Studies on the Performance of ITER90 H-P Fusion Reactor Considering the D-T and D-^3^He Fuel in the Perturbation State

S. Nasrin Hoseinimotlagh, Samaneh Kian-Afraz, and Sara Sadeghi

Abstract—ITER is based on the ‘tokamak’ concept of magnetic confinement, in which plasma is contained in a doughnut-shaped vacuum vessel. The fuel – a mixture of deuterium and tritium, two isotopes of hydrogen – is heated to temperatures in excess of 150 million °C, forming hot plasma. Strong magnetic fields are used to keep the plasma away from the walls; these are produced by superconducting coils surrounding the vessel, and by an electrical current driven through the plasma. ITER is the next generation of experimental fusion device and it is hoped it will point the way to fusion as a sustainable energy source for the future. To exploit the full potential of the device and to guarantee optimal operation, a high degree of physics modeling and simulation is needed. In addition, the possibility of higher Q operation will be explored if favorable confinement conditions can be achieved. In this work, perturbation state is called the difference between dynamical and steady state. So, we study on the variations of dynamical system respect to steady state for two fusion fuels DT and D-3He. Our studies show that, the maximum fusion gain that is accessible for D-T is about 23 at t=50s and for D-3He 25 at t=250s.

Index Terms—Fusion, deuterium, tritium, helium, perturbation.

I. INTRODUCTION

The ITER project was initiated in 1985 as a symbol of the ending of the Cold War in talks between the then Soviet Secretary-General, Gorbachev, and the Presidents of France and the USA, Mitterrand and Reagan. In 2003 China and South Korea joined the project; the USA also rejoined. After prolonged negotiations on the siting of the test device – in Japan or Europe – the partners agreed in 2005 to the European proposal: Cadarache in France. Shortly thereafter India joined the project. The ITER project [1] will provide a basis for the scientific and technological feasibility of a fusion power reactor. It aims to exploit the full potential of the device and to guarantee optimal operation and to develop methodologies for the projection of plasma performance to the scale of ITER have been basically formulated in the ITER Physics Basis [2], which has been developed from broadly based experimental and modeling activities within the magnetic fusion programs of the ITER parties.

II. REACTIVITY PARAMETER FOR D – T AND D–^3^He FUSION REACTIONS

This paper, presents a strategy for the development of D-^3^He fusion for terrestrial and space power. The approach relies on modest plasma confinement progress in alternate fusion concepts and on the relatively less challenging engineering, environmental and safety features of a D-^3^He fueled fusion reactor compared to a D - T fueled fusion reactor. The D-^3^He benefits include full-lifetime materials, reduced radiation damage, less activation, absence of tritium breeding blankets, highly efficient direct energy conversion, easier maintenance and proliferation resistance. The main fusion fuels are: D + T → ^4^He + n + 17.6 MeV, D + ^3^He → ^4^He + p + 18.4 MeV. Also another important parameter is reactivity of D - T and D-^3^He which depends on the temperature.

A. Bucky Reactivity Is Temperature Dependent (T (keV)) and Is Given by

\[ \langle \sigma \nu \rangle_{BT} = \exp \left( \frac{a_1}{T} + a_2 + a_3T + a_4T^2 + a_5T^3 + a_6T^4 \right) \] (1)

Here \( a_i \) and \( r \) are given in ref. [2] (1)

B. Bosch-Hale Reactivity Is Given by the Following Formula(3)

\[ \langle \sigma \nu \rangle = C_0 e^{-3T} \sqrt{\sqrt{m/C_{T^3}}} \] (2)

\[ \xi, \theta \] and \( B_G \) are:

\[ \xi = \left( \frac{B_G^2}{4\theta} \right)^{\frac{1}{2}} \] (3)

\[ \theta = \frac{T}{1 + T \left( C_1 + T \left( C_2 + T C_3 \right) \right)} \] (4)

Manuscript received November 9, 2013; revised January 17, 2014. This work was supported in part by the Department of Physics, Shiraz branch Islamic Azad University, Shiraz, Iran.

