FUSION ENERGY

Joint EPS-SIF School on Energy 2019
Varenna
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Outline

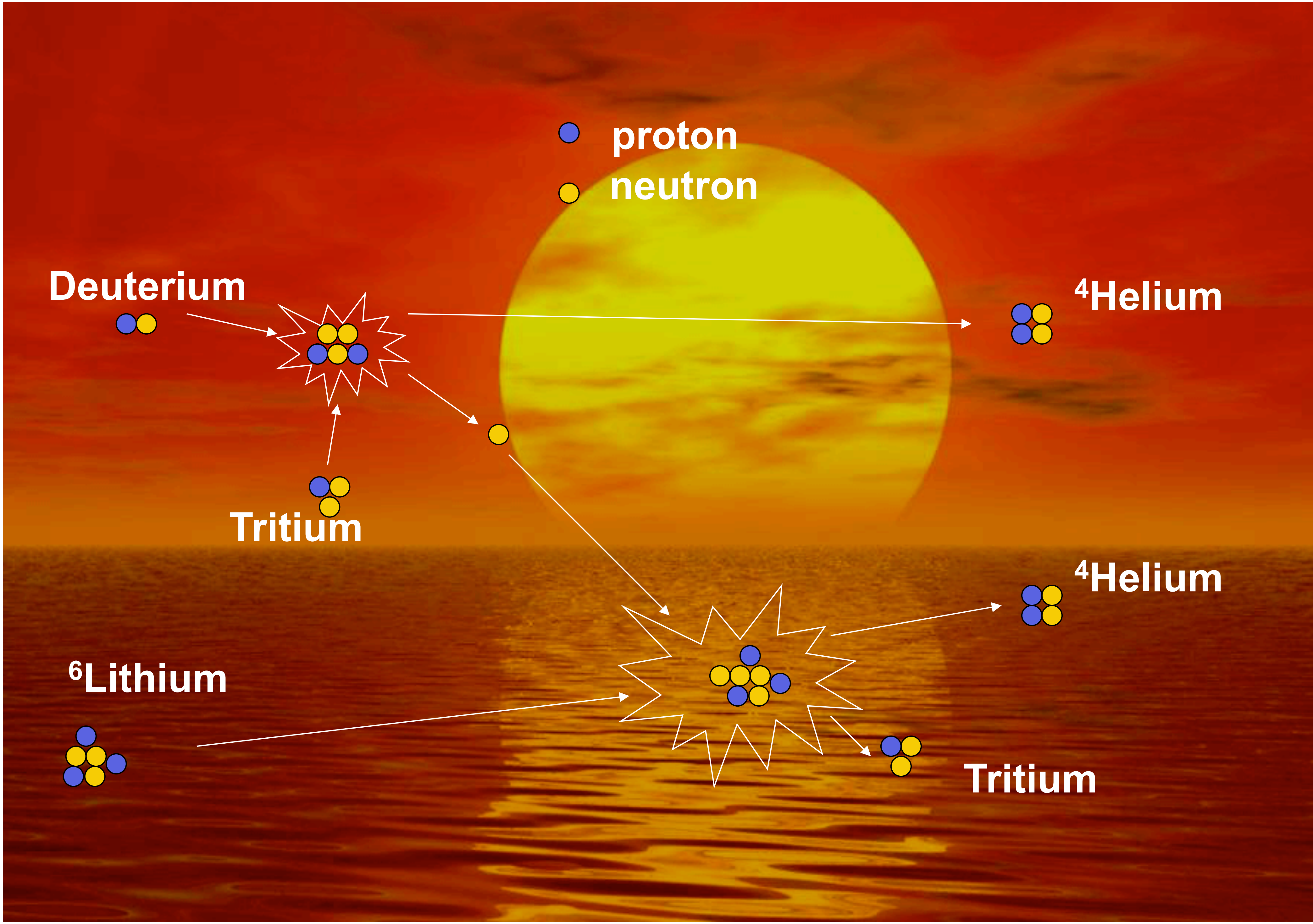
1. Background: how thermonuclear plasmas are confined.
2. The physics of burning plasmas - ITER
3. Fusion electricity – DEMO

Energy challenges for Europe

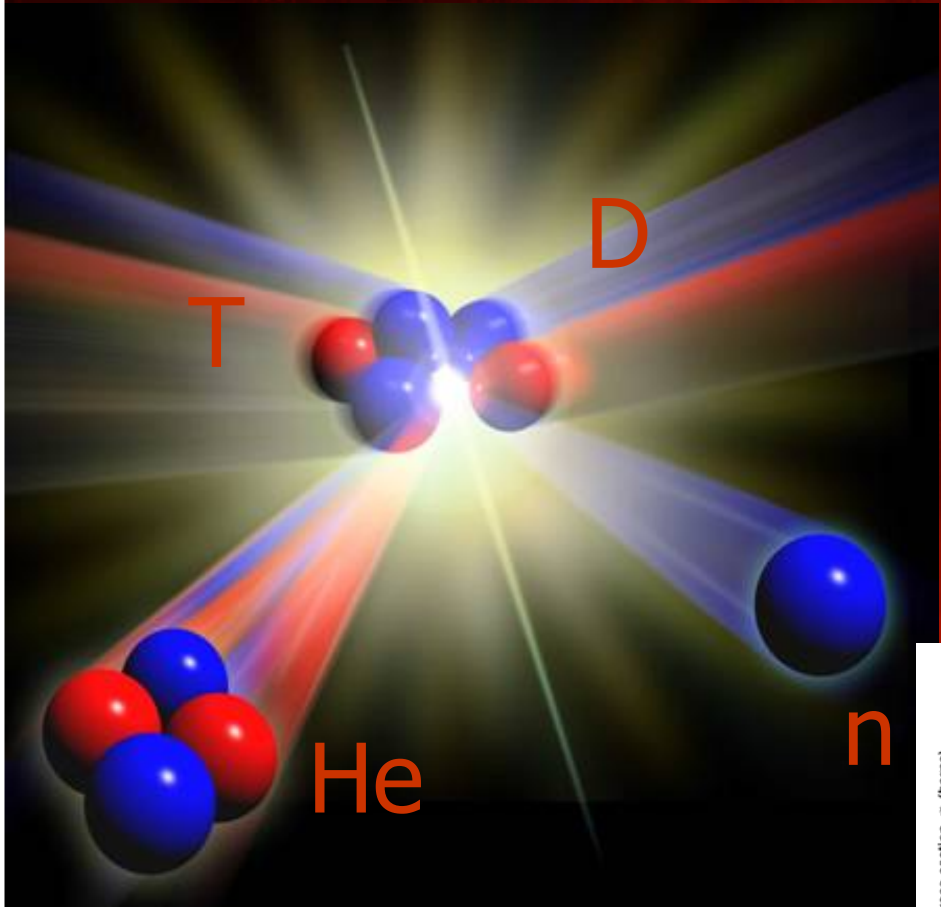
- Sustainability
- Security of supply
- Economic competitiveness

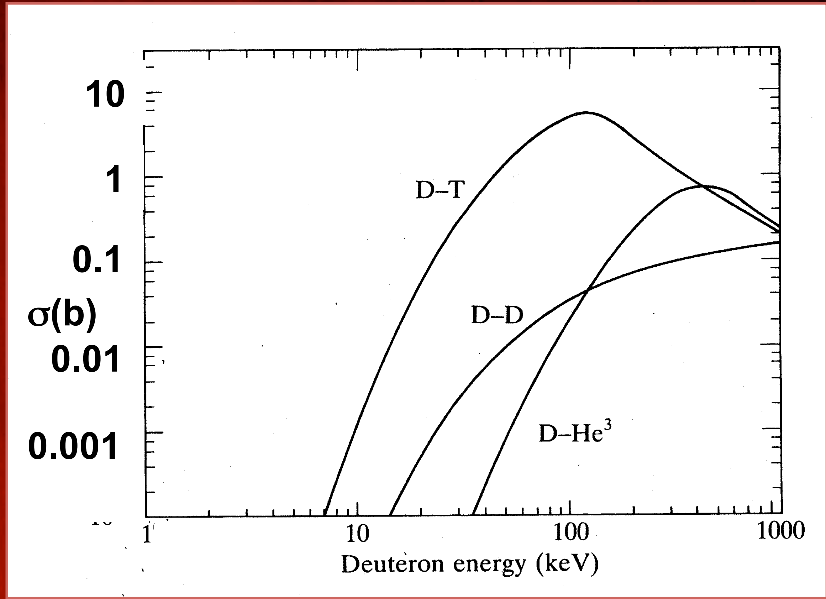
Fusion Energy

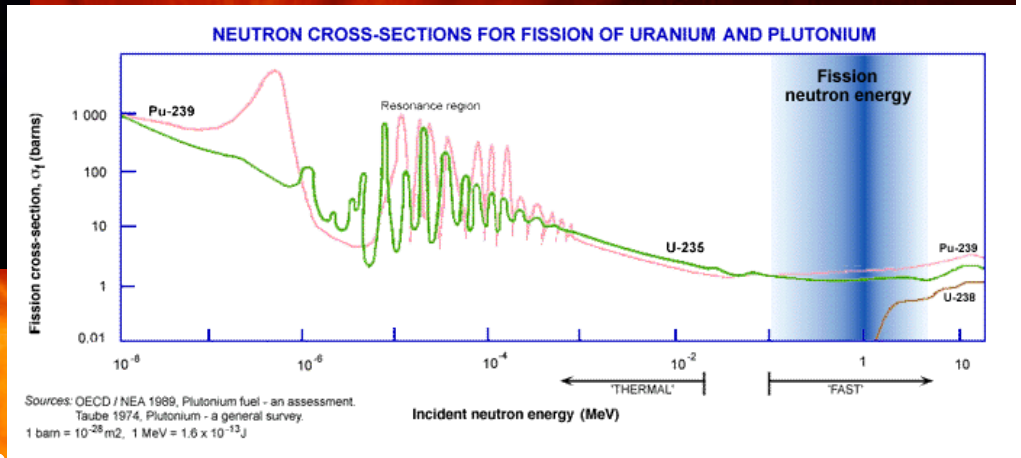
- Unlimited and diffuse energy source
- No greenhouse gases
- Intrinsically safe
- Environmentally responsible


proton
neutron
Deuterium
4Helium
Tritium
4Helium
6Lithium
Tritium

Background on fusion







Reacting nuclei are charged

⇒ they repel each other

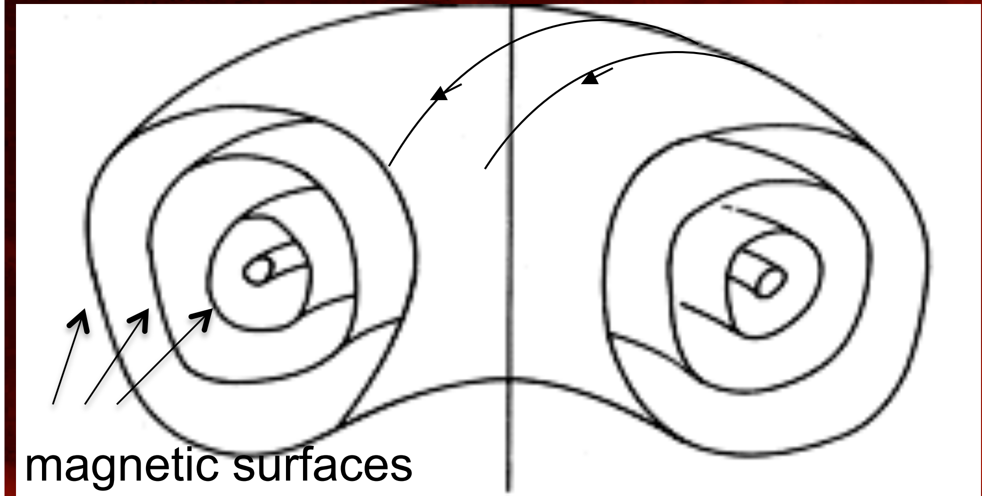
⇒ Heat nuclei up to 200Million °C

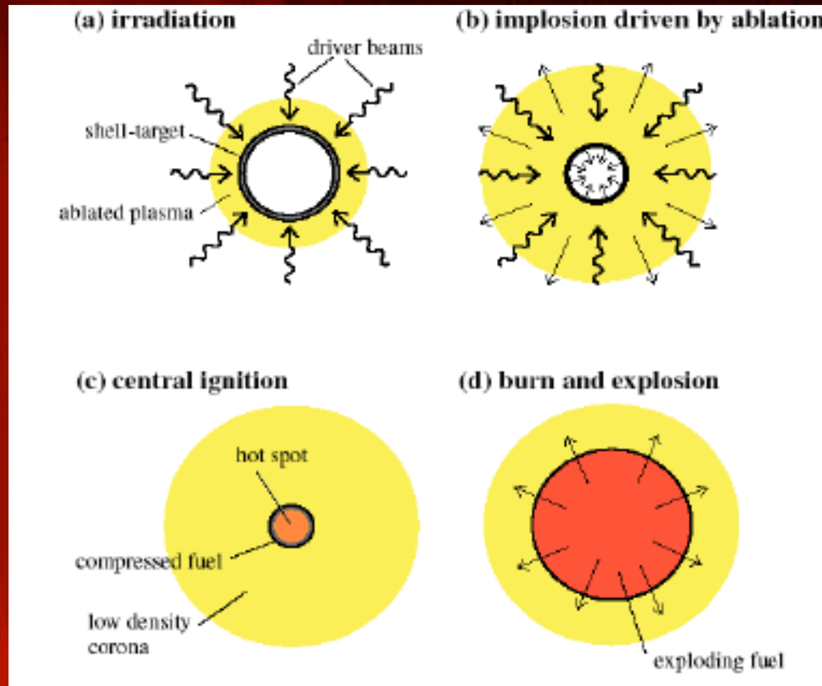
Matter is in the *plasma* state

1eV ~ 11600 K

Inertial confinement

Magnetic confinement

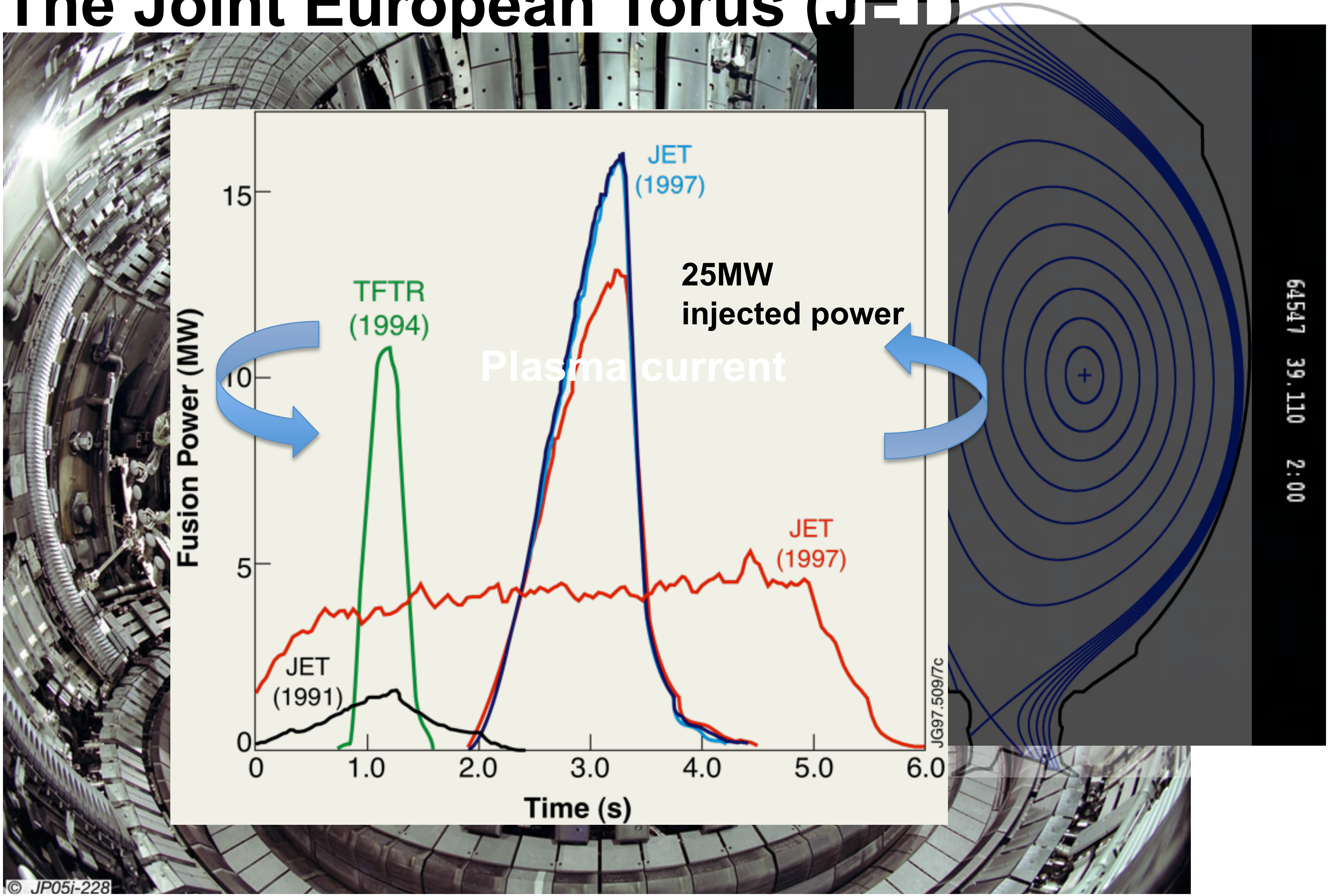




- **Intense magnetic field** (100000 x the earth magnetic field) produced by external coil and plasma current
- **Toroidal shape**

