A Roadmap to the realization of fusion energy (see www.efda.org)

Working Group on Energy (AKE)
Dresden

Acknoledgments: P. Barabaschi,D. Borba, G. Federici, L. Horton, R. Neu, D. Stork, H. Zohm

Francesco Romanelli
European Fusion Development Agreement
EFDA Leader and JET Leader
4 March 2013

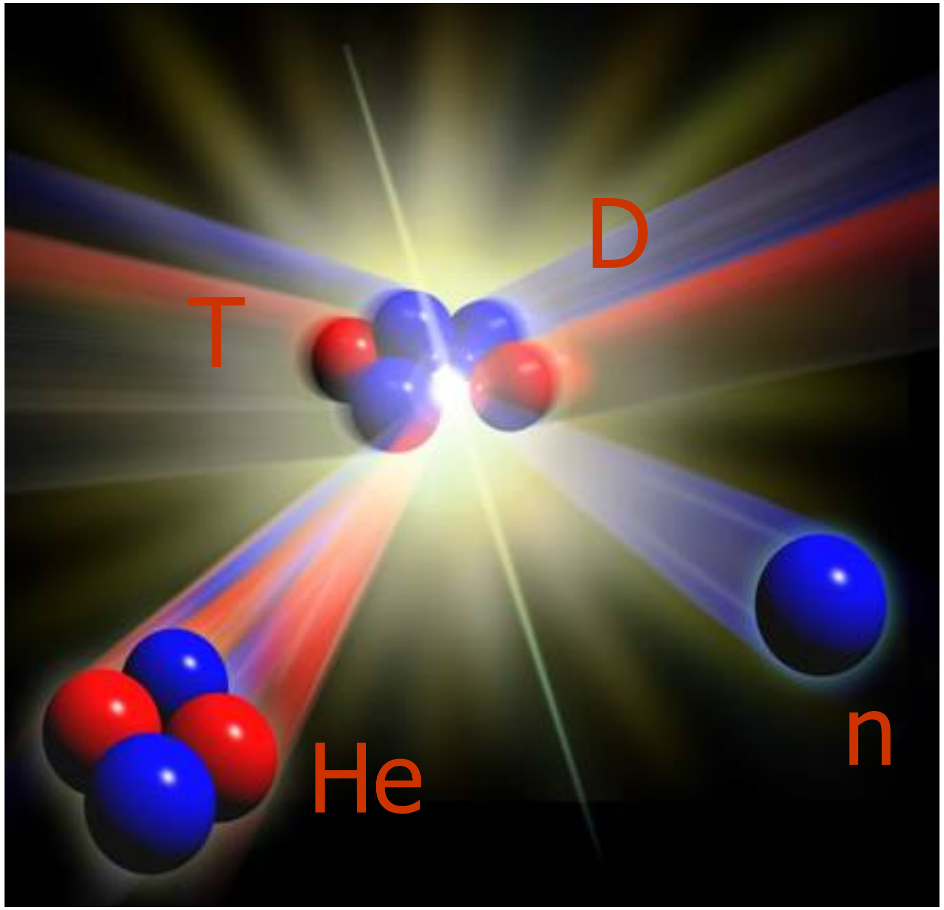
Energy challenge for Europe

Sustainability
Security of supply
Economic competitiveness

Fusion Energy

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

How to make fusion?

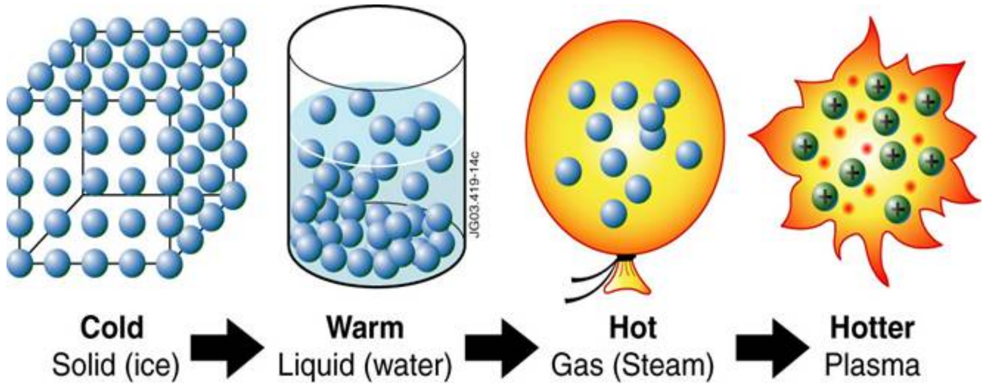


Reacting nuclei are charged

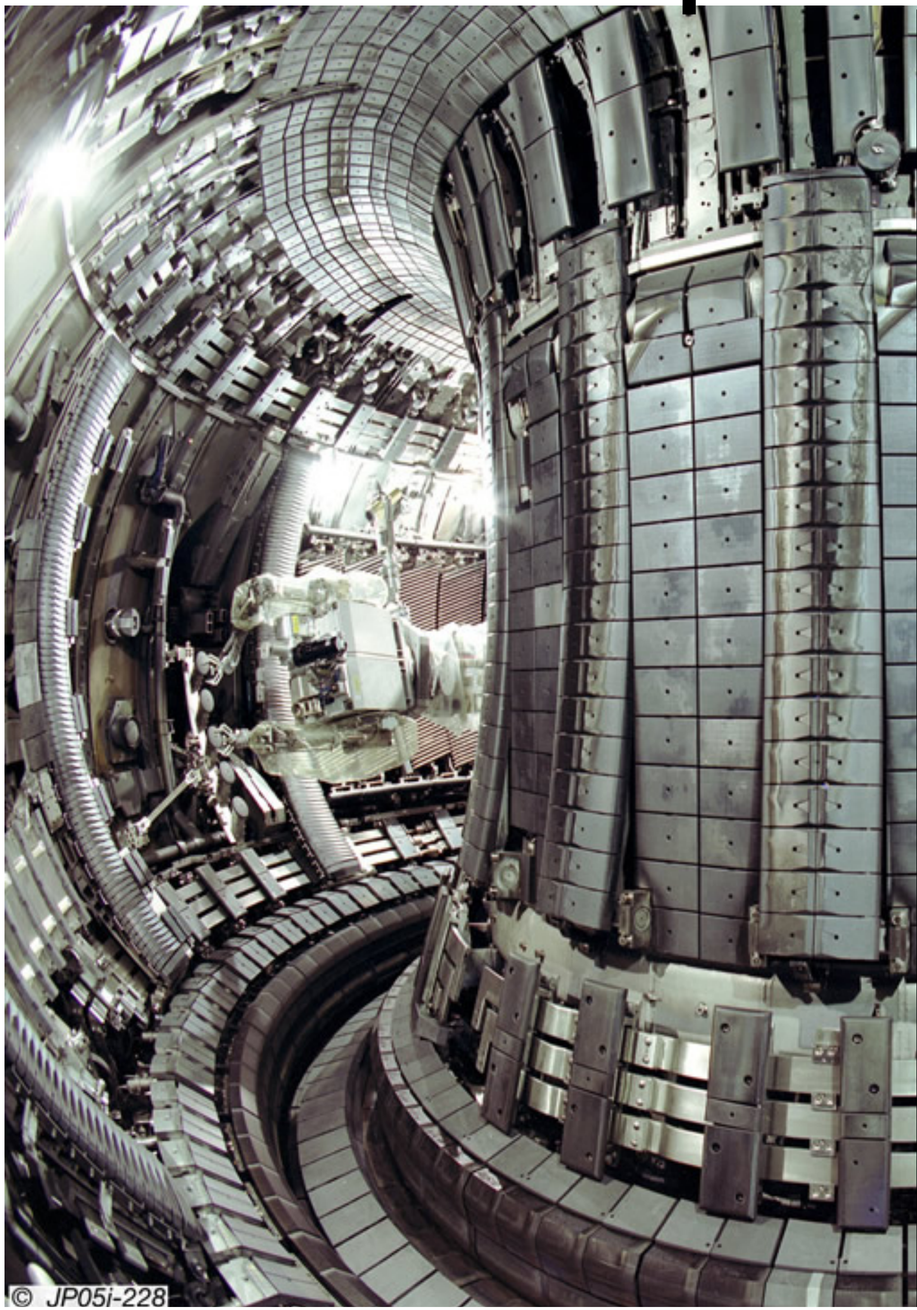
⇒ they repel each other

Heat nuclei up to 200Million °C

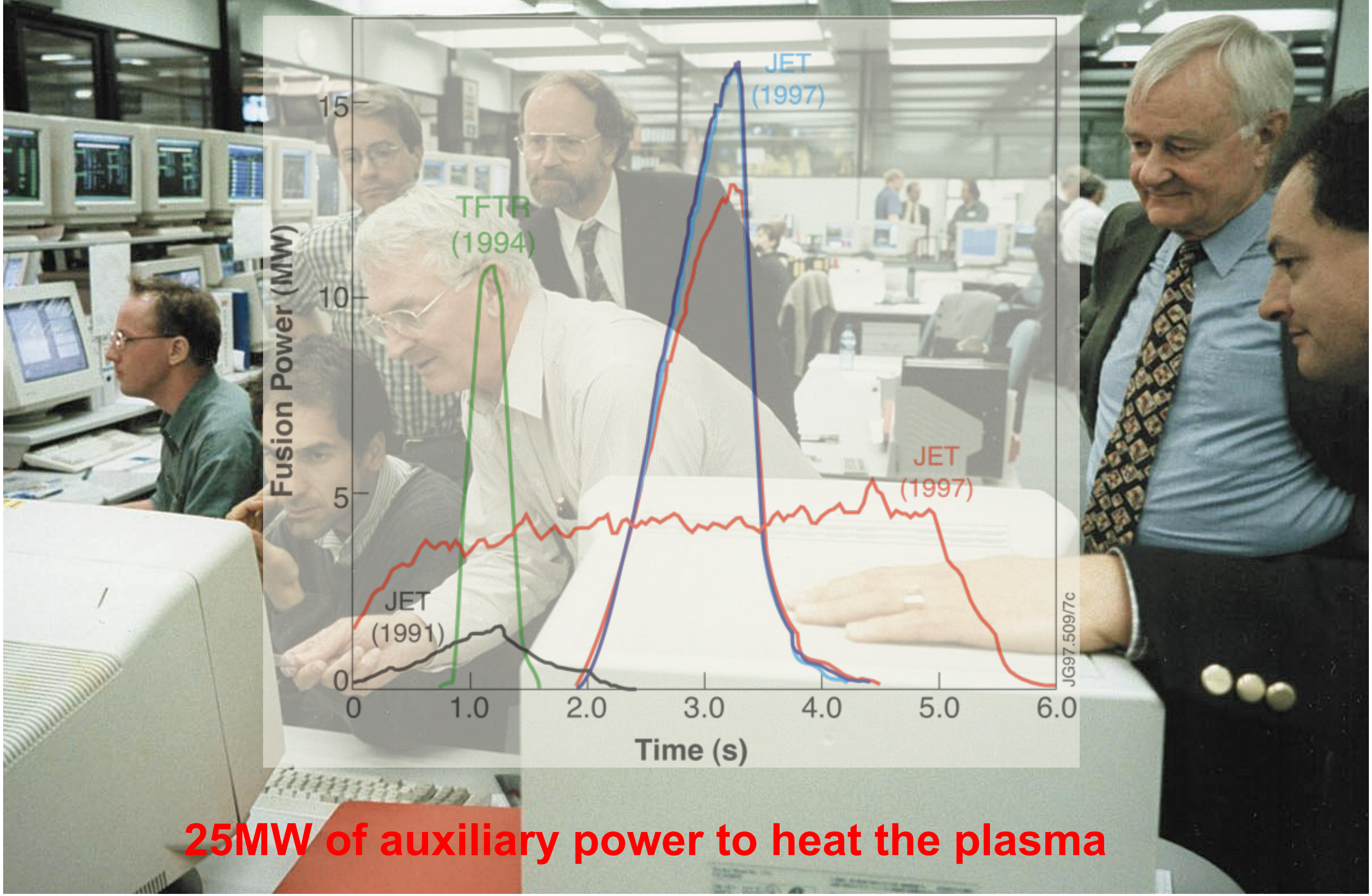
Matter is in the *plasma* state



The Joint European Torus (JET)



Fusion power has been produced on JET



25MW of auxiliary power to heat the plasma

The challenge of confining a hot plasma is achieved!

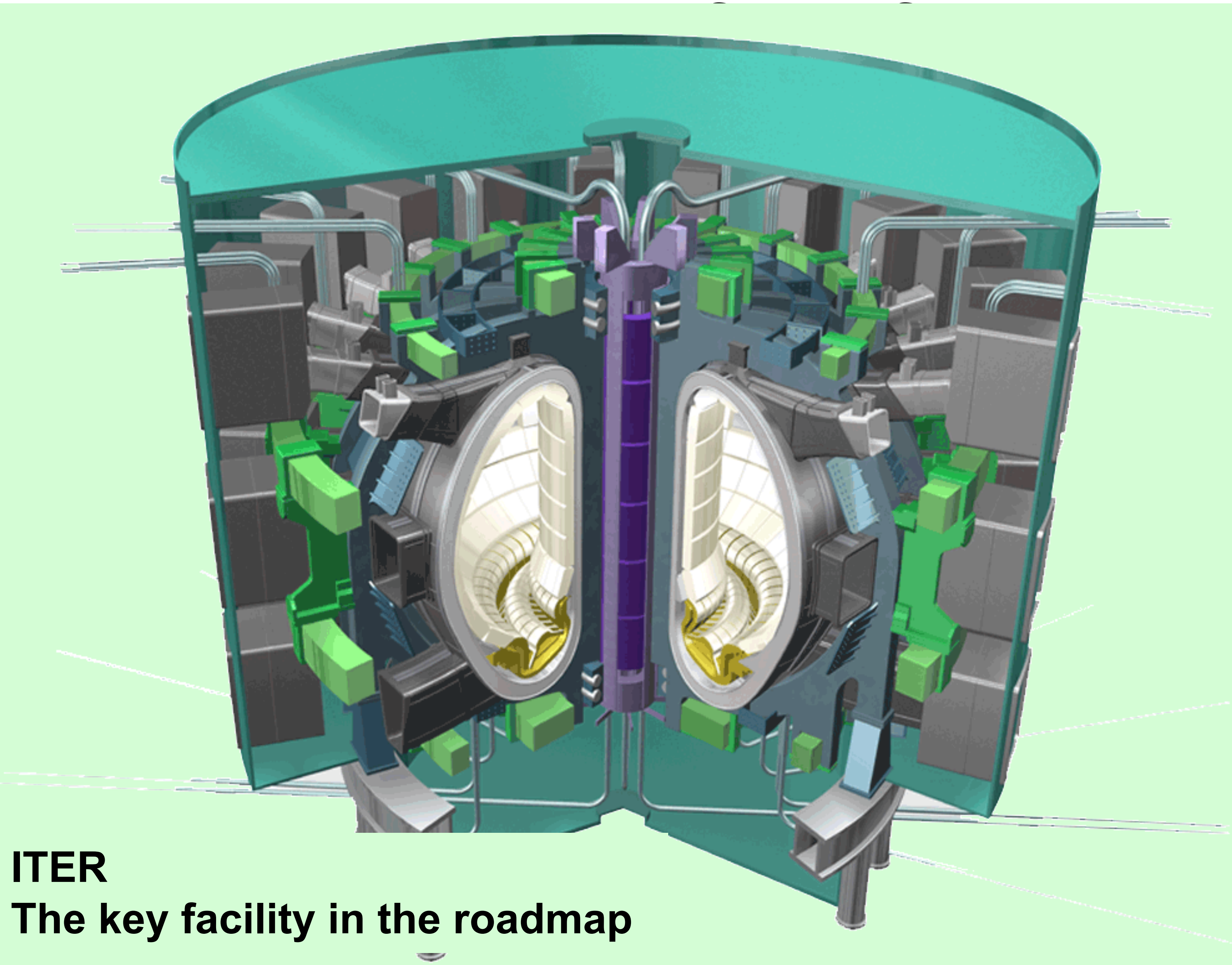
What do we need to make a power plant?

