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IRRADIATION OF D-^{3}HE FUEL BY D-BEAM TO ENHANCE FUSION ENERGY GAIN VIA ICF USING INNOVATIVE WHISTLER WAVE COLLAPSE BY MCNPX SIMULATION

In this article, we used as another new method to achieve higher fusion energy gain. In this approach, the ultimate goal is to heat the ions to a large amount of temperature to enhance the number of nuclear reactions. In the design of laser fusion, as much as possible, it is necessary to convert the laser energy into the energy of fuel ions by various types of laser-plasma interactions. But the main problem is that the electrons absorb a lot of laser energy in the first phase of interaction. The transfer of energy from electron to ion through collisional processes happens slowly and is not very efficient. Thus, the matter of transferring energy directly from electromagnetic waves to ions can overcome this basic problem.

Therefore, the aim of this research is to investigate the effective mechanism of energy transfer directly from the laser to the super dense ions of D3He fuel due to the collapse of standing whistler waves (SWW).

In this article, through the numerical solution of coupled point nonlinear kinetic differential equations governing this fuel, taking into account the effect of the collapse of whistler waves, we obtained the desired fuel energy gain of approximately 74 using D-beam along whistler standing waves collapse via MCNPX simulation, which is compared to the mode of without considering these electromagnetic waves is a high gain.

Keywords: ignition, deuteron beam, collapse, energy gain, whistler waves.

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MCNPX симуляциясын пайдалана отырып, инновациялық ысқырық толқынының құлдырауымен инерциалдық отынды басқару арқылы энергия тиімділігін арттыру үшін D-шоғымен D-^{3}Не отынын сәулелендіру

Бұл мақалада термоядролық синтез энергиясын өндірудің жоғары жылдамдығына қол жеткізу үшін жаңа әдіс пайдаланады. Бұл тәсілде негізгі мақсат – иондарды ядролық реакциялардың санын арттыру үшін жоғары температураға дейін қыздыру. Лазерлік синтезді жобалағанда, мүмкіндігінше, лазер-плазмалық әрекеттесулердің әртүрлі түрлері арқылы лазер энергиясын отын ионының энергиясына түрлендіру қажет. Дегенмен, негізгі мәселе электрондар өзара әрекеттесудің бірінші кезеңінде лазерлік энергияның көп бөлігін жұтады. Соқтығыс процесі арқылы энергияның электрондардан иондарға ауысуы баяу және онша тиімді емес. Осылайша, энергияны электромагниттік толқындардан иондарға тікелей беру мүмкіндігі бұл негізгі мәселені жеңеді.

Бұл зерттеудің мақсаты тұрақты ысқырық толқындарының (SWW) күйреуі салдарынан лазерден D-^{3}Не отынының ультра тығыз иондарына тікелей энергия берудің тиімді механизмін зерттеу болып табылады.

Бұл жұмыста осы отынды сипаттайтын біріктірілген бейәсызықты кинетикалық дифференциалдық теңдеулер жүйесін сандық шешу арқылы ысқырық толқынның құлау әсерін ескере отырып, MCNPX симуляциясын пайдаланып, тұрақты ысқырық толқындары бойымен D-сәулесінің көмегімен шамамен 74 отын энергиясының шығымына қол жеткізілді. Бұл осы электромагниттік толқындарды есепке алмаған режимде энергия өндіру коэффициентінен айтарлықтай асып түседі.

Түйін сөздер: тұтану, дейтрон шоғы, коллапс, энергия коэффициенті, ысқырық толқындары

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Облучение топлива D-^{3}He пучком D для усиления энергетического прироста синтеза посредством инерциального УТС с использованием инновационного коллапса свистящей волны с помощью моделирования MCNPX

В данной статье использован новый метод для достижения более высокого коэффициента выработки энергии термоядерного синтеза. В этом подходе конечной целью является нагревание ионов до высоких температур для увеличения числа ядерных реакций. При проектировании лазерного синтеза необходимо, насколько это возможно, преобразовывать энергию лазера в энергию ионов топлива с помощью различных типов взаимодействий лазера с плазмой. Однако основной проблемой является то, что электроны поглощают большую часть энергии лазера на первом этапе взаимодействия. Передача энергии от электронов к ионам через процесс столкновений происходит медленно и не очень эффективно. Таким образом, возможность прямой передачи энергии от электромагнитных волн к ионам позволяет преодолеть эту основную проблему. Цель данного исследования – изучение эффективного механизма прямой передачи энергии от лазера к сверхплотным ионам топлива D-3He за счет коллапса стоячих свистящих волн (SWW). В данной статье с помощью численного решения системы связанных нелинейных кинетических дифференциальных уравнений, описывающих это топливо, с учетом эффекта коллапса свистящих волн был достигнут коэффициент энерговыработки топлива приблизительно равный 74 при использовании D-пучка вдоль стоячих свистящих волн с помощью симуляции MCNPX. Это значительно превышает коэффициент выработки энергии в режиме без учета этих электромагнитных волн.

Ключевые слова: зажигание, дейтронный пучок, коллапс, коэффициент энерговыработки, свистящие волны.

Introduction

Under extreme temperatures and pressures, two nuclei can overcome the Coulomb barrier and join together via the tunneling effect to create a larger nucleus, releasing high amount of energy in the process. This reaction is known as NF (NF). During NF, lighter nuclei fuse to produce heavier nuclei and produce energy, so that the energy of the sun and stars is also released based on the NF process [1]. NF has the ability to produce almost super-high energy for human society because fuel sources are highly abundant [2] and there is no risk of sudden meltdown. It also does not produce long-lived radioactive waste or greenhouse gases. [3]. In this way, the possibility of building a star on Earth and using the energy from the NF reaction has been announced as the key to solving all of the energy problems of human society [4]. NF was observed before nuclear fission. The first experiment of NF was performed by Oliphant, Hartek and Lord Rutherford in 1934. They observed that, by bombarding deuterium-containing target compounds with deuterium ions, a new isotope of hydrogen and a neutron can be produced [5]. They reported that a "hydrogen conversion effect" had occurred [6] and this effect was later proven to be the deuterium-deuterium NF reaction. Although this reaction was discovered before World War II, despite the efforts made, the use of the fusion reaction as an energy source was not realized until the 1950s [7].

In the early 1960s, scientific understanding of nuclear fission reaction energy production methods led to the rapid commercialization of fission technology. But in the same period, NF studies was very slow [8]. However, unlike nuclear fission, which occurs spontaneously in some cores in nature, NF only occurs in stars with intense gravitational pressure and high temperatures. Considering the complexity of the conditions required for NF, it was obvious that imitating a star and exploiting the energy resulting from NF reaction on Earth is a challenging issue.

Interesting test results were reported by the Soviet Union in 1965 on a tokamak fusion device. A tokamak is a donut-shaped device used to confine fusion plasma using a strong magnetic field. Initially, the experimental results of the tokamak were ignored by the NF research scientists. Following that, in the early 1970s, the effectiveness of the tokamak was noticed and number of countries developed their own tokamak devices, which continue to operate today, to the point where the European Union currently includes the countries of India, Japan, and Russia. the United States, South Korea and China are jointly involved in the construction of the ITER (International Nuclear Experimental Reactor) tokamak. ITER is one of the most important NF reactors in the world today. Currently, access to the first D-D fusion plasma at ITER is scheduled to begin in 2025, but full-power D-T fusion plasma operations will begin in 2035.

In 2017, Sano and colleagues investigated the interaction of a dense plasma with an ultra-high intensity laser by applying a strong B_{ext} (external magnetic field). They found that if the ω_c (cyclotron frequency) of the environment magnetic field is more than the ω_0 (laser frequency), the laser electromagnetic wave propagates in the form of a whistle along the field line .Due to the whistler wave behavior, the laser beam stops inside the compressed plasma and superheated electrons are created through cyclotron resonance. As a result, the emission of a whistling wave with a large amplitude can increase the probability of heating the plasma and accelerating the particles in the depth of the dense plasma [9]. In 2018, Sakata and colleagues conducted studies on how to isochorically heat a pre-condensed fusion plasma.

This work was done with a short pulse ultra-intense laser to create states with extremely high energy density such as ICF. In this research, they used a B-field of about hundreds of Teslas [10]. In 2019, Sano and his colleagues, considering the problem that the energy of laser waves is quickly transferred to plasma electrons, they focused on the rapid energy transfer of wave particles to ions caused by the collapse of SWW through numerical and theoretical simulations. They concluded that ions in SWW obtain high energy directly from waves in a very short time scale compared to wave oscillation period [11]. The heated T_i (ion temperature) enhances proportionally to the wave amplitude square and becomes much more than T_e (electron temperature) in a wide interval of fusion plasma conditions. In the same year, Kli and his colleague researched laser emission in hyperdense magnetic plasma.

Another method to increase the energy gain of the D-^{3}He fuel is to irradiate the fuel pellet by a high-energy deuteron beam. According to this method, the deuteron (D)- beam is introduced for FI. [12] These deuteron beams have very high energy to create a hot-spot (HS).

These deuteron beams can be produced with the help of a laser-plasma accelerator. Deuterons not only exhibit ballistic focusing, but also fuse with the considering fuel (here both D and ^{3}He), and producing "reward" energy and increasing the energy gain of fusion. Depending on the desired plasma conditions, this increase in fusion gain can have a special role. Therefore, if we can achieve a very high deuteron flux, a FI D- beam can be very desirable. [13] In this paper, we use this idea to calculate the reward energy released by using high-energy deuterons with the desired fuel ions in the range of 10-190 keV. This reward energy increases the energy released in the desired system. We use a modified energy enhancement factor φ to estimate the additional energy in terms of additional HS heating in the target D+^{3}He fuel. The deposited energy of deuteron beam is calculated here by MCNPX code.

