The Race to Fusion Energy

June 2024

Fusion, the process that powers stars like our Sun, promises an inherently **safe**, **near-limitless clean electricity** source for the long term, using small amounts of fuel that can be sourced worldwide from inexpensive materials.

Once realized, fusion energy will be abundant, economic, clean, safe, and globally deployable. Fusion energy will open limitless opportunities for revolutionary advancements in human civilizations.

To put in perspective: all the atomic energy stored in 1g fusion material can power NYC peak demand for 10s, assuming 100% system efficiency.

Source: energysingularity.cn
Inspirations: https://understand-energy.stanford.edu/energy-resources/nuclear-energy/nuclear-fusion

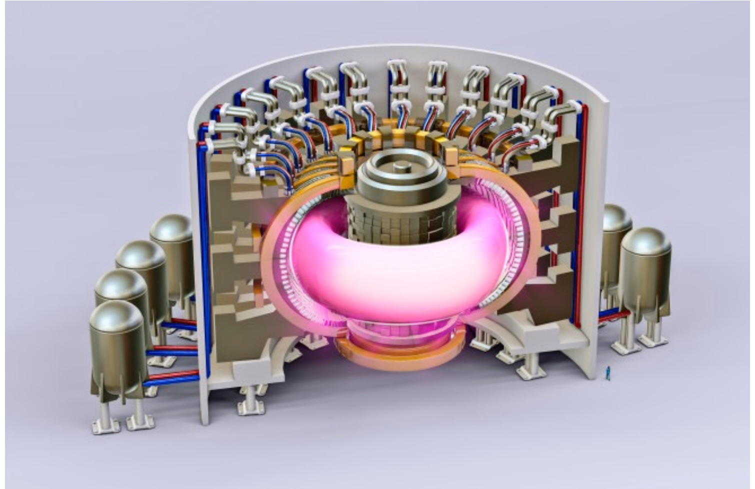
Summary

A few words on fusion technology

The science is well understood
- Fusion is conceptualized in the 1920s

There is a popular way of doing things
- **D-T** fusion is the most popular approach
- **Tokamaks** are still the favorite design for startups

Fusion is an engineering challenge
- Startups are racing to design the best reactor for energy generation
- Everyone is building a demo reactor



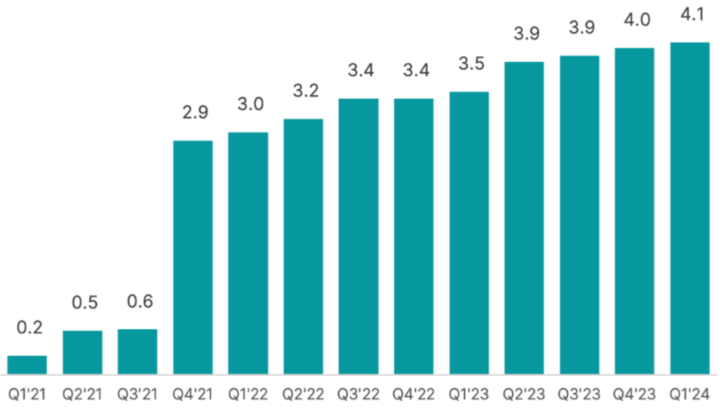
The market and the fusion business

The market is (perhaps overly) optimistic
- Lots of public & private funding (~**$4bn** in the US).
- Demonstrated demand as **AI revolution** unfolds.
- Aggressive timelines for commercialization.

Business models are simple
- Build a commercially reactor, produce electricity
- Sell peripheral technologies or systems

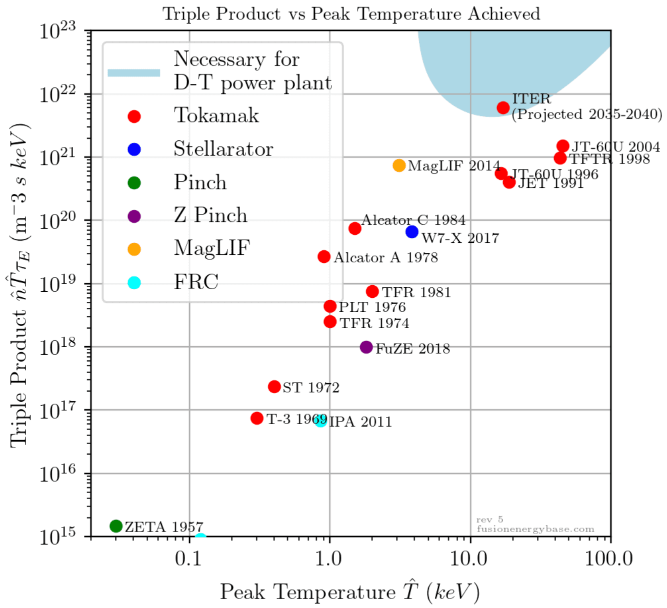
Big economic uncertainty exists
- No one can predict its CAPEX and OPEX yet.

Cumulative investment in nuclear fusion, Q1'20-Q1'24 ($bn)



Questions to ask every fusion startup

Where is your triple product at?
What is your plan to increase Q?



$$Q^* = \frac{Fusion\ Power}{Power\ Injected}$$

Nuclear Fusion History

Brief History of Fusion Energy

Theoretical Foundations & H-bomb

📆**1920s:** Arthur Eddington proposes hydrogen fusion as energy source for stars.

📆**1951:** First H-bomb test demonstrates uncontrolled fusion detonated by the US at Marshall Islands in the Pacific Ocean.

Magnetic Confinement Fusion

📆**1958:** Soviet scientists introduce the Tokamak design.

📆**1968:** T-3 Tokamak achieves significant milestone with temperatures and confinement times.

📆**1970s:** Major tokamak projects like JET (Joint European Torus) and TFTR (Tokamak Fusion Test Reactor) are built.

Inertial Confinement Fusion

📆**1960s:** Concept of inertial confinement fusion (ICF) proposed.

📆**1972:** First successful ICF experiment at Lawrence Livermore National Laboratory.

📆**2000s:** National Ignition Facility (NIF) becomes operational, focusing on achieving ignition.

The present and future

Recent News

📆**November 2021:** Sam Altman invests $375 million into Helion Energy.

📆**December 2022:** Lawrence Livermore National Lab's NIF first achieved net energy gain (a.k.a. ignition).

📆**May 2023:** Microsoft signs PPA with Helion Energy to purchase electricity from Helion's first fusion plant in 2028

📆**2020-2024:** Billions are being poured into fusion…

Is fusion energy forever 50 years away or are we already at the doorstep of infinite clean energy?

Illustration credit: CTVC

Endeavors to pursue fusion energy

50+ countries
Involved in research on plasma physics and nuclear energy technology development

ITER
35 countries collaborating build the world's largest fusion reactor

$4.1 Billion
Cumulative investment in fusion up to Q1'24

9 national labs
Involved in fusion research

50 universities
Conducting fusion research

40+ private companies
In the fusion space

$50 million
Investment from US Government into private ventures

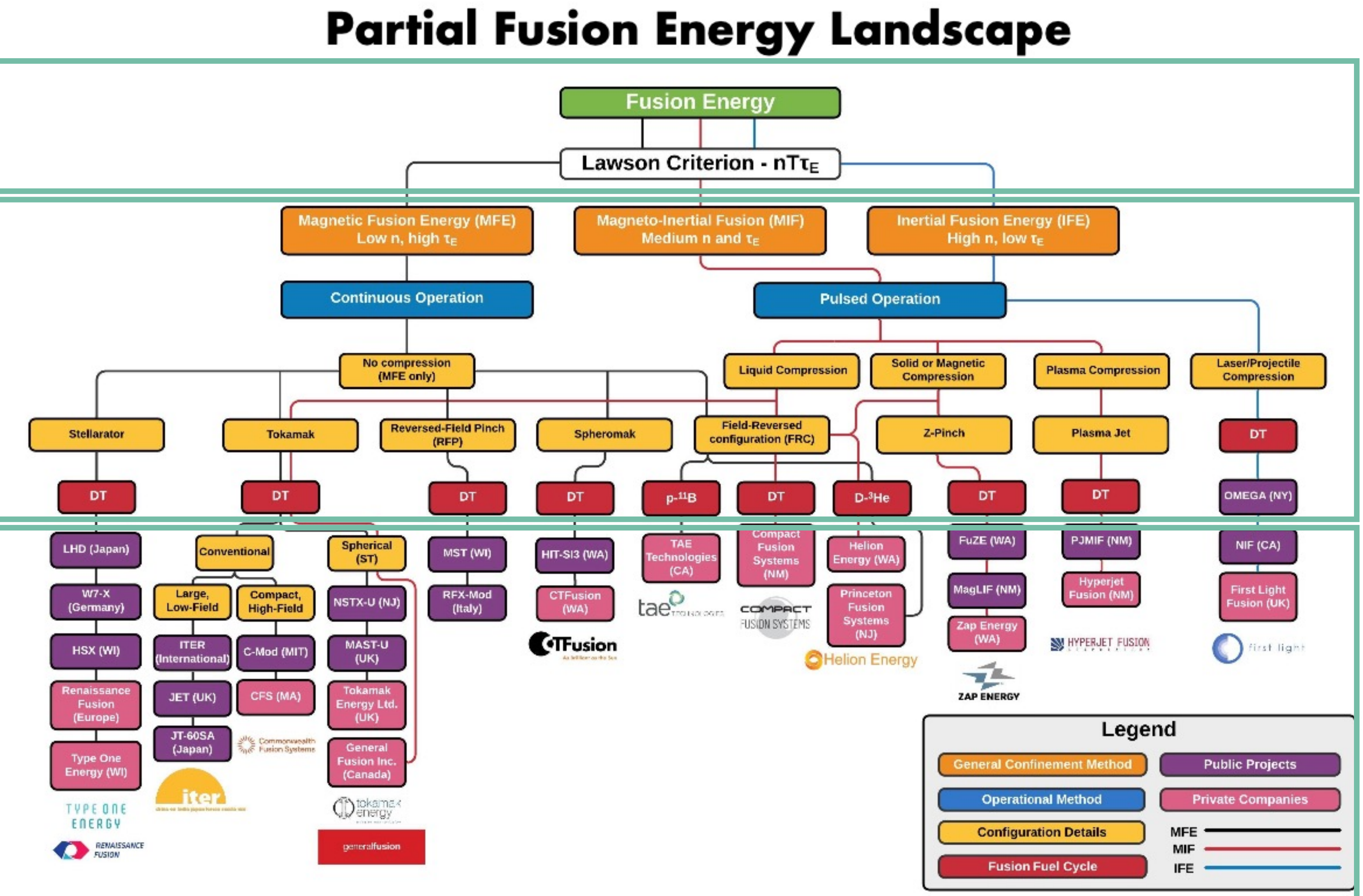
https://understand-energy.stanford.edu/energy-resources/nuclear-energy/nuclear-fusion
https://www.ctvc.co/fusion-powers-ahead-189/

