The future of fusion: Putting the sun in a box

Hans van Eck

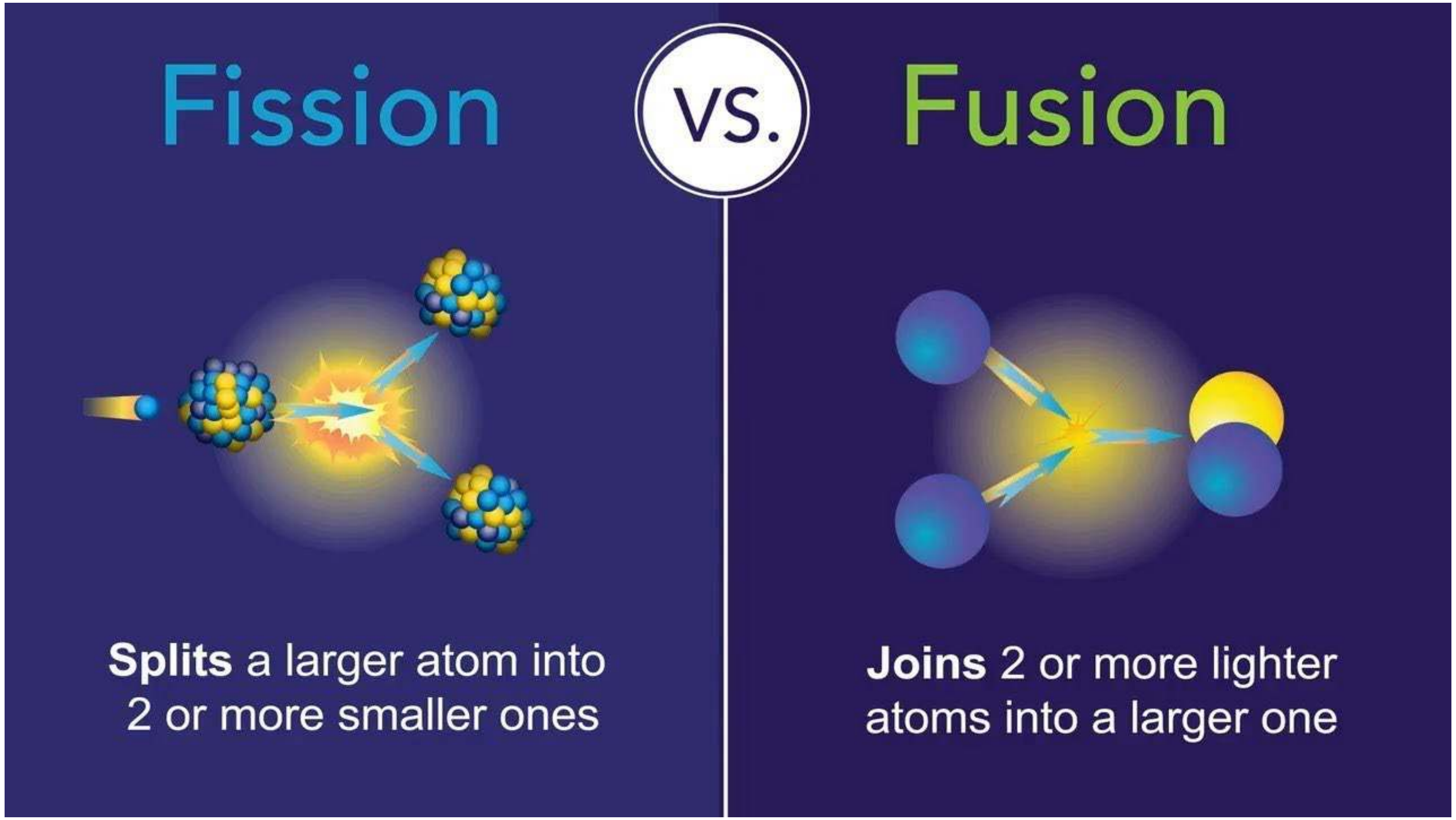
DIFFER

EUROfusion

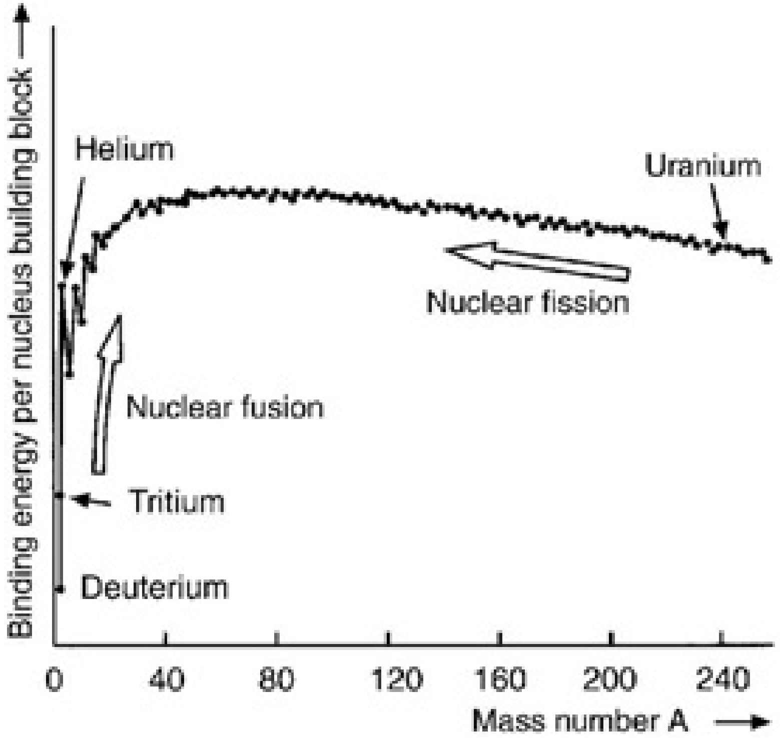
NWO

What is nuclear fusion?

Fission vs Fusion

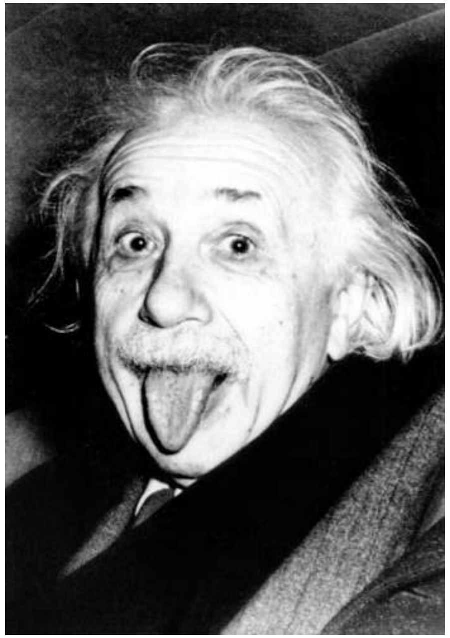


Both reactions shift towards higher bounded nuclei



European Nuclear Society

Fusion reaction



Deuterium (^{2}H)
2.014 u

Tritium (^{3}H)
3.016 u

$E = mc^2$

Helium-4 (^{4}He)
4.003 u

Neutron
1.009u

Proton

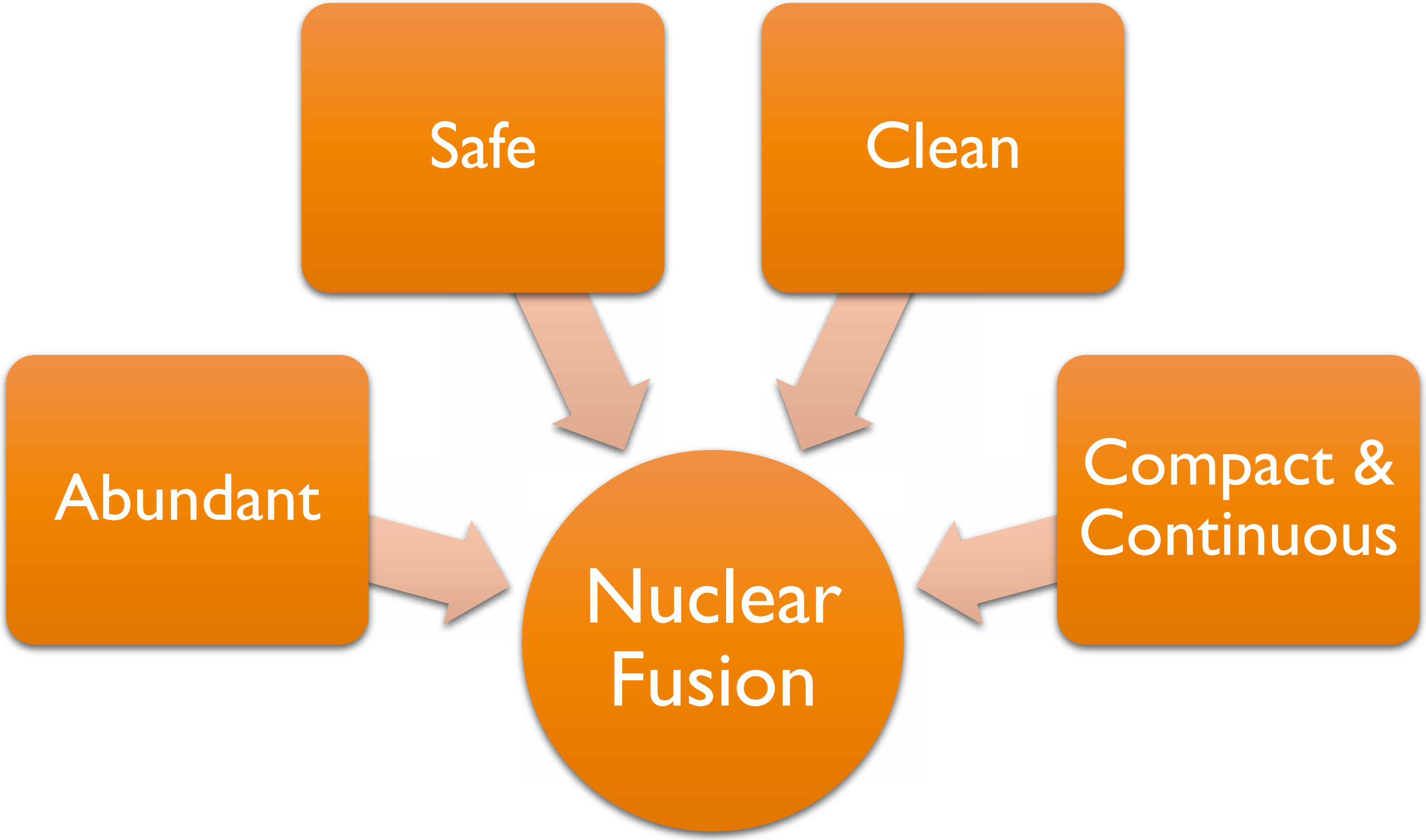
Neutron

5.030 u	-	**5.012 u**	=	**0.018 u**

0.018 u x (1.66 x 10^{-27}) ≈ 2.988x10^{-29}

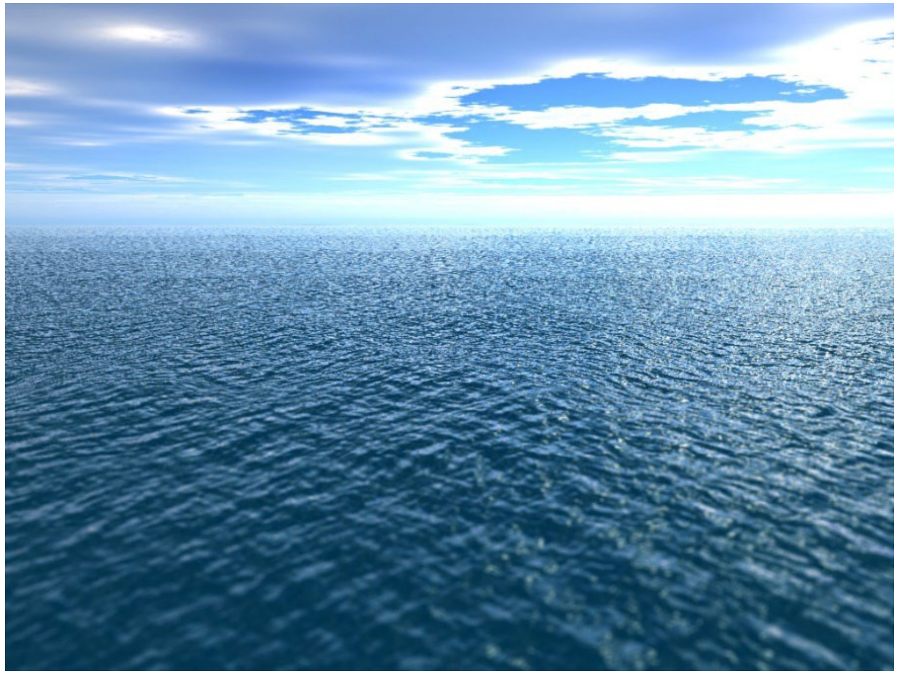
1 atomic mass unit (u) ≈ 1.66x10^{-27} kg

Why do we want fusion?



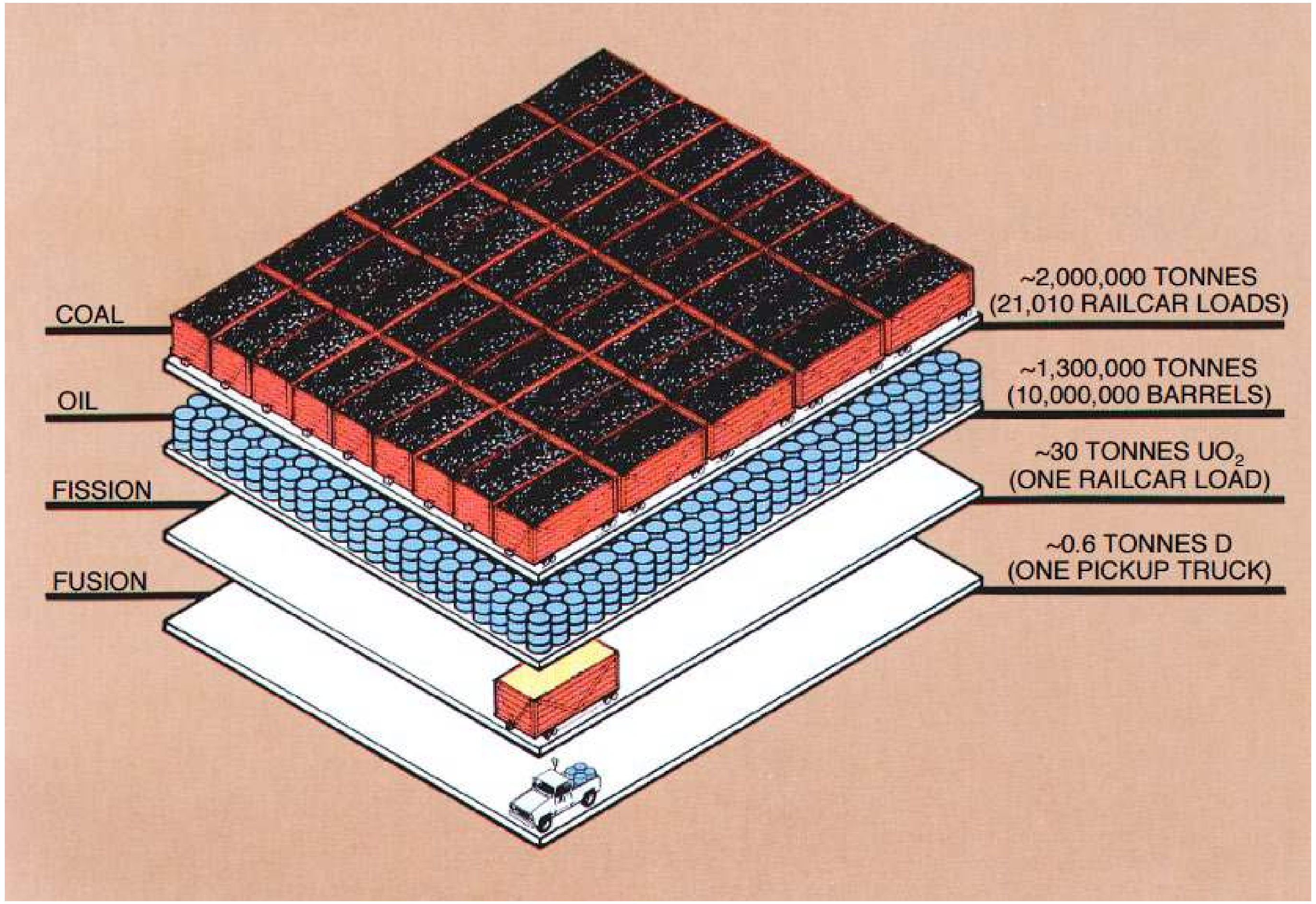
Fusion resources are nearly limitless

30 million years of Li supply
in seawater and Earth's crust



Billions of years of D supply
(1 in 6420 H_2O is an HDO)

Fuel for 1 year for a 1 GW power plant



Bathtub half full of water

Li from a laptop battery

Energy for average family for 30 years

No pollution, meltdown, nuclear weapons or long-lived waste

No CO2, continuous and compact: a good compliment to renewables

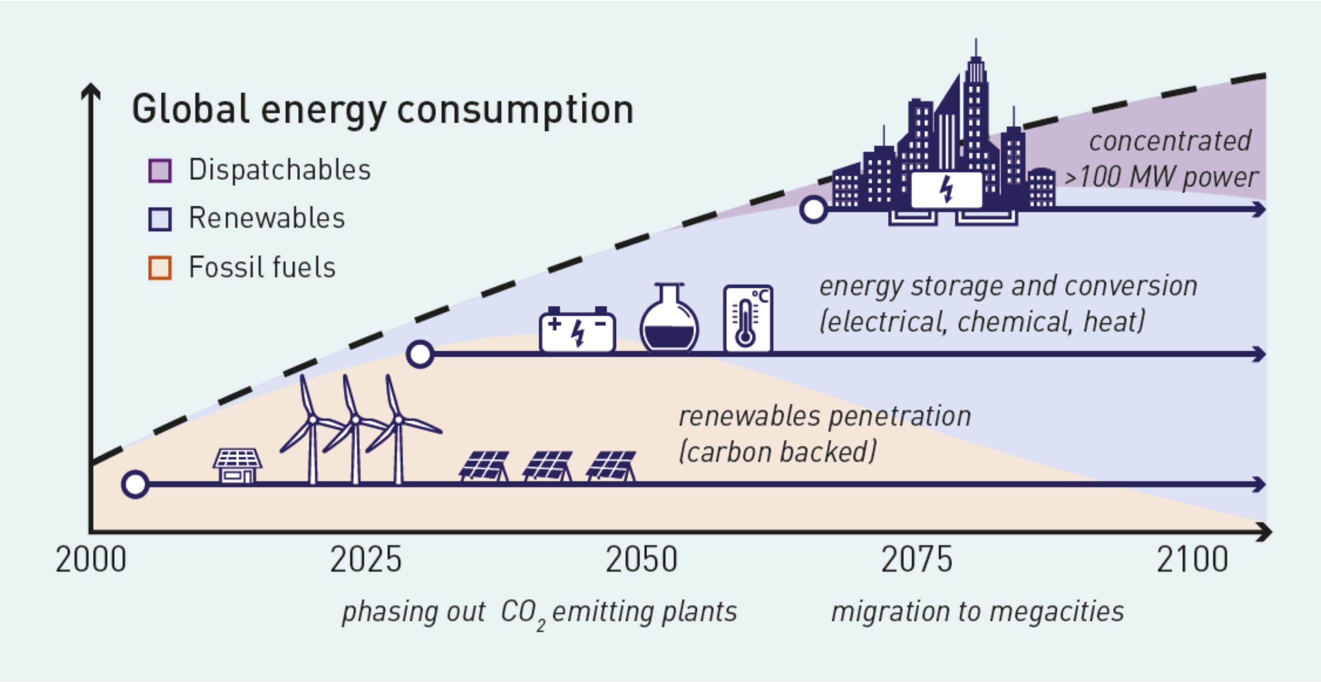
Green

Can operate 24 hours a day

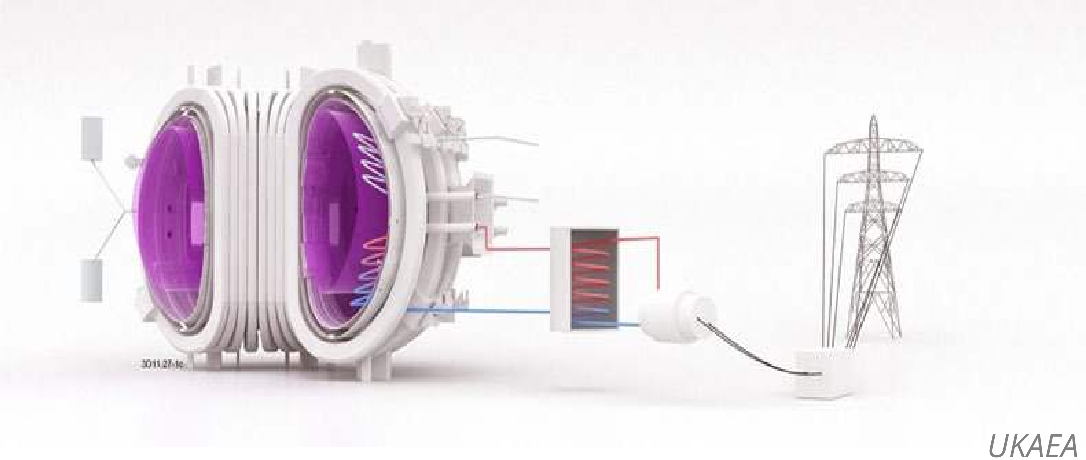
Compact site (like typical power plant)

The role for nuclear fusion in the energy transition

2100: 10 billion population with rise of megacities.
We need new sustainable energy sources.



