# Privately funded fusion research status and fusion regulation

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Research done by privately funded fusion companies is advancing and the amount of funding has risen significantly. A new feature is that traditional energy companies are funding fusion research and development. According to surveys conducted by the Fusion Industry Association in 2021 and 2022 most private fusion companies expect fusion energy production to start in the 2030:s. This time scale is similar to what the fission companies developing Small Modular Reactors are aiming for. Fusion needs a licensing and regulation framework, which can take into account the very different characteristics of fusion reactors compared to fission reactors. The process of creating a framework for fusion is ongoing in the UK and the USA. In Finland there is currently work to take into the account SMR requirements, but as the time scale of fusion and fission is possibly similar the requirements of fusion should also be considered in Finland.

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# Introduction

The first to understand that fusion powers the sun and the stars were:

- **Harkins** 1915, an American physical chemist, first to propose fusion
- **Perrin** 1919, a French Nobel awarded physicist, fusion in the stars [1]
- **Eddington** 1920, fusion in the stars

Why is controlled fusion so hard that is has not been solved in a more than a hundred years time?

- The positively charged nuclei repel each other
  - The repulsion can be overcome by heating a plasma enough
- The probability for nuclear fusion is much smaller than that for Coulomb scattering
  - The small fusion probability can be overcome by doing enough trials
- Achieving stable plasma **confinement** retaining the heat and allowing for enough collision trials has proved to be very difficult due to plasma **instabilities**

# Introduction

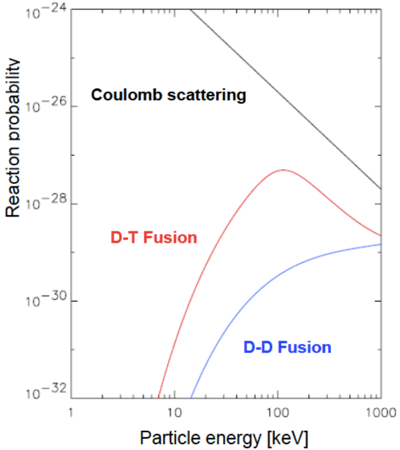


Figure: The cross section in $m^2$ for Coulomb scattering and fusion. Picture by D. Whyte.

# Introduction

**The most important fusion reactions for energy production:**

$\mathrm{D} + \mathrm{T} \rightarrow$

$\mathrm{He}(3,52\ \mathrm{MeV}) + \mathbf{n}(14,07\ \mathrm{MeV})$

$\mathrm{D} + \mathrm{D} \rightarrow$

$^{3}\mathrm{He}(0,82\ \mathrm{MeV}) + \mathbf{n}(2,45\ \mathrm{MeV})$, 50 %

$\mathrm{T}(1,01\ \mathrm{MeV}) + \mathrm{p}(3,02\ \mathrm{MeV})$, 50 %

$\mathrm{D} + {}^{3}\mathrm{He} \rightarrow$

$\mathrm{He}(3,67\ \mathrm{MeV}) + \mathrm{p}(14,68\ \mathrm{MeV})$

$\mathrm{p} + {}^{11}\mathrm{B} \rightarrow$

$3\mathrm{He}(8,68\ \mathrm{MeV})$

$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow$

$\mathrm{He}(12,86\ \mathrm{MeV}) + 2\mathrm{p}$

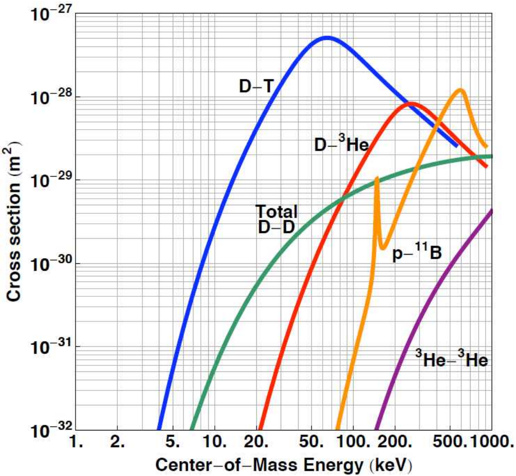


Figure: Cross sections as a function of center of mass energy for the most important fusion reactions [2]. (1 keV ≈ 12 MK)

# Introduction

The conditions needed for fusion were first studied by J.D. Lawson [3]. The Lawson criterion has been generalized to the **triple product**, the fusion performance metric:

$$NT\tau_E \tag{1}$$

where $N$ is the particle density, $T$ is the temperature and $\tau_E$ is the energy confinement time.

