Challenges and progress on the path towards fusion electricity

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Programme Manager EURO*fusion*

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30 EUROfusion Consortium Members – 28 countries

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Ecole Royale Militaire Laboratory for Plasma Physics
BELGIUM

Bulgarian Academy Of Sciences
BULGARIA

Ruđer Bošković Institute
CROATIA

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FINLAND

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LATVIA

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LITHUANIA

Institute of Plasma Physics And Laser Microfusion
POLAND

IPFN Instituto de Plasmas e Fusão Nuclear Técnico Lisboa
PORTUGAL

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ROMANIA

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Jožef Stefan Institute
SLOVENIA

Laboratorio Nacional de Fusión Ciemat
Centre for Energy, Environment And Technology Research
SPAIN

Swedish Research Council
SWEDEN

EPFL
SWITZERLAND

DIFFER Dutch Institute for Fundamental Energy Research
THE NETHERLANDS

KIPT Kharkov Institute of Physics and Technology
UKRAINE

CCFE Culham Centre for Fusion Energy
UNITED KINGDOM

+150 Universities

Fusion works

The sun and the stars shine thanks to fusion reactions
taking place in their core.

Can we mimic this tremendous energy source on Earth?

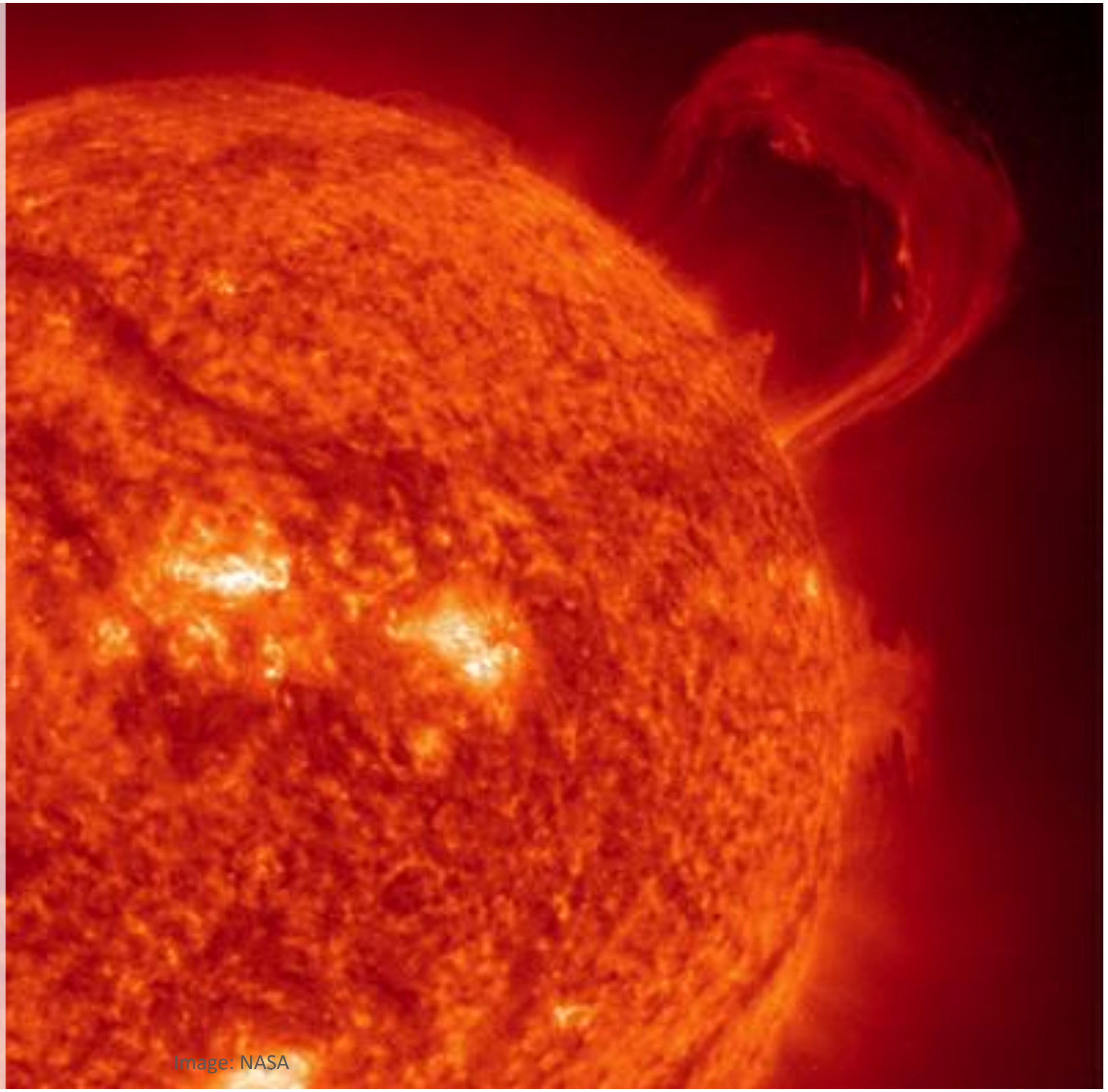


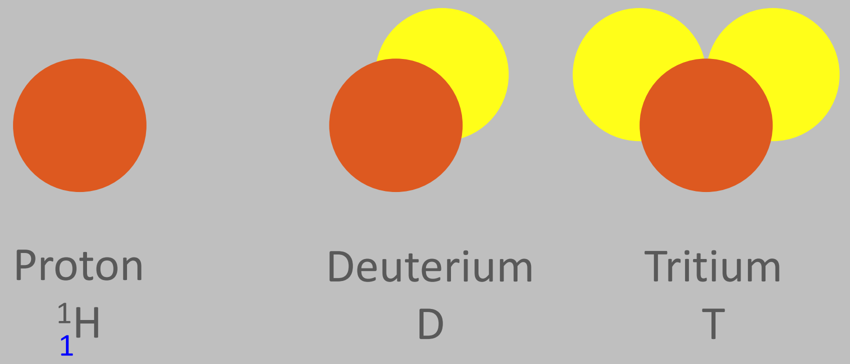
Image: NASA

What is the best reaction for fusion on Earth?

The Sun fuses Hydrogen (H) nuclei into Helium (He).

On Earth, the most efficient approach is to use two isotopes of Hydrogen:

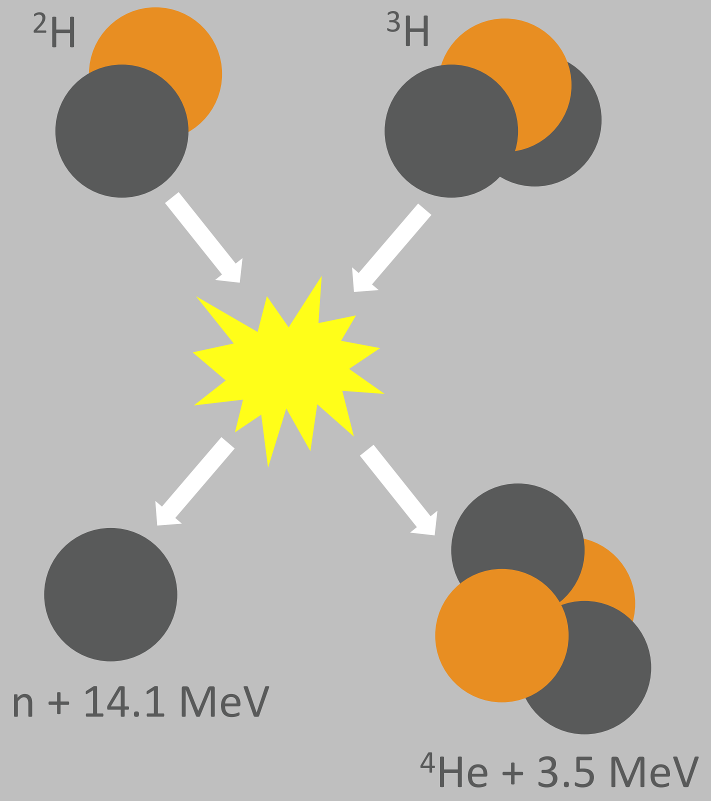
- Deuterium (D)
- Tritium (T)



Fusion vs. Fission

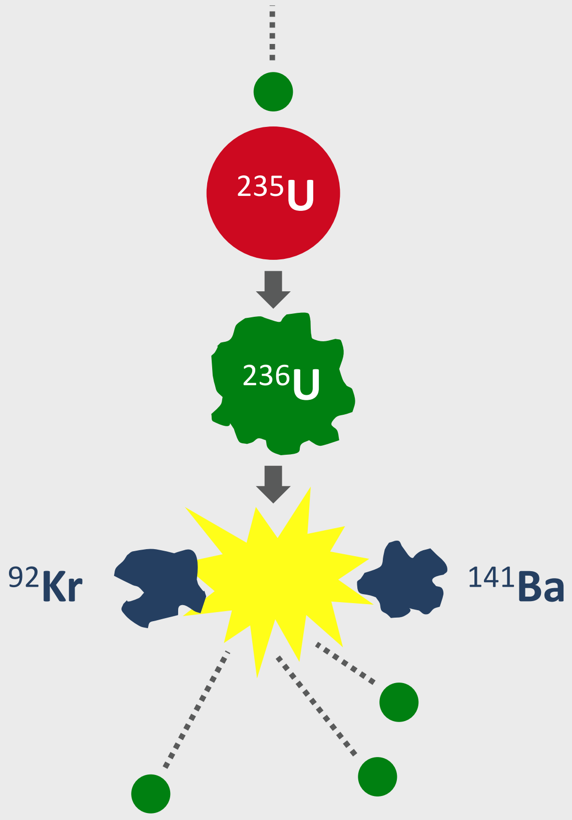
FUSION

Two small nuclei bind making a bigger one.



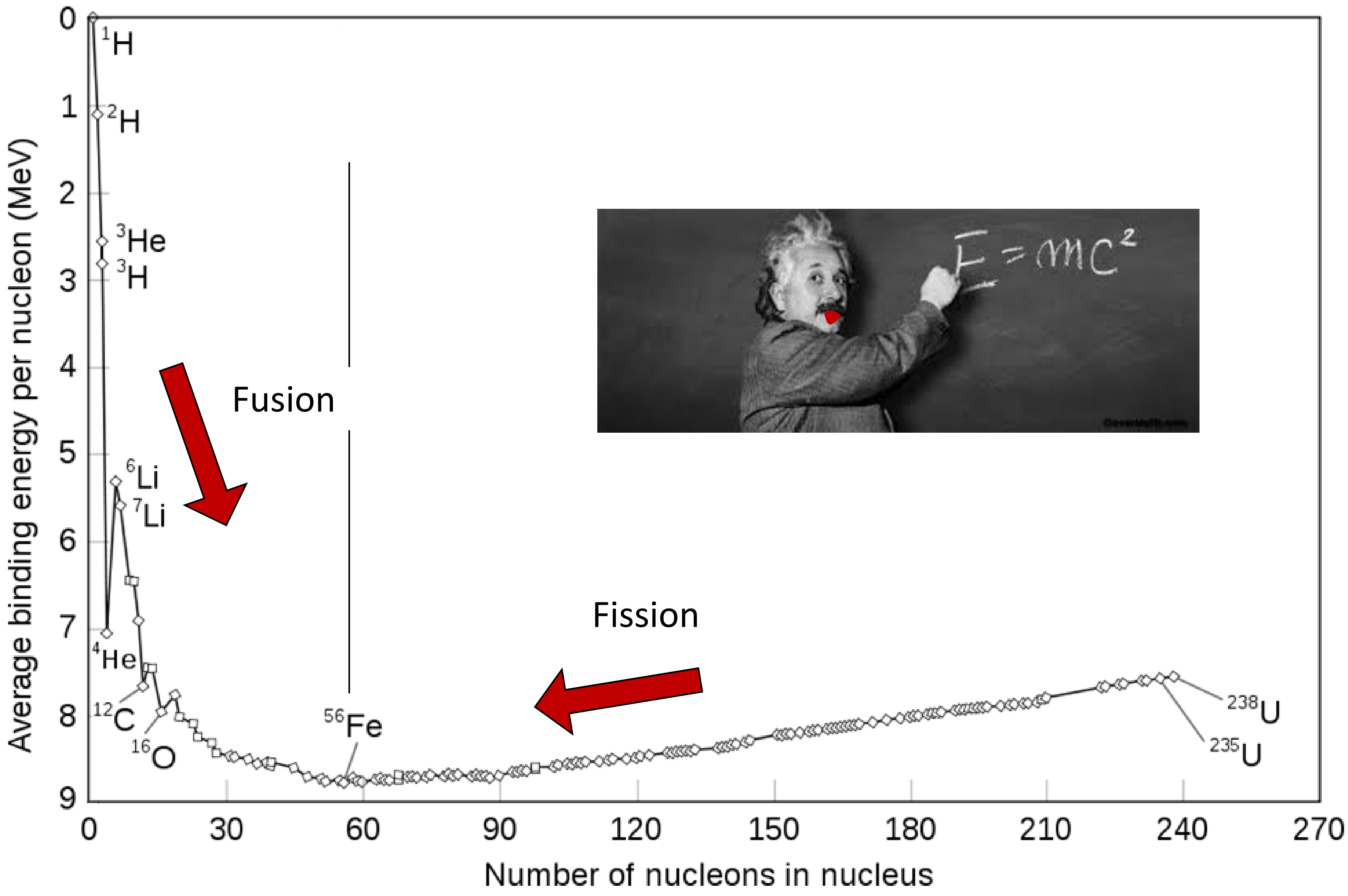
FISSION

One large nucleus breaks up into smaller ones.



Graphic: EUROfusion, Reinald Fenke, CC BY 4.0, www.euro-fusion.org

$E = mc^2$


Average binding energy per nucleon (MeV)
0
1
2
3
4
5
6
7
8
9
Number of nucleons in nucleus
0
30
60
90
120
150
180
210
240
270
1H
2H
3He
3H
6Li
7Li
4He
12C
16O
56Fe
238U
235U
Fusion
Fission
E = mc²

Plasma confinement is the key

Images(left to right): NASA, CCFE, green picture replace with https://en.wikipedia.org/wiki/National_Ignition_Facility#/media/File:Preamplifier_at_the_National_Ignition_Facility.jpg,
image: Lawrence Livermore National Laboratory, CC BY-SA 3.0, http://tinyurl.com/hj7qvan

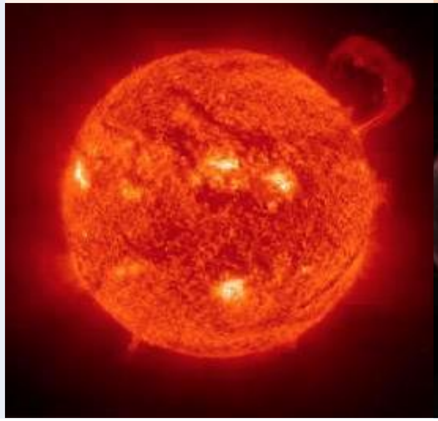
Stars are so massive that they rely on

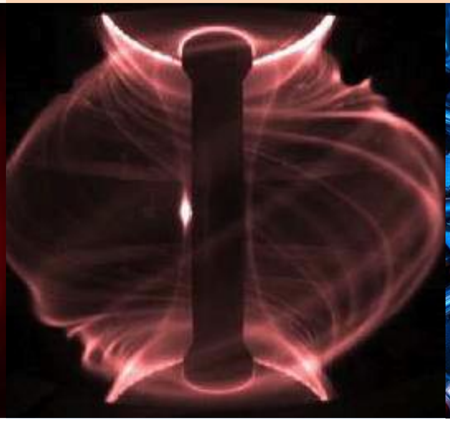
On Earth nuclear fusion does not happen naturally, so we rely mainly on two approaches

