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ORIGINAL RESEARCH

Preliminary Results of Experimental Studies from Low Pressure Inertial Electrostatic Confinement Device

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Abstract In this study, Turkey's first low pressure inertial electrostatic confinement (IEC) device, constructed at the Saraykoy Nuclear Research and Training Center (SNRTC-IEC), is introduced and the first results are reported. This device was designed for neutronic fusion studies in terms of D–D reaction. The SNRTC-IEC device consists of spherical chamber 300 mm in diameter and a grid-type spherical cathode in which high negative voltage is applied at the center of chamber. The outer surface of the device held at ground potential has 10 ports to connect the vacuum pump, high voltage load, residual gas analyzer, ion sources and other peripherals. Cathode voltage is 85 kV and it is particularly emphasized that the SNRTC-IEC device is studied at low pressure ($1-10 \times 10^{-4}$ mbar). The maximum total neutron production rate is measured at around 2.4×10^{4} neutrons per second for the medium grid cathode.

Keywords Fusion · Electrostatic confinement · D–D reaction · Neutron production rate

Introduction

Nuclear fusion is attractive as it is a potentially inexpensive, environmentally friendly, and practically unlimited source of energy [1]. Nuclear fusion technology, when perfected to fusion-burn only deuterium, will have a fuel supply lasting millions of year, even if energy consumption continues to grow as in the past [2]. Since thermonuclear fusion is considered a feasible solution to the worldwide energy problem stemming from the global decrease in fossil fuels, research into new fusion devices arouses great interest [3]. One such fusion device is the Inertial Electrostatic Confinement (IEC) device. IEC is a concept of confinement that stands as an alternative to Magnetic (Tokamaks, Stellarators, etc.) and Inertial (laser, heavy and light ions) fusion [1]. The IEC concept utilizes spherically concentric electrodes to accelerate fusion ions to high center of mass energies, allowing the fusion reactions to take place [4]. Its main advantage is that the concept is relatively simple and inexpensive.

Alternatives to the gridded IEC system are the Penning Trap [5] and Polywell [6] concepts. In a Penning Trap charged particle can be stored with the superposition of a homogeneous magnetic field and a spatially inhomogeneous static electric field [5]. The basis of the Polywell concept is the idea of trapping high densities of energetic electrons within a quasi-spherical magnetic field, into which a current of high energy electrons is injected to form a deep negative potential well without the use of mechanical grids [6]. These types of systems will probably be desired if IEC moves towards a reactor scenario because they eliminate the loss of ion energy into a metal cathode [4].

The IEC concept relies on two spherical electrodes made of wire to confine and accelerate fusion ions to energies in the 40–200 keV range. Electrodes having smaller dimensions are located concentrically inside the larger electrode [7, 8]. A large negative voltage is applied to the cathode while the anode is held at ground potential [9]. An ion

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source is located outside of the anode, or a glow discharge mode can be used. Ions are accelerated into the center of the device where they may fuse with one another. In an ideal system the ions would re-circulate long enough for breakeven to occur. This confinement approach does not form a Maxwellian plasma, in which much of the input energy goes to useless low energy ions and electrons [4].

The first IEC study was made in the late 1960s by Farnsworth and Hirsch [10]. Farnsworth first patented the idea behind IEC [11], and Hirsch built on the work using a strong, negative electrostatic potential well to promote fusion reactions. Hirsch was able to produce 3×10^9 n/s for the D-T reaction at a cathode voltage of 150 kV by using with six ion guns [10].

A limited number of IEC projects have taken place around the world in recent years. In the United States the University of Illinois [12, 13] along with Daimler-Benz [14] first used IEC for a low power commercial neutron generator. The Los Alamos National Laboratory is doing work on a unique approach to the IEC concept called the Periodically Oscillating Plasma Sphere (POPS) [15]. The University of Wisconsin group has been running D–D since 1991 and is unique in that it also focuses on the D-^{3}He reaction [16]. There are currently five IEC projects in Japan and one in South Korea. The Tokyo Institute of Technology, Kyoto University, Kansai University, Kyushu University, and Hitachi Ltd. are all focusing on D–D [17–21]. Seoul National University and Hanyang University have started working on an IEC project in South Korea [22]. Recently, Iran's first IEC device has been designed as a neutron generator [23] and various studies of this device have been made [24].

