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

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***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 ℃, 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-^{3}He 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 create for the first time, sustained deuterium/tritium plasma, predominantly heated by α-particles produced by the fusion reactions ("burning" plasmas). It is a major step in the world fusion program, and a culmination of almost fifty years of magnetic confinement fusion research. In addition, the possibility of higher Q operation will be explored if favorable confinement conditions can be achieved. The rules and 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.

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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 $\rightarrow^4$ He + n + 17.6 MeV, *D* + ^3He $\rightarrow^4$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

$$\langle\sigma v\rangle_{DT} = \exp\left(\frac{a_1}{T^r} + a_2 + a_3T + a_4T^2 + a_5T^3 + a_6T^4\right) \quad (1)$$

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

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

$$\langle\sigma v\rangle = C_1\theta e^{-3\xi}\sqrt{\xi\big/\left(m_rC^2T^3\right)} \quad (2)$$

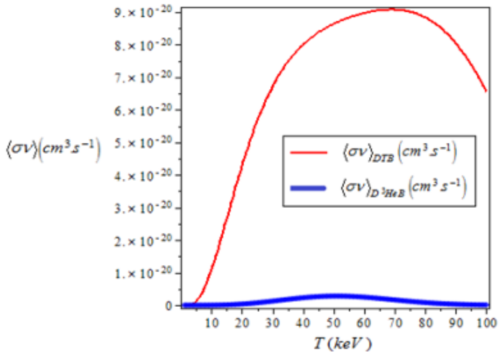
ξ 、 θ and B_G are:

$$\xi = \left(\frac{B_G^2}{4\theta}\right)^{1/3} \quad (3)$$

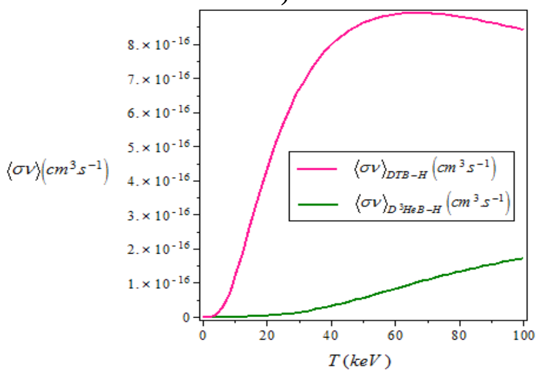
$$\theta = T\Bigg/\left[1-\frac{T\left(C_2+T\left(C_4+TC_6\right)\right)}{1+T\left(C_3+T\left(C_5+TC_7\right)\right)}\right] \quad (4)$$

$$B_G = \pi \alpha Z_1 Z_2 \sqrt{2 m_r c^2} \quad (5)$$

The constants values o C_1 to C_7 and $m_r c^2 (keV)$ in the see quations 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-^{3}He for both of Bucky and Bosch-Hale formulae.



a)



b)

Fig. 1. Comparison of the graphs of fusion reactions reactivity variations for a)D - Tand b) $D - {}^3He$ versus temperature by the two methods, Bucky ($\langle \sigma v \rangle_{DT.B} (cm^3.s^{-1})$ ، $\langle \sigma v \rangle_{D\,^3He.B} (cm^3.s^{-1})$ and Bosch-Hale($\langle \sigma v \rangle_{DT.B-H} (cm^3.s^{-1})$ ، $\langle \sigma v \rangle_{D\,^3He.B-H} (cm^3.s^{-1})$).

As shown in Fig. 1, the reactivity of D – T fusion reaction is greater than D-^{3}He .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-^{3}He.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-^{3}He 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, weignoret he presence of impurities. Since, there so Nance temperature for the D – Treaction 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-^{3}He physical parameters such as perturbation neutral fuel density ($\tilde{n}_{n_i}$), perturbation Injection rate ($\tilde{S}_i$),perturbation energy($\tilde{E}_i$),perturbation auxiliary power($\tilde{P}_{aux_i}$), perturbation density of alpha particles ($\tilde{n}_{\alpha_i}$),perturbation Injection rate impurity($\tilde{S}_{I_i}$),density of impurity particles in a perturbation state($\tilde{n}_{I_i}$), particle density, T, D, in a perturbation state,($\tilde{n}_{DT}$) and the particle density of , D and ^3He 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-^{3}He .in which in above mentioned parameters and in the following equations for D - T and D-^{3}He the index i imply that $(i = DT, D\,^3He)$.

