The Study of A Improve Model For The D-D Nuclear Fusion Reaction Cross Section

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Abstract

The study of improved model for measuring the total nuclear fusion cross section characteristics the D-D reaction may play an important role in deciding or determining the hot plasma parameters such as mean free path , the reaction rate , reactivity and energy for emitted neutrons or protons in our work we see the it is necessary to modify the empirical formulas included the total cross section in order to arrive or achieve good agreement with the international publish result.

Keyword: Dense plasma focus; the mean free path; the reactivity; D-D cross section; fusion reaction

Introduction

Dense Plasma Focus (DPF) machines are pulsed discharges in which microinstabilities and turbulence lead to generation of powerful beams of electron, ions, large emission of x-rays and of fusion neutrons when the filling gas is deuterium. The plasma Focus (PF) belongs to the family of the dynamic Z-pinch. The first systematic study of Z-pinches started in the 1950s in connection with the controlled thermonuclear fusion research. It is a non-cylindrical Z-pinch formed on the axis at the end of a coaxial electrode system of a plasma accelerator. They were originally developed in early 1960s independently in the former Soviet Union (Filippov type), and the USA (Mather type) as shown in fig (1). Most realizations belongs to one of two of the following geometrical types:

- Mather-type characterized by a small anode aspect ratio (diameter / length < 1)
- Filippov-type, characterized by a large aspect ratio. [1, 2, 3]

Plasma Focus produces a short living, rather dense plasma, the properties of which are dominated by the occurrence of macroscopic and microscopic instabilities. At present, DPF is one of the most efficient sources of neutron emission. Also scaling laws of neutron yield prepared on the basis of long experience with different devices of this type are very promising. Unfortunately, it was found that neutron emission saturates at an energy level of several hundreds kJ. [1]
In typical DPF the z- pinch is typically confined for ~100ns and intense x-ray, ion, and electron beams are generated though a complex combination of non-linear instabilities and other mechanisms that result in effective acceleration gradients of ~100MV/m. [5]
When deuterium is used as a working gas, neutron is emitted from the pinch due to following nuclear fusion reactions:

$$ {}_{1}^{2}D + {}_{1}^{2}D \rightarrow {}_{0}^{1}n\,(2.45\,MeV) + {}_{2}^{3}He\,(0.82\,MeV) $$
$$ {}_{1}^{2}D + {}_{1}^{2}D \rightarrow {}_{1}^{1}H\,(3.02\,MeV) + {}_{1}^{3}T\,\,(1.01\,MeV) $$

PF-type facilities emit both neutrons, and hard X-rays with quantum energies of tens and hundreds electron volts. [3]
The dominant part of neutrons (70%) with energies in the range of (2.6-3.2 MeV) was produced by deuterons moving downstream.
The deuterons generating these neutrons have the energy in the range of (20-200 keV) with most probable value of 50 keV.
From these energies, we can calculate the mean free paths of D-D reaction for the convenient deuteron densities of (10^{18}-$10^{20}cm^{-3}$). On the basis of these results, we can estimate the number of fast deuterons lower than $10^{18}$and the density of the deuteron target higher than $10^{19}cm^{-3}$.
The D-D reaction is tested for the determination of basic parameters of hot plasma-temperature, density and duration of high value of these parameters. This reaction is tested mainly in Tokomaks [6], High power lasers [7] and Z-pinches (DPF) [8].
The D-D reaction is realized in 2 branches with the probability of 50%.
These qualities make possible the usage of neutrons as a convenient tool for the diagnostics of fast deuterons with energies above 20 keV.
In this paper we refer about the determinations of velocities and number of fast deuterons producing neutrons in D-D reaction and the estimations of densities of the targets in plasma focus PF-1000 facility. [9]
Fast neutrons from deuteron –deuteron fusion reaction were used for a study of fast deuterons in the PF-1000 plasma focus device. Neutron energy-distribution enabled the determination of axial and radial components of energy of deuterons producing the fusion neutrons, as well as

a rough evaluation of the total energy distribution of all fast deuterons in the pinch. It was found that the total deuteron energy-distribution function decreases with the deuteron energy more slowly than the tail of the maxwellian distribution for (1-2 keV) [10].

