# Fusion

Per Petersson

# Content

What is fusion
Inertial confinement
Magnetic confinement
Tokamak
  - JET
  - ITER
  - DEMO
  - ARIES-AT
  - ARC/SPARC

Fusion research at KTH

# Fusion in media

Generally used as a miraculous solution

- Iron Mans arc reactor
- Mr Fusion in Back to the Future II
- Propulsion of spacecrafts
    - Star Trek
    - …

- Dr. Octopus is the result of a failed fusion experiment

# To capture the Sun in a box

Fusion is compared to capturing the sun in a box, but it is not that easy:

The sun is huge: 1.4 x $10^{18}$ $km^3$, $2x10^{30}$kg, $4x10^{26}$ W

But the energy production is low: 0,2 mW/kg

There are several reactions that together gives the net reaction:

$4\ H+2\ e\text{->}{}^4He + 2\ v_e + 27\ MeV$

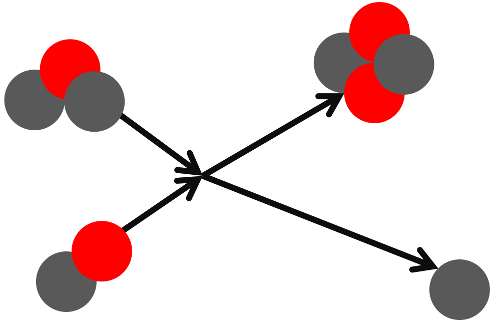
2 $GW_{Thermal}$ requires $1x10^{13}$ kg, 7 $km^3$, sphere of 2,4 km

# Nuclear Reactions

Instead this reaction can be used:

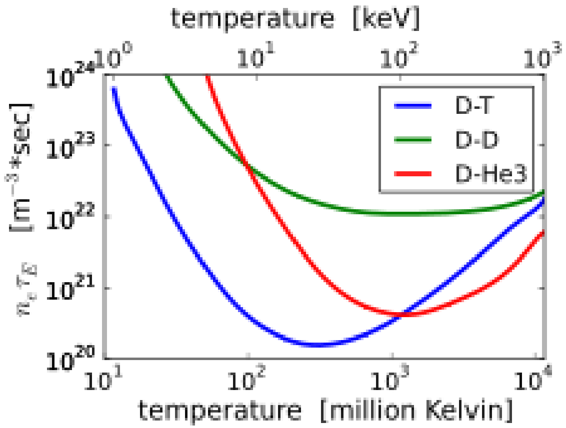
T+D -> $^4$He+ n + 17,6 MeV

Typically: $^4$He 3,5 MeV, n 14 MeV



2 GW requires ca 2g plasma

(Depending on reactor)



1 MeV = 1,6x10$^{-13}$ J

(Physically correct)

1 keV = 1,16x10$^7$ K

(Simplification based on Boltzmans constant)

# Fuel production

- D is easy to find (One in ~6000 hydrogen atoms are Deuterium)
- Tritium has a half life of 12,3 years and is hard to find and keep
- All tritium has to be produced
- Can be made in the reactor:
    - **$T+D \rightarrow {}^4He+n + 17{,}6\ MeV$**
    - **$n+{}^6Li \rightarrow {}^4He+T+ 4{,}8\ MeV$**
    - $(n+{}^7Li \rightarrow {}^4He+T+n\ -2{,}8\ MeV)$
    - $(D+D \rightarrow T+p + 4{,}0\ MeV)$
- This requires a blanket containing Lithium surrounding the plasma
    - Also used for energy extraction
    - To get enough T a neutron multiplier is required in most designs i.e. Be or Pb

# Inertial confinemnt

Compresses and heats a target with X-rays created by strong lasers

National Ignition Facility (USA)

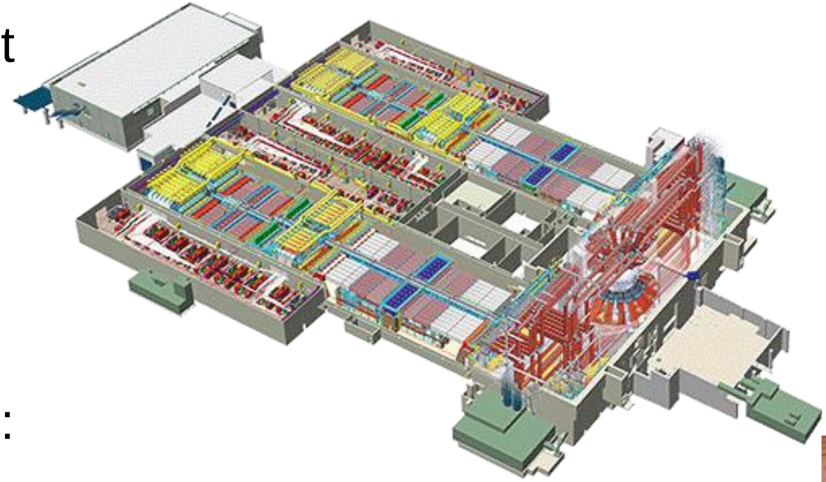
2 MJ pulse, 5 ns

1 pulse/day

Requirements for a powerplant:

2-3 MJ, 5 ns, ~10 Hz

Methods to capture the energy and produce tritium

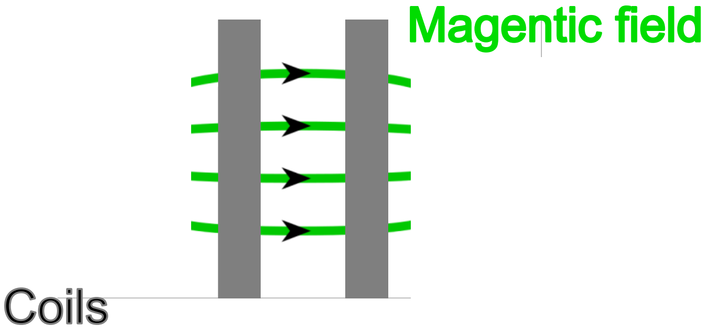


**Useeful for material studies**

# Magenetic confinement

Reactor requires that hydrogen is made into plasma and heated to millions of K but material typically melts at 1000 K.

Can use the fact that charged particles in a plasma follows magnetic field lines.



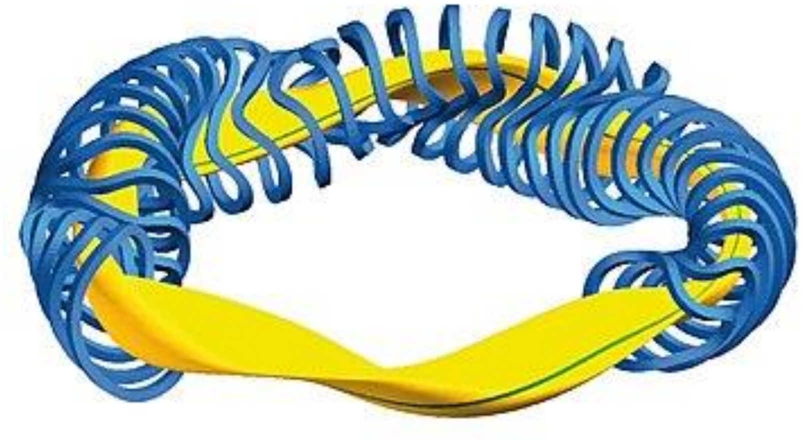
Very difficult to make the ends tight, some of the plasma will leak out.