In addition to obtaining the deposited energy, they also had studies in the fields of inertial confinement fusion. In 2020, Sano and his colleagues conducted research on thermonuclear fusion through the collapse of SWW [14]. Because in both MCF and ICF methods, high energy gain has not yet been achieved and some of the problems have not been solved. For this reason, in this work we present another new method for the first time to achieve higher energy gain in D-^{3}He fusion reactors, which includes D-beam irradiation D-^{3}He fuel pellet along with collapse SWW via MCNPX simulation. Therefore, in order to achieve this goal, NF methods are briefly introduced. After that, the reasons for choosing aneutronic fuel D-^{3}He compared to D-T fuel and major challenges on the way of fusion reactors are introduced. Also, the sources of ^{3}He in the solar system is described. Then, we conduct a study on the heating process of the SWW in creating NF based on the theoretical model. Also, we write the particle and energy balance equations to control D-^{3}He fusion. After that, we present the results of our numerical calculations with Maple 20 programming. Also, simulation results via MCNPX are given and finally we present conclusions.

Materials and Methods

NF methods

Although there are several methods for controlling and restraining fusion plasmas, the two main methods that are discussed are based on the concepts of MCF and ICF. MCF reactors use B fields created by superconductor coils to confine the NF plasma in a donut-shaped container. One torus fusion device is the ITER tokamak, which uses magnetic coils, which create a primary toroidal B field to enclose the fusion plasma and a secondary poloidal B field to drive currents in the fusion plasma. [15]. Another type of tokamak available is the spherical tokamak device, which has a smaller aspect ratio, and shows better plasma performance, but it does not have a simple engineering design [16]. One of the other of MCF devices is Stellator, which uses as superconductor coils in a helical configuration around a plasma chamber, creating a helical B field that is applied to conduct current. Stellators are considered as a high-potential and long-term solution, and therefore fusion reactors based on Stellators are actively being analyzed, but like spherical tokamaks, they are associated with a great engineering design challenge [17]. Unlike MCF, ICF researchers are trying to achieve the higher temperatures and densities needed to initiate NF by heating and compressing fusion fuel targets. It should be noted that in most ICF approaches, ultra-intense lasers are used to heat and compress the target. Another method that has been of interest to scientists is magnetized target fusion (MTF) or magnetic inertial fusion (MIF). In this method, fusion plasma with higher density is used compared to MCF, while low power lasers and other drivers are used compared to ICF methods.

Selection of D-^{3}He fuel as an alternative to D-T fuel

NF is a nuclear reaction in which the Coulombic repulsion between two nuclei is overcome and as a result producing heavier nucleus and subatomic particles, releasing a large amount of energy. Some types of NF reactions to produce energy are those that use hydrogen isotopes (deuterium and tritium), ^{3}He or ^{11}B as reactants:

$$D + D \rightarrow T + p + 4.03MeV \qquad (a)$$

$$D + D \rightarrow {}^3_2He + n + 3.27MeV \qquad (b)$$

$$D + T \rightarrow {}^4_2He + n + 17.60MeV \qquad (c)$$

$$D + {}^3_2He \rightarrow {}^4_2He + p + 18.3MeV \qquad (d)$$

$$p + {}^{11}_5B \rightarrow 3\,{}^4_2He + 8.68MeV \qquad (e)$$

$$ {}^3_2He + {}^3_2He \rightarrow {}^4_2He + 2p + 12.86MeV \qquad (f)$$

Figure 1 shows the NF reactivity for common fusion reactions in terms of temperature [18,19].

A better option than D-T reactors is to use D-^{3}He, which includes the main reaction (d) and side D-D fusion reactions ((a) and (b)). Each of a) and b) reactions will occur with a probability of 50%, and it can be seen that even this fuel cycle is neutron productive, although it creates less energy and neutrons than the D-T reaction. However, the D^{3}He target becomes nearly neutron-free [4-7] when the amount of deuterium is equal or less than the ^{3}He. There are two reasons why the D^{3}He fuel cycle has never been seriously considered for a fusion reactor. The first reason, which is also significant, is the severe lack of ^{3}He in the earth. Fortunately, samples of moon soil sent back to Earth by the astronauts and revealed the presence of a lot of ^{3}He on the moon surface, which had been deposited on the moon surface through the solar winds over many years.

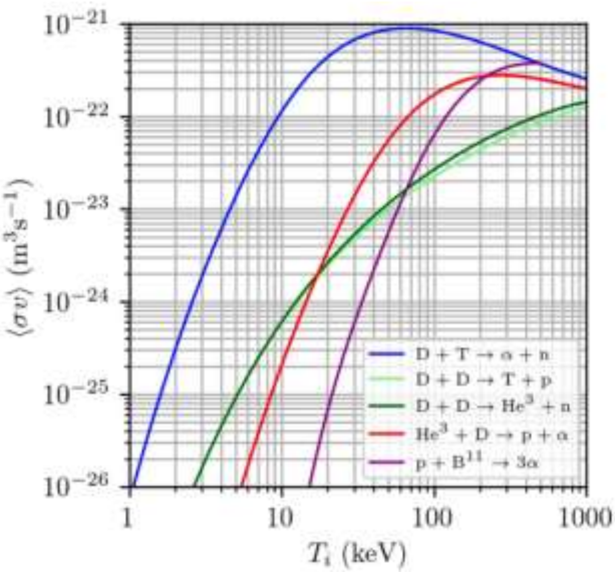


Figure 1 – Fusion reactivity as a function of temperature [18,19].

Researchers have stated that there is about 10^6 tons of ^{3}He on the surface of the moon and up to a depth of several meters. How to extract and transfer it to the earth in the article by Schmidt [8] described in detail. Undoubtedly, extracting ^{3}He on the moon will be a very expensive task, but considering that it produces high electrical power, it is worth considering [6]. Another reason is that the $<\sigma v>$ parameter of D^{3}He is lower than that of D-T, therefore the reactor must operate at much higher densities and temperatures compared to D-T. This creates a fundamental problem for ITER tokamaks because the beta of plasma cannot be increased by a few percent and therefore the utilizing of ^{3}He requires high B fields [9]. In fact, the tokamak required for D^{3}He ignition experiments requires a 13T toroidal B-field and a 17T transformer. Therefore, such a model for a tokamak device is very complex, if not impossible.

Challenges governing the realization of NF power plant

There are many challenges such as science, engineering and technological in the commercialization of NF. Basically, to have a D-T reactor of MCF type, the leading technical issues that should be considered are [15]:

(i) steady state operation of NF plasmas, (ii) construction of advanced diverter system, (iii) development of materials resistant to neutrons, (iv) providing low-cost tritium production technology, and (v) improving reliable magnetic confinement systems.

Controlling a high efficiency fusion plasma is critical to the success of any fusion device. The development of methods to prevent NF plasma instabilities and disturbances in the commercialization of power plants is the subject of many researches around the world and currently the main focus is on the ITER project [17]. Additionally, a divertor is required to control the NF plasma heat, and to remove the helium "ash" created via the deuterium-tritium reaction itself. Diverters are specific to MCF power plants, or perhaps even MTF approaches. Also, special materials must be made to create a radiation shield to protect the magnets, diagnostic and control equipment, and allow neutrons to enter the tritium breeding blanket to maintain the fusion fuel cycle.

Since the neutrons released from D-T fuel have high energy, fusion reactor manufacturers must ensure that long-lived radioactive waste is not created via the neutrons interaction with the vessel structure containing the NF core [11]. Excluding special isotopes, the required materials list for applying in NF reactors is limited, thus an additional challenge added to the previous problems [17]. In the construction of tritium breeding blankets, the materials of neutron resistant have a special role. Tritium production blankets pursue the following two important goals: a) producing new tritium fuel from neutrons interaction created by the D-T NF reaction with lithium and b) extracting the energy transferred by neutrons in heat form. There are many problems in the design, construction and selection of tritium breeding blankets. The thermo-hydraulic, tritium breeding process, and heat removal challenges all create complex problems, so an integrated solution is essential.

Although a series of different plans based on the concept of tritium breeding technology have been presented, no evidence of the concept of tritium breeding technology has been presented yet, however, even if tritium breeding technology is developed, the challenges related to the sustainability of the tritium breeding blankets is still standing [17]. Therefore, one of the main reasons that we have chosen D^3He fuel is that there is no need to design a tritium breeding blanket.

One of the main challenges in NF through MCF is the development of efficient networks of magnetic superconductors, which are required to create a strong B-field in order to confine the NF plasma. To date, most of the efforts of scientists focused on the application of low-temperature superconducting (LTS) magnets which have the ability to carry high currents and B-fields in the MCF reactors with large-scale. Today, we are witnessing the development of high-temperature superconductors (HTS), which are capable of generating stronger field currents than LTS and with higher cooling efficiency due to the operating temperature. The improvement of HTS systems can lead to the development of smaller and more efficient NF reactors, because these systems will be able to work in stronger B-fields [18,19]. These challenges are interdependent and require an integrated solution [20-23].