The authors are with Department of Physics, Shiraz branch Islamic Azad University, Shiraz, Iran (e-mail: hoseinimotlagh@hotmail.com, s_kianafraz@yahoo.com, sara_sadeghi1368@yahoo.com).
\[ B_G = \pi \alpha Z, Z \sqrt[2]{2m}c^2 \]  

(5)

The constants values of \( c_1 \) to \( c_5 \) and \( m, c^2 \text{ (keV)} \) in the see equations are given in ref. [3]. According to the above equations and the data in Fig. 1 we plotted the \( \langle \sigma v \rangle \) versus temperature for the fusion reaction of D - T and D-3He for both of Bucky and Bosch-Hale formulae.

\[ \langle \sigma v \rangle_{\text{Bucky}} \text{ (cm}^2 \text{s}^{-1}) \]
\[ \langle \sigma v \rangle_{\text{Bosch-Hale}} \text{ (cm}^2 \text{s}^{-1}) \]

As shown in Fig. 1, the reactivity of D – T fusion reaction is greater than D-3He. Because \( \langle \sigma v \rangle_{DT} \) at 70 keV temperature has a maximum value thus 70 keV is temperature resonance. The value of D – T reactivity at this temperature approximately 10 times is greater than D-3He. By viewing the obtained numerical values and Fig. 1 we find that the difference between the two ways of calculating reactivity is minimal and since that the method of Bucky is newer than Bosch-Hale in our calculations we use this.

III. PERTURBATION NONLINEAR POINT KINETIC EQUATIONS GOVERNING ON THE ITER 90 HP FUSION REACTOR ITER 90 HP FOR THE D – T AND D-3He FUEL.

In this work, perturbation state is called the difference between dynamical and steady state [4], [5]. So, in this part, we will study on the variations of dynamical system respect to steady state. Therefore, to achieve this goal we use the assumptions \( \bar{n}_i = 0 \) and \( \bar{S}_i = 0 \). In other words, we ignore the presence of impurities. Since, there so Nance temperature for the D – T reaction is equal to 70(keV) thus, in this temperature we have maximum gain fusion in both static and dynamics of D – T fusion. Under these conditions, for two fuels D – T and D-3He physical parameters such as perturbation neutral fuel density \( (\bar{n}_{DT}) \), perturbation Injection rate \( (\bar{E}_i) \), perturbation energy\( (\bar{E}_i) \), perturbation auxiliary power\( (\bar{P}_{aux}) \), perturbation density of alpha particles \( (\bar{n}_{\alpha}) \), perturbation Injection rate impurity\( (\bar{S}_i) \), density of impurity particles in a perturbation state\( (\bar{n}_{Si}) \), particle density, \( T, D, \) in a perturbation state\( (\bar{n}_{Si}) \) and the particle density of \( D \) and \( ^3\text{He} \) in perturbation will be introduced. With assuming \( \bar{n}_i = 0 \) and \( \bar{S}_i = 0 \) we will determine in the following the deviations from equilibrium values for two fuel D – T and D-3He. In which in above mentioned parameters and in the following equations for D – T and D-3He the index \( i = DT, D^3\text{He} \).

\[ \bar{n}_{DT} = n_{DT} - \bar{n}_{DT} \]

(6)

\[ \bar{S}_i = S_i - \bar{S}_i \]

(7)

\[ \bar{E}_i = E_i - \bar{E}_i \]

(8)

\[ \bar{P}_{aux} = P_{aux} - \bar{P}_{aux} \]

(9)

\[ \bar{n}_{\alpha} = n_{\alpha} - \bar{n}_{\alpha} \]

(10)

\[ \bar{S}_i = S_i - \bar{S}_i = \bar{S}_i \]

(11)

\[ \bar{n}_i = n_i - \bar{n}_i \]