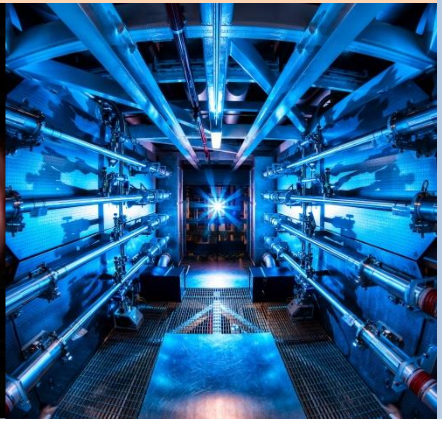
gravitational confinement

magnetic confinement

inertial confinement







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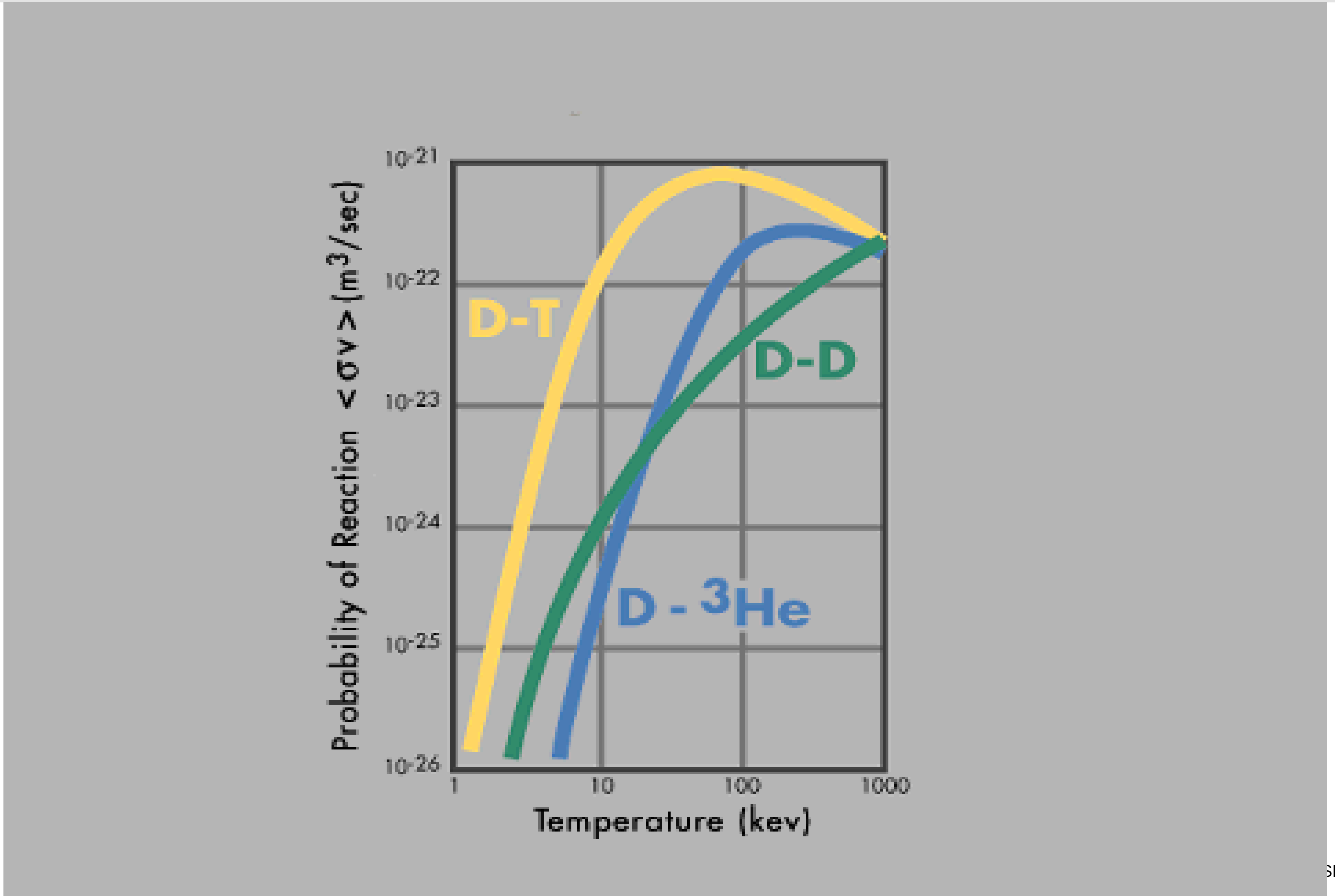
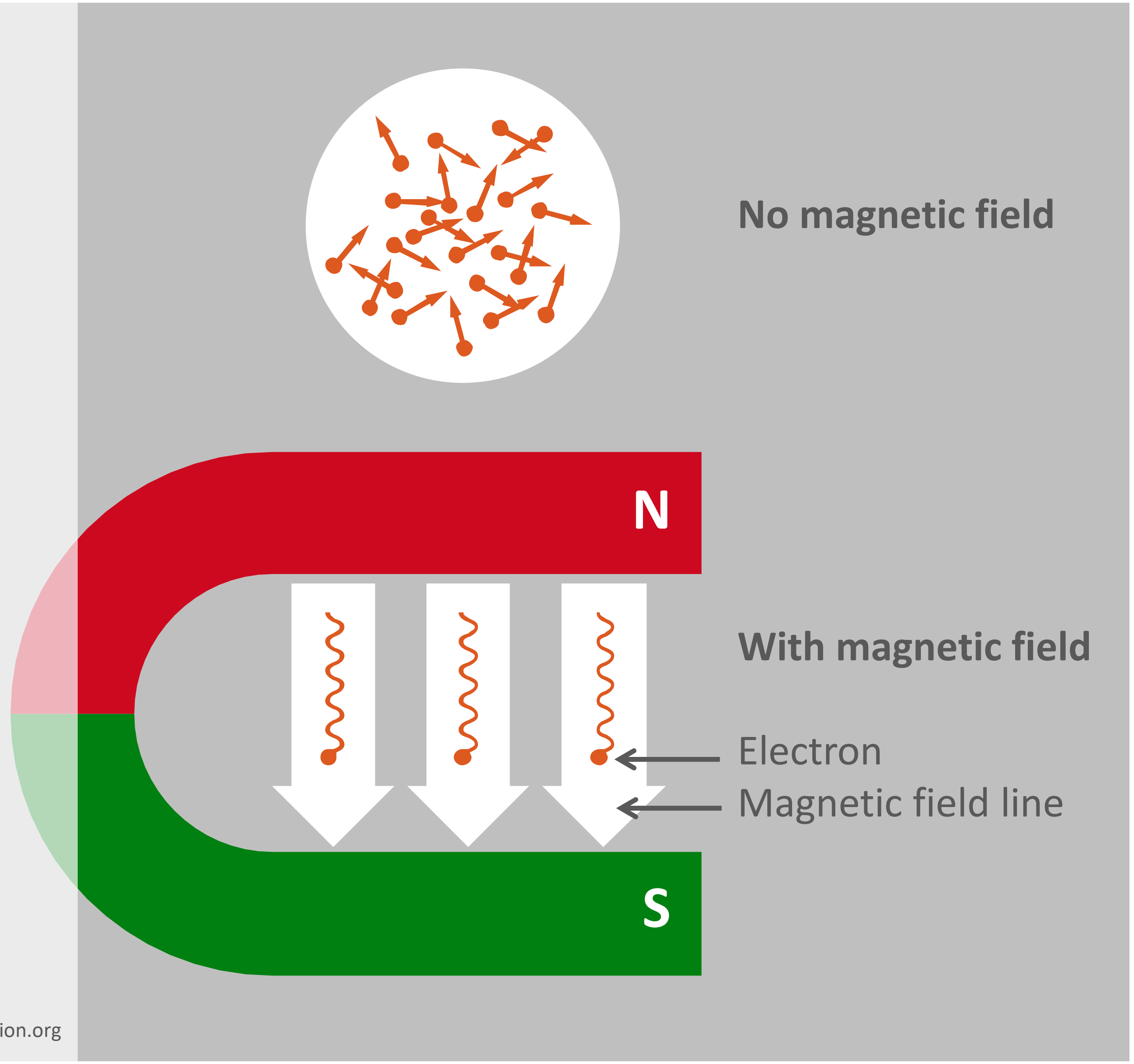


Magnetic confinement fusion

The plasma is squeezed and its particles spiral along **magnetic field** lines, while **electric fields** heat it

Density is very low: 250 thousand times less than the Earth's atmosphere

Confinement time is long: >seconds



Graphic: EUROfusion, Reinald Fenke, CC BY 4.0, www.euro-fusion.org

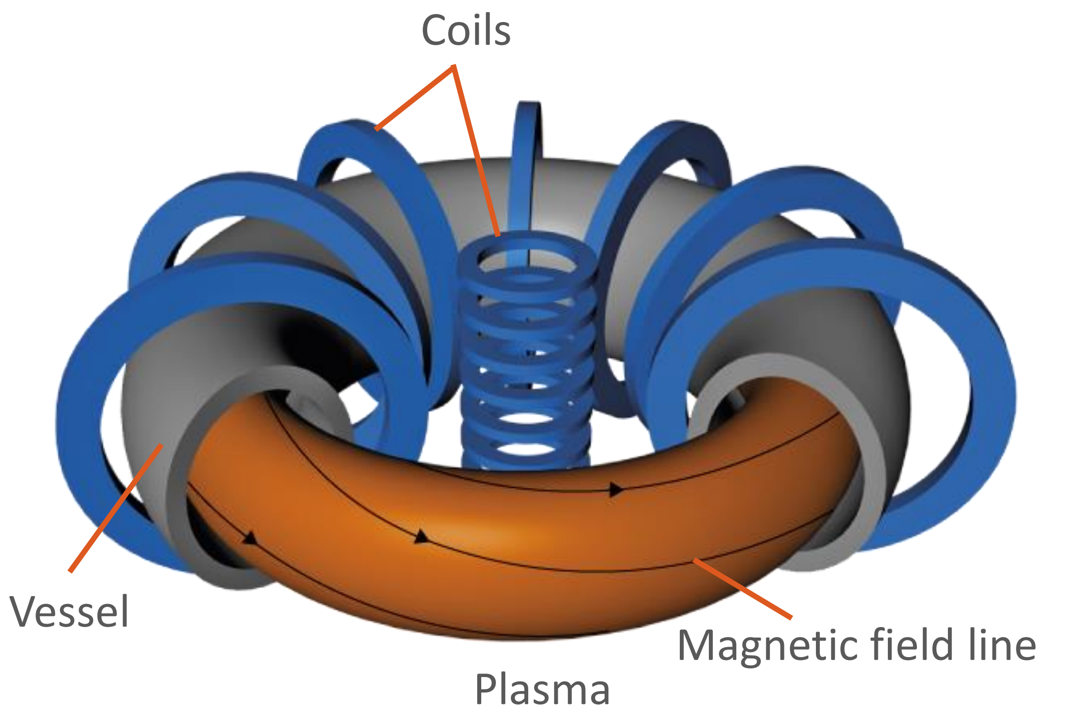
A promising magnetic confinement concept

BASICS OF A TOKAMAK

It consists of

Metallic vessel to contain the plasma

Magnetic field coils to
- guide the plasma particles
- generate a current in the plasma
- shape the plasma



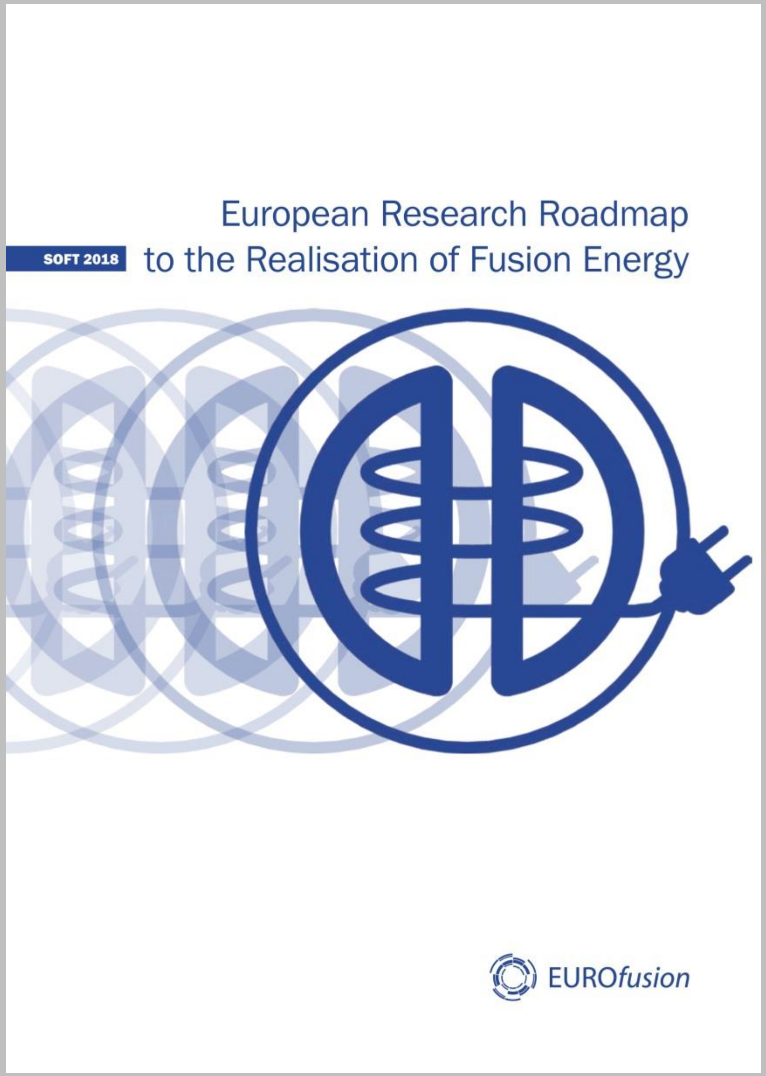
Graphic: EUROfusion, Reinald Fenke, CC BY 4.0, www.euro-fusion.org

A stellarator has in contrast to a tokamak all fields generated by external coils. A stellarator is in first-order current-less and can be operated steady state.
- See later in this talk and also the talk by S. Gunter on Thu.

Fusion Roadmap

DEMONSTRATE FUSION ELECTRICITY EARLY IN THE SECOND HALF OF THE CENTURY

- Based on a number of technical assessment reports
- Provides coherent EU programme with a clear objective
- Avoids open-ended R&D
- Published September 2018



What is the EUROfusion roadmap about?

- a comprehensive goal-driven programme aimed at fusion electricity on the path to commercial deployment, in time to address climate change challenges

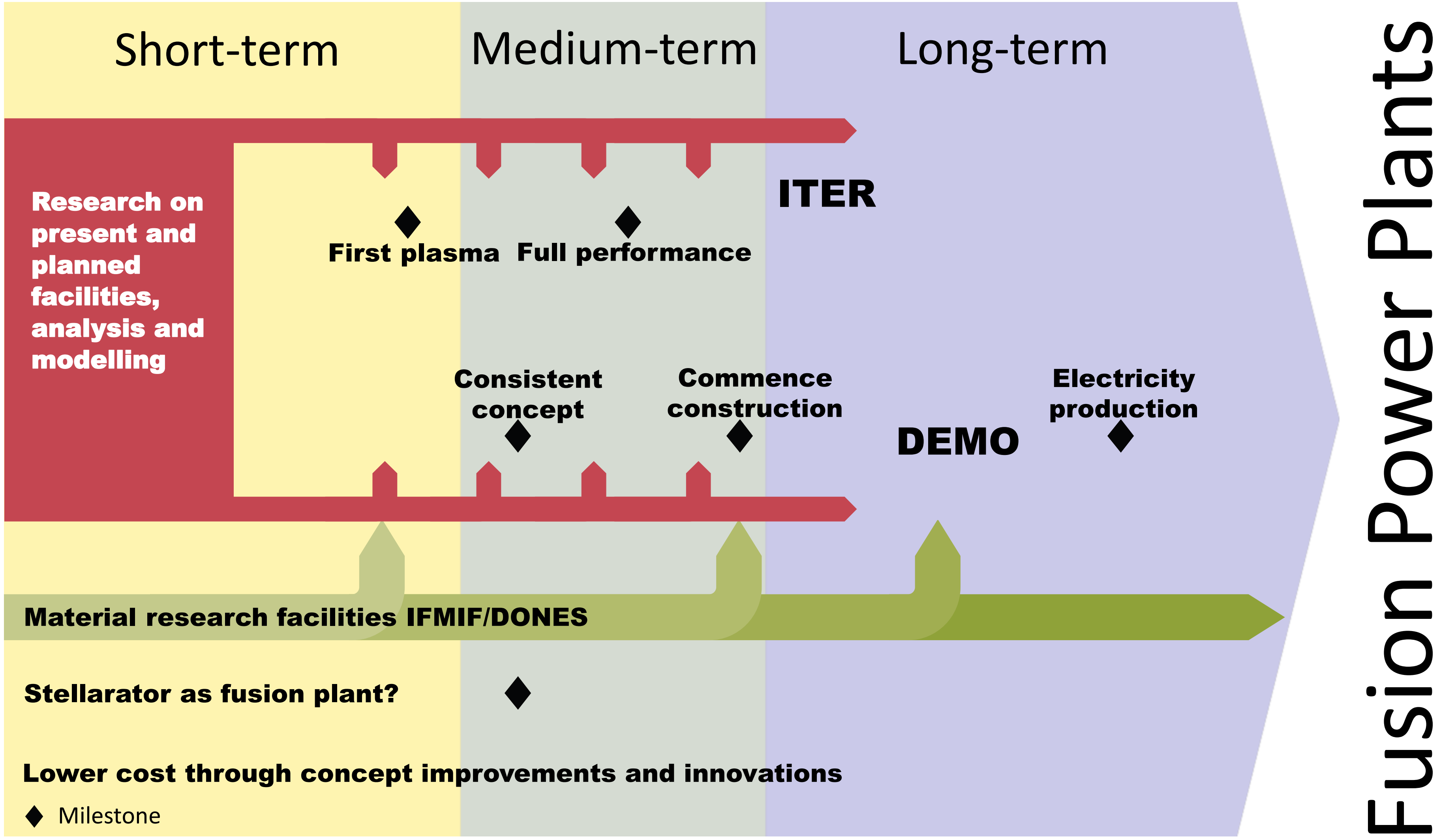
- it translates this overarching vision into an implementation programme combining, science, engineering, technology and, increasingly, industry

- event-driven with a strong time incentive

It

- ➢ helps ITER succeed and be used effectively
- ➢ has a credible path to a licensed electricity-producing DEMO
- ➢ has a view to the next stages after DEMO (prepare industry)
- ➢ has back-up strategies
- ➢ Can be used to prioritise research

EU Fusion Roadmap



(JA, KO, CN have fairly similar roadmaps)

