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NUCLEAR FUSION FOR SUSTAINABLE DEVELOPMENT?

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ABSTRACT

The attainment of an energy gain factor ($Q \geq 1$) in fusion energy development on 5 December 2022 represents a momentous milestone, signifying the feasibility of sustainable power generation through fusion. Nonetheless, the journey towards achieving commercial fusion power and its implications for sustainable development present additional challenges and necessitate ongoing research.

Mainstream fusion devices such as ITER (magnetic confinement fusion) and NIF (inertial confinement fusion) are progressing steadily towards the goal of fusion power generation. However, the scale of these facilities is becoming enormous, presenting challenges for achieving commercial viability. Fortunately, recent developments, particularly in high-temperature superconductors, offer promising solutions for more compact magnetic confinement devices, potentially enhancing commercial feasibility.

In addition to mainstream development, the fusion community is exploring alternative concepts that require smaller facilities, thereby enhancing their economic viability. These concepts include reducing (tightening) the aspect ratio in conventional Tokamak geometry, utilizing different drivers and compressional mechanisms for inertial confinement, and combining magnetic and inertial approaches in hybrid devices. Initial numerical modeling and experimental results suggest that these alternate concepts have significant potential for achieving commercially more viable power generation.

1. INTRODUCTION

1.1 Sustainable Development and Nuclear Power

Sustainable development is essential for the well-being of our planet, but it is not without its challenges. Two of the most pressing challenges are global warming and energy shortage. The current reliance on fossil fuels for energy not only contributes to climate change but also depletes finite resources and causes environmental harm.

While renewable energy is a crucial component of sustainable development, certain renewable sources such as wind and solar, have their limitations. They are weather-dependent and require effective and viable storage solutions to address fluctuations in power generation. Nuclear power plays a significant role in

reducing carbon emissions. The International Energy Agency (IEA) envisages that to help achieve the carbon neutrality of Net Zero, the nuclear power capacity in the world will be doubled by 2050 [1].

- China is the leader in nuclear power expansion, with several new plants under construction. The China Nuclear Energy Association estimates that nuclear power capacity will reach 100-120 GW by 2030. As at January 2023, 55 nuclear power plants are in operation in the Mainland China with a total installed capacity of 53 GW.
- The United Kingdom has plans to build a new fleet of nuclear power stations, starting with Hinkley Point C and followed by Sizewell C, with the hope to reach 24 GW nuclear capacity by 2050. The UK government sees nuclear as a critical part of its strategy to decarbonize the electricity sector and achieve net-zero emissions by 2050.
- India has a significant expansion plan for nuclear power as part of its commitment to the Paris Agreement. The country aims to increase its nuclear capacity to 22.5 GW by 2030.
- Russia: Russia has been actively building new nuclear power plants both domestically and abroad. To reduce its carbon footprint, Russian has envisaged a plan to develop 12 new nuclear reactors by 2035 and a programme for 17 additional reactors by 2045. Power generation from Russian nuclear plants is expected to reach 373 TWh in 2045 (225.5 TWh in 2021).

However, it is important to recognize that the current generation of nuclear fission power is not without its drawbacks and limitations. These concerns, such as production and management of irradiated nuclear fuel, the potential for accidents, and the high cost of building and maintaining nuclear power plants are being addressed to various degrees in the new generations (Generation 3 and Generation 4) of nuclear power plants [2].

1.2 Nuclear Fusion for Sustainable Development

At present, nuclear power generation is based on nuclear fission, a process that involves splitting atoms to generate energy. However, there is growing interest in nuclear fusion, which is often referred to as

the holy grail of nuclear power due to its many advantages.

One advantage of nuclear fusion is that it uses hydrogen isotopes, deuterium (D) and tritium (T), as fuel. Abundant supply of D can be extracted from seawater and T converted from lithium, ensuring a nearly limitless supply of fuel.

Fusion reactors also produce no long-lived radioactive waste, unlike fission reactors. The only byproduct of fusion is helium, which is non-toxic and does not pose any environmental risks.

Fusion reactions are inherently safe, as they require precise conditions of temperature and pressure to sustain the fusion process. If any disruptions occur, the fusion reaction stops immediately, without the risk of a runaway chain reaction or a severe accident.

