FUSION:
status and perspectives
A roadmap to the realization of fusion energy

Universita' di Milano - Bicocca
Universita' di Pavia
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Outline

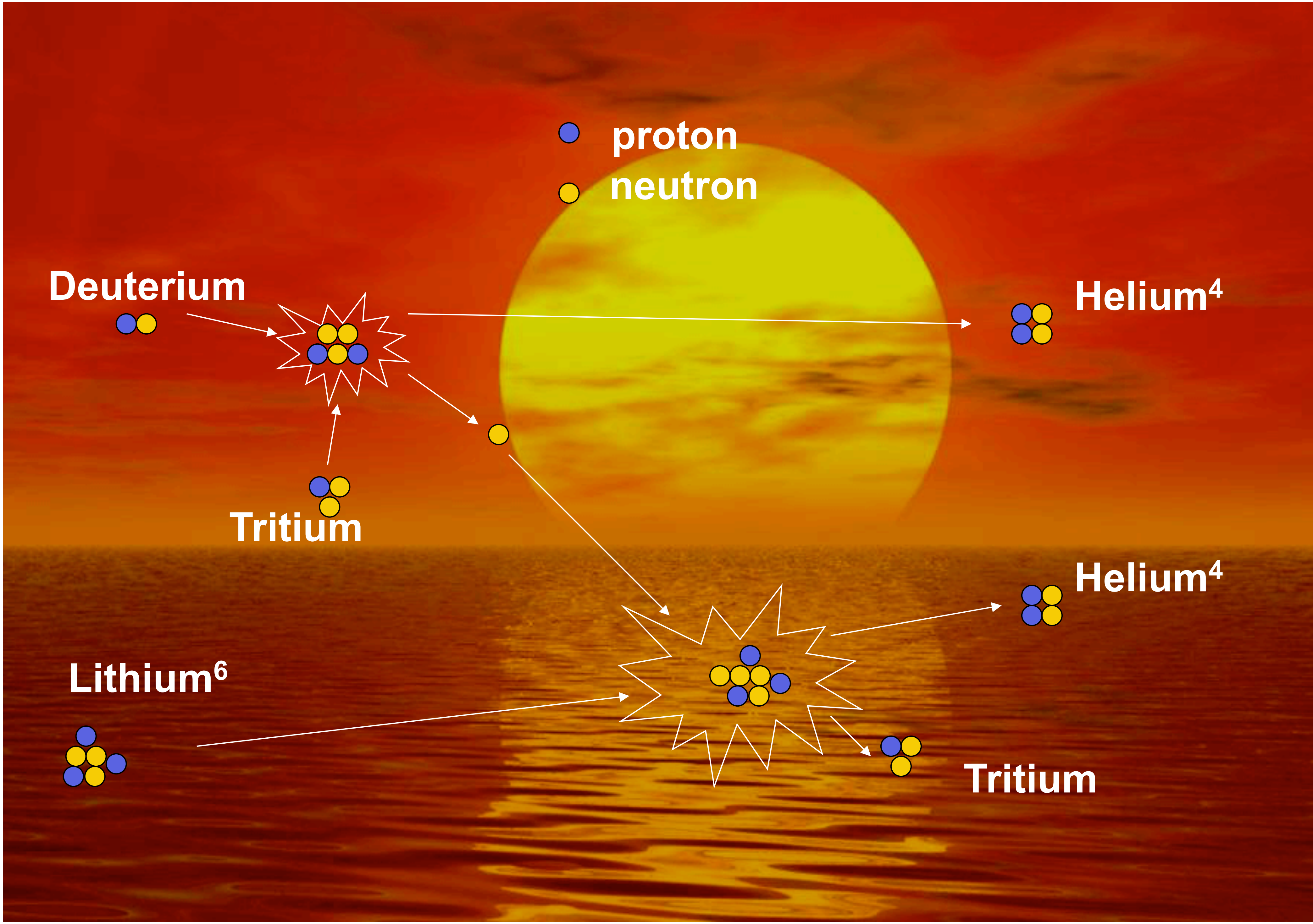
1. Background: how thermonuclear plasmas are confined.
2. The physics of burning plasmas - ITER
3. Fusion electricity - DEMO
4. Opportunities for education and training in fusion.

Energy challenges for Europe

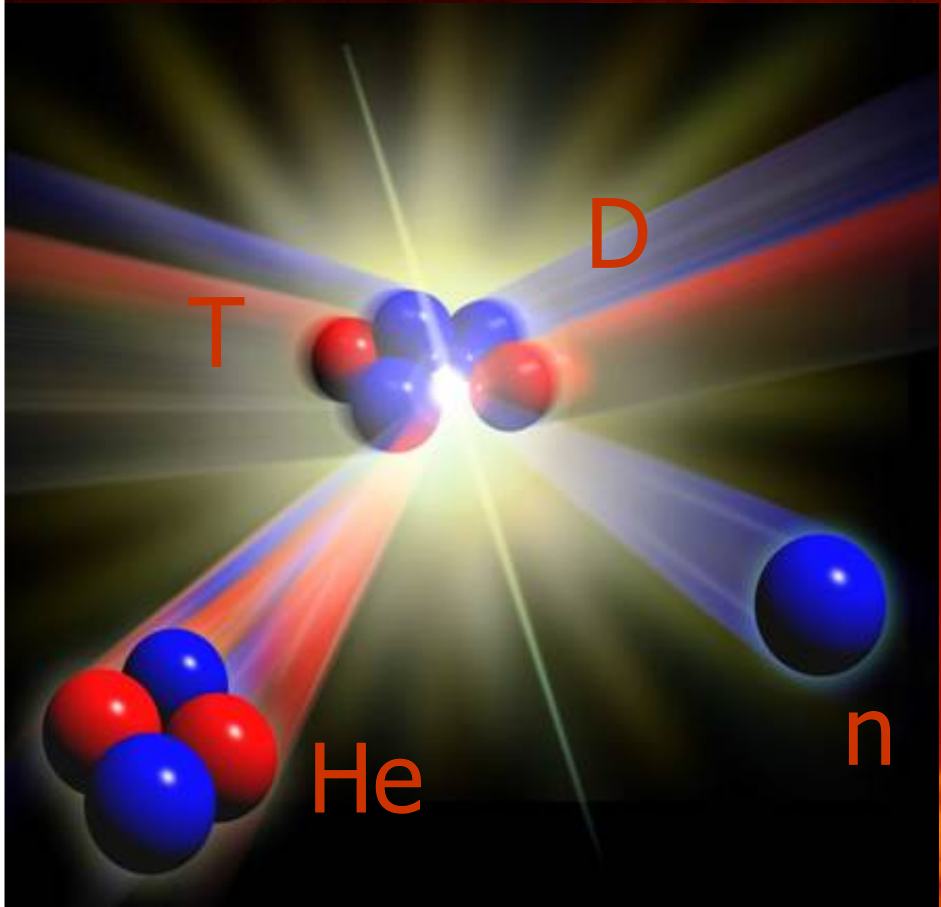
Sustainability
Security of supply
Economic competitiveness

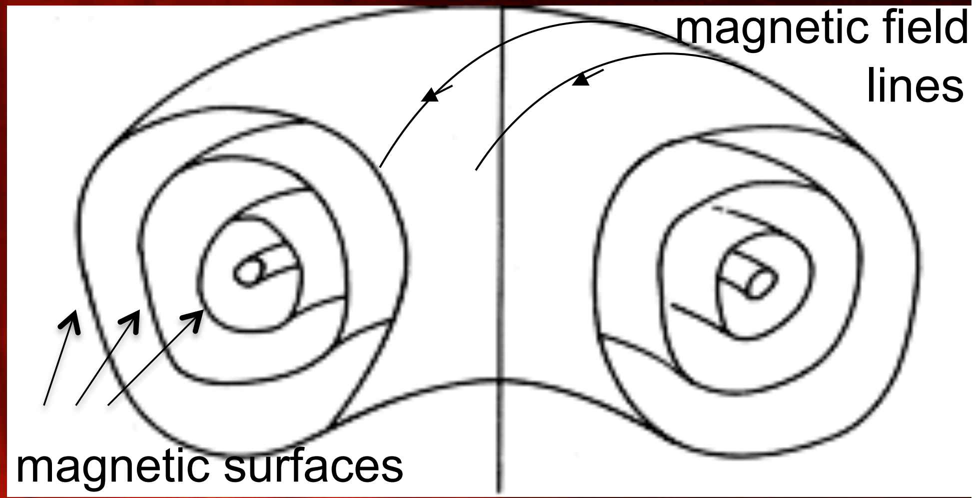
Fusion Energy

Unlimited and diffuse energy source
No greenhouse gases
Intrinsically safe
Environmentally responsible


proton
neutron
Deuterium
Helium⁴
Tritium
Helium⁴
Lithium⁶
Tritium

Background on fusion





Reacting nuclei are charged

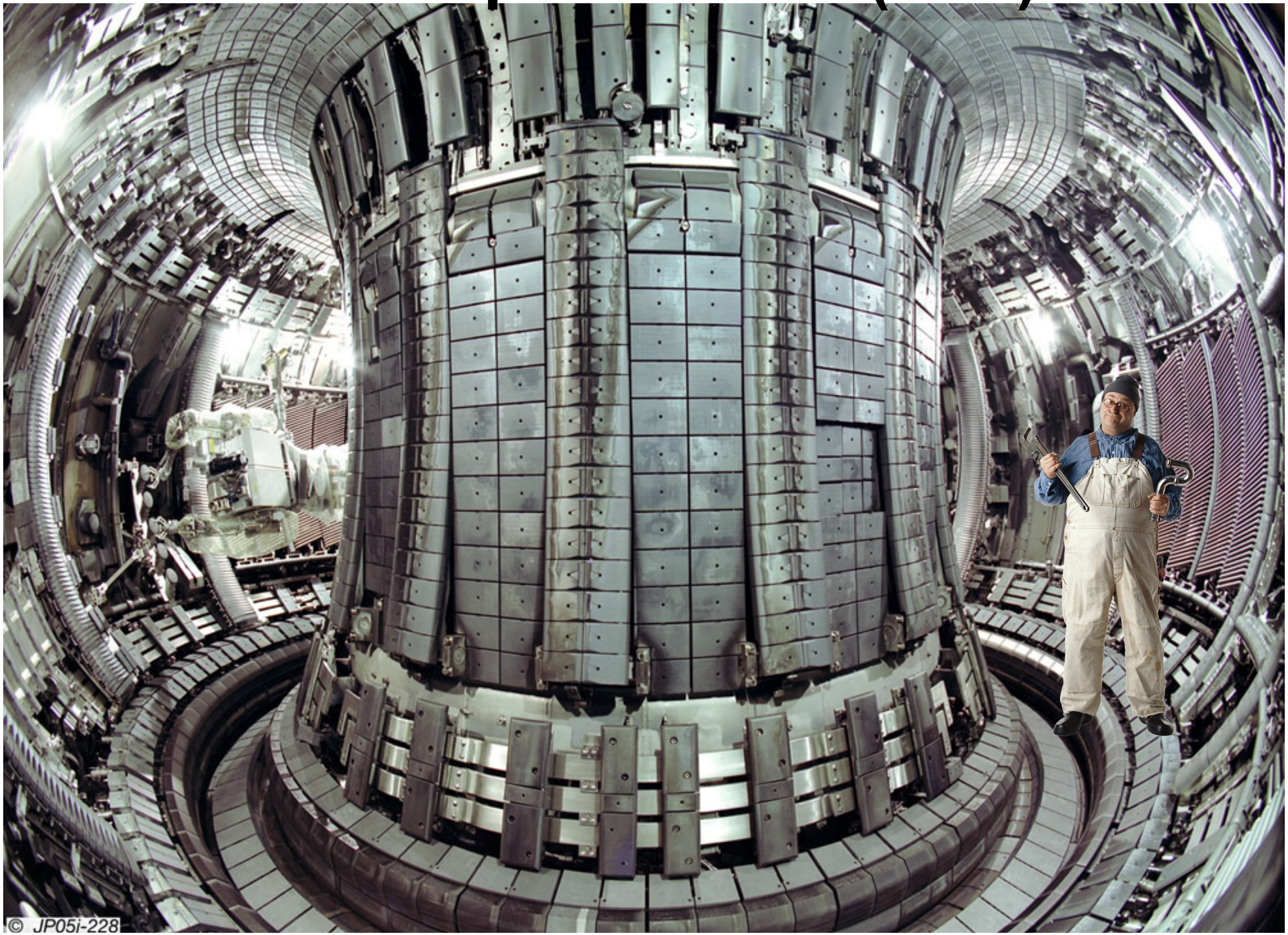
⇒ **they repel each other**

⇒ **Heat nuclei up to 200Million °C**

Matter is in the *plasma* state

- **Intense magnetic field** (100000 x the earth magnetic field) produced by external coil and plasma current
- **Toroidal shape**

The Joint European Torus (JET)



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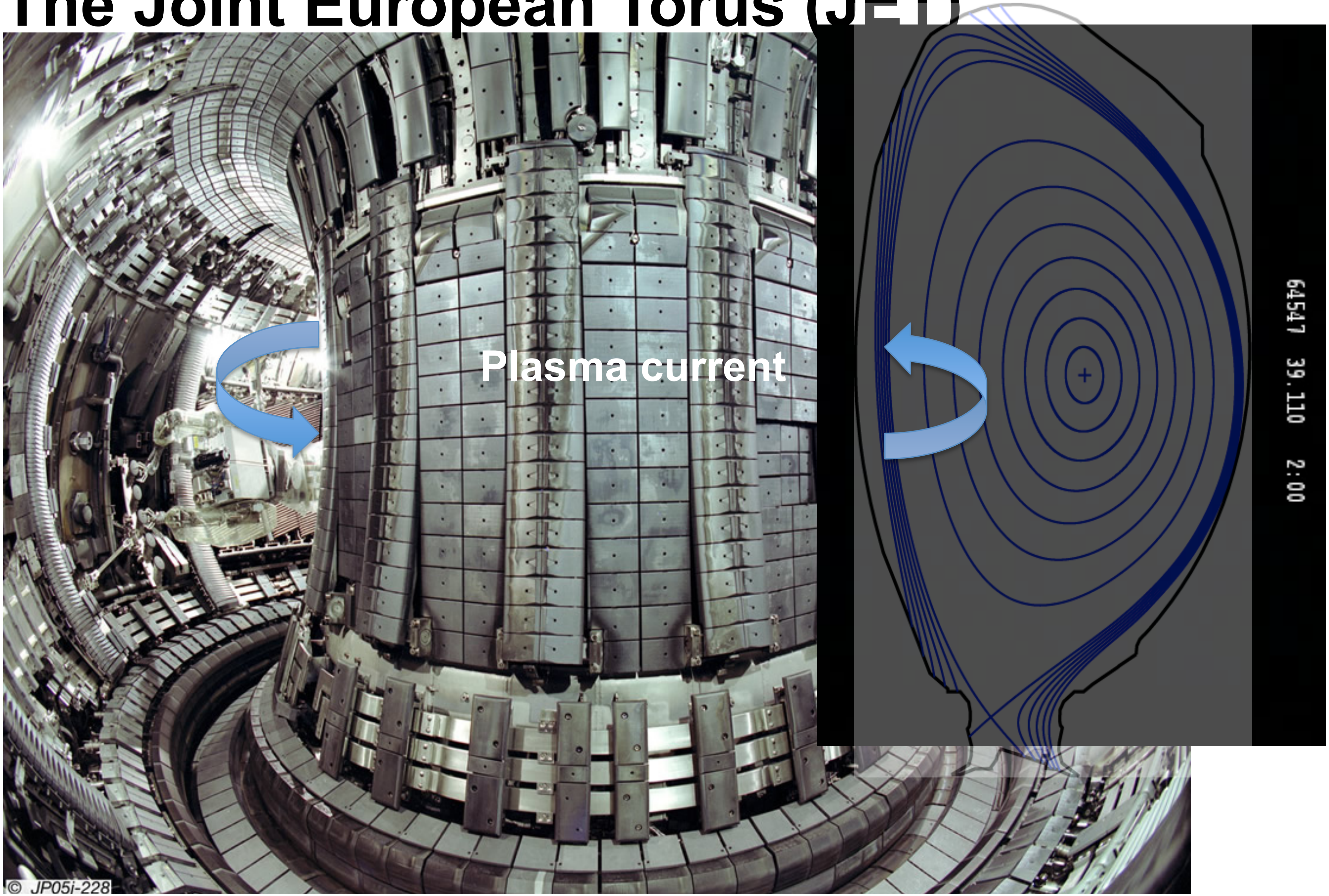

