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The Feasibility of using ^{3}He-^{3}He Fuel in a Fusion Reactor

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ABSTRACT

The possibilities of using advanced aneutronic fuels such as ^{3}He-^{3}He for a clean and efficient fusion power generation are regarded as the most important topics in nuclear engineering. This fuel is completely neutron-free thus, no material activation inside the fusion reactor and no dangerous consequence of accidental radioactive release occurs but it requires high demanding conditions for present-day technology. The investigations show that the radiation power losses are the main problems in the use of this fuel in a fusion reactor. The losses have a principal role in determining the operating temperature of this fuel. The results demonstrate that even under almost optimistic operating conditions, the bremsstrahlung loss power is more than fusion power. To dominate the bremsstrahlung radiation, it would be desired to reduce the electron temperature less than their normal equilibrium values. To improve the performance of ^{3}He-^{3}He fusion reactor and to minimize bremsstrahlung and synchrotron radiation, it is essential that the energy transmitted from ions to electrons is minimized. When the electron temperature is low enough, the bremsstrahlung loss is manageable; however, the ion-electron energy transfer rate is very large. The studies indicate that the reduction in the bremsstrahlung power fraction is more useful than the reduction in the ion-electron energy transfer fraction. To restrict he bremsstrahlung power to logical theory level (less than half the fusion power), it is essential to reduce the ion-electron energy transfer rate to the possible minimum in ^{3}He-^{3}He fuel.

Keywords: Fusion, Reactor, Fuel, Radiation, Power

1. Introduction

The choice of suitable fuel for fusion reactors is very important and should substantially consider the various status including economic, safety, and environmental parameters that is very difficult to satisfy all of them. The DT fuel has the highest energy yield, the lowest ignition requirements and burns easily among all reactions in a fusion reactor. But this fuel has two major disadvantages, first, it requires the use of tritium, a radioactive gas and the second is the production of 14MeV neutrons in the reaction which causes severe structural damage to the reactor walls. The DD reaction is very attractive since deuterium is abundant and it eliminates the need for breed tritium. The produced neutrons are not a lot and they have less energy than DT reaction. There is an atmospheric pollution due to tritium production through DD fusion plasma. D^{3}He reaction produces few neutrons relatively and nothing is needed for breeding. The reaction products, being charged particles, can be manipulated by electric and magnetic fields and as a result they can be used for direct energy conversion which is more efficient than thermal conversion [1-3]. The helium-3's isotope can be produced through tritium decay and DT reaction and can be safely transported to power plants. This reaction requires a higher temperature to ignite than DT reaction [4]. Deuterium-based fuels have the advantage of operating at relatively low temperatures, but involve more neutron and tritium production via side DD reaction. The p^{11}B reaction

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produces no neutrons and the released energy is carried away doubly by energetic ionized alpha particles. Another advantage is the much larger cross-section at lower energies. The high electric charge of boron (it has five protons) makes the task of designing an energy producing system very difficult. The p^7Li reaction has no advantage over $p^{11}B$ and it somewhat has a lower cross-section. The p^6Li reaction is often considered because of the low charge of both constituents. The proton-based fuels due to the high temperature is required and almost the low energy released per reaction, seems much harder to burn successfully, forcing the use of more advanced confinement approaches [5]. The ^3He -^3He reaction releases two protons and one ^4He ion as follows:

$$^3_2He + ^3_2He \rightarrow ^4_2He + 2^1_1H + 12.86\ \text{MeV} \qquad (1)$$

This reaction does not produce neutrons in the whole process of decay and total energy is released through charged particles. Knowledge of the ^3He- ^3He reaction is very important because of its important role in energy production in the solar proton-proton I chain. Helium isotopes are not used for the weapons craft therefore there is no hazard of multiplication, unlike for the DT fuel cycle. The abundance of helium-3 is more on the moon than on earth. Unlike most nuclear fusion reactions, the fusion of helium-3 atoms release large amount of energy without causing radioactive substances around them. This fuel is the only solar, nuclear reaction which the cross section has been measured down to solar energies (≈ 20 keV) [6]. Because of the higher coulomb barrier, the energy required for ^3He-^3He fusion will be much higher than the conventional DD or DT fusion. The ^3He-^3He fuel has some advantages, including decreased neutron production, increased fusion energy carried by charged particles, the elimination of a need for tritium breeding, decreased need of heat to energy conversion and heat radiation, decreased reactor mass due to reduced shielding, closer positioning of the magnets to the reactor, no structural damage, no neutron radiation endangering and a presumably longer reactor lifetime [7,8]. Using this fuel in fusion reactors, it is possible to convert high-performance electrical energy instead of low-efficiency thermal conversion (>70%) [9].

