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NUCLEAR FUSION: COMPARISON OF NUCLEAR FUSION PERFORMANCE WITH INERTIAL AND MAGNETIC CONFINEMENT

Suryabh Prakash

Research Scholars Program, Harvard Student Agencies In collaboration with Learn with Leaders

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Research Paper

ABSTRACT

This research paper provides an initial summary of nuclear fusion and the physics behind the process of creating a successful fusion reaction. Ultimately, the paper compares the performance of nuclear fusion reactors that use inertial confinement techniques to those using magnetic confinement. The analysis of existing fusion reactor data was taken into account by analyzing the triple product for existing fusion reactors. Data has shown that the highest triple product to be achieved by NIF, which is an inertial confinement reactor, and the triple product indicated for inertial confinement are greater. The conclusive reason for the greater triple product for inertial confinement is the higher plasma density achieved despite the confinement time being in the order of nanoseconds.

KEYWORDS: Nuclear Fusion, Nif, Inertial Confinement, Magnetic Confinement, Lawson Criterion, Plasma Density, Tokamak, Stellarator, Magneto-Inertial Confinement, Energy Confinement

INTRODUCTION

How does the process of nuclear fusion work?

Simply stated, nuclear fusion is a process in which two lighter nuclei are fused to create a larger one. The creation of this heavier nucleus also releases energy due to the difference in mass before and after the reaction, known as the “mass defect.” The energy released in this is very high, and if harnessed, it can provide the needs of modern power requirements without any carbon emissions. However, this process requires many conditions to be kept in check in order to ensure functionality.

In a typical nuclear fusion reaction, the reactants are deuterium and tritium. The reaction’s product is a helium-4 particle and a neutron. The mass defect of this can be calculated in order to determine the energy released from one of these reactions, as given below.

Deuterium + Tritium → Helium + Neutron

$$^{2}H_{1} + ^{3}H_{1} \rightarrow ^{4}He_{2} + ^{1}n_{0}$$

The mass defect can be calculated using the atomic mass of the reactants and subtracting from the atomic mass of the products (u = 1.66\cdot(10^{-27}) kg), as given below.

Atomic mass of deuterium = 2.014102 u Atomic mass of Helium = 4.002602 u

Atomic mass of tritium = 3.016049 u Atomic mass of neutron = 1.008665 u

$$u\ (2.014102 + 3.016049\ -\ (4.002602 + 1.008665))\ =\ 0.018884\ u$$

The value above is the mass defect of the reaction. In order to get the energy released from this reaction, we can use the formula $E=mc^2$. Since we already have the atomic mass, we can multiply by 931.5 MeV/u.

This will yield:

$$0.018884\ u \cdot 931.5\ \frac{MeV}{u}\ =\ 17.59\ MeV\ \approx 2.81(10^{-12})\ Joules$$

(Tsokos, 2023)

FUSION OVERVIEW

Conditions for Fusion

It is also important to expatiate how nuclear fusion reactions work on a larger scale, with billions of reactions occurring every second. The concept of creating nuclear fusion reactors on Earth is to develop a source of energy similar to the sun to use large amounts of energy. To facilitate a nuclear fusion reaction, the following three necessary conditions must be met:

- The first condition that must be met is the temperature required, which must be high enough (at a minimum of 100 million Kelvin for a nuclear reactor) for the deuterium and tritium to overcome the electric force between them since both have like charges and therefore repel. The increase in temperature increases the kinetic energy of both deuterium and tritium to get them in a range 10^{-15}m from the center of the nucleus. The strong nuclear force at this distance causes the fusion to occur as the electric coulomb force has been overcome.
- The second necessary condition is the density of the ions, as they must be confined in order

to self-sustain the process required for nuclear fusion. The high ion density also increases the rate of reaction as the collisions increase when the ions are closer together.

- The third condition that is necessary is confinement time. Confinement time is the length of time for which the ions are present in the plasma. This parameter is important as the confinement time is the duration for which the fusion reactions take place and energy is actively being released. Increased confinement time can help in creating more energy than is being used in order to heat the plasma. (IAEA, 2016)

Types of Fusion

To maintain these conditions, two types of confinement processes are used to maintain these 3 parameters, also known as the "Triple Product." The two types of confinements are:

1. Inertial Confinement: In order to confine the deuterium and tritium, inertial confinement uses lasers that target a pellet containing the deuterium and tritium from every direction. These lasers create high pressures and temperatures by compressing the deuterium and tritium and forcing the deuterium and tritium to fuse by providing enough kinetic energy for the fusion to overcome the Coulomb force of repulsion between them. Specifically, the pellets containing the deuterium absorb the incident energy and convert it into kinetic energy, which causes the pellet to implode. This implosion has to reach the critical temperature and pressure required for fusion to occur (Peeva, 2021).

