

National Institute for Fusion Science

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Towards a new era of fusion science

Fusion science is driven by the aspiration to realize the dream of harnessing fusion energy—the “sun on Earth.” This profound motivation stems from both a sense of mission and the innate curiosity of humanity, and it is this blend that gives fusion science its remarkable appeal as a transformative scientific and technological endeavor to bring about a new era in human history.

Fusion science is a comprehensive scientific field with tremendous potential. The journey toward achieving fusion burning experiments, which now lie within our reach, has been replete with encounters of numerous formidable challenges—each one overcome through persistent effort. Solving one problem often leads to the emergence of new mysteries, demonstrating the profound depth and expansive reach of fusion science in enhancing our understanding of nature.

While the fusion reaction itself is already well understood, the “system” required to sustain it—the behavior of ultra-high-temperature plasma—remains abounding with unanswered questions. One of the central goals of fusion science is to unravel the mechanisms of this macroscopic system, which operates autonomously and continuously with immense energy. In parallel, it is also essential to develop the extraordinarily complex engineering systems that will constitute future fusion reactors.

Viewed from this perspective, fusion science is not only about physical principles—it also touches upon the fundamental principles of the universe, of society, and of life itself. With this grand context in mind, we aim to carve a broad path forward through the landscape of academic research and technological development.

The road toward fusion—the ultimate source of energy—is sure to lead us into new realms of unknown science and technology, presenting countless intersections of discovery along the way.

A fusion reaction is, quite literally, a process in which atomic nuclei combine. Since atomic nuclei are ions that carry a positive charge, they naturally repel each other. However, if these nuclei can be brought extremely close—within one quadrillionth of a meter (10^{-15} m)—a different force known as the nuclear force overcomes this repulsion, allowing them to fuse. Achieving this requires the fuel to be heated to an extraordinarily high temperature—over 100 million degrees Celsius.

It is well known that matter transitions through three states—solid, liquid, and gas—as temperature increases. When temperatures exceed several thousand degrees, molecules break apart into atoms. As temperatures climb into the tens of thousands of degrees, atoms themselves become ionized, separating into nuclei (ions) and electrons, forming an ionized gas known as plasma. While plasma might seem rare in nature—lightning is a familiar example—it is actually the most common state of matter in the universe. In fact, 99% of the visible matter in the cosmos exists in a plasma state. The Sun, too, is a massive ball of hydrogen plasma, within which hydrogen nuclei fuse into helium through nuclear fusion, releasing an enormous amount of energy. In other words, a “star” is a self-sustaining and stable system in which fusion reactions continuously occur within a mass of plasma.

On Earth, however, achieving fusion requires a fundamentally different system from that of a star. Fusion science faces the challenge of creating an artificial mechanism—one that doesn’t exist in nature—that can sustain stable fusion reactions. In stars, it is gravity, made possible by their enormous dimensions, that confines the plasma. For the much more compact “fusion on Earth,” magnetic fields are used to confine the plasma instead. Magnetism is a mysterious force that acts like a vortex, and understanding how it forms macroscopic structures remains one of the major unsolved problems in modern science.

To realize fusion energy, both advanced plasma physics and groundbreaking engineering must work together like the two wheels of a cart. For example, just one or two meters away from the ultra-high-temperature plasma core where fusion occurs, cryogenic superconducting magnets are installed to create strong magnetic fields. Additionally, facilities designed to divert and filter out the “ash” (helium) produced by fusion must endure heat levels comparable to those experienced by satellites or meteors during atmospheric re-entry. These systems must effectively remove the heat while ensuring the stability and safety of the surrounding equipment.

The path toward realizing fusion energy has been fraught with challenges—many of which could not have been foreseen when research first began in the mid-20th century. However, encountering unexpected difficulties is not necessarily a misfortune. As many great researchers have testified, “failures often lead to discovery,” because truths that transcend human understanding often lie in the most unexpected places.

Fusion can be seen as a steep and formidable peak for those engaged in development and engineering, and at the same time, as a treasure trove for academic researchers. The very essence of academic inquiry lies in transforming difficult problems into entirely new knowledge. The first generation of fusion reactors—designed and built based on our current knowledge—will be massive in scale and generate extremely powerful magnetic fields. This is due to the uncertainties inherent in our understanding. In the future, continued academic research will be essential in building a more precise and reliable scientific foundation, which will serve as the basis for improving economic viability and ensuring safety.

Moreover, in the process of overcoming these challenges, we can expect to make unexpected discoveries that lead to deeper understanding of nature and technological innovation.

At the National Institute for Fusion Science (NIFS), we are uniting the efforts of all our staff to serve as a beacon illuminating new directions in fusion science within the broader currents of academic research. We aim to form a grand concourse where researchers from across disciplines and borders can come together, collaborate, and expand the scope of fusion science across the vast horizon of academic exploration.

We warmly invite you to take interest in the work of NIFS and to engage with us in a variety of ways as we pursue this exciting endeavor.

YAMADA Hiroshi
Director General of National Institute for Fusion Science