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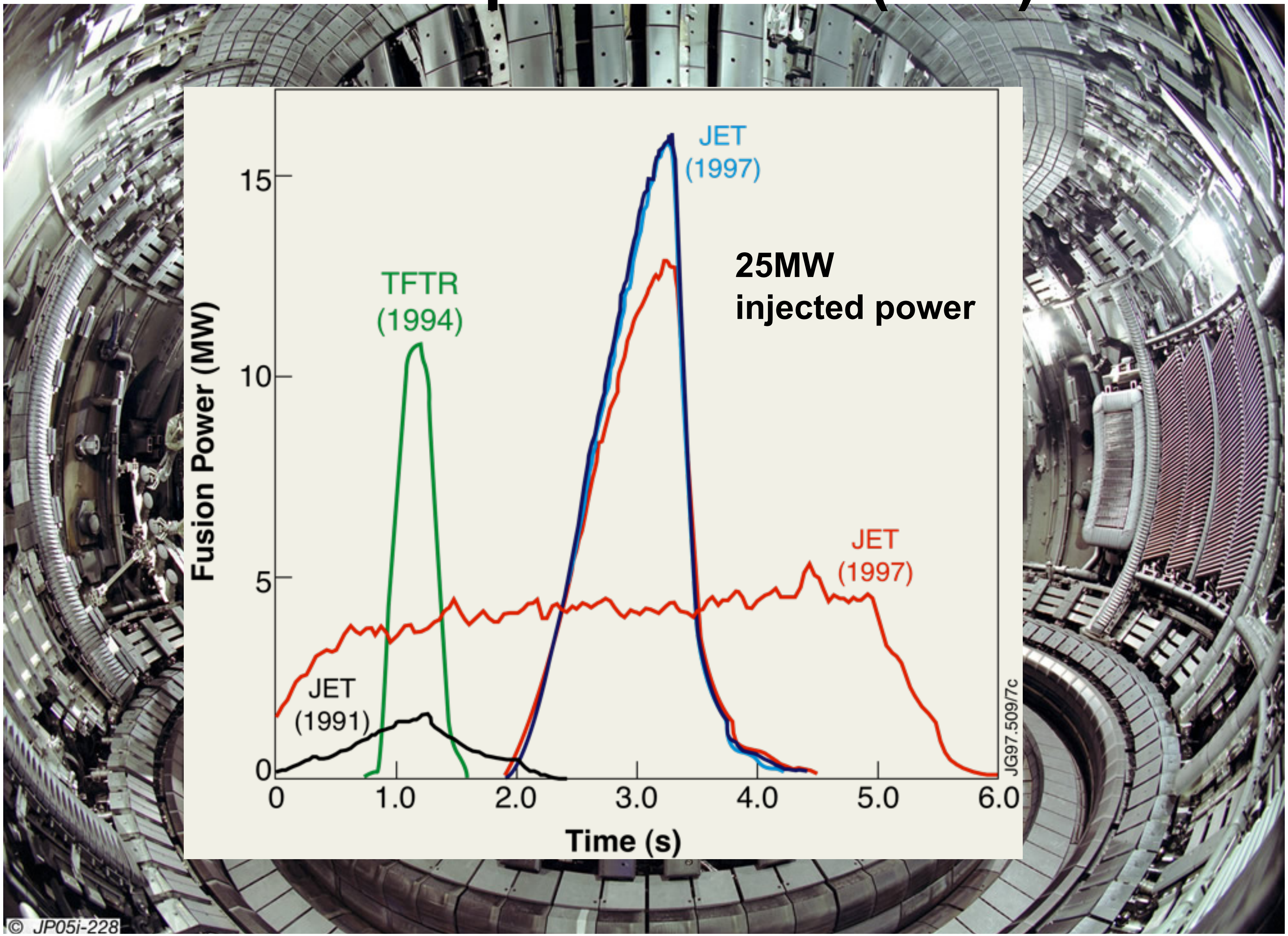


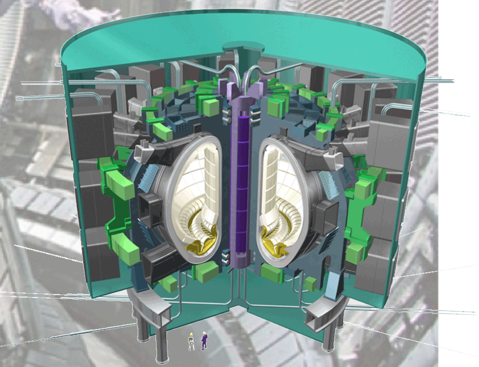
The challenge of confining a plasma

has been already achieved!

What do we need to make a power plant?

Achieve burning plasma conditions

=> ITER



Produce electric energy and demonstrate tritium self sufficiency

=> DEMO

The challenge of confining a plasma

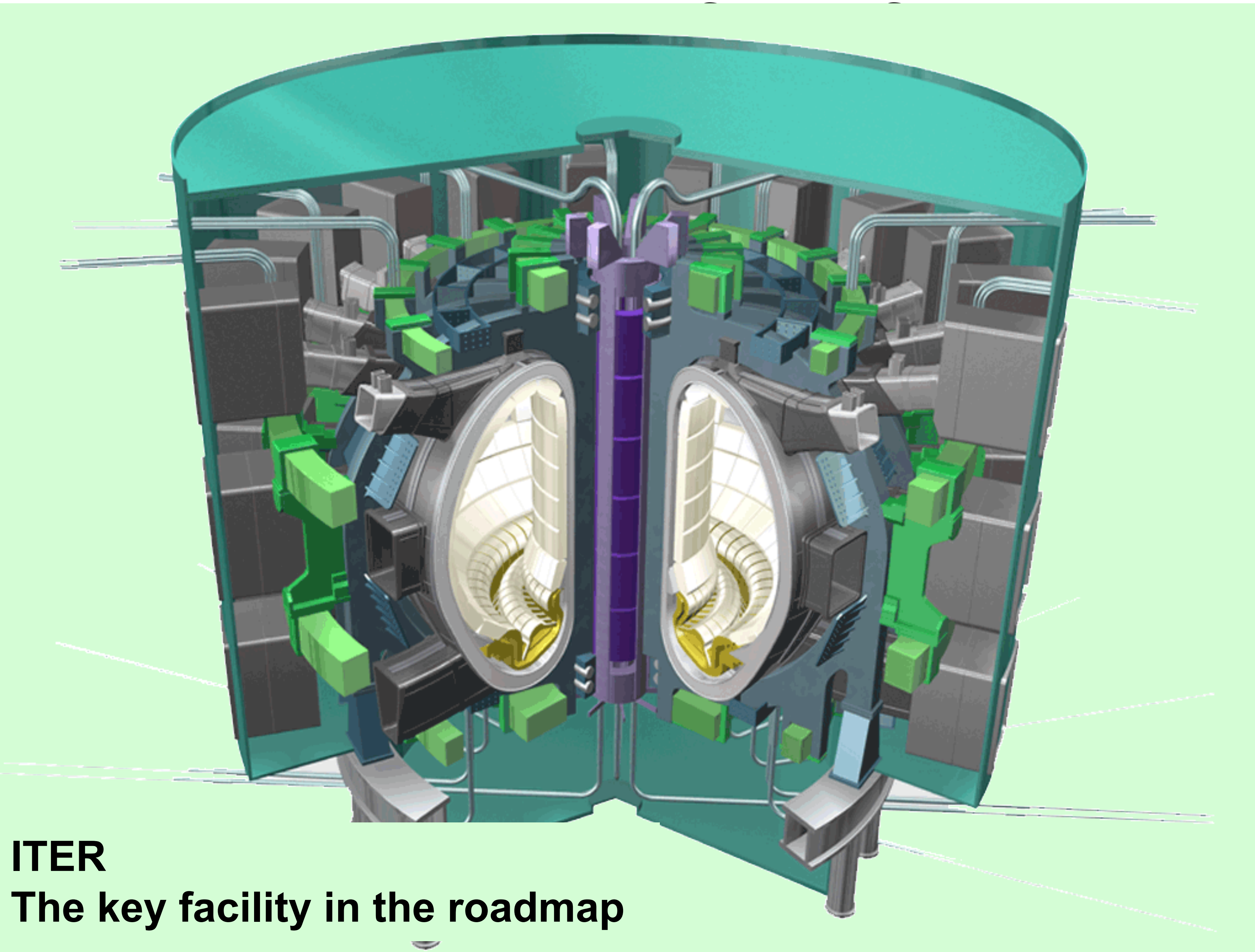
has been already achieved!

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

➔ Require DEMO construction in ~ 2030

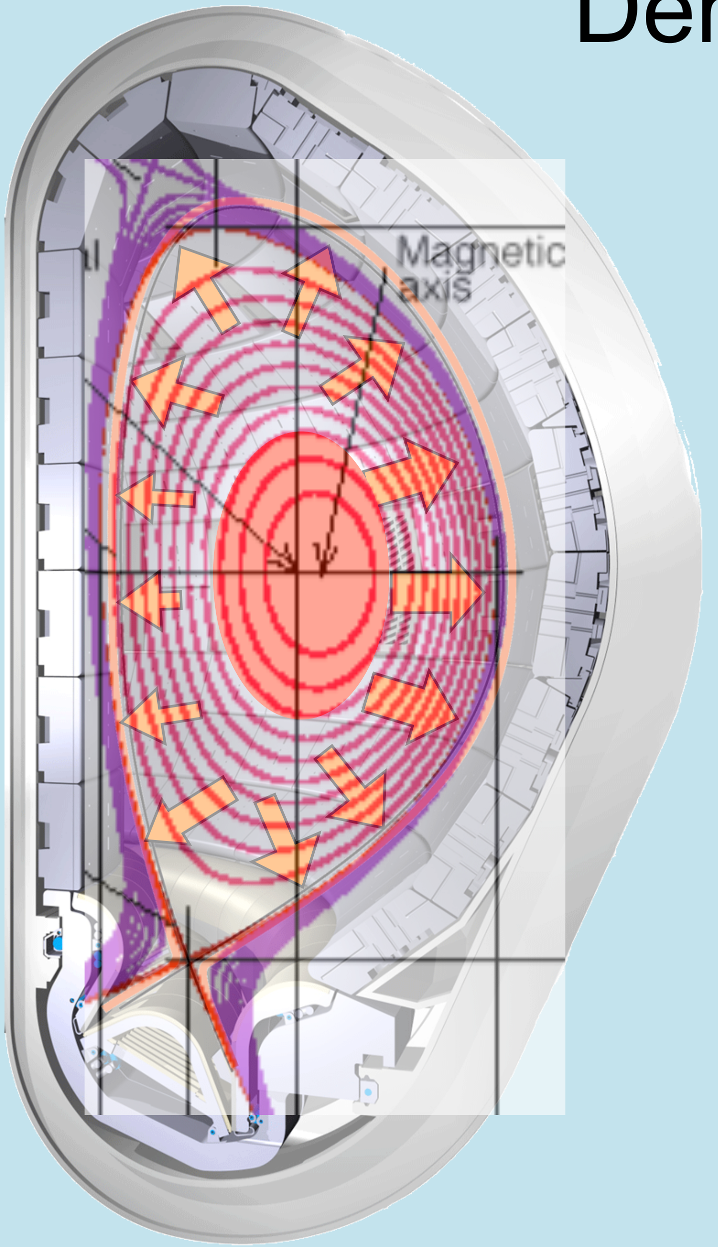
The present roadmap

- **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**



ITER
The key facility in the roadmap

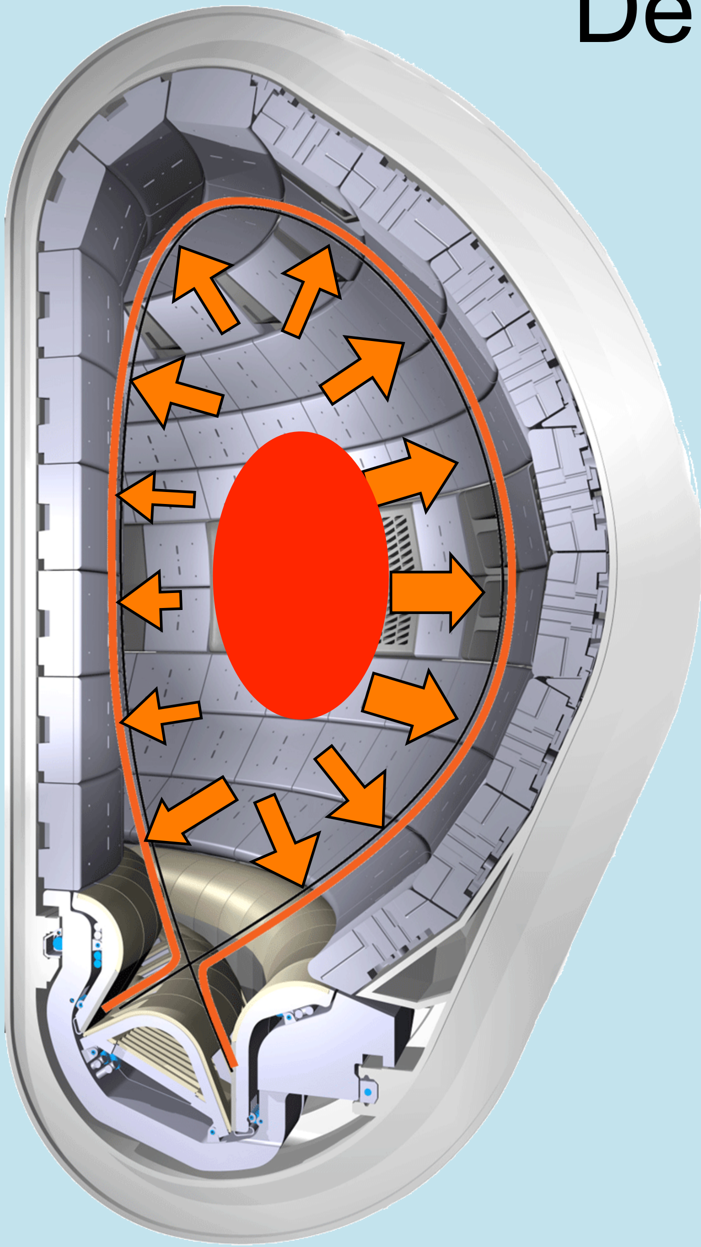
Mission 1: Plasma regimes for a reactor
Demonstrate a net energy gain



Code: **GYRO**

Authors: Jeff Candy and Ron Waltz

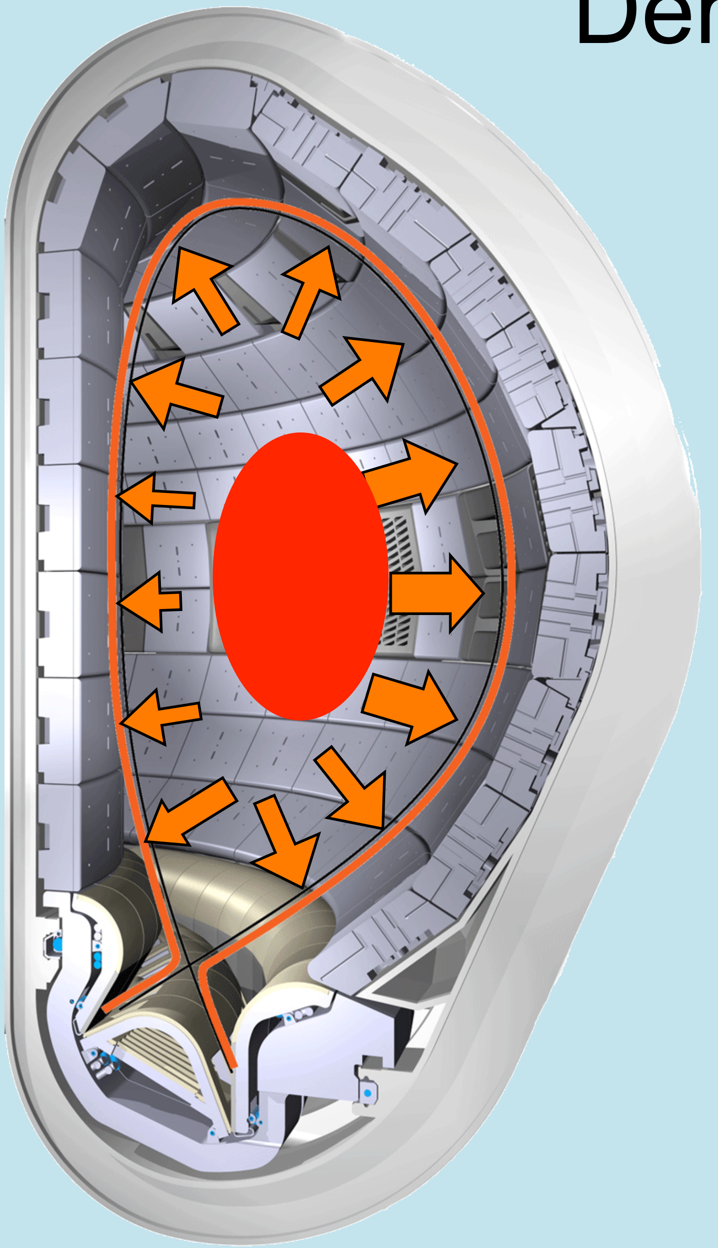
Mission 1: Plasma regimes for a reactor Demonstrate a net energy gain

