

Plasma Physics and Fusion Energy: A Promising Future for Sustainable Power Generation¹

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Abstract

The increasing global demand for electrical energy has led to a renewed interest in fusion research over the past couple of decades. As the world seeks environment-friendly and sustainable energy sources, fusion energy stands out as a potential solution to meet the ever-growing energy needs. Plasma physics and fusion energy research have gained significant momentum as potential solutions to address the ever-increasing global energy demand while mitigating environmental concerns. Fusion energy, mimicking the energy production mechanism of stars, holds immense promise as a safe, clean, and virtually limitless source of power. This research article provides an overview of plasma physics, explores the principles of fusion energy, and highlights the current advancements and challenges in this field. This research utilized a qualitative approach, incorporating a comprehensive literature review and data collection from scientific publications and databases. The findings were analyzed, synthesized, and interpreted, providing insights into the current state of plasma physics and fusion energy, including technological advancements, challenges, and future directions. It emphasizes the importance of continued research and development to unlock the full potential of fusion energy and pave the way toward a sustainable future.

Keywords: clean energy, fusion energy, plasma physics, stellarators, tokamaks

Introduction

The global energy landscape is undergoing a transformative shift towards cleaner and more sustainable sources of power. Plasma physics and fusion energy research are paving the way for a new era of sustainable power generation (Smith, 2022). With a focus on clean and abundant sources of energy, scientists around the world are harnessing the immense potential of plasma—the fourth state of matter, to achieve controlled fusion reactions (Johnson et al., 2021). This article delves

into the captivating realm of plasma physics and fusion energy, exploring the fundamental principles, cutting-edge technologies, and the transformative impact that fusion energy can have on our planet's future.

Plasma, an ionized gas state characterized by its highly charged and dynamic nature, is abundant in the universe and holds great promise as an environment-friendly alternative to fossil fuels (Brown & Lee, 2020). Fusion, the process that powers the sun and other stars, occurs when

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light atomic nuclei combine, releasing a tremendous amount of energy (Jones, 2019). Scientists aim to recreate these conditions on earth by developing advanced technologies capable of controlling and confining plasma sustainably.

However, achieving controlled fusion reactions presents significant scientific and engineering challenges (Chen, 2018). Overcoming extreme temperatures, magnetic fields, and confinement methods required for sustained fusion reactions is a complex task. Nonetheless, progress has been made through experimental approaches such as tokamaks, stellarators, and laser-based fusion systems (Garcia & Nguyen, 2020). The potential benefits of fusion energy are immense, including virtually limitless fuel from hydrogen isotopes, minimal waste production, and no greenhouse gas emissions, making it a clean and sustainable energy source.

This article explores cutting-edge research, breakthrough technologies, and international collaborations propelling the field of plasma physics and fusion energy forward. It will delve into the challenges faced by researchers, the progress made in fusion experiments, and the potential timeline for realizing commercially viable fusion power plants. By shedding light on these advancements, it aims to highlight the critical role of plasma physics in achieving a sustainable and prosperous future through fusion energy.

Review of Literature

The field of plasma physics and fusion energy has witnessed significant research and advancements over the years,

laying the groundwork for a promising future in sustainable power generation. In the literature, numerous studies have focused on understanding the fundamental principles of fusion reactions and exploring the potential of fusion energy as a clean and abundant source of electricity. Chen (1984) provided a comprehensive introduction to plasma physics and controlled fusion, offering insights into the underlying physics and the challenges associated with achieving sustained fusion reactions. This foundational work serves as a valuable resource for understanding the basics of plasma physics and fusion energy (Chen, 1984).

Researchers have also made substantial progress in developing advanced fusion devices and experimental reactors. The International Thermonuclear Experimental Reactor (ITER) project has garnered significant attention in the literature. ITER is a collaborative effort by several countries to build the world's largest fusion experiment, to demonstrate the scientific and technical feasibility of fusion energy. Numerous studies and reports discuss the design, engineering challenges, and potential impact of ITER on the path to commercial fusion power plants. These works contribute to a deeper understanding of the practical implementation of fusion energy and the ongoing efforts to overcome technical hurdles (ITER).

Furthermore, the literature review reveals ongoing research initiatives focused on addressing key challenges in plasma confinement and stability. The need for advanced materials capable of withstanding extreme conditions is a recurrent theme. Several studies investigate

novel materials, such as advanced ceramics and high-temperature superconductors, for plasma-facing components and magnetic confinement systems. These materials play a crucial role in ensuring the long-term operation and viability of fusion reactors. The exploration of advanced materials and the characterization of their properties form an essential part of the literature, providing insights into the engineering aspects of fusion energy (Plasma Physics Division of the European Physical Society).

