EUROfusion

Challenges on the Roadmap towards Fusion Electricity

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KDM 2017

KONFERENCJA UŻYTKOWNIKÓW KDM

Nowe trendy w użytkowaniu KDM

23-24 maja 2017

KONKURSY Z NAGRODAMI

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EUROfusion coordinates R&D in fusion research

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china eu india japan korea russia usa

FUSION FOR ENERGY

the EU Domestic Agency for ITER: Focus on procurements

EUROfusion

30 Research Units (+ numerous Third Parties) in 28 European countries working together to achieve the ultimate goal of the Fusion Roadmap

Contents

Introduction

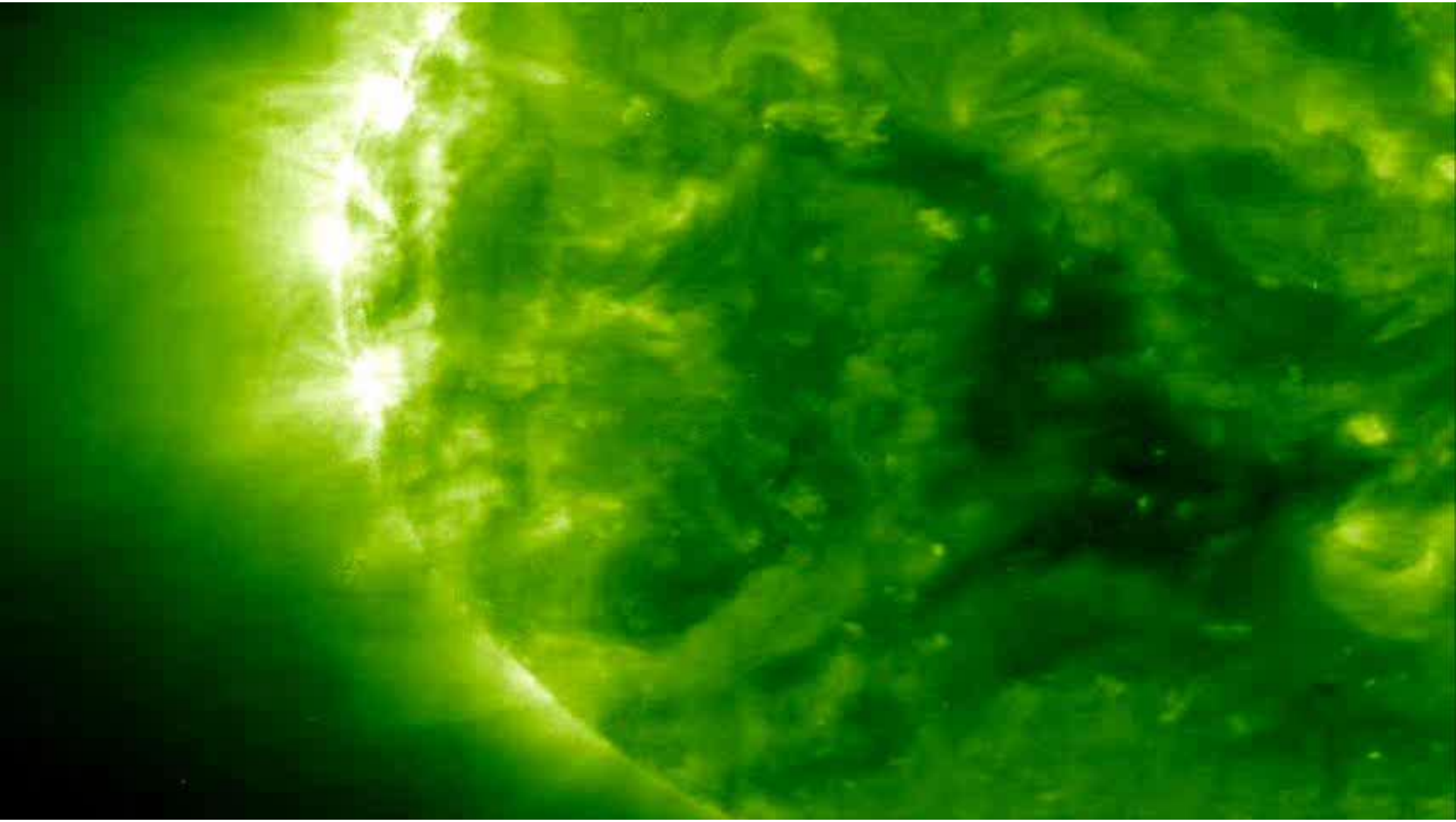
- What is fusion?
- Why do we want it?
- How can we do it on Earth?

European Fusion Roadmap

- Overview
- 8 missions (challenges)
- Focus on some HPC results with the EU-JA HELIOS computer

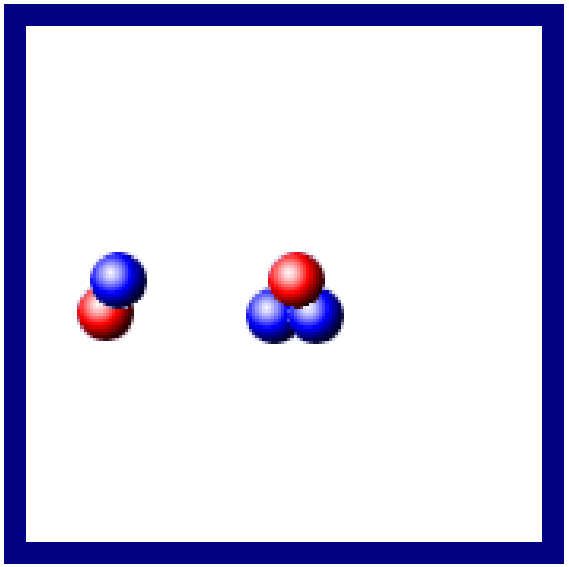
Conclusion

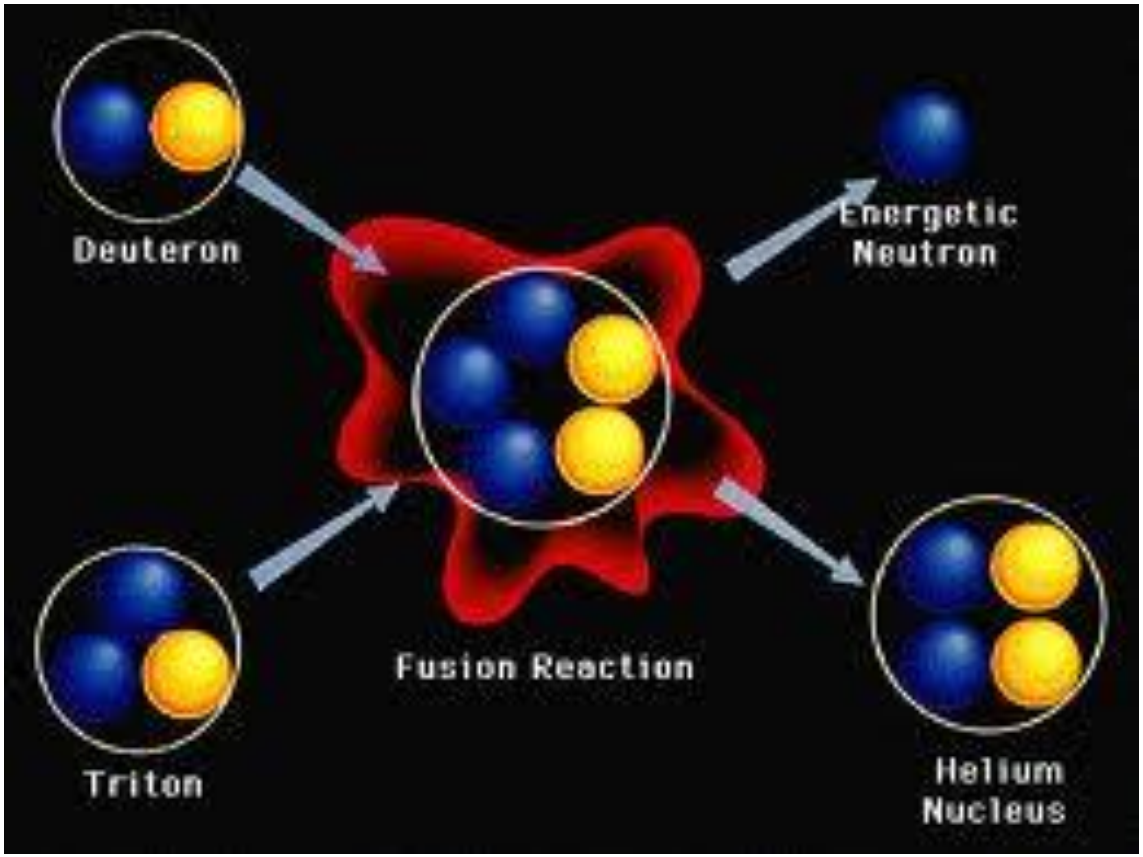
Fusion: the engine of the sun



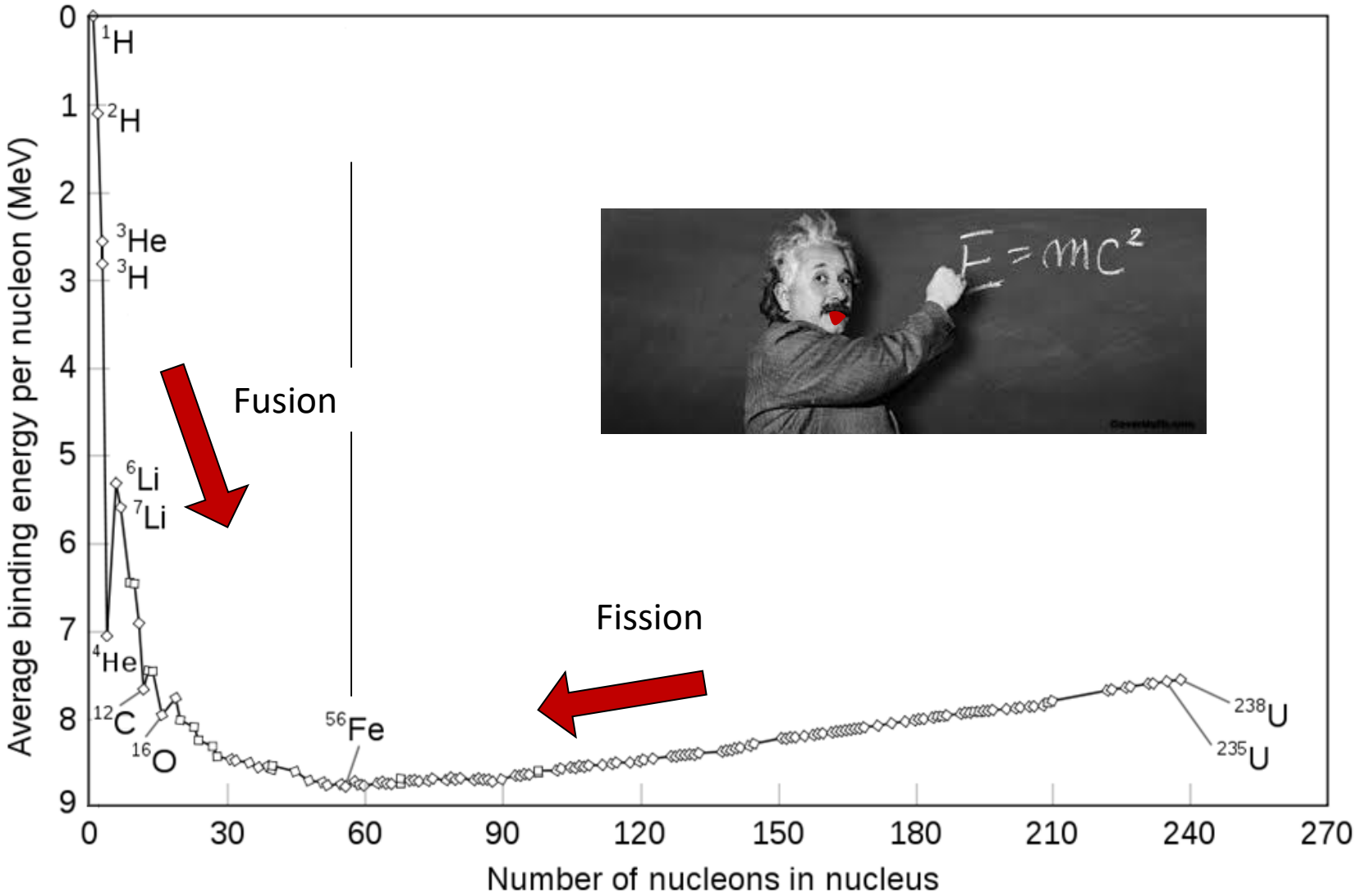
Source: NASA

Nuclear Fusion





$E = mc^2$


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

Europe, USA, Japan, China, Russia, S-Korea and India

want fusion:

- No CO_2 release, clean, safe
- Fuel abundantly available
- No proliferation issues
- Base-load electricity for dense energy needs

But... Fusion is impossible

Source: NASA

Europe, USA, Japan, China, Russia, S-Korea and India

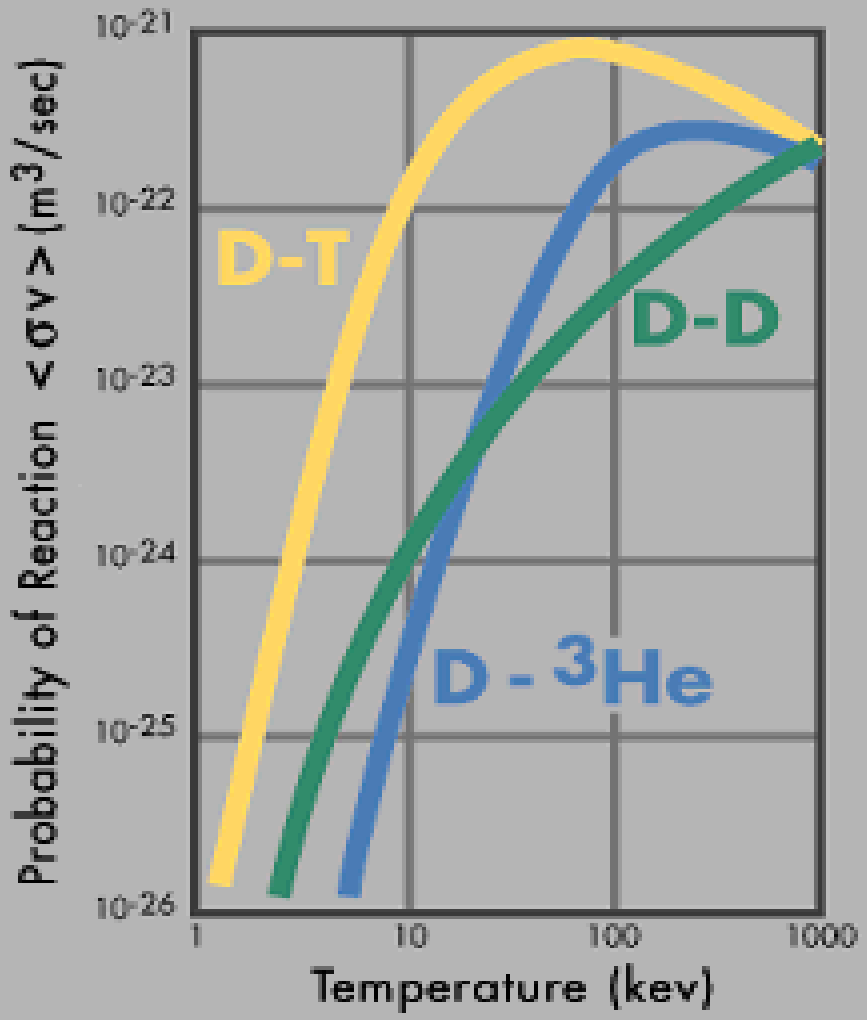
want fusion:

- No CO_2 release, clean, safe
- Fuel abundantly available
- No proliferation issues
- Base-load electricity for dense energy needs

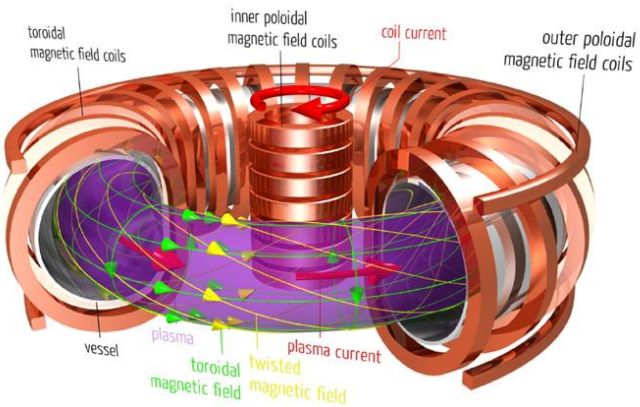
But... Fusion is difficult

Source: NASA

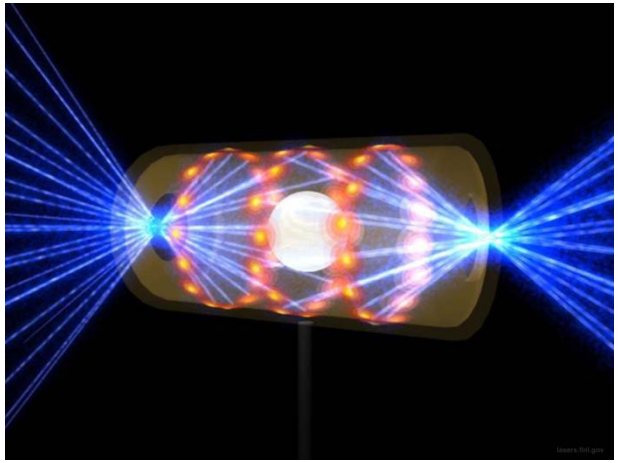
The easiest fusion reactions



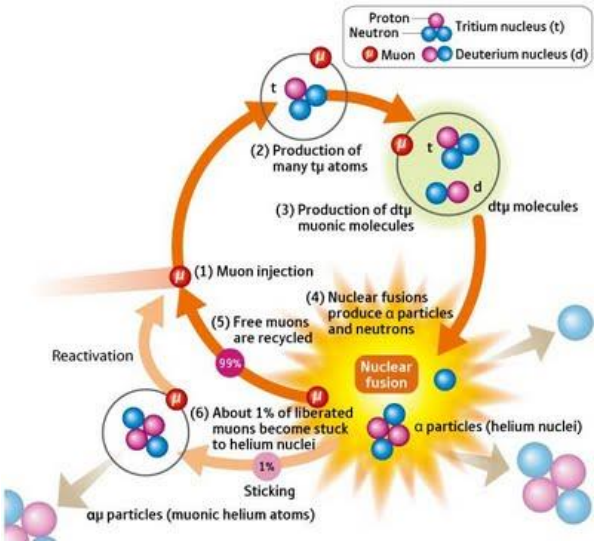
Forms of fusion



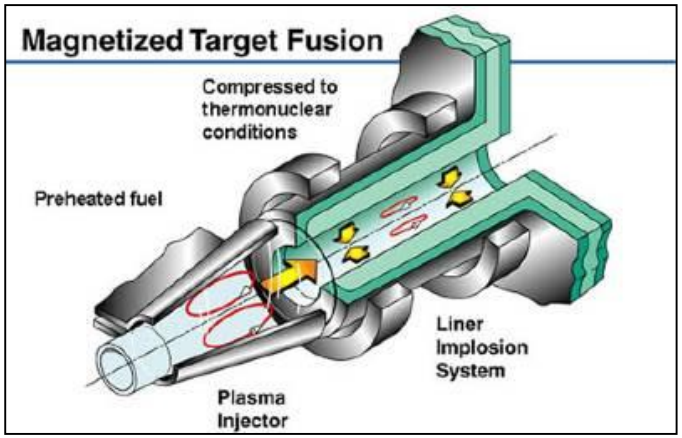
Magnetic Confinement



Inertial Confinement



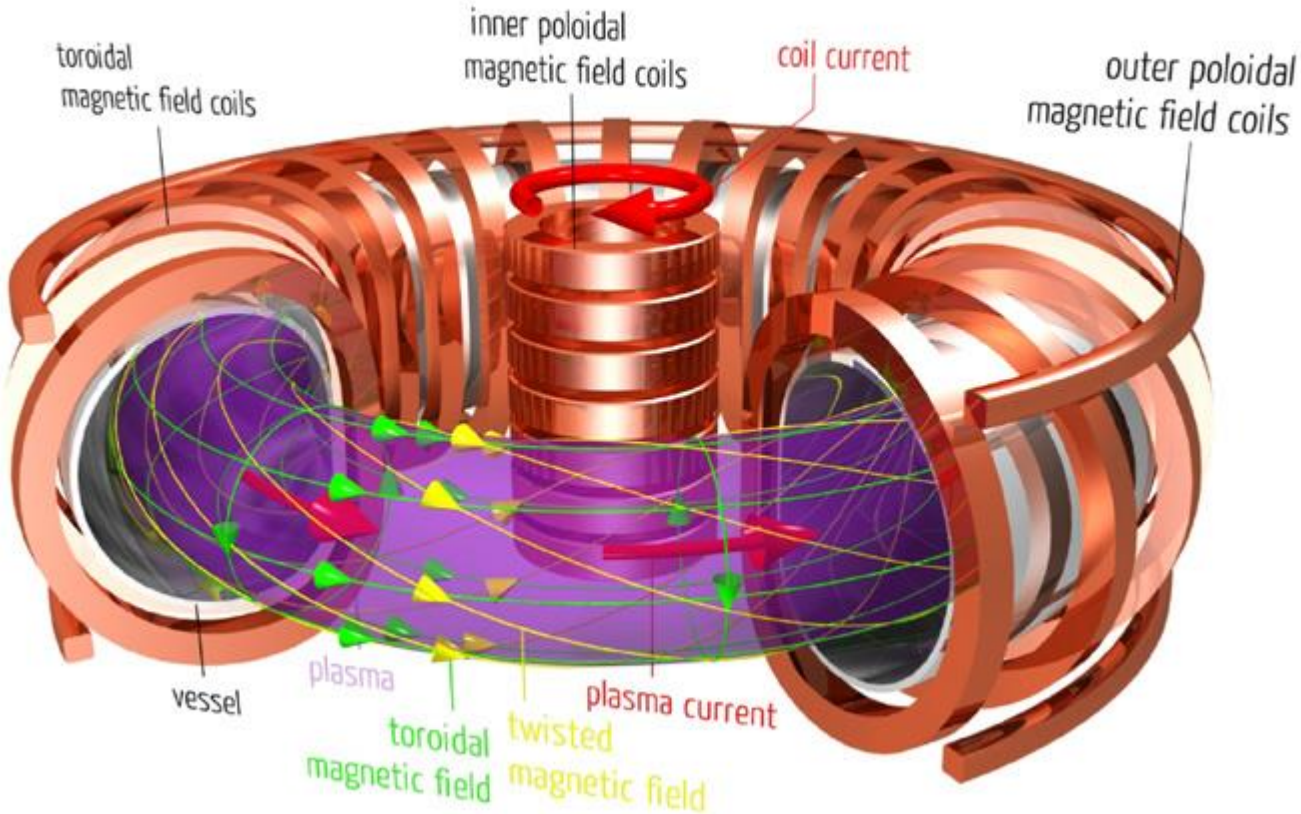
Muon-catalysed



Magnetised Plasma Compression

Con-fusion

Magnetic Confinement Fusion - Tokamak

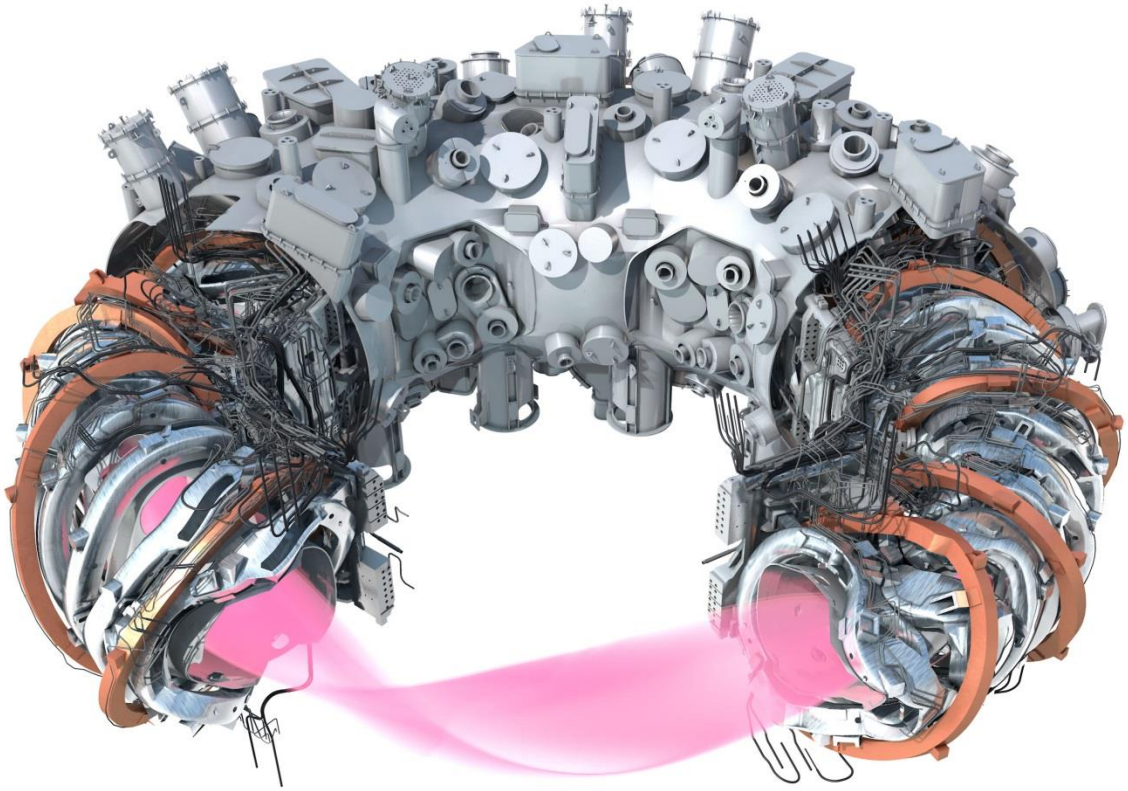


In the tokamak the hot plasma (=charged particles) is confined by a superposition of two fields:

the toroidal field generated by coils around the plasma vessel and
the poloidal field generated by running a current through the plasma.