(12)

\[ \bar{n}_i = n_i - \bar{n}_i \]

(13)

Therefore, the dynamical equations for perturbation state for both of fuel D – T and D-3He are given in the following, respectively [6].

\[ \frac{d\bar{n}_{DT}}{dt} = -\frac{\bar{n}_{DT}}{\tau_{DT}} + \left[ \frac{\bar{E}_i}{2} + \frac{1}{2} \bar{n}_i \bar{E}_i \right] < \sigma v > _i + u_{\alpha} \]

(14)

\[ \frac{d\bar{n}_i}{dt} = -\frac{\bar{n}_i}{\tau_i} - \left[ 2 \left( \frac{\bar{E}_i}{2} \right) - \bar{n}_i \bar{E}_i \right] < \sigma v > _i + \bar{n}_{DT} \]

(15)
\[
\frac{d\bar{n}_i}{dt^*} = S_i^* \tag{16}
\]
\[
\frac{d\bar{n}_i}{dt^*} = \frac{-\bar{n}_i}{\tau_i^*} + S_i \tag{17}
\]
\[
\frac{dE_i}{dt} = -\frac{E_i}{\tau_{E_i}} - \left( E_i - \tau_{E_i} \left[ P_{\text{ohmic}} + P_{\text{rad}} + P_{\text{aux}} \right] \right) \tag{18}
\]
\[
u_i = -\frac{\bar{n}_i}{\tau_{\bar{n}_i}} + \left( \frac{\bar{n}_i}{2} \right) \left< \sigma v \right> \tag{19}
\]
\[
u_i = -\frac{\bar{n}_i}{\tau_{\bar{n}_i}} - 2 \left( \frac{\bar{n}_i}{2} \right) \left< \sigma v \right> + \frac{\bar{n}_i}{\tau_{\bar{n}_i}} \tag{20}
\]
\[
S_i^* = -\frac{n_i n_i}{\tau_{n_i}} + S_i^* = \frac{n_i n_i}{\tau_{n_i}^*} + s_i \tag{21}
\]
\[
\tilde{P}_{\text{aux}} = \tilde{E} - \left( \frac{\bar{n}_i}{2} \right) \left< \sigma v \right> Q_{\bar{n}_i} - \tilde{P}_{\text{ohmic}} + A_{\bar{n}_i} \left( \bar{n}_i + 2n_{\bar{n}_i} \right) \left( \bar{n}_i + 4n_{\bar{n}_i} \right) \left( \frac{2E_i}{3N_i} \right) \tag{22}
\]

The equation of total energy and density in the perturbation form can be written in the following form: [7]

\[
E_i = \frac{2}{3} N_i T_i \tag{23}
\]
\[
N_i = 2\bar{n}_i + 3n_{\bar{n}_i} + (Z_{i+1})\bar{n}_i \tag{24}
\]

Also the perturbation radioactive power loss is given by:

\[
\tilde{P}_{\text{rad}} = A_{\bar{n}_i} \times Z_{\text{eff}} \times \bar{n}_i^2 \times T_i \tag{25}
\]

where the value of \( \lambda \) coefficient, the effective charge of all ions and electron density for the two fuels D-T and D-3He are given by:

\[
A_{\text{eff}} = 4.85 \times 10^{-37} \left( \frac{\text{Wm}^{-1}}{\text{keV}} \right) \tag{26}
\]
\[
A_{\text{D-T}} = 5.35 \times 10^{-37} \left( \frac{\text{Wm}^{-1}}{\text{keV}} \right) \tag{27}
\]
\[
Z_{\text{eff}} = \frac{\bar{n}_i + A \bar{n}_{\bar{n}_i}}{\bar{n}_i + 2A \bar{n}_{\bar{n}_i}} \tag{28}
\]

\[
\bar{n}_i = \bar{n}_i + 2n_{\bar{n}_i} + Z_{i+1} \bar{n}_i \tag{29}
\]