DIFFER



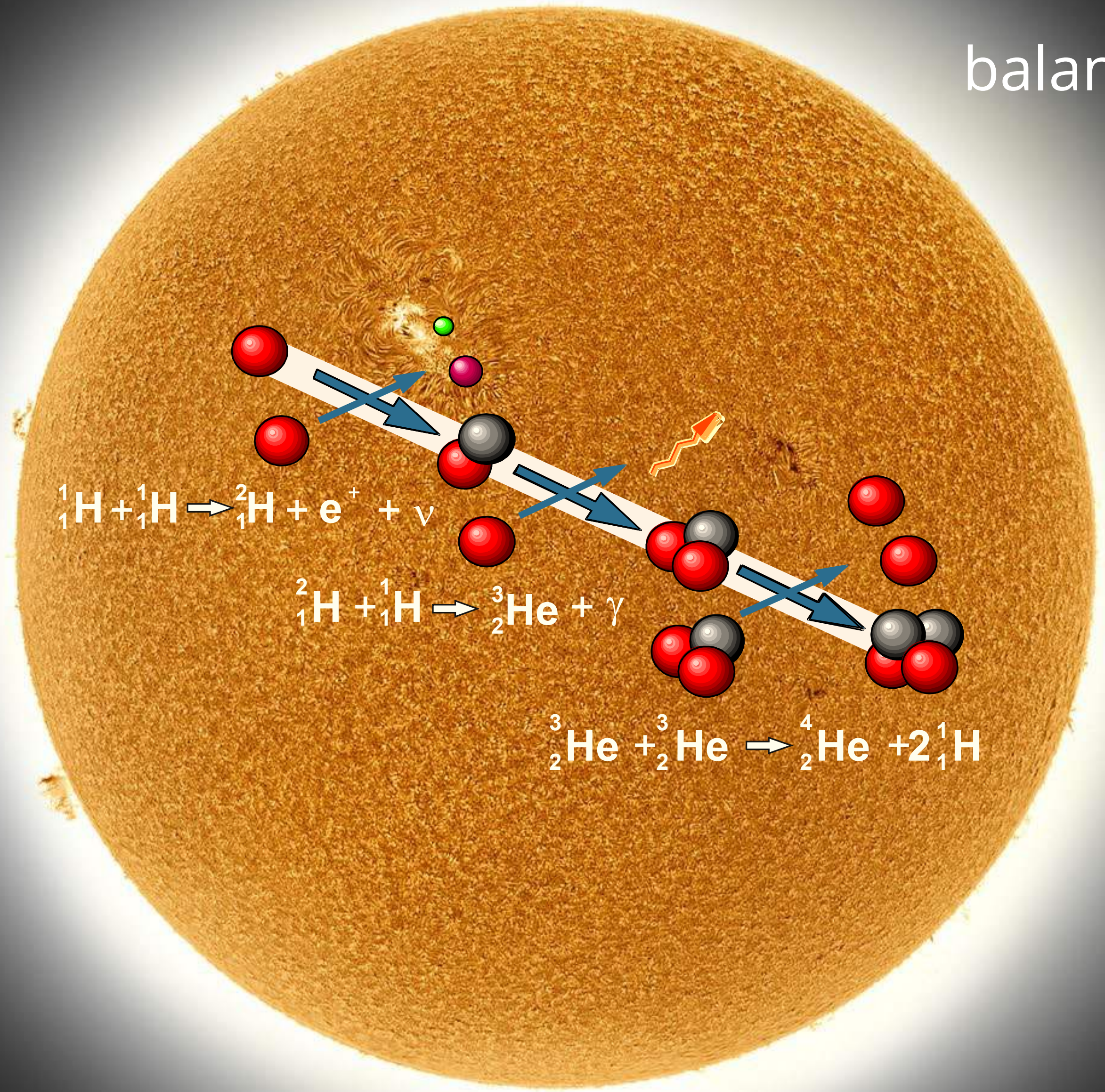
UKAEA

Nuclear fusion energy:

- Zero-CO_2
- Continuous & compact
- Safe & Clean

Fusion process in sun‘s core:
the pp-cycle
balances gravitational force

Scale sized Earth

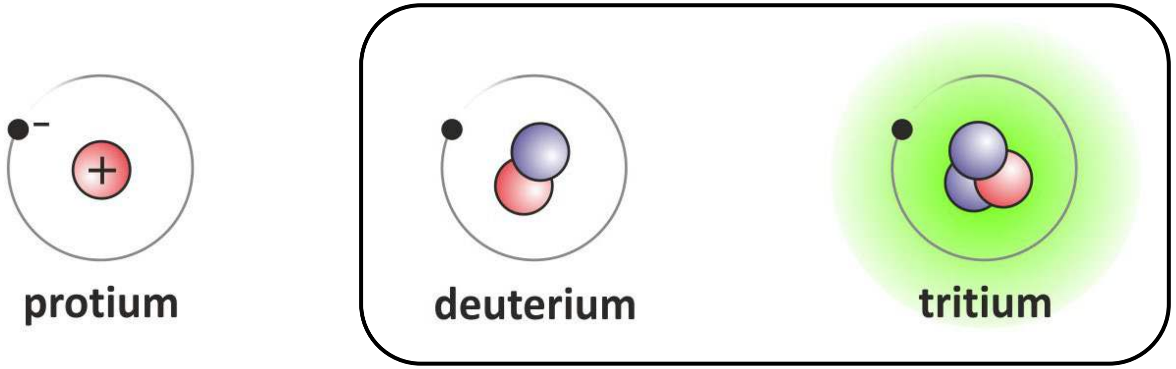


Plasma:
hot ionized gas
15 600 000 K in core
5 800 K on surface

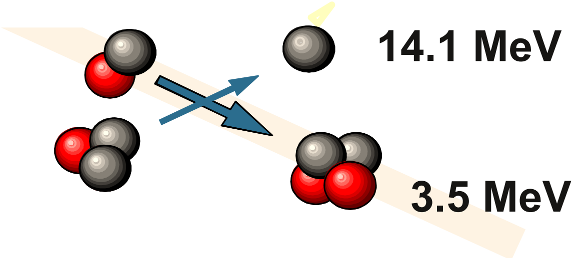
Mass of sun
1×10^{30} kg

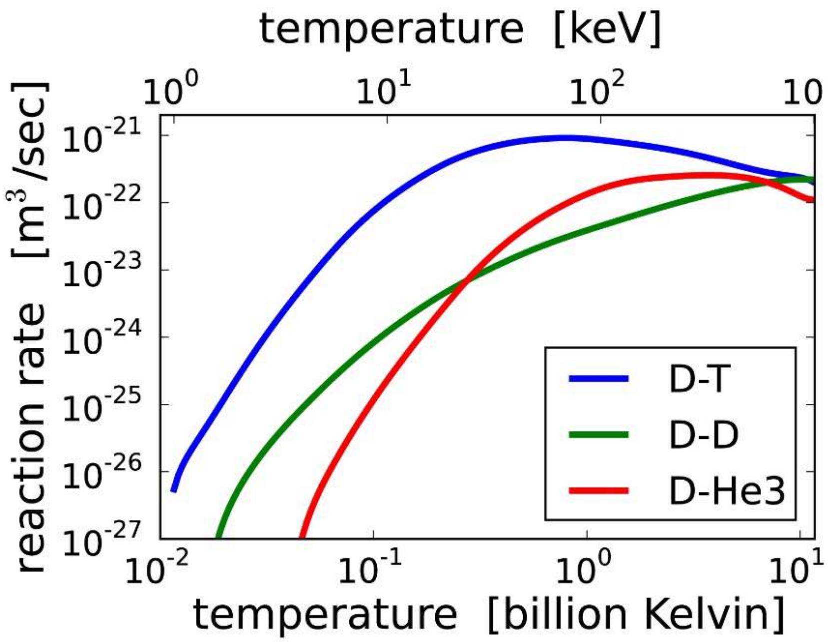
Fusion on Earth

- Gravitational nuclear fusion process (pp-cycle) **not** possible on earth
- Thermo-nuclear reaction with largest fusion cross-section (with magnetic confinement) on earth: **DT reaction**

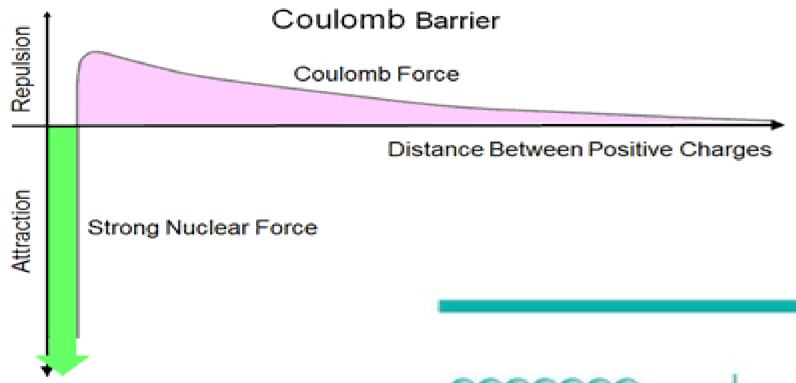


$$Li_6 + n \rightarrow He_4 + T$$

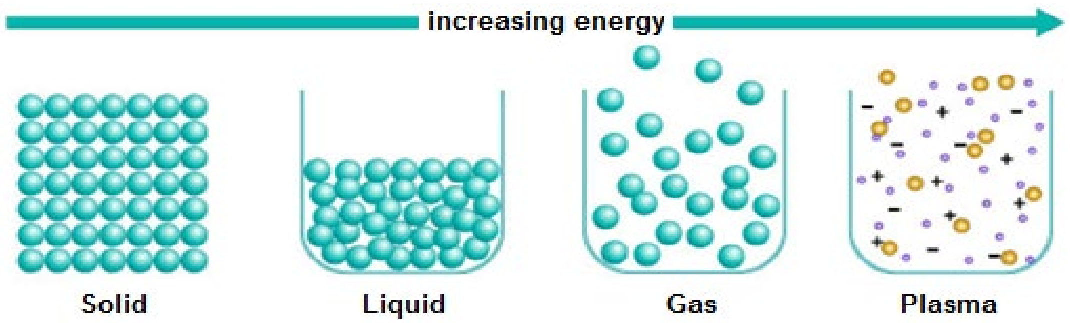




Fusion Challenge



Need hot fuel to have enough energy to overcome Coulomb barrier: needs temperatures of ~150 million °C!



Fuel is a plasma
(soup ionized gas)

Lawson criterion for
DT ignition:

$$n \cdot T \cdot \tau_{th} \geq 5 \cdot 10^{21} \left[\frac{keV\ s}{m^3}\right]$$

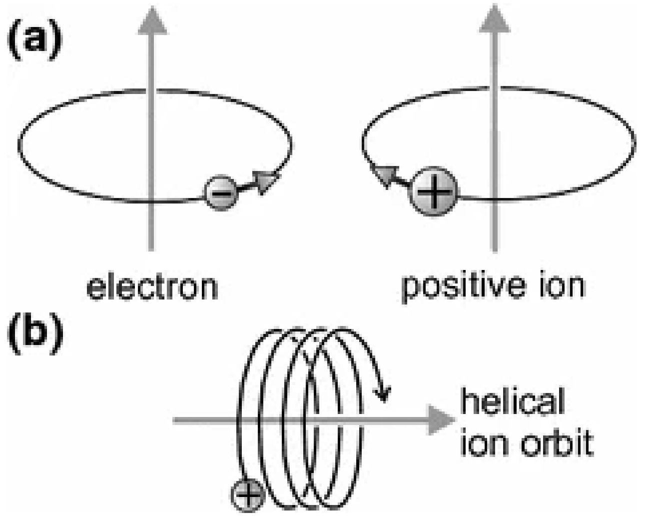
Need to confine to get sufficient reactions taking place to sustain a burning plasma (energy of reactions keeps it going like a fire)

How do we make fusion happen?

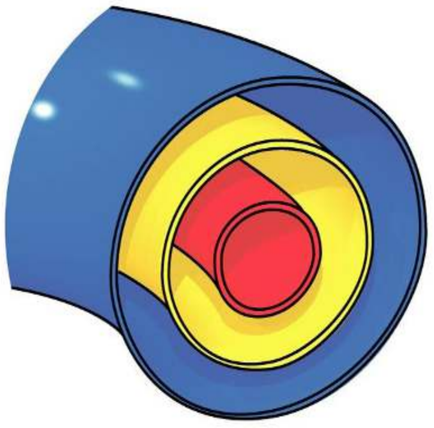
Heating the fuel

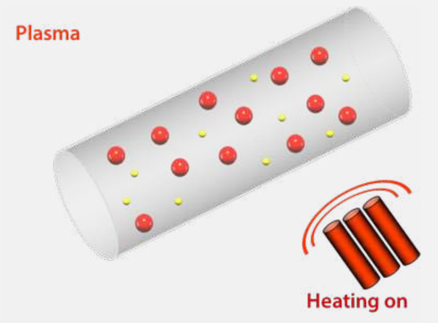
D + T → ^{4}He + n + energy

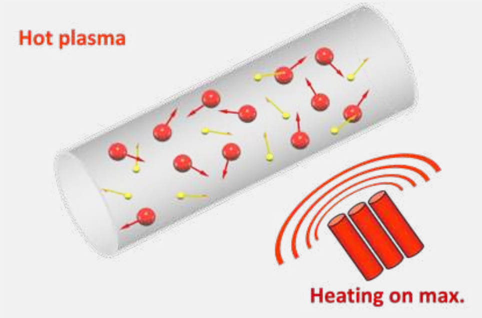
- Highest reaction rate
- ^{4}He: 3.5 MeV
- n: 14.1 MeV
- 150 000 000 Kelvin
- 17.6 MeV from one D-T reaction

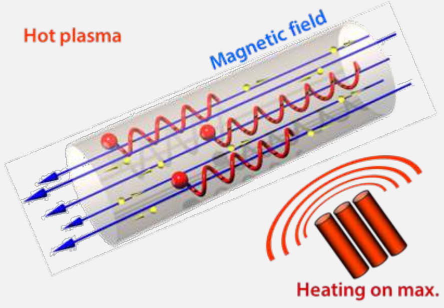


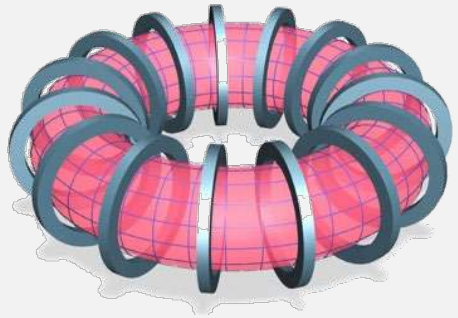
Piel: Plasma Physics (2017)