The energy of the charged products in ^3He-^3He fusion plasma can be converted directly into electric power with the various electrostatic and magnetic direct energy converters. But this fuel makes efficient confinement more difficult due to lower cross sections, higher ion temperature than DT, lack of availability of ^3He, and increased radiation losses. The power lost by radiation should not exceed the input power in a fusion plasma. Some losses of energy can be minimized by suitable selection of designing parameters while some are intrinsic in reactant system. The control of radiation losses is the most important issue in a fusion reactor. In this paper, the feasibility of using ^3He-^3He fuel is investigated in a magnetic confinement fusion (MCF) reactor. In MCF approach uses magnetic fields to confine the hot fusion fuel in the form of a plasma. This paper is organized as follows: In section 2, the fusion cross section and averaged reactivity are reviewed. In section 3, fusion power density is examined. Bremsstrahlung radiation power is calculated in section 4. The synchrotron radiation power is investigated in section 5. Ion- electron energy transfer rate is investigated in section 6. Finally, the conclusion is presented in section 7.

2. The fusion cross section and averaged reactivity

The measurement of fusion cross-sections has been greatly considered since the beginning of fusion research. This parameter shows the probability of a given fusion reaction, depending on the relative velocity of the two nuclei, will happen. Fig.1 shows the-cross -section as a function of the central-of-mass kinetic energy for ^3He-^3He reaction.

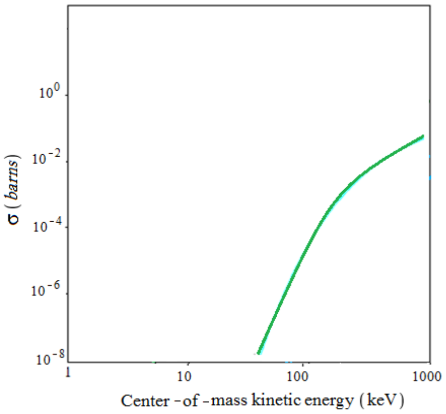

Fig.1 *Cross -section as a function of center-of-mass kinetic energy in the ^3He-^3He plasma*

The investigations show that this reaction has a smaller fusion cross section than other fusion reactions. The cross-section becomes significant only at very high ion temperatures and this is one of the main problems for ^3He-^3He plasma. Maximum cross-section happens for ^3He ions with an energy of more than the 30MeV incident on a target plasma of static ^3He ions [10]. Generally, the fusion gain is determined by reactivity quantity (probability of reaction per unit time and density of the target nucleus) and its average value is displayed $\langle \sigma v \rangle$ (σ and v are cross-section and relative velocity between two nuclei). Fig.2 shows average reactivities for different fusion plasma as a function of ion temperature using reference data [11]. As can be seen, the average reactivity increases with the rise ion temperature and ^3He-^3He reactivity is much less than other fusion plasmas.

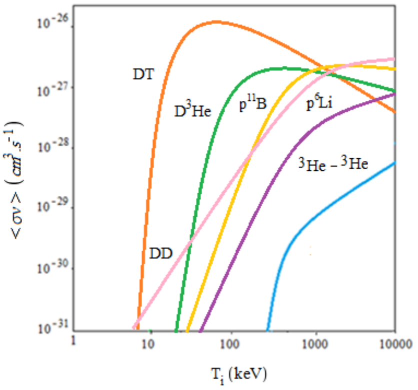

Fig.2 *Average reactivities as a function of ion temperature for different plasmas*