The triple product has to execeed some threshold value for the fusion reaction in question for the fusion power to exceed radiation and other losses and maintain a constant plasma temperature.

For the deuterium-tritium reaction the minimum required value for a thermal plasma is $3 \cdot 10^{21}$ keVs/m$^3$.

- The required temperature is defined by the desired fusion reaction
- Several plasma heating methods exist.
- $N$ and $\tau_E$ can be traded against each other

# Introduction

Examples of plasma **confinement** methods:

- **Magnetic Confinement Fusion** (MCF)
  - Tokamak (JET, SPARC, ITER, ...), stellarator (Wendelstein 7-X), ...
  - $N \approx 10^{14}/\text{cm}^3$, $\tau \approx 1$ s
- **Inertial Confinement Fusion** (ICF)
  - Laser fusion (National Ignition Facility, High Power laser Energy Research facility (HiPER), ...)
  - Heavy Ion Fusion (HIF)
  - $N \approx 10^{25}/\text{cm}^3$, $\tau \approx 1$ ns
- **Magnetized Target Fusion** (MTF) also **Magneto Inertial Fusion** (MIF) (General Fusion, Helion Energy, ...)
  - $N \approx 10^{19}/\text{cm}^3$, $\tau \approx 1\ \mu$s
- **Inertial Electrostatic Confinement** (IEC)

# Introduction

**Plasmoids** or **Compact Torii** are **self confined** plasmas where the magnetic fields are mostly generated by currents circulating in the plasma[4]
The *poloidal* field is contained in planes through the symmetry axis.
The *toroidal* field circulates the symmetry axis.

| Plasmoid | Axial-symmetry | Poloidal field $B_p$ | Toroidal field $B_t$ | $B_t$ on surface |
|---|---|---|---|---|
| **FRC** | yes | yes | no | no |
| **Spheromak** | yes | yes | yes | no |
| **Spherical tokamak** | yes | yes | yes | yes |

FRC = Field Reversed Configuration

# Funding

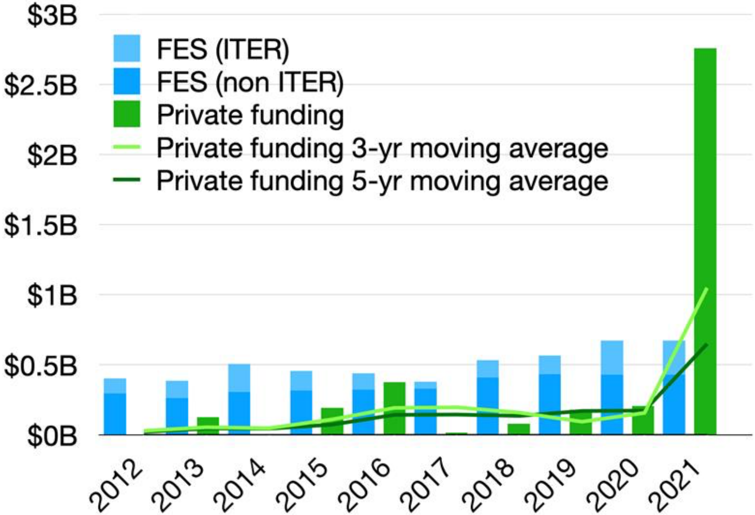


Figure: US public fusion funding excluding DoD funding and worldwide private fusion funding. Plot by Sam Wurzel.

# Funding

**Big investors:**

- Investment companies
- National funds
- Very wealthy persons

**Energy companies that have invested in fusion:**

- Cenovus (General Fusion, MTF, Canada)
- Chevron (Zap Energy, Z-Pinch, USA, TAE Technologies, FRC, USA)
- Eni (Commonwealth Fusion Systems, HTS tokamak, USA)
- ENN (ENN Energy Research Institute, Compact Fusion Technology (ST, FRC), China)
- Equinor (Commonwealth Fusion Systems, HTS tokamak, USA)
- Siemens Energy (Marvel Fusion, ICF, Germany)

Google has also invested in TAE Technologies

# Privately funded fusion research

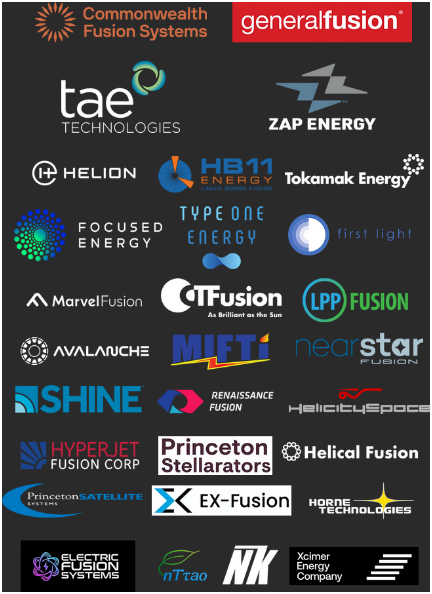


Figure: The Fusion Industry Association has about thirty members.

