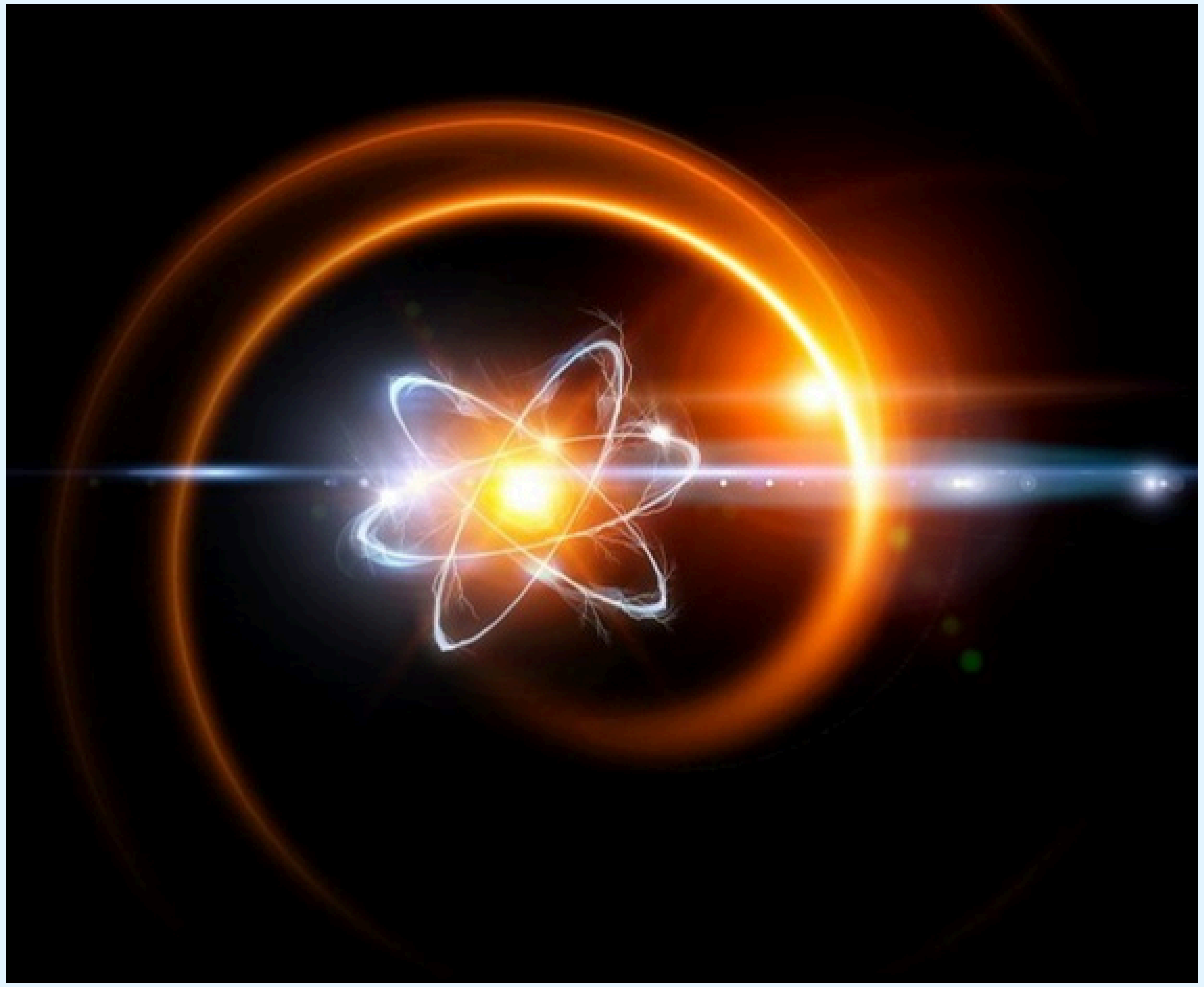


Thermonuclear Reactors

What is thermonuclear fusion?

Nuclear Fusion is the process of combining (or fusing) two light atomic nuclei to form a heavier one, which releases energy

Key points:

- It occurs naturally in stars, including our sun
- Involves isotopes of hydrogen, like deuterium and tritium
- Cleaner than fission: no greenhouse gases, minimal radioactive waste
- Requires extremely high temperatures (over 100 million °C) to overcome the repulsion between nuclei

Scientific Principles

1. Fusion of Light Nuclei

Two light nuclei (like deuterium & tritium) combine to form a heavier nucleus.

2. Overcoming Electrostatic Repulsion

Nuclei naturally repel each other. Fusion needs extreme heat and pressure to push them together.