The tokamak is operated like a transformer and is a pulsed device

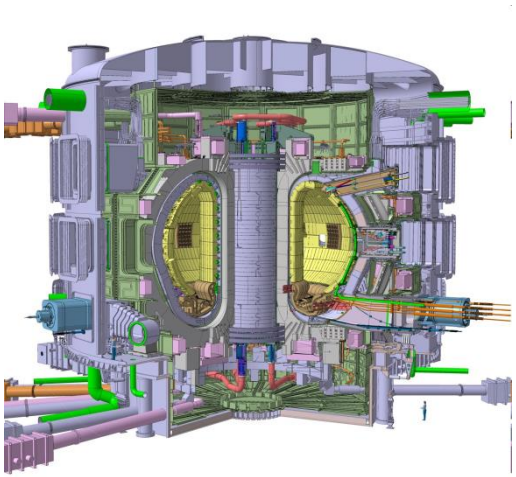
Magnetic Confinement Fusion - Stellarator

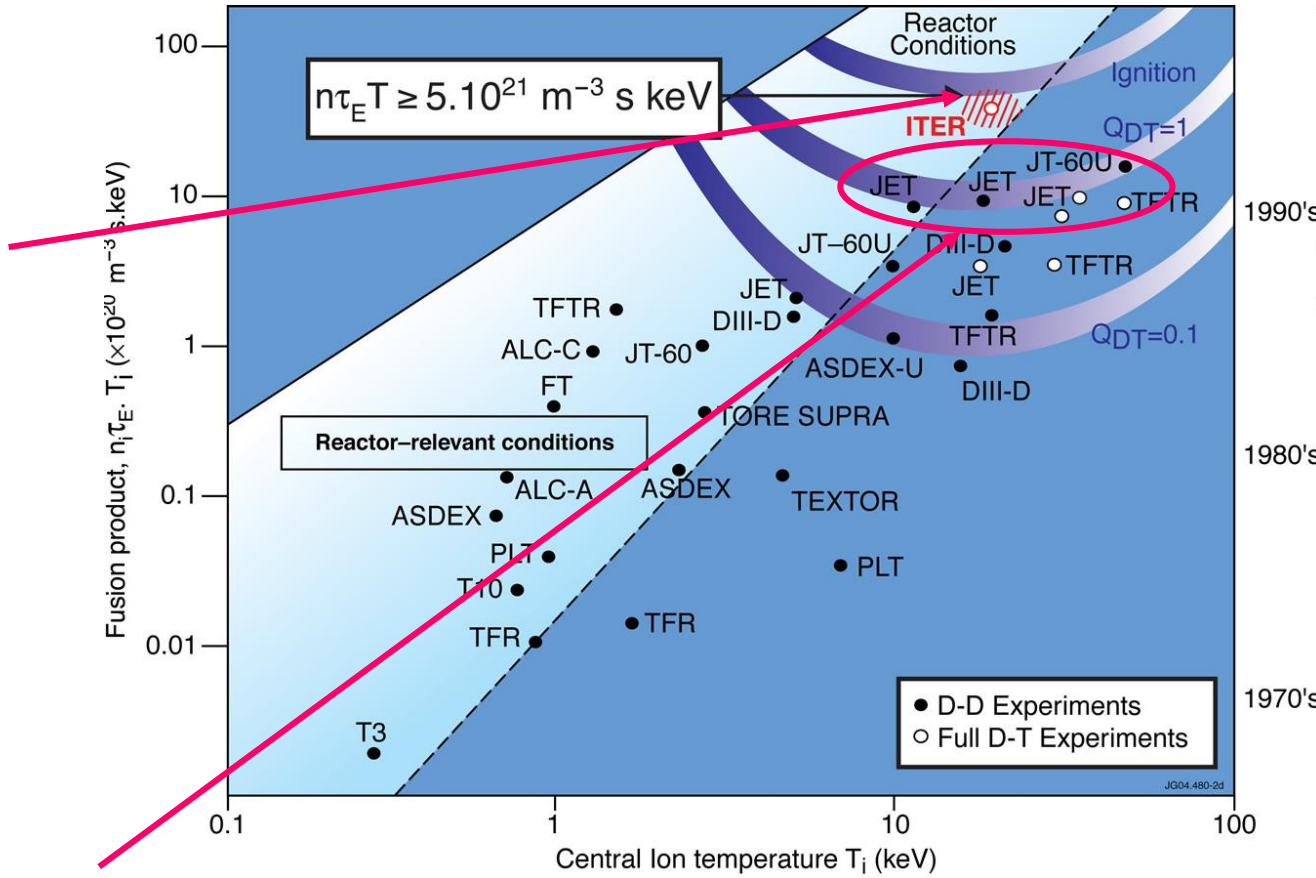


In the stellarator the hot plasma (=charged particles) is confined magnetic fields that are completely generated by external coils.

The stellarator is current-less and is in principle steady state. The plasma is also less prone to instabilities. Technically the stellarator is much more complicated than the tokamak.

Progress in fusion





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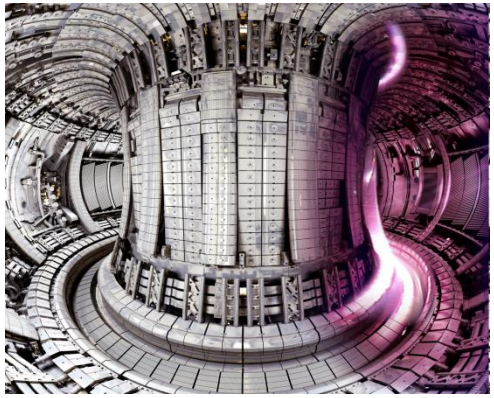
Nett power gain:

$P_{fusion} = 10 \times P_{in}$

Demonstration of technical principles

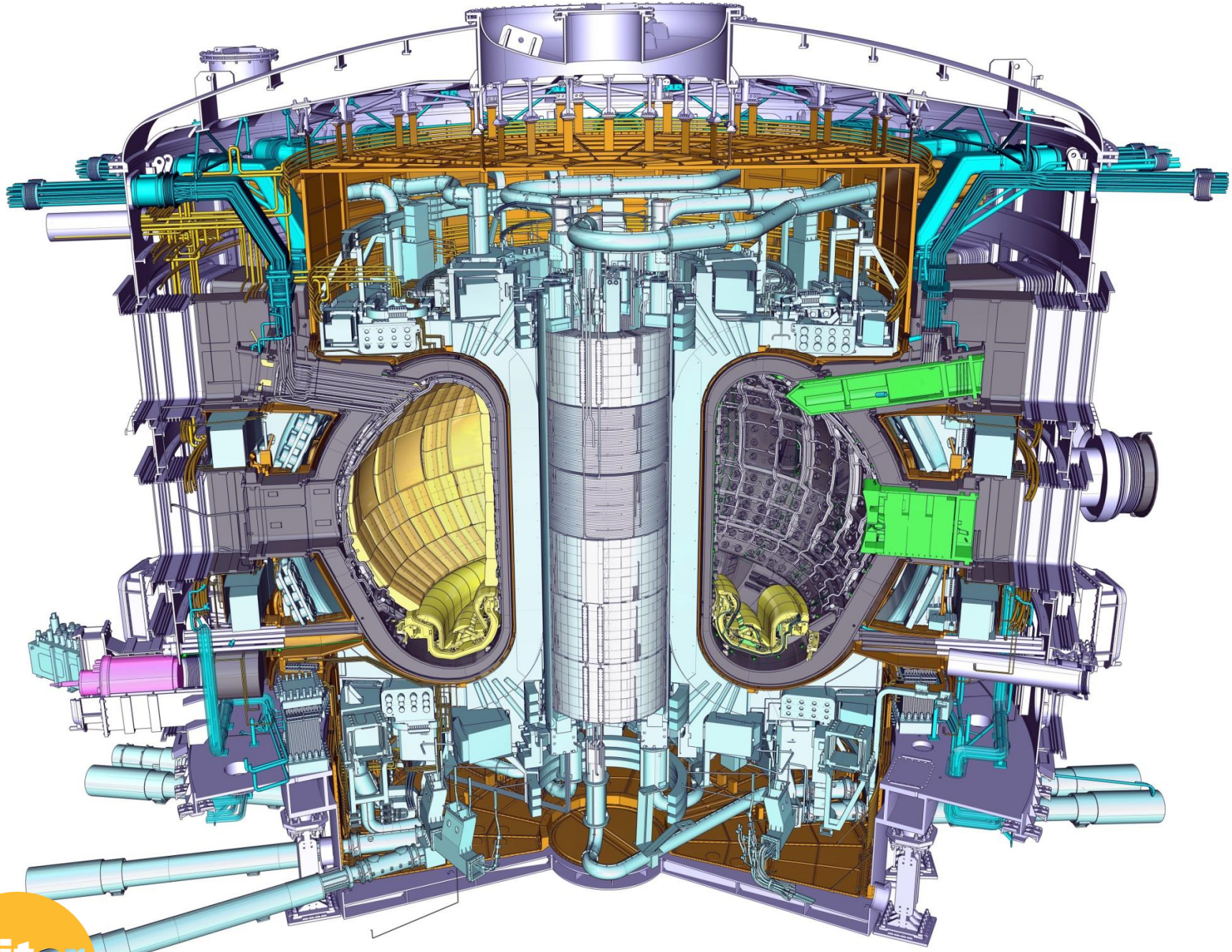


JET (and other machines)

Break-even:

$P_{fusion} = P_{in}$

Emphasis on understanding the science



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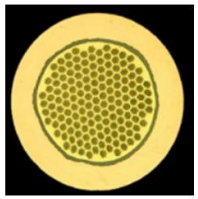
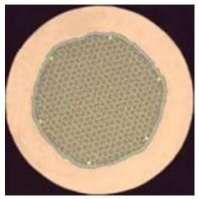
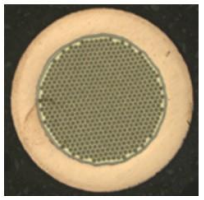
Superconducting cables



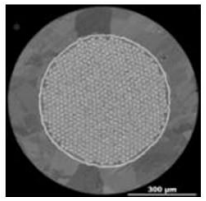
Bruker Energy & Supercon Technologies



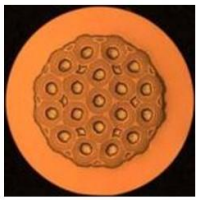
Chepetsk Mechanical Plant



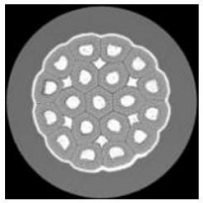
Hitachi



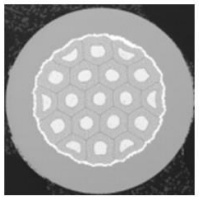
Jastec



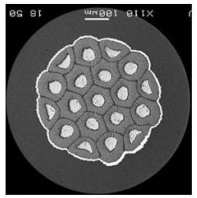
Kiswire Advanced Technology



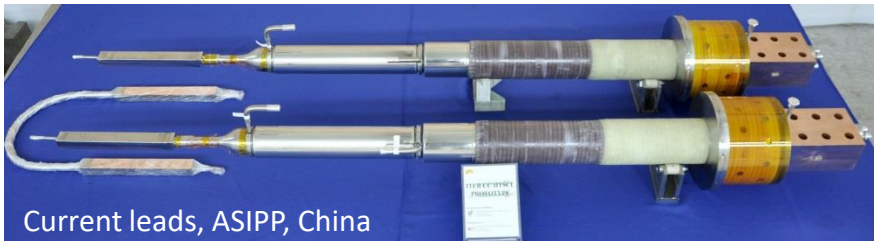
Luvata



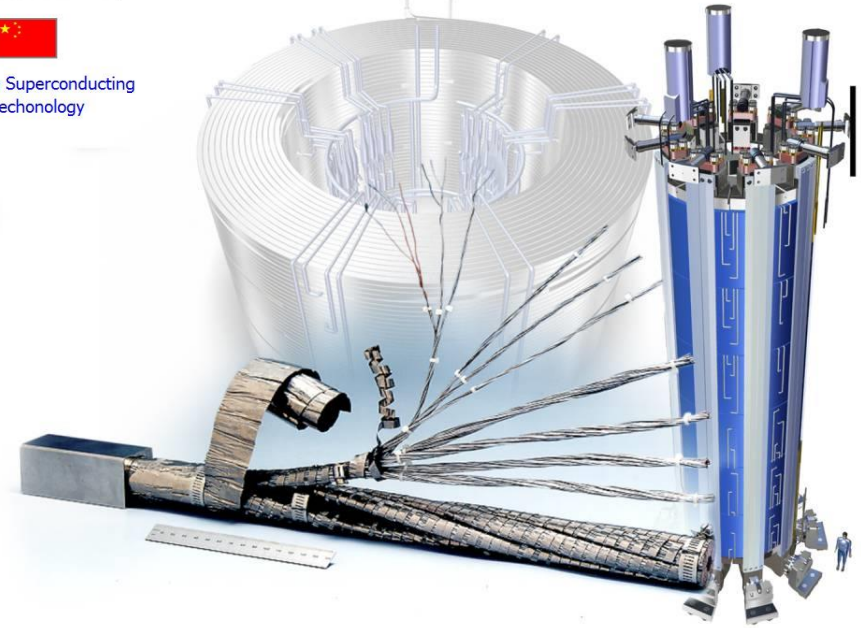
Oxford Superconducting Technology



Western Superconducting Techonology



Current leads, ASIPP, China



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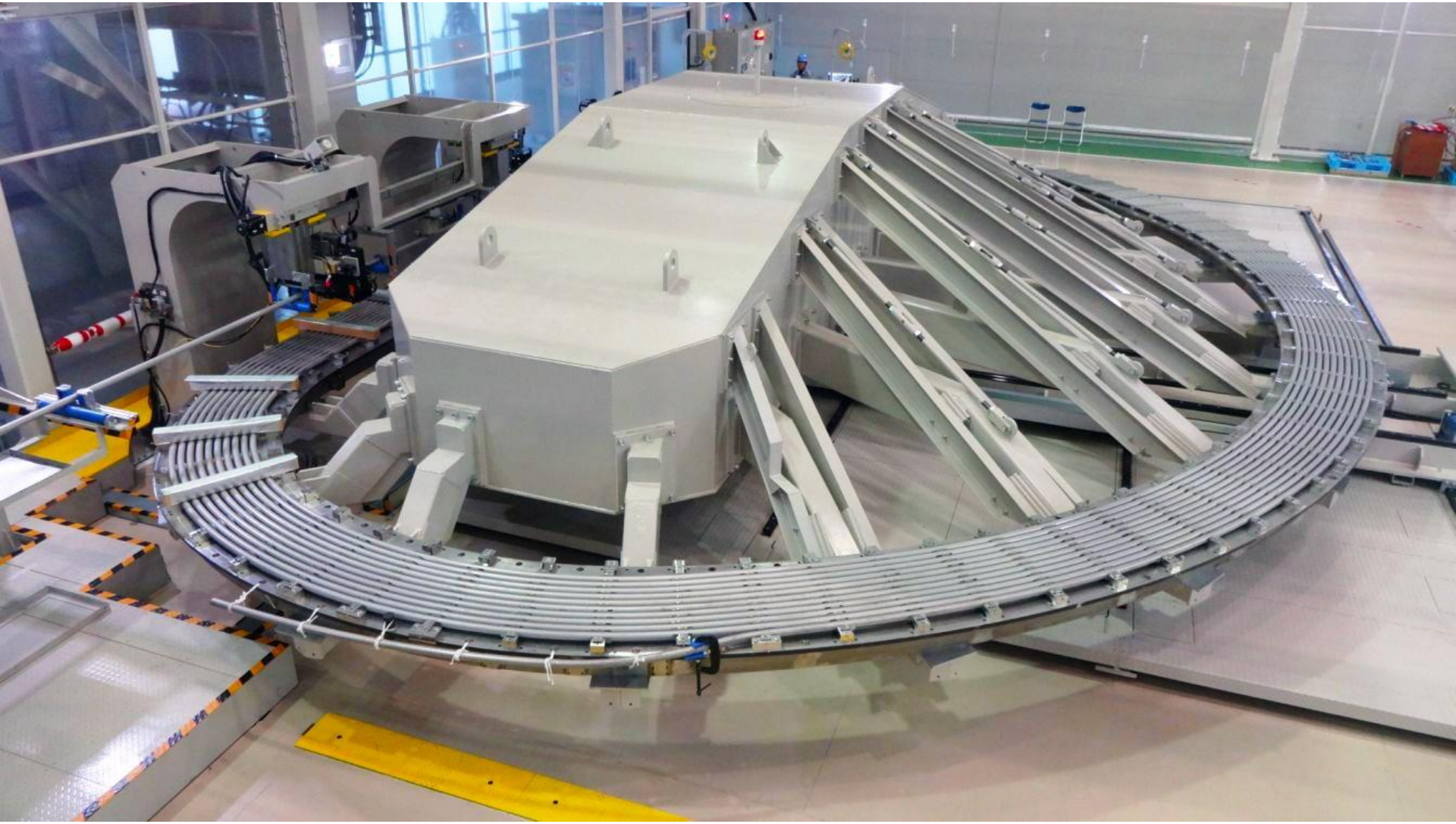
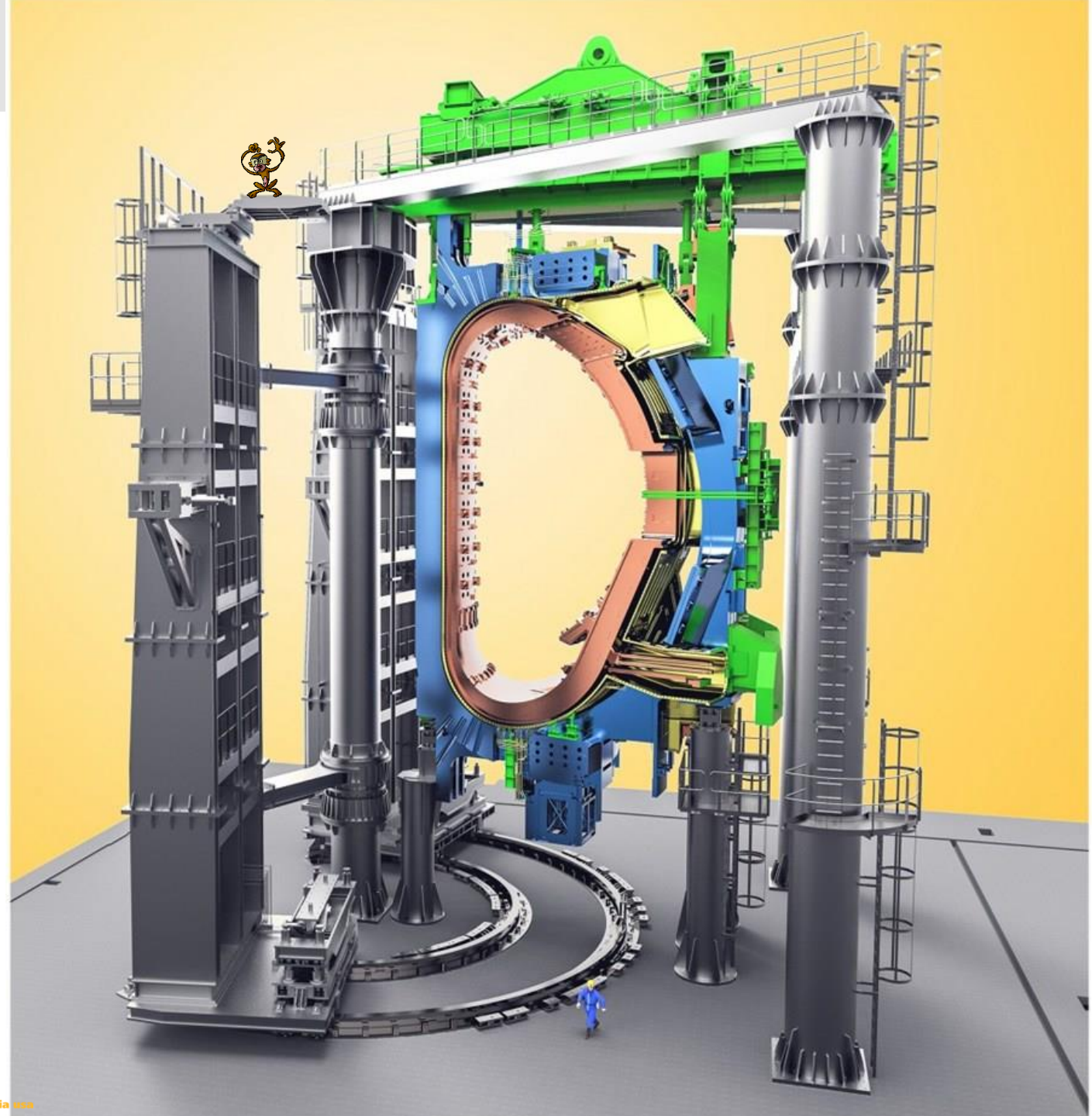
Radial plates for the toroidal field coils

Winding the toroidal field coils





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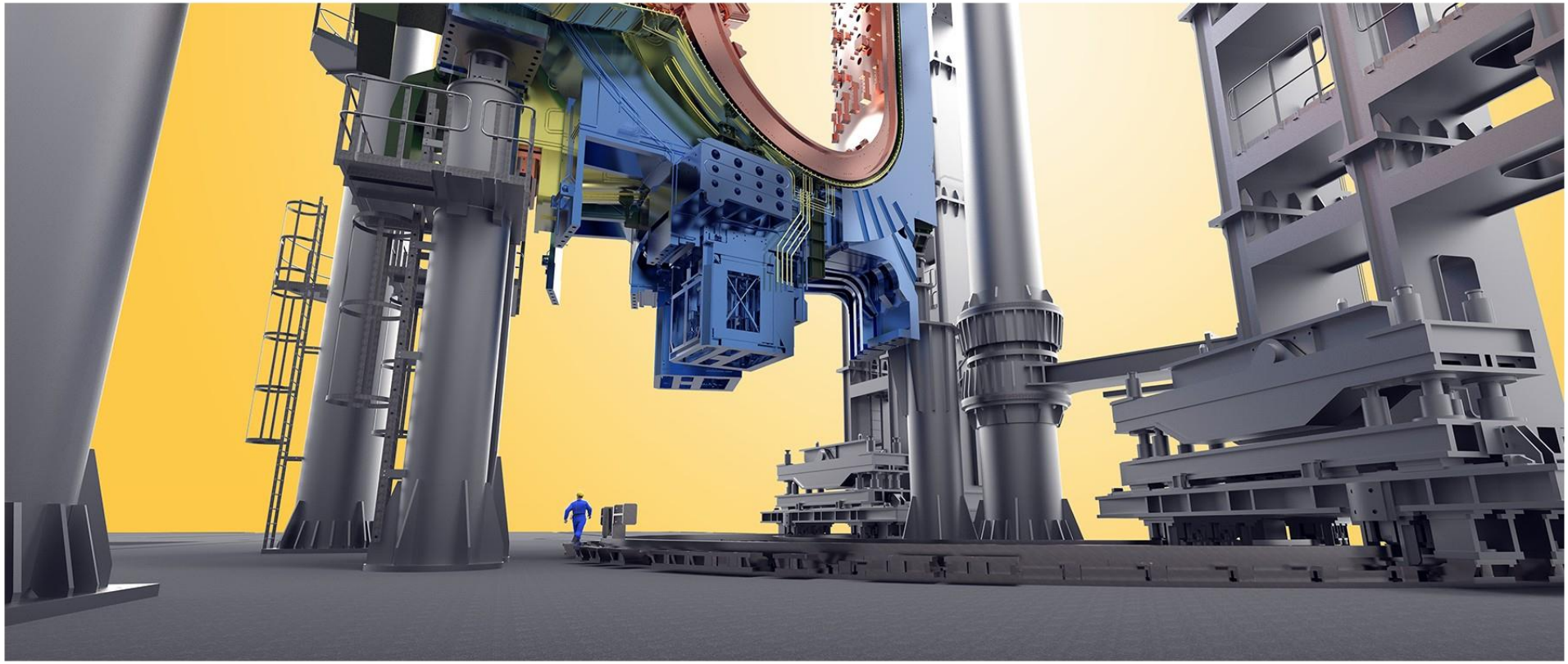

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Assembly hall

What you see from a drone

Fusion Roadmap

Mission statement

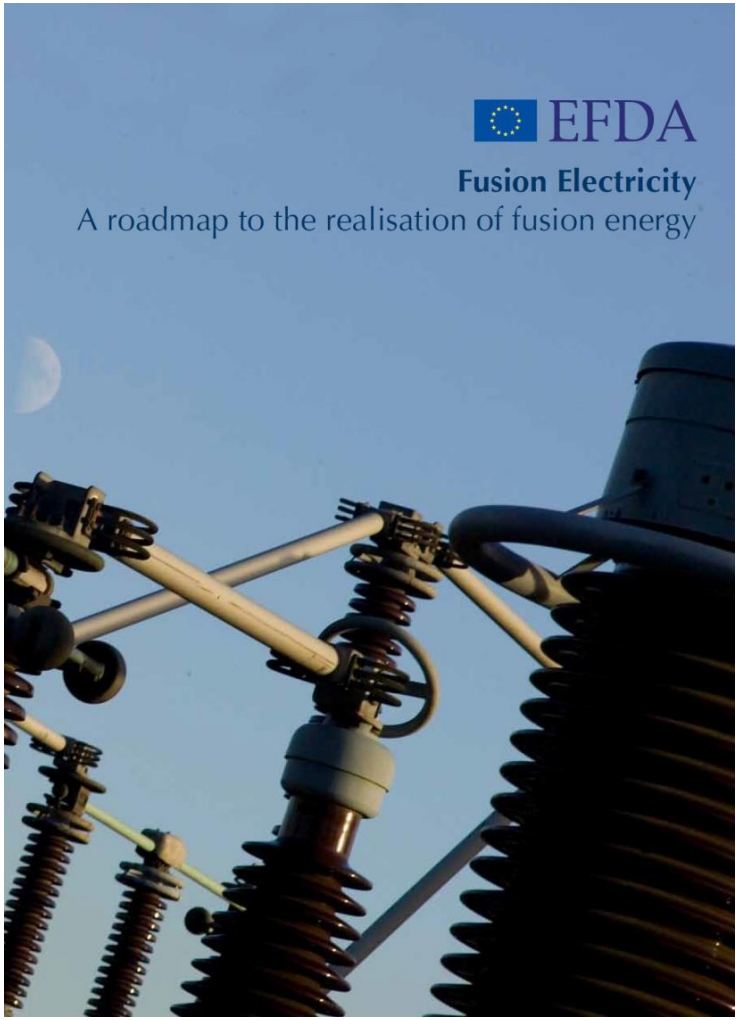
Demonstrate fusion electricity production by the middle of the century

