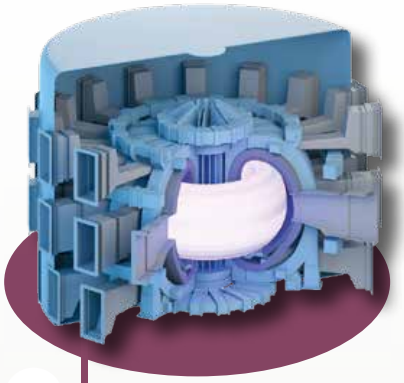
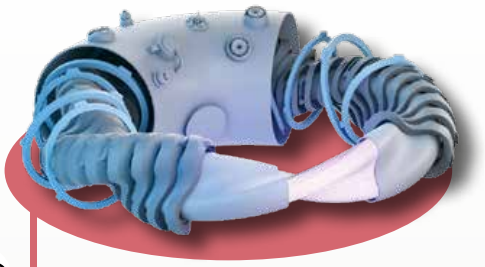


TOKAMAK
The government-funded JT-60U facility, Asdex Upgrade (an MPG project), and the Iter (under construction), enclose plasma with an external magnetic field in a donut-shaped chamber and heat it externally.



ADVANCED STELLARATOR
A coiled magnetic field encloses plasma in a similarly shaped container, such as the one used in the Wendelstein 7-X. The heating is done externally.

PATHWAYS TO A FUSION POWER PLANT

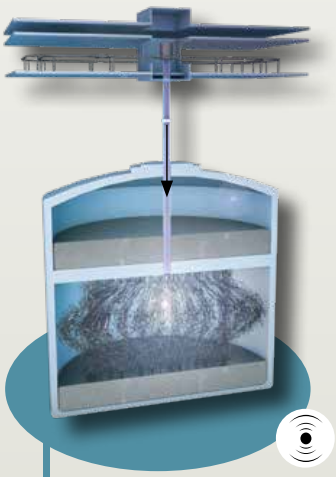
Nuclear fusion occurs when the nuclei of lighter atoms, usually hydrogen, fuse to form heavier ones such as helium, releasing energy in the process. Fusion powers the Sun, but on Earth, the process can only be simulated in plasma at temperatures exceeding a hundred million degrees. No material can withstand such heat. As a result, research facilities and companies are exploring a variety of concepts for controlling plasma. The Max Planck Institute for Plasma Physics, for example, is researching the tokamak and the stellarator.

CONTINUOUS OPERATION VERSUS PULSE OPERATION

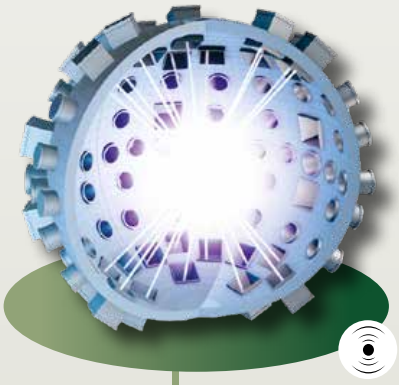
Conventional power plants generate continuous energy. Several fusion concepts likewise provide for continuous operation (∞). In others, nuclear fusion takes place in pulses, or intermittently ((•)). It remains unclear how to trigger successive fusion reactions quickly enough in pulse operation.

∞ **REACTORS IN CONTINUOUS OPERATION**

(•) **PULSED REACTORS**

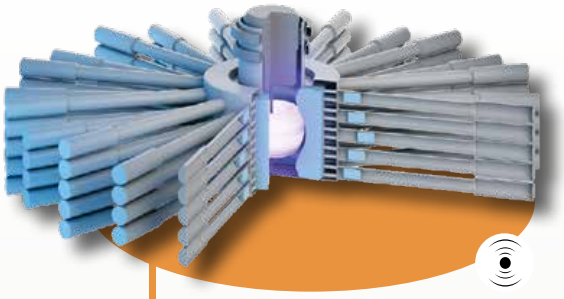


PROJECTILE FUSION
The spin-off First Light Fusion drops a capsule of fusion fuel into a reaction chamber and shoots it with a metal projectile. The impact generates shock waves in the capsule, compressing and igniting the fuel.

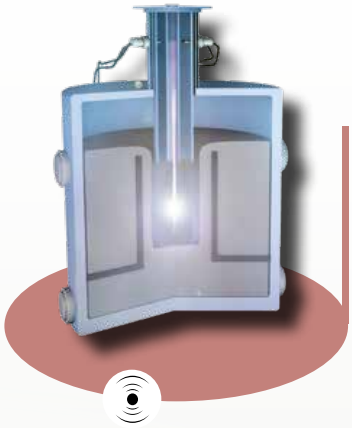


LASER FUSION
Powerful lasers condense and heat plasma in the center. In indirect operation ●, the lasers cause a metal ball to produce X-rays, which heat and compress the fuel inside. As a result, the US research facility NIF was able to generate more fusion energy than it invested in laser energy. In this way, it has spent decades researching the processes involved in the hydrogen bomb. In direct operation ●, a capsule with the fuel is shot directly, causing it to implode.