There is ongoing research to find configurations that solves this problem.

# Stellarator

”Remove the leaky bits” i.e. make a torus: There is still leaks due to the difference in filed strengths on the inside and outside of the torus

Twist the magnetic field: Combine several different magnetic fields or have special magnetic field coils



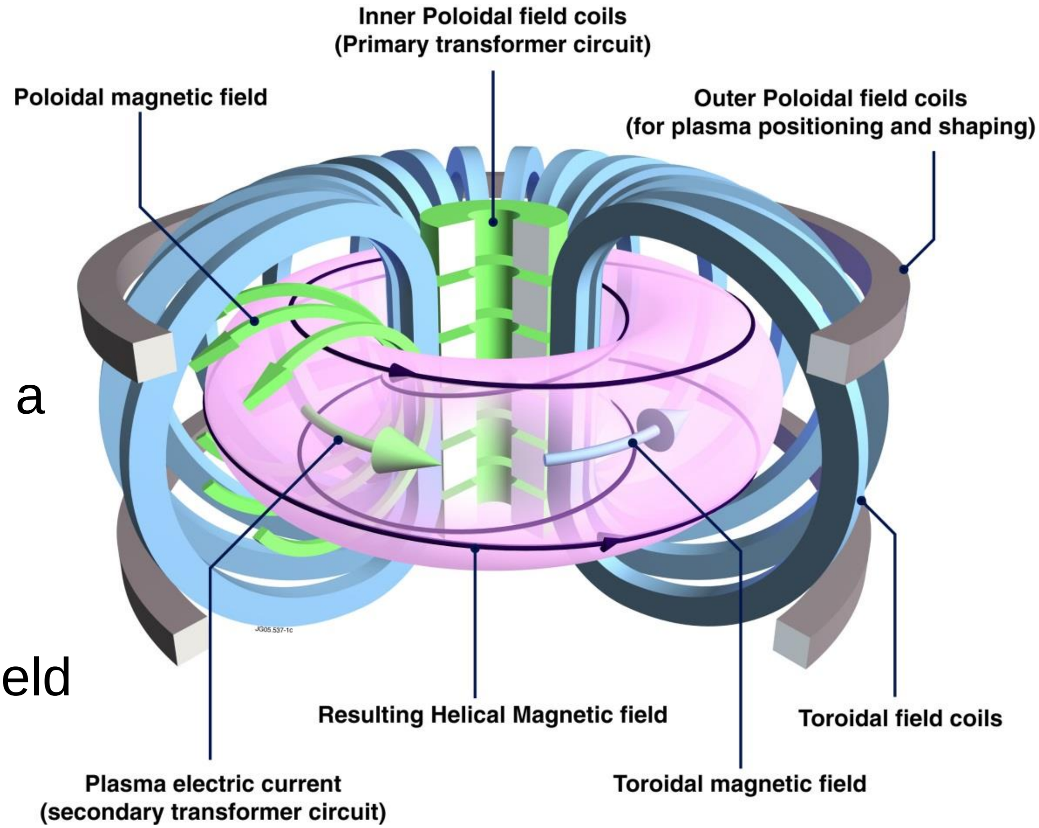
- Continues plasma
- Didn’t work as well as tokmaks
- Renewed interest

Wendelstein 7-X: Greifswald, Germany

30 m$^3$, 3 T, 14 MW heating

# Tokamak

- Developed in Sovjet “toroidal'naja kamera v magnitnych katusjkach”
- A pulsed system based on a transformer
- Generates current through the plasma
  - Rotates the magnetic field
  - Heats the plasma



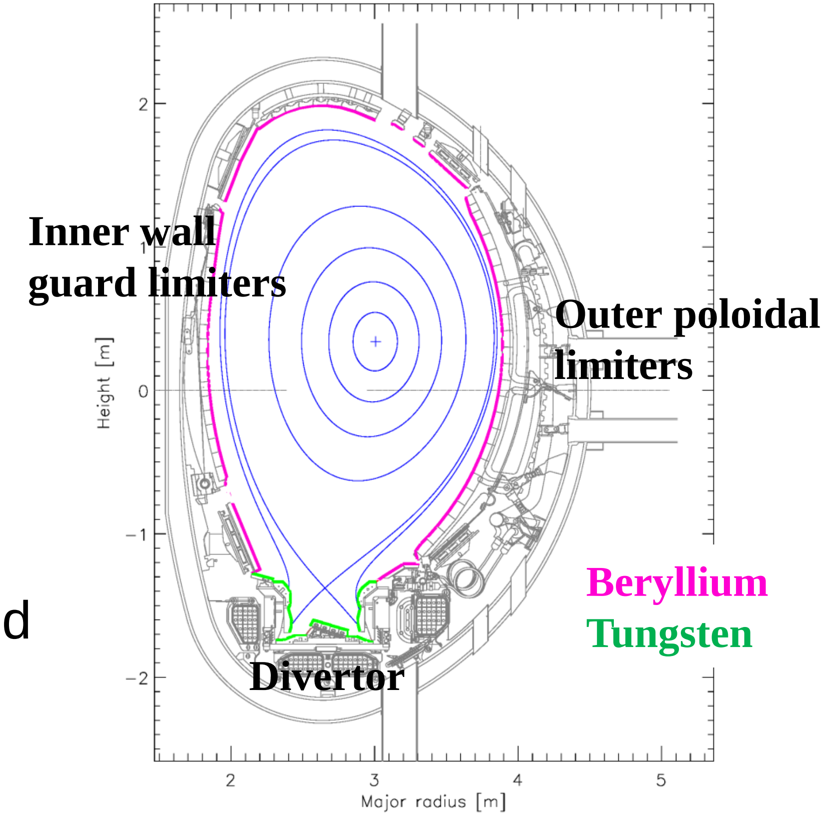
# Walls

In principle a perfect solution but some ions still leaves the plasma:

- Collisions
- Imperfections
- Neutralisation

Also neutrons and photons

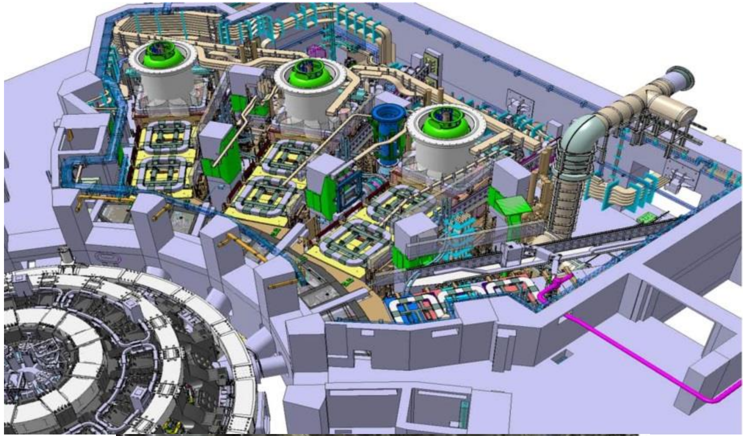
The wall may only have very limited impact on the plasma to prevent cooling.

