Towards Limitless Power
A Primer on Nuclear Fusion

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Executive Summary

- Nuclear fusion is the way the sun and the stars produce energy. It can be limitless and clean and holds great promise for the future. Unlike nuclear fission which involves releasing energy by breaking down isotopes of large atoms like uranium into smaller particles, fusion involves combining the nuclei of two isotopes of hydrogen to produce helium with the release of huge amounts of energy.

- Scientists around the world have been researching nuclear fusion for the last 100 years and it is only now that many of the hurdles to commercialise nuclear fusion look surmountable. Recent progress in achieving greater energy output than the energy input (net energy gain) and ability to maintain plasma for longer periods have given new hope to commercialisation.

- Till recently fusion research was restricted to government laboratories and some international institutions set up by a group of countries. The advent of artificial intelligence and its tremendous energy needs have driven many private companies like Microsoft, Amazon and others to start funding private research in this space.

This document has been formatted to be read conveniently on screens with landscape aspect ratios. Please print only if absolutely necessary.

Author
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Nuclear Fission is Commercialised

Nuclear fission is the process of splitting a heavy atomic nucleus, such as uranium or plutonium, into two or more lighter nuclei. This process releases a large amount of energy, which is the basis for current nuclear power plants and atomic bombs.[1]

Process

Fission occurs when a neutron strikes a heavy nucleus, causing it to become unstable and split into smaller fragments, releasing energy and additional neutrons.

Fuel and Energy

Fission relies on heavy elements like uranium and plutonium, which are mined and processed. Fission releases significant energy, but less energy per unit mass compared to fusion.

Byproducts and Safety

Fission reactions produce radioactive byproducts, some of which have long half-lives and pose significant challenges for waste disposal.

Nuclear Fusion is Still in Laboratories

Nuclear fusion is the process of combining two light atomic nuclei to form a heavier nucleus, releasing a massive amount of energy.[2]

Safe and Sustainable	Powers the Stars	Better than Fission
Nuclear fusion has the potential to offer a safe and sustainable energy source for the future.	Fusion reactions, which power the sun and other stars, involve combining lighter nuclei of hydrogen isotopes, deuterium and tritium, to create helium, releasing a massive amount of energy in the process.	Offers a significant advantage over fission, with no long-lived radioactive waste . The fuel for fusion is relatively plentiful.

Nuclear Fusion and Nuclear Fission: Key Differences

FEATURES	NUCLEAR FUSION	NUCLEAR FISSION
PROCESS	Combining light nuclei	Splitting heavy nuclei
FUEL	Deuterium, tritium (isotopes of hydrogen)	Uranium, plutonium
ENERGY RELEASE	Four times as much energy release per unit of fuel compared to nuclear fission	Four million times as much energy release per unit of fuel compared to coal
BY-PRODUCTS	Helium (non-radioactive) and neutrons (used to breed more fuel)	Radioactive isotopes, some with long half lives
SAFETY	Inherently safe (no risk of runaway chain reaction)	Risk of meltdown and release of radioactive material, requires robust safety systems
CHALLENGES	Achieving sustained fusion, material science, tritium availability, cost	Waste disposal, proliferation concerns, public perception, cost

Sources: nuclear-power.com; International Atomic Energy Agency

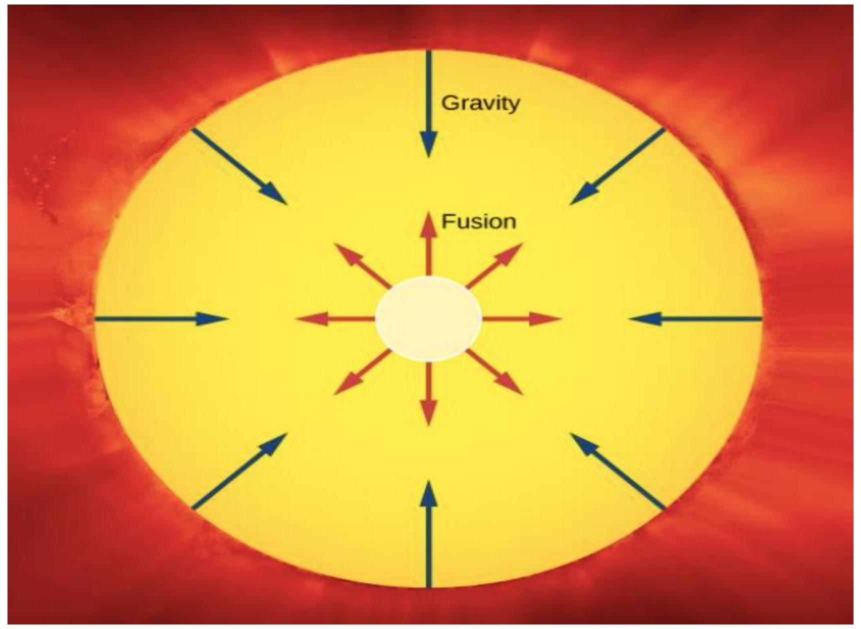
Nuclear Fusion Potential

"When we look up at night and view the stars, everything we see is shining because of distant nuclear fusion"