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

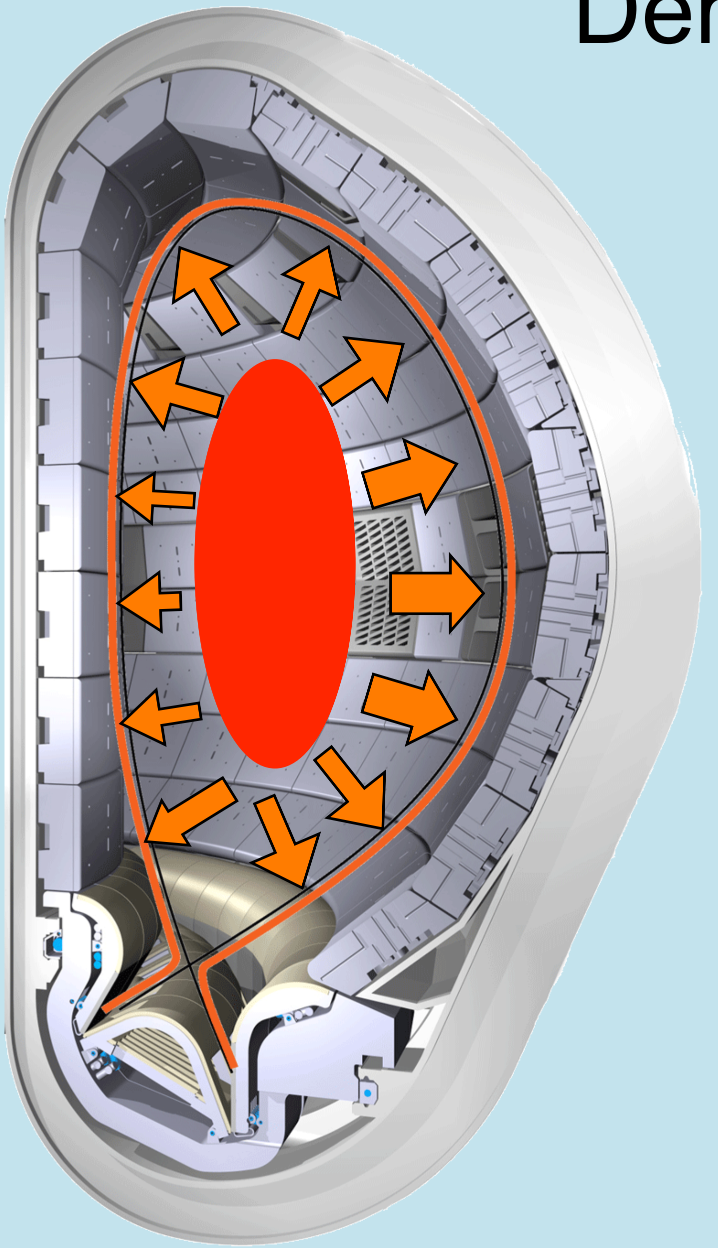
The present roadmap

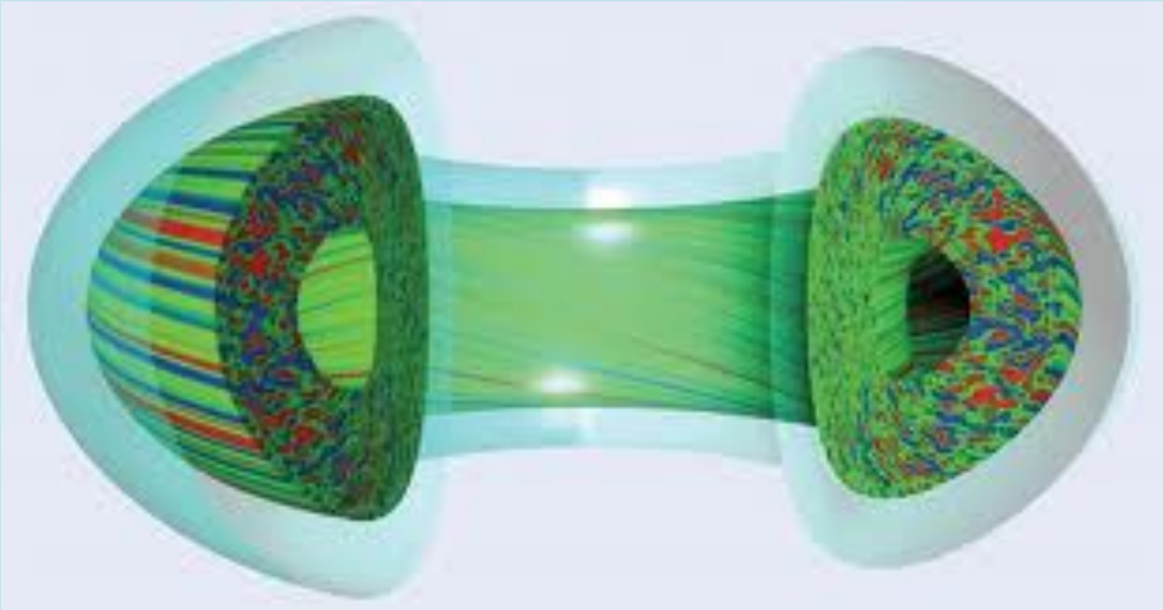
- **Pragmatic approach to fusion energy.**
- **Focus the effort of European laboratories around 8 Missions**
- **Ensure innovation through early industrial involvement**
- **Exploit the opportunities arising from international collaborations**



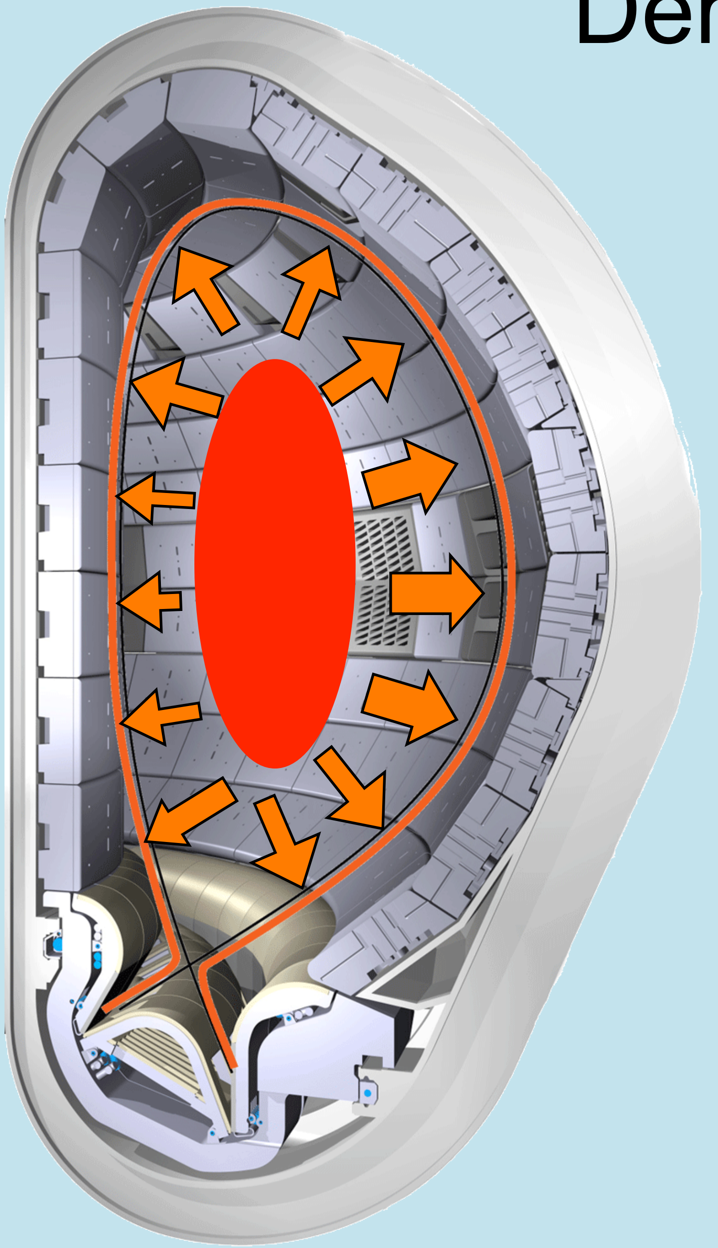
ITER
The key facility in the roadmap

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





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

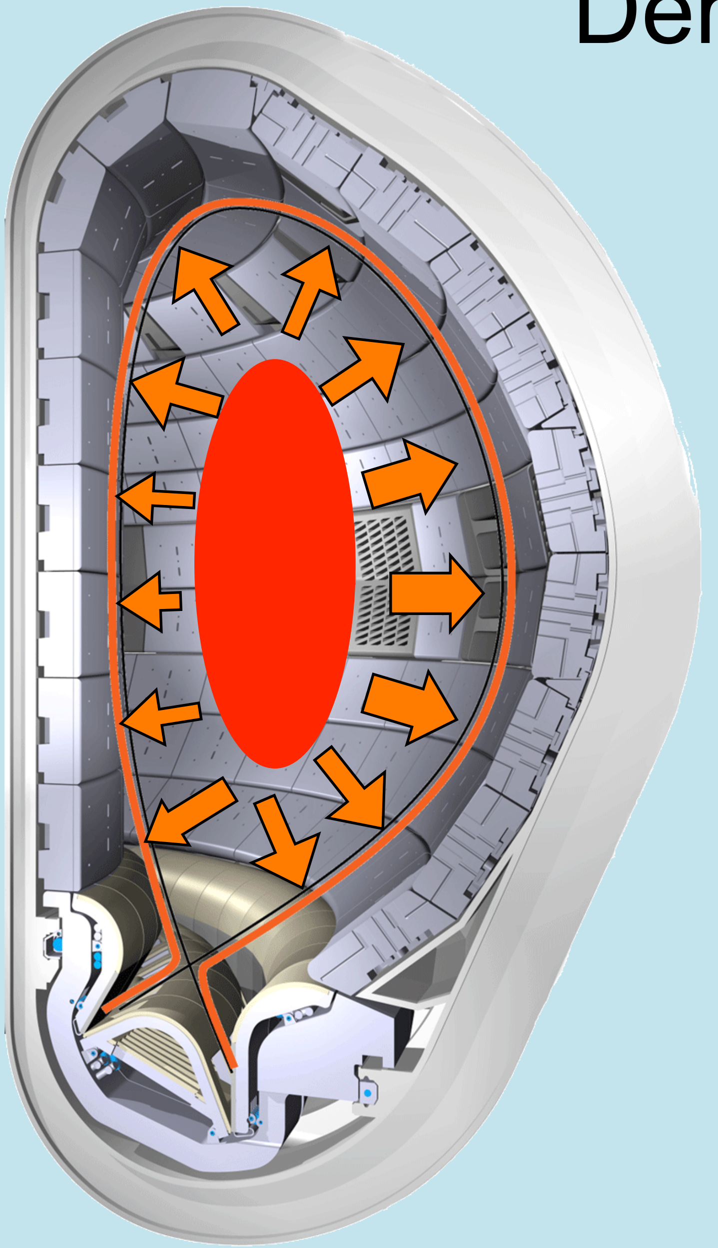


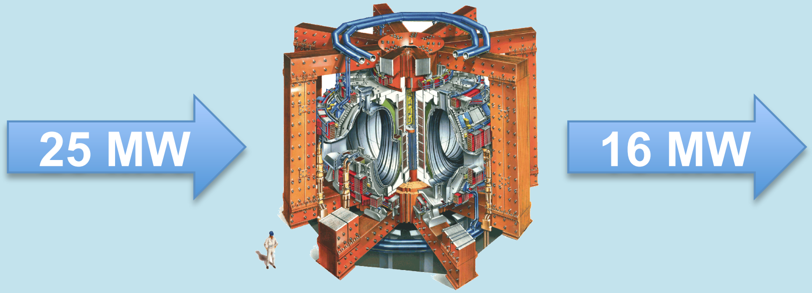
•Energy losses increase at most as the radius R of the device