3. Fusion power density

The power density of nuclear fusion reactions plays an important role in the construction of any power plants. It is clear that the power released by the fusion reaction is strongly depended on the fusion cross - section and reactivity. The power per volume which produced two different ion species i_1 and i_2 by the fusion is :

$$P_f = 1.602\times10^{-19} n_{i_1} n_{i_2} < \sigma\upsilon > E_{fus} \frac{W}{cm^3} \qquad (2)$$

Where $<\sigma\upsilon>$ is the average reactivity plasma in cm^3/s, E_{fus} is the energy released (in eV) by fusion reaction and n_{i_1} and n_{i_2} are the densities of the two ion species. In the case of ^{3}He-^{3}He fusion reaction, in order to avoid counting the same reactions twice $n_{i_1} n_{i_2}$ in the above formula is replaced by $\frac{1}{2} n^2_{^3He}$. Fig.3 shows the fusion power density increases by increasing the average reactivity and electron density in the ^{3}He-^{3}He plasma.

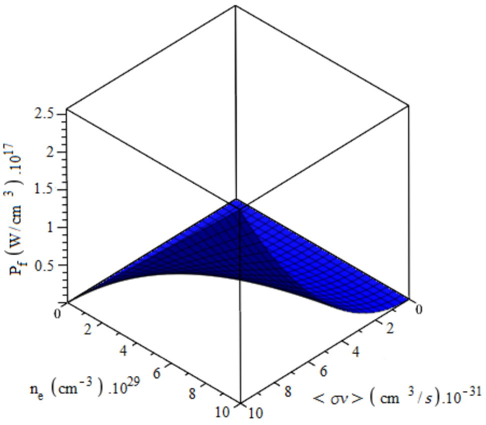

Fig.3 *Fusion power density in terms of electron density and the average reactivity in the ^{3}He-^{3}He plasma*

4. Bremsstrahlung radiation power

Bremsstrahlung radiation emission is an important energy loss mechanism for energetic electrons in plasmas. In this section the effect of bremsstrahlung emission on the performance of the ^{3}He-^{3}He plasma is investigated. This parameter reduces the gain of ^{3}He-^{3}He plasma. It is caused by electrons colliding with ions or with other electrons into the plasma. Taking into account relativistic corrections, bremsstrahlung loss is given by [12]:

$$P_B = 1.62\times10^{-32} n_e^2 \sqrt{T_e} \times \left[\sum_i \frac{Z_i^2 n_i}{n_e}\left\{1+0.7936\frac{T_e}{m_e c^2} + 1.874\left(\frac{T_e}{m_e c^2}\right)^2\right\} + \frac{3}{\sqrt{2}}\frac{T_e}{m_e c^2}\right] \frac{W}{cm^3} \qquad (3)$$

Which, T_i is ion temperature and $m_e c^2$ is the electron rest energy in eV. Calculations show the bremsstrahlung loss power increasing with a rise in the electron temperature and density. Fig.4 shows that the amount of $\frac{P_B}{P_f}$ depends on the exact value of the Coulomb logarithm for ^{3}He-^{3}He plasma. For $\ln\Lambda = 20$ and $\ln\Lambda = 5$ at $T_i = 1MeV$, the amount of $\frac{P_B}{P_f}$ is 1.42 and 0.93 , respectively. Ion temperature is selected based on the lowest value of $\frac{P_B}{P_f}$. It is determined that the operation ion temperature is almost 1MeV. It should be noted that the real ratio of bremsstrahlung to fusion power is probably further for various reasons. Firstly, in the calculations it is assumed that the energy of the fusion products is transmitted to the fuel ions, which then lose energy to the electrons by collisions and this in principle lose energy by bremsstrahlung. However, as the fusion products move much faster than the fuel ions, they will give up a significant fraction of their energy to the electrons directly. Secondly, the ions in the plasma are assumed to be purely fuel ions. In practice, there will be a considerable fraction of impurity ions, which *will lower* the *value of* $\frac{P_B}{P_f}$. In particular, the fusion products themselves must remain in the plasma until they have given up their energy and stay sometime after that in any submitted confinement plan.

