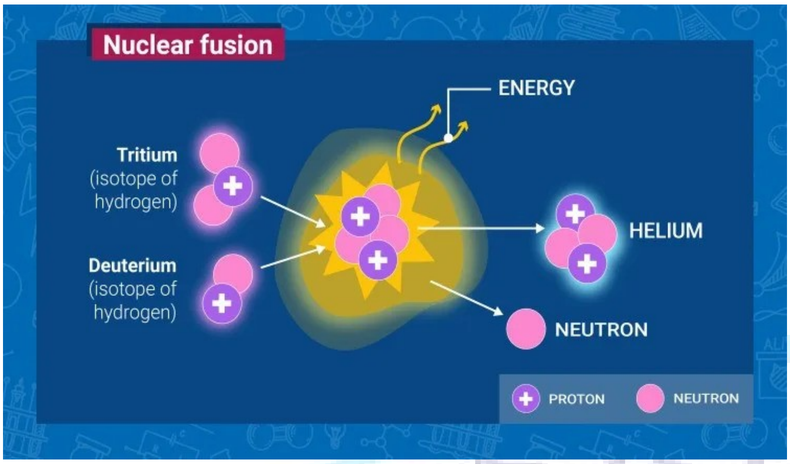
2. India's Nuclear Fusion - Science & Technology



IPR Gandhinagar team proposes roadmap for India's fusion power plans. India has proposed a roadmap for fusion energy, planning to build a hybrid fusion-fission reactor named SST-Bharat. The long-term goal is to commission a full-scale demonstration fusion reactor by 2060 to achieve clean energy security.

India's Roadmap for Fusion Energy

Researchers at the Institute for Plasma Research (IPR), Gandhinagar, have proposed a detailed roadmap for India's fusion energy program. The centerpiece of this plan is the construction of India's first fusion–fission hybrid reactor, the Steady-state Superconducting Tokamak-Bharat (SST-Bharat), with the ultimate goal of commissioning a full-scale demonstration fusion reactor by 2060.

Understanding Nuclear Fusion

Core Process - Fusion is a nuclear reaction where two light atomic nuclei combine to form a single, heavier nucleus. This process releases an immense amount of energy and is the same reaction that powers the sun and other stars.

Required Conditions - To initiate fusion, matter must be subjected to extremely high temperatures (over 100 million °C) and pressures, similar to the conditions found in the core of a star.

Fusion Techniques -

Inertial Confinement - This method uses powerful lasers or X-rays to rapidly compress and heat small fuel capsules, triggering fusion.

Magnetic Confinement - This technique utilizes strong magnetic fields to contain and control the superheated, ionized gas (plasma), preventing it from touching the reactor walls. India's participation in the international ITER project in France focuses on this method, specifically using a tokamak design.

Comparison - Nuclear Fission vs. Nuclear Fusion

Feature	Nuclear Fission	Nuclear Fusion
Process	Splits a single heavy nucleus (e.g., Uranium) into smaller nuclei.	Combines (fuses) two light nuclei (e.g., Hydrogen isotopes) into a heavier one.
Energy Release	Releases a large amount of energy.	Releases significantly more energy per unit of mass than fission.
Radioactive Waste	Produces a significant amount of long-lived, highly radioactive waste.	Produces far less radioactive waste, and its radioactivity decays much faster.
Fuel Source	Relies on finite resources like Uranium.	Uses abundant isotopes of hydrogen, like deuterium (found in water).
Safety	Carries a risk of meltdown and uncontrolled chain reactions.	Inherently safer, as any disruption causes the plasma to cool and the reaction to stop.

Challenges in Achieving Commercial Fusion Energy

Extreme Temperature - Heating plasma to millions of degrees Celsius and sustaining that temperature is a monumental engineering challenge.

Sustained Reaction - Confining the unstable, superheated plasma for long enough to generate net positive energy is extremely difficult.

High Initial Costs - The research, development, and construction of fusion reactors require billions of dollars in investment.