$$\tilde{n}_{n_i} = n_{n_i} - \bar{n}_{n_i} \quad (6)$$

$$\tilde{S}_i = S_i - \bar{S}_i \quad (7)$$

$$\tilde{E}_i = E_i - \bar{E}_i \quad (8)$$

$$\tilde{P}_{aux_i} = P_{aux_i} - \bar{P}_{aux_i} \quad (9)$$

$$\tilde{n}_{\alpha_i} = n_{\alpha_i} - \bar{n}_{\alpha_i} \quad (10)$$

$$\tilde{S}_{I_i} = S_{I_i} - \bar{S}_{I_i} = S_{I_i} \rangle 0 \quad (11)$$

$$\tilde{n}_{I_i} = n_{I_i} - \bar{n}_{I_i} = n_{I_i} \rangle 0 \quad (12)$$

$$\tilde{n}_i = n_i - \bar{n}_i \quad (13)$$

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

$$\frac{d\tilde{n}_{\alpha_i}}{dt} = \frac{-\tilde{n}_{\alpha_i}}{\tau_{\alpha_i}} + \left[\left(\frac{\tilde{n}_i}{2} \right)^2 + \frac{1}{2} \tilde{n}_i \bar{n}_i \right] < \sigma v >_i + u_{\alpha_i} \quad (14)$$

$$\frac{d\tilde{n}_i}{dt} = \frac{-\tilde{n}_i}{\tau_i} - \left[2 \left(\frac{\tilde{n}_i}{2} \right)^2 - \tilde{n}_i \bar{n}_i \right] < \sigma v >_i + \frac{\tilde{n}_{n_i}}{\tau_{d_i}} + u_i \quad (15)$$

$$\frac{d\tilde{n}_{n_i}}{dt} = S_i^* \quad (16)$$

$$\frac{d\tilde{n}_{I_i}}{dt} = \frac{-\tilde{n}_{I_i}}{\tau_{I_i}} + S_{I_i} \quad (17)$$

$$\frac{d\tilde{E}_i}{dt} = -\frac{\bar{E}_i}{\tau_{E_i}} - \{\frac{\bar{E}_i}{\tau_{E_i}} - \left[P_{\alpha_i} + P_{ohmic_i} - P_{rad_i} + P_{aux_i}\right]\} \quad (18)$$

$$u_{\alpha_i} = -\frac{\bar{n}_{\alpha_i}}{\tau_{\alpha_i}} + (\frac{\bar{n}_i}{2})^2 \langle \sigma v \rangle_i \quad (19)$$

$$u_i = -\frac{\bar{n}_i}{\tau_i} - 2(\frac{\bar{n}_i}{2})^2 < \sigma v >_i + \frac{\bar{n}_{n_i}}{\tau_{d_i}} \quad (20)$$

$$S_i^* = -\frac{\widetilde{n}n_i}{\tau_{d_i}} + \tilde{S}_i - \frac{\bar{n}n_i}{\tau_{d_i}} + \bar{S}_i = \frac{n_{n_i}}{\tau_{d_i}} + s_i \quad (21)$$

$$\tilde{P}_{aux_i} = \frac{\tilde{E}}{\tau_{E_i}} - \left(\frac{\tilde{n}_i}{2}\right)^2 \langle \sigma v \rangle_i Q_{\alpha_i} - \tilde{P}_{ohmic_i} + A_{b_i}\left(\tilde{n}_i + 2\tilde{n}_{\alpha_i}\right)\left(\tilde{n}_i + 4\tilde{n}_{\alpha_i}\right)\sqrt{\frac{2\tilde{E}_i}{3\tilde{N}_i}} \quad (22)$$

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

$$\tilde{E}_i = \frac{3}{2}\tilde{N}_i T \quad (23)$$

$$\tilde{N}_i = 2\tilde{n}_i + 3\tilde{n}_{\alpha_i} + (Z_I + 1)\tilde{n}_{I_i} \quad (24)$$