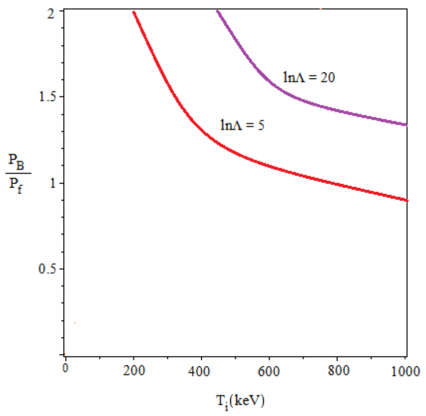

Fig. 4 *Bremsstrahlung loss power fraction in terms of ion temperature in the* ^{3}*He-*^{3}*He plasma* ($T_e = 275\text{keV}$)

The effect of electron temperature on bremsstrahlung loss has been shown in Fig.5. This figure indicates that $\frac{P_B}{P_f}$ reduces when the electron temperature decreases.

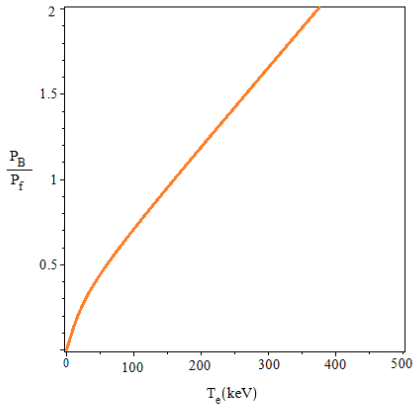

Fig. 5 *Bremsstrahlung loss power fraction in terms of electron temperature in the* ^{3}*He-*^{3}*He plasma* ($T_i = 1\text{MeV}$)

The calculations using electron and ion balance equations show ideal conditions in the Coulomb logarithm range of 5-20. The variations of the Coulomb logarithm in this range affect only the electron temperature and the bremsstrahlung loss slightly. If it is possible to keep the ^{3}He-^{3}He plasma electrons in much less energy then, despite having high bremsstrahlung loss power it is possible to generate net power. Bremsstrahlung radiation is a main challenge for ^{3}He-^{3}He plasma due to large average electron energies. Therefore, it is desirable to decrease the average electron energies below their normal equilibrium values.

5. Synchrotron radiation power

Synchrotron radiation occurs when charged particles are accelerated in a curved path or orbit. The synchrotron radiation is significant in the ^{3}He-^{3}He reaction in magnetic confinement due to high ignition temperature. The synchrotron radiation power density is obtained as [13]:

$$P_{syn} = \frac{4e^4B^2n_e}{3m_e^2c^3}\left(\frac{T_e}{m_ec^2}\right)\left[1+\frac{5}{2}\left(\frac{T_e}{m_ec^2}\right)\right] \qquad (4)$$

where B is the magnetic field. Considering V_{syn} as plasma volume under the effect of magnetic field and the propagation synchrotron radiation and f as the fraction of the radiation which is practically lost (not returned and reabsorb), and the placement of the electron temperature and rest energy in eV, the synchrotron power becomes:

$$P_{syn} = 6.2\times10^{-28}B^2n_eT_e\left[1+\frac{5}{2}\left(\frac{T_e}{m_ec^2}\right)\right]fV_{syn} \qquad (5)$$

Using Eq. (3), the ratio of the total synchrotron to the Bremsstrahlung radiation power can be estimated by the following equation:

$$\frac{P_{syn}}{P_B} \approx 3.67\times10^4 f\,\frac{V_{syn}}{V}\,\frac{B^2\sqrt{T_e}}{\sum_i n_iZ_i^2} \qquad (6)$$

It should be noted that for this estimate, the relativistic corrections have been neglected, because they are almost comparable.

As shown in Fig.6, in order to provide the relation $\frac{P_{syn}}{P_B} \ll 1$, it should select a particular plasma confinement system which maximizes the electron density, but minimizes B, T_e, $\frac{V_{syn}}{V}$ (V is the total plasma volume) and permits a high volume of the synchrotron radiation to be reflected by the walls and reabsorb in the ^{3}He-^{3}He reactor ($f \ll 1$).