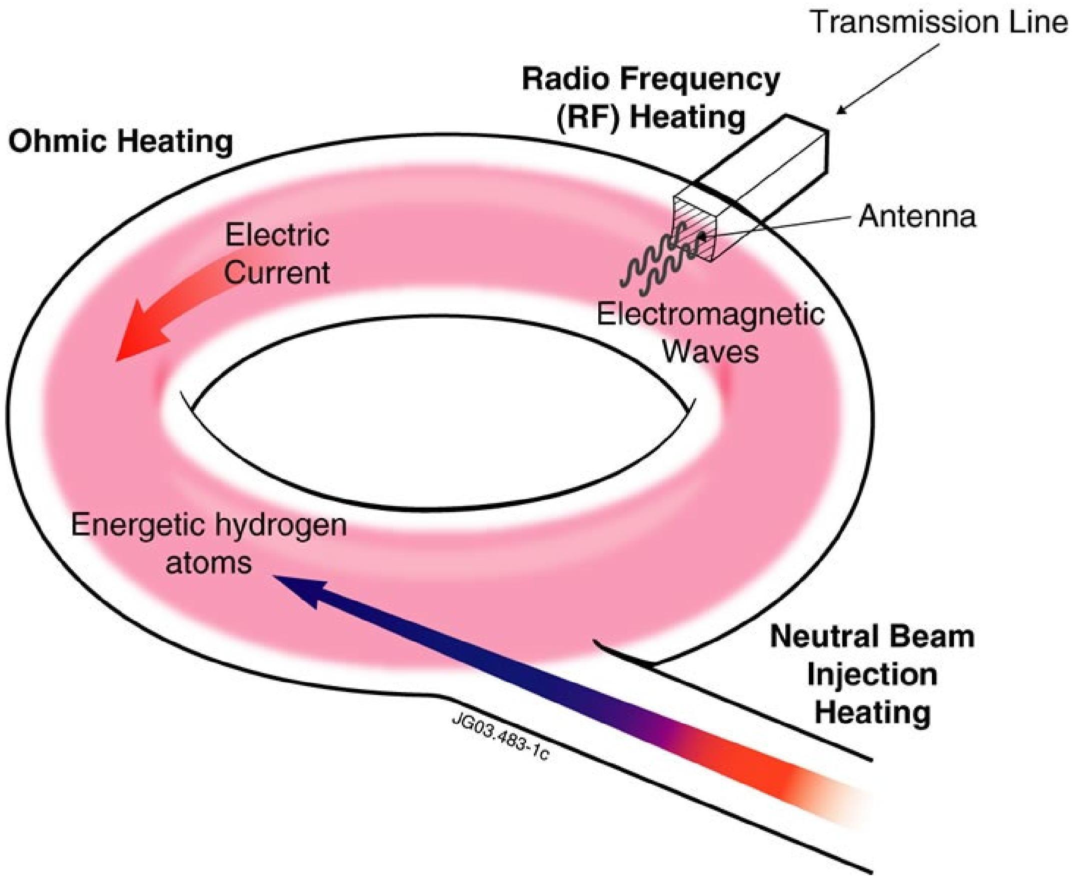


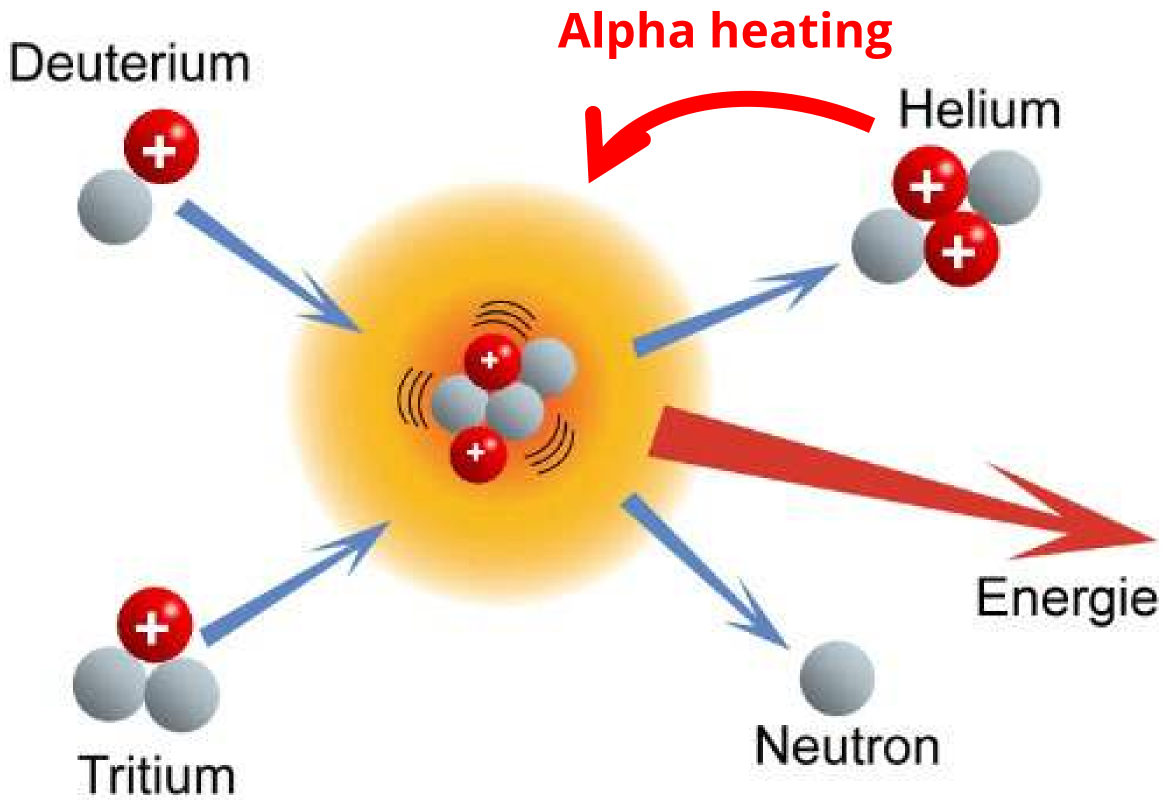






Heating the fuel



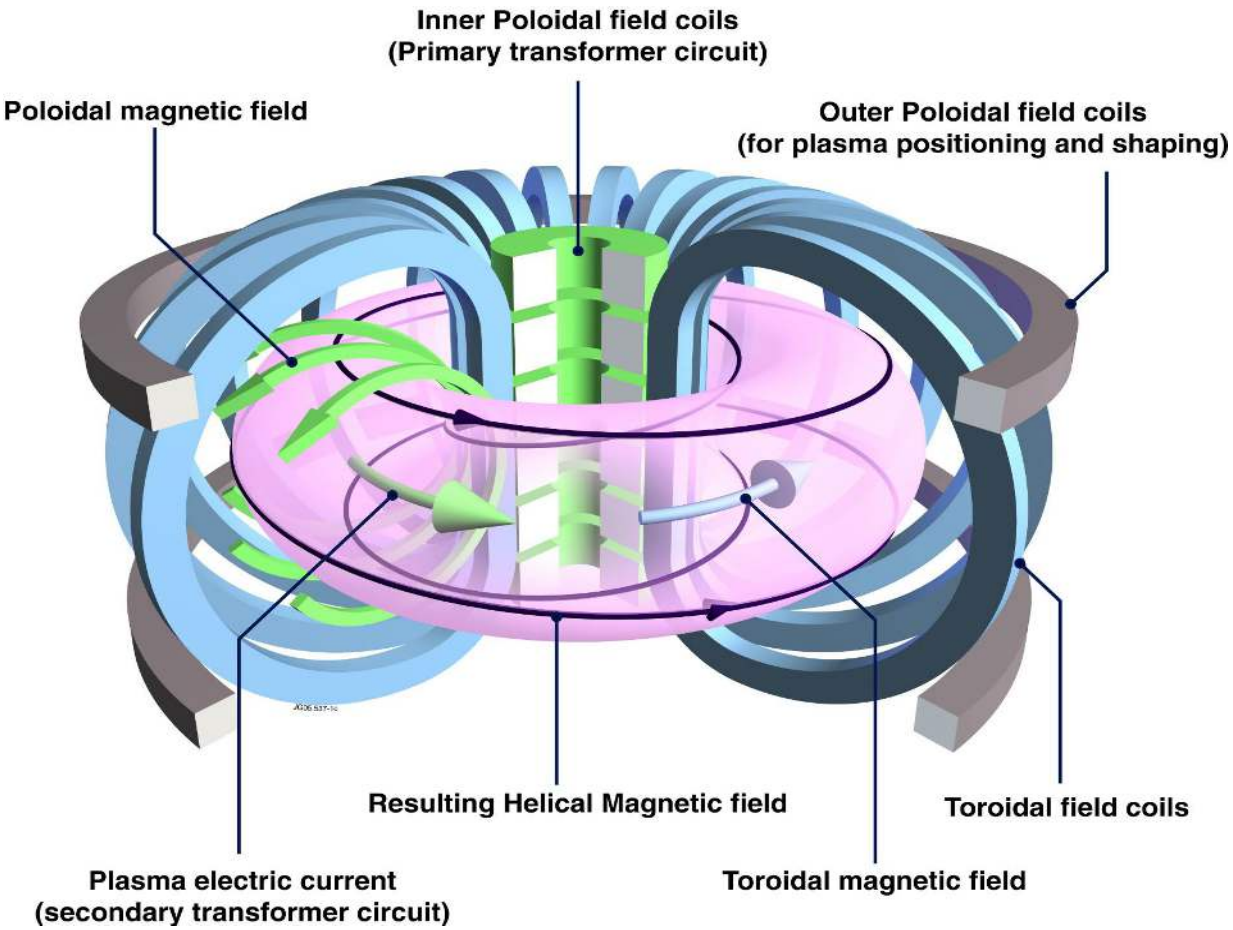


Magnetic confinement fusion

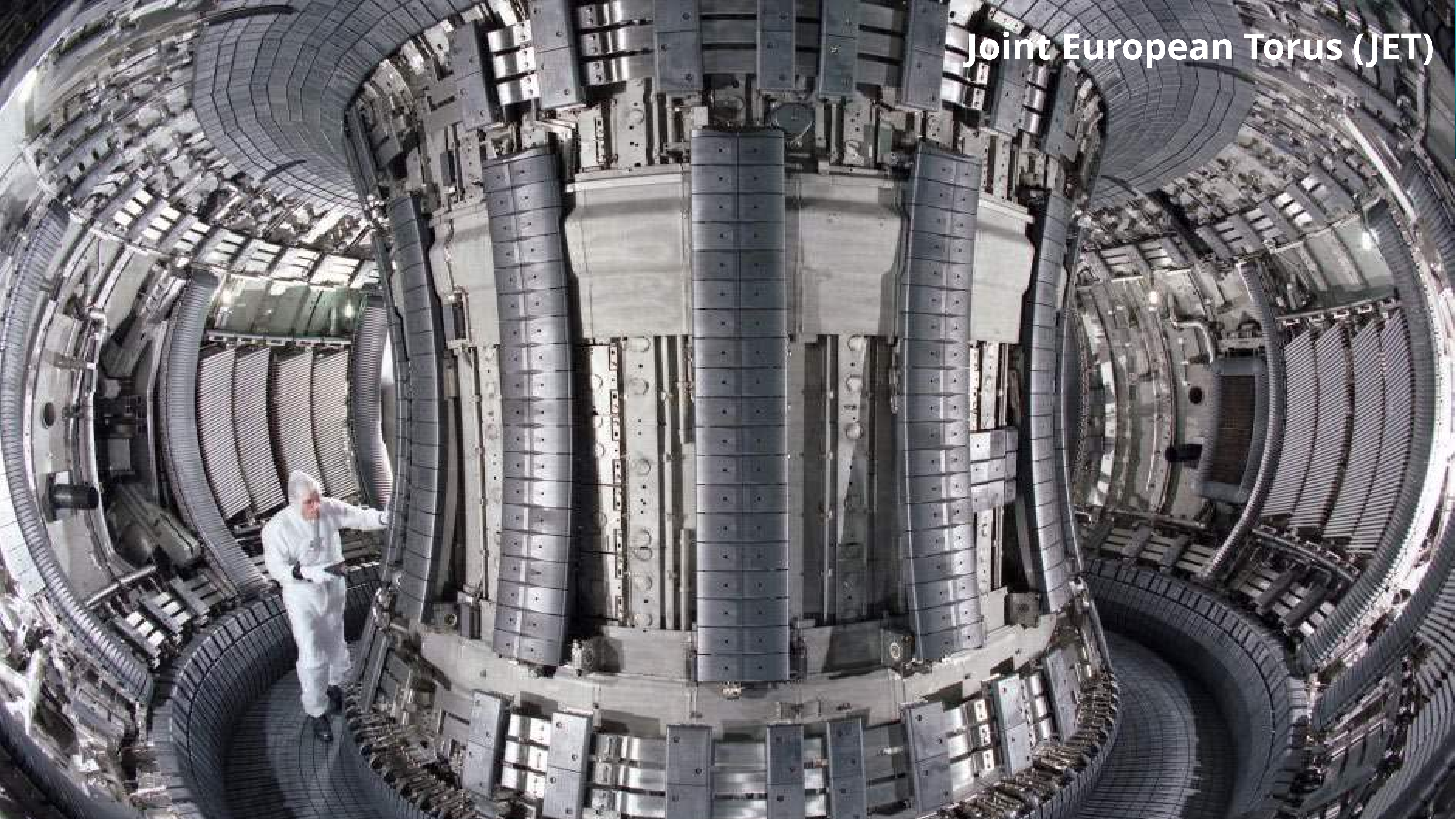
Use magnetic bottle to confine on long timescales:

- Particles gyrate around magnetic field lines
- Bend magnetic field in a circle to form toroidally nested surfaces
- Twisted magnetic field counters drifts and improves confinement
- **Tokamak:** toroidal field created by external coils and poloidal field created by plasma current to create twisted field

The Tokamak



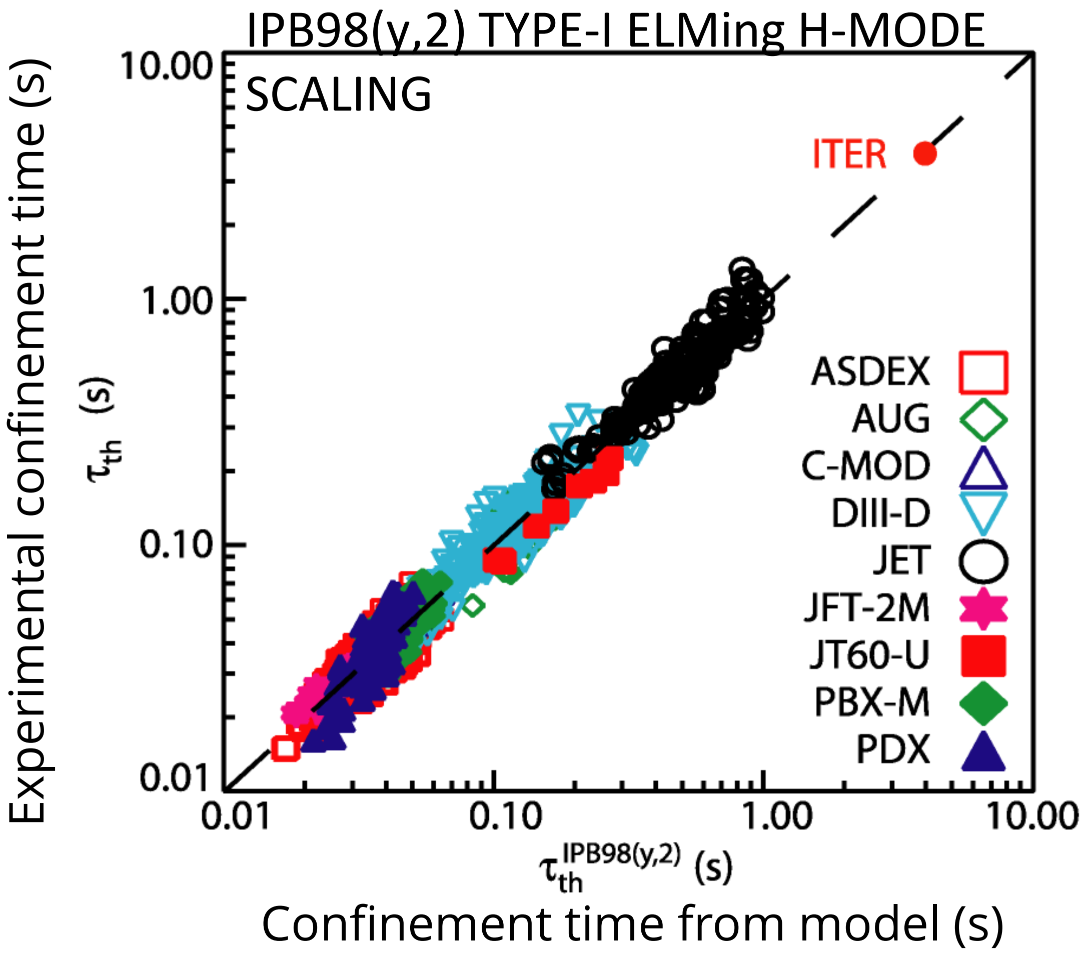
Joint European Torus (JET)



World record DT shot: JET 2023

3rd October 2023: researchers at the Joint European Torus (JET) set a new world record for most fusion energy released in a single 'pulse': **69 megajoules** in a **6 second** pulse. Fusing only **0.2 milligrams** of fusion fuel, this released about the same energy (**20 kWh**) as is stored in the battery of this electric car:

Scaling laws mean that fusion reactors should be big

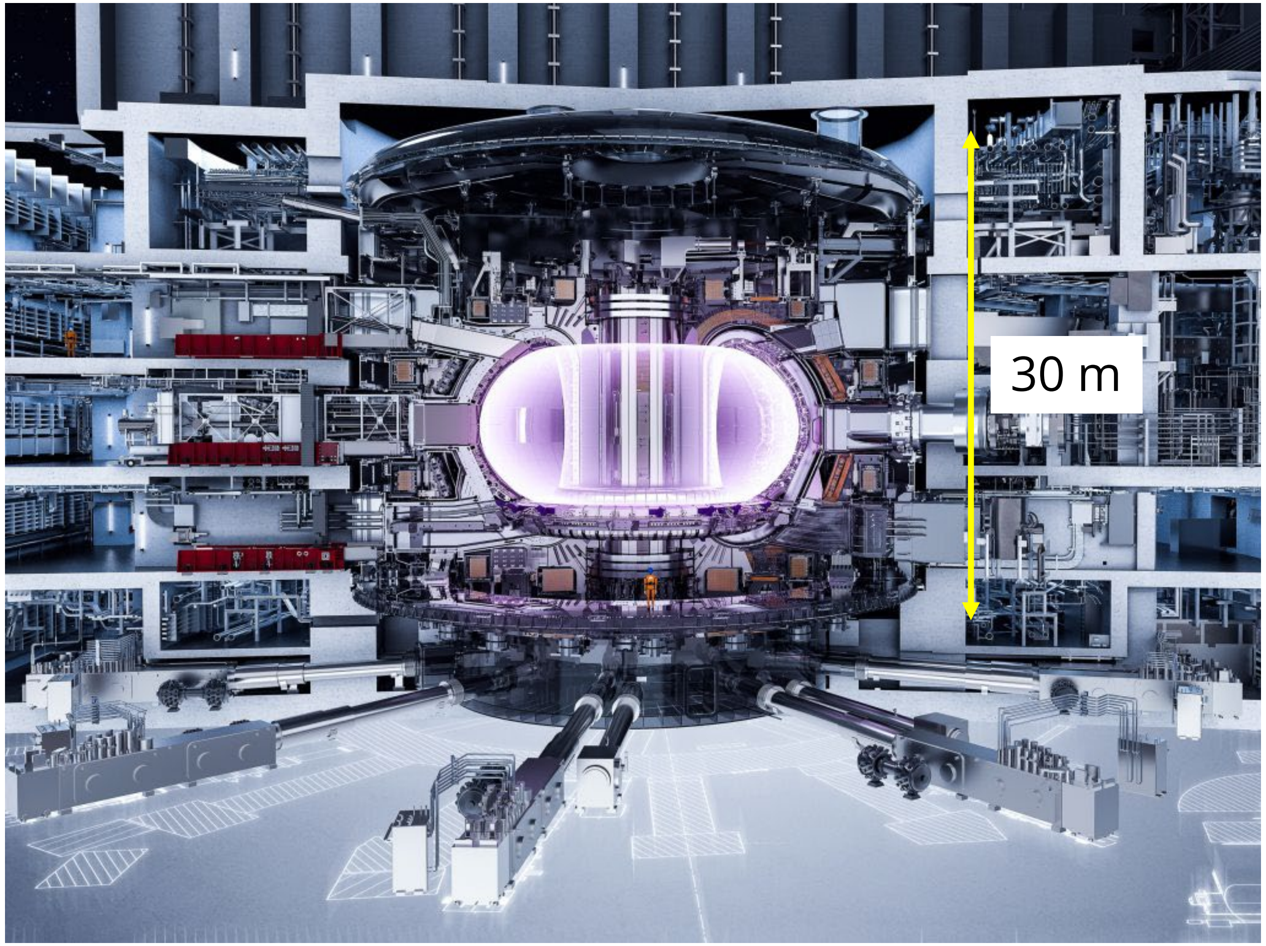


Easiest route to a fusion reactor is large volume with large magnetic field strength

$$P_{\mathrm{fus}} = c_{\mathrm{fus}} \frac{\beta_{\mathrm{N}}^{2} B^{4} R^{3}}{q^{2} A^{4}}.$$

Zohm Phil.Trans.R.Soc. A (2019)

ITER



Under construction, complete in ~2035

500 MW of fusion power from 50 MW of plasma heating, for 10 minutes at a time

0 Watts of electricity – ITER is an experiment

Test materials under neutron loads, wall components, breeding blanket for tritium