3. High Temperature = High Kinetic Energy

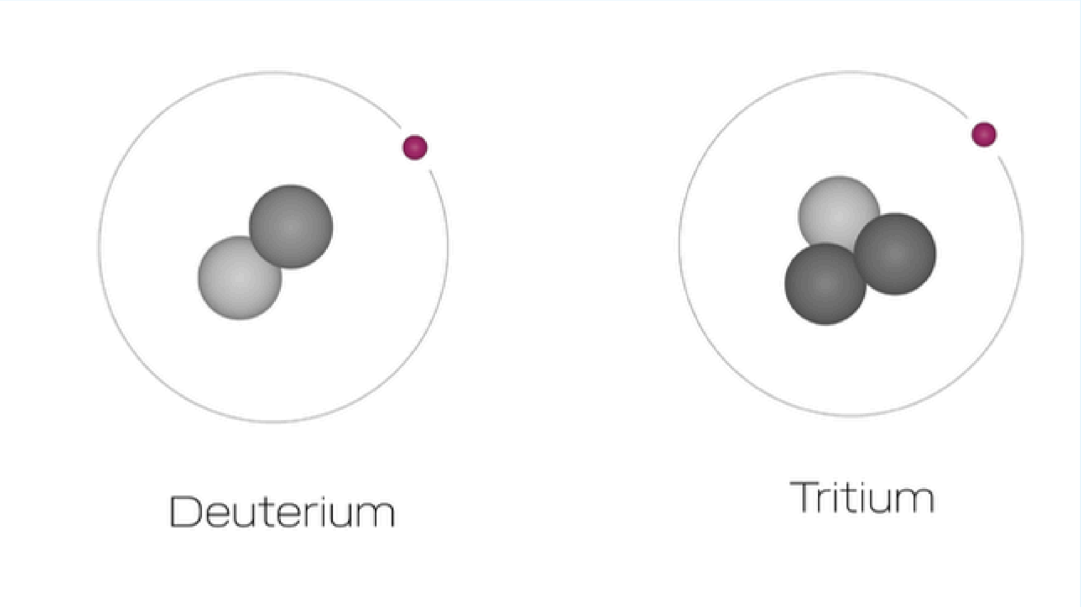
At over 100 million °C, particles move fast enough to overcome repulsion and fuse.

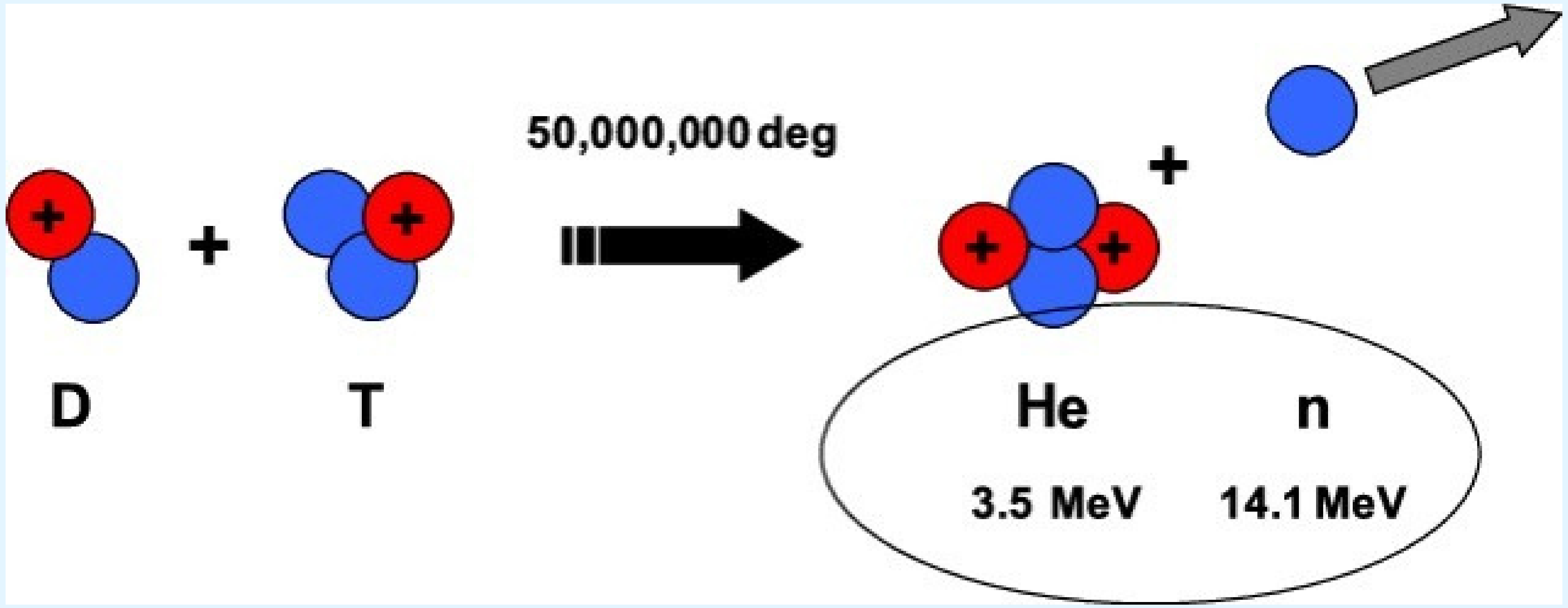
4. Plasma State

At these temperatures, matter becomes plasma — a hot, charged gas controlled by magnetic fields in reactors.