Spherical target irradiated
Ablated material drives implosion
If compression sufficiently large the plasma ignite
Energy released as a small Explosion
S. Atzeni and J. Meyer-ter-Vehn
***The Physics of Inertial Fusion* 2004**

The Joint European Torus (JET)

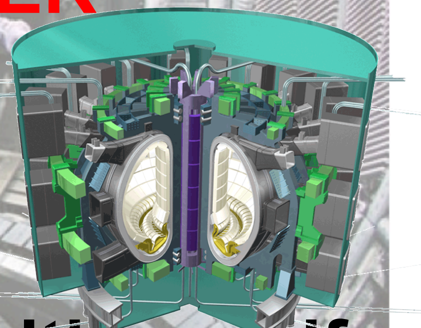


The challenge of confining a plasma

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**

The Roadmap to fusion electricity

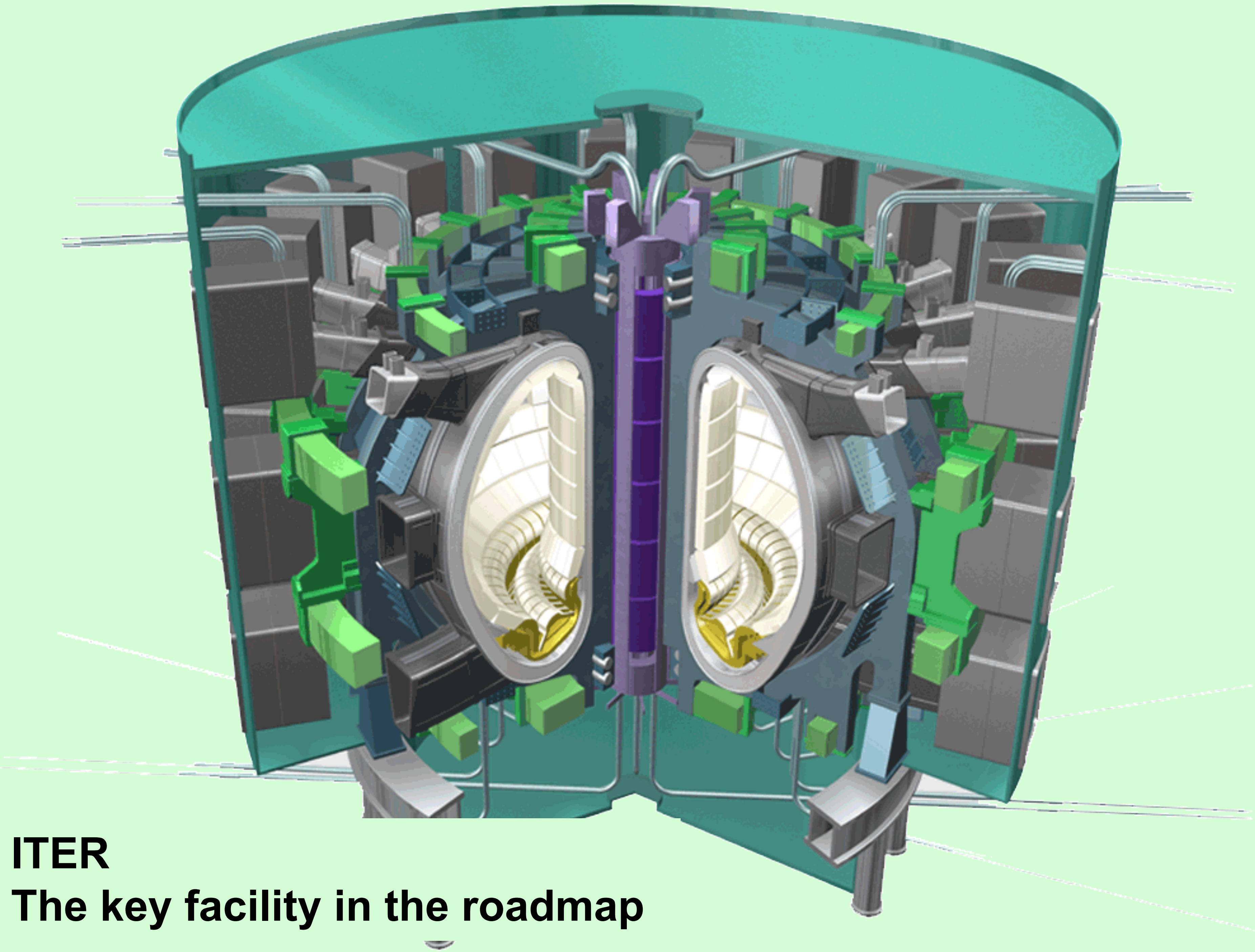
European Commission proposal for Horizon 2020 stated the need of *an ambitious yet realistic roadmap to fusion electricity by 2050*.

➔ Require DEMO construction in ~ 2030

A Roadmap was elaborated in 2012

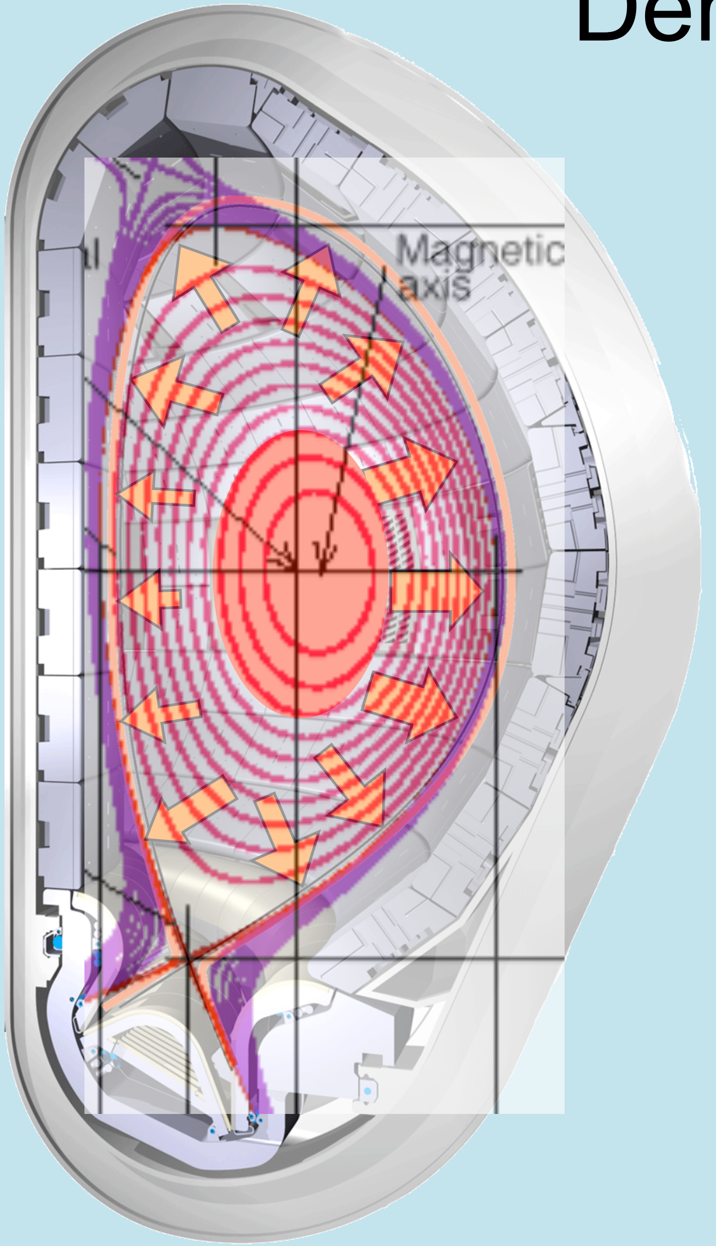
- **Pragmatic approach to fusion energy.**
- **Focus the effort of European laboratories around 8 Missions**
- **Ensure innovation through early industrial involvement**
- **Exploit the opportunities arising from international collaborations**

Latest Roadmap update available on the EUROfusion web site



ITER
The key facility in the roadmap

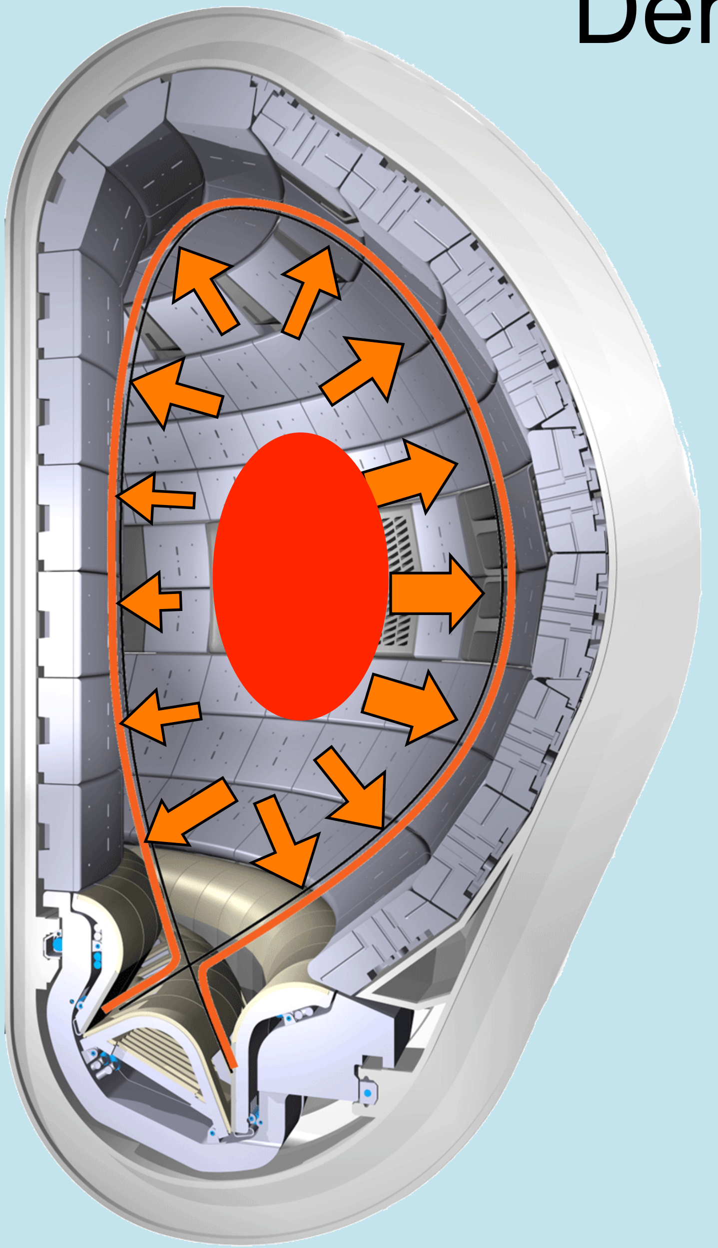
Challenge 1: Plasma regimes for a reactor
Demonstrate a net energy gain



Code: **GYRO**

Authors: Jeff Candy and Ron Waltz

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

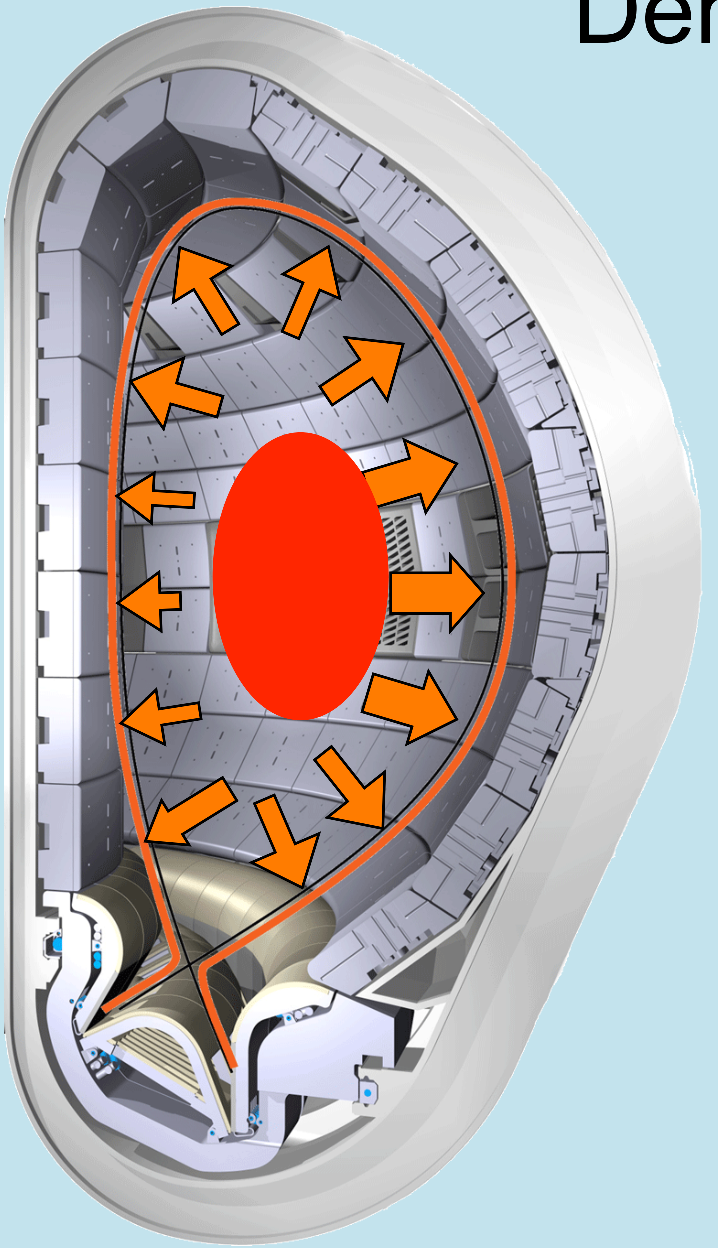


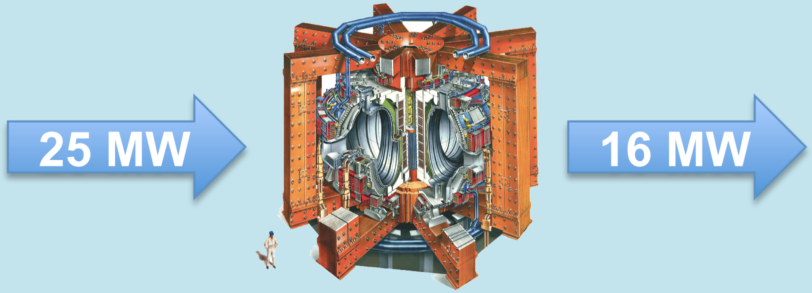
- Power losses increase at most as the radius R of the device

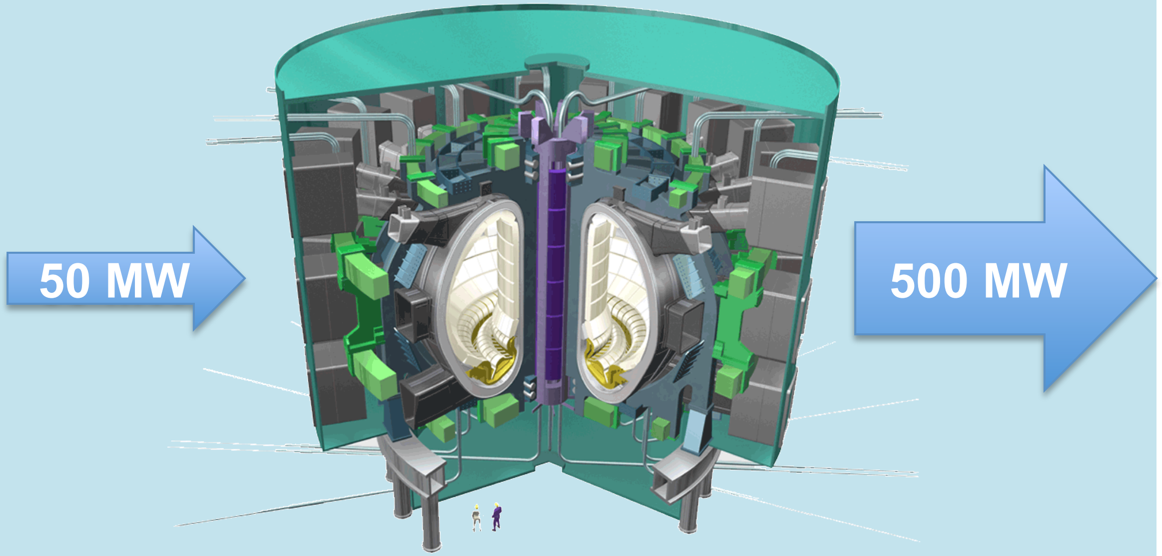
- Fusion power increases as the volume ($\approx R^3$)

