A Roadmap to the realization of fusion energy

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
SOFE 11 June 2013

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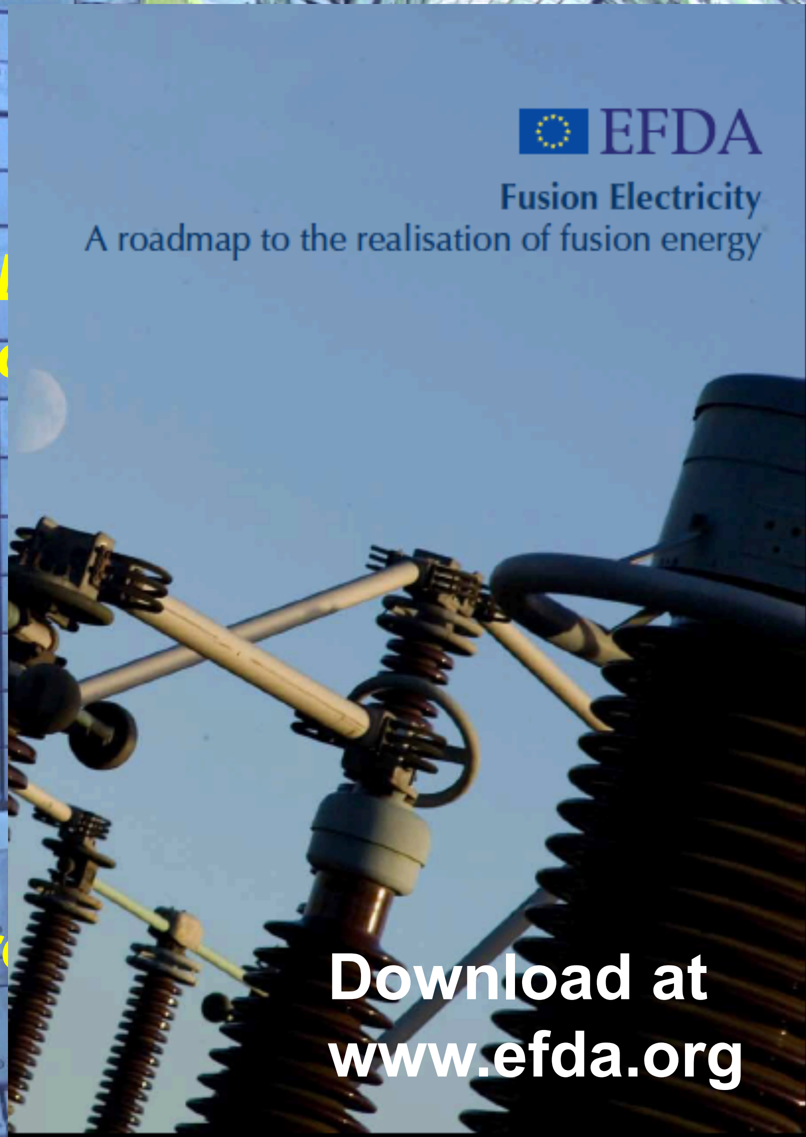

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See also G. Federici contribution at this conference
D. Stork et al. Material Assessment Report

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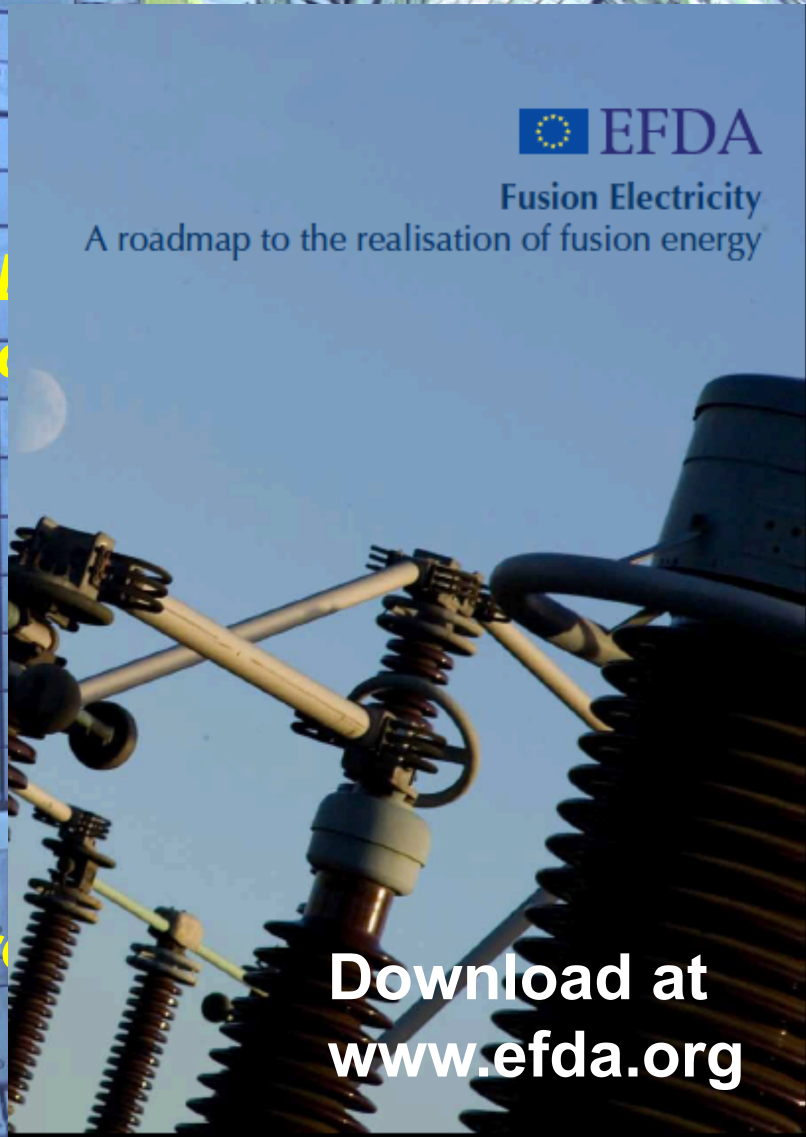

Outline

- Background on the Roadmap
- The Missions for the realization of fusion
- Resources

Background

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

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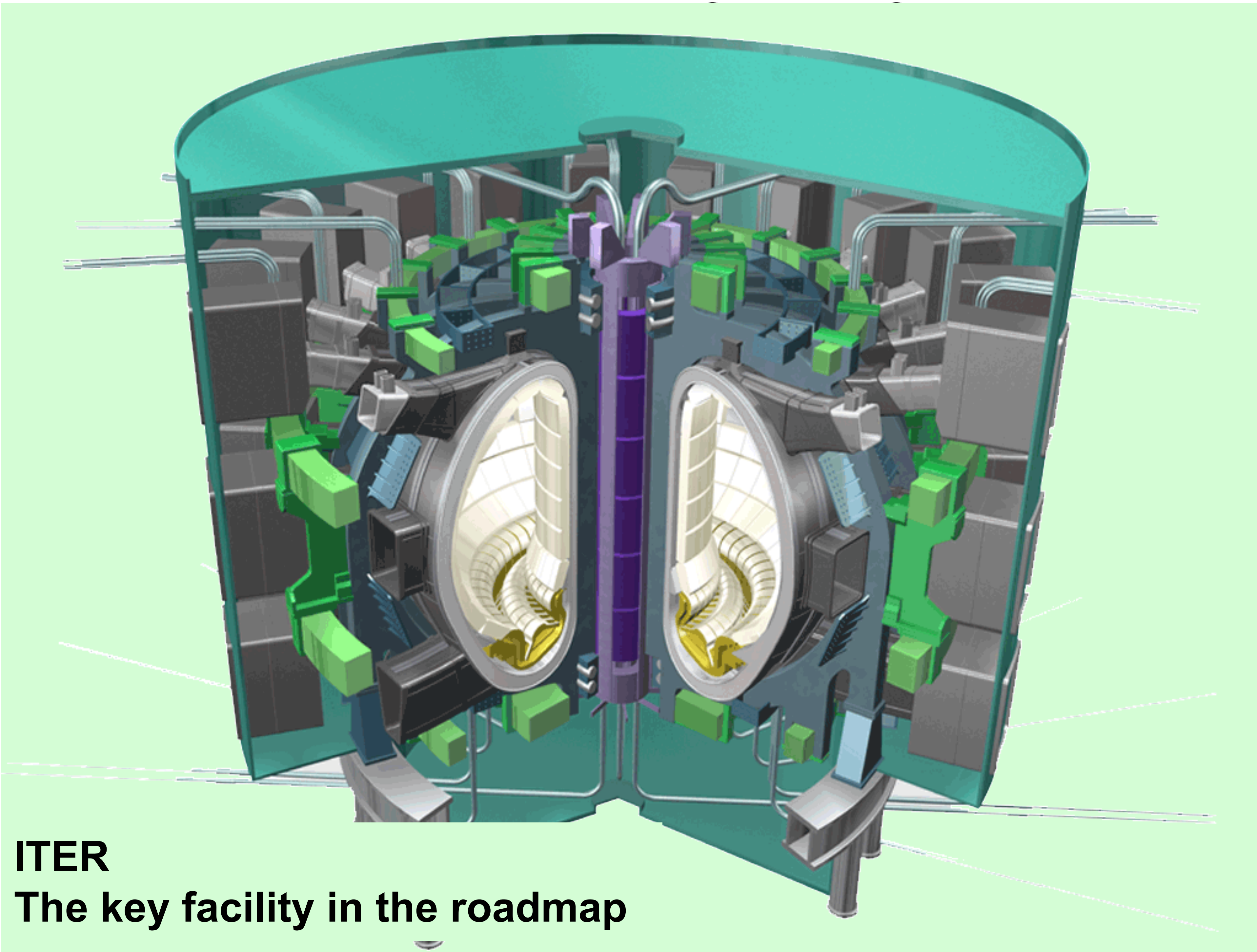
➔ Require DEMO construction in ~ 2030

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**



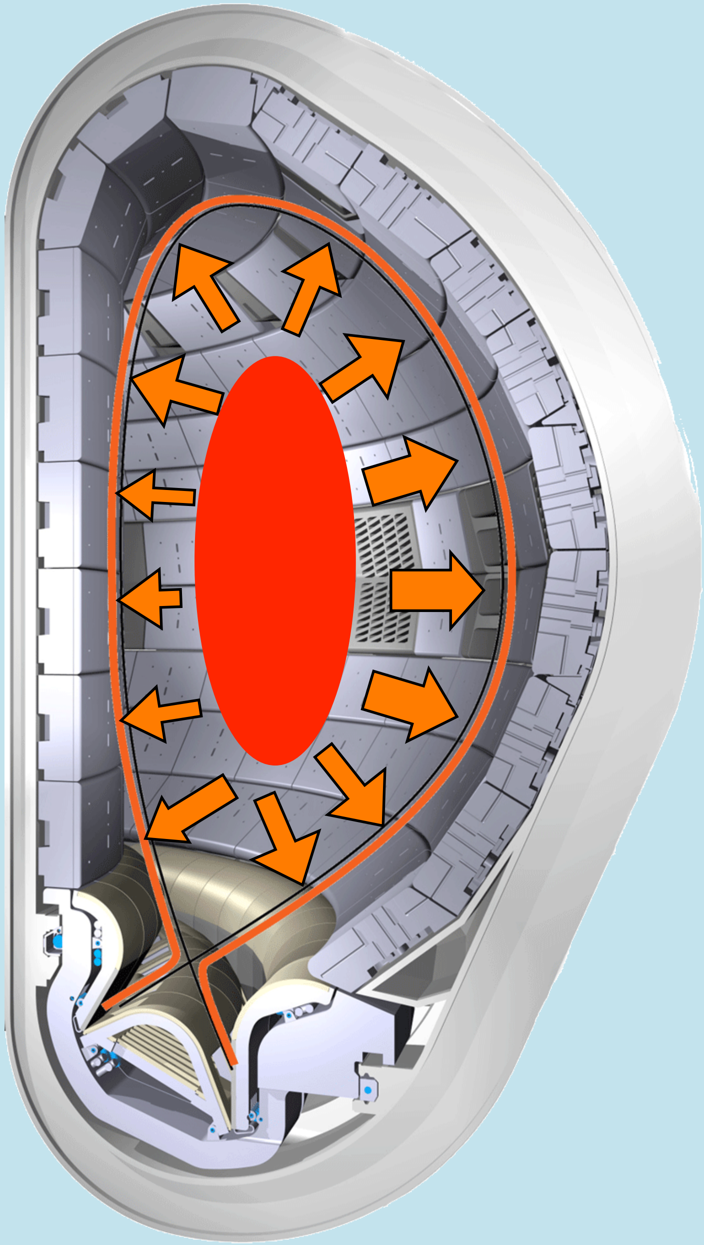
ITER
The key facility in the roadmap

A pragmatic approach to DEMO

Operation Mode	Pulsed
P_{th} (GW)	2.2
P_{rec} (MW)	235
Ro (m)	9.0
A	4
B_t(T)	7.1
$\langle n_{e,line} \rangle / n_G$	1
I_p (MA)	16
f_{BS}	36%
γ_{CD}	0.3
P_{aux} (MW)	50
H,	1
$\beta_{N,}$ ($\beta_{N,th}$)	2.4, (2)
P_{NW} (MW m^{-2})	1.3
Lifetime n-fluence (MW*yr/m^2)	<10

- Rely on robust technical solutions and established regime of operation.
- DEMO n-damage (Gilbert et al. FEC 2012)
  - FW steel 15dpa/fpy
  - W armour and Cu divertor 5dpa/fpy
- Two phase exploitation
  - 1. component test – limited availability (~30%)
    - starter blanket up to 20dpa; (vs.150dpa in a reactor)
  - 2. high availability
    - advanced components/materials
  - Same coolant for both phases
- Areas where more innovation is needed
  - Heat exhaust
  - Tritium breeding + electricity production
  - Materials

Mission 1: Plasma regimes for a reactor



- Demonstrate a net energy gain
- Operation with suppressed ELMs
- Avoid/mitigate disruptions
- Control plasma instabilities
- Ensure compatibility of high confinement with first wall materials
- Determine optimum particle throughput
- Optimise fast ion confinement
- Integrated regimes with controller
- Steady state operation

Mission 1: Plasma regimes for a reactor

•Demonstrate a net energy gain

No major gaps (i.e. no need of other devices in addition to those existing or under construction)

