FUSION ENERGY II
Technological challenges

Joint EPS-SIF School on Energy 2021
Varenna
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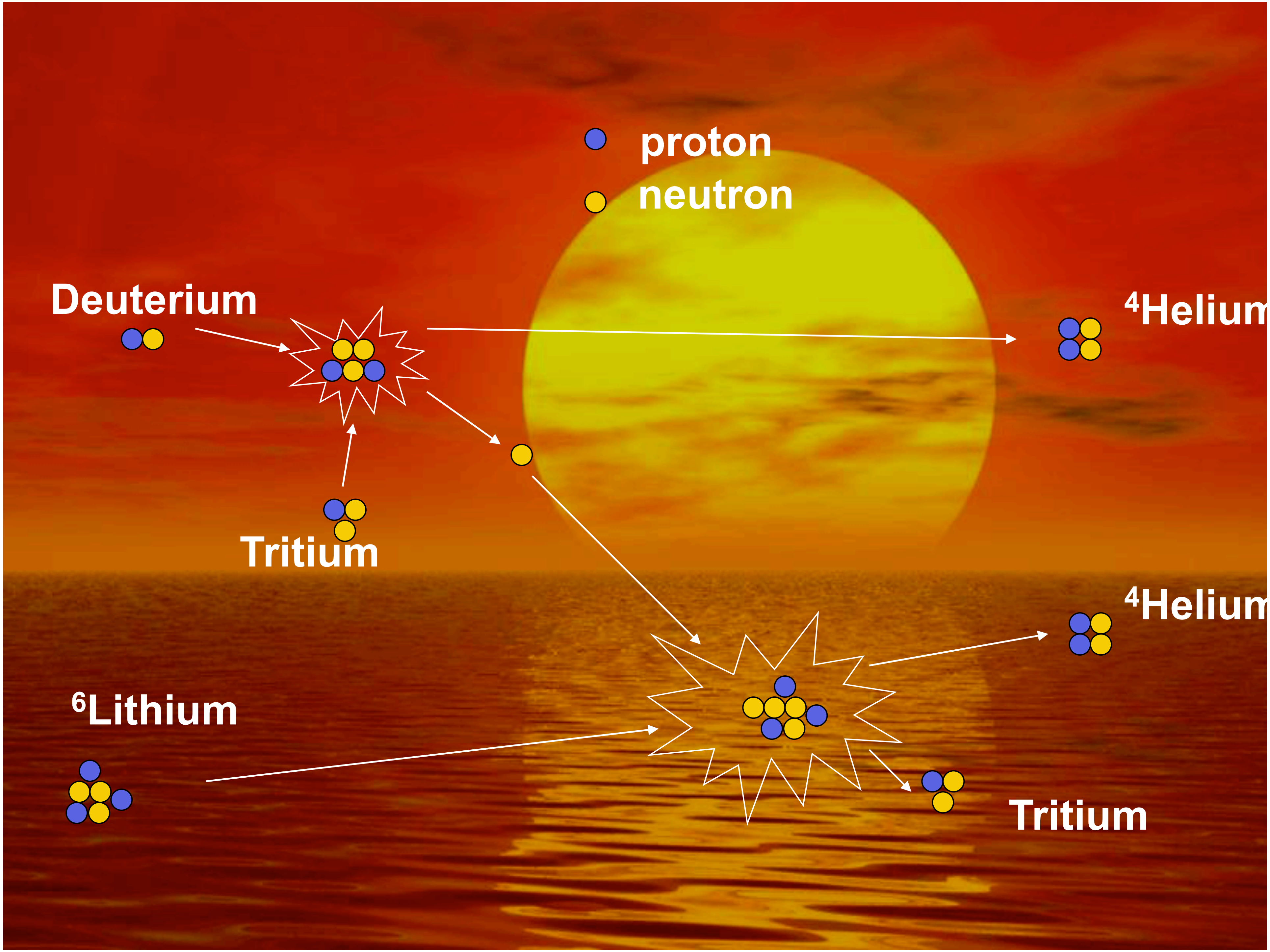
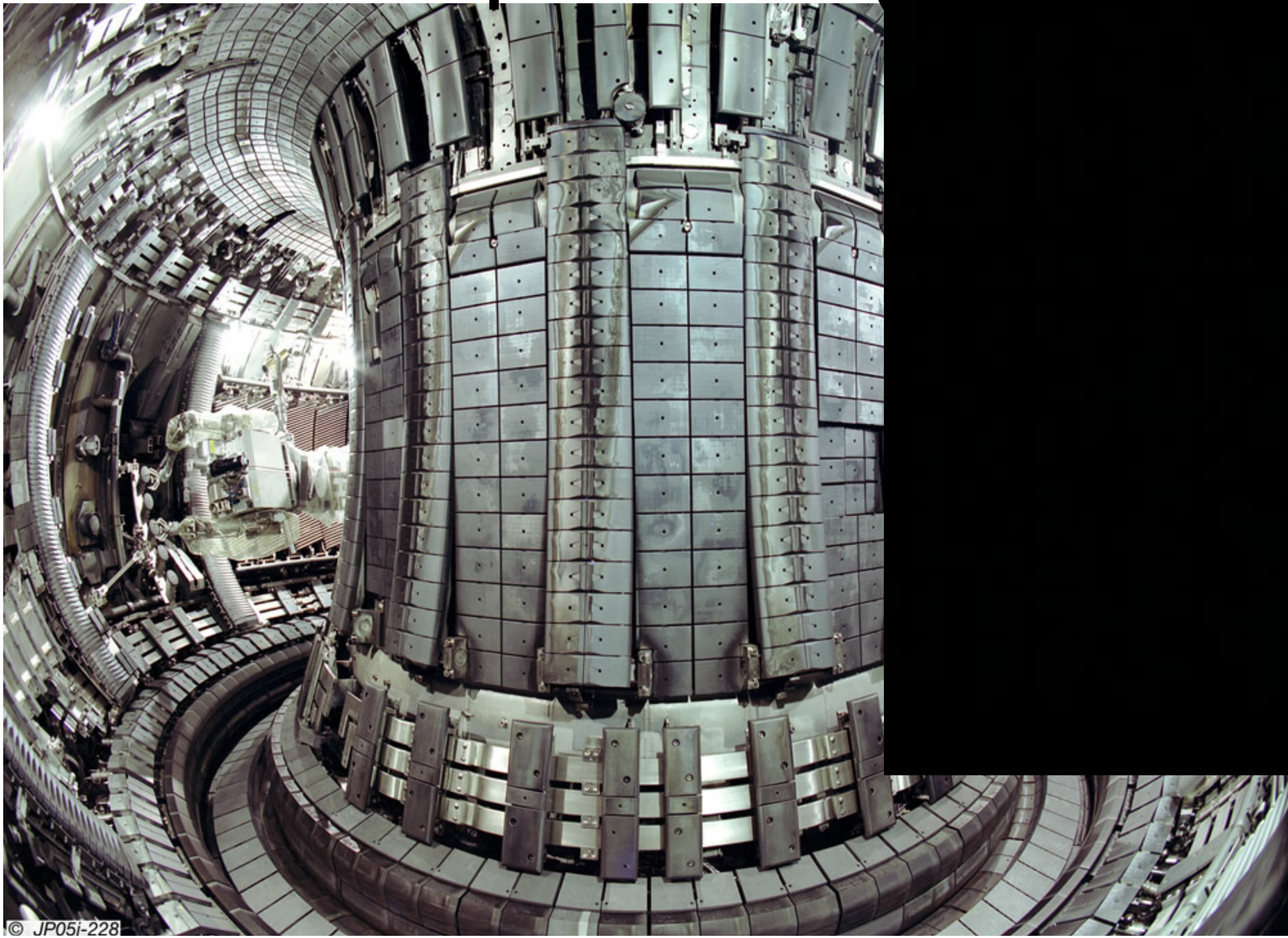
Outline

1. Background: how thermonuclear plasmas are confined.
2. Components that can survive on the surface of the Sun
3. Neutron resistant materials
4. Tritium self sufficiency
5. Safety
6. Integrating different technologies


proton
neutron
Deuterium
4Helium
Tritium
4Helium
6Lithium
Tritium

The Joint European Torus (JET)

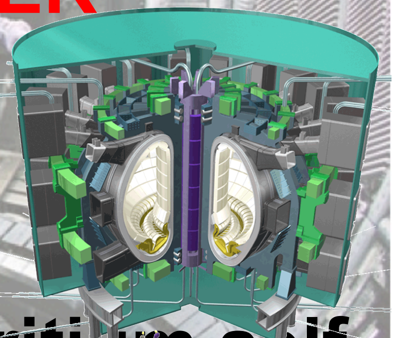


The challenge of confining a plasma

has been already achieved!

What do we need to make a power plant?

Achieve burning plasma conditions => ITER



- Plasma regimes
- Heat exhaust

Produce electric energy and demonstrate tritium self sufficiency => DEMO

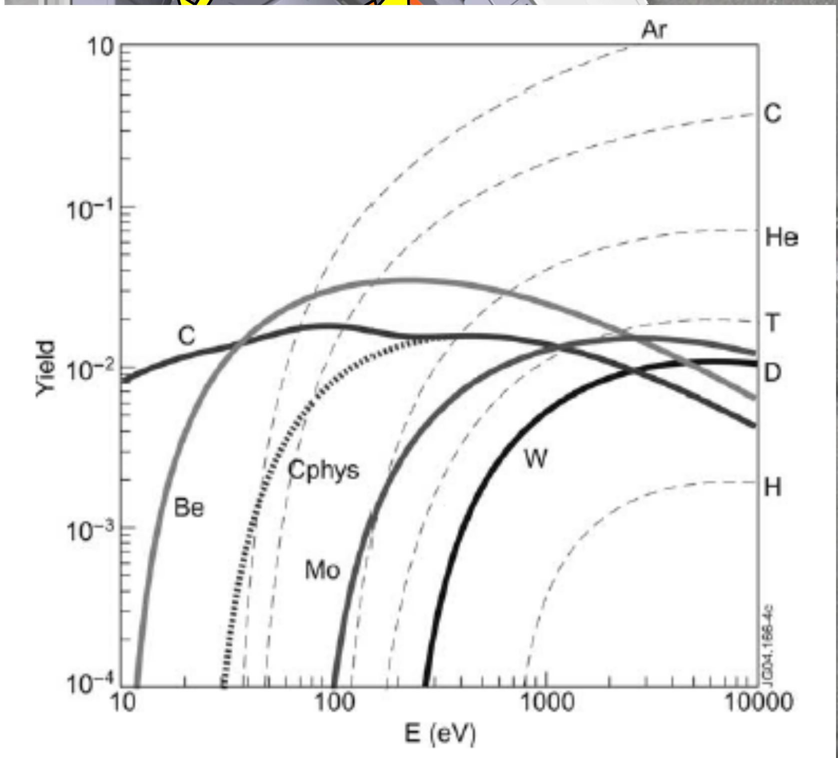
- Materials
- Tritium breeding
- Low cost of electricity

Components that can survive on the surface of the Sun

Up to 60MW/m^2 in a reactor

~ heat flux on the surface of the Sun!

