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Applications of fusion reactions by laser technology

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Abstract:

One of the fully oriented, dimensionless plasma simulation programs has now matured and is used to study advanced accelerator concepts, particularly particle acceleration using a laser wave field. The program incorporates fluid models and intracellular particle models, which can be used independently or in combination to perform hybrid simulations. Its reliance on advanced mathematics and numerical and finite element methods, as well as multivariable analysis, has contributed significantly to the study of high-energy ionic cases. It is used in current knowledge. VORPAL is distinguished by its moving window and the ability to fire laser pulses from the boundary or prime pulses in the plasma. VORPAL can handle a variety of problems in laser wave field particle acceleration, including frequency-modulated pulses, pulse propagation in plasma channels, and particle beam injection. The boundary conditions for the initial simulation are essential for obtaining logical and reasonable results. Based on the above, the mathematical and primary principles were adopted to activate the work of computer simulation in linking it to one-dimensional and two-dimensional programs.

The use of LILAC, a two-dimensional simulation used to model inertial fusion (ICF) with lasers, and VORPAL (a more advanced three-dimensional, multi-dimensional radiation dynamics program) adds realism and confirms the feasibility of fusion by simulating complex particle and energy interactions. This demonstrates its ability to create suitable conditions for fusion. Therefore, this simulation is used in the research.

Keywords

laser, technology, nuclear fusion, ignition, analytic, simulations

Introduction:

The energy distribution of the reactants in the plasma state is given by the Maxwell-Boltzmann law, which relates the plasma temperature to the average particle energy as follows:

$$E = 3kBT/2 \quad (5)$$

where β is the Boltzmann constant. We assume that the particles undergo elastic collisions [1].

The actual ignition temperatures for D-D and D-T reactions are approximately 4.5×10^8 K 1.5×10^8 K respectively.

Fusion energy may finally become part of our daily lives and uses. Bloomberg Intelligence reported that the nuclear fusion market could reach a $40 trillion valuation, [2] and Forbes declared that nuclear fusion is entering a new era. [3] What has happened to turn things upside down? How have long-held beliefs changed? And, most importantly, regarding the climate and energy crisis:

Recent studies conducted at the Laser Engineering Institute at Osaka University in Japan indicate that low-temperature ignition can be achieved.

The pursuit of clean and virtually unlimited energy has led to research into nuclear fusion methods, particularly the use of repeated stimulation

Powered by the world's largest lasers in academia, top scientists, engineers, and students from leading universities, national labs, and private industry come here to further and laser-based science and technology [2].

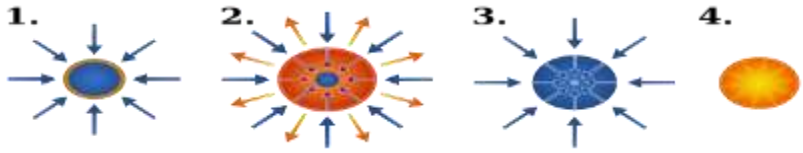
The method employed in this project involves focusing 192 laser beams onto the small capsule simultaneously. This concentration causes the capsule to absorb the laser energy, raising its temperature to approximately 100 million degrees and its internal pressure to over 100 billion atmospheres! This triggers the fusion reaction. It is important to understand that this entire process occurs in a fraction of a billionth of a second! After obtaining energy from nuclear fusion, ceramic beads will be heated, and the resulting heat will be used to generate electricity for everyday human use in factories and homes [3]. This enormous laser is expected to produce 1.8 million joules of energy! The plan

is to generate electricity in this way by 2025. This is what the developed world is thinking about, planning for, and calculating for the future. But what alternative do we have? Have we prepared ourselves and thought about future generations, or is the matter left to chance, whether good or bad, and there are many such chances?

In an inertial fusion reactor (ICF), a small, solid-state fuel pellet—such as deuterium-tritium (DT)—is compressed. This compression is achieved by focusing a concentrated laser beam or a beam of charged particles, This means that, under compression, the product of the pellet's mass density and its radius must exceed approximately 3 grams per square centimeter [4].

