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AN ACCELERATED BEAM-PLASMA NEUTRON/PROTON SOURCE AND EARLY APPLICATION OF A FUSION PLASMA

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Abstract

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We measured the number of the neutrons and protons produced by D-D reactions in an accelerated beam-plasma fusion and curried out the numerical simulations. The linear dependence of the neutron yield on a discharge current indicates that the fusion reactions occur between the background gas and the fast particles, i.e. charge exchanged neutrals and accelerated ions. The neutron yield divided by (fusion cross section $\times$ ion current $\times$ neutral gas pressure) still possesses the dependence of the 1.2 power of discharge voltage, which shows the fusion reactions are affected by the electrostatic potential built-up in the center. The measured proton birth profiles suggest the existence of a double potential well, which is supported by the numerical simulations.

1. INTRODUCTION

An accelerated beam-plasma neutron/proton source is based upon the device of spherically conversing ion focus (SCIF)[1,2,4]. The principle can be realized by a relatively simple device, where the ions are produced by a glow discharge between the spherical anode (serving as the vacuum chamber) and the concentric sphere hollow cathode. The ions are accelerated towards the cathode and go through to focus the center, where the fusion reactions occur. Some ions hit the cathode to produce the secondary electrons, which are also accelerated towards the center by the electric field produced by the ions. The electrons neutralize the space charge of ions and increase the ion density in the center. Under proper conditions, the ion and electron flows create a space-charge induced "double potential" well that is a negative potential well nested inside a positive potential well. This structure traps high-energy ions within the virtual anode created by the double potential, providing a very high fusion rate in this trap region.

An SCIF offers a unique approach to a fusion, since it develops a possibility of the use of advanced fuels such as D-^{3}He, and yields intermediate products along the path to fusion power. A SCIF is used as a portable, low-cost fusion neutron source with applications expected as follows[2]: (1) well-logging, (2) therapeutic treatment of cancers, (3) sulfur qualification in coal, (4) testing drugs and explosive materials for safeguards, (5) neutron source for benchmark testing.

In this paper, we demonstrated the neutron generation by an SCIF device, and study the scaling of neutron yield vs. discharge current and voltage. A special experiment was designed to verify double potential well formation and ion trapping by the measurement of the radial birth (source) profile of energetic (3-MeV) protons produced by D-D fusion reactions in a deuterium discharge [3]. The numerical simulations were carried out in order to give a physical interpretation of the experimental results.
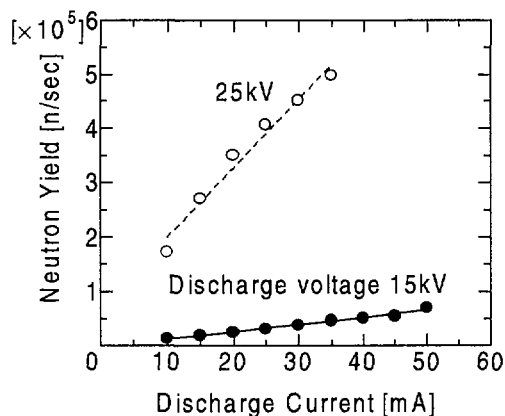
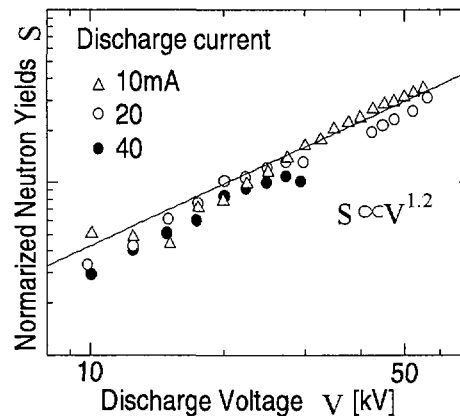FIG.1. Neutron yield vs. discharge current for different voltage