Components that can survive on the surface of the Sun

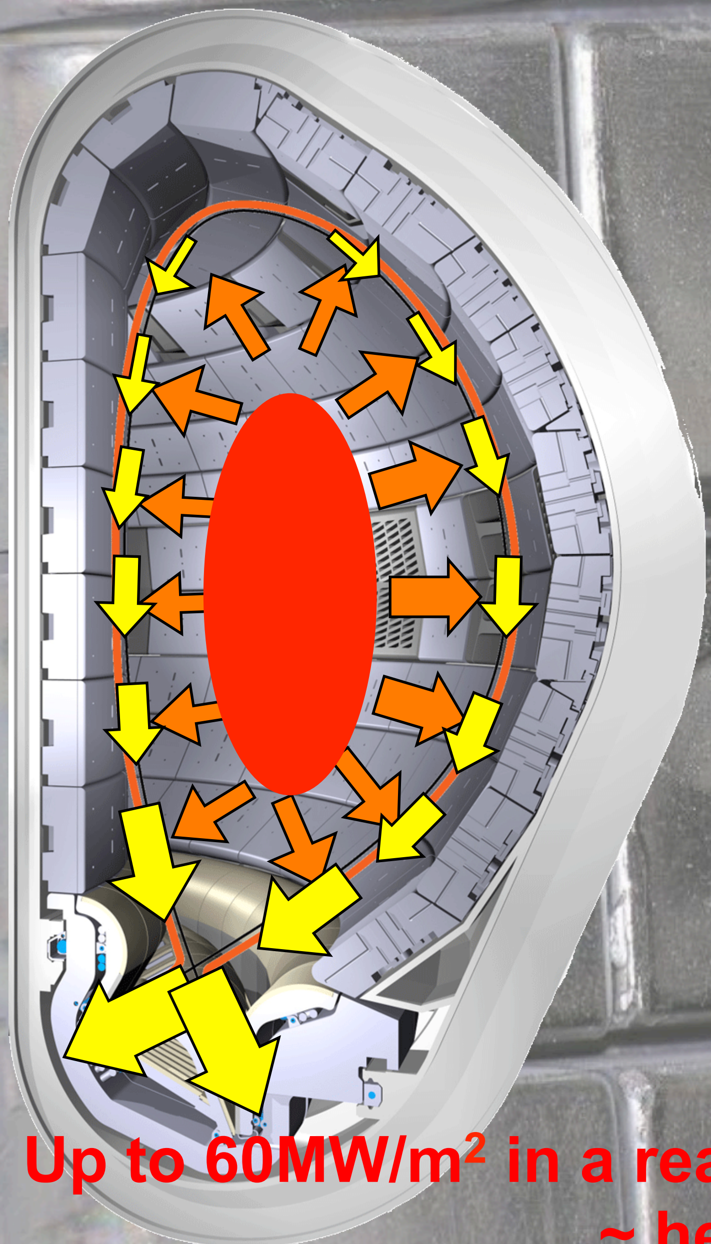


- Erosion
  - About 10^{22}p/s arriving on the wall/divertor
  - If extraction probability is 10^{-5} 1mm eroded (and redeposited) every year.
  - Transient loads reduce lifetime
  - Solution: use tungsten and very low temperature of the plasma in the divertor

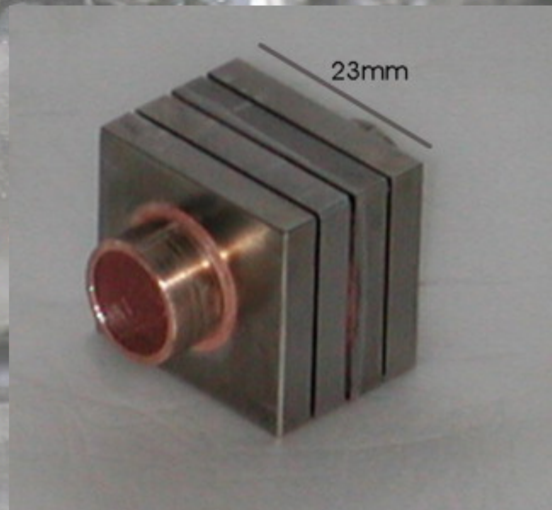
Up to 60MW/m^2 in a reactor

~ heat flux on the surface of the Sun!

Components that can survive on the surface of the Sun



- Erosion
- First wall material properties
  - Recrystallization
  - Cracking
  - De-bonding



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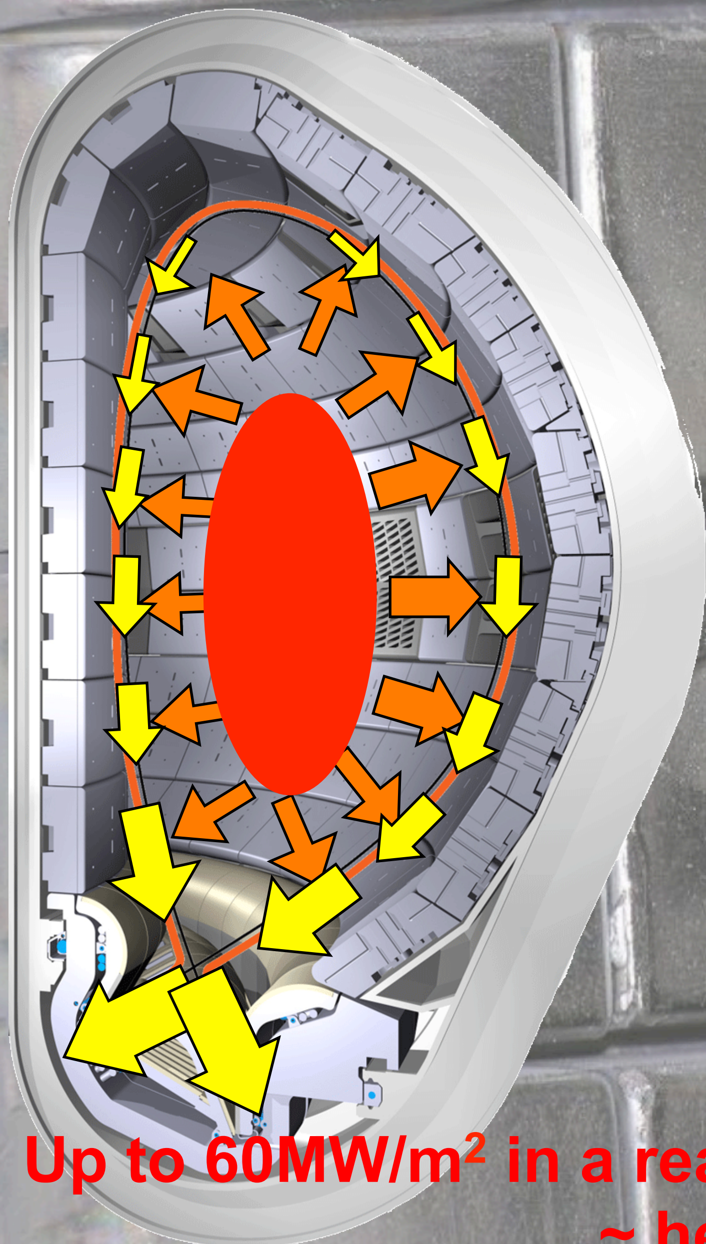
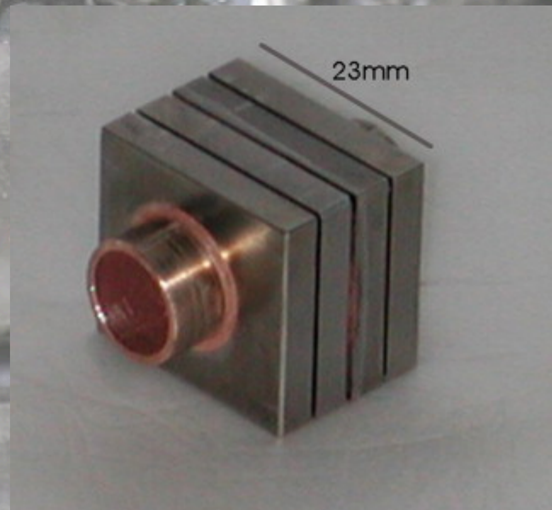
Components that can survive on the surface of the Sun



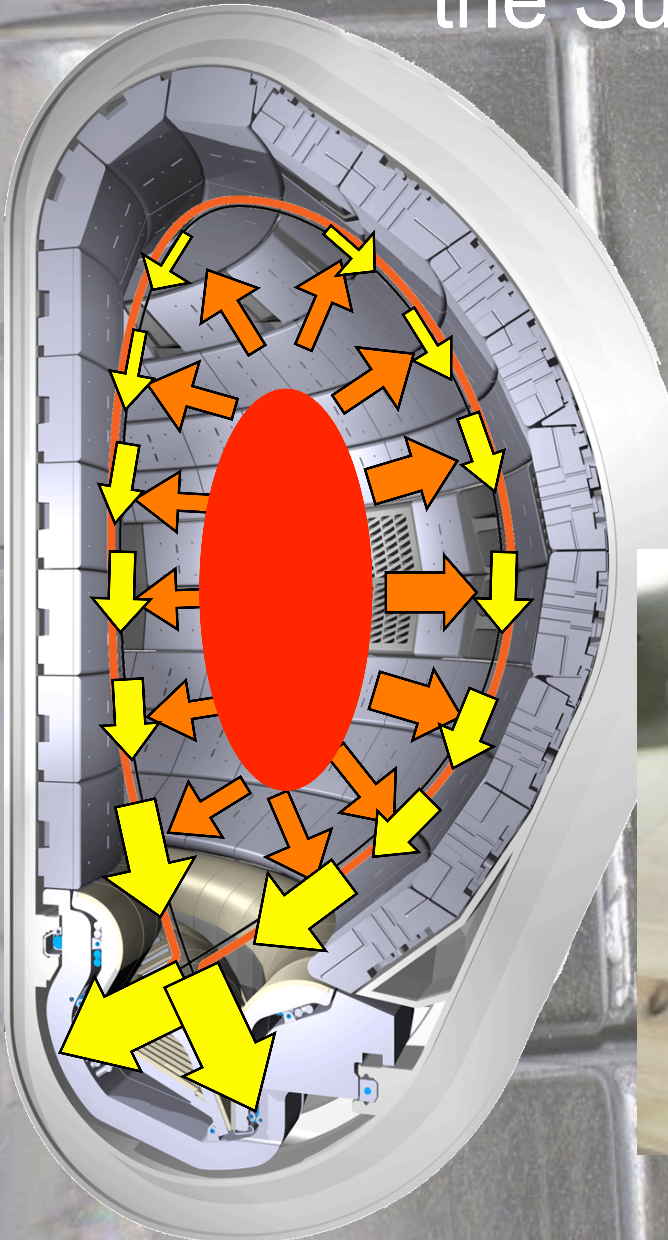
- Erosion
- First wall material properties
- Critical flux on divertor



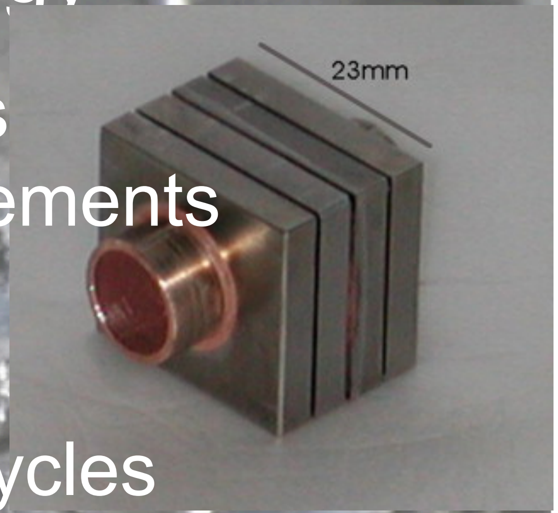
Up to 60MW/m^2 in a reactor

~ heat flux on the surface of the Sun!