A key document

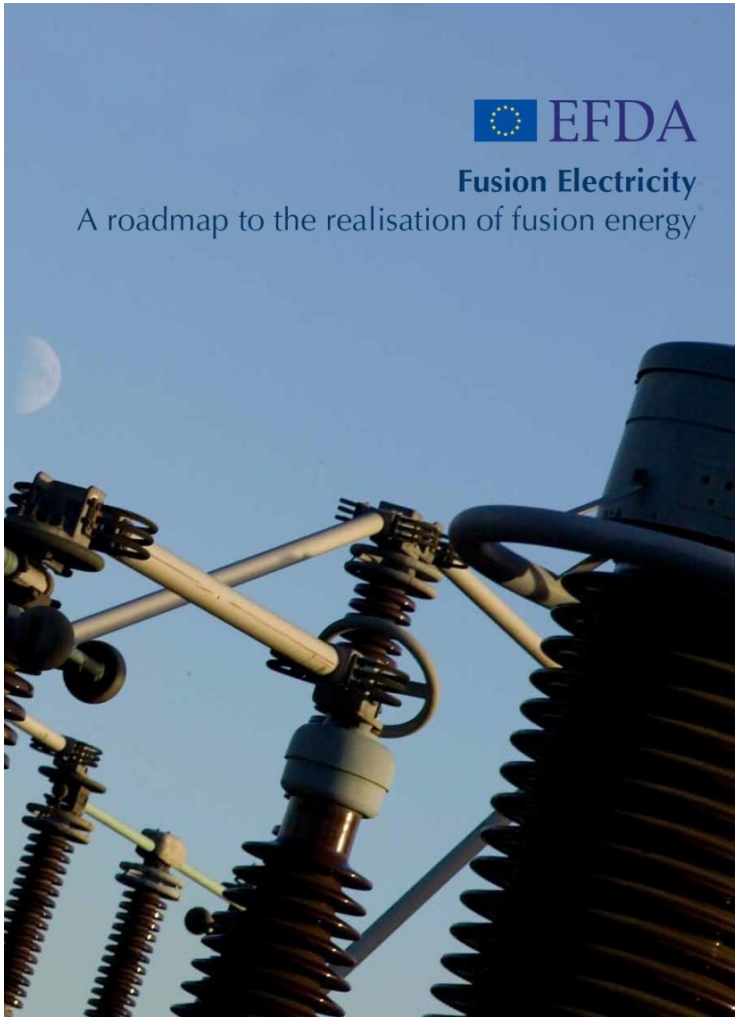
- Founded on technical assessment reports (existing and new)
- Provides coherent EU programme with clear goal and indicative dates
- Avoids open-ended R&D

Importance

- The ‚Bible‘ for EUROfusion (all work funded is fully aligned with Roadmap)



Fusion Roadmap



http://www.euro-fusion.org/

Eight important missions

- For each mission:
  - overview present status
  - list of unresolved and urgent issues
  - research & development plan
  - estimation of required resources

Three periods

- Short Term
  (Building ITER & Supporting Experiments)
- Medium Term
  (Exploiting ITER and Designing DEMO
- Long Term (Building and Exploiting DEMO)

Important to gradually intensify the involvement of industry

Eight missions

1 Plasma Regimes of Operation

2 Heat-Exhaust Systems

3 Neutron Resistant Materials

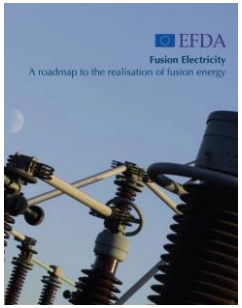
4 Tritium Self-Sufficiency

5 Implementation of Intrinsic Safety Features of Fusion

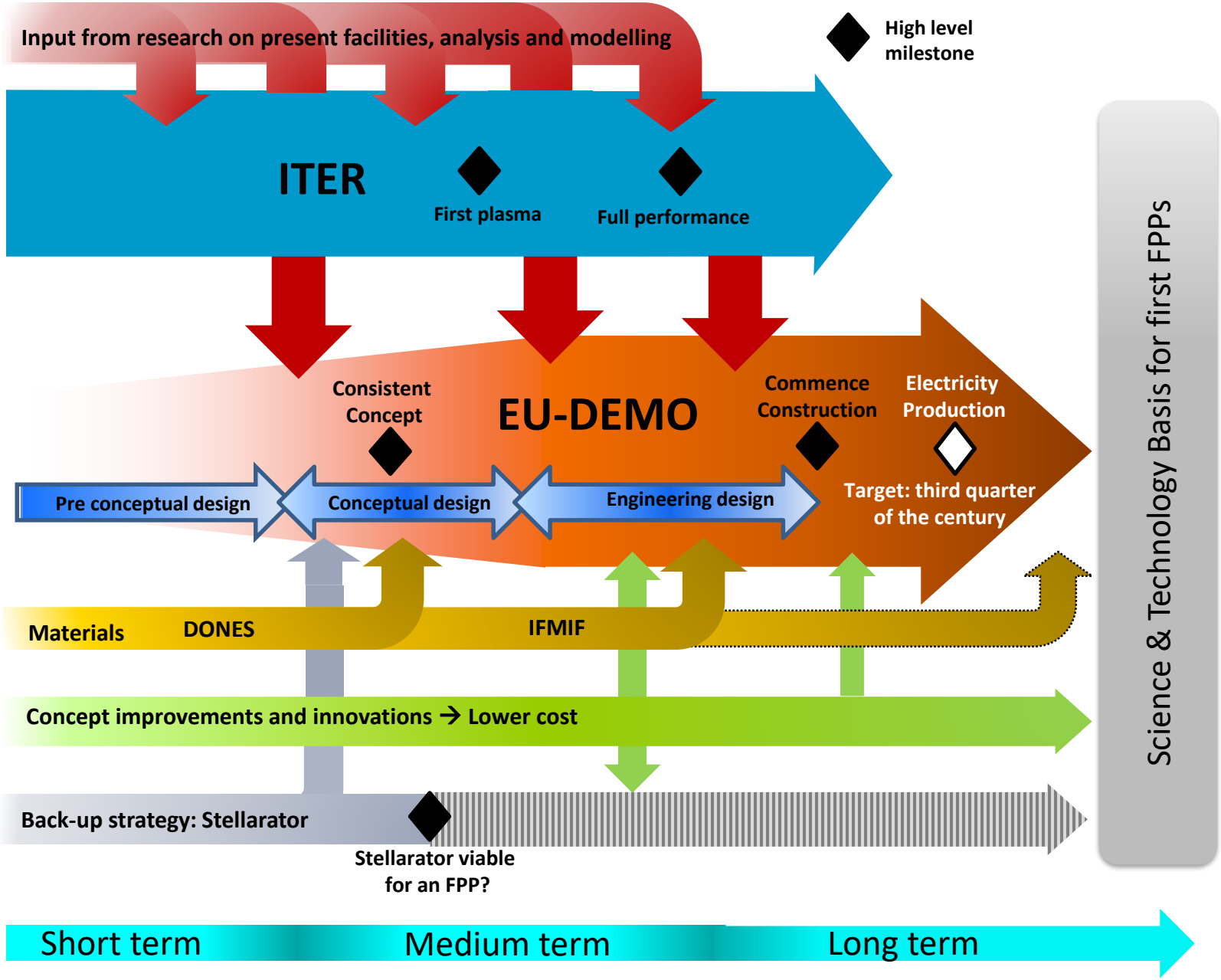
6 Integrated DEMO design and system development

7 Competitive cost of Electricity

8 Stellarator



The Fusion Roadmap



HPC Inauguration

The new HPC, Marconi-Fusion, has been officially inaugurated on 14 September 2016

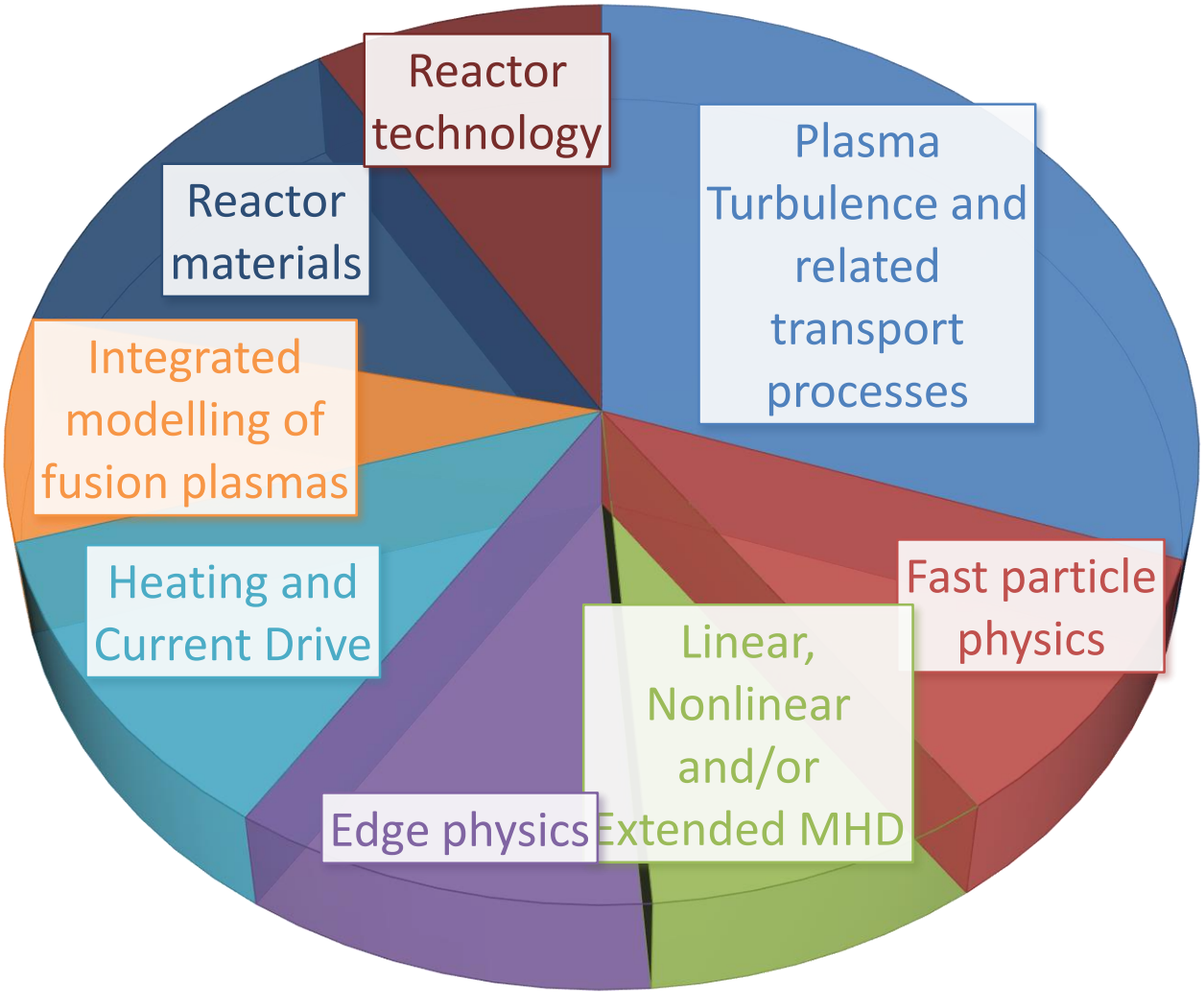
The first call for proposals in June was already very successful and has led to 109 applications that have been reviewed by referees. The outcome of the first call will be soon announced.

	MARCONI A2	MARCONI-FUSION
Model:	INTEL SERVER BOARD	
Architecture:	Intel **OmniPath** Cluster	
Nodes:	**3600**	**340**
Processors:	Intel Knights Landing (KNL) 1 x Xeon Phi 7250 (KNL) at 1.4 GHz	
Cores:	68 cores/node – Total=244800	Total=**27200**
RAM:	**96 GB/node**	
Racks:	**50 + 1** (mgmt.shared)	**~6+1** (mgmt. shared)
Peak Perfomance:	= 3 TF × 3600 nodes=**10.8 PFlops**	= 3TF x 340 nodes=**1.02 PFlops**
Disk Space:	**17 PB** (raw)	**5 PB** (raw) of MARCONI A1
Power:	**720 kW**	**80 kW**

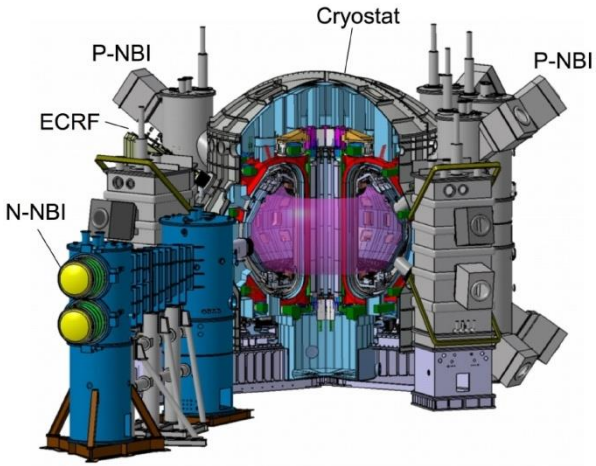
Tab.1: MARCONI A1/FUSION main characteristics

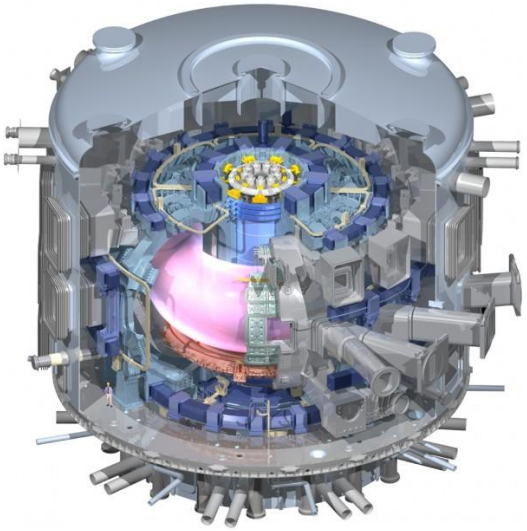
Preparation of 1st Cycle

109 Proposals Received: Covering the different topics



Mission 1: Plasma regimes of operation



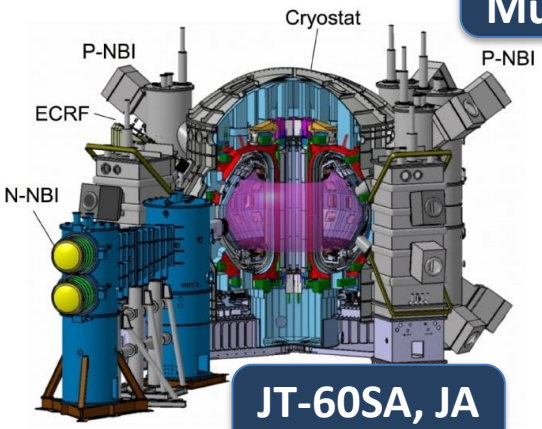


Preparation on existing devices: JET, Medium Sized Tokamaks, JT-60SA
+ other international collaborations

- Demonstrate and qualify regimes that meet the needs of ITER and DEMO
- High fusion performance with metallic PFCs by improving transport and by controlling MHD instabilities.
- Acceptable power depositions in the W divertor, radiate as much as possible power while keeping high performance
- Develop integrated scenarios with controllers (MHD, detached divertor, dilution…)
- Try to achieve steady state conditions

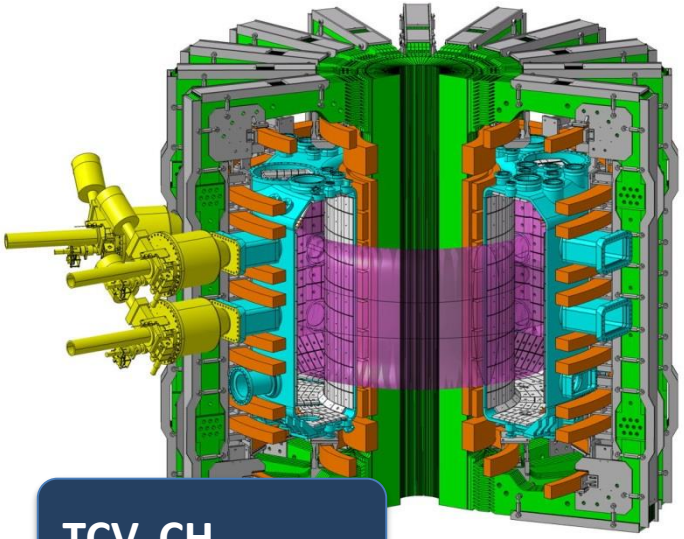
Mission 1: JET and Medium-Size Tokamaks

JET, UK

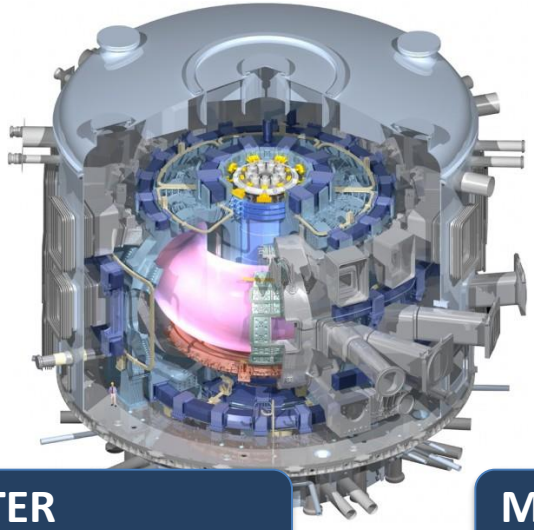


JT-60SA, JA
(Start in 2020)

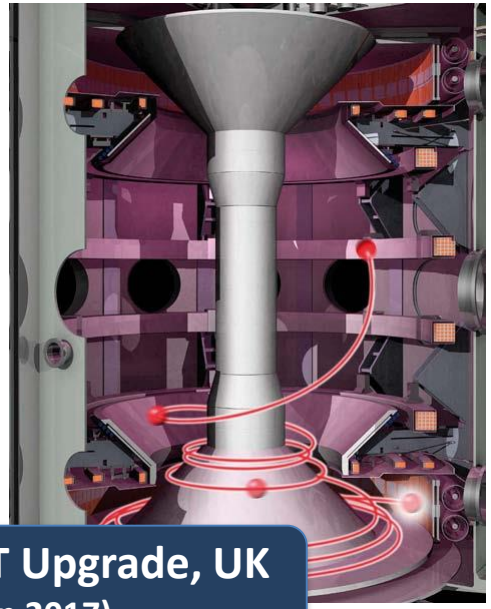
ASDEX Upgrade, Munich, DE



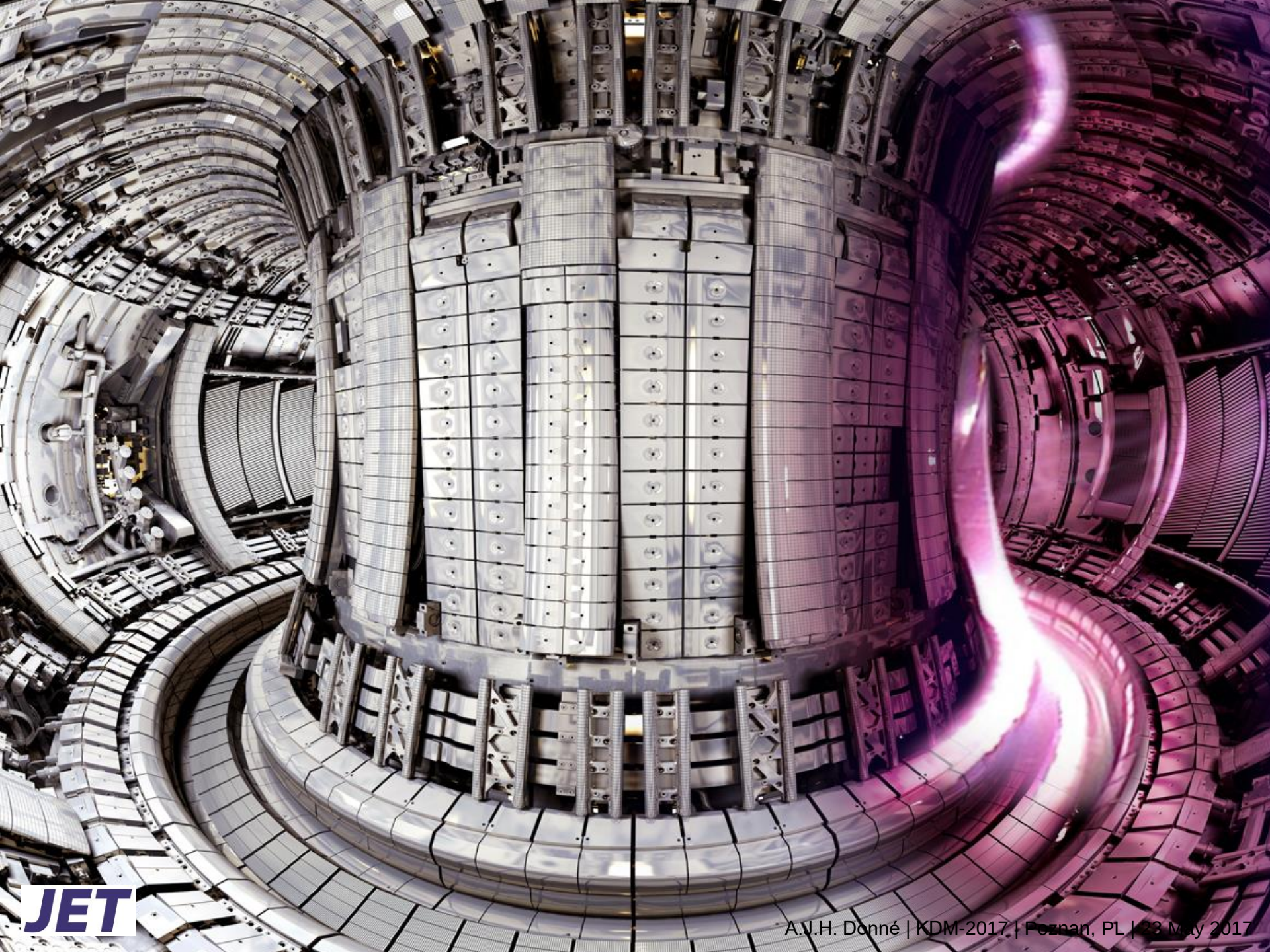
TCV, CH



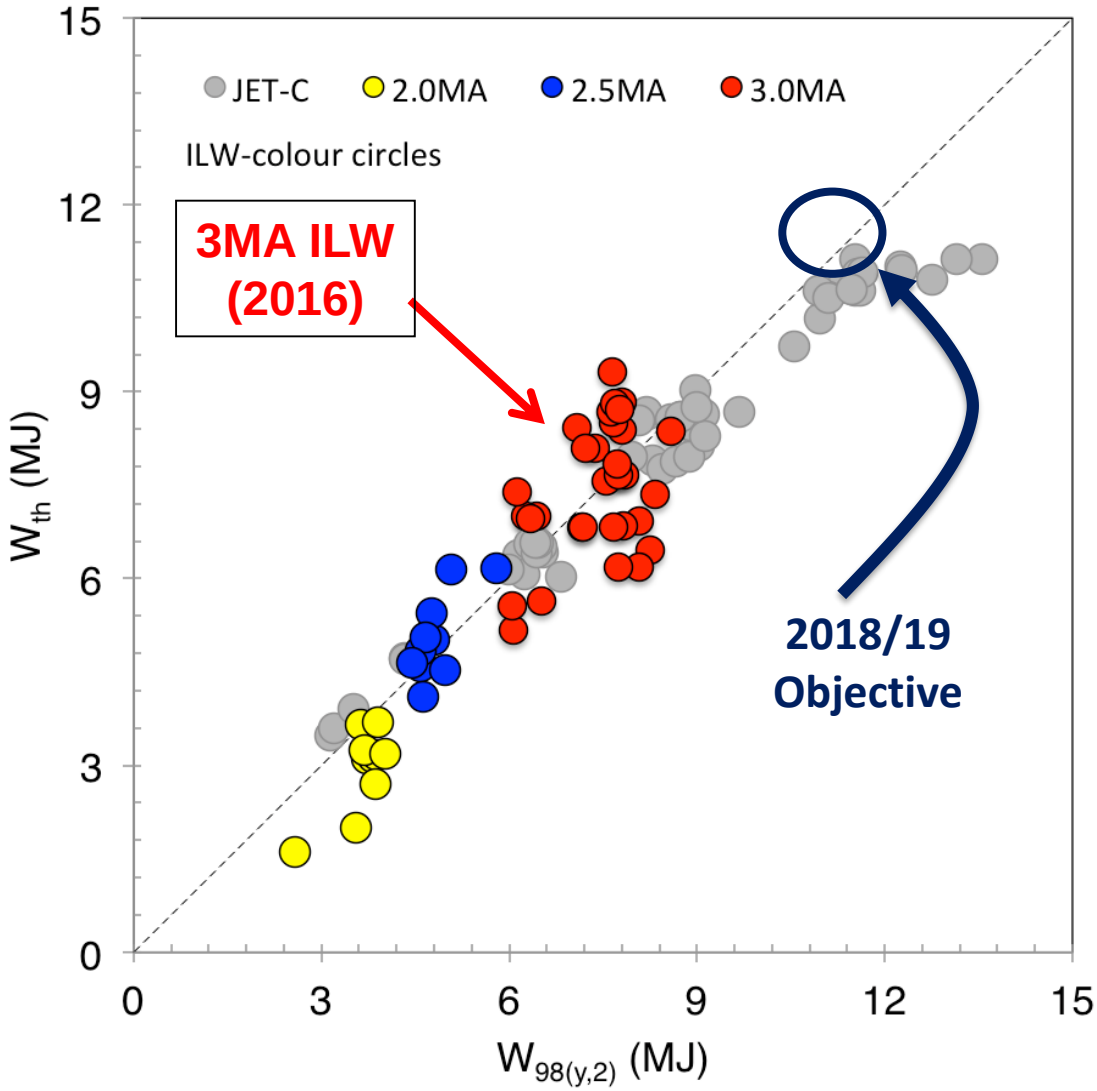
ITER
(Our target device)



MAST Upgrade, UK
(Start in 2017)



Latest progress:
ITER Baseline Operation at ~30MW 3MA/2.7T



[Nunes 2016]

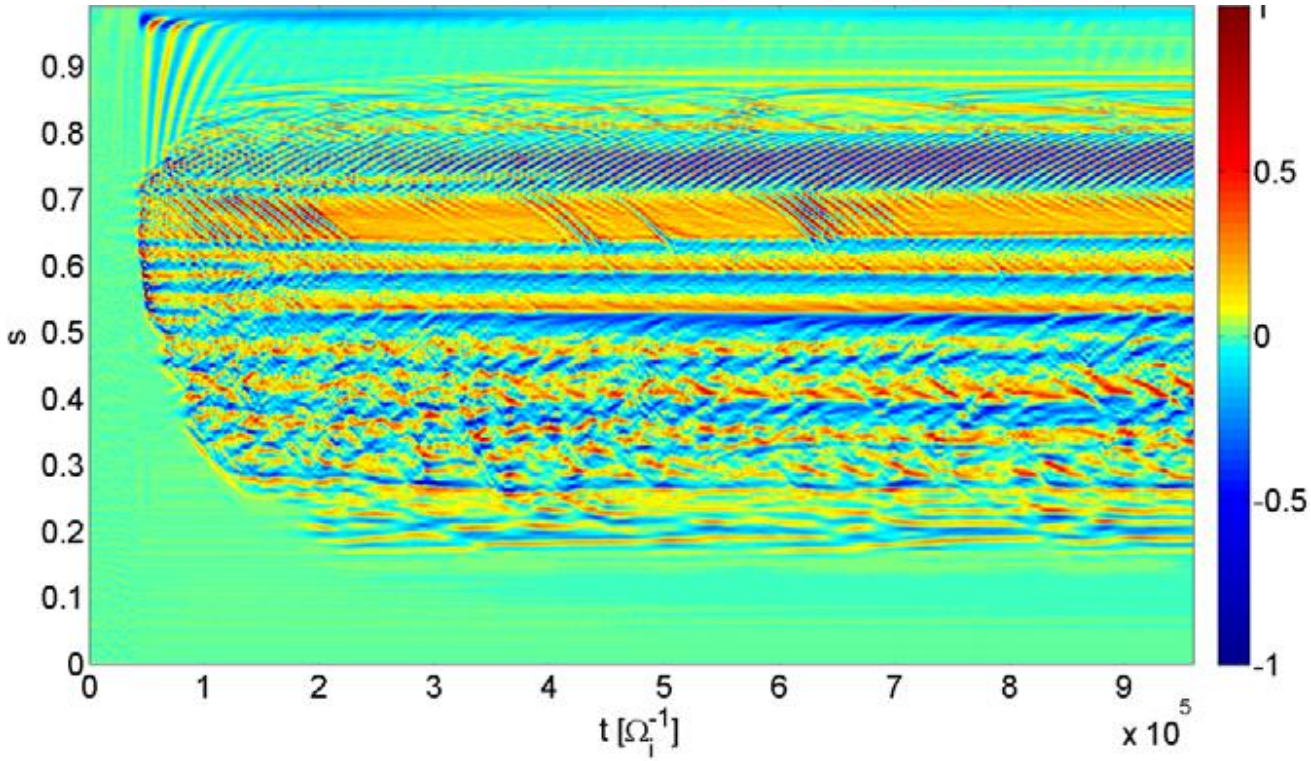
Plasma turbulence simulations

Plasma turbulence simulations have moved towards full torus calculations and the inclusion of more sophisticated physics models for the:

- electromagnetic effects,
- role of fast ions,
- momentum transport,
- electron dynamics
- 3D effects with applications to Tokamaks and Stellarators;
- with more detailed comparisons with experimental data and predictive simulations of future devices such as JT60-SA and ITER.

