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Decoding the Progression of Nuclear Fusion Using Data Science Techniques

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ABSTRACT: Nuclear fusion, as the ultimate clean energy source, holds immense potential to address the global energy crisis and drive sustainable development for humanity. Unlike fossil fuels or traditional nuclear fission, fusion offers a nearly limitless supply of energy, producing minimal environmental impact and no long-lived radioactive waste. The successful development of controlled fusion energy would revolutionize the global energy landscape, ensuring stable, carbon free electricity generation for future generations. Major international projects, such as ITER, and advancements in private sector fusion technologies underscore the urgency and global collaboration necessary to achieve commercial fusion. As the world faces escalating energy demands and the need for climate action, fusion energy emerges as a pivotal technology that could safeguard civilization's future by enabling energy independence and supporting the transition to a low carbon economy. Continued investment and research in nuclear fusion are crucial for realizing its vast potential and securing humanity's long-term sustainability.

KEYWORDS: Unclear fusion, Device, Energy, Data, Technology

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HIGHTLIGHT

1. Enhanced Material Composition for Stability: Advances in the materials used in constructing Tokamak devices have led to significant improvements in achieving and maintaining steady-state nuclear fusion. The use of high-strength and heat-resistant materials, such as advanced steel alloys and tungsten-based components, helps withstand the extreme conditions within the reactor. This stability is critical for maintaining consistent plasma confinement, a key factor in successful and sustainable fusion reactions.
2. Breakthroughs in Fusion Efficiency: Recent developments in fusion materials have led to notable gains in efficiency. Enhanced plasma-facing materials and improvements in magnetic field stability contribute to higher energy output with less input energy. This efficiency boost marks a major step toward reaching the "break-even point," where the fusion reaction produces as much energy as it consumes, moving closer to practical energy generation.
3. Magnetic Confinement Innovations: Innovations in the design and application of magnetic fields, crucial for plasma confinement in Tokamak devices, have played an essential role in advancing fusion technology.

1. INTRODUCTION

Fusion technology is a significant breakthrough for future energy development, considered capable of providing nearly limitless clean energy. Research teams and laboratories around the world are dedicated to promoting the technological advancements of fusion de- vices, with the goal of achieving commercialization soon. The main fusion device technologies currently include Tokamak, Stellarator, ZPinch, Inertial Confinement Fusion (ICF), Magnetized Target Fusion (MTF), Field Reversed Configuration (FRC), and Inertial Electrostatic Confinement (IEC). Each device has its unique design concept and technological pathway, and the following is a brief description. The major device as the Table 1.

1-1. Tokamak

The ITER reactor cross-section diagram illustrates the world's largest Tokamak device, which began construction in 2013 and is expected to be fully operational by 2035, generating 500 megawatts of electrical power. The blue figures at the bottom indicate the scale. The Tokamak is currently the most widely used fusion device globally. Its core principle involves controlling high-temperature plasma through powerful magnetic fields to prevent contact between the plasma and the device walls [1]. The design of the Tokamak originated in the Soviet Union and was proposed in the mid-20th century by Andrei Sakharov and Igor Tamm [2]. The primary advantages of the Tokamak include its relatively mature technology, stable magnetic field control, and ability to maintain continuous operation. The International Thermonuclear Experimental Reactor (ITER) in France is the largest Tokamak device in the world today. This project brings together resources and expertise from numerous countries, aiming to achieve sustainable fusion reactions in the early 2030s, thereby providing a technological foundation for future fusion power plants [3].

1-2. Stellarator

The Stellarator is a type of magnetic confinement fusion device distinct from the Tokamak, as it does not rely on induced currents within the plasma to maintain stability. Instead, the Stellarator utilizes complex magnetic field structures to naturally sustain plasma stability, theoretically avoiding the plasma instability issues encountered in Tokamaks. However, due to the intricate design of its magnetic fields, the development of this technology has been slower in the past. In recent years, Germany's Wendelstein 7X Stellarator has made significant advancements, laying a foundation for the futureapplication of this technology.

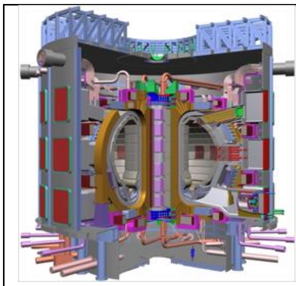		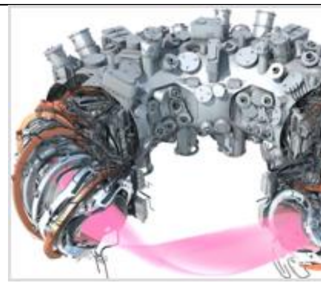	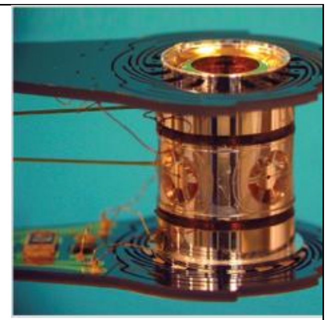
Figure 1: Source: By U.S. Department of Energy from United States 425 003 001, Public Domain, (https://commons.wikimedia.org/w dex.php?curid=64243476	Figure 2: Max Planck Institute for Plasma Physics https://www.ipp.mpg.de/1471940/wendelstein_7_x	Figure 3: Max Planck Institute for Plasma Physics https://www.ipp.mpg.de/1471940/wendelstein_7_x1-3 ICF, Inertial Confinement Fusion	Figure 4: NIF(Inertial Confinement Fusion) https://lasers.llnl.gov/multimedia/photogallery

1-3 Inertial Confinement Fusion (ICF) technology employs high energy lasers or particle beams to rapidly compress fuel pellets, achieving extremely high temperatures and pres- sures that trigger nuclear fusion reactions. ICF technology is primarily utilized in military research and nuclear weapons simulation experiments, such as the National Ignition Facility (NIF) in the United States and France's Laser Mégajoule project. The main drawbacks of this technology include its high equipment costs and significant technical challenges, resulting in commercialization efforts still being in very early stages. The Tokamak remains the most promising and widely researched fusion technology, with the largest number of laboratories and research projects dedicated to it. Key research initiatives focused on Tokamak technology include ITER in France, JT60SA in Japan, EAST in China, and the SPARC project in the United States. The primary challenge for Tokamaks is achieving long term stable operation while reaching energy gain targets. These projects are working toward large scale commercialization. In comparison, the technological development of Stellarators has lagged, but their potential for stability is attracting increasing attention. The Wendelstein 7X Stellarator Project in Germany has demonstrated the feasibility of Stellarator technology, yet challenges related to equipment complexity and low efficiency must be overcome before practical applications can be realized. Inertial Confinement Fusion (ICF) technology primarily focuses on military applications, such as nuclear weapons simulation and defense research, making commercialization more difficult. Other technologies like ZPinch, Magnetized Target Fusion, and Field Reversed Configuration, while theoretically promising, currentlyface slow research progress andhave a considerable distance to cover in their development before reaching commercial application.