ITER

First plasma in 2025

DT operation to start in 2035

$Q = P_{in}/P_{fusion}$ ~10

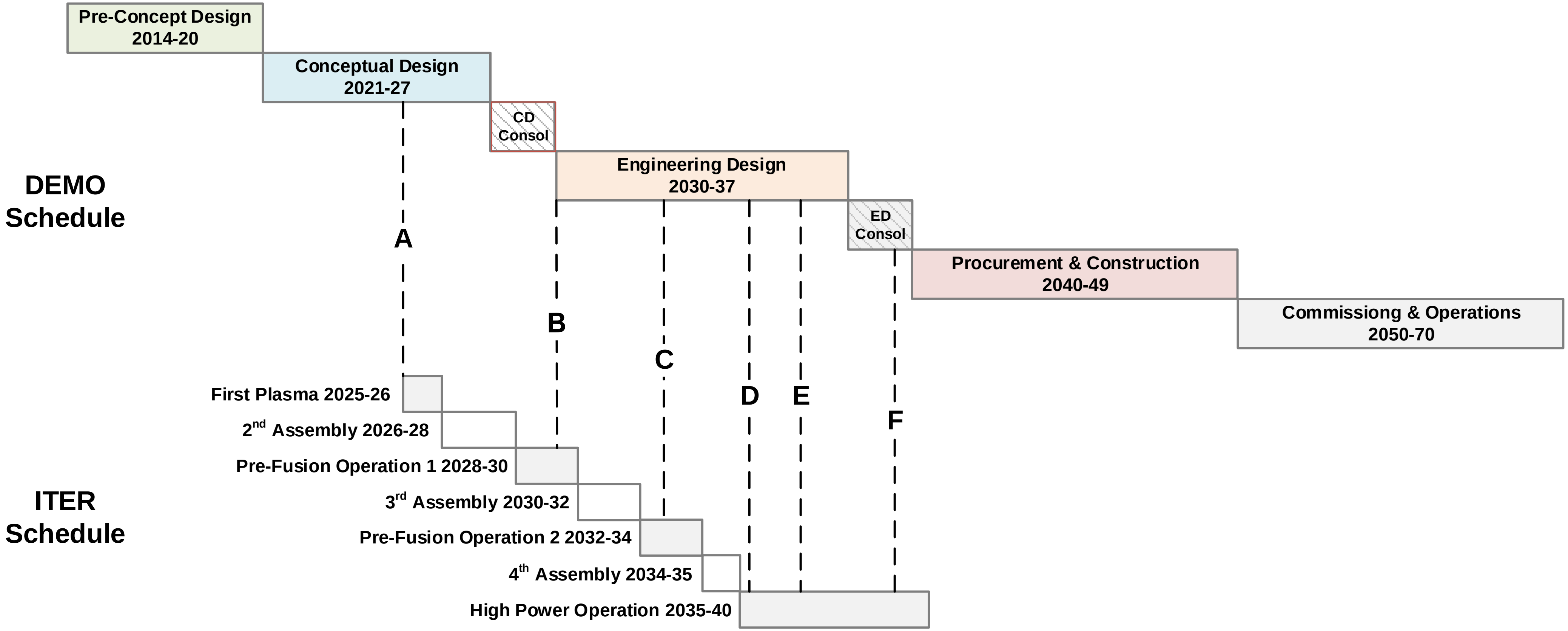
ITER will demonstrate the feasibility of fusion

ITER will test breeding of tritium

iter

china eu india japan korea russia usa

DEMO schedule critically depends on ITER



A
Validated Assembly,
Integrated Design,
Testing & Commissioning,
SC magnets,
VV fabrication validation

B
Integrated diagnostics validation,
ECRH performance,
disruption characterisation,
divertor remote maintenance validation

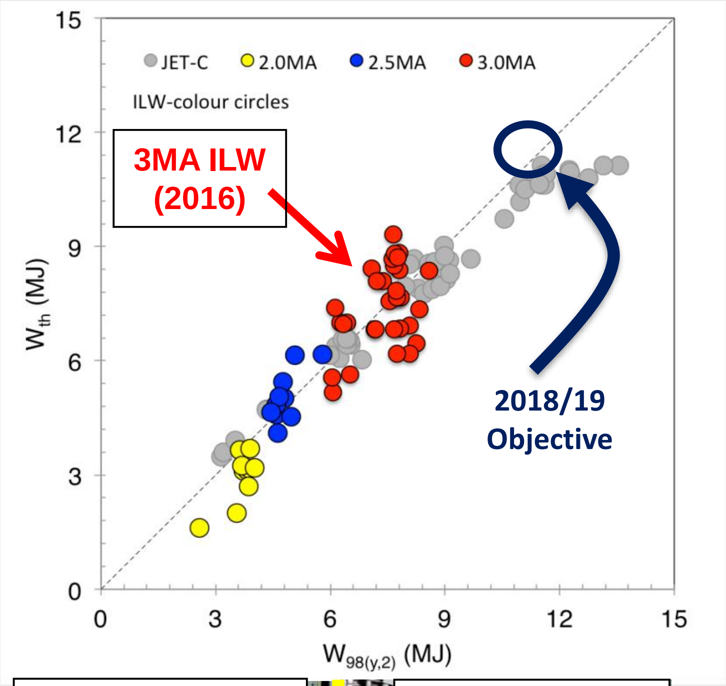
C
H-mode transition threshold,
Validation of ELM control & disruption mitigation,
NB & ICRH performance,
diagnostics validation,
validation of BB fabrication

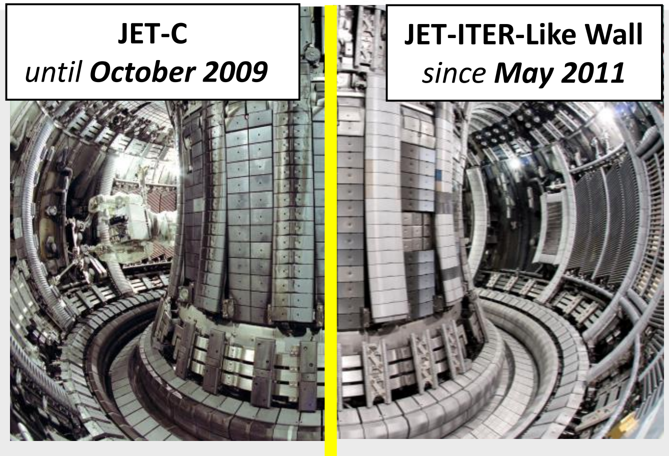
D
Burn scenarios,
bootstrap fraction,
first wall heat loads,
tritium plant validation,
full H&CD validation

E
TBM Validation,
Operational scenario refinement,
Q=10 (short pulse)

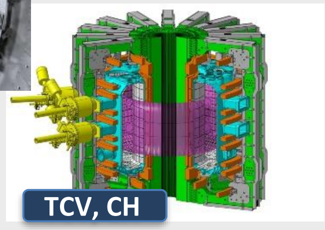
F
Q=10 (long pulse)

Eight missions (challenges)





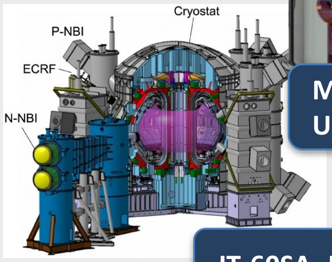
JET, UK



TCV, CH

ASDEX Upgrade, Munich, DE

MAST Upgrade, UK



JT-60SA, JA

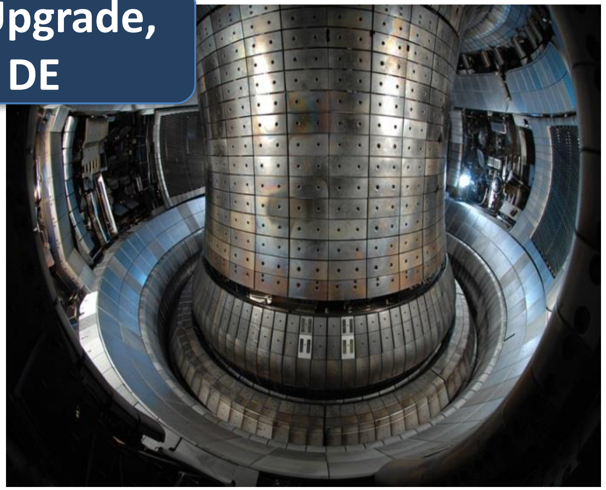
1

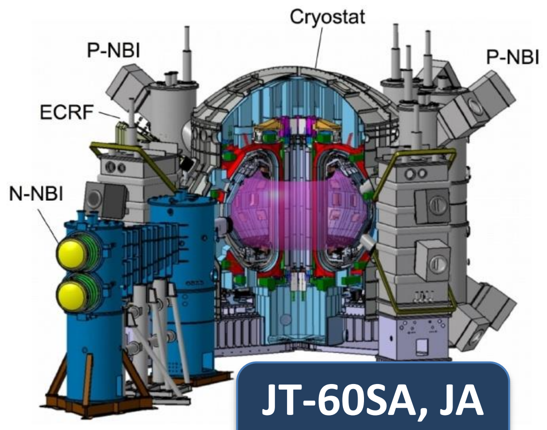
Plasma Regimes of Operation

Tokamak devices

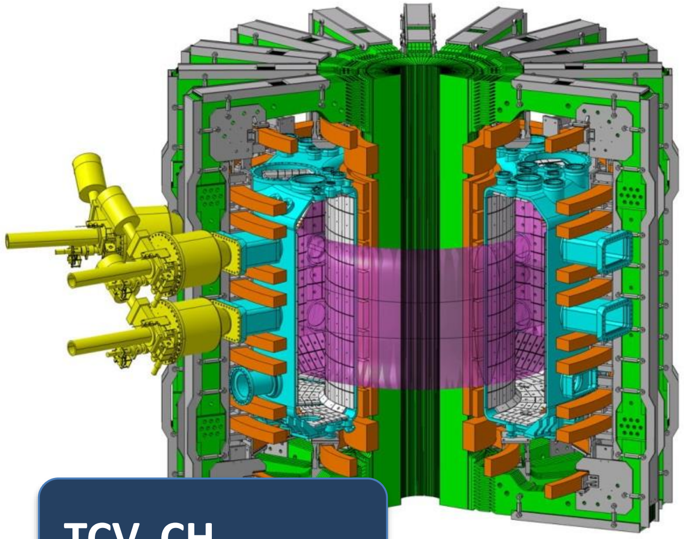
JET, UK

ASDEX Upgrade, Munich, DE

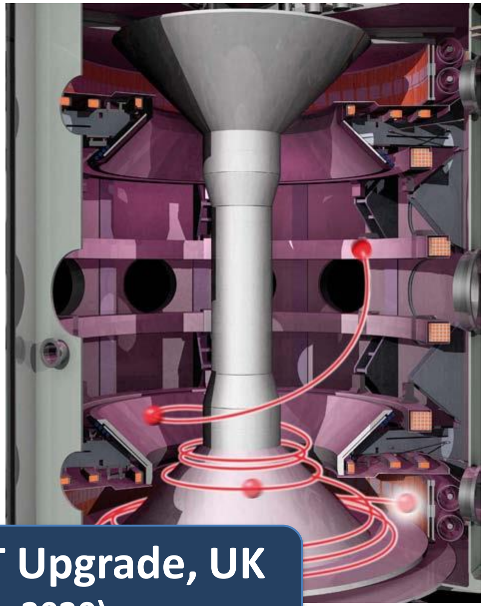




JT-60SA, JA
(Start in 2020)



TCV, CH



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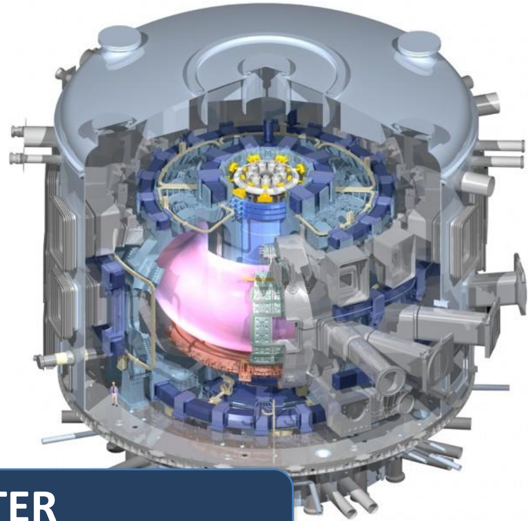
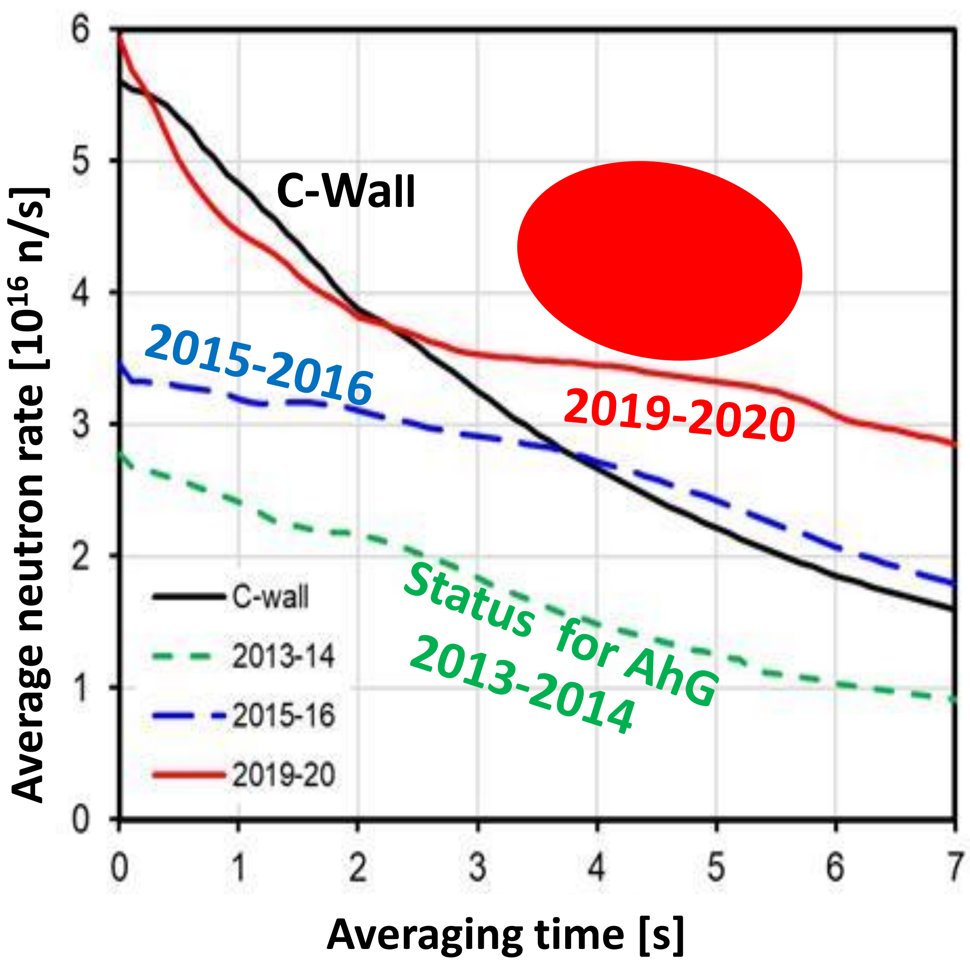


ITER
(Our target device)

JET Fusion Performance: Significant Progress

Stationary fusion performance (5s) above C- Wall record

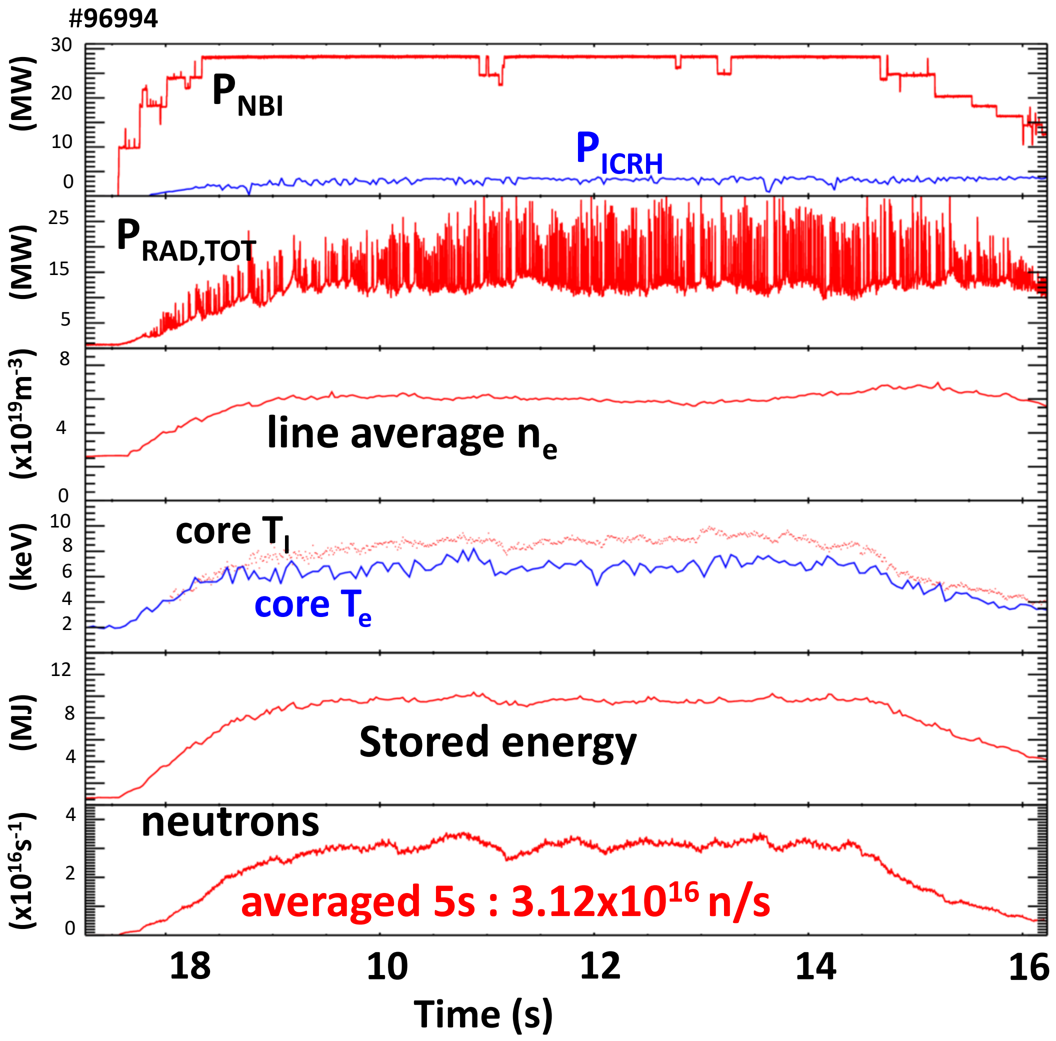


[C. Challis, J. Mailloux, et al. 2020]