Components that can survive on the surface of the Sun. Baseline strategy



Present R&D results exceed ITER requirements



W monoblock:

10 MW/m² x 5000 cycles

20 MW/m² x 1000 cycles

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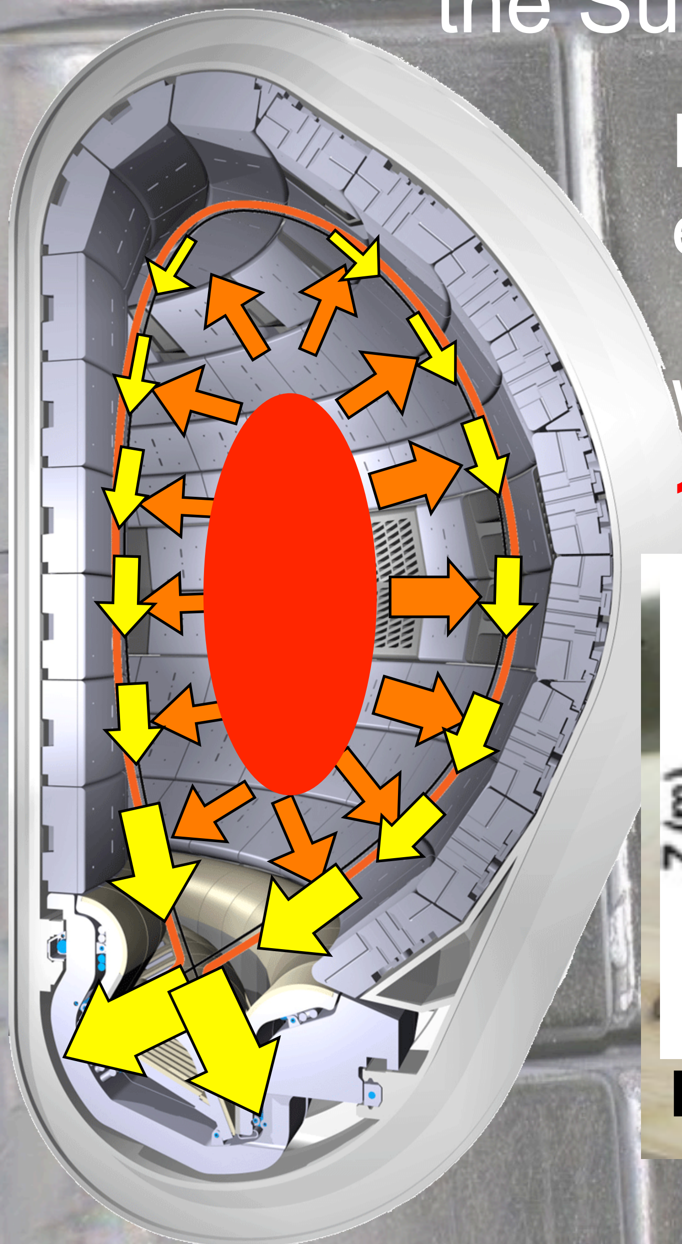

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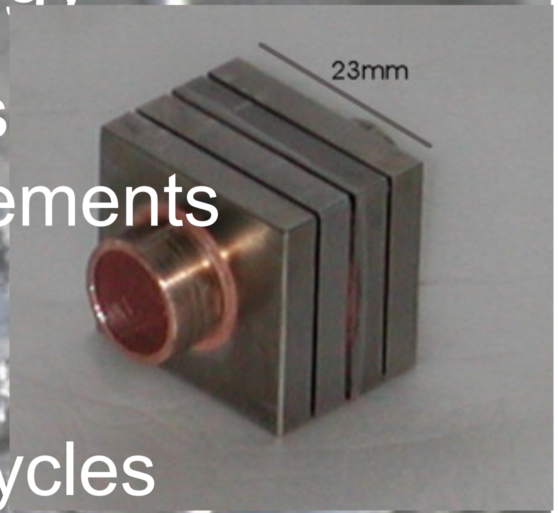

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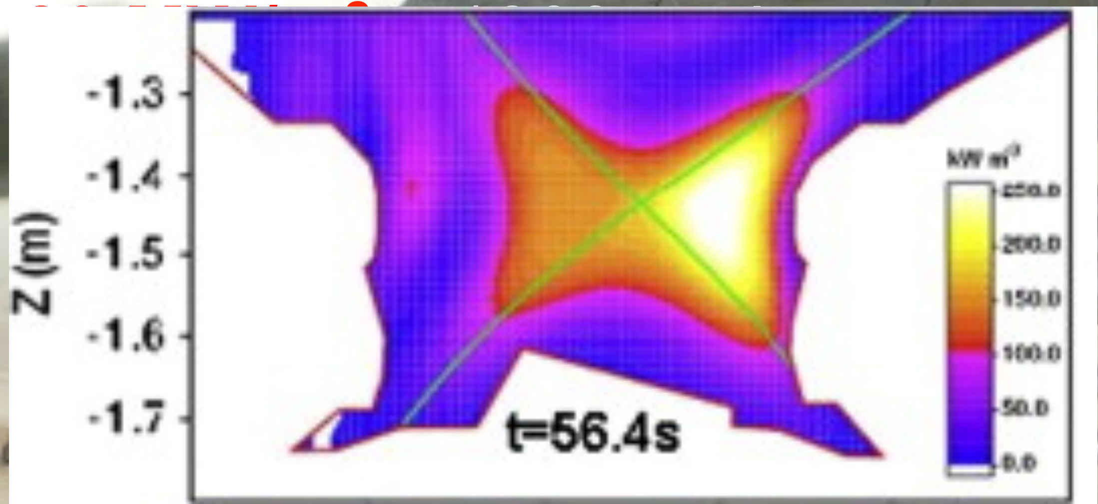
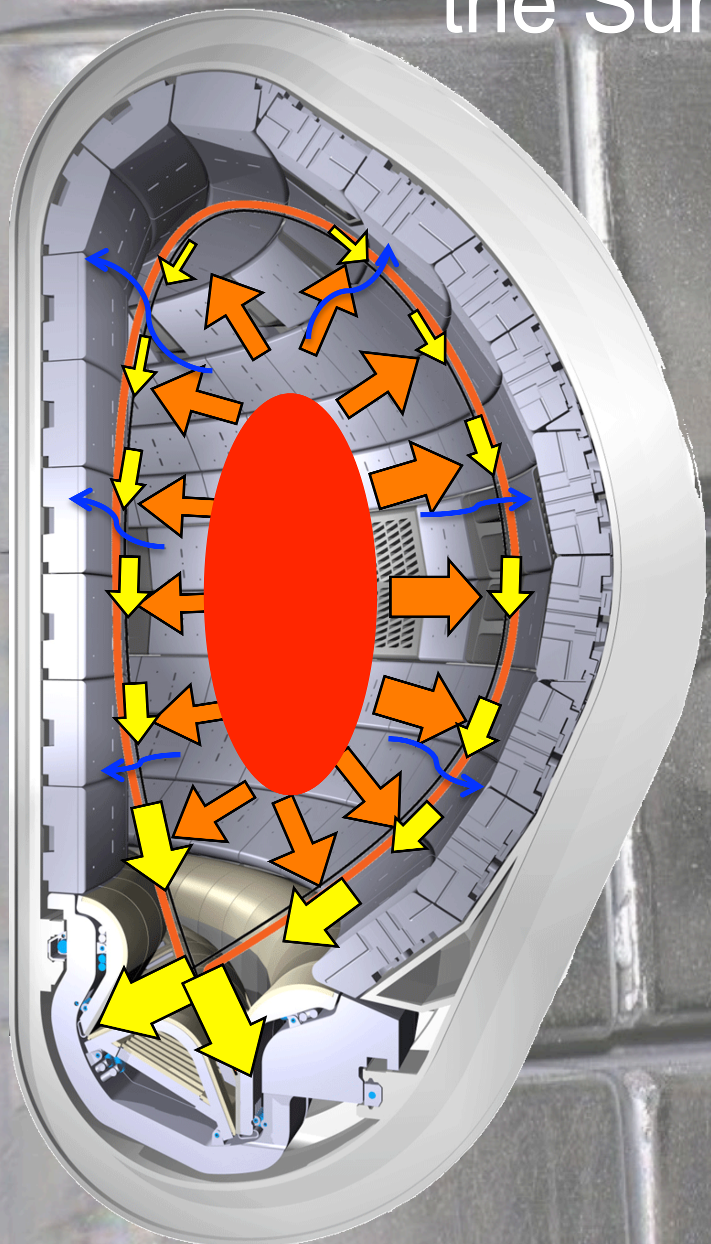


ENEA - Ansaldo

Detached divertor conditions

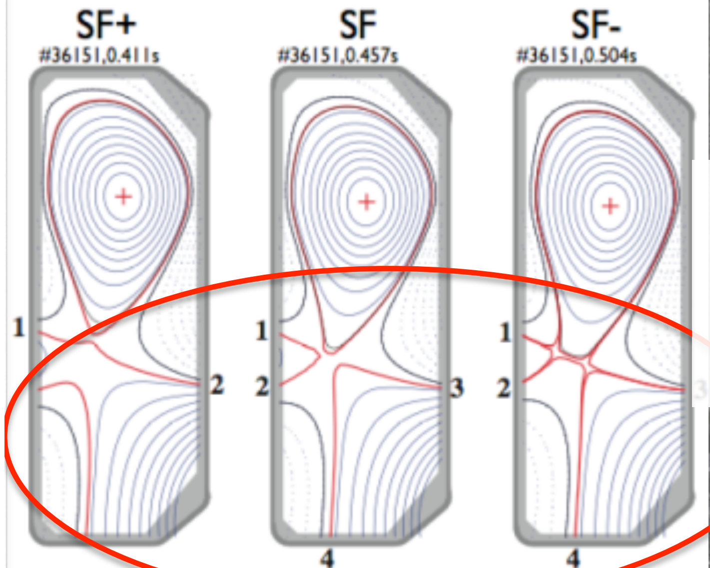
Components that can survive on the surface of the Sun. Baseline strategy



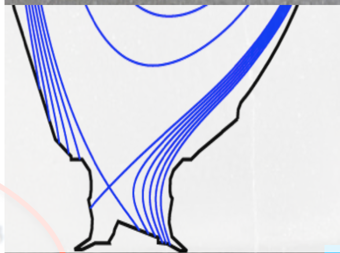
Extrapolation to DEMO of the baseline strategy requires to radiate a large fraction of the heating power (alpha + externally injected) on the main chamber wall.

Need to develop and qualify highly radiative regimes of operation

Components that can survive on the surface of the Sun. Alternative strategies

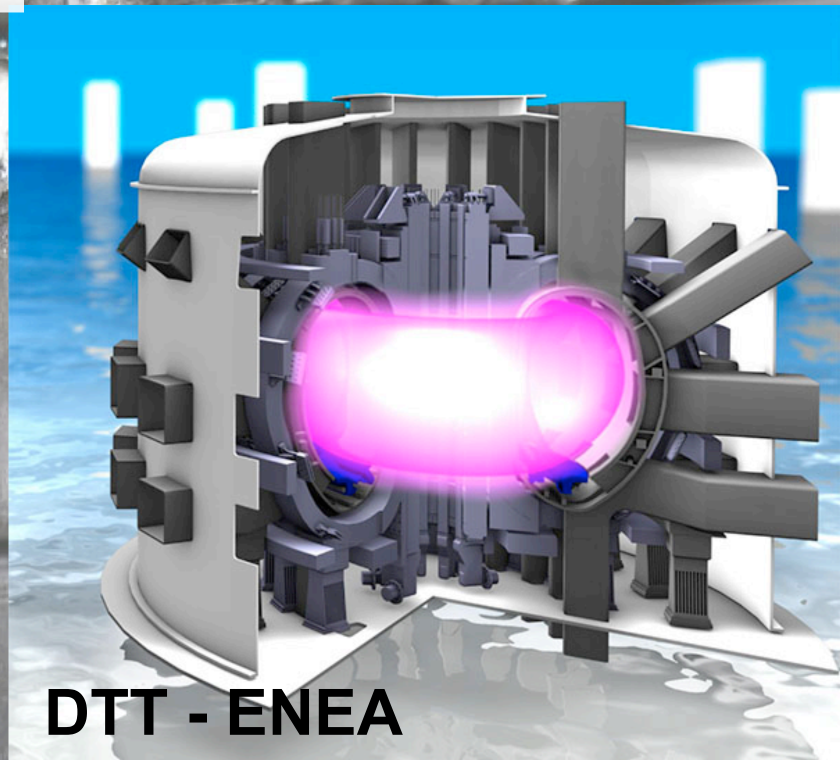


TCV – CRPP-EPFL



Main alternative strategy: Enlarge area in the divertor wetted by the plasma

Divertor Tokamak Test facility (DTT) proposed in the European Roadmap.
ENEA DTT proposal part of the EUROfusion activities.
DTT being built in Frascati