Enhancements of ITER and JT60-SA needed

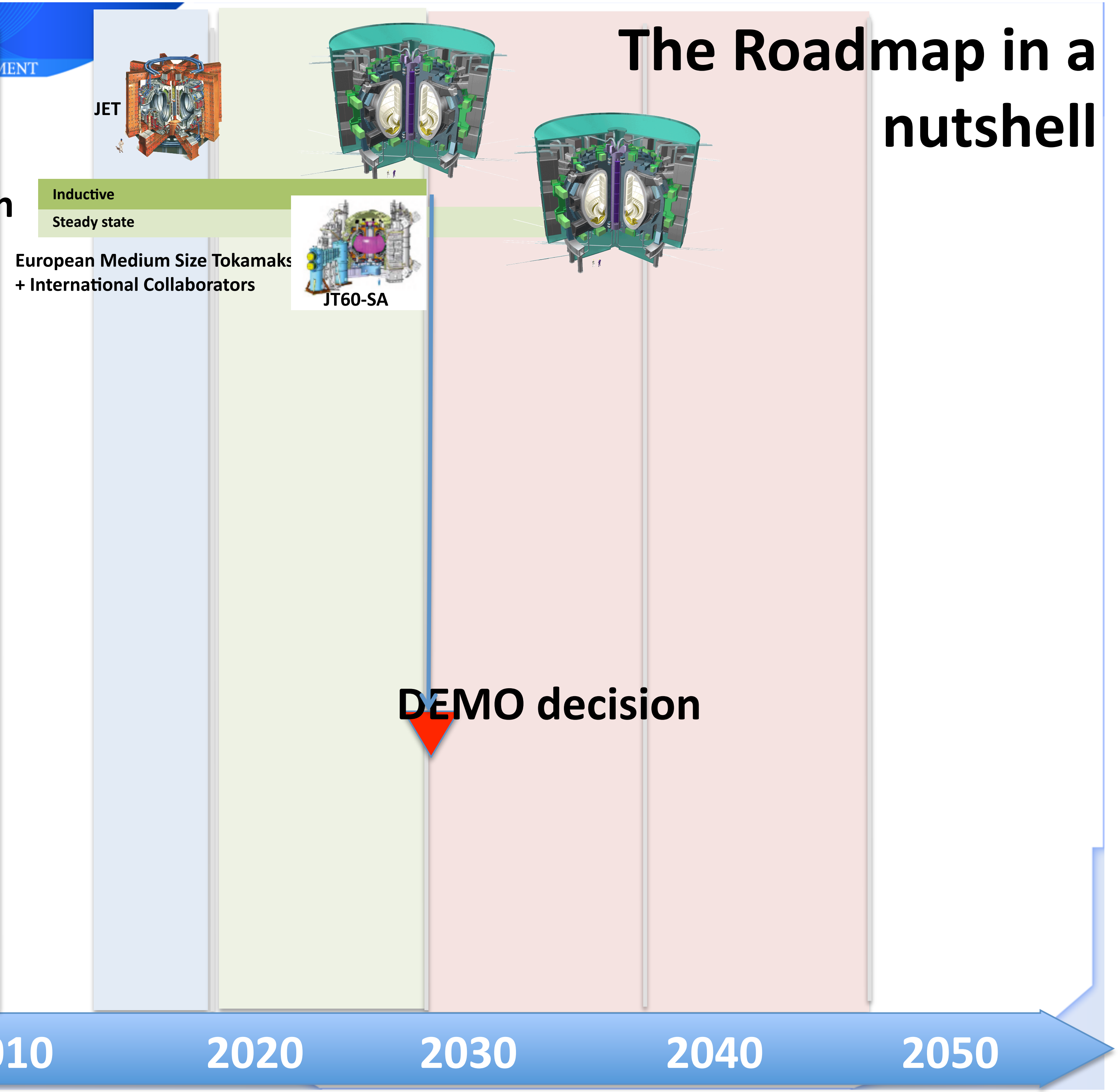
Increase in heating power

Operation with a full W wall in preparation to DEMO operation (Note: not needed for DEMO decision)

•Steady state operation

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

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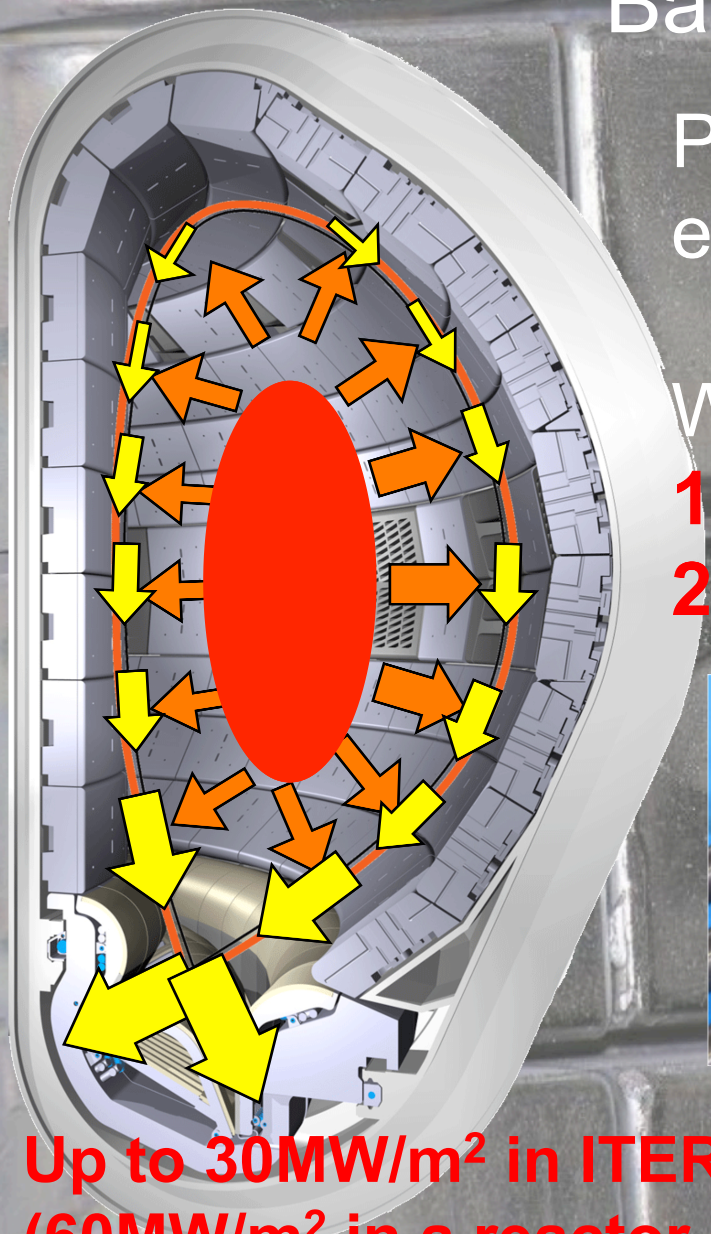
Baseline strategy

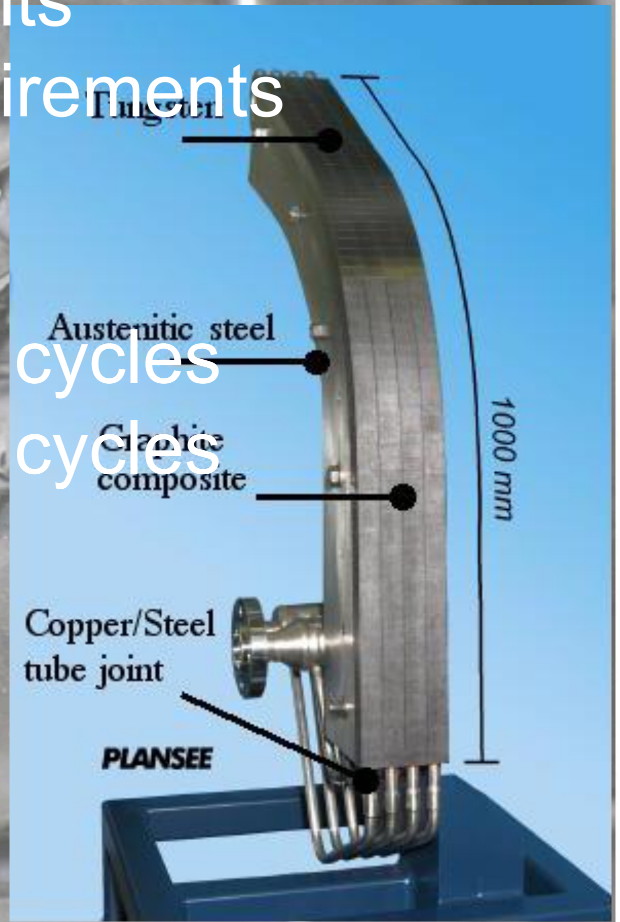


Present R&D results exceed ITER requirements

W monoblock:

10 MW/m^2 x 5000 cycles

20 MW/m^2 x 1000 cycles



Up to 30MW/m^2 in ITER

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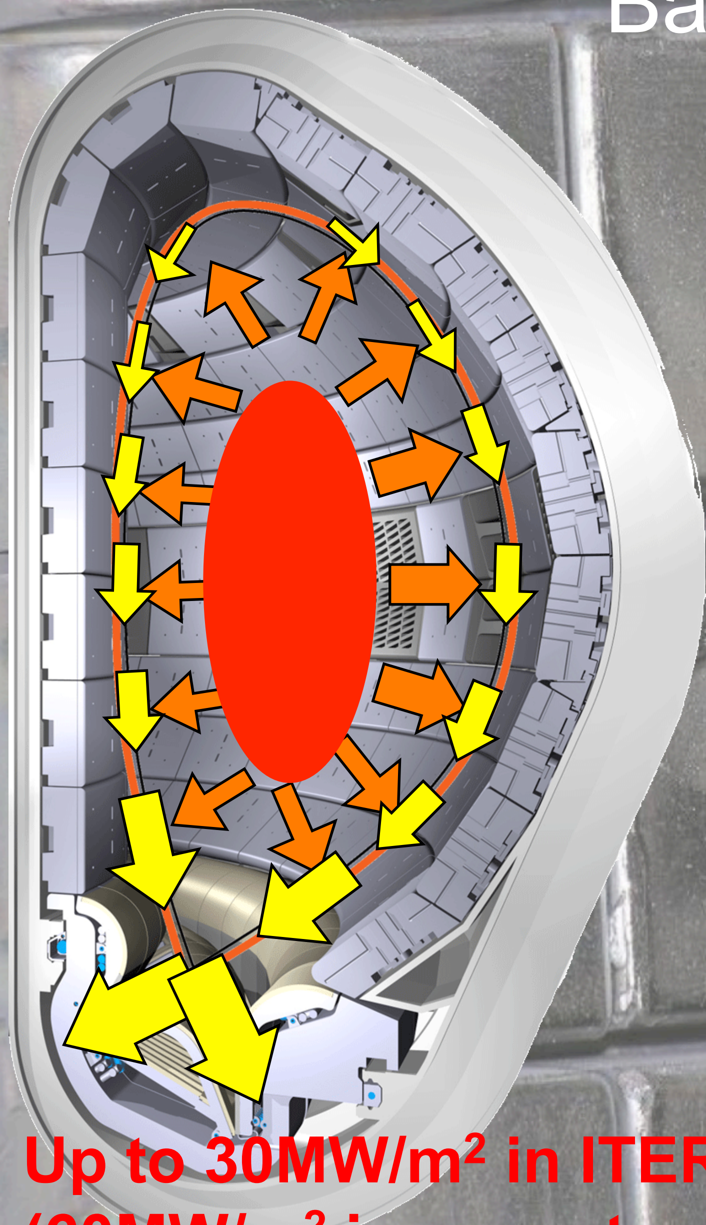
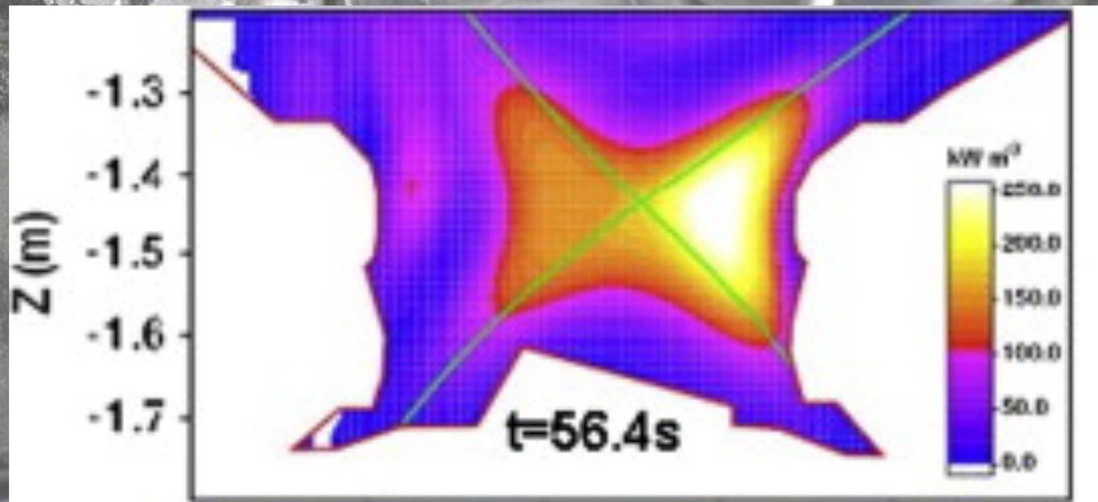
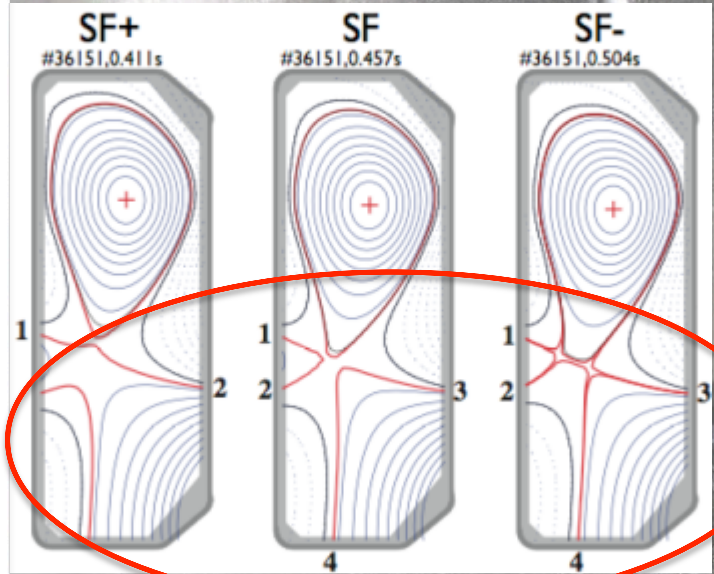


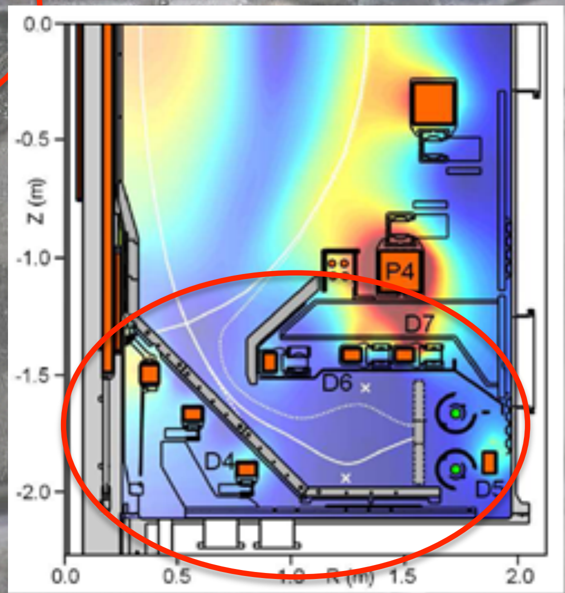


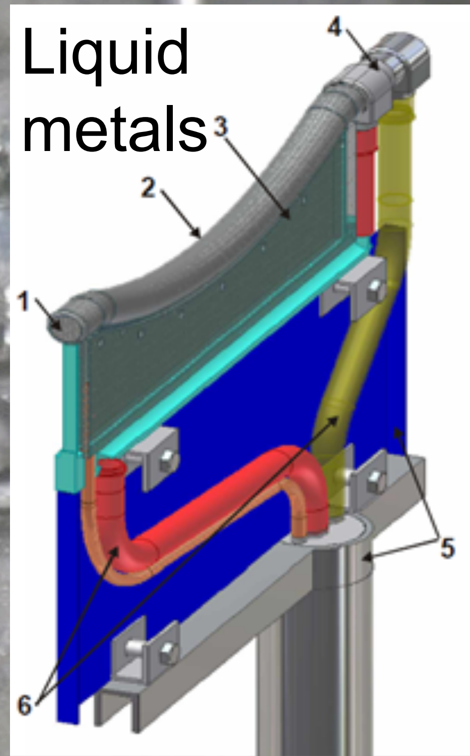
Divertor detachment

Up to 30MW/m^2 in ITER
(60MW/m^2 in a reactor ~ heat flux on the surface of the Sun!)