- **Fast progress with reliable & steady high NBI power**
- **Peak (50ms) neutron rate significantly higher than in 2016, and slightly above C-wall reference!**

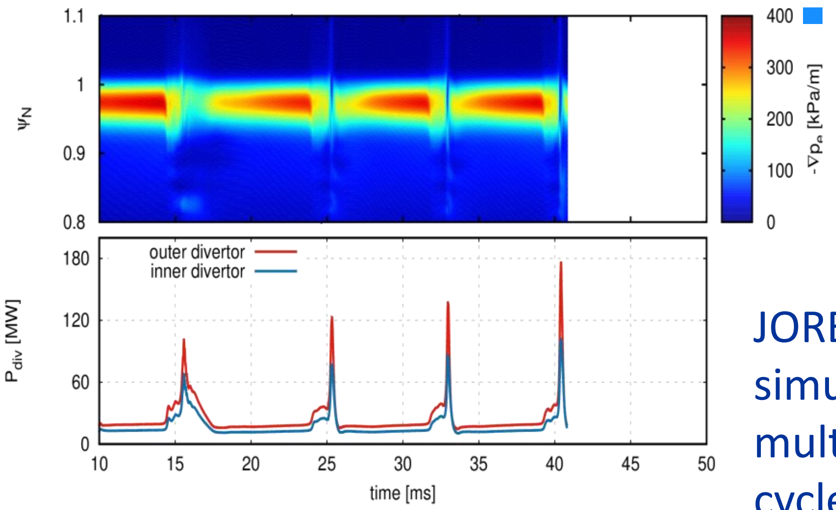
ITER Baseline Scenario: Stationary Performance at P_{tot} =32MW

3.0MA/2.85T, $H_{98(y,2)} = 1$, $\beta_N = 2.2$, $f_{GW} = 0.68$



- **P_{fus}(DT-eq.) ~ 8.6-9MW**
  - margin for improvement at higher I_P and P_{TOT}
- **ELMs (pellet pacing) and P_{RAD} controlled**
- **Neon injection ($0.5x10^{22}$e/s, ~half of D_2 throughput) but attached Divertor**

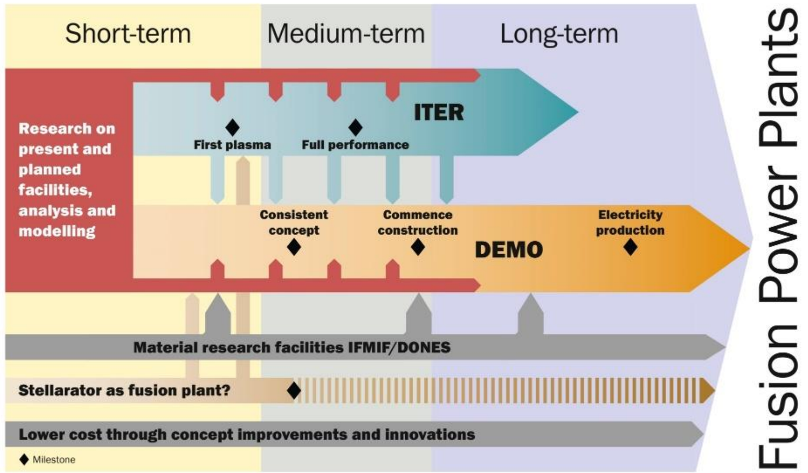
Missions 1 and 2: Plasma scenarios

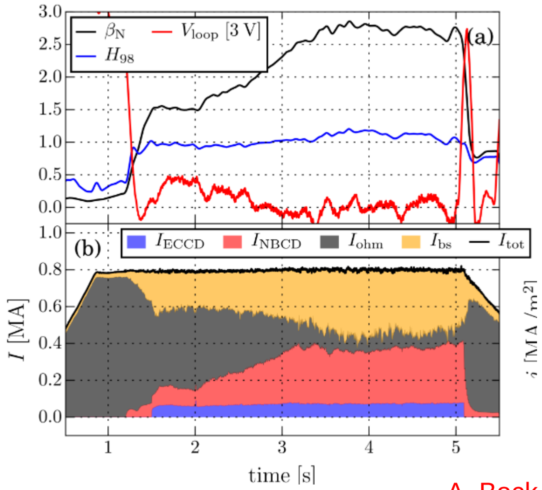


Midplane toroidally averaged ∇p (top) and divertor incident power (bottom) during a series of ASDEX Upgrade ELM cycles simulated with JOREK

A. Cathey Cevallos et.al. subm. to PRL

JOREK simulations of multiple ELM cycles

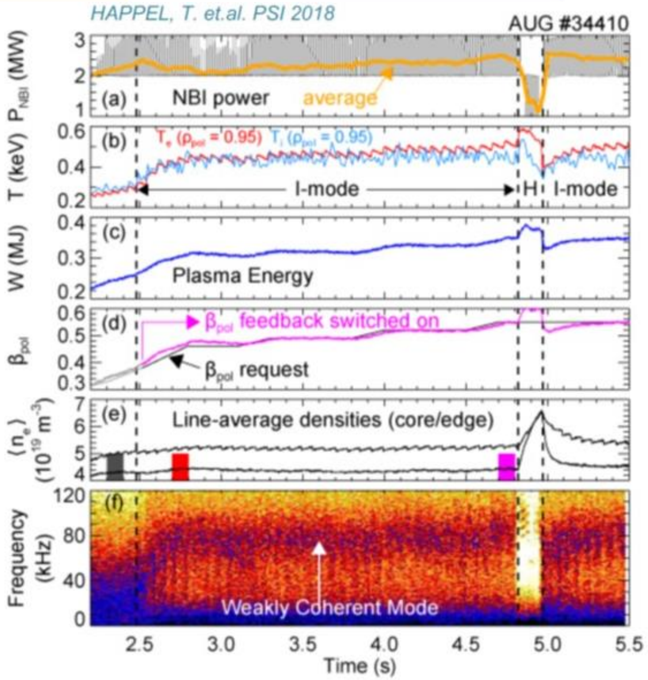




Steady state?

AUG

No-ELMs? (I-mode)

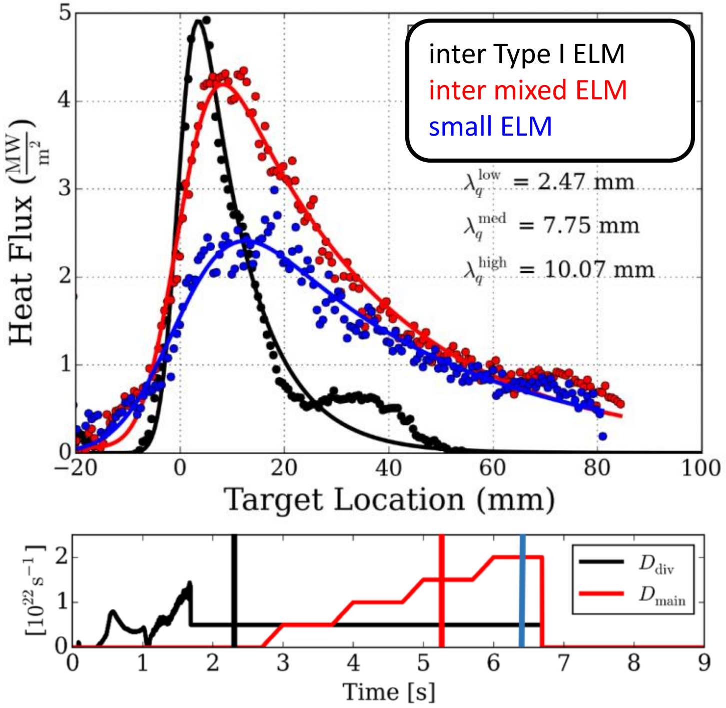


T Happel et al., PSI, IAEA 2018

A. Bock et al., Nucl. Fusion 2017

Small ELMs show strongly widened “quasi steady state” heat flux profile

- Inter ELM “steady state” heat flux is hard to predict
- Compare power fall-off length measured with high-resolution IR



$$\lambda_q^{low} = 2.47\ mm$$
$$\lambda_q^{med} = 7.75\ mm$$
$$\lambda_q^{high} = 10.07\ mm$$

M. Faitsch, G. Harrer (T05: Validation of high-density small ELM regimes for ITER & DEMO)

AUG

- Transient heat flux during type-I ELMs will degrade target life-time.
- Small ELMs so frequent
  $\Longrightarrow$ “quasi steady state” for the divertor IR

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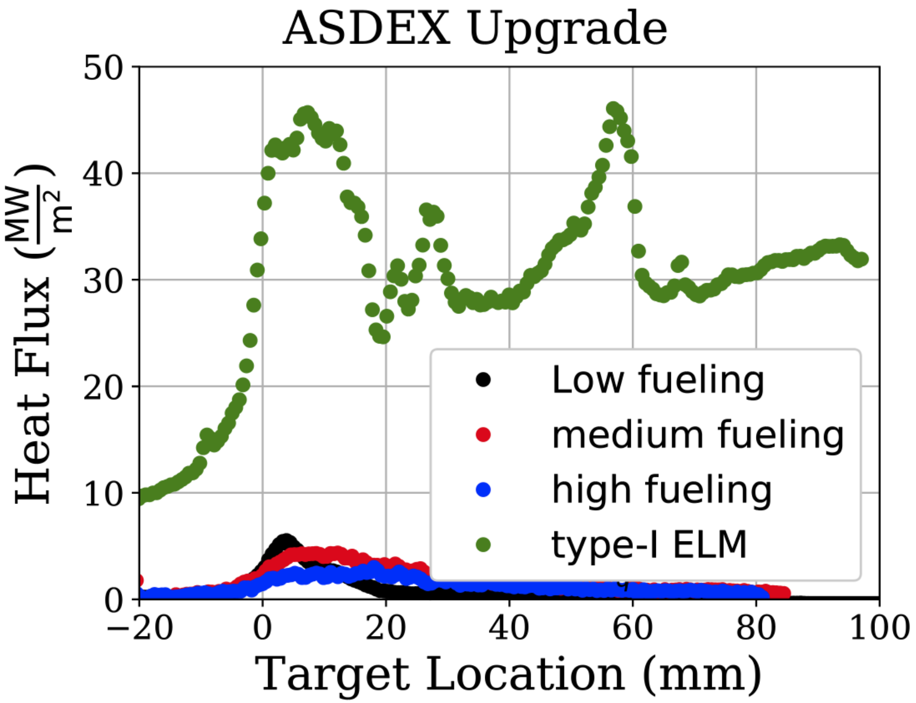

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AUG

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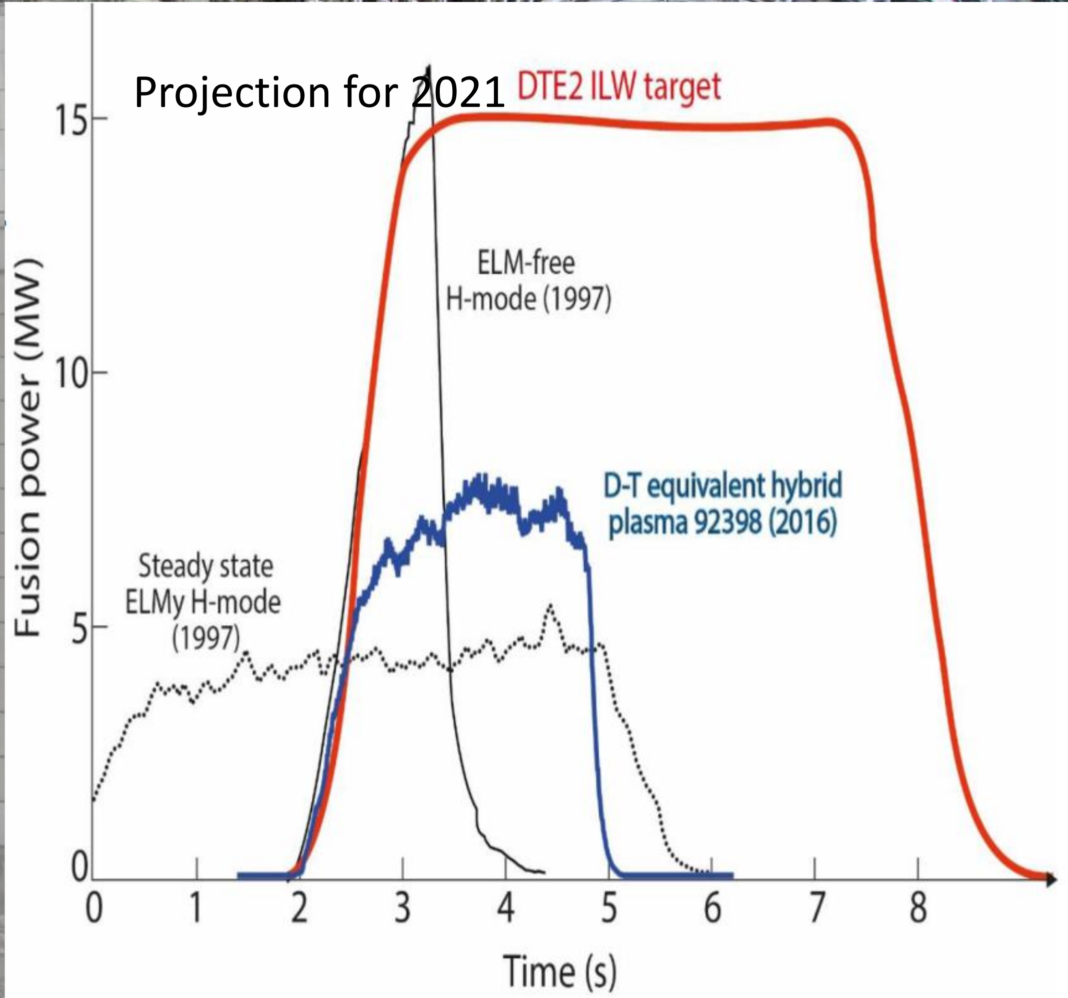
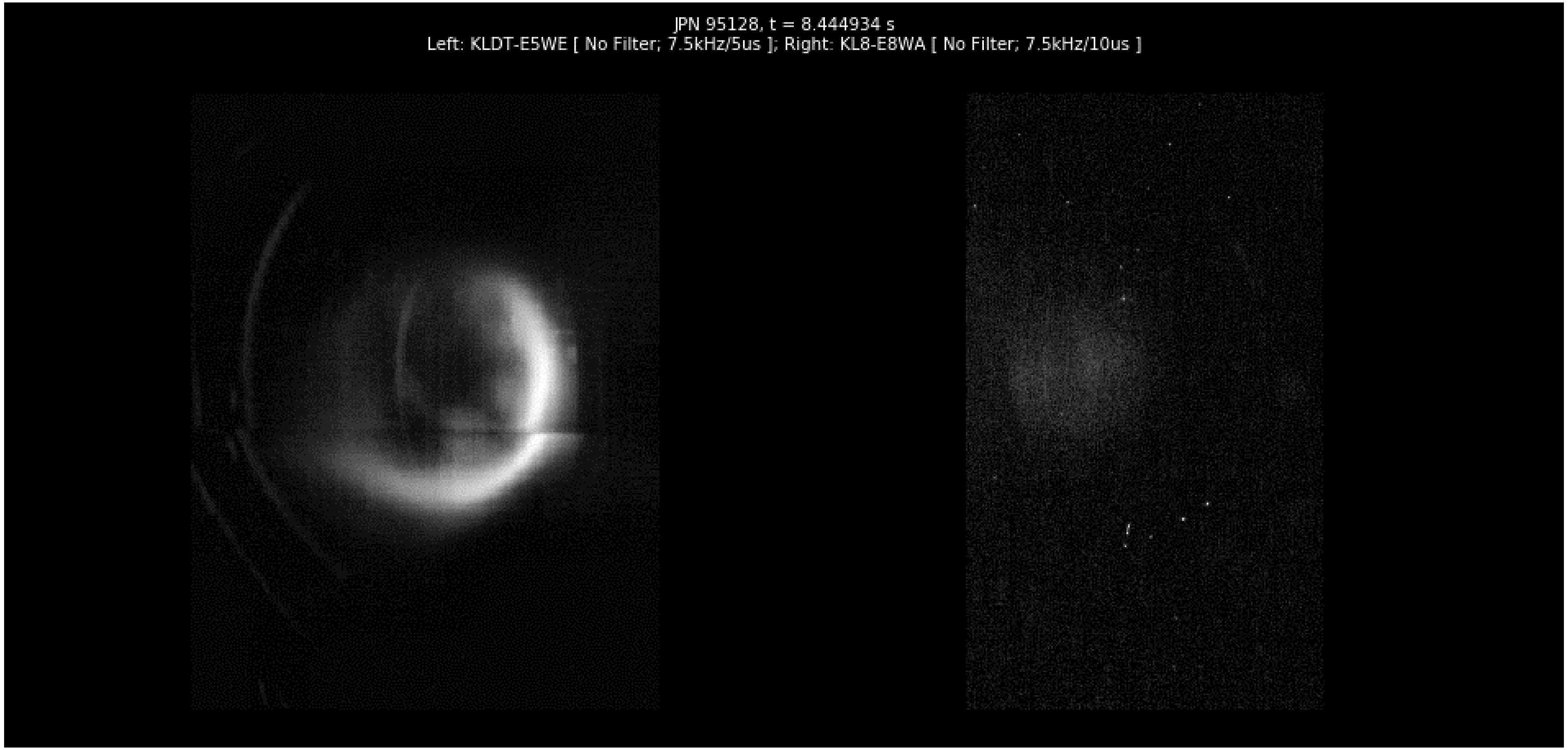
JET – world's largest tokamak

Unique ITER-Relevance:
- Be-wall, W-divertor
- Only device currently able to use tritium
- Remote Handling
- Closest in performance

Programme
- To 2021: high performance DT, disruption management, isotope effects, etc
- After 2020: tbc