# Privately funded fusion research

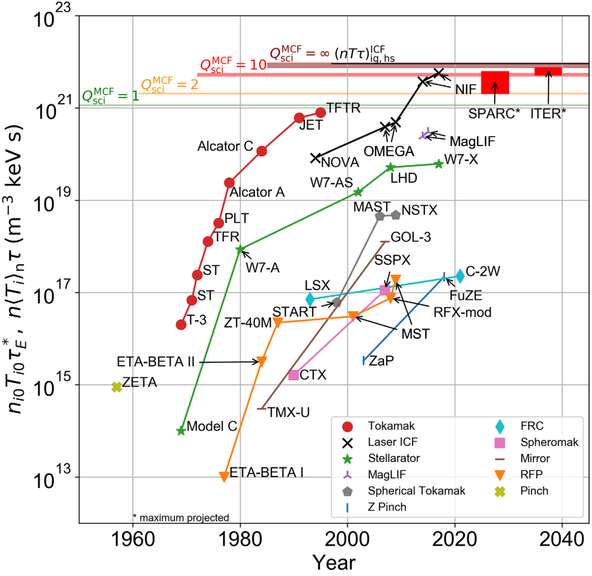


Figure: *Fusion triple product* record values for some fusion experiments [5].

# Zap Energy

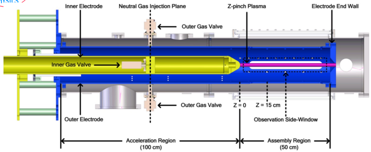


Figure: The ZE FuZE device. Picture by ZE.

Figure: The ZE reactor. Picture by ZE.

- Z-pinches were popular, but instabilities ended their development
- The sheared flow stabilized Z-pinch has been developed by the University of Washington and LLNL during the past twenty years
- No magnets, $\beta = 1$, low cost & simple, DT reaction, $f_{pulse} > 1$ Hz
- $E_{fusion} \propto I^{11}$ under ideal assumptions, [6, 7]
- FuZE results: 0.5 MA reached, $T_i$>2.5 keV, $T_e$>1.5 keV
- FuZE-Q, designed for Q=1, *goal to reach Q=1 during 2023*, [8]
- Q=1: pinch current 600–700 kA, a reactor would have 1.2–1.5 MA
- Zap Energy (2017) has raised 200 MUSD so far
- A fusion core could have a power of $\approx$ 200 $MW_{th}$
- Challenges: scaling to larger currents, electrode erosion

# Helion Energy

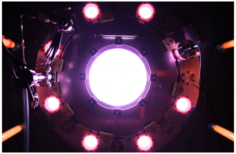

Figure: The divertor of the Trenta experiment. Picture by Helion Energy.

- MIF: HE collides two FRC:s with 300 km/s each to produce a FRC
- The FRC is compressed with ordinary magnets [9]
- The expanding fusion plasma inductively generates electricity
- D-$^3$He aneutronic reaction
- **Trenta**: The current device has reached, $\mathbf{T_t = 9}$ **keV**, 7 T in 2020
  - The density after compression $10^{21}/\mathrm{m}^3$ – $10^{24}/\mathrm{m}^3$
  - 2021: **500 MUSD** för Polaris + **1,7 GUSD** conditionally
- **Polaris**: under construction, testing to start in 2022
  - Goal: Demonstrate $^3$He generation from DD fusion
  - *Plans to demonstrate net electricity generation on a small scale in 2024*
  - Aims to reduce the pulse interval from 10 min (Trenta) to 1 s (Polaris)
- **Antares** the Polaris successor is also being planned
- *The long term goal is to build 20 units/day with 50 MW$_e$ each*

# TAE Technologies

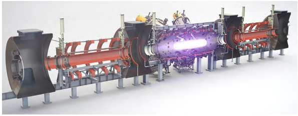

Figure: The current experiment **C-2W** (2017), length 30 m. Picture by TAE.

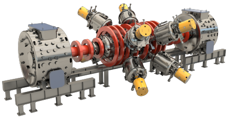

Figure: The next device **Copernicus**, length 30+ m. Picture by TAE.