The risk of nuclear proliferation is low due to the fact that fusion reactors do not produce fissile materials (such as plutonium) that can be used in nuclear weapons. The fuel used in fusion reactions does not lend itself to weapons proliferation.

Despite these advantages, achieving controlled fusion reactions at high temperatures and maintaining them for a sustained period is a significant technical challenge. The extreme conditions required for fusion, such as plasma temperatures of over 100 million °C, pose numerous engineering and technological difficulties.

Nevertheless, scientists and engineers are working towards overcoming these challenges and making nuclear fusion a viable and sustainable source of energy. If successful, nuclear fusion has the potential to transform the energy landscape by providing a near-limitless and clean source of energy for generations to come.

2. NUCLEAR FUSION

Nuclear fusion is the process of combining two atomic nuclei into a single, more massive nucleus, releasing a large amount of energy in the process. This process is the source of energy for stars, including our sun. Since nuclei are positively charged, high velocities (or temperatures) are required to overcome the repulsive Coulomb force to bring them close enough to undergo fusion. The primary challenges in harnessing fusion power involve maintaining the fuel plasma at extremely high temperatures, around 10^8 °C, while ensuring sufficient density and confinement time.

Magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) are the two primary approaches for achieving controlled nuclear fusion. There are many different devices developed to study fusion power [3]. In MCF, a plasma of the fuel (D-T) is confined by magnetic fields. The plasma is heated

Ohmically and via auxiliary heating to extremely high temperatures, causing the nuclei to collide and fuse, releasing energy in the process. In ICF, a small target containing the D-T fuel is rapidly compressed and heated, for example by intense laser pulses, causing the fuel to fuse and release energy.

Both MCF and ICF have their own unique challenges and advantages. Tokamak is the mainstream development of magnetic confinement, represented by the International Thermonuclear Experimental Reactor (ITER) and laser fusion is the mainstream development of inertia confinement, represented by the US National Ignition Facility (NIF).

2.1 Advancements in Magnetic Confinement Fusion

Significant progress has been made in the field of MCF, which is approaching the demonstration of fusion power generation. The progress is supported by technology innovation in superconductor for stronger and more efficient magnetic fields; plasma auxiliary heating for efficient heating and longer plasma sustainment; diagnostic to better characterize energy deposition profile, plasma heating and current drive; advanced simulation, and modelling to predict and optimize fusion device performance.

In an operational cycle or discharge, the fuel plasma is initially heated through Ohmic heating and the plasma current is maintained inductively using magnetic coils. Advanced plasma auxiliary heating methods, including neutral beam injection, electron cyclotron heating, ion cyclotron resonance heating, and lower hybrid current drive, are utilized to supplement heating and current drive. The recent advancements in these methods have successfully raised the plasma temperature to fusion conditions and facilitate a near steady-state operation for over 1,000 seconds.

Another notable innovation is the superconductor, particularly the discovery of the high-temperature superconductor (HTS) which allows for construction of more compact magnets to generate stronger and more efficient magnetic fields, see for example, [4].

The performance of fusion reactor increases with the major radius (R) and more so with the magnetic field (B) as can be seen from the scaling relationships [5] at fixed Tokamak aspect ratio and shape for the thermal fusion power gain via the triple-product,

$$nT\tau_E \sim \frac{\beta_N H_{89}}{q_*^2} R^{1.3} B^3 \quad (1)$$

and for the fusion power P_{fusion} loading over the wall/blanket surface area S_{wall} ,

$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N^2}{q_*^2} R B^4 \quad (2)$$

It can be seen from (1) and (2) that a small high magnetic field device can achieve the same level of performance as a much bigger low field device. This can lead to cost savings and make fusion reactors more economically viable. A summary figure (extracted from [7]) shows high Q can be achieved with a smaller device (smaller major radius, R_0) and hence a smaller plasma volume (V_p) with a higher magnetic field (toroidal field on axis, B_0).