DTT - ENEA

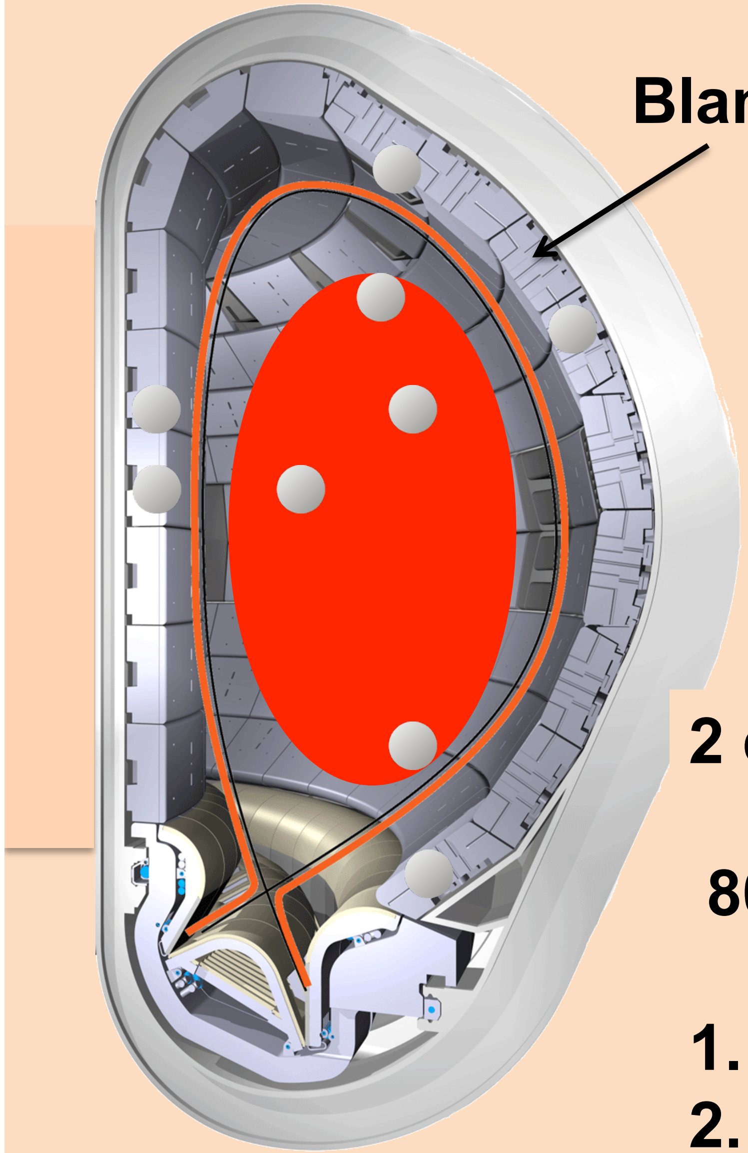
Components that can survive on the surface of the Sun. DTT

https://www.dtt-project.it/index.php/about/who.html

	DTT	ITER	DEMO
R (m)	**2.14 (2.19)**	6.2	9.1
a (m)	**0.64**	2	2.93
A	**3.3**	3.1	3.1
I_p (MA)	**5.5**	15	19.6
B (T)	**6**	5.3	5.7
Heating P (MW)	**45**	50	50
P_{sep} /R (MW/m)	**15**	14	17
l_q(mm)	**0.7**	0.9	1.0
Pulse length (s)	**95**	400	7600

Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Neutron resistant materials



S. Dudarev

2 displacements per atom (dpa) in ITER end of life

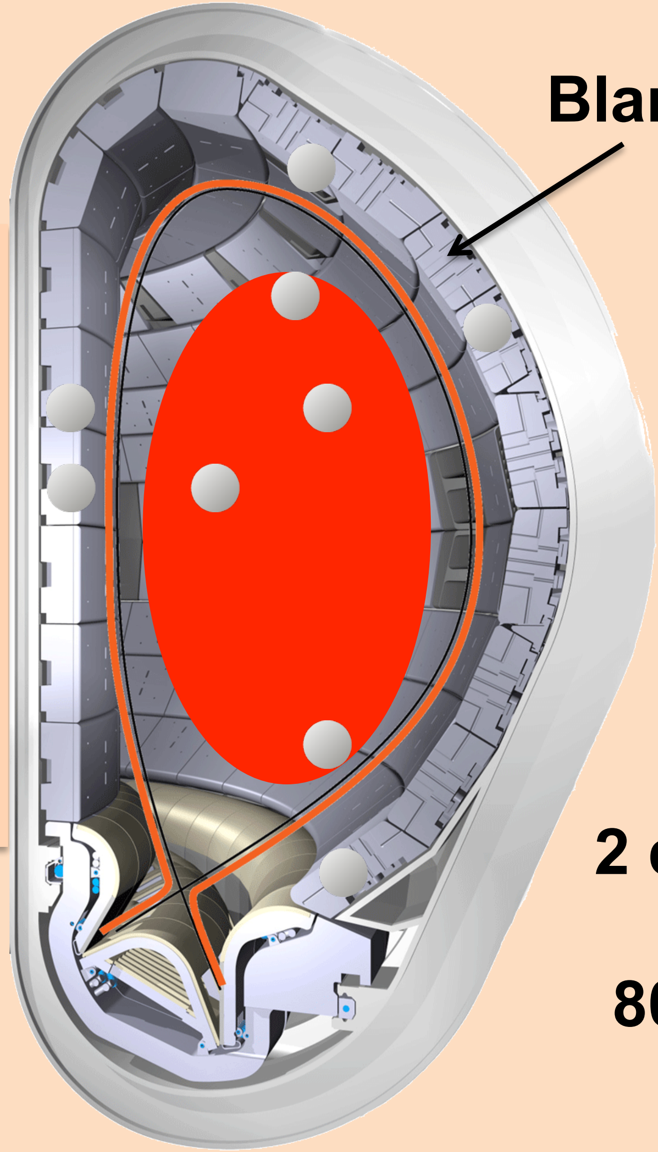
80 dpa in DEMO after 4 full power years

1. **Reduction of structural properties**
2. **Activation**

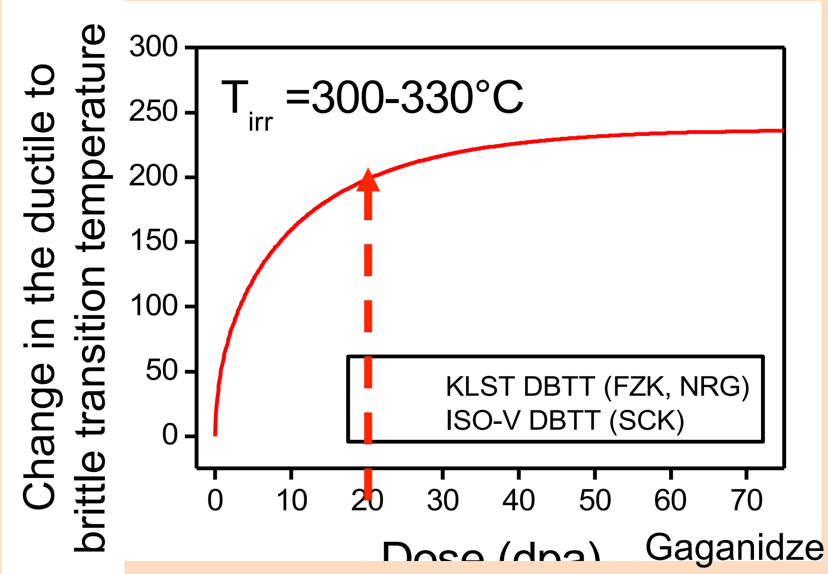
D. Stork et al.
Material Assessment Report

Not a problem for ITER but must be solved for a reactor!

Neutron resistant materials



1. Steel becomes brittle under irradiation!



Gaganidze 2011

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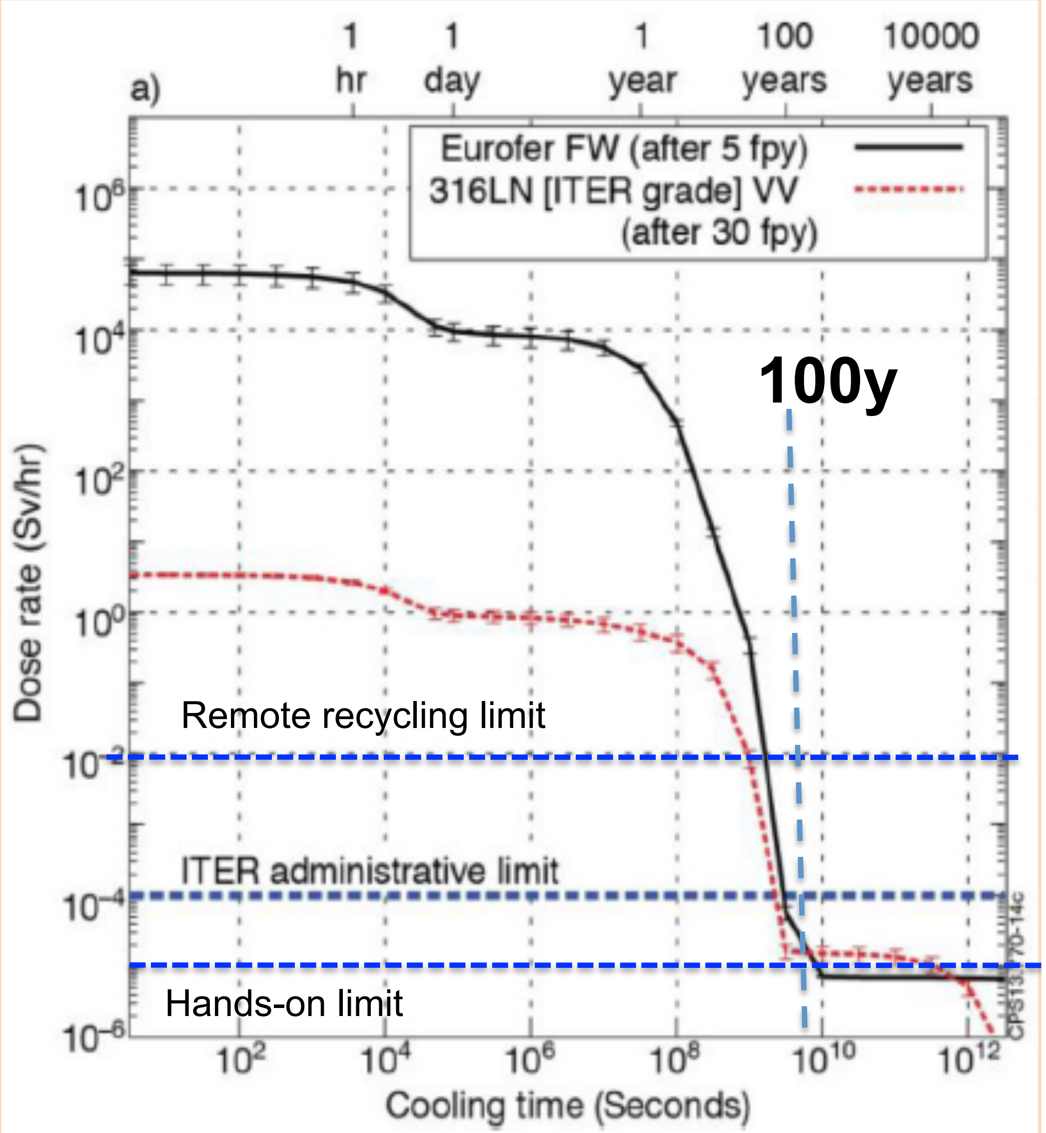
Neutron resistant materials

2. Structural materials become activated

Fusion neutrons do not produce significant quantities of long-term radioactive elements

Radioactivity decays in ~100 years down to levels that allow remote recycling

No geological repository required.