-Carl Sagan [3]

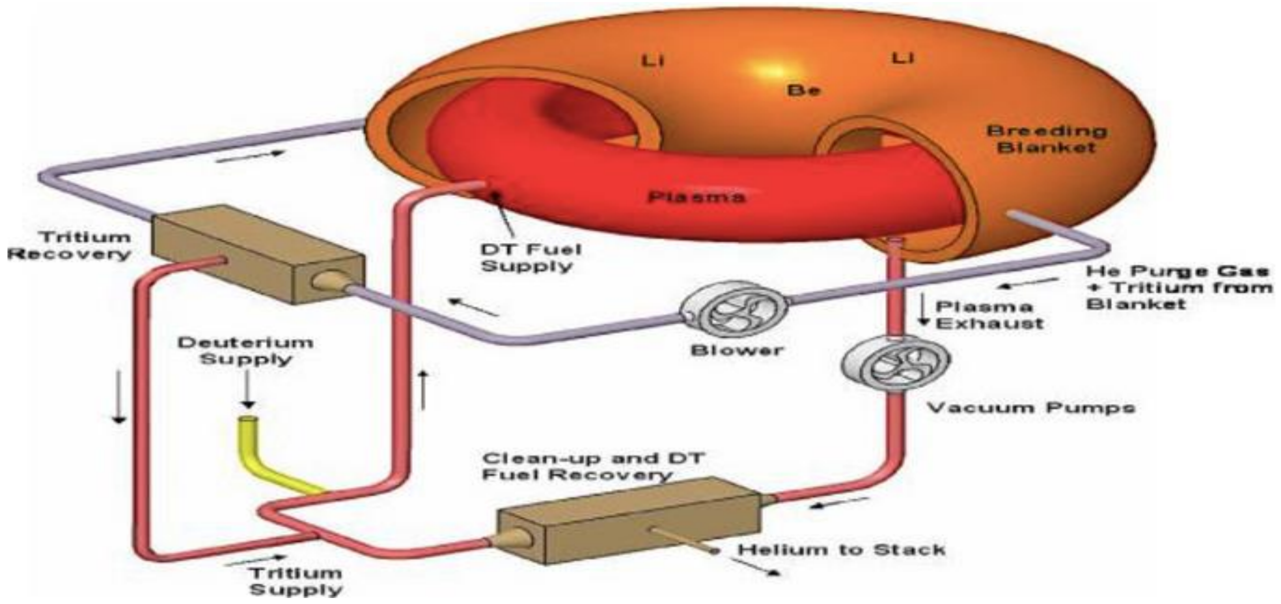
Different Approaches to Nuclear Fusion

There are three main approaches to nuclear fusion.



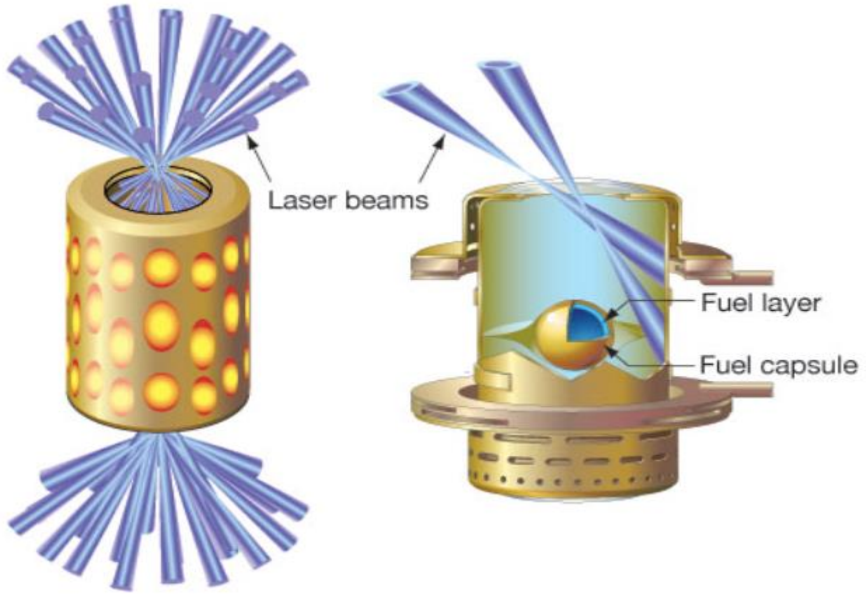
Gravitational Confinement

- Uses the force of gravity to contain plasma in nuclear fusion.
- Stars (including the Sun): Here, gravity compresses hydrogen atoms to the point of fusion.



Magnetic Confinement

- Uses powerful magnetic fields to confine plasma (a hot, ionised gas).
- This approach is adopted at the International Thermonuclear Experimental Reactor (ITER), Joint European Torus (JET), Princeton Plasma Physics Laboratory and Wendelstein 7-X.



