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Design of a linear neutron source

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HIGHLIGHTS

- This paper reports the design of a linear neutron source based on inertial electrostatic confinement fusion scheme.
- The voltage and current that is to be applied to the grid is computed theoretically.
- Neutron production rate is theoretically estimated and found to be of the order of 10^7–10^8 neutrons/s.
- Electric potential distribution and ion trajectories are studied using SIMION code.
- Optimized condition for the inner grid transparency has been found out.

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ABSTRACT

In this paper, we present the design of a linear neutron source based on the concept of inertial electrostatic confinement fusion. The source mainly comprises of a concentric coaxial cylindrical grid assembly housed inside a double walled cylindrical vacuum chamber, a gas injection system, a high voltage feedthrough and a high voltage negative polarity power supply. The inner grid will be kept at a high negative potential with respect to the outer grid that will be grounded. The effect of grid transparency on electric potential distribution and ion trajectories has been studied using SIMION. A diffuse deuterium plasma will be initially created by making filament discharge and subsequently, on application of high negative voltage to the inner grid, deuterons will be accelerated towards the axis of the device. These deuterons will oscillate in the negative potential and consequently fuse in between the grids to produce neutrons. This source is expected to produce 10^7–10^8 neutrons/s. The proposed linear neutron source will be operated both in the continuous and pulse modes and it will be utilized for a few near term applications namely fusion reactor material studies and explosive detection.

1. Introduction

Inertial electrostatic confinement fusion (IECF) draws attention of fusion community due to its multidimensional aspects starting from the basic fusion studies to near term applications [1]. By burning the advanced fuels (D-D, D-T, D-^{3}He) in this simple, compact and cost effective device one can have various radiations such as neutrons, protons, high energy photons, etc. The working principle of the device relies on acceleration of the fuel ions to the central core region in a high electric field environment and subsequent oscillation of those ions to facilitate fusion reaction. The design criteria for such a device is essentially achieved by placing two concentric gridded electrodes (anode and cathode) in a spherical or cylindrical geometry. For improvement of fusion working conditions and the products obtained due to consequent reactions, additional arrangements such as electrostatic charged particle trap, ion guns, external magnetic field, etc. have been employed in some cases [2,3].

Elmore et al. [4] were the first to present a theoretical interpretation of a spherical IECF system in which electrons were directed inward for the confinement of plasma at thermonuclear temperature. On the other hand, Fransworth [5] was first to design a spherical space charge device and demonstrated the method of fusing ions in an electrostatic inertial confinement. In order to inject ions directly into the anodic space he used additional ion guns for controlling the quantity of ions which enhanced the fusion products. Formation of periodic potential well for the confinement of fuel ions in spherical geometry was proposed theoretically by Hirsch [2] and later an experimental model consisting of symmetrical arrangement of ion guns was conceived by him to verify his theoretical propositions. The guns were assumed to be a workable substitute for the uniform ion source in the central cavity region of the device and this resulted in a steady and reproducible neutron emission of the order of 10^8–10^{10} neutrons/s from it. The high

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neutron production rate was attributed to the unstable behaviour of the potential [6].

In recent years efforts are being made to realize novel, portable, compact and cost effective neutron sources apprehending their near term attractive applications in neutron activation analysis [7], oil well logging [8], security inspection system [9], ion thrusters [10], etc. Further attempts have been made to improve fusion efficiency by using various geometries so as to find their applications in the areas of radioisotope production [11], detection of explosives and landmines [12], and fusion material irradiation testing [13].

Much of the work on IECF were carried out in the United States and Japan and major contributors are University of Wisconsin [1,11,13], University of Illinois [7,9], Los Alamos National Laboratory [14], Kyoto University [15] and Tokyo Institute of Technology [16]. Their pioneering works made significant contribution to the field of practical importance such as medical isotopes production [11], fissile materials [17] and explosives [12] detection, space propulsion studies [10], etc. Besides the conventional spherical IECF device, the advent of cylindrical type device [18,19] which is an extended linear neutron source has obviously added momentum in this field of research.

Two different types of cylindrical sources (gridded [18,19] and hollow cathode types [7]) have been explored so far. The gridded concept was first conceived by Dolan et al. [20] whereas Miley et al. [7] proposed hollow cathode type in order to retain long axial reaction without the grids. Recent encouraging results on neutron emission from gridded type source [18,19] prompted us to adopt the design for building our cylindrical IECF device.

