India’s Roadmap for Fusion Power

For Prelims: **Nuclear fusion**, **Difference between Nuclear Fusion & Nuclear Fission.**

For Mains: Strategic significance of fusion research for India’s technological autonomy,

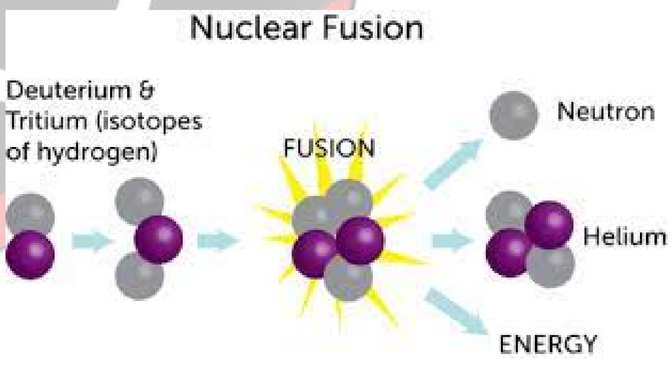
Source:TH

Why in News?

Researchers at the **Institute for Plasma Research (IPR), Gandhinagar,** proposes a **roadmap for India’s** **fusion power**, focusing on the development of the **Steady-state Superconducting Tokamak-Bharat (SST-Bharat)** reactor, marking a major step in **India’s energy strategy.**

What is Fusion?

- **About:** Fusion is the process where **two small, light atoms** (like hydrogen isotopes) come together to form **a bigger, heavier atom**, releasing vast amounts of **energy.** This is the energy process that powers the Sun and stars.
    - For example, in the Sun, **hydrogen nuclei fuse to form helium** and release energy in the form of light and heat.
- **Energy Release**: The fusion of nuclei releases energy because the fused product **has less mass than the sum of the individual atoms.** This "lost" mass, known as the **mass defect,** is converted into **energy** according to **Einstein's theory of special relativity ($E=mc^2$).**



- **Conditions for Fusion**:
    - **High Temperature**: Around **100 million°C**.
    - **High Pressure**: Forces atoms nuclei close enough to fuse.
    - **Plasma**: The material is in a high-energy state where atoms are broken into ions and electrons.
- **Tokamaks**: A tokamak is a **fusion reactor** that uses **magnetic fields** to confine and **control plasma** within a **doughnut-shaped vessel**. Its effectiveness is measured by how long it **can hold the plasma without dissipation**.

- Longer confinement times bring reactors closer to achieving continuous and reliable fusion reactions.
- **Q Value (Energy Gain Factor)**: The **Q value** measures the **efficiency** of a fusion reactor.
  - It is the ratio of **output energy to input energy**. A **Q value > 1** means the reactor produces more energy than it consumes.
- **Fusion vs Fission:** Fission is the process used in nuclear reactors. In fission, a **heavy nucleus (like uranium) splits into smaller nuclei,** releasing energy.
  - Fusion, on the other hand, combines lighter nuclei to release energy. Fusion produces **much less radioactive waste than fission,** making it a more **attractive option for clean energy.**

	Fission	Fusion
Definition	Fission is the splitting of a large atom into two or more smaller ones.	Fusion is the fusing of two or more lighter atoms into a larger one.
Occurrence	Fission reaction does not normally occur in nature.	Fusion occurs in stars, such as the sun.
Energy Requirement	Takes little energy to split two atoms in a fission reaction.	Extremely high energy is required to bring two or more protons.
Energy Released	The energy released by fission is a million times greater than that released in chemical reactions, but lower than the energy released by nuclear fusion.	The Energy released by fusion is three to four times greater than the energy released by fission.
Energy production	Fission is used in nuclear power plants.	Fusion is an experimental technology for producing power.

What is India's Roadmap for Fusion Power?

