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Analytical and numerical study of the burn performance in central ignition

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Abstract

Neutrons energy deposition and energy gain of deuterium-tritium fusion targets in the central ignition inertial confinement fusion scheme are studied by numerical calculations. These calculations are based on a description of the stagnation phase where the rate of change of energy in the hot spot is determined by the competition of the energy losses due to thermal conduction and radiation with the heating due to compressional work and alpha particle energy deposition. As a result, the target gain is obtained as a function of the beam energy input on the target, for different values of the isentrope parameter α and hydrodynamic coupling coefficient η. Results show that the growth procedure of target gain decreases with the incident driver energy, whereas, increase in the hydrodynamic coupling coefficient causes the target gain increases considerably. In addition, the neutrons deposition energy is calculated by the MCNP code. Our calculations show that the neutrons energy deposition causes the target gain decreases considerably, in comparison with a case that the deposited energy of neutrons is ignored, as the percent of gain reduction is 10% for low values of the incident driver energy and 50% for high values of it.

PACs: 25.60.Pj; 52.57.Kk; 52.58.Mf; 52.57.Bc; 52.55.Pi

Keywords: *central ignition*, *Deuterium, Fusion target, Tritium energy gain*

1. Introduction

One of the methods for the production of energy by nuclear fusion is inertial confinement fusion (ICF) consisting different approaches [1-5]. In this method a spherical shell of cryogenic deuterium and tritium (DT) filled with DT gas is accelerated by direct laser irradiation (direct drive) or x-rays produced by a high-Z enclosure (indirect drive). When an intense laser light is uniformly impinged on a spherical target, with an intensity of the order $10^{14}-10^{15}\,Wcm^{-2}$, the laser energy is absorbed on the surface to generate high temperature plasmas of 2-3 keV and an extremely high pressure of a few hundred megabars is generated. This pressure accelerates the outer shell of the target towards the target center. The mechanism of the acceleration is the same as for rocket propulsion. When the accelerated fuel collides at the center, compression and heating occur. If the dynamics is sufficiently spherically symmetric, the central area is heated up to 5-10 keV and the fusion reaction starts to generate a large amount of energetic alpha particles and neutrons [6]:

$$D+T\rightarrow n+a+17.6\,MeV. \quad (1)$$

The major scientific requirement for assessing the feasibility of ICF is the achievement of relatively high energy gain. The target gain G is defined as

$$G=\frac{E_{tn}}{E_{be}}, \quad (2)$$

where E_{tn} is the thermonuclear energy output and E_{be} is the beam energy input on the target. Central ignition, which is being considered for reaching a high energy gain, is required to drive the bulk of the fuel to a lower specific entropy than that of the innermost part by producing a suitable sequence of shocks and rarefactions during the shell implosion. Here, we use an isobaric ignition configuration. According to isobaric model of fusion targets in ICF, it is assumed that at the final stage of hydrodynamic implosion, target configuration is composed of two distinct regions called hot spot and cold fuel [7]. The hot spot is an ideal plasma of hydrogen isotopes with density, temperature and a radius of ρ_{hs}, T_{hs} and r_{hs}. On the other hand, the cold fuel region is a degenerate electron gas with density of ρ_{cf}. It is also assumed that pressure is constant across the whole target at stagnation (maximum compression) time. This configuration can be generated by a high intensity incident beam of laser or heavy charged particles.

In numerous cases it is assumed that the fusion reactions produced neutrons pass through the fuel without substantial interaction with the cold fuel. However, in this paper, by the MCNP code, we demonstrate that the neutrons deposition energy is considerable in the target and it reduces energy gain, and we find the magnitude of the percent of gain reduction for different values of the incident driver energy.

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2. Central ignition and the neutrons energy deposition

2.1. Ignition and burn

A hot spot with given values of the temperature T_{hs} and confinement parameter $H_{hs} = \rho_{hs}\, r_{hs}$, can be produced by a hydrodynamic implosion process which then ignites and propagates burning waves in the cold region. Here, there exist processes which cool and dissipate the hot spot. Most important of them are Bremsstrahlung energy losses of hydrogen isotope plasma and electron thermal conductivity.