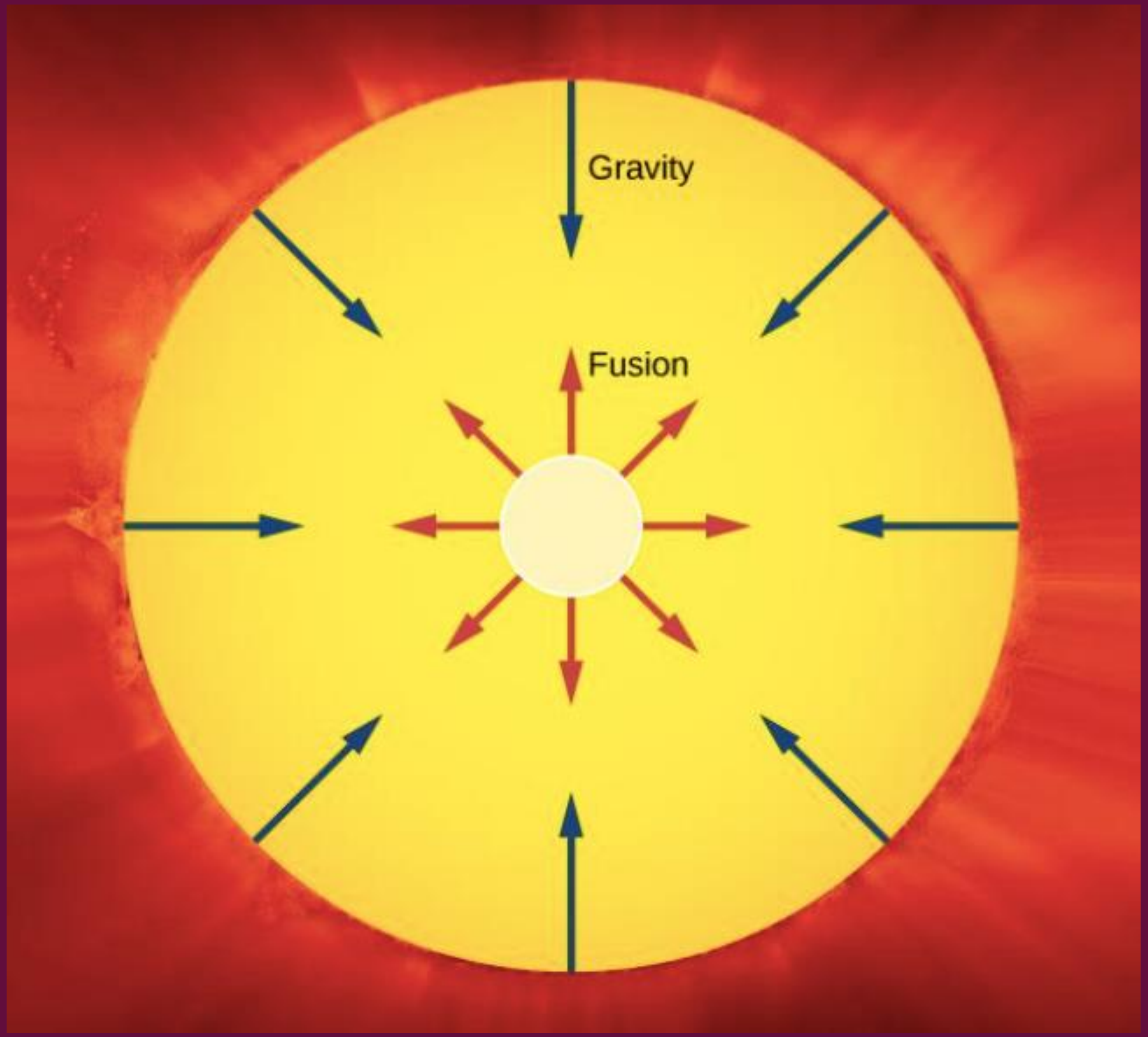
Inertial Confinement

- Uses high-powered laser beams or other drivers to rapidly heat and compress a small target containing fusion fuel, typically a mixture of deuterium and tritium.
- This method is being used by the National Ignition Facility (NIF), Omega Laser Facility and Laser Megajoule (LMJ).

Note: Companies like Helion are using a magnetised target fusion which combines magnetic confinement with inertial confinement.[4]