- **India's Current Fusion Capabilities**: India's **Steady State Superconducting Tokamak (SST-1)** at IPR has achieved **plasma confinement for 650 milliseconds** (and it's designed to go up to 16 minutes), however it is **not designed for electricity generation** but serves as an experimental base.
  - India is already part of the **International Thermonuclear Experimental Reactor (ITER)** project in France, the world's largest fusion experiment using magnetic confinement techniques. ITER aims to achieve a **Q value of 10**.
- **SST-Bharat: SST-Bharat is planned as the next step beyond experiments, aimed at producing actual electricity.**
  - The SST-Bharat Vision aims to initially build a 130 MW **fusion-fission hybrid reactor with a Q value of 5.**
  - The team plans to commission a full-scale demonstration reactor by 2060, targeting an ambitious **output-to-input power ratio (Q) of 20** and generating 250 MW.
- **Technology Measures:**
  - **Digital twins:** Virtual replicas of tokamaks to simulate conditions and test designs.
  - **Machine learning:** Leveraging artificial intelligence and machine learning helps in predicting and managing plasma behavior, crucial for better plasma confinement.
  - **Development of Radiation-Resistant Materials:** Focus on designing materials that can withstand the extreme radiation levels in fusion reactors.
  - **Superconducting Magnets:** Research into high-performance superconducting magnets

to create stronger magnetic fields for better plasma confinement.

Global Advances in Fusion Power

- **United Kingdom:** UK STEP programme aims for a prototype fusion power plant by 2040.
- **US**: Several private firms claim they will deliver grid-connected fusion power in the 2030s.
- **China**: China's Experimental Advanced Superconducting Tokamak (EAST) tokamak has already set records for plasma holding duration (for about 1,066 seconds).

What are the Challenges for India's Roadmap for Fusion Power?

- **High Costs**: Fusion research requires significant investment in advanced technology, infrastructure, and reactors, putting pressure on India's public-sector budget.
- **Long Development Timeline**: India's target of **2060** for a fusion reactor is slower compared to global efforts, making the path to commercialization longer.
  - Countries like **China** and the **US** are progressing faster with fusion, putting pressure on India to keep pace.
- **Limited Private Sector Involvement**: Unlike the **US** and **EU**, India's private sector plays a smaller role in fusion research, slowing innovation and progress.
- **Technological Hurdles**: Challenges include **plasma containment**, achieving the necessary **energy gain (Q value)**, and developing **radiation-resistant materials**, which complicate fusion's realization.
- **Competition with Other Energy Sources**: Fusion competes with **solar, wind**, and **nuclear fission**, while India's broader energy commitments, such as **net-zero by 2070**, may divert focus.
- **Uncertain Commercial Viability**: Even if fusion succeeds, its **cost-effectiveness** compared to existing energy sources remains uncertain.

How can India Ensure Strategic Gains from Investing in Fusion Power R&D?

- **Policy and Funding Support**: Allocate **long-term, mission-mode funding**, akin to ISRO or nuclear fission missions.
  - Involve **private-sector partnerships**, especially in advanced materials, AI, and digital simulations.
- **Global Collaborations**: Expand engagements beyond ITER, include **bilateral partnerships** with fusion labs in the US, UK, and EU.
  - Participate in international **fusion data sharing** initiatives and **joint training** of Indian scientists.
- **Realistic Targeting**: Fusion energy should be seen as a **strategic R&D frontier**, not a near-term energy source.
  - Align milestones with global benchmarks but **prioritize indigenous innovation** and technology localization.
- **Leveraging Fusion R&D for Broader Advancements: Use fusion research to enhance capabilities in superconducting materials, radiation shielding, plasma control, and AI-driven simulations.**
  - Strengthen India's independence in key sectors like defense and space technology through innovations from fusion research.

Conclusion

India's fusion roadmap is ambitious but cautious, aiming for a **2060 demonstration plant** while the UK, US, and China target earlier prototypes. Though costly and uncertain, it could yield **valuable technological and strategic gains** for India's energy future.

Drishti Mains Question:

Q. Fusion power is often described as the 'holy grail' of clean energy. Critically analyze the opportunities and challenges of adopting fusion in India's energy mix.

UPSC Civil Services Examination, Previous Year Questions (PYQs)

Prelims

Q. The function of heavy water in a nuclear reactor is to (2011)

(a) Slow down the speed of neutrons

(b) Increase the speed of neutrons

(c) Cool down the reactor

(d) Stop the nuclear reaction

Ans: (a)

Mains

Q. With growing energy needs should India keep on expanding its nuclear energy programme? Discuss the facts and fears associated with nuclear energy. (2018)