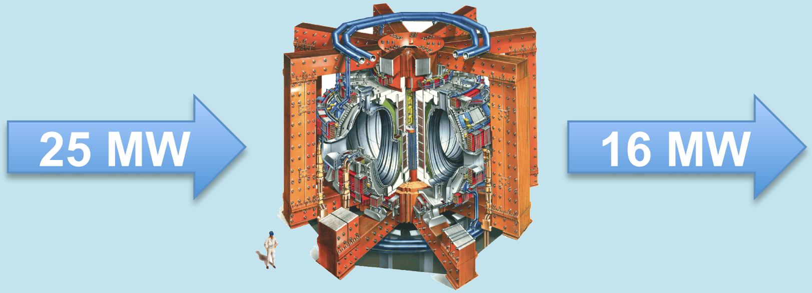


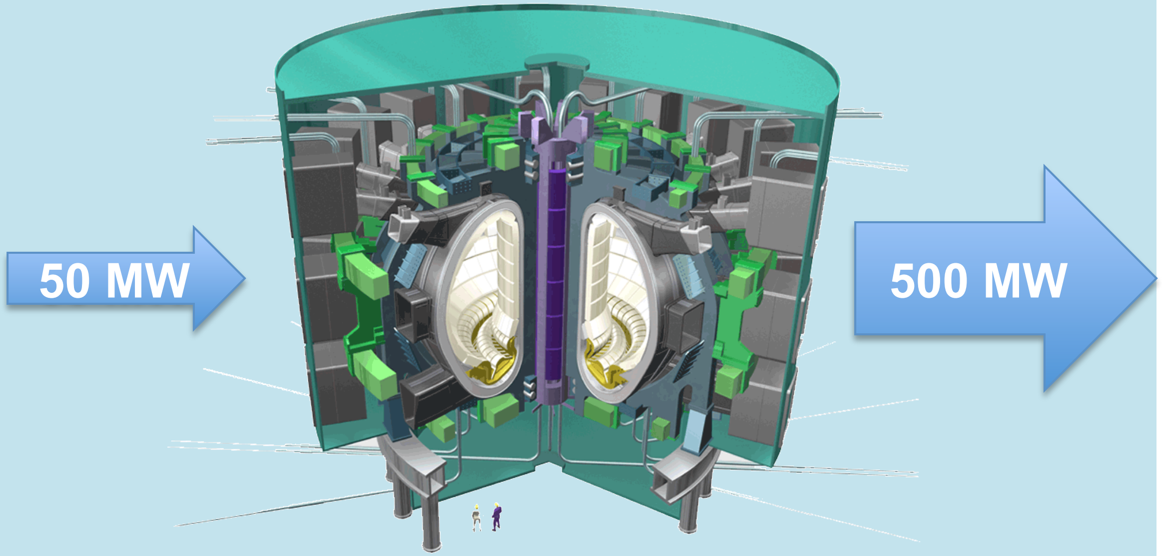
- Energy losses increase at most as the radius R of the device
- Fusion power increases as the volume ($\approx R^3$)

MAKE LARGER DEVICES

Mission 1: Plasma regimes for a reactor
Demonstrate a net energy gain

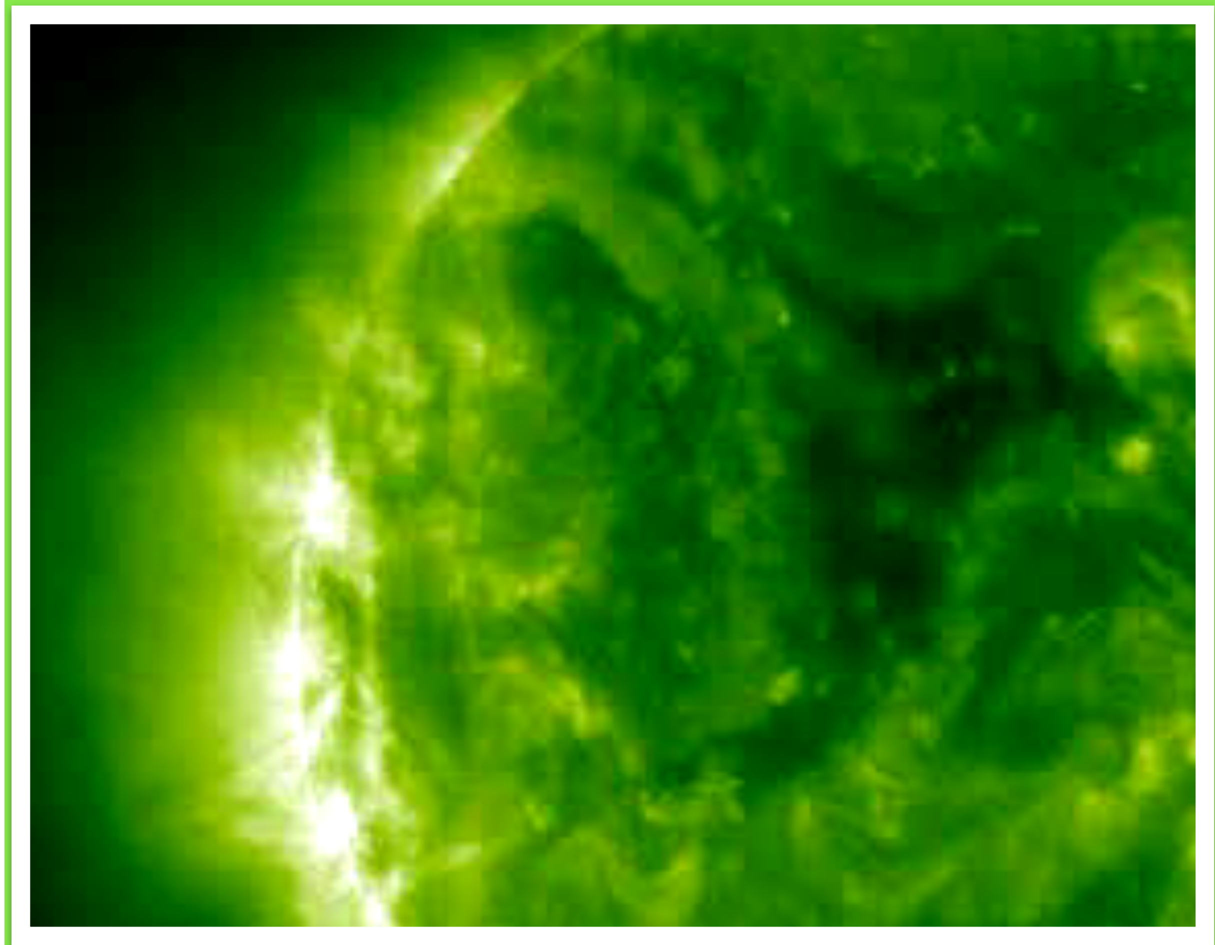






Mission 1: Plasma regimes for a reactor

Control plasma instabilities



Mission 1: Control plasma instabilities in burning plasmas

- Plasmas are intrinsically unstable.

- Instabilities belongs to two classes:
  - Those that lead to a sudden loss of confinement (disruptions). Must be avoided, prevented or mitigated
    - Operation far from the stability boundaries
    - Redundancy of control systems to allow appropriate preventive actions
    - Real time prediction and mitigation of event (e.g. impurity injection) to reduce loads on the internal components

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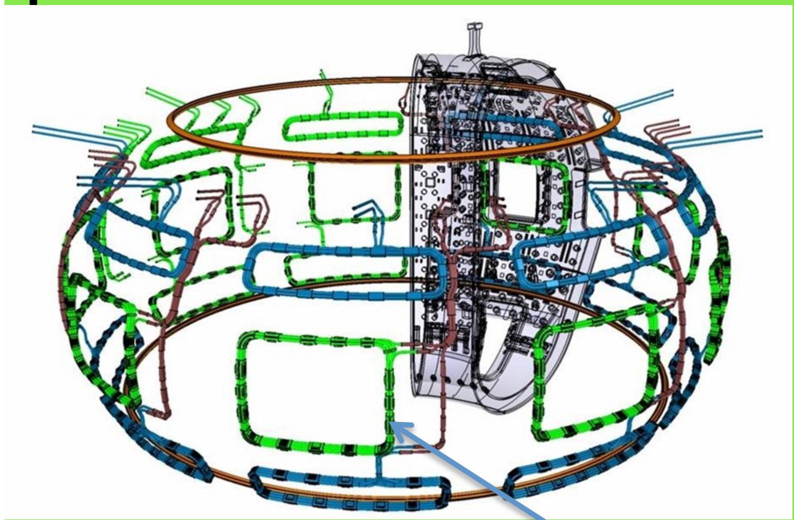
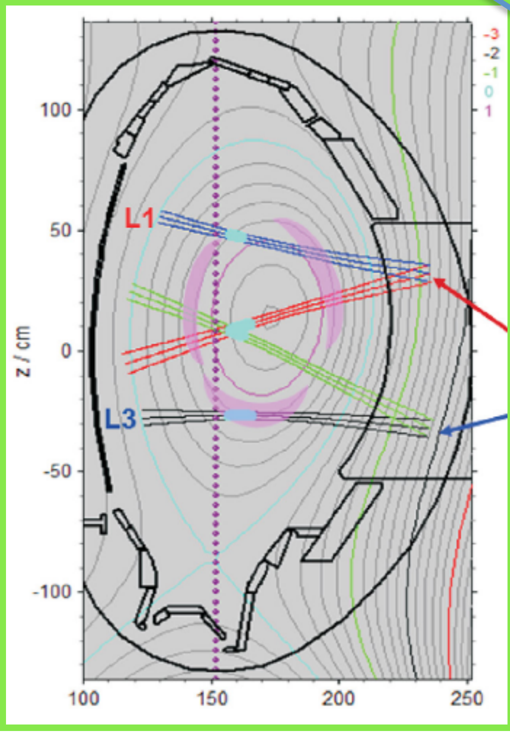
  - Those that produce minor plasma redistribution and can help to eject impurities. Must be controlled

Mission 1: Control plasma instabilities in burning plasmas



coils



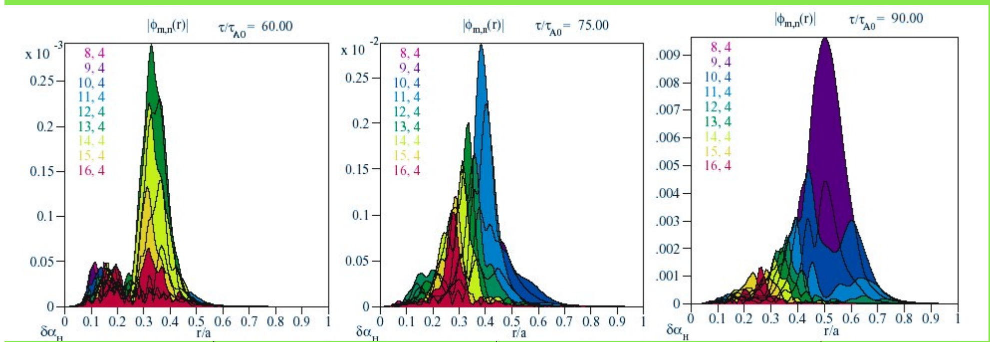
e.m. waves

- Several control systems have been successfully tested
  - Resonant magnetic perturbation to control *Edge Localised Modes* (ELMs – see movie)
  - Millimiter wave injection to control *Neoclassical Tearing Modes*
- ITER will clarify if their use is compatible with burning plasma conditions

Mission 1: Control plasma instabilities in burning plasmas

New!

Zonca et al 2002



Distance from the magnetic axis

ITER will break new ground on this subject!

High energy alpha-particles may generate new instabilities that, in turn, may produce alpha-particle redistribution.

Investigated in present day experiment by accelerating plasma ions e.g. using electromagnetic waves.

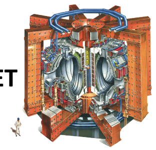
Expected to be close to marginal stability for the regimes of operation investigated by ITER in the first phase.

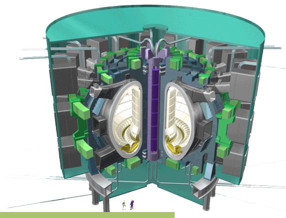
Mission 1: Other challenges

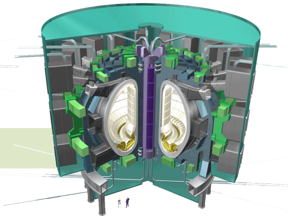
- Aim at fully steady-state plasmas
  - Require plasma current to be mostly generated by the plasma itself (bootstrap mechanism). **Demonstrated.**
  - Exhibit lower turbulent transport. **Smaller reactor size!**
  - Regimes not fully qualified yet. **ITER goal in its 2nd phase**
  - Unclear if diagnostic and controls can be extrapolated to a fully nuclear environment. **ITER and JT60-SA to play a major role.**
  - A DEMO reactor can be designed to work in a pulsed plasma mode + a storage system.
- Ensure compatibility of plasma operation with first wall materials
  - Metallic walls (beryllium and tungsten in ITER) to avoid tritium retention. **Proven by JET**
  - Tungsten foreseen in a reactor but high-Z impurity accumulation must be avoided.
- Operation with a large fraction of heating power being radiated (see next mission)

The Roadmap in a nutshell

1. **Plasma operation**
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
7. Low cost
8. Stellarator







Inductive

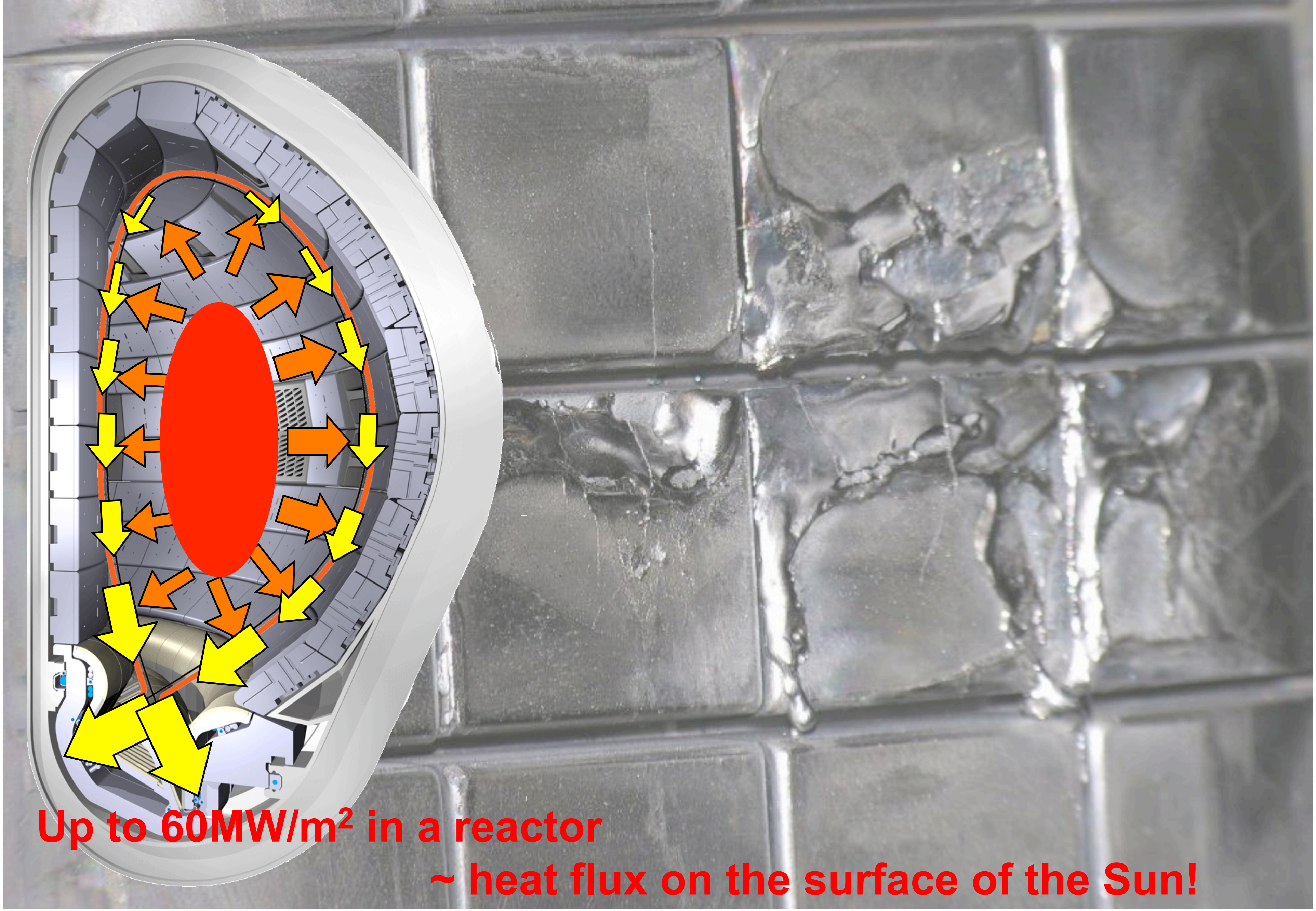
Steady state

European Medium Size Tokamaks
+ International Collaborators

DEMO decision

2010 2050

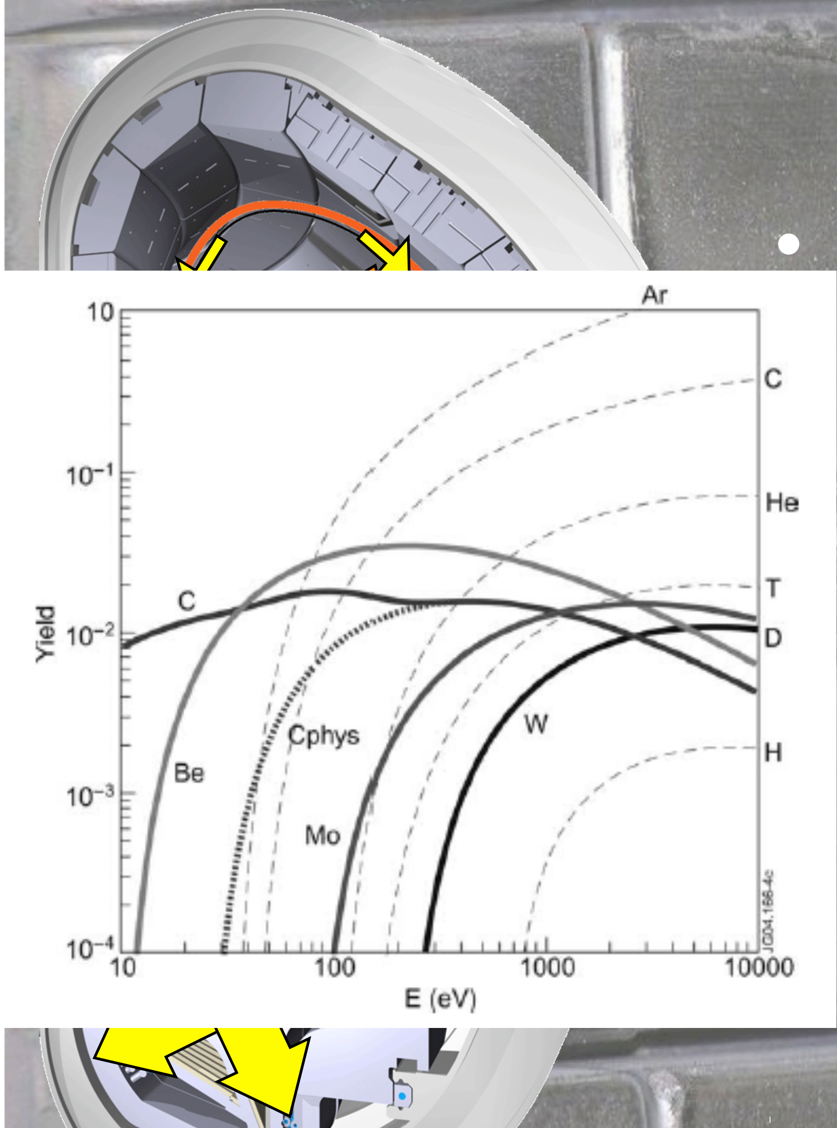
Mission 2: Heat and particle exhaust



Up to 60MW/m^2 in a reactor

~ heat flux on the surface of the Sun!