Gravitational Confinement

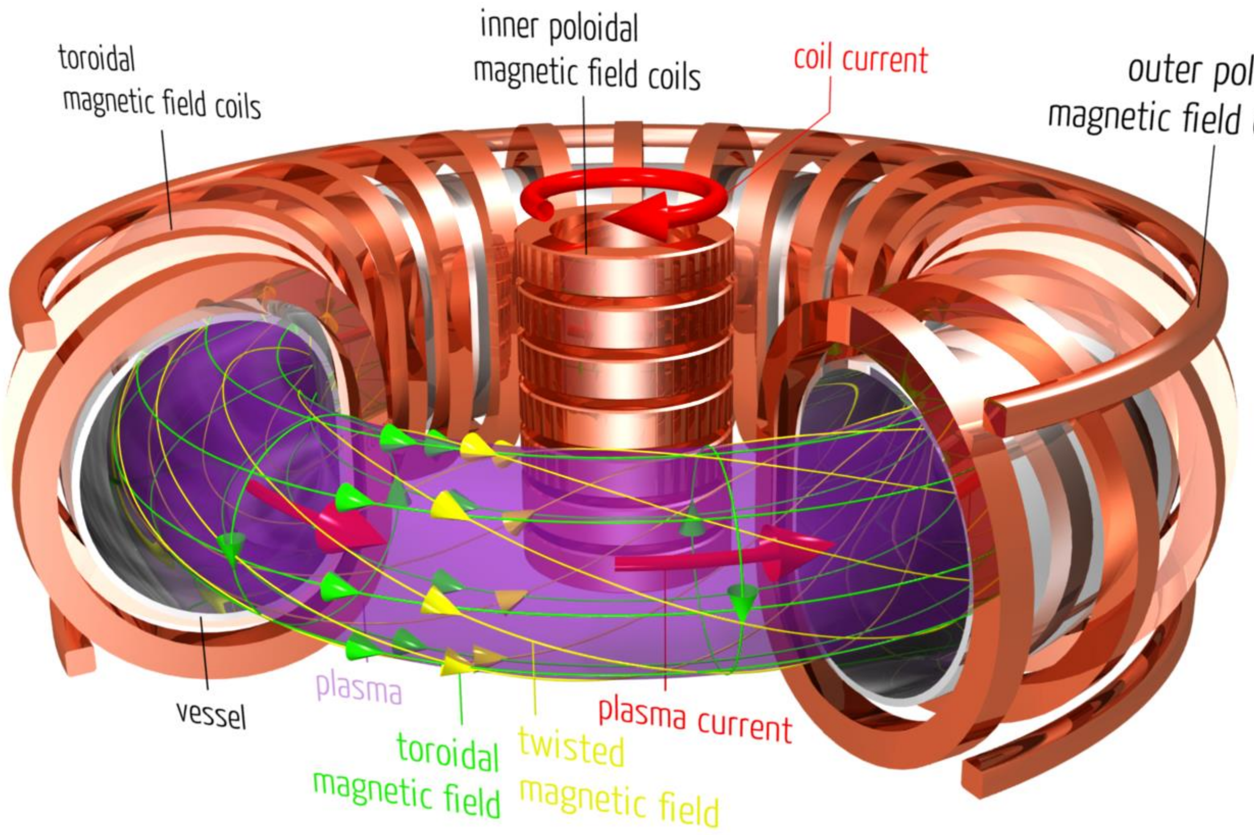
- This method naturally occurs in stars, where gravity compresses plasma to high densities and temperatures.[5]
- It relies on the mass of the plasma for creating fusion conditions.
- It is not feasible for controlled fusion on Earth due to the enormous mass required. The mass of the sun for example is 333,000 times that of the earth. The smallest star is about 83-85 times the size of Jupiter, the largest planet in the solar system.



Magnetic Confinement

- It involves using powerful magnetic fields to confine a hot, ionised gas called plasma.
- The plasma is heated to extremely high temperatures, over 100 million degrees centigrade, causing the atomic nuclei to overcome their electrostatic repulsion and fuse together, releasing energy.
- The tokamak is the most common type of magnetic confinement fusion reactor, which uses a torus-shaped magnetic field to confine the plasma.
- Stellarators, another type of magnetic confinement reactor, offer inherent stability due to the lack of toroidal plasma current which occur in tokomaks and cause magnetohydrodynamic instabilities, but are more complex to design and build.[6]

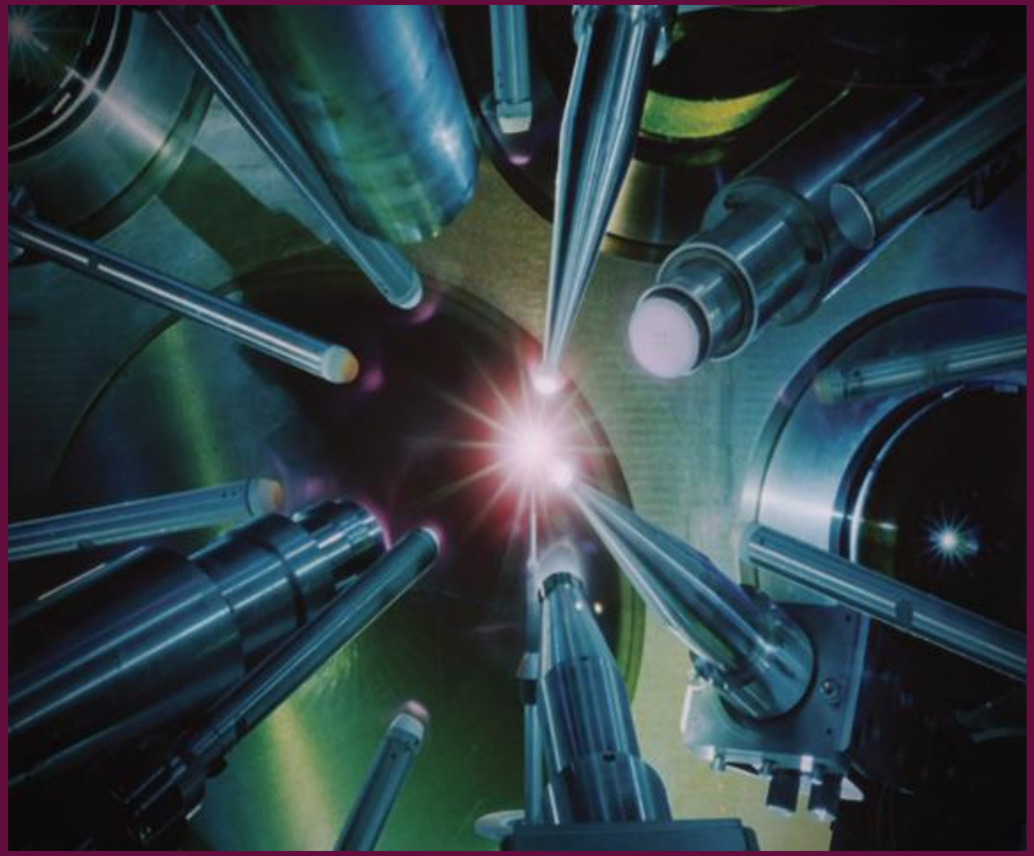
Adopted from: EUROfusion; US Fusion Energy; ITER