MAKE LARGER DEVICES

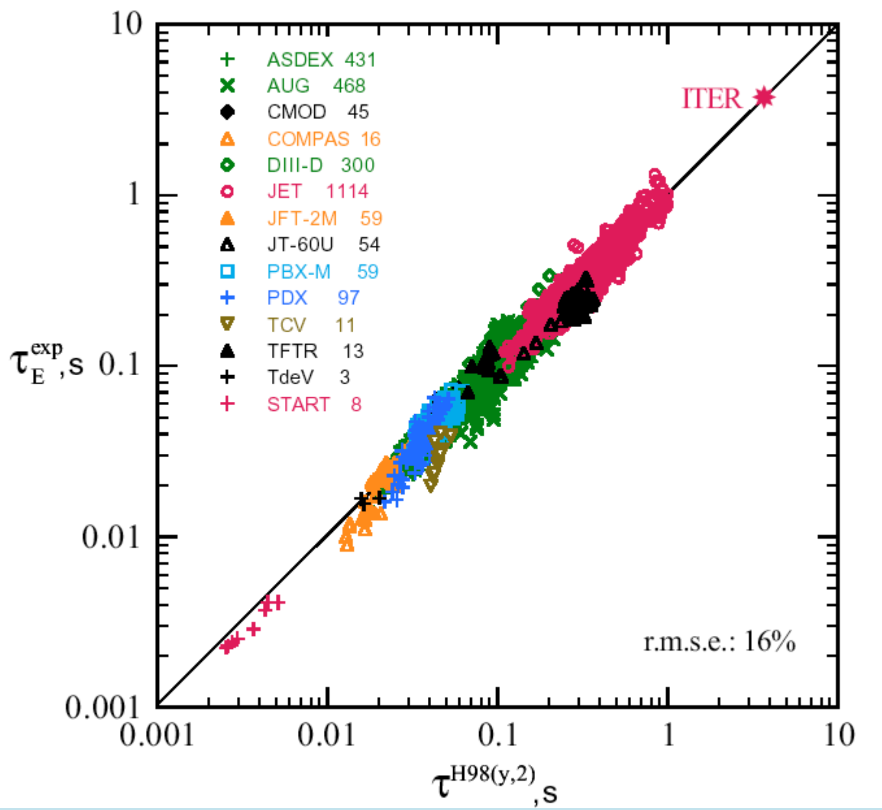
Challenge 1: Plasma regimes for a reactor
Demonstrate a net energy gain







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



- Power losses

$$P_{losses} \sim (3/2)\, nTV/\tau_E$$

- Fusion power

$$P_{fus} \sim n^2 <\sigma v> E_{fus} V \sim$$

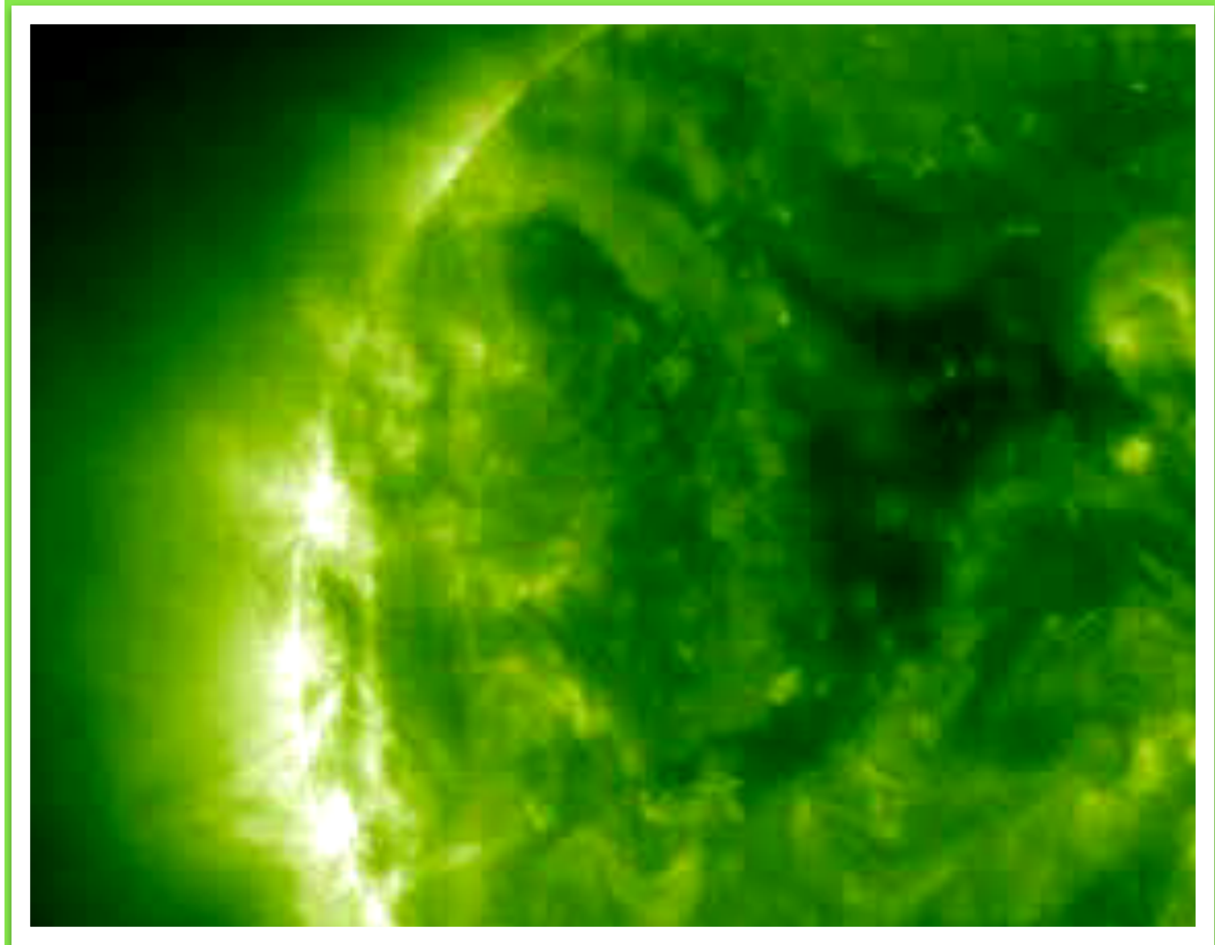
$$\sim n^2 T^2 E_{fus} V$$

- $P_{fus} > P_{losses}$ ➔

$$n\, T\, \tau_E > (n\, T\, \tau_E)_c$$

n = density
T = temperature
V = volume

Challenge 1: Plasma regimes for a reactor
Control plasma instabilities



Challenge 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). <u>Must be avoided, prevented or mitigated</u>
    - 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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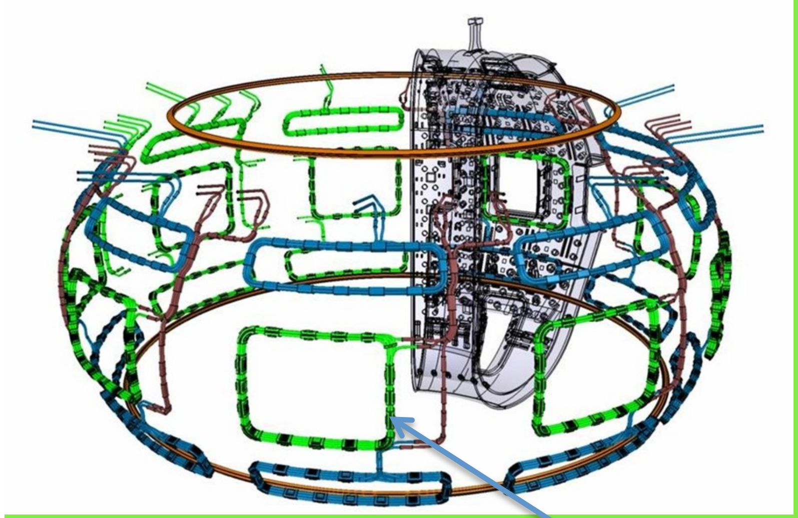
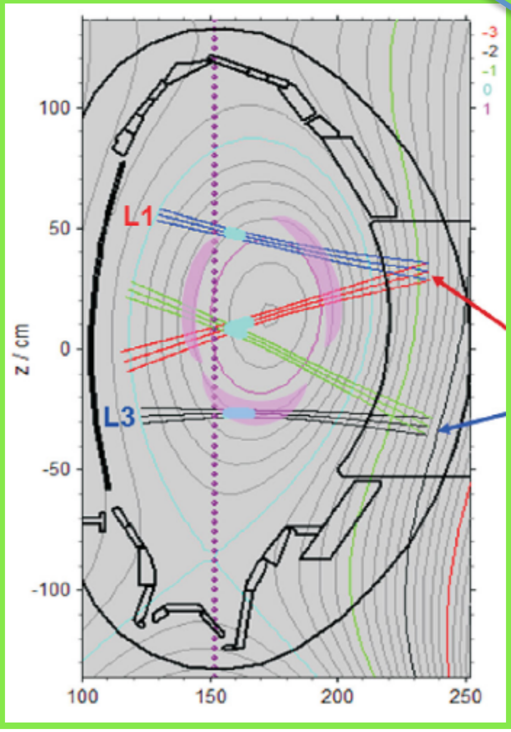
    - Operation far from the stability boundaries
    - Redundancy of control systems to allow appropriate preventive actions
    - Real time prediction and mitigation of event (e.g. impurity injection) to reduce loads on the internal components
  - Those that produce minor plasma redistribution and can help to eject impurities. <u>Must be controlled</u>

Challenge 1: Control plasma instabilities in burning plasmas



coils



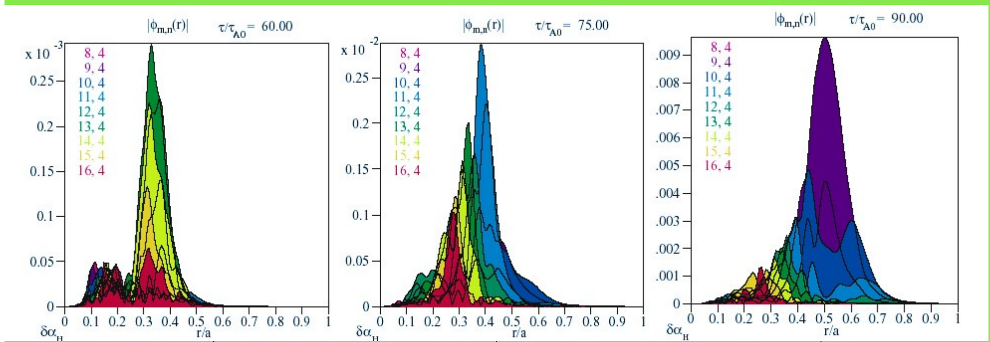
e.m. waves

- 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

Challenge 1: Control plasma instabilities in burning plasmas

New!

Zonca et al 2002



Distance from the magnetic axis

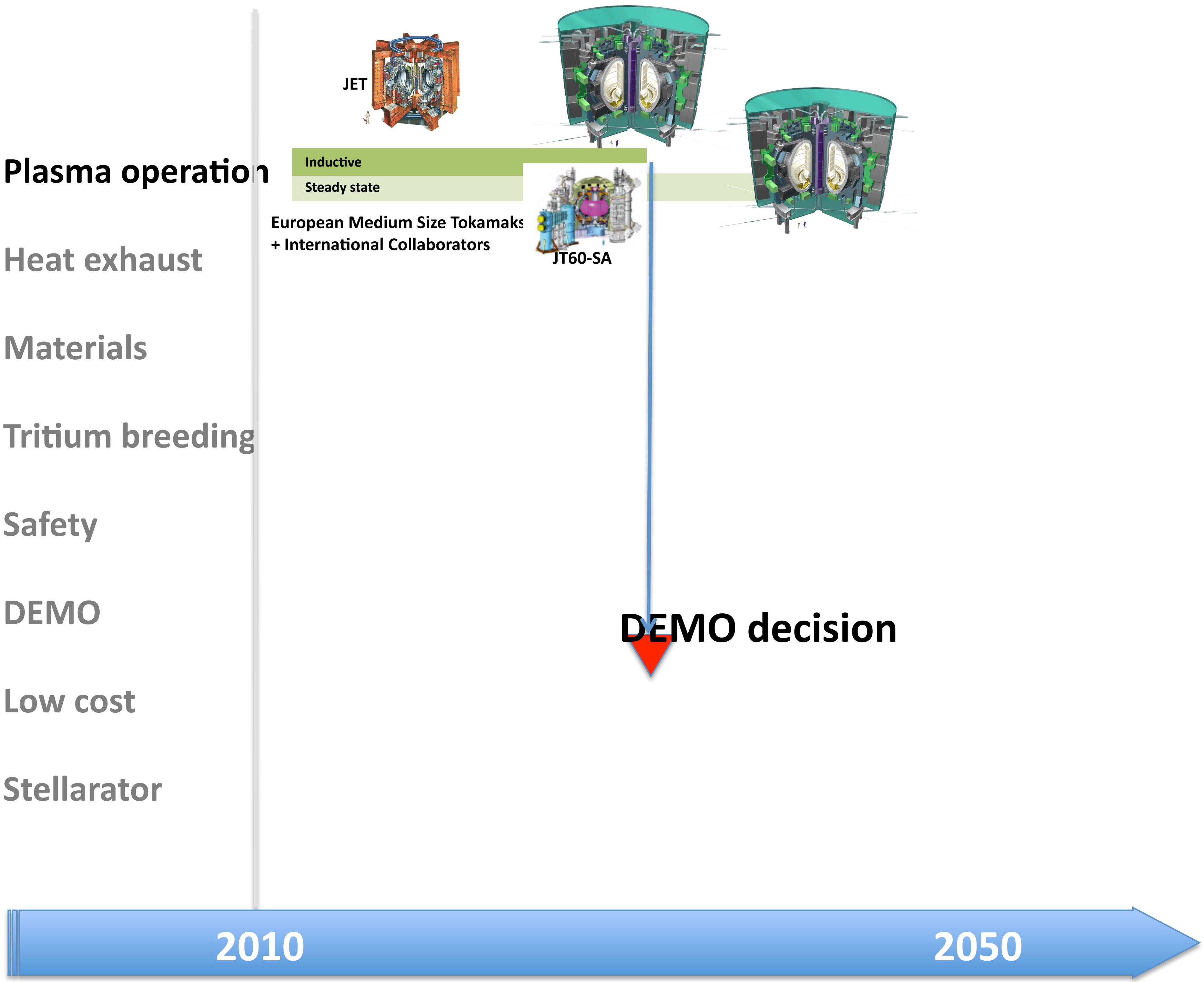
ITER will break new ground on this subject!

Fusionalpha-particles produce new instabilities
➔alpha-particle redistribution.

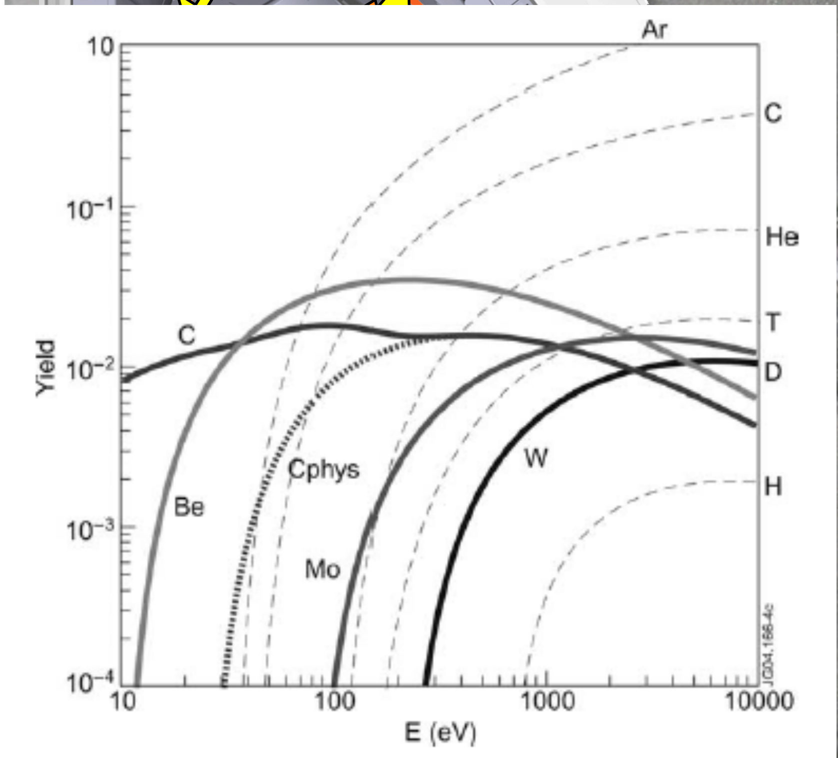
Investigated in present experiments using ions accelerated e.g. by electromagnetic waves.