Not a power plant

ITER ~ 2010

ITER April 2014

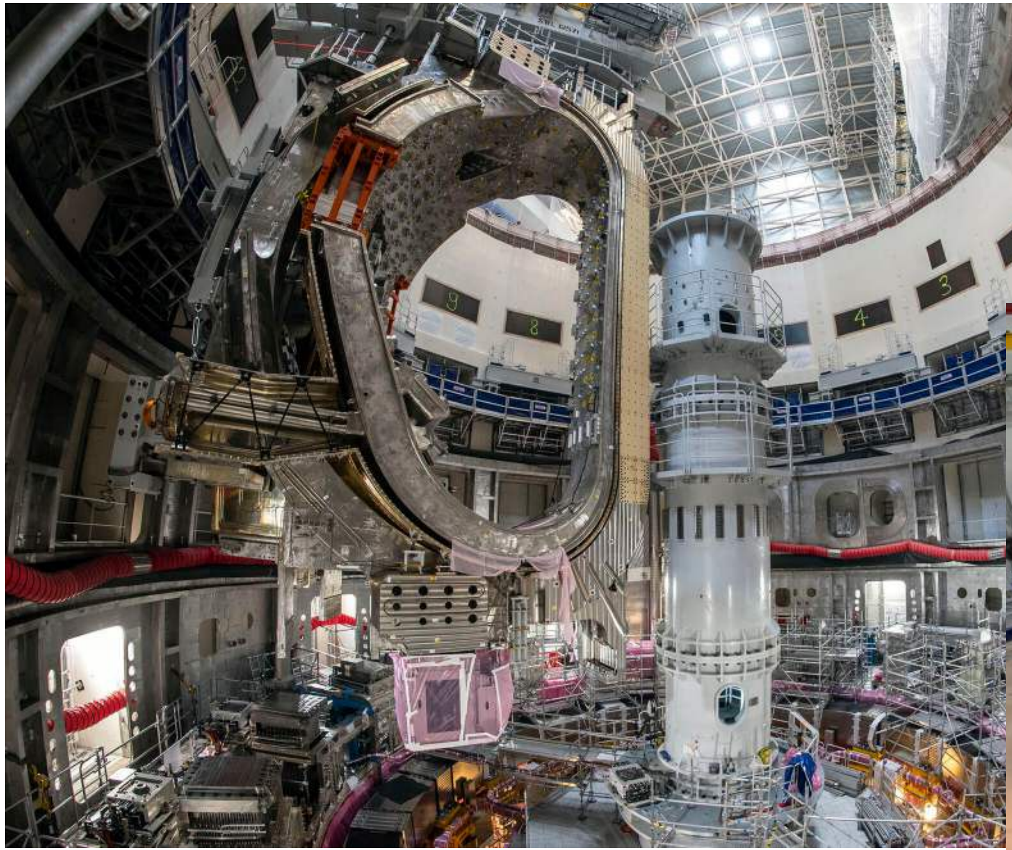
ITER October 2018

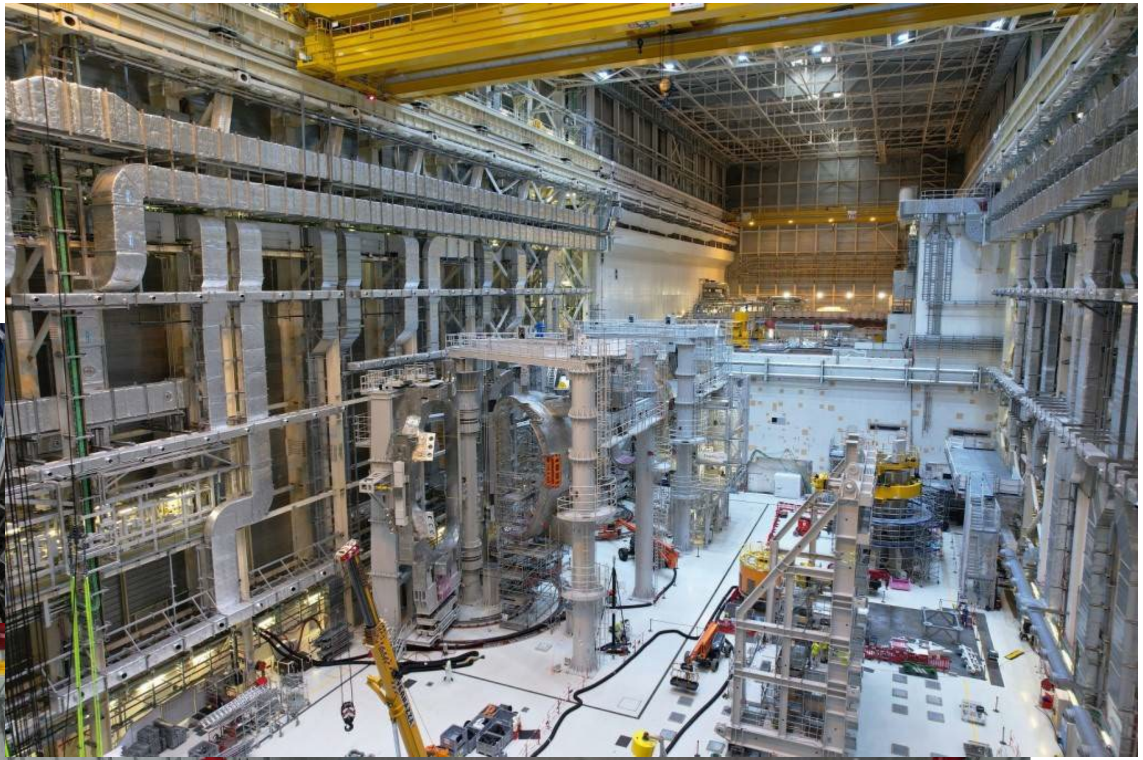
ITER November 2020

ITER site

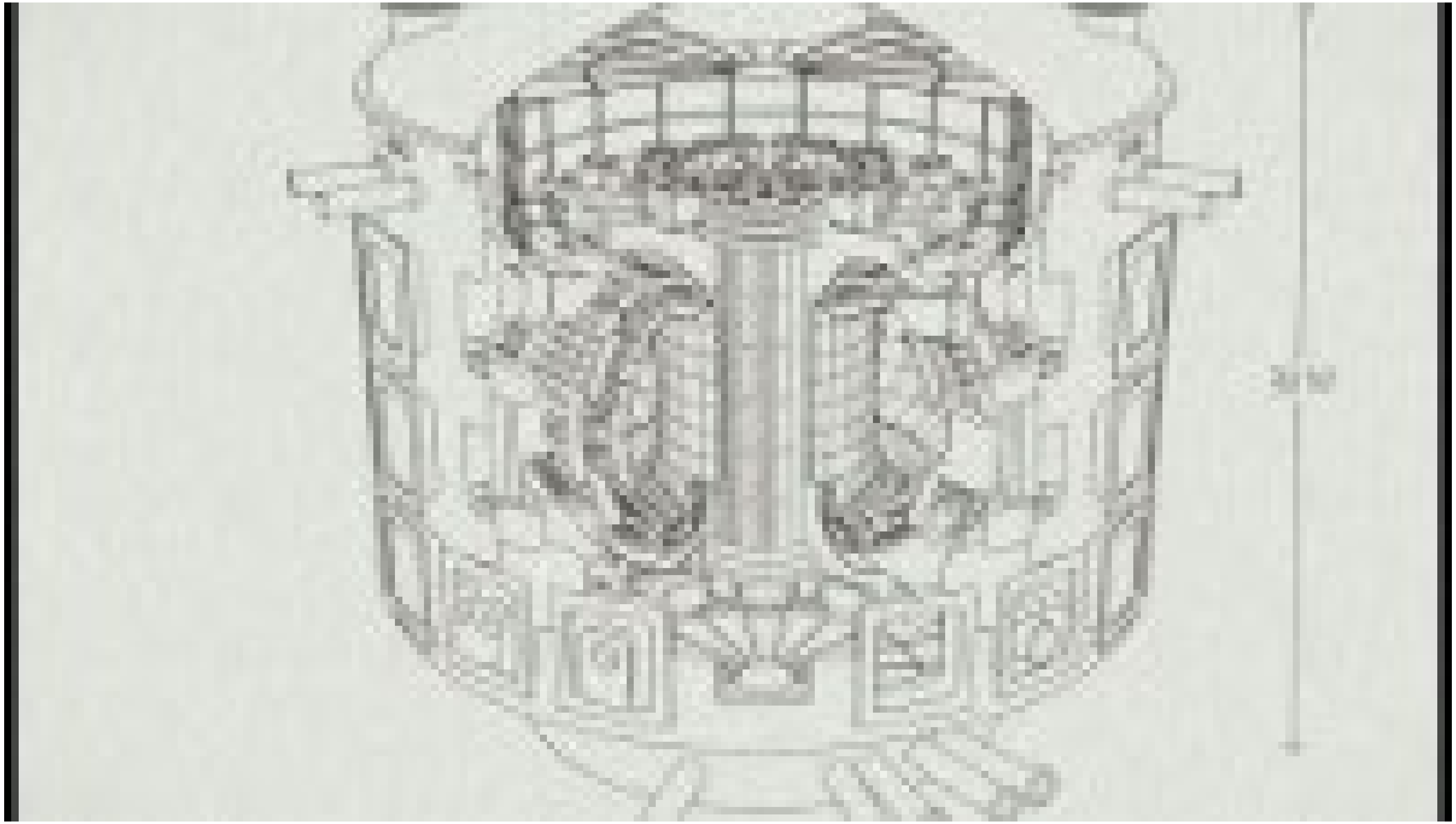
1. Tokamak building
2. Cryostat workshop
3. Poloidal field coil winding
4. Coil storage
5. Cryobridge
6. Fast discharge units
7. Cryostat sections
8. Heat rejection system
9. Control building
10. Neutral beam power supply
11. Cryoplant
12. Diagnostics building
13. Radiofrequency building

ITER progress



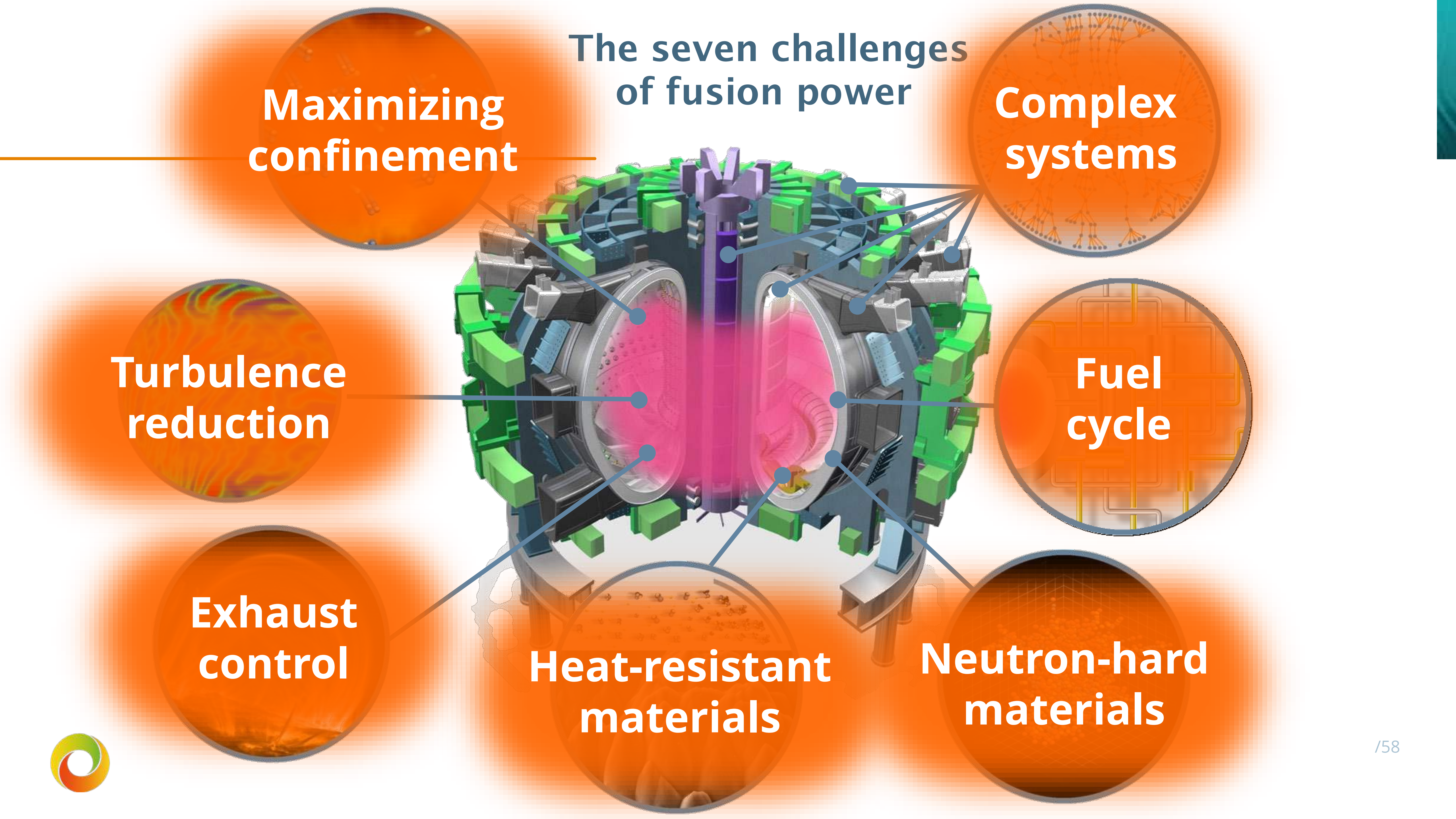


ITER movie



Fusion challenges and research

The seven challenges of fusion power



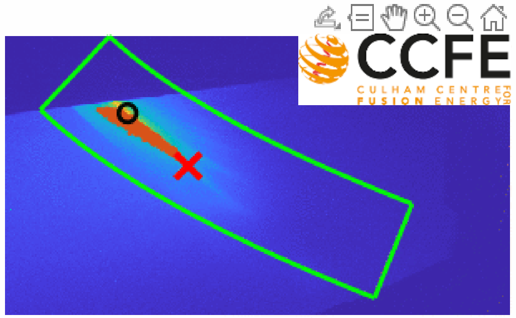
Fusion Research in Eindhoven

DIFFER

National Fusion lab

TU/e

Master’s Nuclear Fusion



Developing advanced diagnostics for control and exhaust

Control engineering of heat-exhaust and fuelling

Machine learning for integrated modelling

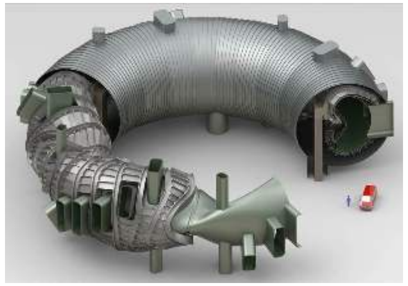
High fidelity turbulence simulations

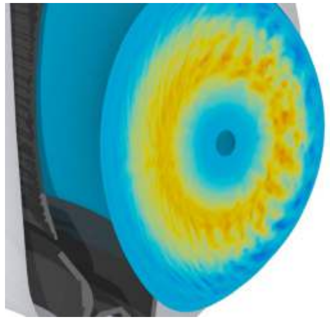
Plasma-surface interactions

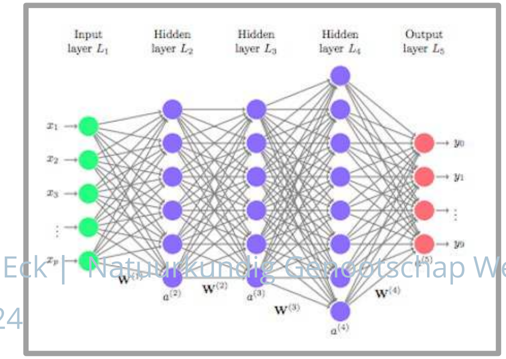
Exhaust plasma modelling

Fusion reactor design

Fusion materials







Fusion Energy research strategy DIFFER

Divertor

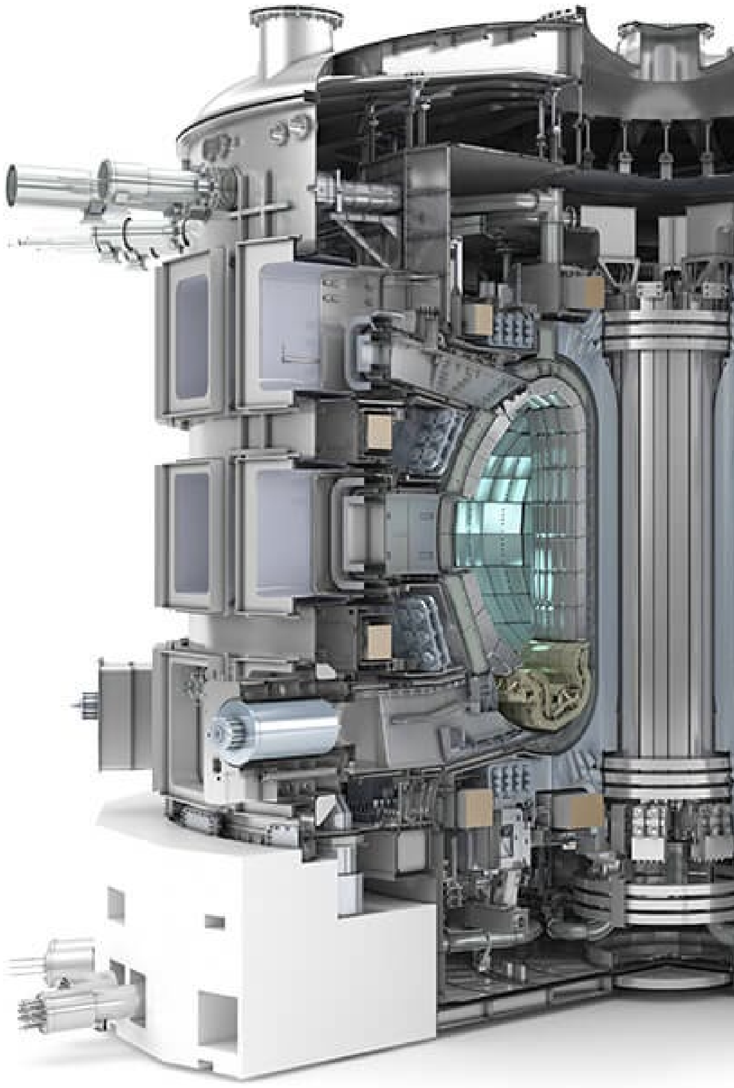
Which materials can withstand the heat and particle loads of a fusion reactor?

Control

How to keep the fusion plasma burning without destroying the divertor?

Modelling

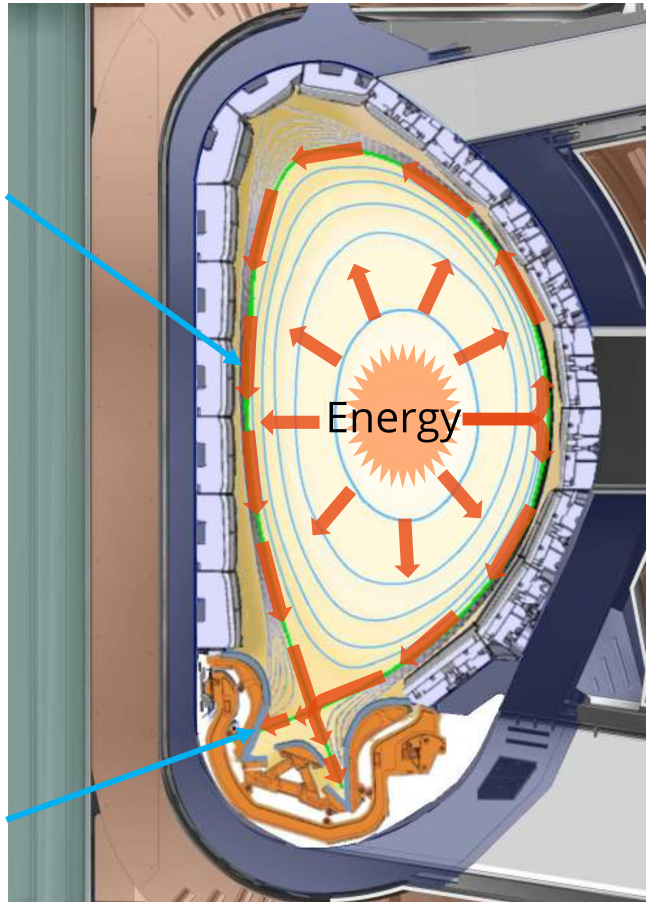
How to develop a "flight simulator" for fast and accurate reactor modelling?