Due to the high energy needed and the symmetrical uniformity of lasers required for the confinement of the reaction, there are various properties that the lasers used in fusion reactions must have. Since the lasers must provide a high level of energy, we can use the Planck relation equation to understand the type of laser that must be used, given below.

$$E = hf \quad E: energy\ (joules)\ \ h: planck's\ constant\ \ f: frequency\ (Hz)$$

Based on this relation, the lasers being used would have a high frequency in order to maximize the energy provided, and thus the wavelength of the lasers will be very low.

2. Magnetic Confinement: Magnetic confinement is a method of controlling the plasma present in a nuclear fusion reaction. Plasma is a result of heating gas to temperatures where the electrons are removed from the nuclei. This gives rise to plasma, which is the fourth state of matter and is highly conductive. To ensure that the plasma does not expand and damage the walls of a nuclear fusion reactor or become a short-lived reaction due to heat loss, magnetic fields are used. This is because magnetic fields can exert a force on the charge. Since plasma contains moving electrons, the magnetic field can produce a force that is perpendicular to both the field and the motion of the electron. This can result in a centripetal force, which can cause the plasma to stay confined in a region if the magnetic field is strong enough. The force that a single charge in the plasma will face can be given as follows:

$$F = qVB\sin(\theta) \quad q = charge\ of\ particle\ (C)$$

$$v\ = velocity\ of\ the\ charged\ particle\ (m\cdot s^{-1})$$

$$B = Magnetic\ field\ (Tesla)$$

$$\theta\ is\ the\ angle\ between\ the\ B\ field\ and\ the\ velocity\ of\ a\ particle$$

The magnetic field is used in both toroidal and poloidal arrangements to confine the plasma to maintain high density and pressure. A current can also be added to the plasma for better confinement, as the current can be used to manipulate the direction of confinement due to the force produced by the interaction of current and magnetic field.

METHODOLOGY

Research Approach

This study employs a comparative analytical approach to evaluate the performance of nuclear fusion reactors utilizing inertial and magnetic confinement techniques. The analysis is based on existing experimental data from various fusion reactor projects, with a focus on the triple product—density, temperature, and confinement time—as a key performance metric. This methodology was chosen to provide a quantitative and objective basis for comparison, allowing for an evidence-based assessment of the two confinement methods.

Data Collection

The data used in this study were sourced from published research papers, reports, and experimental results from leading fusion research facilities. The primary sources of data include:

1. National Ignition Facility (NIF): Experimental results on inertial confinement fusion (ICF) performance, including plasma density, temperature, and confinement time.
2. Tokamak and Stellarator Facilities: Data on magnetic confinement fusion (MCF) from prominent reactors such as ITER, JT-60U, and JET.
3. Scientific Literature and Reports: Peer-reviewed journal articles and reports from institutions like the International Atomic Energy Agency (IAEA, 2016) and the Department of Energy (DOE).

The data were selected based on their credibility, relevance to the study, and consistency in reporting key fusion parameters. Only experimental results that were peer-reviewed or officially reported by research institutions were considered.

Analytical Framework

The study utilizes the triple product ($nT\tau$) as the primary metric for evaluating fusion reactor performance. The triple product is given by:

$$n \cdot T \cdot \tau$$

where:

- n is the plasma density (particles per cubic meter),
- T is the ion temperature (keV),
- τ is the energy confinement time (seconds).

This parameter was chosen because it directly correlates with the Lawson criterion, a fundamental requirement for achieving net energy gain in fusion reactions. The collected data for different reactors were normalized and plotted to visualize trends over time.

Justification for Method Selection

A comparative analytical approach was chosen for the following reasons:

1. Quantitative Comparison: The use of the triple product allows for an objective, numerical comparison between inertial and magnetic confinement reactors.
2. Historical Data Availability: Given the extensive research and experimental results available for both confinement methods, a data-driven approach provides the most reliable means of assessment.
3. Reproducibility and Verification: The methodology relies on published experimental data, ensuring that the results can be cross-verified with existing literature and future studies.

Data Processing and Interpretation

The collected data were analyzed using statistical and graphical techniques. Key steps in the data analysis included:

1. Trend Analysis: Evaluating historical improvements in the triple product for both inertial and magnetic confinement reactors.
2. Comparative Graphical Representation: Plotting the triple product for different fusion reactors over time to identify which method demonstrates superior performance.
3. Error Consideration: Accounting for uncertainties in experimental data by referencing error margins reported in original sources.