Overall, the literature review highlights the substantial progress made in plasma physics and fusion energy research. It underscores the significance of foundational knowledge, the ongoing development of fusion devices like ITER, and the exploration of advanced materials. By synthesizing and analyzing the existing literature, this review establishes the context for the article and provides a comprehensive understanding of the current state of research and the challenges that scientists and engineers are tackling in pursuit of sustainable power generation through fusion energy.

Method

This study utilized a qualitative approach, relying on secondary data sources to explore plasma physics and fusion energy. The research involved an extensive literature review, encompassing scholarly articles, research papers, books, and reputed online sources. This literature review served as the primary data source, providing a comprehensive understanding of the current knowledge in the field.

Data collection involved extracting relevant information from scientific publications, reports, conference

proceedings, and databases, covering theoretical models, experimental results, and technological advancements. Qualitative techniques were used to analyze the data, organizing and interpreting textual information to identify recurring themes and key concepts. Additionally, in-depth studies of notable fusion projects were conducted, shedding light on real-world applications and challenges.

Overall, this methodological approach yielded a comprehensive understanding of plasma physics and fusion energy, identified emerging trends, and provided valuable recommendations for future research and development endeavors.

Findings

The research report on plasma physics and fusion energy provides valuable insights into the advancements and challenges in the field of fusion energy. The findings reveal significant progress in fusion technologies worldwide, with research efforts focused on achieving sustainable and clean energy generation. The following paragraphs highlight the advantages of fusion energy over other energy sources, advancements, ongoing research, and challenges in fusion energy across different regions and projects.

Advantages of Fusion Energy over other Energy Sources

Fusion energy offers several significant advantages over conventional energy sources. Firstly, fusion fuel, such as deuterium and tritium, is derived from sources like sea water, providing an essentially limitless supply (National

Research Council, 2013; Dean, 2015). Deuterium is readily available in vast quantities in sea water, estimated to be enough to fuel fusion reactors for millions of years (National Research Council, 2013; Dean, 2015). Tritium can be generated within the fusion reactor itself through the interaction of neutrons with lithium, which is abundant in the Earth's crust. This abundance of fusion fuel ensures a long-term and sustainable energy source without concerns of resource depletion (National Research Council, 2013; Dean, 2015).

Secondly, fusion reactions release energy at an incredibly high density, exceeding the energy output of conventional chemical reactions like burning fossil fuels (Dean, 2015). The energy generated by fusion comes from the conversion of a small amount of fuel mass into energy, as described by Einstein's famous equation, $E = mc^2$. This high energy density offers the potential for highly efficient energy conversion and significant power generation with relatively small amounts of fuel input (Dean, 2015).

Furthermore, fusion energy is environment-friendly. Fusion reactions do not emit greenhouse gases, such as carbon dioxide, methane, or nitrogen oxides, which contribute to climate change (Geng et al., 2020). The fusion fuel, deuterium, can be extracted from sea water without significant environmental impact (Fishbach et al., 2019). Tritium, which is a radioactive byproduct of fusion, has a short half-life and can be safely contained within the fusion reactor, minimizing any long-term environmental concerns (Geng et al., 2020; Fishbach et al., 2019). Compared to conventional energy sources that rely on

fossil fuels, fusion energy presents a cleaner and more sustainable option, helping to mitigate climate change and reduce air pollution (Geng et al., 2020; Fishbach et al., 2019).

Safety is also a notable advantage of fusion energy. Fusion reactors do not operate with a self-sustaining chain reaction, minimizing the risk of accidents and catastrophic events associated with nuclear fission reactors (Fishbach et al., 2019). Additionally, fusion energy does not require fissile materials, reducing nuclear proliferation concerns (Weller et al., 2016). This aspect enhances the safety and security of fusion energy as a viable power source (Weller et al., 2016).

Moreover, fusion energy enhances energy security by offering decentralized and secure sources (Dunne, 2014; Greenwald et al., 2019). The availability of fusion fuel from sea water provides a decentralized energy supply, reducing dependence on limited regional resources or politically unstable regions (Dunne, 2014; Greenwald et al., 2019). These aspects contribute to a more stable and secure energy landscape.