Shattered Pellet Injection in JET

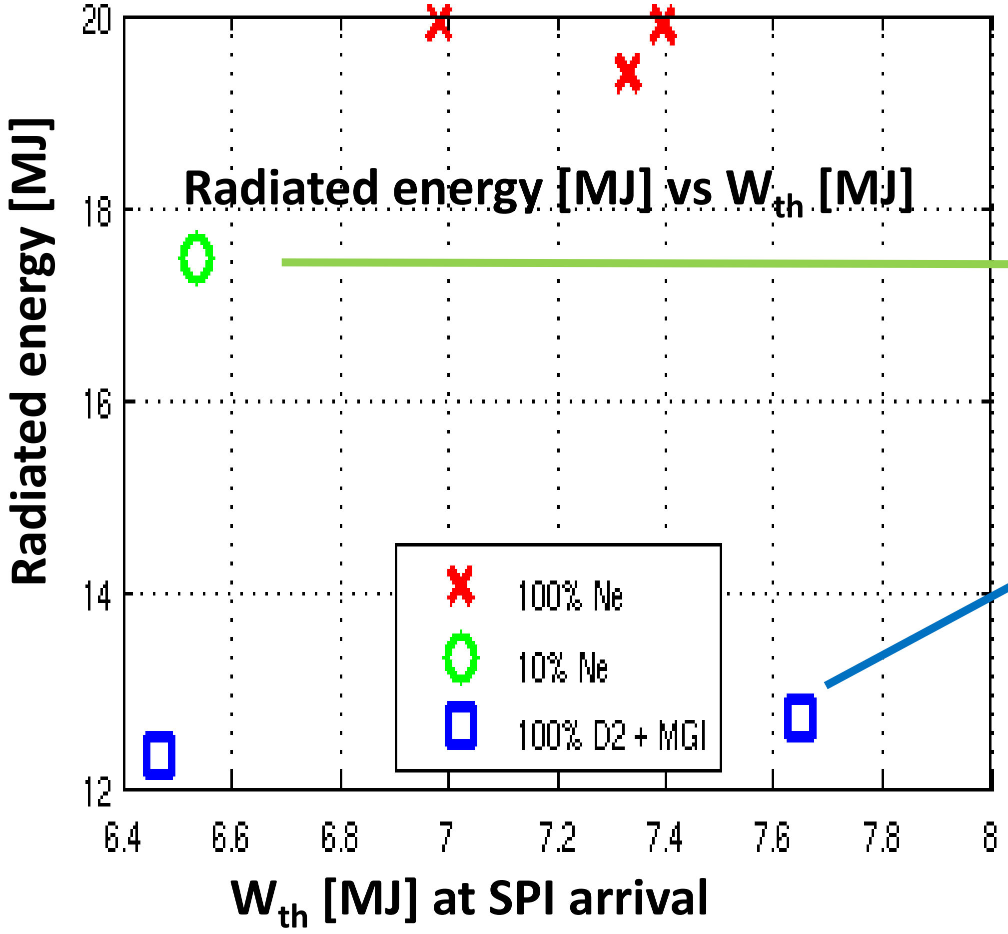


Mitigation of disruption thermal load with SPI at 3MA

(Previous 2019 exp. W_{th} < 4 MJ)

Worldwide unique data for ITER at W_{th} ~ 7.6MJ/3MA:
Essential for ITER extrapolation in terms of size, current and energy

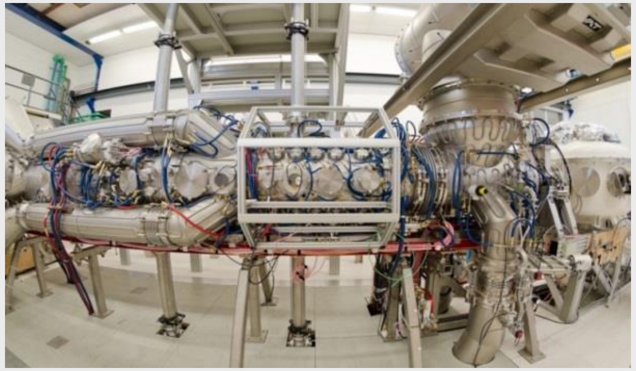
Potential to impact ITER disruption strategy

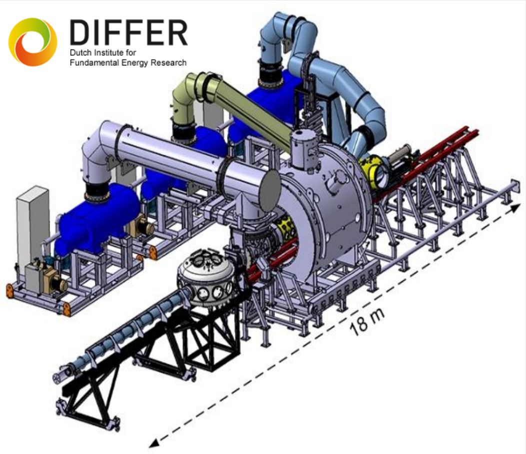


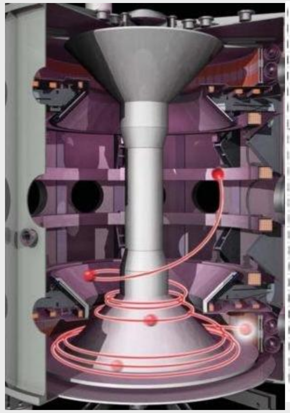
Variation of Ne content in pellets

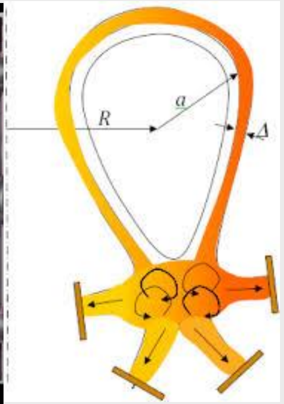
- **10% Ne pellets : Just 10% reduction in radiated energy compared to 100% Ne**
- **pure D_2: avoid large energy deposition during final loss of RE-beam**
- **new and un-expected results**

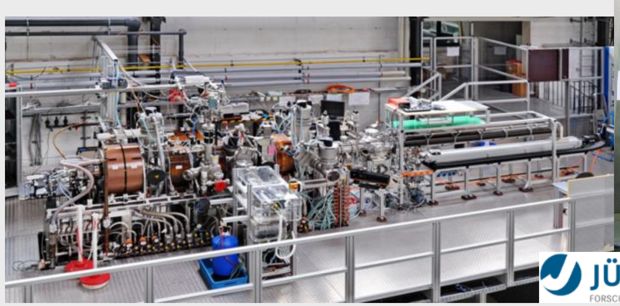
Eight missions (challenges)

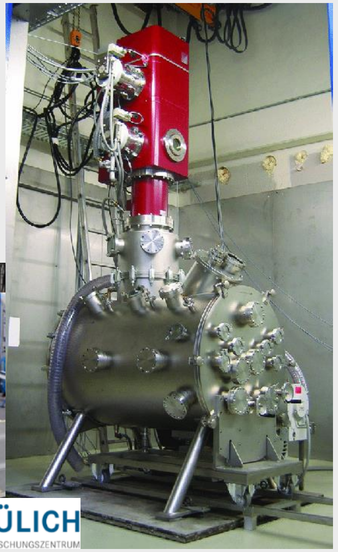












1

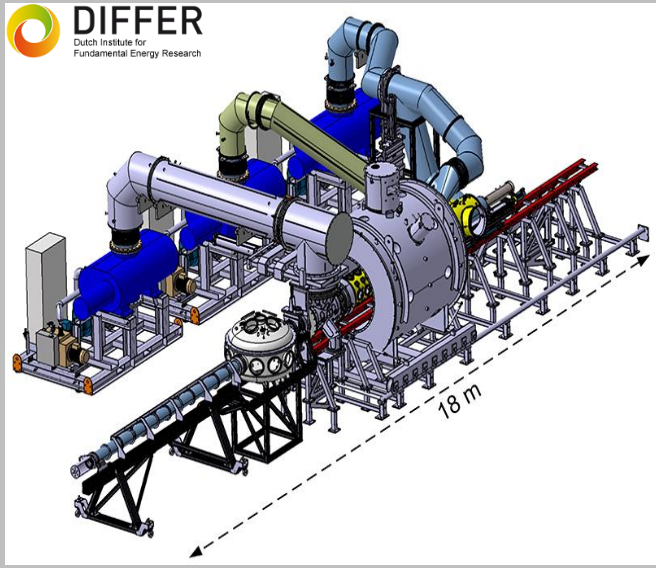
Plasma Regimes of Operation

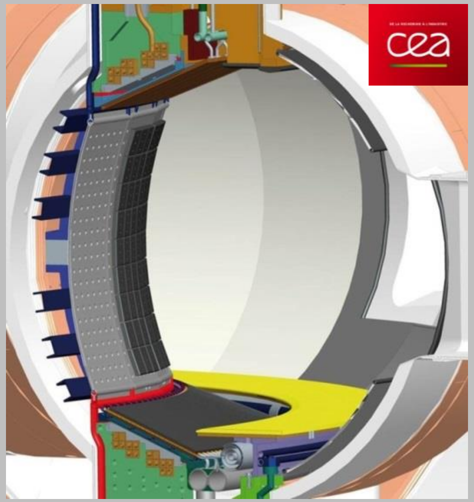
2

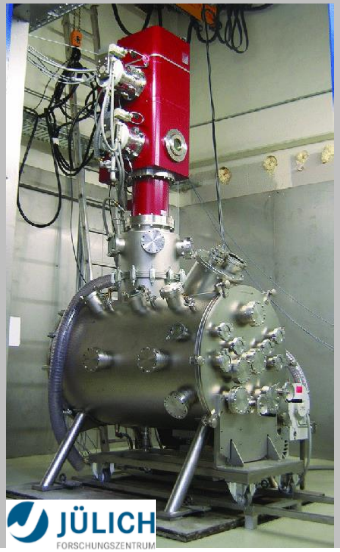
Heat-Exhaust Systems

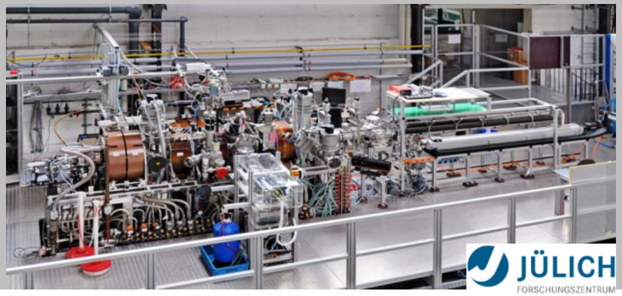
Plasma Facing Component Testing

Devices to study the behaviour of plasma facing components



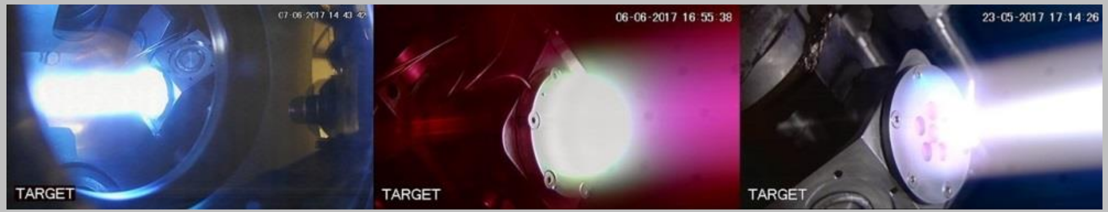






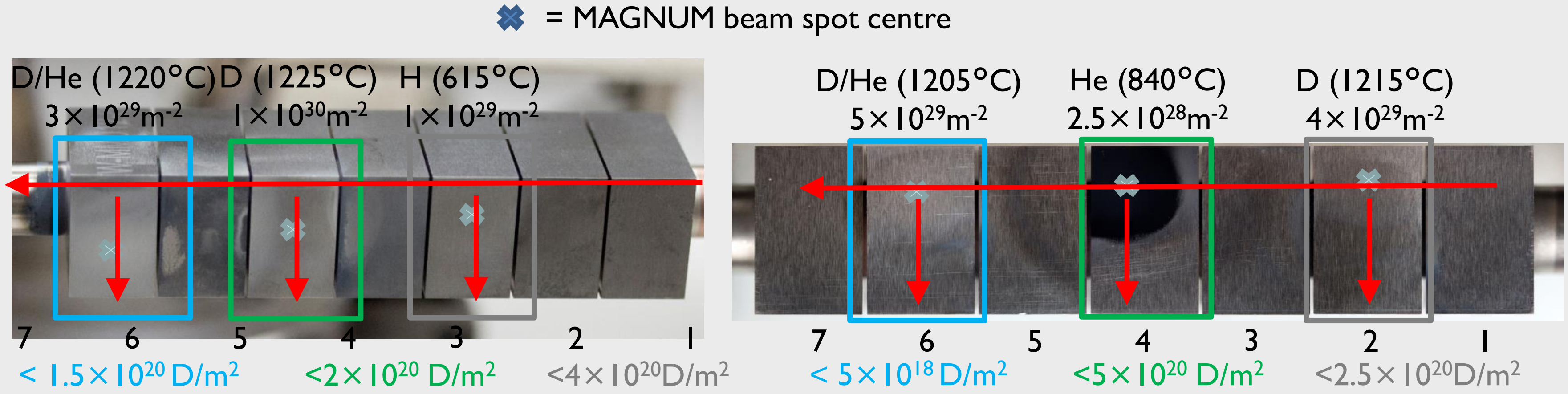
World record exposure in MAGNUM-PSI

T. Morgan, PFMC 2019
M. Balden, PFMC 2019

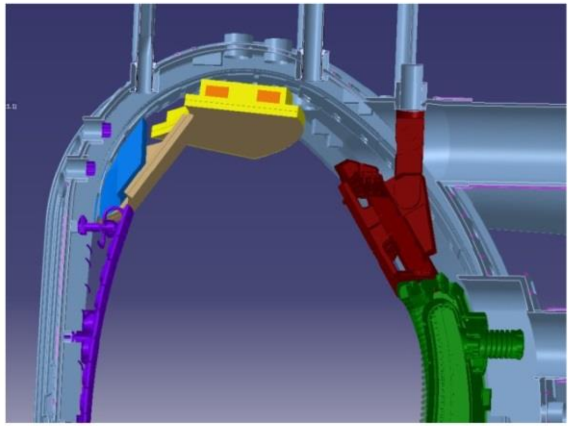


ITER relevant conditions (~1 Full Power Year):

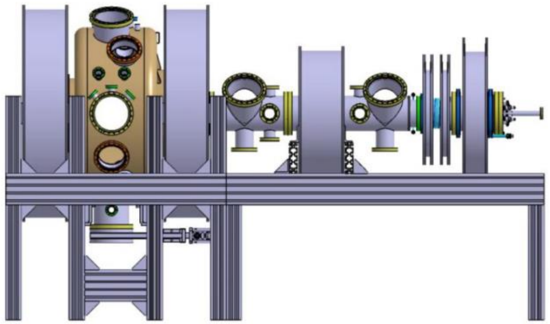
Target	1200 C°
Heat load	20 MWm^{-2}
Particle load	1.5 10^{25} particles $m^{-2}s^{-1}$
Duration:	18,5 hours