The most important quantity for the analysis of nuclear reactions is the cross section, which measures the probability per pair of particles for the occurrence of the reaction. Another important quantity is the reactivity, defined as the probability of reaction per unit time per unit density of target nuclei. In the present simple case, it is just given by the product $\sigma\upsilon$. In general, target nuclei move, so that the relative velocity υ is different for each pair of interacting nuclei. In this case, we compute an averaged reactivity

$$\langle\sigma\upsilon\rangle = \int_0^\infty \sigma(\upsilon)\upsilon f(\upsilon)d\upsilon$$

Where $f(\upsilon)$ is the distribution function of the relative velocities, normalized in such a way that $\int_0^\infty f(\upsilon)d\upsilon = 1$. It is to be observed that when projectile and target particles are of the same species, each reaction is counted twice. [11]

And in turn the reaction rate can be evaluated by using the following:

$$R_{12} = \frac{n_1 n_2}{1+\delta_{12}}\langle\sigma\upsilon\rangle$$

The Kronecker symbol δij (with $\delta ij = 1$, if $i = j$ and $\delta ij = 0$ elsewhere)

$R_{12}=n_1 n_2\langle\sigma\upsilon\rangle$

If the particles are dissimilar. Where R is the reaction rate [12].

Theory

The energy of fast deuterons producing neutrons can be calculated from the known neutron energy using the equilibrium of the momentum and energy. The required energy of deuterons is about 200keV. The dominant part of neutrons with the energy of 2.6-2.8 MeV is produced with deuterons in the energy range between 20 and 80 keV. The deuterons with the energy below 20 keV have very low and cross-section for the D-D fusion reaction and we do not take them into account. [9]

The hot plasma parameters such as the mean free path of D-D reaction ($\lambda_{D\text{-}D}$), the number of fast deuterons (N_D) and the probability of D-D reaction are strongly depending on the total cross-section of the D-D reaction ($\sigma(E_D)$). The total cross-section is calculated by some empirical formulas given below [12]:

$$\sigma_{E_D} = \frac{288}{E_D} e^{-\left(\frac{45.8}{\sqrt{E_D}}\right)} ------ (1) Barns$$

Here E_D is energy for deutereron in keV, is the cross section in barns [12]. σ_{E_D} and

In order to get suitable values for hot plasma parameters as in following:

$$\lambda_{DD} = \frac{1}{n_i \sigma_{E_D}} ------ (2)$$

Where n_i is the ion density of the target (per m^3).

$$N_D = N_x * \lambda_{DD} / L ------- (3)$$

Where N_D is the number of fast deuterons N_x Is the total neutron yield= 10^{11} in the target with length mean free path [9]. λ_{DD} L=1cm,

It is necessary to note that the above empirical formulas for the total cross-section given in equation (1) are not compatible with a given agreement between the recently calculated parameters and the published experimental values. For this reason and to avoid the error factor in calculating the hot plasma parameter, we must find to need of inserting a correction factor for all the above formulas which described the hot plasma parameters. A good approximation for the reactivity for the two main branches of the DD reaction are provided by slightly modified Gamow expressions (Hively 1977) [11]:

$$\langle \sigma\upsilon \rangle_{DDP} = 2\times10^{-14} \frac{1+0.00577T^{0.949}}{T^{2/3}} \exp\left(-\frac{19.31}{T^{1/3}}\right) \quad (cm^3/s) \quad \ldots\ldots (4)$$

and

$$\langle \sigma\upsilon \rangle_{DDn} = 2.72\times10^{-14} \frac{1+0.00539T^{0.917}}{T^{2/3}} \exp\left(-\frac{19.80}{T^{1/3}}\right) \quad (cm^3/s) \quad \ldots\ldots (5)$$

Here the subscripts DDp and DDn indicate the reaction branches (4) and (5), releasing a proton and a neutron respectively, T is the temperature in keV [11].

Results

Our calculated results deal with the total cross-section for the D-D reaction , the mean free path of D-D reaction (λ_{DD}) for various values of ion densities and the number of the fast deuterons (N_D) before inserting the correction factor are listed in table(1) and these results are plotted in figures(2-4).

We can conclude from the figures that there is a shift between the calculated results and the acceptable published experimental results, thus it is necessary to make an agreement between the two values by inserting a correction factor about (1.86) in the formulas previously described and for this case we found results yield a good agreement as it is presented in table (2) and plotted in figures (5-7).

The variation of reactivity for temperatures ranging from (0 - 100 keV) are completely described in fig (8).

Discussion and Conclusions

The reason for inserting a correction factor is related to the fact that the empirical formula for the total cross-section of D-D reaction present an old and applied to sum facilities that are designed for previous decades and we found that it cannot be applied for the recent facilities such as the modern (PF-devices) so that we conclude that it is very important to modify these formulas by testing them for calculating sum fundamental hot plasma parameters. We have got a compatible formula by inserting a correction factor of values (1.86) which therefore makes a good agreement between the calculated and experimental data.