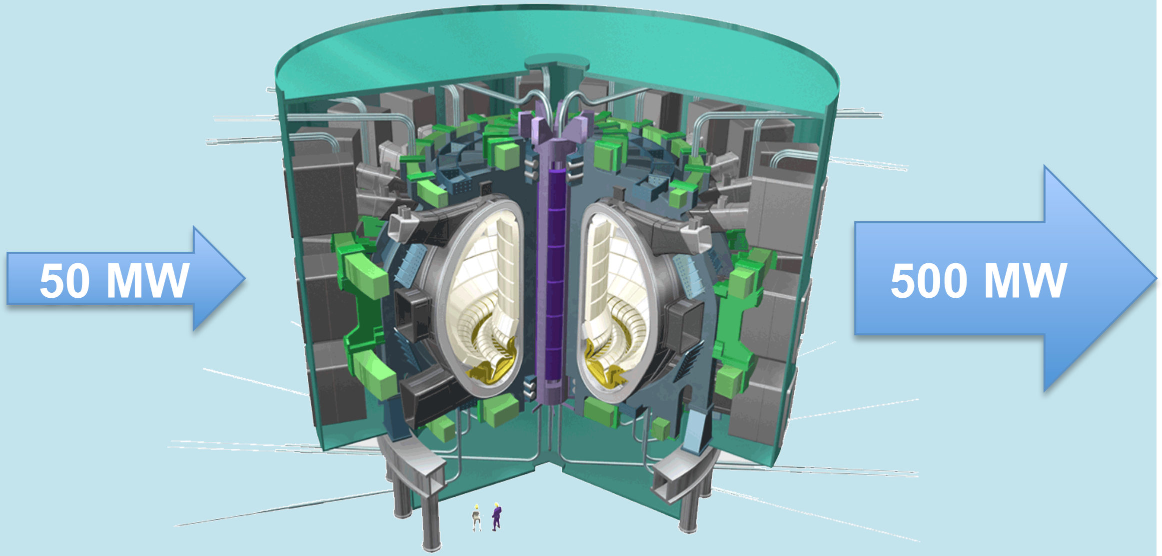
•Fusion power increases as the volume ($\approx R^3$)

MAKE LARGER DEVICES

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

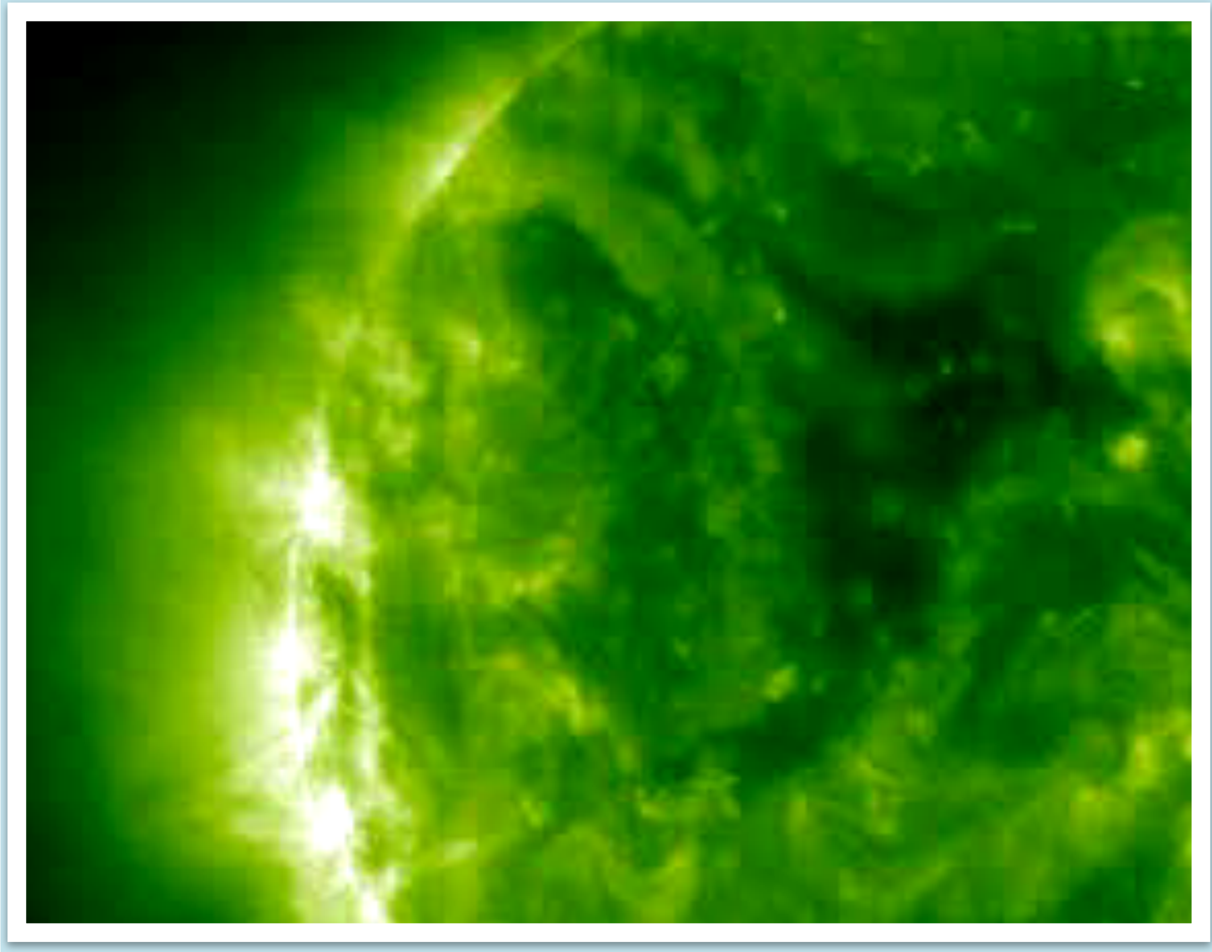


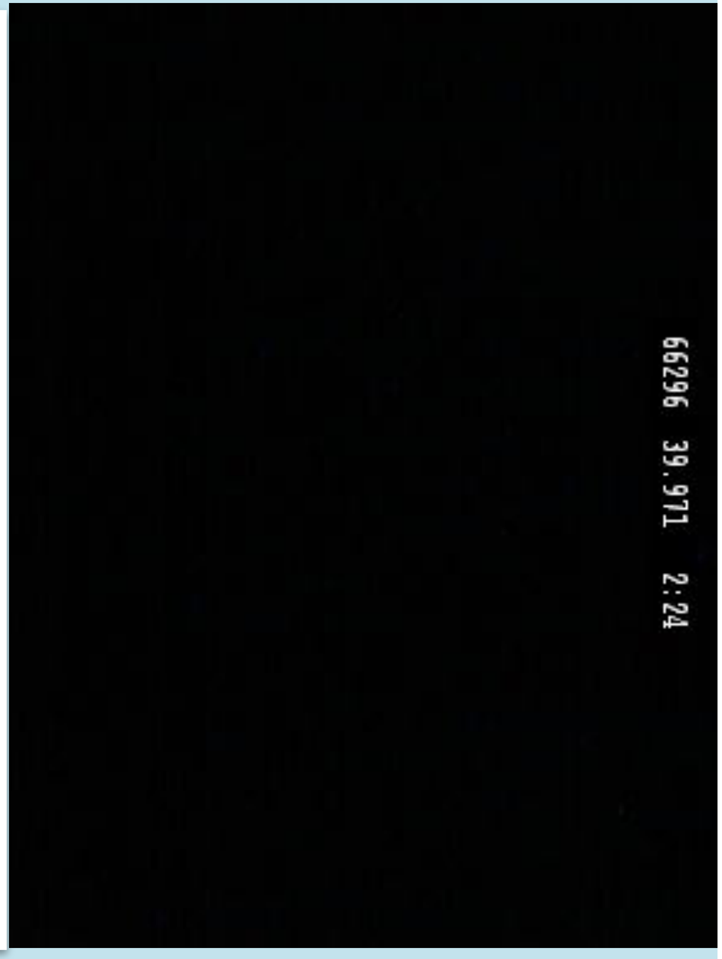




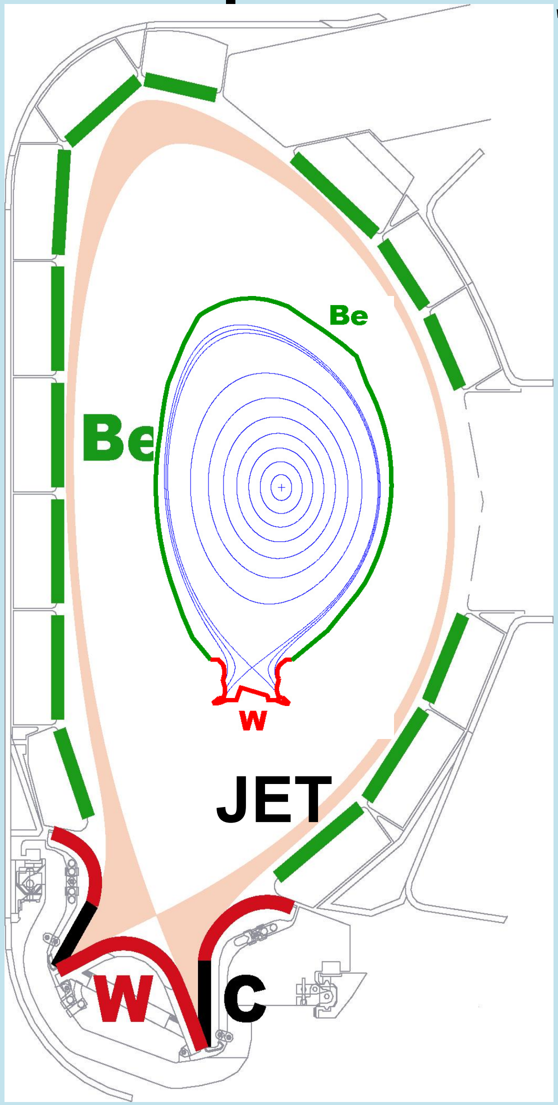
Mission 1: Plasma regimes for a reactor

Control plasma instabilities





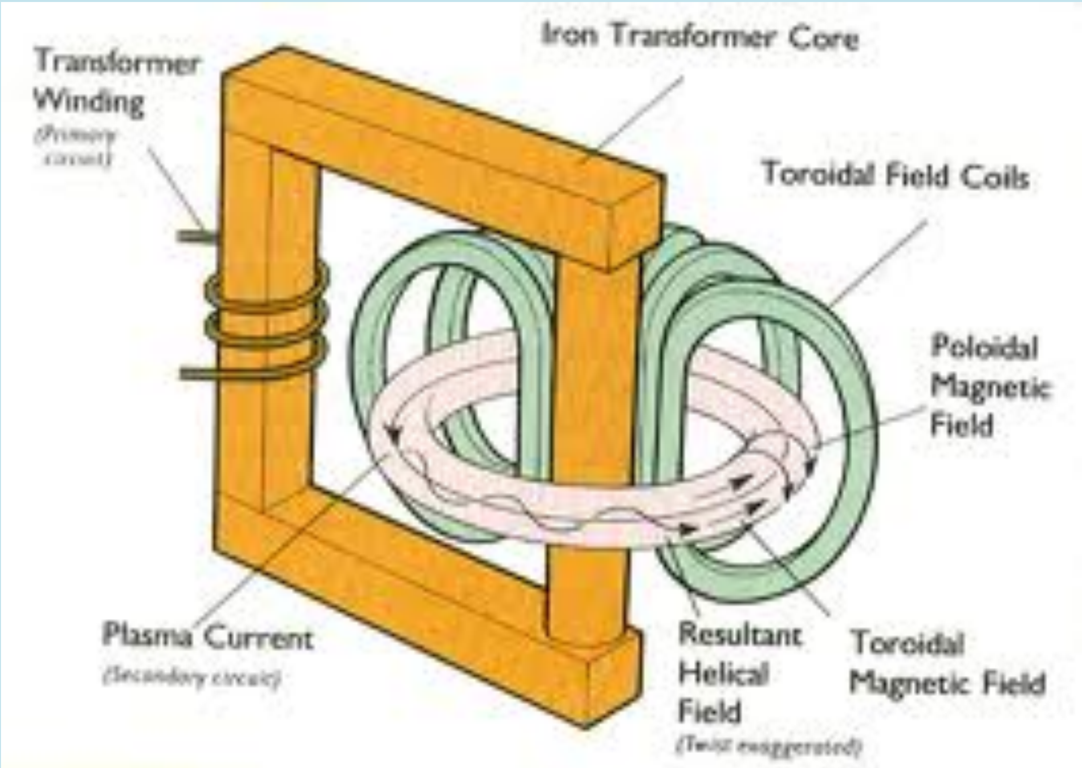
Mission 1: Plasma regimes for a reactor Compatibility between plasma and wall materials



ITER

Tungsten foreseen for a reactor to minimize erosion

Mission 1: Plasma regimes for a reactor Steady state regimes

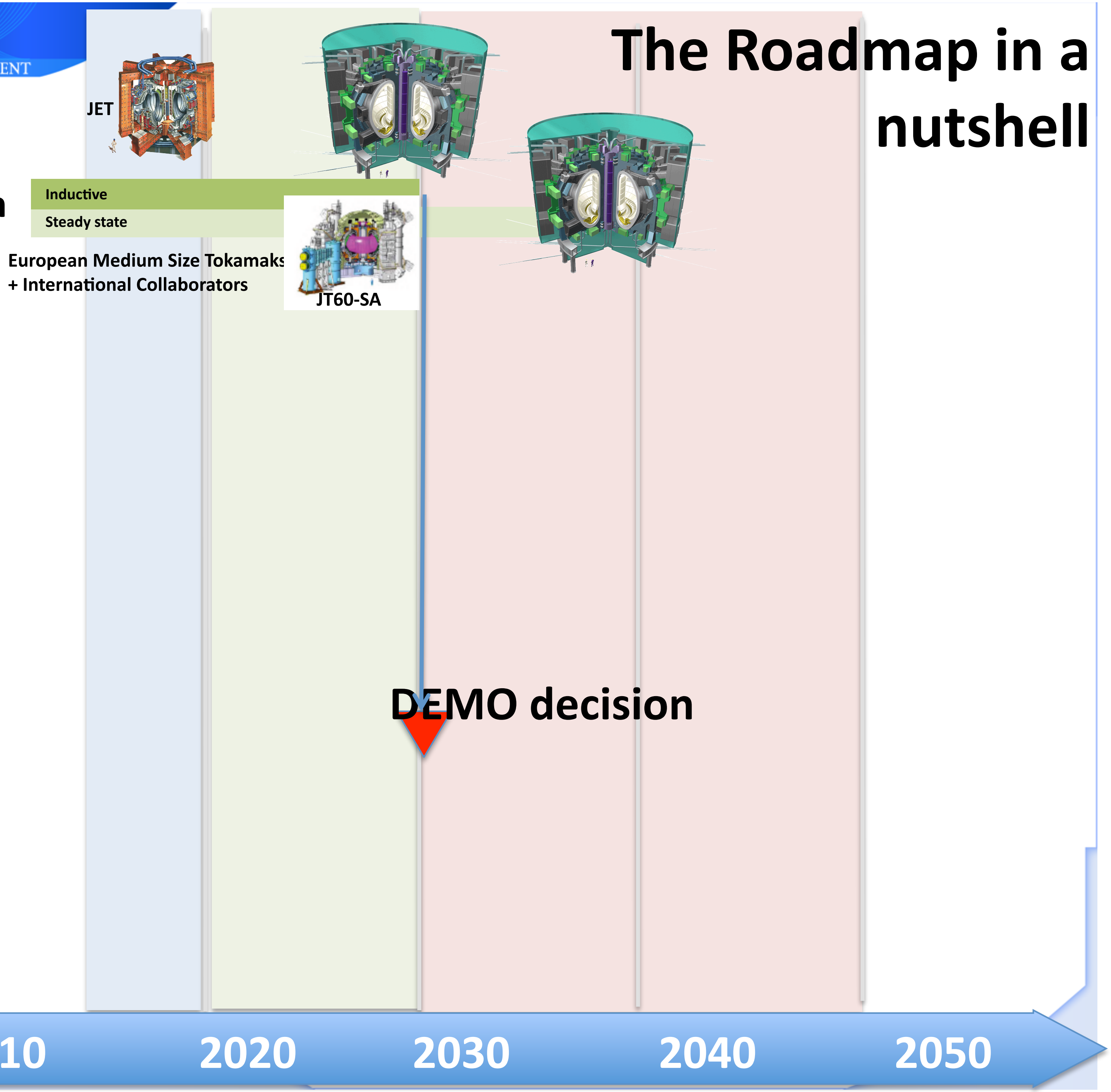


At high plasma pressure most of the current can be generated by the plasma itself (bootstrap mechanism)