The source of ^3He in the solar system

The ^3He isotope is not that abundant in the Earth, and currently, only 30 kg of it exist on Earth [14]. ^3He occurs naturally in the Earth's atmosphere, as well as in natural gas wells, but the amount is very small, as described by Ref. [15]. One important aspect is that the Earth itself does not produce ^3He, because it is only a fusion product of the sun in our solar system, which only the sun can produce naturally. For this reason, it can be found in the solar wind, where the $^4He/^3He$ ratio is about 500 ppm: the wind has been depositing ^3He throughout the solar system for billions of years, but the Earth's atmosphere cannot retain it, except to a relatively small extent. Another way to produce it is as a result of the radioactive decay of tritium. There are also many interstellar sources for this isotope, including the Moon, because the Moon has collected and stored all the ^3He from the solar wind during its lifetime. And this has made the moon a great source of ^3He. [15]. ^3He may also exist on Mars, Venus and Mercury. Studies show that if we use the ^3He available on the moon, considering that deuterium is abundantly available in the ocean waters, we will have 163 million terawatt hours of energy available as a result of the D-^3He reaction.

Theoretical role of SWW in heating of NF plasma

The ICF laser driven is divided into two types: (i) direct and (ii) indirect laser driven fusion. In type (i) a spherical fuel is directly exposed to very intense laser radiation .In practice, it is very difficult to achieve a spherically symmetrical explosion with laser beams.

A lot of progress has been made in this field and today, the most energetic laser in the world has 60 beams and it is designed at the Omega center with direct drive principles. In the NIF, the ICF concept is also used through a direct drive. This approach is simple and relatively cheap and has a higher energy efficiency than the indirect drive. But due to the significant target sensitivity to the intense variations of the laser beams and their asymmetry effect, there is a possibility of destroying the surface of the fuel capsule and destroying it due to Rayleigh-Taylor hydrodynamics instability. The indirect derive is such that laser beams shine on the surface of a cylindrical chamber, which is usually made of gold, and excite the gold atoms, X-rays are released and the fuel capsule is exposed to radiation. The main drawback of this method is spending a lot of initial energy to produce beams inside the chamber. Therefore, the gain of energy of this approach is not high. Now, in this article, we use fusion through inertial confinement and introduce it further below [24].

The plasma momentum of a spherical target containing an expanding deuterium-tritium fuel is balanced by the momentum of the interior of the fuel. This action causes the target to explode and compress the fuel. Decreasing the explosive target volume is possible by increasing the temperature within it and growing the density of the fuel (the process is almost isobaric). As the volume decreases sufficiently, the temperature in the center of a carefully designed fuel pellet reaches values above 10 keV. A HS is created, which allows for self-ignition of the target. This type of fuel ignition is called "central HS ignition".

Since the fusion energy resulting from the desired fusion reaction (E_{fus}) must be greater than the laser driven energy (E_{las}) (i.e., $G = {E_{fus}}/{E_{las}} > 1$), therefore, the density of the compressed fuel pellet must be very large, and its mass must exceed a special limit. Acquiring such a high temperature and density in a supercritical mass deuterium-tritium target using the central HS ignition approach requires the use of a 10 ns laser with energy higher than $10^6 J$. Also, it is technically very difficult to achieve a very high symmetry of the target illumination and apply several conditions [25]. To decrease these requirements, several alternative methods for fuel ignition have been proposed, including: 1) FI [26]; 2) Shock Ignition [27] and 3) Impact Ignition [28,29]. Among these three types of ignitions, FI is a modern laser fusion approach. This ignition will have the potential to generate a much higher gain than common ignition in HS. In the first step, the fuel shell detonates at a low speed, ideally forming an isochoric compact core. Then, a laser with significant energy and ultra-intensity causes ignition in a small area of the compressed area. This action is performed by electrons or ions with high energy as a result of laser-fuel interactions. Since an explosion creates at a much slower rate than common ignition in the HS, more mass will accumulate for the same energy of the laser, and in case of fuel ignition, it will lead to energy growth. In general, there are two methods of hole boring and cone guided for rapid ignition, both of these methods aim to eliminate the large barrier of FI. This barrier is such that the ignition laser can only propagate to the extent that the frequency of the laser is the same as the frequency of the plasma electrons. It is not possible to carry out FI by hole boring method due to the presence of instabilities during propagation, and the laser light cannot penetrate much and goes back. There are also problems in the path of the channel towards the dense center, so that the beams tend to return to lower densities.

As a result, the densest areas are completely lost [30]. As a result, the propagation of strong pulses in this method is complicated. Therefore, in order to solve these problems, a new method for FI called "cone guided method" has been predicted. This method consists of a hollow gold cone with a closed top, which is placed inside a spherical fuel capsule. The hollow cone is applied to provide the igniter laser pulse path to reach the dense fuel [31]. In this case, the plasma corona with a lower density interacts with the laser and the explosion occurs around the compressed plasma at the tip of the cone. The installation of a hollow cone causes the laser light to converge and focus within it, and very hot electrons are created at its tip close to the compressed plasma.

In this paper, the guided cone FI is used. ICF differs from MCF because in ICF the fuel pellet is confined and compressed through its inertia at high fusion densities and temperatures. In both methods of inertial and magnetic confinement fusion, high energy gain has not yet been achieved and some of the problems are not still solved. For this reason, in this work, we present another new method for the first time to achieve higher energy gain. In this method, the main purpose of fusion is to raise the temperature of the ions to a high level to increase the NF reactions.

In the design of fusion through laser confinement, it is necessary to transfer the laser energy to the fuel ions as much as possible via different types of laser-plasma interactions.[32] But, the main problem is that the electrons receive a large amount of laser energy in the first step of the interaction. The transfer of energy from electron to ion through collision processes is slow and generally not very efficient. The development of energy transfer directly from electromagnetic waves to ions can overcome this fundamental problem. The question raised in the FI scheme is how to increase T_i of the explosive plasma [20]. The purpose of the authors in presenting our work is to investigate how to transfer energy from the laser to ultra-dense ions directly and efficiently. Now the question that exists is what is ion heating and how is it created. In response, it should be said that ion heating occurs when circular polarization electromagnetic standing waves are formed inside the ultra-dense plasma, where the n_e(electron density) exceeds the critical value, $N_c = {\epsilon_0 m_e \omega_0^2}/{e^2}$.

This newly proposed mechanism stems from collapse of SWW [33]. In order to propagate electromagnetic waves in ultra-dense environments, the existence of an external magnetic field (B') is a necessary condition. When B' is greater than the critical magnetic field, $B_c = {m_e \omega_0}/{e}$, the whistling branch of right-handed circularly polarized light with a smaller frequency is seen in the dispersion equation. Whistling waves are defined as electromagnetic waves that move along magnetic field lines. This wave can be propagated in any plasma density due to the absence of cut-off density. Then it finds the necessary condition for direct interaction with ultra-dense plasma. A SWW is essentially generated by the head-on collision of two propagating whistler waves. SWW heating appears only in a standing wave.

On the other hand, left-handed light has a cut-off density N_L, which is defined by $N_L = N_c(1 + {B'}/{B_c})$. However, the SWW can also propagate in ultra-dense conditions under $B' > B_c$. Of course, we focus our studies on whistling waves, because the high density and relatively weak field intensity and preferred conditions of plasma core are compatible with our demand. The appropriate advantage for this FI design is energy transfer to ions with high efficiency in an ultra-fast time scale of the order of laser periodicity. The component of the electric field tangential to the right and polarized in the direction B' is right-handed circular polarization. Thanks to the non-interruption of the whistler wave, the energy of laser is transferred to ultra-dense plasma. This allows the direct interaction of electromagnetic waves with plasma ions. Electrons behave on the time scale of the laser frequency, similar to a fluid in a ultra-dense plasma. If n_e is less than N_c, the standing wave energy is mainly given to electrons via random acceleration [23-28].

The appearance of the electromotive force redistributes the density of electrons and the electrons tend to move towards the anti-nodes of the standing waves. Therefore, the longitudinal electric field component is produced in balance with the $E_x = -(v \times B)_x$. This electromotive force becomes zero in the longitudinal direction, $(v \times B)_x$, wherever the whistler wave exists alone. Note that v and B are the tangential components of the electron vibration speed and the magnetic field of the whistler's special mode, respectively. It is reminded that based on the behavior of the SWW, the electromotive force is limited and the amplitude of the longitudinal force does not change with time and is sinusoidal in the x-direction in a half period of the whistler's wavelength. On the other hand, the electromotive force has no effect on the ion equation of motion. The ions are accelerated via the longitudinal electric field component and move towards the antinodes. Fluctuation of ion density causes the amplitude of the electric field to decrease. However, as long as there is a standing wave, the electromotive force remains unchanged .In addition, the electron density condensation balances the longitudinal component of the force in the electron fluid. Therefore, the longitudinal component of electric field remains stable in a constant domain. This positive feedback ensures the acceleration of the ions in the SWW until the acceleration of the ions is interrupted by the collapse of the wave.