Mission 2: Heat and particle exhaust
Alternative strategies







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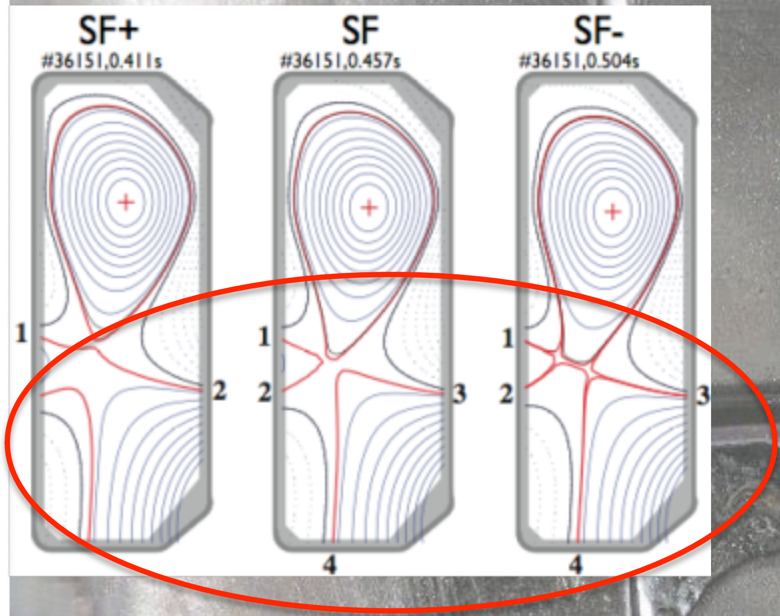
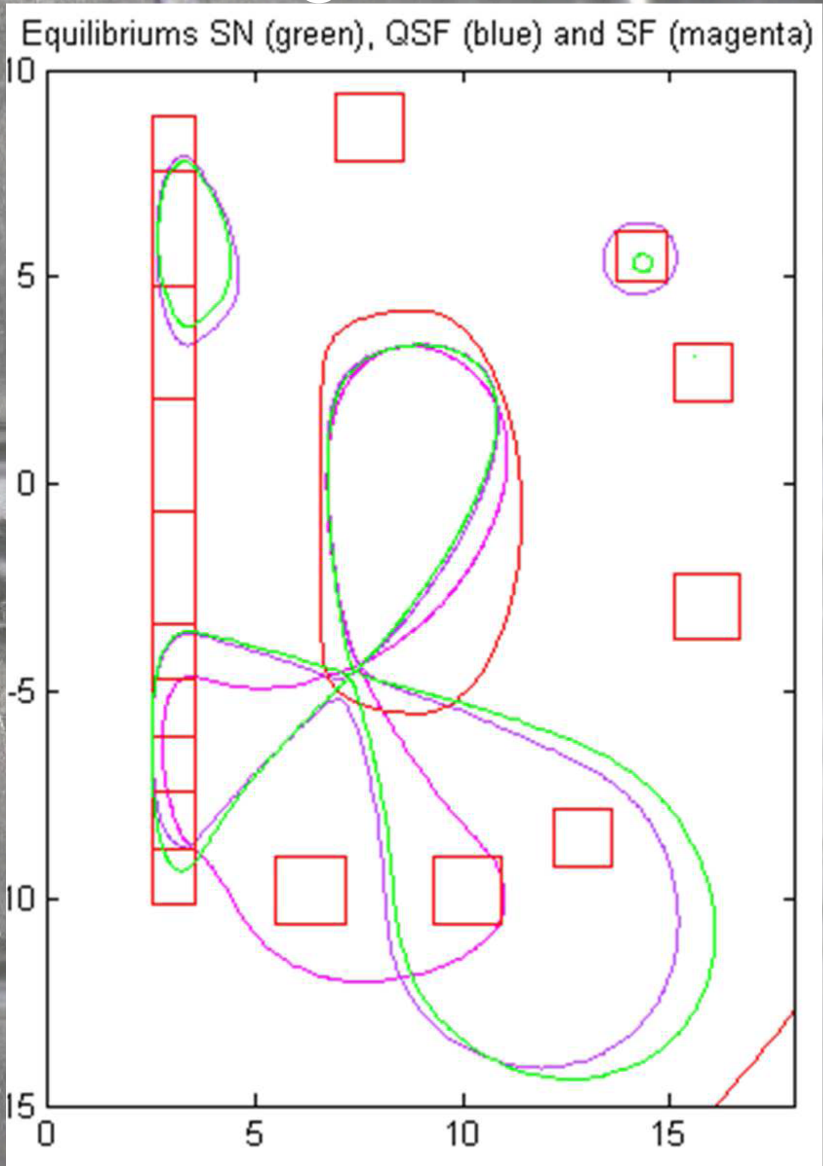
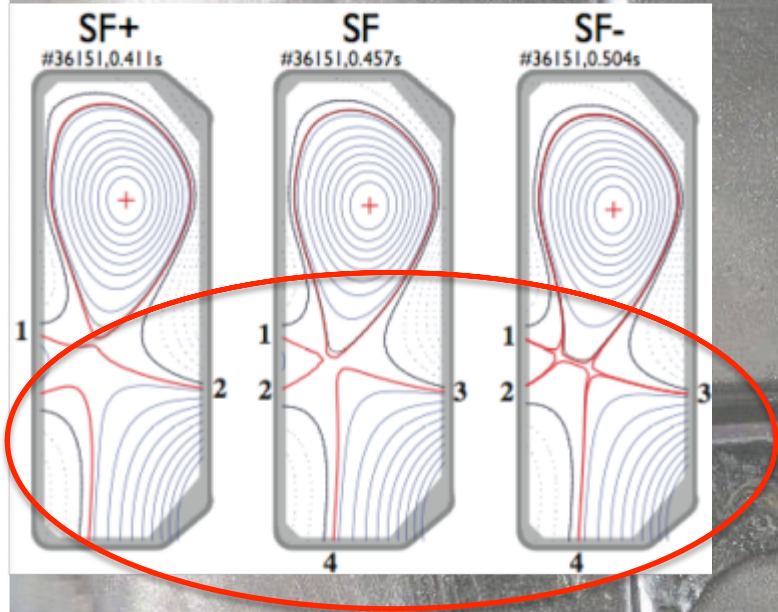
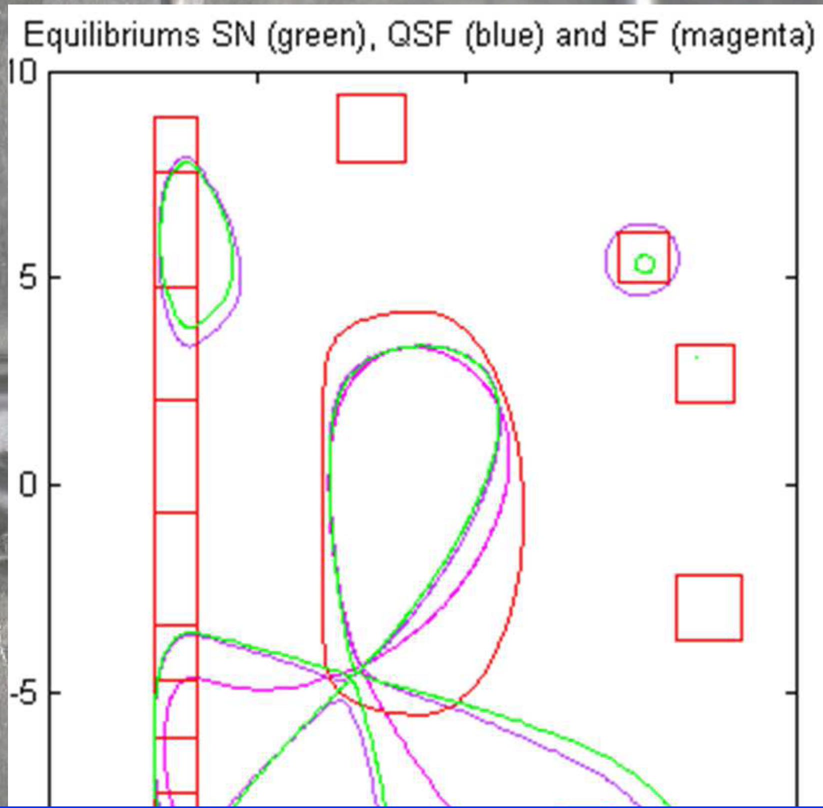




R.Albanese, R.Ambrosino, M.Mattei (CREATE/ ENEA Italy)

Mission 2: Heat and particle exhaust
Alternative strategies





Proof-of-principle on medium size experiments

Assess reactor-relevance in parallel

EUROPEAN FUSION DEVELOPMENT AGREEMENT

The Roadmap in a nutshell

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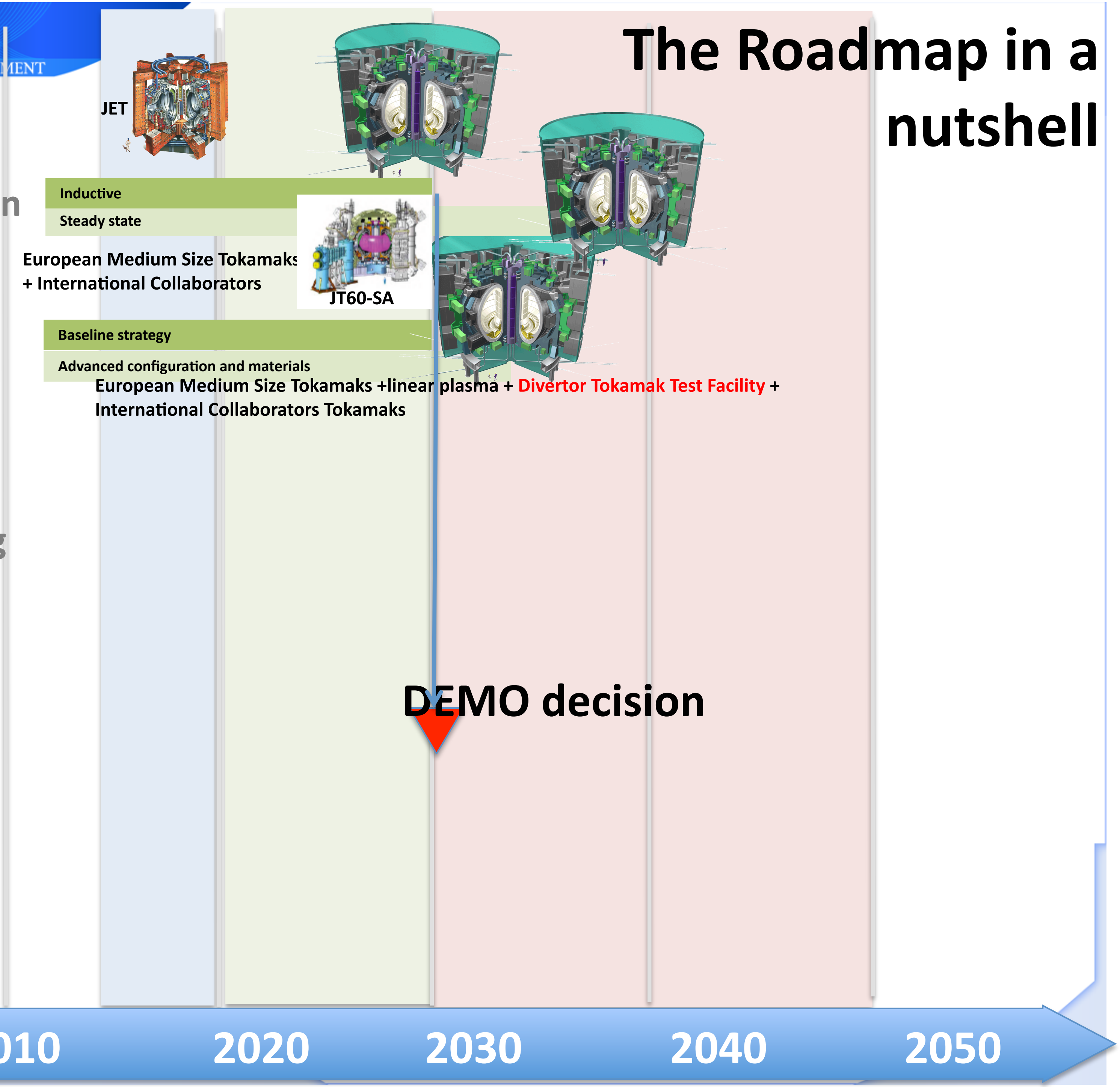
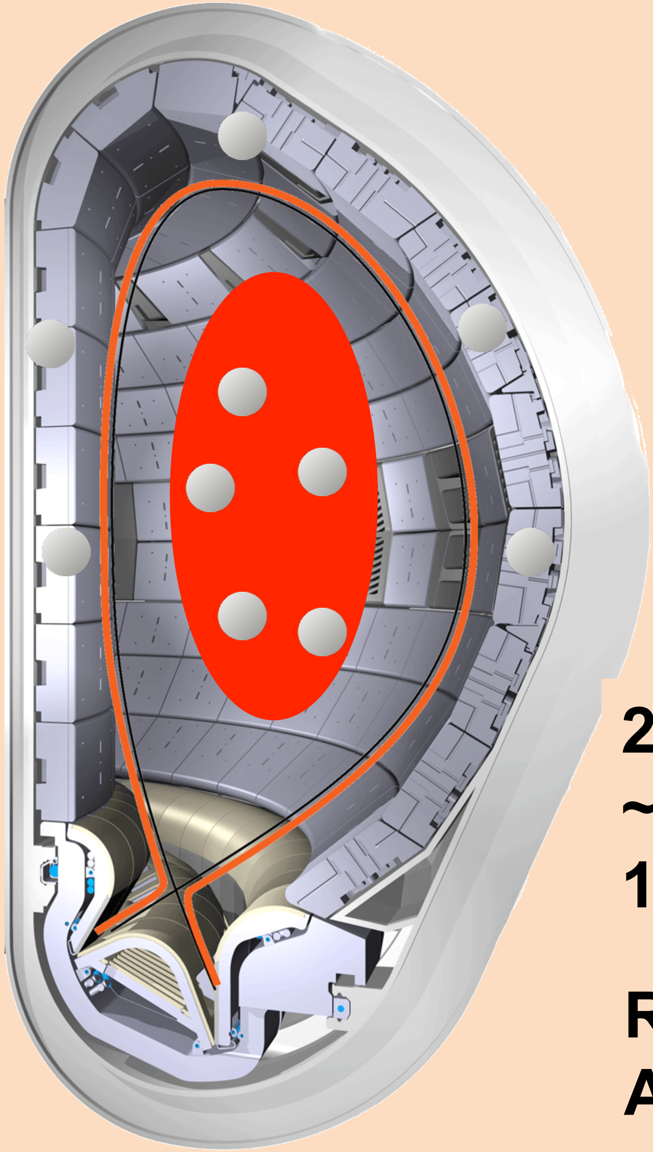