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

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



Challenge 2: Heat and particle exhaust

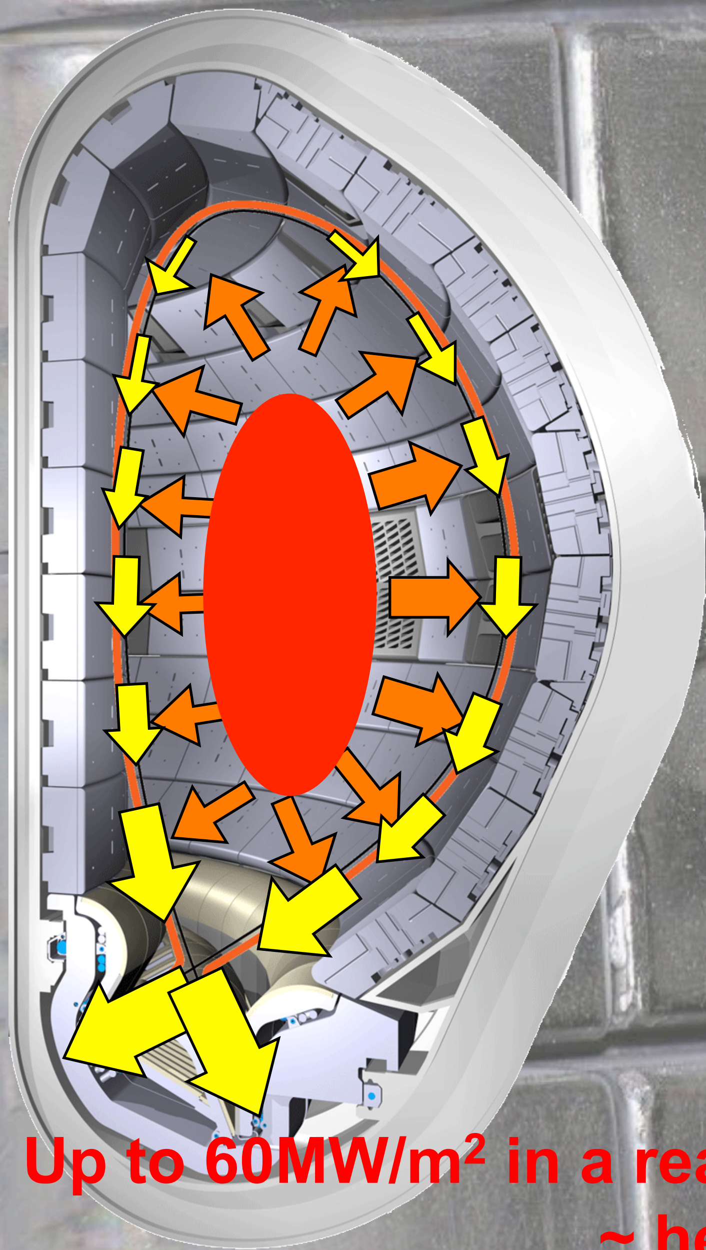


- Erosion
  - About 10^{22}p/s arriving on the wall/divertor
  - If extraction probability is 10^{-5} 1mm eroded (and redeposited) every year.
  - Transient loads reduce lifetime
  - Solution: use tungsten and very low temperature of the plasma in the divertor

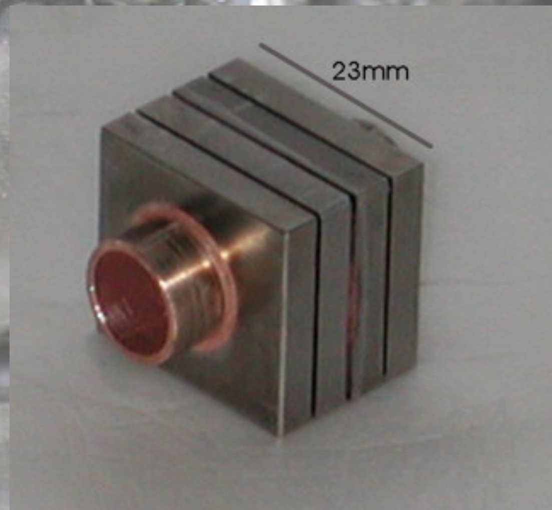
Up to 60MW/m^2 in a reactor

~ heat flux on the surface of the Sun!

Challenge 2: Heat and particle exhaust



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



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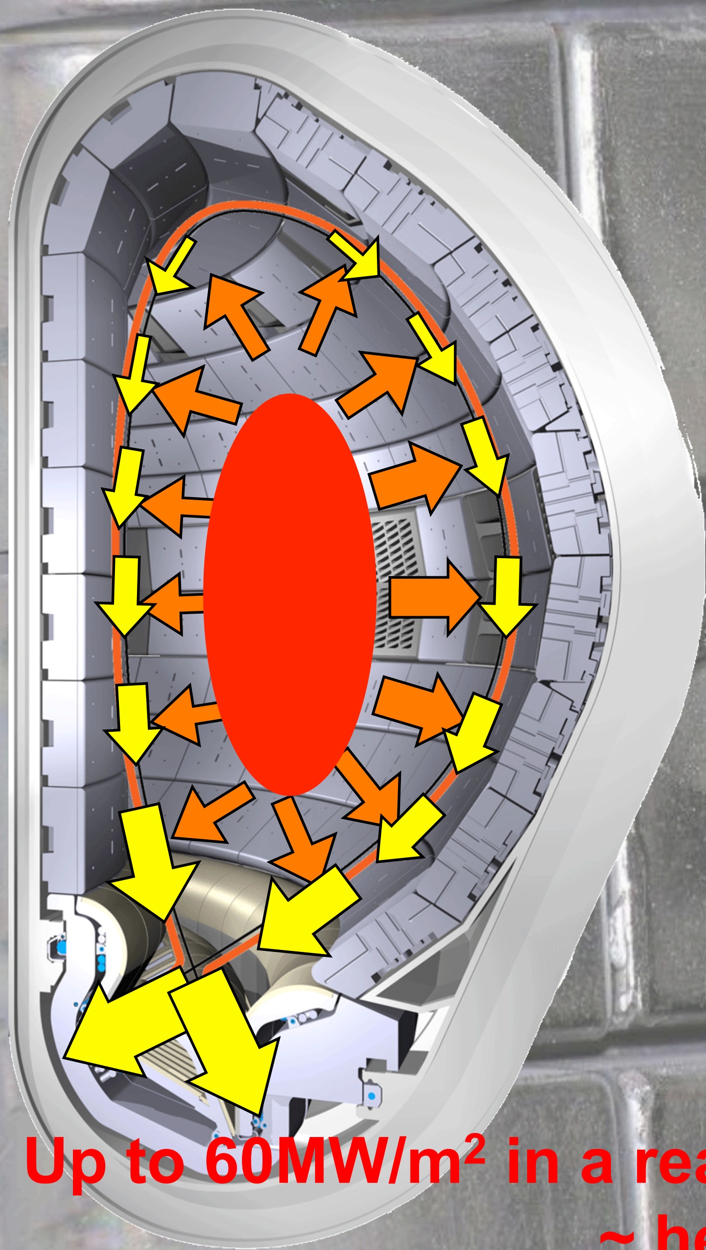
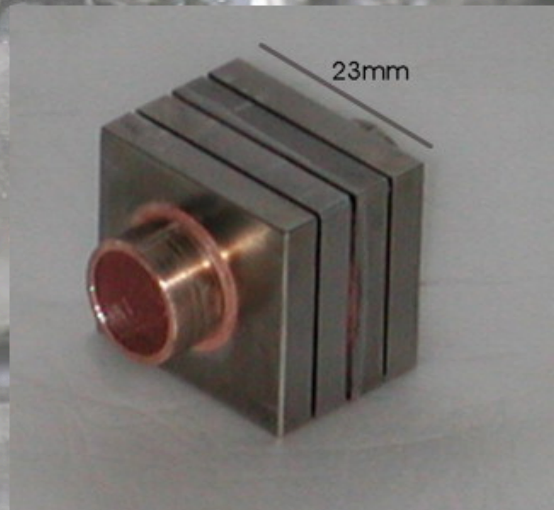


- Erosion
- First wall material properties
- Critical flux on divertor



Up to 60MW/m^2 in a reactor

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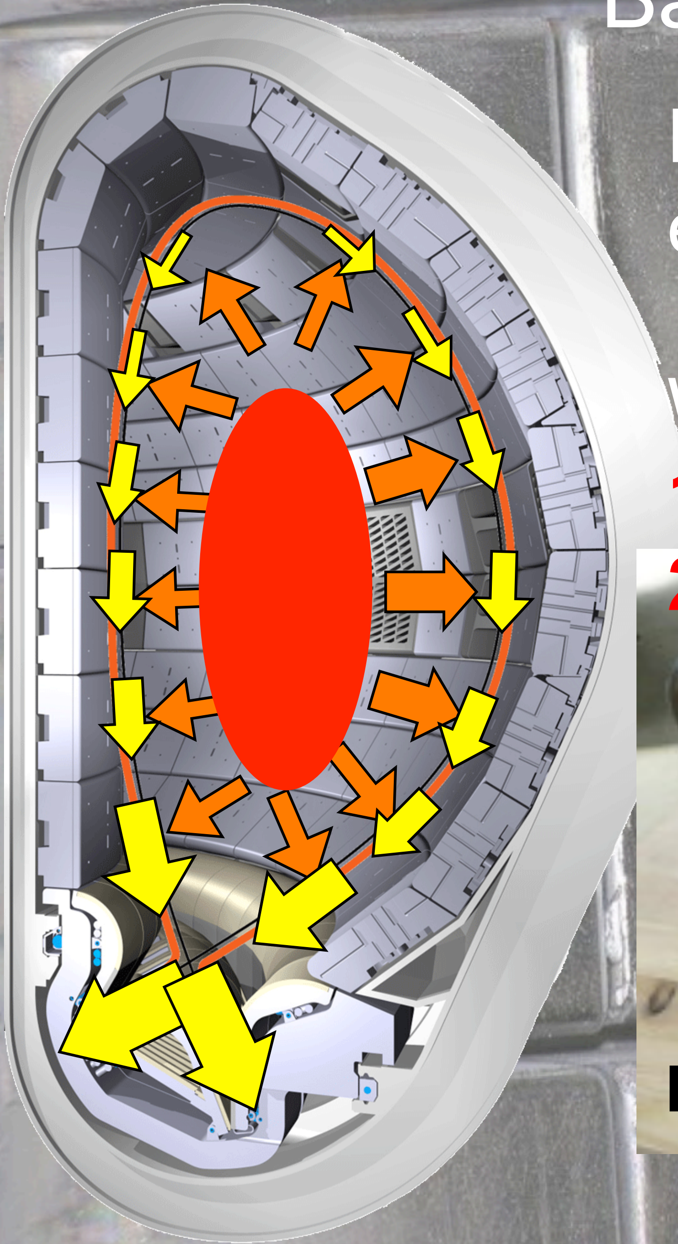
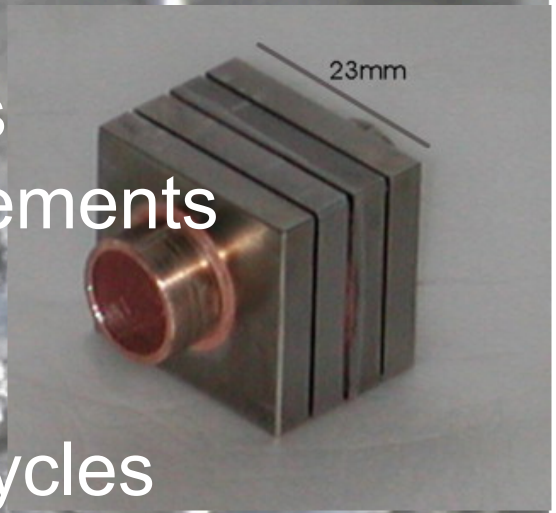
Challenge 2: Heat and particle exhaust
Baseline strategy



Present R&D results exceed ITER requirements

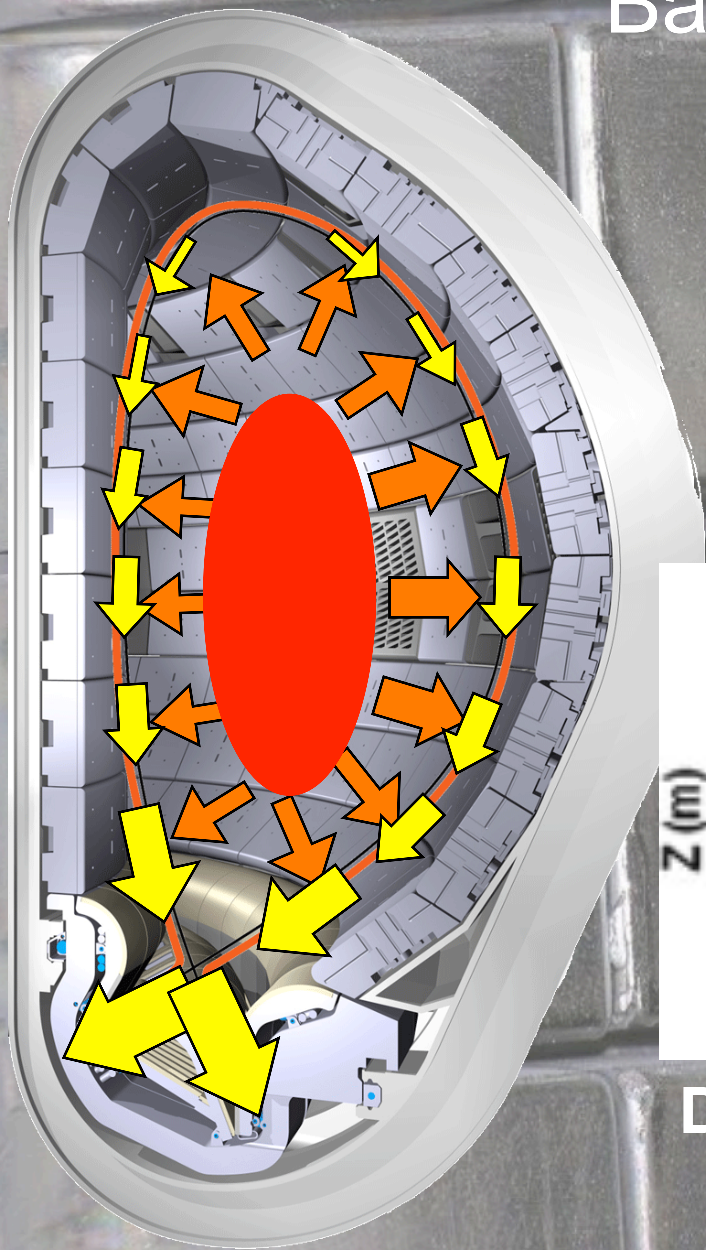


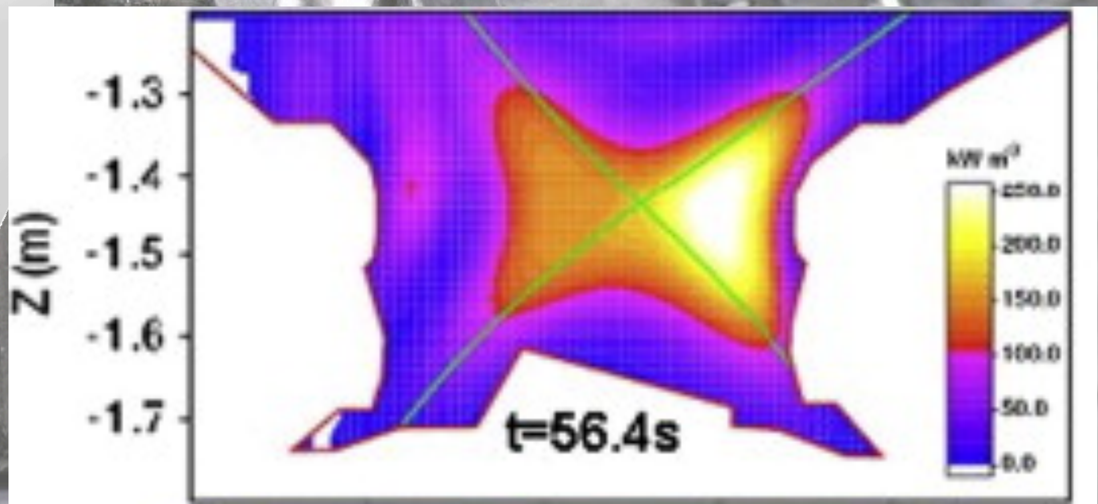
W monoblock:

10 MW/m^2 x 5000 cycles

20 MW/m^2 x 1000 cycles

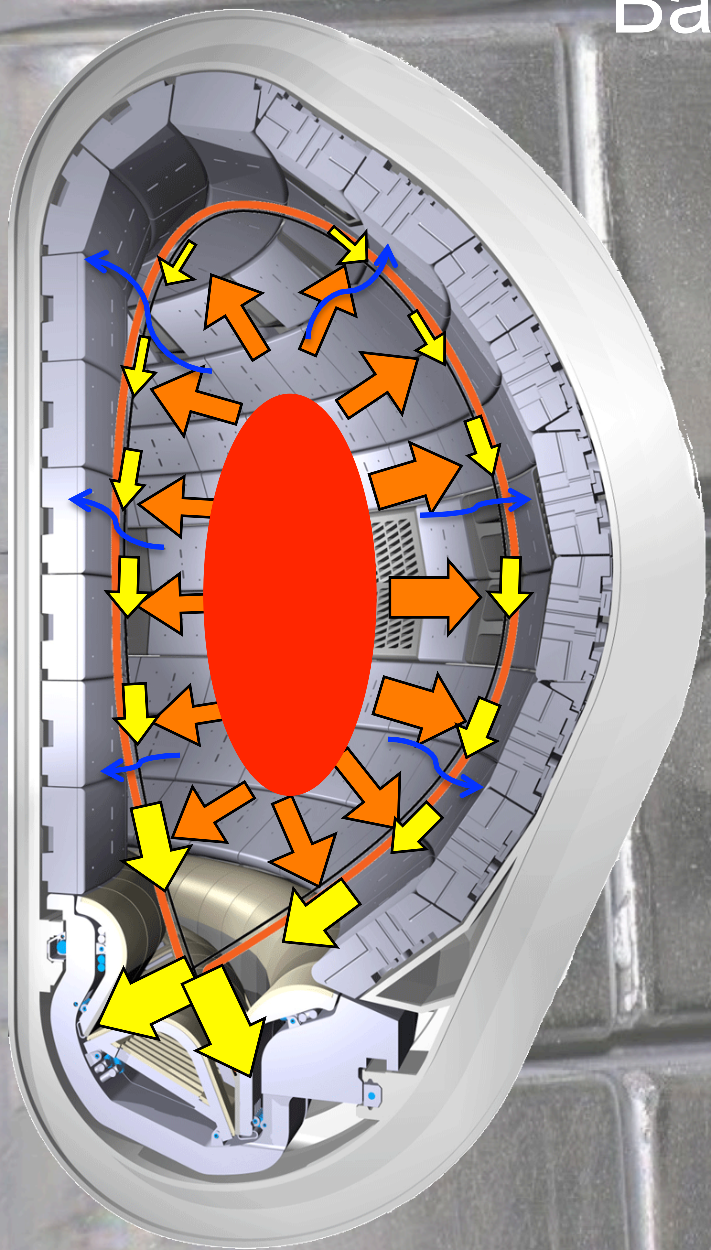
Challenge 2: Heat and particle exhaust
Baseline strategy





Detached divertor conditions

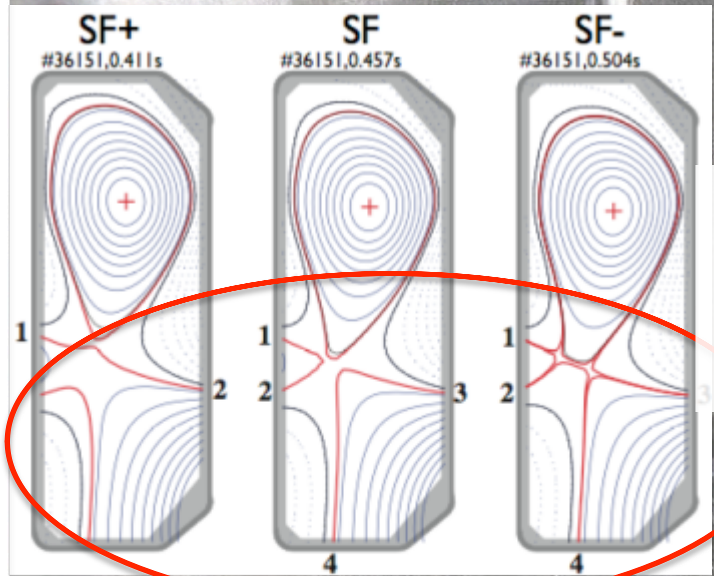
Challenge 2: Heat and particle exhaust
Baseline strategy

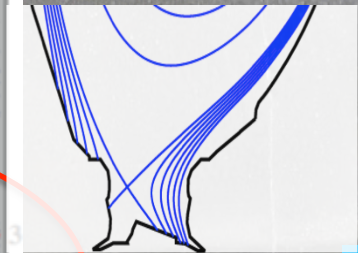


Extrapolation to DEMO of the baseline strategy requires to radiate a large fraction of the heating power (alpha + externally injected) on the main chamber wall.

Impact on Mission 1!

Challenge 2: Heat and particle exhaust
Alternative strategies

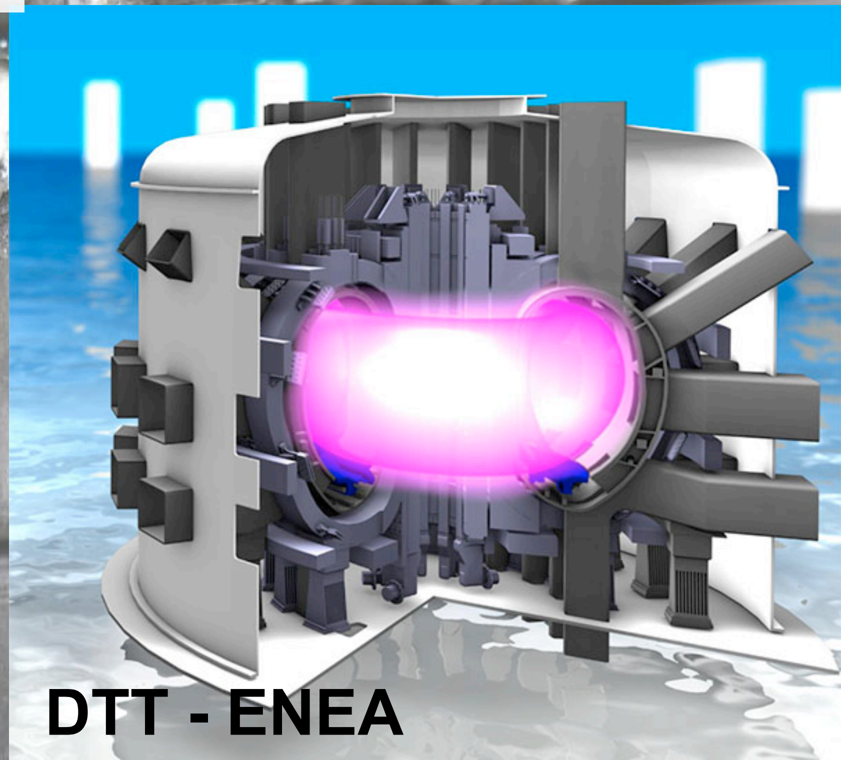




Main alternative strategy: Enlarge area in the divertor wetted by the plasma

TCV – CRPP-EPFL

Divertor Tokamak Test facility (DTT) proposed in the European Roadmap.
ENEA DTT proposal to be part of the EUROfusion activities.
Italian site selection ongoing.



DTT - ENEA

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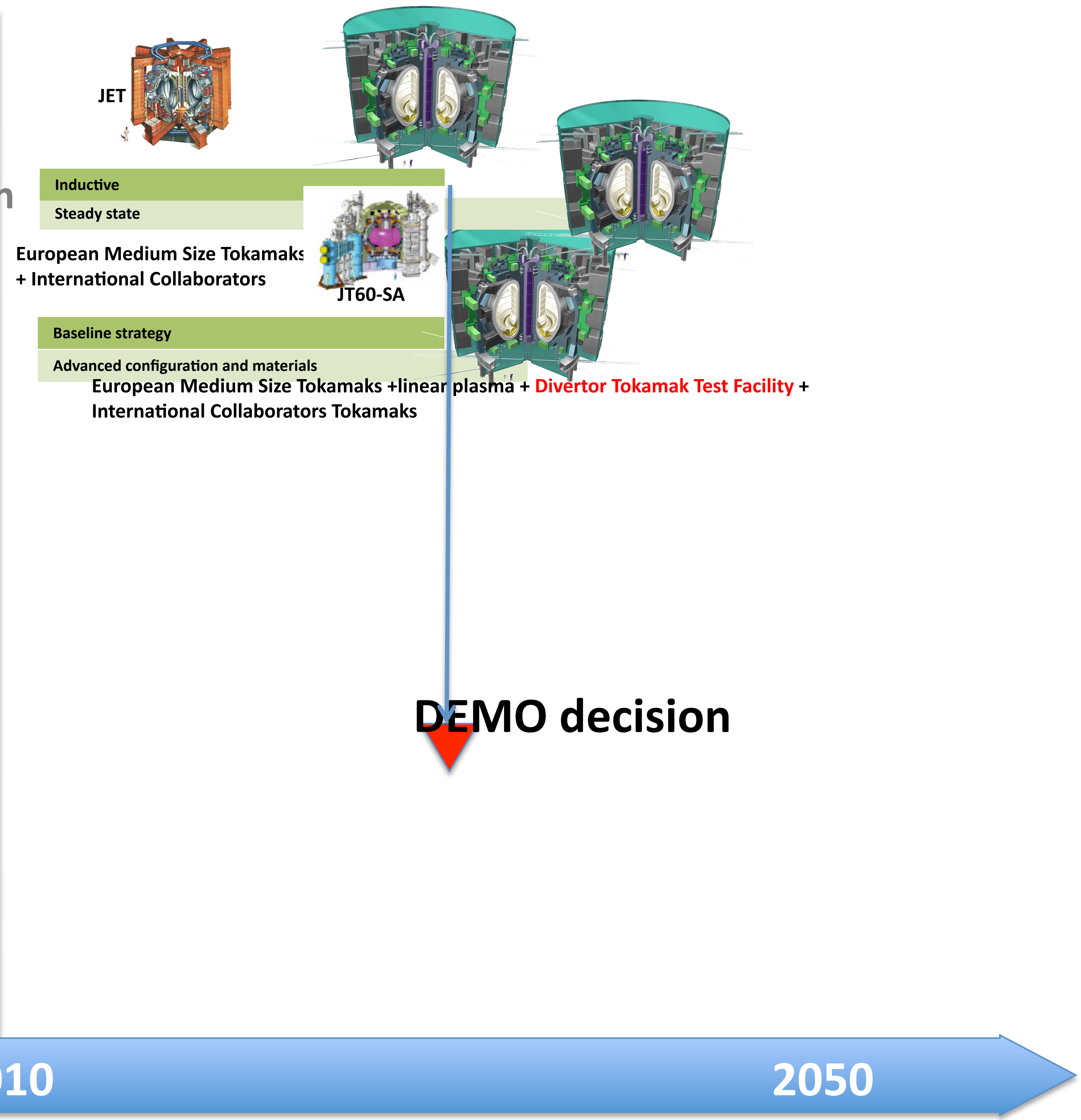
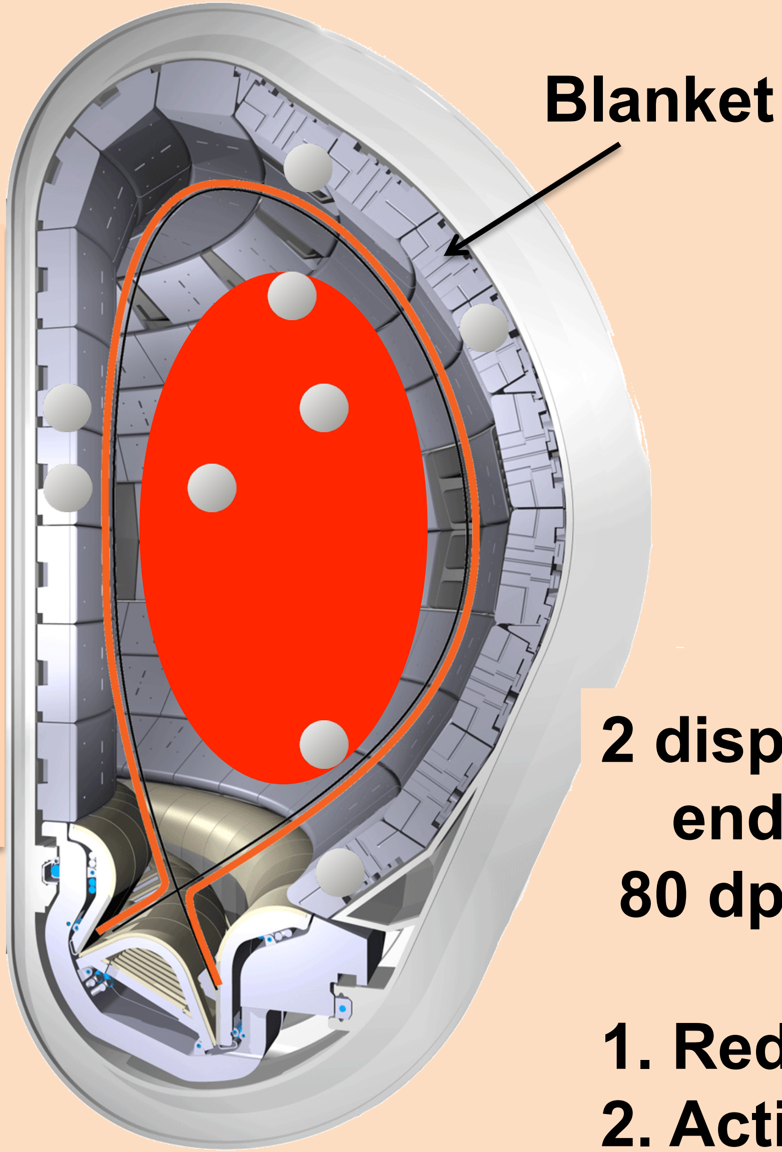


Challenge 3: Develop neutron resistant materials



S. Dudarev

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

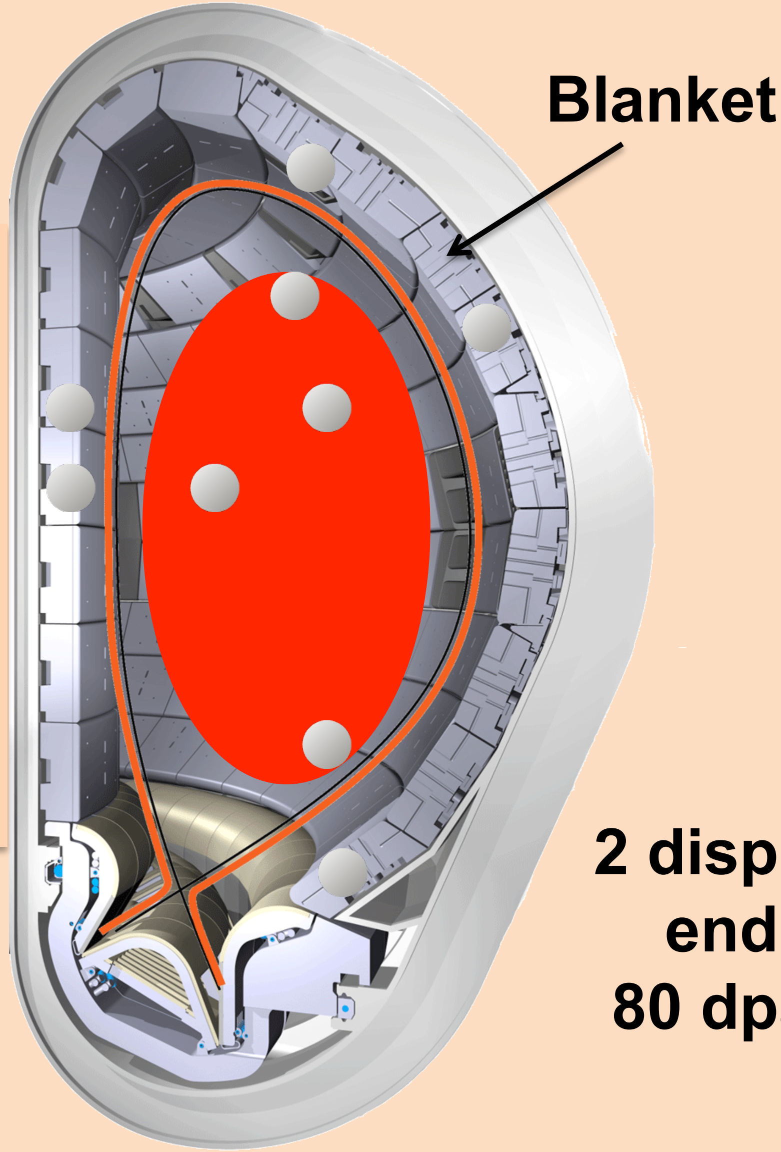
80 dpa in DEMO after 4 full power years

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

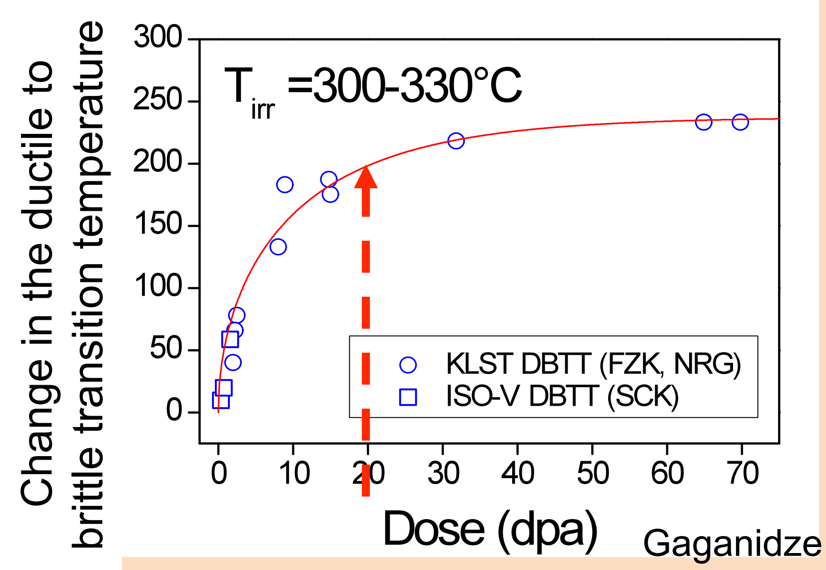
D. Stork et al.
Material Assessment Report