Mission 2: Heat and particle exhaust



- 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

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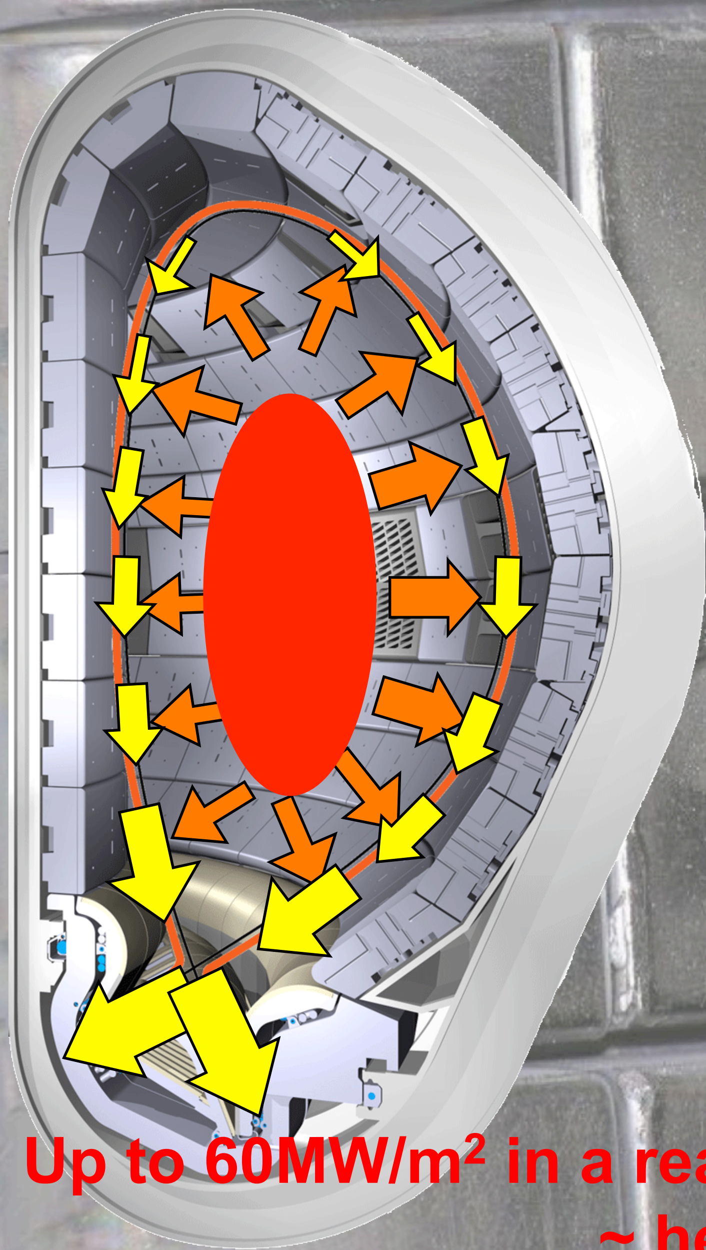
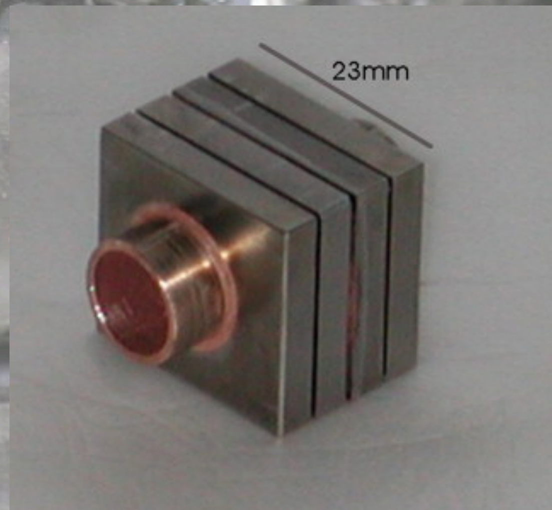


- Erosion
- First wall material properties
  - Recrystallization
  - Cracking
  - De bonding



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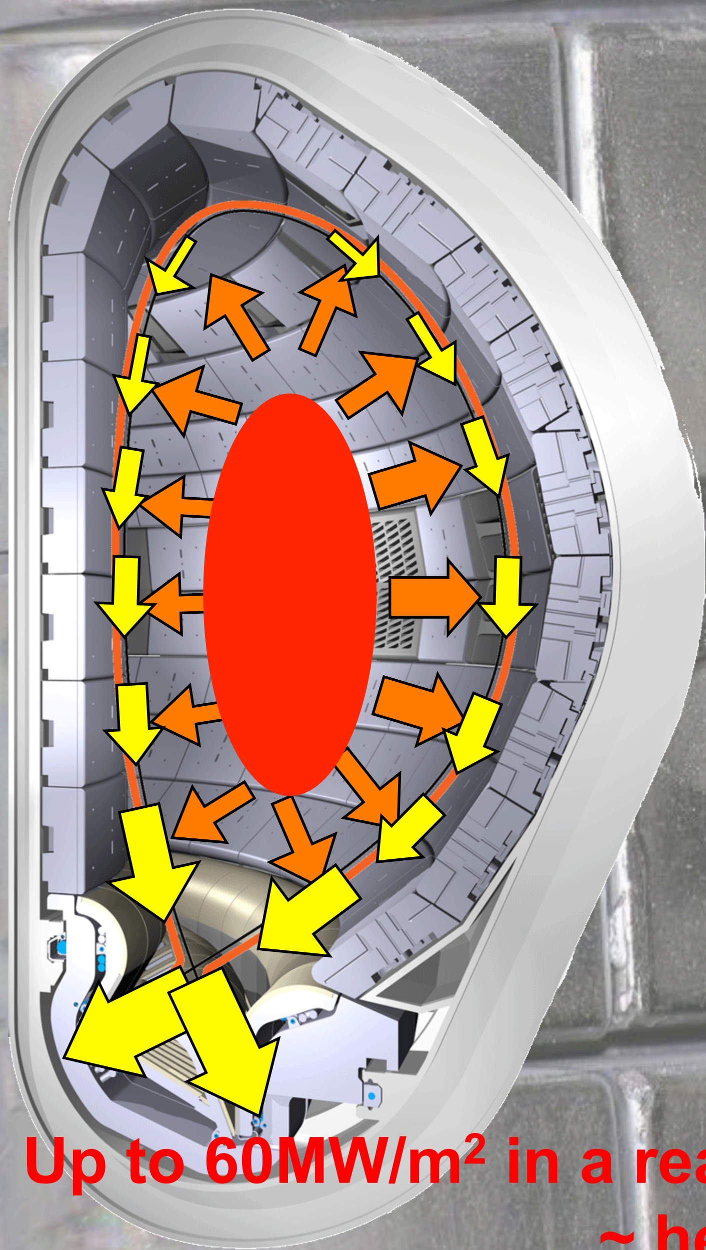
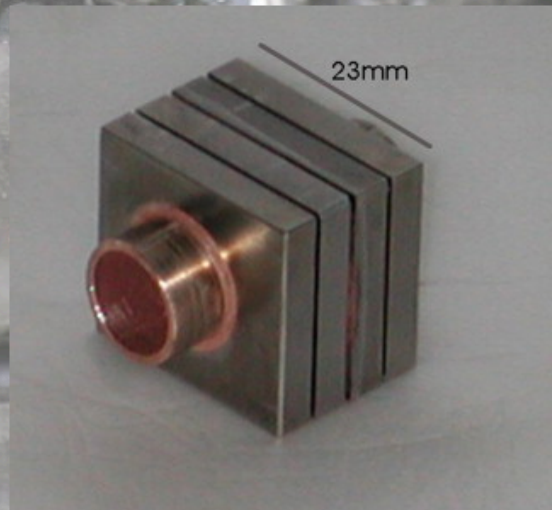


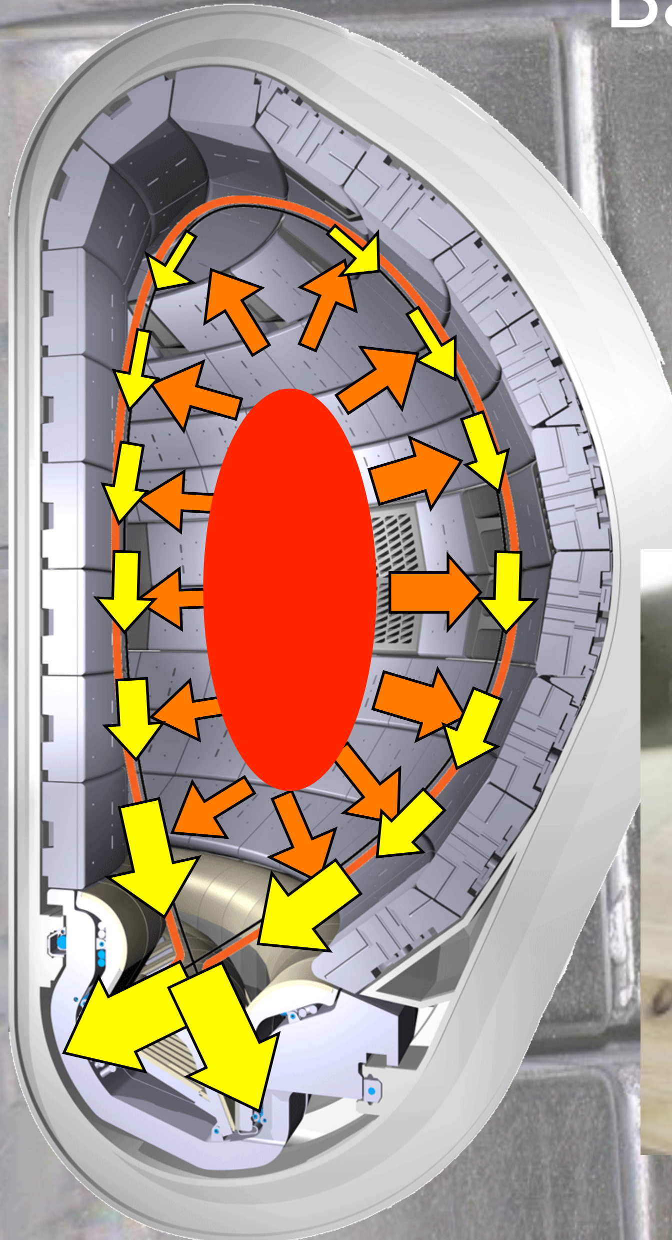
- Erosion
- First wall material properties
- Critical flux on divertor



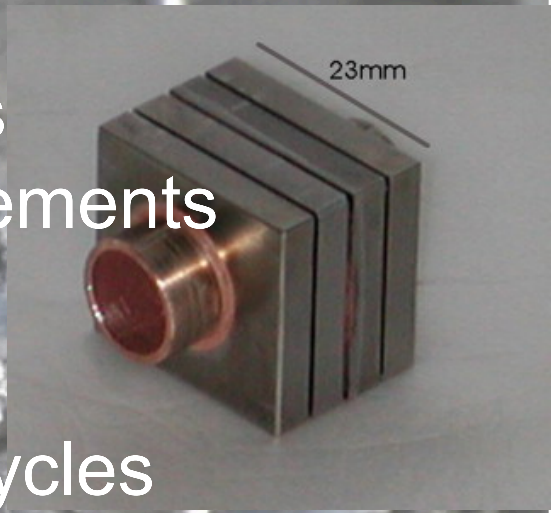
Up to 60MW/m² in a reactor

~ heat flux on the surface of the Sun!

Mission 2: Heat and particle exhaust
Baseline strategy



Present R&D results exceed ITER requirements

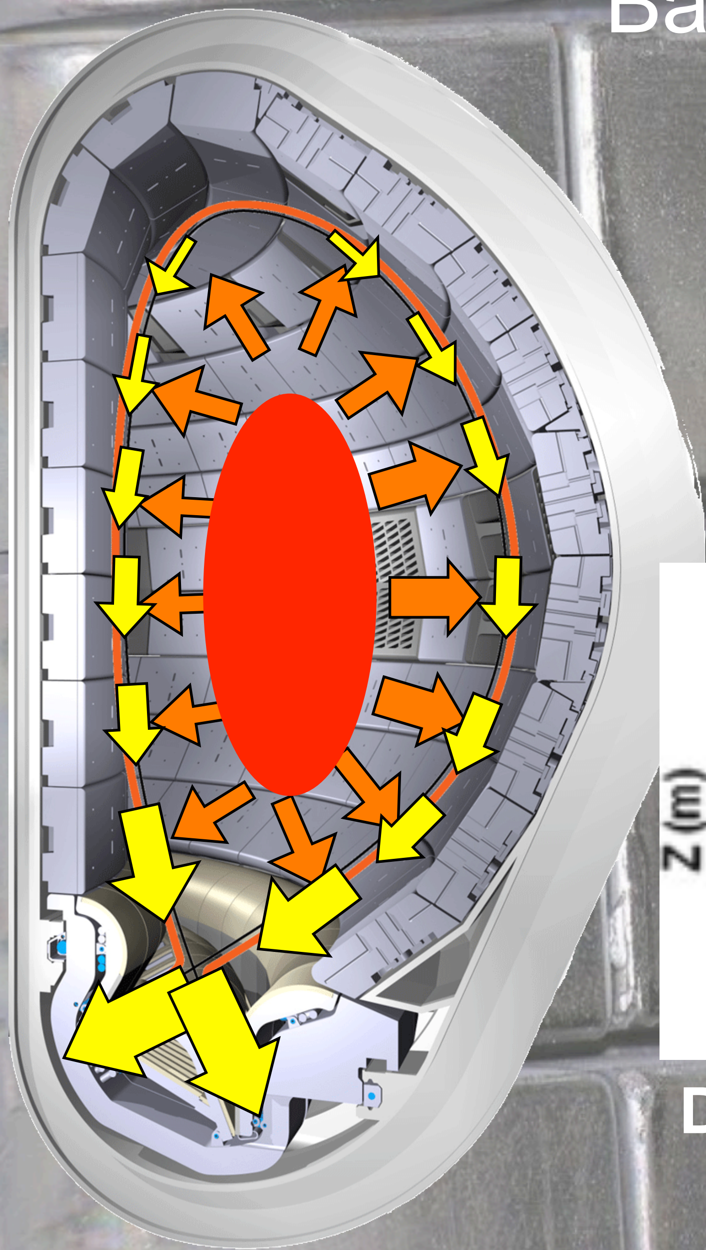


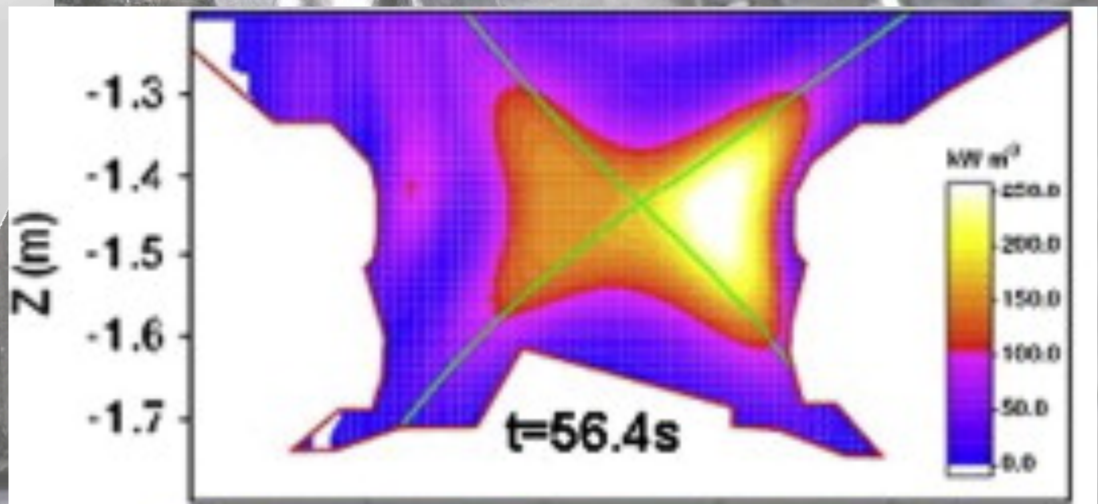
W monoblock:

10 MW/m² x 5000 cycles

20 MW/m² x 1000 cycles

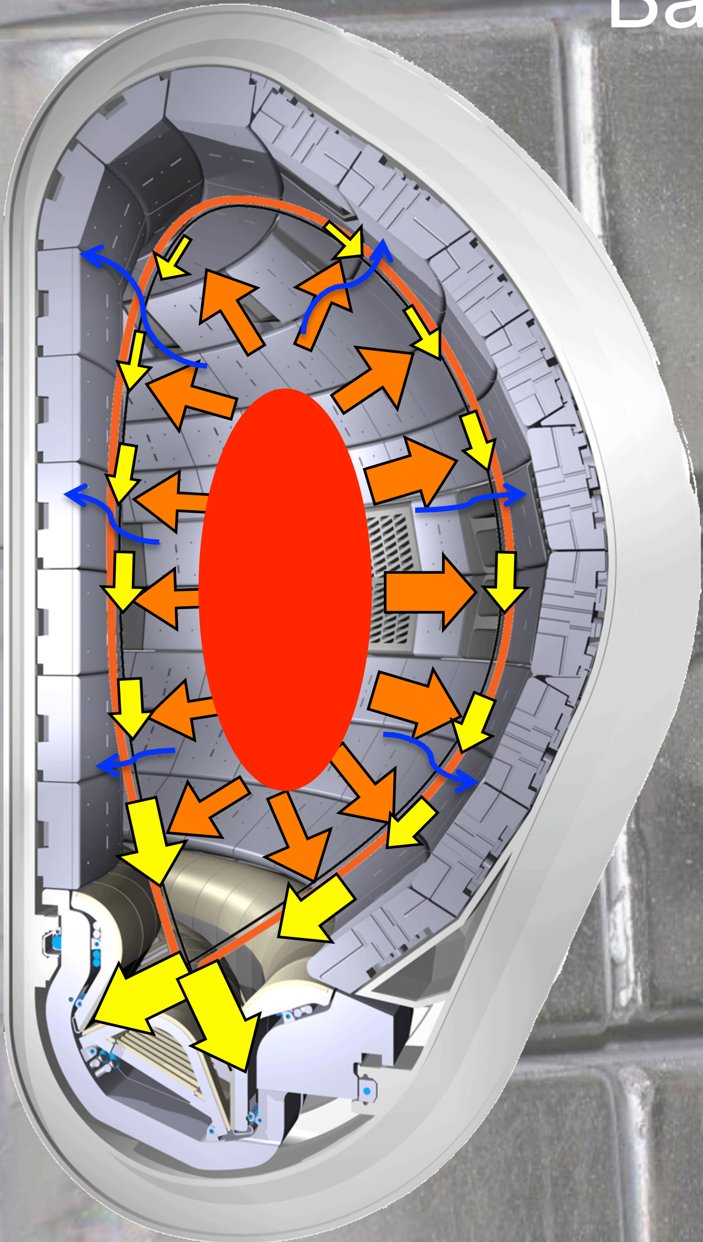
Mission 2: Heat and particle exhaust
Baseline strategy





Detached divertor conditions

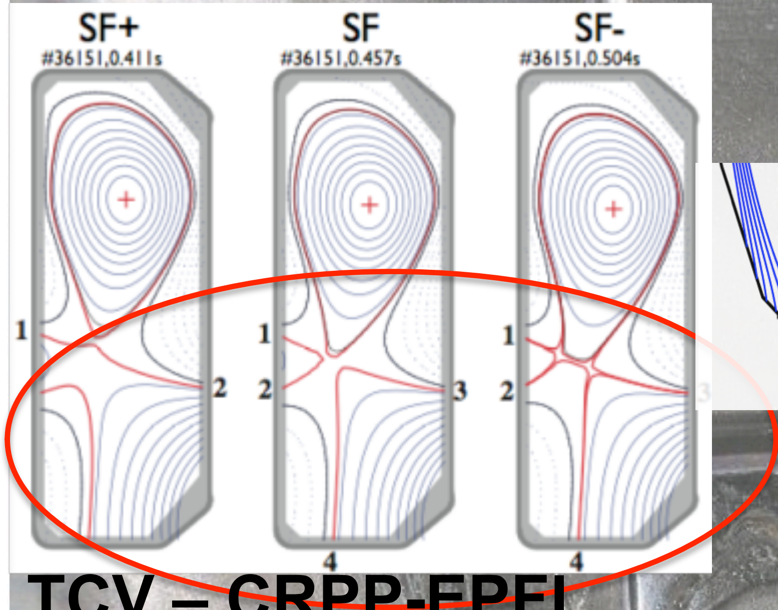
Mission 2: Heat and particle exhaust
Baseline strategy

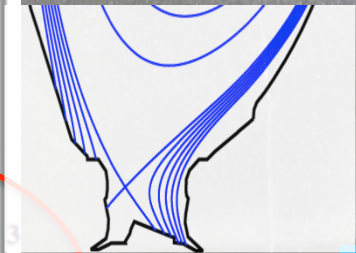


Extrapolation to DEMO of the baseline strategy requires to radiate a large fraction of the heating power (alpha + externally injected) on the main chamber wall.

Impact on Mission 1!

Mission 2: Heat and particle exhaust
Alternative strategies

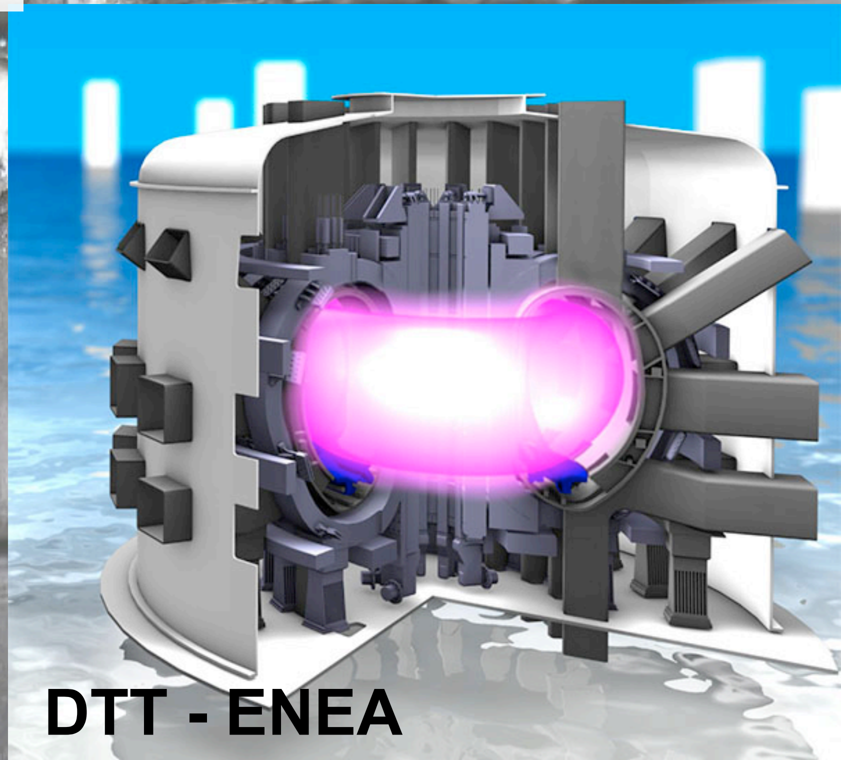




TCV – CRPP-EPFL

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 to be part of the EUROfusion activities.
Italian site selection ongoing.



The Roadmap in a nutshell

1. Plasma operation
2. **Heat exhaust**
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
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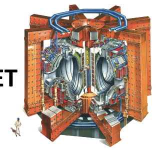
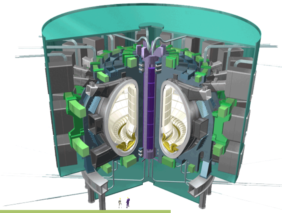
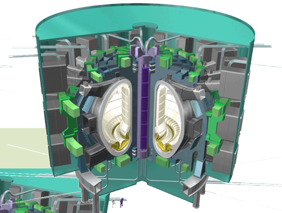
JET

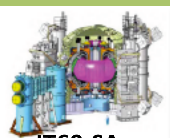






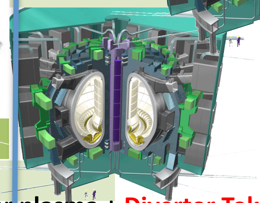
Inductive

Steady state



JT60-SA

European Medium Size Tokamaks + International Collaborators



Baseline strategy

Advanced configuration and materials

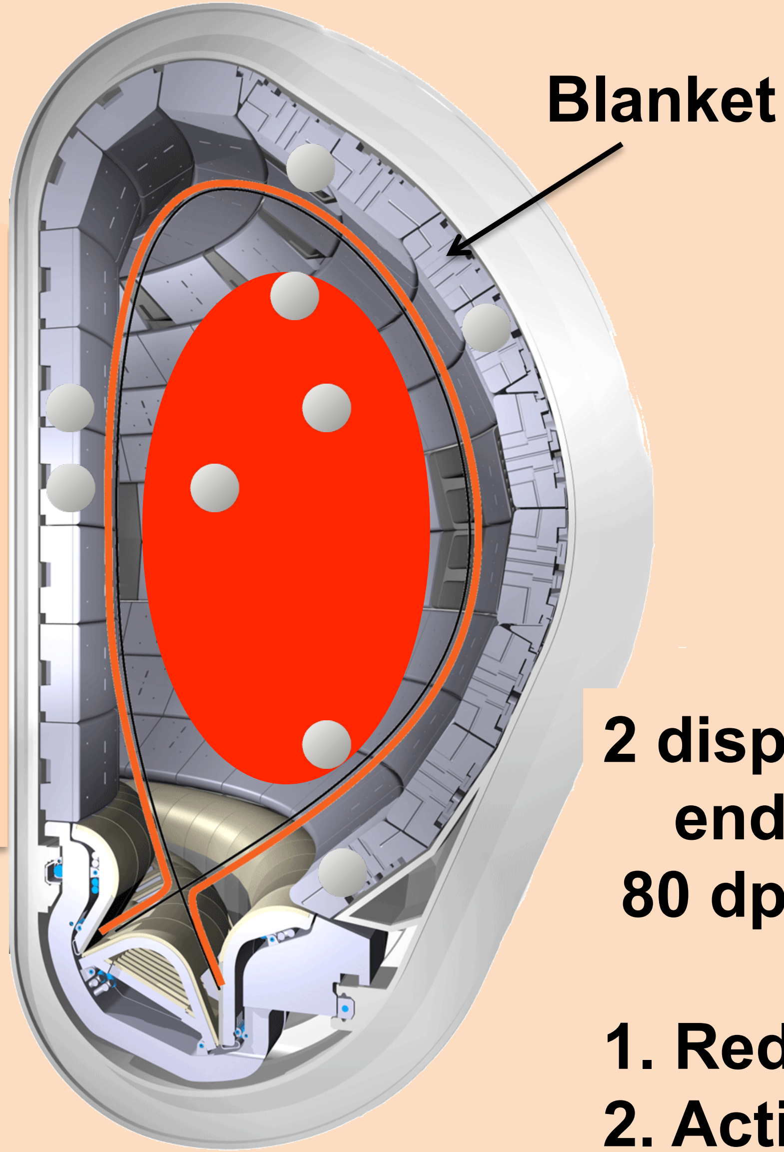
European Medium Size Tokamaks +linear plasma + Divertor Tokamak Test Facility + International Collaborators Tokamaks

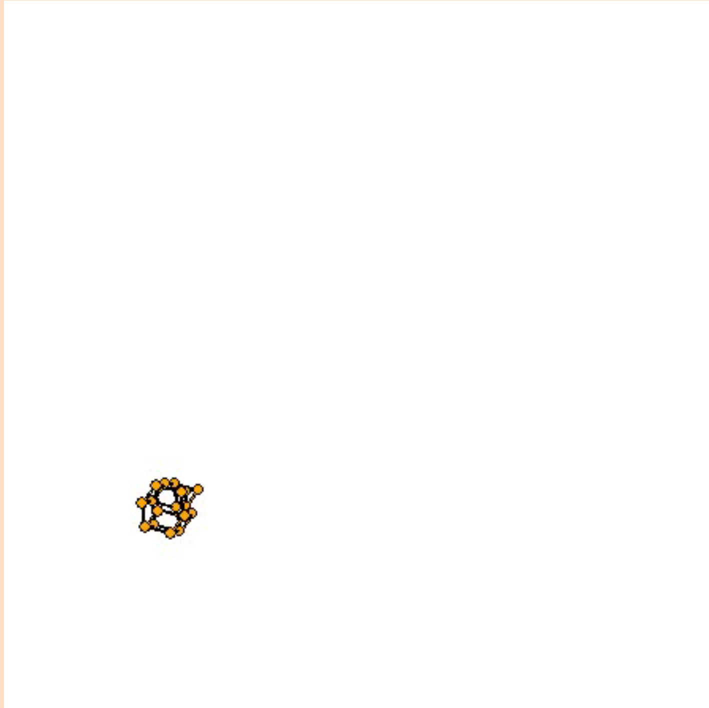
DEMO decision

2010

2050

Mission 3: Develop neutron resistant materials





S. Dudarev

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

80 dpa in DEMO after 4 full power years

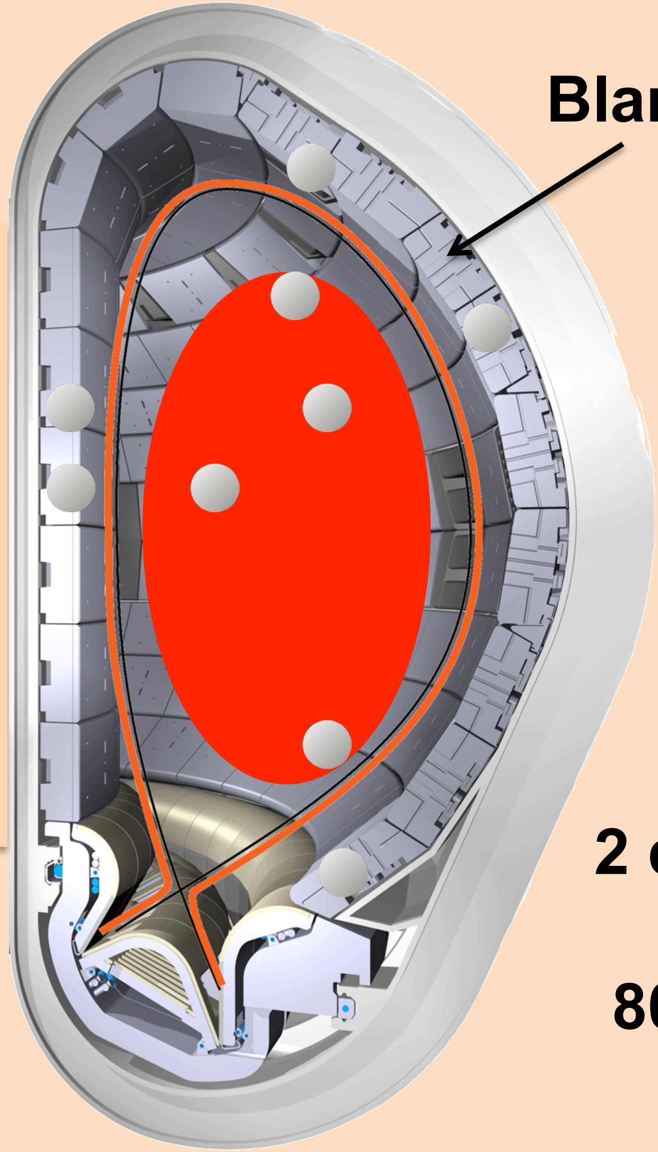
1. Reduction of structural properties

2. Activation

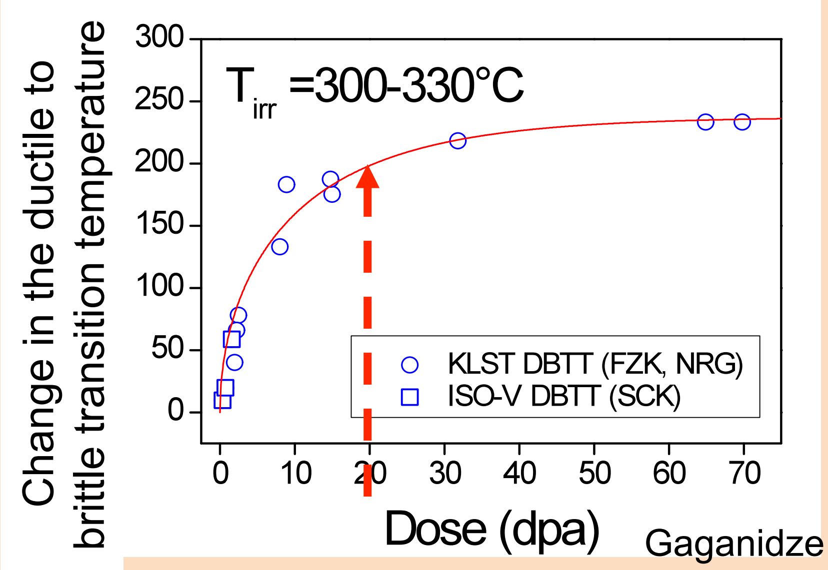
D. Stork et al.
Material Assessment Report

