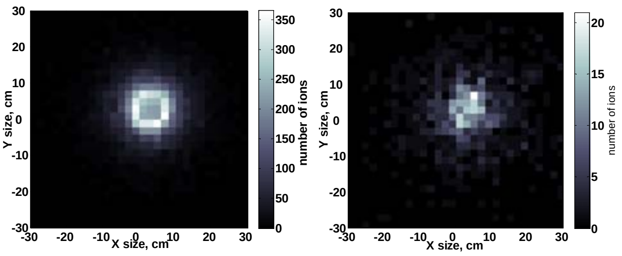

Fig.5. Simulated ion images at z = 22 cm for deuterons of energy in a range 0.1 – 5 keV (right) and > 5 keV (left)

5. SUMMARY AND CONCLUSIONS

The recent experimental measurements delivered valuable characteristics of the ion beams emitted from RPI-IBIS. Results of the theoretical simulation appear to be consistent with the experimental observations.

The computer modeling has also showed that deuteron trajectories are localized mostly near the rod electrodes, and only deuterons of higher energies can penetrate through the near-axis region. The computed energy spectrum is very similar to the experimental one. The simulated ion images are also similar to these observed experimentally.

One can conclude that the single-particle modeling of RPI-type discharges gives reasonable results and it should be performed also for other initial conditions.

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ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ И МОДЕЛИРОВАНИЕ ИОННЫХ ПУЧКОВ, ЭМИТИРУЕМЫХ ИНЖЕКТОРАМИ RPI-IBIS

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Представлены результаты исследований ионных пучков, эмитируемых стержневым инжектором RPI-IBIS, и некоторые предварительные результаты теоретического моделирования. RPI-IBIS оснащен коаксиальными электродами в виде тонких молибденовых стержней и быстодействующим электромагнитным клапаном для инжекции рабочего газа. Разряд инициировался с варьируемым временем задержки по отношению к напуску газа при напряжении на конденсаторной батарее 30 кВ. В первой части описаны измерения пространственных распределений и энергий интенсивных ионных пучков. Детальный анализ массовых и энергетических спектров проведен с использованием анализатора Томпсона. Вторая часть посвящена численному моделированию движения ионов в RPI-IBIS, которое проведено на основе одночастичной модели.

ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ І МОДЕЛЮВАННЯ ІОННИХ ПУЧКІВ, ЕМІТУЄМИХ ІНЖЕКТОРАМИ RPI-IBIS

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Представлено результати досліджень іонних пучків, емітуємих стрижневим інжектором RPI-IBIS, і деякі попередні результати теоретичного моделювання. RPI-IBIS оснащений коаксіальними електродами у виді тонких молібденових стрижнів і швидко діючим електромагнітним клапаном для інжекції робочого газу. Розряд ініціювався з варіацією часу затримки стосовно напуску газу при напрузі на конденсаторній батареї 30 кВ. У першій частині описано виміри просторових розподілів і енергій інтенсивних іонних пучків. Детальний аналіз масових і енергетичних спектрів проведено з використанням аналізатора Томпсона. Друга частина присвячена чисельному моделюванню руху іонів у RPI-IBIS, що проведено на основі одночасткової моделі.