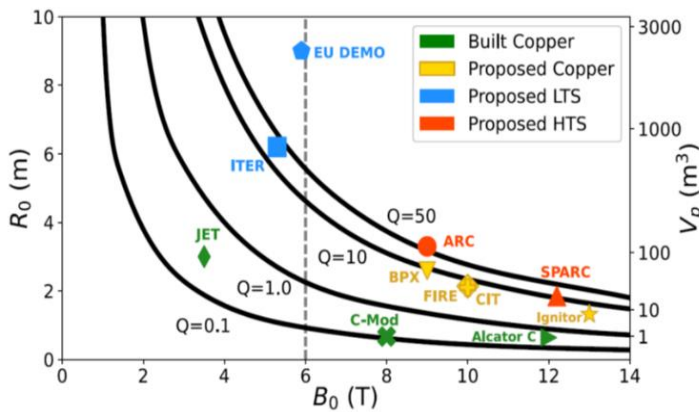


Fig. 1 - The Relationship of Fusion Gain Q to Toroidal Field on Axis B_0 and Major Radius R_0 (Source: From [7])

Furthermore, HTS can reduce the energy consumption of fusion reactors by reducing the Ohmic loss of the magnets. This, in turn, can lead to lower operating costs and make fusion more competitive. HTS can also enable longer sustained plasma pulses, which is important for practical fusion power generation. For example, the Experimental Advanced Superconducting Tokamak (EAST) achieved a plasma pulse lasting 1056 seconds in December 2021 [6].

In addition to the mainstream Tokamak approach, there have been several advances in alternate concepts, aimed at improving the efficiency, stability, and economic feasibility. One alternate concept is the Spherical Tokamak (ST) which in essence is a conventional Tokamak with a small aspect ratio (a ratio of major to minor radius), but has a more compact and spherical shape. The compactness allows for stronger magnetic fields and higher plasma pressure, leading to improved plasma performance and a smaller device. ST typically have a hollow plasma current profile, with current more concentrated towards the outer edge of the plasma. This current profile helps to stabilize the plasma and reduce instabilities.

Advances in ST designs, such as the MAST Upgrade of UK and the NSTX-U of US, have demonstrated improved plasma performance in heat exhaust and impurities control, and reduced energy losses. ST together with the use of HTS leads to a compact, spherical-shaped fusion devices that have shown promise in achieving high plasma pressure and stability, making MCF more commercially viable.

2.2 Advancements in Inertia Confinement Fusion

ICF aims to achieve fusion reaction by compressing and heating a target containing fusion fuel. Laser fusion is the mainstream development wherein powerful lasers are used as the drive to compress and heat the fuel. The process begins with the laser pulses interacting with the outer surface of the fuel pellet, creating a plasma and ablating the pellet surface materials. The ablation and the expanding plasma exert a reaction force that compresses the remaining fuel material inwards and the plasma also drives a strong shock wave inward through the fuel pellet, further compressing the fuel. The compression increases the temperature and pressure within the fuel pellet, creating conditions necessary for fusion reactions to occur.

Laser fusion has made steady progress through advances in high power laser system, better design of the hohlraums (the cylindrical housing for the D-T, fuel), and a better understanding of the compression process. Computer simulation plays an important role to provide insights into the design of the hohlraum, the behaviour of the induced X-rays, the implosion dynamics and the physics of a burning plasma.

On 5 December 2022, for the first time, the energy gain factor $Q_{sci} \geq 1$ had been achieved in NIF, signifying that fusion energy released is more than the heating power injected and a sustainable power generation is feasible. To achieve the breakthrough, NIF used 192 lasers to deliver 2.05 MJ of energy onto a pea-sized gold hohlraum containing a frozen pellet of D-T fuel, which caused the pellet to collapse, reaching temperatures of 10^8 °C, and initiated D-T fusion reactions which released 3.15 MJ to yield a Q_{sci} of 1.54 [8]. Beyond the significant scientific achievement are enormous engineering challenges:

- Energy conversion efficiency: the lasers consumed 322 MJ to generate the X-rays that actually spark fusion, resulting only about 1% of the input energy for heating the fuel.
- High energy drivers: much higher output than the 3.15 MJ is needed.
- Repetition rate: the facility can fire laser only once a day at a single target but 3-10 Hz is needed.