Plasma turbulence simulations

Global (full torus) simulations of plasma driven turbulence in an ITER plasma have been performed. Plasma shaping have major repercussions on the turbulent heat flux. The implications are very favourable for **ITER**

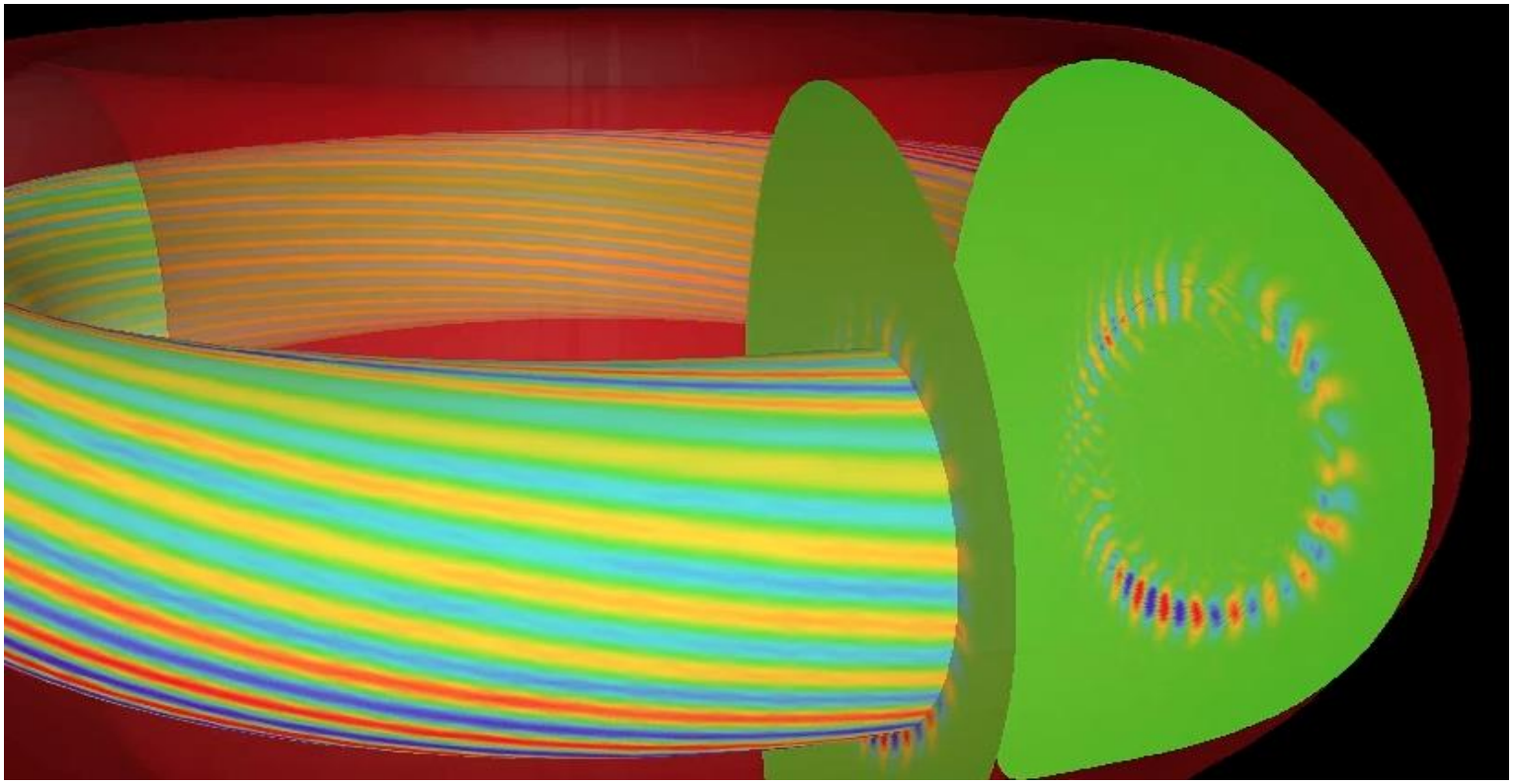


Contours of the Plasma Flow versus radial coordinate *s* and time, for the ITER an case

IFERC-CSC Lighthouse Project

L. Villard, et al PPCF 55, 074017 (2013)

Large-Scale Simulation of Energetic Particle Driven Magnetohydrodynamic Instabilities in ITER Plasmas

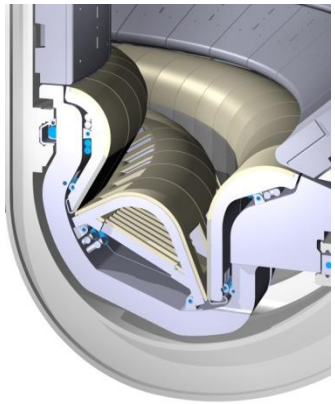


Todo el al, Plasma Fusion Res. 9, 3403068 (2014)

Mission 2: Materials one can lay on the sun

Rolls Royce Trent 900

ITER steady-state



ITER transients

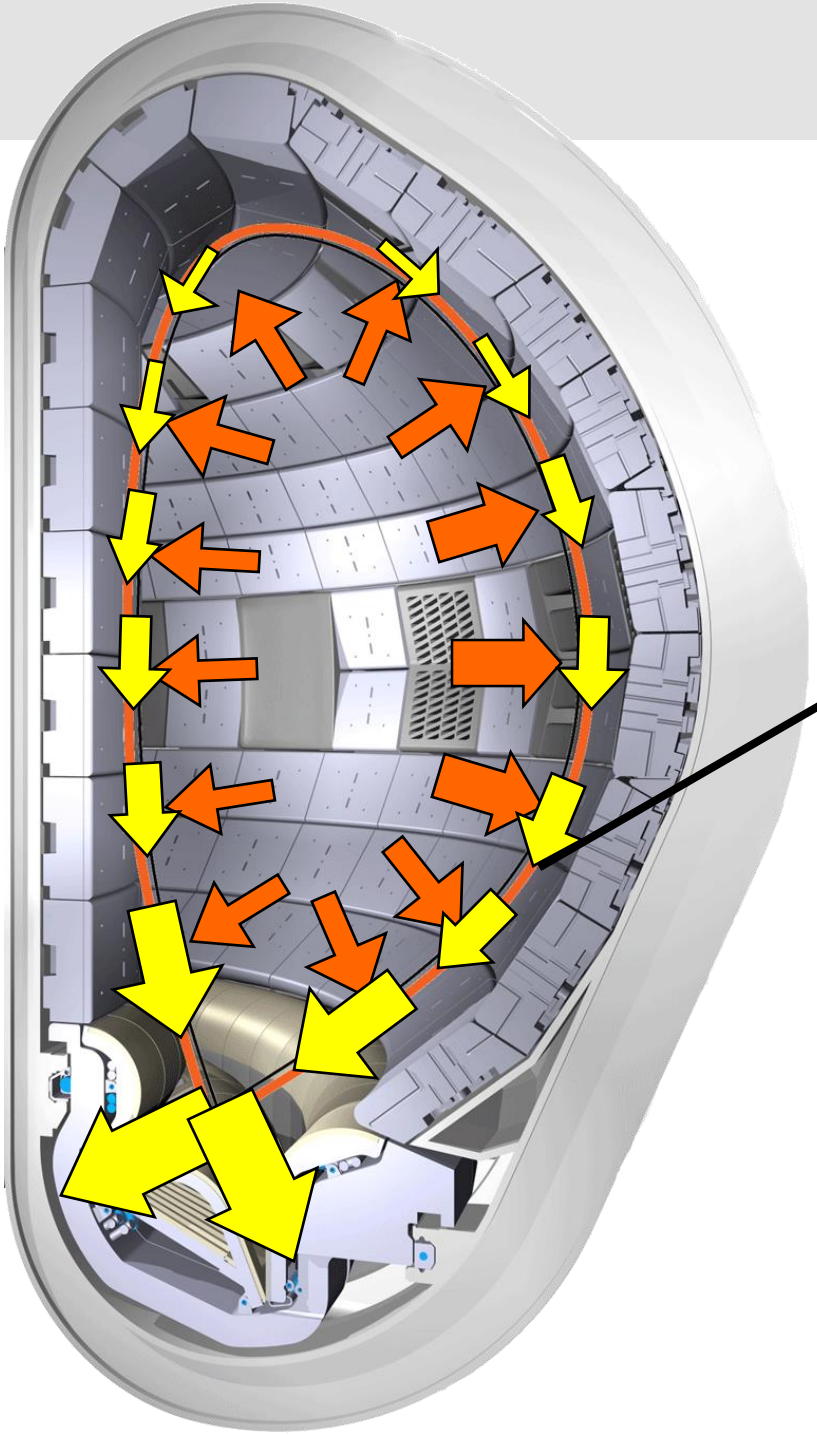
~1 <10 85 2000

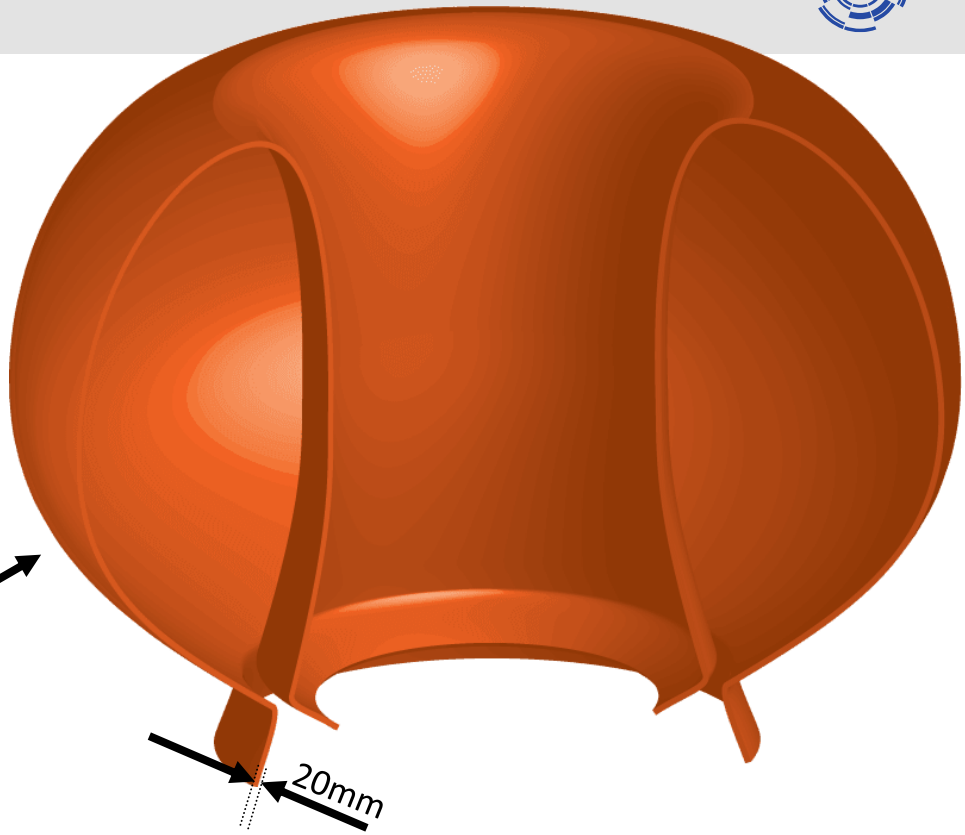
Power load [MW/m^2]

HWR

Re-entry vehicle

Ariane 5/Vulcain 2





Scrape-off layer ~ 2 cm thick

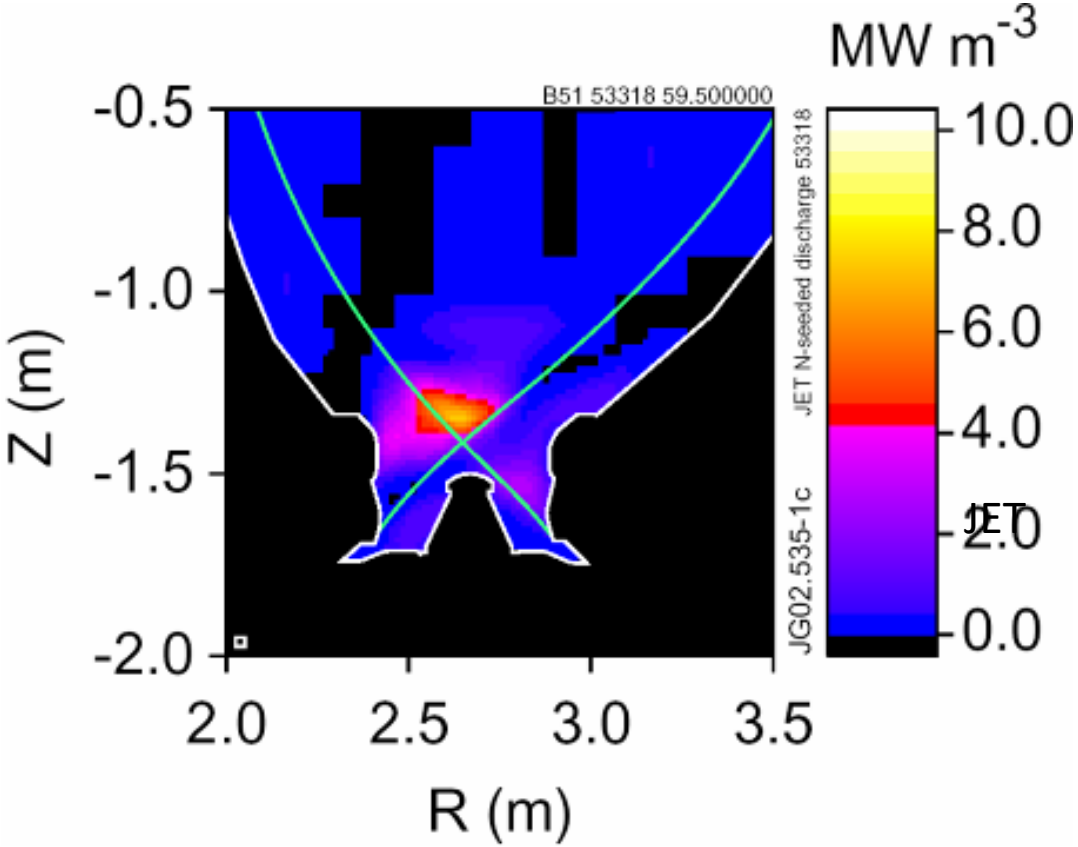
Power density 1 GW/m²

How to reduce the power loads of 1 GW/m²

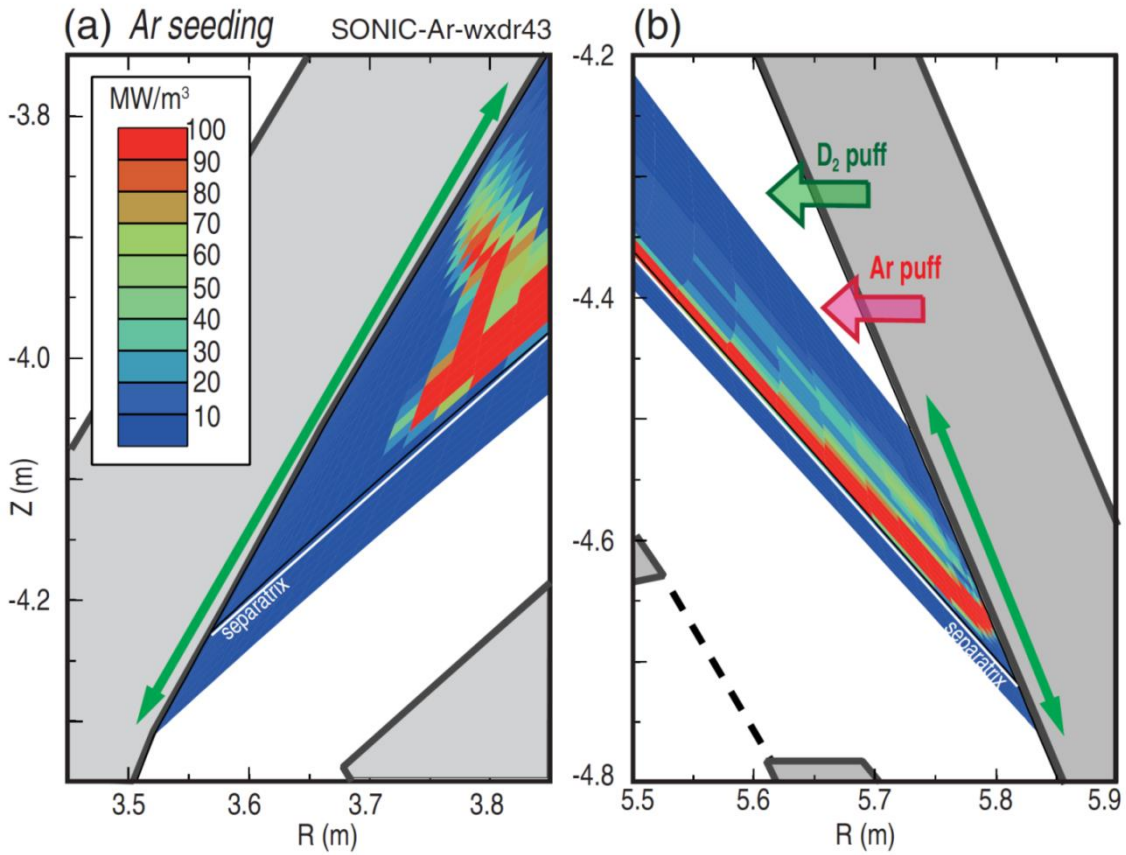
Proper choice of the divertor geometry

Radiate >90% of the power away (uniform distribution)

Decouple (detach) the plasma from the divertor (T<10 eV)



Distributions of Argon radiation power density in the (a) inner divertor and (b) outer divertor plasma simulations of the DEMO divertor

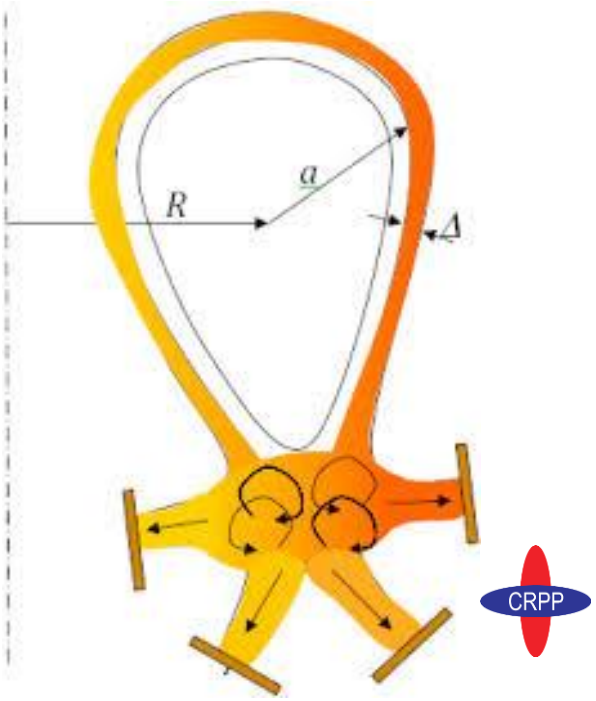


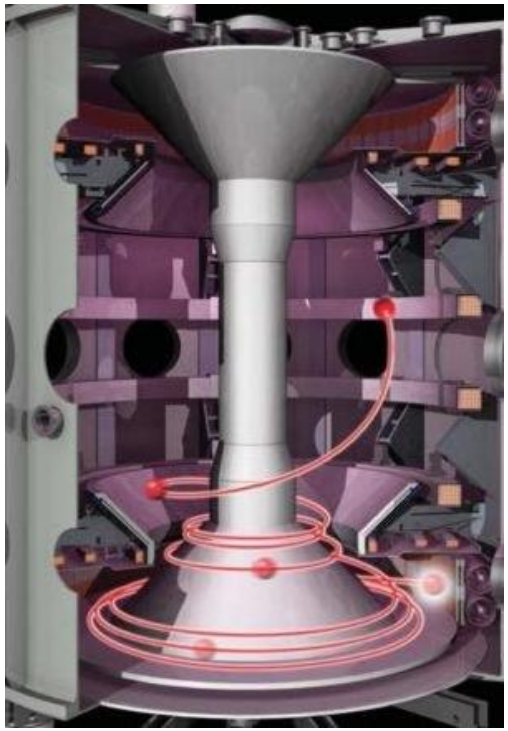
Asakura et al. NF 53 (2013) 123013

Heat Exhaust Research in Tokamaks

Research in alternative divertor solutions (Super-X, snowflake, liquid metal divertors)