Also the perturbation radioactive power loss is given by:

$$\tilde{P}_{rad_i} = A_{b_i} \times \tilde{Z}_{eff_i} \tilde{n}_{e_i}^2 \sqrt{T} \quad (25)$$

where the value of A_b coefficient, the effective charge of all ions and electron density for the two fuels D–T and D-^{3}He are given by:

$$A_{bDT} = 4.85 \times 10^{-37}\left(\frac{Wm^3}{\sqrt{keV}}\right) \quad (26)$$

$$A_{bD^3He} = 5.35 \times 10^{-37}\left(\frac{Wm^3}{\sqrt{keV}}\right) \quad (27)$$

$$\tilde{Z}_{eff_i} = \frac{\tilde{n}_i + 4\tilde{n}_{\alpha_i}}{\tilde{n}_i + 2\tilde{n}_{\alpha_i}} \quad (28)$$

$$\tilde{n}_{e_i} = \tilde{n}_i + 2\tilde{n}_{\alpha_i} + Z_I \tilde{n}_{I_i} \quad (29)$$

Z_I is the atomic number of the impurity.

$$\tilde{P}_{fu_i} = \frac{(\tilde{n}_i)^2}{4} < \sigma v >_i Q_i \quad (30)$$

$$\tilde{Q}_i = \frac{\tilde{P}_{fui}}{\tilde{P}_{auxi}} \quad (31)$$

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-^{3}He Fuel

From the numerical solution of equations (13) to (29),for the two fuels D – T and D-^{3}He we determine the perturbation particle densities of both and perturbation energy density in the time range of 0 to400secondsand 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-^{3}He in terms of time at three temperatures $(keV)100,70,10$

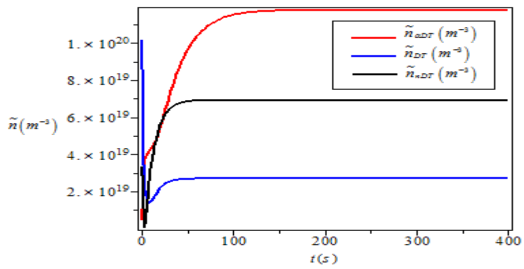


Fig. 2. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, tritium densities in D-T fuel temperature10 Kevand time range from 400 to 0s.

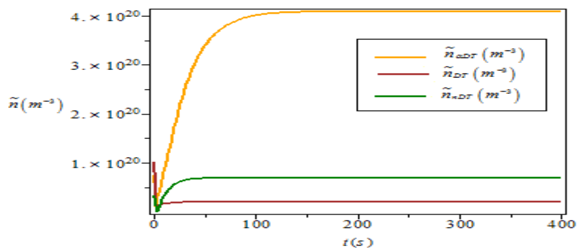


Fig. 3. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, tritium densities in D-T fuel temperature70 Kevand time range from 400 to 0s.

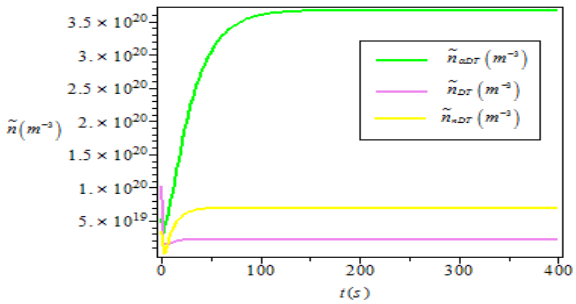


Fig. 4. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, tritium densities in D-T fuel temperature100 Kevand time range from 0 to 400s.