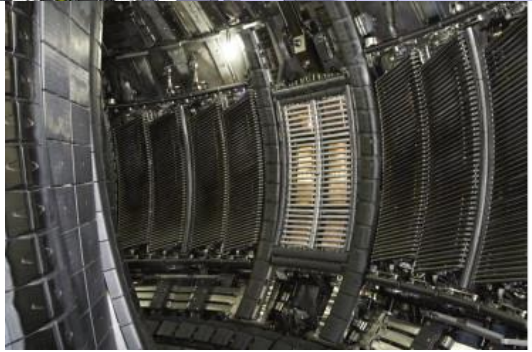


# Heating

Four methods are used to heat the plasma

- Plasma current
  - Limited max temperature
- Radio waves
  - Can also induce a current in the plasma
- Neutral beam injection
  - Largest amount of power today
- Nuclear reactions in the plasma
  - $^4$He from D-T reaction, important for energy production





# Joint European Torus (JET)

- Built to hande tritium (in limited amounts)
- Aimed at Q~1, was seen as step towards a power plant
- Mainly used with deuterium
- Vacuum vessel made of Inconell
- Inner walls of Inconell, Carbon, Beryllium, Tungsten, …

First plasma: 1983

Plasma volume: 90 $m^3$

Magnetic field: <4T

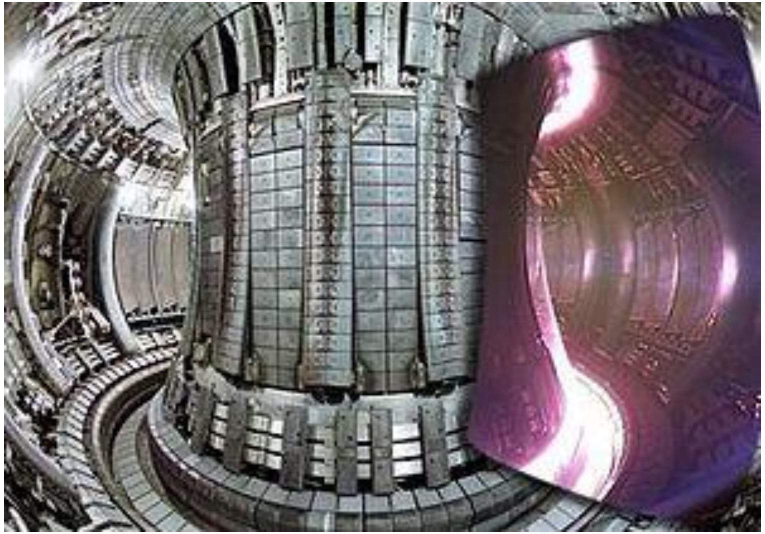
Plasma current: <5 MA

Extern heating: 34+10+7 MW

$Q_{record}$:0,67

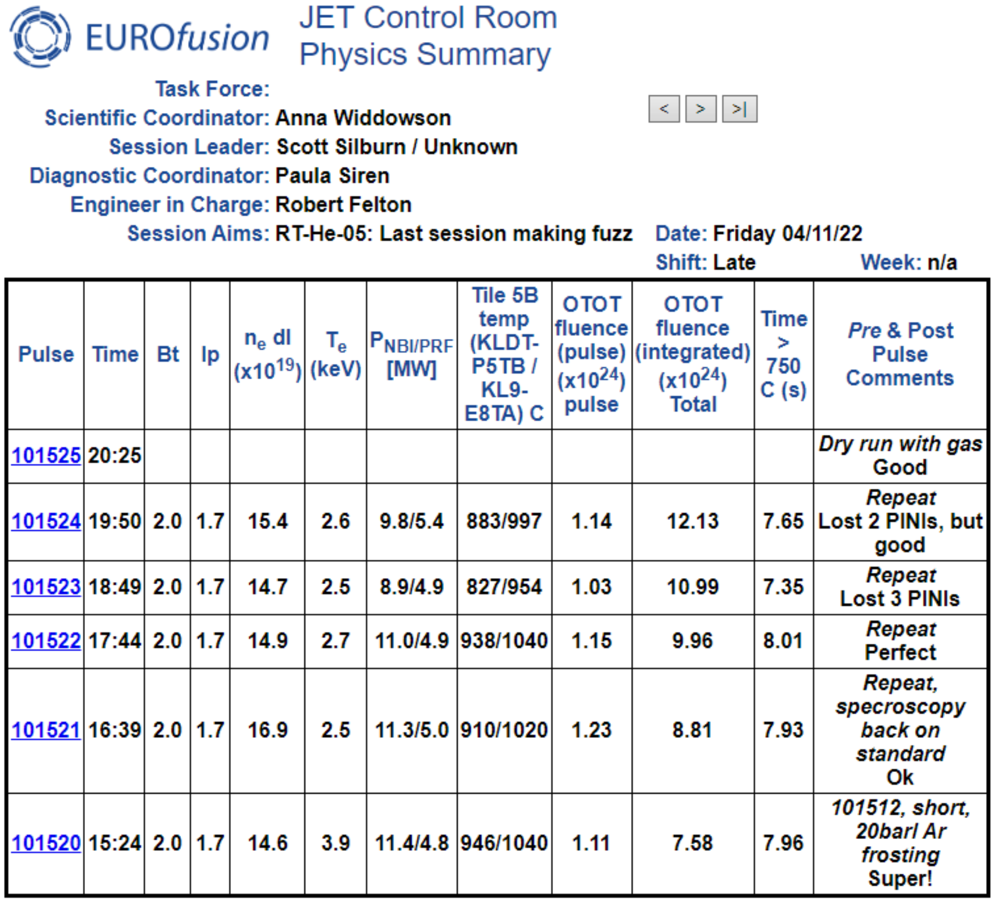
Conventional magnets (Oil cooled)

# JET



# A day at JET

- Two shifts/day 7-14,14-22 each with one experiment
- Several pulses per/shift
- Planed 1-2 years in advance, details finalized in the last month
- The results are studied for years after the experiment