The D-T Fusion Reaction

In this process, two hydrogen isotopes—deuterium and tritium—are fused together.





1 proton & 1 neutron
Can be easily extracted from seawater

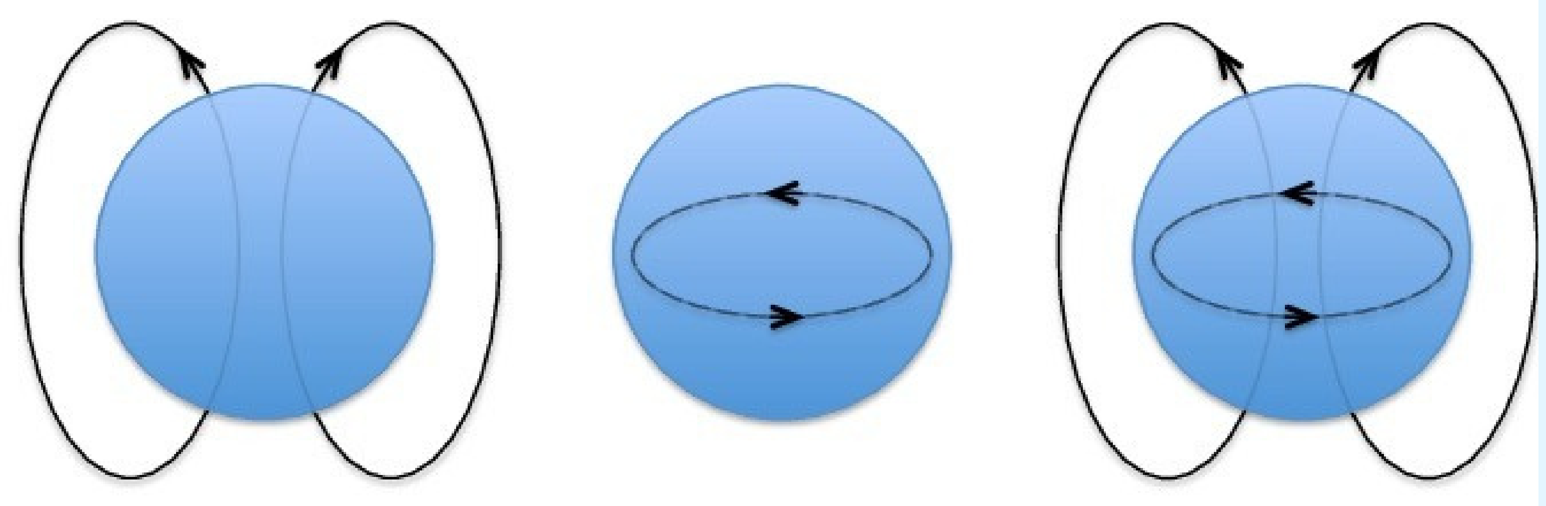
1 proton & 2 neutrons
Rarer in nature
Produced inside the reactor using lithium

- Collisions at extremely high temperatures
- They overcome their natural repulsion and fuse
- Creates a helium nucleus and a high-energy neutron
- The helium stays safely contained in the plasma, but the neutron escapes the magnetic field and carries most of the energy released.

Magnetic Confinement

Plasma can reach temperatures of over 150 million °C.
No material can withstand these conditions, so strong magnetic fields are used to contain the plasma without making contact with the reactor walls.