Therefore, the accelerated ions are completely heated by this action, and T_i is obtained by: $\frac{k_B T_i}{m_e c^2} \sim \frac{2\pi Z}{3} \frac{a_0^2}{(n-1)^2(\widetilde{B'}-1)}$, here k_B, Z, a_0, and n are Boltzmann's constant, ion charge the laser amplitude, and refractive index of the whistler mode of the laser, respectively. The whistling wave amplitude is given by: $a_w^{\pm} = 2\, {a_0}/{(n+1)}$. The refractive index of the whistler mode is expressed by the relation n: $n = (1 + {\widetilde{n_{e0}}}/{(\widetilde{B'}-1)})^{1/2}$. Then, the transmitted energy of laser gradually decreases with growing density of target. To reach ion saturation acceleration, a limited time is needed [23], which is defined through the relation $\widetilde{\tau_{sat}} \sim \left(\frac{\pi}{16} \frac{m_i}{Z m_e} \frac{(n+1)^2(\widetilde{B'}-1)}{N^2 a_0^2}\right)^{1/2}$. The saturation time scale is determined by ion movements and T_e caused by resistive heating is given by: $\frac{k_B T_e}{m_e c^2} \sim \left(\frac{40\sqrt{2\pi} ln\Lambda}{9} \frac{Z r_e}{\lambda_0} \frac{\widetilde{n_{e0}} a_0^2}{(n+1)^2(\widetilde{B'}-1)^2} \tilde{t}\right)^{2/5}$ [24, 28], where $r_e = {e^2}/{(4\pi\epsilon_0 m_e c^2)}$ is classical electron radius. It can be seen that the T_i is heated by the collapse of SWW and is often higher than T_e. What affects the ions is longitudinal component of electric field. Therefore, the electric field amplitude which is defined as: $a_x \sim \frac{8 N a_0^2}{(n+1)^2(\widetilde{B'}-1)} \sin(2k_w x)$ should be maximized.

It can be seen that the maximum value of electric field amplitude depends on the initial value n_e of the target, external B field, and on the laser amplitude. Now, if these three items increase, we reach the maximum electric field, and the ion acceleration grows. This causes the growth of the n_i (ion density) and the subsequent collapse of the standing wave. After the collapsing of the ion wave, the ion beams face to face coexists in many places. Subsequently, a high amount of accelerated ions energy is converted into thermal form via two-stream instabilities. Considering the periodic structure of the longitudinal electric field component in addition to the small-scale wavelength of the whistler wave, the significant advantage of this process is the existence of an efficient mechanism for the acceleration of ions and their simultaneous heating. The main requirement for SWW heating is the presence of a magnetic field stronger than the critical intensity. So far, several research groups have reported how to achieve strong magnetic fields in the kilo-tesla range in laser labs [28-32]. In this case, the magnetic field caused by the laser is compressed due to the explosion, and it is possible to increase the intensity of this field by an order of magnitude and reach the critical value B_c Although, the maximum intensity of the available magnetic field is not enough to propagate whistler waves in ultra-dense plasma, but soon it will be possible to use ultra-intense lasers in acceptable supercritical field conditions to excite relativistic whistler waves. Moreover, the intensity of the critical magnetic field is proportional to the inverse of the laser wavelength. In fact, this process can occur with a suitable field intensity in the conditions governing the laboratory plasma [33-35].

We note that in addition to the external B-field, creating a magnetic field inside the plasma produced by the laser is one of the important points. This is especially important when one micrometer lasers are used. This field, originally proposed by Korobkin and Servo, is effective in preventing thermal conduction in the corona of target. They generated a plasma spark using a focal ruby laser and reported the generation of a magnetic field through the induced current in the coil. We know that the efficiency of energy conversion from whistling waves to ions depends on the laser and plasma parameters. The method used in this article is the use of whistler waves. This method can be considered as a new model for the production of thermal fusion plasma even with smaller heating lasers. By using this model, we can achieve higher energy gain for aneutronic and neutronic fuels.

Balance equations of particles and energy for NF control

In our research, we used as the balance equations of particles and energy related to aneutronic D^{3}He fuel in order to determine the density of consumed and produced particles, the NF power density and finally the fusion gain. Therefore, we write these equations as follows:

Point kinetic nonlinear coupled differential equations for D^{3}He fusion fuel

$$\frac{dn_\alpha}{dt} = -\frac{n_\alpha}{\tau_\alpha} + n_{\mathrm{D}} n_{^3He}\langle\sigma v\rangle, \quad (1)$$

$$\frac{dn_{\mathrm{D}}}{dt} = -\frac{n_{\mathrm{D}}}{\tau_{\mathrm{D}}} - n_{\mathrm{D}} n_{^3He}\langle\sigma v\rangle + S_{\mathrm{D}}, \quad (2)$$

$$\frac{dn_{^3He}}{dt} = -\frac{n_{^3He}}{\tau_{^3He}} - n_{\mathrm{D}} n_{^3He}\langle\sigma v\rangle + S_{^3He}, \quad (3)$$

$$\frac{dn_p}{dt} = -\frac{n_p}{\tau_p} + n_{\mathrm{D}} n_{^3He}\langle\sigma v\rangle, \quad (4)$$

$$\frac{dE}{dt} = -\frac{E}{\tau_E} + Q_{\mathrm{D^3He}} n_{\mathrm{D}} n_{^3He}\langle\sigma v\rangle - -P_{rad} + P_{aux} + P_{ohmic} - \mathrm{P_{syn}} \quad (5)$$

where n_α, n_D, $n_{3_{He}}$ and n_{p} are the density of alpha, deuterium, helium3 and proton particles, respectively. Control inputs include fueling rates for deuterium (S_D), helium3 ($S_{3_{\mathrm{He}}}$), as well as auxiliary power P_{aux} and $Q_{\mathrm{D^3He}} = 18.34\ MeV$.

The $\langle\sigma v\rangle$ parameter of D^3He fuel is a function of plasma temperature T, which is expressed by:

$$\langle\sigma v\rangle(D^3He) = C_1\zeta^{-5/6}\xi^2 \exp\left(-3\zeta^{1/3}\xi\right) + + \left(\exp\left(-\frac{148}{T}\right) \times 5.41 \times 10^{-15} T^{-3/2}\right). \quad (6)$$

Here $\zeta = 1 - \frac{C_2T + C_4T^2 + C_6T^3}{1 + C_3T + C_5T^2 + C_7T^3}$ and $\xi = C_0/T^{1/3}$. In this equation, the parameters a_i, C_i and r are determined from Ref [19]. E is the energy density and parameters τ_α, τ_D, $\tau_{^3He}$, τ_{p} and τ_E are the confinement time of alpha, deuteron, helium3, proton, and energy particles, respectively. The net heat power of plasma is $P = P_{fusion} - P_{rad}$ and fusion power is defined by the following relation:

$$P_{fusion} = Q_{DT} n_D n_T \langle\sigma v\rangle. \quad (7)$$

In this work, the dissipation radiation, P_{rad} ,is approximately expressed as follows:

$$A_{b(D^3He)} = 4.85 \times 10^{-37} \frac{Wm^3}{\sqrt{KeV}}, \quad (8)$$

$$Z_{eff}(D^3He) = \sum_i \frac{n_i Z_i^2}{n_e} = = \frac{n_D + 4n_{^3H} + 4n_\alpha + n_p}{n_e}, \quad (9)$$

$$n_e(D^3He) = n_D + 2n_{^3He} + 2n_\alpha, \quad (10)$$

$$n(D^3He) = 2n_D + 3n_{^3He} + 3n_\alpha + n_p \quad (11)$$

here, $A_{b(D^3He)}$, Z_{eff}, n_e, n, and T are the bremsstrahlung coefficient, the effective atomic number, the electron density, the plasma density, and the plasma temperature, respectively. The produced NF energy gain is determined by: $G = E_{fusion}/E_d$, where E_d is the energy of the laser driven pulses and E_{fusion} is the released fusion energy related to the desired fusion reaction.

Results and Discussion

In Figure 2, using equation (6), we have shown the variations of $< \sigma v >$ in terms of temperature for D-^{3}He fuel. It can be seen that $< \sigma v >$increases non-linearly with increasing temperature.

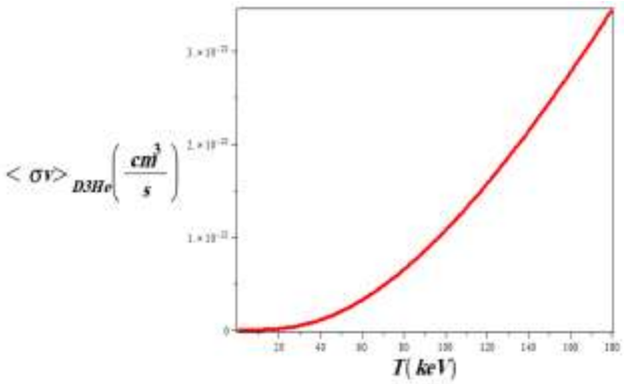


Figure 2 – Two-dimensional diagram of $< \sigma v >$ variations in terms of temperature for D-^{3}He fuel using equation (6)

In the next step, with the help of MAPLE programming we solve the point kinetic nonlinear coupled differential equations (Equations 1 to 5) numerically for determining the different parameters such as the density of fusion particles ($n_D$and $n_{^3He}$) ,the density of produced particles ($n_p$and $n_{^4He}$), fusion energy density (E), fusion gain (G), fusion power density (p_{fusion}), bremsstrahlung power density (p_{rad}) and synchrotron power density (p_{syn}) have been determined as a function of time and temperature and we have given their graphs in Figures 3 to 6, respectively.