Stages of Inertial Fusion Ignition:

1. A laser or X-ray beam heats the fuel disk to produce plasma
2. . 2. The fuel material is affected and compressed inwards.
3. 3. The fuel material in the disk reaches a critical state that meets Lawson's condition.
4. The fusion reaction begins, releasing more energy than the energy used. Note: Blue arrows represent inward radiation processes, orange arrows represent outward processes, and purple arrows represent inward thermal compression.



The adjacent figure illustrates the stages of igniting a nuclear fusion reaction in a small fuel droplet or disk containing a mixture of deuterium and tritium. The droplet is suspended inside a capsule and remains suspended spontaneously due to inertia during the reaction by directing a large number of high-energy laser beams (see figure) [3,5].

Theory:

The mathematical basis of computational engineering theories generally relies on circular or toroidal lasers. I(r) is mathematically assumed to be the intensity, and radius r from the center with respect to nuclear target, the

symmetry can be relied upon, let's say cylindrical in this theory, for the toroidal laser system, and is represented as follows [4,5]:

$$I(r)=P/2\pi rh \quad (1)$$

Where P represents total power and h denoted as height of reaction area.

$$\alpha=z2e6neni3(2\pi)3/2\varepsilon30m1/2e(kBTe)3/2c\omega2ln\Lambda \quad (2)$$

Where Z is the state of charge of the ion, e is the charge of the electron, ne and ni are the densities of the electron and ion, ε_0 is the permittivity of free space, me is the mass of the electron, kB is Boltzmann's constant, Te is the temperature of the electron, c is the speed of light, ω is the angular frequency of the laser, and lnΛ is the natural logarithm [5].

$$Qabs(r)=\alpha I(r)e-\alpha z \quad (3)$$

Mass Conservation represent as: $\partial\rho/\partial t+\nabla\cdot(\rho u) = 0$ (4)

The Conservation of Momentum is represent as :

$$\rho(\partial u\partial t+u.\nabla u)= -\nabla p+flaser \quad (5)$$

Energy Conservation represent as:

$$\partial/\partial t(\rho e)+\nabla\cdot((\rho e+p)u)=Q_{abs}(r) \quad (6)$$

The reaction rate of the fusion is Rf, $R_f=(n^2/2)\langle\sigma v\rangle$ (7)

n the ion density, $\langle\sigma v\rangle$ represent average velocity fusion of cross-section, and Bush-Hill parameters [6]:

$$\langle\sigma v\rangle=C_1\xi^{-5/6}e-^3{}_\xi{}^{1/3} \quad (8)$$

where

$$\xi=E_G/k_BT$$

, where EG is the Gamow energy, and C1 is a constant the total fusion product Y calculated as [7]:

$$Y=\int^{\tau}_{0}\int_{V} RfdVdt \quad (9)$$

Lawson's criterion requires

$$_{n\tau}T \geq (n\tau T)_{crit} \quad (10)$$

Accurate evaluation of equations using numerical analysis simulations with the structure of the ring laser configurations [8].

Methodology:

Setting up the simulation process sequentially requires hydrodynamic evaluation of the one-dimensional transformation software, then by two-dimensional asymmetry of modeling using LILAC software, culminating in three-dimensional kinetic simulation using VORPAL software [9] The sequential data for each one-, two-, and three-dimensional state form the infinite shape of the computational process based on virtual simulation. Integrating multiple simulations provides a coherent and comprehensive understanding of the processes of stimulated nuclear fusion using the ring laser method. Specifying the pre-studied conditions may subsequently contribute to increasing the productivity of deuterium-deuterium fusion, leading to the maximum possible occurrence of the desired process [10].