Mission 3: Develop neutron resistant materials



S. Dudarev

2 displacements per atom (dpa) in ITER
~20 dpa DEMO Phase 1
150 dpa in a fusion plant

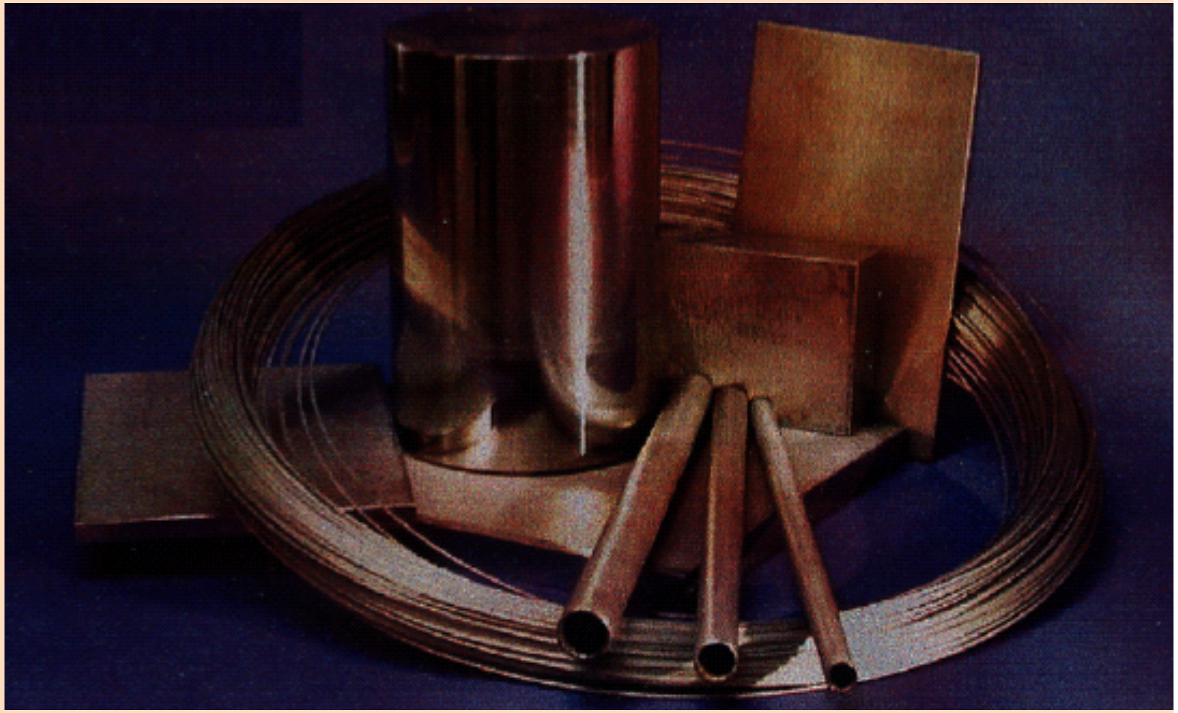
Reduction of structural properties
Activation

D. Stork
MAG 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 fission reactors up to 60 dpa



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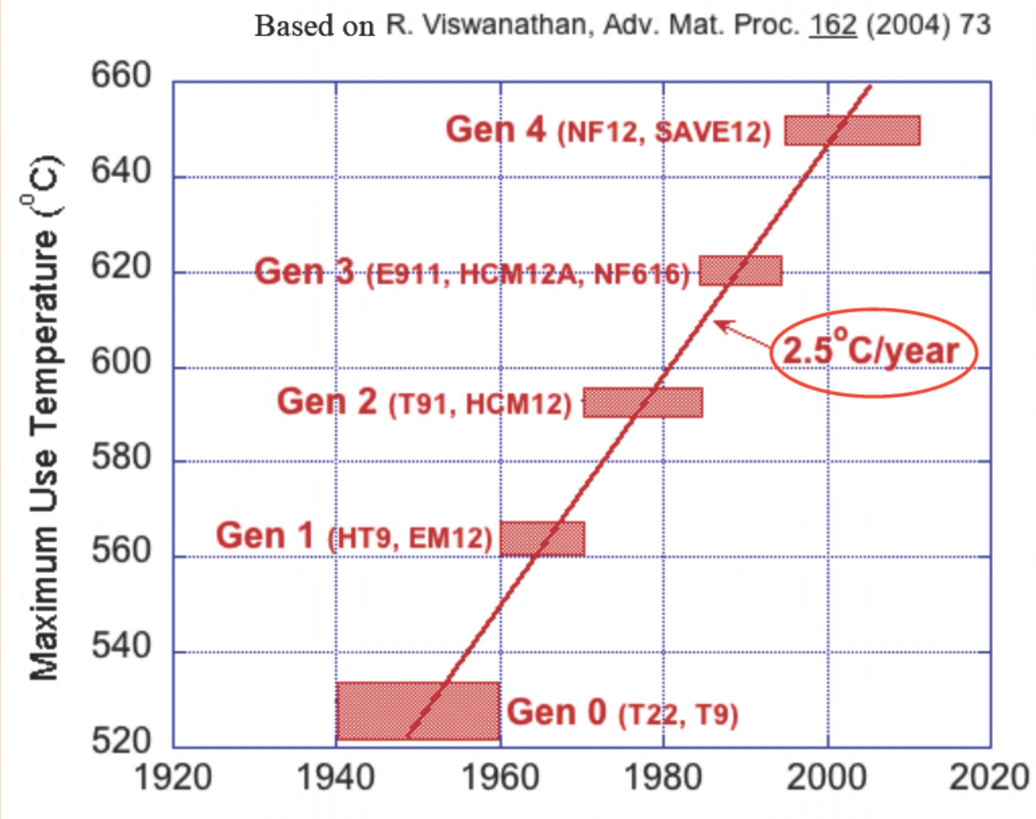
Advanced materials under examination
ODS steels (650°C)
High-Temperature Ferritic-Martensitic steels



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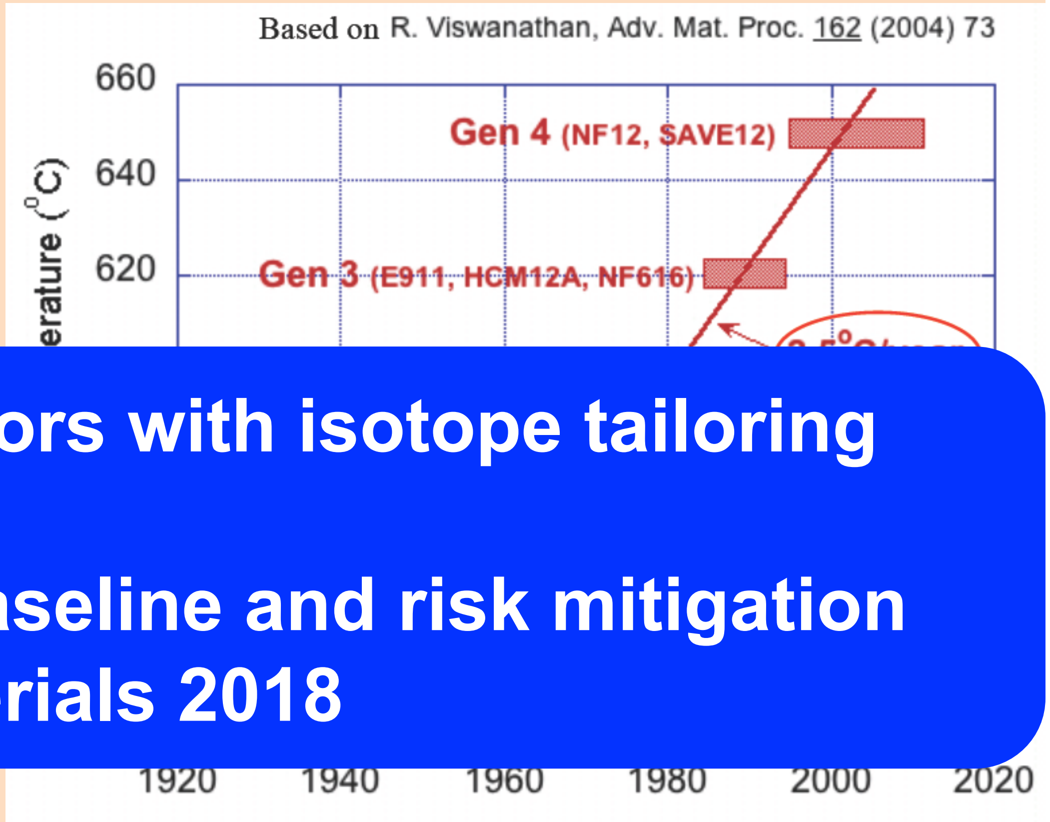
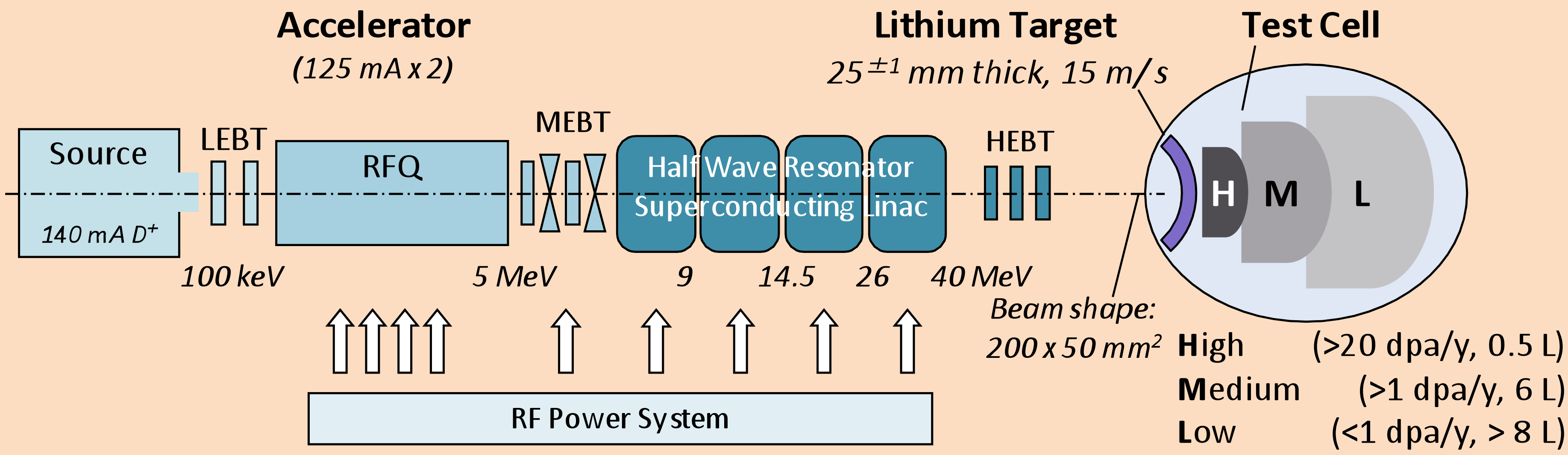


Test in fission reactors with isotope tailoring

Down selection of baseline and risk mitigation materials 2018

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



IFMIF

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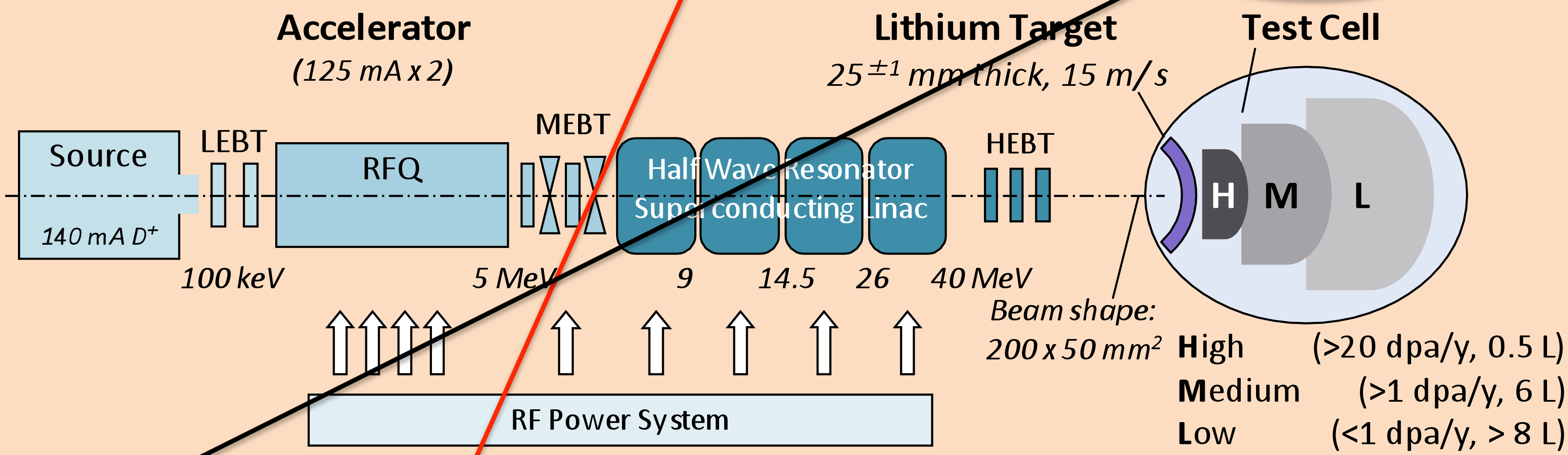