It can be seen from Figure 3 that at the initial time t = 0, the densities of fusion nuclei D and ^{3}He are $N_D = 16 \times 10^{17} cm^{-3}$ and $N_{3\mathrm{He}} = 8.5 \times 10^{16} cm^{-3}$, respectively. These densities gradually decrease with the increase of time because they perform the fusion reaction of D-^{3}He and are consumed until in the time range of 7.2-10ns the density of ^{3}He nuclei is equal to $N_{3\mathrm{He}} = 0.09 \times 10^{16} cm^{-3}$ which is reached to characteristic of the steady state, while in the time range of 10-7.2 ns, the density of D nuclei reaches the value $N_D = 0.07 \times 10^{16} cm^{-3}$ belong to characteristic of the steady state. Also, increasing the temperature does not have much effect on the numerical values of these densities.

Figure 4 shows the time and temperature variations of the D-^{3}He fusion reaction products. It can be seen from this figure that the densities of N_p and $N_{4\mathrm{He}}$ gradually increase with increasing time due to the increasing of the number of D-^{3}He fusion reactions until reach the maximum value, then due to the fact that the number of fusion fuels is reduced, the density of the fusion products decreases gradually until its value reaches the characteristic amount of steady state. Also, since the $< \sigma v >$ of the D-^{3}He increases with temperature increasing, the amount of the D-^{3}He NF reaction products increases. It should be noted that the D-^{3}He NF reaction has the highest reactivity at the resonance temperature of 190keV. At this temperature, we have the highest production of reaction products.

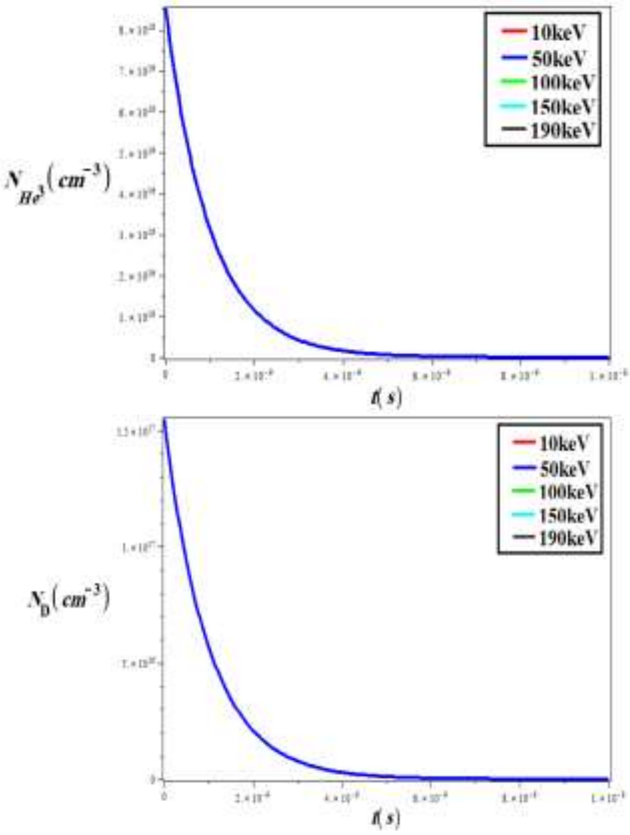


Figure 3 – Two-dimensional variations of fused particles densities versus time at various T(keV), taking into account the production of whistler waves (For $N_{3\mathrm{He}}$ is top and N_D is bottom figures)

According to Figure 5, it can be concluded that the time and temperature variations of the NF energy density and the energy resulting from the D-^{3}He NF reaction gradually increase with the increase of time due to the increase the of NF reactions. After that, due to the reduction of the initial amount of fuel, it is gradually reduced until its value reaches the steady state characteristic value. Also, for this selected fusion fuel, the amount of E and G increases with increasing temperature due to its reactivity increasing, although it should be noted that at the resonance temperature of T = 190 keV, D-^{3}He fuel has the highest amount of E and G, so that in this temperature G = 69 and $E = 6.9 \times 10^6 \ J/cm^3$.

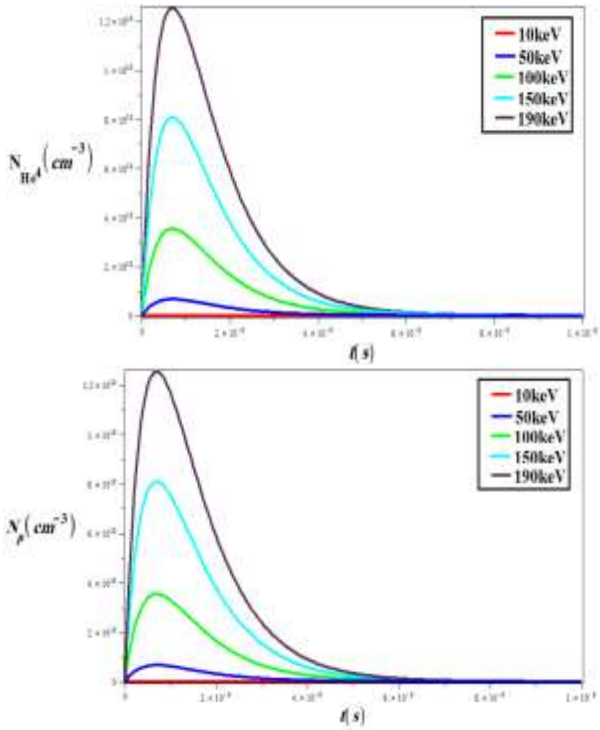


Figure 4 – Two-dimensional variations of fusion products densities obtained from D-³He target versus time at varies(keV), taking into account the production of whistler waves.
(For $N_{4\mathrm{He}}$ is top and N_p is bottom figures)

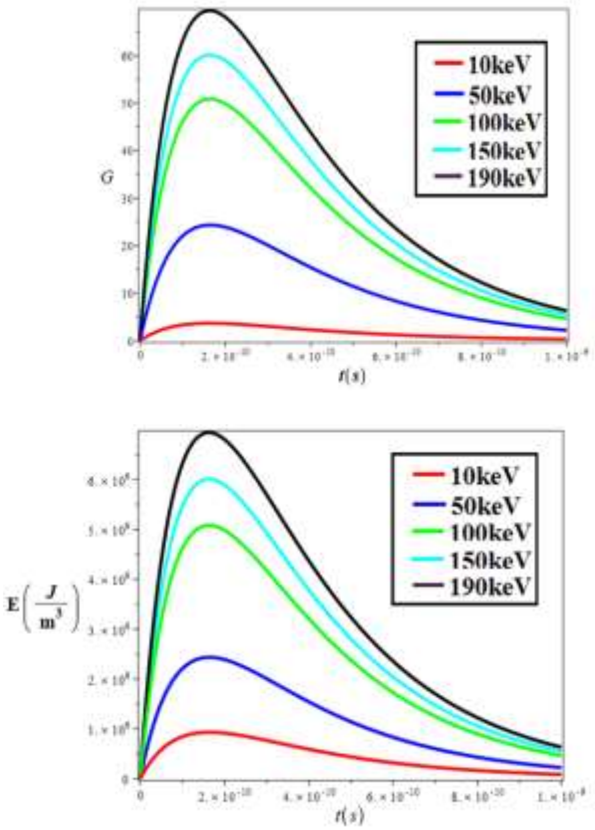


Figure 5 – Two-dimensional diagram of changes in fusion energy and fusion energy gain from D-³He target versus at various T(keV), taking into account the production of whistler waves.

It should be noted that the flux of protons and alpha particles produced from the D-³He fusion reaction are determined by the relations: $\varphi_p = \mathrm{v}_p \times \mathrm{n}_\mathrm{p}$and $\varphi_\alpha = v_\alpha \times n_\alpha$, respectively, where v_p and v_α represent the speed of protons and alpha particles, which are given by $v_p = \sqrt{\frac{2E_p}{m_p}}$ and $v_\alpha = \sqrt{\frac{2\mathrm{E}_\alpha}{\mathrm{m}_\alpha}}$, respectively, where m_p and $\mathrm{m}_\alpha$are the mass of proton and alpha, as well as E_p and E_α are the energies of protons and alpha particles resulting from D-³He fusion reaction.

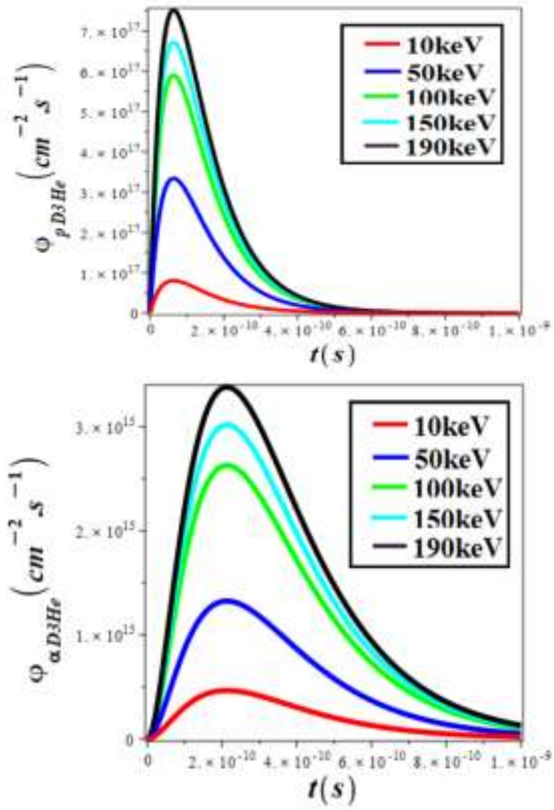


Figure 6 – Two-dimensional variations of particles flux produced from D-³He target versus various T(keV), taking into account the production of whistling waves.