No Commercial Viability Yet - Despite decades of research, no fusion experiment has successfully generated more energy than it consumes over a sustained period to produce electricity for the grid.

India's Proposed Fusion Roadmap

SST-Bharat (Steady-state Superconducting Tokamak-Bharat) -

Overview - This proposed reactor will function as a fusion–fission hybrid. It represents a crucial step in India's journey towards pure fusion power.

Projected Output - It is designed to produce an output-to-input power ratio of 5. The total power will come from two sources - 100 MW from fission and 30 MW from fusion.

Estimated Cost - The project is estimated to cost ₹25,000 crore.

Long-Term Goal (by 2060) - The roadmap aims for the commissioning of a full-scale demonstration fusion reactor (DEMO) by 2060. This reactor is targeted to have a power ratio (Q value) of 20, which is considered commercially viable, with a total power output of 250 MW.

India's Current Capability - The SST-1 tokamak at IPR has successfully sustained plasma for about 650 milliseconds. It is being upgraded to reach a target of 16 minutes. For comparison, the WEST tokamak in France set a global record in February 2025 by maintaining plasma for 22 minutes.

Key Technology - The Tokamak

Definition - A tokamak is a device that uses a powerful magnetic field to confine plasma in the shape of a torus (donut). It is the leading design for magnetic confinement fusion research.

Working Principle -

1. A vacuum chamber is created in the donut-shaped vessel.
2. Hydrogen isotopes like deuterium and tritium are injected and heated to extreme temperatures, forming a plasma.
3. Powerful superconducting magnets generate a toroidal magnetic field that confines the plasma, keeping it away from the reactor's walls.
4. As the plasma is heated further, the nuclei overcome their repulsion and fuse, forming helium and releasing enormous energy in the form of neutrons.

Innovations Proposed in India's Roadmap

Digital Twins - Creating highly detailed virtual replicas of a tokamak to simulate real-time plasma behavior. This allows researchers to test designs and predict outcomes without costly physical experiments.

Machine Learning (ML) Integration - Using ML algorithms to improve plasma confinement, predict instabilities, and enhance the overall control and stability of fusion reactions.

Radiation-Resistant Materials - A strong focus on developing advanced materials that can withstand the intense neutron radiation produced inside a fusion reactor, which is crucial for durability and safety.

Advanced Superconducting Magnets - Developing next-generation magnets and sophisticated plasma modeling techniques to improve the efficiency and reliability of the fusion process.

Key Hurdles and Strategic Value

Primary Challenges -

Technical - Achieving stable, long-duration plasma confinement and scaling up the technology to commercial levels.

Economic - The high estimated cost and R&D expenses make funding a major challenge.

Policy & Funding - India's efforts are largely public-sector-driven, lacking the private-sector dynamism seen in the US. Fusion research also competes for funding with prioritized renewables like solar and wind.

Strategic Value of Fusion R&D -

Technological Spin-offs - Research drives innovation in materials science, magnet technology, AI, and high-temperature engineering.

Industrial Upgradation - These advancements can significantly boost India's domestic industrial capabilities and technological self-reliance.

Global Partnerships - Participation in projects like ITER provides access to global expertise and cutting-edge technology.

The Way Forward

1. **Increase Investment** - India needs to significantly enhance funding for fusion research to match its ambitious goals.
2. **Foster Private Sector Role** - Create policies to encourage private industry and start-ups to participate and invest in the fusion ecosystem.
3. **Strengthen Global Collaboration** - Actively partner with advanced programs in the UK (STEP) and China (EAST) for technology sharing and joint research.
4. **Align with National Goals** - Integrate fusion R&D into India's broader energy security and net-zero strategy, ensuring it complements renewable and fission power.
5. **Develop Human Capital** - Invest in specialized training programs and international fellowships to build a skilled workforce in plasma physics, materials science, and nuclear engineering.

Source - https - //www.thehindu.com/sci-tech/science/ipr-gandhinagar-team-proposes-roadmap-for-indias-fusion-power-plans/article70083807.ece# - ~ - text=Researchers%20at%20