IFMIF

Early Neutron Source

Mission 3: Develop neutron resistant materials

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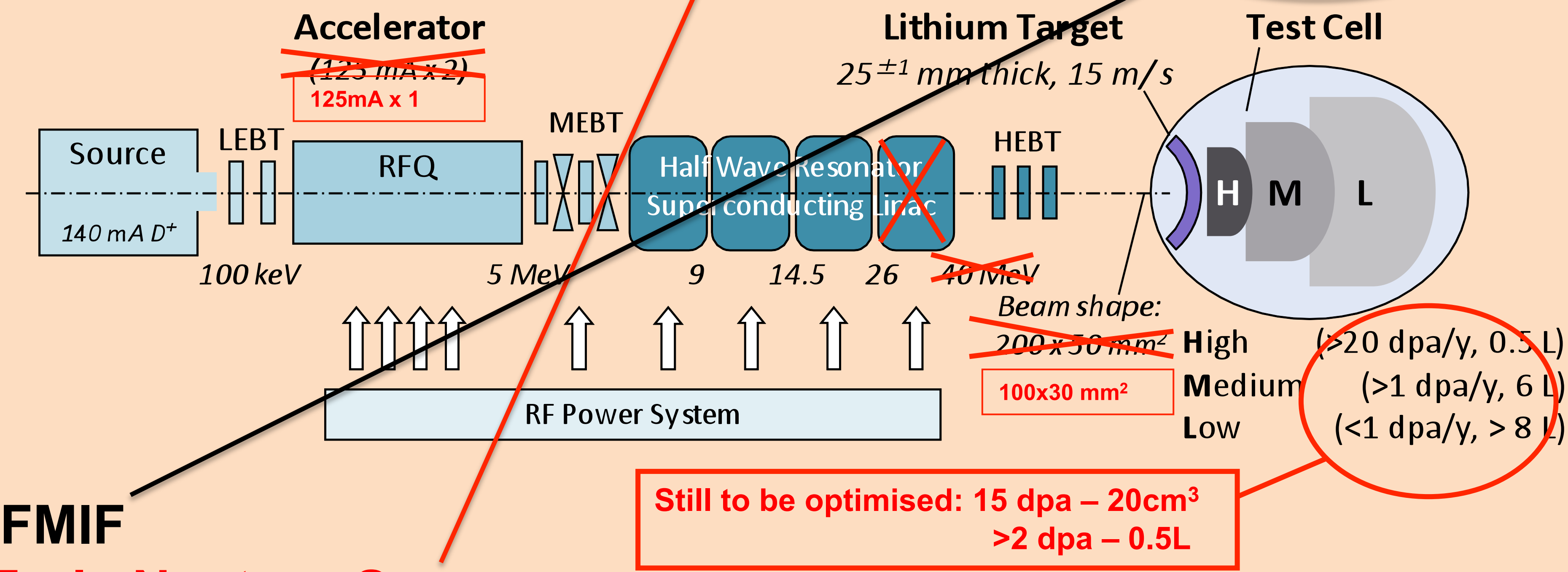


IFMIF

Early Neutron Source

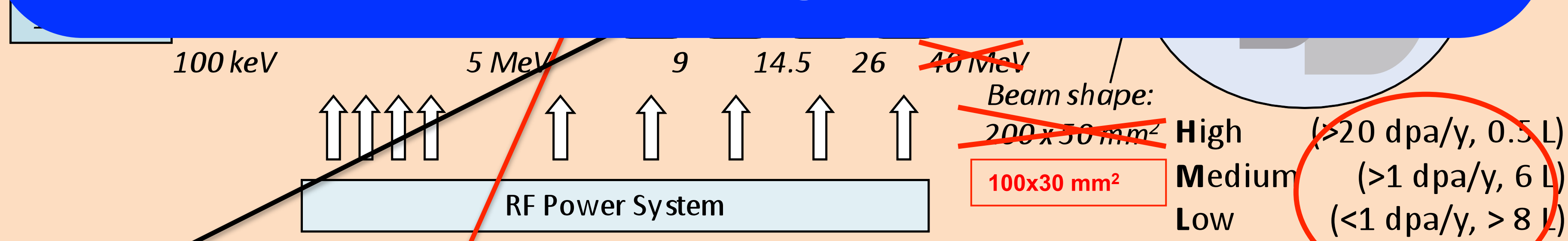
Mission 3: Develop neutron resistant materials

	Onset of 14MeV effects	Calibration of 14Mev effects	Full database for the full exposure
DEMO Phase1	20dpa (Fe)	20dpa (Fe)	20dpa (Fe)

Start construction 2017

30dpa testing 2022-2026. Code and standard 2028

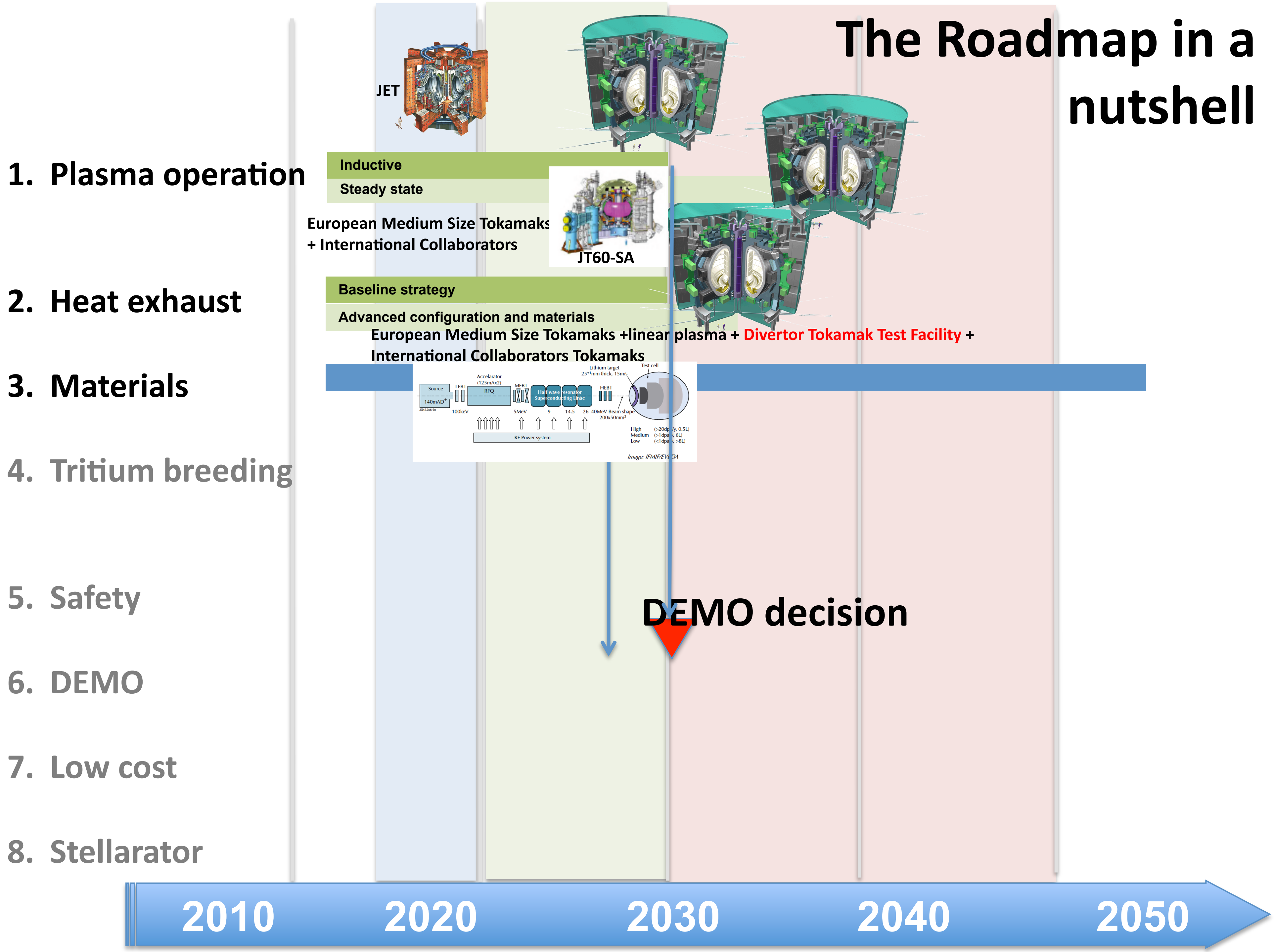
70 dpa testing 2028-2032



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

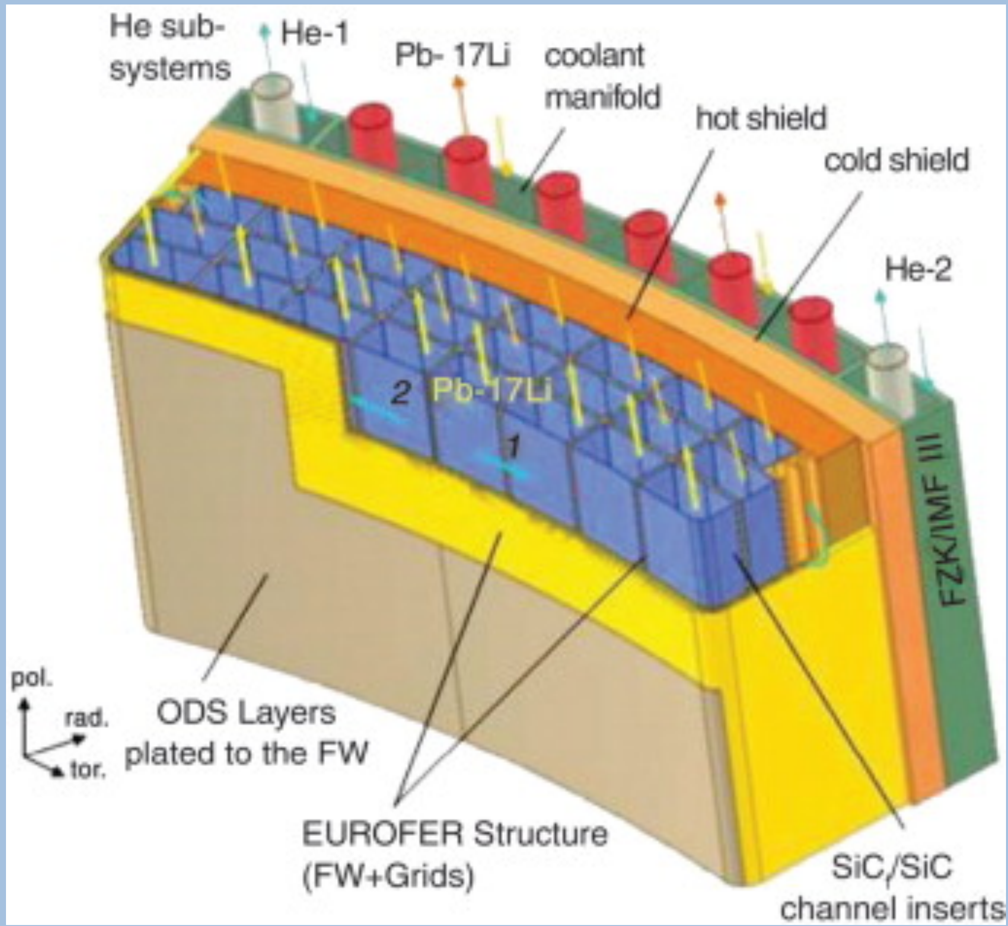
IFMIF

Early Neutron Source



The Roadmap in a nutshell
1. Plasma operation
2. Heat exhaust
3. Materials
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
RF Power system
DEMO decision
2010
2020
2030
2040
2050

Mission 4: Ensure tritium self-sufficiency



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

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

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

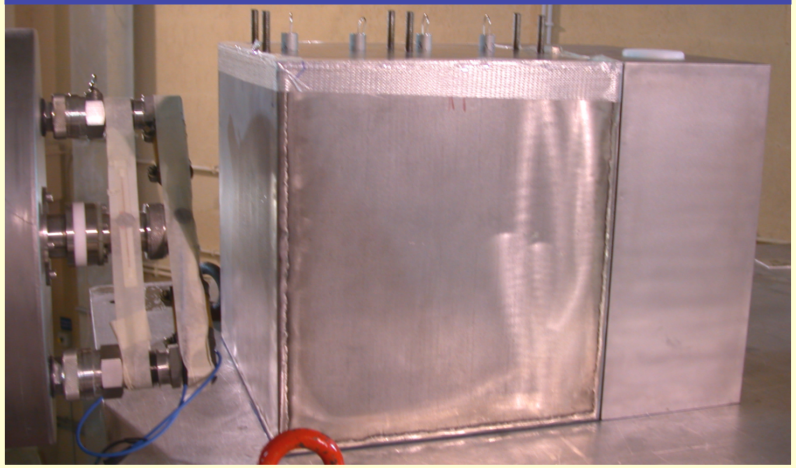
Efficient T extraction

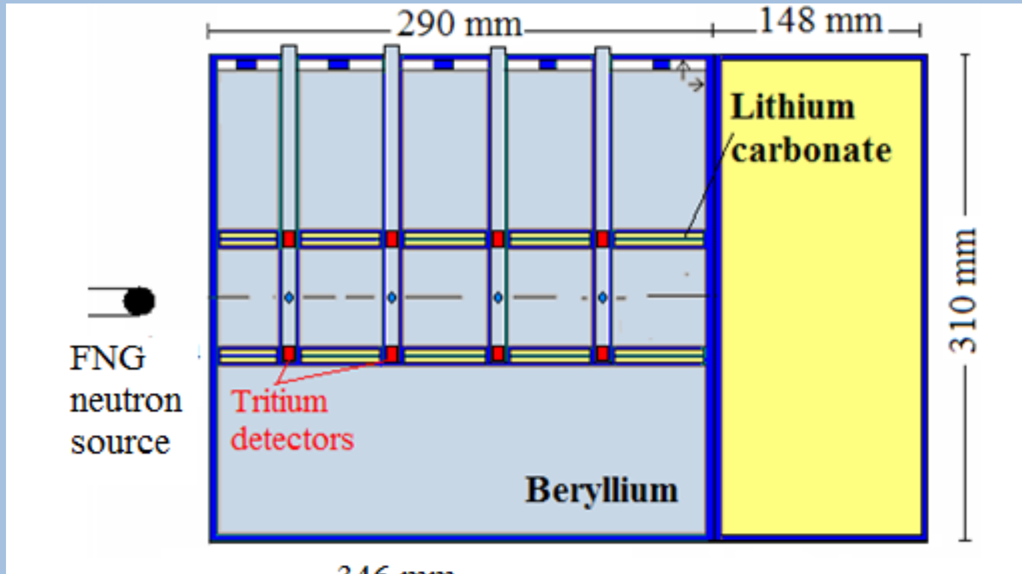
Efficient electricity generation (balance of plant)