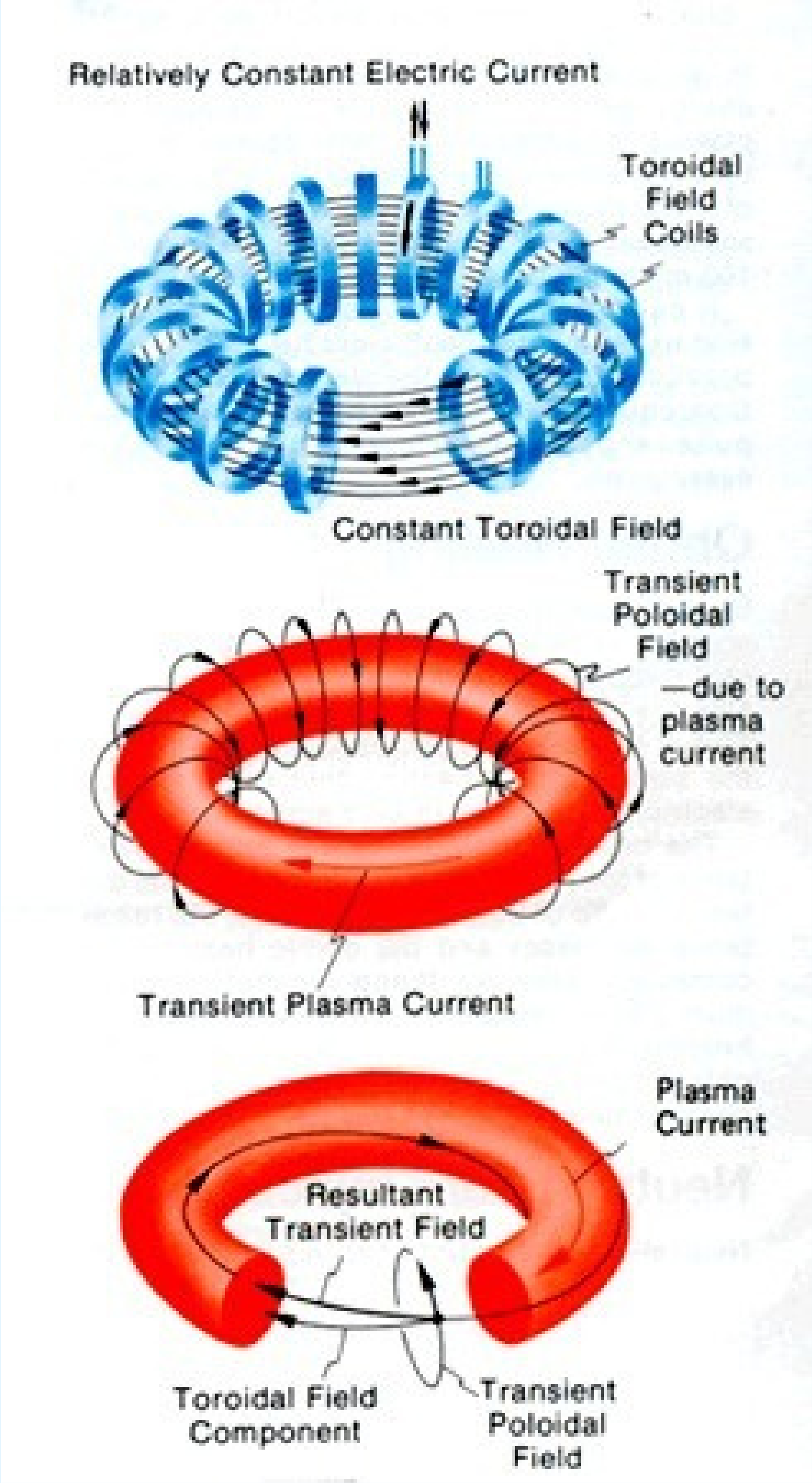
Tokamak Fusion Reactor - uses a doughnut-shaped toroidal chamber where the magnetic field is guided and trapped in a closed loop. It relies on two magnetic fields to work together:
.