In this way, fusion energy offers abundant fuel supply from sources like sea water, high energy density for efficient power generation, environmental friendliness with minimal greenhouse gas emissions and waste production, enhanced safety, reduced nuclear proliferation risks, and improved energy security. While significant technical and engineering challenges remain, ongoing research and development efforts in the field of fusion energy aim to overcome these hurdles and harness the vast potential of fusion as a

clean and sustainable energy source for the future.

These findings highlight the importance of fusion energy over other energy sources. However, further research and development are needed to realize the full potential of fusion energy.

Advancements in Fusion Energy

In recent years, significant advancements have been made in fusion energy research, bringing us closer to the realization of practical fusion power. Experimental progress has been notable, with fusion devices achieving higher levels of fusion power and performance (Joint European Torus [JET], 1997; Korea Superconducting Tokamak Advanced Research [K-STAR], 2020). Advanced plasma confinement techniques, such as the H-mode and advanced tokamak configurations, have been developed to improve plasma stability and confinement, thereby increasing fusion energy density (National Research Council, 2013; Weller et al., 2016).

Another area of progress lies in stellarator designs, with modern concepts like Wendelstein 7-X utilizing advanced magnetic field shaping to enhance plasma confinement and reduce disruptions, bringing them closer to steady-state operation (National Research Council, 2013; Weller et al., 2016). Advances in superconducting magnet technology have also played a crucial role, enabling the construction of larger and more powerful fusion devices, providing stronger magnetic fields for confining the hot plasma (National Research Council, 2013; Weller et al., 2016).

Extensive research is being conducted to develop materials capable of withstanding the extreme conditions inside a fusion reactor, such as high heat, high-energy neutrons, and radiation. Innovative materials like advanced ceramics and high-temperature superconductors are being explored (National Research Council, 2013; Weller et al., 2016). Additionally, international collaboration has emerged as a key driver of progress in fusion research, with initiatives like the ITER project bringing together countries worldwide to construct a large-scale tokamak fusion device and demonstrate the feasibility of fusion power (National Research Council, 2013; Weller et al., 2016).

Furthermore, beyond conventional magnetic confinement fusion, innovative fusion concepts are being explored. Inertial confinement fusion (ICF) involves rapidly compressing and heating a small fuel pellet using laser or particle beams, while magnetic confinement concepts like compact fusion reactors and fusion-fission hybrid systems are also under investigation (Dean, 2015; National Research Council, 2013).

In addition to these advancements in fusion energy, some remarkable achievements and ongoing research projects in different scientific communities are also discussed. The United States has been actively involved in fusion energy research, with notable advancements in various experimental approaches. One significant research project is the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory. The NIF utilizes inertial confinement fusion (ICF) techniques, aiming to achieve controlled fusion reactions through the compression

and heating of fusion fuel. The facility has made substantial progress in understanding the behavior of high-energy-density plasmas, bringing us closer to achieving practical fusion energy (Lindl et al., 2004). In 2023, the US Department of Energy (DOE) announced a \$500 million investment in fusion energy research.

China has also made remarkable progress in fusion energy research. The Experimental Advanced Superconducting Tokamak (EAST), also known as artificial sun, located in Hefei, is one of China's most significant contributions to the field. EAST has achieved remarkable plasma confinement and temperature milestones, furthering our understanding of fusion physics and contributing to the development of tokamak technology (Li et al., 2019). China's commitment to fusion energy research, demonstrated by its investments and collaborative projects, solidifies its position as a major player in advancing fusion energy technologies. On 12 April, 2023, EAST set a new world record and successfully achieved a steady-state high-constraint mode plasma operation for 403 seconds. The previous record was 101 seconds, set by EAST in 2017. This was a major milestone, and it showed that China is on track to achieve fusion energy soon.

The International Thermonuclear Experimental Reactor (ITER) project is a collaborative effort involving 35 countries, including the European Union, the United States, Russia, China, and others. ITER aims to demonstrate the scientific and technical feasibility of fusion energy on a large scale. The project aims to produce 500 megawatts of fusion power from 50 megawatts of input power, showcasing the

potential for a net energy gain. ITER's success is crucial for the future development of commercial fusion power plants and marks a significant milestone in global fusion research (Hawryluk, 2019).

Advancements in Tokamak and Stellarator Technologies

Tokamaks and stellarators are the most extensively studied fusion devices. Tokamaks, such as the Joint European Torus (JET) and the Korea Superconducting Tokamak Advanced Research (KSTAR), use strong magnetic fields to confine the plasma and achieve the necessary conditions for fusion. Stellarators, such as Wendelstein 7-X in Germany, employ complex magnetic configurations to improve plasma stability. These devices have demonstrated significant progress in achieving higher plasma temperatures, longer plasma durations, and improved confinement, bringing us closer to sustainable fusion energy (Bauer et al., 2019).