Research in order to understand detached divertor conditions

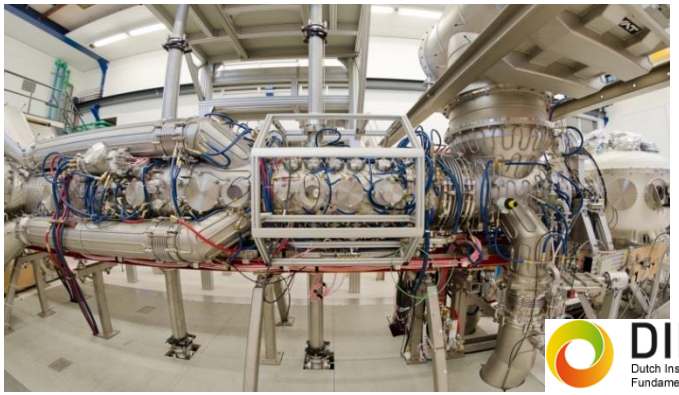




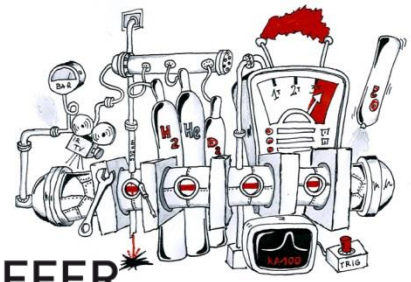
CCFE CULHAM CENTRE FOR FUSION ENERGY

CRPP

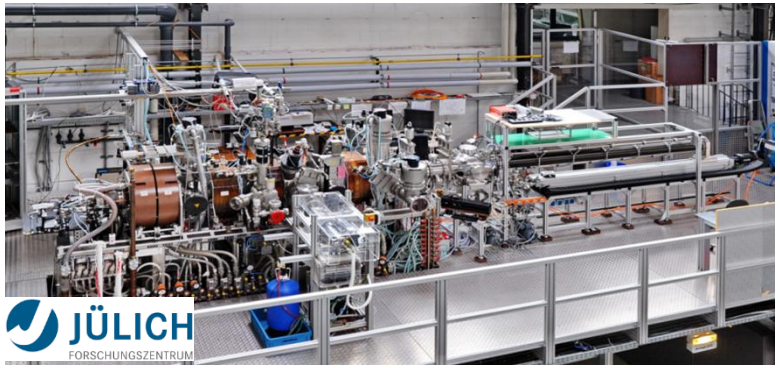
Studying Plasma Facing Components



Magnum-PSI



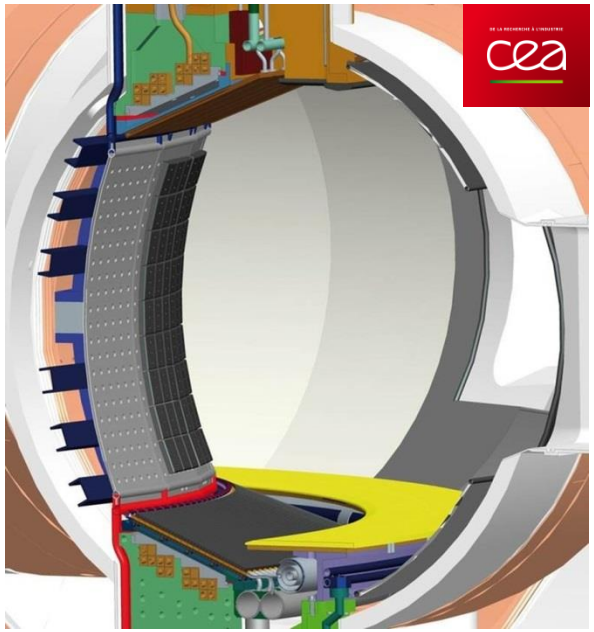
Pilot-PSI



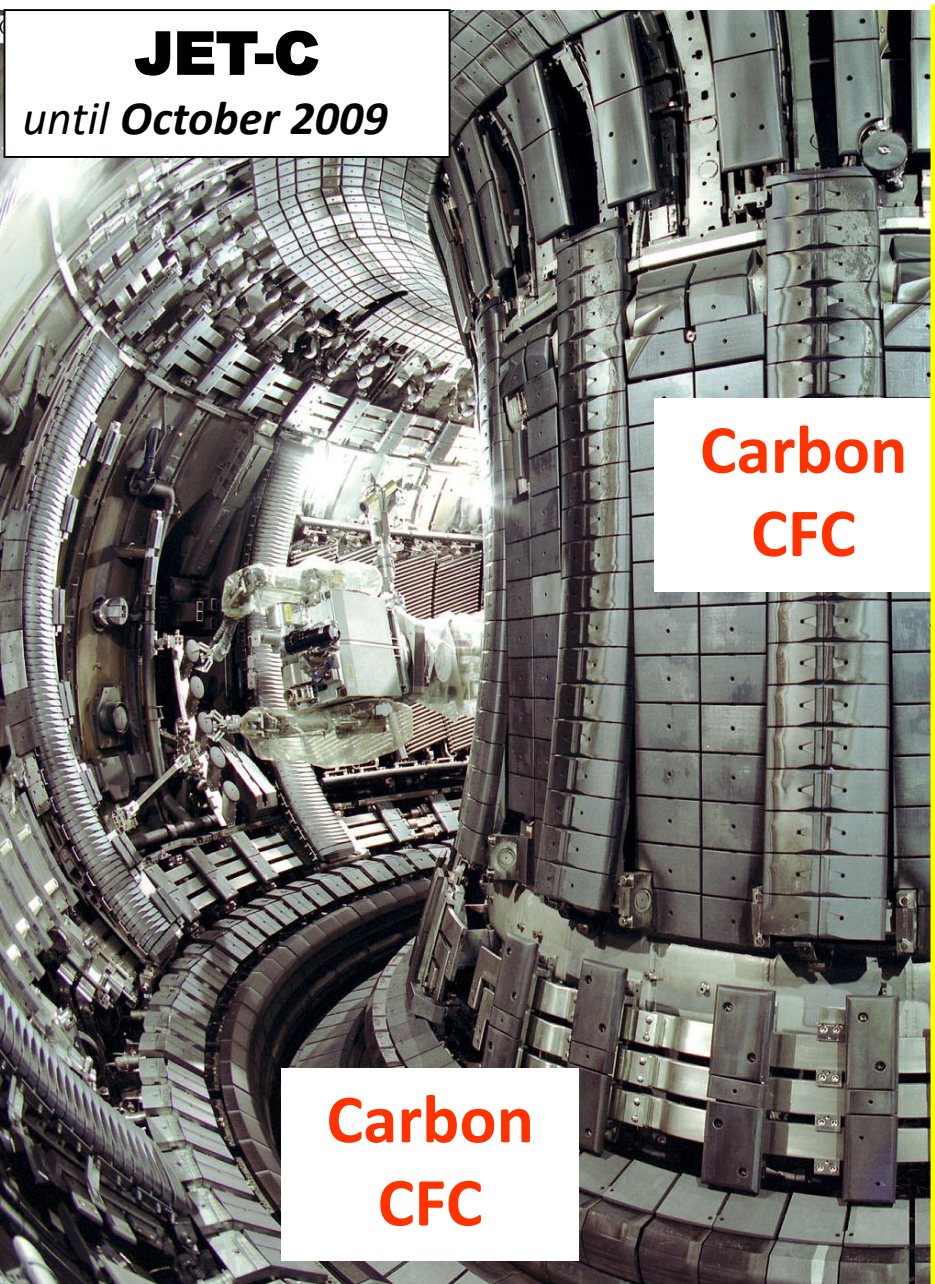
PSI-2

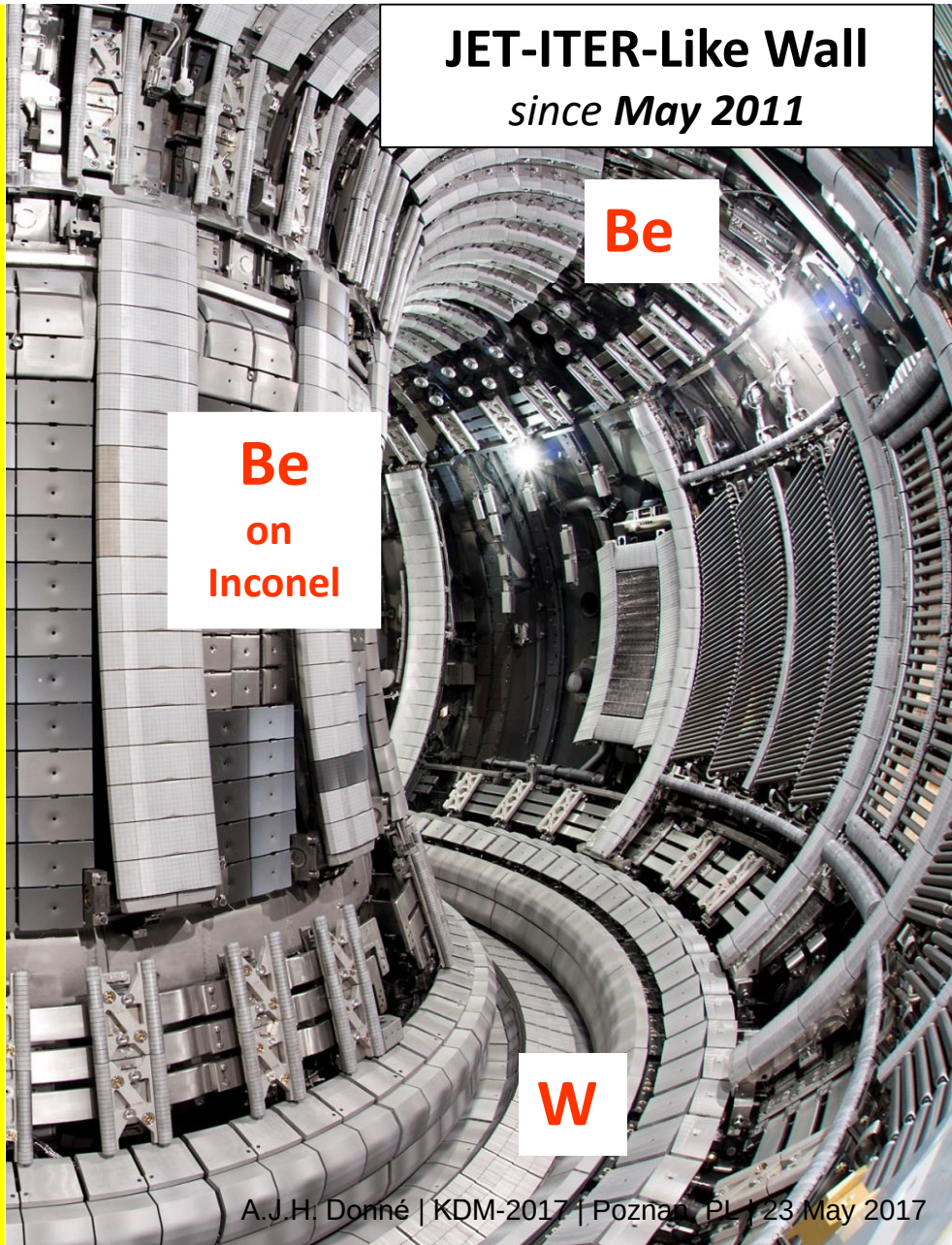
JUDITH-1/2

WEST



The Change of the JET Wall

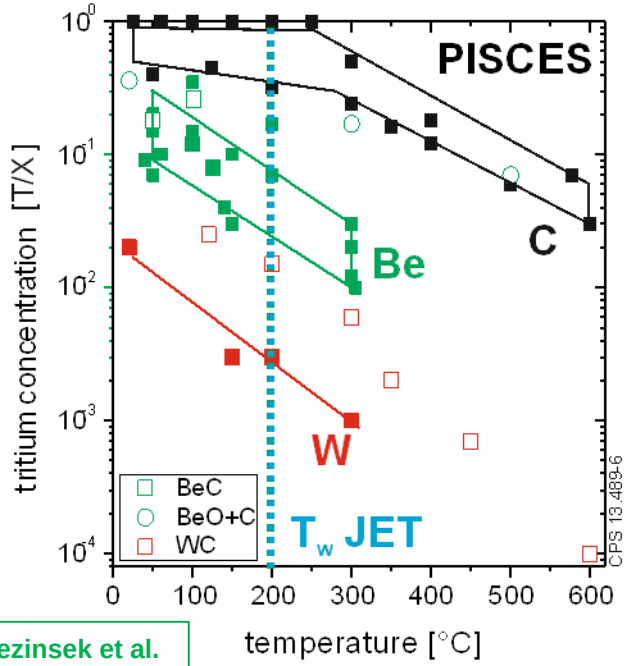




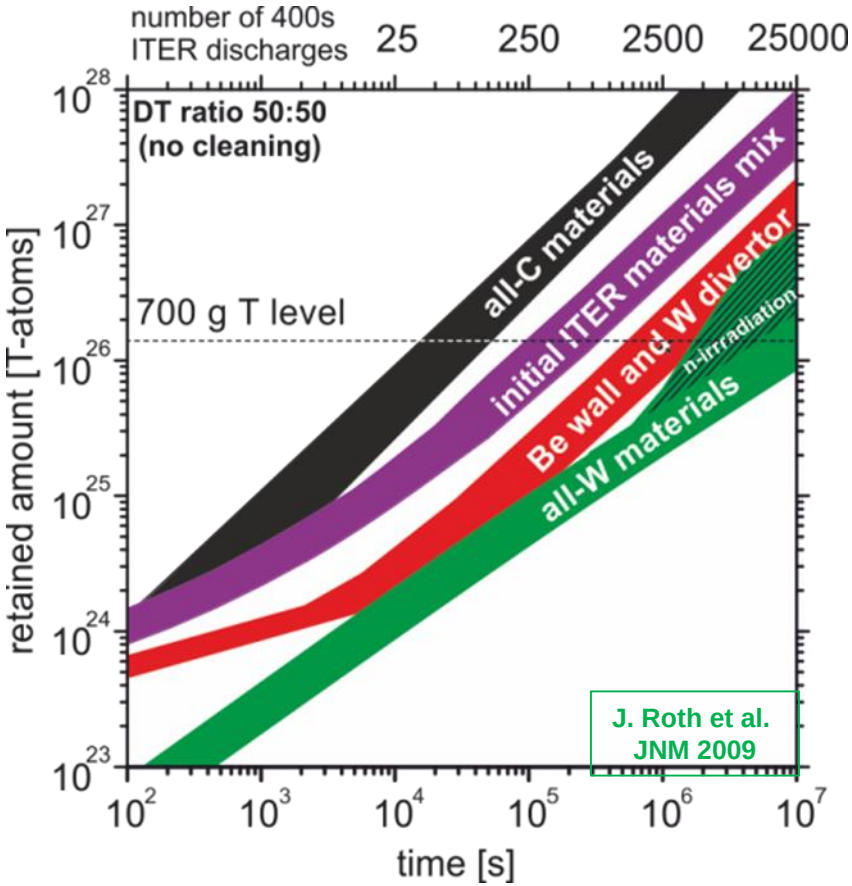
Why not Continue to Operate with a Carbon First Wall?

DT experiment in JET revealed unacceptable safety conditions for ITER or a reactor:

- tritium retention of 20% due to co-deposition in divertor [P. Andrew. et al JNM 1999]
- multistep transport of carbon to inaccessible/remote areas of the divertor => dust



S. Brezinsek et al. NF 2013

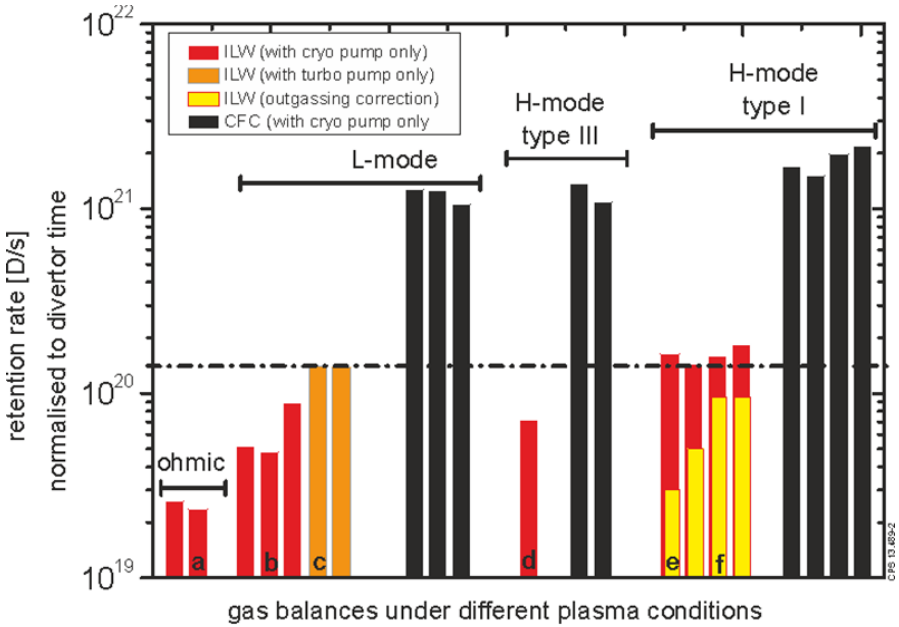


J. Roth et al. JNM 2009

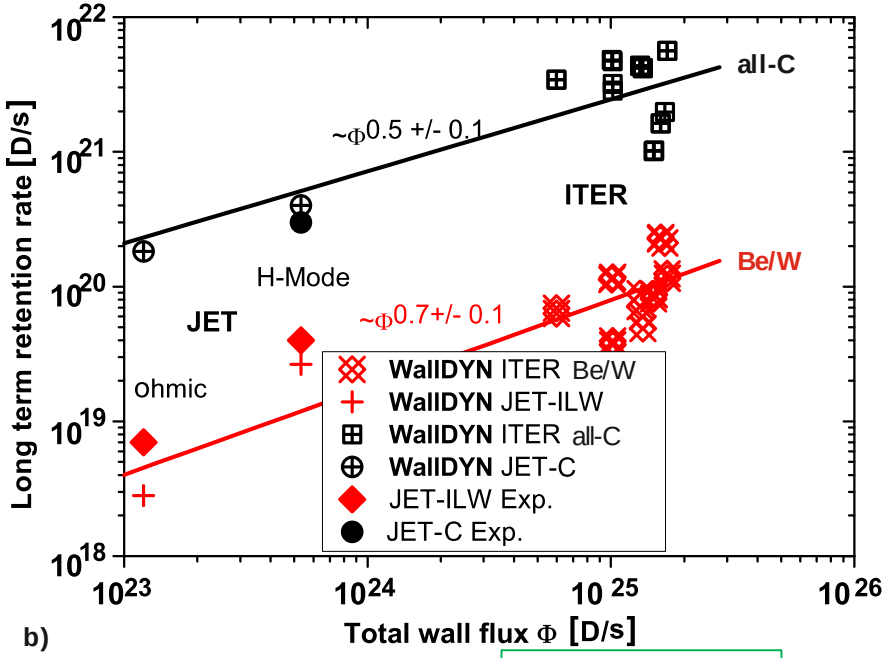
Impossible to breed enough T in a reactor with C walls to compensate for loss in co-deposits!

Fuel Retention in JET-ILW vs. JET-C

- Strong reduction od retention rate by more than one order of magnitude with JET-ILW
- The deposition pattern and the absolute value of the retention have been reproduced by WallDYN & ERO simulations, providing a benchmark for ITER predictions



S. Brezinsek NF 2013

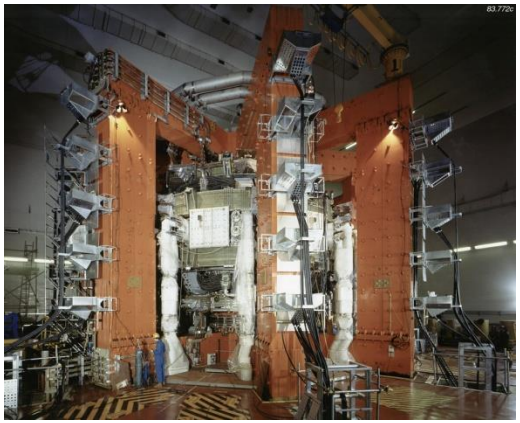
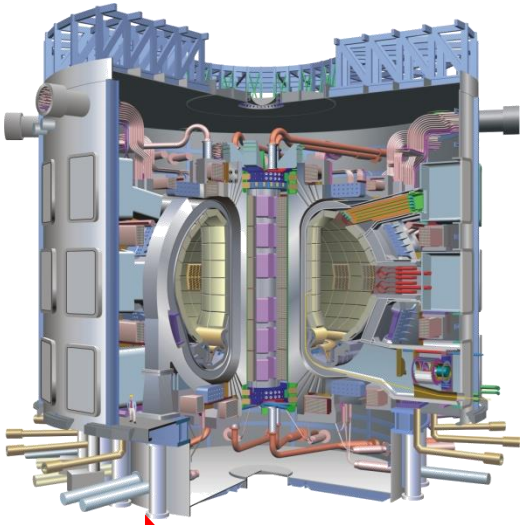
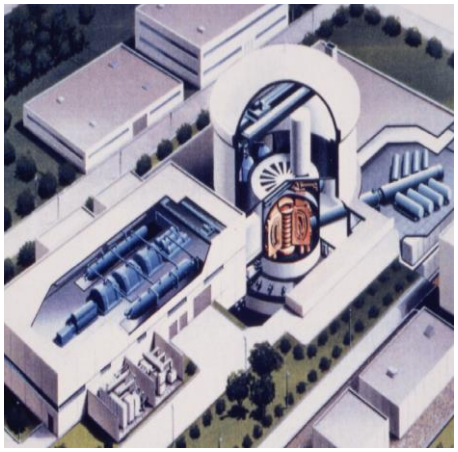


K. Schmid NF 2015

Long-term retention mechanism:
- implantation (1/3) and co-deposition (2/3)
- deuterium outgassing important

Fuel retention limit in ITER with Be+W walls: 3000-20000 discharges

Mission 3: Materials for the fusion reactor

JET	ITER	DEMO
		

50 times higher ion fluxes

5000 times higher ion fluence

up to 5 times higher ion fluence

10^4 times higher neutron fluence

100 times higher neutron fluence

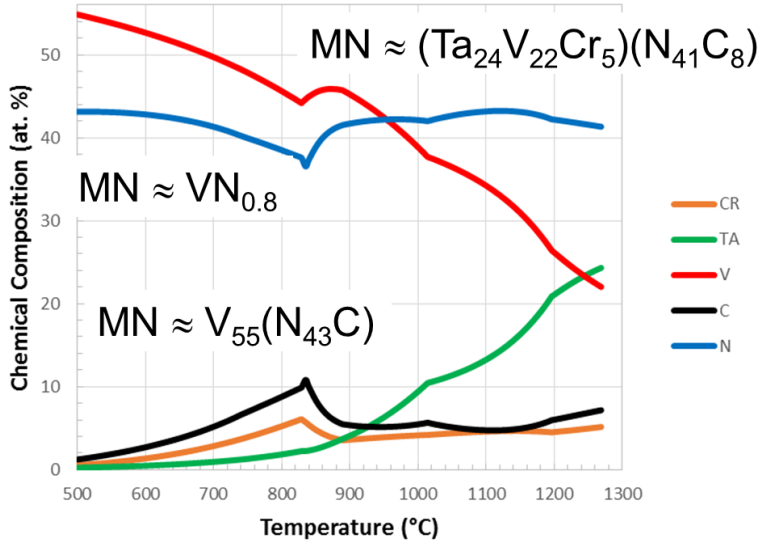
Advanced Steels: High Temp. Applications

Steel development based on thermodynamic calculations

→ low temperature steel: **two** 80 kg batches produced

→ high temperature steel: **nine** 80 kg batches produced, **four** 100 kg batches in production

→ alternative ODS steel production: **23** lab-scale batches produced (250 – 550 g each)



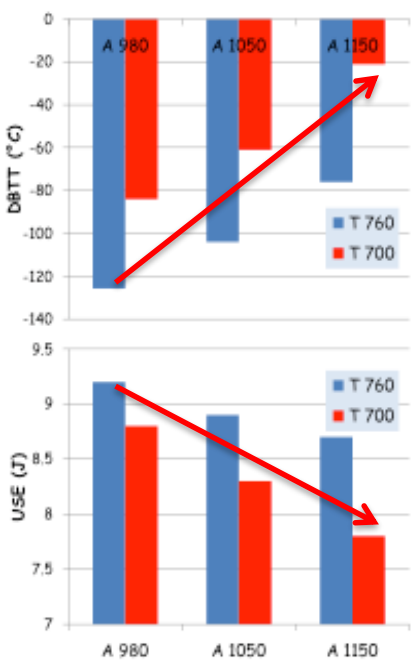
M. Rieth (KIT) and WPMAT Team

Adjustment of EUROFER properties by varying heat treatment temperatures

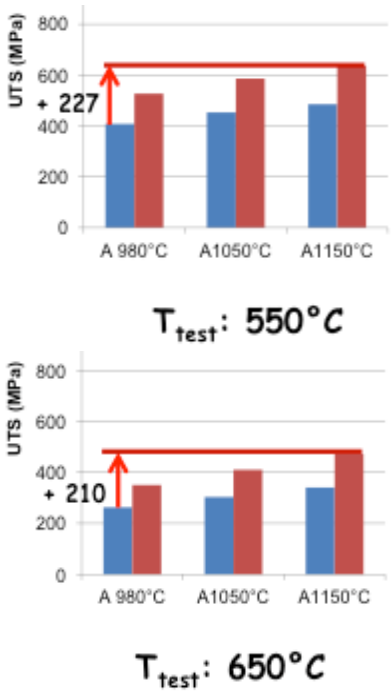
- **Austenitisation: 980 °C – 1150 °C**
- **Tempering: 700 °C – 760 °C**