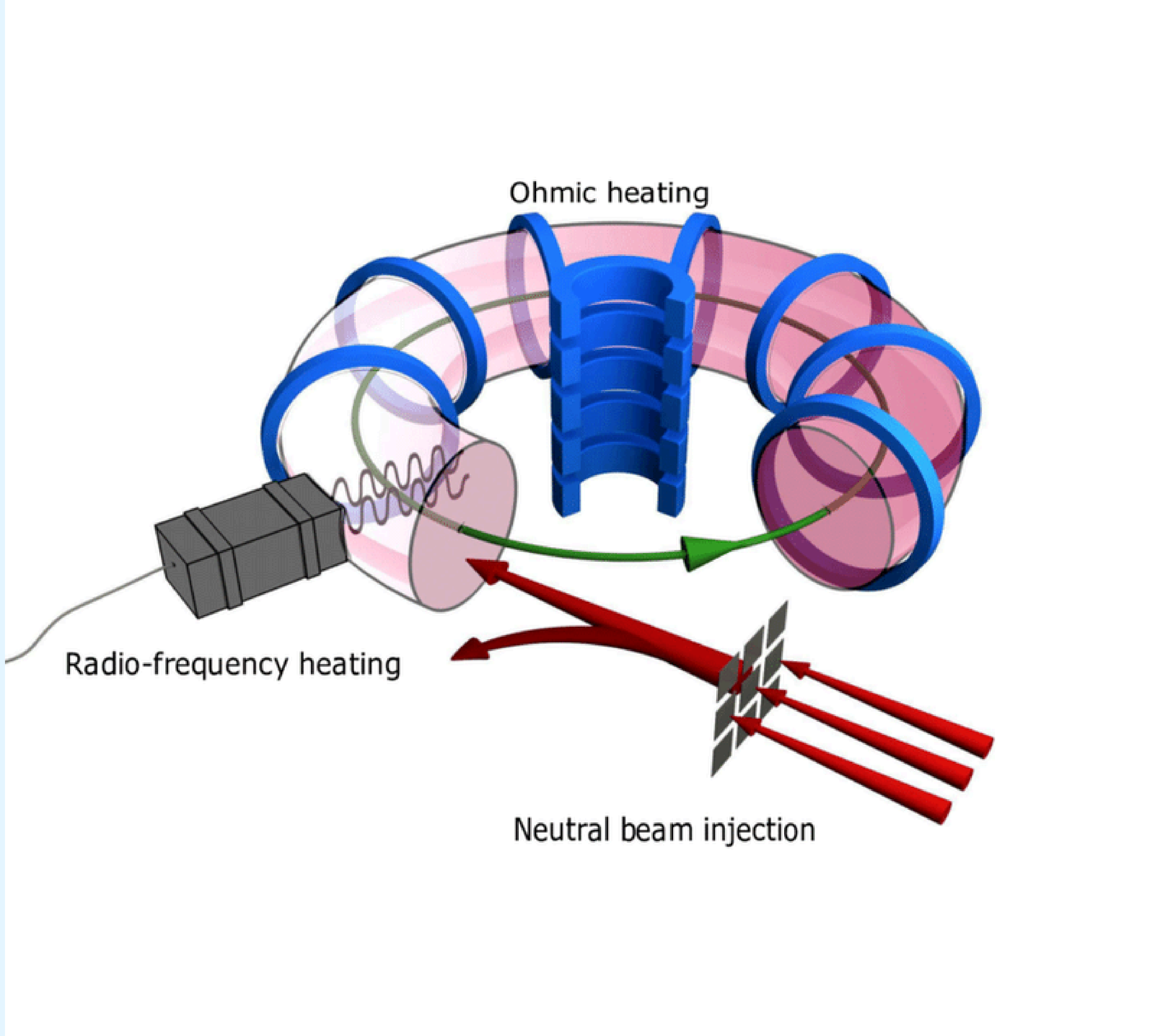
Poloidal magnetic fields
The electric current inside of the plasma generates fields that loop around the cross section

Toroidal magnetic fields
The field is created by coils surrounding the vessel and wrap the plasma around

Both fields join to form a **Helical Magnetic Field** to stabilise the plasma



Heating Mechanisms



The temperatures required for fusion to occur are over 10 times hotter than the core of the Sun.

How do we recreate the conditions of the sun on earth?

Ohmic Heating

An electric current is passed through the plasma, creating internal resistance, which is what generates heat.

Neutral Beam Injection (NBI)

High-energy neutral atoms are injected into high-speed plasma. These atoms collide, and the collision and ionise, confining them in the magnetic field. The collisions transfer energy, heating the plasma.

Radio Frequency (RF) Heating

High-frequency electromagnetic waves are sent into the reactor in waves that match the natural movements of the particles so they absorb energy from the waves, causing them to move faster and heat the plasma.

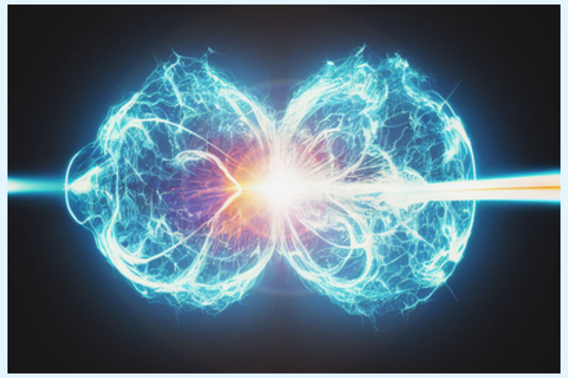
Energy Extraction and Conversion

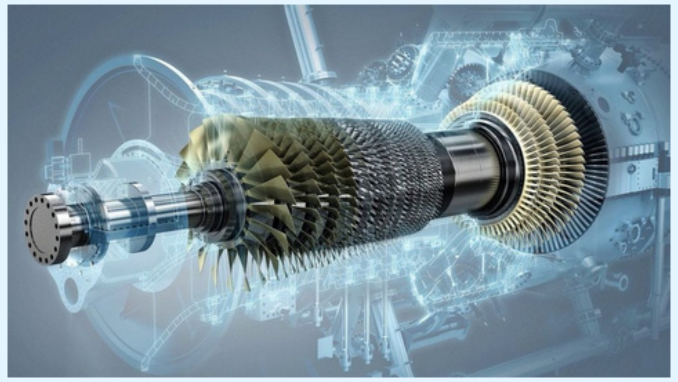
How does energy extraction work in practice?