In this paper, we present the designing of a gridded cylindrical neutron source based on the concept of electrostatic confinement that will produce 10^7–10^8 neutrons/s. This device will operate in both continuous and pulse modes. Continuous mode of operation will enable us to test the fusion reactor materials for a longer duration and its outcome will certainly provide necessary feedback to use these materials as armour for tokamak device. On the contrary, in pulse mode of operation, we expect to get more neutron flux at the expense of less input power which would enable to test materials at a relatively higher neutron flux environment. The obvious issue of neutron damage is clearly our primary concern, but equally important issue would be to examine the effect of plasma radiation and particle flux on those materials. Nevertheless, the fusion neutrons from the device will be employed for explosive detection. Operational principle of this device is discussed in section 2. The theoretical equations taken into account for the conceptual design of the device is discussed in section 3 which enable us to predict the neutron production rate (NPR). The relationship between the operating voltage and NPR is also mentioned in that section. Section 4 describes the experimental configuration of IECF device along with its subunits. Electric potential distribution and ion trajectories obtained from SIMION code are described in section 5. Last section contains the concluding remarks.

2. Operational principle of cylindrical IECF device

Inertial electrostatic confinement is a fusion concept in which fuel ions ($^2D^+$, $^3T^+$ and $^3He^+$) are trapped with purely electrostatic fields in a convergent geometry. The device based on this concept has a transparent inner grid which is biased at negative high voltage. The outer grid and the chamber are kept at the ground potential. By making filamentary discharge the fuel gas gets ionised and the glow discharge plasma appears in between the outer and inner grids. The ions produced in the discharge are extracted from the plasma by the inner (cathode) grid, accelerated and focused at the axis of the cylinder where nuclear fusion reaction primarily occurs. The three primary fusion reactions for IECF device are given below.

$$\mathrm{D} + \mathrm{D} \rightarrow {}^3\mathrm{He}\,(0.82\,\mathrm{MeV}) + \mathrm{n}\,(2.45\,\mathrm{MeV}) \quad (1)$$

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}\,(1.01\,\mathrm{MeV}) + \mathrm{p}\,(3.02\,\mathrm{MeV}) \quad (2)$$

$$\mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He}\,(3.5\,\mathrm{MeV}) + \mathrm{n}\,(14.1\,\mathrm{MeV}) \quad (3)$$

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

To obtain more NPR, it is expected that low pressure operation [21] is effective where high voltage can be applied safely to the cathode grid that will mainly provide the accelerating voltage to the ions. In order to accelerate ions to the energy equivalent to the applied potential, it is necessary to reduce gas pressure and increase ion mean free path. However, lowering the gas pressure will reduce the target particle density and thereby decreases the fusion reactions occurring in between ions and the background neutral particles. It is well known that the cross section of fusion reaction increases with ion energy up to a threshold value and total fusion reaction is proportional to the discharge current. Therefore, higher discharge voltage and current is a simpler way to obtain high NPR [22]. Next section will describe the theoretical interpretation on NPR and the neutron flux distribution from D–D fusion reactions occurring in our cylindrical IECF device.

3. Theoretical estimation

3.1. Neutron production rate

It is noticed from the literature that almost all IECF experiments are operated at significant background neutral pressure so that most of the fusion reaction occurs between the ion beam and background neutrals [3,23]. Moreover, it is seen from the experiment [3] that NPR increases by increasing the background gas pressure upto a certain value and subsequently it decreases with further increase. So one can expect that the beam background fusion reaction is to be dominant than the others at higher pressure mode of operation. In this work, we are primarily interested in calculating the contribution of beam–background fusion reaction which will be the dominating reaction mechanism in our device. The NPR can be deduced using the standard formula given below [24].

$$\frac{\mathrm{d}N}{\mathrm{d}t} = n_i(v) v_c \sigma(v) n_g \quad (5)$$

where $n_i(v)$ —ion density, $\sigma(v)$ —fusion cross section, n_g —background gas density, and v_c —ion velocity.

Now, ion density can be calculated using the formula derived by Thorson et al. [3]

$$n_i(v) = \frac{\eta I_{meas}}{(1-\eta^2)(1+\delta_e)(2\pi e v_c r_c h)} \quad (6)$$

$$I_{meas} = I \times (1-\eta^2)(1+\delta_e) \quad (7)$$

Here, $2\pi r_c h$ —the curved surface area of the cylindrical cathode, r_c and h are the radius and the height, respectively, η —transparency factor of cathode, δ_e —number of secondary electrons emitted from the source, I—applied current at the cathode, and I_{meas} —measured cathode current. Ion velocity can be expressed as [21]

$$v_c = \sqrt{\frac{2q\Phi_c}{M}} \quad (8)$$

where Φ_c —applied potential, M—mass of ion, and q—ion charge.

For different cathode voltages and currents and for a particular cathode transparency (92%), the measured cathode current, ion velocity and density, NPR, etc. are estimated using equations (5) to (8) and are tabulated in Table 1.