In Figure 6, we see that the 2D variations of particles flux produced from D-³He fusion fuel versus time at various T(keV), taking into account the production of whistler waves. According to this Figure 6, it can be concluded that the time and temperature variations of the particles flux produced from the D-³He fusion reaction gradually increase with the increasing of time due to the increasing of the number of NF reactions, and then it tends to its maximum value, after that, due to the reduction of the initial amount of fuel, it gradually decreases from its amount until it reaches its steady state characteristic value. Also, for the desired fusion fuel, with increasing temperature, due to its reactivity increasing, the amount of particles flux produced increases, although it should be noted that at the resonance temperature T = 190keV of D-^{3}He fuel, we have the highest amount of produced particles flux. It is worth mentioning that this flux of produced particles can be used as a source of protons and alpha particles in the treatment of cancer tumors.

From the observation of Figure 7, it can be concluded that with time increasing, the numerical values of the fusion, synchrotron and radiation power densities (P_{fusion}, P_{syn} and P_{rad}) gradually decrease until they reach the characteristics values of the steady state. Because gradually with time increasing the desired fusion fuel is consumed and decrease. Of course, with temperature increasing, the numerical values of P_{fusion}, P_{syn} and P_{rad} densities increase and reach their maximum value at the resonance temperature T = 190 keV. This is due to the fact that at this temperature, the largest number of D-^{3}He NF reactions occur and we have the highest reactivity ($< \sigma v >$) .

The laser-created D-beam is a interest design for receiving the required energy for igniting a pre-compressed target in the FI approach in the ICF. D-beam creates reward energy via beam-fusion reactions during the HS creation in the pre-compressed target. In fact, D-beams are also considered for FI. Xiaoling Yang et al investigated an accelerated D-beam with very high energy deuterons of about 8 MeV to form the desired HS. Not only deuterons provide proven ballistic focusing, but also as they decelerate, they combine with the target fuel D and ^{3}He, and increase the produced fusion energy known as "reward " energy. Depending on the plasma conditions, the additional reward fusion energy can cause a significant contribution to the amount of final fusion energy gain of D-^{3}He fuel. Therefore, if a high flux of deuterons can be gained, D-beam FI could be very attractive. The energetic D-beam is known as a fast igniter (see Fig.8)

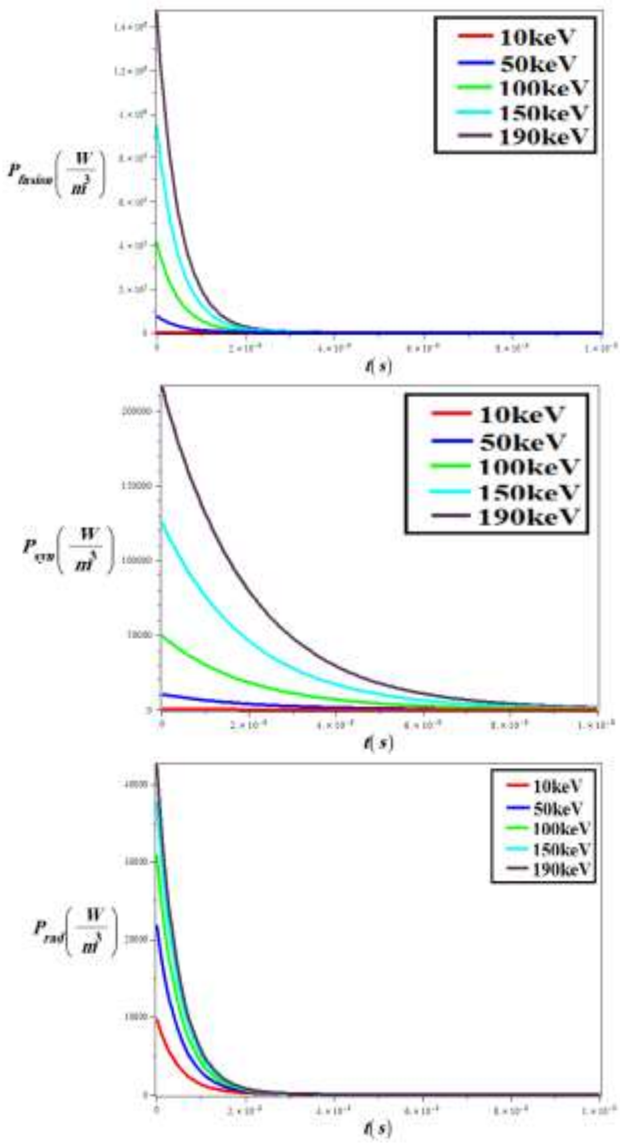


Figure 7 – Two-dimensional variations of fusion power, synchrotron power and Bramsstrahlung power density resulting from D-^{3}He fusion fuel versus at various T(keV), taking into account the production of whistler waves

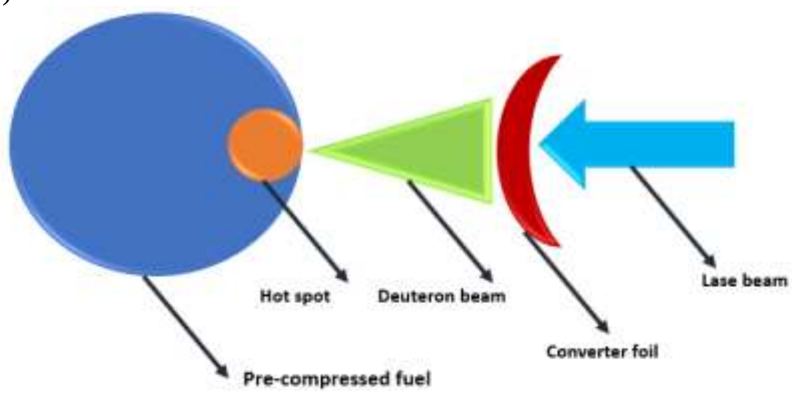


Figure 8 – The pre-compressed target during the HS creation for D-beam driven FI by converter foil method; L is the diameter of HS for the deuteron stopping distance.

In this section we will determine the deposited energy of D-beam along laser beams based on selected geometrical fuel pellet (Fig.9) via MCNPX simulation. In this simulation, we use D- beam (8MeV) driven FI which provides not only the HS ignition spark, but also extra "reward" NF energy via reactions in the fuel pellet. Deuterons would not only provide proven ballistic focusing, but also fuse with the target both D and ^{3}He as they slow down, providing a "reward" gain of fusion energy. Therefore, if we can produce a high flux of deuterons, FI driven by D- beam can be very attractive. To produce a deuteron ion beam, we can use the laser (petawatt) collision mechanism with a converter foil. Indeed, the additional beam-target-fusion gain with deuterons is a unique feature that can be used to relax the required total deuteron flux or intermittently decrease the required input laser energy [13].

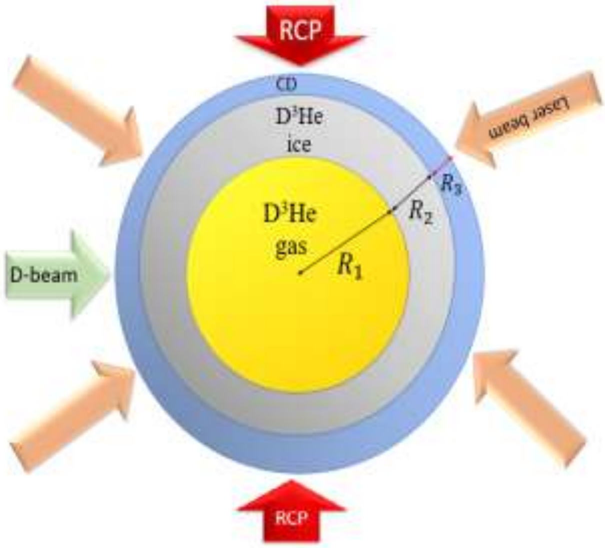
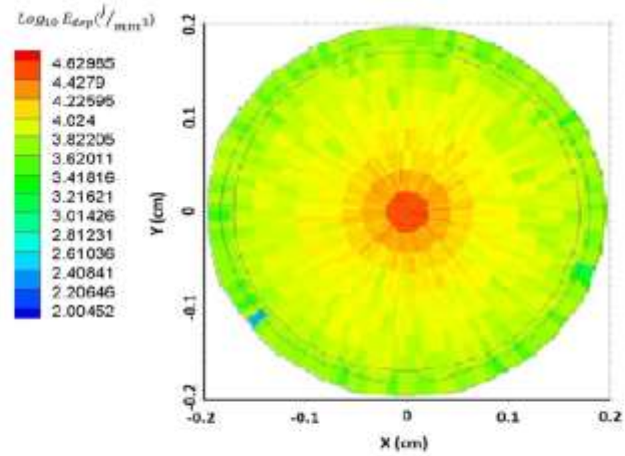


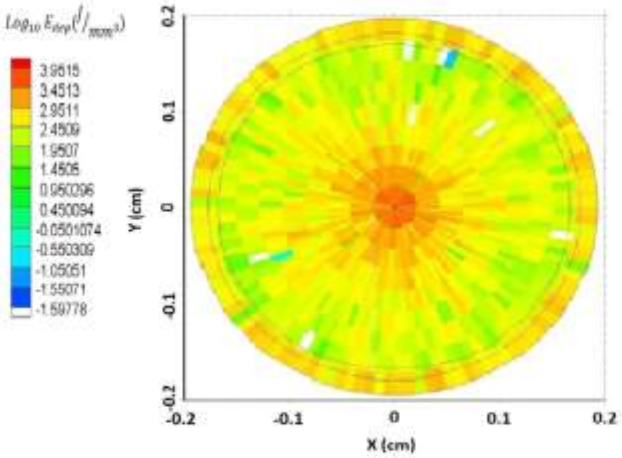
Figure 9 – Two-dimensional generic cross-section of a selected ignited pellet. The shell dimensions $R_1 = 1416\mu m, R_2 = 407\mu m$, and $R_3 = 177\mu m$ with right-circular polarization (RCP), KrF-laser energy range 0.2 MJ, and deuton beam with 8 MeV.