Simulation setup:

The setup of simulation can represent as:

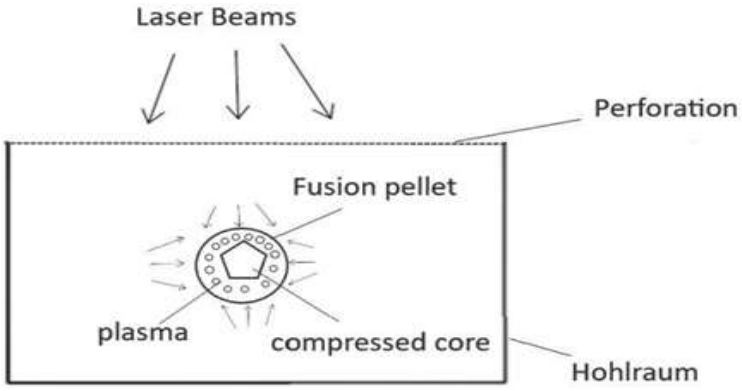


Figure 1. Fusion process representation [11].

Following characteristics of Initial conditions by using for hypothetical target:

Target of radius hypothesis as 1 mm, basic density equal to 0.1 g/cm³ and the basic temperature represent as 100 eV.

Material: Pure deuterium. Laser Preparation. Peak Intensity: 1×10^{15} W/cm².

The Pulse of Duration represent as 1 ns[12] .

Simulation Stages

The complex, multi-scale physics that governs and controls the resulting fusion is subject to sophisticated simulation. With three sequential and sequential stages, the exchange of data between the sequential and interconnected programs leads to a high probability of ensuring the success of the entire process [13].

LILAC – represents asymmetric and two-dimensional modeling [14].

This stage represents the second simulation using LILAC. It is designed for a three-cylinder coordinate system and here it depends on two axes, (r-z)[15].

The resolution of grid is 600 × 800 (radial × axial)

Key of the outputs:

Maximum ion temperature: ~9 keV. density: ~35 g/cm³

The Production of Neutron flux is 7.8×10^{9} neutrons per pulse

VORPAL – 3D

Simulation value: 1 mm³. Grid resolution: ~1 μm, with ~1000 particles per cell

Peak for ion temperature is ~8.5 keV

The Maximum of density is ~30 g/cm³

Yield of Neutron: 6.5×10^{9} neutrons per pulse.

Further conclusions:

Instability

Neutron emissions are not isotropic along the symmetry axis of the loop

Self-generated magnetic fields (a few kilo tesla)

The simulation of the developed multilevel reactor has shown relative success, and the main objective is to achieve nuclear fusion via a D-D reaction. Table 1.

Code	Dimensionality	Geometry Of Laser	Peak T (keV)	Density (g/cm³)	Yield of Neutron (n/pulse)	conclusions
LILAC	2d(r-z)	Rings (equatorial)	8	34	7.5×10^{9}	Instability in RT, weak and slight symmetry
VORPAL	3D.	Full REM	7.3	29	5×10^{9}	Loss of stability, kinetic effects, variation

Simulation procedure

The typical value for inertial fusion experiments is 10^{15} W/cm², ensuring sufficient energy flow to achieve high compression[16]. The initial condition of the D-D density approaches to 0.1 g/cm³. The initial heat of the process is 100 electron V, The simulation setup includes target design, laser configuration, initial conditions[17].

Results and discussion and Data analysis:

The One-dimensional of the simulation by using HYADES software showed performance limitations, achieving near-ideal pressure with an ion temperature with 12 keV and the density of central around 45 g/cm³, resulting in a neutron output is 1.1×10^{10} per pulse (Figure 3) [18]. The 2-D simulation, which observed the geometric effect of the ring laser, revealed axial asymmetry and Rayleigh-Taylor instability [19]. It demonstrated that achieving conditions suitable for nuclear fusion requires approximately 9

keV, a density of approximately 35 g/cm³, neutron intensity of 7.8×10^9 neutrons per pulse (Figure 6). Three-dimensional simulation showed instability, indicating that neutron emission was not present and unavailable under the pre-assumed parameters of the virtual factors used, Despite the actual asymmetry and kinetic instability (Figure 7), D-D target producing large quantities of neutrons, as demonstrated by the neutron yields from HYADES (one-dimensional) (Figure 8), LILAC (two-dimensional), and VORPAL (three-dimensional) simulations [20].