A 1.5GWe reactor uses ~0.5kg Tritium/day

Mission 4: Ensure tritium self-sufficiency

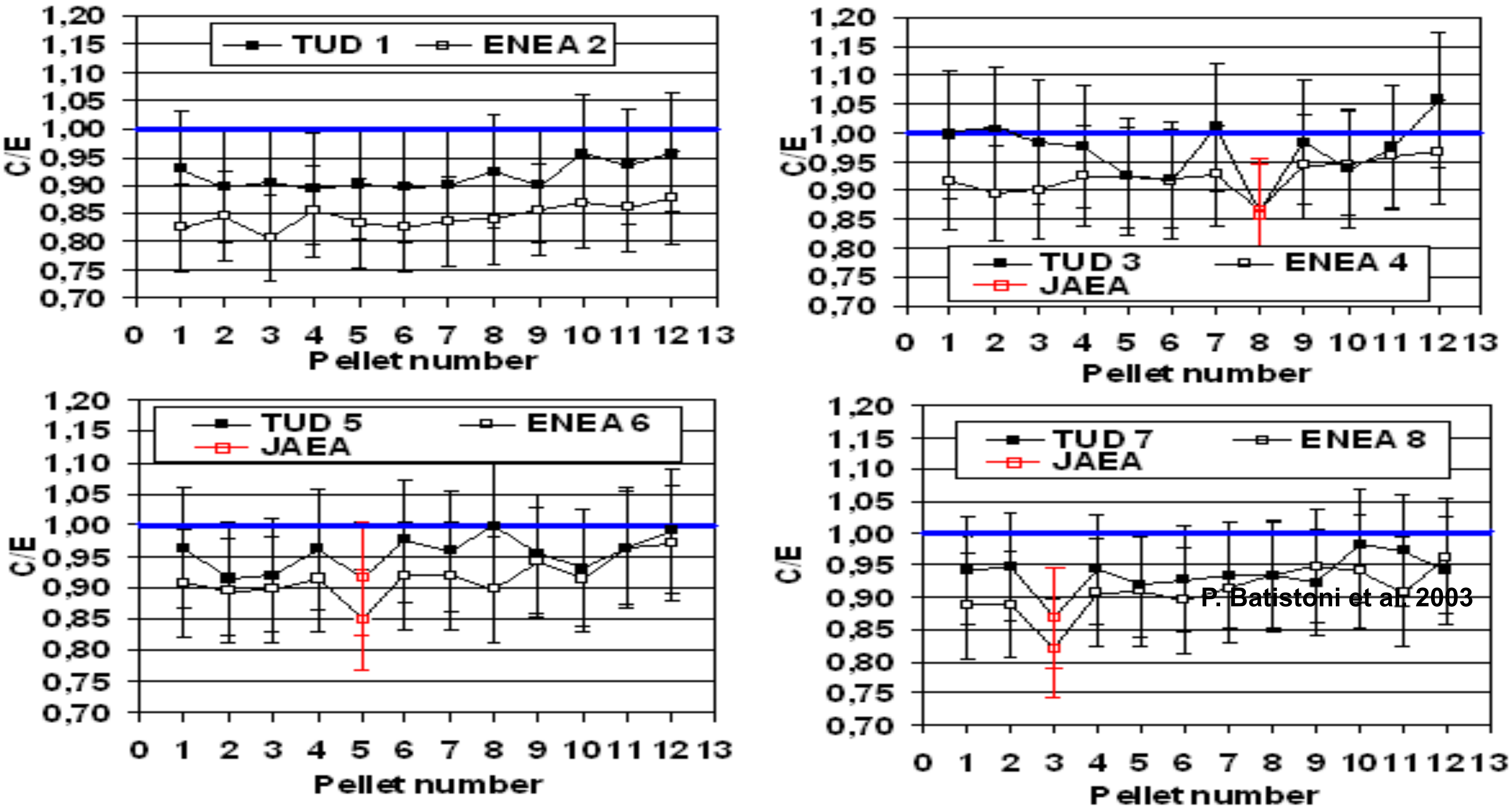
TBM-HCPB mockup





P. Batistoni et al. 2003

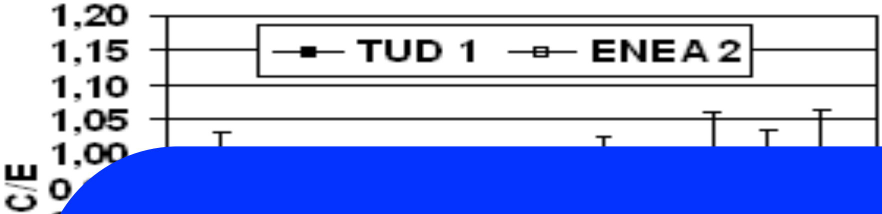
Mission 4: Ensure tritium self-sufficiency

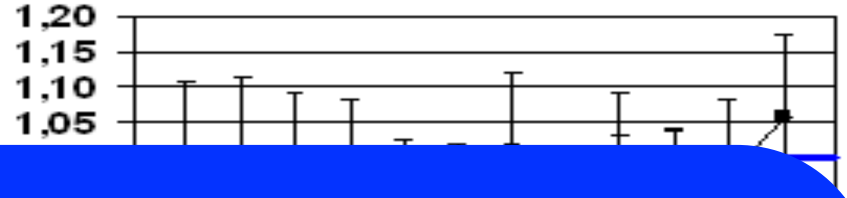


Tritium production:

Larger by 5-10% in average than code prediction

Mission 4: Ensure tritium self-sufficiency





Blanket/conversion system (BoP) integration

Support to the ITER TBM programme

Evaluation/development of WCLL and DCLL lines

Selection of coolant by 2020

Tritium production:
Larger by 5-10% in average than code prediction

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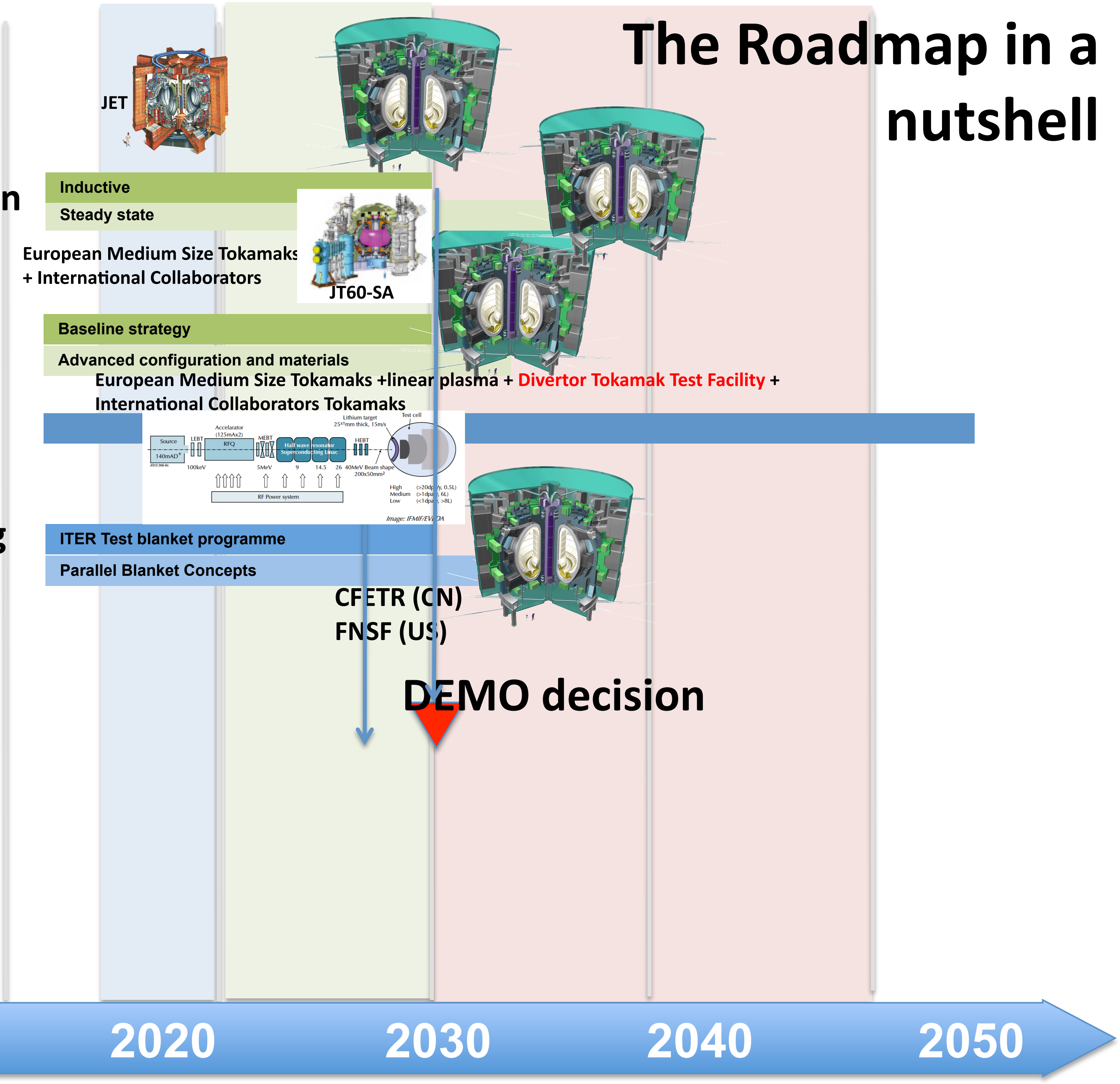
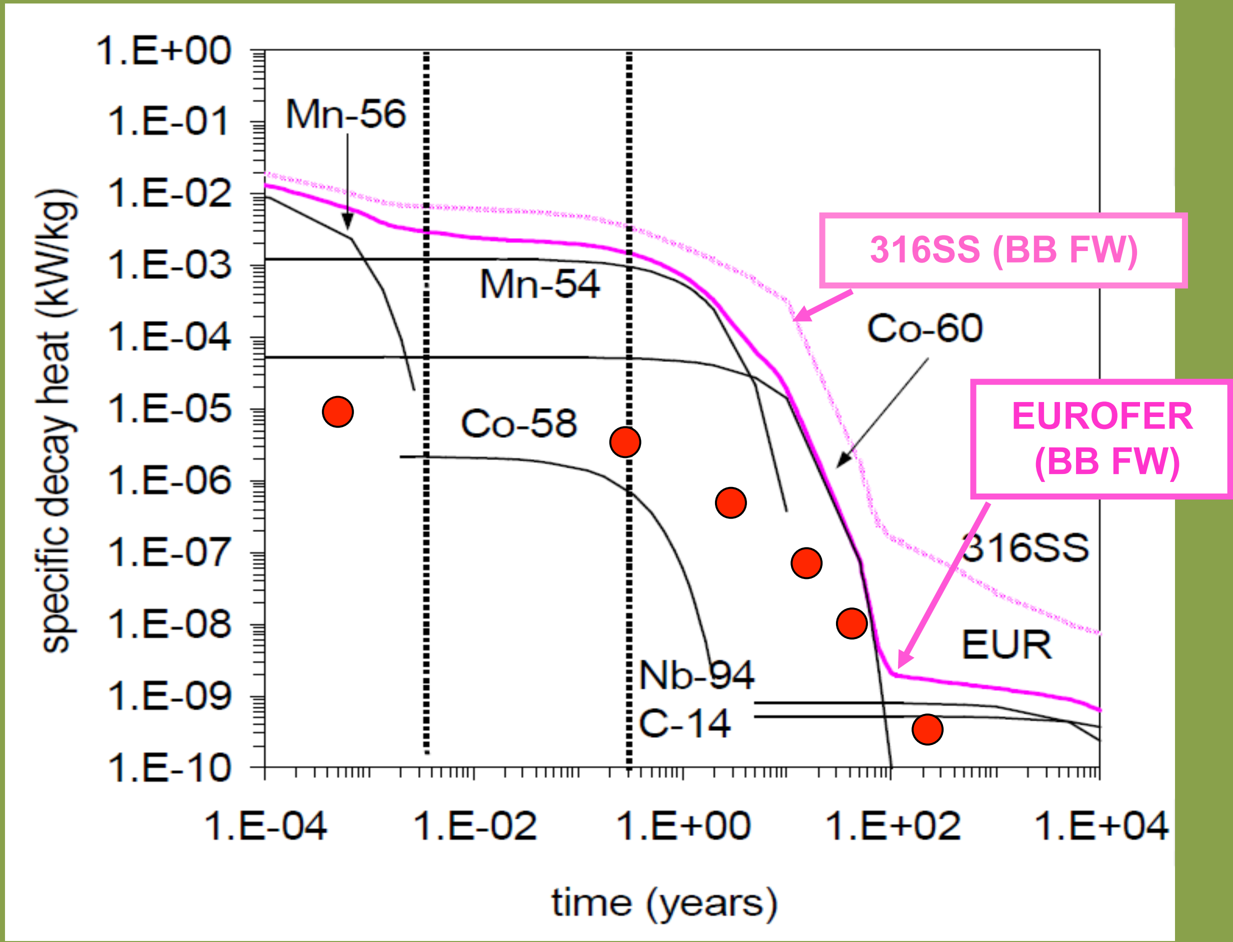


Mission 5: Implementation of inherent fusion safety features in DEMO design

Specific activation of outboard midplane first wall materials after 25 years full power operation – blanket replacement every 5 years for the EU PPCS model reactors.

→ EUROFER cf 316SS



● **VV 316SS irradiated for 50 years at attenuation factor of 10^4 over first wall neutrons flux**

Blanket – PPCS Study: R J Pampin-Garcia and M J Loughlin

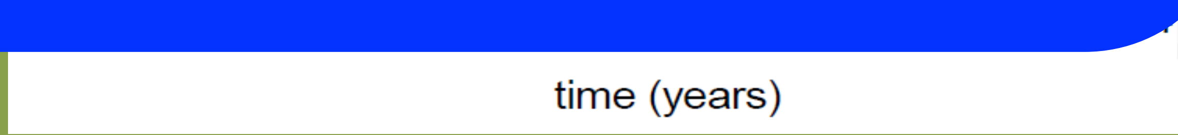
Mission 5: Implementation of inherent fusion safety features in DEMO design

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.