Step 1
Fusion in the plasma core creates fast neutrons and helium. Neutrons carry most of the energy

Step 2
Neutrons escape the magnetic field and hit the surrounding blanket, converting kinetic energy into heat. (Some neutrons also react with lithium to produce tritium fuel.)

Step 3
Coolants like helium, water, or molten salts absorb the heat and carry it to a heat exchanger.





Step 4
The heat exchanger converts this thermal energy into high-pressure steam.

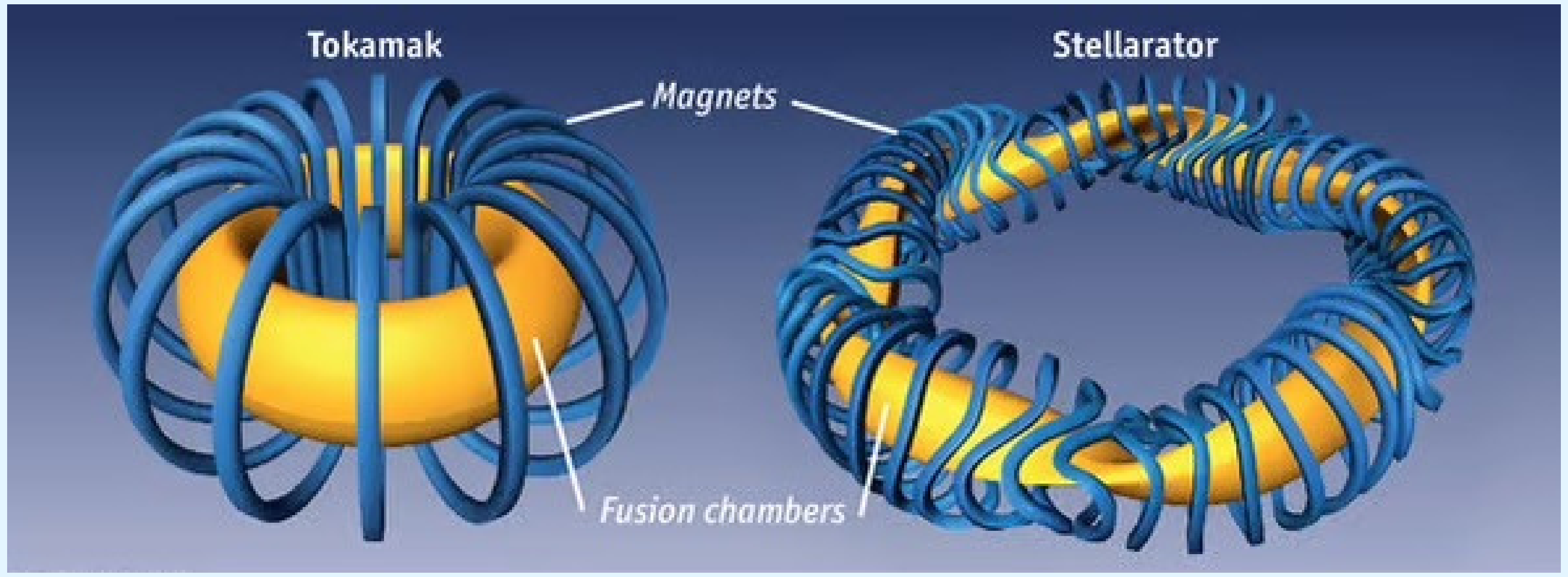
Step 5
Steam drives a turbine, which powers a generator to produce electricity.

Step 6
Electricity enters the grid, completing the cycle from fusion core to usable energy.

Reactor Types

1. Tokamak

. Most researched fusion reactor type
. Uses strong magnetic fields shaped like a donut (torus) to contain hot plasma
 Example: ITER (International Thermonuclear Experimental Reactor)