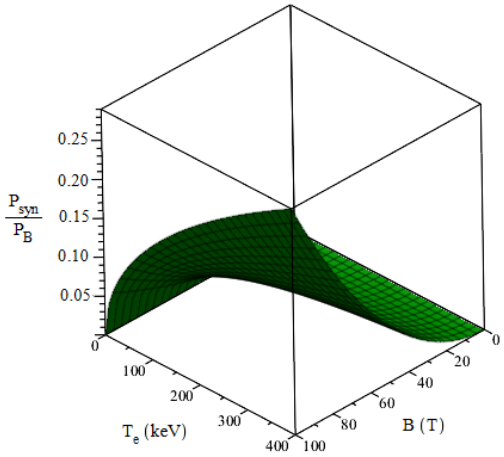

Fig.6 *The ratio of the synchrotron to the Bremsstrahlung radiation power in terms of electron temperature and the magnetic field in the ^{3}He-^{3}He plasma (Considering* $n_{^3He} = 10^{25} cm^{-3}$, $f = 0.001$ *and* $\frac{V_{syn}}{V} = 0.01$*)*

In order to minimize the synchrotron power some approaches such as multipolar configurations [14], ring magnets and plasma diamagnetism can be used [15]. The quality of the magnetic confinement is defined by the plasma beta, which is the ratio of plasma pressure to magnetic pressure [16].

$$\beta = \frac{P_{th}}{P_m} = \frac{nk_B(T_i + T_e)}{B^2 / 2\mu_0} \qquad (7)$$

where μ_0 is the magnetic permeability. In a tokamak, for a stable plasma, the beta value is always smaller than one. In principle, in an MCF reactor at a high value of beta, the minimum amount of magnetic force is required for confinement and the magnet cost for a fusion reactor will be minimized. Assuming a constant plasma beta of 0.9 for ^{3}He-^{3}He fusion reaction can estimate the necessary magnetic field strengths for the confinement corresponding Eq. (7). by increasing plasma beta to 0.9999, the synchrotron power is less for a favorable energy balance. Unfortunately, the current high beta plasma confinement performance is not sufficient. Also, the fusion power density scales with beta ($\frac{P_{fus}}{V} \propto \beta^2 B^4$) in a constant magnetic field. Therefore, concepts with high beta plasma have high power density and tend to follow a path driven by engineering constraints. The synchrotron radiation can be limited by selecting the geometry of the magnetic field to the acceptable level. It is necessary to avoid the use of strong magnetic fields in most of the inner volume multipoles.

6. Ion- electron energy transfer rate

When the ion temperature is higher than the electron temperature, the energy of the ions will be flowing into the electrons by coulomb collisions. The power transfer due to ion-electron collisions can be determined by using a modified version of the usual Spitzer rate [17]:

$$P_{ie} = 7.61\times10^{-28} n_e \sum_i \frac{Z_i^2 n_i \ln\Lambda}{\mu_i T_e^{\frac{3}{2}}} \left(1 + \frac{m_e}{m_i}\frac{T_i}{T_e}\right)^{-\frac{3}{2}} \times \left(1 + \frac{0.3T_e}{m_e c^2}\right)(T_i - T_e) \quad \frac{W}{cm^3} \qquad (8)$$

where the ion mass $m_i = \mu_i m_p$ is in terms of the proton mass m_p and density n_e is in cm^{-3}. The Coulomb logarithm is given by $\ln\Lambda \approx 31 - \ln(\frac{\sqrt{n_e}}{T_e})$ that T_e and n_e are in keV and cm^{-3} ,respectively [18,19]. The results show that Coulomb logarithm decreases with rising electron temperature and decreasing electron density. Fig.7 shows that ion-electron energy transfer fraction is reduced when the electron temperature increased and Coulomb logarithm decreased.

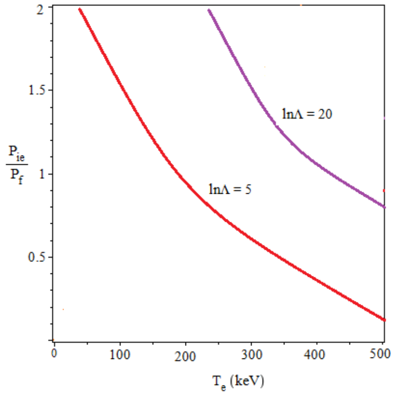

Fig.7 *Ion-electron energy transfer fraction in terms of electron temperature in the ^{3}He-^{3}He plasma(*$T_i = 1MeV$*)*