Very successful

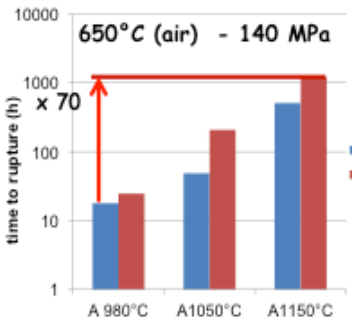
Charpy Properties



Tensile Strength



Creep Strength



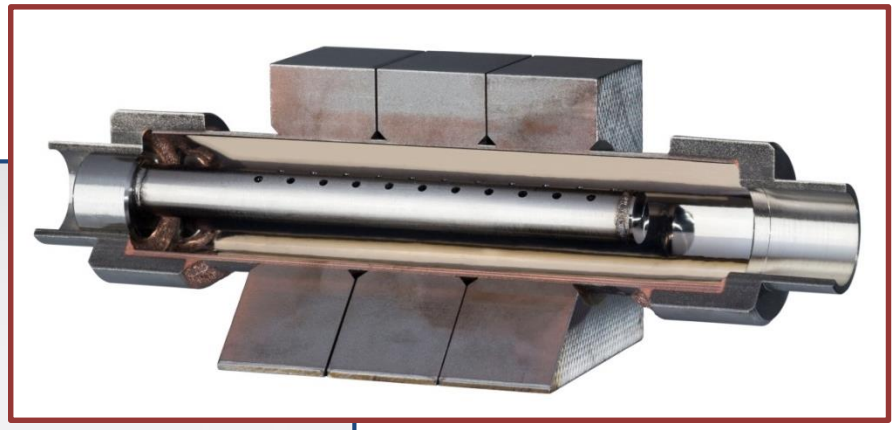
J. Henry, CEA

13 new heats ready,
9 under investigation

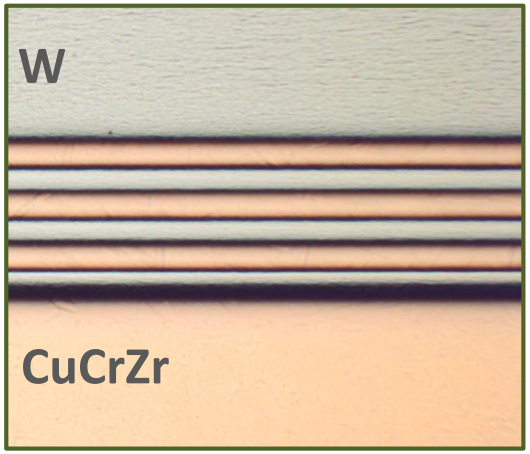
Achievements – High Heat Flux Materials

W-Cu laminated pipe length up to 1000 mm

Appl. 1: divertor heat sink

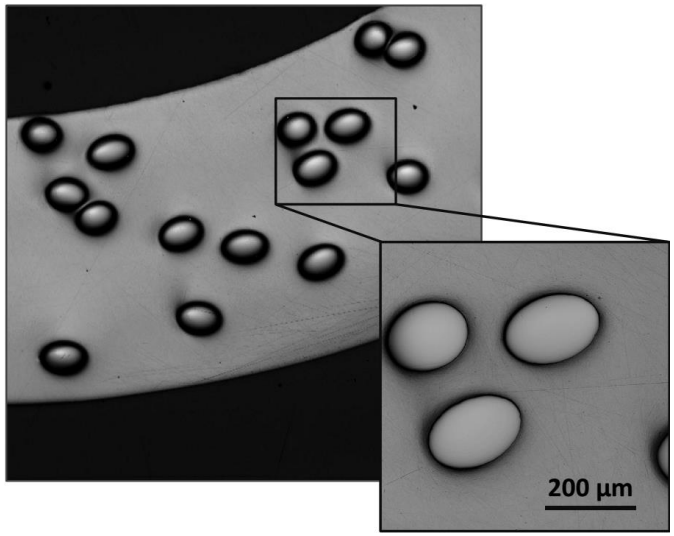


Appl. 2: Interface



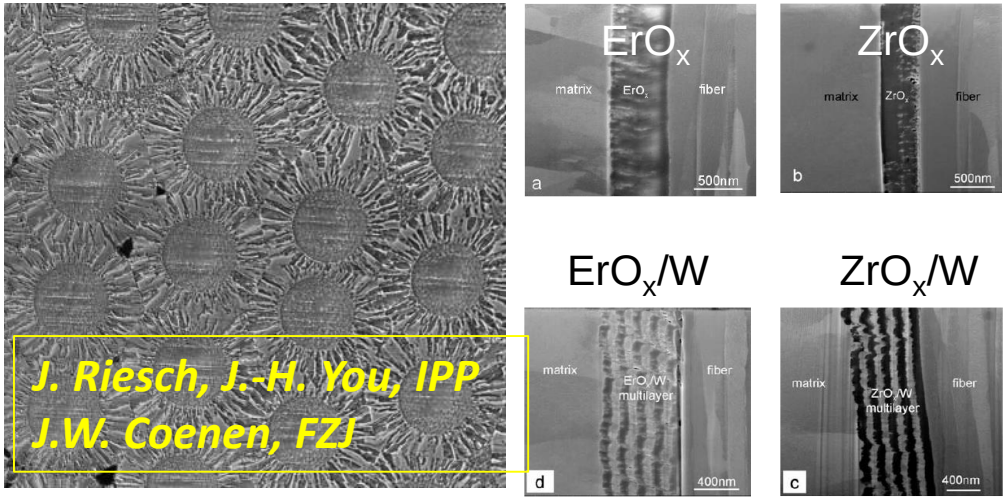
Achievements – High Heat Flux Materials

Cu-W(fiber) composite tubes



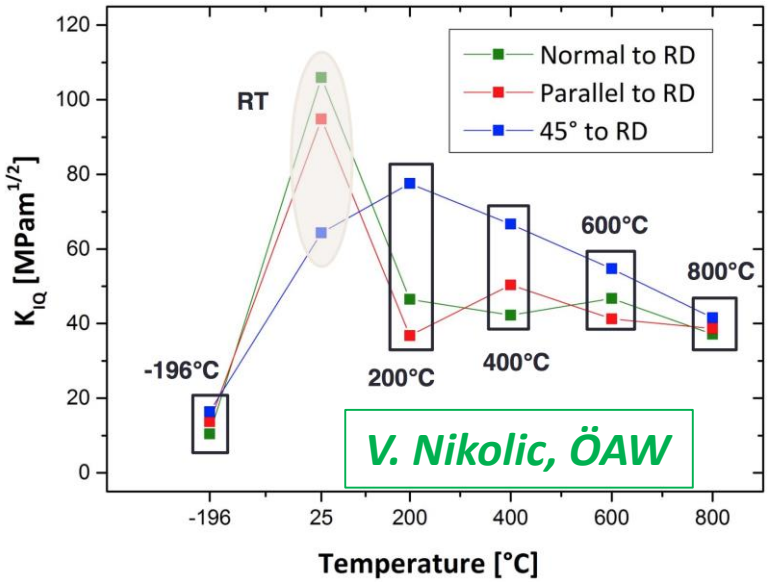
A. v. Müller, J.-H. You, IPP

W-W(fiber) composite



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

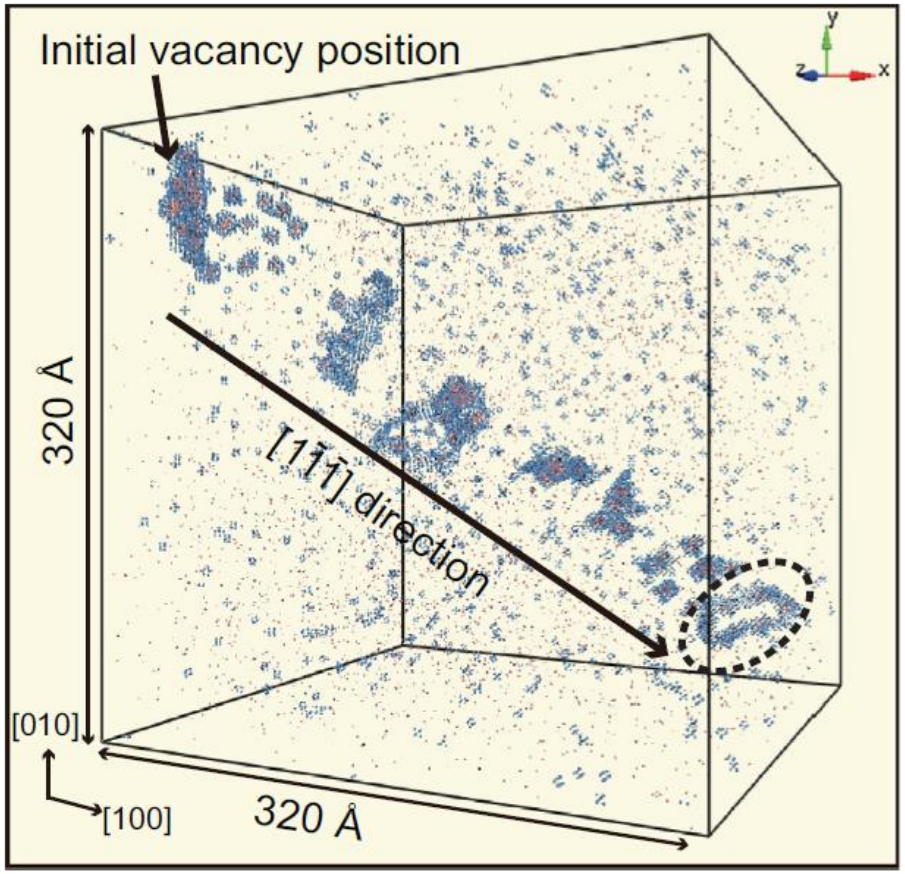
Fracture Mechanics



V. Nikolic, ÖAW

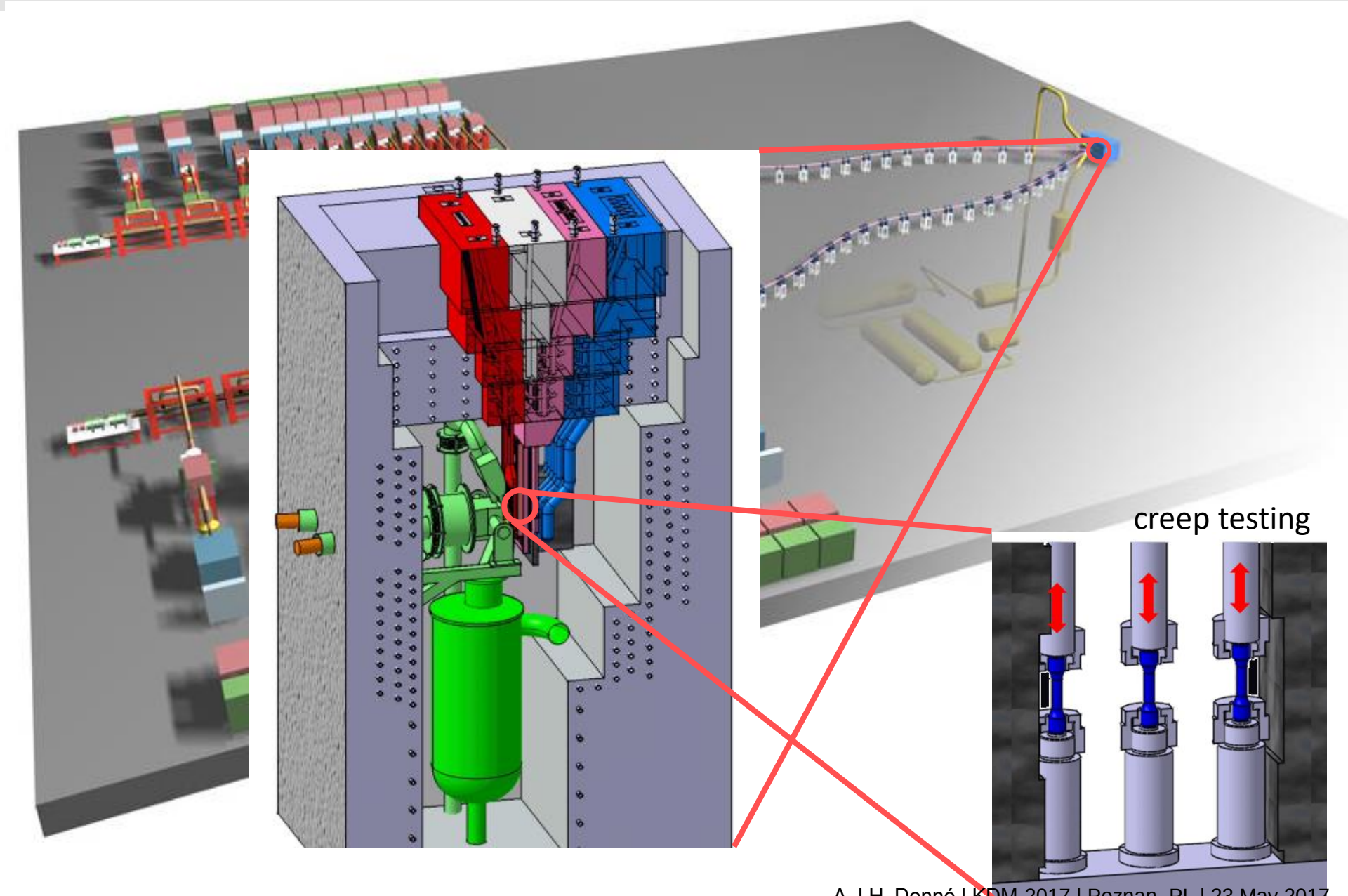
Reactor Materials studies

Density Functional Theory and Molecular Dynamics calculations of the interaction between defects in metals and hydrogen/helium showed that in bulk tungsten He atoms attract each other into clusters, and the migration barrier for these clusters (at least 3 atoms) is lower than for a single He atom



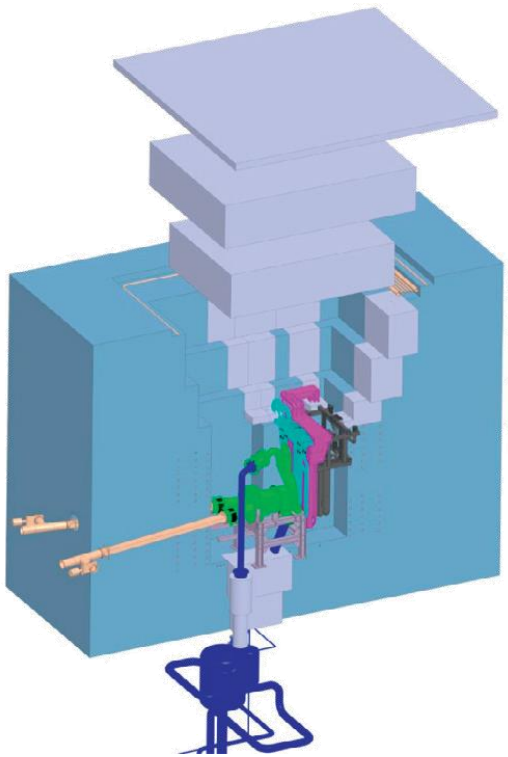
Kobayashi et al, JNM 463 (2015), 1071–1074

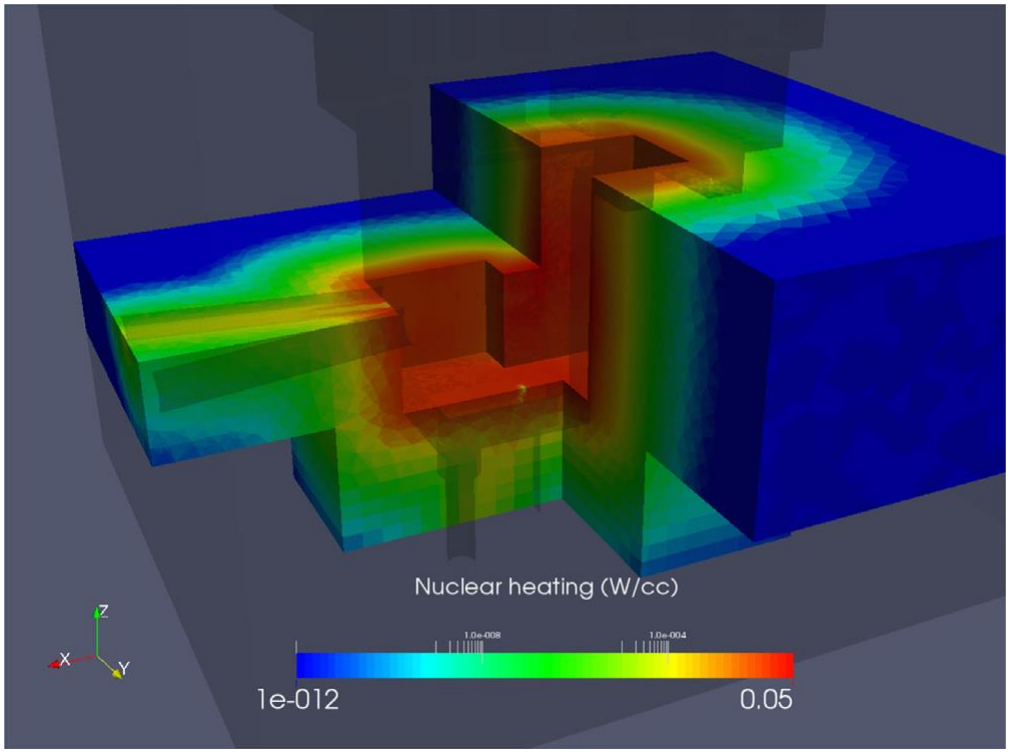
IFMIF - International Fusion Materials Irradiation Facility



Reactor technology studies

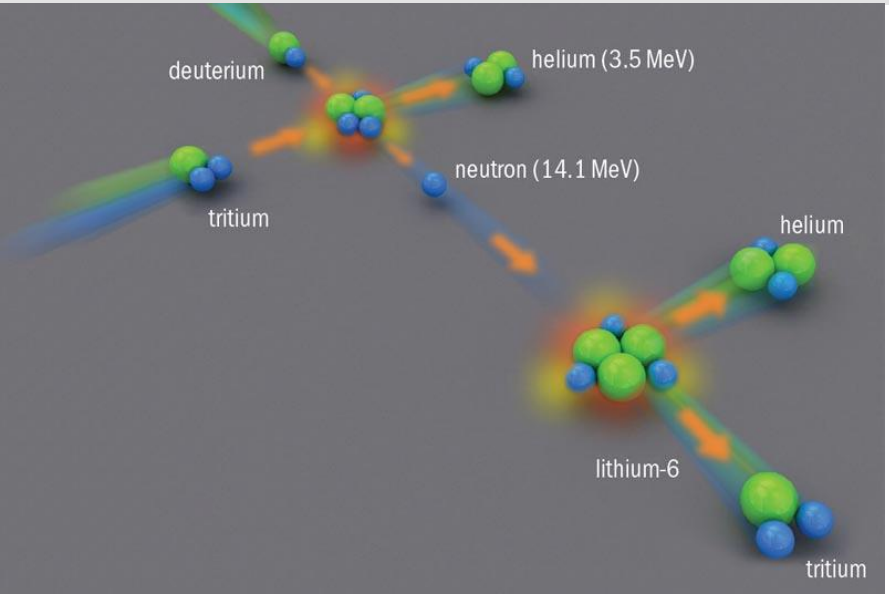
Very detailed neutronics analyses have been carried out in order to examine the neutron streaming effect caused by pipe penetrations and gaps around removable shielding plugs of the IFMIF Test Cell.



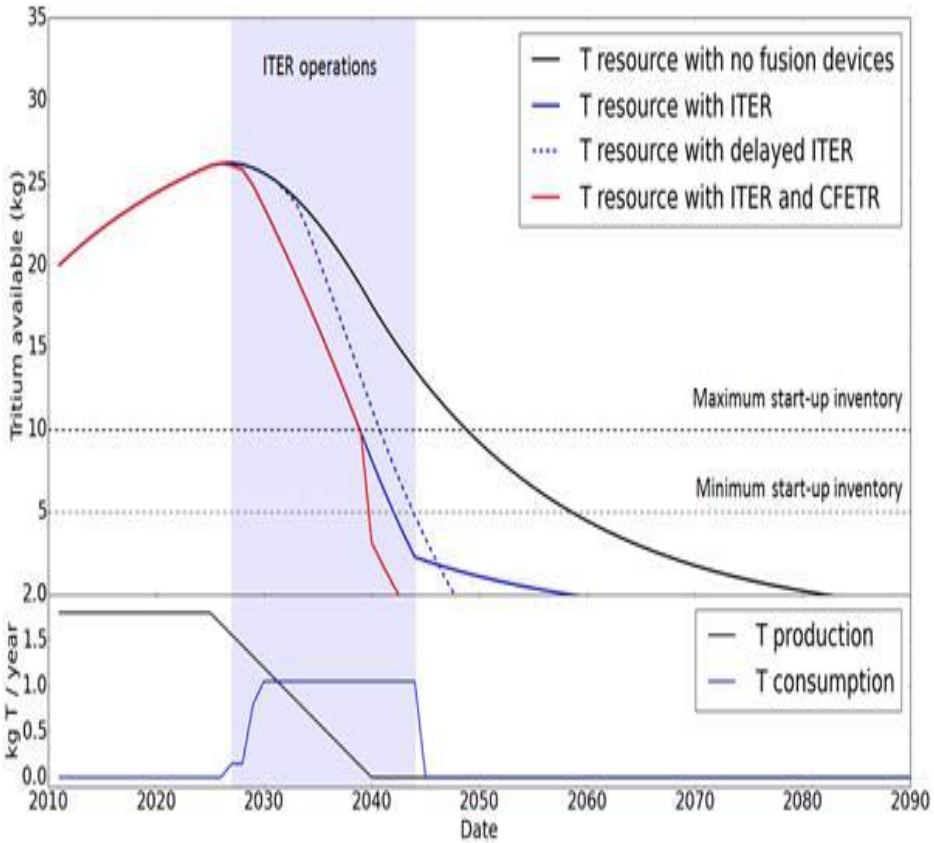


Kondo et al, FED 98-99 (2015) 1998-2002

Mission 4: Tritium cycle & tritium self-sufficiency

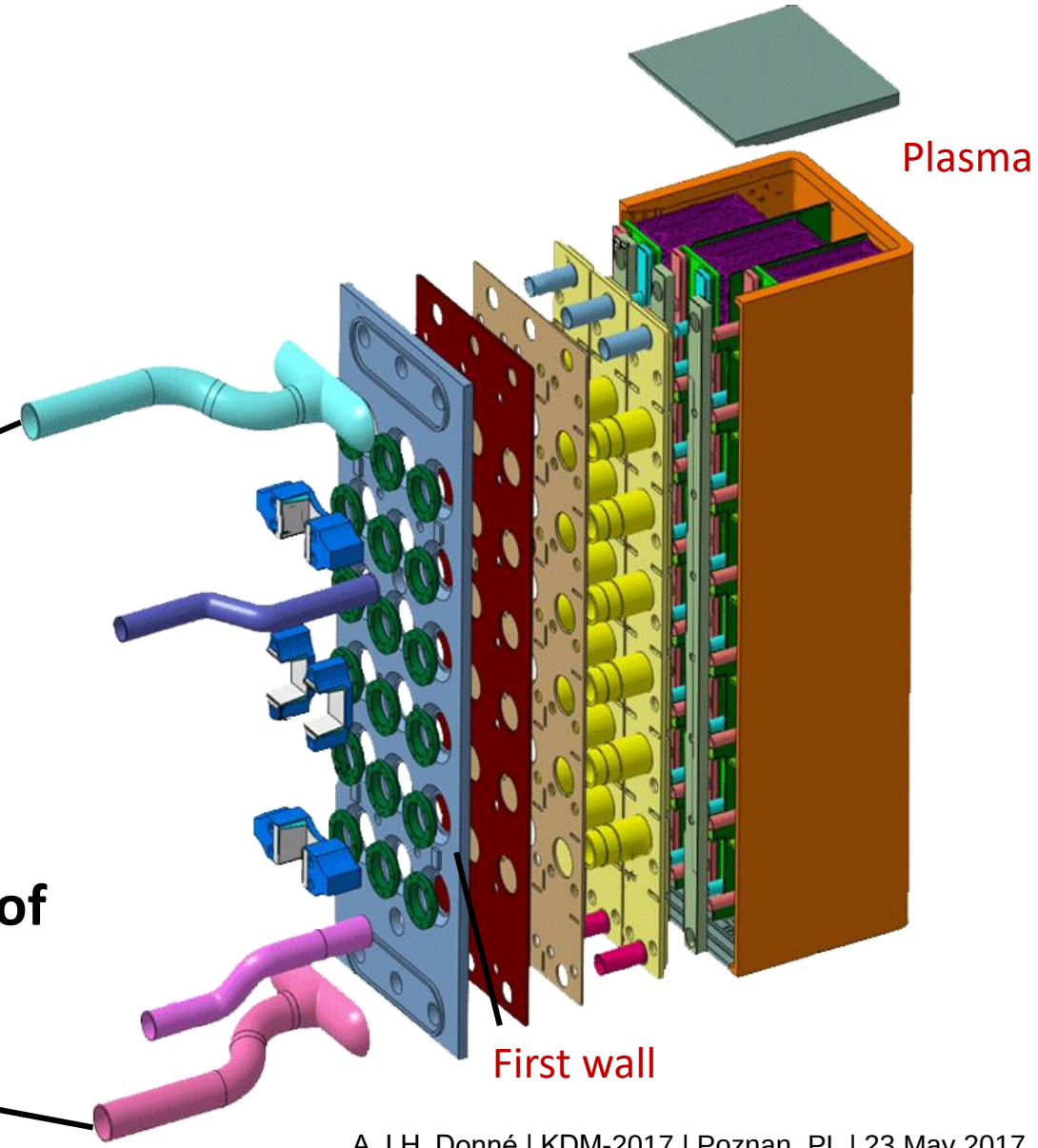


Available T inventory



- **~112kg T/year for 500MWe reactor**
- **Efficient breeding & extraction**
- **DEMO MUST produce its own tritium**

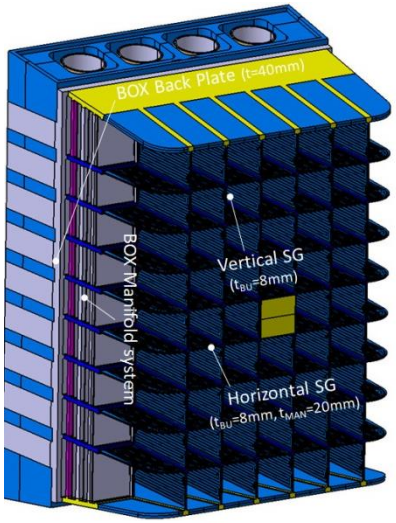
ITER Test Blanket Module

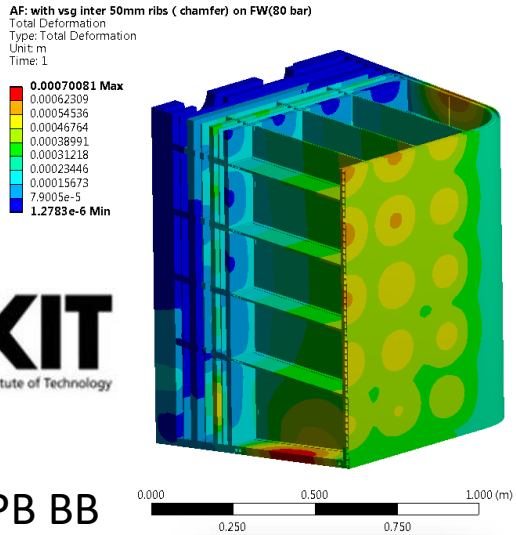


Tritium must be used at least 1000 × without being lossed

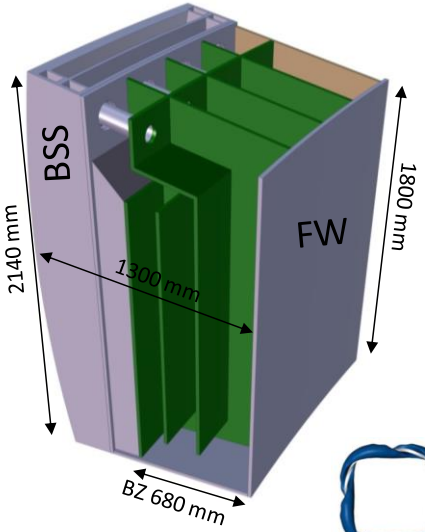
(each fusion reaction in the plasma must lead to creation of a new tritium atom in the blanket)

Breeding Blanket Design





HCPB BB



DCLL BB

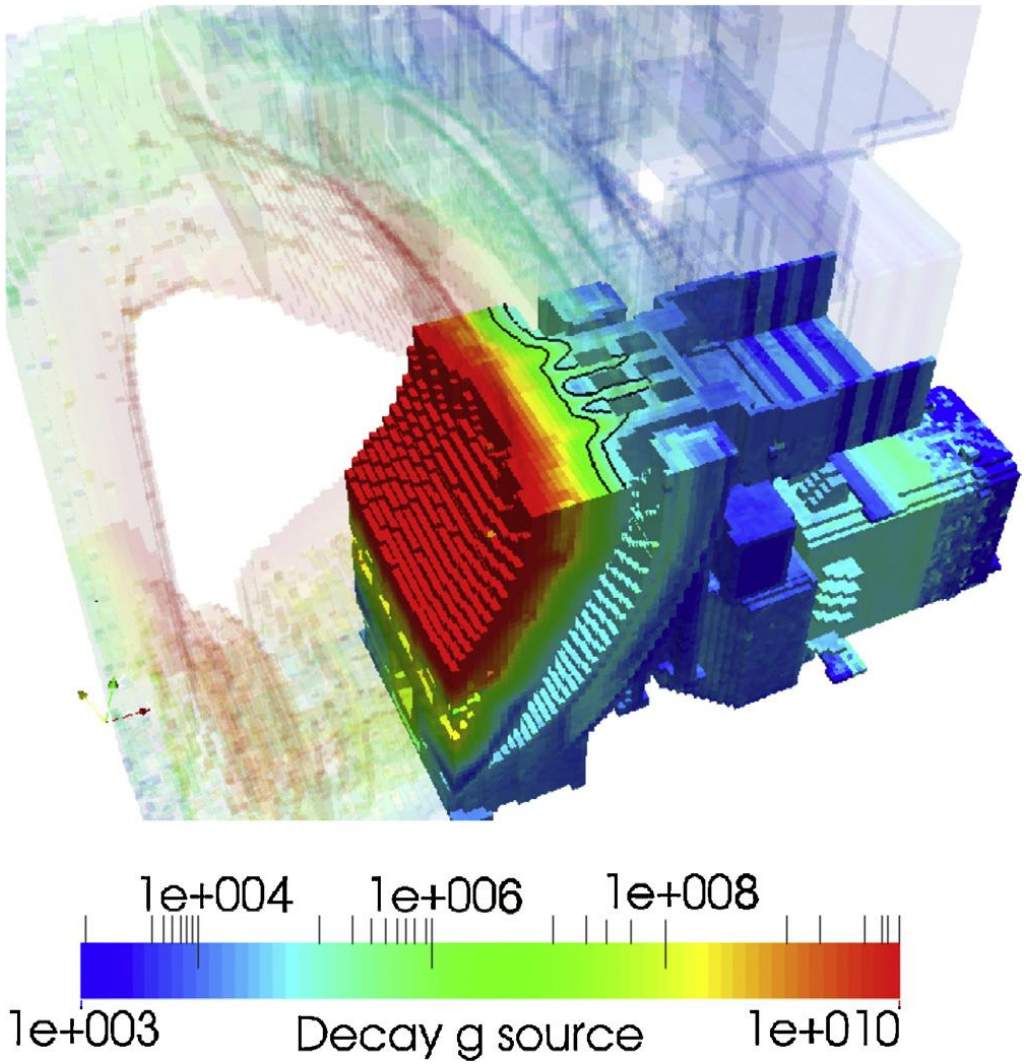
- The Breeding Blanket (BB) concept considered in PPPT have been adapted (e.g. HCPB and DCLL in the figure) at the current DEMO configuration.
- Neutronics, thermo-hydraulics and structural-mechanics performance were evaluated. Issues were identified in TBR and coolant performances.
- New design features have been evaluated and performances increased

L. Boccaccini (KIT) and WPBB Team

Breeding Blanket Project in EUROFusion

Reactor technology studies

Neutronics calculations aimed at the comparison of various blanket module DEMO concepts were performed in order to improve reactor safety and calculations aiming at understanding ITER port shutdown dose rates were performed.



