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BEYOND SCIENCE FICTION: A COMPREHENSIVE STUDY OF NUCLEAR FUSION PROPULSION

Abstract

Interstellar space exploration was considered science fiction since it posed countless technological challenges that engineers believed mankind was not yet ready for. However, since Voyager broke out of the solar system, Hubble showed us worlds we had never seen before, and James Webb discovered the origin of the universe, we have achieved what was once only a dream. For decades, ever since humanity first set foot on the moon, we have been trying to figure out how to achieve this ambition of traveling through deep space. The primary challenge has always been converting matter into enough energy to propel us through this vast expanse of space within a realistic timescale. Many concepts in physics have been explored for enabling such propulsive power, such as antimatter drives, ion drives, and nuclear propulsion. However, it is crucial to examine whether they are feasible in the ensuing decades. Recent advancements in physics and engineering have renewed interest in the potential of nuclear fusion as a propulsion system for space exploration. It offers the promise of reducing travel time to distant planets to a few years and enabling frequent missions to nearby asteroids, planets, and moons. Nuclear fusion involves two protons crossing the Coulomb barrier to overcome their mutual repulsion, releasing a tremendous amount of energy. The energetic plasma can either be directly exhausted at high specific impulse (Isp) or combined with more hydrogen to increase thrust. With specific powers of 2.5 to 10 kW/kg and Isp of 20,000–50,000s, fusion rockets could permit round-trip flights to Jupiter in less than a year. Controlling nuclear fusion is a challenge in itself, which has led this field to explore different methods to make it viable. This paper provides a comprehensive review of the current state of research on nuclear fusion propulsion, including magneto-inertial, pulsed inertial, and inertial confinement concepts, as well as promising new approaches such as Z-pinch-based propulsion. Their engineering challenges and advantages are discussed, with a trade-off study to help the reader understand their feasibility. This paper is a valuable resource for researchers seeking to understand the recent progress in nuclear fusion propulsion and its competitive edge as a propulsion system for deep space missions.