- TAE uses a beam stabilized FRC configuration
- Two 500 km/s colliding FRCs produce a FRC
- The FRC is maintened by neutral beams and electromagnetic fields
- C-2W FRC lifetime 30+ ms, limited by the power supply
- $T_{tot}$ 5+ keV, $T_e \leq 1$ keV, the density 1–5*$10^{19}$m$^{-3}$, B$\leq$ 0.3 T [10]
- Confinement and active feedback plasma control has been studied
- TAE cooperates with Google, spinoffs BNCT and power control
- **Copernicus** comissioning late 2023, $T_i$ 10+ keV goal, reactor studies
- **Da Vinci** $\mathrm{p^{11}B}$, prototype reactor, end of 2020s
- **Plasma Electric Generator (PEG)**, $\mathrm{p^{11}B}$, also other fuels
  - $P_e = 400 - 500$ MW, superconducting magnets

# Commonwealth Fusion Systems (CFS)

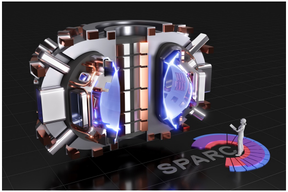


Figure: A SPARC tokamak model by CFS. Picture by CFS.

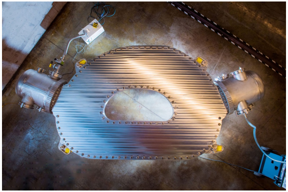

Figure: The 20 T SPARC prototype TF coil is 2 m tall and weights 9265 kg. It is the worlds largest HTS magnet. Picture by CFS.

- CFS continues the MIT strong field tradition from Alcator C-Mod
- **SPARC** 100 $MW_{th}$, to be completed in 2025, initially Q>2 [11]
- The **20 T TF coil** built in 2021 uses 267 km HTS-conductor.
- **1,8 GUSD** funding in 2021
- Builds a factory in Devens, Massachuttes
- Affordable, robust, compact (**ARC**), a strong field compact tokamak
- ARC - commercialization, Q>10, $P_e \approx 200$ MW, early 2030s
- CFS has contracts with UKAEA on HTS magnet technology for STEP

# Tokamak Energy

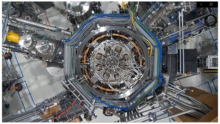

Figure: The ST40 tokamak. Picture by TE.

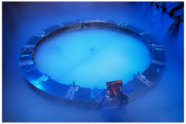

Figure: HTS Demo 4. Picture by TE.

Develops spherical tokamaks (ST) with strong fields and HTS magnets[12]

- Spinoff from Culhamn Center for Fusion Energy (CCFE)
- ST25 (2013), ST25-HTS (2014)
- ST40 (2017-), 3 T, $LN_2$-cooled copper, H and DD used
  - Study strong field confinement, divertor solutions, solenoid free startup, high performance reactor relevant operation
  - $T = \mathbf{100\ MK}$ and $NT\tau_E = 6 \pm 2 \cdot 10^{18}$ keVs/m$^3$ reached in 2022
- HTS Demo 3, small magnet, **24,4 T** at 21 K and 26,2 T at 4,2 K.
- HTS Demo 4, Demonstrate HTS 10 T magnets in ST25-configuration
- ST80-HTS (2026), goal of $NT\tau_E$ near reactor level, 900 s pulses
- ST-E1 is planned as a 200 $MW_e$ pilot plant
- TE plans energy production to the grid in the 2030s
- TE has a five year ST development contract with UKAEA
- Challenges: Mechanics, HTS radiation hardness?

# General Fusion

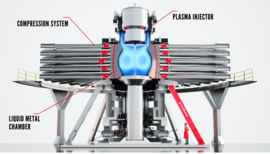


Figure: The Fusion Demonstration Plant (FDP) to be built by 2027 at Culham in the UK. Picture by General Fusion.

Hundreds of steam pistons compress the plasma in a MTF device [13]

- The planned reactor is a cylinder with a rotating molten PbLi liquid, DT reaction, $P = 115$ MW$_e$, $f = 1$ Hz, a compression ratio of 6,5
- A spherical tokamak (ST) is injected through the vortex in the middle
- Computer controlled pistons heat the ST to fusion conditions
- Advantages of the GF concept:
  - No solid ”inner wall” problem, no divertor needed
  - PbLi is a coolant and neutron multiplicator for T-generation
  - Can be retrofitted to existing power plants
- Challenges: Compression and stability, plasma-liquid interactions
- The goal of the FDP is to reach 10 % of the Lawson criterion
- GF has sites in Canada, the UK & the USA, collaborates with UKAEA
- GF cooperates with Bruce Power & Nuclear Innovation Institute to find a reactor site in Ontario, Canada