As a capsule implodes, alpha particle deposition from a thermonuclear burn of DT try to heat the central hot spot. The volumetric rate of energy production due to alpha particles self-heating is given by [8]:

$$P_a = n_D n_T \langle\sigma v\rangle_{DT} E_{0a}, \tag{3}$$

where n_D and n_T are deuterium and tritium densities, respectively. $\langle\sigma v\rangle_{DT}$ is the Maxwellian averaged fusion rate of a DT mixture and E_{0a} is the alpha particle birth energy at the hot spot center as it equals 3.52 MeV. Assuming equal number densities ($n_D = n_T = n_{hs}/2$) of deuteriums and tritiums in hydrogen plasma (n_{hs} is the ion density of the hot spot) we have:

$$P_a = 0.25\, n_{hs}^2 \langle\sigma v\rangle_{DT}\, E_{0a}. \tag{4}$$

Therefore, the volumetric rate of increase of energy due to alpha particles energy deposition is given by:

$$P_{da} = 0.25\, n_{hs}^2 \langle\sigma v\rangle_{DT}\, E_{0a}\, (1 - f_{ee}). \tag{5}$$

Here, f_{ee} is the fraction of the alpha energy that escapes from the hot spot and it is defined as [9]:

$$f_{ee} = \begin{cases} 1 - 2\tau + \frac{8\tau^2}{5} & \tau \le 0.25 \\ \frac{1}{4\tau}\frac{1}{32\tau^2} + \frac{1}{640\tau^3} & \tau \ge 0.25 \end{cases}, \tag{6}$$

where

$$\tau = \frac{r_{hs}}{\lambda}. \tag{7}$$

Here, λ is the alpha particle range in the hot core, given by:

$$\lambda = 1.1 \times 10^{-2}\, \frac{T_{hs}^{3/2}}{\rho_{hs}}, \tag{8}$$

where T_{hs} and ρ_{hs} are in keV and gcm^{-3}, respectively. On the other hand, electron conduction from the hot spot to cold surrounding fuel, as well as radiative losses, act to cool the hot spot. The volumetric rates of energy dissipation due to electron conduction and Bremsstrahlung emission are given by [10]:

$$P_{ec} = 3.684 \times 10^{-19} \left(\frac{n_{hs}}{H_{hs}}\right)^2 T_{hs}^{7/2} \quad keV \cdot cm^{-3} \cdot s^{-1}, \tag{9}$$

$$P_{br} = 3.35 \times 10^{-15}\, n_{hs}^2 T_{hs}^{1/2} \qquad keV \cdot cm^{-3} \cdot s^{-1}, \tag{10}$$

where n_{hs}, T_{hs} and H_{hs} are in cm^{-3}, keV and gcm^{-2}, respectively. If conduction and radiative losses from the hot spot are too large, ignition never occurs. To achieve ignition by the time the implosion process has stopped, the hot spot must have a $\langle\rho r\rangle_{hs}$ equal to about $0.3 - 0.4\, gcm^{-2}$, and must achieve a central temperature of about 5-10 keV. Under this condition, alpha particle energy deposition can overcome losses processes, and a self sustaining burn wave will be generated. This expanding burn wave propagates into the outer fuel layer, hopefully heating the entire target before hydrodynamic disassembly. If the thermonuclear burn wave ignites the entire fuel region well before disassembly, the target can be sufficiently depleted in fuel ions (fractional burn up greater than 30%) to reduce the reaction rate, at which point the target has reached its maximum potential. These targets are defined as strongly burning.

Conservation of energy indicates that the rate of change of energy in the hot spot is given by the identity [11]:

$$\dot{U} = \frac{d}{dt}\left(\frac{4}{3}\pi r_{hs}^3 n_{hs} T_{hs}\right) = \frac{4}{3}\pi r_{hs}^3 n_{hs}\, \dot{T}_{hs} + 4\pi r_{hs}^2 n_{hs} T_{hs} \dot{r}_{hs}. \tag{11}$$

If the hot spot radius remains constant, we can write:

$$\dot{U} = \frac{4}{3}\pi r_{hs}^3 n_{hs}\, \dot{T}_{hs}. \tag{12}$$

At the same time, according to what we said, we have:

$$\dot{U} = \frac{4}{3}\pi r_{hs}^3 \left[0.25\, n_{hs}^2 \langle\sigma v\rangle_{DT} E_{0a}(1 - f_{ee}) - 3.684 \times 10^{-19} \left(\frac{n_{hs}}{H_{hd}}\right)^2 T_{hs}^{7/2} - 3.35 \times 10^{-15} n_{hs}^2 T_{hs}^{1/2}\right] keV.s^{-1}. \tag{13}$$