The D–D, D-T, D-^{3}He and ^{3}He-^{3}He fusion reactions have been studied using IEC. These reactions are listed below. The D–D reaction has two equally probable reaction paths to release either high-energy neutrons or protons. Both D–D and D-T reactions can be used as a source of neutrons [1, 4, 25–30].

$$D + D \rightarrow {}^3He\ (0.82\ MeV) + n\ (2.45\ MeV) \quad (\%50)$$
$$\rightarrow T(1.01 MeV) + p(3.02 MeV) \quad (\%50)$$

$$D + T \rightarrow {}^4He(3.52 MeV) + n(14.07 MeV)$$

$$D + {}^3He \rightarrow {}^4He(3.67 MeV) + p(14.68 MeV)$$

$${}^3He + {}^3He \rightarrow {}^4He + 2p(12.86 MeV)$$

In the present study, the features of a newly constructed low pressure inertial electrostatic device are presented, and the preliminary fusion studies carried out in the SNRTC-IEC device are reported on. While Sect. 2 includes the introductory features of this device, Sect. 3 mentions some experimental procedures. Section 4 gives the main results of the experiments and discusses the data. The final section notes the conclusions and discusses future prospects.

Features of SNRTC-IEC-IEC

Figure 1 represents a sketch of SNRTC-IEC device. The SNRTC-IEC device consists of a spherical vacuum chamber made of stainless steel as an anode and a central grid made of stainless steel rings as cathode with insulator surrounding the dip. The anode is 300 mm in diameter. There are three different size grid-type cathodes. These cathodes have been named as "small cathode", "medium cathode" and "large cathode" and their outer diameters are 50, 80 and 110 mm respectively. The corresponding feedthrough insulator lengths surrounding the dip are 245, 315 and 315 mm respectively. All grid wires are constructed of 3 mm stainless-steel wire spot welded into open spherical grids having 70 % transparency for the small cathode, 82 % transparency for the medium cathode and 85 % transparency for the large cathode. These cathodes are shown in Fig. 2. The device has 10 ports with which to connect the ion gauge, vacuum pump, high voltage load, residual gas analyzer, ion sources and other peripherals. A photo of SNRTC-IEC is shown in Fig. 3.

In this device Inductive Coupled Plasma (ICP) deuterium ion sources are used to obtain a high concentration of ions in the center of chamber. It has coil with three turns measuring 30 mm in diameter. The inductance of this coil is around 600 nH. The addition of an ion source to the IEC fusion device enhances fusion reactions by allowing a lower operating gas pressure and by providing a beam-like ion energy distribution [31, 32].

The high voltage power supply has 100 kV output. However, the cathode voltage is limited to 85 kV in the present experiments because of isolation problem. A mechanical vacuum pump and turbo pump are used for creating vacuum conditions. The base pressure is measured using an ion gauge. The operating pressure range is

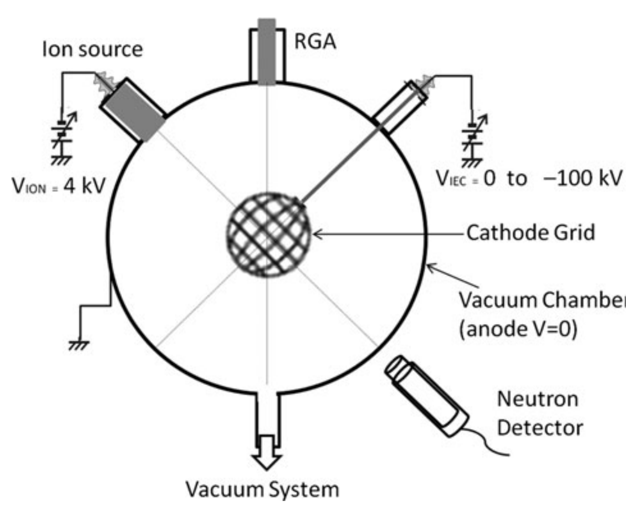

Fig. 1 Sketch of SNRTC-IEC device

Fig. 2 Photo of cathodes

Fig. 3 Photo of SNRTC-IEC

(1–10) $\times$ 10^{-4} mbar. Table 1 shows some of the design and operational parameters of SNRTC-IEC.