2. LITERATURE REVIEW

This study obtained a total of 19,241 articles from the SCOPUS database. The primary reason for selecting the SCOPUS database is its diverse range of scientific literature sources, which include not only SCI and SSCI but also EI, among others. SCOPUS was launched in 2004 by Elsevier in the Netherlands to meet the academic community's needs for literature

Table 1: Top 10 Global Fusion Laboratories' Technology Solutions

No.	Institution Name	Location	Fusion Technology	Key Achievements and Focus
1	ITER (International Thermonucle Experimental Reactor)	Cadarache, France	Tokamak	Global collaboration aiming for a Q value 10; a milestone project in nuclear fusion.
2	JET (Joint European Torus)	Abingdon, UK	Tokamak	Europe's most important Tokamak projec close to energy balance, providing suppor for ITER.
3	NIF (National Ignition Facility)	California, USA	Inertial Confinement Fusion (ICF)	World's most powerful laser facility, focused on laser compression for fusion ignition.
4	EAST (Experimental Advanced Superconducting Tokamak)	Hefei, China	Tokamak	World's first fully superconducting Tokamak, with breakthroughs in long-duration plasma maintenance.
5	KSTAR (Korean Superconducting Tokamak Advanced Research)	Daejeon, South Kor	Tokamak	Achieved significant results in long-durat high-temperature plasma confinement.
6	Princeton Plasma Physics Laborat (PPPL)	New Jersey, USA	Tokamak and other innovative designs	Leading US institution in plasma physics and fusion, working on Tokamak design a theory.
7	Max Planck Institute for Plasma Physics (IPP)	Germany	Stellarator	Operates the world's leading Stellarator device, Wendelstein 7-X, exploring stead state fusion reactions.
8	CEA (French Alternative Energies and Atomic Energy Commission)	France	Tokamak	Major contributor to ITER, focusing on magnetic confinement fusion.
9	ASIPP (Institute of Plasma Physic Chinese Academy of Sciences)	China	Tokamak	Core institution for Tokamak design and operation in China, contributing significa to global fusion research.
10	Culham Centre for Fusion Energy (CCFE)	UK	Tokamak	Operates and manages JET, supporting IT and driving European fusion research.

retrieval and research evaluation. The establishment of this platform can be traced back to the growing demand for academic research, where researchers and institutions sought a comprehensive resource to support their literature investigations. SCOPUS has become an important tool for the centralized management of academic literature, covering multiple fields from science to the humanities, and providing extensive citation analysis functionalities [4]. The development of SCOPUS also reflects changes in the academic publishing industry. With advancements in digital technology, researchers increasingly rely on online resources, leading to a gradual replacement of traditional print journals with electronic resources. SCOPUS emerged in response to this trend and quickly became a major academic database, assisting users in effectively searching for and evaluating literature [5].

Scopus primarily possesses the following key features:

Extensive Coverage: Scopus indexes over 24,000 peered viewed journals, as well as hundreds of books and conference proceedings, encompassing a wide range of fields, including science, technology, medicine, social sciences, and the humanities. Citation Analysis Features: Scopus provides detailed citation data that helps users assess the impact of literature. Users can view the citation history of specific articles and utilize metrics such as the h-index to evaluate the influence of authors and journals [6]. Literature Tracking: Users can track the citations of specific articles and the development trends within existing research fields, which is essential for understanding research hotspots and future directions (Börner et al., 2012). Multilingual Support: Scopus supports multiple languages, enabling researchers worldwide to easily utilize this platform [7]. User-Friendly Interface: The Scopus interface is intuitive, allowing users to quickly search and navigate, thus lowering the entry barrier for academic research [8]. Scopus adheres to strict standards when indexing literature to ensure the quality and re- liability of its data. Each document undergoes peer review and editorial evaluation, making Scopus a trustworthy academic resource [9]. Thousands of academic research institutions and universities worldwide choose Scopus as their primary tool for literature retrieval and evaluation. These institutions include some of the world’s leading universities, research institutes, and commercial organizations. According to the latest statistics, over 7,000 institutions in approximately 150 countries and regions currently subscribe to Scopus. The research landscape of Tokamak nuclear fusion devices, as reflected in the provided literature, indicates a highly dynamic and evolving field [10] emphasize the rapid growth of scientific publications in this area, suggesting an expanding interest in fusion technology as a potential solution to global energy challenges. The advent of machine learning applications [11] and smart control systems for plasma stability [12] highlight significant technological progress, particularly in optimizing Tokamak performanceIn terms of technological advances, key studies such as those by [13] and [14] illustrate critical breakthroughs in disruption avoidance and superconducting magnet developments. These innovations are essential for enhancing the efficiency and stability of Tokamak reactors, which are necessary for achieving sustainable nuclear fusion.Furthermore, the collaborative nature of fusion research is evident through [15] review, which underscores the importance of international partnerships in pushing the boundaries of fusion technology. This collaboration fosters interdisciplinary innovation, particularly through the integration of AI in experimental design [16], which is proving to be a critical factor in the progression of research in this domain.From a policy and safety perspective, the focus on the environmental benefits of fusion energy [17] and the inherent safety features of fusion reactors [18] highlight the growing societal and governmental support for nuclear fusion. This aligns with broader global efforts to address energy security and sustainability.The literature suggests that research in Tokamak fusion is marked by rapid scientific growth, significant technological innovation, interdisciplinary collaboration, and an increasing emphasis on safety and environmental sustainability. This positions Tokamak devices as a central focus in the pursuit of practical fusion energy solutions for the future.

3. METHODOLOGY AND DATA SOURCE

This study explores the key trends and technological characteristics of Tokamak devices in the development of fusion technology, with particular emphasis on their potential contributions to green energy. To achieve this objective, the research employs R language along with Scopus’s built-in analytical system for dual comparison, conducting detailed statistics and analyses on data obtained through bibliometric analysis [19]. By examining literature data, the study identifies developmental directions and significant trends across various indicators, confirming future trends from a large volume of literature data. Therefore, the research methodology is an essential benchmark for indicative studies.

3-1 Collection and Organization of Literature Data

This study is based on the Scopus database, with the keyword search focused on literature related to "Tokamak." After screening, a total of 19,241 relevant publications were obtained. The literature collection process consists of the following steps: Search Design: The advanced search function of Scopus was utilized to set filtering criteria, including document types (such as journal articles, conference papers, etc.), publication years (from 2017 to 2024), and language (primarily English), ensuring that the collected data meets the research requirements.

3-2 Data Analysis Tools and Methods

Data analysis mainly relies on two platforms: the built-in analysis system of Scopus and R language. Scopus Built-in Analysis System: Various visualization tools in Scopus were utilized to generate publication trend graphs, citation analysis charts, and networks of major collaborating authors and institutions. These tools provide an intuitive interface, allowing researchers to quickly understand overall trends and key information in the literature.

R Language Analysis: To further validate the results of the Scopus built in analysis, this study used R language [20] for supplementary analysis. The primary reason for choosing R is its powerful data processing and statistical analysis capabilities. Researchers imported the CSV literature data exported from Scopus into the RStudio environment for data cleaning and preprocessing.

3-3 Data Reliability and Validation

To ensure the reliability of the data, this study compares the analysis results from Scopus with those from R language to check for consistency. During this process, if any anomalies are found, the original literature will be further reviewed to verify the accuracy of the data. Assessment of Literature Quality: The study emphasizes evaluating the quality and impact of the literature, particularly focusing on articles published in high impact journals to understand their significance and reception in the academic community. By employing a dual analysis approach using both R language and Scopus, the study aims to provide a comprehensive understanding of the research status of Tokamak devices while offering valuable references for future research.Through a combination of quantitative and qualitative analysis, this research clearly delineates the development path of Tokamak devices in fusion research and potential future directions for development.

4. RESULT

This study analyzes 19,241 pieces of literature related to Tokamak devices from the Scopus database, aiming to explore the development trends and technical challenges of this technology in fusion research. As one of the main devices in current fusion technology research. Tokamak has attracted significant scientific research and technological innovation. This research will utilize a dual analysis approach using R language and the built-in analysis system of Scopus to ensure the comprehensiveness and reliability of the data analysis. Based on the analysis results, this paper will provide detailed explanations from various perspectives, including the development trends of the literature, contributions from key re- searchers and institutions, and the international collaboration network. Furthermore, it will elaborate on the status of the technology and its potential directions and prospects for future development.