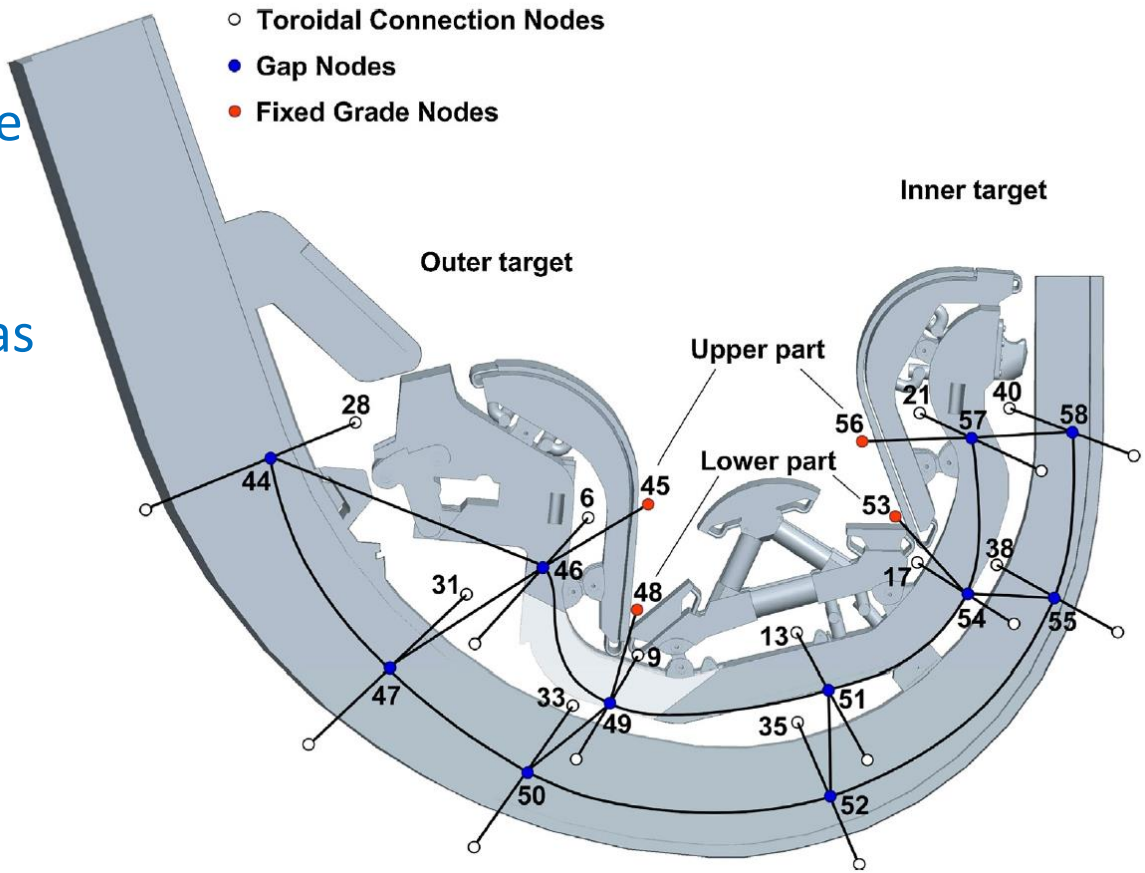
R. Juárez et al FED online 24 November 2015

Mission 5: Safety

- DEMO will be a full blown nuclear device
- Safety is an extremely important issue and needs to be taken aboard already in the earliest design phases

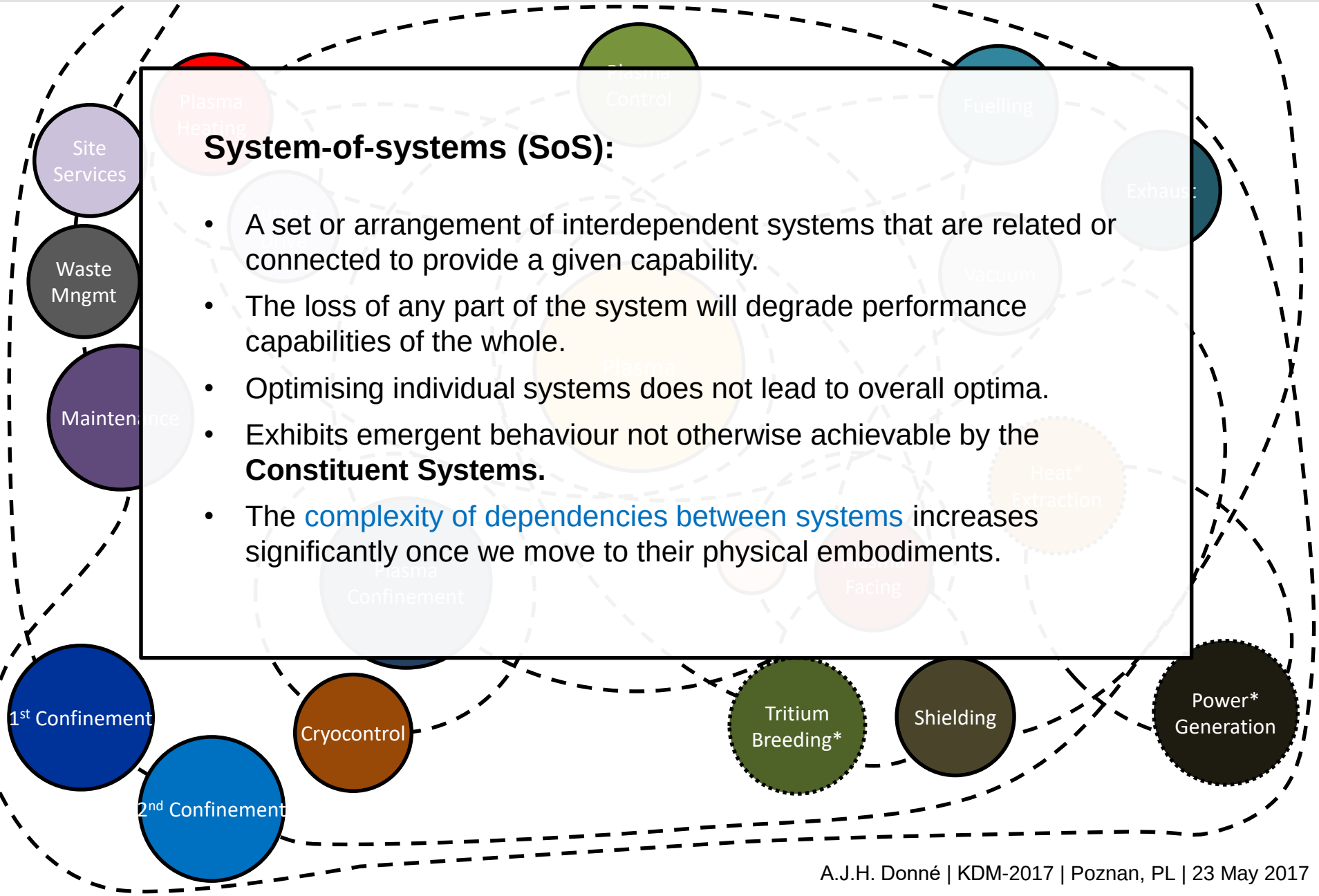
Reactor technology studies

Schematic presentation of the pipe network approximating the geometry of the actual gas flow between ITER adjacent cassettes



Vasileiadis et al. FED 103 (2016) 125–135

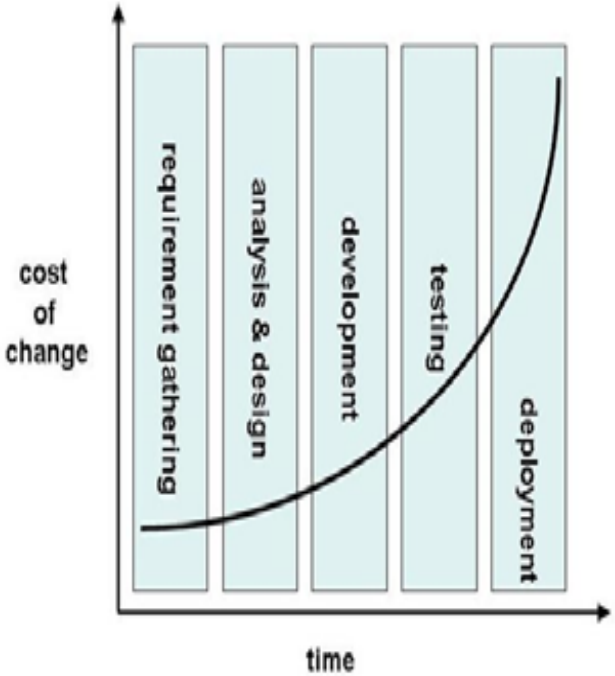
Mission 6: Integrated DEMO Deisgn



System-of-systems (SoS):

- A set or arrangement of interdependent systems that are related or connected to provide a given capability.
- The loss of any part of the system will degrade performance capabilities of the whole.
- Optimising individual systems does not lead to overall optima.
- Exhibits emergent behaviour not otherwise achievable by the **Constituent Systems.**
- The complexity of dependencies between systems increases significantly once we move to their physical embodiments.

Costs of change to a system



	systems cost factors
requirements	1x
design	3-8x
build	7-16x
test	21-78x
operations	29-1615x

[Source: INCOSE UK, Z3, Issue 3, March 2009]

Freezing of design options should be done in a very careful way – changing a design at too late a stage increases the costs

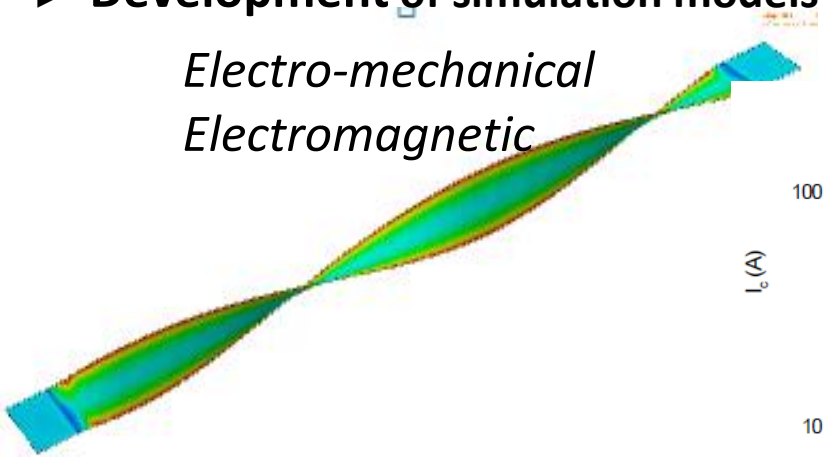
Mission 7: Lower the costs of fusion electricity
High temperature superconductors (HTS)

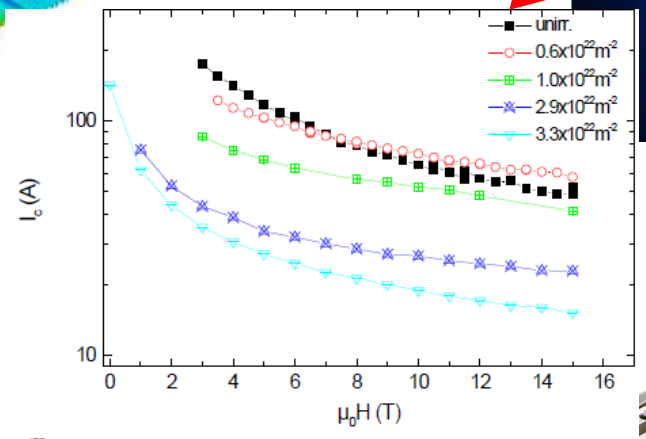
- **Several HTS Tapes tested & irradiated**

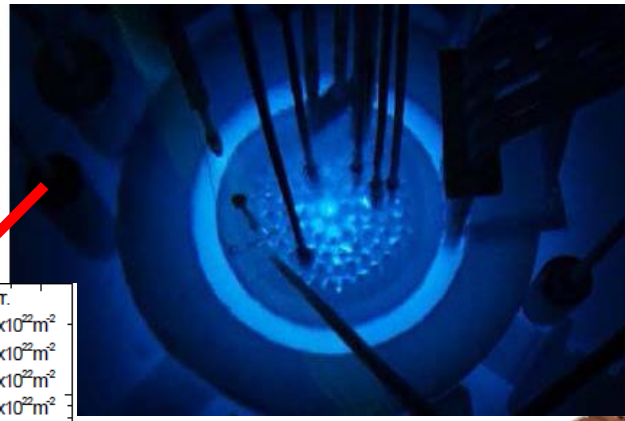
  comparative approach led to survey technology

- **Development of simulation models**

  Electro-mechanical
  Electromagnetic

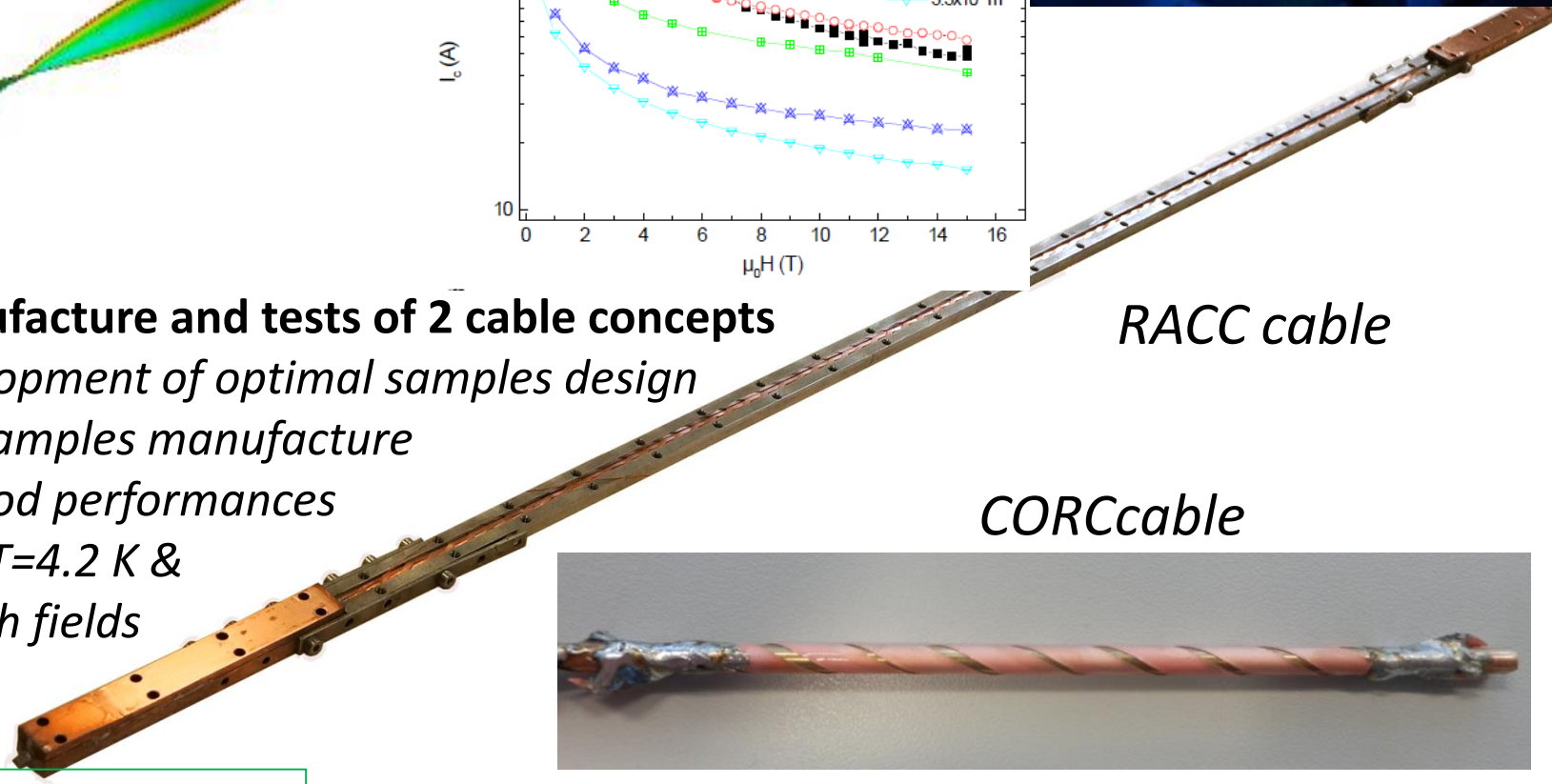






- **Manufacture and tests of 2 cable concepts**

  Development of optimal samples design
  2 samples manufacture
  Good performances
  at T=4.2 K &
  high fields

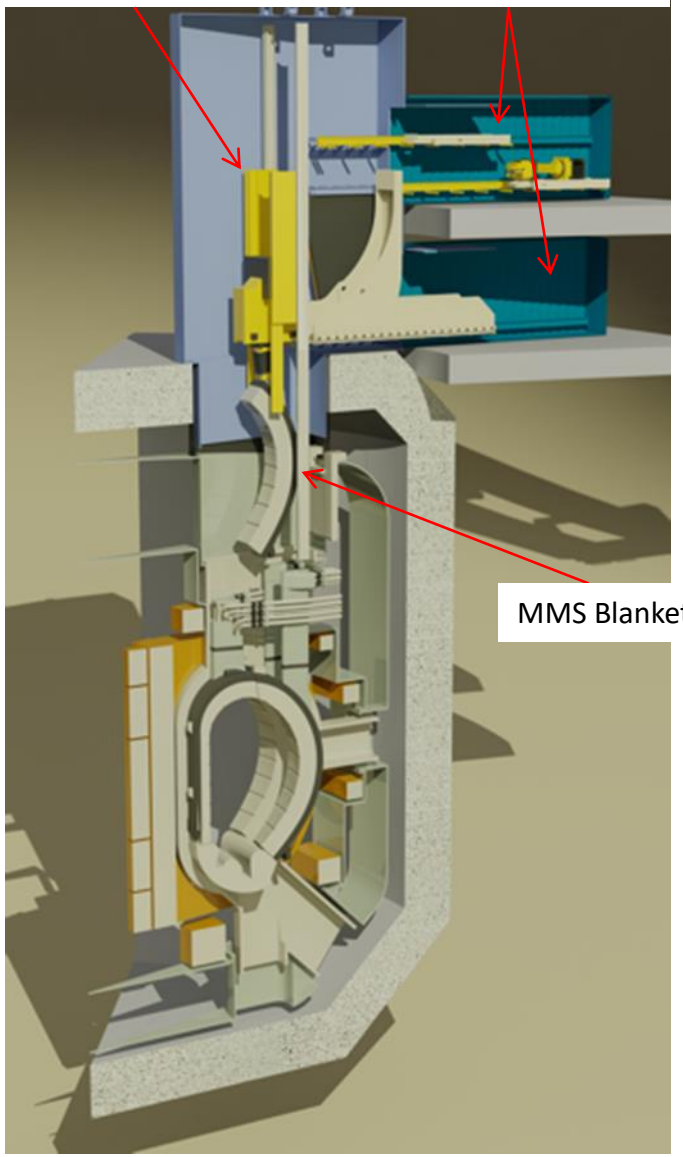


RACC cable

CORCcable

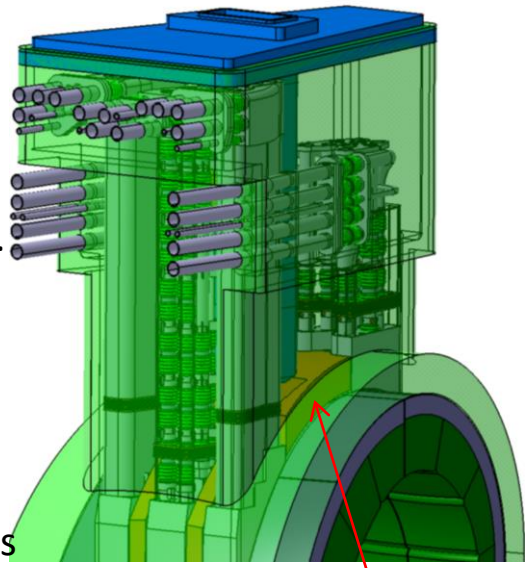
L. Zani (CEA) and WPMAG Team

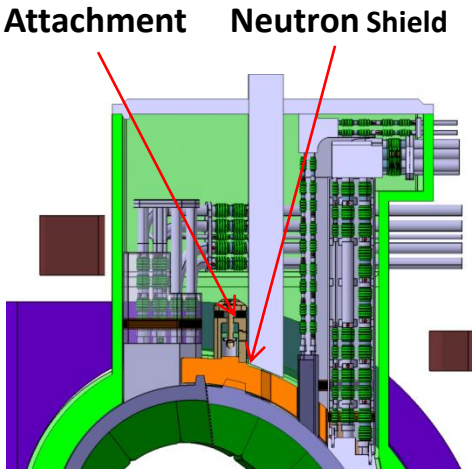
Mission 7: Lower the costs of fusion electricity
Remote Maintenance



Revaluation of the in-vessel remote maintenance:

- Improve flexibility allows for more cooling systems and access for diagnostics H&CD.
- Independent blanket and divertor maintenance
- Improved maintenance durations
- Near vertical lifts for blankets increase robustness of remote handling equipment
- Includes a neutron shield plug
- Independent port closure plate
- No in-vessel mover
- ITER-like cask transportation
- Improved unplanned single blanket maintenance

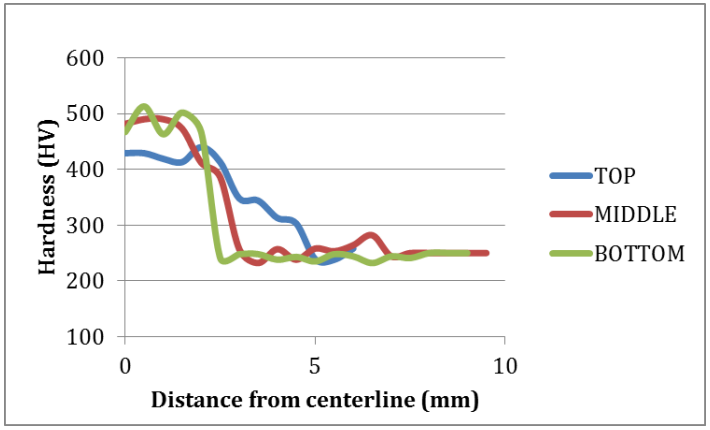




A. Loving (CCFE) and WPRM Team

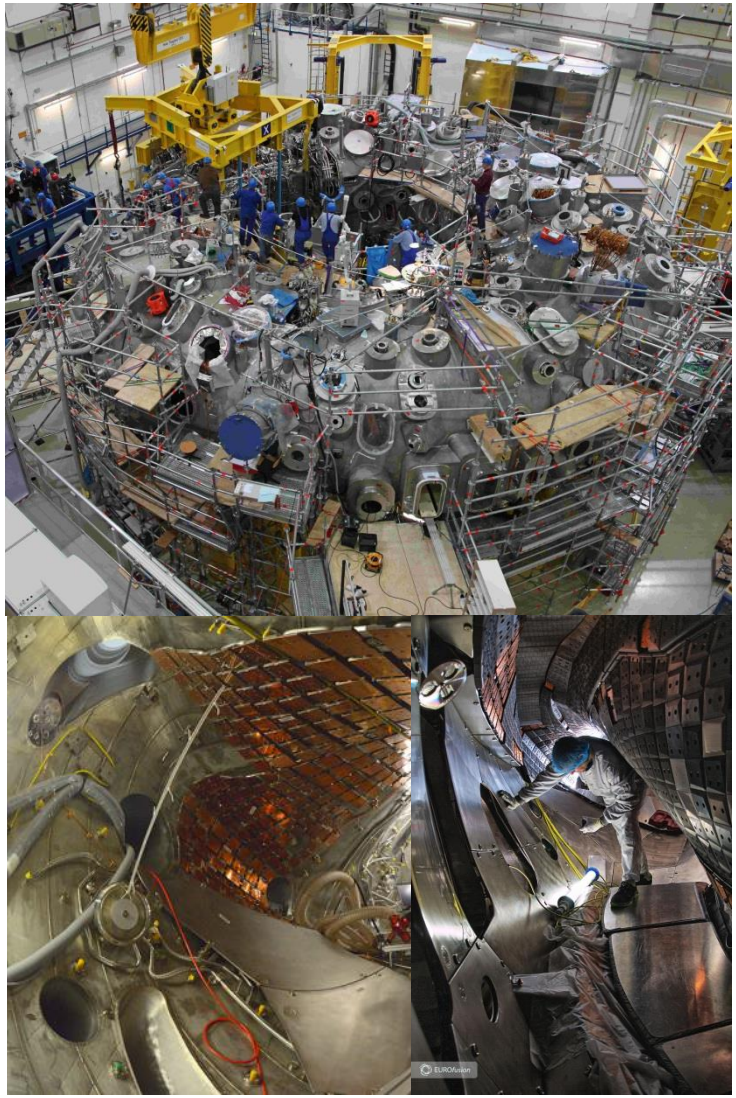
Mission 7: Lower the costs of fusion electricity
Remote maintenance

- 75% of blanket and divertor cassette maintenance duration is attributed to removal and installation of services
- Technology evaluation shows Laser to be favourable for in-bore cutting and welding
- Laser welding trials using P91 as a substitute for Eurofer have been undertaken
- Diffused laser has potential to provide extra heat input and can be used for post weld heat treatment



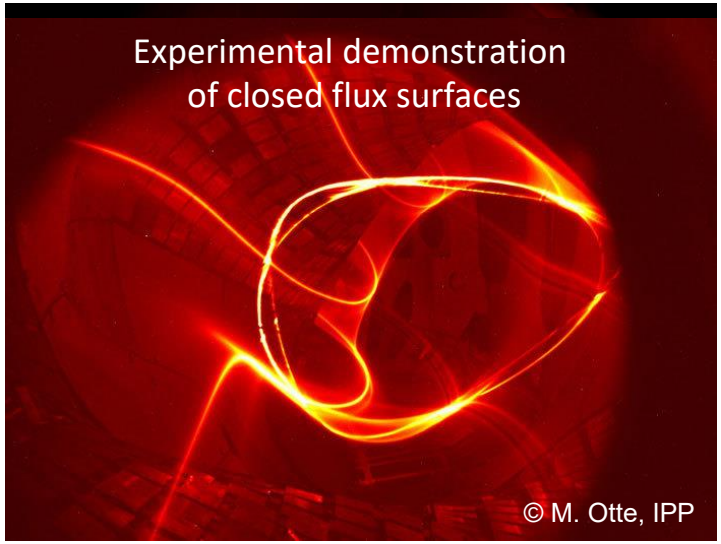
A. Loving (CCFE) and WPRM Team

Mission 8 : Bring the stellarator line to maturity



- Bring stellarator to maturity as a possible long-term alternative to tokamaks, EU programme focuses on the Helical Axis Advanced Stellarator, HELIAS, line
- For 2014-2020 : main priority scientific exploitation of the W7-X including theory development & modelling
- Impact on the progress of the basic understanding of plasma physics in support of Mission 1 and 2 and in support of the ITER preparation