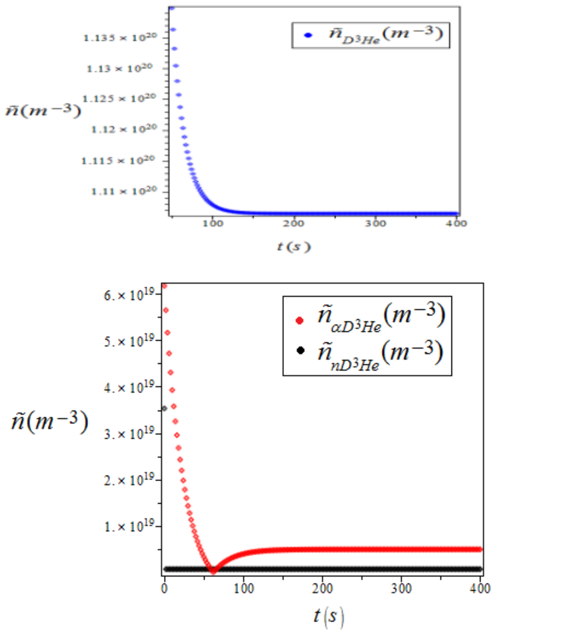


Fig. 5. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, helium densities in D-^{3}He fuel temperature10 Kev and time range from 400 to 0s.

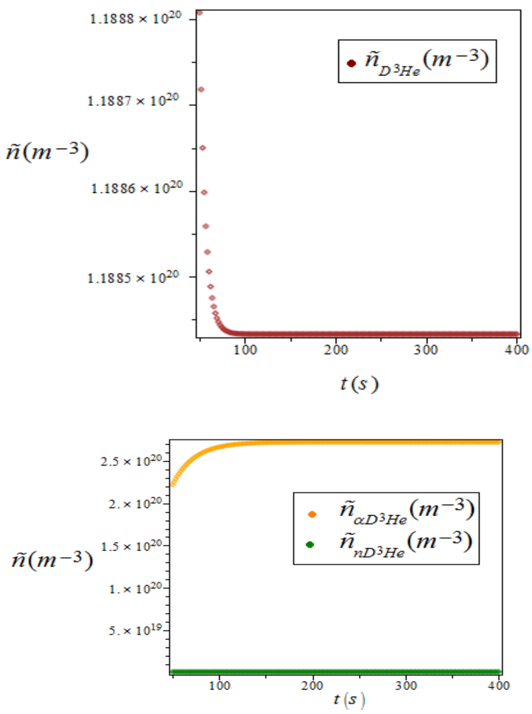
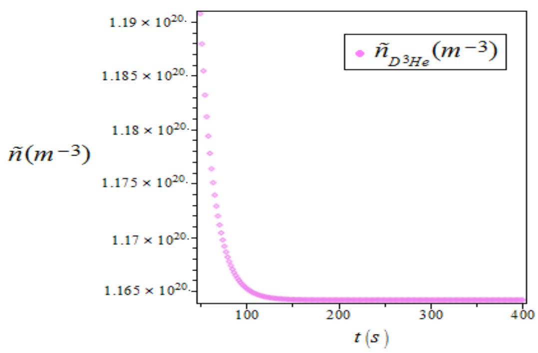


Fig. 6. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, helium densities in D-^{3}He fuel temperature 70 Kevand time range from 400 to 0s.



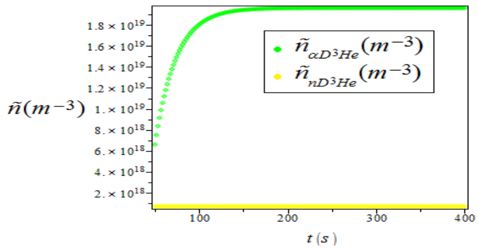


Fig. 7. Comparison of perturbation variations of neutral fuel density, alpha particles, deuterium, helium densities in fuel temperature 100 Kev and time range from 400 to 0s.

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

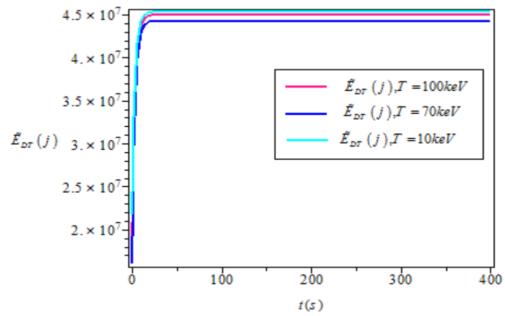


Fig. 8. Comparison of perturbation time variations of energy density for $D-T$ fuel in three of temperature at 10, 70 and100 Kev in the time range from 0 to 400s.