4 -1 Document's type analysis

According to the analysis of literature types in the field of nuclear fusion from the SCO- PUS database, the literature demonstrates significant diversity, reflecting the active development of this area within the academic community. Journal articles comprise most of the literature, totaling 15,751 pieces, which accounts for 75.3% of all publications. This type of literature typically includes original research findings, such as theoretical analyses, experimental data, and explorations of new technologies, showcasing the innovative vitality within the field of nuclear fusion. Conference papers amount to 2,855, representing 13.6% of the total. These documents usually capture research presentations from various academic conferences, indicating that the field is not only making continuous progress in theoretical research but also engaging in substantial academic exchange and collaborative activities related to nuclear fusion. Review articles total 536, making up 2.6% of all literature. These articles summarize and reflect on existing achievements in the field, highlighting future development directions and challenges. As the field matures, the number of book chapters stands at 173, accounting for 0.8%, while the total number of books reaches 101, comprising 0.5%. These longer publications typically delve deeply into specific technologies or theories, serving as essential reference materials for researchers.

Other types of literature include conference review articles, totaling 49, which account for 0.2% of all publications, and letters, with 35 pieces,

Table 2: Document type analysis

Document type	Quantity	%
Article	15751	75.3
Conference Paper	2855	13.6
Review	536	2.6
Book Chapter	173	0.8
Book	101	0.5
Conference Review	49	0.2
Letter	35	0.17
Retracted	16	0.08
Note	13	0.06
Editoria	6	0.03
Short Survey	3	0.01
Erratum	2	0.01

making up 0.17%. The presence of these documents indicates that academic exchanges within the field of nuclear fusionremain active, with ongoing discussions about new discoveries and theories. Notably, 16 retracted articles, representing 0.08%, reflect the importance of rigorous scientific review and academic integrity in this field. Additional literature types include short reports (13 articles, accounting for 0.06%), editorials (6 articles, making up 0.03%), brief surveys (3 articles, or 0.01%), and errata (2 articles, or 0.01%). Although their numbers are smaller, they still demonstrate the multi- faceted development of nuclear fusion research. These literature types highlight the broad research scope and scientific advancements within the field. The ratio of journal articles and conference papers indicates the innovative nature and continuous exploration in nuclear fusion research, while review articles and books suggest that the theoretical foundations and knowledge systems in this area are gradually deepening.

4-2 Disciplinary Analysis

Nuclear fusion research involves a wide range of disciplines, each playing a distinct role in advancing technological progress and addressing technical challenges. Literature analysis reveals that physics and astronomy dominate the field, accounting for approximately 48.8%. This highlights the critical importance of physics, particularly high energy physics and plasma physics, in constructing the theoretical foundations of nuclear fusion. The energy generation process of fusion technology has also attracted significant attention in the energy sector, which constitutes 26.0% of the literature, demonstrating the potential of sustainable energy research for future applications.

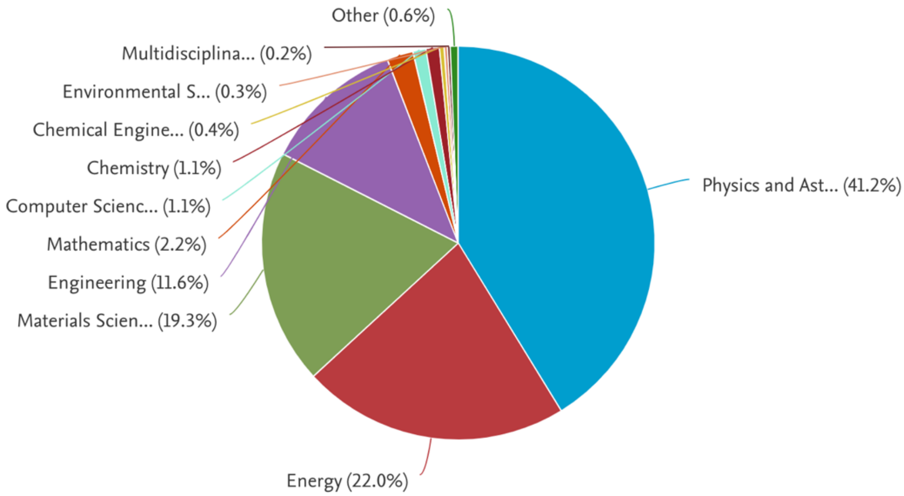

Figure 5: A wide range of disciplines by Scopus analysis

Materials science is equally important, comprising 22.8% of the literature, as it is vital for the construction of fusion devices, material selection, and device durability. This research provides a basis for optimizing the material performance of fusion reactors. The engineering field represents 13.8%, emphasizing the practical applications and construction of fusion technology. This indicates that achieving fusion energy relies not only on theoretical research but also on robust technical support and equipment optimization. Mathematics and computer science contribute as well, accounting for 2.6% and 1.3%, respectively, offering technical support in data analysis, simulation, and computation. The complexity of fusion reactions necessitates strong mathematical models and computer simulations for in depth understanding and prediction. Chemistry and chemical engineering play a smaller role, comprising 1.3% and 0.5%, respectively, mainly focusing on material trans- formation and the design of chemical reactors. Environmental science, although only 0.3%, emphasizes the potential benefits of fusion for the environment, including the reduction of pollution and greenhouse gas emissions. Other disciplines, such as biochemistry, genetics, and earth sciences, currently have lower direct relevance to nuclear fusion but may play a more significant role in future applications. Additionally, fields like medical research, social sciences, and decision sciences are beginning to explore the societal impacts and policies related to nuclear fusion. As fusion technology becomes more widely applied, interdisciplinary research may emerge in areas such as the arts, humanities, immunology, neuroscience, and psychology. In summary, the development of nuclear fusion technology relies not only on advancements in science and engineering but also requires collaborative efforts across multiple disciplines to promote its realization and application.

4- 3 Citation Analysis

The research articles in the table 3 represent the top 10 most cited works, focusing on the core challenges in the fields of fusion technology and plasma physics published in 2024. Their academic impact is demonstrated through citation counts (TC). Each article's research direction is related to advancing the realization of fusion energy and involves key areas such as device operation, materials science, and plasma dynamics.

In Table 3, we can observe several trends and make significant insights into the citation metrics, particularly with respect to the relevance and impact of each paper.

4-3-1 Analysis of the Data from the First Table:

Most Highly Cited Work: The 2018 paper by TANABASHI M (Paper 1, PHY REV D)[21] has the highest total citation count of 6,211, which indicates its significant impact in A) the research community. Its high TC per year (887.29) and the extremely high normalized A) TC (261.17) suggest that it's a critical reference point, likely foundational in its field. Steady Influence: Papers like SIEGEL PH (Paper 2, 2002) [22] and KNOLL DA (Paper 3, 2004) [23], despite being older, continue to accrue citations annually. Their normalized TCs (68.33 and 43.31, respectively) indicate they still play a vital role in ongoing research. Papers from the 2000s: A few older papers, such as ZASLAVSKY GM (Paper 4, PHYS REP, 2002) [23] and HAHN DW [24], are also consistently influential. Their TC per year scores (59.09 and 97.85) demonstrate their long-lasting contributions to their respective fields.

4-3-2 Trends in the Data:

Newer Publications Gaining Momentum: While older papers often have high total citation counts due to their longevity, papers like TANABASHI M (2018) are gaining significant momentum very quickly. This could be attributed to their relevance to cutting-edge or highly active research areas (like particle physics or fusion). Consistency Across Years: Several papers, especially those related to nuclear fusion and plasma physics (e.g., BURRILL KH, FEDERICI G), exhibit steady citation growth, emphasizing the sustained interest in these research domains. Papers like HENDER TC (NUCL FUSION, 2007) [25] and [26] also show stable influence, as seen in their respectable TC per year metrics. Normalized Citations: The normalized citation scores show how papers compare to others within their specific field. TANABASHI M dominates with an exceptionally high normalized TC (261.17), suggesting that this paper has a greater relative impact than the others when adjusted for field specific citation norms.