Roadmap

1. The science

2. The engineering

3. The companies



NRC.gov: https://www.nrc.gov/docs/ML2102/ML21026A315.pdf

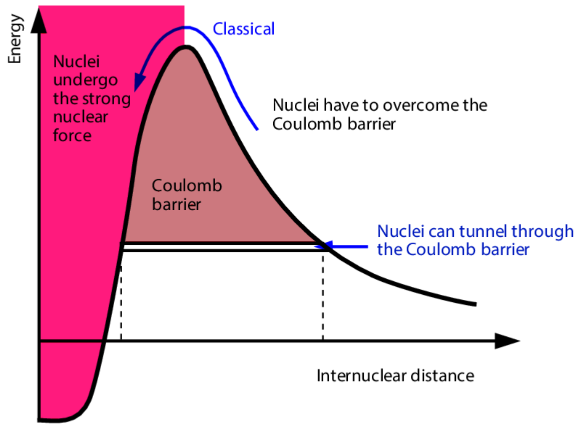
What is Fusion?

Fusion, the process that powers stars like our Sun, promises an inherently **safe**, **near-limitless clean electricity** source for the long term, using small amounts of fuel that can be sourced worldwide from inexpensive materials.

Nuclear Energy	What it is
Fusion	Combining lighter atoms to form a heavier one
Fission	Splitting a heavier atom into lighter ones

Fusion fuel is **abundant** and extremely **energy dense** <insert example>.

However, the most difficult part of fusion is overcoming the electromagnetic force to fuse positively charged protons (aka getting over the coulomb barrier).



Fusion Reactions

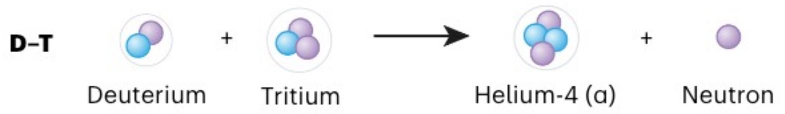
Fuel Mix

Fusion, where?	What reaction(s) typically
In the sun	Proton + proton
On earth	Heavier H isotopes like D, T

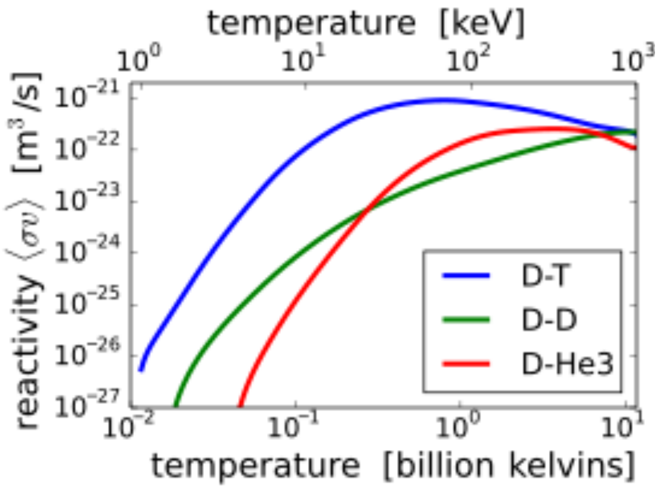
(1)	${}^2_1D + {}^3_1T \to {}^4_2He$ (3.52 MeV) + n^0 (14.06 MeV)		
(2i)	${}^2_1D + {}^2_1D \to {}^3_1T$ (1.01 MeV) + p^+ (3.02 MeV)		50%
(2ii)	$\to {}^3_2He$ (0.82 MeV) + n^0 (2.45 MeV)		50%
(3)	${}^2_1D + {}^3_2He \to {}^4_2He$ (3.6 MeV) + p^+ (14.7 MeV)		
(4)	${}^3_1T + {}^3_1T \to {}^4_2He + 2\,n^0$	+ 11.3 MeV	
(5)	${}^3_2He + {}^3_2He \to {}^4_2He + 2\,p^+$	+ 12.9 MeV	
(6i)	${}^3_2He + {}^3_1T \to {}^4_2He + p^+ + n^0$	+ 12.1 MeV	57%
(6ii)	$\to {}^4_2He$ (4.8 MeV) + ${}^2_1D$ (9.5 MeV)		43%
(7i)	${}^2_1D + {}^6_3Li \to 2\,{}^4_2He$ + 22.4 MeV		
(7ii)	$\to {}^3_2He + {}^4_2He + n^0$	+ 2.56 MeV	
(7iii)	$\to {}^7_3Li + p^+$	+ 5.0 MeV	
(7iv)	$\to {}^7_4Be + n^0$	+ 3.4 MeV	
(8)	$p^+ + {}^6_3Li \to {}^4_2He$ (1.7 MeV) + ${}^3_2He$ (2.3 MeV)		
(9)	${}^3_2He + {}^6_3Li \to 2\,{}^4_2He + p^+$	+ 16.9 MeV	
(10)	$p^+ + {}^{11}_5B \to 3\,{}^4_2He$	+ 8.7 MeV	

Deuterium-Tritium Fusion

Deuterium-Tritium fusion is the **most promising** hydrogen fusion reactions. ${}^2_1D$ can be found in the ocean, and ${}^3_1T$ can be synthesized from Li blankets in the fusion reactor.



Alternative fusion reactions are deuterium-deuterium fusion, deuterium-helium-3 fusion, proton-boron fusion, etc. It also produces a free neutron, which we can use for tritium breeding using a lithium breeder blanket, so the intent is we can produce self-sustaining tritium within the chamber.



D-T fusion has the largest reactivity (reaction cross section/probability) due to fewer nuclei, higher reactivity at lower conditions, higher energy output

It takes a few steps for a fusion plant to keep the lights on…

$$Q^* = \frac{Fusion\ Power}{Power\ Injected}$$

Steps to produce endless energy in a fusion plant

Energy Gain Factor

Initial Fusion Reaction

$Q^* \geq 0$

Inject fuel, heat up fuel.

Goal: Achieve extremely high **temperature** (*100 million Kelvin*) and **pressure** (*20 billion atm*) to supercharge the internal energy of atoms in the fusion fuel, creating a **fusion plasma**.

Why: to bring atomic nuclei so close that they penetrate **the coulomb barrier**, produce **strong interaction force**, and therefore, release a large amount of energy (ΔE).