EUROfusion

JET Control Room
Physics Summary

Task Force:
Scientific Coordinator: **Anna Widdowson**
Session Leader: **Scott Silburn / Unknown**
Diagnostic Coordinator: **Paula Siren**
Engineer in Charge: **Robert Felton**
Session Aims: **RT-He-05: Last session making fuzz**
Date: **Friday 04/11/22**
Shift: **Late**
Week: **n/a**

| Pulse | Time | Bt | Ip | $n_e$ dl ($x10^{19}$) | $T_e$ (keV) | $P_{NBI/PRF}$ [MW] | Tile 5B temp (KLDT-P5TB / KL9-E8TA) C | OTOT fluence (pulse) ($x10^{24}$) pulse | OTOT fluence (integrated) ($x10^{24}$) Total | Time > 750 C (s) | *Pre* & Post Pulse Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 101525 | 20:25 | | | | | | | | | | *Dry run with gas*<br>Good |
| 101524 | 19:50 | 2.0 | 1.7 | 15.4 | 2.6 | 9.8/5.4 | 883/997 | 1.14 | 12.13 | 7.65 | *Repeat*<br>Lost 2 PINIs, but good |
| 101523 | 18:49 | 2.0 | 1.7 | 14.7 | 2.5 | 8.9/4.9 | 827/954 | 1.03 | 10.99 | 7.35 | *Repeat*<br>Lost 3 PINIs |
| 101522 | 17:44 | 2.0 | 1.7 | 14.9 | 2.7 | 11.0/4.9 | 938/1040 | 1.15 | 9.96 | 8.01 | *Repeat*<br>Perfect |
| 101521 | 16:39 | 2.0 | 1.7 | 16.9 | 2.5 | 11.3/5.0 | 910/1020 | 1.23 | 8.81 | 7.93 | *Repeat, spectroscopy back on standard*<br>Ok |
| 101520 | 15:24 | 2.0 | 1.7 | 14.6 | 3.9 | 11.4/4.8 | 946/1040 | 1.11 | 7.58 | 7.96 | *101512, short, 20barl Ar frosting*<br>Super! |

# JET puls

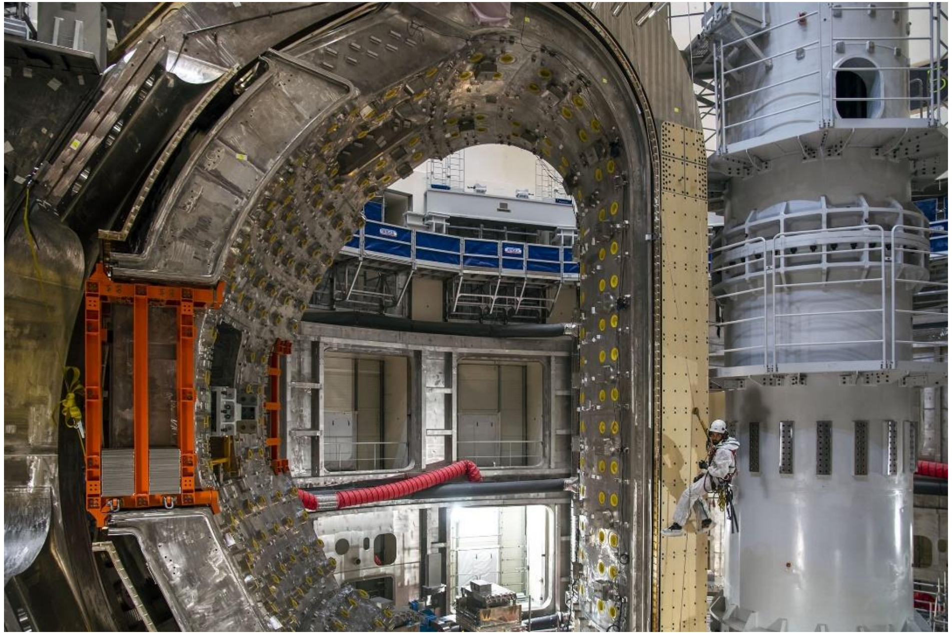
- Campaign with tritium
- World record in fusion energy: 59MJ in 7s
- 3.86 T magnetic filed
- 2.5 MA plasma current
- 28-30 MW NBI heating
- 3.7 MW RF heating
- Brightest areas are often the coolest as fully ionized plasma radiates less

# International Thermonuclear Experimental Reactor (ITER)

- International cooperation to make fusion energy available to the whole world (almost)
- Demonstrate the integrated operation of technologies for a fusion power plant
- Achieve a deuterium-tritium plasma in which the reaction is sustained through internal heating
- Test tritium breeding
- Demonstrate the safety characteristics of a fusion device
- Constructed in Cadarache in France

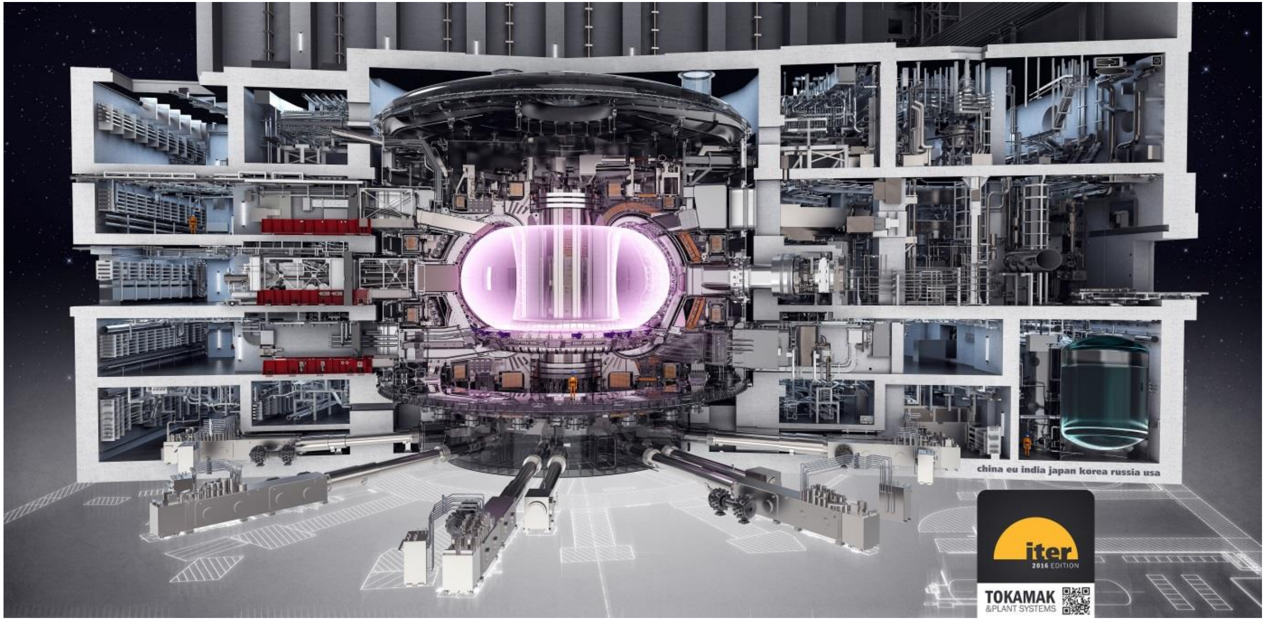
# ITER construction

- All partners contribute ”in kind”
- A lot of politics determines where things are manufactured
- Some identical parts are manufactured at opposite sides of the globe
- Cost >20 billion euro
- Large focus is also on safety plans and permits for running nuclear energy facilities