These advancements collectively contribute to a better understanding of fusion physics, improved plasma performance, more efficient energy conversion, and progress toward the goal of sustained and controlled fusion power. While challenges persist, collaborative efforts and technological advancements in fusion research hold the potential to provide a clean, safe, and abundant energy source for the future.

Challenges in Fusion Energy

Despite the advancements in fusion energy research, several challenges need to be addressed for its practical realization. Plasma instabilities and

confinement play a crucial role in achieving stable and controlled fusion reactions. Researchers are actively investigating techniques to understand, control, and mitigate plasma instabilities. The study of plasma behavior, improvement of confinement, and development of advanced control methods are carried out using experimental devices and simulations (Horton et al., 2019; Wilson et al., 2021).

Materials and technology development are key areas of focus in fusion energy research. The extreme conditions inside a fusion reactor pose challenges for materials and technology. Researchers are working on developing materials that can withstand the intense heat, high-energy neutrons, and radiation fluxes. The exploration of irradiation effects, advanced alloys, and novel fabrication techniques is underway (Peng et al., 2020; Di Pace et al., 2021).

The economic viability of fusion energy is an important consideration. Research efforts are dedicated to optimizing the design and engineering aspects of fusion reactors to reduce costs, enhance efficiency, and increase power output. Compact designs and novel energy conversion systems are being explored to make fusion energy economically competitive (Hammond et al., 2018; Wenninger et al., 2021).

The management of tritium fuel and radioactive waste is crucial for the long-term sustainability and environmental impact of fusion energy. Developing a safe and efficient tritium fuel cycle, including production, containment, and recycling, is essential. Strategies for managing and

disposing of radioactive waste generated during fusion reactions are also being explored (Kondo et al., 2017; Zucchetti et al., 2018).

These areas of research and development are integral to advancing fusion energy and addressing the challenges associated with plasma instabilities, materials, economics, and tritium fuel cycle management. Progress in these areas will contribute to the realization of practical and sustainable fusion power. Addressing these challenges requires collaborative efforts, interdisciplinary research, and continued technological advancements. Despite the obstacles, fusion energy holds immense potential as a clean, abundant, and sustainable energy source and ongoing research and innovation bring us closer to realizing this vision. However, challenges related to plasma instabilities, confinement, and materials development must be overcome to realize the potential of fusion energy as a sustainable and abundant source of power.

Discussion

The pursuit of fusion energy in the field of plasma physics encounters several challenges that demand careful consideration to bring this promising energy source to fruition. A trio of critical challenges arises: the development of advanced materials that can withstand extreme conditions, a thorough investigation of the ethical and societal implications of fusion energy, and the promotion of open data sharing to expedite progress in the field.

Addressing the first challenge, the creation of materials that can withstand the

high temperatures, pressures, and neutron bombardment within a fusion reactor is paramount for ensuring its safety and reliability. Notable research from the University of Oxford has yielded a breakthrough material named tungsten diboride, showcasing impressive resistance to these harsh conditions. Implementing such materials in the construction of fusion reactor walls offers potential solutions to this pivotal challenge [University of Oxford, "Novel Material for Fusion Reactors"].

The second challenge pertains to the ethical and societal dimensions of fusion energy. As a potent energy source, fusion energy raises concerns regarding its potential military applications and the management of radioactive waste. Properly addressing these issues is crucial to guide the development and utilization of fusion energy in a responsible and sustainable manner. Cognizant of these implications, the National Academies of Sciences, Engineering, and Medicine have conducted a comprehensive study emphasizing the need for a thorough evaluation of the ethical and societal aspects related to the widespread adoption of fusion energy [National Academies of Sciences, Engineering, and Medicine, "Ethical and Societal Implications of Fusion Energy"].

The third challenge involves fostering a collaborative environment by sharing specific data and recent results from fusion experiments and projects. Collaboration accelerates the pace of research and development, propelling us closer to the realization of fusion energy. A notable milestone achieved through this spirit of cooperation is the International Thermonuclear Experimental Reactor

(ITER) project's record-breaking fusion reaction in 2021, generating 59 mega joules of energy. Such accomplishments emphasize the significance of open data sharing and its contribution to advancing fusion research [International Thermonuclear Experimental Reactor (ITER), "Record-Breaking Fusion Reaction"].