Net Energy Gain

$Q^* \geq 1$

Energy output from fusion exceeds the energy input ($Q^* \geq 1$), as described by the **Lawson Criterion**, which compares the rate of energy generation vs dissipation via radiation and conduction; it is a triple product of high **pressure** (ensure plasma density), **temperature** (more energy), and high **confinement time** (τ_E, time for which plasma retains energy before losing it to the surroundings) dictate if the **rate of fusion energy gain surpasses the rate of energy dissipation** via radiation and conduction.

$$\text{Pressure} \times \text{Temperature} \times \text{Confinement Time}$$

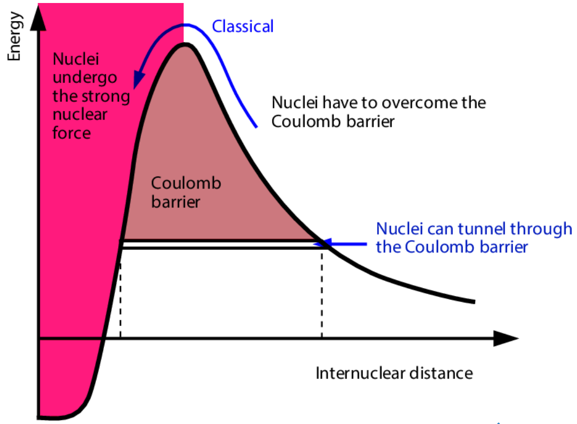
Self Sustaining/Ignition

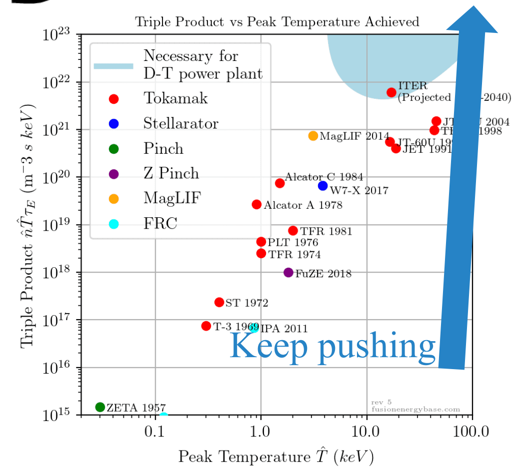
$Q^* \gg 1$

$Q > 5$[1]

After achieving net energy gain, self-sustaining reaction requires fusion to produce more energy than (1) energy dissipation and (2) energy required to maintain Lawson Criterion.

Specifically, we could manipulate (1) temperature (RF heating, ECRH, NBI), (2) density (control injection rate and location), (3) increase energy confinement time, (4) alpha particle self heating, etc.





Do we need self sustaining reactions in IC

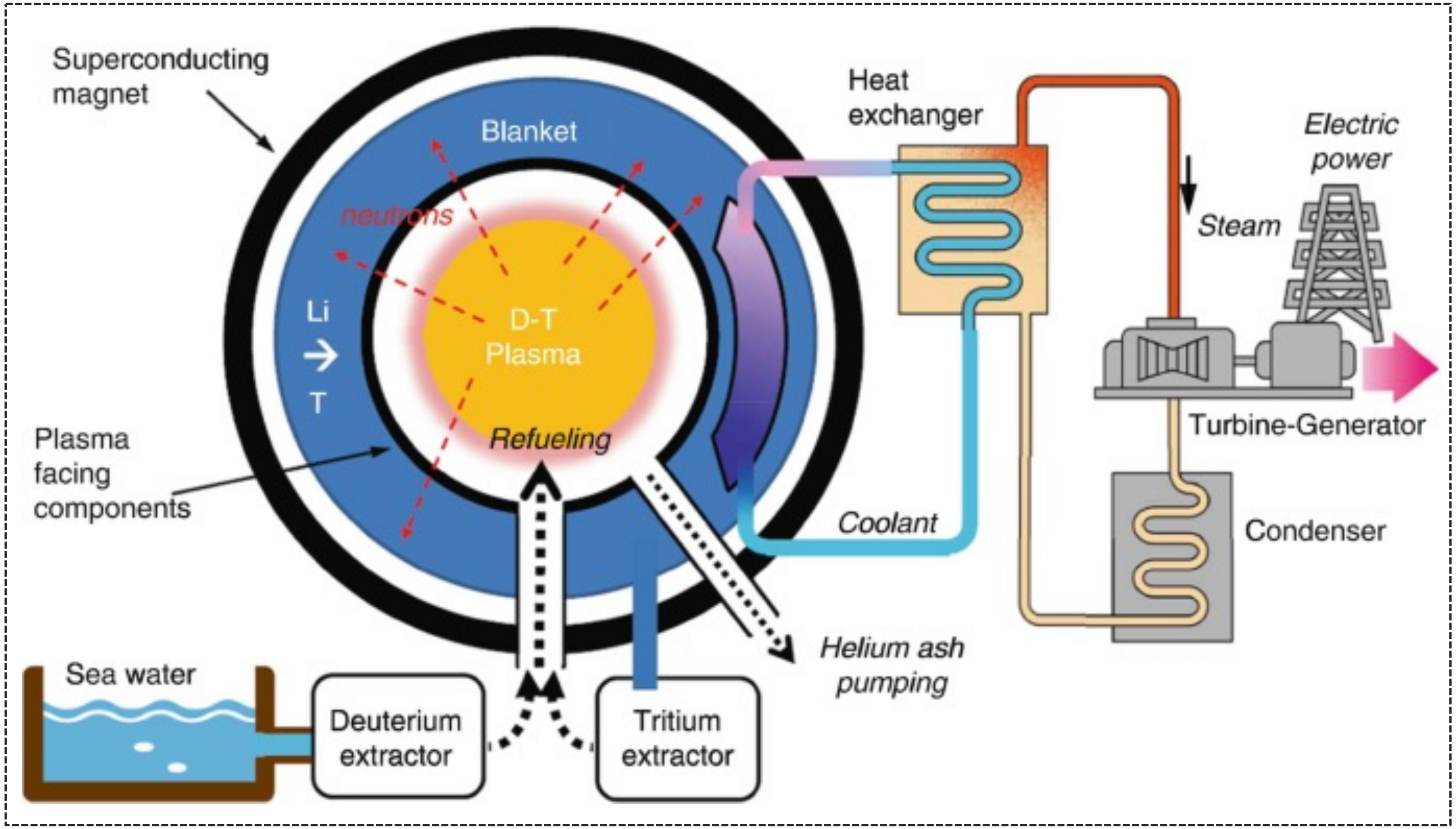
Is pulse generation ICF specific, and conti generation MCF specific?

To further increase Q, do we need to furthe energy in system?

*Q = fusion power out/power injected

[1] Fusion: The Energy of the Universe

Fusion Reactor Archetype & Key Metrics



A spectrum of reactor attempts will optimize different factors of the **Lawson Criteria**:
Pressure × Temperature × Confinement Time

What systems are here, generally

- Fusion fuel cycle system
- Reactor chamber
- Thermal cycle

Fusion Energy "Breakevens"

Terms	What it means
Scientific Breakeven	$Q^* \geq 0$
Engineering breakeven	Fusion power can self-power the reactor system.
Economic Breakeven	In addition to above, fusion power plant can sell electricity to the grid.

Reactors aim to "confine" the fusion plasma to achieve self-sustaining reactions upon ignition; there two extremes of approaches: MCF and ICF

Optimizing | Pressure × Temperature × Confinement Time | Pressure × Temperature × Confinement Time

Magnetic Confinement Fusion (MCF)

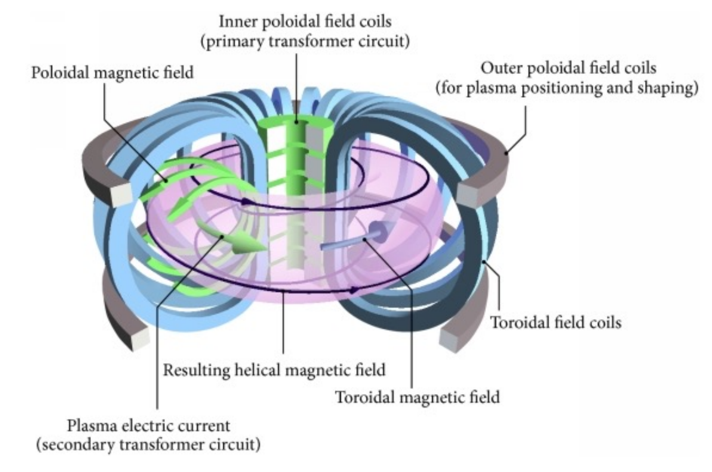
Specialized configurations of magnetic fields confine charged particles in the burning plasma

Inertia Confinement Fusion (ICF)

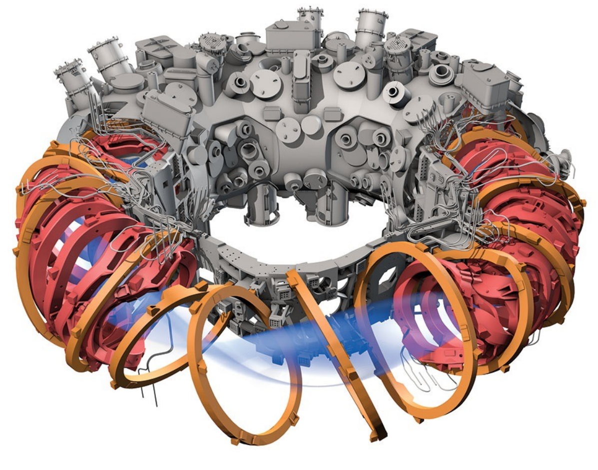
An impulsive laser burn while the fuel is confined by its own inertia