INFOGRAPHIC: P. BALL, THE RACE TO FUSION ENERGY, NATURE, VOLUME 599 ISSUE 7886, 25 NOVEMBER 2021; GCO ACCORDING TO NIF, ZAP ENERGY AND FIRST LIGHT FUSION



TOKAMAK WITH EXTERNAL COMPRESSION
General Fusion generates a tokamak plasma in a container made of rotating liquid metal, which is compressed and heated with pistons until it ignites.



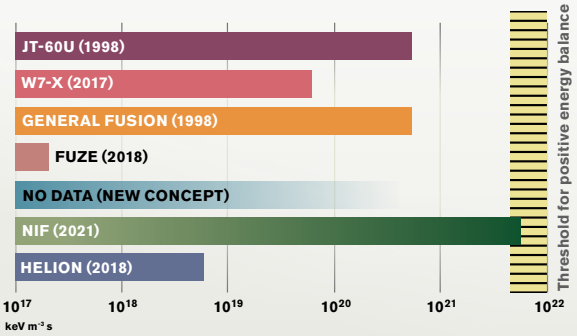
STABILIZED Z-PINCH
The startup Zap Energy generates a thin plasma tube between two electrodes with current flowing through it. The current creates a cylindrical magnetic field around the tube, which compresses and heats the plasma to extreme levels.

STATE OF DEVELOPMENT

Three criteria give a rough assessment of how much progress is being made with each fusion concept:

TRIPLE PRODUCT

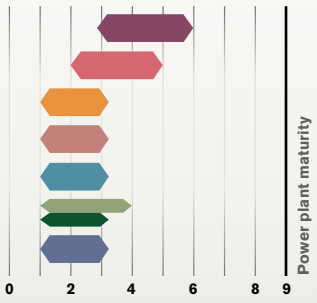
Product of the plasma density, temperature, and how long the temperature can be maintained without heating. The higher the value, the higher the energy yield from the fusion reaction. The vertical bar indicates the threshold at which a positive energy balance is achieved. The threshold values differ slightly depending on the plasma control.



Source: US Department of Energy; doi: 10.1063/5.0083990

STATUS OF POWER PLANT MATURITY

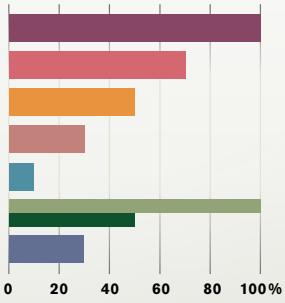
A fusion concept with a physically positive energy balance still faces technical obstacles, for example, the total energy balance of the power plant (energy required for magnets, lasers or heating plasma) or the need for frequent ignitions in the case of pulsed fusion.



Source: Müller & Zohm 2022 (hdl.handle.net/21.11116/0000-000D-EBAF-6); Häfner et al. 2023 (publikationen.bibliothek.kit.edu/1000164488)

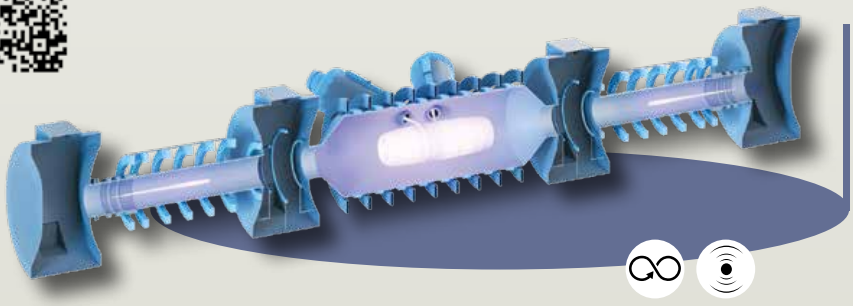
AGREEMENT WITH PIONEER CONCEPTS

Decades of research have been done on tokamaks and stellarators, as well as on laser fusion at the NIF. The more a concept deviates from these established processes, the less clear it is how long the road to a power plant might be.



Source: K. Lackner, IPP

More information on the different concepts for nuclear fusion:



STABILIZED FIELD-REVERSED CONFIGURATION (FRC)
The companies TAE and Helion shoot two plasma packets at each other, causing them to fuse into a hot ellipsoid. This plasma is heated further, either through compression by an external magnetic field or by being enriched with fast particles.