By observing these figures and tables for two fuels D-T and D-^{3}He 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.

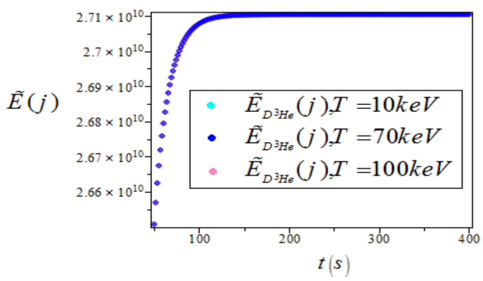


Fig. 9. Comparison of perturbation time variations of energy density for D-^{3}He fuelin three of temperature at 10, 70 and100 Kev in the time range from 0 to 400s.

But because of the time increasing, particles T with D and D with ^{3}He 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 afixed 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-^{3}He at the resonance temperature $70(keV)$ (see Fig. 10).

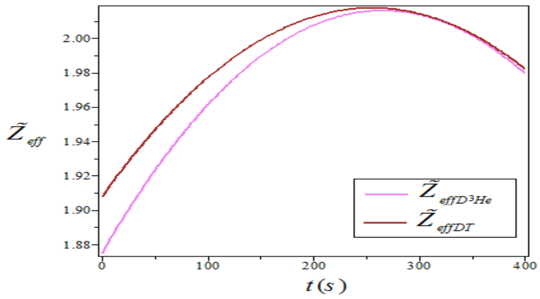


Fig. 10. Comparison of the effective charge of the all ions for two fuel D-T andlin the perturbation state at thetemperature70 Kev and time interval 0 to400s.

From this figure we see that with time increasing for the two fuels D – T and D-^{3}He in the time interval 0 to210s, 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 ($\tilde{n}_e$) versus time for the two fuels D –T and D-^{3}He 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-^{3}He at resonance temperature $70(keV)$ (see Fig. 12).

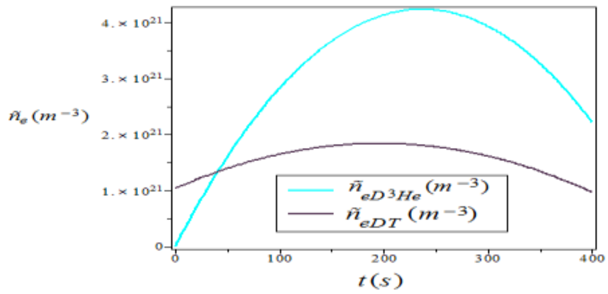


Fig. 11. Comparison of the perturbation electron density for two of the fuel D-T and the temperature and time interval 0 to400s.

According to Fig. 4, Fig. 5, and Fig. 14 we can find that the perturbation variations of radioactive power loss of D-^{3}He 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 at resonance temperature $70(keV)$(see Fig. 13).

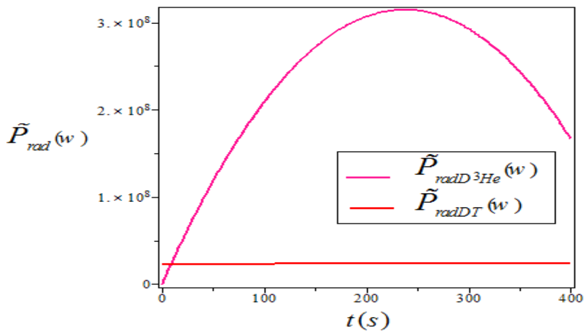


Fig. 12. comparison of perturbation radiative power loss of thea) DT and b) D-^{3}He fuelsin the resonance temperature $70(keV)$ and time interval 0 to400s.

Fig. 13 shows that the density of the D-^{3}He 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-^{3}He at $70(keV)$ resonance temperature (see Fig. 14). According to Fig. 14 we can find that perturbation variations of total energy of D-^{3}He is greater than D - T.