Advanced ignition schemes have been explored in order to lessen the requirements on high power laser to improve the overall efficiency. One of the schemes, shock ignition, involves the rapid compression of a fuel capsule using one set of lasers, followed by another powerful laser pulse (ignitor) that generates a strong shockwave. The shockwave heats and ignites the fuel, initiating fusion reactions. Another scheme is the fast ignition whereby after the fuel is compressed using one set of lasers, a short high power fast ignitor beam at

proper time generates fast electron beam that increases the temperature of the central part of the target leads to an effective hot spot that completes the ignition process of fuel.

An alternate approach to ICF is to use other type of drivers, such as gas gun or railgun, instead of a powerful laser system. In the Projectile Fusion (PF) or impact fusion scheme as depicted in Figure 2 below, a driver accelerates a projectile to high velocity. The projectile collides with the target, causes cavity collapse to create a shockwave that facilitates compression and heat of the fuel.

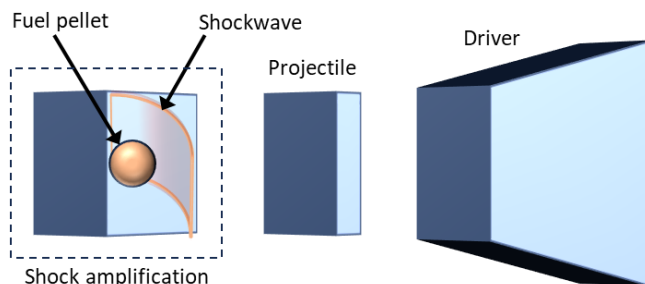


Fig. 2 - Schematic of the Projectile or Impact Fusion Approach

Interest in this PF approach started in the early 1960s and some of the early investigations can be found in the Proceedings of the Impact Fusion Workshop, 1979. The Impact Fusion Workshop determined some basic requirements for impact fusion.

- The minimum velocity of the projectile is 200 km/s and with a kinetic energy of about 10 MJ.
- A characteristic thickness of the macroparticle and plasma cavity might be a few mm, and the time scale (burn) might be 5 - 10 ns.
- One challenge is to convert the linear kinetic energy into a 3-dimensional compression without energy losses.

It was considered that a major block to PF is the development of drivers capable of accelerating the projectile to the necessary high velocity with sufficient impact precision.

Recently in 2022, the First Light Fusion (FLF) team made a significant step forward to demonstrate achieving fusion using a 2-stage light gas gun [9].

The breakthrough was resulted from a better understanding of the shock amplification effect arising from cavity collapse. Computer simulations as well as the development of high-speed X-ray imaging system (with an effective frame rate reaching Mfps for images separated by 10^{-7} s) played a crucial role in gaining understanding of the collapse dynamics and providing

insight into the behavior of the target [10]. The fusion results were confirmed by a UKAEA diagnostic team [11] with their report stated that "... neutrons have been produced which would be consistent with the energy of those produced in D-D fusion processes".



Fig. 3 - The Two-stage Light Gas Gun used to Accelerate Projectiles Up to 6.5 km to Achieve Projectile Fusion (©First Light Fusion Limited, 2021)

The Projectile Fusion approach, recently revitalized by the FLF team, offers a compelling alternative to traditional Tokamak and laser fusion concepts. By utilizing an external driver, such as a pulsed power machine, to propel projectiles and create the extreme temperatures and pressures required for fusion, this approach introduces a simpler and more cost-effective design. It eliminates the need for massive magnetic coils or complex laser systems, potentially reducing both construction and operational costs associated with fusion research and development. Through numerical simulations, FLF was able to optimize the target design to better harness the shock amplification effect to enhance compression to achieve higher fusion gain.

The advancement of railgun technology for the driver offers a more reliable and controllable means to propel the projectiles, providing a greater precision generation of the shockwave for a stronger amplification effect.