Equating equations (12) and (13) gives:

$$t = \int_{T_{si}}^{T_{hs}} \frac{dT_{hs}}{0.25\, n_{hs}\langle\sigma v\rangle_{DT} E_{0a}(1 - f_{ee}) - 3.684 \times 10^{-19} n_{hs} \frac{1}{H_{hs}^2} T_{hs}^{7/2} - 3.35 \times 10^{-15} n_{hs} T_{hs}^{1/2}}, \tag{14}$$

where t is the burn time of the fuel in the hot spot and T_{si} is the self-ignition temperature (the hot spot temperature at t = 0). Considering that the temperature dependence of $\langle \sigma v \rangle_{DT}$ is determined, we can obtain the time dependence of the hot spot temperature by above integration for different values of T_{hs}. In Fig. 1 we have shown the hot spot temperature as a function of time, supposing that $T_{si} = 5\ keV$, $\rho_{hs} = 40\ gcm^{-3}$ and $H_{hs} = 0.4\ gcm^{-2}$, for the temperatures of less than 25 keV. At further temperatures, importance of lossing factors outrun granting factors, and consequently the denominator of integrand becomes negative in equation (14).

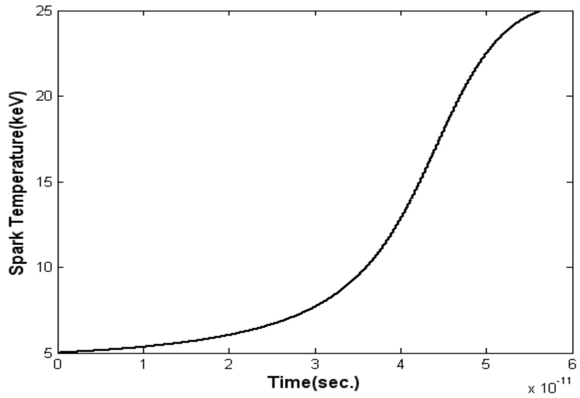

Fig. 1. The hot spot temperature as a function of time for fixed values of T_{si}, ρ_{hs} and H_{hs}.

2.2. Determination of target gain

Considering that we have the time dependence of the hot spot temperature, we can calculate the time dependence of temperature of a region where it is under the heating in the cold fuel due to the exited alpha particles from the hot spot. The mentioned region has a thickness as size as the alpha particle range in the cold fuel. However, we can determine the occured number of fusion reactions and the produced fusion energy in it. This energy is transfered to next layer of cold fuel by alpha particles repeatedly, and consequently the internal energy of this layer is increased. In this manner, the burn wave propagates through the whole target well before hydrodynamic disassembly. Here, we have assumed that the energy transfer coefficient of alpha particles from a layer to other layer equals 1. The energy released from the fusion reactions, E_{tn}, equals sum of the alpha particles energy of final cold fuel layer and neutrons energy produced from the fusion reactions. Also, we have:

$$U_f = \eta\, E_{be}, \tag{15}$$

where U_f is the total internal energy of the target during the time of ignition and η is hydrodynamic coupling coefficient. On the other hand, we can write:

$$U_f = U_{hs} + U_{cf}. \tag{16}$$

Here, U_{hs} and U_{cf} are the hot spot and cold fuel internal energies, respectively, and they are given by [7]:

$$U_{hs} = 3kT_{hs}N_{hs}, \tag{17}$$

$$U_{cf} = 2.188 \times 10^{21}\ \alpha M_{cf}\rho_{cf}^{2/3} \qquad keV, \tag{18}$$

where k, N_{hs}, α and M_{cf} are the Boltzman constant, the total number of hot spot ions during the time of ignition, the isentrope parameter (the deviation of the cold fuel from complete degeneracy) and the mass of the cold fuel, respectively. Besides, according to isobaric model, we can write:

$$U_f = \frac{3pV_f}{2} = 2\pi p R_f^3, \tag{19}$$

where p, V_f and R_f are the fuel pressure, the total volume of fuel and target radius. The pressure p can be written as:

$$p = p_{hs} = \frac{2\rho_{hs}kT_{hs}}{\mu_{DT}}. \tag{20}$$

Here, μ_{DT} is the reduced mass of DT mixture. According to what we said concerning the calculation of E_{tn} and using equations (2) and (15-20), we have represented the target gain G as a function of the beam energy input on the target, E_{be}, in Fig. 2 for different values of the isentrope parameter α and coupling coefficient η. As can be seen, the growth procedure of target gain decreases with the incident driver energy. Also, increase in the hydrodynamic coupling coefficient to the extent that is possible, causes the target gain increases considerably. For the reason that a suitable designing of target causes its symmetry is retained, during the beam radiation on the target and the implosion, and the hydrodynamic instabilities reach the least value. Furthermore, increase in the isentrope parameter (decrease in the cold fuel density) causes the target gain decreases considerably.