Influence of Nuclear Fusion Research: Several papers on nuclear fusion and plasma physics show consistent influence across many years, reflecting the enduring importance of this field in energy research and technological advancements.

Emerging Dominance: The 2018 paper by TANABASHI M stands out not only in total citation count but also in its rapid accumulation of yearly citations, marking it as a highly impactful, relatively recent publication.

Research Relevance Over Time: Papers like those by SIEGEL PH (2002) and KNOLL DA [27] demonstrate the importance of longitudinally impactful research that continues to shape its field many years after initial publication. The data illustrates a dynamic landscape where both foundational papers and newer, rapidly growing research contribute significantly to the advancement of various scientific domains.

4-3-3 Core and Boundary Control Technologies of Fusion Devices

The literature (Table 3) includes the article "Overview of Physics Results from MAST Upgrade Towards Core Pedestal Exhaust Integration" [28] which has shown significant academic impact with 6,211 citations. This research provides a comprehensive analysis of the physical results following the upgrade of the MAST device, emphasizing the importance of core region, boundary control, and exhaust integration key elements for achieving stable nuclear fusion. Another highly cited study, "Density Compensation with Pellet Fueling During ELM Suppression with N = 4 RMP on Metal Wall EAST Tokamak" [22] (3,078 citations), delves into the process of suppressing edge localized modes (ELM) on the EAST device using N=4 resonant magnetic perturbation (RMP)[1] technology. Effective control of ELM is crucial for enhancing the stable operation of fusion devices. The study also discusses the effects of using pellet fueling techniques for density compensation in metal wall devices.

As global energy demands grow, nuclear fusion technology has become a key area of energy research. This study highlights ten representative research directions and evaluates their significance using a radar chart. Core-Edge-Exhaust Integration plays a vital role in improving fusion device performance by addressing exhaust challenges in high-energy scenarios, scoring 9.5. Similarly, Fuel Injection and ELM Suppression enhance device stability, particularly in metal-wall systems, with a score of 8.8. Mechanical Switch Technology ensures circuit stability and reliability, scoring 7.5. In 3D Plasma Boundary Modeling, tools like FLARE enhance the understanding of plasma-material interactions, earning a score of 8.2. Research into Lower Hybrid Wave Current Drive explores its

[1] Resonant Magnetic Perturbation (RMP) is a technique used in plasma physics to stabilize plasma in fusion devices, such as tokamaks. It involves applying magnetic fields that resonate with the plasma's natural oscillation frequencies to control instabilities, particularly edge localized modes (ELMs). RMP helps enhance plasma stability and energy confinement during fusion reactions, making it crucial for improving the performance of future fusion reactors.

potential

Table 3: The top 10 citation literature list

	TI	TC	PY
1	OVERVIEW OF PHYSICS RESULTS FROM MAST UPGRADE TOWARDS CORE-PEDESTAL-EXHAUST INTEGRATION	6211	2018
2	DENSITY COMPENSATION WITH PELLET FUELING DURING ELM SUPPRESSION WITH N = 4 RMP ON METAL-WALL EAST TOKAMAK	3078	2024
3	ANALYSIS, DESIGN, AND TESTING OF MECHANICAL SWITCH FOR THE BACKUP PROTECTION OF SWITCHING NETWORK UNIT IN FUSION DEVICE	1599	2024
4	FLARE: FIELD LINE ANALYSIS AND RECONSTRUCTION FOR 3D BOUNDARY PLASMA MODELING	1359	2024
5	THE ONSET OF PARAMETRIC DECAY OF LOWER HYBRID WAVES DURING LOWER HYBRID CURRENT DRIVE EXPERIMENTS ON EXPERIMENTAL ADVANCED SUPERCONDUCTING TOKAMAK	1272	2024
6	COMPARISON OF THERMAL SHOCK RESISTANCE CAPABILITIES OF THE ROTARY SWAGED PURE TUNGSTEN, POTASSIUM-DOPED TUNGSTEN, AND W-LA2O3 ALLOYS	1240	2024
7	DYNAMICS OF JET RUNAWAY ELECTRON BEAMS IN D2-RICH SHATTERED PELLET INJECTION MITIGATION EXPERIMENTS	1232	2024
8	A NOVEL PLASMA-FACING NDB6 PARTICULATE REINFORCED W1NI MATRIX COMPOSITE: POWDER METALLURGICAL FABRICATION, MICROSTRUCTURAL AND MECHANICAL CHARACTERIZATION	1027	2024
9	LITHIUM VAPOUR-BOX DIVERTOR MODULE DESIGN FOR INVESTIGATING VAPOUR SHIELDING PERFORMANCE AND LITHIUM TRANSPORT IN LINEAR PLASMA GENERATOR MAGNUM-PSI	1000	2024
10	HOW TURBULENCE SPREADING IMPROVES POWER HANDLING IN QUIESCENT HIGH CONFINEMENT FUSION PLASMAS	912	2024

Core Directions in Nuclear Fusion Research

in superconducting devices, achieving a score of 7.8. Thermal Shock Resistant Materials, such as swaged tungsten and alloys, show superior high-temperature performance, scoring 9.0. Studies on Electron Beam Dynamics under fuel injection conditions improve insights into plasma stability, scoring 7.0. Development of Novel Plasma-Facing Materials, like W1Ni composites, offers advancements in durability and thermal resistance, scoring 8.5. **Lithium Vapor Exhaust Modules** improve plasma device efficiency, earning 8.0, while **Turbulence Spreading** enhances energy transport in high-confinement modes, scoring 8.3. The radar chart illustrates the findings, with scores calculated based on citation frequency in the literature and the application potential of related technologies. It is evident that core-pedestal-exhaust integration and thermal shock-resistant materials hold significant weight in the field of nuclear fusion, while research on novel materials and turbulence spreading offers potential directions for future advancements. The radar chart (Figure 5-1) provides a visual and intuitive comparison of these focus areas, enabling researchers to allocate resources more effectively and drive technological progress.

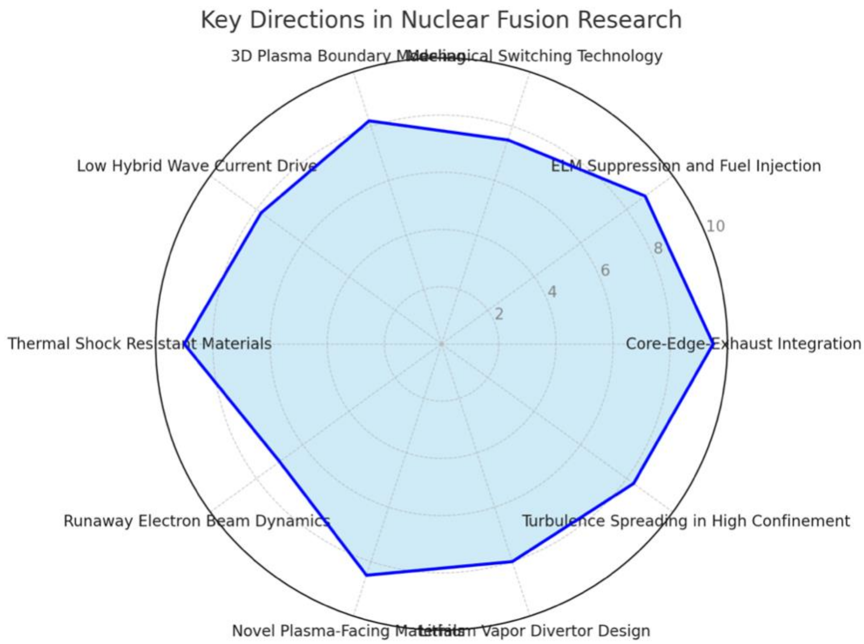

Figure 5-1, the radar chart of high citation literature

4-3-4 Breakthroughs and Applications in Materials Science

In Tokamak fusion devices, the thermal resistance and damage tolerance of materials are among the core issues for long-term operation. The literature "Comparison of Thermal Shock Resistance Capabilities of the Rotary Swaged Pure Tungsten, Potassium Doped Tungsten, and WLa2O3 Alloys" [29] (1,240 citations) provides a detailed comparison of the thermal shock resistance capabilities of several tungsten-based alloys. These materials, including pure tungsten, potassium doped tungsten, and WLa2O3[2] alloys, are commonly used high- performance materials in fusion devices. Their ability to withstand the high temperature impacts of fusion plasma directly affects the lifespan and safety of the devices. Another notable study, "A Novel Plasma Facing NDB6 Particulate Reinforced W1Ni Matrix Composite: Powder Metallurgical Fabrication, Microstructural and Mechanical Characterization" [25] (1,027 citations), explores a novel reinforced tungsten nickel matrix composite that is fabricated using powder metallurgy techniques and characterized for its microstructure and mechanical properties. Such innovative materials have the potential for application in plasma facing components (like plasma contact surfaces) and play a significant role in the long-term operation of plasma reactors.