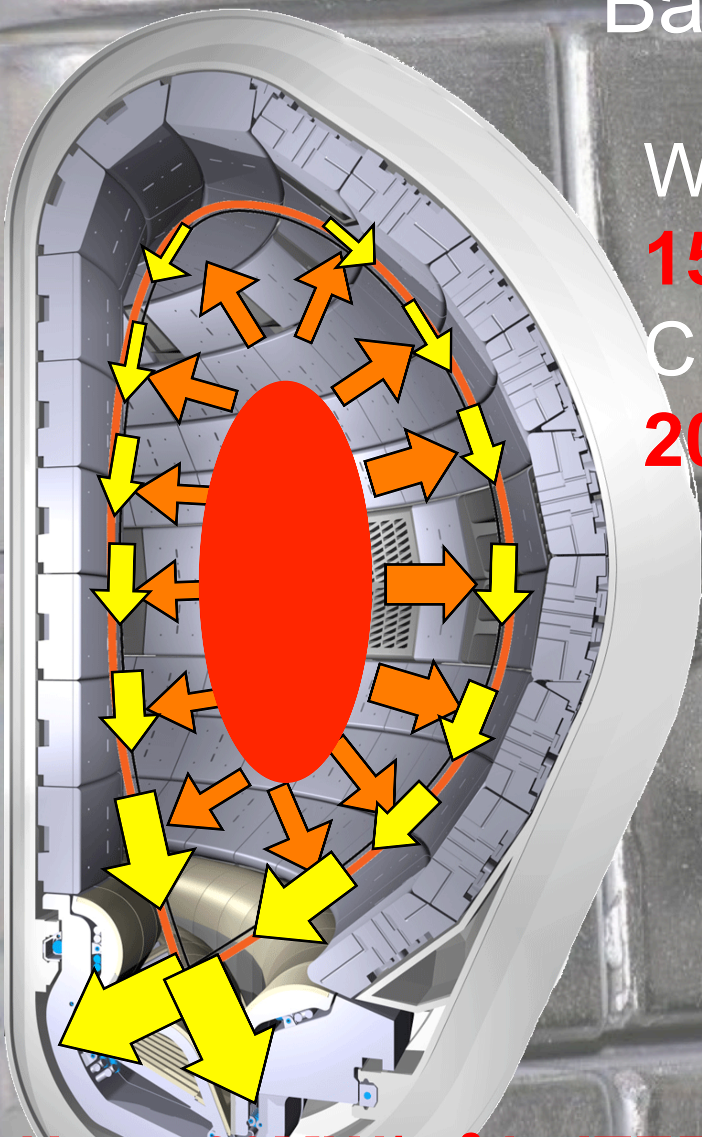
These regimes are still under development in tokamaks and will be demostrated in ITER beyond 2030.

The Roadmap in a nutshell

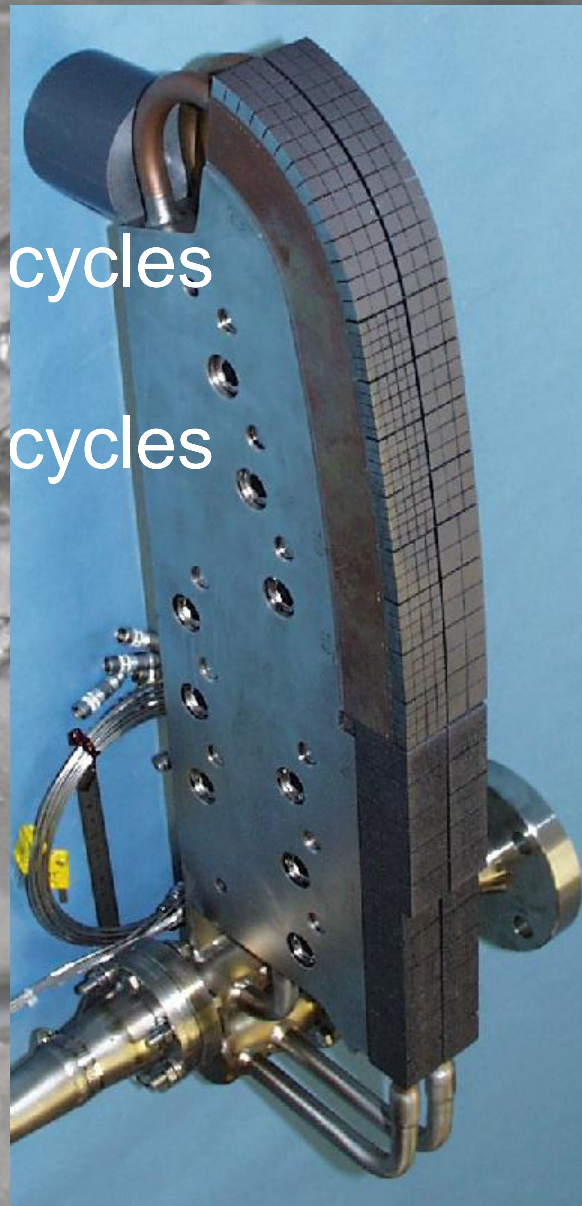
1. **Plasma operation**
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
7. Low cost
8. Stellarator



Mission 2: Heat and particle exhaust
Baseline strategy

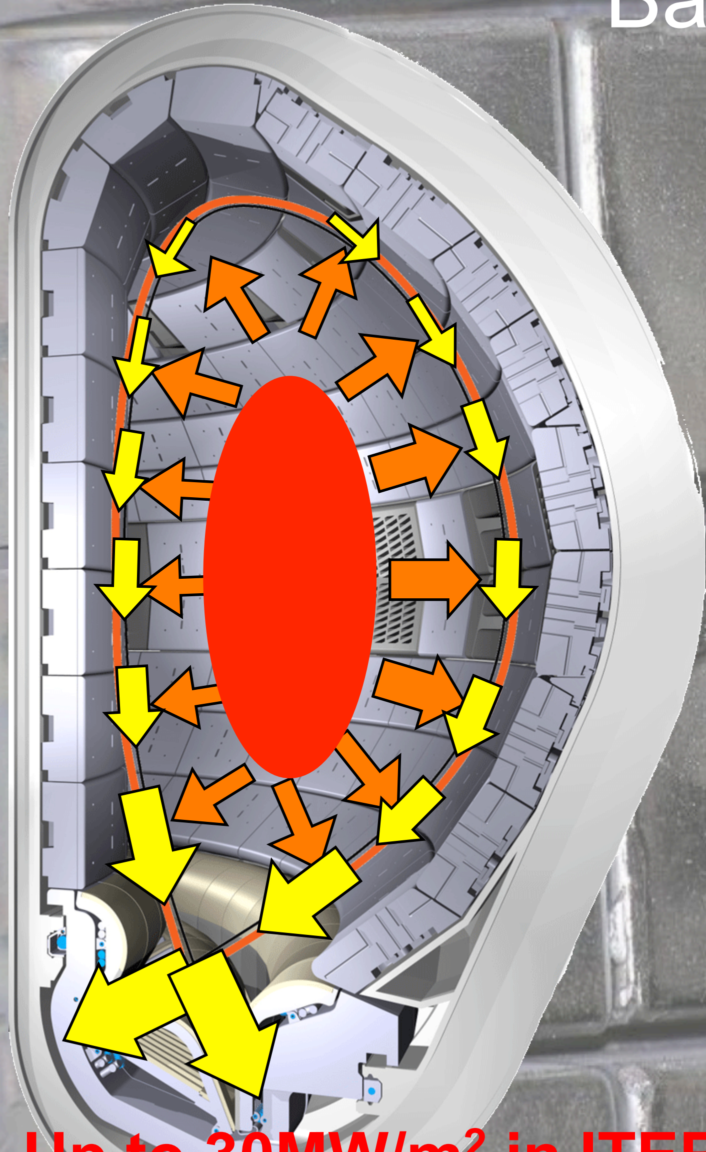


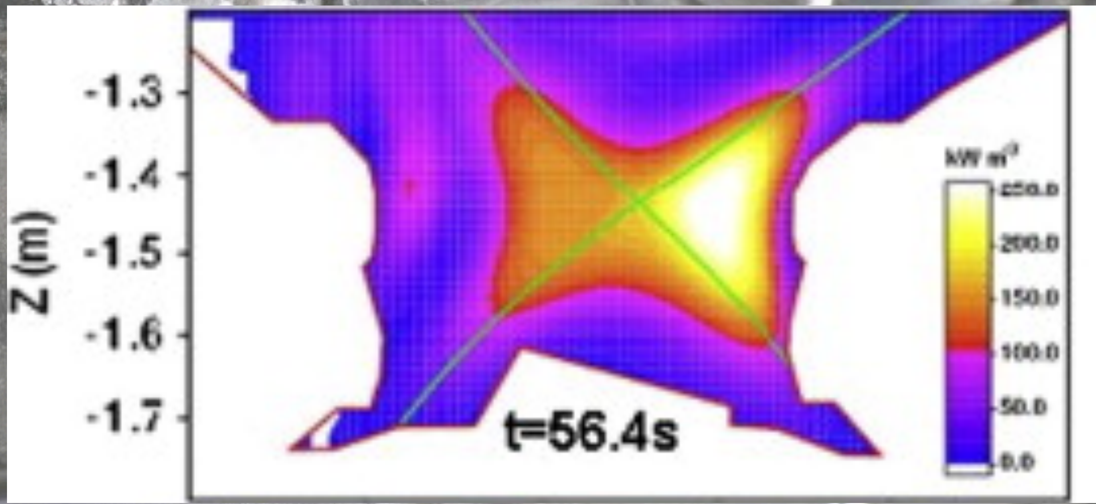
W macrobrush:
15 MW/m² x 1000 cycles
CFC monoblock
20 MW/m² x 2000 cycles



Up to 30MW/m² in ITER
(60MW/m² in a reactor ~ heat flux on the surface of the Sun!)

Mission 2: Heat and particle exhaust
Baseline strategy

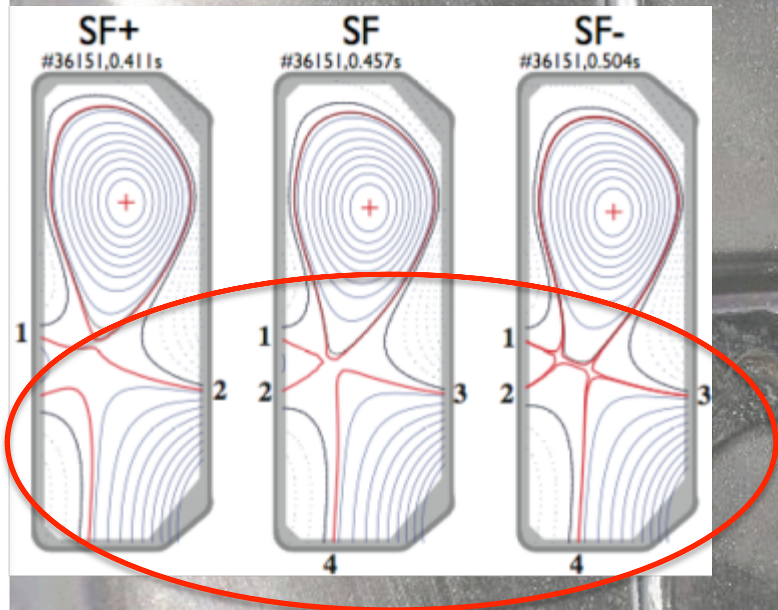


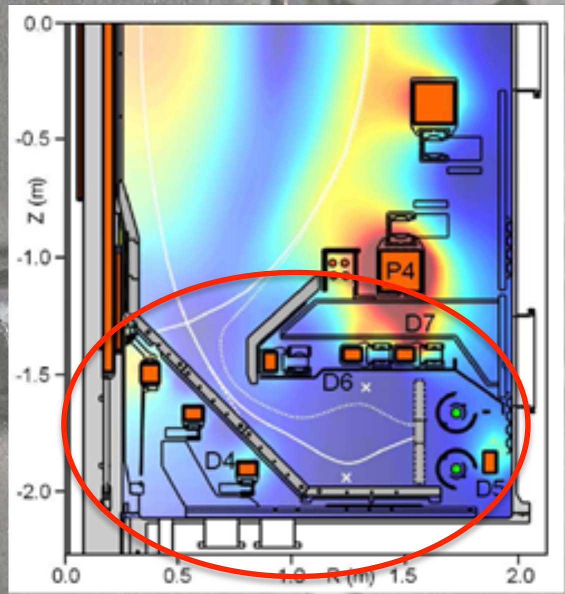


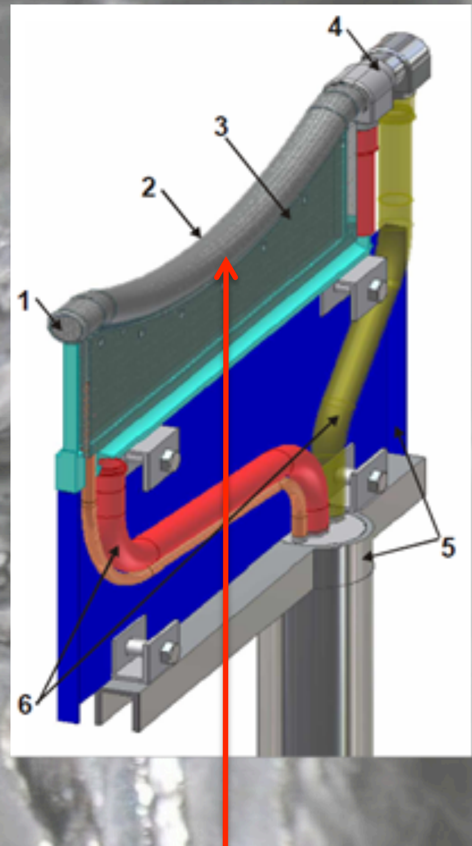
Divertor detachment

Up to 30MW/m² in ITER
(60MW/m² in a reactor ~ heat flux on the surface of the Sun!)