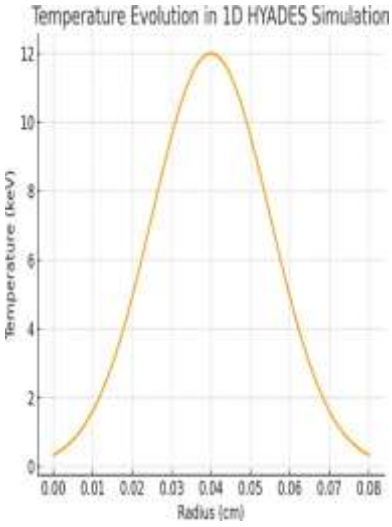


Figure (2): Density Profile for 2D Simulation.

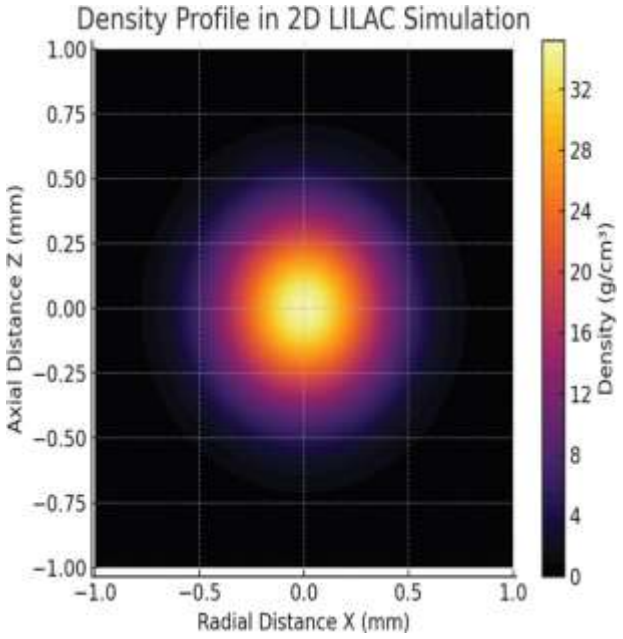
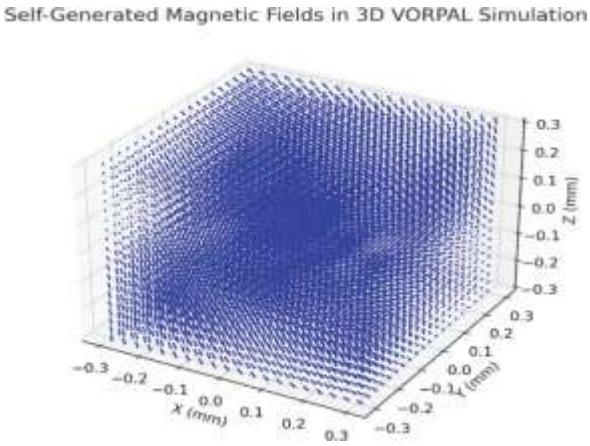
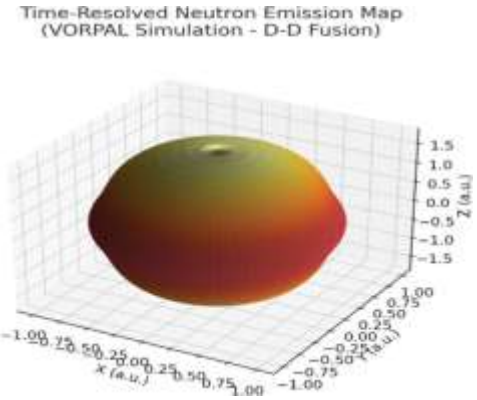


Figure (3): Temperature Evolution in 1D Simulation.