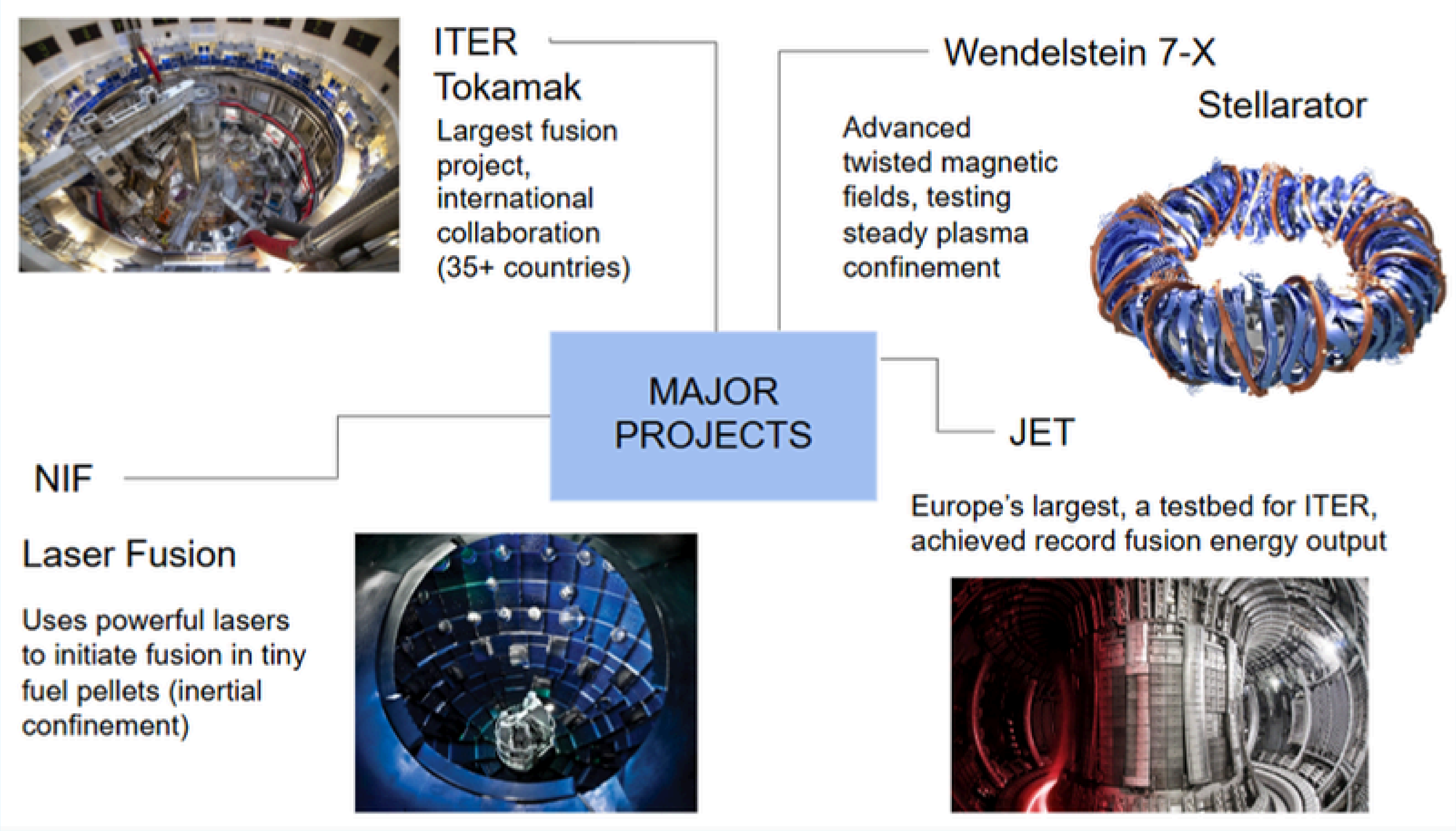
2. Stellarator

. Similar to tokamak but uses twisted magnetic fields to confine plasma more steadily
. Complex design but better for continuous operation

3. Inertial Confinement Fusion (ICF)

. Uses powerful lasers or ion beams to compress tiny fuel pellets, causing fusion
. Experiments done at places like the National Ignition Facility (NIF) in the USA

Major Projects



Advantages and Disadvantages of Thermonuclear Reactors

✅ Good	❌ Bad
Produces no greenhouse gases	Requires extremely high temperatures (100+ million °C)
Creates no long-lived radioactive waste	Plasma is unstable and hard to control
Massive energy potential from small amounts of fuel	Very expensive and complex to build and operate
No meltdown risk – reaction shuts down if unstable	Long time before it may become commercially available

Global Significance

Clean Energy for the Planet
Helps fight climate change and reduce our dependence on oil, coal, and gas.

Limitless Energy Supply
Fuel comes from seawater and lithium, which are abundant worldwide.

International Collaboration
Huge global projects like ITER (France) involve over 35 countries working together.