Mission 2: Heat and particle exhaust
Alternative strategies







Liquid-metals

- Proof-of-principle on medium size experiments
- Assess reactor-relevance in parallel

EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

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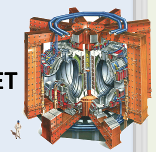
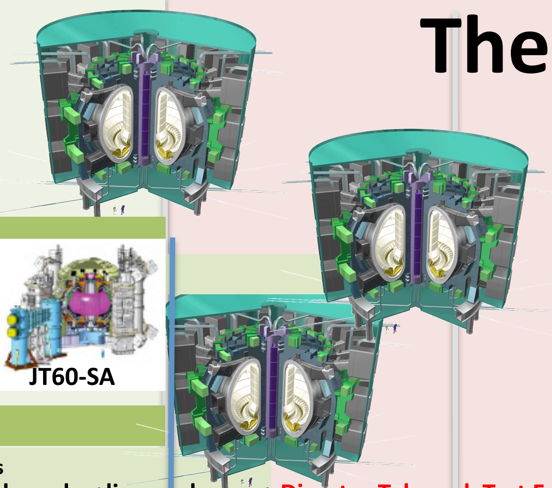
JET





Inductive

Steady state

European Medium Size Tokamaks + International Collaborators

JT60-SA

Baseline strategy

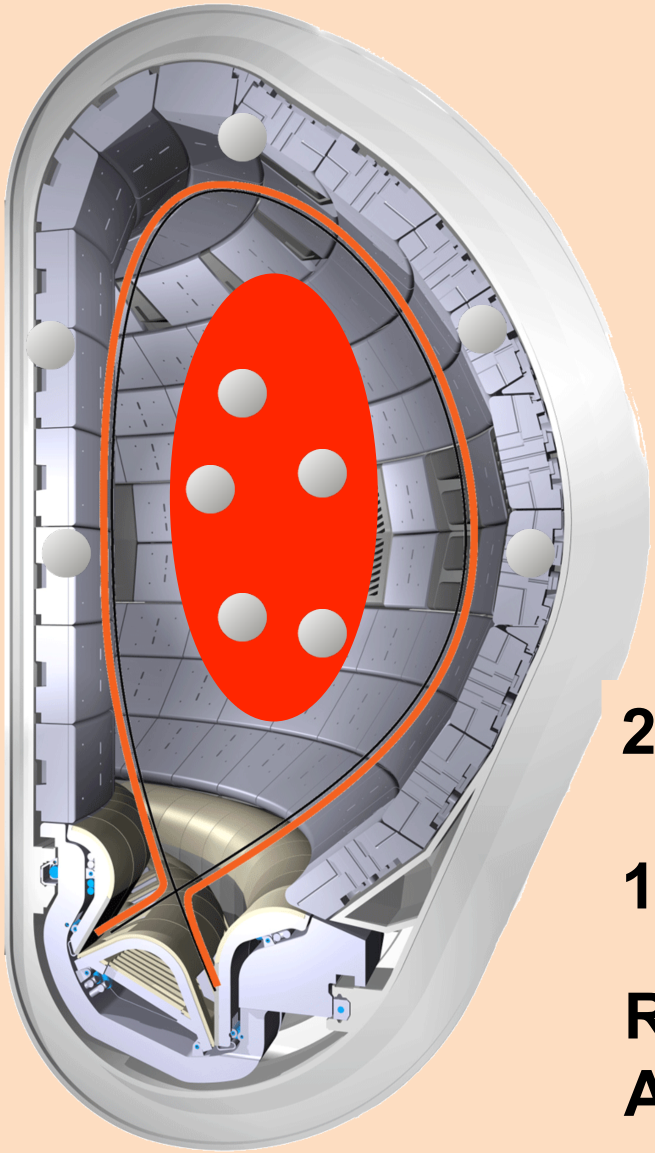
Advanced configuration and materials

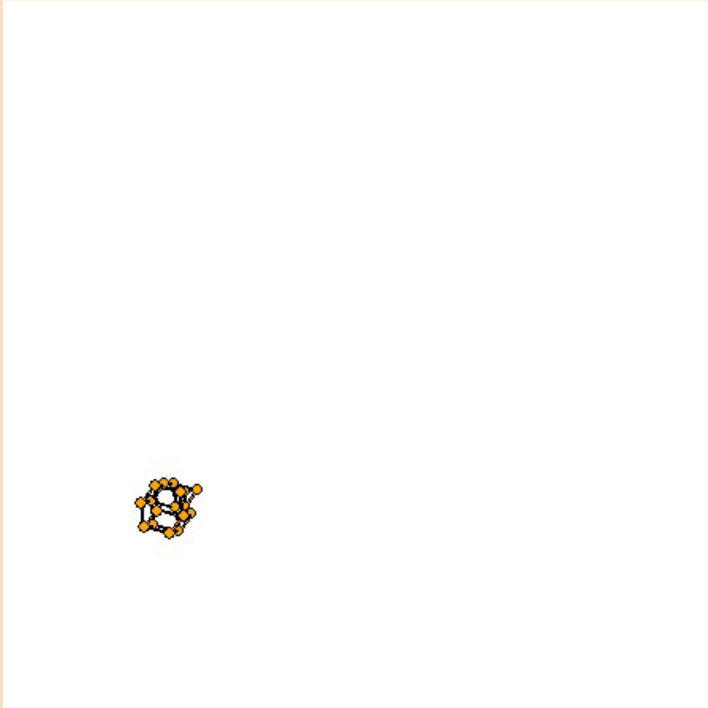
European Medium Size Tokamaks +linear plasma + Divertor Tokamak Test Facility + International Collaborators Tokamaks

DEMO decision

2010 2020 2030 2040 2050

Mission 3: Develop neutron resistant materials





S. Dudarev

2 displacements per atom (dpa) in ITER

150 dpa in a fusion plant

Reduction of structural properties

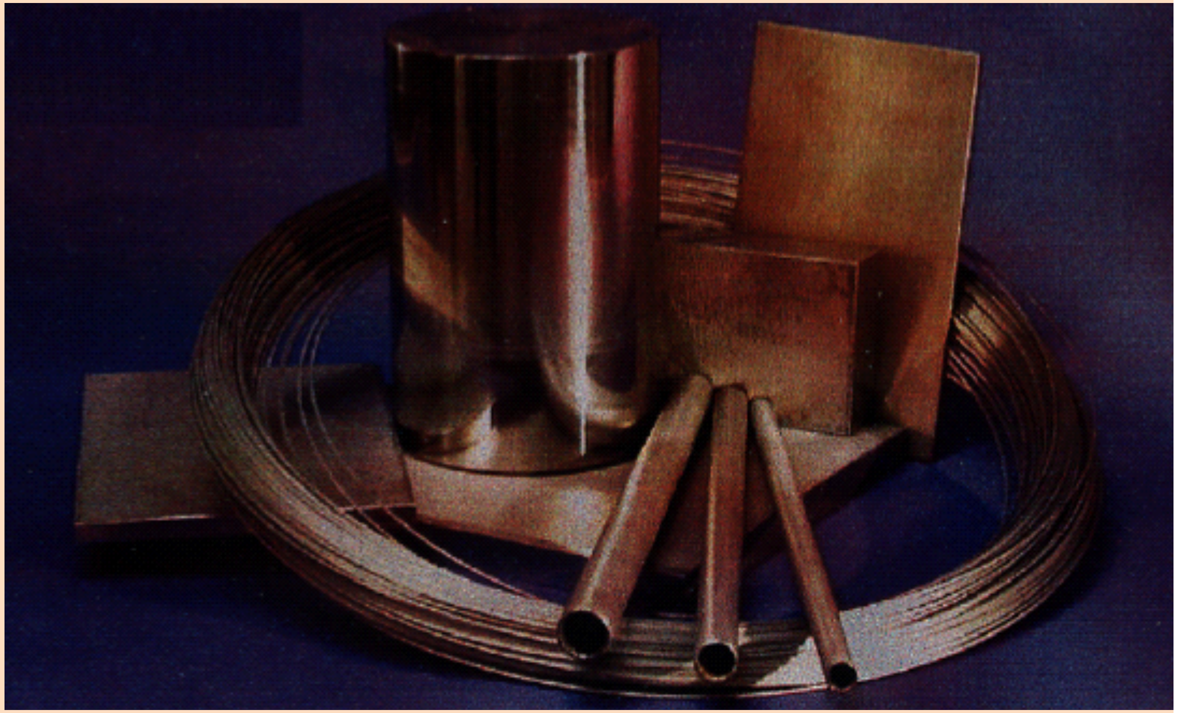
Activation

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

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



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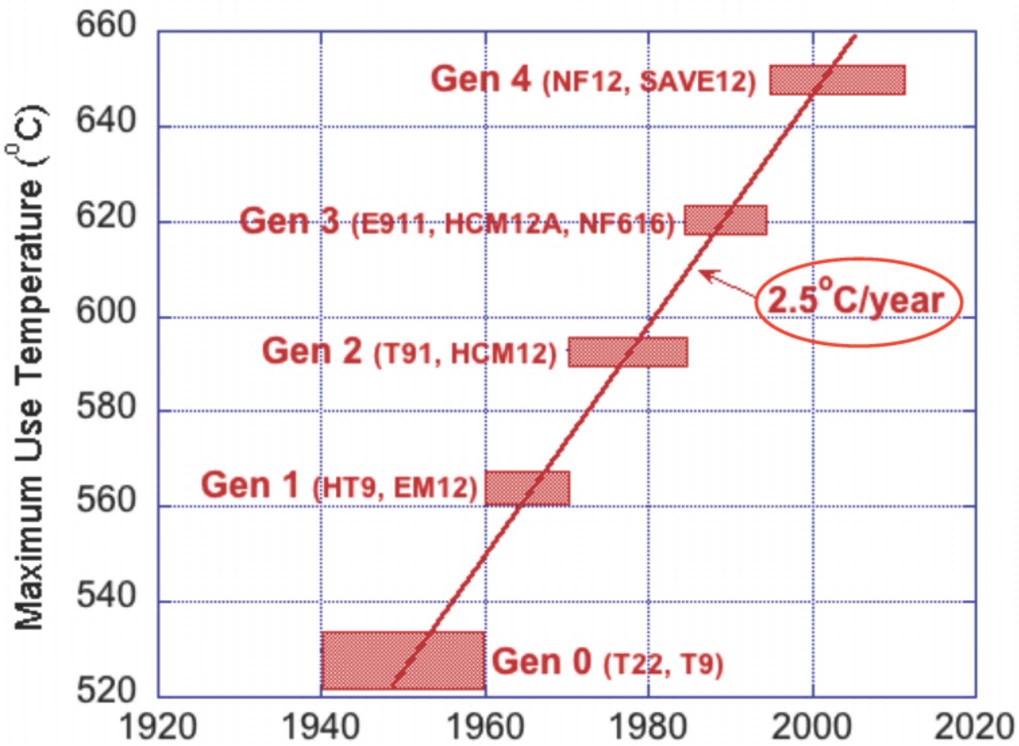
Advanced materials under examination
ODS steels (650^{o}C)
High-Temperature Ferritic-Martensitic steels

Based on R. Viswanathan, Adv. Mat. Proc. 162 (2004) 73



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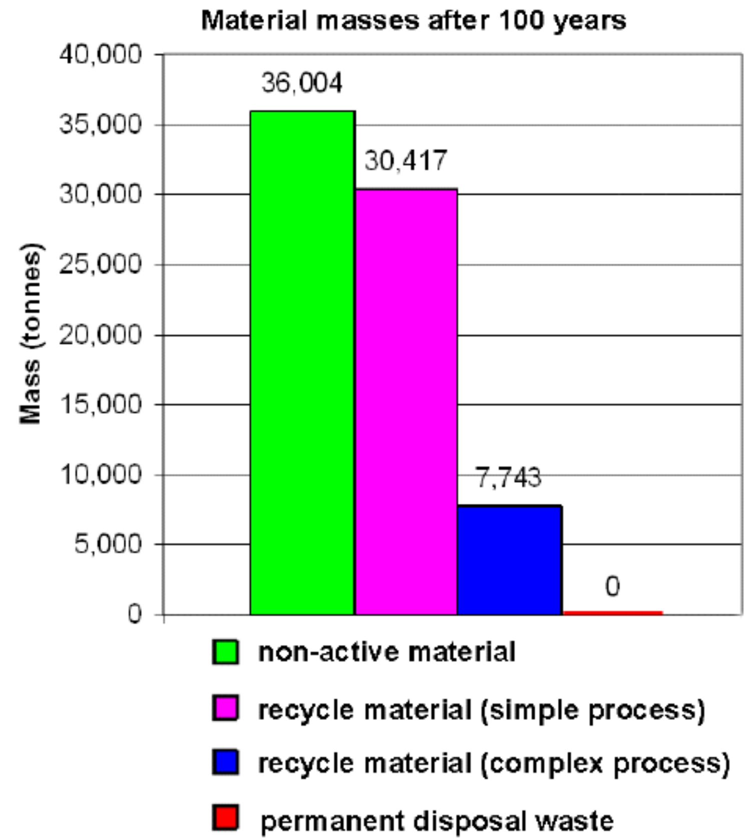
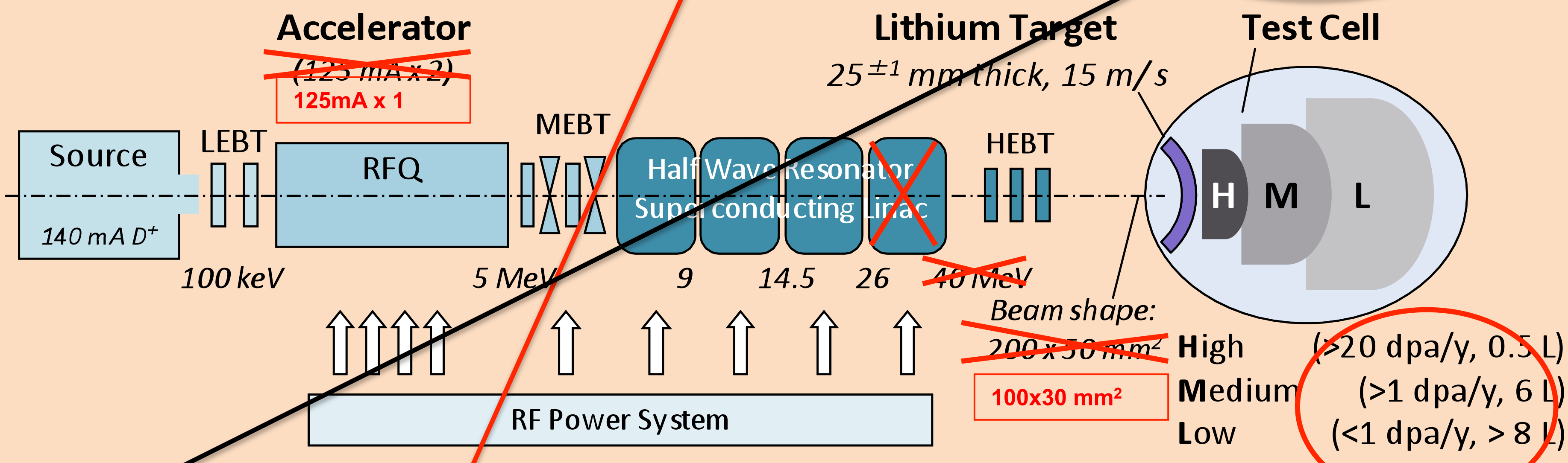
Advanced materials under exam
ODS steels (650°C)
High-Temperature Ferritic-Martensitic steels