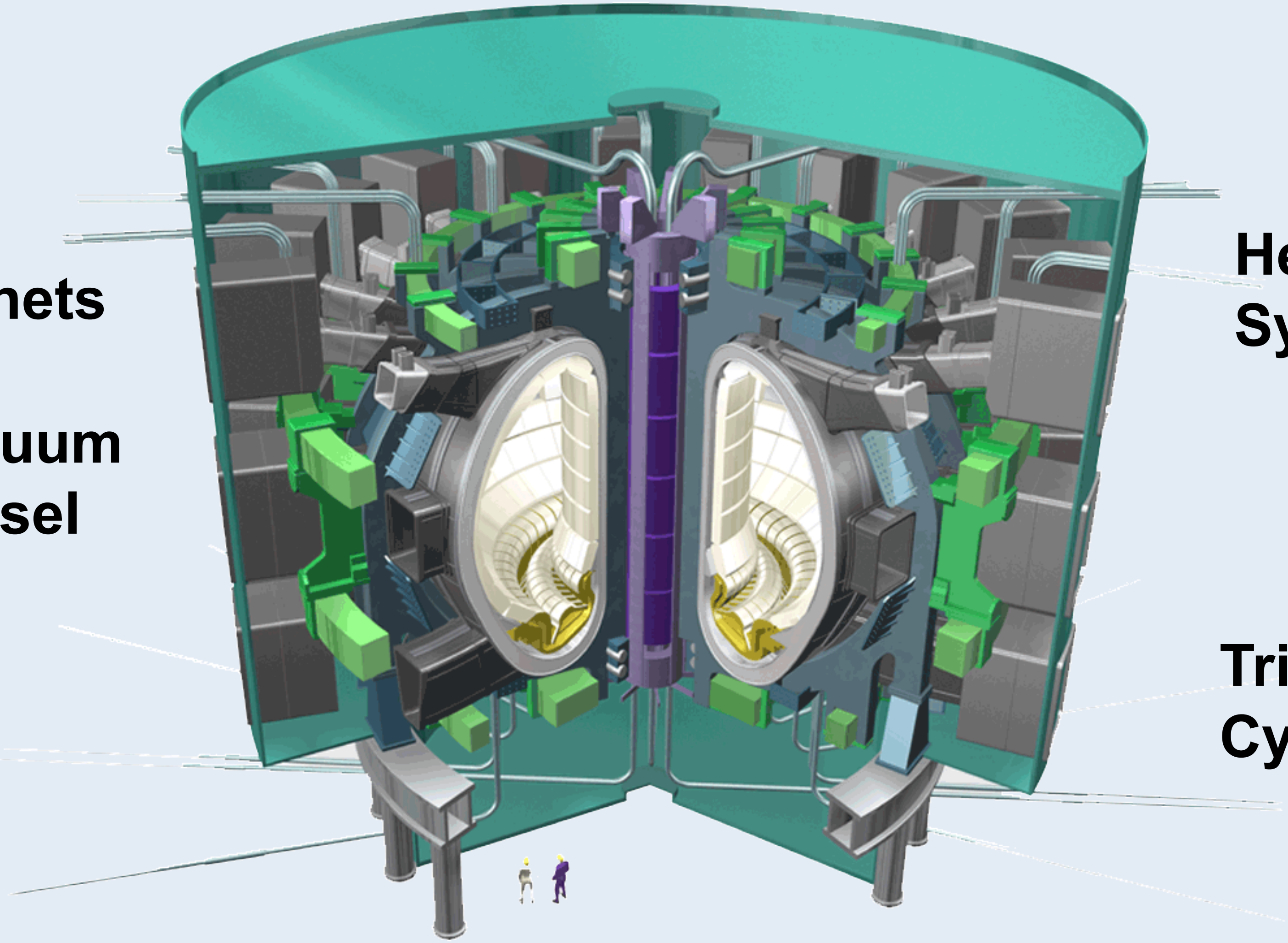
- **VV ... years at attenuation factor of 10^4 over first wall neutrons flux**



Blanket – PPCS Study: R J Pampin-Garcia and M J Loughlin

Mission 6: DEMO design

Balance of Plant



Magnets

Vacuum Vessel

Heating Systems

Tritium Cycle

Remote Handling

Mission 6: DEMO design

Targeted R&D

- Rely on LTSC magnet technology
  - Limit in performance due to higher e.m. loads?
- Vessel experience coming from ITER
- Divertor - Water cooled/advanced Cu alloys
- Heating and current drive
  - NB – increase efficiency by energy recovery
  - EC – increase frequency to 250GHz
- Tritium management - Efficient tritium processing
  - Reduce on site inventory?
- Balance of Plant
- Diagnostic and control – minimum set of actuator/ controller
- Remote maintenance

DEMO

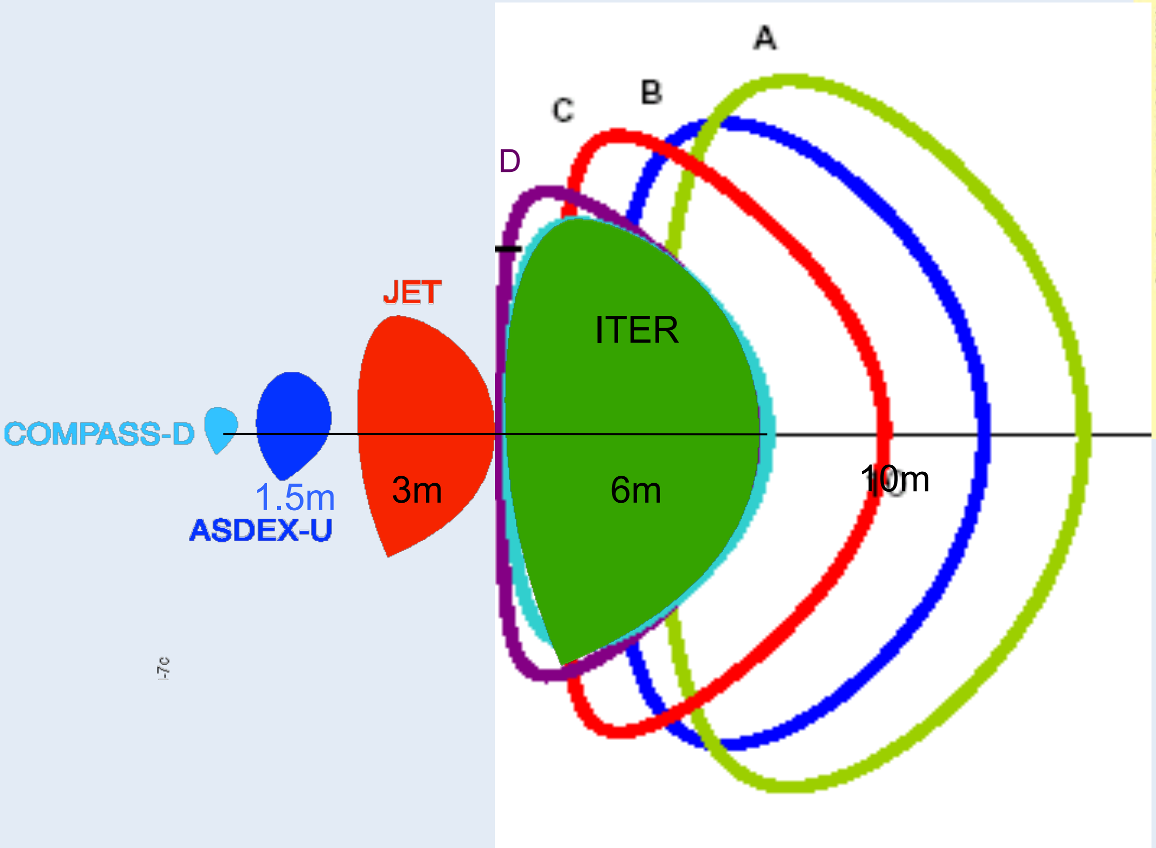
Blanket Remote Replacement

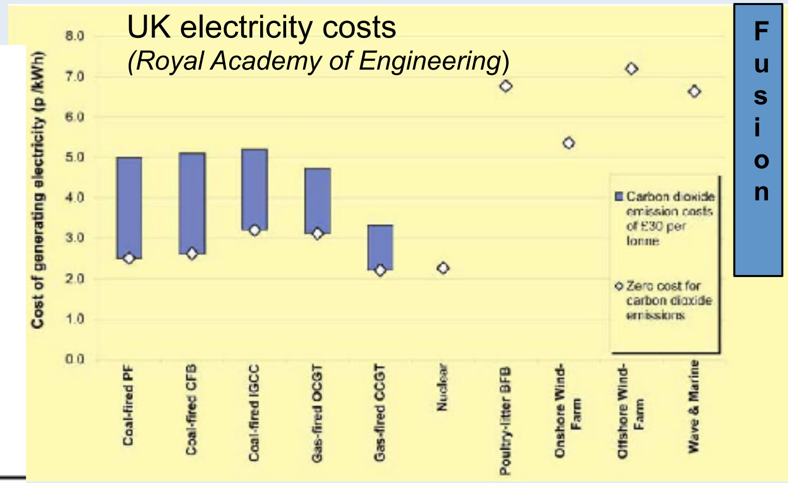
CCFE Remote Handling Unit

EFDA

CCFE
CULHAM CENTRE FOR FUSION ENERGY

Mission 7: Low cost of electricity





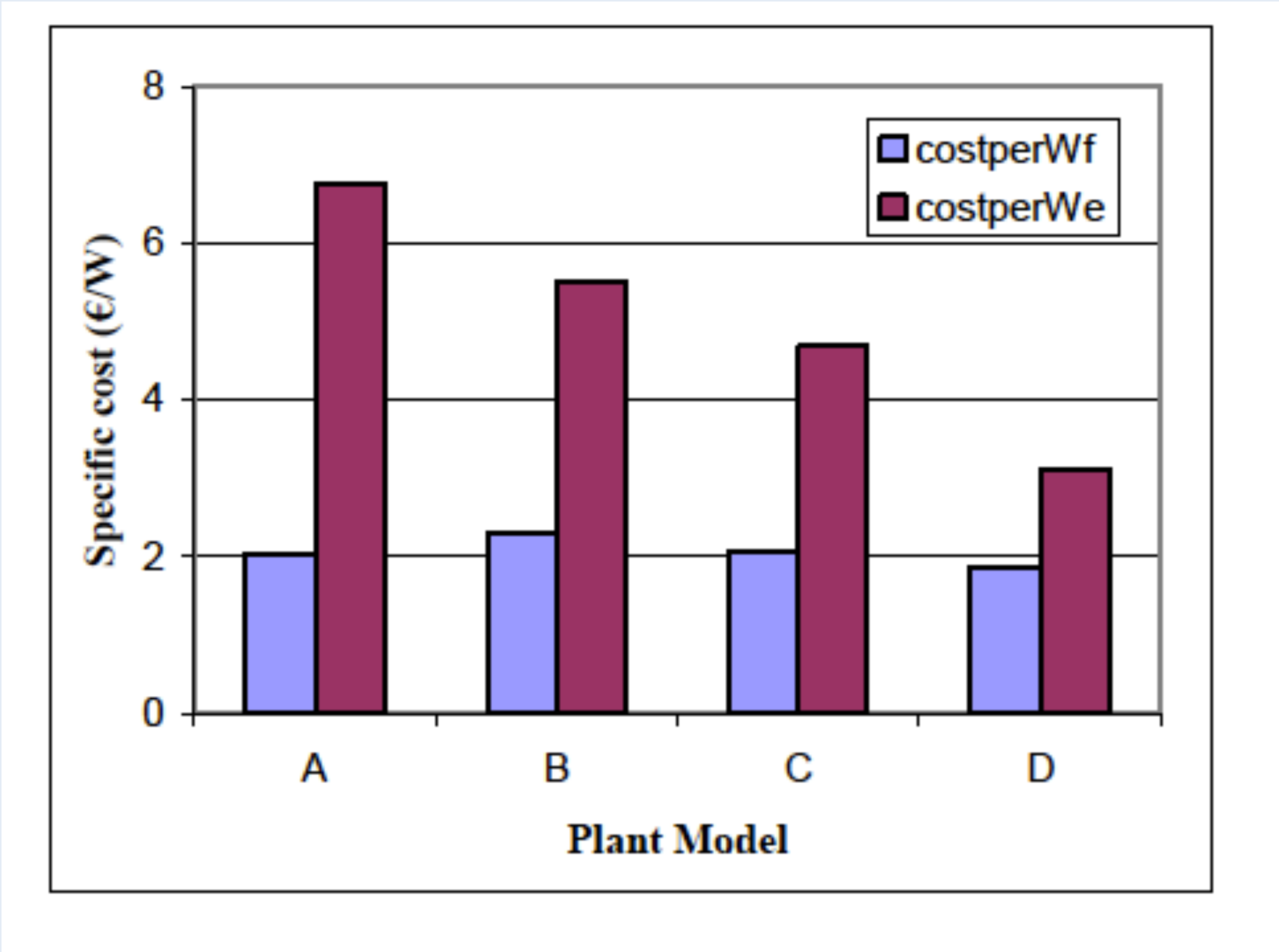
Cost of electricity from fusion expected to be competitive with other sources (IEA Levelised Cost Approach)

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)

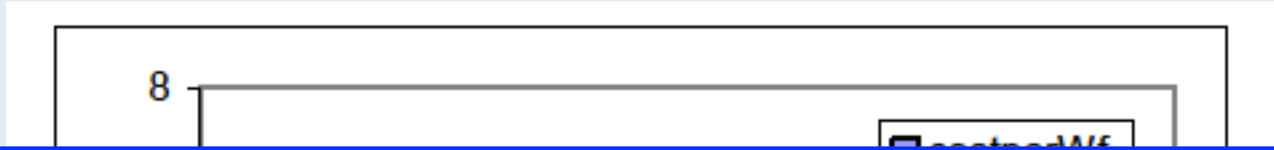
EFDA Power Plant Conceptual Study

Mission 7: Low cost of electricity



Cost for a 10th of a kind (EFDA PPCS)

Mission 7: Low cost of electricity

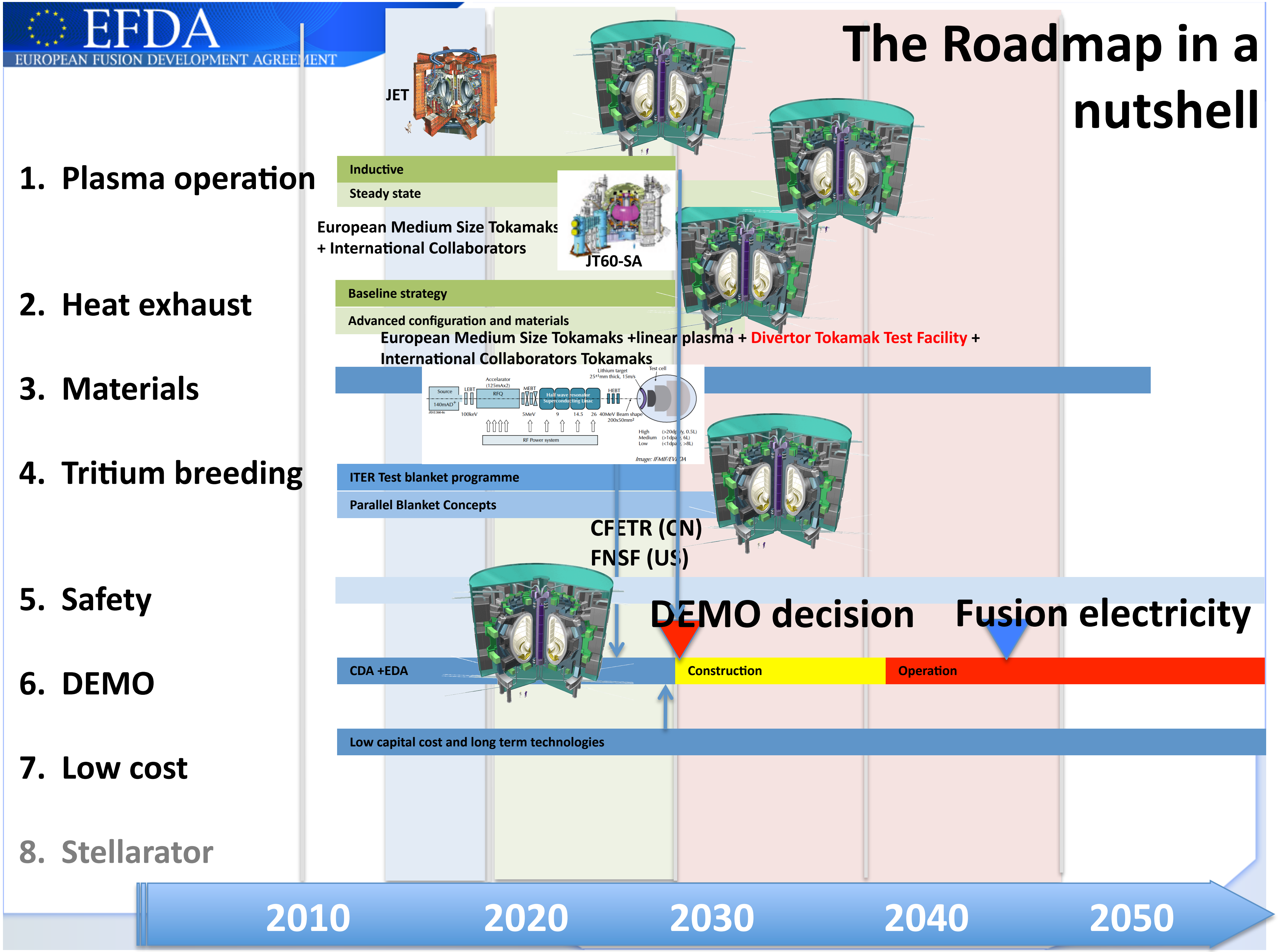


Low cost of kWh not a DEMO target but DEMO capital costs must be compatible with the economic perspective of fusion!