Common Approaches

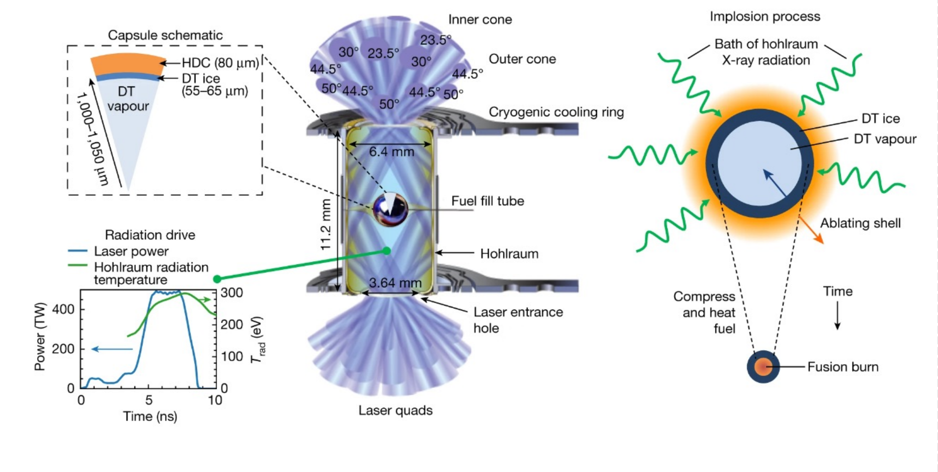
Tokamak Engines



Stellarator



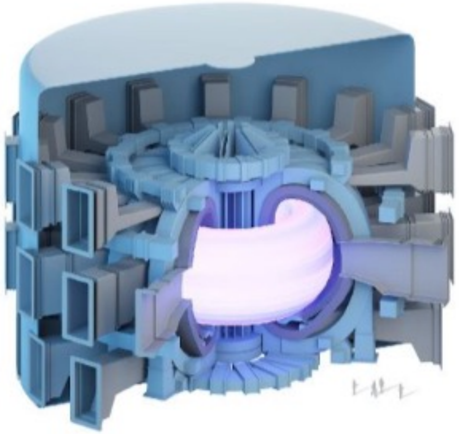
Laser-Hohlraum Device



	Tokamak Engines	Stellarator	Laser-Hohlraum Device
What	Symmetrical **donut-shaped** vacuum chamber, relies on currents inside the plasma, poloidal coil in the middle	**Twisted donut** vacuum chamber, doesn't rely on currents inside the plasma, no poloidal coil in middle	Fuel pellets directly hit by lasers, rapidly heated and compressed to achieve ignition
Pros	Technically simple, cheaper than stellarator, scalability, most researched approach	Require less injected power to sustain plasma, greater design flexibility, steady-state operations	Compact device, doesn't need a steady-state magnetic field
Cons	Risk of instability in plasma, pulsed operations	Increasing complexity, high manufacture cost	Low laser efficiency(5%-20%), pulsing ignition puts strain on the power grid, low scalability
Example Facility	Experimental Advanced Superconducting Tokamak (EAST) 📍China	Wendelstein 7-X (W7-X) 📍Germany	National Ignition Facility (NIF) 📍USA

Six fusion reactor designs, by both private firms and governments, using MCF, ICF, or somewhere in between.

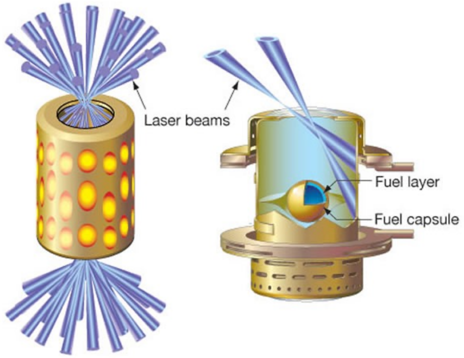
Government Endeavors



Tokamak

(ITER, EAST, and other government facilities)

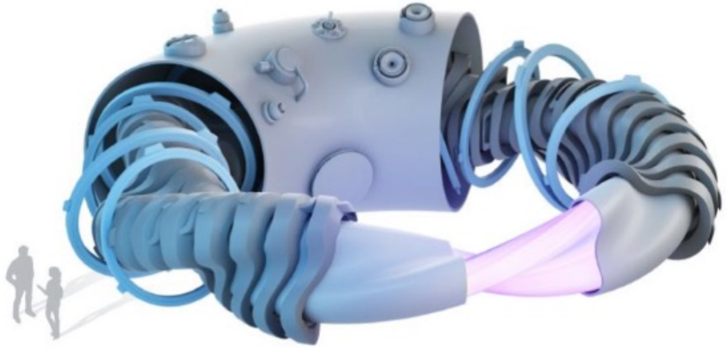
The traditional approach. Superconducting magnetic coils – cooled by liquid helium – hold plasma in a toroidal vessel. The most common plasma confinement approach.



Laser Hohlraum Device

(NIF)

Laser compressing and heating fuel pellets to replicate conditions in the cores of stars.

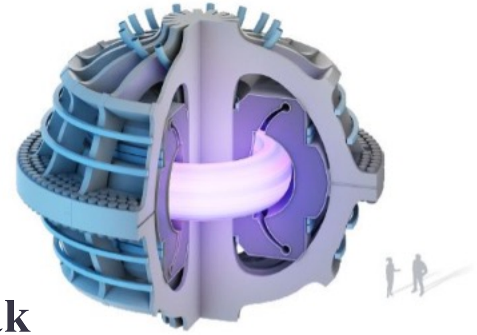


Stellarator

(Wendelstein 7-X)

A complicated twisted loop of magnetic fields confines the plasma easier than Tokamaks. High simulation complexity, high manufacture cost.

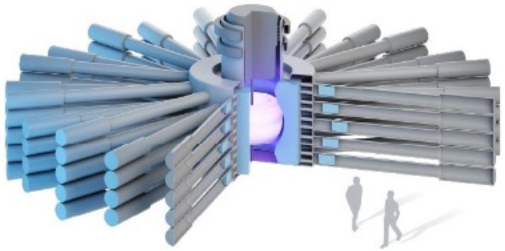
Private Companies



Mini Tokamak

(Tokamak Energy, Commonwealth Fusion and others)

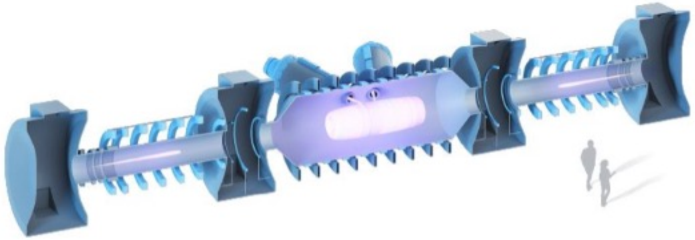
High temperature superconductors that generate stronger magnetic fields. More compact, low cost.



Magnetized Target Reactor

(General Fusion)

Pistons rapidly compresses the liquid metal-confined plasma to induce fusion. Low-cost path to fusion*.



Linear (Colliding Beams) Reactor

(TAE Technologies)

Packets of plasma fired into a central chamber and rapidly rotate inside a solenoid.

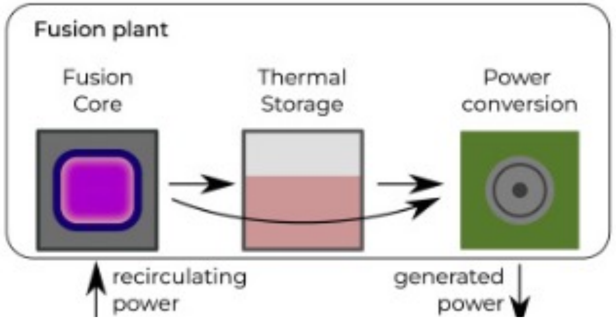
Illustration credit: nature.com

*Los Alamos (https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.82.2681)

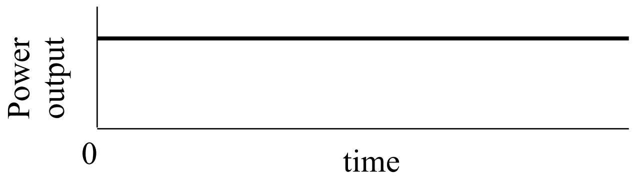
Roadmap to Commercialization

Grid Integration: fusion plants (assume tokamaks) pulsed and steady-state operation to generate electricity

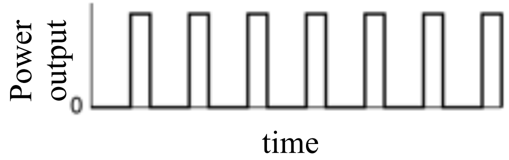
Function like baseload
Operating like a traditional power plant