Activation falls 10000 times after 100 years
No need for permanent waste repository



Mission 3: Develop neutron resistant materials

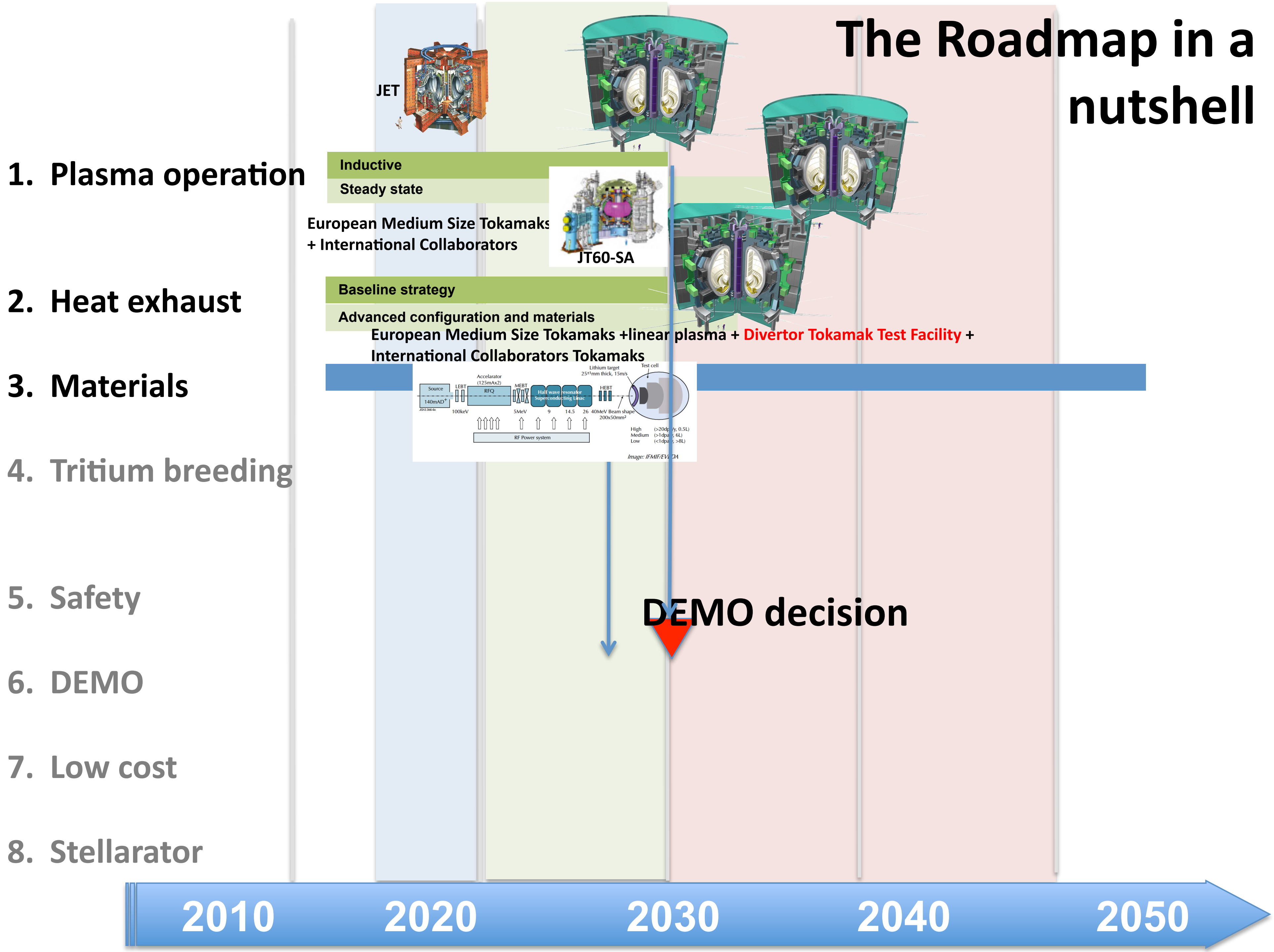
	Onset of 14MeV effects	Calibration of 14Mev effects	Full database for the full exposure
DEMO Phase1	20dpa (Fe) 250-350ºC 20cc	20dpa (Fe) 250-550ºC 70cc	20dpa (Fe) 250-550ºC 300cc
DEMO Phase2	50dpa (Fe) 250-350ºC 20cc	50dpa (Fe) 250-550ºC 70cc	50dpa (Fe) 250-550ºC 300cc
Reactor		100dpa (Fe) 250-1200ºC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



Still to be optimised: 15 dpa – 20cm³
>2 dpa – 0.5L

IFMIF

Early Neutron Source



The Roadmap in a nutshell
1. Plasma operation
2. Heat exhaust
3. Materials
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5. Safety
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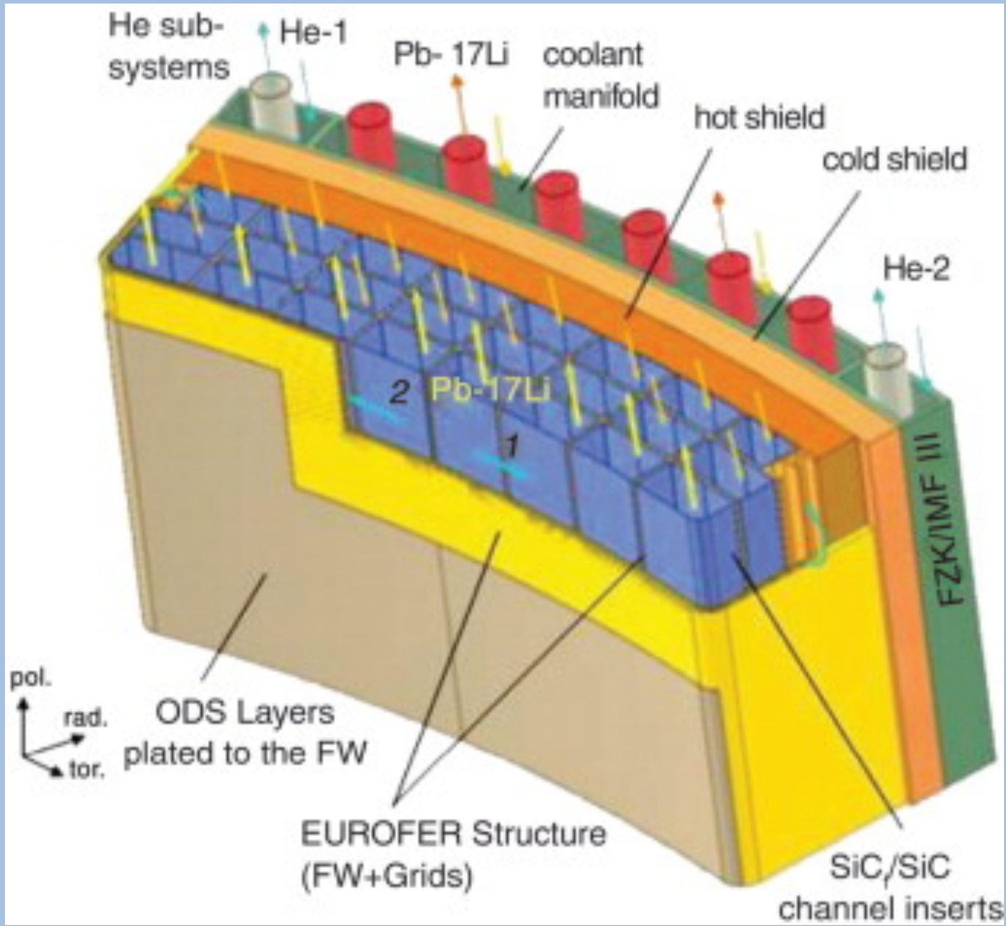
7. Low cost
8. Stellarator
JET
Inductive
Steady state
European Medium Size Tokamaks
+ International Collaborators
JT60-SA
Baseline strategy
Advanced configuration and materials
European Medium Size Tokamaks +linear plasma + Divertor Tokamak Test Facility +
International Collaborators Tokamaks
DEMO decision
2010
2020
2030
2040
2050

Mission 4: Tritium breeding



Breeder
- **solid**
- **liquid**

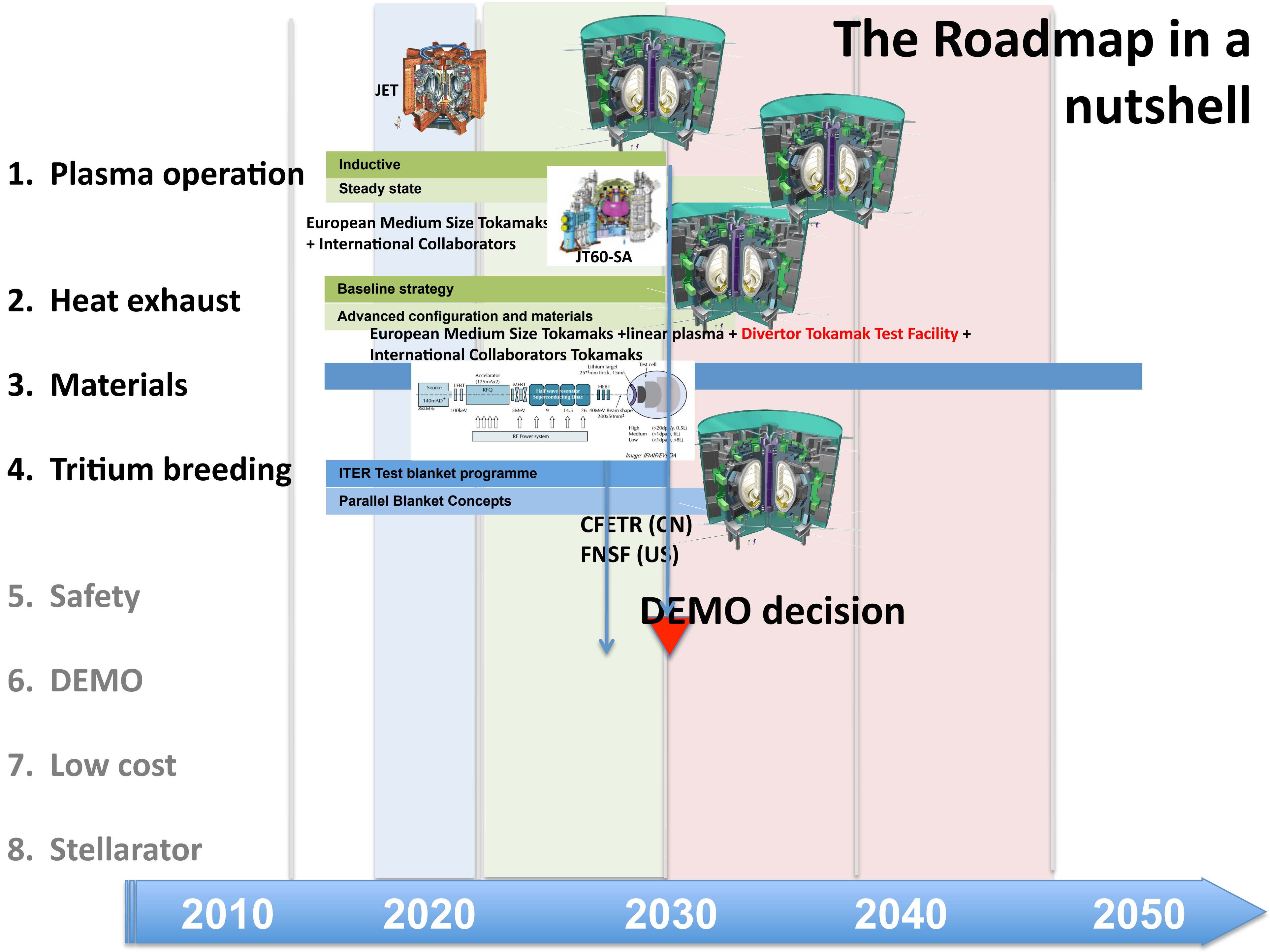
Coolant
- **water**
- **helium**
- **self-cooled**