First Plasma in W7-X (Greifswald)



Wendelstein 7-X
from assembly to operation

12.05.2014: Start of commissioning

16.07.2015: First flux surface measurements

09.12.2015: Operation permit granted

10.12.2015: First helium plasma

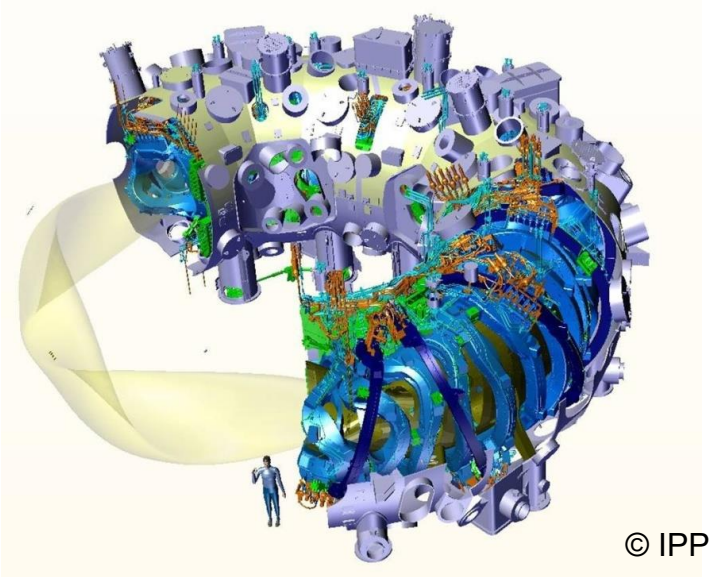
03.02.2016: First hydrogen plasma

< 10.03.2016: First experimental campaign

(W7-X Team = IPP, EUROfusion, US, Japan)

Wendelstein 7-X

Max-Planck-Institut für Plasmaphysik
Greifswald (Germany)



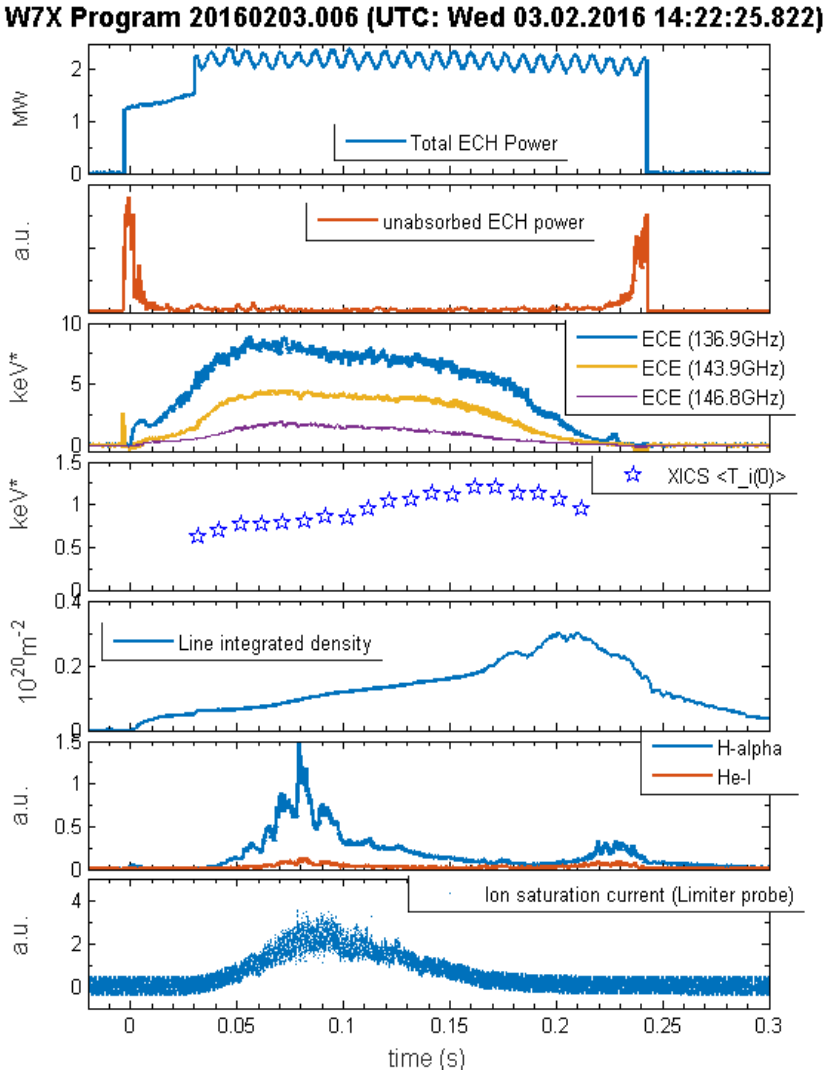
HELIAS-type stellarator

- N_f=5, R/a = 5.5m/0.53m
  → **~30 m³ plasma volume**
- 50+20 **superconducting** coils (2.5T)
- ~8+7MW (**ECRH**, NBI) + ICRH (later upgrades)

Merkel-induced Hydrogen Plasma in W7-X

3.2.2016, 15:21:25.822 (local time)

… 60 s later

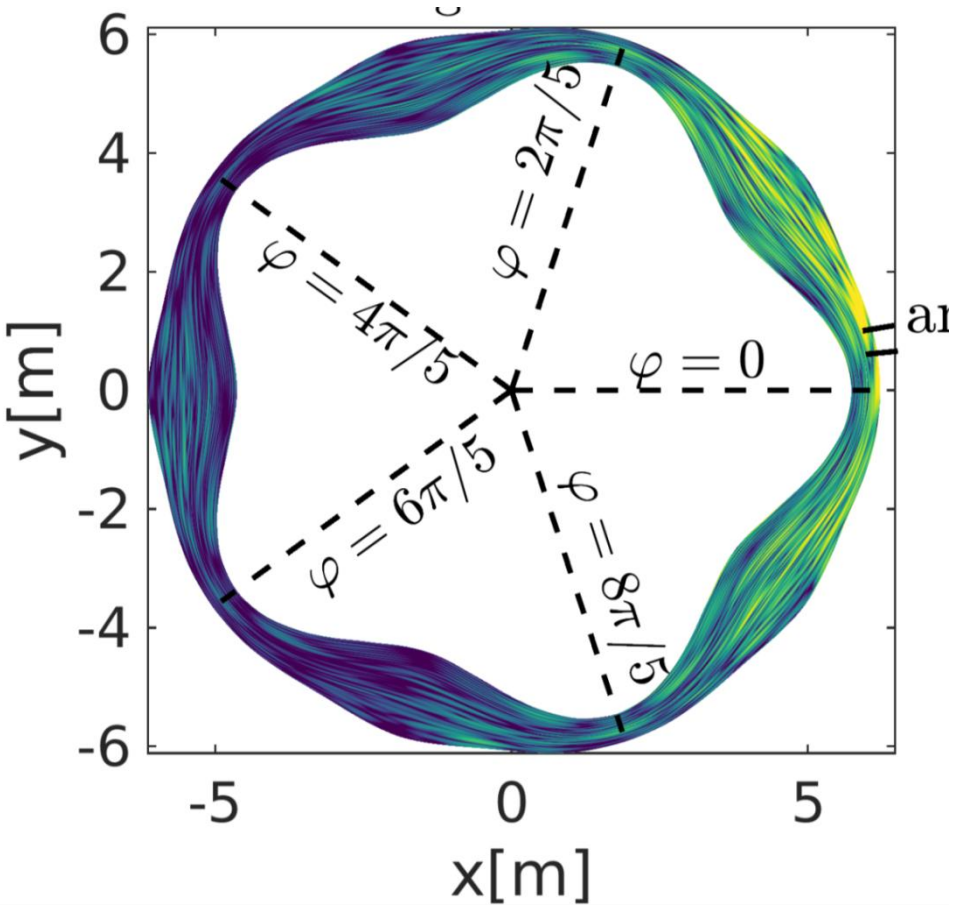


First hydrogen plasma in Wendelstein 7-X

- total heating power: ~ **2 MW**
- pulse lengths: ~ **250 ms**
- T_e ~ **7 keV**, T_i ~**1.2 keV**
- <n> ~ **2 x10^{19}m^{-3}**
- a < **49 cm** (V ~ **26 m^3**) (plasma touched the limiter)

Reactor technology studies

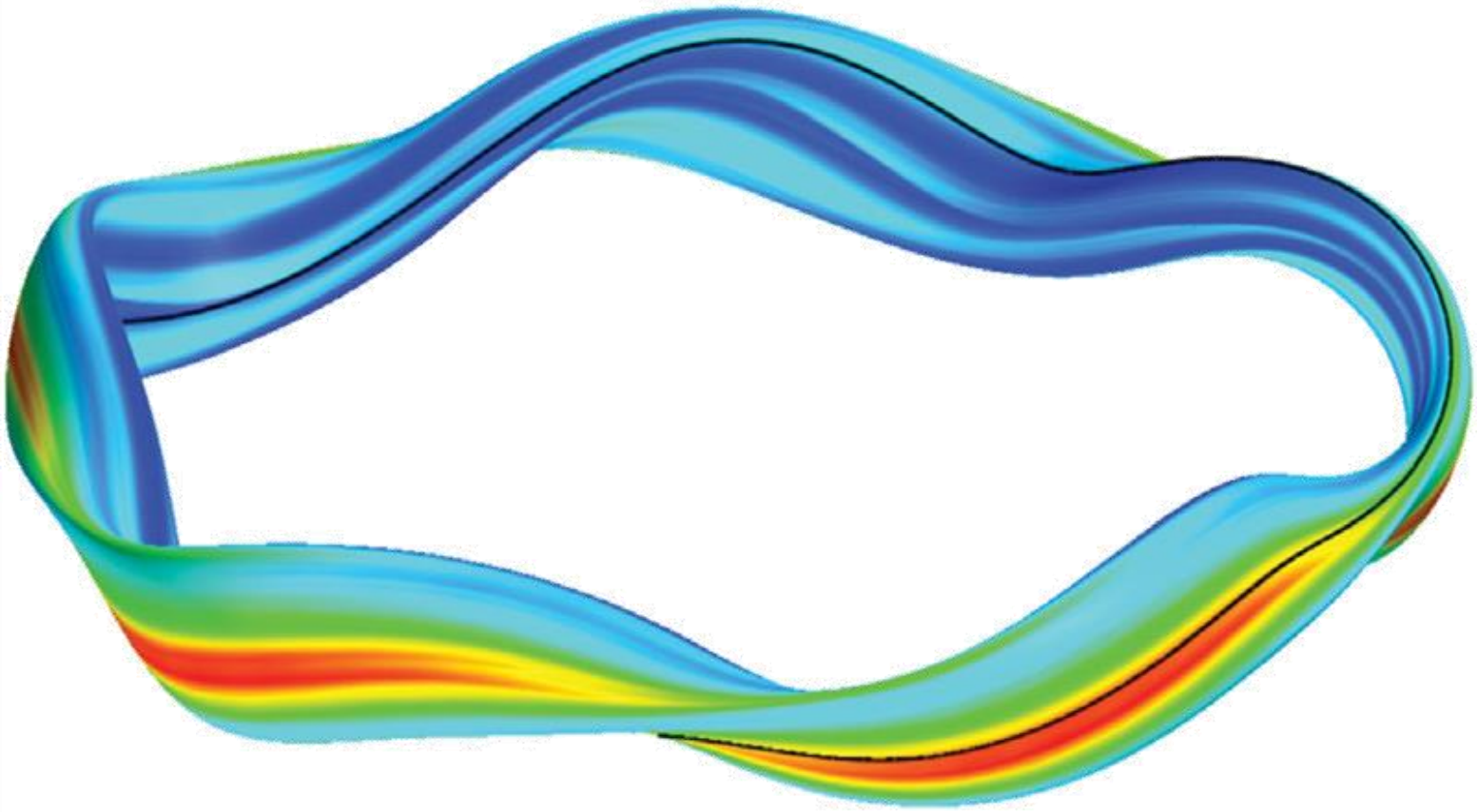
Global wave deposition using a localised auxiliary heating antenna design foreseen in W7-X.



[Faustin et al. PPCF 58(7) 2016]

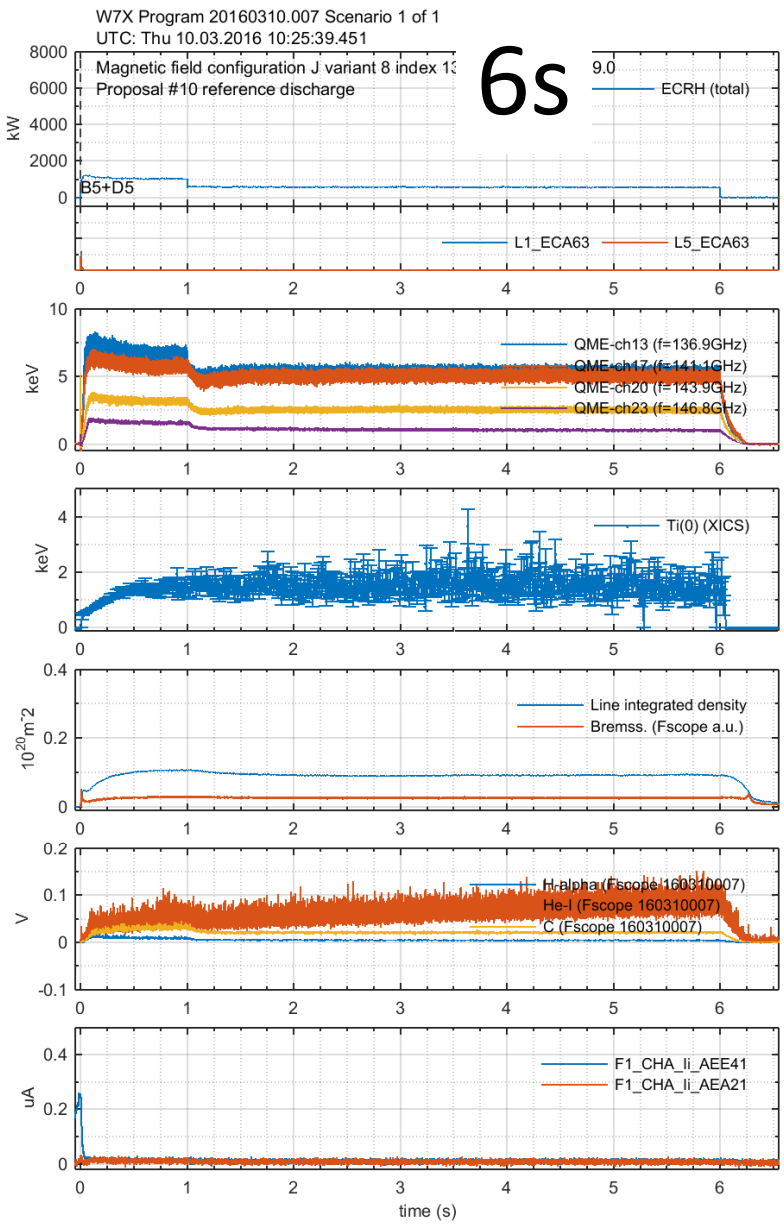
Plasma turbulence simulations

First turbulence-optimized stellarator configuration stemming from an existing design.



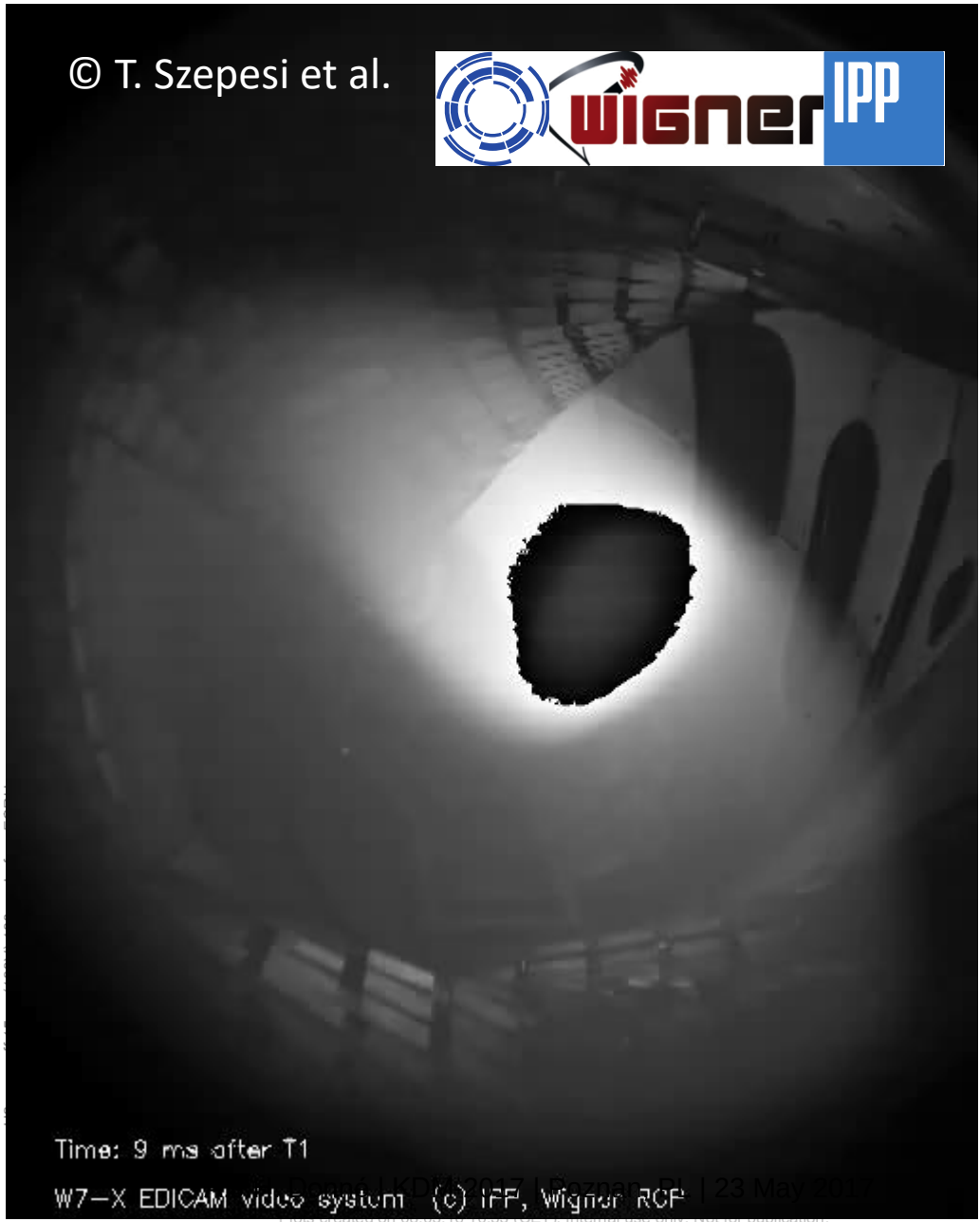
Xanthopoulos et al, PRL 113 155001 (2014)

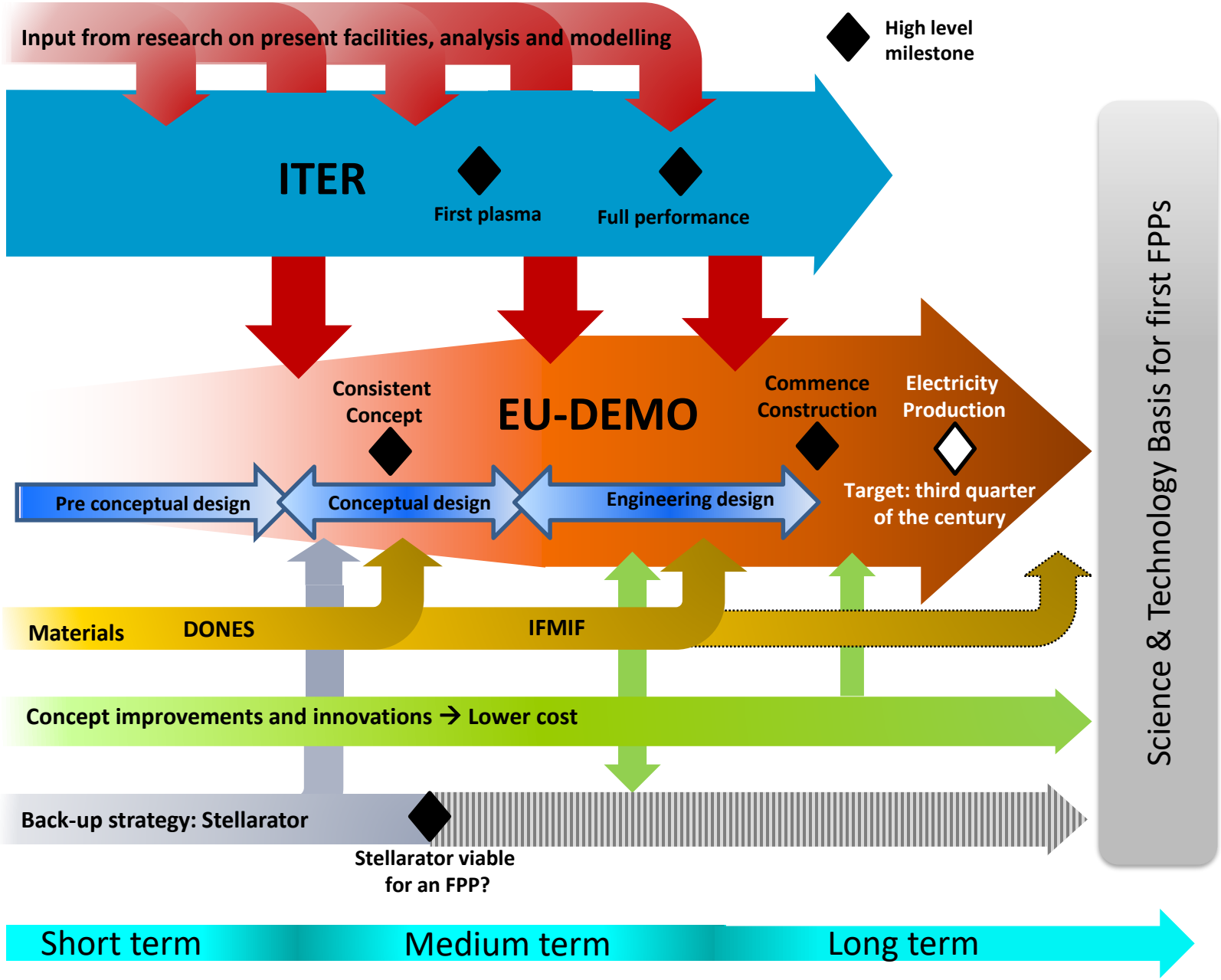
Some achievements by Mar. 10, 16



Reference Discharge.

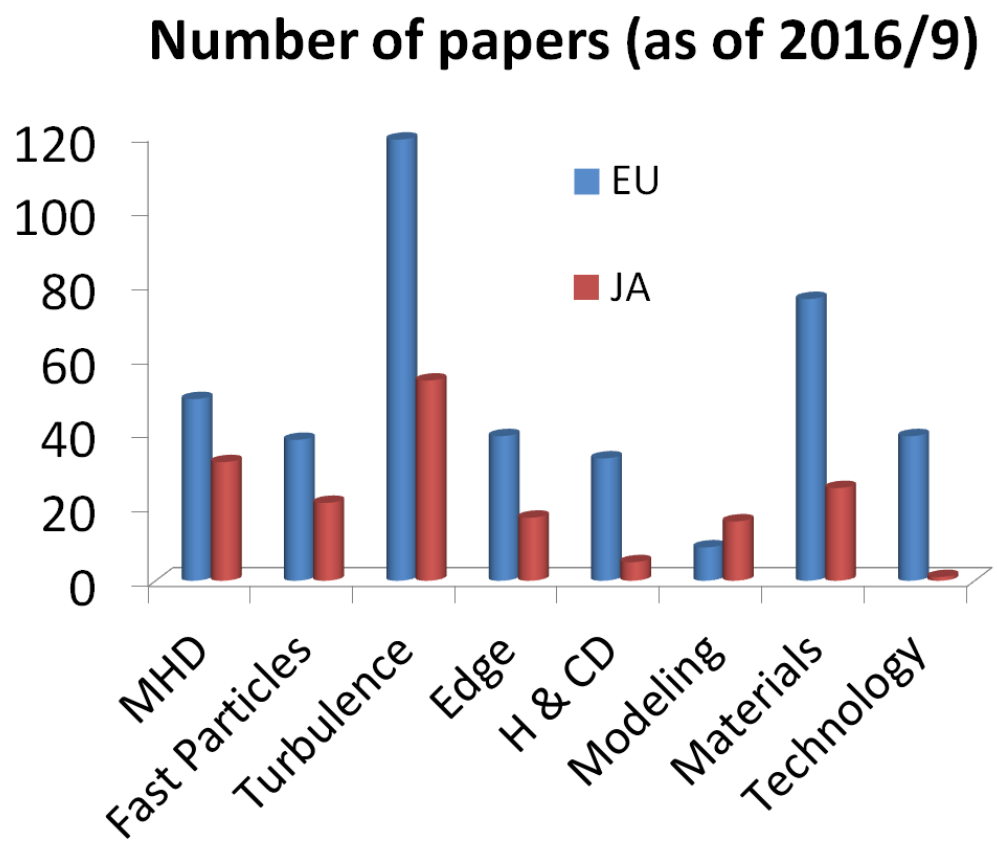
Plots created on 11.03.16 11:23 (CET). Internal use only. Not for publication.




Input from research on present facilities, analysis and modelling
High level milestone
ITER
First plasma
Full performance
Consistent Concept
EU-DEMO
Commence Construction
Electricity Production
Pre conceptual design
Conceptual design
Engineering design
Target: third quarter of the century
Materials
DONES
IFMIF
Concept improvements and innovations → Lower cost
Back-up strategy: Stellarator
Stellarator viable for an FPP?
Science & Technology Basis for first FPPs
Short term
Medium term
Long term

Impact

The use of the Helios computer has been rather successful with a large scientific output expressed in the number of peer-reviewed publications of around 1 per project per year.



Take home message

Fusion is possible, challenging and fun

ITER is steadily going forward – first operation late 2025

DEMO pre-conceptual design is in full swing

First fusion electricity by the middle of the century

EURO*fusion* is coordinating the fusion research in Europe

High-Performance Computers are indispensable


The End