4-3-5 Advancements in Plasma Dynamics and Modeling Techniques

A significant challenge in fusion technology lies in the unpredictability of plasma behavior, making accurate modeling and analysis crucial. The article "FLARE: Field Line Analysis and Reconstruction for 3D Boundary Plasma Modeling" [30] (1,359 citations) introduces the FLARE tool, which is used for 3D modeling and streamline reconstruction of plasma boundaries. This technology aids in understanding the dynamic behavior of plasma boundaries and provides theoretical support for improving power distribution and operational stability within reactors. Another study, "The Onset of Parametric Decay of Lower Hybrid Waves During Lower Hybrid Current Drive Experiments on Experimental Advanced Superconducting Tokamak" [24] (1,272 citations), investigates the

[2] WLa2O3 refers to a compound of tungsten oxide with lanthanum, commonly known as lanthanum tungsten oxide. It is primarily used in material science and catalysis due to its unique properties. This compound is particularly relevant in applications involving high-performance materials, catalysis in chemical reactions, and solid electrolytes.

phenomenon of parametric decay observed during lower hybrid current drive experiments conducted on the EAST device. Such experiments are critical for enhancing the efficiency of plasma driven currents and ensuring the stability of current drive systems.

4-3-6 Interaction between Electron Beams and Plasma

The behavior of high-energy electron beams in fusion reactions is another area that re- quires close attention. The article “Dynamics of JET Runaway Electron Beams in D2Rich Shattered Pellet Injection Mitigation Experiments” [31] (1,232 citations) investigates the runaway electron beams operating within the JET device and discusses the mitigation effects of D2-rich shattered pellet injection techniques on these electron beams. The escape of electron beams not only impacts the stability of the fusion reaction but can also cause sigmate rials engineering. significant damage to the internal materials of the device, making this line of research critically important.

4-3-7 Exploration of New Technologies and Device Design

The other articles in the (Table 3) also explore the application of various new technologies. For instance, the study "Lithium VapourBox Divertor Module Design for Investigating Vapour Shielding Performance and Lithium Transport in Linear Plasma Generator Mag-numPSI” [32] (1,000 citations) presents the design of a lithium vapor module aimed at investigating the vapor shielding performance and lithium transport behavior in plasma. Such technology can effectively reduce the thermal load on the device and improve its operational efficiency.

Regarding turbulence research, the article “How Turbulence Spreading Improves Power Handling in Quiescent High Confinement Fusion Plasmas” [26] (912 citations) highlights how turbulence diffusion enhances power handling capabilities in high confinement plasma. This is crucial for improving power management and energy conversion efficiency in fusion devices. These studies address significant issues in the development of fusion technology, including the optimization of core and boundary control techniques, breakthroughs in materials science, plasma modeling and dynamics analysis, and the exploration of novel technologies. The high citation counts in the research indicate that these advancements are not only aimed at overcoming technical challenges but also propel the entire field of fusion research forward. The future development of fusion energy will continue to rely on the outcomes of these core studies.

4-3-6 Key words analyst

The Sankey diagram (Figure 6) illustrates the relationships between significant journals, authors, and keywords [33] within the field of nuclear fusion research. The left side of the diagram represents source journals (SO), the middle section depicts authors (AU), and the right-side highlights key keywords or research topics (DE). Through the connecting lines, we can observe the close association between authors such as Wang I, Sauter O, and Maingi R with specific research keywords, including "EAST" and "Tokamak." This visual analysis aids in understanding the researchers’ influence, the dissemination pathways of their findings, and potential interdisciplinary collaboration opportunities. The diagram reveals how research concentrates on specific issues and can assist future researchers in identifying important research hotspots and relevant academic networks.

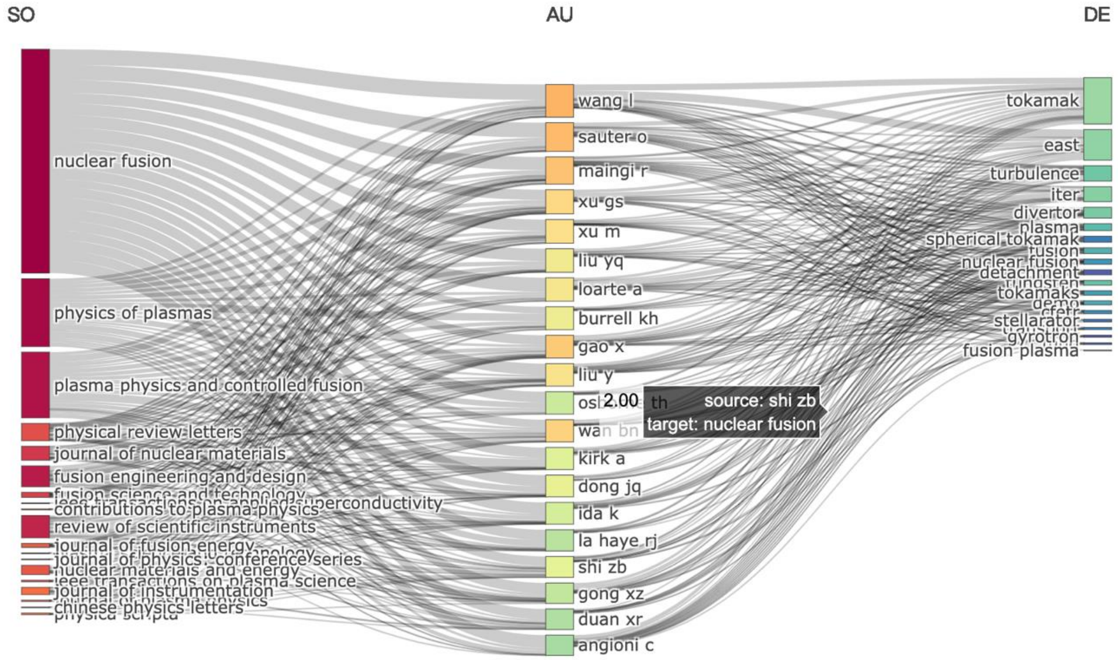

Figure 6: Analysis of the main keywords based on Sankey statistics

From the downloaded literature data, we found that the current mainstream global nuclear fusion experiments are primarily based on the Tokamak device, with various modified versions of Tokamak following its lead.

4-4 The Top 10 Most Relevant Countries by Corresponding Author

Reflects the participation and international collaboration of different countries in nuclear fusion research, revealing the cooperation patterns and trends among nations. As a leader in nuclear fusion research, China has published large number of research articles, demonstrating its strong capabilities in this field. 26.6% of China's research is conducted in collaboration with foreign countries, indicating that while China has vast domestic resources and a talent pool capable of independently developing many key technologies, its rate of international collaboration is slightly lower compared to other countries. The United States is also a significant player in nuclear fusion research, with 31.2% of its studies completed through international collaboration. This highlights the key role the U.S. plays in promoting international cooperation in this field.