Finally, from fig (8) we observe agreement with the published result [11] for the D-D reactivity.

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Table (1): dependence of the total cross-section, mean free path, and the number of fast deuterons for the D-D fusion reaction on incident deuteron.

keV(E_d)	σ (E_D) E-28 (m^2)	$n_i=10^{24}(m^{-3})$						$n_i=10^{25}(m^{-3})$						$n_i=10^{26}(m^{-3})$					
		* λ_{DD} (m)	** λ_{DD} (m)	*** λ_{DD} (m)	* N_D (m^{-3})	** N_D (m^{-3})	*** N_D (m^{-3})	* λ_{DD} (m)	** λ_{DD} (m)	*** λ_{DD} (m)	* N_D (m^{-3})	** N_D (m^{-3})	*** N_D (m^{-3})	* λ_{DD} (m)	** λ_{DD} (m)	*** λ_{DD} (m)	* N_D (m^{-3})	** N_D (m^{-3})	*** N_D (m^{-3})
20	5.13 E-4	3.6 E-7	1.94 E-7	3.61 E7	-------	1.94 E20	3.61 E20	3.6 E6	1.94 E6	3.61 E6	3.6 E20	1.94 E19	3.61 E19	3.6 E5	1.94 E5	3.61 E5	3.6 E19	1.94 E18	3.61 E18
50	8.860 E-3	2.2 E6	1.11 E6	2.09 E6	-------	1.12 E19	2.09 E19	2.2 E5	1.11 E5	2.09 E5	2.2 E19	1.12 E18	2.09 E18	2.2 E4	1.11 E4	2.09 E4	2.2 E18	1.12 E17	2.09 E17
75	0.01938	----	5.15 E5	9.59 E5	-------	5.15 E18	9.59 E18	----	5.15 E14	9.59 E4	----	5.15 E17	9.59 E17	----	5.15 E3	9.59 E3	----	5.15 E16	9.59 E16
100	0.02953	6.2 E5	3.38 E5	6.29 E5	-------	3.38 E18	6.29 E18	6.2 E4	3.38 E4	6.29 E4	6.2 E18	3.38 E17	6.29 E17	6.2 E3	3.38 E3	6.29 E3	6.2 E17	3.38 E16	6.29 E16
125	0.03831	----	2.61 E5	4.85 E5	-------	2.61 E18	4.85 E18	----	2.61 E4	4.85 E4	----	2.61 E17	4.85 E17	----	2.61 E3	4.85 E3	----	2.61 E16	4.85 E16
150	0.04562	3.7 E5	2.19 E5	4.07 E5	-------	2.19 E18	4.07 E18	3.7 E4	2.19 E4	4.07 E4	3.7 E18	2.19 E17	4.07 E17	3.7 E3	2.19 E3	4.07 E3	3.7 E16	2.19 E16	4.07 E16
175	0.05159	----	1.93 E5	3.60 E5	-------	1.93 E18	3.60 E18	----	1.93 E4	3.60 E4	----	1.93 E17	3.60 E17	----	1.93 E3	3.60 E3	----	1.93 E16	3.60 E16
200	0.05647	2.8 E5	1.77 E5	3.29 E5	-------	1.77 E18	3.29 E18	2.8 E4	1.77 E4	3.29 E4	2.8 E18	1.77 E17	3.29 E17	2.8 E3	1.77 E3	3.29 E3	2.8 E15	1.77 E16	3.29 E16

***** *Published [9],*** *before using correct factor,*** *after using correct factor*, *E#=10*$^{\#}$

Table (2): variation the D-D fusion Reactivity with deuteron temperature.

T(keV)	$<\sigma\upsilon>_{DDp}$ (cm^3/s) $\times 10^{-14}$	$<\sigma\upsilon>_{DDn}$(cm^3/s) $\times 10^{-14}$
0	0	0
10	0.0003	0.0003
20	0.0016	0.0019
30	0.0041	0.0047
40	0.0072	0.0084
50	0.0108	0.0128
60	0.0147	0.0176
70	0.0188	0.0226
80	0.0231	0.0279
90	0.0274	0.0333
100	0.0319	0.0388