The SNRTC-IEC device has been constructed in order to explore D–D reactions. D–D reaction produces neutrons at 2.45 MeV and ^{3}He nucleus (ions) or protons and tritium nucleus. In this study, the neutrons generated were detected using a helium-3 filled neutron detector Thermo FHT 752 SH having a polyethylene moderator and calibrated with Am-241 Be-9 3.7 GBq neutron source. The detector was placed 175 mm distance from the center of the device and at different angles from the vacuum chamber. Experiments showed that the spatial distribution of 2.45 MeV neutrons is almost isotropic and found that the placement of the detector has almost no bearing on the detected neutrons. Thus, the position of the detector was fixed in all experiments. A residual gas analyzer was used to determine which gases are present in the chamber.

Table 1 Some design and operational parameters of the SNRTC-IEC

Parameter	Value
Anode diameter	300 mm
Small cathode diameter	50 mm
Medium cathode diameter	80 mm
Large cathode diameter	110 mm
Cathode voltage	85 kV
Cathode current	80 μA
Pressure range	$1-10 \times 10^{-4}$ mbar

Experimental Procedure

The system was operated for three different size cathodes at 85 kV cathode voltage, 80 μA cathode current including any charged species between the anode and the cathode, and 4.5 $\times$ 10^{-4} mbar pressure in order to determine the effect of cathode diameter. 4 kV DC voltage was applied to the ion source. The neutron production rates for these cathodes are compared in Table 2.

A comparison of neutron production rates for the three different size cathodes at the same pressure are shown in Table 2. It appeared that the medium sized cathode had the highest neutron production rate (1.6 $\times$ 10^{4} n/s) under the same conditions, and so the most acceptable cathode for the SNRTC-IEC device was the medium cathode. Therefore, subsequent studies were carried out using the medium cathode.

In order to determine pressure range for the medium cathode the system was operated at between $1-10 \times 10^{-4}$ mbar using the single deuterium ion source. The neutron production rates versus the operating pressure are plotted in Fig. 4. Thus, it can be seen which pressure gives the highest neutron production rate.

A qualitative spectral analysis was also made. Qualitative spectral analysis involves identifying the peaks in the spectrum. Figure 5 represents gas rates with mass = 3,4 in the form of a bar graph both before and after the operation in the vacuum chamber. It can be seen from spectrum that mass = 3 species have increased. This increase could be

Table 2 A comparison of neutron production rates from the three cathodes

Cathode	Cathode voltage (kV)	Operating pressure (mbar)	Ion source voltage (kV)	RF power (Watt)	Neutron production rate (n/s)
Small					2.0×10^3
Medium	85	4.5×10^{-4}	4	40	1.6×10^4
Large					1.1×10^4