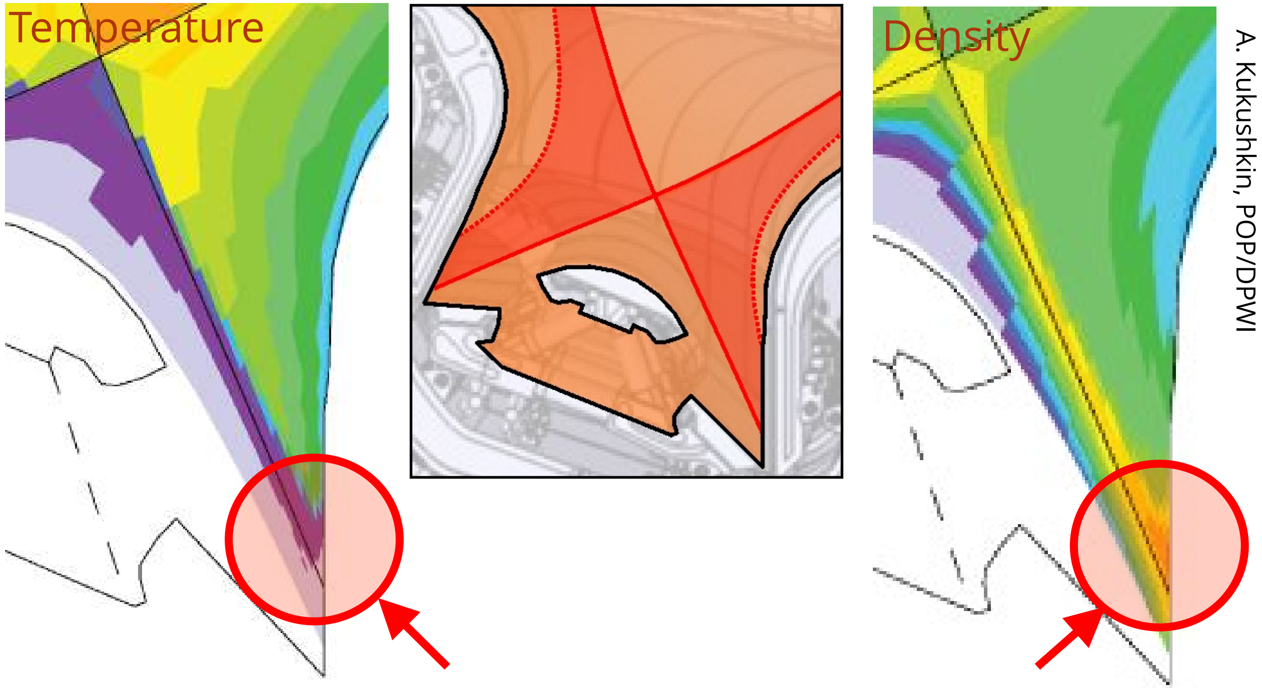
Research example: The heat exhaust problem

Waste heat flow

Exhaust area (divertor)



lasttechage.com



A. Kukushkin, POP/DPWI

Low temperature (~10.000 °C)

High density (1/10.000 of an atmosphere)

Heat

10MW.m^{-2} steady-state

+

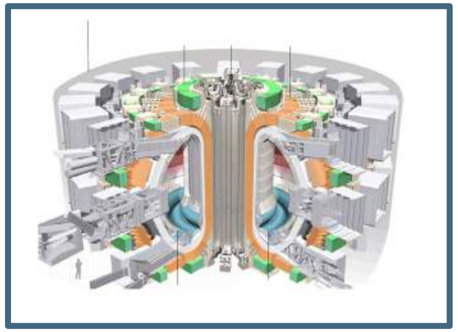
Particles

10^{24} m^{-2}s^{-1}

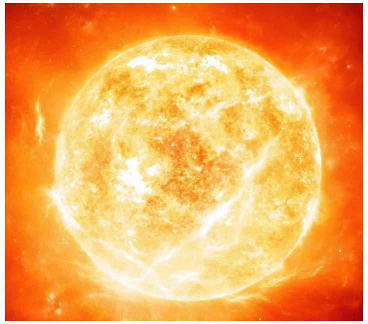
How much heat is that?

~100 kW m^{-2}
(take-off/landing)

~1 MW m^{-2}
(a few minutes)



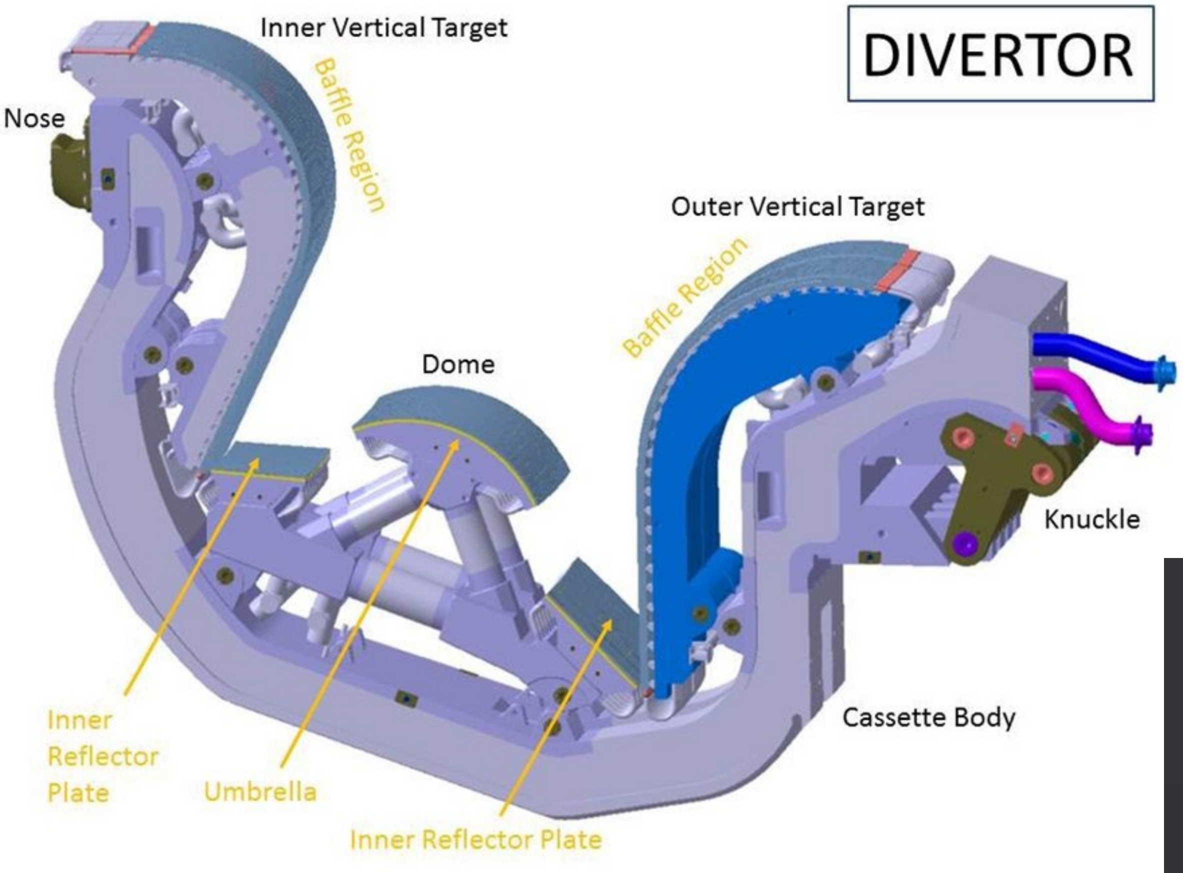
~10 MW m^{-2}
(~5 years)

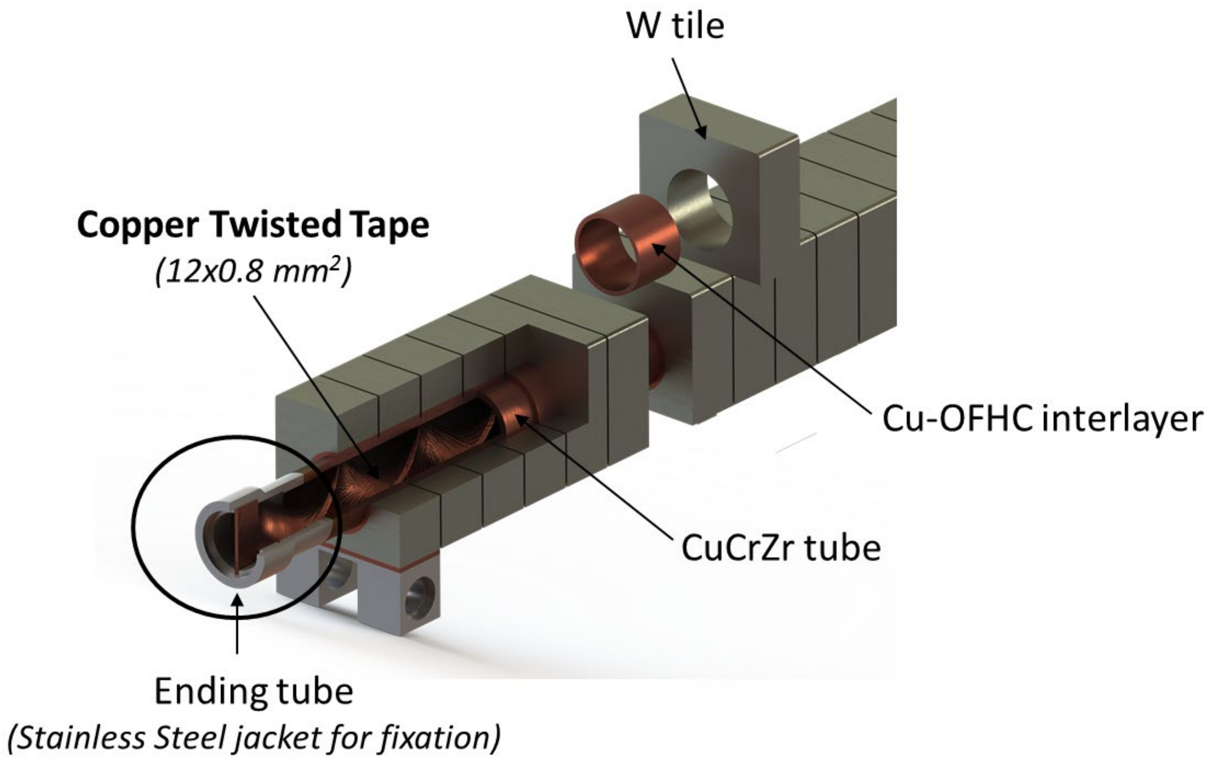


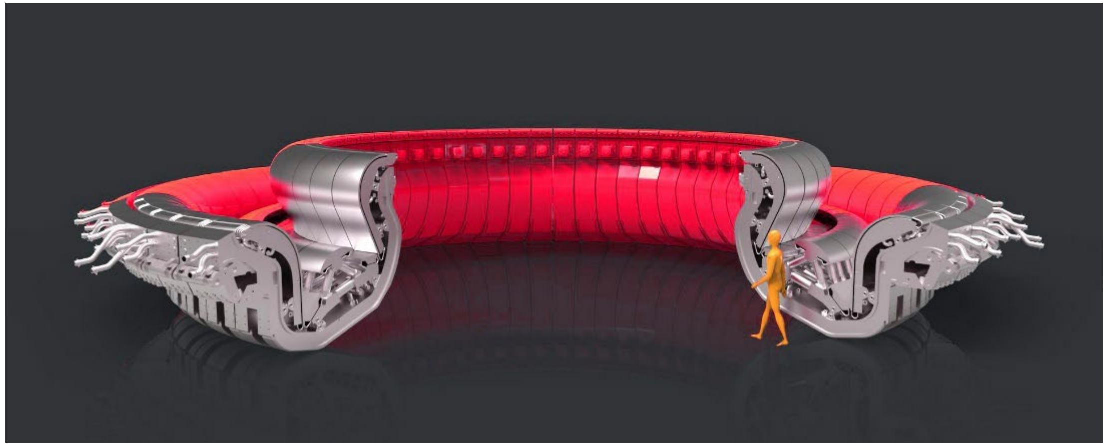
63 MW m^{-2}
(4.6 billion years)

~80 MW m^{-2}
(~2 minutes)