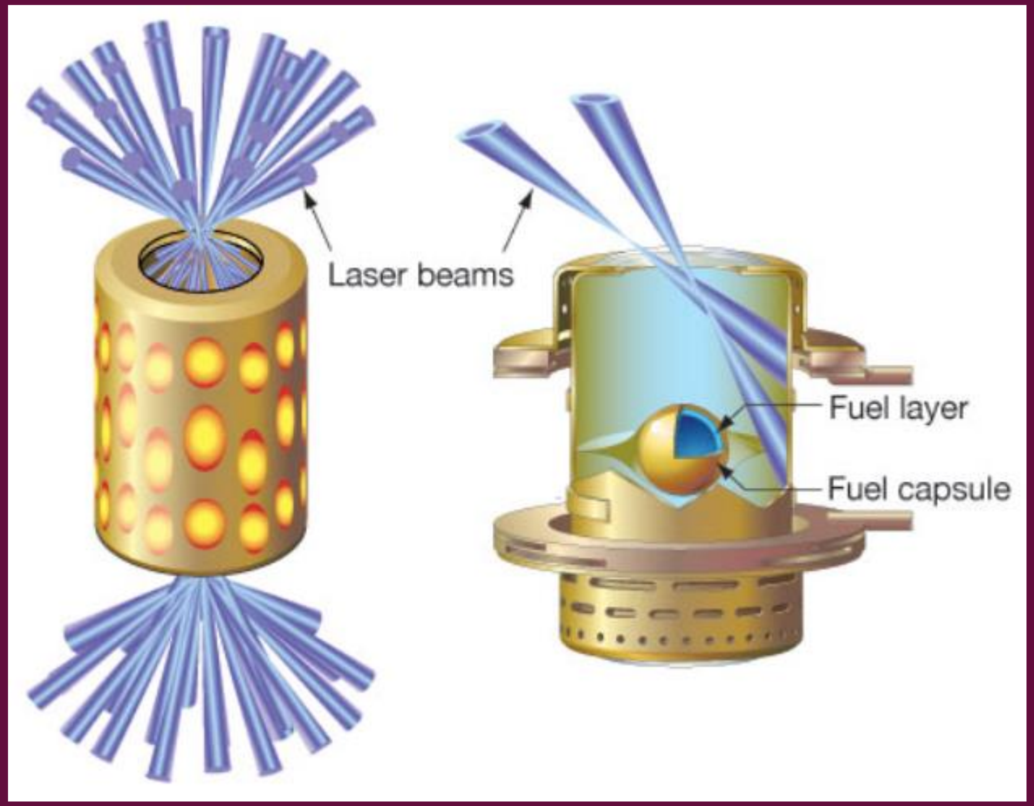


Note: A torus is a geometric shape that resembles a doughnut or the inner tube of a tyre.

Inertial Confinement

- It uses high-powered laser beams or other drivers to rapidly heat and compress a small target containing fusion fuel, typically a mixture of deuterium and tritium.
- The intense pressure and temperature created by this implosion cause the atomic nuclei in the fuel to fuse together.
- This process is similar to how a hydrogen bomb works, but inertial fusion energy aims to achieve controlled and sustained fusion reactions for energy production.
- First Light Fusion is an example of a company pursuing inertial fusion technology, utilising a hyper-velocity gas gun and electromagnetic propulsion to achieve mechanical compression of the fuel target.[7]





Timeline of Progress in Nuclear Fusion

1920s
Arthur Eddington suggests that stars obtain energy from fusing hydrogen into helium

1930s
Mark Oliphant discovers helium-3 and tritium

1950s
Andrei Sakharov and Igor Tamm propose the Tokamak design for magnetic confinement fusion

1961
The first IAEA fusion energy conference is held

1968
USSR releases information about the Tokamak design leading to a shift in fusion research focus

1971
IAEA establishes the international Fusion Research Council for global collaboration

1973
European countries start developing the Joint European Torus (JET)

1983
First plasmas achieved in JET

1985
At the Geneva Summit, Gorbachev proposes a collaborative international fusion project, initiating the International Thermonuclear Experimental Reactor ITER