First section of vacuum vessel ITER on the 9th of June 2022 (Photo iter.org)

# ITER



First plasma: 2025

Plasma volume: 840 $m^3$

Magnetic field:  5 T

Plasma current: 15 MA

External heating:
33+10+24 MW

Q:10

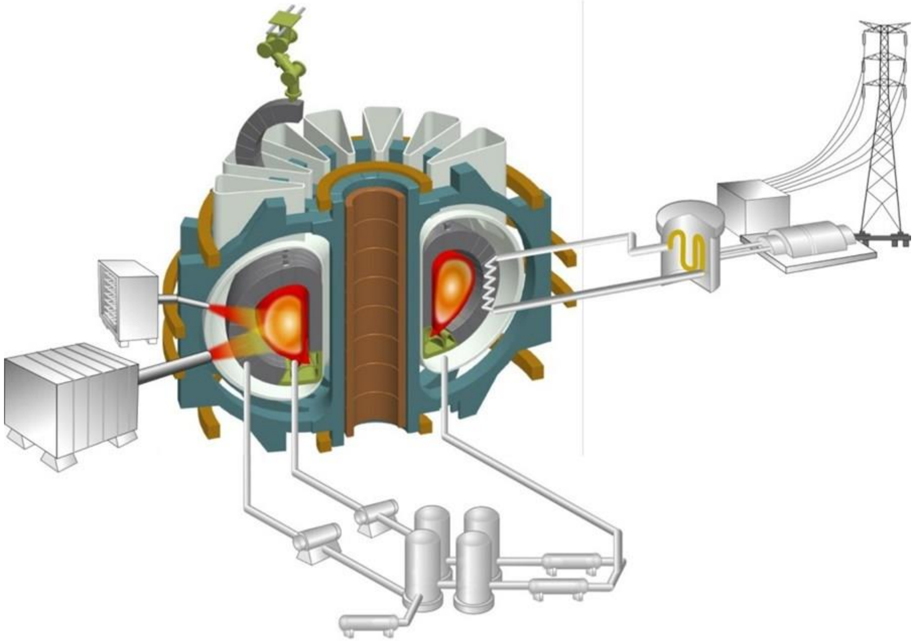
Pulse length: 400s >

$Nb_3Sn$ Superconductors

Be walls, W divertor

# Demonstration Power Station (DEMO)

- Slightly bigger than ITER
- 2-3 GW
- Complete blanket:
  tritium self-sufficient
  extracting energy
- High availability
- Not as flexible
- Not an international co-operation
- Tungsten walls

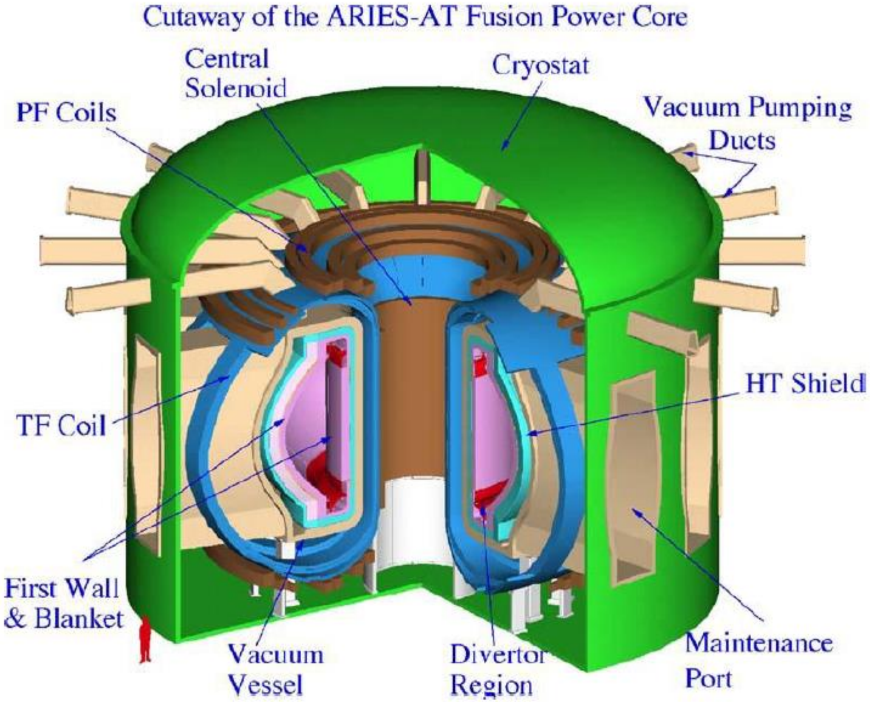


# ARIES background

- US-DEMO before DEMO
- More to indicate directions then to be a complete design
- To show what is important and where improvements are needed
- Made for several different configurations
- Generally very advanced solutions
  - Silicon carbide
  - Helium cooling
  - Liquid blanket
- Very modular constructions

# AREIS-AT construction

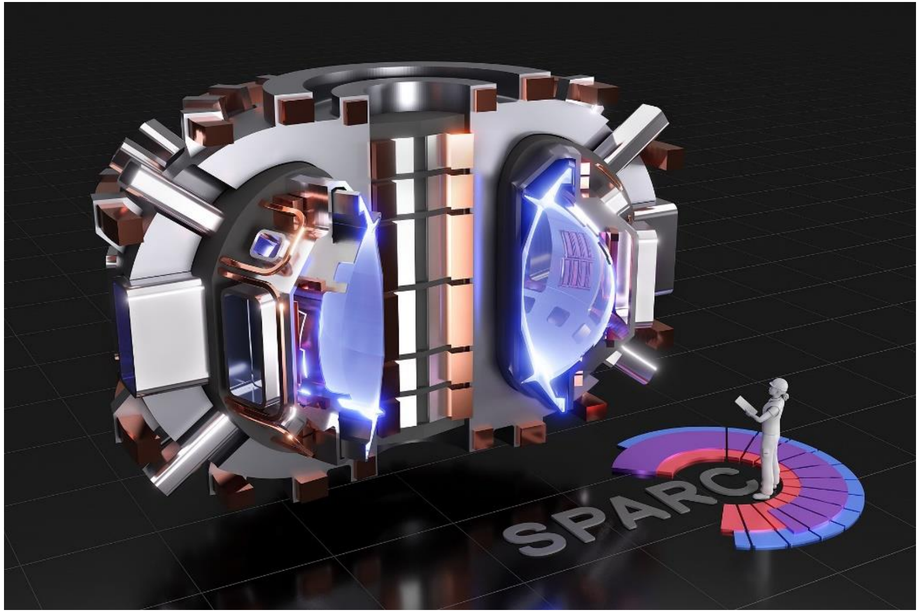
Major radius: 5.2 m
On-axis field: 5.8 T
Average wall load: 3.3 MW/m$^2$
Plasma current: 13MA
Bootstrap current fraction: 0.91
Thermal efficiency: 0.59
Cost of electricity:5 ¢/kWh
Superconductor: Nb$_3$Sn el. NbTi