\( Z_i \) is the atomic number of the impurity.

\[
\tilde{P}_{\text{fu}_i} = \left( \frac{\bar{n}_i}{A_{\bar{n}_i}} \right)^2 \sigma v > Q_i \tag{30}
\]

\[
\tilde{Q}_i = \frac{\tilde{P}_{\text{fu}_i}}{P_{\text{aux}}} \tag{31}
\]

IV. NUMERICAL SOLUTIONS OF PERTURBATION NONLINEAR POINT KINETIC EQUATIONS GOVERNING ON THE ITER 90 HP FUSION REACTOR ITER 90 HP FOR THE D - T AND D-3HE FUEL

From the numerical solution of equations (13) to (29), for the two fuels D - T and D-3He we determine the perturbation particle densities of both and perturbation energy density in the time range of 0 to 400 seconds and at the three temperatures (keV) 100,70,10. Fig. 2 to Fig. 7 compare that the perturbation density of the fuels D - T and D-3He in terms of time at three temperatures (keV) 100,70,10

![Fig. 2. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, tritium densities in D-T fuel temperature10 Kevand time range from 400 to 0s.](image)

![Fig. 3. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, tritium densities in D-T fuel temperature70 Kevand time range from 400 to 0s.](image)

![Fig. 4. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, tritium densities in D-T fuel temperature100 Kevand time range from 0 to 400s.](image)
Fig. 5. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, helium densities in D-^3He fuel temperature 10 keV and time range from 400 to 0s.

Fig. 6. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, helium densities in D-^3He fuel temperature 70 keV and time range from 400 to 0s.

Fig. 7. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, helium densities in fuel temperature 100 keV and time range from 400 to 0s.

Also perturbation variations of energy density for both fuel D–T and D–^3He in three temperatures (keV) 100, 70, 10 are given in the Fig. 8 and Fig. 9.

Fig. 8. Comparison of perturbation time variations of energy density for DT fuel in three of temperature at 10, 70 and 100 keV in the time range from 0 to 400s.

By observing these figures and tables for two fuels D–T and D–^3He at three temperatures (keV) 100, 70, 10 in the perturbation state, we find that since by increasing time these fuels more consumed therefore density of them are decreased.

Fig. 9. Comparison of perturbation time variations of energy density for D–^3He fuel in three of temperature at 10, 70 and 100 keV in the time range from 0 to 400s.

But because of the time increasing, particles T with D and D with ^3He fuse with together, so with time increasing the number of alpha particles from the fusion of the particles increase. Also with increasing time, neutral particles in the system is reduced therefore the density of them quickly reduced. Also the energy density with increasing time rapidly is increased and reaches to fixed value. Since $T = 70 (keV)$ is the resonance temperature of the D–T reaction, in this temperature we have maximum of fusion power thus the rest of our calculations are performed in this temperature [8], [9]. Also from equation (28) we can plotted the time variations of for the two fuels D–T and D–^3He at the resonance temperature 70(keV) (see Fig. 10).
Fig. 10. Comparison of the effective charge of the all ions for two fuel D-T and D-3He in the perturbation state at the temperature 70 Kev and time interval 0 to 400s.

From this figure we see that with time increasing for the two fuels D – T and D-3He in the time interval 0 to 210s, they have large difference and then by increasing time, they are nearly equal and are declining. Also from equation (29) we can plotted the perturbation time variations of electron density ($n_e$) versus time for the two fuels D – T and D-3He In the resonance temperature 70(keV) (see Fig. 11). Also from equation (25) we can plot the radiative power loss versus time for the two fuels D – T and D-3He at resonance temperature 70(keV) (see Fig. 12).

Fig. 11. Comparison of the perturbation electron density for two of the fuel D-T and the temperature and time interval 0 to 400s.