Stork et al. 2014

Neutron resistant materials

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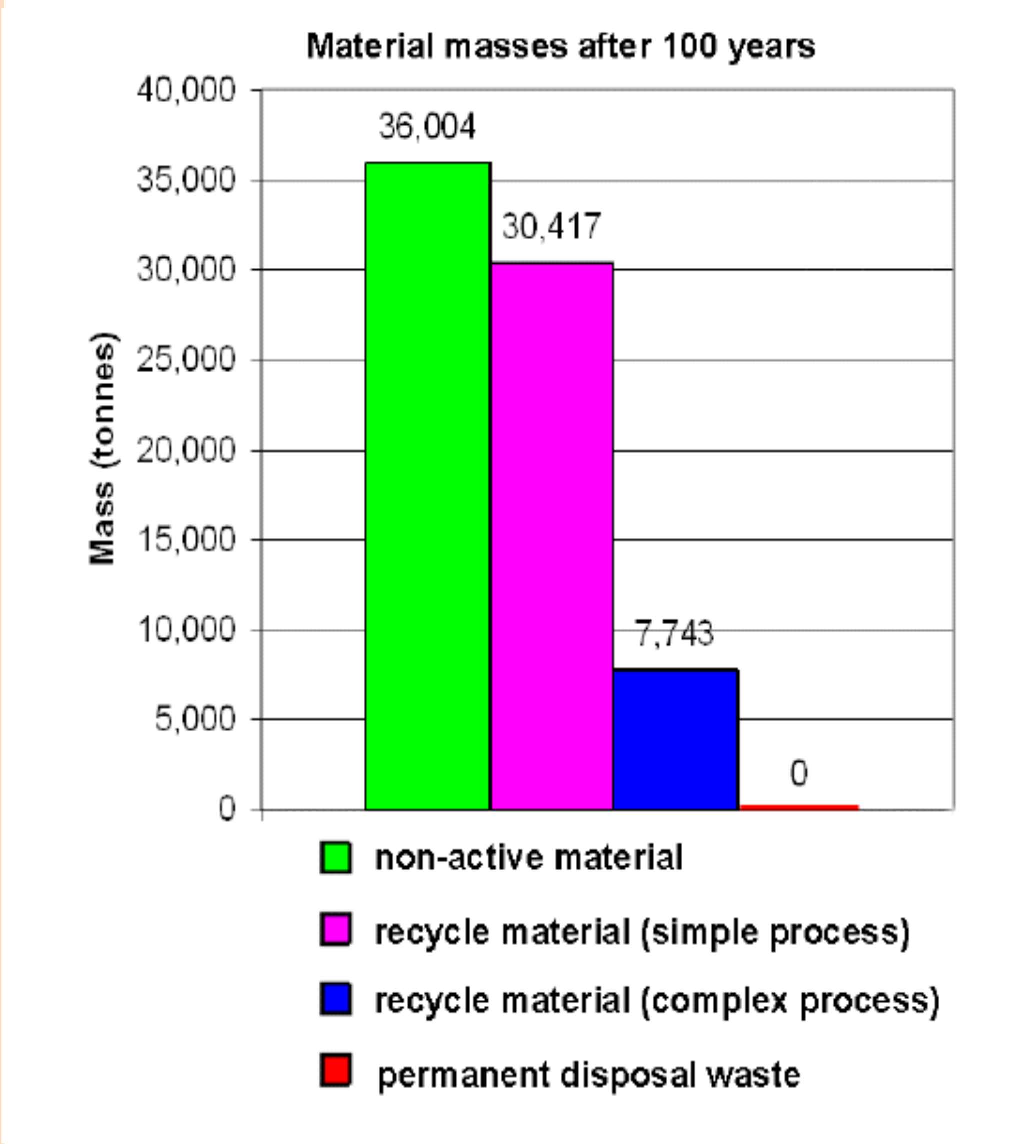
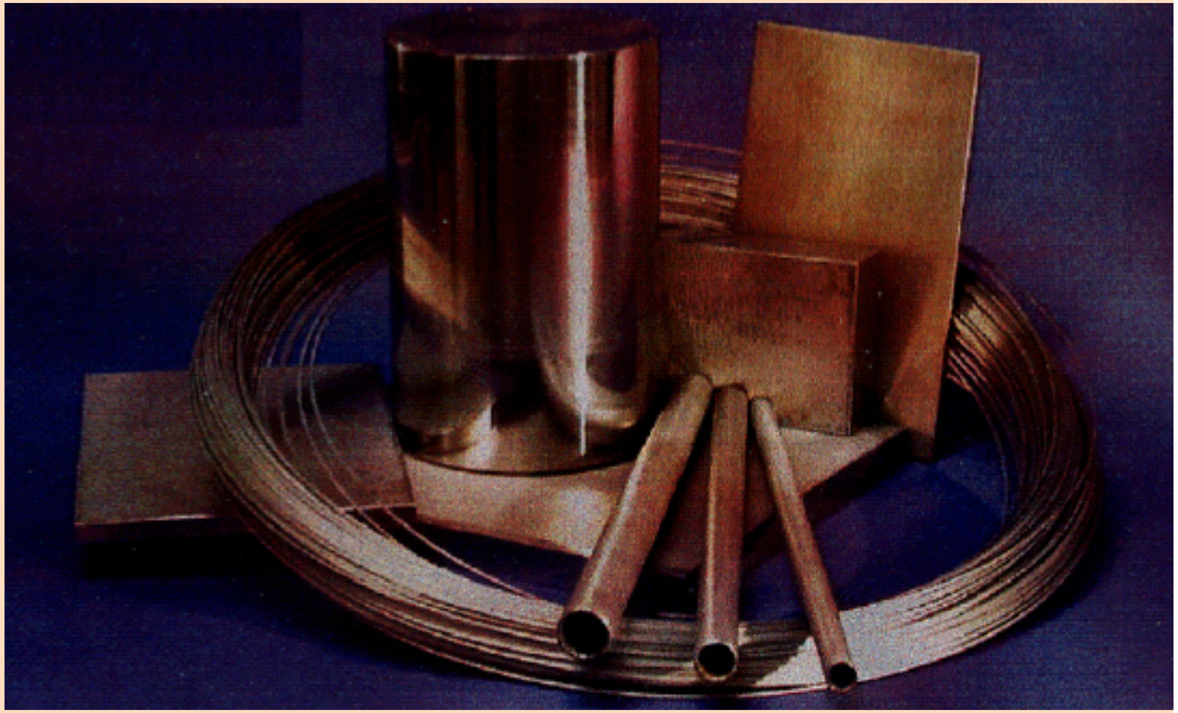


Stork et al. 2014

Neutron resistant materials

Existing candidate:
Low activation EUROFER
Selected range of temperature (300/550^{o}C)
Tested in <u>fission</u> reactors up to 60 dpa

Advanced materials under examination
ODS steels (650^{o}C)
High-Temperature Ferritic-Martensitic steels

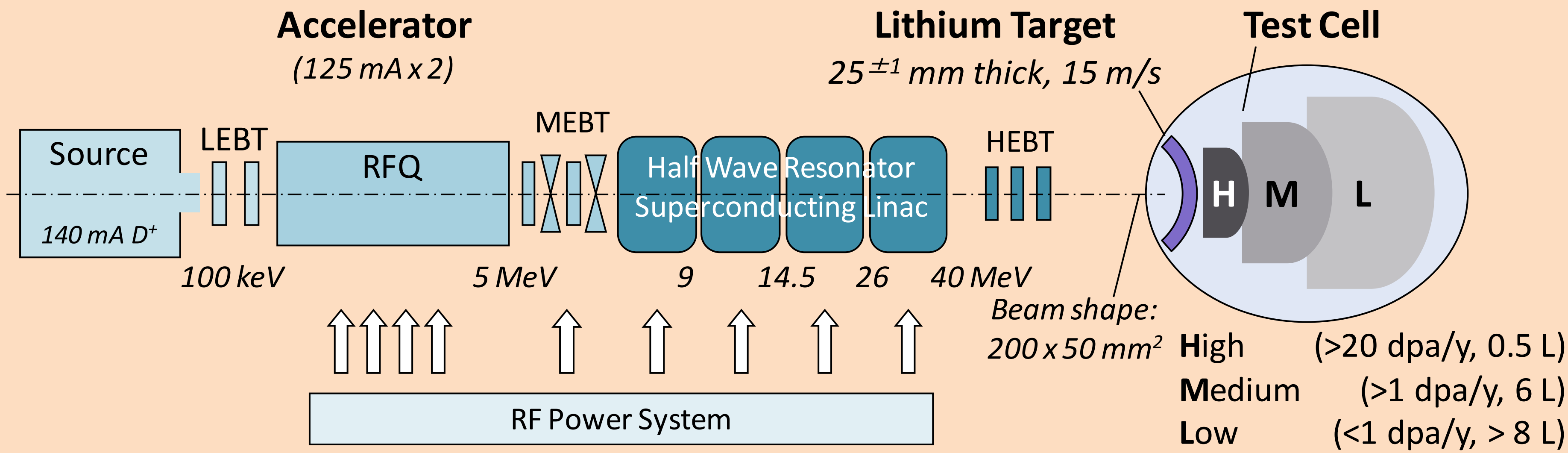


Neutron resistant materials

- Presently available materials can be probably used on DEMO (with minor adaptations) up to 20dpa.
- Material qualification up to 60dpa requires a dedicated facility. An intense 14MeV neutron source (**IFMIF**) is being designed within a collaboration EU-Japan with a large Italian contribution (INFN, ENEA, CNR)
- **DEMO exploitation in two phases**
  - **1st phase (lower availability and neutron damage) test of components and proof of electricity production.**
  - **2nd phase (higher availability and neutron damage) demonstration of reactor operation.**

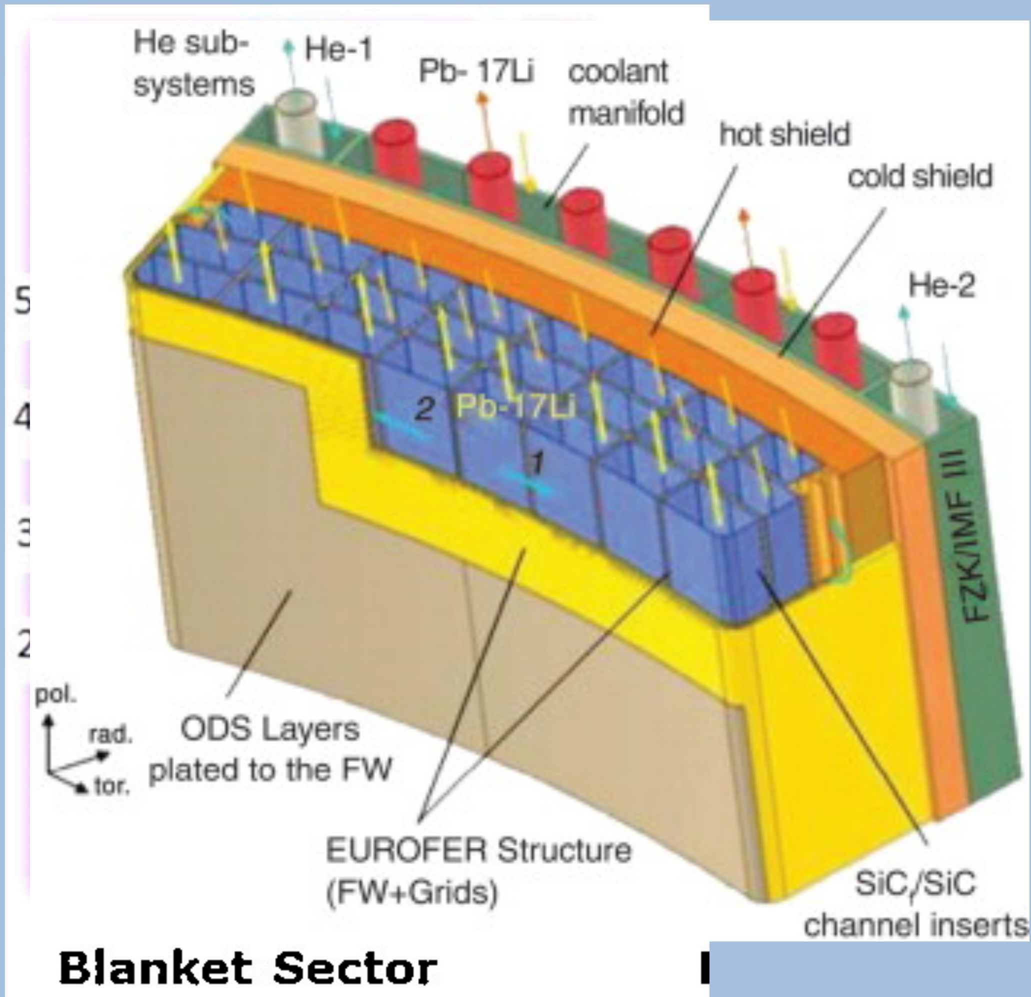
Neutron resistant materials

	Onset of 14MeV effects	Calibration of 14Mev effects	Full database for the full exposure
DEMO Phase1	20dpa (Fe) 250-350ºC 20cc	20dpa (Fe) 250-550ºC 70cc	20dpa (Fe) 250-550ºC 300cc
DEMO Phase2	50dpa (Fe) 250-350ºC 20cc	50dpa (Fe) 250-550ºC 70cc	50dpa (Fe) 250-550ºC 300cc
Reactor		100dpa (Fe) 250-1200ºC 70cc	100dpa (Fe) 250-1200ºC 300cc



IFMIF

Tritium self-sufficiency



A 1.5GWe reactor burns ~0.5kg Tritium/day

Blanket functions

1. Breed Tritium

$^{6}Li + n \rightarrow T + {}^{4}He$

$^{7}Li + n \rightarrow T + {}^{4}He + n$

extract, store and purify.