In the Figure 10, we have given the logarithm of the deposited energy in the desired fuel pellet as a result of our simulation without (Figure 10-a) and with (Figure 10-b) considering SWW.

From looking at Figures 10a and 10b, it can be concluded that the maximum value of deposited energy by the D-beam in the desired fuel pellet with and without considering the formation of SWW is equal to 283002.32 and 57.67 erg/mm^3 respectively, which shows a significant increase due to formation of whistling waves along with D-beam radiation. Therefore, the findings of our simulations represent that the use of D-beam along to the collapse of SWW in the desired fuel pellet gives a maximum reward energy gain of 3.8.



a)



b)

Figure10 – The two dimensional deposited energy in the desired fuel pellet in terms of x and y and z=0 in the desired fuel pellet by direct drive fusion a) under the irradiation of 190 identical laser beams with intensity$10^{16} W.cm^{-2}$ and two laser beams (RCP) symmetric and opposite with intensity$10^{21} W.cm^{-2}$ and applying a strong external magnetic field) considering whistler waves b) under the irradiation of 192 identical laser beams centered from all directions symmetrically with the intensity $10^{16} W.cm^{-2}$,without two laser beams (RCP) and an external magnetic field using MCNPX code.

Conclusions

In this research, we presented another new method for the first time to achieve higher fusion energy gain. In this method, the main purpose of nuclear fusion is to heat the ions to the appropriate temperature to enhance the NF reactions. In the ICF mechanism using a laser, as much as possible, the laser energy should be converted into the energy of fuel ions through different types of laser-plasma interactions. However, one of the main problems is that the electrons often gain laser energy in the first phase of the interaction. The mechanism of energy transfer from electron to ion occurs slowly through collisional processes and is generally not very efficient. Therefore, to overcome this problem, the development of direct energy transfer from electromagnetic waves to ions has a valuable meaning. The aim of this work is to analyze the efficient mechanism of laser energy transfer to ultra-dense ions. The newly proposed ion heating process is caused by the collapse of SWW. Due to the problems that exist in the neutron-producing deuterium-tritium fusion reaction, in this work we use aneutronic D-^{3}He fuel. We used it to overcome the problem of producing unwanted neutrons. Finally, by numerically solving the coupled point nonlinear kinetic equations, related to aneutronic D-^{3}He fusion fuel, taking into account the effect of the collapse of the whistler waves, we determined the energy gain of the desired fuel. And finally, we found that when we consider the effect of the collapse of the whistler waves, the gain increases significantly compared to the case when we do not consider the mechanism of the whistler waves, and the D-^{3}He fuel has the highest gain at the resonance temperature of 190keV, which is almost equal to 70, while T Ohmura et al reported a maximum gain of 60 through FI [34], which indicates that the collapse of whistler waves as a new design almost increases the gain by 10 units. Therefore, taking into account the reward energy gain resulting from the irradiation of D- beam in the target together with the calculated energy gain resulting from D-^{3}He fuel caused by SWW collapse in section 6, we will achieve the maximum energy gain is equal to 74 (at the temperature resonance of 190keV).

References

1 Burbidge E.M., Burbidge G.R., Fowler W.A., Hoyle F. Synthesis of the elements in stars // Reviews of Modern Physics. – 1957. – Vol.29(4). – P.547. DOI: 10.1103/RevModPhys.29.547

2 Bradshaw A.M., Hamacher T., Fischer U. Is nuclear fusion a sustainable energy form? // Fusion Engineering and Design. – 2011. – Vol. 86, No. 9-11. – P. 2770-2773. DOI: 10.1016/j.fusengdes.2011.04.056.

3 Ueda Y., Inoue T., Kurihara K. Intelligible seminar on fusion reactors (1) Introduction to fusion reactors // Journal of the Atomic Energy Society of Japan. – 2004. – Vol. 46, No. 12. – P. 27-34.

4 Armaroli N., Balzani V. The future of energy supply: Challenges and opportunities // Angewandte Chemie International Edition. – 2007. – Vol. 46, No. 1-2. – P. 52-66. DOI: 10.1002/anie.200602373.

5 Browne E., Dairiki J.M., Doebler R.E. Table of Isotopes. – Fort Belvoir, VA: National Standard Reference Data System, 1978.

6 Oliphant M., Harteck P., Rutherford L. Transmutation effects observed with heavy hydrogen // Procs of the Royal Society of London Series A, Containing Papers of a Mathematical and Physical Character. – 1934. – Vol. 144, No. 853. – P. 692-703. DOI: 10.1098/rspa.1934.0076.

7 Arnoux R. Who invented fusion? // Saint-Paul-lès-Durance: ITER Organization [Internet]. – 2014. Available from: https://www.iter.org/newsline/-/1836 [Accessed: 2018-06-01].

8 Braams C.M., Stott P.E. Nuclear Fusion: Half a Century of Magnetic Confinement Fusion Research. – Boca Raton, FL: CRC Press, 2002.

9 Sano T., Mori K., Matsumoto T., Nishida Y., et al. Broadening of cyclotron resonance conditions in the relativistic interaction of an intense laser with over dense plasmas // Phys. Rev. E. – 2017. – Vol. 96. – P. 043209. DOI: 10.1103/PhysRevE.96.043209.

10 Sakata S., Nagatomo H., Nakamura T., Fujioka S., et al. Magnetized fast isochoric laser heating for efficient creation of ultra-high-energy-density states // Phys.Rev.E. – 2018. – Vol.9. – P.397. DOI: 10.1038/s41598-017-18825-w.

11 Sano T., Mori K., Matsumoto T., Nishida Y., et al. Ultrafast Wave-Particle Energy Transfer in the Collapse of Standing Whistler Waves // Phys. Rev. E. – 2019. – Vol. 100. – P. 053205. DOI: 10.1103/PhysRevE.100.053205.

12 Schwoerer H., Pfotenhauer S., Jackel O., Amthor K.U., Liesfeld B., Ziegler W., Sauerbrey R., Ledingham K.W.D., Esirkepov T. Laser-driven proton beam therapy: Application of ultra-short pulses of protons for tumor **therapy** // Nature (London). – 2006. – Vol. 439. – P. 445. DOI: 10.1038/nature04492.

13 Yang X., Miley G.H., Flippo K.A., Hora H. Energy enhancement for deuteron beam FI of a precompressed inertial confinement fusion target // Physics of Plasmas. – 2011. – Vol. 18. – P. 032703. DOI: 10.1063/1.3555640.

14 Sano T., Mori K., Matsumoto T., Nishida Y., et al. Thermonuclear fusion triggered by collapsing standing whistler waves in magnetized over dense plasmas // Phys. Rev. E. – 2020. – Vol. 101. – P.013206. DOI: 10.1103/PhysRevE.101.013206.

15 Kamada Y., Ueda Y., Inoue T., Kurihara K. Intelligible seminar on fusion reactors (2) Introduction of plasma characteristics for fusion reactor design // Journal of the Atomic Energy Society of Japan. – 2005. – Vol. 47, No. 1. – P.45-52.

16 Lawson J.D. Some criteria for a power producing thermonuclear reactor // Proceedings of the Physical Society Section B. – 1957. – Vol. 70, No. 1. – P. 6. DOI: 10.1088/0370-1301/70/1/303.

17 Donné A.J.H., Federici G., Litaudon X., McDonald D.C. Scientific and technical challenges on the road towards fusion electricity // Journal of Instrumentation. – 2017. – Vol. 12, No. 10. – P. C10008. DOI: 10.1088/1748-0221/12/10/C10008.

18 Sykes A., Costley A., Windsor C., Asunta O., Brittles G., Buxton P., et al. Compact fusion energy based on the spherical tokamak // Nuclear Fusion. – 2017. – Vol. 58, No. 1. – P. 016039. DOI: 10.1088/1741-4326/aa7f70.

19 Brown D.A., Chadwick M., Capote R., Kahler A., Trkov A., Herman M., et al. NDF/B-VIII.0: The 8th major release of the nuclear reaction data library with CIELO-project cross sections, new standards, and thermal scattering data // Nuclear Data Sheets. – 2018. – Vol. 148. – P. 1–142. DOI: 10.1016/j.nds.2018.02.001.

20 Abdou M., Morley N.B., Smolentsev S., Ying A., Malang S., Rowcliffe A., et al. Blanket/first wall challenges and required R&D on the pathway to DEMO // Fusion Engineering and Design. – 2015. – Vol. 100. – P. 2-43. DOI: 10.1016/j.fusengdes.2015.07.021.