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

Mission 3: Develop neutron resistant materials



1. Steel becomes brittle under irradiation!



Gaganidze 2011

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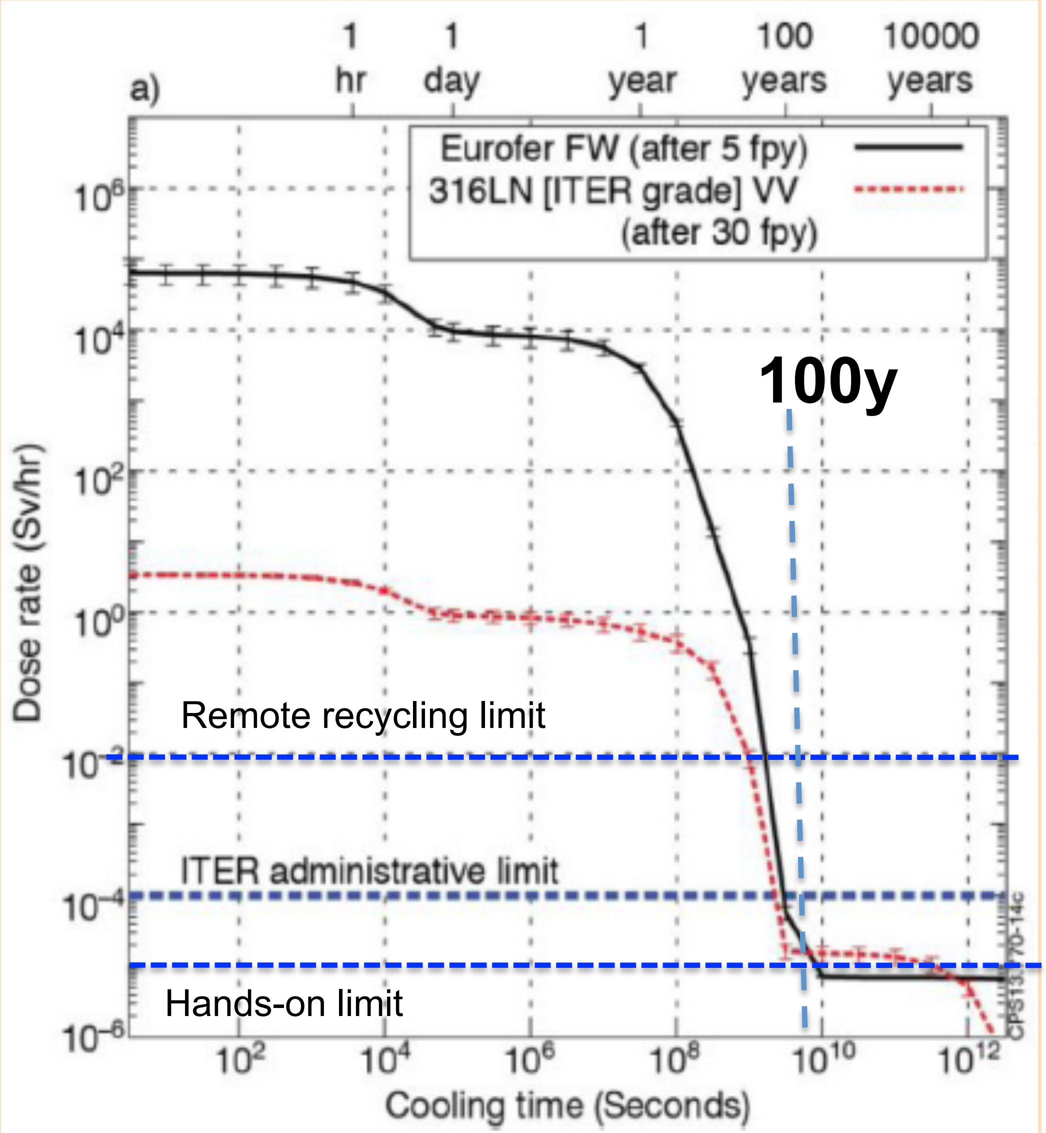
Mission 3: Develop neutron resistant materials

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

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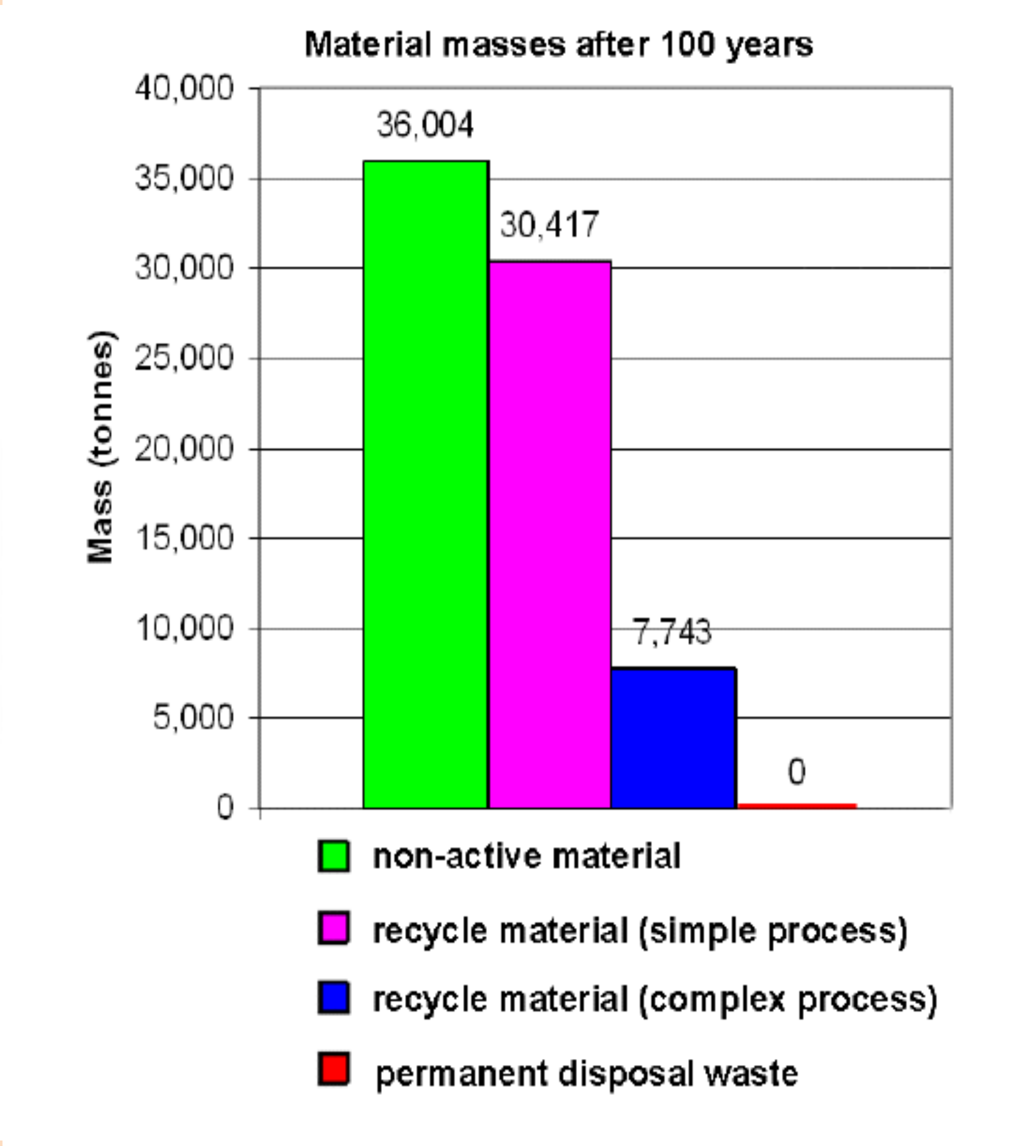
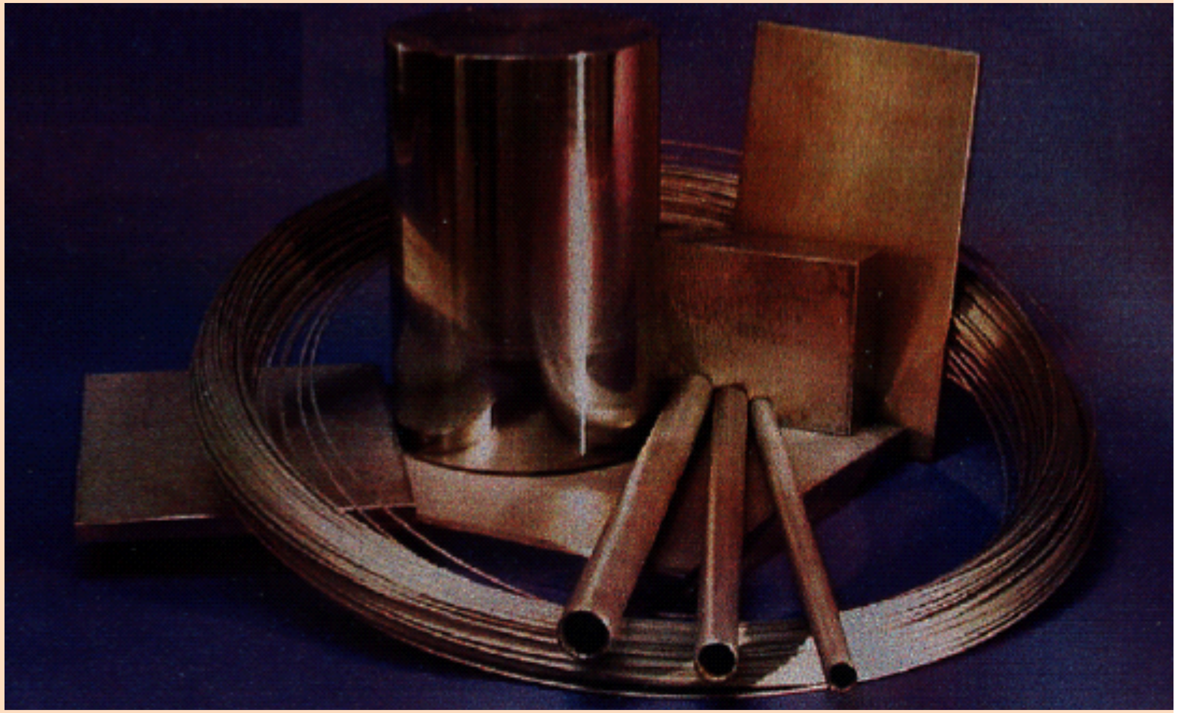


Stork et al. 2014

Mission 3: Develop neutron resistant materials

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

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



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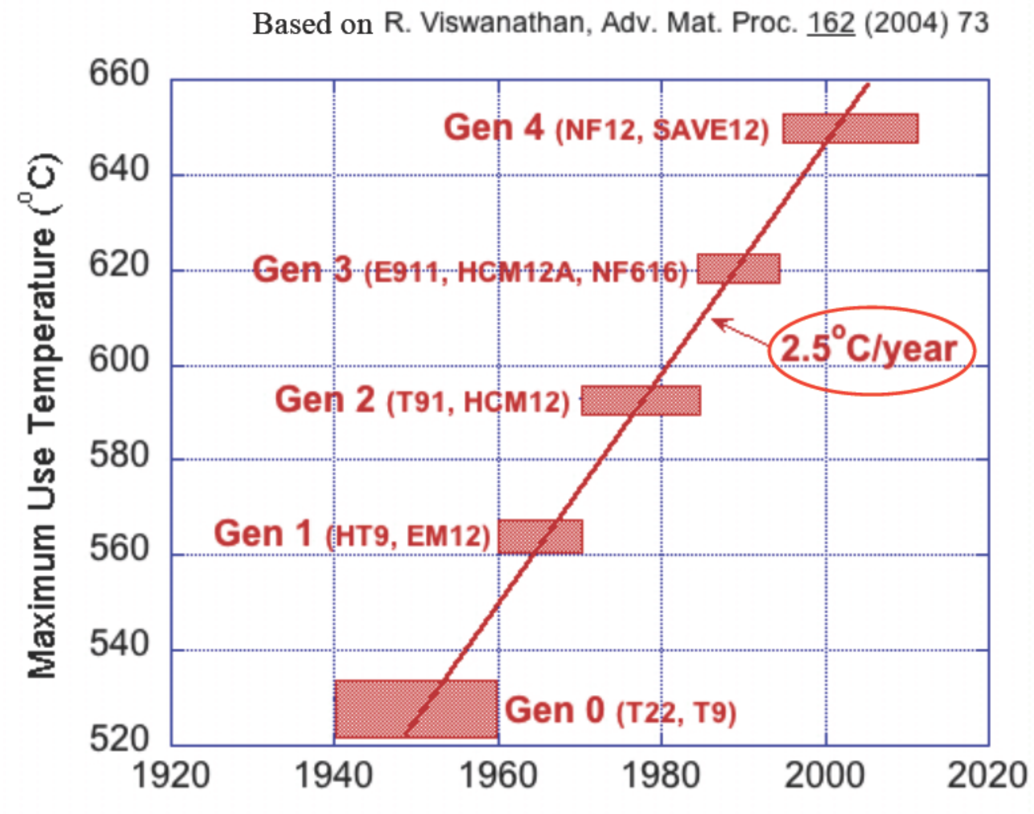

Mission 3: Develop neutron resistant materials

- 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.**

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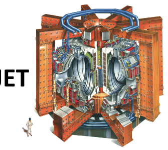
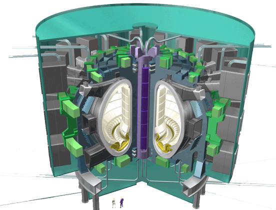
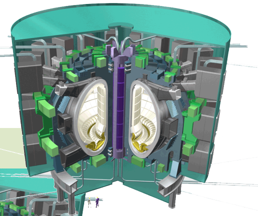
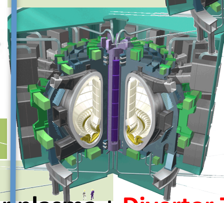
JET









Inductive

Steady state

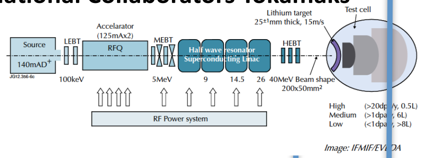
European Medium Size Tokamaks
+ International Collaborators

JT60-SA

Baseline strategy

Advanced configuration and materials

European Medium Size Tokamaks +linear plasma + Divertor Tokamak Test Facility +
International Collaborators Tokamaks

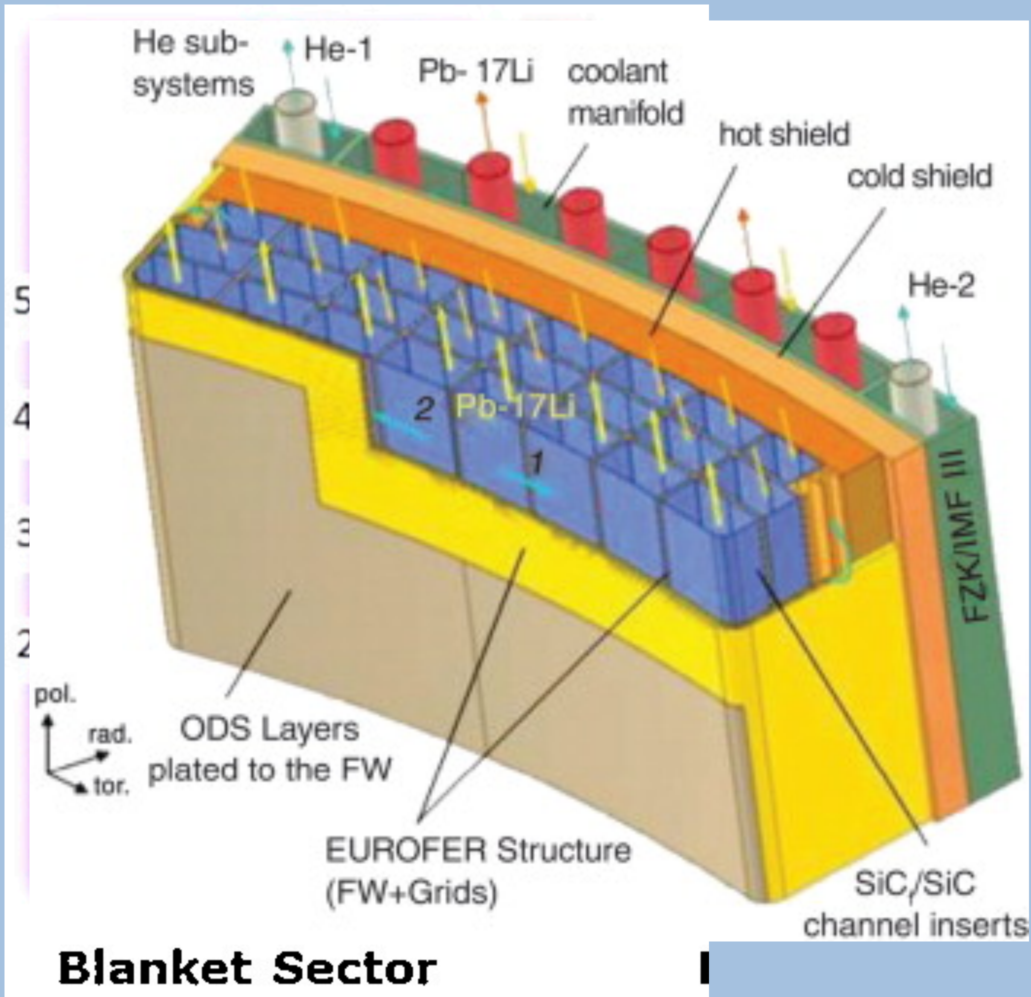


DEMO decision

2010

2050

Mission 4: Ensure 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.