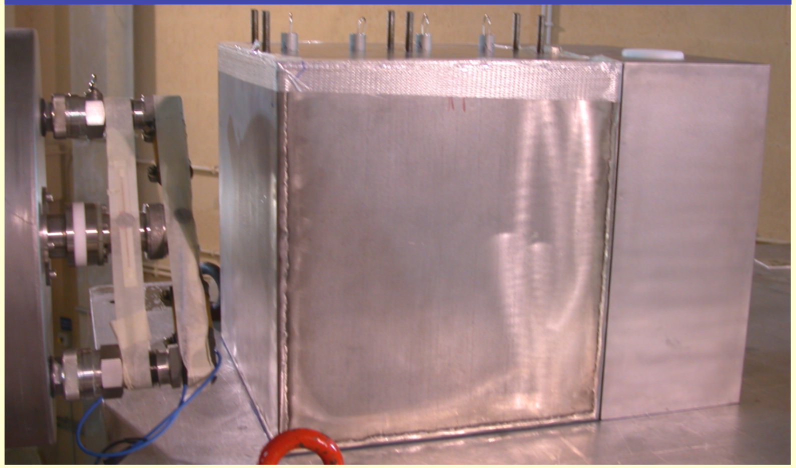
2. Multiply the neutrons (using Be or Pb) to ensure a tritium breeding ratio >1

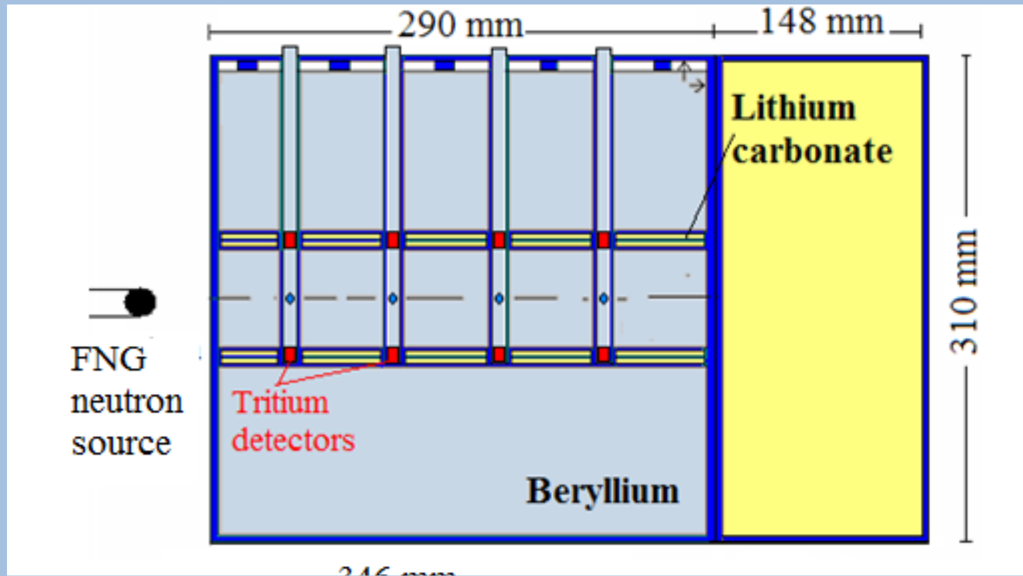
3. Collect the neutron energy as high temperature heat by suitable cooling systems (He or H2O)

4. Shield vessel and magnet from neutrons.

Tritium self-sufficiency

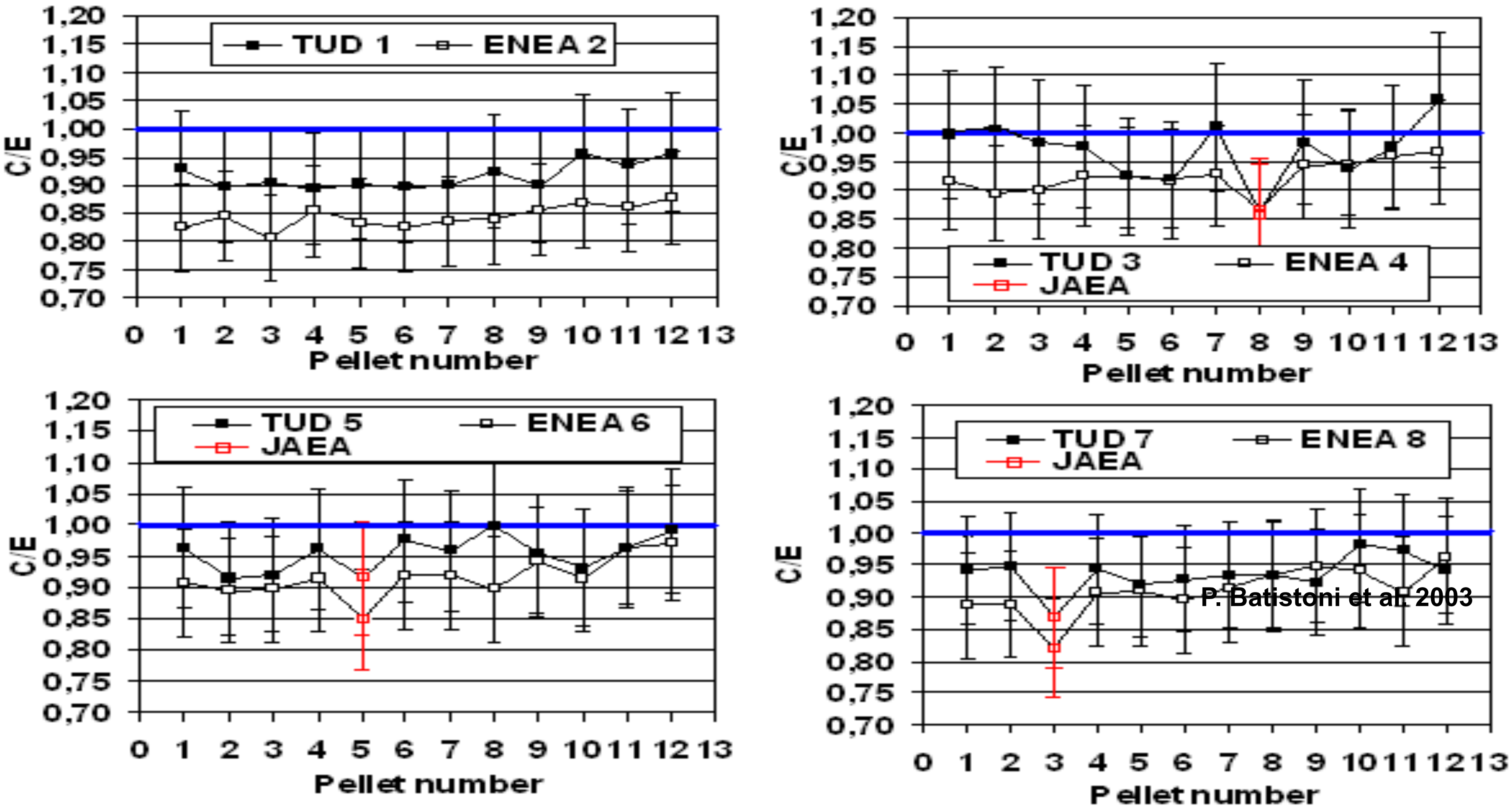
TBM-HCPB mockup





P. Batistoni et al. 2003

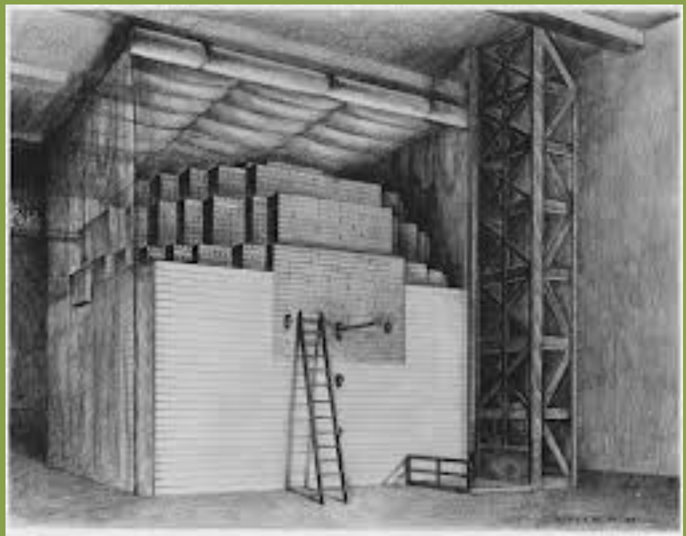
Tritium self-sufficiency



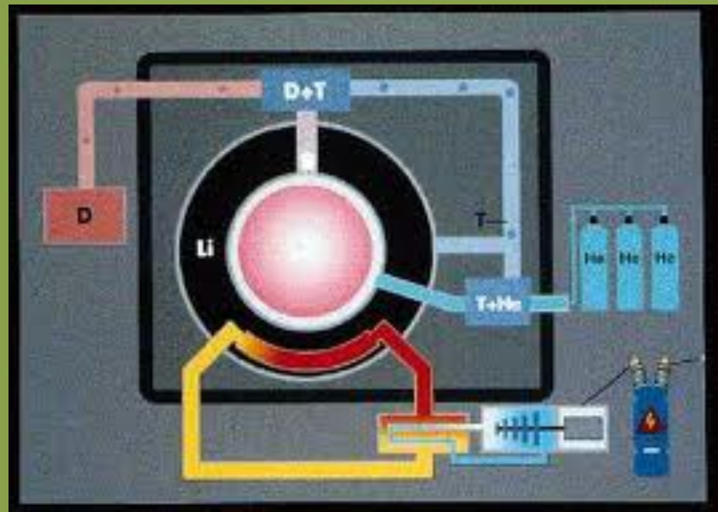
Tritium production:

Larger by 5-10% in average than code prediction

Implementation of inherent fusion safety features in DEMO design

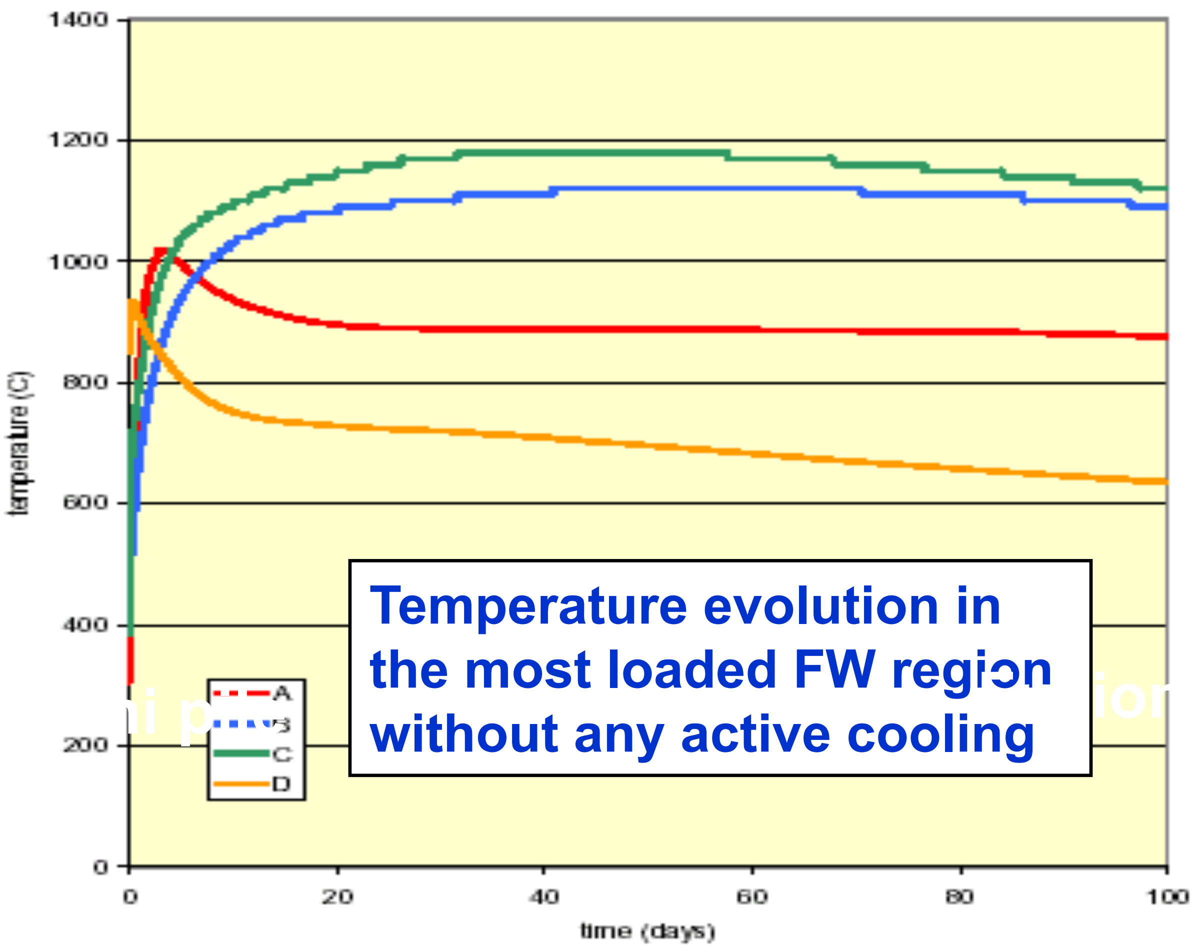


Fermi pile

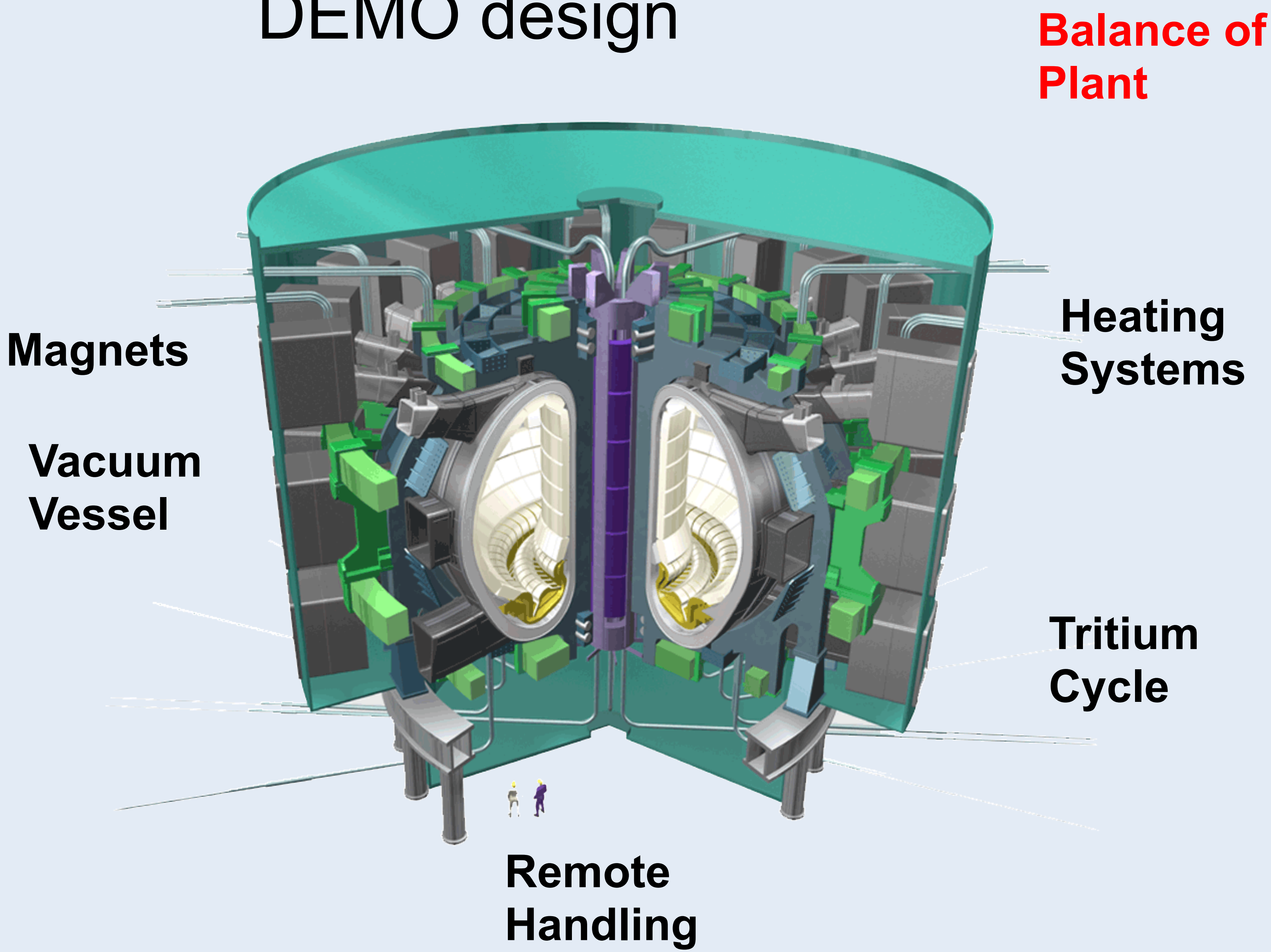


Fusion reactor

Implementation of inherent fusion safety features in DEMO design



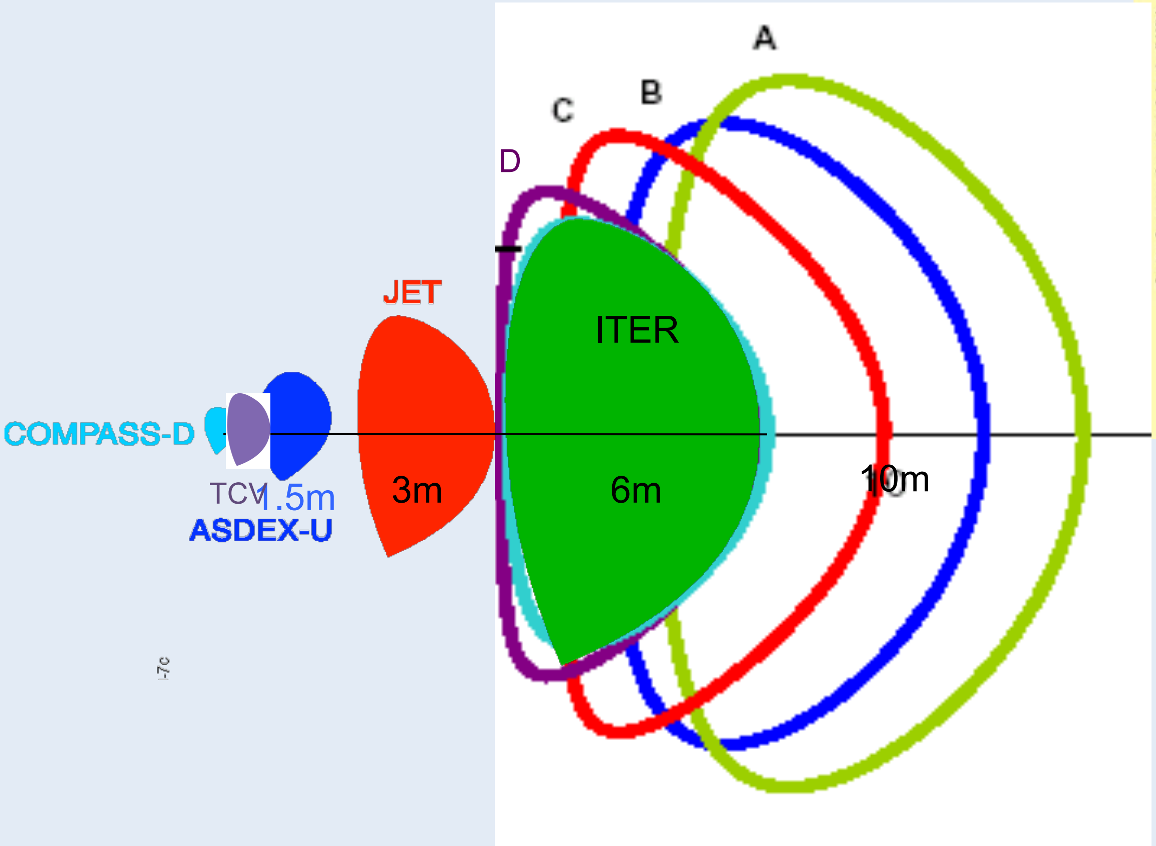
DEMO design

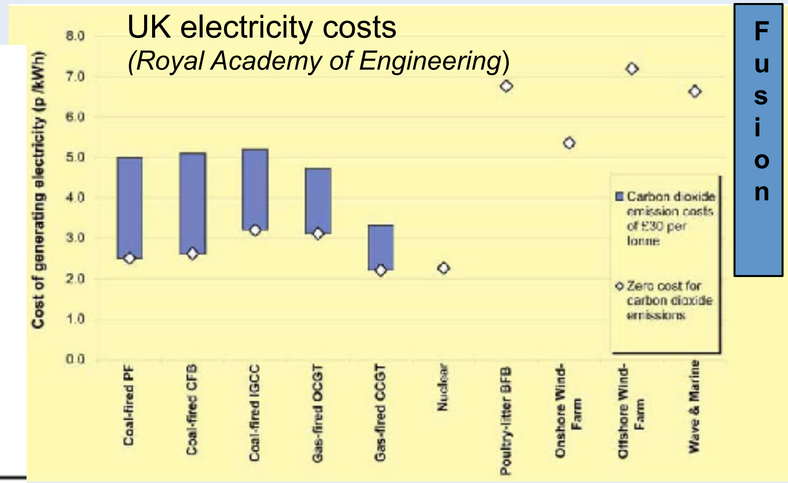

Balance of Plant
Magnets
Vacuum Vessel
Heating Systems
Tritium Cycle
Remote Handling

[redacted]

[redacted]