Steady-State Generation
Constant power output

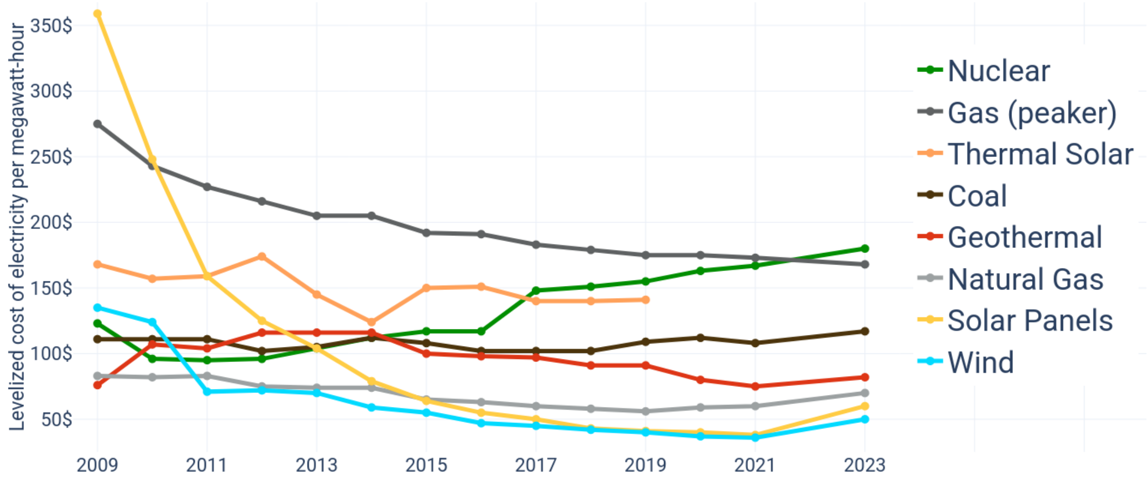


Pulsed Generation
Requires shutdown for a short time and restart



Schwartzman et. al 2023: The value of fusion energy to a decarbonized United States electric grid

To fulfill climate promise, fusion needs to have the most beautiful cost curve in history



Schwartzman et. al claims that capital cost for fusion is $2,700-$7,500/kW.

Utility-scale solar PV + battery cost is conservatively $1,800/kW.

Will fusion be able to compete with the cost of wind/solar + storage?

Will the true role of fusion not to solve the climate crisis but advance human civilization?

Notable startups in the space

tae

NIO

Neo Fusion

HELION

KYOTO FUSIONEERING

Commonwealth Fusion Systems

TYPE ONE ENERGY

MarvelFusion

能量奇点

ENERGY SINGULARITY

generalfusion

Tokamak Energy

ZAP ENERGY

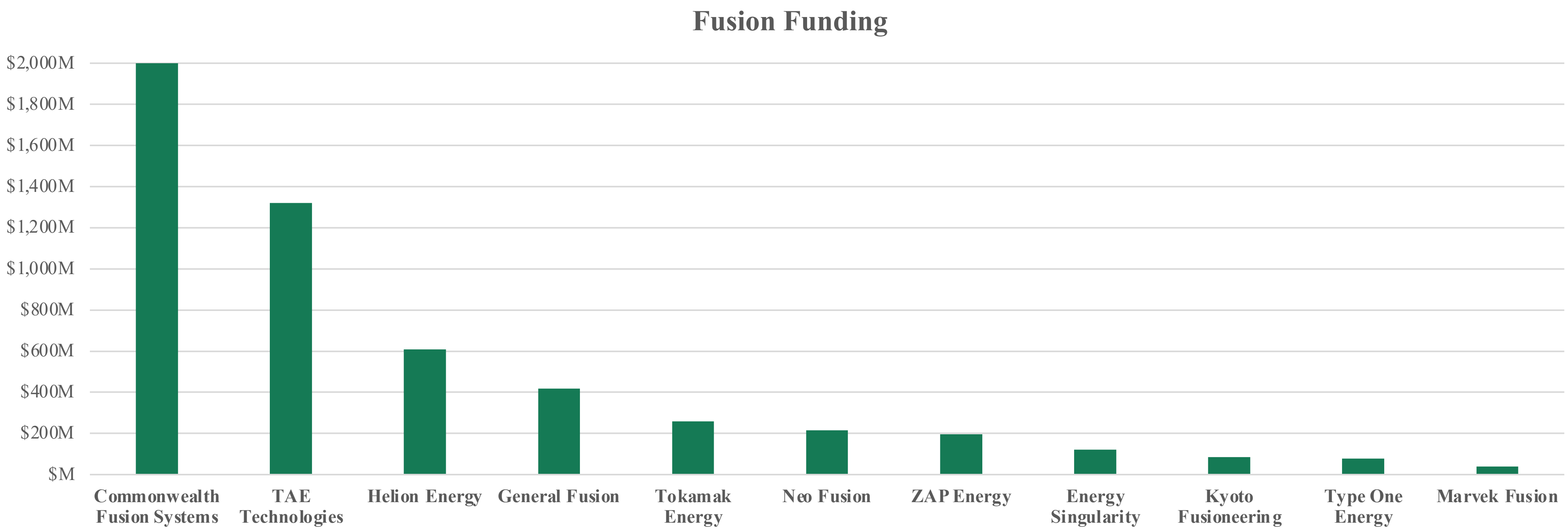
Funding Landscape

11
Startups surveyed

$5.3 Bn
Total funding raised

$13.3 Bn
Total valuation

60%
Founded after 2010



Fusion startups landscape

Most concentration of funding amount and companies

Fusion Reaction Route / **Reactor Technology**

Fusion Reaction Route	MCF Magnetic Confinement Fusion	MIF Magneto-inertial fusion	ICF Inertial Confinement Fusion	Other
D-T Fusion	Commonwealth Fusion Systems; 能量奇点 ENERGY SINGULARITY; Tokamak Energy	tae; generalfusion; HELION		ZAP ENERGY
D-He3 Fusion		HELION		
P-B Fusion		tae		
Unknown	TYPE ONE ENERGY		MarvelFusion	Neo Fusion; KYOTO FUSIONEERING

D-T Fusion is the most popular reaction route.

MCF and **MIF** are the most popular confinement routes.

Each Startup has their unique differentiation point, some have business models other than just "building a fusion reactor"

Company	Amount Raised	Reaction Route	Confinement Method	Reactor Tech	Differentiation
Commonwealth Fusion Systems	2,000M	D-T fusion	MCF	Compact Tokamak with HTS magnets	High temperature superconducting (HTS) magnets that allow for significantly stronger magnetic fields that can enable smaller, high performing systems at significantly lower cost.
TAE Technologies	1,320M	p-B fusion	MCF (FRC)	Magneto-inertial fusion	Reaction route (proton Boron fusion), pulsed fusion system.
Helion Energy	608M	D-He3, D-D, D-T	MCF (FRC)	Magneto-inertial fusion	Reaction route (D-He3), pulsed non-ignition fusion system, direct electricity generation w/o steam cycle
General Fusion	418M	D-T fusion	MCF + ICF	Magneto-inertial fusion	• Liquid lithium around the machine to solve the first wall problem, help tritium rebreeding, and aid heat transfer. • Pistons for compression is driven by steam.
Tokamak Energy	258M	D-T fusion	MCF	Compact spherical tokamak with HTS magnets	• They have HTS magnet business selling to other sectors. • Key advantages: efficiency (less of the energy produced is needed to run the device), spherical shape enhances plasma stability and confinement, cost-effectiveness.
Neo Fusion	217M	N/A	N/A	N/A	N/A
ZAP Energy	197M	D-T fusion	Current	Z-Pinch	Z-Pinch technology with electric currents (original proposed way to achieve fusion)
Energy Singularity	121M	D-T fusion	MCF	Compact Tokamak with HTS magnets	High temperature superconducting (HTS) magnets that allow for significantly stronger magnetic fields that can enable smaller, high performing fusion systems.
Kyoto Fusioneering	85M	N/A	N/A	N/A	Design and sell peripheral fusion systems (plasma heating (gyrotron) system, fusion fuel cycle system, fusion thermal cycle system)
Type One Energy	79M	N/A	MCF	Stellarator	Stellarator allows lower energy input to sustain plasma, high-performance computing to optimize reactor design
Marvek Fusion	40M	N/A	ICF	Laser Hohlraum	Nanostructure rods in fusion fuel pallets

Reality Check:
Commercial fusion will not come as quickly as we hoped

Milestones	Who has achieved (among startups)
100 million Kelvin in plasma (key milestone)	• **Helion Energy** (with their reaction route this doesn't mean much) • **Tokamak Energy**
Scientific Breakeven	None (only National Ignition Facility)
Engineering breakeven	None
Economic Breakeven	None

This is where every startup wants to be, but no one is here yet.