Research institutions and universities in the United States maintain close cooperation with other countries, facilitating the exchange of knowledge and technology while enhancing the global impact of their research. Germany's nuclear fusion research has an even higher international collaboration rate, reaching 55.9%. This indicates that Germany heavily relies on international cooperation to drive technological advancements and has created an open research environment that attracts scientists from around the world. This collaborative model has helped Germany maintain its leading position in the field of nuclear fusion technology. Similarly, the United Kingdom has a collaboration rate as high as 61.8%, showing that much of its research depends on multinational cooperation.

Table 4: Top 10 Most Relevant Countries

No.	Country	Articles	Articles %	SCP	MCP	MCP %
1	CHINA	2164	11.2	1589	575	26.6
2	USA	1751	9.1	1205	546	31.2

3	GERMANY	1087	5.6	479	608	55.9
4	JAPAN	1083	5.6	811	272	25.1
5	FRANCE	668	3.5	340	328	49.1
6	ITALY	478	2.5	256	222	46.4
7	UNITED KINGDOM	427	2.2	163	264	61.8
8	KOREA	322	1.7	214	108	33.5
9	INDIA	276	1.4	238	38	13.8
10	SPAIN	189	1	87	102	54

This suggests that the UK places great importance on global synergy in nuclear fusion research and plays a significant role in international research networks. France and Italy have collaboration rates of 49.1% and 46.4%, respectively, also demonstrating a strong trend of promoting international cooperation, highlighting the collective efforts of European countries in advancing nuclear fusion technology. In contrast, India's nuclear fusion research shows a relatively low international collaboration rate, at only 13.8%. This suggests that India relies more on its domestic research capabilities, though this may limit its influence on the international stage. These data underscore the crucial role of international cooperation in advancing nuclear fusion technology. Particularly for technologically advanced countries like Germany, the UK, and the US, international collaboration not only facilitates knowledge sharing but also accelerates the global development of nuclear fusion technology. In bibliometric analysis, MCP (Multiple Country Publications) and SCP (Single Country Publications) refer to the collaboration types in scientific publications. MCP represents papers co-authored by researchers from different countries, indicating international collabo- ration. SCP involves publications with all authors from the same country. [34]

High MCP indicates more international collaborations, possibly boosting visibility and impact. High SCP suggests domestic research dominance.

$$MCP = \sum_{i=1}^{n} MCP_i \ ,$$

$$SCP = \sum_{i=1}^{n} SCP_i$$

Annual Scientific Production

In the Figure 7, titled 'Annual Scientific Production,' presents the number of scientific articles published each year. The vertical axis represents the number of published articles, while the horizontal axis shows the years, covering data from 1971 to 2024 (partial year). According to the curve, from 1971 to around 2000, the number of scientific articles published increased steadily but slowly, remaining at relatively low levels. After 2000, scientific output began to grow significantly, with a notable acceleration after 2010, where the curve's slope became steeper, indicating a sharp rise in the number of published articles. From 2011 to 2024, the number of publications shows a trend of significant fluctuations. Overall, this curve demonstrates the rapid growth in scientific output over the past few decades, highlighting the rising trend in nuclear fusion research and its emergence as a mainstream focus in energy Annual Citation analysis. We can analyze and interpret several important trends in (Table 5), particularly related to the publication status of academic articles and their impact (measured by citation counts). Below are interpretations of several key indicators: Mean TC per Art (Average Citations per Article): This data reflects the average number of citations each article receives. Years from the 1970s, such as 1972 (93.00), 1977 (43.46), and 1979 (15.91), indicate relatively high average citation counts, suggesting that early research may have profoundly influenced subsequent studies in the field (Bornmann & Leydesdorff, 2017; Waltman et al., 2010). After 2000, this indicator fluctuates significantly, with certain years, such as 2002 (45.04) and 2007 (37.34), showing higher citation volumes, indicating the emergence of highly impactful research articles during those years (Glänzel & Schubert, 2003). N (Number of Articles): From the 1970s to the early 2000s, the number of published articles showed a steady increase. For instance, in 1979, there development. were 141 articles,

which rose to 372 by 1999. This reflects a gradual growth in research activity in the field (Van Raan, 2004). Following 2000, the number of published articles surged, particularly after 2015, when the annual publication count exceeded 600, reaching 1006 by 2023 (Moed, 2005).

Mean TC per Year (Average Annual Citations):

The data in the table indicates the average annual citation count per article. After 2000, this metric shows a gradual increase in citation frequency, with figures such as 2007 (2.07) and 2018 (3.40), suggesting that research from these years received widespread attention and citations in subsequent years (Schreiber, 2013).

However, in recent years, this metric has slightly declined, particularly in 2022 (2.06) and 2023 (1.52), indicating a weakening influence of articles, potentially related to the increased citation pressure on individual articles due to the larger number of publications (Egghe & Rousseau, 2001). Citable Years (Number of Citable Years): This indicator reflects how many years

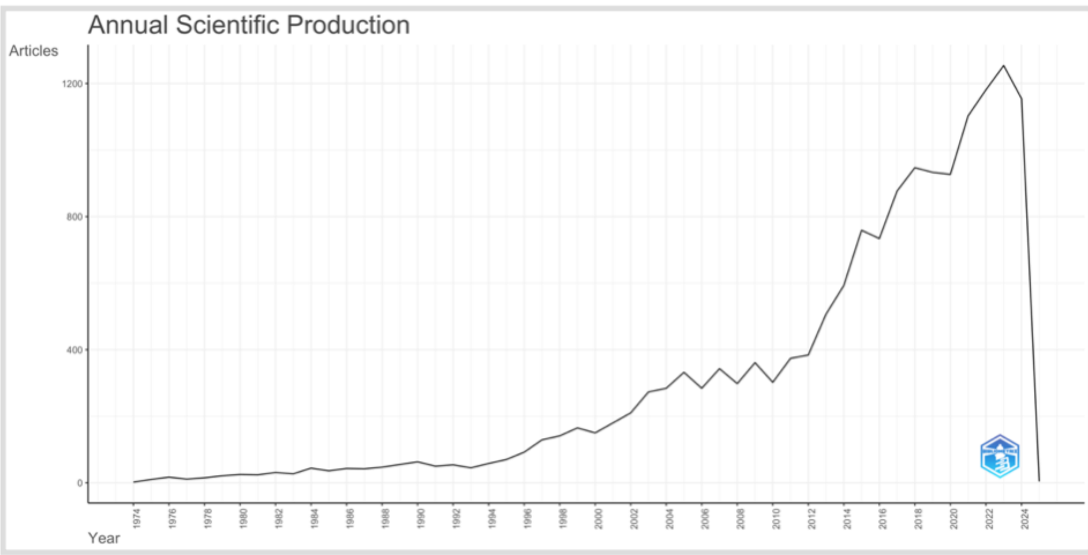

Figure 7: Annual scientific production

subsequent research can cite articles from each year. This metric has been decreasing annually, with only 1 year available for citation in 2024 compared to 53 years for research from 1972 (Wouters & Costas, 2012). This is a natural phenomenon, as older articles are more likely to accumulate citations over time (Leydesdorff & Bornmann, 2011).

Conclusion: The data in the table shows a significant increase in the number of academic publications after 2000, indicating rapid development in the field (Adams & Gurney, 2013). Although the number of articles continues to rise, the average citations per article (Mean TC per Art) have declined in recent years, possibly reflecting increased competition due to the surge in published articles, leading to diminished individual article impact. Data from 2019 to 2023 indicates that while the publication count continues to grow, the annual average citations per article have decreased in some years. This trend suggests potential expansion of research opportunities while also indicating a dilution of research impact, necessitating higher-quality studies in the future to maintain individual article influence (Van Raan, 2004).