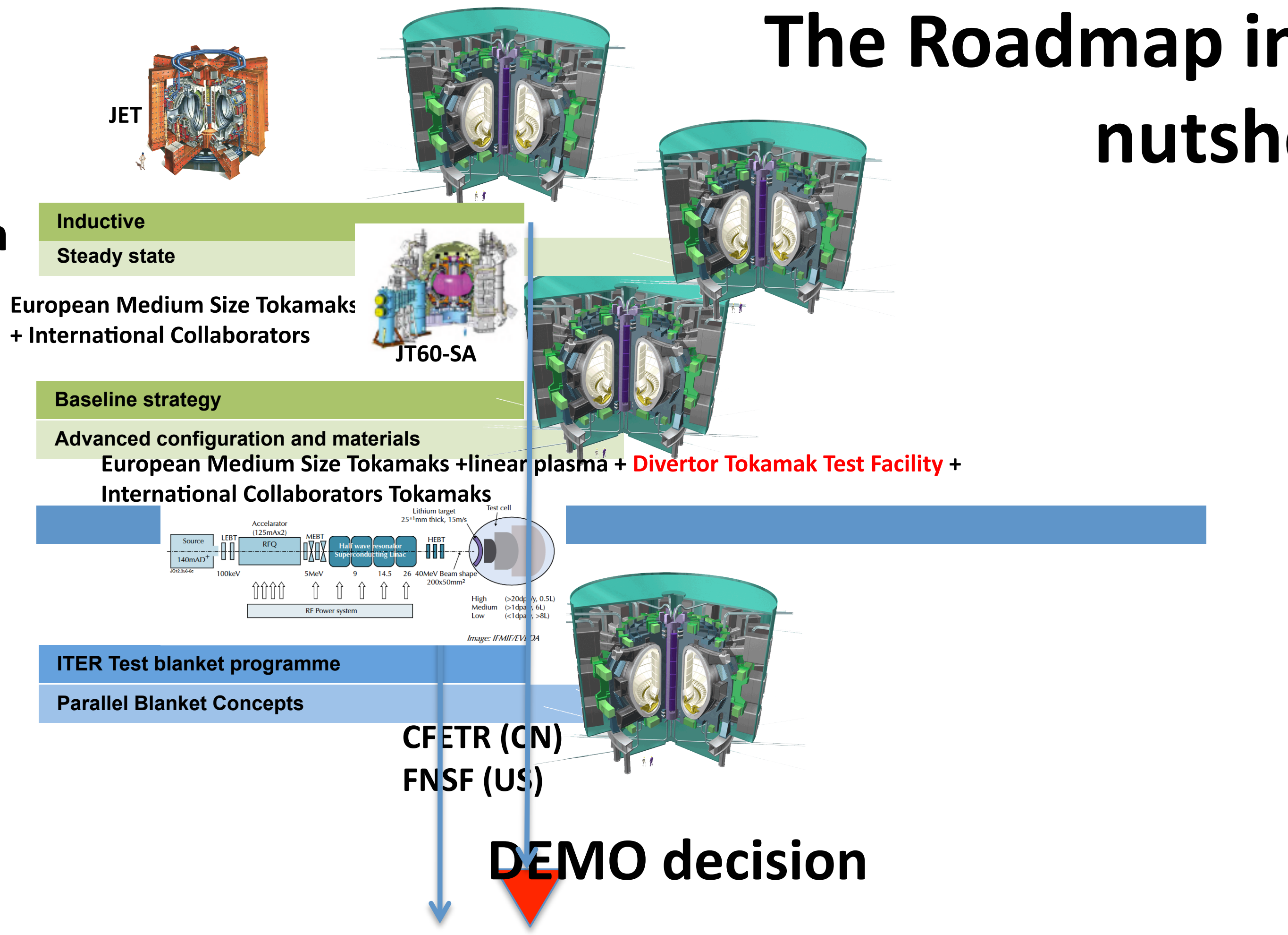
2. Multiply the neutrons (using Be or Pb) to ensure a tritium breeding ratio >1

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

4. Shield vessel and magnet from neutrons.

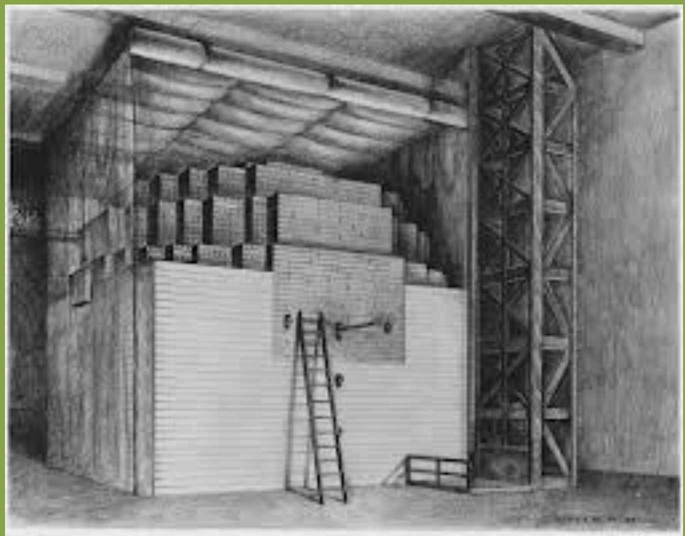
The Roadmap in a nutshell

1. Plasma operation
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
7. Low cost
8. Stellarator

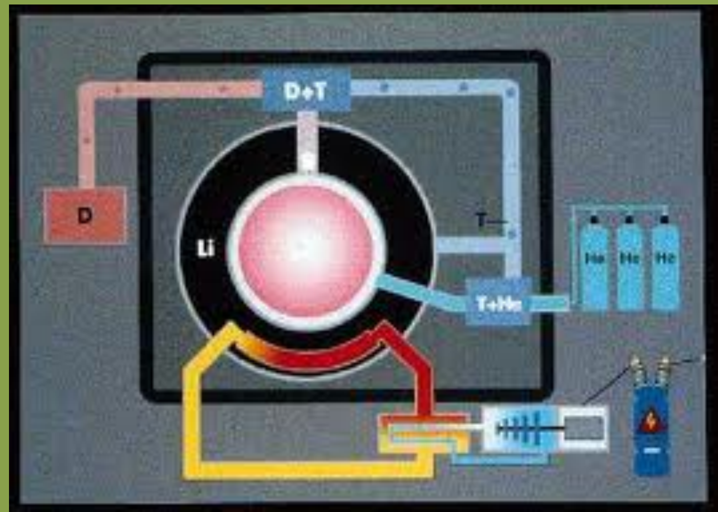


2010 — 2050

Mission 5: Implementation of inherent fusion safety features in DEMO design

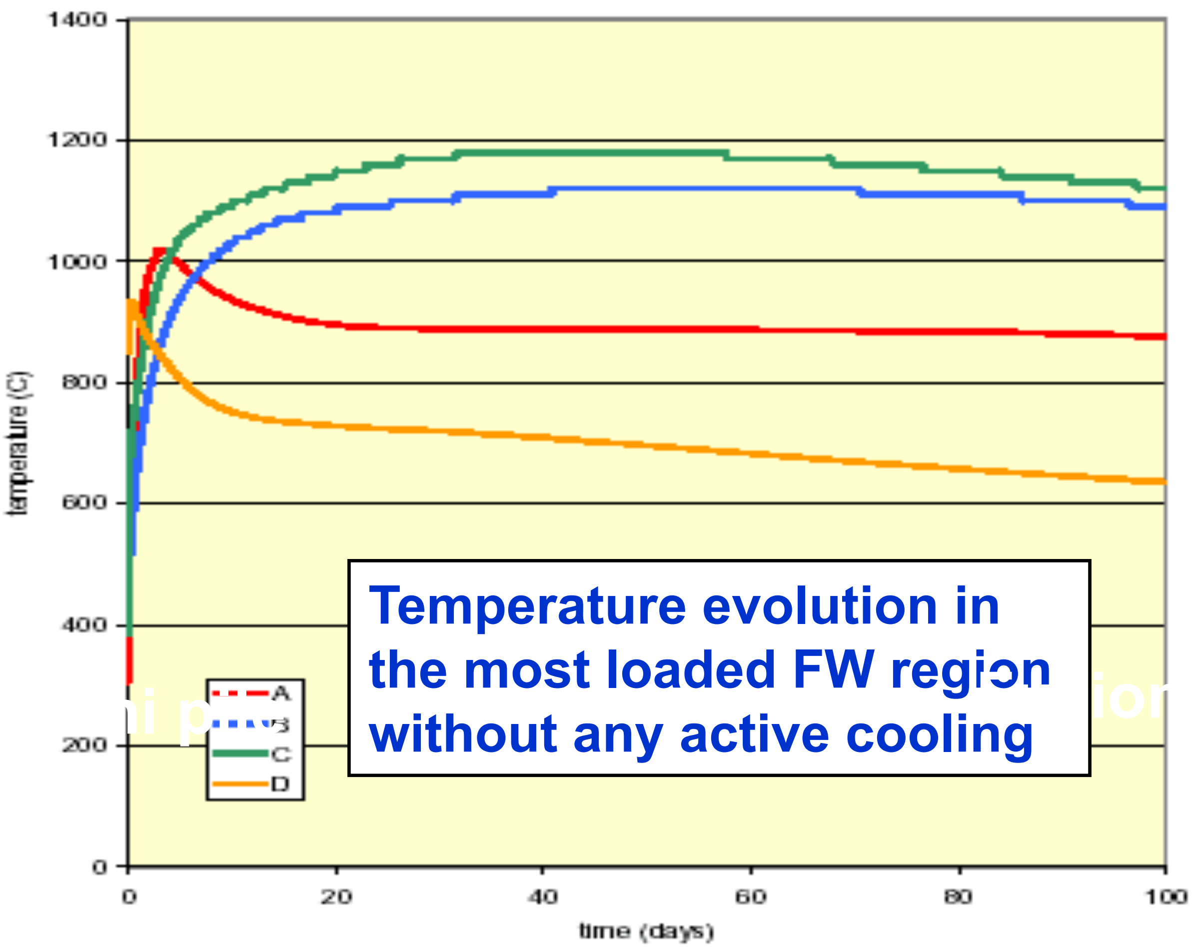


Fermi pile



Fusion reactor

Mission 5: Implementation of inherent fusion safety features in DEMO design

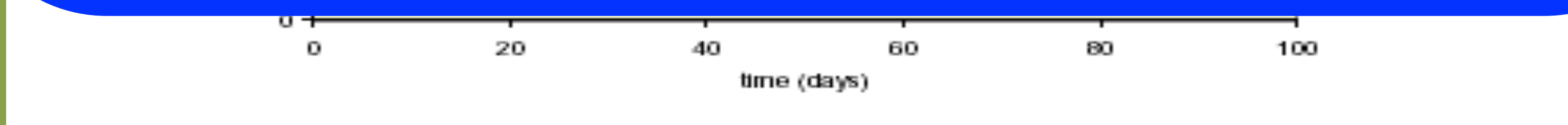


Mission 5: Implementation of inherent fusion safety features in DEMO design

Primary safety boundary the vacuum vessel (ITER approach)

Tritium management: define appropriate detritiation techniques and disposal routes

Reduced activation features expected to be incorporated already for the first set of DEMO components.