Low cost of electricity

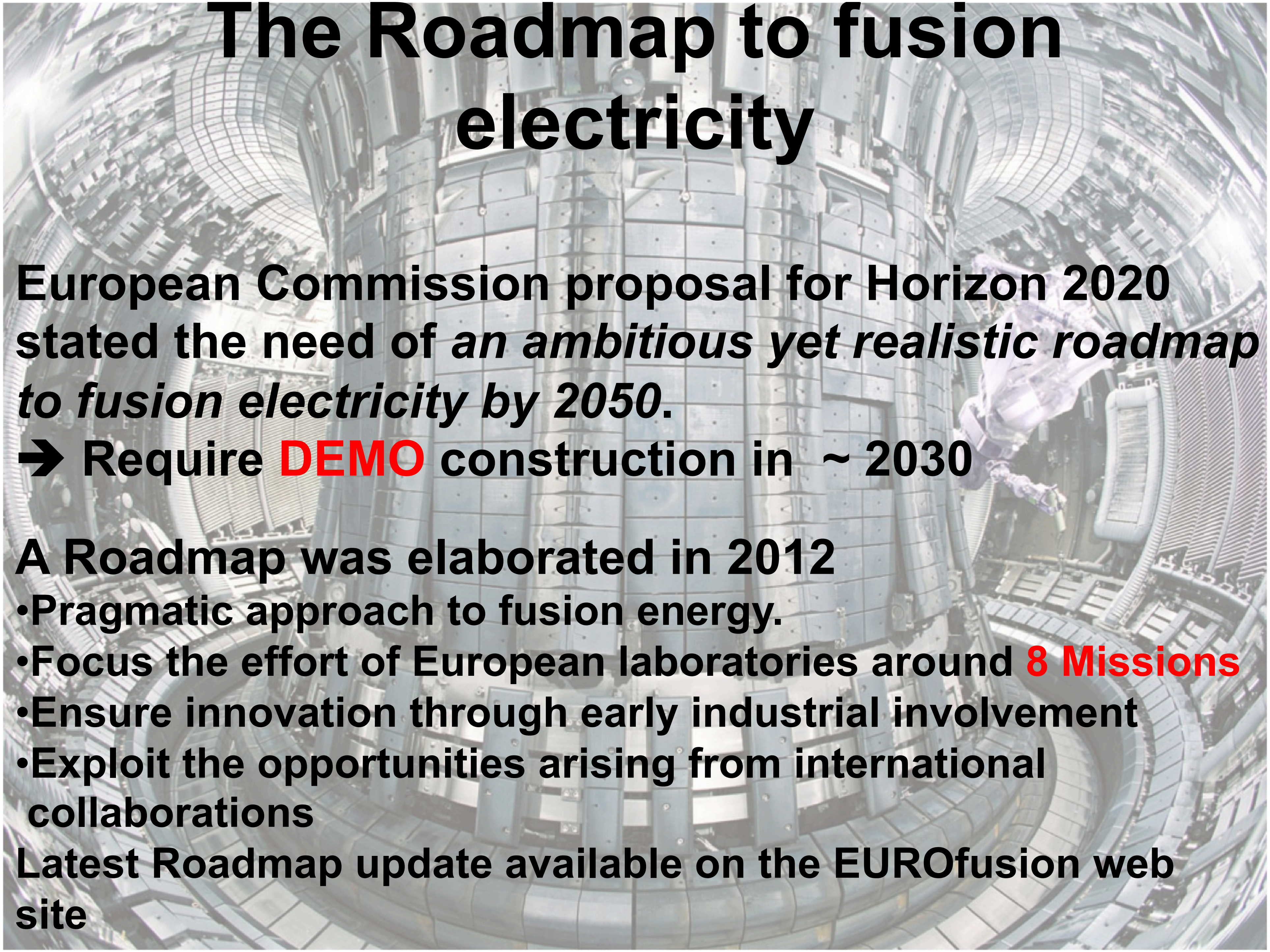




Cost of electricity from fusion expected to be competitive with other sources (IEA Levelised Cost Approach)

ITER is a moderate extrapolation from JET (x2)

The Power Plant (1.5GWe) expected to be a moderate extrapolation from ITER (x1-1.5) depending on the assumptions on physics and technology solutions (A=conservative; D=advanced)
EFDA Power Plant Conceptual Study



The Roadmap to fusion electricity

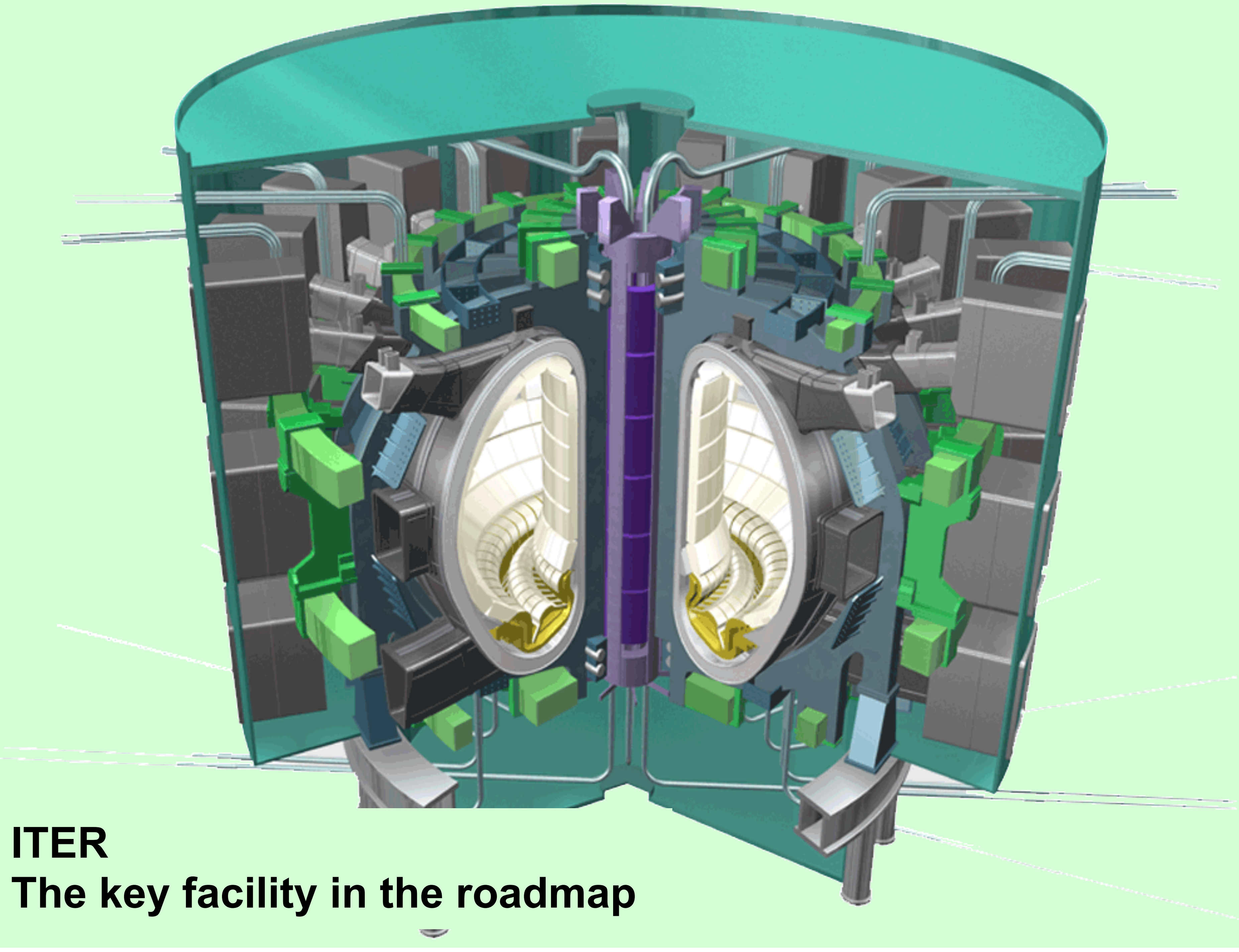
European Commission proposal for Horizon 2020 stated the need of *an ambitious yet realistic roadmap to fusion electricity by 2050*.

➔ Require DEMO construction in ~ 2030

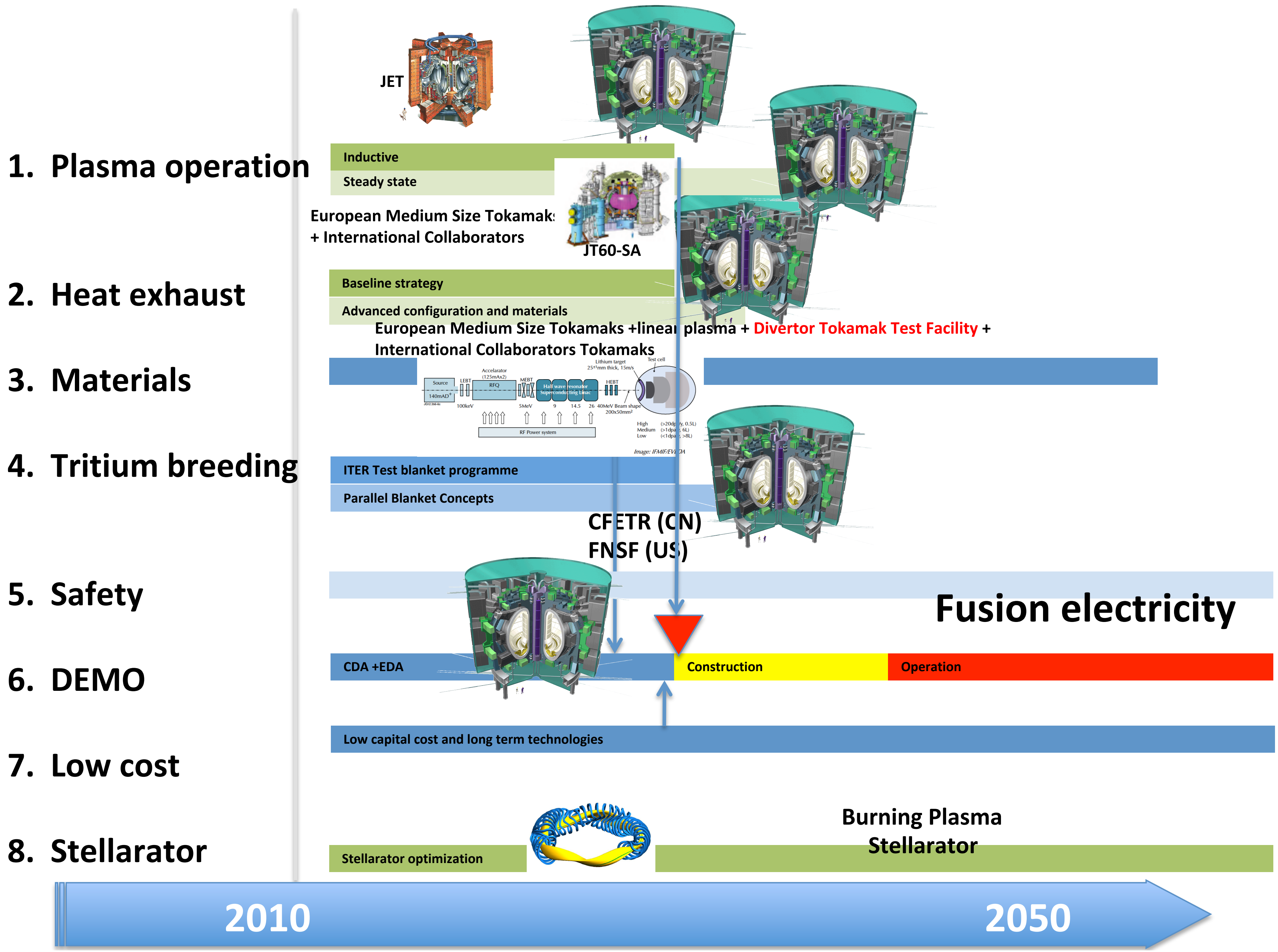
A Roadmap was elaborated in 2012

- **Pragmatic approach to fusion energy.**
- **Focus the effort of European laboratories around 8 Missions**
- **Ensure innovation through early industrial involvement**
- **Exploit the opportunities arising from international collaborations**

Latest Roadmap update available on the EUROfusion web site



ITER
The key facility in the roadmap


1. Plasma operation
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
7. Low cost
8. Stellarator
JET
Inductive
Steady state
European Medium Size Tokamaks
+ International Collaborators
JT60-SA
Baseline strategy
Advanced configuration and materials
European Medium Size Tokamaks +linear plasma + Divertor Tokamak Test Facility +
International Collaborators Tokamaks
ITER Test blanket programme
Parallel Blanket Concepts
CFETR (CN)
FNSF (US)
Fusion electricity
CDA +EDA
Construction
Operation
Low capital cost and long term technologies
Burning Plasma
Stellarator
Stellarator optimization
2010
2050

Conclusions

- Fusion will be an important element of the future energy mix
- ITER will demonstrate the operations of a small reactor – the key facility of the programme
- We are in the (pre) conceptual design process of DEMO – an opportunity for young physicists and engineers
- With a pragmatic approach and well focussed programme fusion electricity could be produced around the middle of ths century - we need to ha the solutions in our hands in 15 years from now!