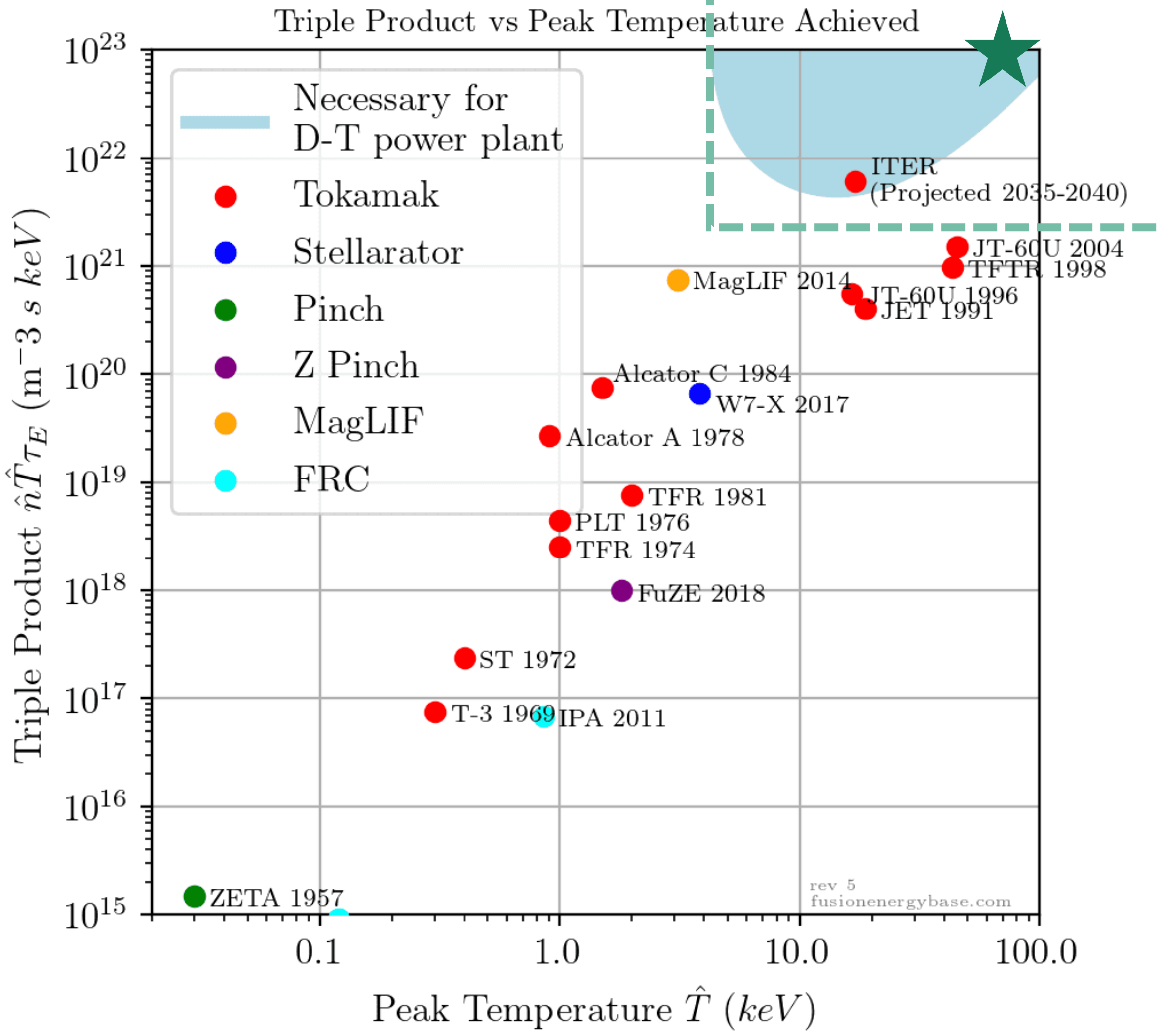


Figure from 2019, so likely outdated

The cutting-edge, new frontier for fusion technologies

- **Fusion fuel:** Tritium is very scarce and expensive
- **Reactor material:** to avoid neutrons (first wall, metal blanket, etc)
- **Energy conversion:** steam cycle (30-40% efficiency) vs convert to direct current
- **Value chain:** from fuel to peripheral systems to core reactor manufacturing to grid integration
- **Breaking the cost curve & finding its best application:** powering AI & data centers? How can these reactors be made cheaper and more efficient?

Regulatory and Policy Landscape

- NRC regulatory policy: fusion will not be regulated as fission but will be regulated as a particle accelerator, due to inherent differences in risk levels

WIP

Company Analysis – Helion Energy

HELION

Information

Year Founded/HQ	2013 Everett, WA
Description	Plasma accelerator to harness fusion energy
# Employees	213

Technical Fundamentals

D-He3 Fusion	• Pro 1: Produces less neutrons, • Pro 2: Charged particle can directly be used as electricity. • Con 1: Fuel mix much less (50X drop) reactive -> more engineering challenges. • Con 2: D-D fusion (produces neutron) is more reactive under ~300 million K
Reactor Analysis	• Due to technical constrains of reaction route, they likely will need neutron blankets just like all other startups with D-T fusion.

WIP

Appendix

Fusion Fuel Cycles

D-T

Benefits: The lowest temperature for a fusion reaction to occur; fastest reacting fuel cycle, with very large energy output per reaction.

Challenges: Tritium is a radioactive element – it does not occur in nature and must be bred; its associated neutrons will accelerate aging in power plant materials.

D-He-3

Benefits: Substantially less radioactivity and production of tritium than with D-T fusion, leading to longer power plant life; most energy output per reaction, largely in the form of energetic protons, which makes direct energy conversion possible.

Challenges: Residual radioactivity; reacts slower than the D-T fuel cycle; no terrestrial He-3 resources – must be mined on the lunar surface.

p-B11

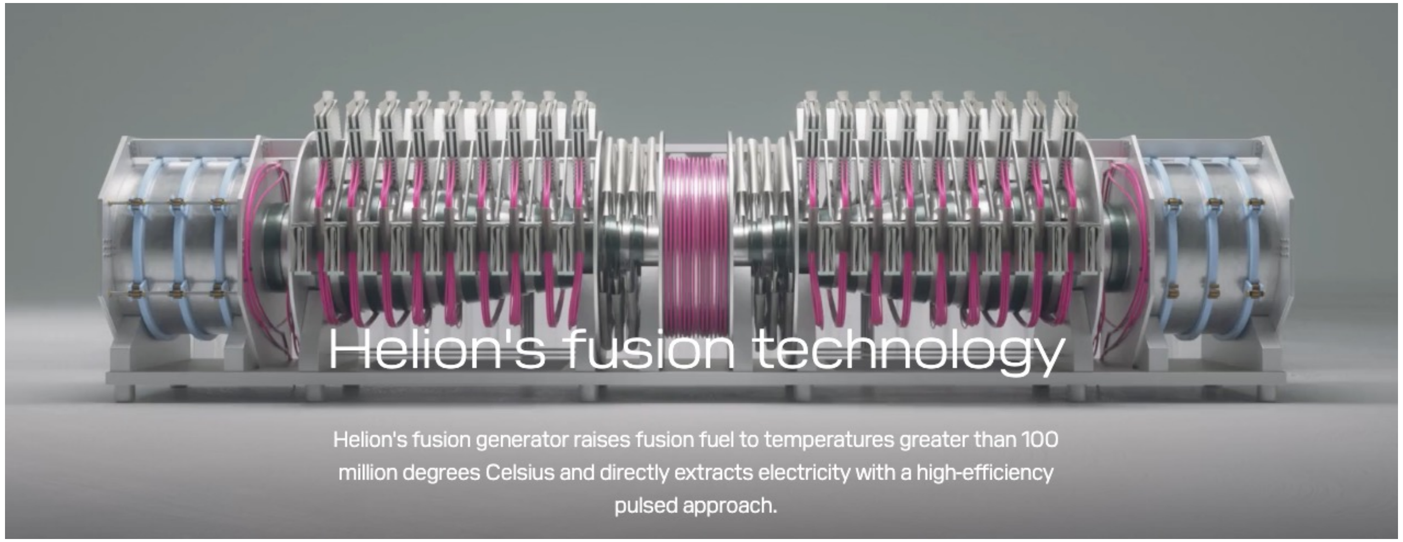
Benefits: Aneutronic (primary reaction yields no neutrons); cleanest, safest, highly abundant, and environmentally friendly fusion pathway; enables scalable, cost-competitive electricity.

Challenges: Requires superior confinement and operational conditions to reach the considerably higher temperatures needed; reacts more slowly than other fuel cycles; less energy output per reaction.