# SPARC reactor

- Based on the possibility to have higher magnetic fields :REBCO superconductor
- To be finished 2025
- Demonstrator for ARC reactor

Fusion power: 140 MW
Power multiplication factor (Q): 2-10
Plasma volume: 20 $m^3$
Toroidal magnetic field: 12 T
Plasma current: 9 MA

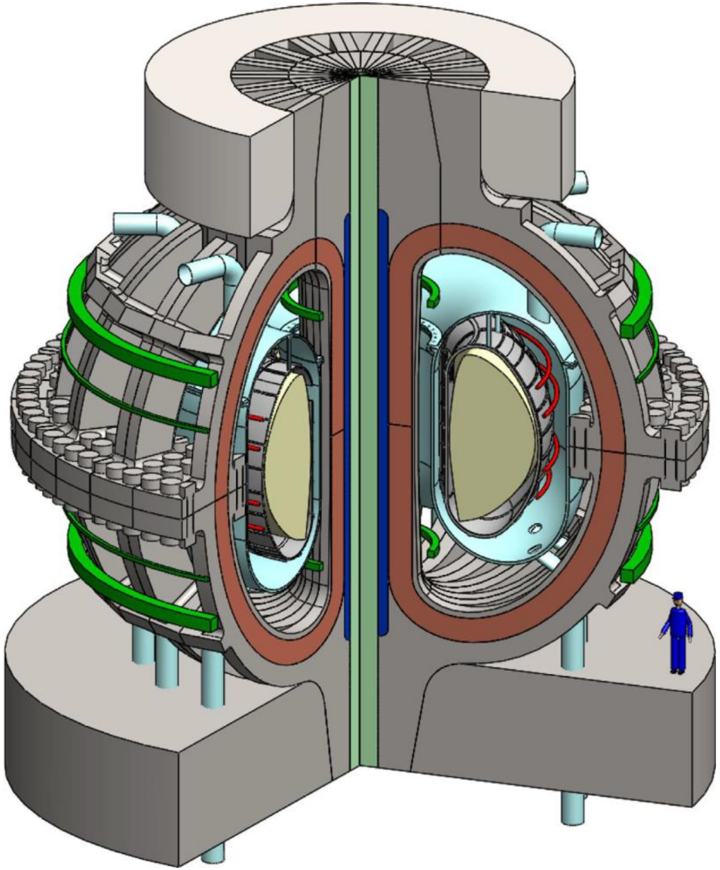


Rendering of SPARC by. Henderson, CFS/MIT-PSFC

# ARC

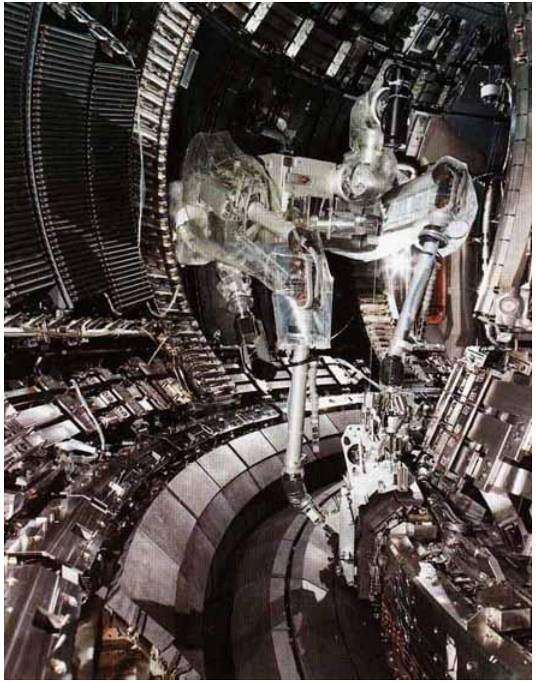
- Developed at MIT (started as student exercise)
- Combines advances in superconducting technology with advanced solutions e.g liquid salts  etc.

Fusion power: ~500 MW
Electrical power: ~200 MW
Plasma volume: 141 m$^3$
Toroidal magnetic field: 9.2 T
Plasma current: 7.8 MA
Bootstrap fraction: 0.63
Tritium breeding ratio: 1.1