Multiplier
- **Be**
- **Pb**

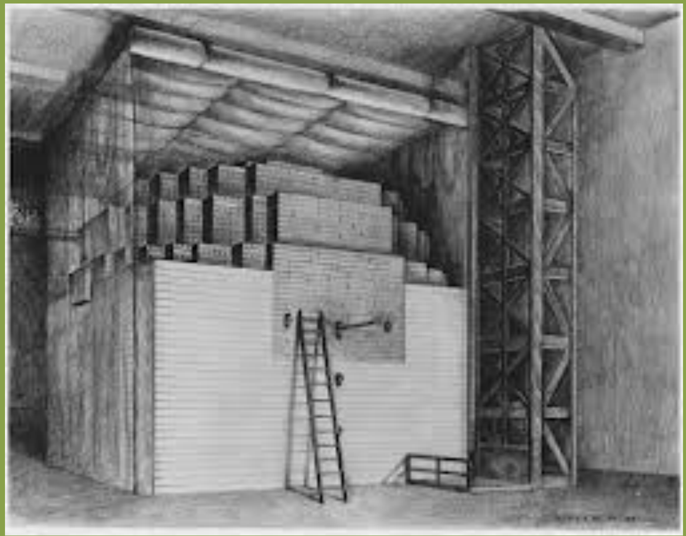
Efficient T extraction
Efficient electricity generation (balance of plant)

A 1.5GWe reactor uses ~0.5kg Tritium/day

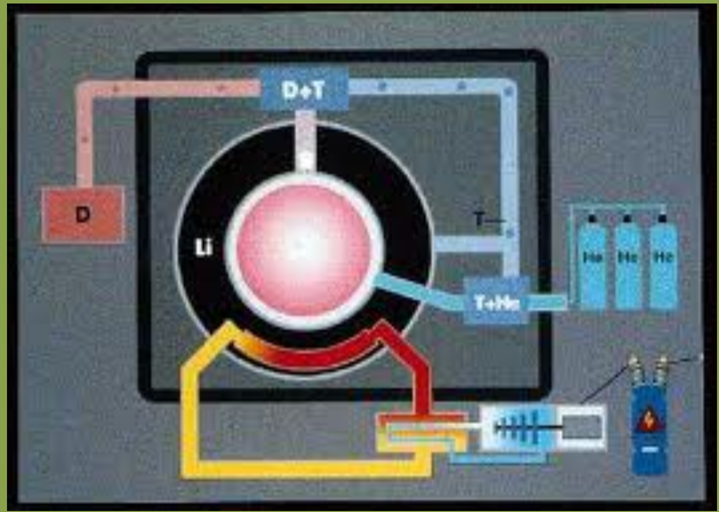
The Roadmap in a nutshell



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

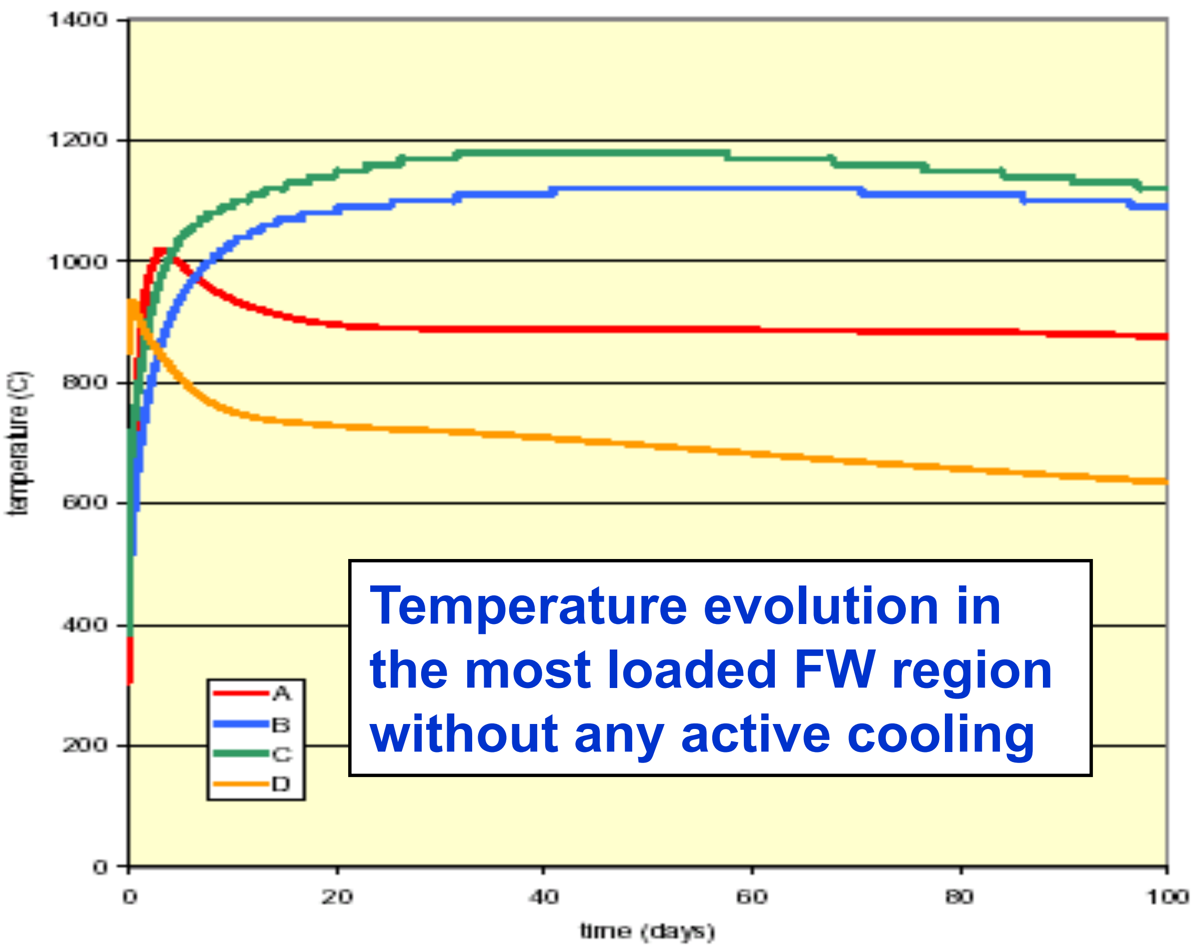


Fermi pile



Fusion reactor

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

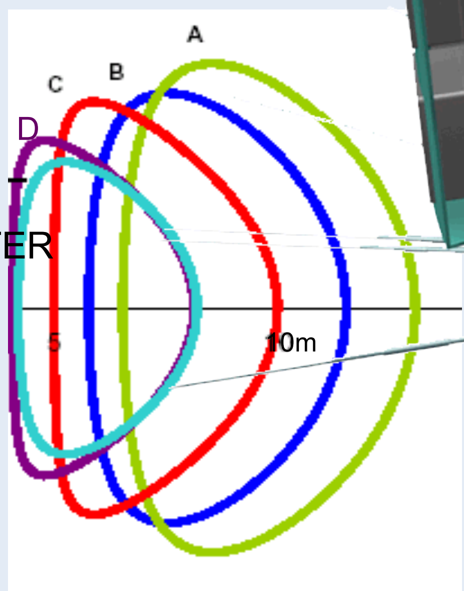


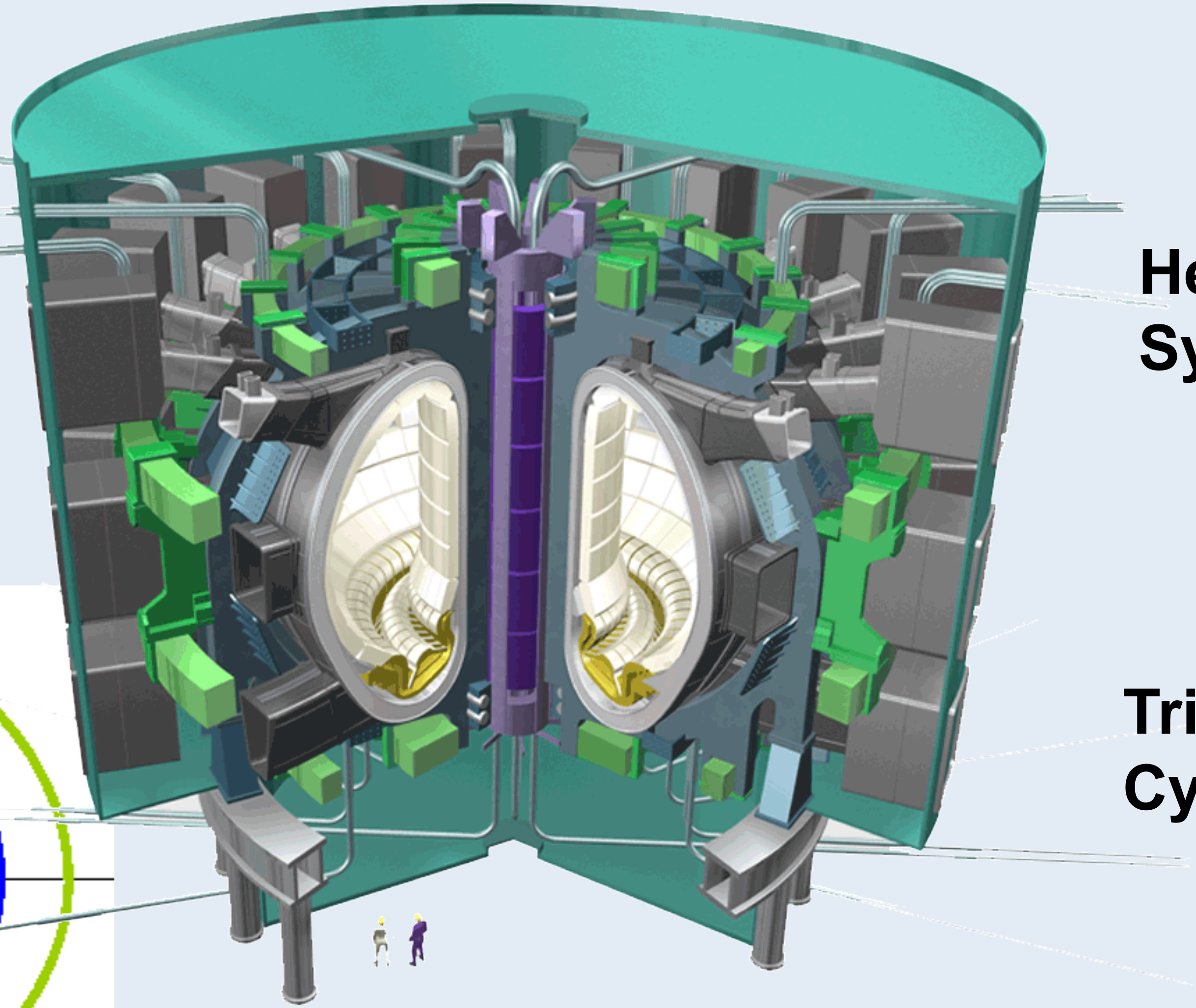
Mission 6: DEMO design

Balance of Plant

Magnets

Vacuum Vessel





Heating Systems

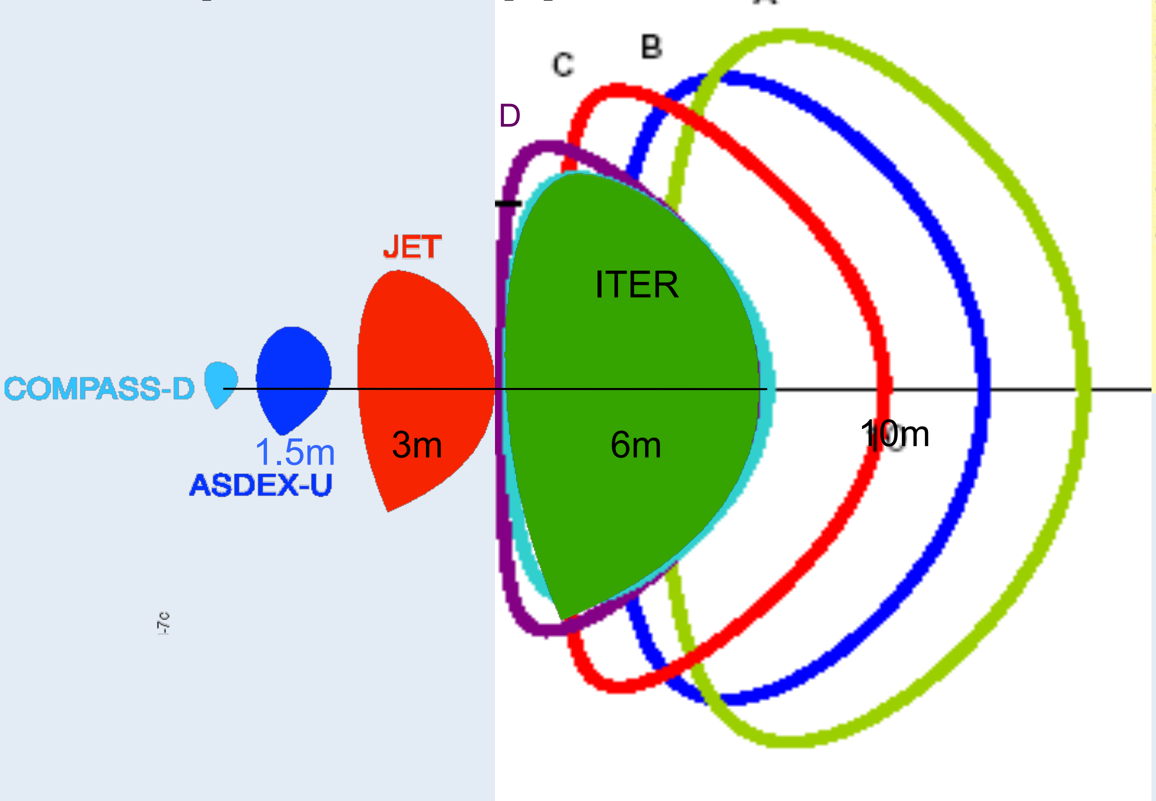
Tritium Cycle

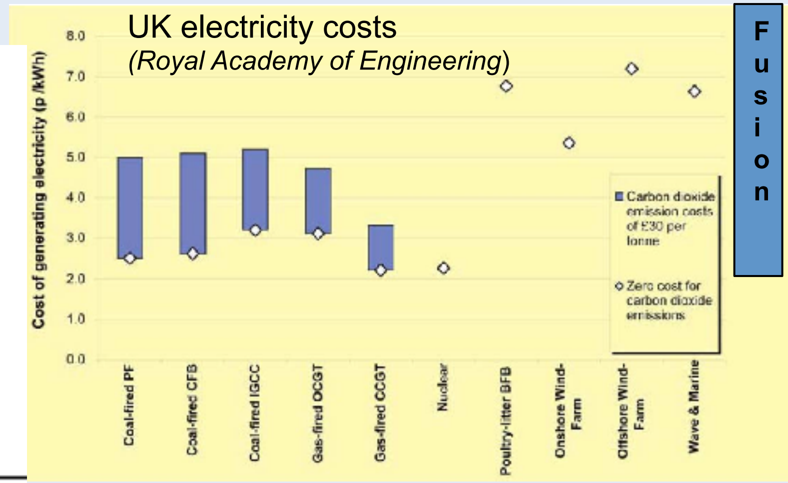
Remote Handling

[redacted]