The solution for ITER

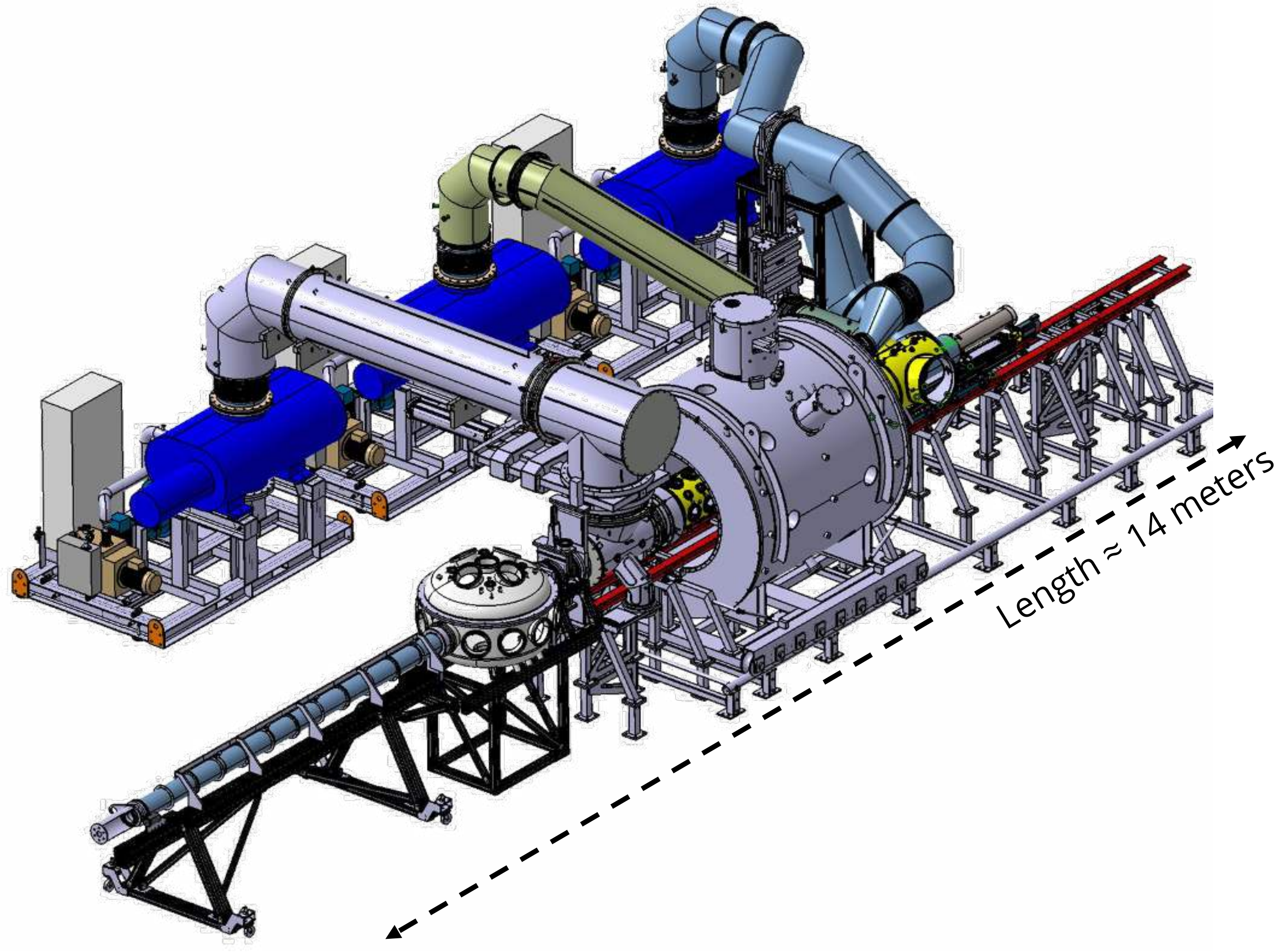




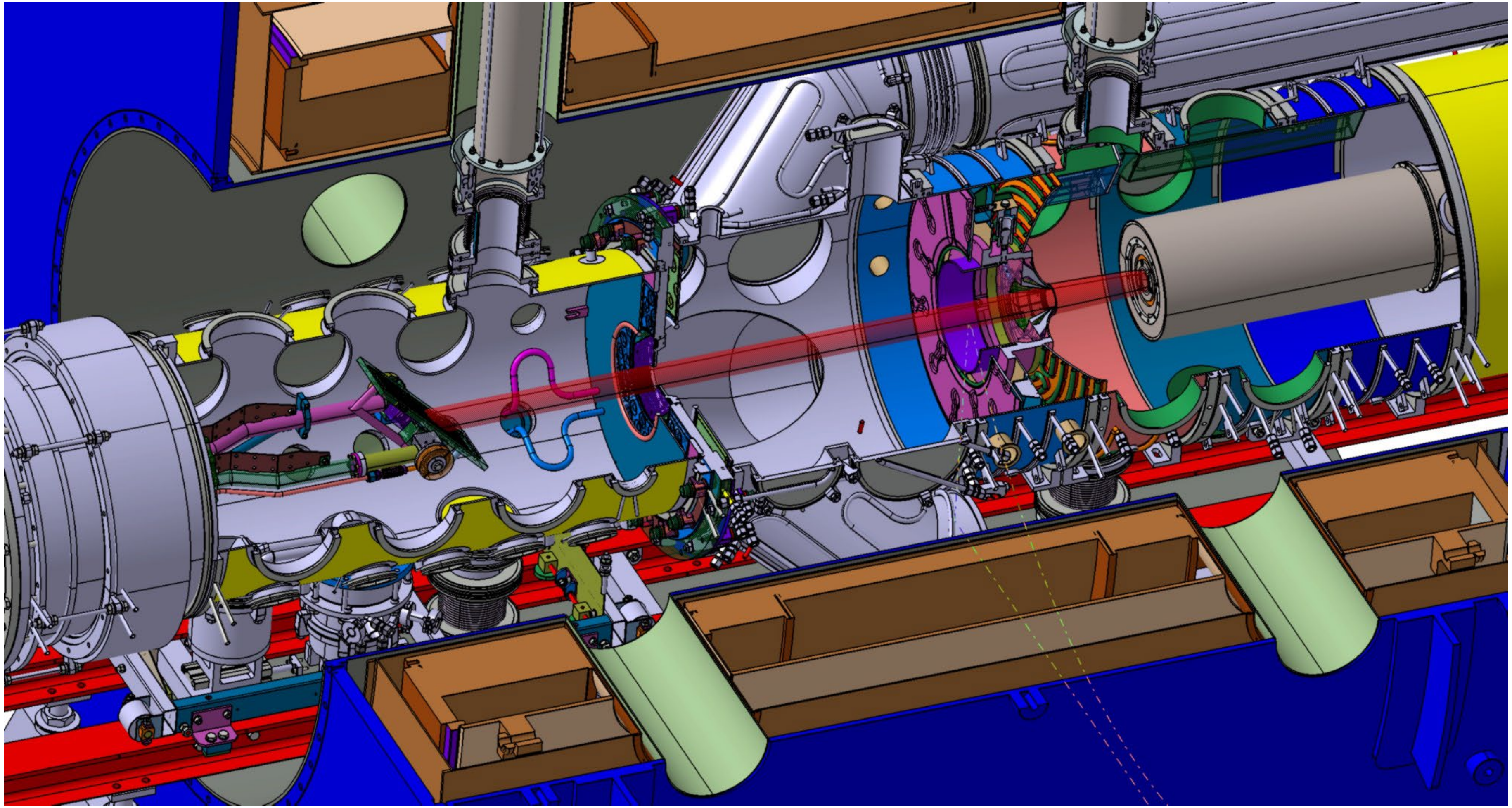


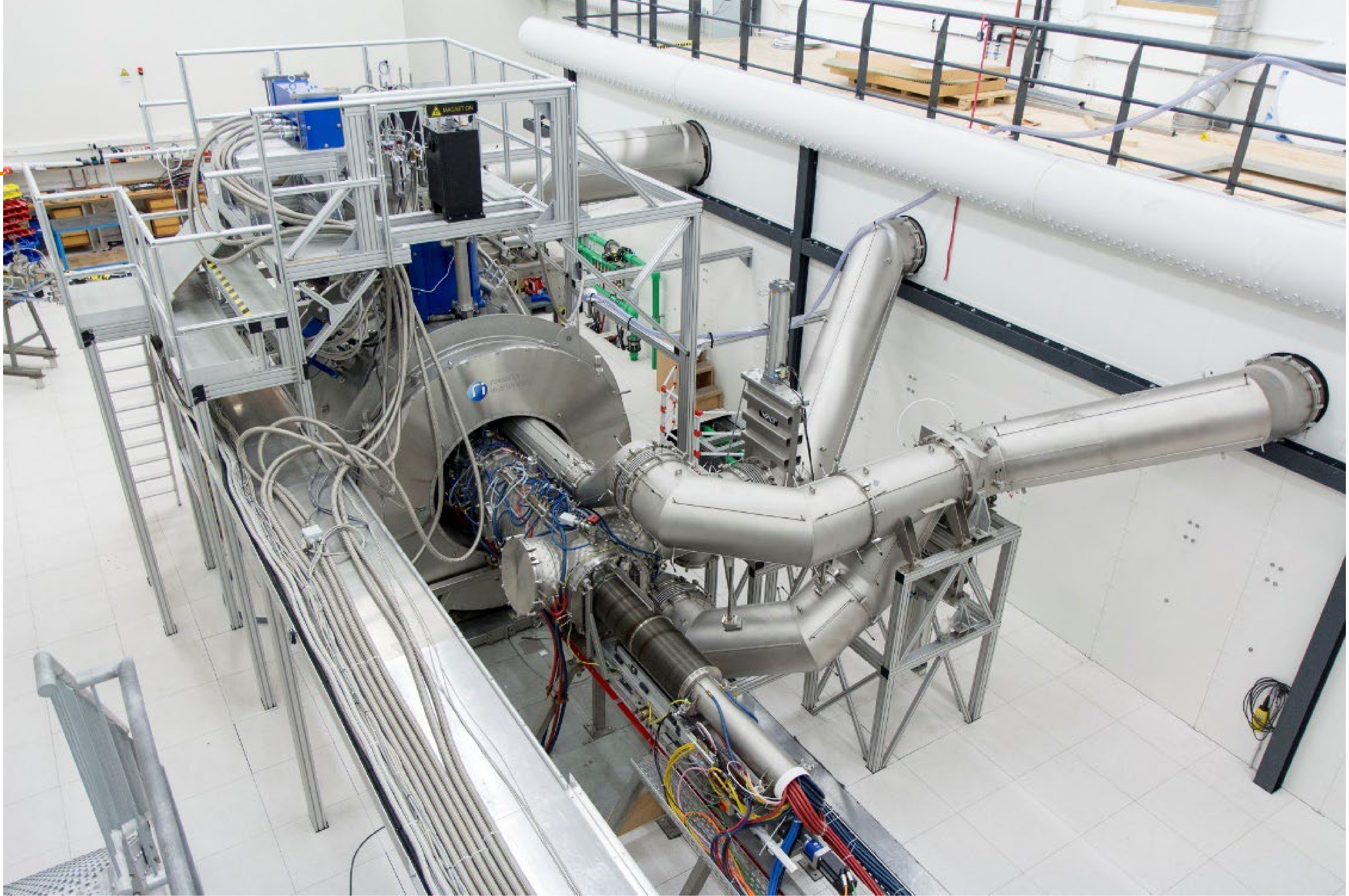
Magnum-PSI

- Unique high flux and high fluence linear plasma device
- Heat and particle fluxes comparable to ITER/DEMO divertor
- Transient plasma loading capabilities
- Extensive diagnostic suite (incl. in situ ion-beam analysis)
- PSI studies (e.g., sputtering, retention, surface modification)



Magnum-PSI: inside view



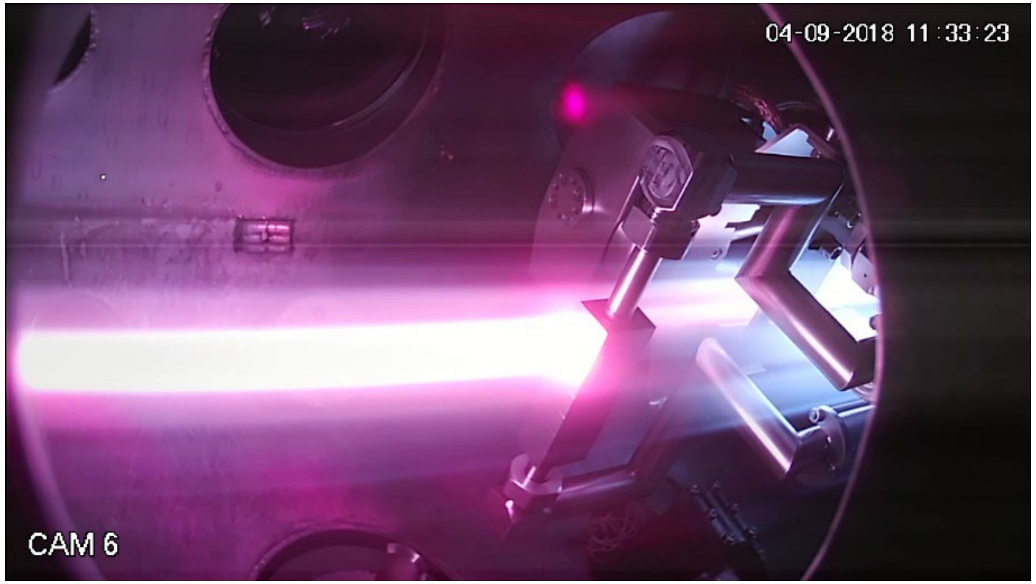


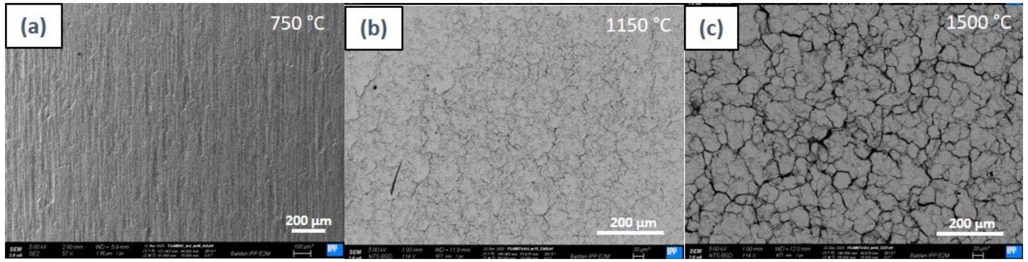
Research highlight: accelerated lifetime testing of ITER divertor mock-up

- Tested ITER monoblock mock-up under realistic conditions up to 10^{30} m^{-2} fluence (equivalent to 1 year full-power ITER operation)

- Further testing to explore effect of impurity seeded discharges, plasma transient (ELM-like) loading, high temperatures carried out – see strong temperature influence on damage

- High fidelity study of component performance under loading with ITER-like divertor plasma gives confidence for operation and helps determine limits





Morgan et al. Phys. Scripta 95 (2020)
Morgan et al. Nucl. Fusion 61 (2021)

Liquid metal divertors as an alternative strategy for fusion

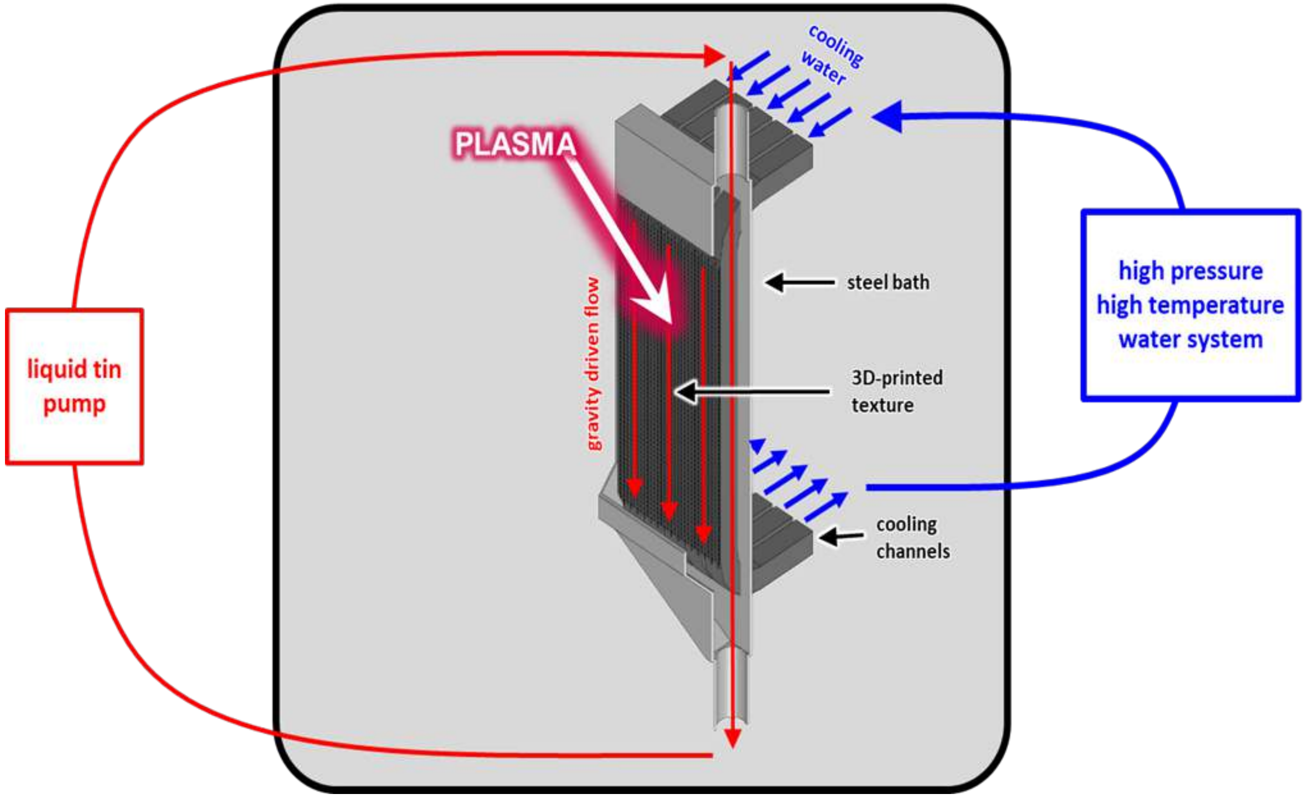
Fusion rectors will produce more heat and neutrons and operate continuously

Significant challenges when using water cooled tungsten wall components in fusion reactors

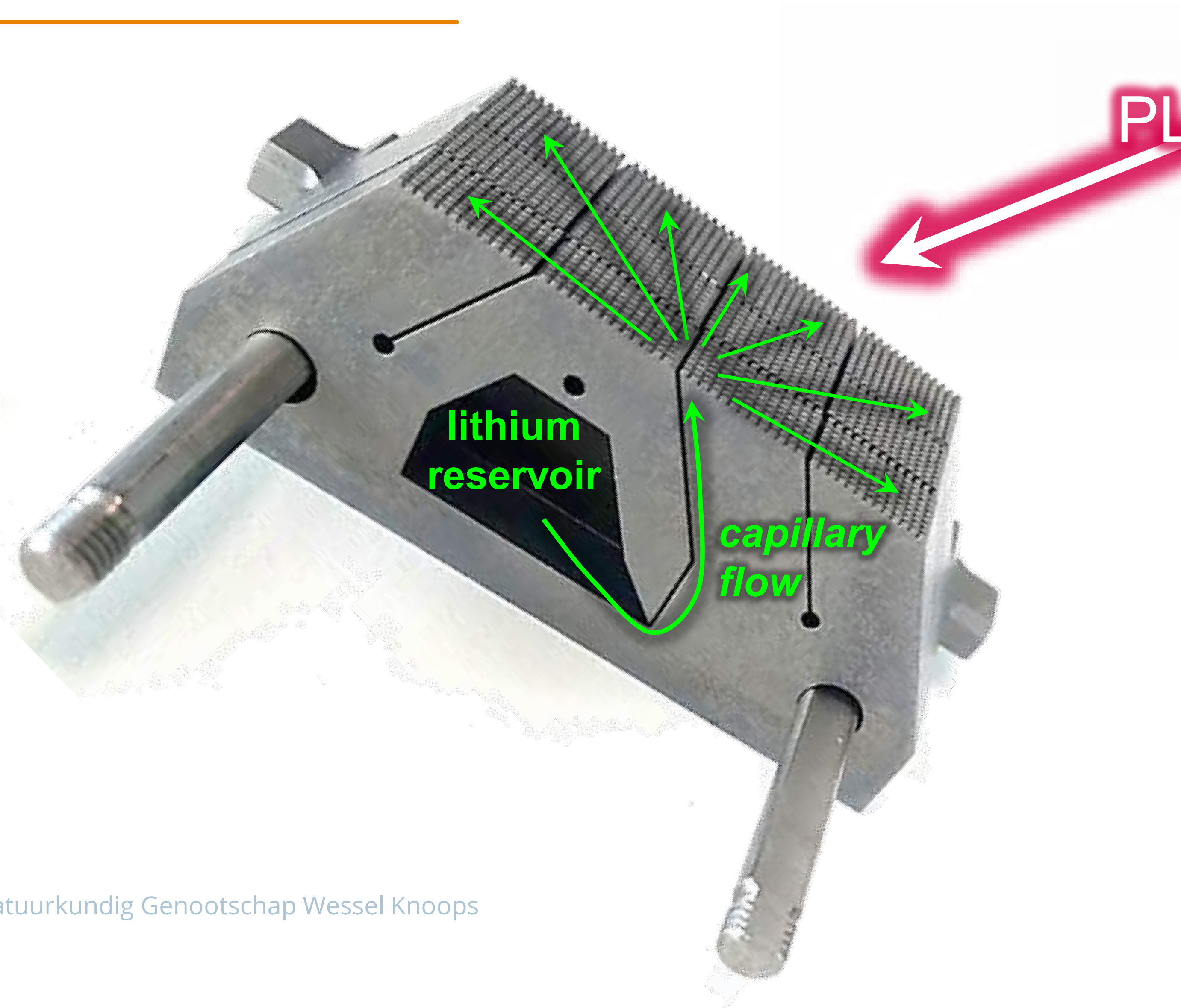
- Erosion lifetime
- Vulnerable to cracking
- Irreversible damage (melting)
- Neutron damage

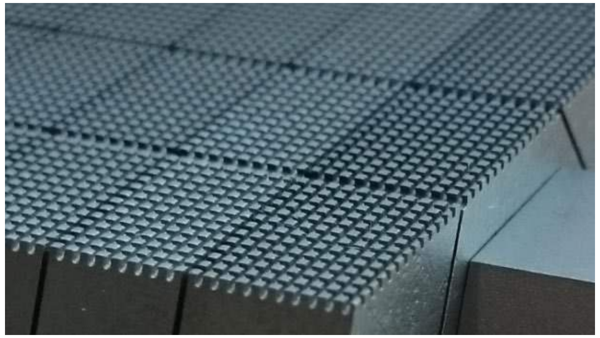
Liquid metal walls have significant potential to avoid/mitigate these issues

- Self healing
- No cracking
- Already molten, vapour shielding
- Neutrons only affect substrate, not liquid metals



Technological challenge- performance on long timescales via surface replenishment





LiMeS-lab: an integrated laboratory for the development of Liquid Metal Shield technologies for fusion reactors

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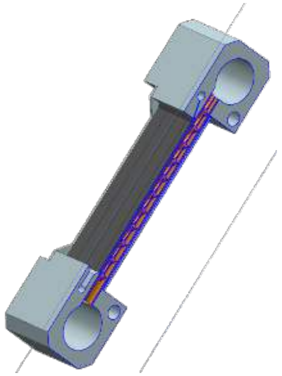
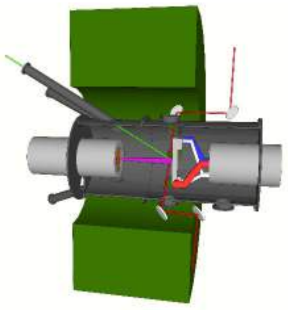
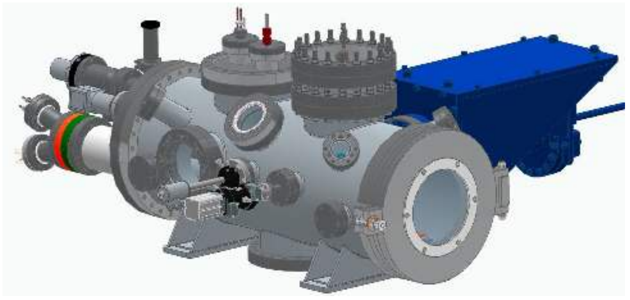
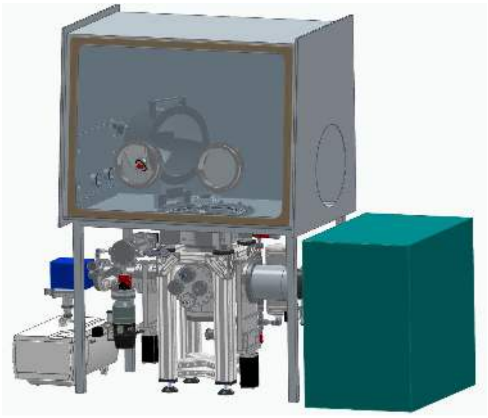




- Design and manufacture mock-up
- 3D printing on to mock-up
- Wetting liquid metal
- Experiments linear plasma device
- Post-mortem analysis