Future Outlook

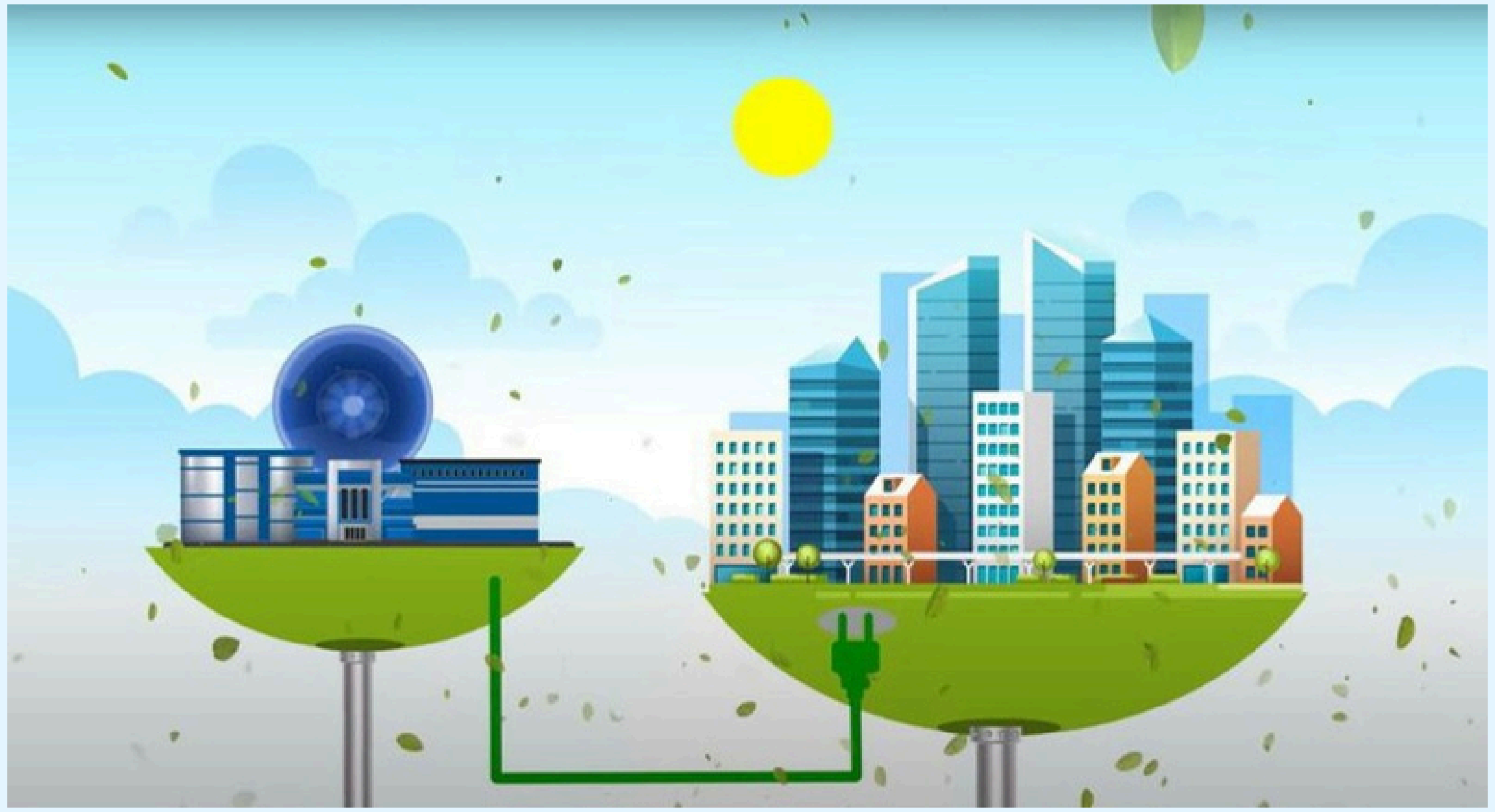
- **Smaller, Advanced Reactor Designs**
  - Compact tokamaks with strong magnets (e.g. Tokamak Energy, TAE Technologies)
  - Exploring alternative fuels like Helium-3 and proton-boron (low neutron output)
- **New Materials & Superconductors**
  - Radiation-resistant materials extend reactor lifespan
  - High-temperature superconductors enable stronger, more efficient magnets
- **AI & Real-Time Plasma Control**
  - AI uses sensors to stabilize unstable plasma in real time
  - Enables faster, more precise adjustments than traditional control systems
- **Commercialisation & Private Sector**
  - Companies like CFS and Helion accelerating fusion timelines
  - Commercial reactors possible within the next 10–20 years

Conclusion

Clean & Abundant
Fusion offers zero emissions and uses widely available fuels like deuterium.

Low Waste
Produces far less radioactive waste than nuclear fission.

Global Impact
Fusion could power a clean, secure energy future for all.



Challenges Remain
Plasma control, material limits, and high costs still need solving.

Rapid Innovation
AI, superconductors, and compact designs are driving progress.

Ethical Focus
Development must be safe, fair, and globally accessible.