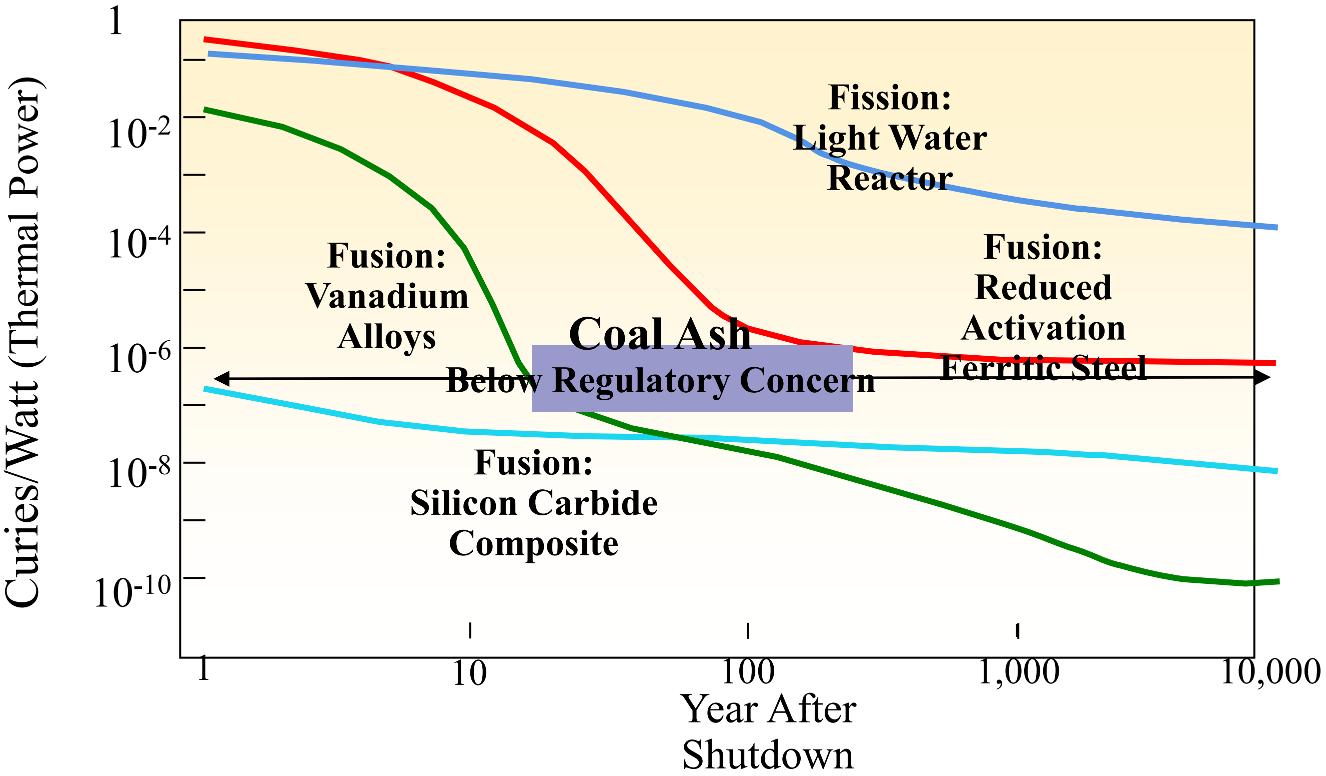


# Safety

- Tritium is radioactive and the main focus for ITER safety (release of 1 kg T causes only 50 mSv at 1 km distance so evacuations planes are not needed)
- Components and wall materials will be activated
- Disruptions can damage the wall and quench the superconducting magnets
- If liquid metals or salts are used for cooling they can be very chemically reactive
- Interactions inside a started fusion reactor will have to be done by remote handling.



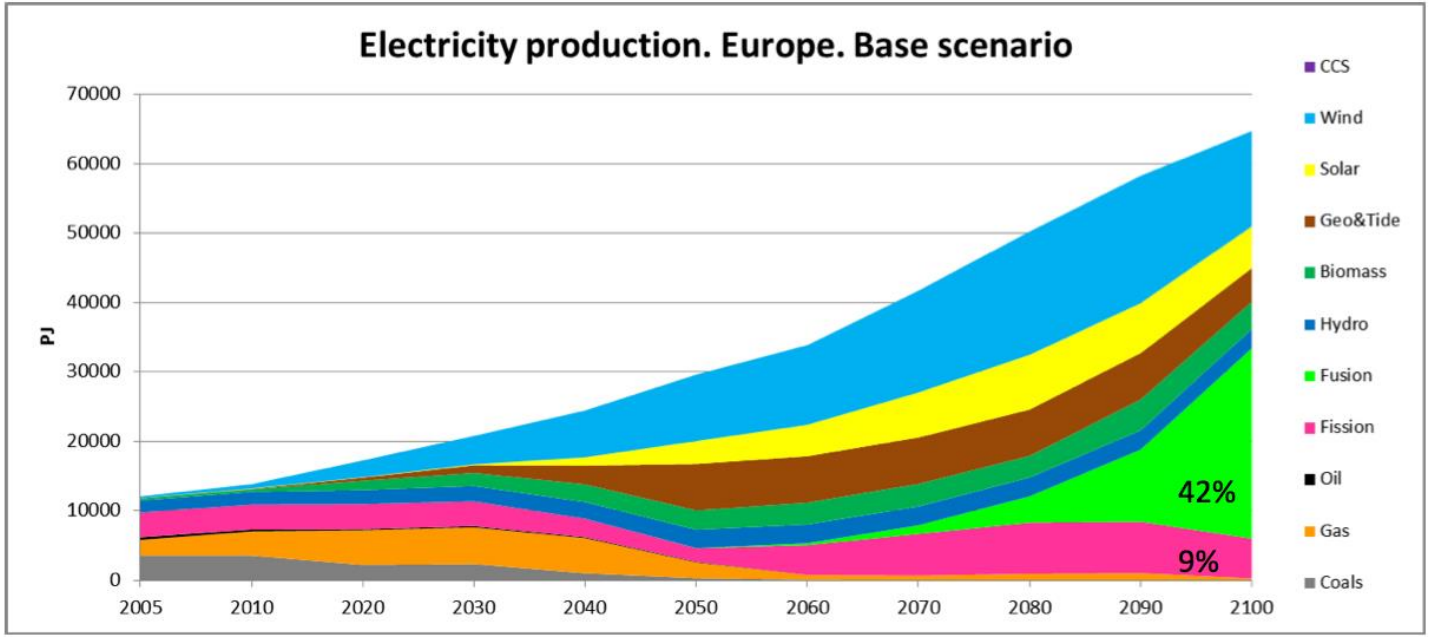
# Long term radioactive activity



# Times scales for development

EUROPEAN FUSION DEVELOPMENT AGREEMENT

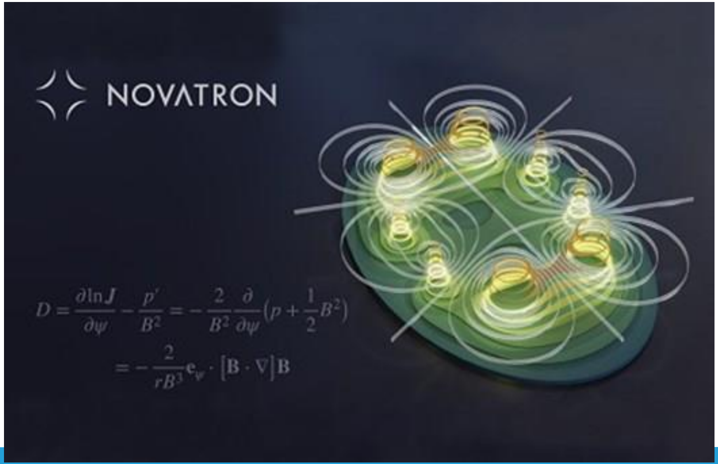
Cost-optimized for max 550 ppm $CO_2$ year 2100



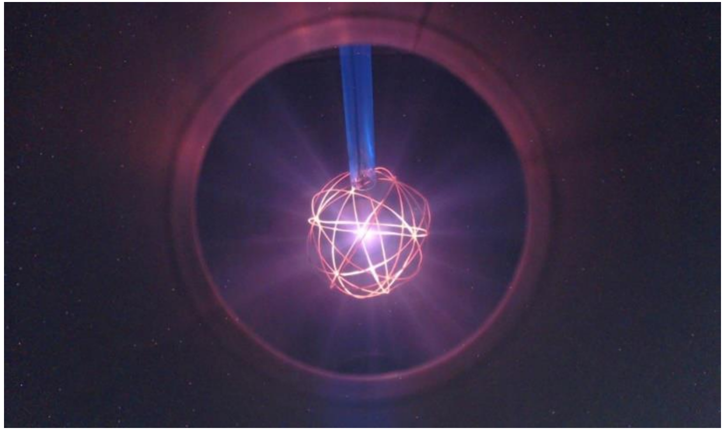
# Alternativ solutions

**General Fusion**
Compresses plasma by focus of mechanical energy
Planning demonstrator with UKAEA at Culham Campus

**Novatron/Jäderberg Future Power**
Swedish startup with KTH connection
More stable method to control a linear plasma.
https://www.jfpower.se



# Alternativ solutions



**FUSOR**

Simple to build

Has been tested for a long time

Can be useful as neutron sources

**Muon catalysed fusion**

Muons are heavy (207ggr) and instable versions of electrons. As the size of an atom is dependent on the mass of the electron, muons can bring the nucleus much closer together and increase the chance of nuclear reactions between them. However the energy needed to produce the muon is to high for net energy production.