Magnetized target fusion

- It’s a combination of MCF and ICF.
- Like MCF, fuel confined at lower density while heating into plasma
- Like ICF, fusion initiated by squeezing target to greatly increase fuel density and temperature
- The key idea is that longer confinement times and better heat retention will let MTF operate
- https://generalfusion.com/fusion-demo-plant/

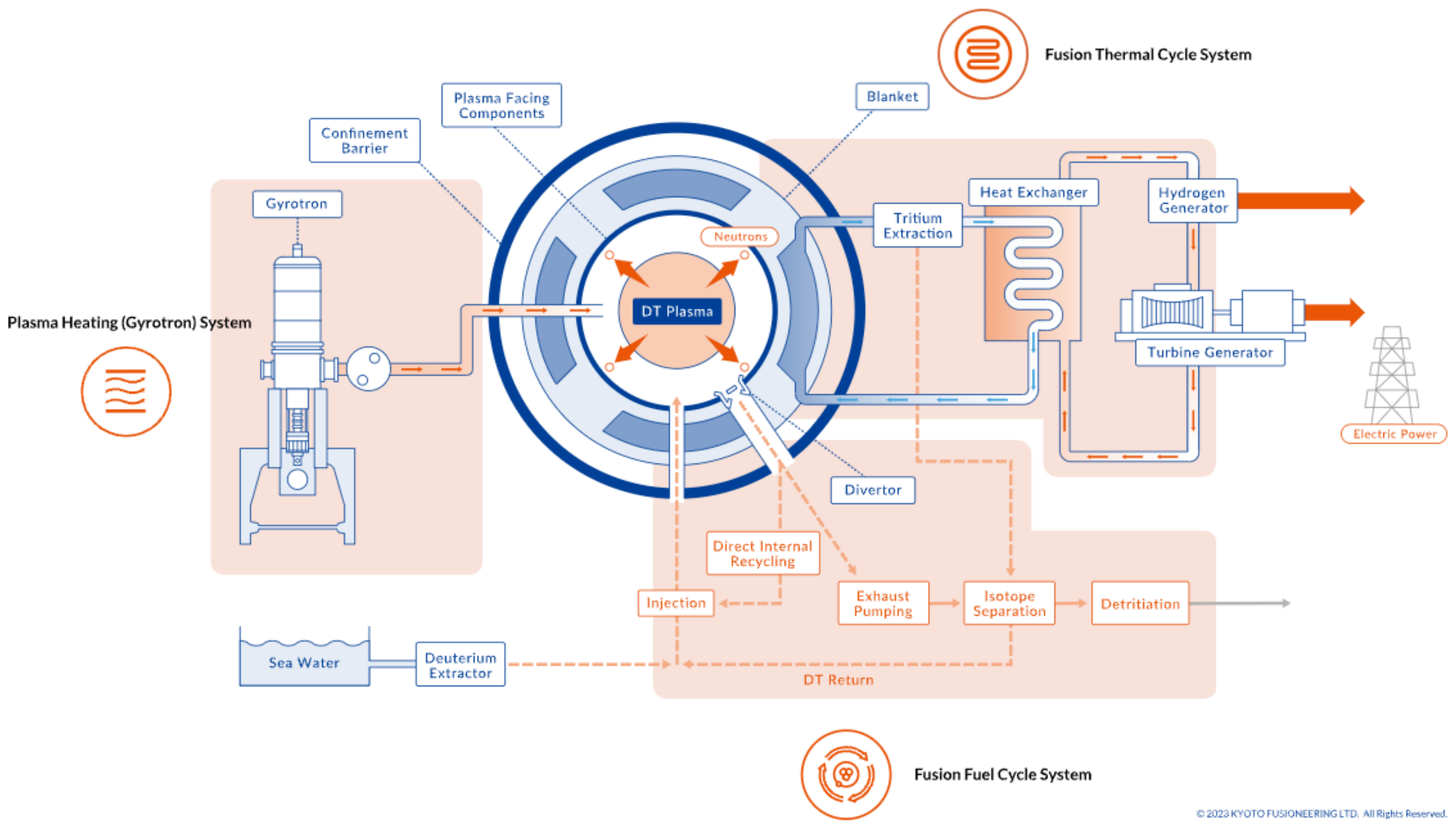
Helion Energy



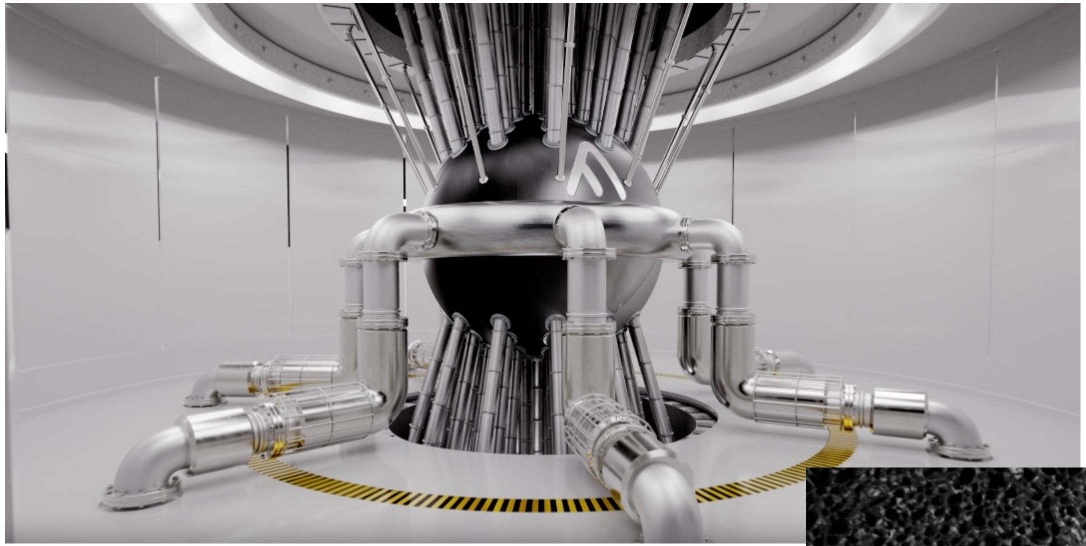
- Formation: Deuterium and helium-3 fuel is heated to plasma conditions. Magnets confine the plasma in a field reversed configuration (FRC)
    - It confines a plasma on closed magnetic field lines without a central penetration.[1][2] In an FRC, the plasma has the form of a self-stable torus, similar to a smoke ring.
- Acceleration: magnets accelerate two FRCs to 1 million mph from opposite ends of the device - they collide in the center.
- Compression: FRCs collide in the center of the system, further compressed by magnetic field until they reach fusion temp: (>100Mil C aka 9 keV)
- Fusion: as they fuse, plasma expands.
- Direct Electricity capture: as plasma expands, it pushes back on magnetic field from machine's magnets. Change in magnetic field induces current (faraday's law) will directed get recaptured as electricity (skip the steam cycle)

Kyoto Fusioneering

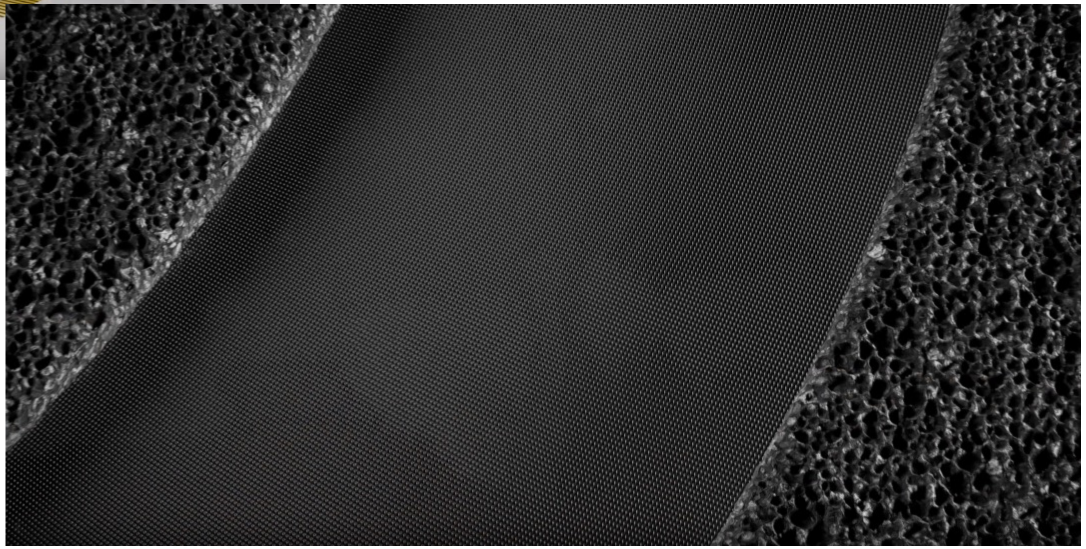
Illustrating Fusion Energy Power Plant and Our Enabling Technology Focus



Marvel Fusion GmbH



Laser strips away the electrons in nanostructure rods and the protons get released to hit other parts of the fuel pellet to produce fusion reaction



Tokamak Energy: Compact Spherical Tokamak

1. 更高的等离子体压缩效率
- **磁约束效能**：球形托卡马克由于其更高的纵横比（即短径与长径之比更大），可以在较小的体积内产生更强的磁场，从而更有效地约束等离子体。这种高效的磁约束使得等离子体可以在更小的体积内达到更高的密度和温度 [oai_citation:1,Status of the Organization](https://www.iter.org/legal/status)。

2. 更高的β值
- **β值**：β值是等离子体压力与磁场压力的比值。球形托卡马克的设计能够支持更高的β值，这意味着它能够在较低的磁场强度下保持等离子体的稳定性。较高的β值有助于提高聚变反应的效率和能量输出 [oai_citation:2,Status of the Organization](https://www.iter.org/legal/status) [oai_citation:3,ITER - Performance - European Commission](https://commission.europa.eu/strategy-and-policy/eu-budget/performance-and-reporting/programme-performance-statements/iter-performance_en)。