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

Challenge 3: Develop neutron resistant materials



1. Steel becomes brittle under irradiation!



Gaganidze 2011

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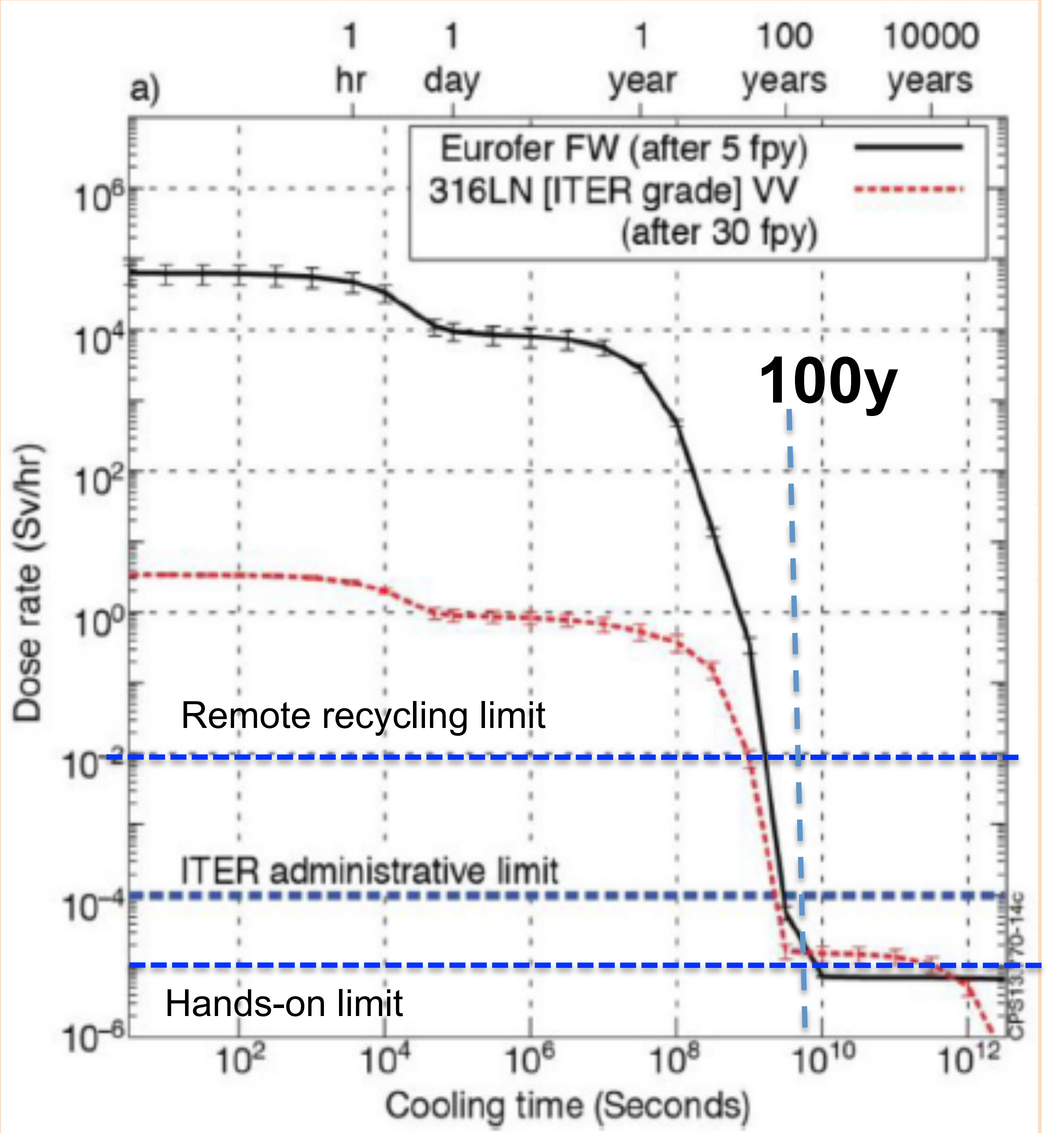
Challenge 3: Develop neutron resistant materials

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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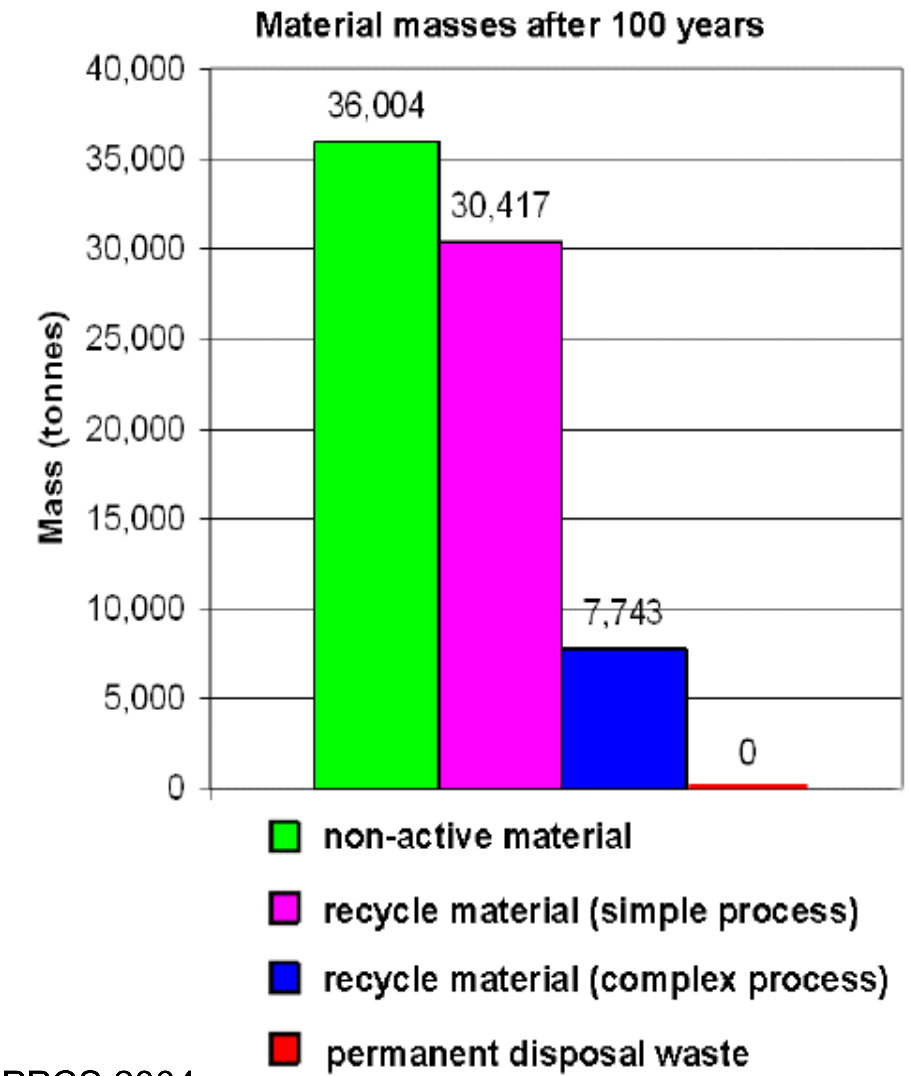
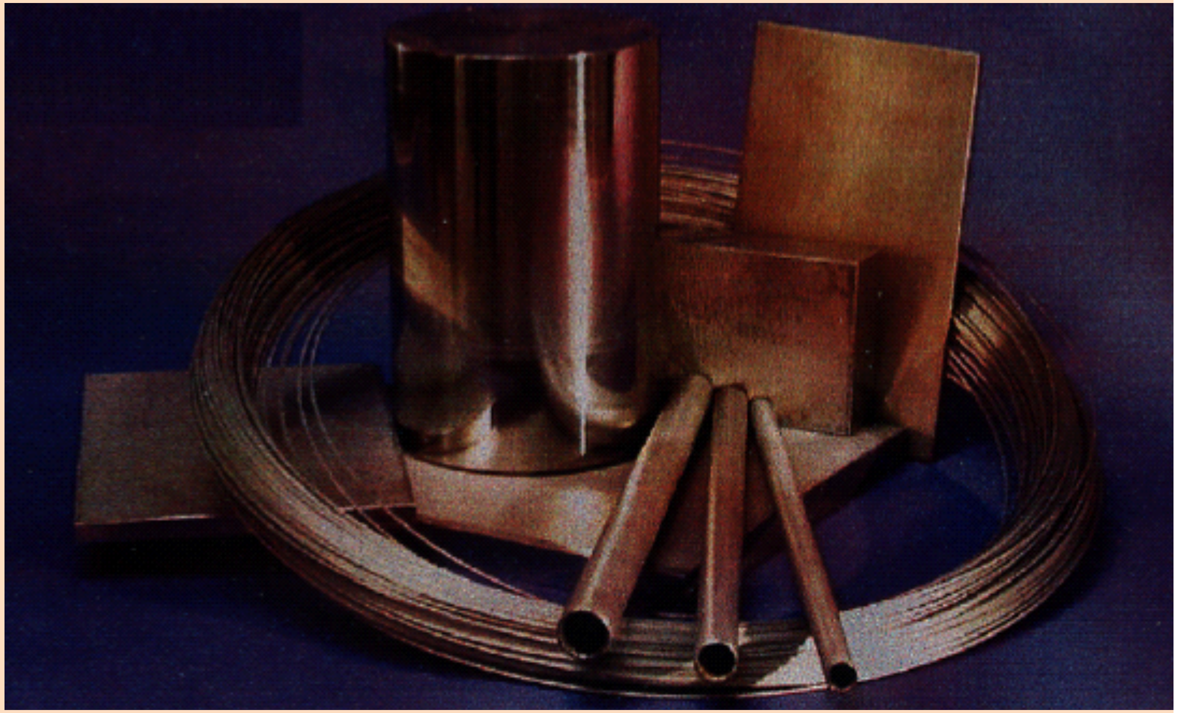


PPCS 2004

Challenge 3: Develop 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



Challenge 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.**

1. Plasma operation
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
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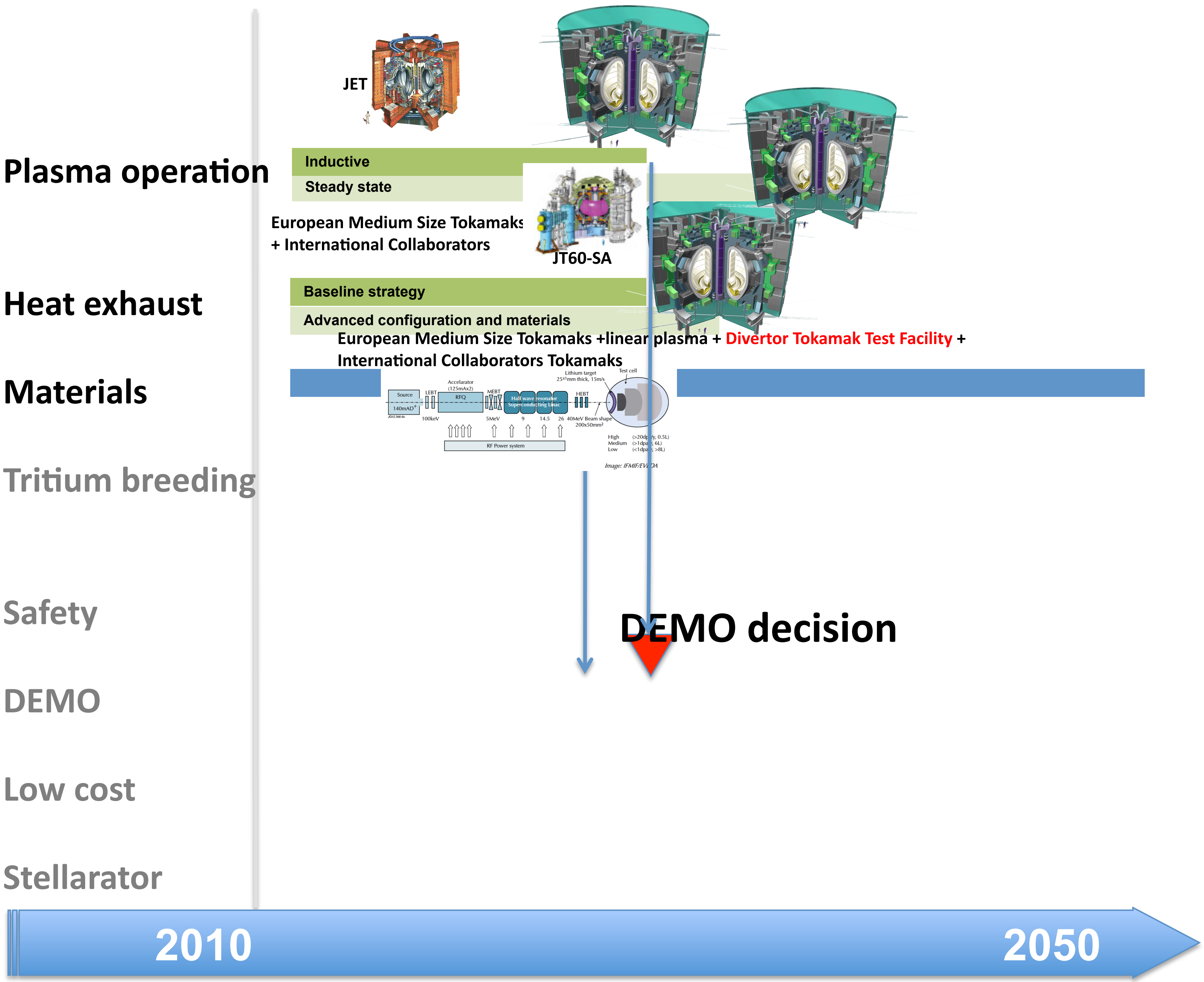
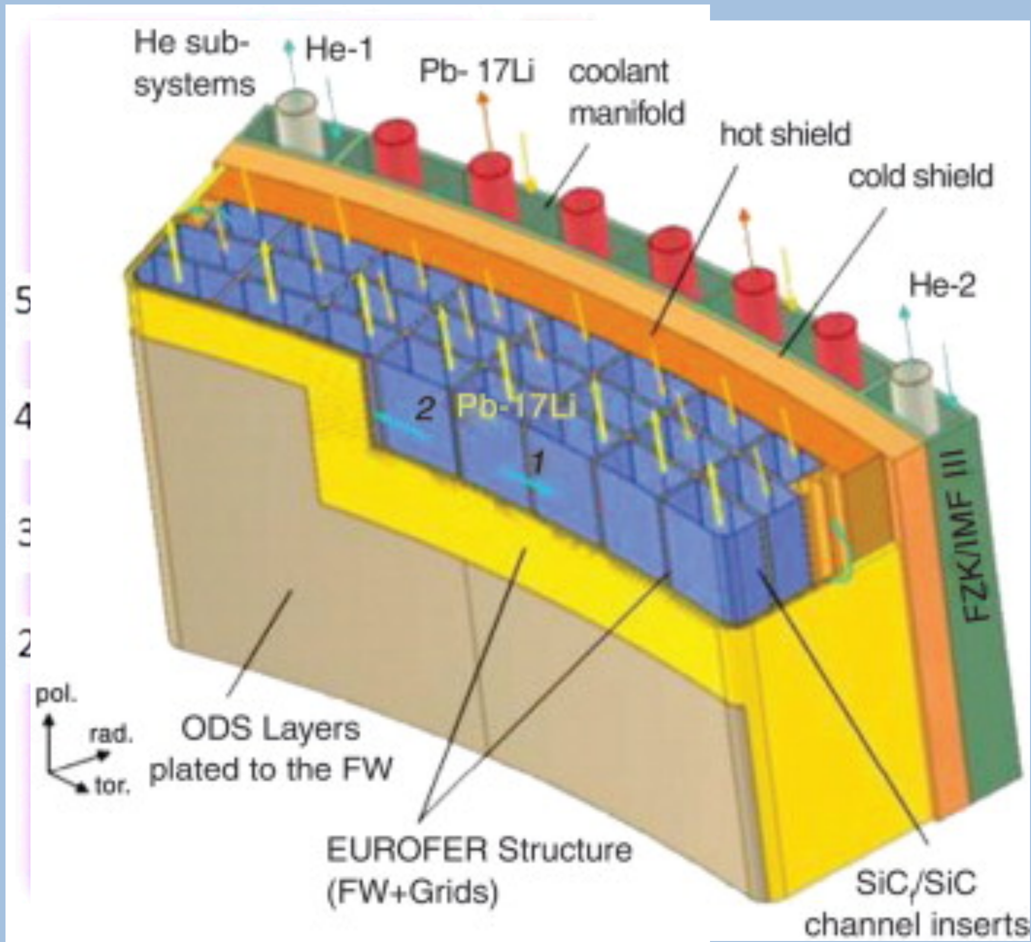


Challenge 4: Ensure tritium self-sufficiency



Blanket Sector

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.