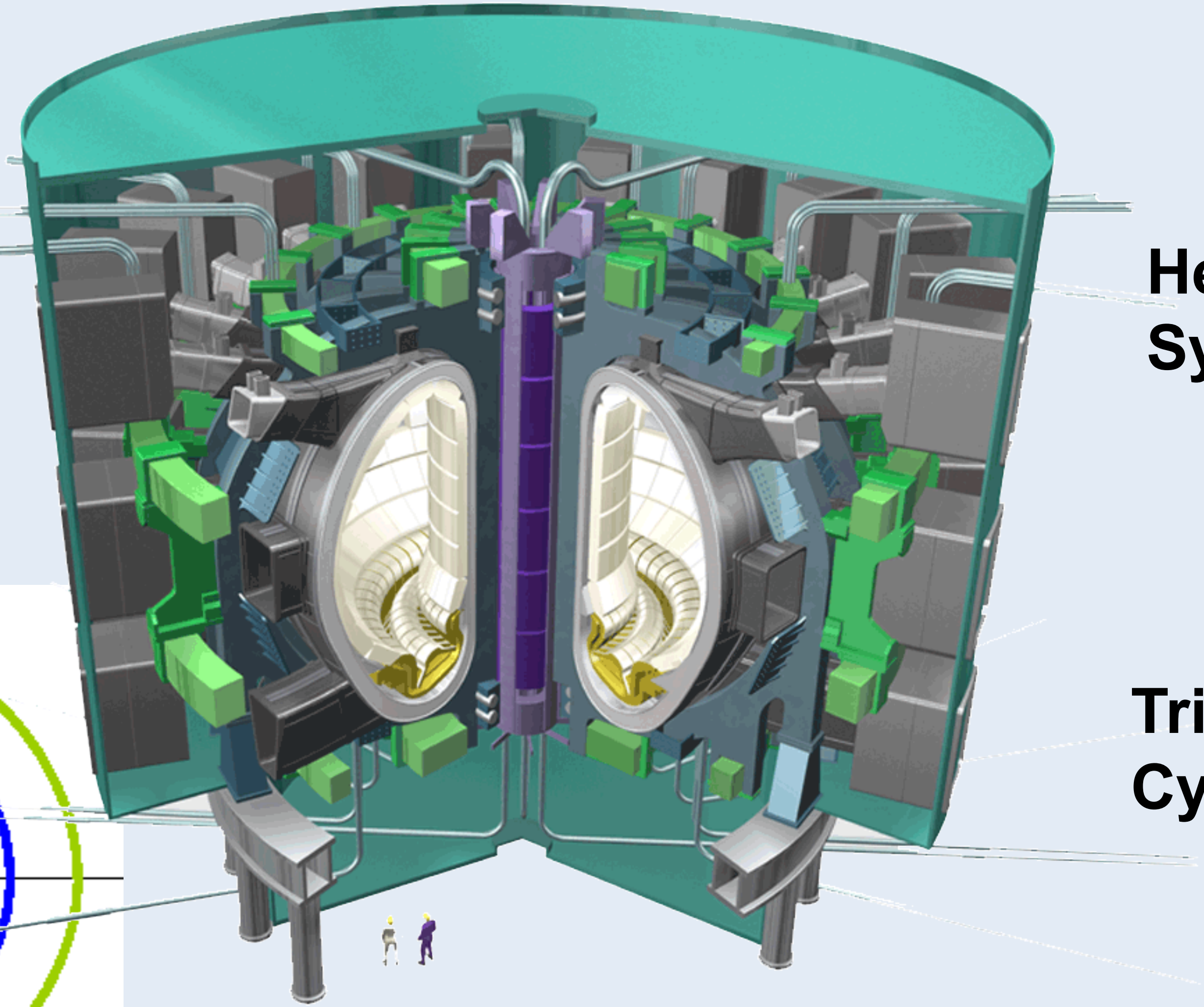
Mission 6: DEMO design

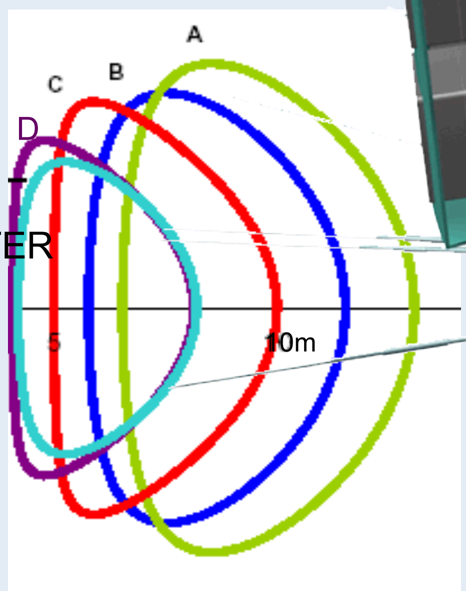
Balance of Plant

Magnets

Heating Systems

Vacuum Vessel



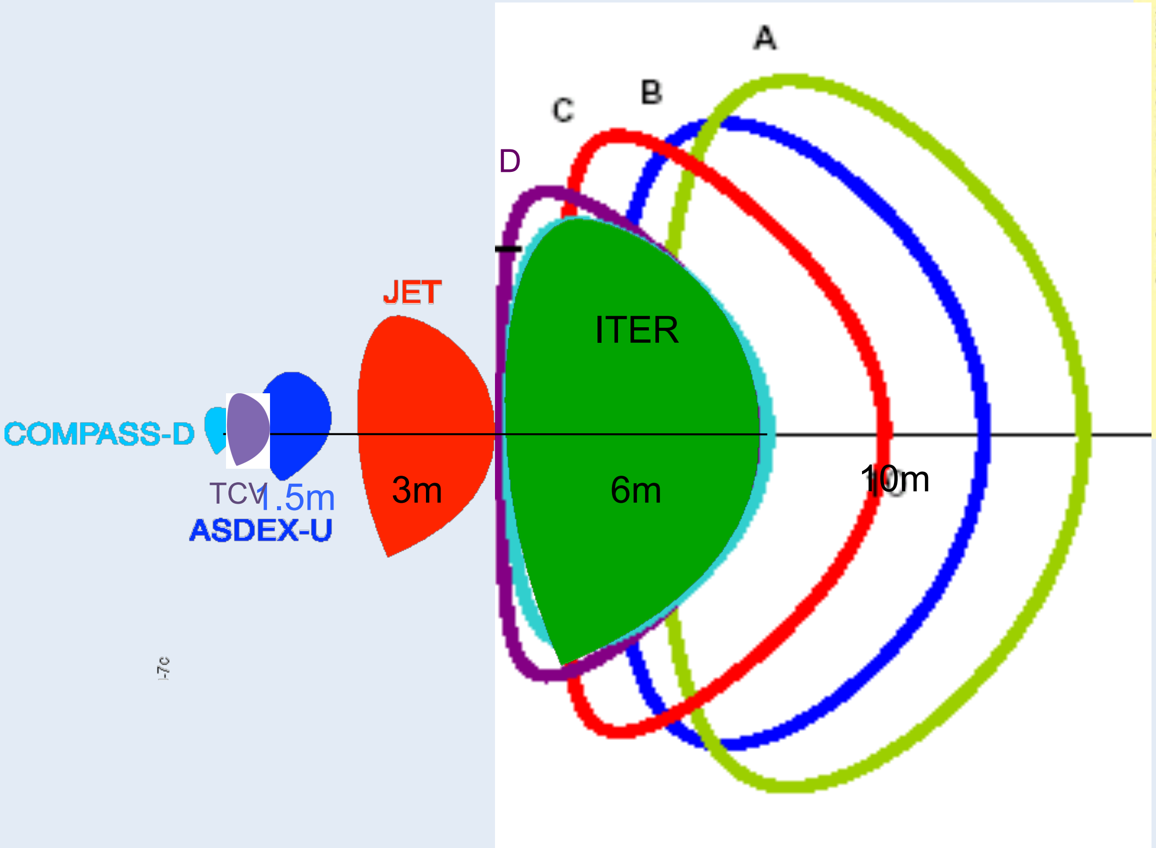


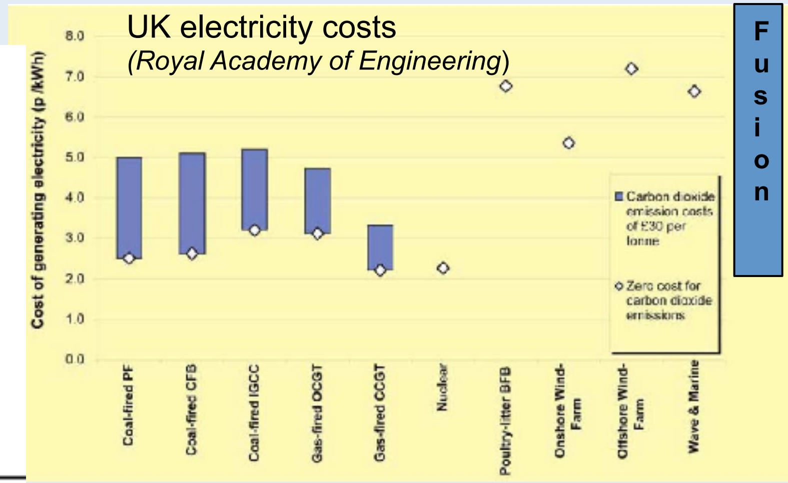
Tritium Cycle

Remote Handling

[redacted]

Mission 7: Low cost of electricity

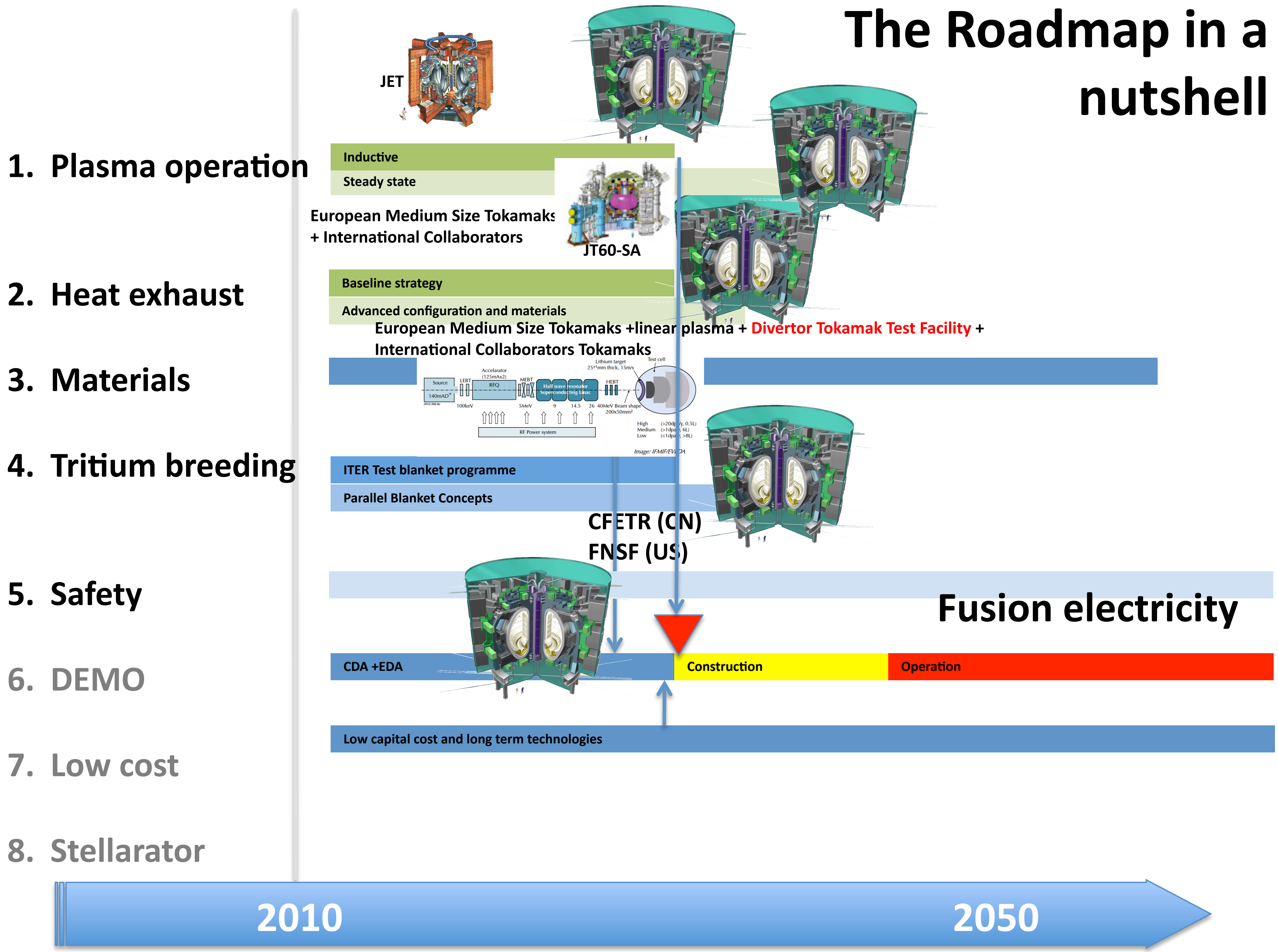




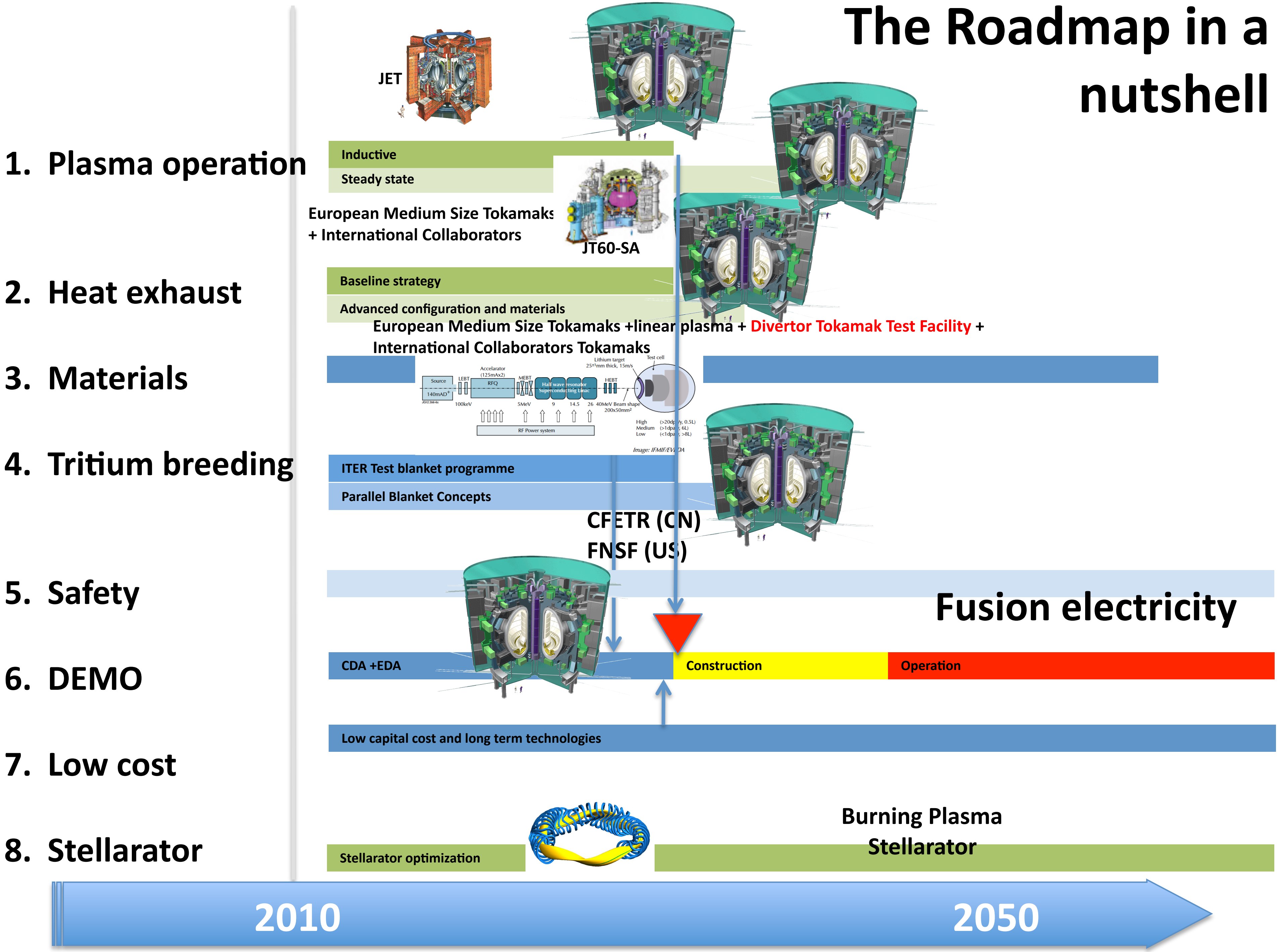
Cost of electricity from fusion expected to be competitive with other sources (IEA Levelised Cost Approach)

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 in a nutshell
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
2010
2050

The Roadmap in a nutshell



Opportunities for education and training in Fusion

- The Roadmap supports education in fusion (8M€/y for PhD) and training (7M€/y) with about 30 post-doc positions per year.
- A number of initiatives exist in Italy in support of education in fusion

2nd level Master in Fusion Energy at University of Rome “Tor Vergata”

1. **Physics basis.**
2. **Plasma control and diagnostics.**
3. **Additional heating.**
4. **Inertial confinement.**
5. **Neutronics.**
6. **Plasma-wall interaction and material development.**
7. **Fuel cycle, safety and health physics.**
8. **Reactor engineering 1.**
9. **Reactor engineering 2.**

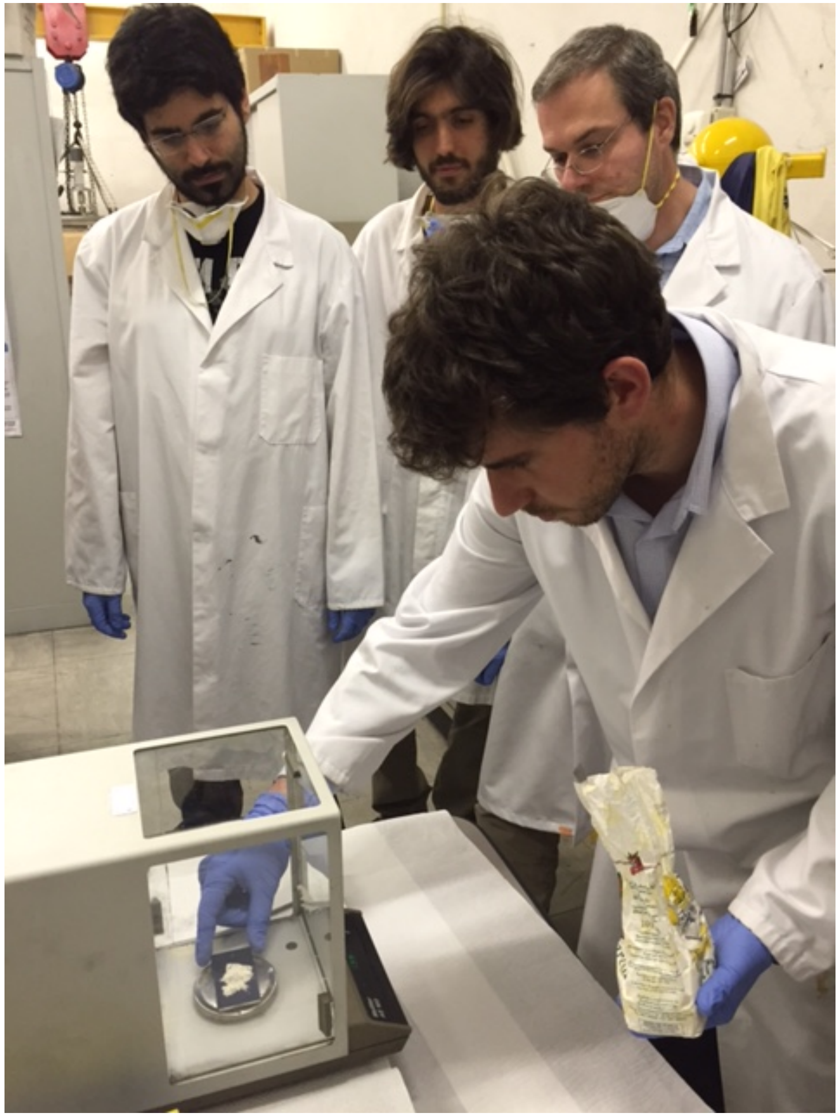
10a Physics II.

10b Project management and quality control

Industrial partners involved with the Master in Fusion Energy

- The Italian industry is heavily involved in the ITER construction (~1Beuros of industrial contracts).

Master in Fusion Energy Organization



- For each module
  - 1 week of frontal lectures
  - 2 weeks for the remote preparation.
  - Final test on the Monday of the next module
  - Stages are foreseen starting from Module 5
- The stage includes:
  - Laboratory activities
  - Seminars and meeting with industries.
  - Extra interaction (on request) with the lecturers
- **After the completion of the modules it is foreseen a stage of a duration of 2-3 months for the preparation of the Master thesis in the industrial partners, ENEA and Tor Vergata**

Link with the Doctorate

- A certain number of PhD student positions financed by industries operating in fusion energy will be reserved for those already possessing a Master in Fusion Energy with the PhD work mostly undertaken at the laboratories and plants of the financing industry.
- The PhD students with a Master in Fusion Energy can access directly the second year of the PhD course.