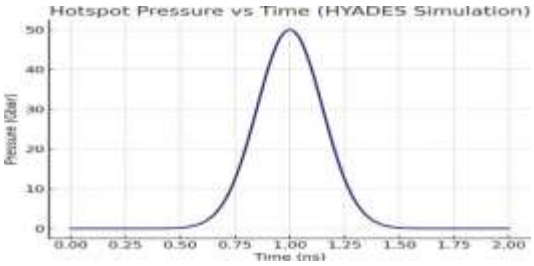




Figure(5):

Representation of Neutron Emission Map and Time-Resolved.

Figure (4): Self-Generated Magnetic Fields in 3D Simulation.



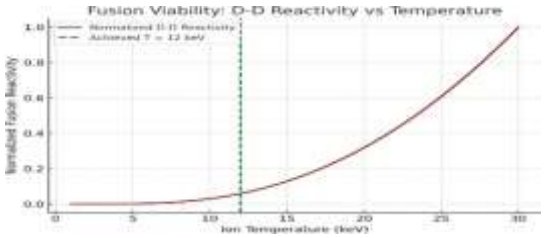


Figure (6): Hotspot Pressure vs Time (HYADES Simulation).

Figure (7):Fusion Viability – D-D Reactivity vs Achieved Temperature.

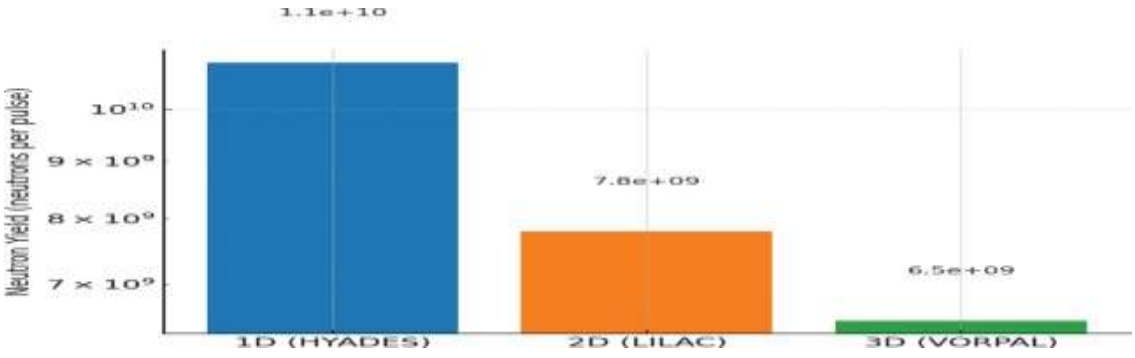


Figure (8): Compression Symmetry as function of D-D Fusion Yield.

Conclusion:

Graphical correlations illustrate describe dimensional complexity with symmetry influence the fusion products. Furthermore, the directional of the neutron emissions notes in the three-dimensional simulation supports new avenues for optimizing and improving the non-isotropic, long-range control of future fusion energy, based on simulations of the space-time continuum, to enter the realm of advanced and controlled nuclear fusion. The graphical correlations illustrate that influence dimensional is symmetry with fusion products. Furthermore, the directional nature of neutron emissions in the three dimension simulations supports new avenues for improving and developing long-range, non-isotropic control of future fusion energy, based on space-time simulations, to enter the realm of advanced and controlled nuclear fusion. The ideal outcome is achieved through careful planning. The use of mathematical programs associated with the computational architecture is crucial for obtaining truly reliable results. Various techniques have been employed, particularly the use of invariant imbedding technic to find the hiding the unknown constants with applications of numerical mathematical calculations.

References:

1-Betti R, Hurricane O (2016) Inertial-confinement fusion with lasers. Nature Physics 12: pages 435–448. https://doi.org/10.1038/nphys3736

2-Biedron SG, Chae YC, Dejus RJ, Faatz B, Freund HP, Milton SV, Nuhn H-D, Reiche S (2000) Multi-dimensional free-electron laser simulation codes: a comparison study. Nuclear Instruments and Methods in Physics Research – section A 445: 1–3. https://doi.org/10.1016/S0168-9002(00)00124-8