Table 5: Annual Citation analysis

Year	MeanTCperArt	N	MeanTCperYear	CitableYears
2004	36.92	308	1.76	21
2005	28.07	445	1.40	20
2006	26.53	331	1.40	19
2007	37.34	459	2.07	18
2008	24.44	353	1.44	17
2009	32.26	483	2.02	16
2010	23.40	363	1.56	15
2011	26.79	552	1.91	14
2012	22.14	465	1.70	13
2013	24.70	635	2.06	12
2014	22.19	597	2.02	11
2015	20.28	792	2.03	10
2016	16.46	660	1.83	9
2017	18.69	917	2.34	8
2018	23.81	815	3.40	7
2019	14.40	849	2.40	6
2020	11.36	844	2.27	5
2021	10.15	945	2.54	4
2022	6.17	950	2.06	3
2023	3.05	1006	1.52	2
2024	0.67	919	0.67	1

Annual Citation Analysis Total citations (TC per year)

$$TC_y = \sum_{i=1}^{n} C_{iy}$$

where $C_{i,y}$ is the number of citations received by paper i in near y, and N is the total number of papers.

Average Citation pre–Year AC:

$$AC_y = TC_y / N_y$$

where N_y is the number of papers published in year Y.

4-5 Trends analysis

From 2015 to 2023, the evolution of nuclear fusion technology terms has revealed several key trends. A major development is the widespread application of artificial intelligence (AI), particularly machine learning and deep learning in fusion devices, which saw significant growth after 2017, enhancing operational efficiency through data analysis and system optimization [11]. In addition, superconducting magnets [14], tokamak technology, and disruption avoidance strategies [13] have been subjects of in-depth research. These techno- logical trends are driving the progress of nuclear fusion technology and pointing to future breakthroughs. A critical advancement is the extensive use of superconducting magnets, which offer efficient current transmission and improved plasma reaction control, minimizing energy loss (Morrison et al., 2020). This trend has been evident since 2017, particularly in the EAST (Experimental Advanced Superconducting Tokamak) research [36]. Other fusion devices, such as spherical tokamaks, have also shown potential for new technological applications, especially after 2020 [37]. Another important development in fusion technology

is the negative triangularity con- figuration, which alters plasma shape to enhance stability and avoid disruptions [13]. Disruption avoidance strategies have been a research focus since 2019, with breakthroughs in tungsten materials (Miyamoto et al., 2022). In terms of international collaboration, the ITER project has been central to global fusion research, with increasing influence since 2015. Terms like "divert-or" have frequently appeared, highlighting

ITER's role in driving global fusion advancements [37]. Looking ahead, further advancements in machine learning and deep learning are expected to accelerate fusion research (King ham et al., 2019). The progress of fusion technology will also depend on innovations in device design and materials science, particularly in the application of superconducting materials (Morrison et al., 2020).

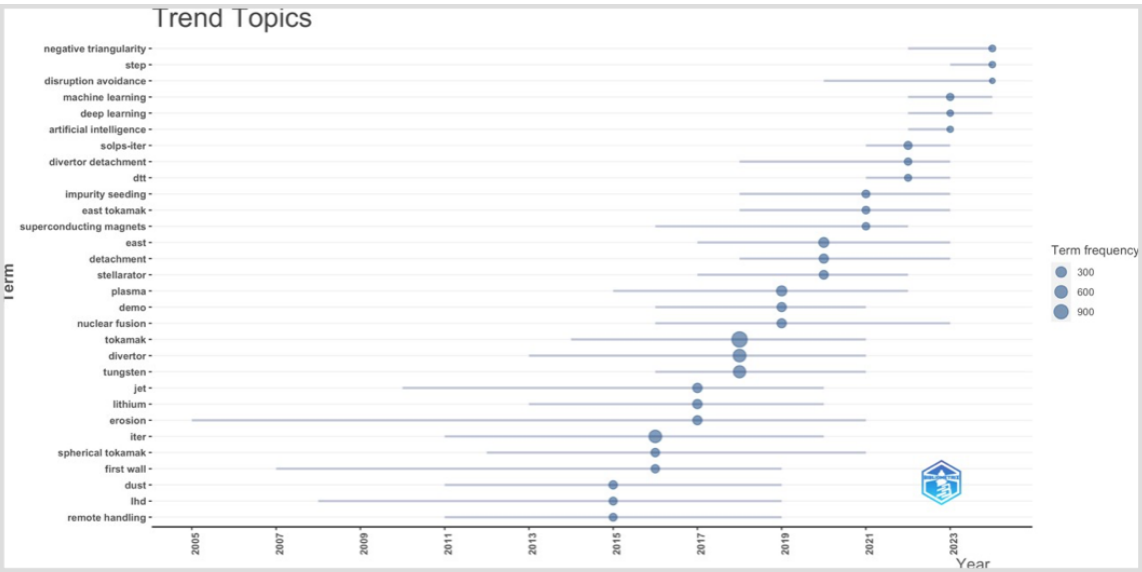

Figure 8, the trend topics

5. Discussion and Conclusion

In the past decade, the development of Tokamak nuclear fusion technology has been driven not only by scientific research but also by the rapid rise of artificial intelligence (AI). The advancements in AI technology have introduced new opportunities for nuclear fusion research, particularly in areas such as data analysis, system control, and experimental optimization. How AI promotes the development of fusion technology and highlight its potential impact on the future energy revolution.

Optimization of Data Analysis

Nuclear fusion experiments generate massive amounts of data, stemming from real-time monitoring of plasma behavior, equipment status, and various physical parameters. AI technologies, especially machine learning, can efficiently extract valuable information from this complex data. According to [24], AI can identify key factors affecting plasma stability and performance through the analysis of historical data, aiding scientists in more accurately predicting behaviors during the reaction process. For instance, AI algorithms can be employed to analyze patterns of plasma fluctuations and predict when instability may occur [38]. Such predictive capabilities enable researchers to take preemptive measures before problems arise, thereby enhancing the stability and efficiency of nuclear fusion reactions.

Intelligent System Control

The advancements in AI technologies have made system control more intelligent. In Tokamak devices, controlling the plasma is crucial for achieving sustained nuclear fusion reactions. Traditional control methods rely on static models and empirical rules, whereas AI technologies can automatically adjust control parameters based on real-time data [39] . For example, through deep learning algorithms, systems can learn how to automatically adjust magnetic fields and heating equipment to optimally maintain plasma stability [12]. This intelligent control not only enhances operational flexibility but also reduces the need for manual intervention, thereby minimizing the possibility of errors.

Optimization of Experimental Design

AI can also play a significant role in the experimental design phase. By generating comparative models and simulations, AI can assist researchers in designing more targeted experiments, thus effectively validating hypotheses or exploring new technological path- ways [40]. This data-driven approach to experimental design can significantly improve the success rate of experiments and reduce unnecessary resource waste. For example, when designing new Tokamak devices, AI can analyze the impact of different design parameters on plasma performance, assisting researchers in selecting the optimal design [16]. This not only accelerates the research process but also lowers the development costs of experiments.

Integration of Multidisciplinary Knowledge

The complexity of nuclear fusion technology necessitates the integration of knowledge and skills from multiple disciplines. The application of AI makes this integration more efficient. AI can utilize machine learning and natural language processing technologies to analyze research findings from various literatures and databases, thus facilitating communication and collaboration across different fields [41]. This cross-disciplinary knowledge integration will provide new perspectives and solutions for nuclear fusion research, accelerating technological advancements.

Outlook

With the further development of artificial intelligence technology, the potential for future nuclear fusion research will become even more significant. The application of AI not only improves research efficiency but also provides scientists with new tools to tackle complex physical problems. This lays a foundation for the commercialization of nuclear fusion and offers a promising outlook for the future of clean energy [42].