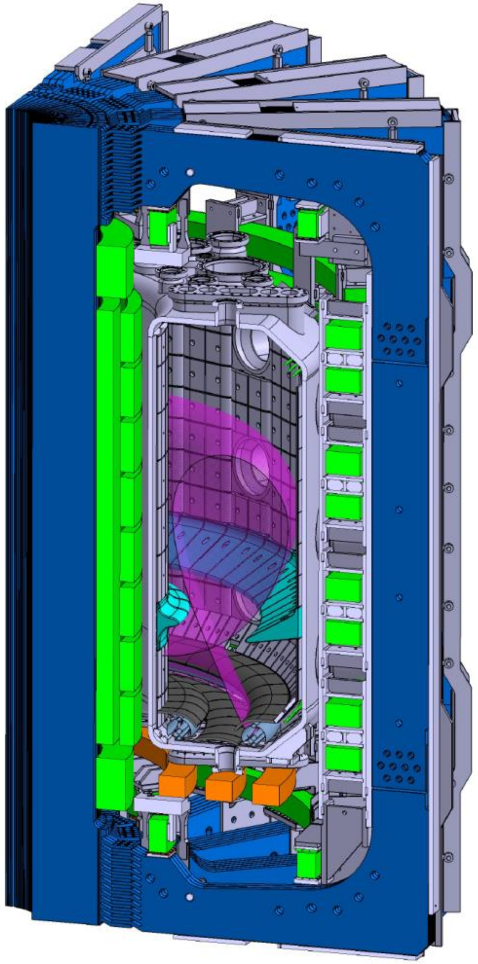
Plasma Exhaust – newly funded upgrades



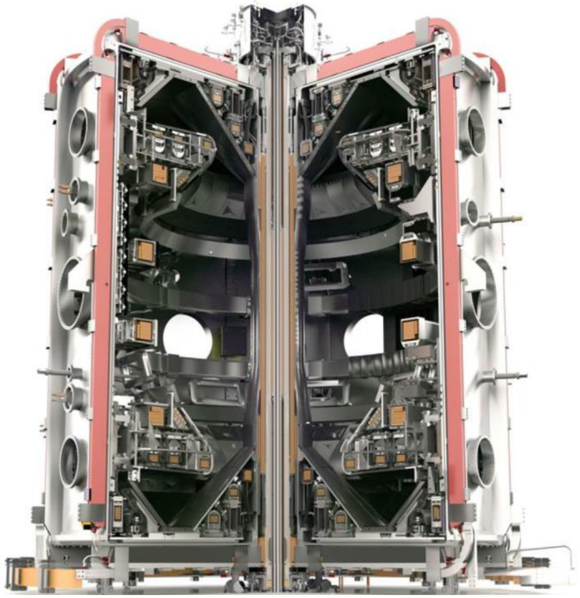
Upper divertor in ASDEX-Upgrade



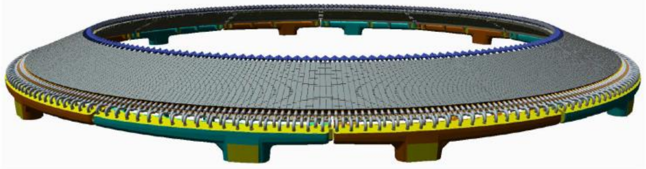
JULE-PSI and JUDITH-3



Baffles and cryopump in TCV

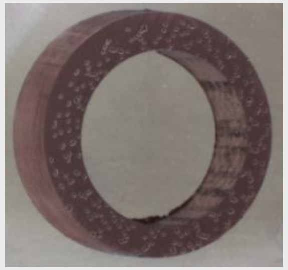


NBI and Divertor diagnostics for MAST-Upgrade

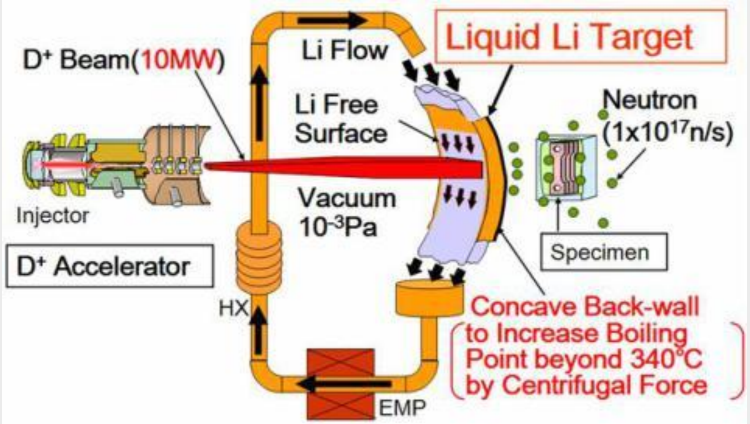


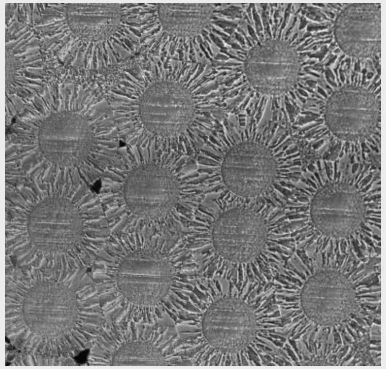
Actively-cooled divertor in WEST

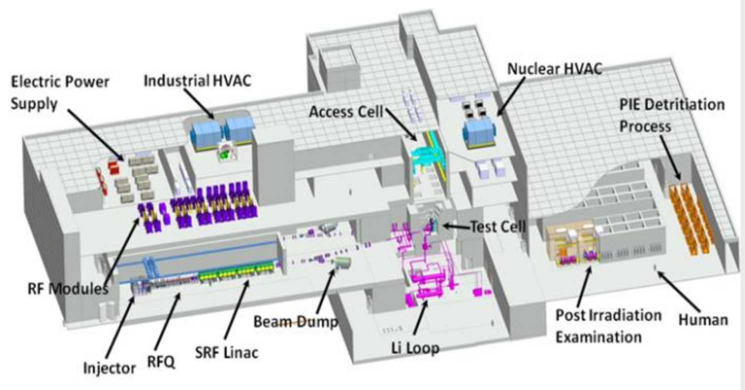
Eight missions (challenges)

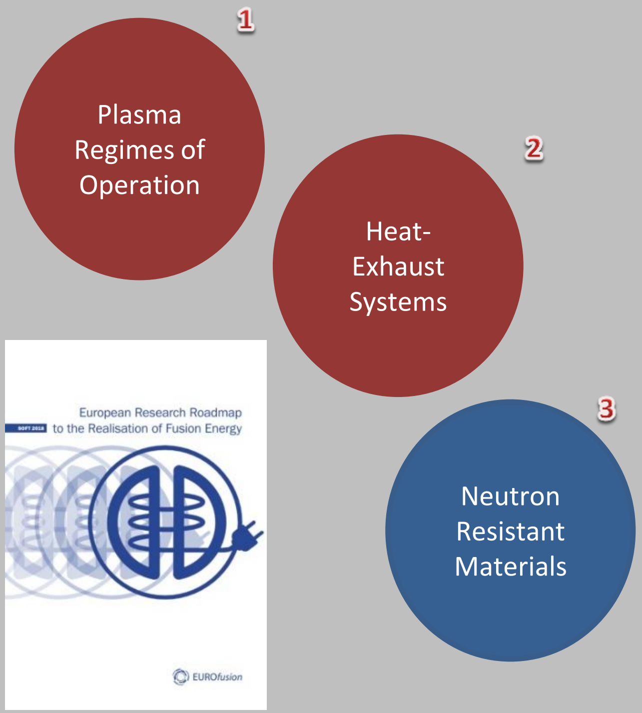


Decision to build IFMIF/DONES in Granada expected in 2021





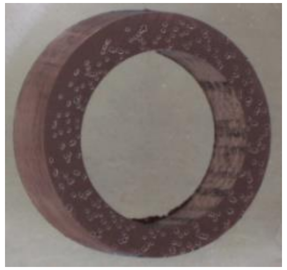


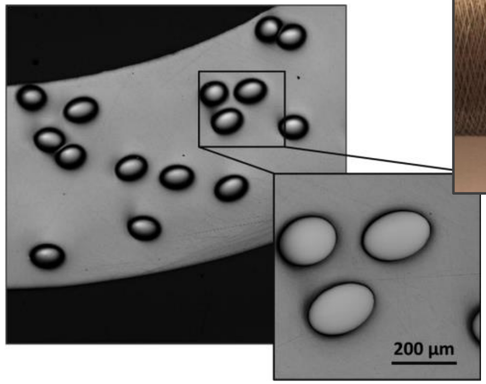


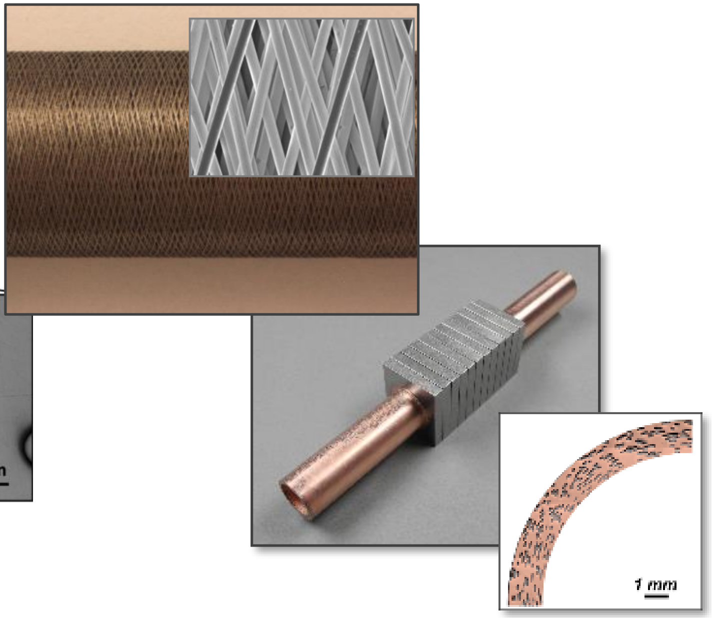
High Heat Flux Materials

Cu-W(fiber) composite tubes



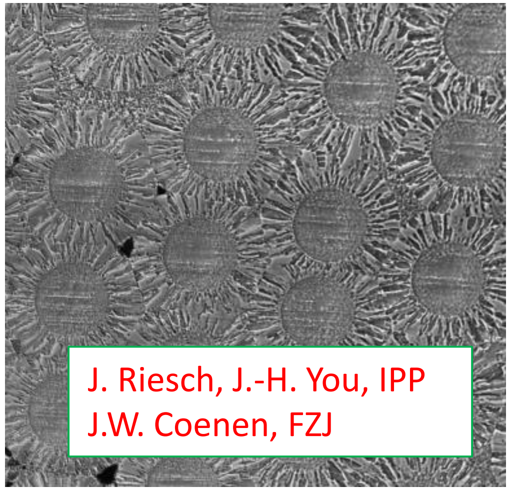




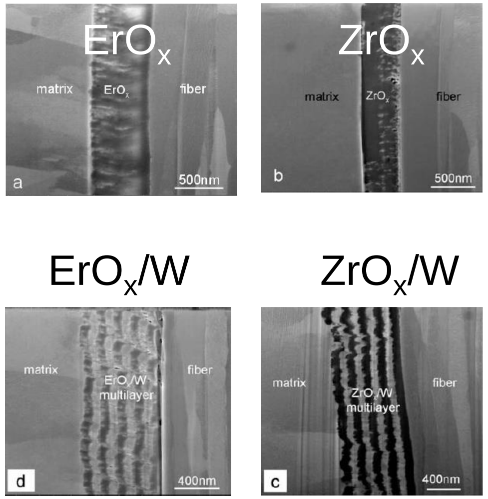


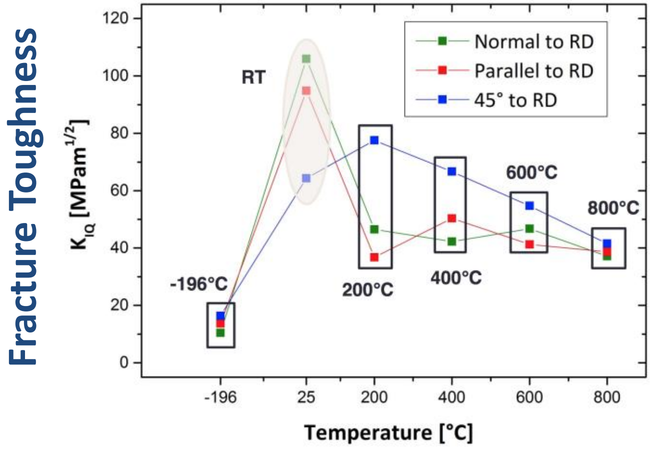
A. v. Müller, J.-H. You, IPP

W-W(fiber) composite



J. Riesch, J.-H. You, IPP
J.W. Coenen, FZJ





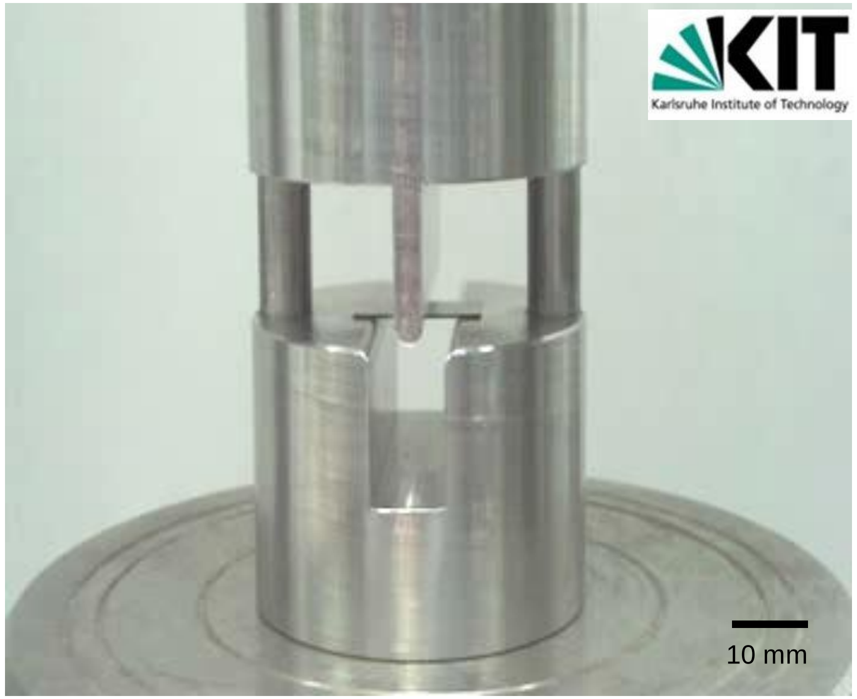
V. Nikolic, ÖAW

Ductile tungsten

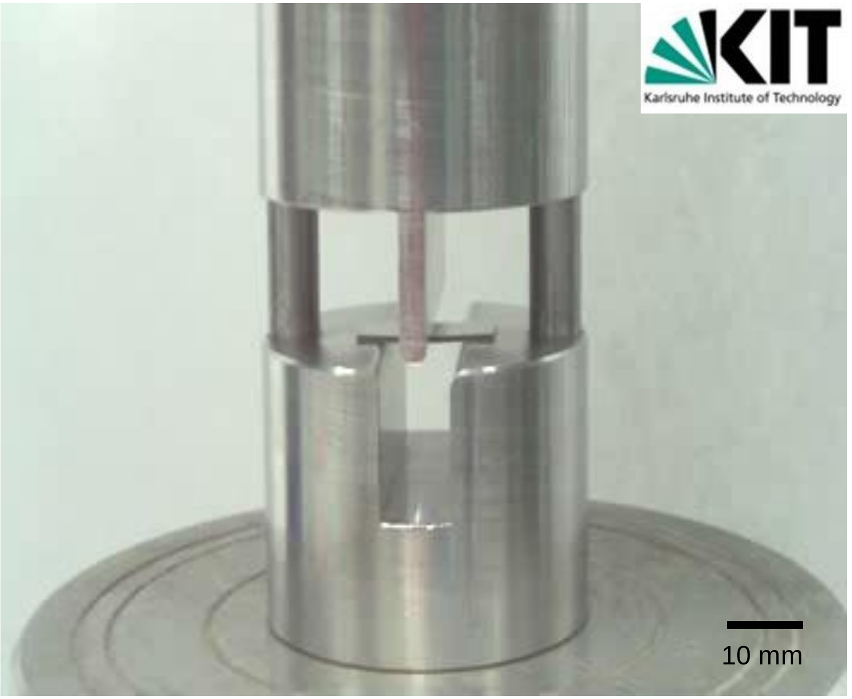
Refractory Materials for DEMO Divertors

In close cooperation with Plansee company

Hot-rolled, coarse-grained W
Test temperature: RT



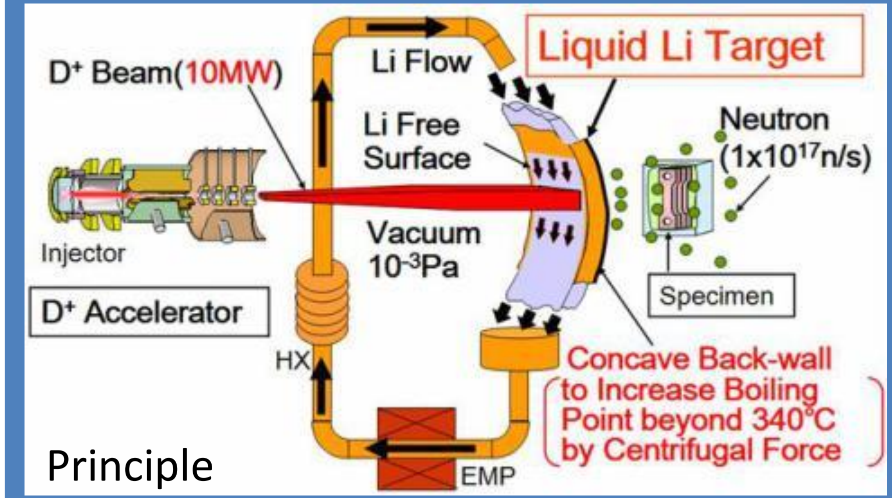
Severely cold-rolled, ultrafine-grained W; Test temperature: RT