3-Bingren S (2005) Core Plasma Characteristics of a Spherical Tokamak D-3He Fusion Reactor. Plasma Sources Science and Technology7: 2767. https://doi.org/10.1088/1009-0630/7/2/019

4-Bosch H-S, Hale GM (1992) Improved formulas for fusion cross-sections and thermal reactivities. Nuclear Fusion 32: 611. https://doi.org/10.1088/0029-5515/32/4/I07

5-Cao SH, Patel D, Lees A, Stoeckl C, Rosenberg MJ, Gopalaswamy V, Wen H, Huang H, Shvydky A, Betti R, Ren C (2022) Predicting hot electron generation in inertial

confinement fusion with particle-in-cell simulations.Physical Review E 106: 055214. https://doi.org/10.1103/PhysRevE.106.055214

6-Colaïtis A, Follett RK, Palastro JP, Igumenschev I, Goncharov V (2019) Adaptive inverse ray-tracing for accurate and efficient modeling of cross beam energy transfer in hydrodynamics simulations. Physics of Plasmas 26: 072706. https://doi.org/10.1063/1.5108777

7-Diels J, Arissian L (2011) Lasers: The Power and Precision of Light.Wiley-VCH. https://doi.org/10.1002/9783527640034

8-Ditmire T, Zweiback J, Yanovsky VP, Cowan TE, Hays G, Wharton KB (1999) Nuclear fusion from explosions of femtosecond laser-heated deuterium clusters. Nature 398: 489–492. https://doi.org/10.1038/19037

9-Imasaki K, Li D (2008) A new approach of laser induced nuclear fusion in plasma by intense laser propagation. Journal of Physics: Conference Series 112: 042071. https://doi.org/10.1088/1742-6596/112/4/042071

10-Krása J, Klír D (2020) Scaling of Laser Fusion Experiments for DD-Neutron Yield. Frontiers in Physics 8: 310. https://doi.org/10.3389/fphy.2020.00310

11-Larsen J, Lane S (1994) HYADES—A plasma hydrodynamics code for dense plasma studies. Journal of Quantitative Spectroscopy and Radiative Transfer 51(1–2): 179–186. https://doi.org/10.1016/0022-4073(94)90078-7

12-Lawson J (1957) Some Criteria for a Power Producing Thermonuclear Reactor. Proceedings of the Physical Society, Section B 70: 6. https://doi.org/10.1088/0370-1301/70/1/303

13-Lindl JD, Amendt P, Berger RL, Glendinning SG, Glenzer SH, Haan SW, Kauffman RL, Landen OL, Suter LJ (2004) The physics basis for ignition using indirect-drive targets on the National Ignition Facility. Physics of Plasmas 11: 339–491. https://doi.org/10.1063/1.1578638

14-Siegman A (1986) Lasers. University Science Books.

15-Sudan R (2009) Inertial confinement fusion with magnetically compressed ion rings. Laser and Particle Beams 11(2): 415–422. https://doi.org/10.1017/S0263034600004997

16-Tabak M, Hammer J, Glinsky ME, Kruer WL, Wilks SC, Woodworth J, Campbell EM, Perry MD, Mason RJ (1994) Ignition and high gain with ultrapowerful lasers. Physics of Plasmas 1: 1626–1634. https://doi.org/10.1063/1.870664

17-Trickey W, Goncharov V, Betti R, Campbell EM, Collins TJB, Follett RK (2024) The physics of gain relevant to inertial fusion energy target designs. Physics of Plasmas 31: 012702. https://doi.org/10.1063/5.0167405

18-Zimmerman G, Kruer W (1975) Numerical simulation of laser-initiated fusion. Comments on Plasma Physics and Controlled Fusion 2(2): 51–60.

19-Kim, Y.E., *Surface reaction mechanism for deuterium-deuterium fusion with a gas/solid-state fusion device.* Fusion Technol., 1991. 19: p. 558.
20- K Grigoryev1,2, N Chernov1, R Engels2, I Ivanov1," Double polarized dd-fusion experiment" Journal of Physics: Conference Series 295 (2011) 012168.
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