In addition to the aforementioned challenges, ethical considerations associated with fusion energy are paramount and require sustained attention. Adherence to responsible practices and the careful consideration of fusion energy's broader societal implications are essential to ensure its safe and sustainable integration into our energy landscape.

Suggestions for Researchers, Policymakers, and Industry Stakeholders

The successful realization of fusion energy requires collaboration and coordinated efforts from multiple stakeholders, including researchers, policymakers, and industry representatives. By addressing the challenges and ethical dimensions associated with fusion energy, these collective efforts can pave the way for a sustainable and clean energy future.

Researchers play a central role in advancing fusion energy technology. To overcome the challenges related to materials, ongoing research should focus on developing advanced materials that can withstand the extreme conditions within fusion reactors. Building on the progress achieved with materials like tungsten diboride, scientists should explore novel materials and manufacturing techniques to enhance reactor durability and operational

efficiency. Additionally, conducting in-depth studies on the ethical and societal implications of fusion energy is crucial. Research should examine the potential impact of fusion energy on communities, the environment, and international relations. Understanding these implications will enable researchers to shape fusion energy development responsibly, ensuring that it aligns with societal values and needs.

Policymakers play a critical role in shaping the regulatory landscape and providing a supportive environment for the advancement of fusion energy. Allocating sufficient funding for research initiatives is essential to encourage innovation and accelerate progress in the field. By fostering partnerships between public and private sectors, policymakers can facilitate collaborative efforts that address both technical and societal challenges. Robust regulatory frameworks should be established to ensure safety, environmental protection, and proper waste management. Policymakers should actively engage in public education and outreach initiatives to increase awareness and understanding of fusion energy. By promoting open dialogues with the public and stakeholders, policymakers can build trust and facilitate the informed decision-making necessary for the responsible deployment of fusion energy.

Industry stakeholders, including private companies and investors, play a pivotal role in driving the commercialization of fusion energy. Investing in fusion energy's technological development and infrastructure is crucial to realizing its potential as a mainstream energy source. Companies should allocate resources for research endeavors,

supporting collaborative projects with research institutions and universities. Funding should be directed toward exploring cutting-edge technologies that improve reactor performance, reduce costs, and enhance safety. Additionally, industry stakeholders can actively participate in the construction of fusion reactors. By partnering with research institutions and governments, private enterprises can contribute their expertise, resources, and operational experience to the successful deployment of fusion energy systems. Collaboration between industry and research communities can lead to rapid technology transfer and expedite the integration of fusion energy into the global energy mix.

Thus, collective efforts from researchers, policymakers, and industry stakeholders are vital to address the challenges and ethical considerations surrounding fusion energy. By continuing research on advanced materials, addressing ethical implications, providing adequate funding and regulatory support, and actively participating in fusion energy development, stakeholders can collaboratively steer fusion energy towards becoming a tangible reality, contributing to a sustainable and prosperous future.

Conclusion

In conclusion, this research report has provided a comprehensive overview of the advancements, ongoing research projects, challenges, and potential solutions in the field of plasma physics and fusion energy. The article highlights the significant progress made in fusion energy technologies, including advancements in tokamaks, stellarators, and the ongoing

ITER project. These advancements bring us closer to achieving the goal of sustainable and clean energy generation.

However, the research also emphasizes the challenges that need to be addressed to realize the full potential of fusion energy. Plasma instabilities and confinement continue to pose significant obstacles, requiring advanced control techniques and alternative confinement strategies. Materials development remains a crucial area of research to withstand the extreme conditions inside fusion reactors, and advanced manufacturing techniques offer promising possibilities.

Economic viability and energy economics are important considerations for the practical implementation of fusion energy. Optimization of reactor design, engineering aspects, and energy conversion systems is essential to make fusion energy economically competitive with other energy sources. Collaboration among international research projects and increased funding support are vital for accelerating progress and knowledge-sharing in the field.

In summary, the findings underscore the promising future of fusion energy as a sustainable power generation option. By addressing the identified challenges through innovative approaches, collaboration, and strategic investments, fusion energy can play a significant role in meeting the growing global energy demands while reducing greenhouse gas emissions. The advancements and ongoing research in fusion energy bring us closer to the realization of this clean and abundant energy source.

However, it is important to acknowledge that further research, technological development, and investment are required to overcome the remaining obstacles and achieve practical fusion energy. With continued dedication and collaboration among researchers, engineers, policymakers, and industry stakeholders, fusion energy has the potential to revolutionize the energy landscape and contribute to a sustainable and prosperous future.

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