Work with industry for solutions that minimize investment costs.

Investigate long term technologies (e.g. HTS)

Cost for a 10^{th} of a kind (EFDA PPCS)


EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT
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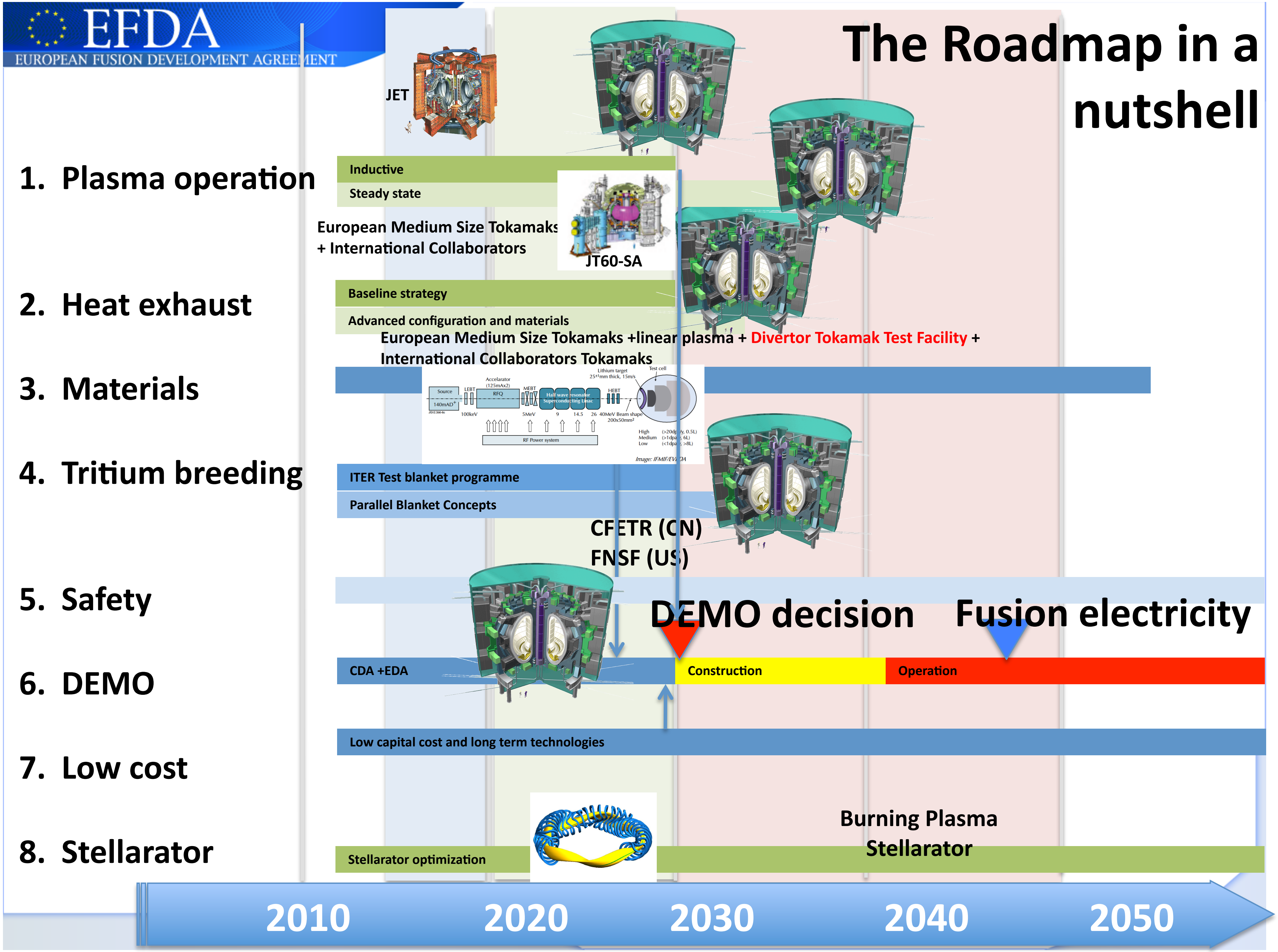
ITER Test blanket programme
Parallel Blanket Concepts
CFETR (CN)
FNSF (US)
DEMO decision
Fusion electricity
CDA +EDA
Construction
Operation
Low capital cost and long term technologies
2010
2020
2030
2040
2050



EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT
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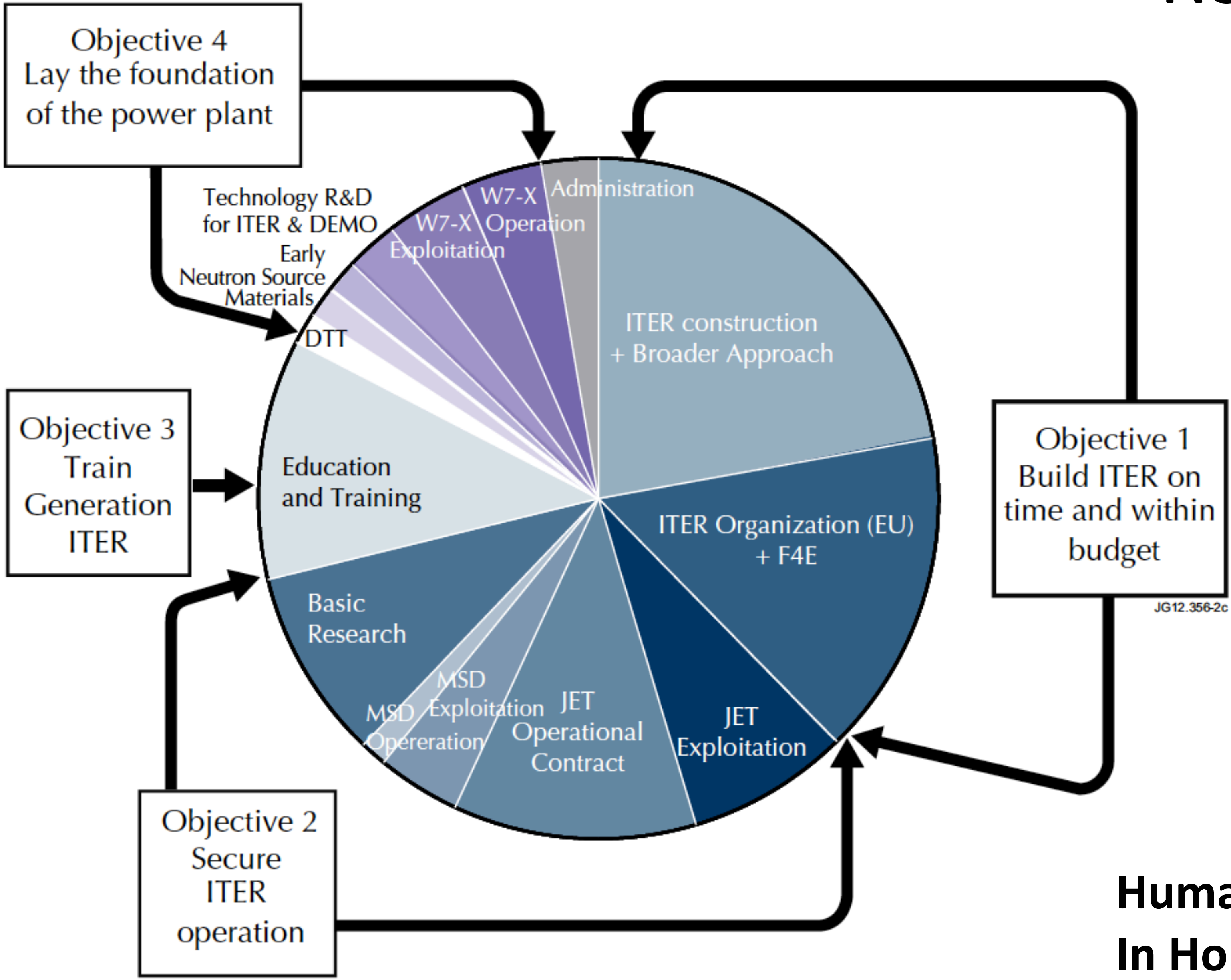
1. Plasma operation
Inductive
Steady state
European Medium Size Tokamaks + International Collaborators
JT60-SA
2. Heat exhaust
Baseline strategy
Advanced configuration and materials
European Medium Size Tokamaks +linear plasma + Divertor Tokamak Test Facility + International Collaborators Tokamaks
3. Materials
4. Tritium breeding
ITER Test blanket programme
Parallel Blanket Concepts
CFETR (CN)
FNSF (US)
5. Safety
DEMO decision
Fusion electricity
6. DEMO
CDA +EDA
Construction
Operation
7. Low cost
Low capital cost and long term technologies
8. Stellarator
Stellarator optimization
Burning Plasma Stellarator
2010
2020
2030
2040
2050

Resources



Human resources
In Horizon 2020

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Resources

	2014-2018 average	2019-2020 average	2021-2030 average
	M€	M€	M€
Mission 1 w/o JET & ITER	20	33	33
Mission 2 w/o JET & ITER	36	70	44
Mission 3	39	67	33
Mission 4 w/o JET & ITER	19	14	In Mission 6
Mission 5	3	2	In Mission 6
Mission 6	13	9	200
Mission 7	5	5	5
Mission 8	45	50	50
Basic research	35	35	35
Computing resources	8	2	8
Education	9	9	9
Training	15	15	15
Administration & Mobility	10	10	10
JET operation	56	68	0
JET exploration	32	30	0
TOTAL w/o ITER	**344**	**418**	**441**
ITER construction	511	115	0
ITER operation	0	0	99
ITER exploration	0	0	42
ITER & JT60SA enhancement	0	0	9

Financial resources EC + Member States
(FP7 350-400M€)

Note: this are annual figures

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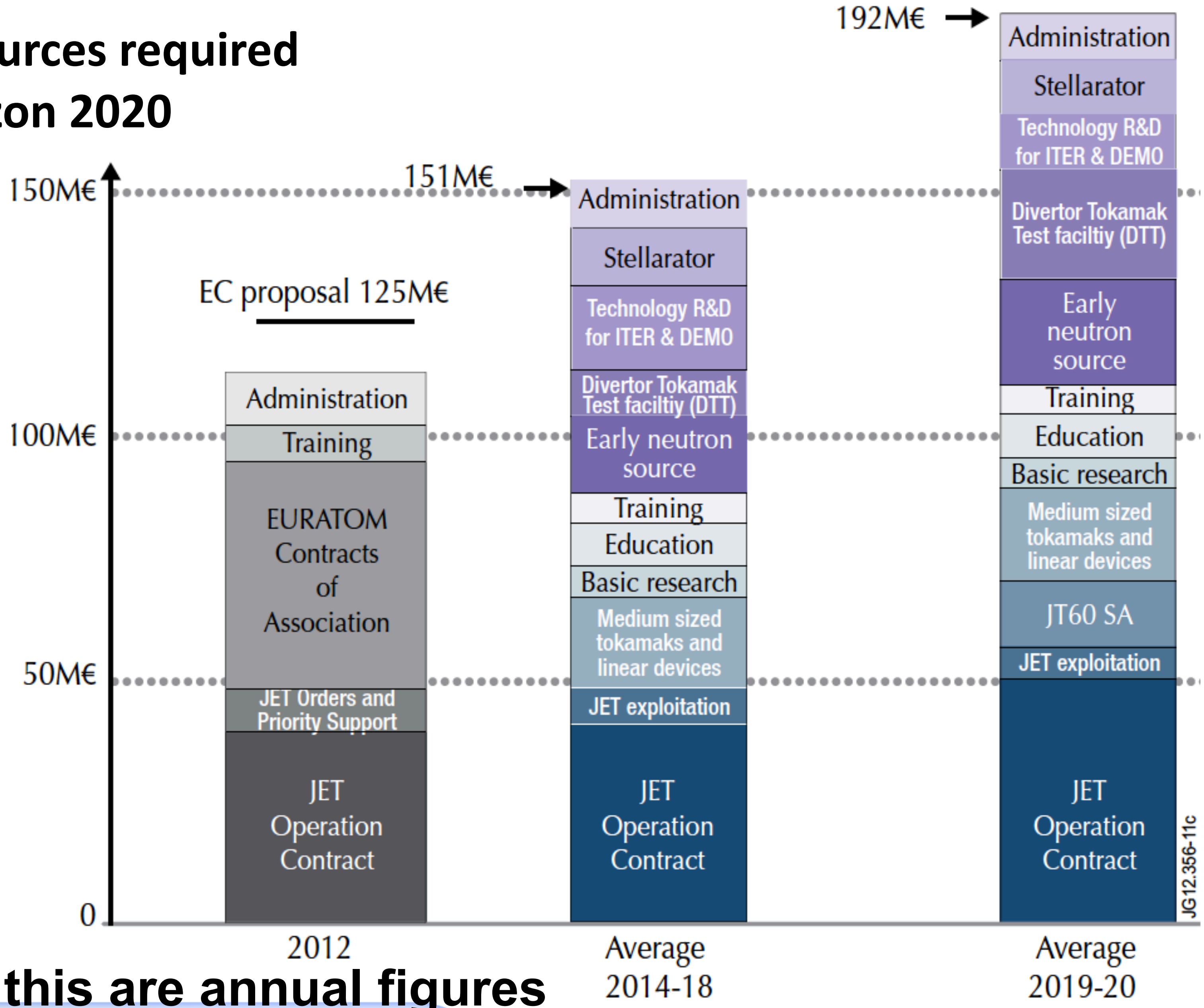
Resources

EC resources required in Horizon 2020



Note: this are annual figures

Conclusions

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

International collaborations

- In addition to the ITER exploitation and the BA projects, the following opportunities are underlined:
  - The exploitation of JT-60SA in collaboration with Japan for the preparation of ITER Phase 2;
  - The construction of a pilot IFMIF plant (Early Neutron Source) in collaboration with Japan within a post EVEDA phase;
  - The collaboration on a joint Divertor Tokamak Test facility;
  - The collaboration on other smaller scale DEMO R&D (for example making use of the infrastructure developed with Japan during the BA for that purpose);
  - The use of the Chinese Fusion Experimental Tokamak Reactor (CFETR) facility with China and of the Fusion Neutron Science (FNSF) facility in US;
  - The share of know-how on the TBM programme with other ITER parties whenever a win-win situation is expected;
  - The use of non-EU research fission reactors;
  - The collaboration on stellarator lines other than the HELIAS (i.e. Heliotron and compact stellarator).
- Europe can offer to the other parties the participation in its facilities, and specifically to JET as training facility for ITER. Specific funds also foreseen for participation to machines abroad.