1997
JET sets a world record for fusion output (16 MW) and Q*Value (0.67)

2000-2010
China, South Korea and India join the ITER project. Construction of the ITER scientific installation starts

2021
JET achieves a new fusion energy record of 59 MJ in a 5 second pulse

2022
Scientists at the Lawrence Livermore National Laboratory achieve net energy gain for the first time

2023
JET concludes its experiments and commences decommissioning after 40 years of operation.

* Note: Q is net energy gain and is the ration between output energy and input energy in a fusion reaction

Recent Achievements

- Achieving Net Energy Gain: Scientists at the Lawrence Livermore National Laboratory (LLNL) in California accomplished "net energy gain" in fusion ignition in 2022 and repeated the achievement in 2023.[8] This proves that fusion can be a viable net energy source and not just a mere science experiment.

- Extended Plasma Confinement: The Joint European Torus (JET) experiment achieved a record duration of five seconds of stable plasma which is progress towards the longer durations of continuous generation required in commercial operations.[8]

- High-Temperature Superconducting Magnets: Researchers at MIT and Commonwealth Fusion Systems (CFS) have demonstrated that smaller, more efficient magnets can achieve fusion using high-temperature superconductors (HTS). They also successfully tested the Central Solenoid Model Coil (CSMC) and the Toroidal Field Model Coil (TFMC). They have plans to build a 400 MW power plant in Virginia.

- Private Sector Investment Surge: The growing interest from private companies and investors has fuelled significant investment in fusion research which should lead to reduced development timelines in the journey to commercial viability. [9]

- Increased Public Funding and International Collaboration: Governments worldwide are recognising the potential of fusion energy and launching initiatives to increase public funding and foster public-private partnerships.[10]

The Global Race to Develop Fusion Energy

- **Europe**: The European Union has a long history of collaborative fusion research, primarily through the JET project, which has played a crucial role in developing technologies for ITER [11], the world's largest fusion experiment currently under construction in France. While the UK has decided to pursue national research programs like the Spherical Tokamak for Energy Production (STEP), the EU is actively exploring public-private partnerships to accelerate fusion energy commercialisation.

- **United States**: The US boasts a vibrant private fusion sector with significant venture capital backing. The government is increasingly supporting private companies through initiatives like the Milestone-Based Fusion Development Program, which provides grants and cost-share opportunities for pilot plant designs. This strong public-private synergy is driving rapid innovation and positioning the US as a potential frontrunner in commercialising fusion energy.[12]

The Global Race to Develop Fusion Energy

- **China**: China has ambitious goals for fusion energy, aiming to have a demonstration fusion reactor by the 2030s and large-scale commercialisation by 2050.[13] While China has traditionally focused on government-led research, it is now actively seeking to foster public-private partnerships and build a skilled fusion workforce. China's growing investments in fusion research, coupled with its manufacturing prowess and strategic focus on clean technologies, position it as a strong contender in the global fusion race.[14]

- **India**: India has been working on fusion technology for decades, initiating its Plasma Physics Programme in 1982. It developed its own tokamak, ADITYA, in 1989, and a larger one, SST-1, in 2013, with plans for SST-2 by 2027. India is also a key member of the ITER project. While private investment lags, India is outlining a fusion roadmap, including two new machines before the Indian DEMO (demonstration power plant) launch in the late 2040s. One machine will be a fusion neutron source, and another will be a conventional tokamak.[15]

Geopolitics of Nuclear Fusion

- Giant strides have been made in artificial intelligence and the US and China are in a race to establish dominance in this space.[16] Even as the technology promises hyper growth in world economy, climate change is threatening the survival of the planet and artificial intelligence is an energy guzzler. The need of the hour is clean, green energy and nuclear fusion is one technology that holds tremendous promise but is yet to be commercialized.

- The country that establishes this technology first will have the ability to grow its economy unhindered by the limitations of fossil fuel. Success in commercialising nuclear fusion will reduce dependence on fossil fuels and diminish the political and economic power of oil-producing nations.

- China and the US are the leaders in this area but the challenges in commercialising the technology are delaying the availability of patient capital.[17]

- The trade wars between US and China could hamper progress, especially in ITER, and halt much-needed international collaboration between the Western nations and China.

Challenges to commercialisation of nuclear fusion

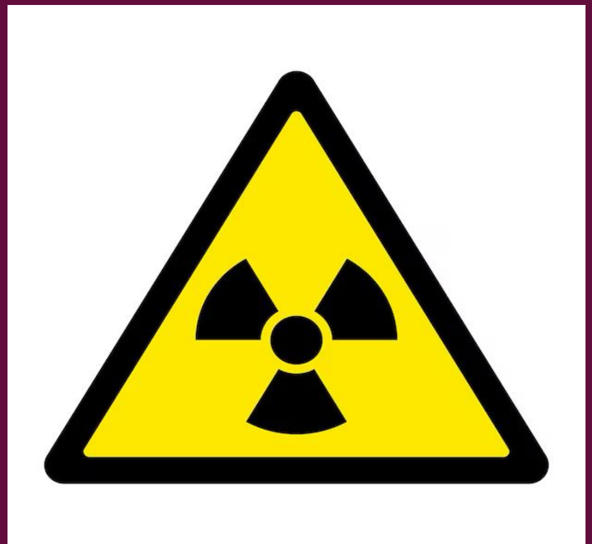
Understanding the potential of nuclear fusion and the obstacles in achieving sustainable energy solutions is essential for future advancements. Continued and increased investment, both public and private, is necessary for making nuclear fusion commercially viable.[18][19]

Energy Production at scale

Sustaining fusion reactions and securing the material supply chain especially for tritium is a key concern.