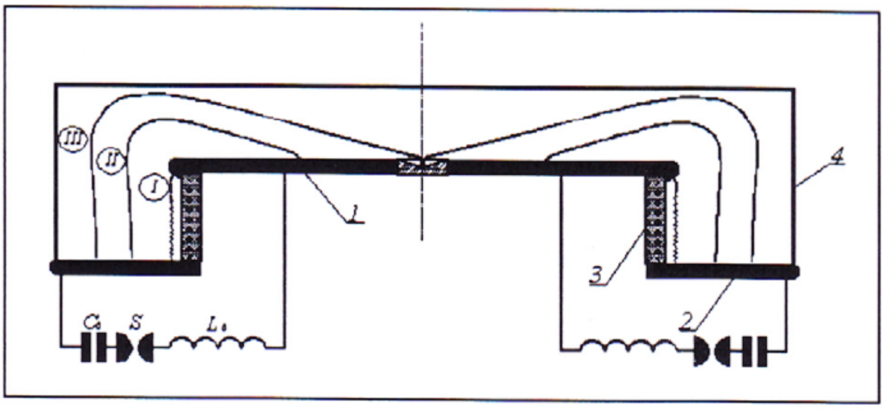

Fig.(1,A): Schematic view of PF machine- Filippov type: 1- anode;2- cathode; 3- insulator; 4- vacuum frame; C_0-capactive bank, L_0-external inductance, S- spark gap switch.[3]

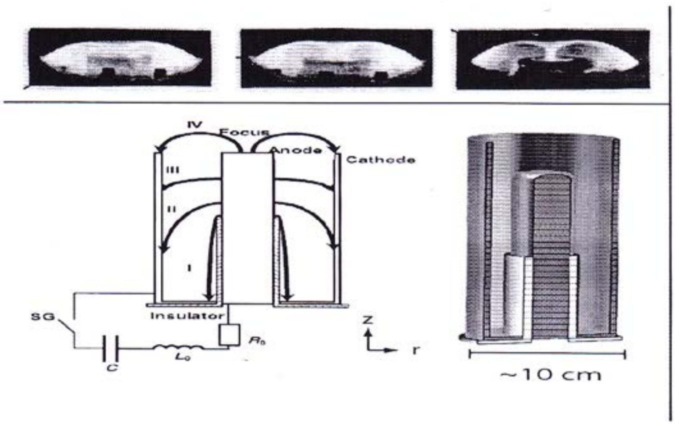

Fig. (1,B): Coaxial gun of the Mather type.[4]

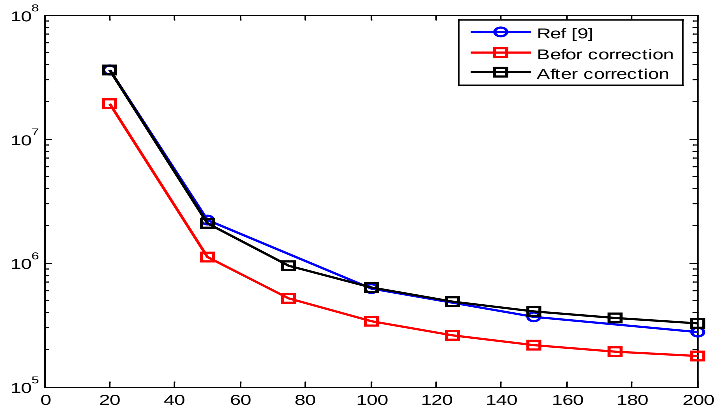

Fig.(2): Mean free path for D-D reaction versus incident deuteron energy for $n_i=10^{24}$ m^{-3}

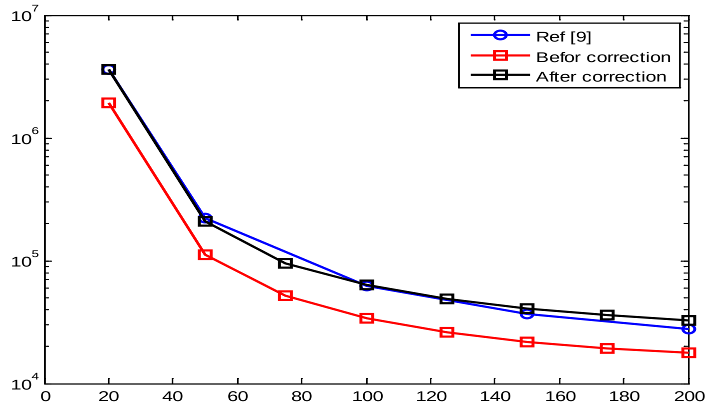

Fig.(3):Mean free path for D-D reaction versus incident deuteron energy for $n_i=10^{25}$