Limitations

While this study provides an insightful comparison, certain limitations must be acknowledged:

- Variability in Reactor Designs: Different reactors may have operational and design-specific factors affecting their performance beyond the triple product.
- Incomplete Data: Not all experimental reactors report comprehensive datasets, potentially leading to gaps in comparison.
- Assumptions in Normalization: Data normalization techniques were applied to allow fair comparison, but slight variations may still exist in reported parameters.

The methodological approach used in this study ensures a structured, evidence-based comparison of inertial and magnetic confinement fusion reactors. By focusing on the triple product, this research provides a scientifically rigorous assessment of fusion performance, contributing to the broader discourse on the future of nuclear fusion as a viable energy source.

ANALYSIS & DISCUSSION

Analysis of Fusion run times

Data from existing interior confinement fusion sites and magnetic confinement fusion sites can be analyzed in order to determine which offers a better overall performance. To analyze which method of confinement is better, data from the National Ignition Facility and Tokamak will be taken in order to compare the triple product.

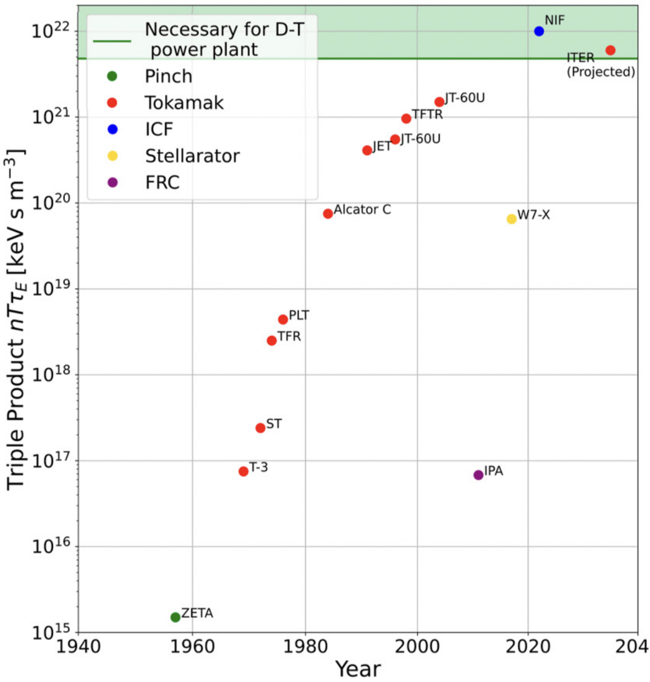

Figure 1: Triple product for various nuclear fusion reactors
Source: Samuele Meschini et al. (2023)

The graph above shows the triple product achieved for various nuclear fusion reactors. Based on the graph, it is evident that the triple product is increasing over time, with the NIF having the greatest recorded triple product of 10^{22} keV • S • m^{-3}. The green section of the graph represents the triple product needed to achieve ignition. The only other nuclear fusion site in the green section is the ITER which is not yet constructed but is estimated to achieve ignition. The closest to being in the ignition section is the JT-60U which is a magnetic confinement fusion reactor. Based on this evidence it can be seen that inertial confinement may produce better results than magnetic confinement fusion reactors. However, it is important to analyze other factors as well in order to reach conclusions about the performance (Meschini et al., 2023).

Comparison of Inertial and Magnetic Confinement

When the individual components for the triple product are compared, the confinement time seen for the magnetic confinement fusion is greater. In comparison, the confinement time for inertial confinement fusion reactors is on a scale of 1-10 ns. This indicates the strength of magnetic confinement fusion in sustaining longer fusion times. The density of the fusion reaction in an inertial confinement reaction, however, is much greater than in a magnetic confinement nuclear reaction, and thus the overall triple product of the inertial confinement fusion reactor is greater.

CONCLUSION

In conclusion, the overall fusion performance is better for inertial confinement as compared to magnetic confinement fusion due to the magnitude of difference in the plasma density being greater than the magnitude of difference in the confinement time. The magnitude of the confinement time is 10^8 seconds greater for the magnetic confinement fusion; however, the plasma density achieved in inertial confinement fusion is 10^{11} greater in magnitude. The temperature for both inertial confinement and magnetic confinement fusion is comparable and stands at 10 keV (Meschini et al., 2023). Based on this data, it is evident that the method of using lasers for rapid ablation in inertial confinement fusion indicates a stronger fusion performance as compared to magnetic confinement fusion, as seen through the triple product.

Future of Nuclear Fusion as a Source of Energy

In the future, a process that combines both the high plasma density achieved in inertial confinement and the longer confinement time in magnetic confinement is required for efficient and large-scale energy production. Magneto-inertial confinement aims to maintain the ablation method using lasers from inertial confinement while incorporating magnetic fields to stabilize the plasma and extend the confinement time. If this technique is successful, it holds immense potential for the future of clean energy.

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