Technological Hurdles

Complex technology and high costs currently limit the widespread adoption and implementation of fusion reactors.



Public Perception of Safety

Public perception and regulatory challenges must be addressed to ensure promotion of fusion energy as a safe source of energy.

Gap 1: Energy Production at scale

- **Sustaining a fusion reaction that produces more energy than it consumes**: While net energy gain has been achieved, achieving and maintaining the extreme temperatures and pressures necessary for sustained fusion reactions is a major challenge.

- **Maintaining plasma stability:** The plasma, a superheated gas where electrons are stripped from atoms, needs to be confined effectively for fusion to occur. Also, maintaining plasma stability and preventing disruptions that could damage the reactor are ongoing areas of research.

- **Supply chain bottlenecks**: The production of necessary components for fusion reactors faces potential constraints, including supply bottlenecks. Supplier investment in precision manufacturing required for fusion reactor construction is inadequate due to uncertainty of demand. With fusion still in experimental stage, the designs are yet to be standardized and causes long lead times for sourcing components including magnets and lasers. Trained workforce for the required level of precision needs to be scaled.

- **Tritium Supply**: Tritium, a crucial component for fusion reactions, is rare and primarily sourced from nuclear reactor moderator pools. The moderator pool is intended to slow down the fast neutrons generated in the process and help them react with lithium-6 to produce tritium. Another way to address the shortage of tritium is to breed it within the fusion reactor itself, using the high-energy neutrons produced during fusion to split lithium into tritium and helium within a blanket surrounding the fusion chamber. This is still an ongoing area of research.[20]

Gap 2: Technological Hurdles

- **Developing materials that can withstand the extreme conditions inside a fusion reactor**: The intense heat and neutron bombardment pose significant challenges for materials in fusion reactors. Tungsten is currently the leading candidate for plasma-facing materials due to its high melting point and resilience to neutron damage. Research is also exploring other potential materials that could potentially surpass tungsten in performance There are experiments on using liquid metal walls of lithium, tin or gallium. There are also attempts to develop high entropy alloys using a mix of tungsten, tantalum, chromium, vanadium and titanium for example.

- **Scaling up from laboratory experiments to commercially viable power plants:** While progress has been made in laboratory settings, scaling up to produce power for the grid requires further technological advancements. Net energy gain Q needs to improve from the current benchmark of 2 and get closer to 10, plasma instability prediction needs to improve, and some strides in integrated systems engineering of reactors besides the development of materials mentioned above is required.

- The technological advancements stated above require additional patient capital before low risk capital can be unlocked.[21]

Gap 3: Safety, Regulation & Collaboration

There are still some outstanding concerns which need to be addressed despite fusion being safer than fission reactors.

- Confinement of tritium, a radioactive isotope with half life of 12.3 years, within the fuel cycle is a safety concern but there are several layers of barriers in the reactor designed to prevent leakage into the environment.
- Material activation is a concern since the fast neutrons produced during fusion may activate the material around the reactor core and make them radioactive, leading to Research is on to develop low activation materials.
- France has regulations for safety that ITER is able to meet. The US has relaxed the regulations for nuclear fusion compared to fission. The IAEA is also working towards sharing knowledge on safety with organisations developing fusion reactors.[22]
- The biggest challenge could be to educate the public regarding the inherent safety of fusion reactors and convincing them that these reactors do not carry the same risk as fission reactors.[23]

Commercial Viability

- **Cost**: The cost of building and operating fusion power plants remains a significant concern. High capital expenditure for the construction of these plants, including expensive materials like beryllium for reactor components, may hinder economic viability. While innovations like high-temperature superconductors aim to reduce costs through more compact designs, the overall economic feasibility of fusion power requires further demonstration.

- **Levelised Cost of Electricity (LCOE)**: Despite significant private investment (exceeding $7 billion), achieving a sufficiently low LCOE to compete with existing energy sources remains uncertain. Current estimates, from a report by engineering group Assystem, suggest that LCOE of nuclear fusion is more than three times that of wind and solar and needs to come down significantly before it can be commercially viable. Similar information is provided in a paper published by Lindley, Ben et al in June 2023 in Energy Policy Vol 177.

- **Continued and substantial investment**, from both public and private sectors, is essential for overcoming technical hurdles and achieving commercially viable fusion energy. While recent government funding for fusion research has increased, the industry acknowledges funding as a major challenge in the coming years.[24]

Funding Fusion Development

- Early Stages (1920s–1990s): Government-led research was the primary source of funding during the initial phases of fusion research. Public programs methodically progressed toward scientific milestones.