3. 结构紧凑，节省成本
- **设备紧凑性**：球形托卡马克的紧凑设计使得整体设备占用的空间更小，从而降低了建设和维护的成本。这种设计还简化了许多工程和技术问题，如冷却系统和磁体布置 [oai_citation:4,Status of the Organization](https://www.iter.org/legal/status)。
- **材料节省**：由于球形托卡马克需要的磁体体积和材料更少，相对于传统托卡马克，其建设成本和资源消耗更低 [oai_citation:5,ITER - Performance - European Commission](https://commission.europa.eu/strategy-and-policy/eu-budget/performance-and-reporting/programme-performance-statements/iter-performance_en)。

4. 提高等离子体稳定性
- **等离子体形状**：球形托卡马克的等离子体形状更加接近球形，减少了不稳定性的发生。更高的纵横比设计能够更好地控制等离子体中的湍流和其他不稳定性，从而提高了反应的稳定性和可控性 [oai_citation:6,Status of the Organization](https://www.iter.org/legal/status) [oai_citation:7,ITER - Performance - European Commission](https://commission.europa.eu/strategy-and-policy/eu-budget/performance-and-reporting/programme-performance-statements/iter-performance_en)。

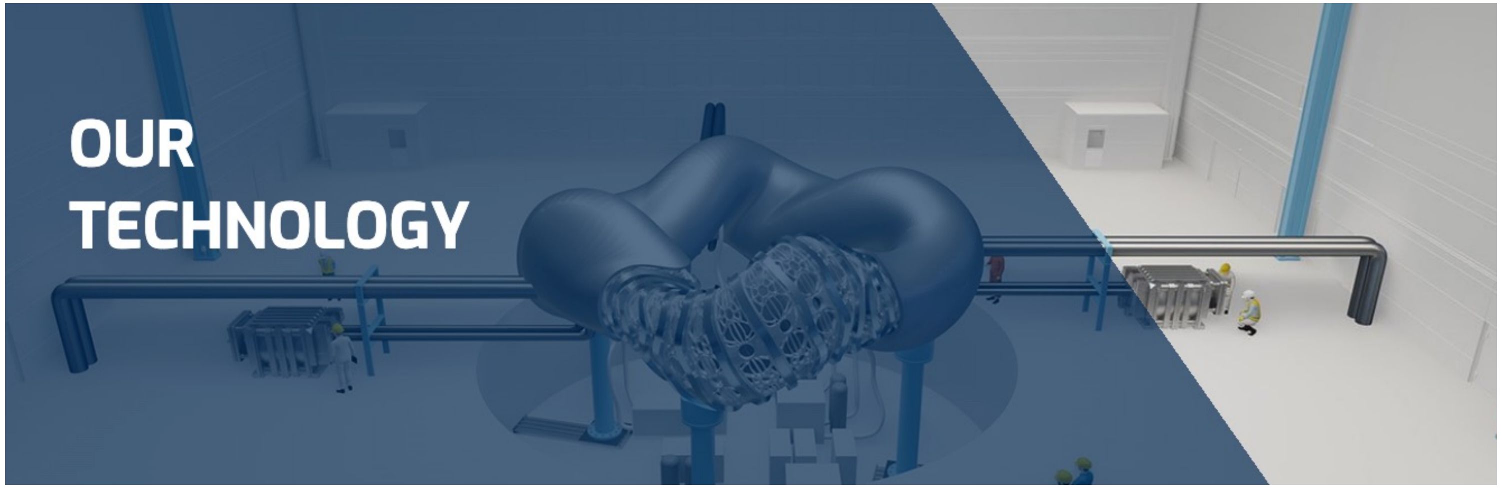
5. 更便于冷却和维护
- **冷却效率**：由于结构紧凑，球形托卡马克的冷却系统设计更加简单和高效，有助于有效散热，维持等离子体的高温状态。
- **维护便捷**：设备的紧凑设计使得组件的更换和维护更加便捷，有助于减少停机时间，提高设备的整体运作效率 [oai_citation:8,ITER - Performance - European Commission](https://commission.europa.eu/strategy-and-policy/eu-budget/performance-and-reporting/programme-performance-statements/iter-performance_en)。

案例研究：MAST和ST40
- **MAST（Mega Amp Spherical Tokamak）**：位于英国，MAST是一个成功的球形托卡马克实验装置，展示了高效的等离子体约束和较高的β值。
- **ST40**：由Tokamak Energy公司开发的ST40是一个球形托卡马克原型机，目标是在紧凑设计中实现高温等离子体，展示了球形托卡马克在商业化核聚变反应堆中的潜力 [oai_citation:9,ITER - Performance - European Commission](https://commission.europa.eu/strategy-and-policy/eu-budget/performance-and-reporting/programme-performance-statements/iter-performance_en)。

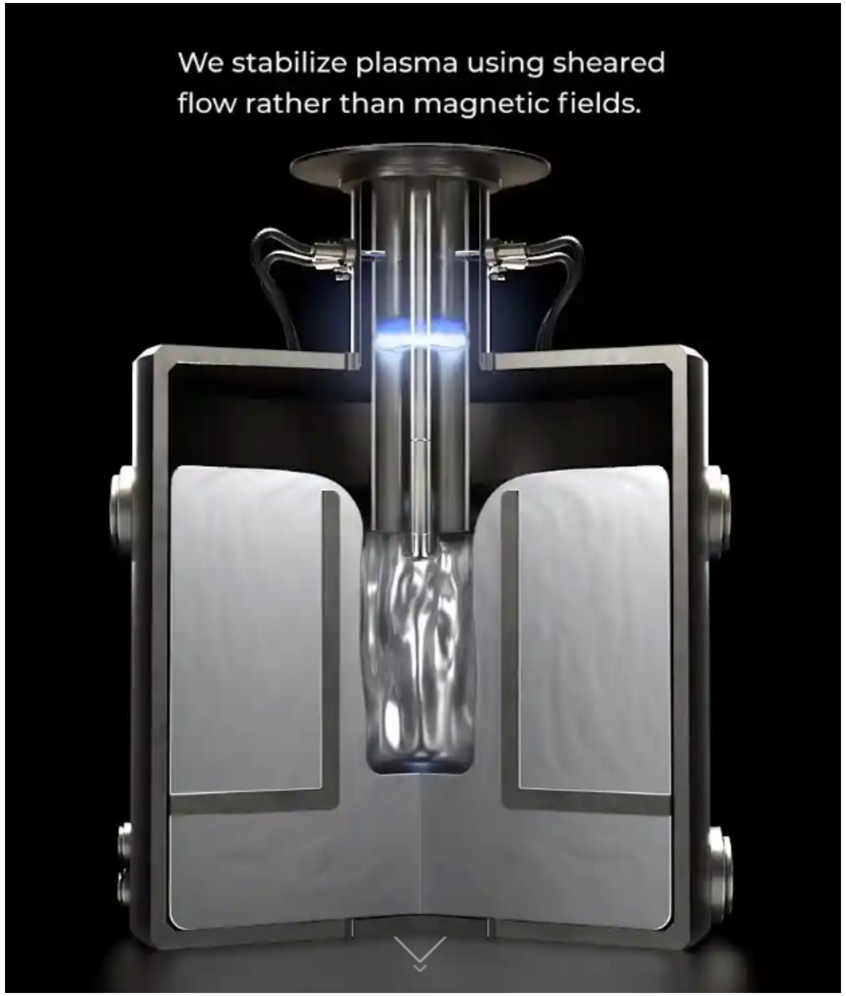
结论
将托卡马克设计成紧凑的球形不仅提高了磁约束效率和β值，还能显著降低成本、提高等离子体稳定性，并简化冷却和维护。这些优势使得球形托卡马克成为未来核聚变反应堆设计的一个更具吸引力的工程解决方案。

参考文献
1. [ITER Official Website](https://www.iter.org/)
2. [Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)](http://english.ipp.cas.cn/)
3. [Southwestern Institute of Physics (SWIP)](http://www.swip.ac.cn/)

Type One Energy: Stellarator



ZAP Energy



Driving current through the flow creates the magnetic field, confining and compressing the plasma.

A current travels in the z-direction through the plasma. The current generates a magnetic field that compresses the plasma. Pinches were the first method for human-made controlled fusion.[35][36] The z-pinch has inherent instabilities that limit its compression and heating to values too low for practical fusion. The largest such machine, the UK's ZETA, was the last major experiment of the sort. The problems in z-pinch led to the tokamak design. The dense plasma focus is a possibly superior variation.

Some useful links on fusion science

- https://en.wikipedia.org/wiki/Fusion_energy_gain_factor#cite_note-FOOTNOTEMcCrackenStott200542-18
- https://en.wikipedia.org/wiki/Lawson_criterion
- https://en.wikipedia.org/wiki/Fusion_ignition
- https://www.llnl.gov/article/50801/llnls-breakthrough-ignition-experiment-highlighted-physical-review-letters
- https://www.fusionenergybase.com/