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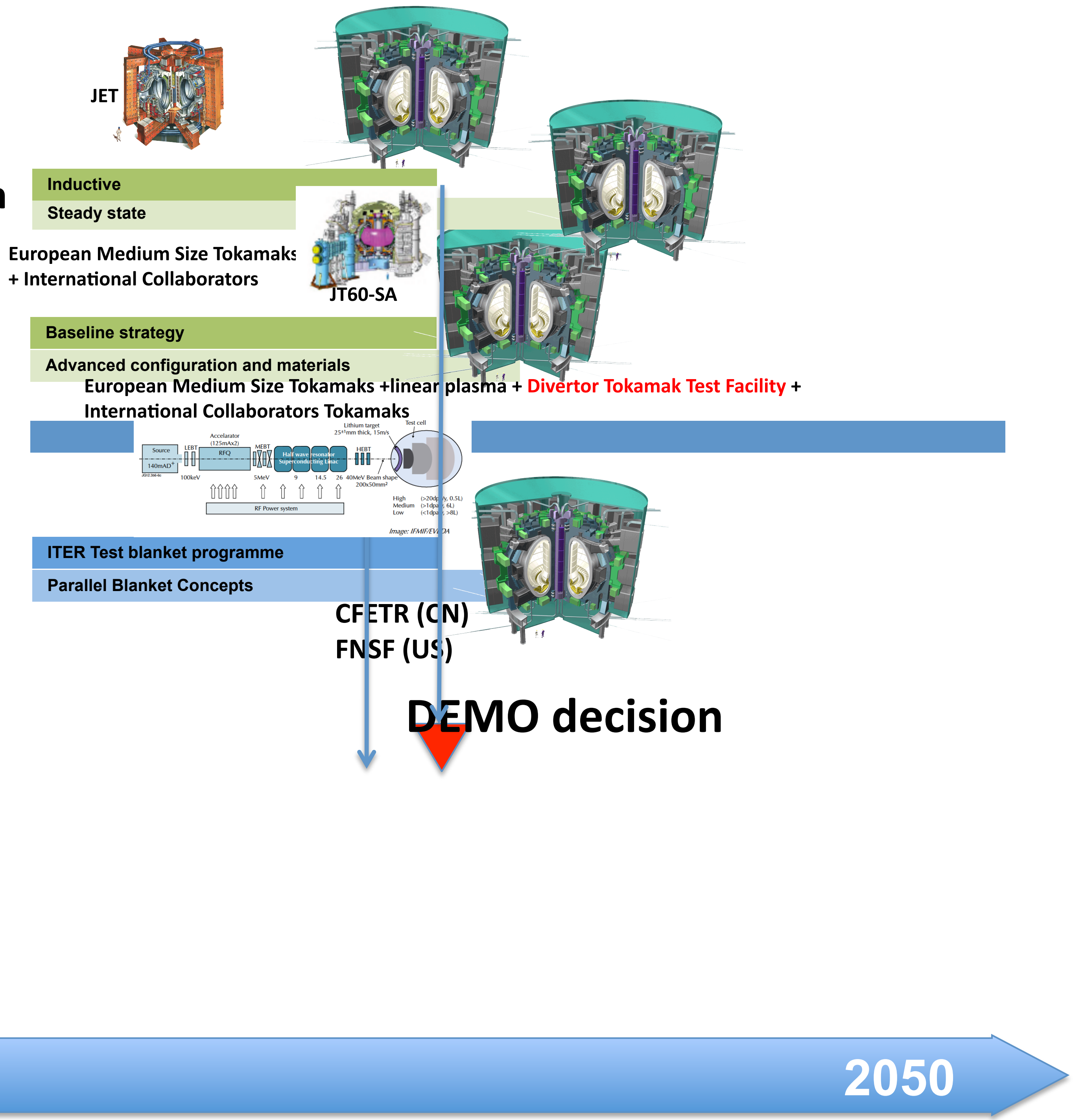
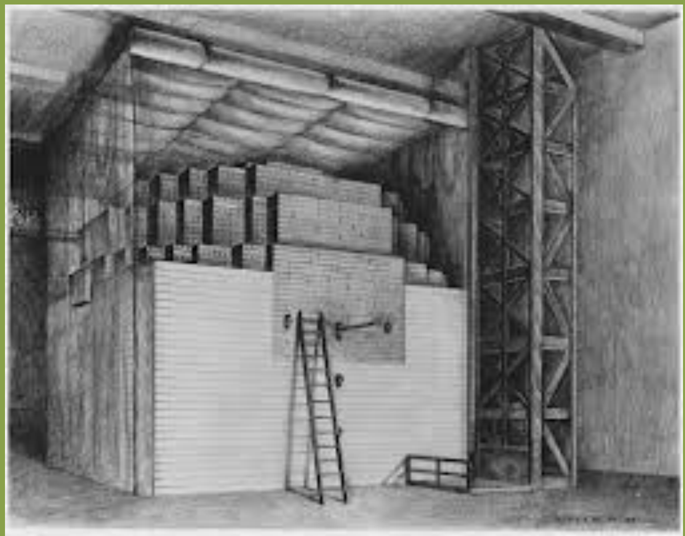
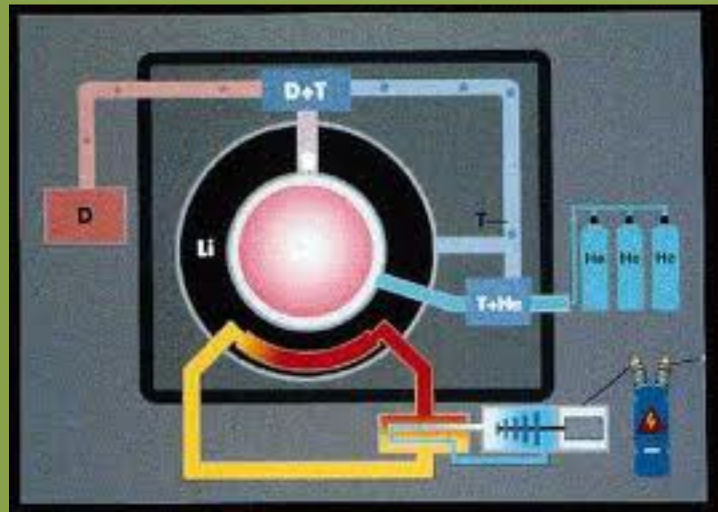