# Cold fusion

## Pons and Fleischmann (1989)

D-D reaction during electrolysis by palladium electrodes of heavy water

Has not been repeated despite many attempts

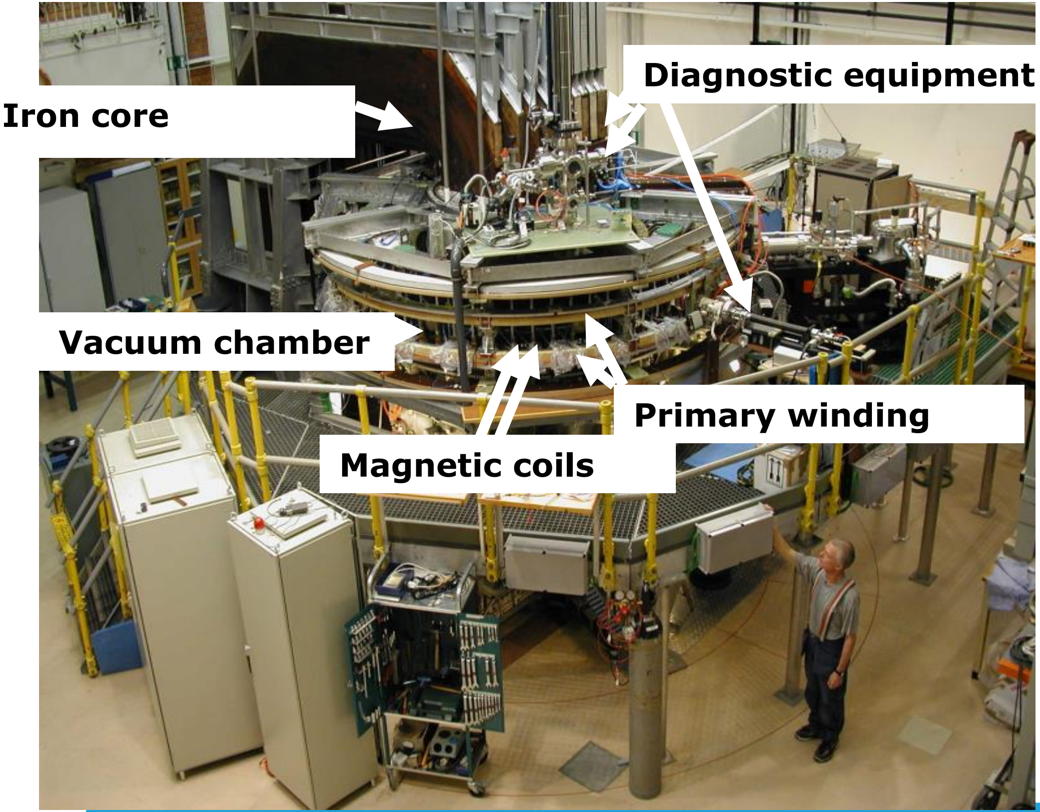
Probably a measuring error

## E-cat Andrea Rossi (2011)

Reaction between hydrogen and nickel

Could be a measuring problem but more likely a deliberate hoax.

# EXTRAP T2-R



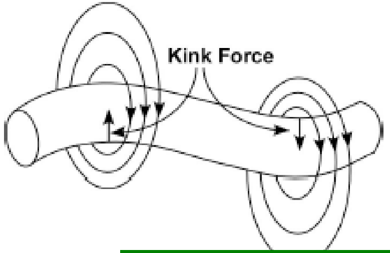
**Reversed field pinch**
Fusion experiment at KTH

Used primary to study plasma stability and plasma control.

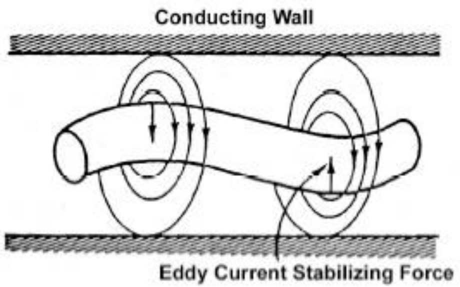
Can also be used for material exposure.

Education and training of students

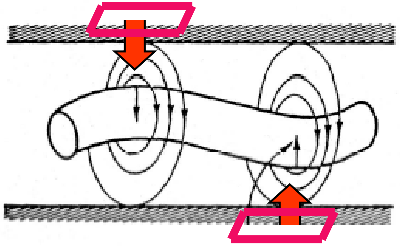
# Plasma stabilisation



1. Plasma instability: In some situations plasma is unstable: Small disturbances grow to large disruptions.



2. Passive stabilization: An electrically conductive shell dampens the disturbance as magnetic field interacts with he shell and causes eddy currents.



3. Active stabilization: Complete dampening can be achieved by adding an external field that opposes the original disruption.

# Fusion reserch at KTH

- Strongly connected to the European EUROfusion program
  - JET
  - Wendelstein 7-X
  - ASDEX-Upgrade, TCV, WEST/Tore Supra, MAST …
- Plasma diagnostics and simulations
  - Simulations of heating by radio waves
  - Measurement of plasma density and temperature at the edge of the plasma
- Material analysis and development
  - What has been eroded and deposited by the plasma
  - Neutron damage in materials

# References and further reading

Fusion in general:

- https://en.wikipedia.org/wiki/Fusion_power
- Chapter 1 in Fusion Physics, Kikuch et.al.
- https://www-pub.iaea.org/books/iaeabooks/8879/fusion-physics

JET

- Nuclear Fusion, Vol. 41, No. 12R (2001)
- Phys. Scr. 2011 014001

ITER

- https://www.iter.org/

ARIES-AT

- Fusion Engineering and Design, Volume 80, Issues 1–4, January 2006

ARC

- Fusion Engineering and Design, Volume 100, 2015 378-405

SPARC

- Journal of Plasma Physics 86 Issue 5 October 2020