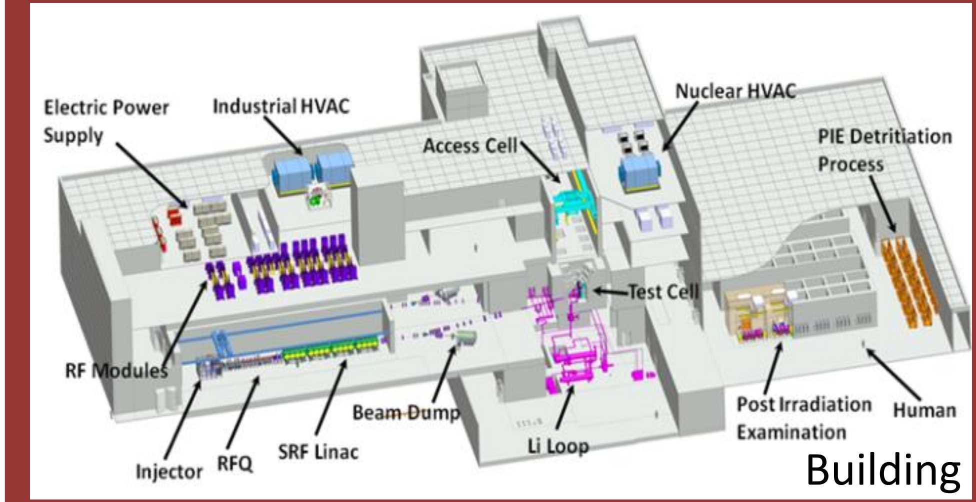


→ Severe cold-rolling makes W ductile

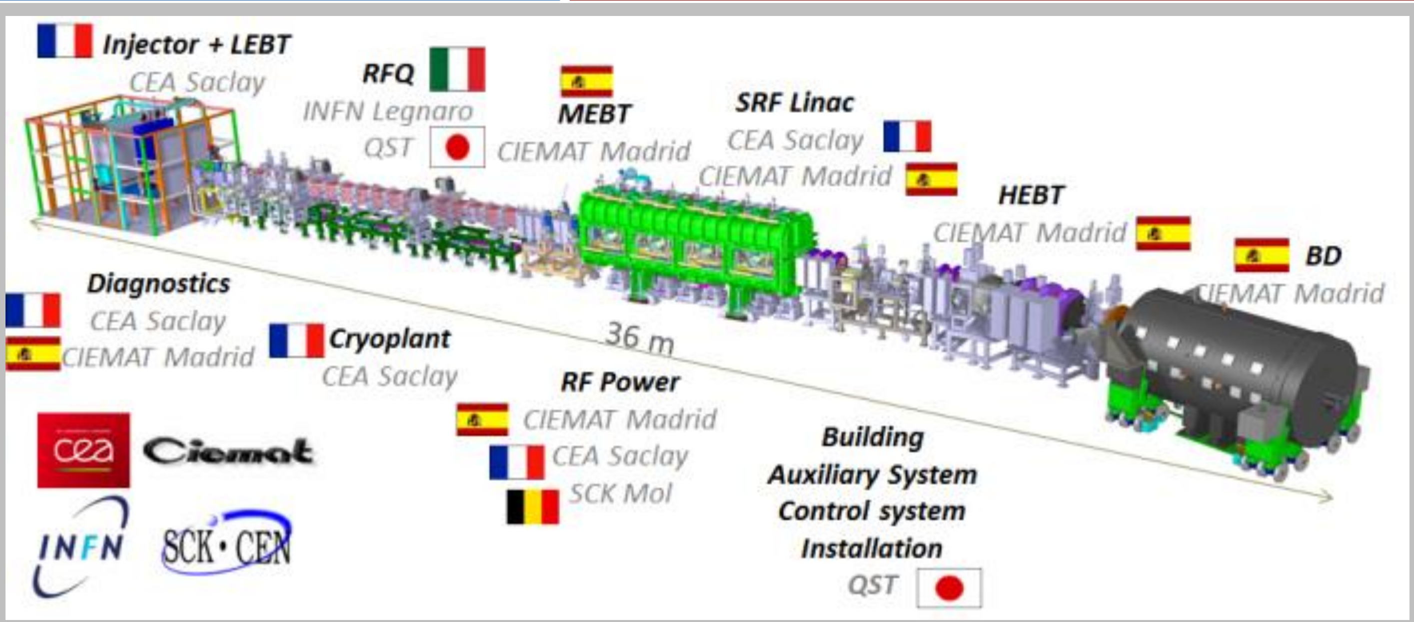
J. Reiser et al., Int. J. Refract. Met. Hard Mater. 64 (2017) 261–278

IFMIF-DONES

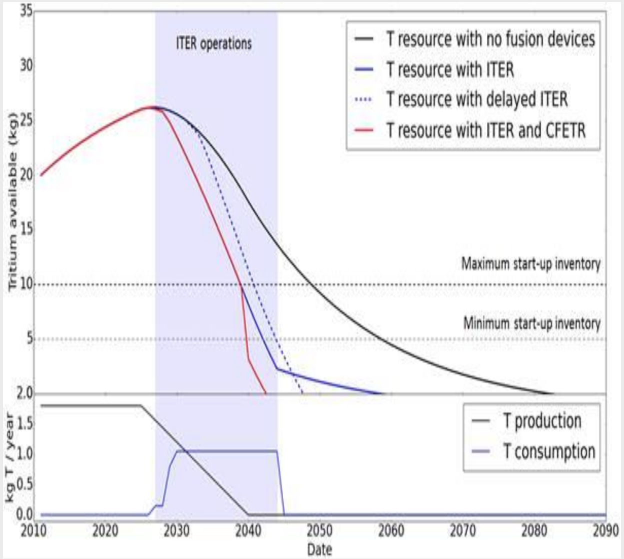


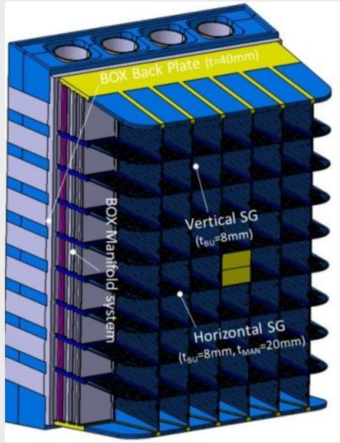


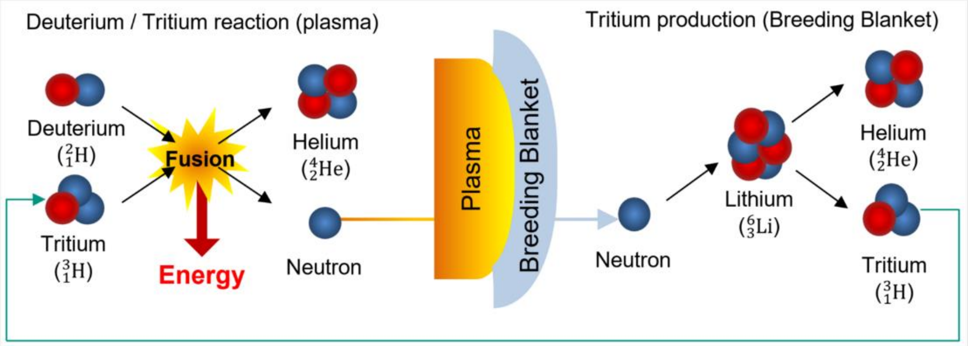
Prototype accelerator (with/in Japan)

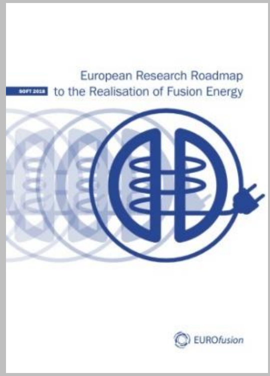


Eight missions (challenges)









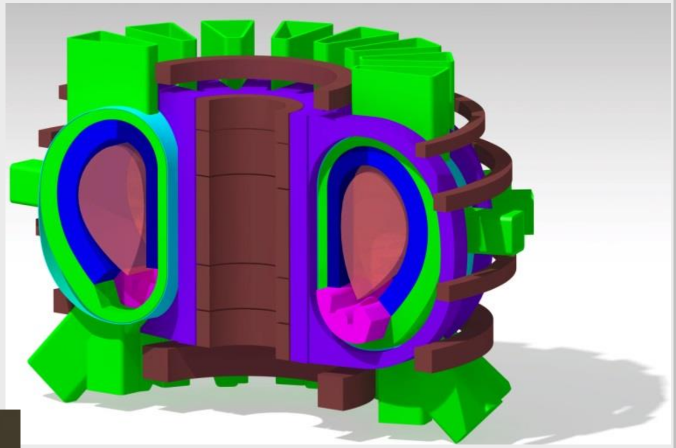
1 Plasma Regimes of Operation

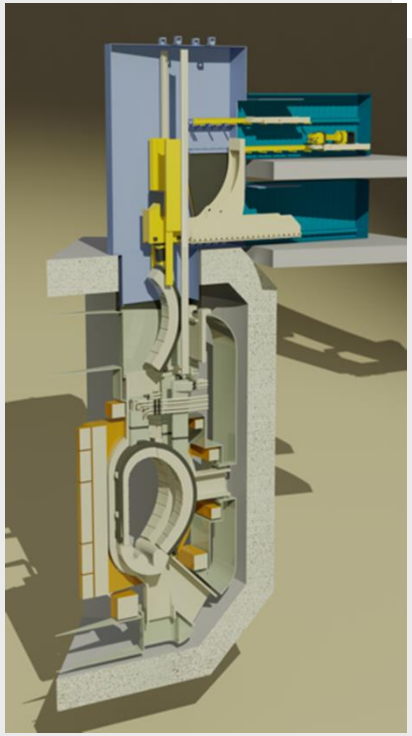
2 Heat-Exhaust Systems

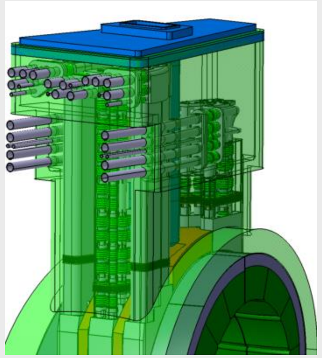
3 Neutron Resistant Materials

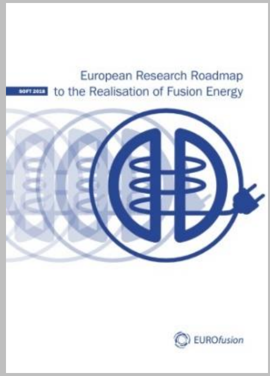
4 Tritium Self-Sufficiency

Eight missions (challenges)





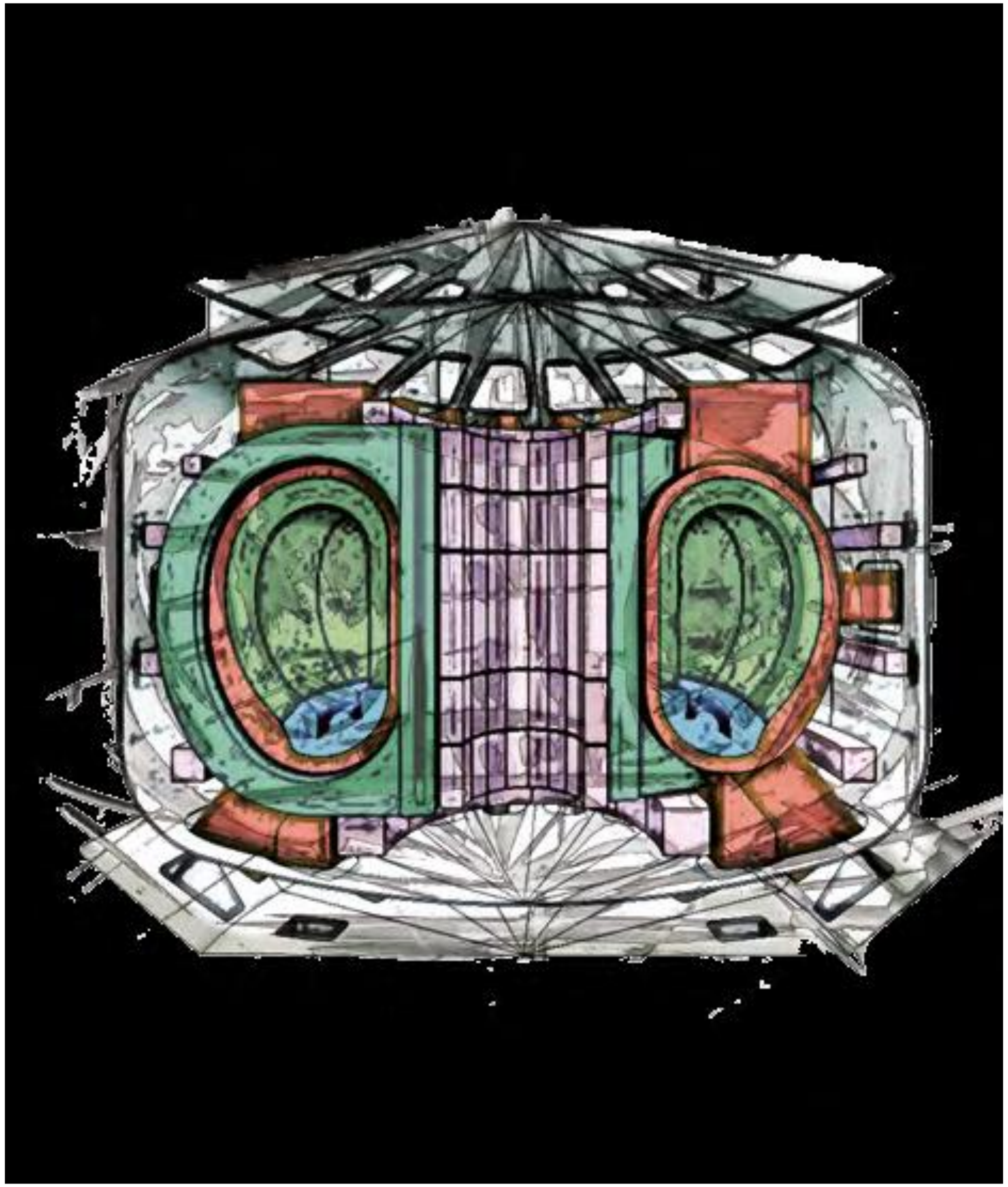




1. Plasma Regimes of Operation
2. Heat-Exhaust Systems
3. Neutron Resistant Materials
4. Tritium Self-Sufficiency
5. Implementation of Intrinsic Safety Features
6. Integrated DEMO design

European DEMO concept is not decided!

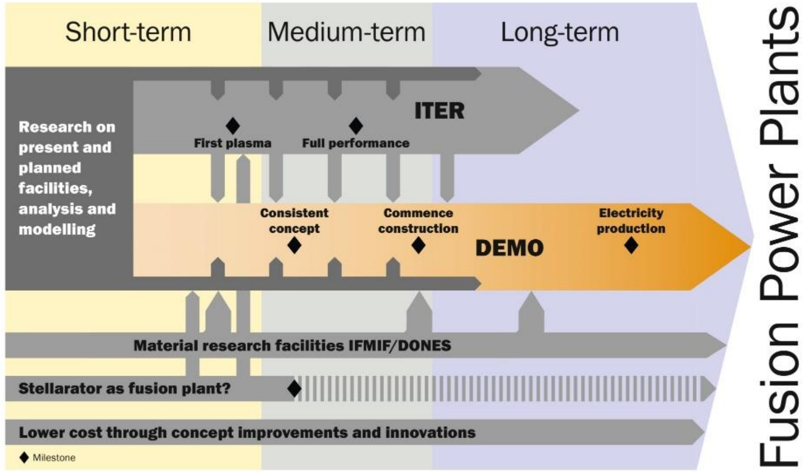
- Close enough to ITER (science & technology) – reduce risk, use ITER experience
- Close enough to a power plant to enable industry – reduce risk
- ➢ Pick a starting point
- ➢ Seek integrated evidence-based concept
- ➢ Adapt as needed
- ➢ Include test zones in DEMO to increase technology output



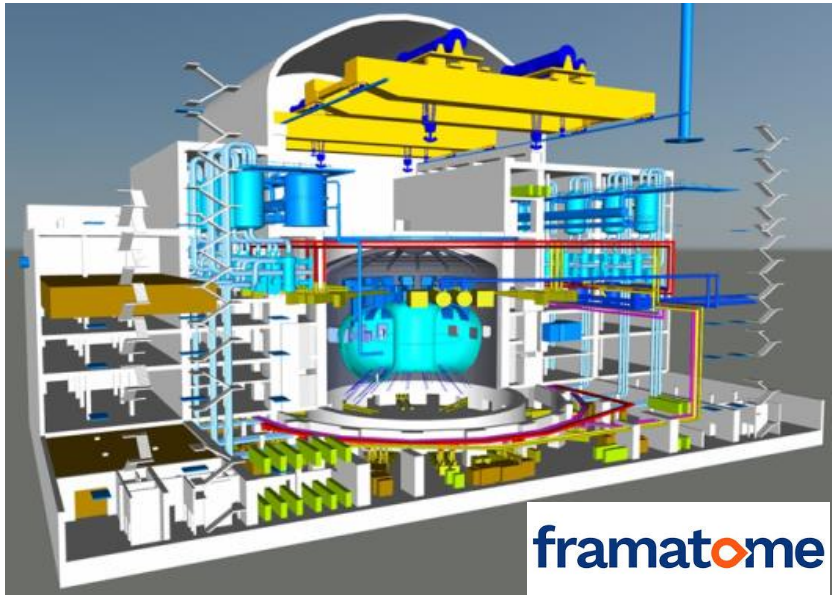
Missions 4-6: DEMO – plasma to grid

Full set of interconnected activities

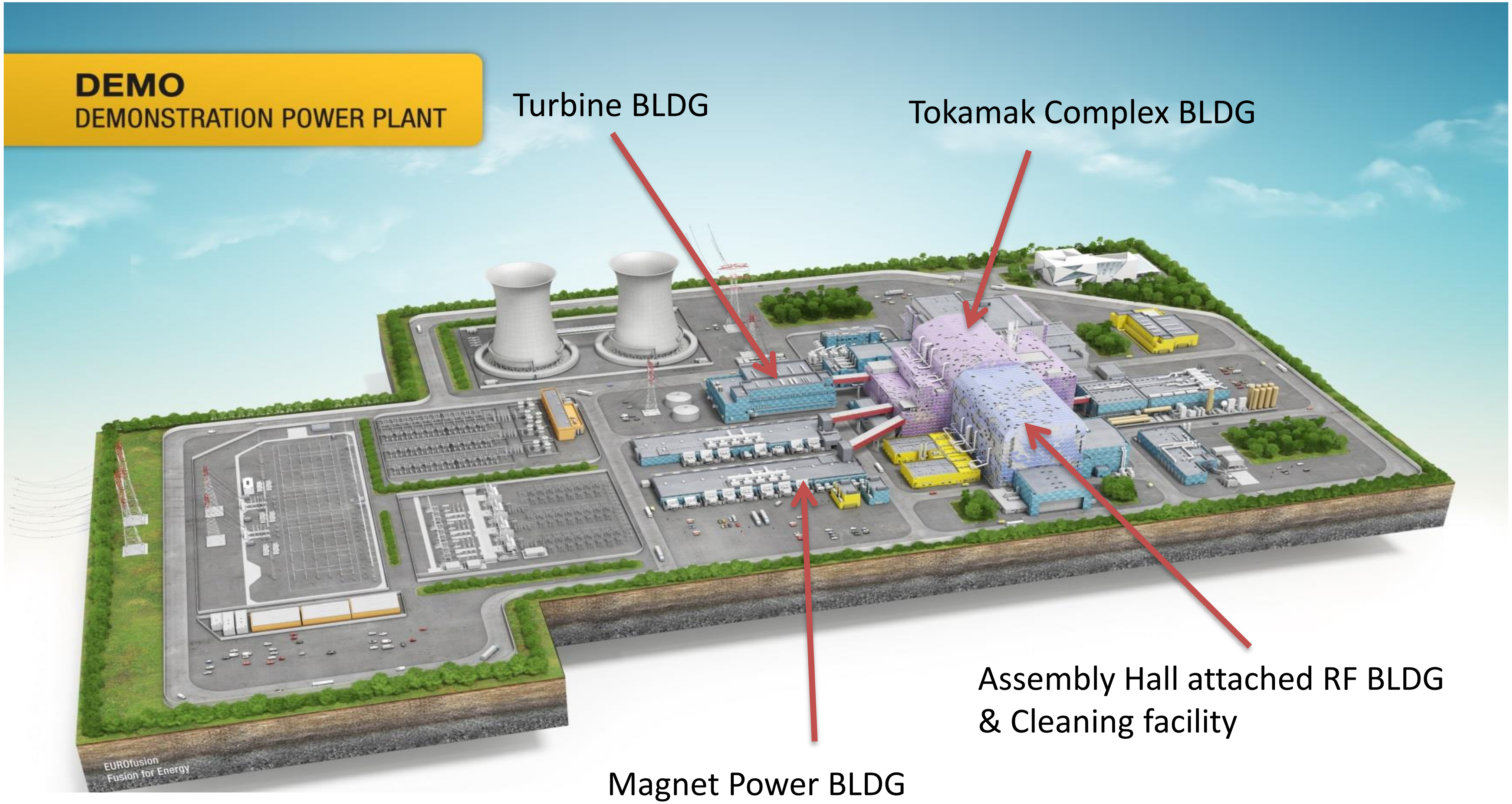
- Consistent plasma (pulsed has advantages)
- Breeding blanket (options)
- Divertor and main chamber plasma facing components
- Containment: vessel, cryostat, buildings
- Balance of plant: heat exchangers, turbines, storage
- Reliable control
- Heating and current drive
- Tritium, fuelling, pumping
- Remote maintenance: design driver
- Safety, environment, waste, recycling
- Materials: structural, functional