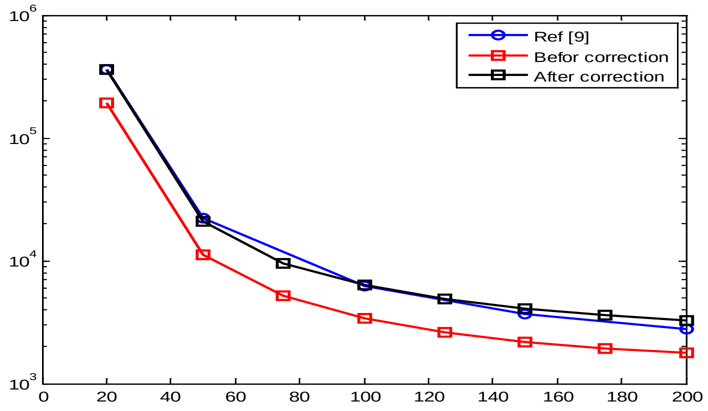

Fig.(4):Mean free path for D-D reaction versus incident deuteron energy for $n_i=10^{26}$

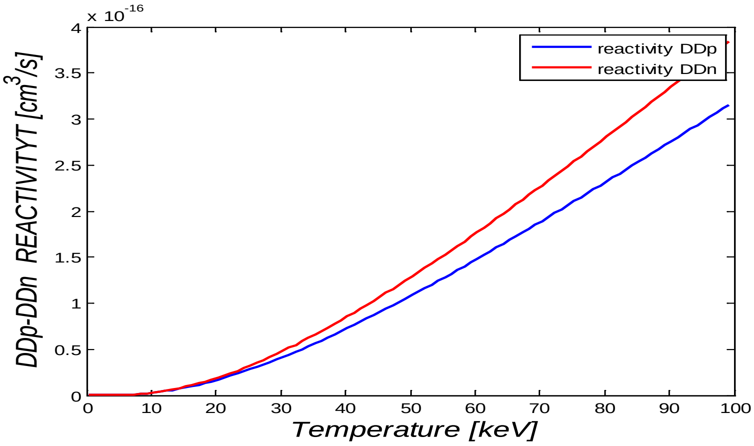

Fig (5): Reactivity versus temperature for DD reaction

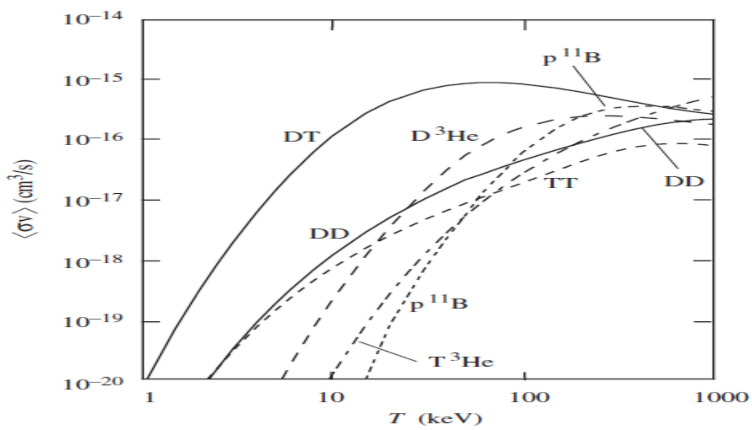

Fig.(6):Mawell-averaged reaction reactivity versus temperature For the interest controlled fusion reactions [Ref 11].

دراسة أنموذج تجريبي لقياس المقاطع العرضية للتفاعل النووي الاندماجي نوع D-D

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الخلاصة

دراسة أنموذج تجريبي لقياس المقاطع العرضية الكلية للتفاعل النووي الاندماجي نوع D-D مهمه لانه لها تأثير مهم في تحديد عوامل البلازما الحاره ،مثل معدل المسار الحرو معدل التفاعل والتفاعليه وطاقة النيترونات او البروتونات المنبعثه .لوحظ في البحث الحالي ان من الضروري جدا تطوير او تحوير العلاقات التجريبية المتضمنة حساب المقاطع العرضية الكلية لبلوغ او تحقيق توافق مقبول مع النتائج العالمية المنشوره.

الكلمات المفتاحية:بؤرة البلازما الكثيفة، معدل المسار الحر،التفاعلية،المقاطع العرضية نوع D-D ،الاندماج النووي.