FIG.2. Normalized neutron yield vs. discharge voltage

2. EXPERIMENTS

2.1. Experimental facilities

The vacuum chamber is made of stainless steel of an inner diameter of 350 mm. It has ten ports for a high-voltage feed-through, an ionization vacuum gauge, a vacuum pump system consists of a 50 liter/sec turbo molecular pump for He gas with a back-up rotary pump. The D_2 gas is fed from a gas bomb through the mass flow controller. The hollow cathode of a diameter of 57 mm is made of the 1mm diameter tantalum wire. Its geometrical transparency is evaluated to be approximately 91%. The ions hit the insulator, which covers the feed-through inside the vacuum chamber, resulting in eventually breakdown. The surface shape of an insulator is so designed as to avoid the ion bombardment normal to the surface, and subsequently breakdown through the pinhole formation is reduced.

2.2. Neutron measurement

The neutron measurement was done by a ^{3}He proportional counter surrounded with polyethylene blocks of a thickness of 175 mm to moderate the fast neutrons produced by D-D fusion events. Typical plots of measured neutron yield versus discharge current are shown in Fig.1 for different discharge voltages. The neutron yield increases linearly to the discharge current similarly to the previous studies [2,4], and reaches 5×10^5 n/s at 35 mA of discharge current and 25kV of discharge voltage. The dependence does not show that the neutrons come from a beam-beam colliding fusion. Figure 2 depicts the neutron yield divided by the fusion cross section evaluated by an applied voltage, the ion current and the neutral gas pressure. The normalized neutron yield is proportional to the 1.2 power of V, which suggests that the electrostatic potential should affect the fusion reactions.

2.3. Proton measurement

This experiment was designed to operate at high perveance where formation of a double well is predicted [1]. Thus measurements were made at relatively low voltages (15 kV) in order to achieve maximum perveances (0.2 to 1.4 mA/kV$^{3/2}$) over the available range of ion currents (10-80 mA). Additional steps taken to aid well formation included: (1) use of the unique Star mode of operation [2] to obtain ion beam focusing down to ~1.6× the ballistic limit, and, (2) the incorporation of a second electrically "floating" grid (in addition to the focusing/accelerating cathode grid) to reduce the ion radial energy spread to <10%. Also, a unique capillary proton collimator which was developed to provide a fine (mm scale) resolution of the spatial profile of escaping protons. The data was taken by pivoting the collimator-detector across the core plasma and then unfolding the data to obtain the radial (cf. spherical geometry) proton source-rate profile.
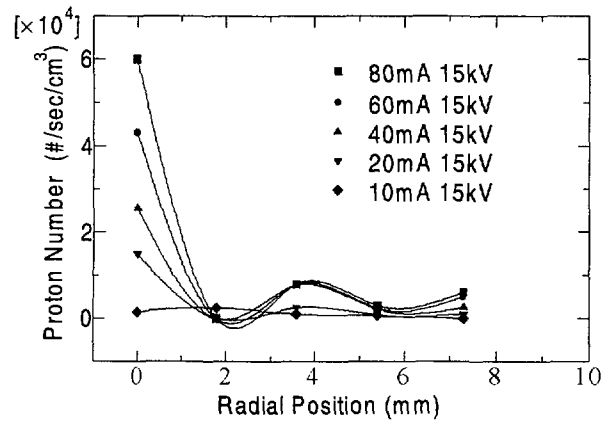
FIG.3.   Measured radial profiles of the proton source rate at 15 kV and currents of 10-80mA (perveances of 0.17 to 1.37 mA/kV$^{3/2}$, respectively).

As shown in Fig.3, a two-peak proton-rate density profile is observed at higher perveances, uniquely demonstrating the evolution of a double potential well for perveances >0.34 mA/kV$^{3/2}$ (~ 20 mA). As the perveance is increased above this threshold, as expected, the depth of the double well also increases. At the maximum perveance studied, 1.38 mA/kV$^{3/2}$ (corresponding to 80 mA and 15 kV), the negative potential well depth, corresponding to the measured proton-rate density, calculated from this data is ~22-27% of the applied cathode voltage, i.e. about 4 kV. The uncertainty limits listed are mainly due to assumptions in the calculation associated with ion recirculation and charge-exchange.