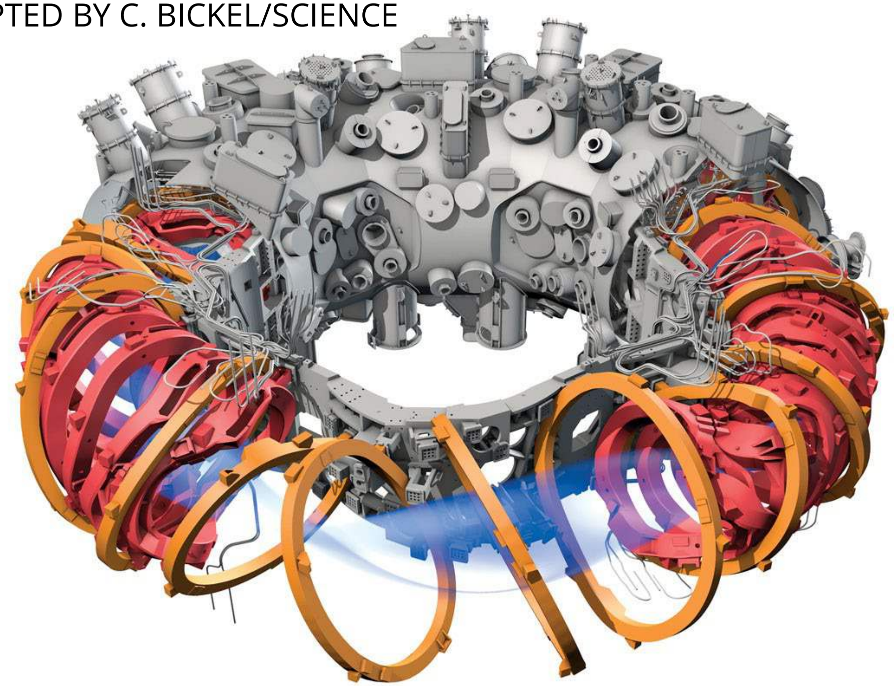




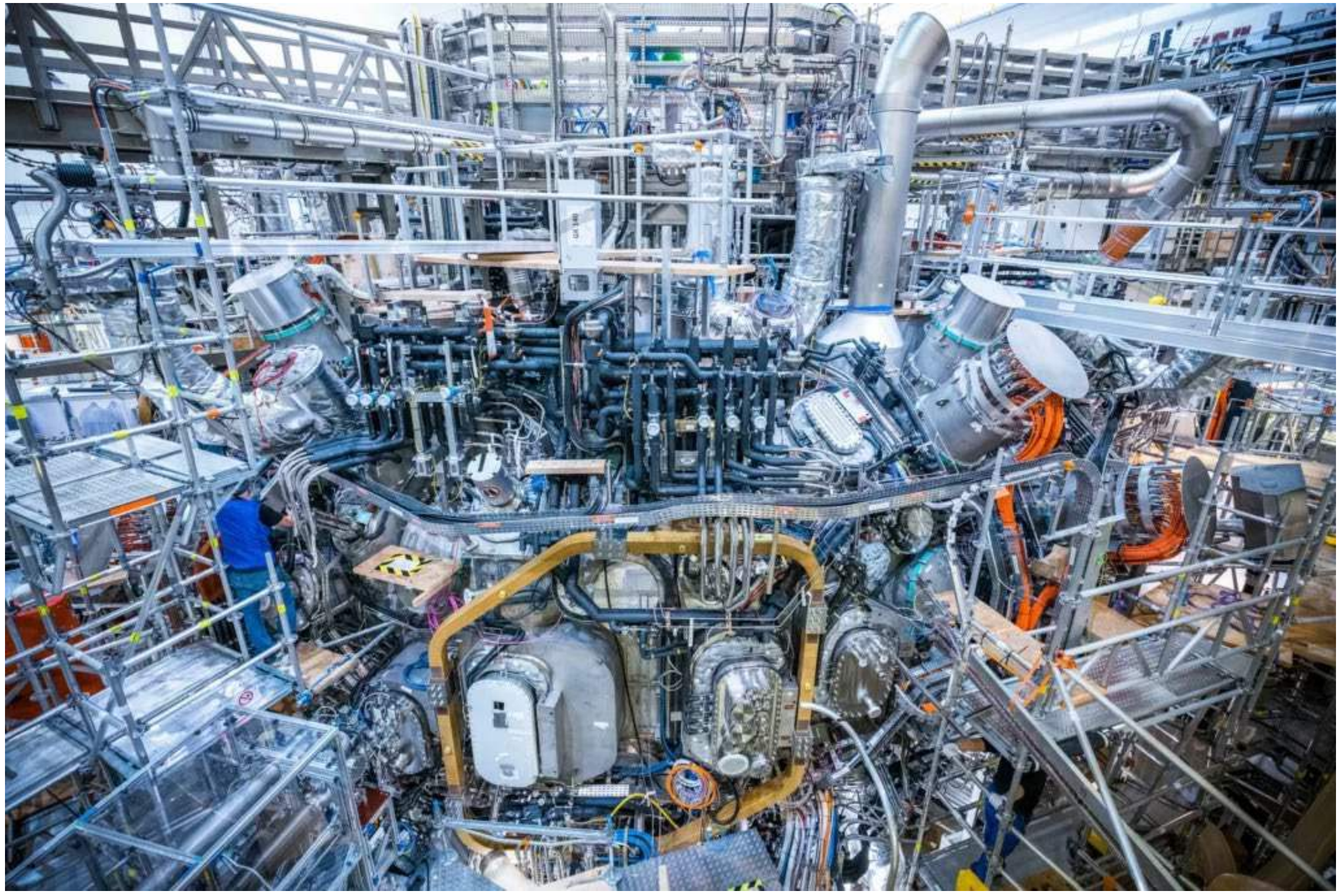
Fusion- the future

Alternatives: stellarator (example Wendelstein 7-X

IPP, ADAPTED BY C. BICKEL/SCIENCE

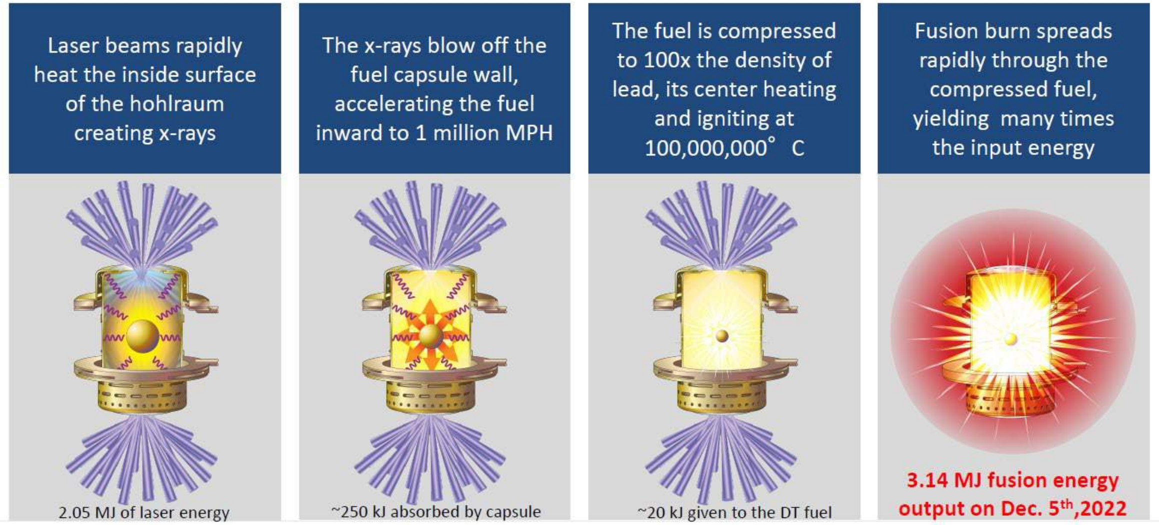


- ✓ Intrinsically steady-state
- ✓ No disruptions!
- ❖ Confinement requires optimisation
- ❖ 3D engineering challenge



MPI for Plasma Physics, Jan Hosan

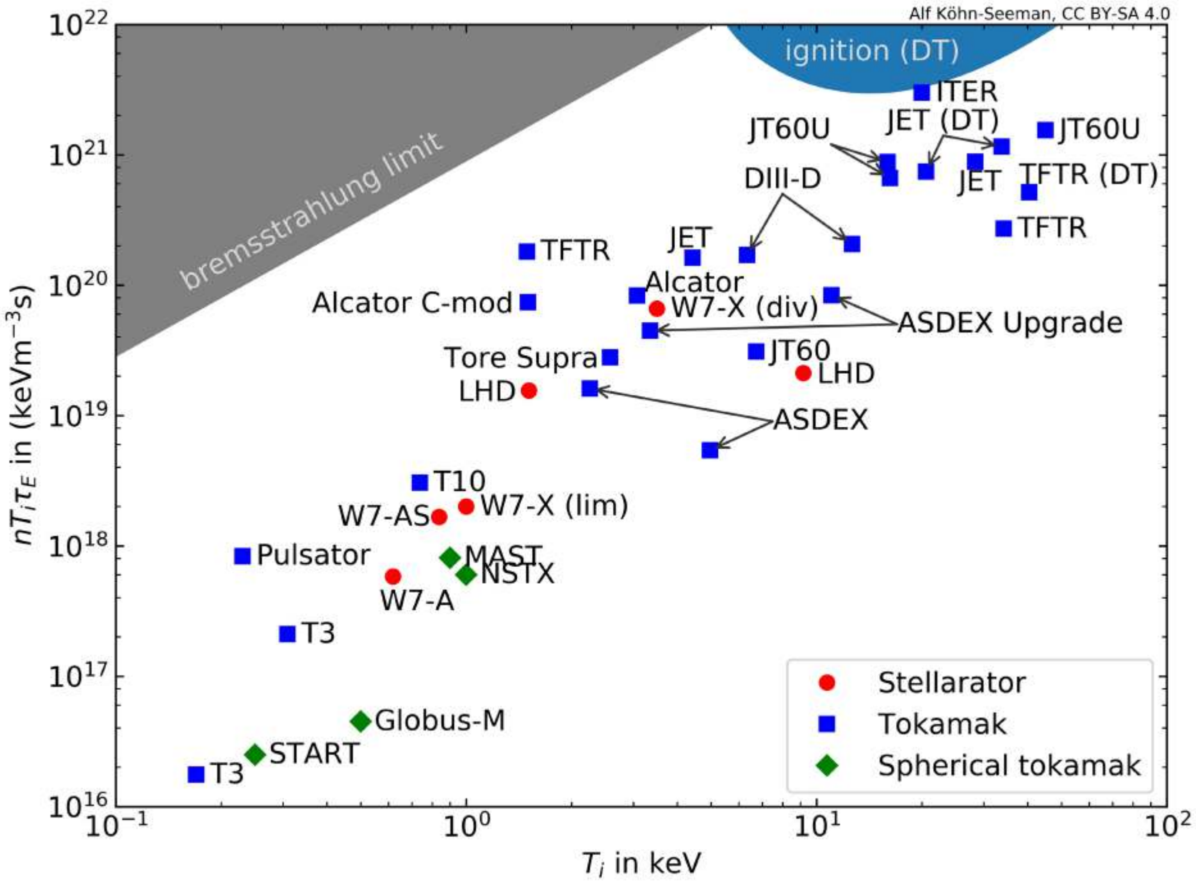
Alternatives: Inertial confinement fusion (NIF)

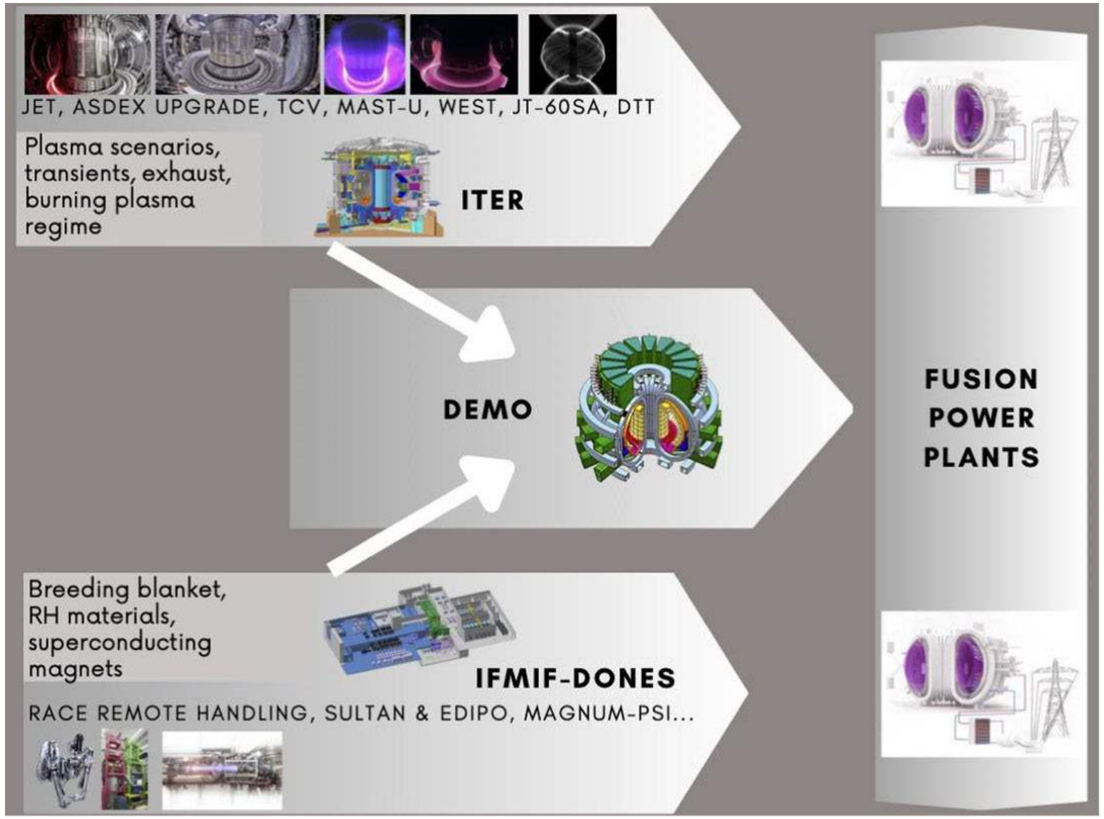


- ✓ More energy out than in shown!
- ✓ Conceptually easier to scale up
- ❖ Efficiency of lasers
- ❖ Cost of pellets
- ❖ Repetition rate

Lawrence Livermore National Laboratory

Other fusion approaches may have advantages, but need to catch up





A. Fasoli et al. PRL 2023

Private fusion enterprises

Research | Research and Analysis

Nuclear fusion market could achieve a $40 trillion valuation

Bloomberg Intelligence December 28, 2021

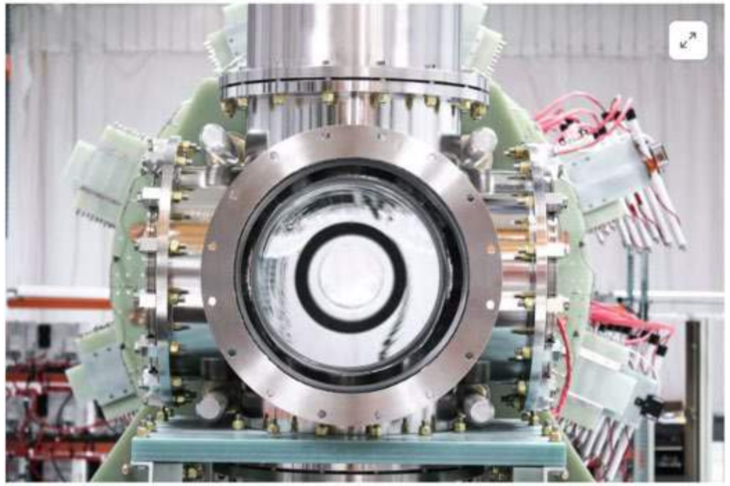
REUTERS World Business Markets Sustainabil

Technology

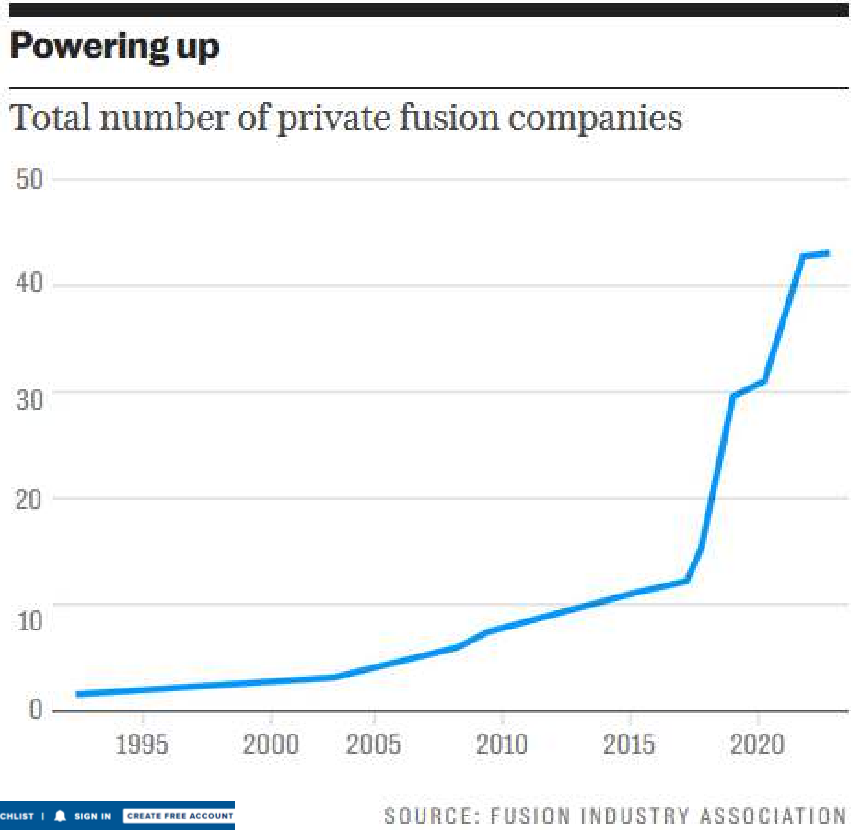
Microsoft signs power purchase deal with nuclear fusion company Helion

By Timothy Gardner

May 10, 2023 9:41 PM GMT+2 · Updated 6 months ago



[1/2] Part of Helion Energy's Polaris prototype for fusion energy reaction experiments is shown in this undated handout photo provided by the company. Helion Energy/Handout via REUTERS *Acquire Licensing Rights*



The Telegraph Mar 13, 2024

CNBC MARKETS BUSINESS INVESTING TECH POLITICS CNBC TV INVESTING CLUB PRO

SUSTAINABLE RETURNS

SUSTAINABLE RETURNS EVENTS

SUSTAINABLE RETURNS

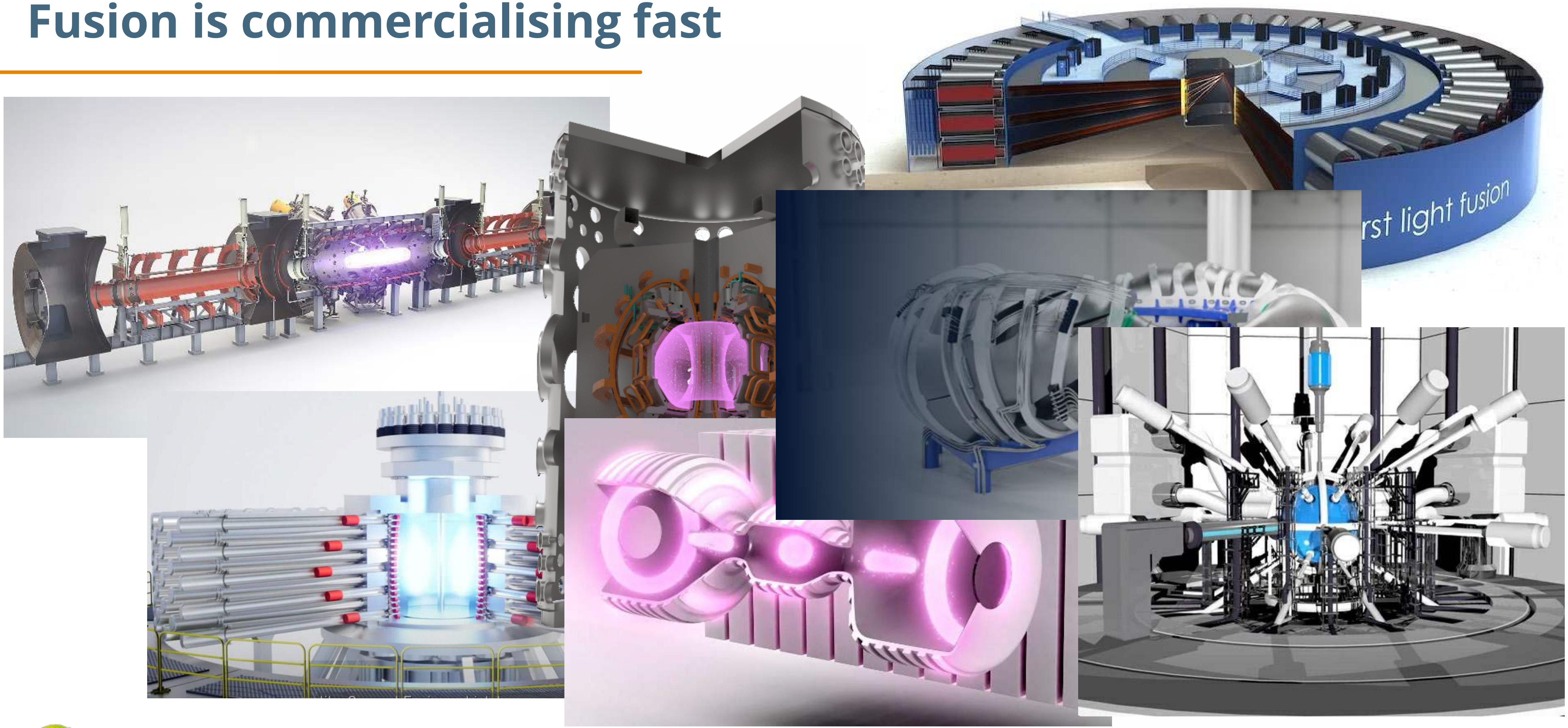
Commonwealth Fusion has raised $2 billion to make energy like the sun and stars — here's a look inside

PUBLISHED THU, JUN 8 2023-12:07 PM EDT | UPDATED THU, JUN 8 2023-5:55 PM EDT

Catherine Clifford @IN/CATCLIFFORD/ @CATCLIFFORD

Smarter?
Faster?
Quicker?