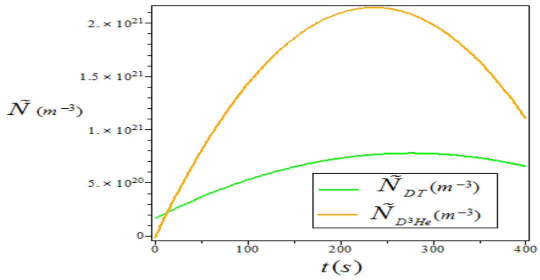


Fig. 13. Comparison of perturbation total density of the fuelD-T and D-^{3}He in the time interval 0 to400s in andtemperature70 Kev.

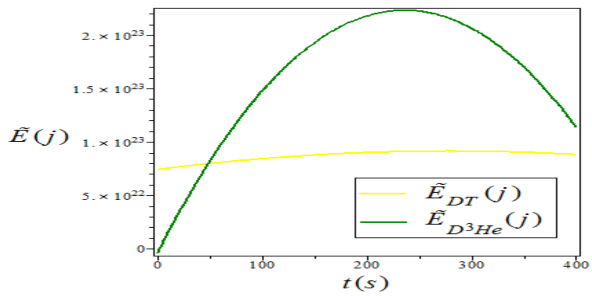


Fig. 14. Perturbation total energy of the fuel D-T and D-^{3}He in the time interval 0 to400s in andtemperature70 Kev.

From Fig. 15 we can find that the perturbation variations of fusion power versus time of D-^{3}He 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-^{3}He at resonance temperature $70(keV)$ (see Fig. 16)

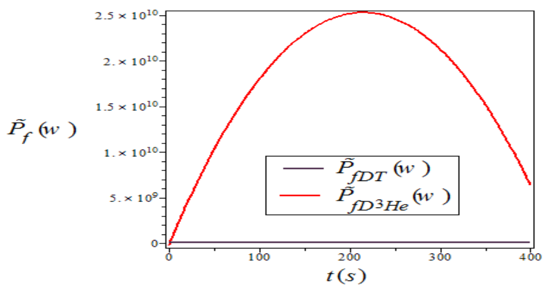


Fig. 15. Comparison of fusion power for D-T and D-^{3}He fuel in time range of 0 to400secondsat temperature $70(keV)$.

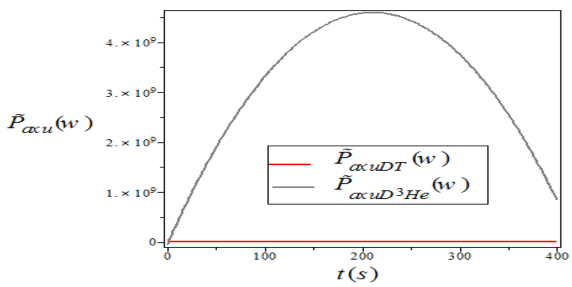


Fig. 16. comparison of the perturbation auxiliary power for two fuels D-T and D-^{3}He at resonant temperature $70(keV)$ in the time interval0 to400s.

With observing Fig. 16 we can find that perturbation auxiliary power of D-^{3}He 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-^{3}He at resonance temperature $70(keV)$ (see Fig. 17).

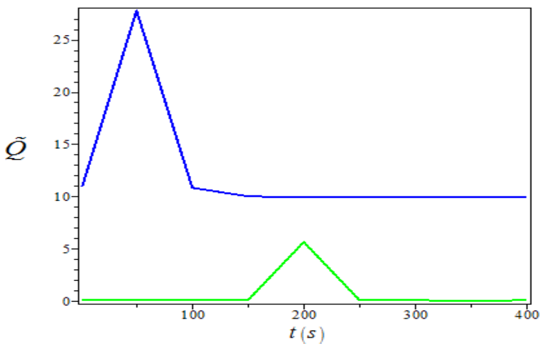


Fig. 17. Comparison of perturbation fusion gain for D-T and fusion fuels at resonance temperature in the time interval 0 to400s.

Form Fig. 17 we find that the perturbation variations of fusion gain for D-T fuelis larger than D-^{3}He. 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-^{3}He, such that their values are equal to 23 for D - T fuel-and the 25 for D-^{3}He, respectively. Fusion using D-^{3}He 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-^{3}He than D – T, because D-^{3}He greatly ameliorates the daunting obstacles caused by abundant neutrons and the necessity of tritium breeding.

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