21 Whyte D., Minervini J., LaBombard B., Marmar E., Bromberg L., Greenwald M. Smaller & sooner: Exploiting high magnetic fields from new superconductors for a more attractive fusion energy development path // Journal of Fusion Energy. – 2016. – Vol. 35, No. 1. – P. 41-53. DOI: 10.1007/s10894-015-0050-1.

22 Federici G., Kemp R., Ward D., Bachmann C., Franke T., Gonzalez S., et al. Overview of EU DEMO design and R&D activities // Fusion Engineering and Design. – 2014. – Vol. 89, No. 7. – P. 882-889. DOI: 10.1016/j.fusengdes.2014.01.078.

23 Wu Y., Team F. Conceptual design activities of FDS series fusion power plants in China // Fusion Engineering and Design. – 2006. – Vol. 81, No. 23-24. – P. 2713-2718. DOI: 10.1016/j.fusengdes.2006.04.053.

24 Atzeni S., Meyer-ter-Vehn J. The Physics of Inertial Fusion // Oxford University Press. – 2004. – 488 p.

25 Tabak M., Hammer J., Glinsky M.E., Kruer W.L., Wilks S.C., Woodworth J., et al. Ignition and high gain with ultrapowerful lasers // Physics of Plasmas. – 1994. – Vol. 1. – P. 1626. DOI: 10.1063/1.870664.

26 Betti R., Zhou C.D., Anderson K.S., Perkins L.J., Theobald W., Solodov A.A. Shock ignition of thermonuclear fuel with high areal density // Physical Review Letters. – 2007. – Vol. 98. – P. 155001. DOI: 10.1103/PhysRevLett.98.155001.

27 Caruso A., Pais V.A. The ignition of dense DT fuel by injected triggers // Nuclear Fusion. – 1996. – Vol. 36. – P. 745–757. DOI: 10.1088/0029-5515/36/6/I05.

28 Murakami M., Nagatomo H. A new twist for inertial fusion energy: Impact ignition // Nuclear Instruments and Methods in Physics Research A. – 2005. – Vol. 544. – P. 67–75. DOI: 10.1016/j.nima.2005.01.328.

29 Kodama M. Strategic community management promoted by innovation communities // Journal of Physics: Conference Series. – 2008. – Vol. 112. – P. 022068. DOI: 10.1088/1742-6596/112/2/022068.

30 Craxton R.S., Anderson K.S., Bainbridge-Smith A., et al. Direct-drive inertial confinement fusion // Physics of Plasmas. – 2015. – Vol. 22. – P. 110501. DOI: 10.1063/1.4934713.

31 Lindl J.D. Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain // Physics of Plasmas. – 1995. – Vol. 2. – P. 3933. DOI: 10.1063/1.871025.

32 Matsuo K., Fujioka S., Nishimura H., et al. Novel Experimental Station for High Energy Density Science // Physical Review Letters. – 2019. – Vol. 23. – P. 09456. DOI: 10.1103/PhysRevLett.123.09456.

33 Santos J.J., Bailly-Grandvaux M., Giuffrida L., et al. Laser-driven strong magnetostatic fields with applications to charged beam transport and magnetized high energy-density physics // Physics of Plasmas. – 2018. – Vol. 25. – P. 056705. DOI: 10.1063/1.5020125.

34 Stenzel R.L. Whistler waves with angular momentum in space and laboratory plasmas and their counterparts in free space // Advances in Physics: X. – 2016. – Vol. 1. – P. 687. DOI: 10.1080/23746149.2016.1230016.

35 Ohmura T., Katsube M., Nakao Y., Johzaki T., Mima K., Ohta M. Ignition and Burn Characteristics of D-3He-Fueled FI Targets // Journal of Physics: Conference Series. – 2008. – Vol. 112. – P.022068. DOI: 10.1088/1742-6596/112/2/022068.

References

1 E.M. Burbidge, G.R. Burbidge, W.A. Fowler, and F. Hoyle, Reviews of Modern Physics 29, 547 (1957). DOI: 10.1103/RevModPhys.29.547.

2 A.M. Bradshaw, T. Hamacher, and U. Fischer, Fusion Engineering and Design 86, 2770–2773 (2011). DOI: 10.1016/j.fusengdes.2011.04.056.

3 Y. Ueda, T. Inoue, and K. Kurihara, Journal of the Atomic Energy Society of Japan 46, 27–34 (2004).

4 N. Armaroli and V. Balzani, Angewandte Chemie International Edition 46, 52–66 (2007). DOI: 10.1002/anie.200602373.

5 E. Browne, J. M. Dairiki, and R. E. Doebler, Table of Isotopes (National Standard Reference Data System, Fort Belvoir, VA, 1978).

6 M. Oliphant, P. Harteck, and L. Rutherford, Proceedings of the Royal Society of London Series A 144, 692–703 (1934). DOI: 10.1098/rspa.1934.0076.

7 R. Arnoux, ITER Organization (2014). Available: https://www.iter.org/newsline/-/1836.

8 C.M. Braams and P. E. Stott, Nuclear Fusion: Half a Century of Magnetic Confinement Fusion Research (CRC Press, Boca Raton, FL, 2002).

9 T. Sano, K. Mori, et al., Phys. Rev. E 96, 043209 (2017). DOI: 10.1103/PhysRevE.96.043209.

10 S. Sakata, H. Nagatomo, et al., Phys. Rev. E 9, 397 (2018). DOI: 10.1038/s41598-017-18825-w.

11 T. Sano, K. Mori, et al., Phys. Rev. E 100, 053205 (2019). DOI: 10.1103/PhysRevE.100.053205.

12 H. Schwoerer, S. Pfotenhauer, O. Jackel, K. U. Amthor, et al., Nature (London) 439, 445 (2006). DOI: 10.1038/nature04492.

13 X. Yang, G.H. Miley, K.A. Flippo, and H. Hora, Physics of Plasmas 18, 032703 (2011). DOI: 10.1063/1.3555640.

14 T. Sano, K. Mori, T. Matsumoto, and Y. Nishida, Phys. Rev. E 101, 013206 (2020). DOI: 10.1103/PhysRevE.101.013206.

15 Y. Kamada, Y. Ueda, T. Inoue, and K. Kurihara, Journal of the Atomic Energy Society of Japan 47, 45–52 (2005).

16 J.D. Lawson, Proceedings of the Physical Society Section B 70, 6 (1957). DOI: 10.1088/0370-1301/70/1/303.

17 A.J.H. Donné, G. Federici, X. Litaudon, and D.C. McDonald, Journal of Instrumentation 12, C10008 (2017). DOI: 10.1088/1748-0221/12/10/C10008.

18 A. Sykes, A. Costley, C. Windsor, O. Asunta, et al., Nuclear Fusion 58, 016039 (2017). DOI: 10.1088/1741-4326/aa7f70.

19 D.A. Brown, M. Chadwick, R. Capote, A. Kahler, et al., Nuclear Data Sheets 148, 1–142 (2018). DOI: 10.1016/j.nds.2018.02.001.

20 M. Abdou, N.B. Morley, S. Smolentsev, A. Ying, et al., Fusion Engineering and Design 100, 2–43 (2015). DOI: 10.1016/j.fusengdes.2015.07.021.

21 D. Whyte, J. Minervini, et al., Journal of Fusion Energy 35, 41–53 (2016). DOI: 10.1007/s10894-015-0050-1.

22 G. Federici, R. Kemp, D. Ward, C. Bachmann, et al., Fusion Engineering and Design 89, 882–889 (2014). DOI: 10.1016/j.fusengdes.2014.01.078.

23 Y. Wu and Team F, Fusion Engineering and Design 81, 2713–2718 (2006). DOI: 10.1016/j.fusengdes.2006.04.053.

24 S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion (Oxford University Press, Oxford, 2004).

25 M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, et al., Physics of Plasmas 1, 1626 (1994). DOI: 10.1063/1.870664.

26 R. Betti, C.D. Zhou, et al., Phys. Rev. Lett. 98, 155001 (2007). DOI: 10.1103/PhysRevLett.98.155001.

27 A. Caruso and V. A. Pais, Nuclear Fusion 36, 745–757 (1996). DOI: 10.1088/0029-5515/36/6/I05.

28 M. Murakami and H. Nagatomo, Nuclear Instruments and Methods in Physics Research A 544, 67–75 (2005). DOI: 10.1016/j.nima.2005.01.328.

29 M. Kodama, Journal of Physics: Conference Series 112, 022068 (2008). DOI: 10.1088/1742-6596/112/2/022068.

30 R.S. Craxton, K.S. Anderson, A. Bainbridge-Smith, et al., Physics of Plasmas 22, 110501 (2015). DOI: 10.1063/1.4934713.

31 J.D. Lindl, Physics of Plasmas 2, 3933 (1995). DOI: 10.1063/1.871025.

32 K. Matsuo, S. Fujioka, et al., Phys. Rev. Lett. 123, 09456 (2019). DOI: 10.1103/PhysRevLett.123.09456.

33 J.J. Santos, M. Bailly-Grandvaux, L. Giuffrida, et al., Physics of Plasmas 25, 056705 (2018). DOI: 10.1063/1.5020125.

34 R.L. Stenzel, Advances in Physics: X 1, 687 (2016). DOI: 10.1080/23746149.2016.1230016.

35 T. Ohmura, M. Katsube, Y. Nakao, T. Johzaki, et al., Journal of Physics: Conference Series 112, 022068 (2008). DOI: 10.1088/1742-6596/112/2/022068.

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