According to Fig. 4, Fig. 5, and Fig. 14 we can find that the perturbation variations of radioactive power loss of D-3He is greater than D - T. Also from equation (24) we can plot the diagrams of perturbation total density versus time for the two fuels D – T and D-3He at resonance temperature 70(keV) (see Fig. 13).

Fig. 12. comparison of perturbation radiative power loss of the a) DT and b) D-3He fuels in the time range of 0 to 400 seconds.

Fig. 13 shows that the density of the D-3He is greater than D - T. Also from equation (23) we can plot the perturbation total energy versus time for the two fuels D-T and D-3He at resonance temperature 70(keV) (see Fig. 14). According to Fig. 14 we can find that perturbation variations of total energy of D-3He is greater than D - T.

Fig. 14. Perturbation total energy of the fuel D-T and D-3He in the time interval 0 to 400s in and temperature 70 Kev.

From Fig. 15 we can find that the perturbation variations of fusion power versus time of D-3He is greater than D-T. Also from equation (22) we can plot the perturbation auxiliary power versus time for the two fuels D – T and D-3He at resonance temperature 70(keV) (see Fig. 16).

Fig. 15. Comparison of fusion power for D-T and D-3He fuel in time range of 0 to 400 seconds at temperature 70(keV).

Fig. 16. comparison of the perturbation auxiliary power for two fuels D-T and D-3He fuel in time interval 0 to 400s.

With observing Fig. 16 we can find that perturbation auxiliary power of D-3He respect to D - T is greater. Also from equation (31) we can plot the perturbation fusion gain in terms of time for both fuel D – T and D-3He at resonance...
temperature $70(keV)$ (see Fig. 17).

![Fig. 17. Comparison of perturbation fusion gain for D-T and fusion fuels at resonance temperature in the time interval 0 to 400s.](image)

Form Fig. 17 we find that the perturbation variations of fusion gain for D-T fuels is larger than $D-^3He$. And perturbation fusion gain in both fuels will increase with time increasing.

V. DISCUSSION AND CONCLUSION

In order to be commercially competitive, a fusion reactor needs to run long periods of time in a stable burning plasma mode at working points which are characterized by a high $Q$, where $Q$ is the ratio of fusion power to auxiliary power. Active burn control is often required to maintain these near-ignited or ignited conditions ($Q = \infty$). Although operating points with these characteristics that are inherently stable exist for most confinement scaling, they are found in a region of high temperature and low density. Our studies show that in the perturbation state above quantities area function of temperature and time such that each has its own specific variations and also at the temperature $70\,(keV)$ these quantities produce the maximum fusion gain for both of fuels $D$–T and $D-^3He$, such that their values are equal to 23 for D - T fuel-and the 25 for $D-^3He$, respectively. Fusion using $D-^3He$ fuel requires significant physics development particularly of plasma confinement in high performance alternate fusion concepts. Countering that cost, engineering development cost should be much less for $D-^3He$ than $D$ – T, because $D-^3He$ greatly ameliorates the daunting obstacles caused by abundant neutrons and the necessity of tritium breeding.

REFERENCES


Seyeddeh Nasrin Hosseinimotlagh received her Ph.D and MS degrees from the Physics Department of Shiraz University in Iran. She is an assistant professor in Department of Physics, Shiraz branch Islamic Azad University, Shiraz, Iran. She has published in various journals, Department of Physics,Sciences College,Shiraz branch Islamic Azad University, Pardis,Sadra town, Shiraz, Iran.

Samaneh Kianafraz received her B.S degree from Physics Department of Shiraz, Islamic Azad University in Iran. She is university student in M.S in nuclear physics. She has published in various journals.

Sara Sadeghi received her B.S from Department of Physics, Shiraz branch Islamic Azad University, Shiraz, Iran. She is university student in M.S in Atomic molecular physics. She has published in various journals Department of Physics,Sciences College,Shiraz branch Islamic Azad University, Pardis,Sadra town, Shiraz, Iran.