Fusion is commercialising fast

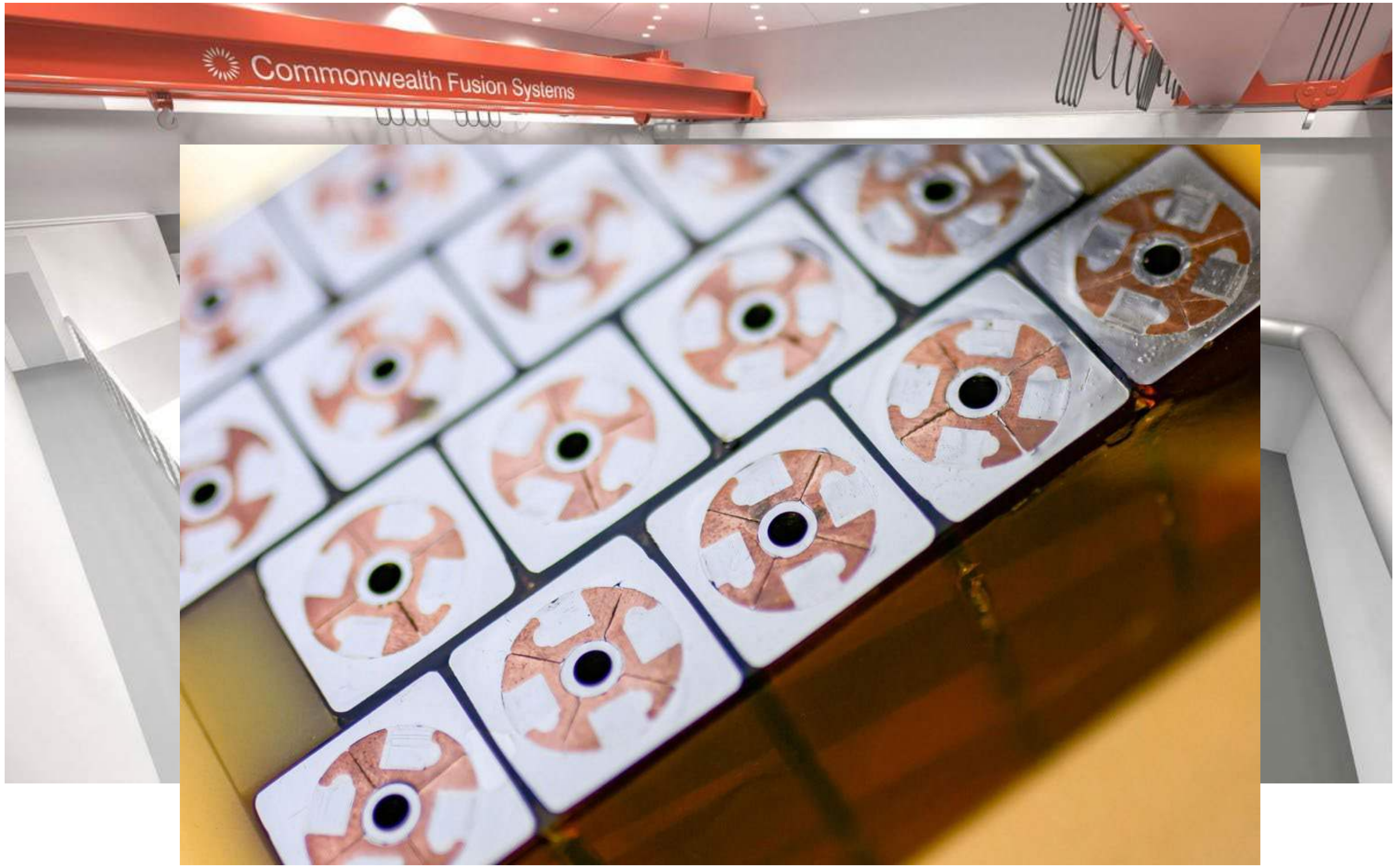


Commonwealth Fusion Systems: HTS enabled high field tokamak

SPARC:
- R = 1.85m; **B = 12T**; I = 8.7 MA
- now being built
- demonstrate Q>2

ARC:
- Early 2030's first power plant

- Raised more than $2 billion private
- Milestone program (US)
- Signed Statement of Work with DIFFER



UK: STEP spherical tokamak for energy production

STEP main parameters:

R = 3.6m; B = 3.2T

2019-2024 Conceptual Design
2024-2032 Engineering Design
2032-2040 Construction

Collaboration with DIFFER on exhaust control

Gauss Fusion

European start-up founded by established fusion supply companies
ALCEN (France), ASG Superconductors (Italy), BRUKER (Germany), IDOM (Spain), RI (Germany)

Single step to reactor size stellarator to be operational by 2040 – conventional LTS coils

Funding from German ministry for production and innovation of demountable magnetic coils

Centre of Excellence with DIFFER October 2024

GAUSS FUSION

European Fusion Association

The primary objective of EFA is to accelerate the transition of fusion energy from research laboratories to large-scale industrial applications

Founding members of the association:

Alsymex (France)	ASG Superconductors (Italy)
Assystem (France)	Bruker EAS (Germany)
Demaco (Netherlands)	Gauss Fusion (Europe)
IDOM (Spain)	RI Research Instruments (Germany)
SIMIC (Italy)	SUBRA (Denmark)
Thales (France)	Trumpf (Germany)

Impact of investors: enable startups to bring fusion fast

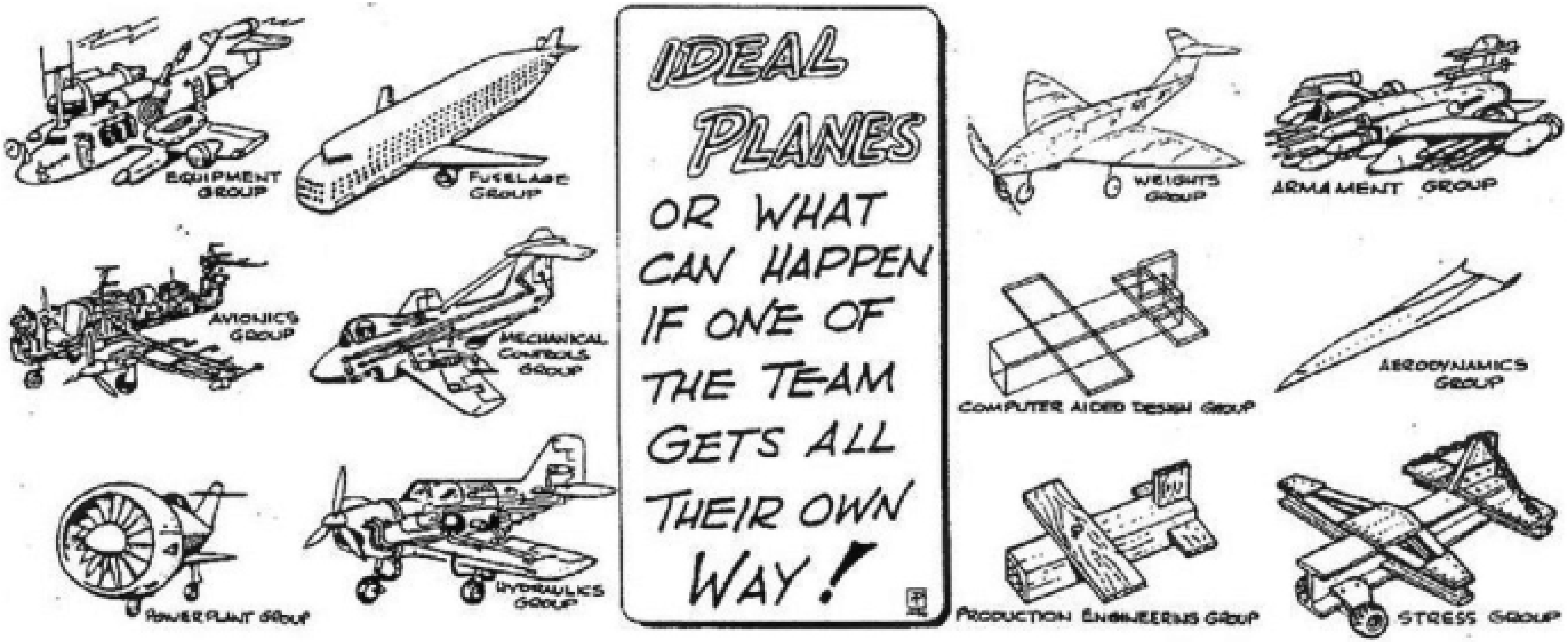
Start-up characteristics

- Focus & speed - simple governance
- Aim for next ”value inflection point” - then attract more money - on to the next problem / hurdle
- Most fail (valley of death) - some sell “flying carpets” - both could backfire
- And this could happen fast (as anything goes faster in startups)

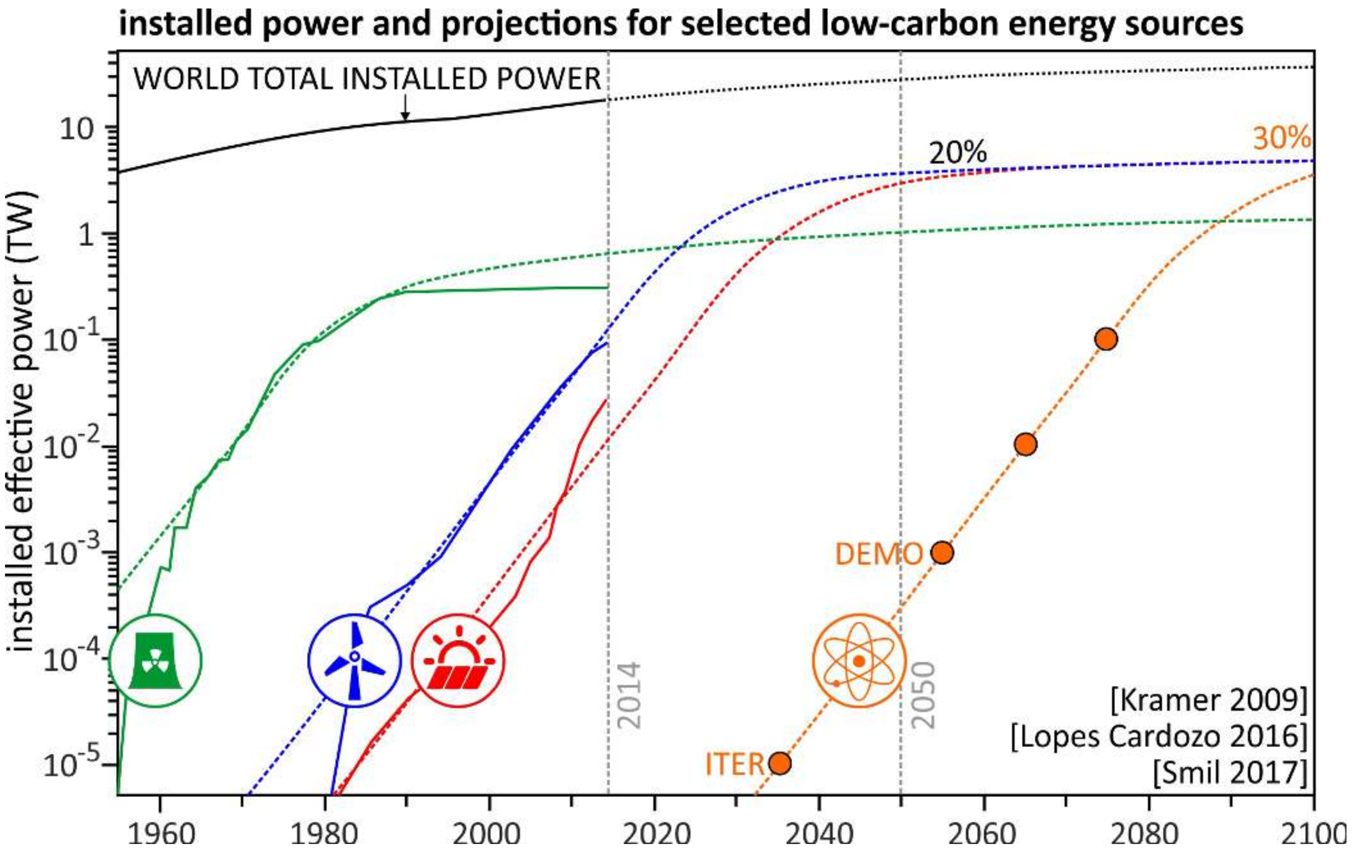
Impact

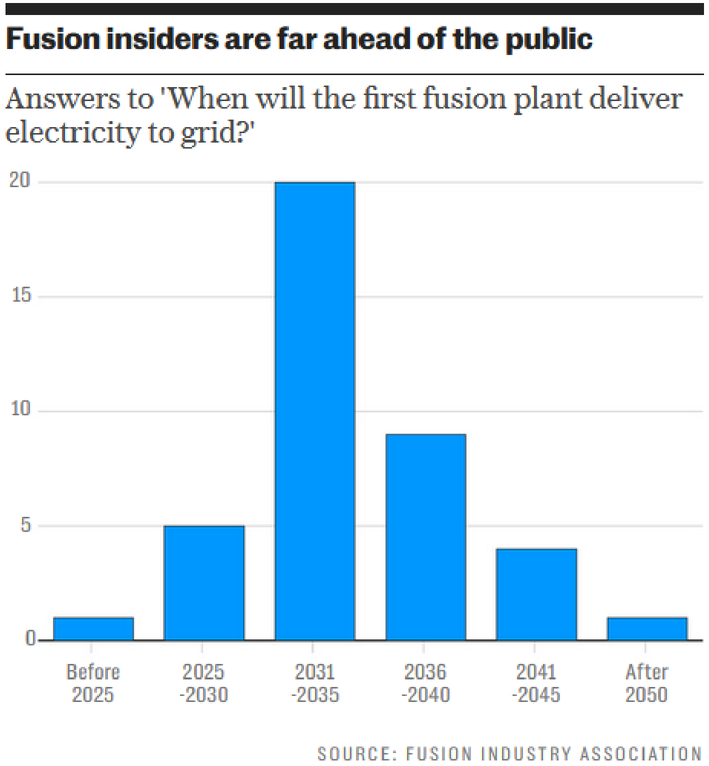
- A single success (e.g. CFS/SPARC achieving Q>2 in 2026) would outweigh 30 failed startups … and trigger even more investments - contest - FOMO
- Fastest way to mobilize resources to bring fusion to the market
- Most startups will become valuable in an indirect way:
  - Deliver technology and/or people (via acquisition, license, supply relation)
  - Yield spin off businesses in other fields
  - Attract & train & inspire people / suppliers to fusion

Integrated approach still needed



The timeline – fusion when?





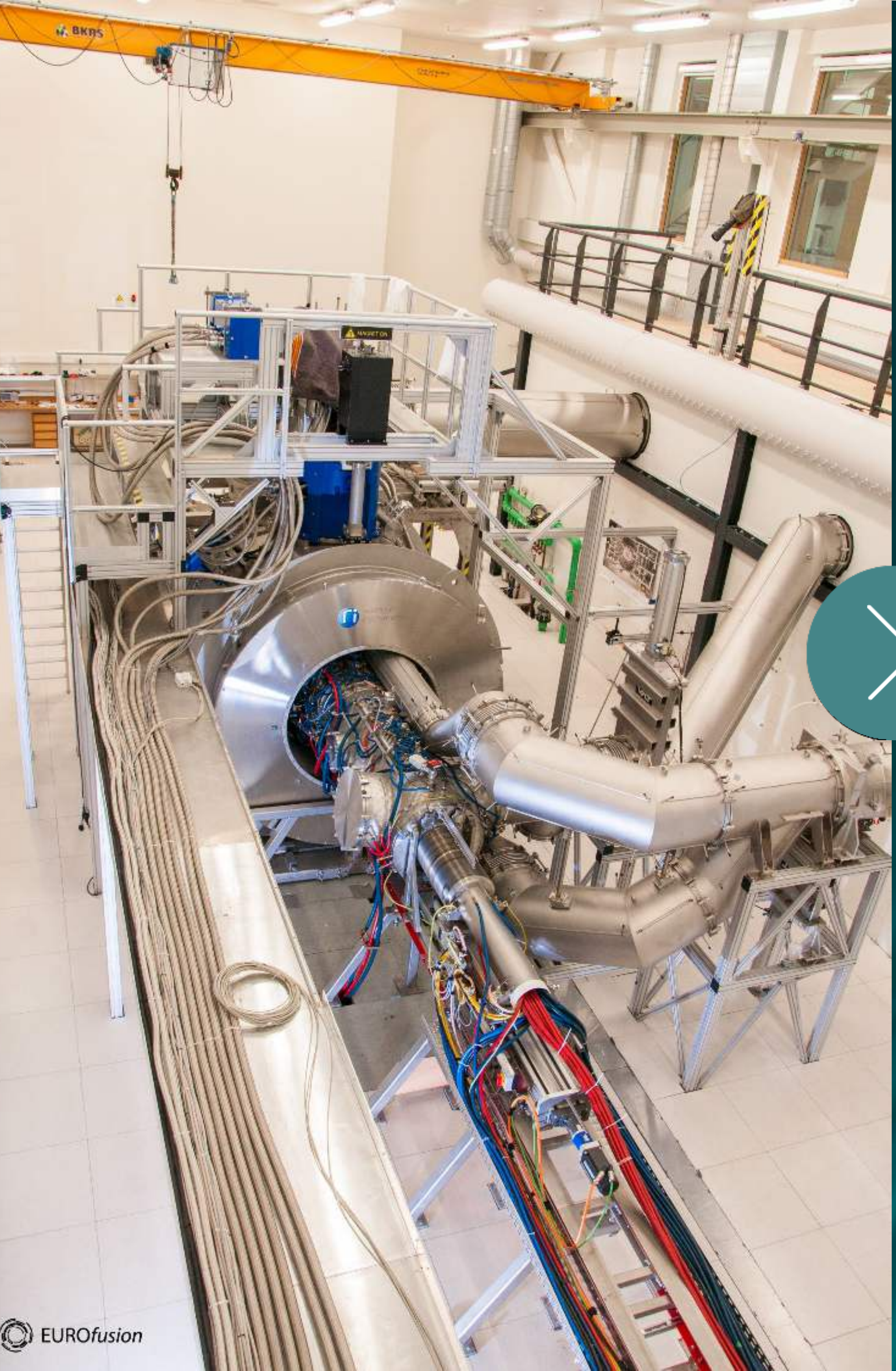
The Telegraph Mar 13, 2024

Conclusions – part 1

- Nuclear fusion has the capability to fill the gap of electricity needs from the 2nd half of the century
- We tackle fusion using magnetic confinement, and are building the ITER tokamak to push this forwards
- The confinement requirements of fusion pushes us towards large devices which come with a large set of challenges which we are tackling
- Heat exhaust is one of many of these and we have a unique device to explore this plasma regime here in the Netherlands
- Future fusion reactors might not be a tokamak, but the first one probably will be - the question is when?

Conclusions – part 2

- Fusion is potentially a source of clean virtually limitless energy
- Technological difficulties and size of investments likely lead to (too) late readiness of complete reactor AND slow market penetration.
- Decarbonization cannot rely on fusion, but will be based on renewables, storage and conversion, (and modern nuclear fission)
- A fusion reactor has to operate in extreme loads of heat and particles with an intrinsic unstable plasma. This make fusion a challenge of integration and optimization → modern design problem aspects of:
  - Materials engineering
  - Control engineering
  - System engineering
  - Robotics



Thanks for your attention

Hans van Eck

DIFFER