3. WHEN WILL FUSION POWER BE AVAILABLE?

Initially, in the late 1950s, there was great optimism, with many scientists and researchers believing that it was only 15 years away. In the following years, the sentiment became more cautious, with suggestions that it would be at least 50 years away. However, recent developments and innovations have sparked a renewed sense of optimism. Table 1 shown some of the targeted achievements of the updated and newly announcements [3, 12, 13]:

Table 1 are just a few examples of the ongoing fusion research efforts with mainstream developments typically expect to demonstrate electricity generation by 2050s. The alternate lines are more optimistic and some expect to see electricity delivery by 2030s. While there is renewed optimism, there are engineering challenges

to be overcome before commercial viability can be achieved in as early as 2030s.

Device	Target Date	Organization
ITER (Tokamak)	2030s, technical feasibility of fusion power, $Q \sim 10$	International Collaboration
CFETR	2040s, $Q_{\text{eng}} > 1$, 200MW _e	China
EU-DEMO	2050s, $Q_{\text{eng}} > 1$, 500 MW _e	EU
JA-DEMO	2050s, $Q_{\text{eng}} > 1$, 500 MW _e	Japan
K-DEMO	2050s, $Q_{\text{eng}} > 1$	Korea
DEMO-RF (Tokamak)	2050s, $Q_{\text{eng}} > 1$ 2050s, $Q_{\text{eng}} > 1$	Russia
SPARC (Tokamak)	2025+, $Q_{\text{sci}} \approx 11$	Commonwealth Fusion Systems & Plasma Science and Fusion Center, MIT
STEP/SPR (Spherical Tokamak)	2030s, deliver electricity	UKAEA
ST80-HTS/ST-E1 (Spherical Tokamak)	2030s, deliver electricity	Tokamak Energy
LM26 (Magnetized Target Fusion)	2020s, $Q > 1$ Early 2030s, net energy gain	General Fusion
C-2W C-2E (FRC)	2020s, net energy gain 2030s, prototype power plant	TAE Technologies
NIF (Laser Fusion)	Dec 2022, achieved Q of 1.54	Lawrence Livermore National Laboratory
M3 (Projectile Fusion)	2030s, net energy gain	First Light Fusion

Table 1 - Target Performance of Some Different Types of Devices

In order to advance MCF to large-scale power generation, further R&D efforts are required to enhance understanding of burning plasma physics, impurity control, disruption avoidance, and instability control. Furthermore, engineering development is needed to establish essential technologies for all subsystems, particularly in plasma-facing materials to address irradiation protection and efficient heat removal, high-temperature superconducting materials, and large auxiliary heating power systems.

In the case of ICF, enhancing the energy conversion efficiency and increasing the repetition rate of the laser system are crucial for scaling up to energy production. While the alternate Projectile Fusion concept has shown considerable promise, further advancements are needed in the precision control of high-power railgun technology and the construction of targets to achieve optimal shockwave amplification. The engineering challenges associated with ash removal and refuelling are yet to be demonstrated.

4. CONCLUSION

Accurately predicting the timeline for achieving commercially viable nuclear fusion power is a challenging task. Nonetheless, the diligent R&D on harnessing fusion energy for many years has resulted in

significant progress. Demonstrations of scientific feasibility in both MCF and ICF have been achieved, exemplified by recent accomplishments such as reaching a Q of 1.5 in NIF.

While mainstream fusion devices are steadily progressing towards realizing fusion power generation, it is still estimated that achieving commercially viable fusion power will be in the 2050s. The development of the HTS for generating stronger magnetic fields offers promising solutions for more compact magnetic confinement devices, making commercial fusion power more viable. In addition to HTS, alternative magnetic confinement approaches, such as the ST, show great potential for reducing the size of fusion reactors even further and offer an attractive and expedited solution, with some experts anticipating commercialization as early as the 2030s.

In laser fusion, alternate ignition schemes hold promise for reducing the requirements on high-power laser systems. This, in turn, can lead to smaller and more cost-effective facilities, accelerating the path to viable commercial fusion power. Additionally, the Projectile Fusion scheme, utilizing alternate drivers like railguns, presents an attractive opportunity to achieve net energy gain as early as the 2030s.

In summary, although challenges and uncertainties persist, progress in fusion research, coupled with technological innovations and exploration of alternate concepts, brings us closer to realize commercially viable fusion power. Continued dedication and collaboration within the scientific community hold the promise of harnessing fusion as a sustainable energy source in the near future.

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