Integration, integration, integration



Preliminary EU DEMO Plant Layout



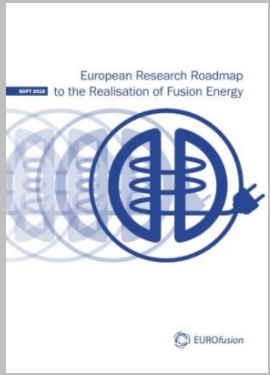
EU DEMO will be designed to deliver net 300 – 500 MWe to the grid

Eight missions (challenges)





1. Plasma Regimes of Operation
2. Heat-Exhaust Systems
3. Neutron Resistant Materials
4. Tritium Self-Sufficiency
5. Implemen-tation of Intrinsic Safety Features
6. Integrated DEMO design
7. Competi-tive cost of Electricity



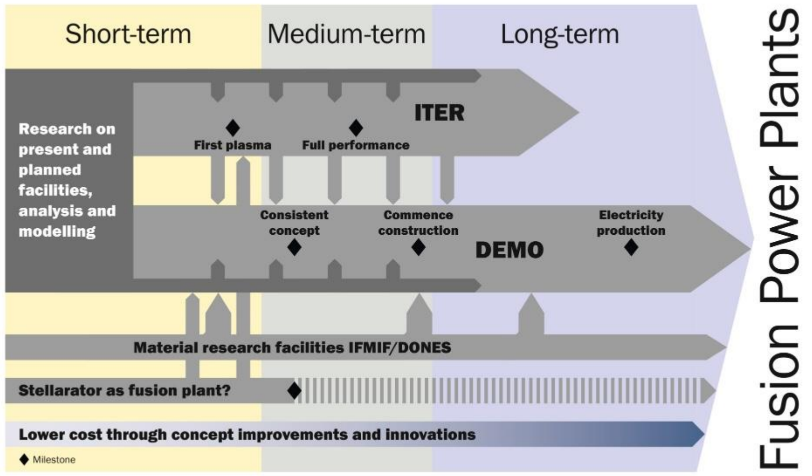
Mission 7: Cost of electricity

Challenges & opportunities for DEMO, FPPs

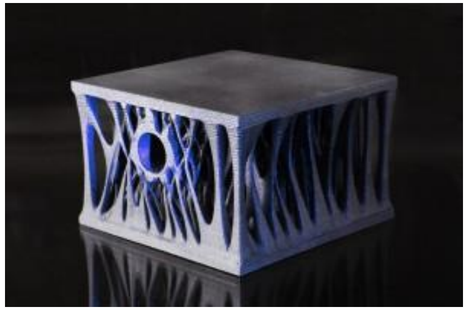
- plant and organisation complexity and interactions:
- shorter design cycle (computers!)
- increased availability (radical remote maintenance?)
- advanced plasmas, magnets, blankets/thermal cycles, materials
- advanced manufacturing and “design for manufacture”

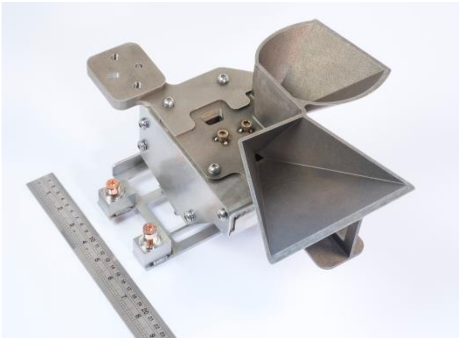
Approach

- Identify cost drivers for DEMO and possible power plants
- Holistic approach to whole plant, whole lifetime, supply chain

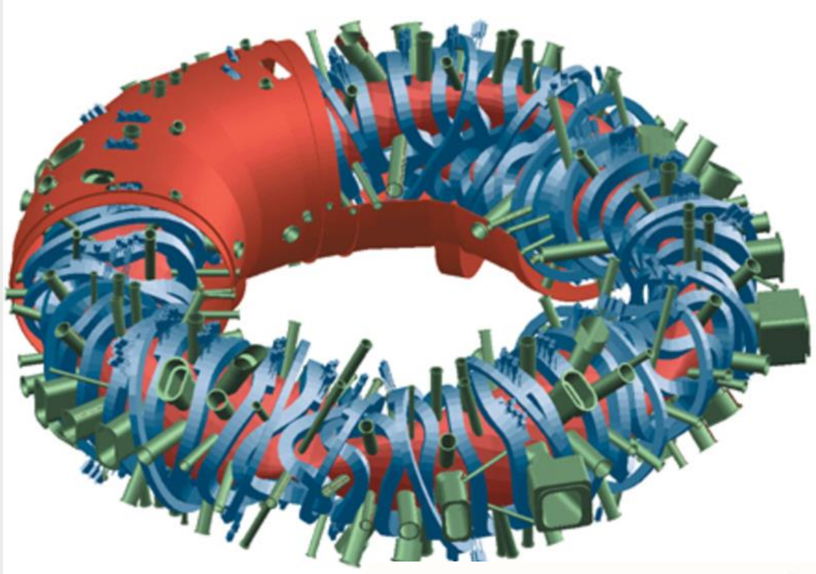


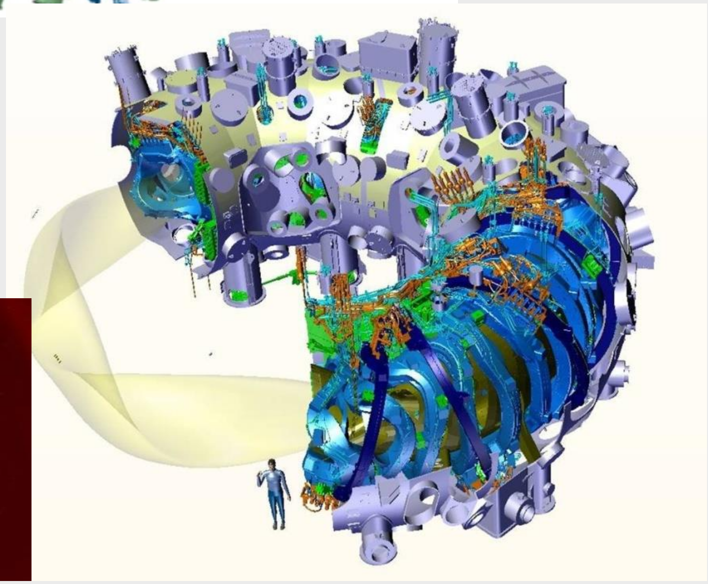
Advanced manufacturing

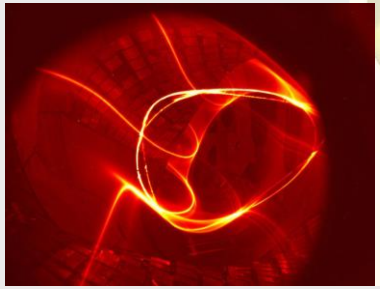




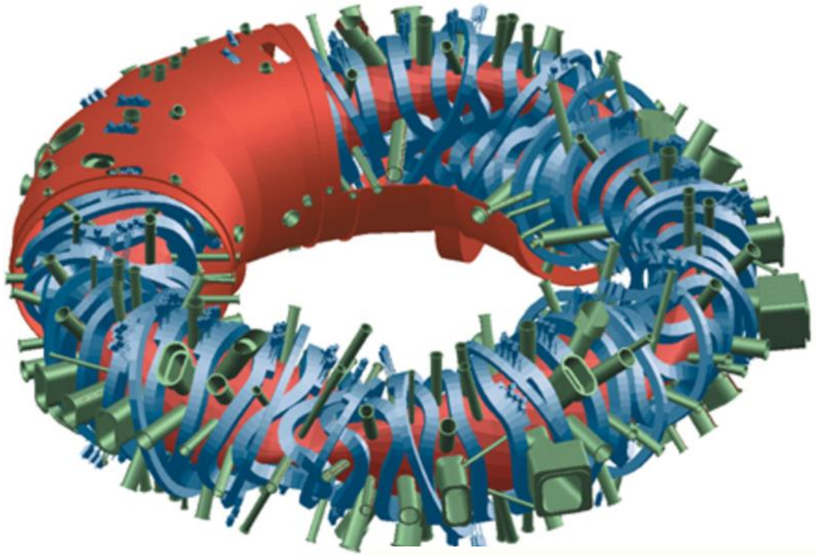
Eight missions (challenges)

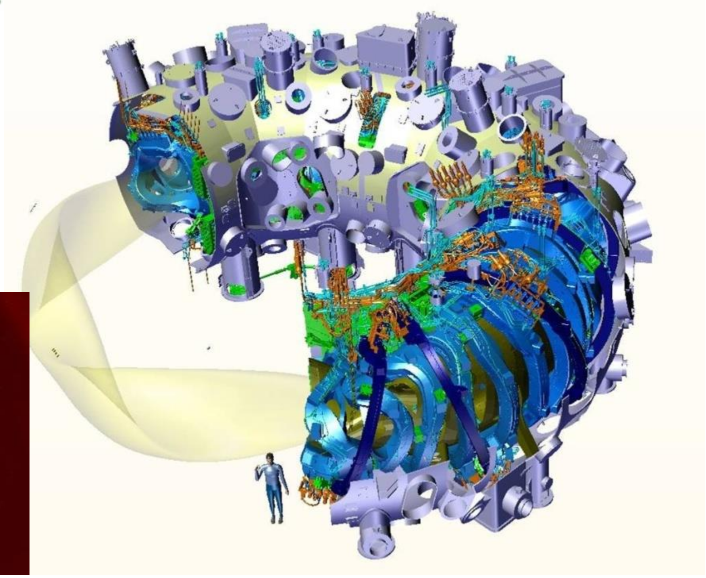


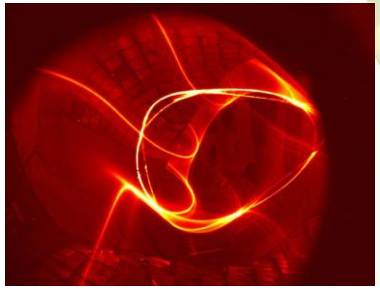


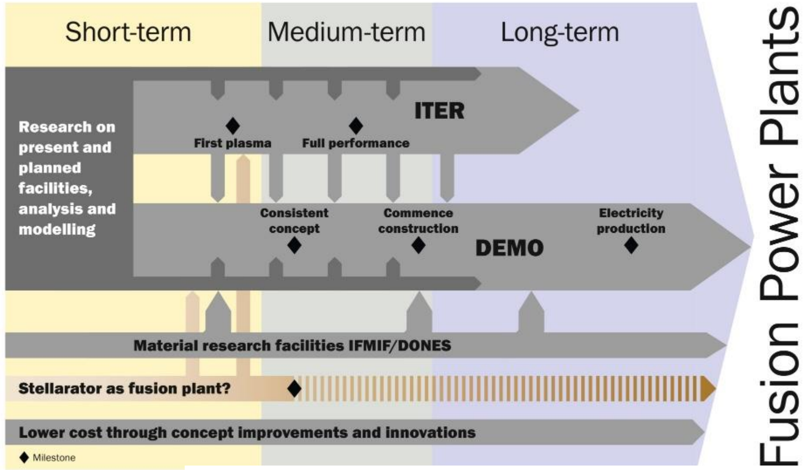


Mission 8 - Stellarators

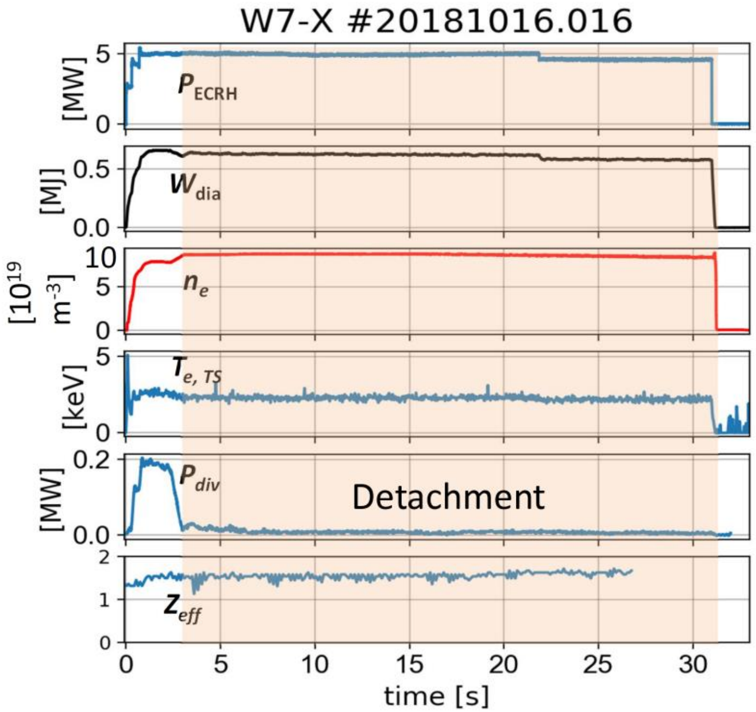








2018: Record triple product for stellarators

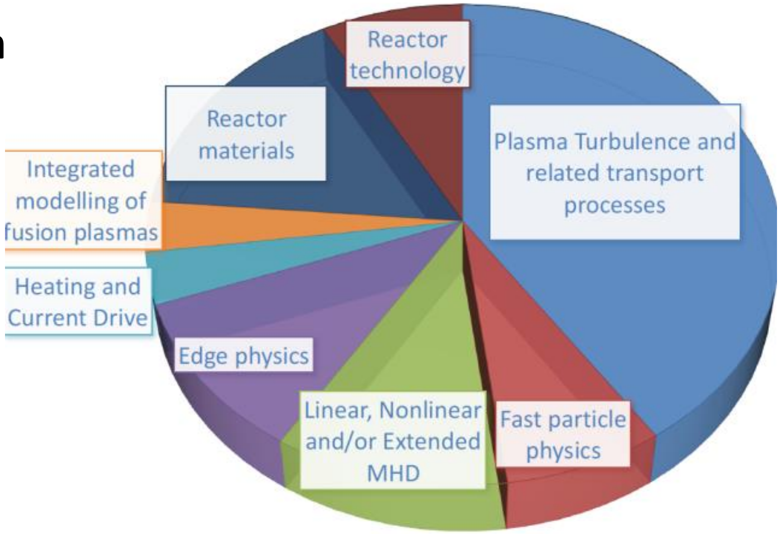


EUROfusion High Performance Computer Marconi-Fusion

- EUROfusion HPC Marconi-Fusion available since mid 2016
  - Performance 8-10 PFlops
- Gateway for integrated modelling transferred to Marconi-Fusion
- Projects selected on a yearly cycle
- High Level Support Team effort is critical to take advantage of the HPC capabilities (codes optimisation for new architecture)

HPC Marconi-Fusion in Italy/Bologna) CINECA

Allocated resources



Spin-offs

Although industry will only build fusion reactors in decades from now they have a direct benefit now from participating:

Health

Superconducting cables employed for Medical Resonance Imaging. Yearly turnover ~1 billion

Materials sciences

A technique pressing metal sheets into the desired shapes.

Today, the company '3D Metal Forming' delivers sophisticated cockpit shapes to the aeronautics industry.

Environment

Palladium alloy membranes developed for cleaning up fusion waste effectively treat effluents from chemical and automobile industries

Remote Handling

oxfordtechnologies

used in EUROfusion's JET Tokamak:

Applied to high-energy physics, space science, nuclear decommissioning, and modern surgical methods

Summary

- The traditional roadmaps (EU, JA, KO, CN) all include ITER and a DEMO-like device and deliver electricity around the middle of the century
- A dedicated 14 MeV neutron-source is needed for materials testing
- Present devices (tokamaks, linear devices, …) give support to ITER and DEMO
- Stellarator is a long-term back-up solution (some advantages/drawbacks compared to tokamaks)
- See also talk by Sibylle Günter (IPP) on Tokamaks and Stellarators

https://www.euro-fusion.org/eurofusion/roadmap/