3. MCNP code

MCNP is a general-purpose Monte Carlo N-Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport, including the capability to calculate eigenvalues for critical systems. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and fourth-degree elliptical tori.
Pointwise cross-section data are used. For neutrons, all reactions given in a particular cross-section evaluation (such as ENDF/B-VI) are accounted for. For photons,

the code takes account of incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation, and Bremsstrahlung. A continuous-slowing-down model is used for electron transport that includes positrons, x-rays, and Bremsstrahlung but does not include external or self-induced fields.

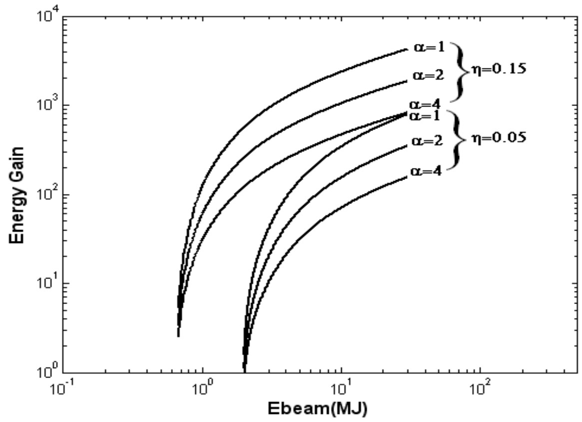

Fig. 2. The target gain as a function of the incident driver energy, apart from the neutrons energy deposition, for different values of the isentrope parameter α and coupling coefficient η, and for fixed values of T_{si}, ρ_{hs} and H_{hs}.

Important standard features that make MCNP very versatile and easy to use include a powerful general source, criticality source, and surface source; both geometry and output tally plotters; a rich collection of variance reduction techniques; a flexible tally structure; and an extensive collection of cross-section data [12].

In the previous section, we assumed that the fusion reactions produced neutrons pass through the fuel without substantial interaction with it. Whereas, the produced neutrons in the hot spot deposit a small amount of their energies in that region, But considering that the hot spot density is very small (in comparison with the cold fuel density), therefore, the mean free path of neutrons is very large in this region (in comparison with its radius). As a result, the neutrons deposition energy is not considerable in the hot spot and we can ignore it. However, it is considerable in the dense cold fuel. For the reason that the mean free path of neutrons is small in this region. We can calculate the deposited energy of any neutron in the target by the MCNP code.

4. Central ignition with planning the neutrons energy deposition

4.1. Investigation of the neutrons energy deposition in target

As we said in section 3, the produced neutrons in the hot spot deposit a large amount of their energies in the cold fuel. On the supposition that the self-ignition temperature , and the hot spot density and confinement parameter are the mentioned values in the section 2. 1., we have represented the ratio of the mean free path of hot spot neutrons in the cold fuel (mfpn) to the cold region thickness as a function of the target radius in Fig. 3 for different values of the isentrope parameter α. As can be seen, the mfpn decreases with the target radius. Also, increase in the isentrope parameter (decrease in the density of fuel) causes the mfpn increases considerably. Meanwhile, according to equation (14), the hot spot temperature has been brought in input file of MCNP in 5 time stage. Also, we have assumed that the cold fuel temperature remains constant and it equals 1 keV. Furthermore, the deposited energy of any hot spot neutron in the cold fuel increases with the target radius, as shown in Fig. 4. On the basis of this Figure, increase in the isentrope parameter causes the deposited energy of any hot spot neutron in the cold fuel decreases.