Fig.8 indicates that in addition to the electron temperature; ion temperature is also effective in $\frac{P_{ie}}{P_f}$ value. $\frac{P_{ie}}{P_f}$ reduces by decreasing ion temperature and increasing electron temperature. When the electron temperature is low enough, the bremsstrahlung losses are manageable and the ion- electron energy transfer rate is very large. Therefore, in order to limit the bremsstrahlung power to logic theory level (less than half of the fusion power) it is essential to reduce the ion-electron energy transfer rate to the possible minimum in the ^{3}He-^{3}He plasma.

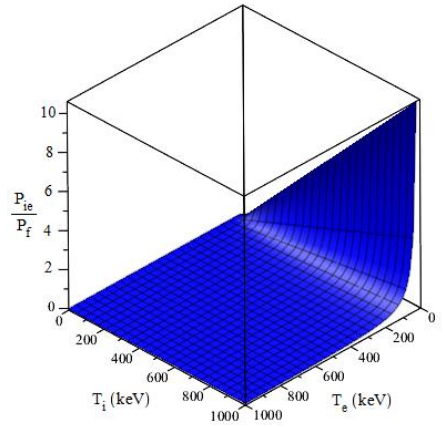

Fig. 8 *Ion-electron energy transfer fraction in terms of electron temperature and ion temperature in the* ^{3}*He-*^{3}*He plasma (* $\ln\Lambda = 5$ *and* $n_e = 10^{25} cm^{-3}$ *)*

The investigations show that the reduction in the bremsstrahlung power fraction is more beneficial than the reduction in the ion-electron energy transfer fraction.

7. Conclusion

The feasibility of achieving ^{3}He-^{3}He reaction is related to the required ignition temperature and the suppression of radiation losses in a fusion reactor. The investigations show that unfortunately ^{3}He-^{3}He fuel requires very high temperature for ignition and operation. The ideal ignition temperature is about 1MeV for this reaction. The ignition of this fuel is impossible if the ion and electron temperature are equal.

There are considerable radiation losses due to bremsstrahlung, electron energy transfer rate, and synchrotron radiation in the ^{3}He-^{3}He plasma. The bremsstrahlung radiation loss resulting from large mean electron energies is a serious problem and increases by rising the electron temperature and density. To overcome this radiation, it would be favorable to decrease the electron temperature less than their common equilibrium values. Even under approximately the appropriate operating condition and by considering the optimistic $\ln\Lambda = 5$ results, the bremsstrahlung loss power is more than the fusion power. If the energy transmitted from ions to electrons is minimized, the loss of energy by bremsstrahlung radiation will also be minimized. At relatively low electron temperatures, the bremsstrahlung loss is controllable, but the ion- electron energy transfer rate is very large. The minimum bremsstrahlung loss is significant in the ^{3}He-^{3}He plasma; thus it should not permit the synchrotron radiation to become a fundamental extra loss. Synchrotron radiation is very hard to determine because the complete propagation is affected by the plasma geometry due to the reabsorption of the radiation and in high beta systems due to the prevention of propagation by the diamagnetic effects shielding the external magnetic field. The ratio of fusion power produced to synchrotron radiation power is proportional to beta and the electron temperature with other fixed parameters. The ^{3}He-^{3}He fuel cycle needs a high beta value and would appear impractical unless as beta approaches unity, the plasma protects the internal magnetic field, as a result of repressing direct synchrotron radiation.

Operation in the hot-ion mode can lead to a large improvement in fusion power density. The only practicable procedure for achieving ignition of ^{3}He-^{3}He reaction is to provide extremely non-Maxwellian condition and large ion-to-electron temperature ratio. Even under these situations, there are many problems when several secondary reactions are observed. For the reasons stated above, reaching ignition would not be easy for ^{3}He-^{3}He reaction in an MCF reactor. Therefore, another method such as inertial confinement fusion (ICF) is suggested for improvement in the heating efficiency. An important advantage of the ICF approach is the absence of externally imposed magnetic fields avoids large synchrotron radiation losses.

Conflict of Interest

The authors have no conflict of interest

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