Mission 7: Low cost of electricity

Step ladder approach





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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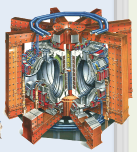
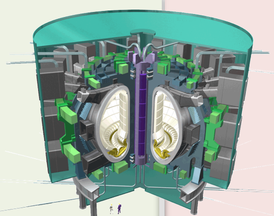
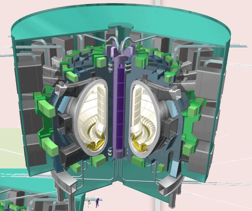
JET





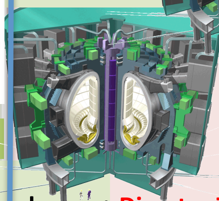


Inductive

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 +
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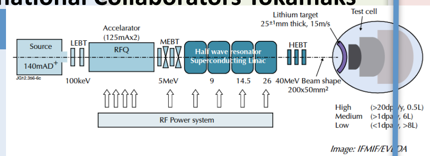
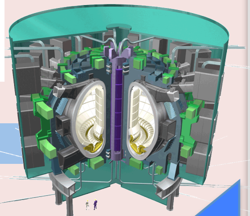
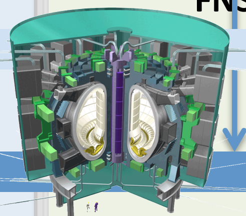


ITER Test blanket programme

Parallel Blanket Concepts



CFETR (CN)
FNSF (US)



DEMO dec

CDA +EDA

Construction

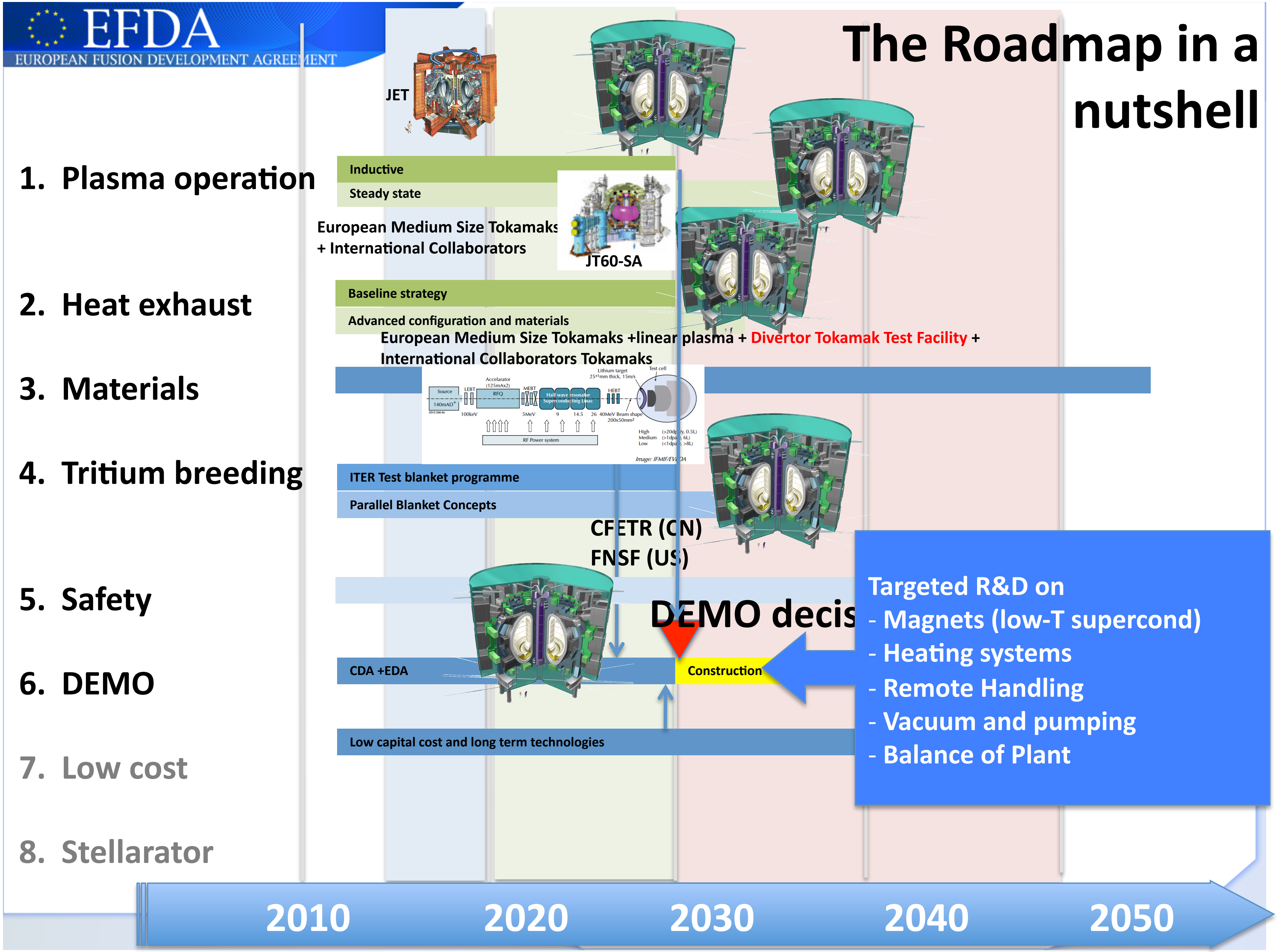
Low capital cost and long term technologies

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.

2010 2020 2030 2040 2050



EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT
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5. Safety
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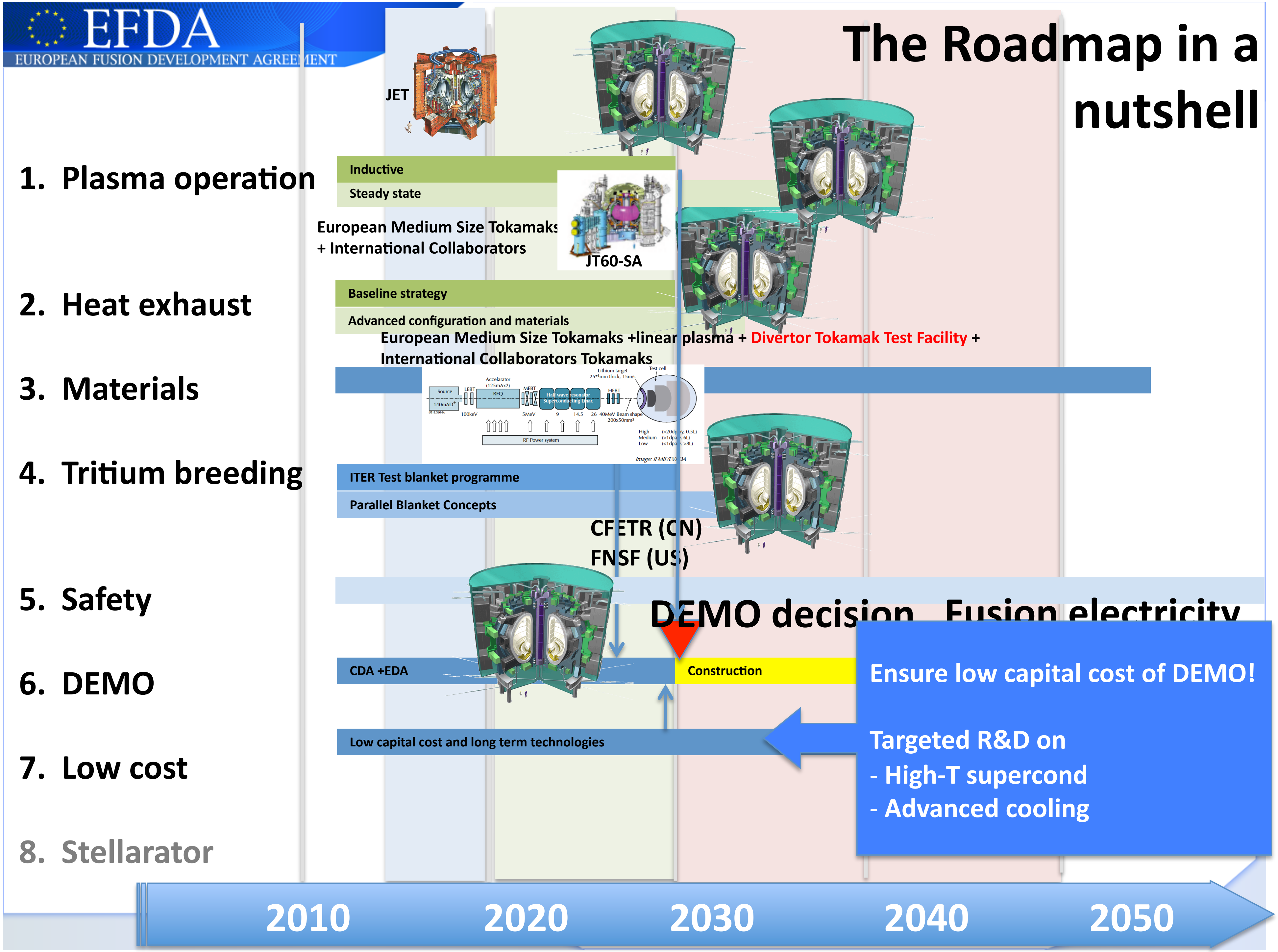
6. DEMO
CDA +EDA
Construction
7. Low cost
Low capital cost and long term technologies
8. Stellarator
Targeted R&D on
- Magnets (low-T supercond)
- Heating systems
- Remote Handling
- Vacuum and pumping
- Balance of Plant
2010
2020
2030
2040
2050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Ensure low capital cost of DEMO!
Targeted R&D on
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- Advanced cooling
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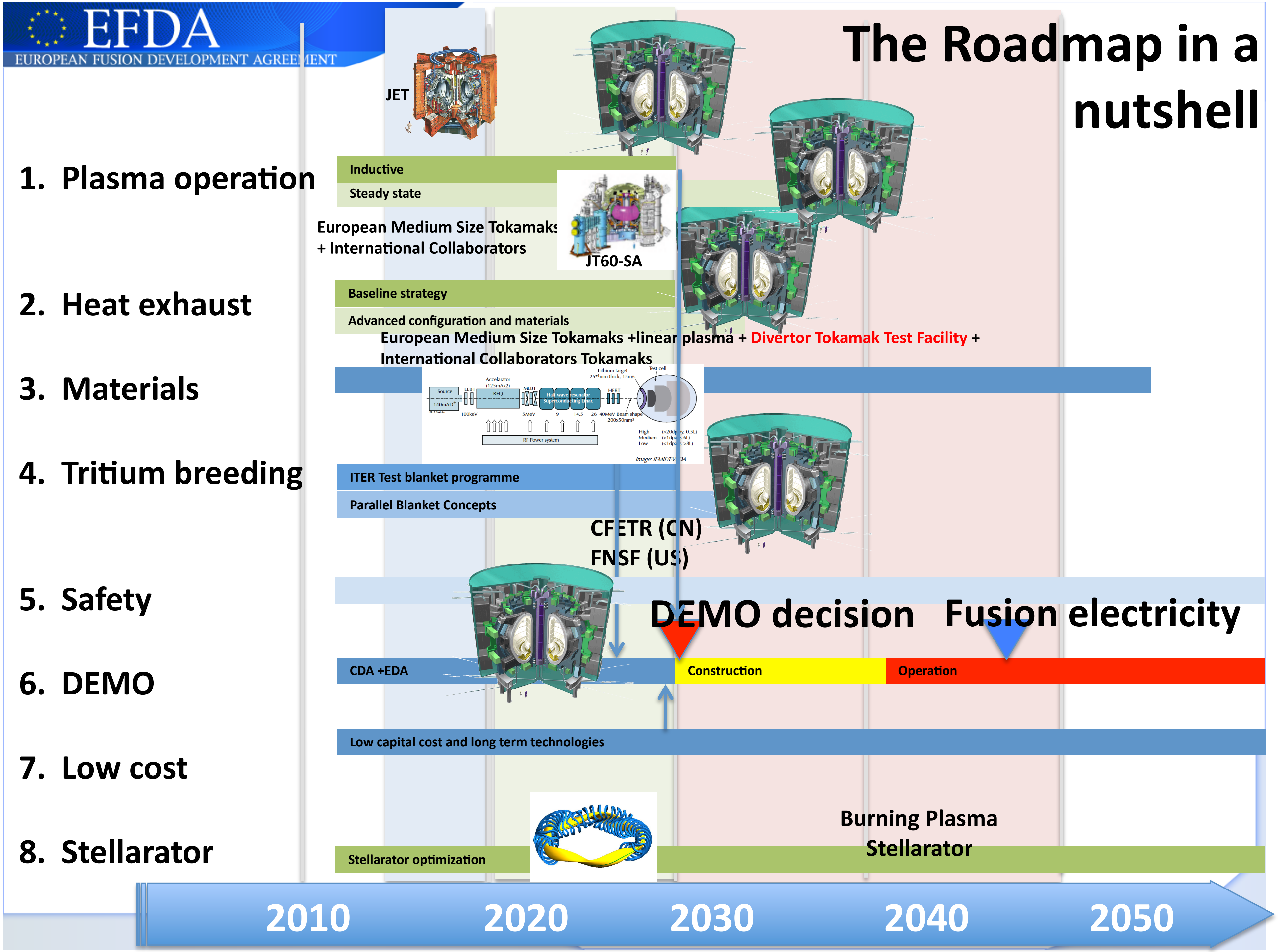

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Inductive
Steady state
European Medium Size Tokamaks
+ International Collaborators
JT60-SA
Baseline strategy
Advanced configuration and materials
European Medium Size Tokamaks +linear plasma + Divertor Tokamak Test Facility +
International Collaborators Tokamaks
ITER Test blanket programme
Parallel Blanket Concepts
CFETR (CN)
FNSF (US)
DEMO decision
Fusion electricity
CDA +EDA
Construction
Operation
Low capital cost and long term technologies
Burning Plasma
Stellarator
Stellarator optimization
2010
2020
2030
2040
2050

Conclusions

- The roadmap will be a living document, reviewed regularly in response to the physics, technology and budgetary developments.