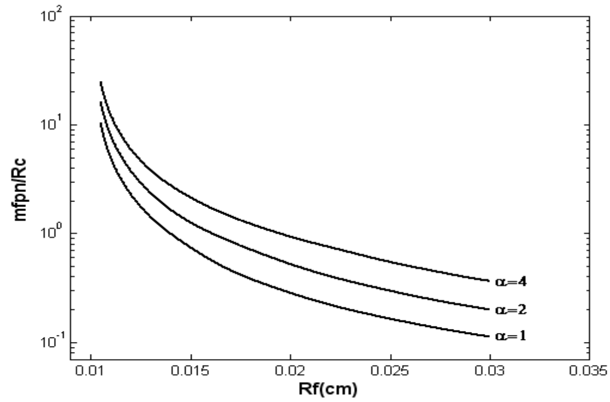

Fig. 3. The mean free path of hot spot neutrons in the cold fuel to the cold region thickness as a function of the target radius for different values of the isentrope parameter α, and for fixed values of T_{si}, ρ_{hs} and H_{hs}.

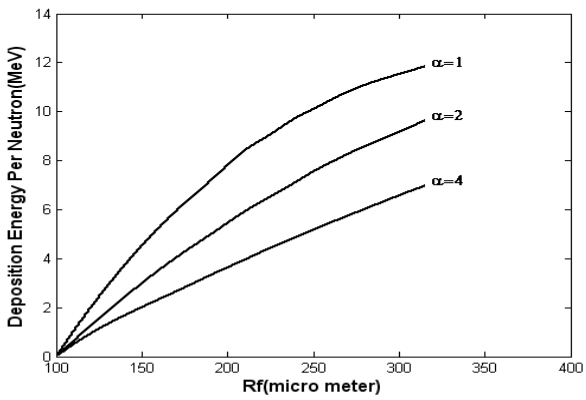

Fig. 4. The deposited energy of any hot spot neutron in the cold fuel as a function of the target radius for different values of the isentrope parameter α.

On the other hand, the neutrons which are produced in the cold fuel in next stages deposit a large amount of their energies in this region, and consequently its temperature increases. In this manner, in spite of the fact that this process supports the fusion reactions, it causes the energy which the neutrons send out, decreases. As a result the target gain decreases. The deposited energy of any produced neutron in the cold fuel increases with the target radius as shown in Fig. 5. As can be seen, increase in the isentrope parameter causes the deposited energy of any produced neutron in the cold fuel decreases.

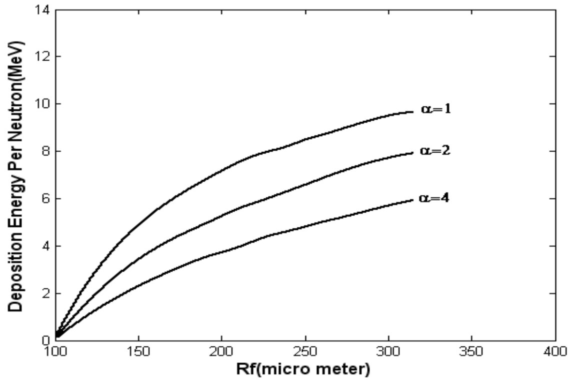

Fig. 5. The deposited energy of any produced neutron in the cold fuel as a function of the target radius for different values of the isentrope parameter α.

4. 2. Determination of target gain

We assume that the exited neutrons from the hot spot cause the ionic temperature increases in the cold fuel before the fusion reactions produced alpha particles exited from it and arrived the cold fuel. Of course this assumption is logical, because the translation velocity of neutrons is four times the translation velocity of alpha particles, approximately. Also, we assume that the produced neutrons in any layer of the cold fuel lose a fraction of their energy in the next layers and send out the rest of it from the target during the burn process in the cold fuel. It is clear that the range of the alpha particles increases as the burn wave propagates to the outer regions of the cold fuel, because the energy loss of the neutrons is increased to the energy of previous layers, and consequently the temperature of these layers increases. Therefore, the range of the alpha particles will become more than the remained thickness of target, finally. Besides, we assume that the lost energy of neutrons in the cold fuel is distributed in this region uniformly. We have represented the target gain G as a function of the beam energy input on the target, E_{be}, in Fig. 6 for different values of the isentrope parameter α and coupling coefficient η. As can be seen, the growth procedure of target gain decreases with the incident driver energy, similar to what we said in section 2.2., but the target gain on the basis of this Figure is less than the case which we considered in that place.