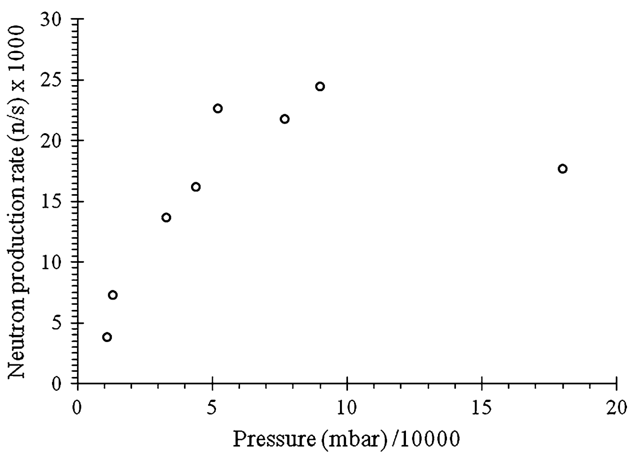

Fig. 4 Neutron production rate versus the operating gas pressure

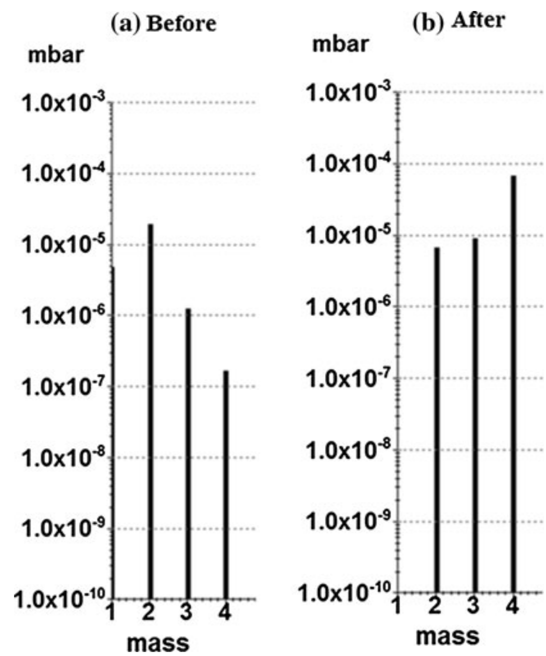

Fig. 5 Gas rates in the vacuum chamber **a** before the operation, **b** after the operation

due to helium-3 atoms or tritium atoms or proton-deuterium molecules. The mass = 4 species represent deuterium–deuterium molecules.

Results and Discussion

The neutron production rate versus the operating gas pressure for the medium cathode are plotted in Fig. 4 for a fixed grid current (80 μA) and fixed cathode voltage (85 kV). It shows that the highest neutron production rate (2.4×10^4 n/s) occurs at the 9×10^{-4} mbar pressure value. It can be seen from Fig. 4 that dark to glow transitions occurred at 9×10^{-4} mbar. In this case, the voltage dropped and the neutron rate decreased due to the current limitations in our power supply.

For this pressure, the mean free path λ of a deuterium molecule can be found by using Eq. 1 [33–35]:

$$\lambda = \frac{RT}{\pi\sqrt{2}d^2NP} \quad (1)$$

where R is the gas constant, T the temperature, d the molecular diameter, N is Avogadro's number, and P the pressure (SI units). Charge exchange and dissociation of molecules have been excluded. It is found that the mean free path of a deuterium molecule is about 18 cm, which is larger than the SNRTC-IEC device radius ($\lambda > R_{cathode}$). In this case, it is predicted that almost all of the ions will reach the center of the device without losing energy and the reacting ions will have acquired nearly all of the cathode voltage.

An IEC device that operates with little energy loss due to collisions with background particles is needed in order to observe the reactions. If this state is achieved, the device will operate with recirculating ions that are unattenuated until they intersect the cathode grid. While recirculating, a very small fraction of the ions will collide and fuse with the low, though still existent, background gas [36].

Neutron production rate, namely fusion rate F, is related to the count rate observed by the detector D, plus geometry and efficiency factors for the detector and is as follows [36]:

$$F = \frac{D\,4\pi R_{\mathrm{det}}^2}{A_{\mathrm{det}}} = \frac{D\,4\pi R_{\mathrm{det}}^2}{\pi r^2} \quad (2)$$

where R_{det} is the distance between the detector and the device center, and A_{det} is the detector surface area. In this study R_{det} is 175 mm, r is detector radius and r is 10.5 mm.

The neutron production rates were calculated using Eq. (2). It can be seen from Fig. 4. that the highest neutron production rate is 2.4×10^4 n/s at a pressure of 9.0×10^{-4} mbar.

Conclusion

In conclusion, the most suitable cathode for the SNRTC-IEC device is the medium cathode as it has the highest neutron production rate (1.6×10^4 n/s). Therefore, subsequent studies were carried out using the medium cathode. For the medium cathode the system was operated and total neutron production rate was calculated at different pressure values. As a result, the maximum total neutron production rate achieved was 2.4×10^4 neutrons per second at the 9×10^{-4} mbar pressure for a fixed grid current (80 μA) and fixed cathode voltage (85 kV). It has been seen from studies with the medium cathode that glow discharge is not observed and that there is no drop in current when the ion source is shut down. It is very likely that this occurs in the Townsend zone of I–V characteristics. Some additional studies are required to optimize the device in order to increase the neutron production rate. To this end, additional ion sources can be added to the system. Moreover, the cathode voltage can be increased by solving the insulation problem because neutron production rate increases as voltage increases in D–D reactions.

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