- Private Sector Entry (2000s): Around the turn of the century, private companies entered the fusion arena, seeking to accelerate development. Private investment has increased significantly, particularly in the last few years, exceeding $7 billion in total.[24]

- Surge in Investment (2020s): There has been a notable surge in private investment, with 2022 seeing a massive $2.8 billion influx. While the rate of increase slowed slightly in 2024, it still reached a total of over $7.1 billion, indicating continued confidence in fusion's potential.

- Public-Private Partnerships (2020s): The emergence of public-private partnerships has become a prominent trend. Governments worldwide are fostering these collaborations to accelerate fusion development. Notable initiatives include:

  - US Milestone-Based Fusion Development Program: This program, launched in 2022, offers $50 million in grants to private companies partnering with national labs to design pilot plants.

  - UK Fusion Industry Program: The UK's program also aims to engage the private sector in tackling specific fusion technology challenges.

  - Government Funding Trends: While private investment has taken centre stage, public funding has also seen a substantial increase. Government funding rose by 57% in the year leading up to July 2024, reaching $426 million.

Commercialisation Timelines

- Commonwealth Fusion Systems (CFS) plans to have its SPARC device operational in 2025 to demonstrate net scientific energy gain, with its successor project, ARC, expected to deliver power to the grid by the mid-2030s.[25]

- Helion Energy, a US-based company, has even signed a power purchase agreement with Microsoft to deliver 50 megawatts of fusion-generated electricity by 2028.

- The IAEA World Fusion Outlook 2024 is less optimistic and believes there is another 20-25 years before commercialisation.[26]

- Experts caution that commercial viability hinges on sustained funding, overcoming technological hurdles, and addressing supply chain constraints.

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Appendix

100 YEARS of Nuclear Fusion Efforts

AI disclosure: List created using notebooklm.google.com

1920s and 1930s

- **1920**: Arthur Eddington suggests that stars obtain energy from fusing hydrogen into helium.
- **1926**: Eddington publishes Internal Constitution of the Stars, laying the foundation for theoretical astrophysics.
- **Late 1920s**: Robert d'Escourt Atkinson and Fritz Houtermans make the first calculations of nuclear fusion rates in stars.
- **1930s**: Ernest Rutherford explores the structure of the atom.
- **1934**: Rutherford demonstrates deuterium fusion into helium, marking the first lab demonstration of fusion.
- **1930s**: Mark Oliphant discovers Helium-3 and tritium.
- **1930s**: Hans Bethe describes the Sun's energy release through proton-proton chain reactions.

1950s to 1970s

- **1950**: Andrei Sakharov and Igor Tamm propose the Tokamak design for magnetic confinement fusion.
- **1951**: Lyman Spitzer proposes the Stellarator concept for fusion research.
- **1961**: The first IAEA Fusion Energy Conference is held.
- **1968**: USSR releases information about the Tokamak design, leading to a shift in fusion research focus.
- **1971**: IAEA establishes the International Fusion Research Council for global collaboration.
- **1973**: European countries begin designing the Joint European Torus (JET).
- **1977**: The European Commission greenlights the JET project, located in Culham, UK.

1980s to 2000

- **1983**: JET construction is completed, marking the largest magnetic confinement plasma physics experiment.
- **1983**: First plasmas achieved in JET.
- **1985**: At the Geneva Superpower Summit, Gorbachev proposes a collaborative international fusion project, initiating ITER.
- **1988**: Conceptual design for the ITER facility begins.
- **1990s**: JET becomes the first reactor to operate on a deuterium-tritium fuel mix.
- **1997**: JET sets a world record for fusion output (16 MW) and Q value (0.67).

2000 to 2010

- **2001**: ITER members approve the final design for the facility.
- **2003**: China and South Korea join the ITER project.
- **2005**: India joins the ITER project.
- **2005**: ITER site is chosen: Cadarache, France.
- **2005**: First teams arrive at the ITER site in Saint Paul-lez-Durance, France.
- **2006**: ITER agreement is signed, establishing a legal international entity.
- **2007**: ITER organization is officially established.
- **2008**: Cooperation agreement is signed between the IAEA and the ITER organization.
- **2010**: Construction of the ITER scientific installation starts.

2010 to Present

- **2010-2014**: Ground support and seismic foundations for the Tokamak are laid.
- **2012**: ITER is classified as a Basic Nuclear Installation under French law.
- **2014-2023**: Construction of the Tokamak Complex takes place.
- **2015**: Wendelstein 7-X stellarator, a potential alternative to Tokamaks, becomes operational.
- **2020**: Assembly of the ITER machine begins.
- **2021**: JET achieves a new fusion energy record of 59 MJ in a 5-second pulse.
- **2022**: ITER project reaches 77.7% completion of work scope towards First Plasma.
- **2023**: Completion of Tokamak Building civil works.
- **2023**: JET concludes its experiments and commences decommissioning after 40 years of operation.
- **2020-present**: Thousands of people across the globe collaborate on the ITER project in France, China, EU, India, Japan, Korea, Russia, and the US.