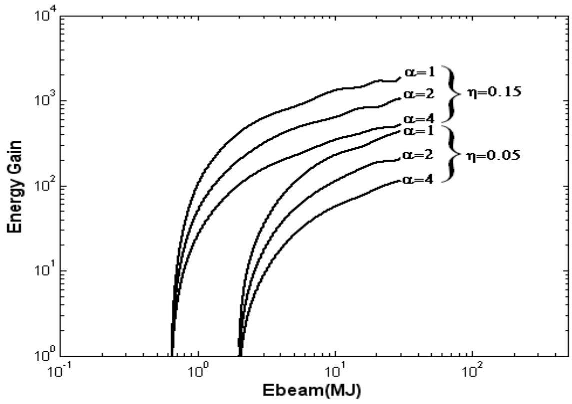

Fig. 7. The target gain as a function of the incident driver energy, with planning the neutrons energy deposition, for different values of the isentrope parameter α and coupling coefficient η, and for fixed values of T_{si}, ρ_{hs} and H_{hs}.

5. Conclusion

We have studied the burn performance in central ignition not only supposing that the fusion reactions produced neutrons pass through the fuel without substantial interaction with it, but also for a case that the neutrons energy deposition is considered in target. We have shown that the neutrons energy deposition causes the target gain decreases considerably, in comparison with a case that the deposited energy of neutrons is ignored. In Fig. 7 we have represented the percent of gain reduction in case which the neutrons energy deposition has been considered in comparison with a case which the neutrons pass through the fuel without substantial interaction with the cold fuel, as a function of the beam energy input on the target, E_{be}, for hydrodynamic coupling coefficient $\eta = 0.1$ and different values of the isentrope parameter α. As can be seen, decrease in the isentrope parameter causes the percent of gain reduction increases considerably. Also, the mentioned percent is 10% for low values of the inci-

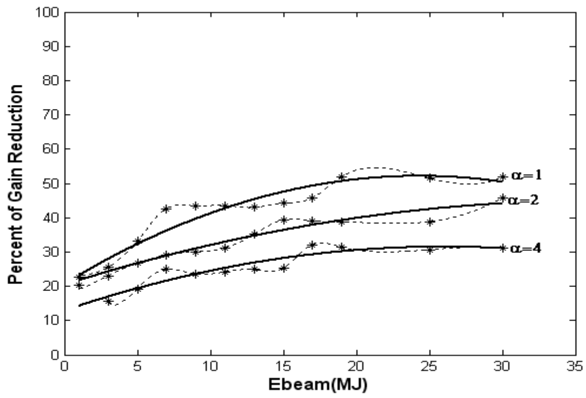

Fig. 6. The percent of gain reduction due to the neutrons energy deposition as a function of the incident driver energy for hydrodynamic coupling coefficient η = 0.1 and different values of the isentrope parameter. The dashed curves have obtained from interpolation of data.

dent driver energy and 50% for high values of it. These facts indicate that the neutrons deposition energy is important in calculations of concerning the ICF reactors. Furthermore, we have shown that increase in the hydrodynamic coupling coefficient to the extent that is possible, causes the target gain increases considerably. For the reason that a suitable designing of target causes its symmetry is retained, during the beam radiation on the target and the implosion, and the hydrodynamic instabilities reach the least value.

References

[1] H. J. Nuckolls, L. Wood, A. Thiessen, Nature. **239**, 139 (1972).
[2] S. Nakai, K. Mima, Rep. Prog. Phys. **67**, 321 (2004).
[3] A. R. Piriz, Nucl. Fusion. **32**, 933 (1992).
[4] M. M. Basko, Plasma Phys. Control. Fusion. **45**, A125 (2003).
[5] M. J. Tabatabaei, A. Ghasemizad, International Review of Phys. **3**, 219 (2009).
[6] S. Nakai, H. Takabe, Rep. Prog. Phys. **59**, 1071 (1996).
[7] J. Meyer-Ter-Vehn, Nucl. Fusion. **22**, 561 (1982).
[8] A. Ghasemizad, M. R. Eskandari, S. Khoshbinfar, Iranian Journal of Science & Technology **29**, 421 (2005).
[9] D. B. Harris, G. H. Miley, Nucl. Fusion. **28**, 25 (1988).
[10] M. M. Basko, Nucl. Fusion. **35**, 87 (1995).
[11] K. A. Brueckner, S. Jorna, Rev. Mod. Phys. **46**, 325 (1974).
[12] F. Briesmeister, Ed., MCNP-A General Monte Carlo N Particle Transport Code, Version 4C, LA-13709-M, (2000).