# Fusion regulation

Fusion has different safety characteristics compared to fission:

- Only a small amount of heat in the plasma
- A reaction that stops by itself when any conditions change
- No long lived waste
- Most of the waste is expected to be short lived
- Low nuclear proliferation concern [14]

*Different fusion reactor concepts are rather different in terms of fuel used.*
The main fusion radiation hazards are:

- Neutron radiation mainly from DT fuel and photon radiation
- Tritium handling needs appropiate measures if used
- Activated materials

The other fusion related risks are mainly found in other industries as well

- Power supplies with high power, high voltage power systems
- Strong magnetic fields with large stored energy
- Cryogenic systems
- Special materials: Li, Be, Pb, molten metals

# Fusion regulation

*The problem is to find the appropriate level of regulation to avoid under-, over- or misregulation.*

A **UK** Fusion Strategy was published in 2021

- A consultancy on fusion regulation was made at the end of 2021
- The UK Government has concluded that: *After our careful review of the feedback received, the Government can now confirm that future fusion energy facilities will be regulated under the legal framework already in place for fusion. ... We are also clear that the fundamental differences between nuclear fission and fusion mean that it would be disproportionate and unnecessary to incorporate fusion energy facilities into nuclear regulations. [15]*
- Fusion regulation: Environment Agency, Health & Safety Executive
- Fission regulation: Office for Nuclear Regulation

The **U.S.** Nuclear Regulatory Commission is considering fusion regulation [16]

- Option 1 - Regulate fusion energy systems under the utilization facility framework
- Option 2 - Regulate fusion energy systems under the byproduct materials framework
- Option 3 - Regulate fusion energy systems under a hybrid approach

The FIA supports Option 2, the current devices have been regulated in this way

# Fusion regulation

The main nuclear energy related laws and regulations in Finland:

- 11.12.1987/990 Nuclear energy act
- 12.2.1988/161 Nuclear energy regulation
- 9.11.2018/859 Radiation act
- 22.11.2018/1034 Government regulation on ionizing radiation

The nuclear energy law refers mainly to fission energy. It is being reformed in general and also for SMR:s.

Fusion power plants might be deployed in the 2030s so there is a need for regulation work to start.

*Fusion has different fuels, reactions, waste, safety, risks and proliferation concerns associated compared to fission, so regulating fusion differently from fission would be well motivated as has been done in the UK.*

A fusion reactor seems to be regarded as a **radiation source** according to the current laws, if the HV is larger than 30 kV and a radiation threshold is exceeded. **Could this be the starting point of fusion regulation?**

# Summary

- *Developments in plasma physics, instrumentation, plasma diagnostics, simulation, AI, computers and advanced manufacturing has enabled new possibilities for fusion research and development*
- Private fusion research is progressing also due to increased funding
- **During the next few years Q$\geq$1 will most likely be demonstrated**
- For fusion to succeed the physics, technology and economics all need to be developed far enough
- Private-public collaboration will be important for fusion development
- **Appropriate fusion regulation is important**
- *It seems that fusion electricity might be available in the 2030s*
- **Fusion could provide baseload energy to replace fossile fuels and to meet increasing demand**
- The rate of deployment in GW/year is important for fusion to make a significant decarbonization impact
- **Fusion regulation work should also be started in Finland**

Reading material on private fusion companies:

- Fusion Industry Association, *The global fusion industry in 2022*, 2022
- Fusion Industry Association & UK Atomic Energy Authority, *The global fusion industry in 2021*, 2021
- W. J, Nuttal et al., *Commercialising Fusion Energy - How small businesses are transforming big science*, IOP Publishing 2020, Bristol, UK

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[9] D. Kirtley, Vacuum vessel and divertor design and results of 16 month operation of the Trenta Magneto-Inertial Fusion prototype, https://www.youtube.com/watch?v=wHirlGXlJ38, to be published in Trans. Plas. Sci. November 2022.

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[14] M. Y. Hua et al., *Nonproliferation and fusion power plants*, arXiv:2207.14348, `https://doi.org/10.48550/arXiv.2207.14348`.

[15] UK Department for Business, Energy & Industrial Strategy, *Towards Fusion Energy: The UK Government's response to the consultation on its proposals for a regulatory framework for fusion energy*, ISBN 9781528634823, E02760952 06/22, CP 694, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1084472/towards-fusion-energy-uk-government-response.pdf.

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