Challenge 5: Implementation of inherent fusion safety features in DEMO design

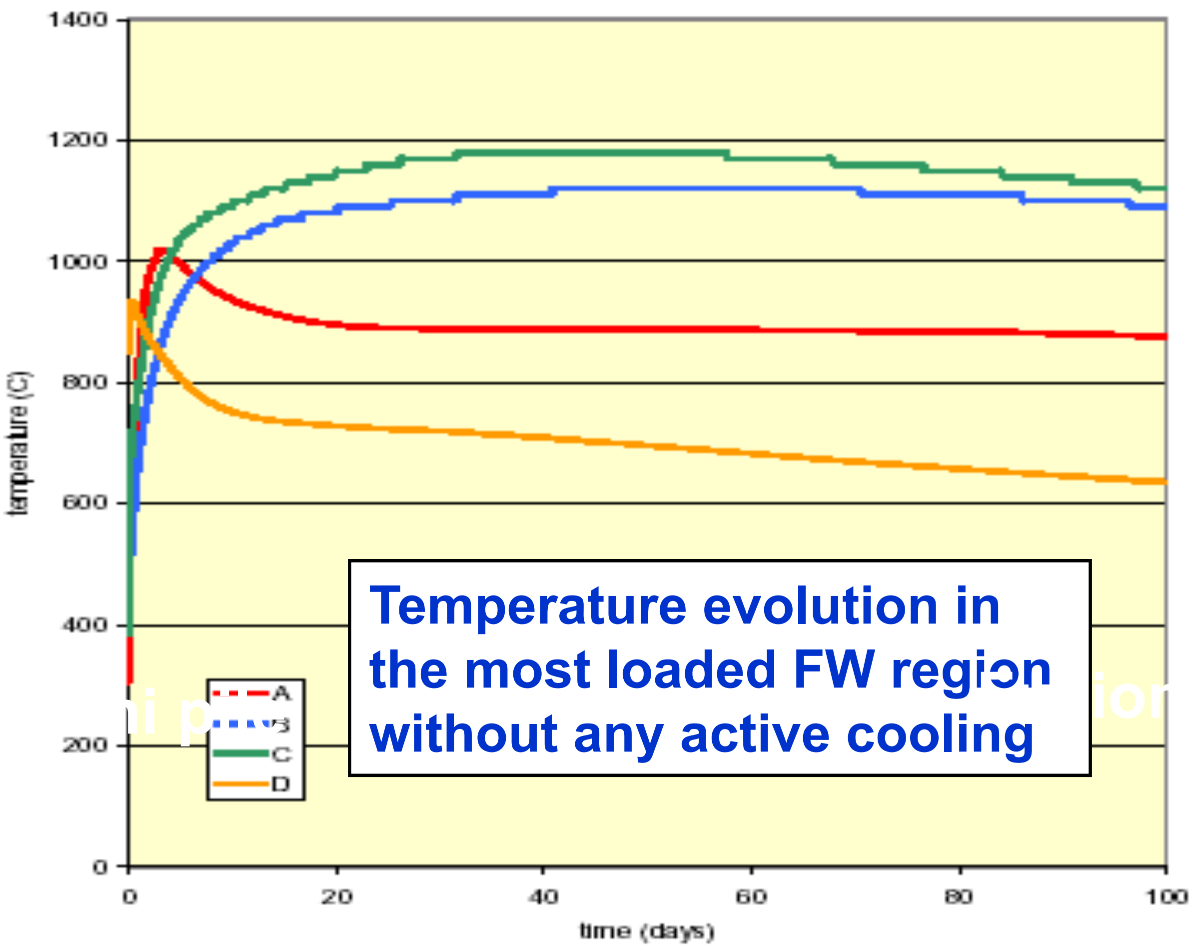


Fermi pile



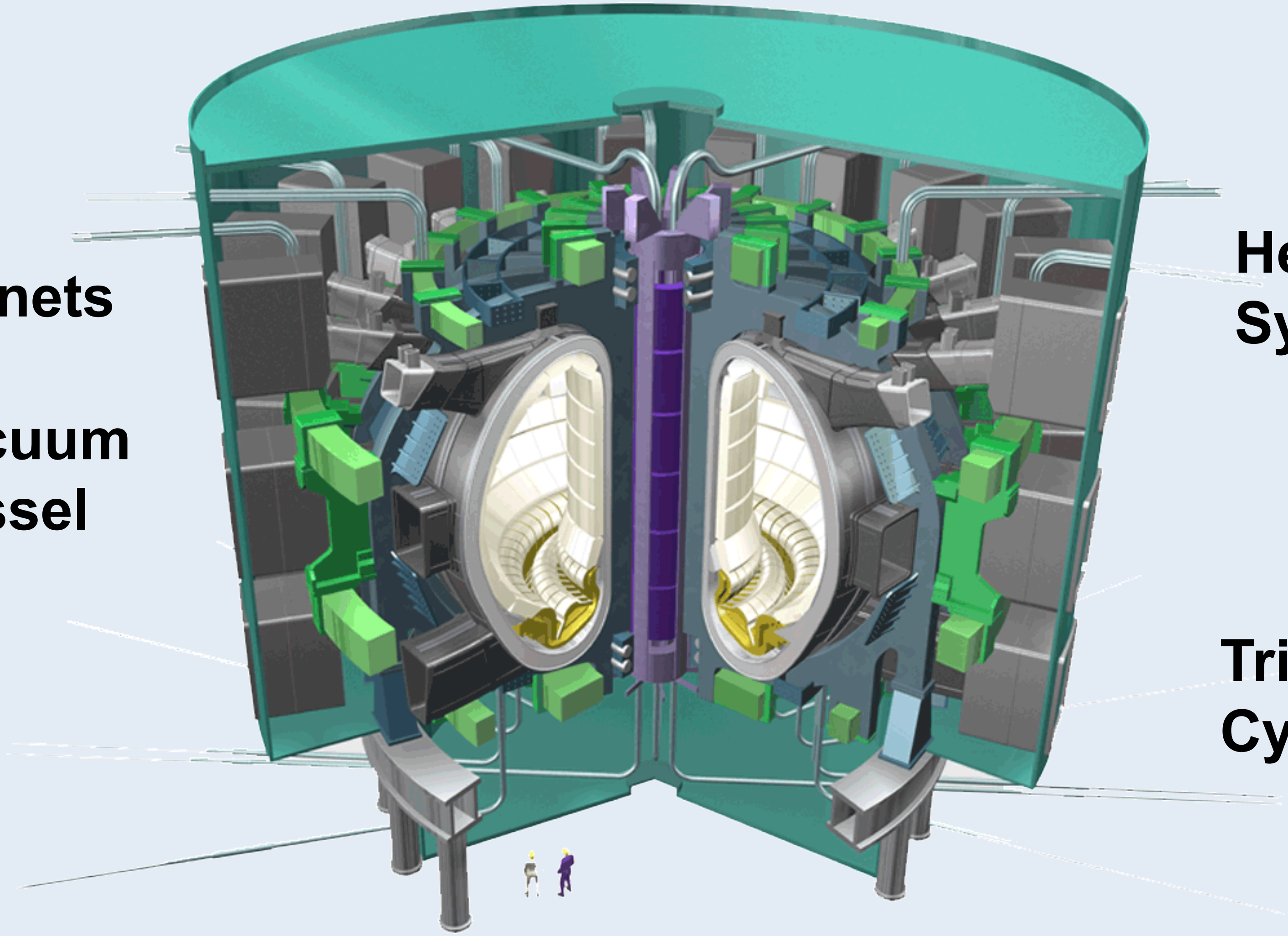
Fusion reactor

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



Challenge 6: DEMO design

Balance of Plant



Magnets

Vacuum Vessel

Heating Systems

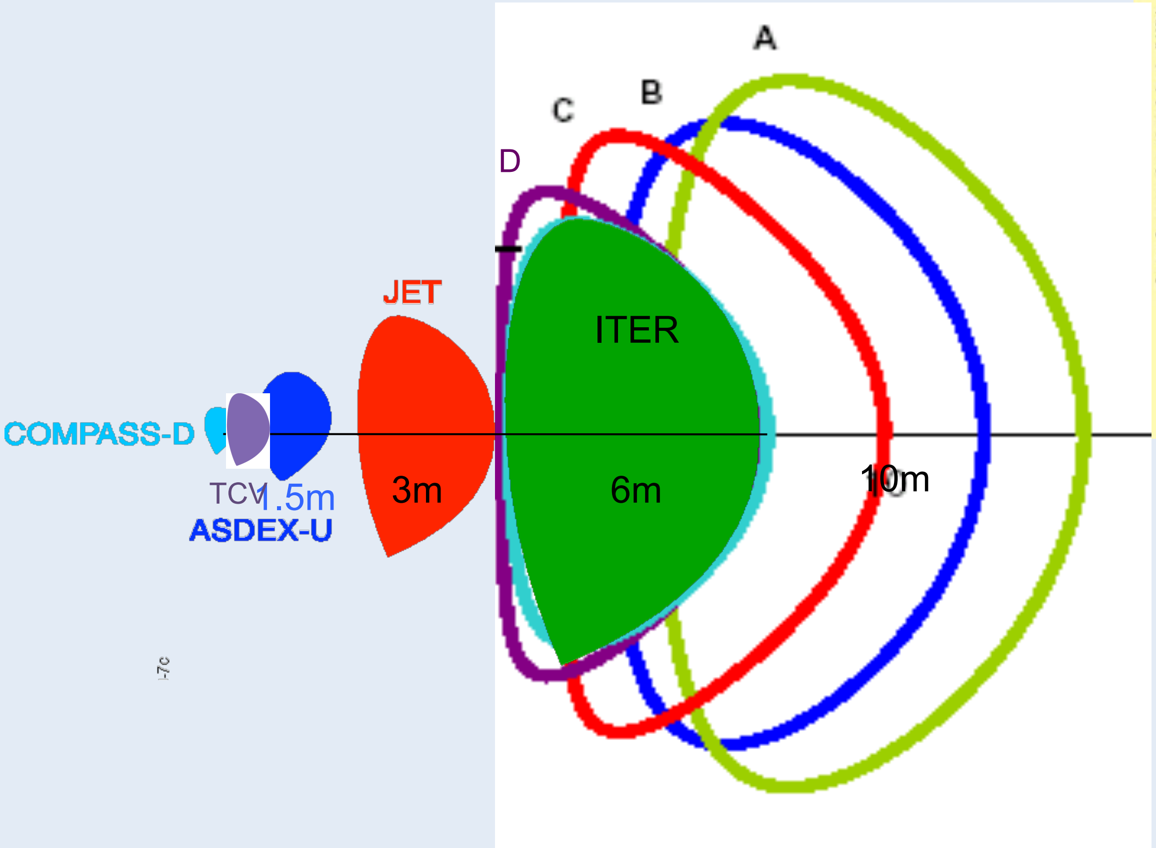
Tritium Cycle

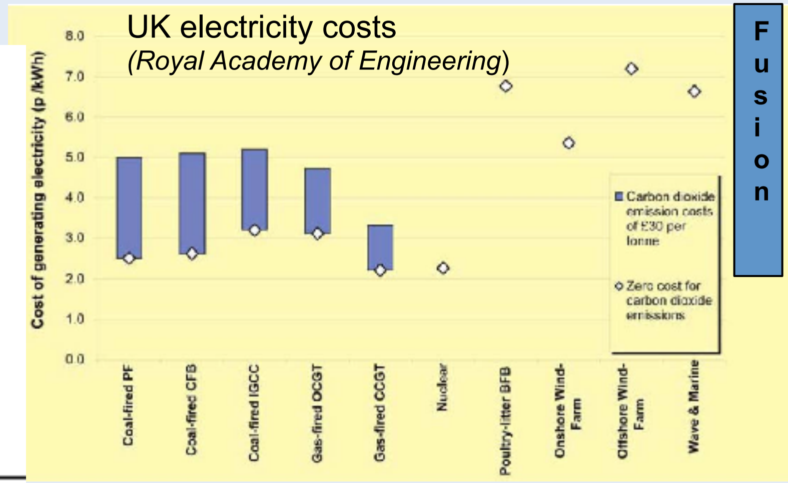
Remote Handling

[redacted]

[redacted]

Challenge 7: Low cost of electricity

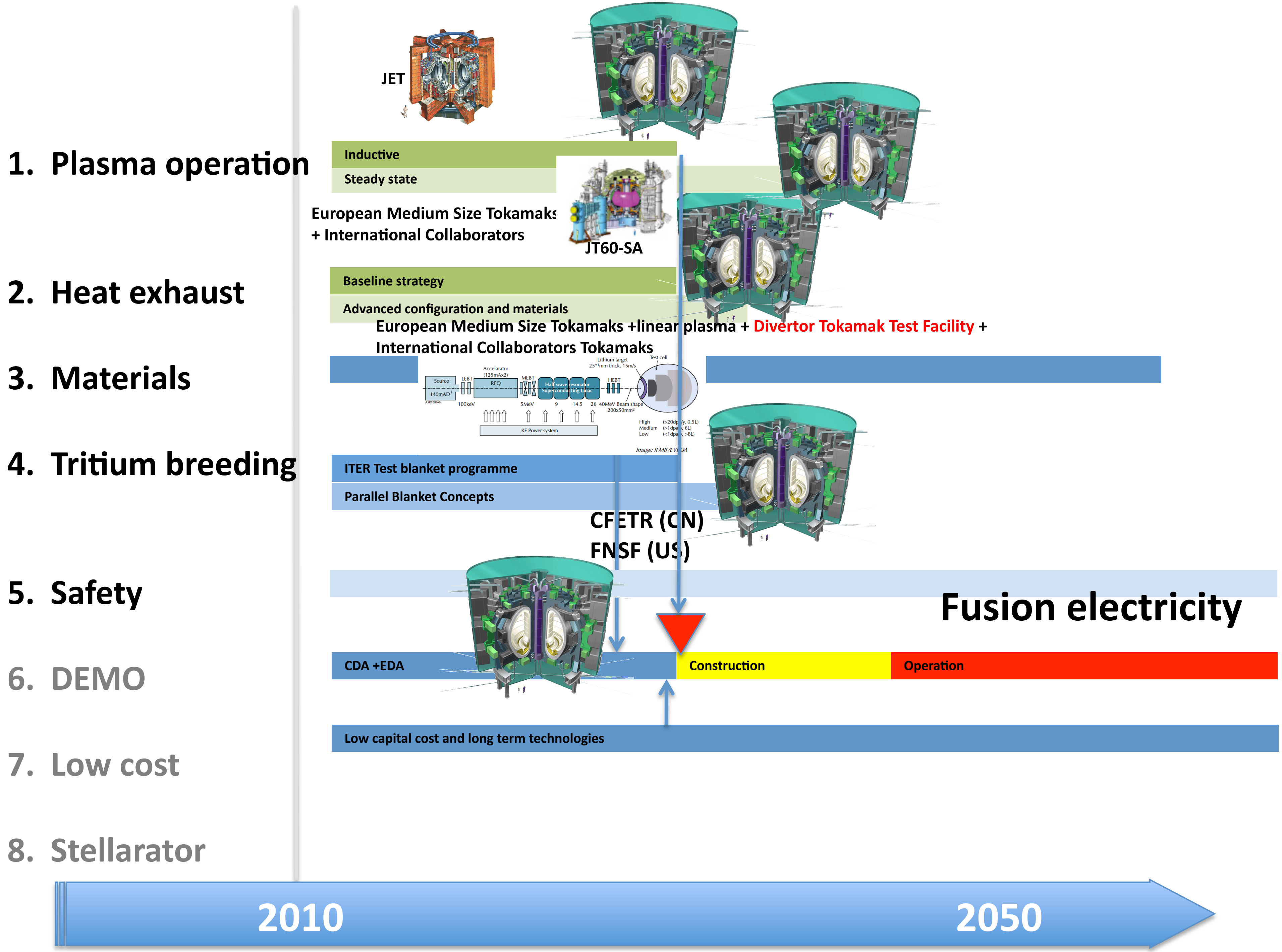




Cost of electricity from fusion expected to be competitive with other sources (IEA Levelised Cost Approach)

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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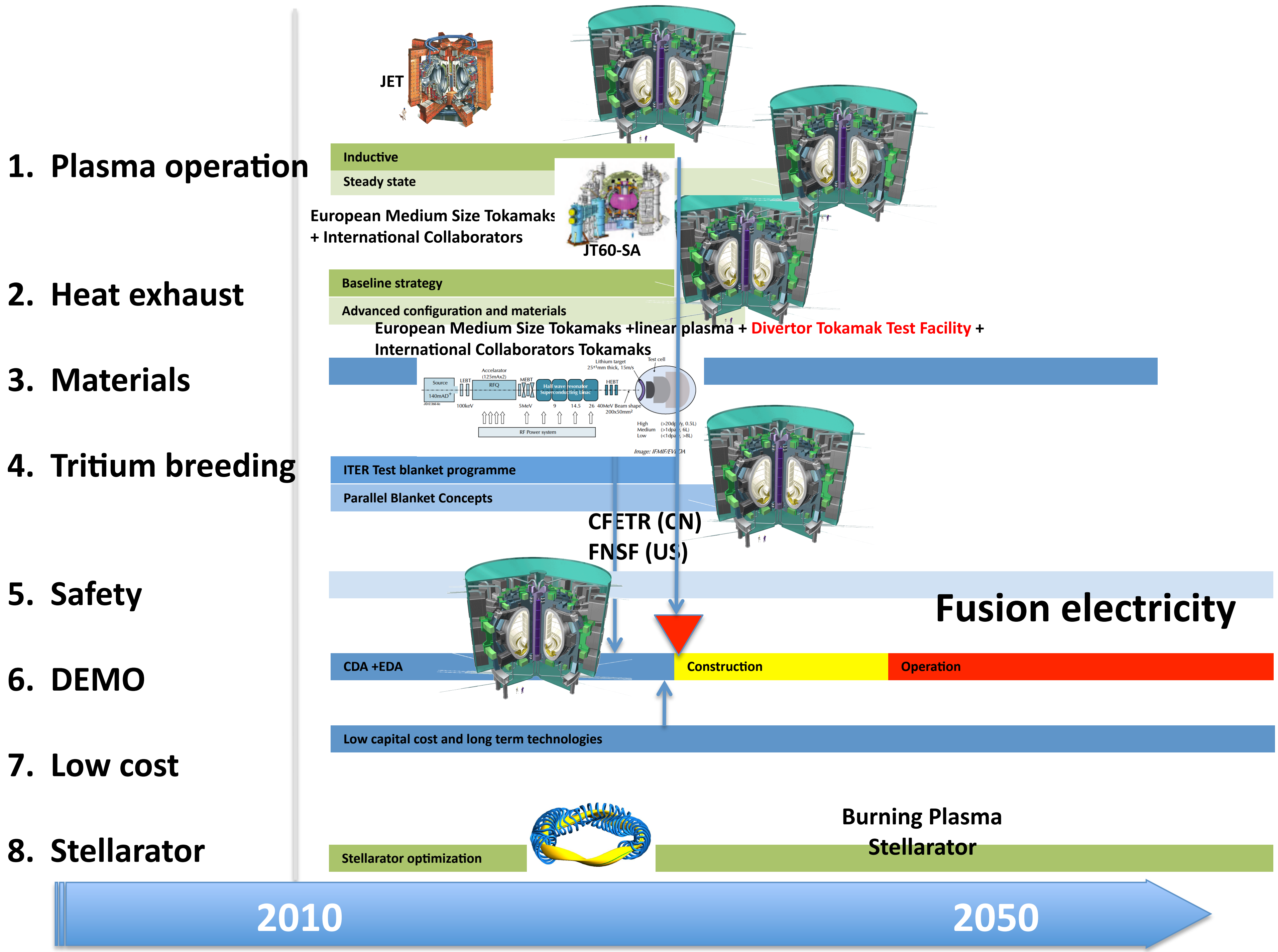
JET
Inductive
Steady state
European Medium Size Tokamaks
+ International Collaborators
JT60-SA
Baseline strategy
Advanced configuration and materials
European Medium Size Tokamaks +linear plasma + Divertor Tokamak Test Facility +
International Collaborators Tokamaks
ITER Test blanket programme
Parallel Blanket Concepts
CFETR (CN)
FNSF (US)
Fusion electricity
CDA +EDA
Construction
Operation
Low capital cost and long term technologies
2010
2050



1. Plasma operation
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
7. Low cost
8. Stellarator
JET
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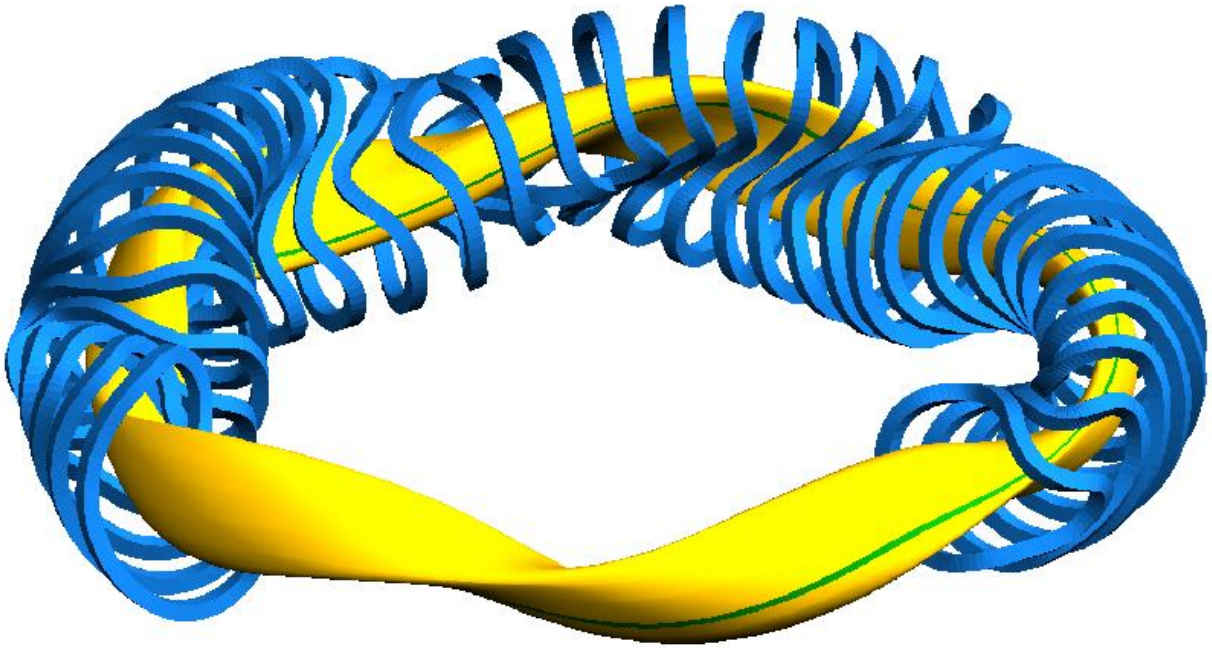
Burning Plasma
Stellarator
Stellarator optimization
2010
2050

Stellarator



W7X

No net plasma current

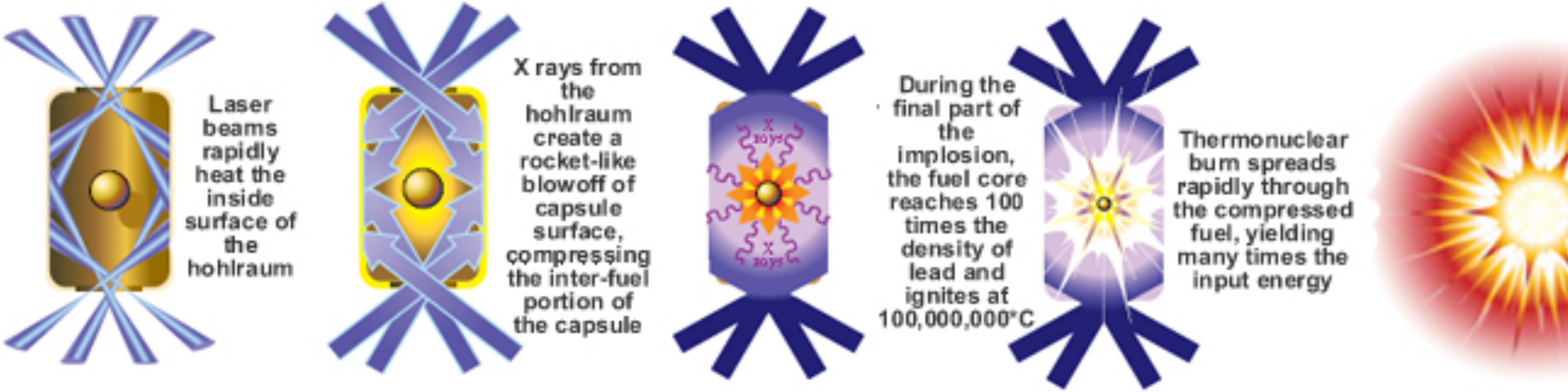
no disruptions

intrinsic steady-state operations

R&D ongoing to bring this configuration to maturity as a long term alternative to tokamaks

Engineering challenges for a reactor under investigation

Where we stand with inertial fusion?



https://lasers.llnl.gov/

National Ignition Facility (NIF)

Laser system performed above the expectations.

So far implosion velocity smaller than expected and pressure much smaller than expected.

Various strategies being investigated to attain ignition

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
- NIF will demonstrate the potential of inertial fusion
- With a pragmatic approach and well focussed programm fusion electricity could be produced around the middle o ths century - we need to have the solutions in our hands 15 years from now!