3.   NUMERICAL SIMULATIONS

We developed the computational code to simulate the core of a SCIF device in order to clarify (1) the effects of neutral gas on the neutron yield and the electro-static potential built-up in the core and (2) the energy distributions of electrons, ions, and neutrals.

3.1. Numerical model

We solved the motion equations of the charged particles as well as the fast neutrals and simultaneously the Poisson equation in the radial direction of the spherical coordinates. The densities of ions and electrons were evaluated by a particle-in-cell model. The species of particles dealt within the code were the electrons, ions (D$^-$, D$_2^+$, D$_3^+$) and fast neutrals (D^0, D$_2^0$). The effects of atomic collisions included ionization, dissociation and charge exchange with both molecular and
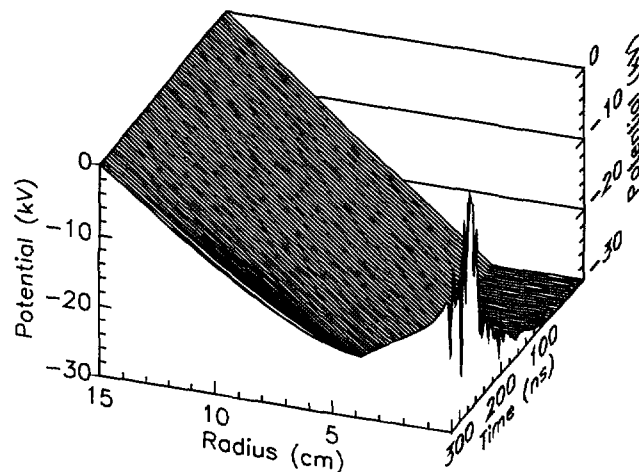

FIG.4.   Time behavior of potential profile

atomic deuterium. The production and extinction of the particles were evaluated every time step by the number of the collisions per a particle during the period dt; *i.e.* $N = \sigma v n_0 dt$ where σ the cross section, v the relative velocity and n_0 the density of the background neutral gas. The computational domain was a whole region within the vacuum chamber. The mass ratio of electron and ion were assumed to be one hundredth to save the computational time. We took into account the selective loss of ions with a low energy as the result of the neutralization of the ions hitting the cathode, which may bring about the steady state.

3.2. Electrostatic potential and neutron generation

Fig.4 shows the time evolution of electrostatic potential profile, when the applied voltage is 30 kV and the current is 10 mA. The potential is minimized at the cathode and gradually increases towards the center. The potential well structure is formed in the center and unstable. The space profiles of neutrons exhibit conspicuous double peaked profiles coinciding with the potential profiles. The reactivity between charge exchanged fast neutrals and background deuterium molecular was approximately twice larger than that of fast ions and background deuterium. The total number of neutrons was roughly consistent with the experimental results.

4. SUMMARY AND CONCLUSIONS

The dependencies of neutron generation on the discharge current as well as the voltage were studied experimentally. The numerical simulations were carried out in order to clarify the distributions of fast particles, i.e. neutral particles and ions as well as the electrostatic potential build-up. The linear dependence of neutron rate indicates that the main fusion events occur between the fast particles and background neutral gas. The numerical studies verified the fact, e.g. showed that one third of the neutrons are born in the fusion events between the fast ions and the background neutral, and the rest comes from the fusion events between the fast neutral and the background gas. The reactivity profile numerically obtained is doubly peaked, which comes from the fact that the double well potential profile exists in the center of core in an SCIF device. The collimated proton measurements represent the first conclusive experimental demonstration of double well formation in an SCIF since prior measurements by other researchers typically yielded marginal or negative results [4]. The demonstration of well formation is a key step in physics understanding since ion trapping by such wells could provide the enhanced confinement needed to scale the SCIF up to much higher neutron rates and ultimately to fusion power production. To accomplish this, however, deeper wells with larger volumes must be established using yet higher ion currents and a controlled ion angular momentum profile as studies by Tzonev et al.,[6]. The direct measurements of electric field through the Stark effect in a core are in progress.

<div align="center">REFERENCES</div>

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