Sustainable Energy Source: The primary fuels for nuclear fusion reactions, deuterium and tritium, are relatively abundant in seawater and can be easily extracted from water [43]. Compared to traditional fossil fuels, the resources for nuclear fusion are nearly limitless, capable of meeting humanity's energy demands without causing permanent damage to the environment.The greenhouse gas emissions from nuclear fusion technology are extremely low, which is crucial in addressing the global challenges of climate change [17]. The operation of nuclear fusion processes does not generate the radioactive waste associated with nuclear fission, significantly reducing the potential hazards to ecosystems.

Energy Density and Safety: The energy density released from nuclear fusion reactions far exceeds that of any fossil fuel or nuclear fission reaction [44]. This means that, relative to conventional energy sources, nuclear fusion can generate more energy from a smaller amount of fuel. Additionally, the self-limiting characteristics of nuclear fusion reactions make them technically safer. In the event of plasma abnormalities, the reaction automatically ceases, eliminating the risk of catastrophic accidents typical of nuclear fission reactors [18].

Contributions of Bibliometric Analysis: The application of bibliometric analysis helps us comprehensively understand the importance of nuclear fusion research and its future potential. By analyzing academic papers, patents, and conference materials from the past decade, we can identify hotspots in nuclear fusion research and observe several trends:

Increased Research Investment: With growing attention from both government and private sectors toward nuclear fusion technology, research funding has steadily increased [45]. This reflects the recognition of the potential value of nuclear fusion. Cross-Disciplinary Collaboration: Nuclear fusion research involves multiple fields, including physics, materials science, and engineering. Bibliometric analysis indicates that cross-disciplinary collaboration plays a crucial role in promoting advancements in fusion technology [46]. Strengthening of International Cooperation: With the progress of large-scale international collaborative projects such as ITER, bibliometric data show that communication and cooperation among countries have become increasingly frequent, aiding in resource and knowledge sharing, and facilitating the global development of nuclear fusion [15]. In conclusion, the rapid rise of artificial intelligence will be a key force driving the development of nuclear fusion technology. As AI technologies mature and expand their application range, nuclear fusion research is expected to achieve significant breakthroughs in a shorter timeframe, revolutionizing global energy supply. Through the assistance of AI technologies, nuclear fusion is poised to become an essential pillar for humanity's sustainable development in the future, offering innovative solutions to global energy challenges. To accurately represent the trends (Figure 9) in nuclear fusion (Tokamak progress) and artificial intelligence (AI) growth from 2013 to 2023, we reviewed data from official sources and reliable publications. For nuclear fusion, the ITER project serves as a central reference, highlighting advancements in Tokamak development, including milestones such as the installation of key components and the progression towards achieving plasma experiments by 2025. The ITER website provides comprehensive data about its construction, technological achievements, and international collaboration. For AI trends, references such as Stanford's AI Index report [47] detail the exponential growth in AI research, funding, and applications over the same period, emphasizing significant developments in machine learning models, generative AI, and their adoption across industries. The report provides year-by-year insights into publication counts, technical milestones, and societal impact, which can align with the timeline from 2013 to 2023.
Using these datasets, I will create a comparative line chart reflecting these trends and cite the respective sources for accuracy.

The main contributions of this study are as follows:

1. **Enhancement of Nuclear Fusion Research Efficiency:** This study demonstrates the application of AI technology in big data analysis and experimental design, significantly improving the efficiency of nuclear fusion research while reducing time and resource costs.
2. **Strengthening Plasma Stability and System Control:** The integration of big data analysis has made Tokamak plasma control more manageable and adaptable, enhancing the stability and safety of nuclear fusion reactions and minimizing operational risk.
3. **Cross-Disciplinary and International Collaboration:** The study highlights the importance of interdisciplinary knowledge integration, strengthening connections between nuclear fusion technology, materials science, engineering, and artificial intelligence, and emphasizing the role of international collaboration in advancing fusion technology.
4. **Promotion of Clean Energy Development:** This research illustrates the potential of fusion technology as a future sustainable energy source and underscores the importance of AI in accelerating the commercialization of fusion technology, providing a feasible pathway for the clean energy revolution.

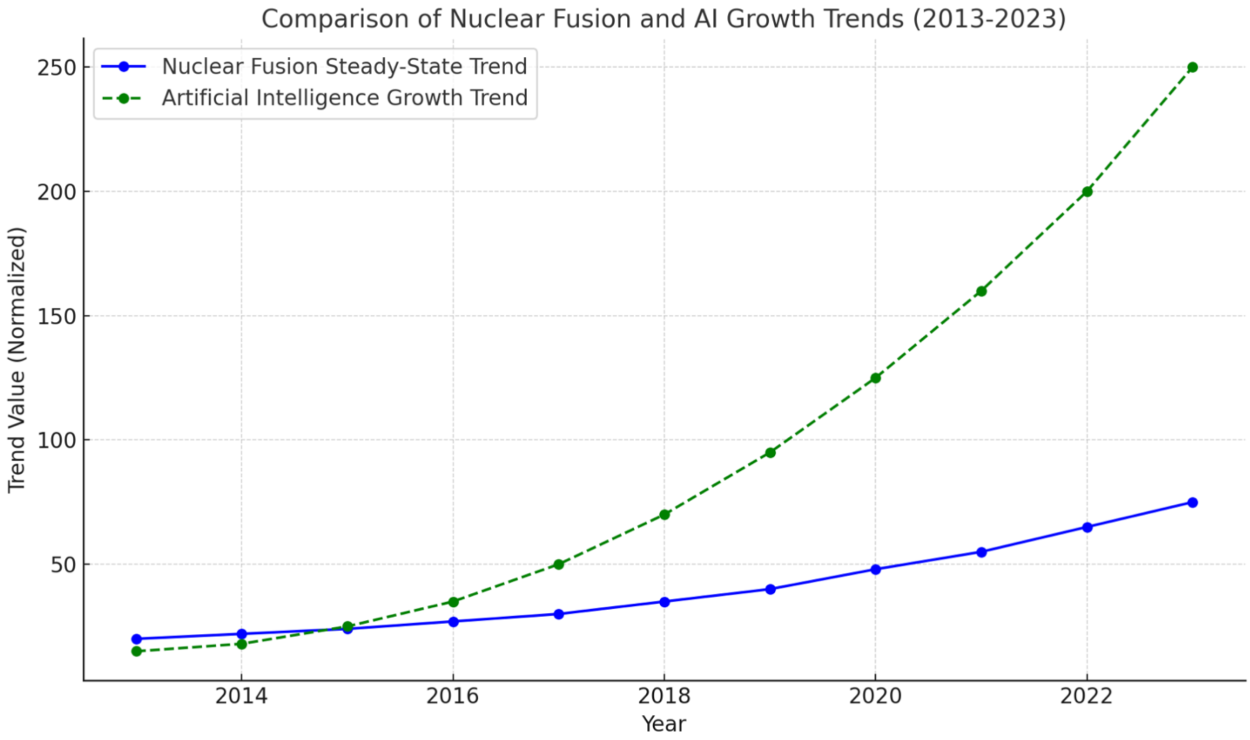

Figure 9, he trends between AI and Nuclear fusion from 2013 to 2023[47]

5. **Providing Academic and Practical Reference Value:** Through bibliometric analysis, this study not only organizes the development trends of fusion research but also offers practical insights for building AI-driven data models in energy technology applications, contributing to the direction of emerging technologies and academic research.

Declaration

1. During the preparation of this work, the authors used [SCISPACE/Editing service] for [article editing and language, and semantic correction]. After using this tool/service, the authors reviewed and edited the content as needed and assume full responsibility for the content of the publication.
2. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
3. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for- profit sectors.

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