Materials for Nuclear Facilities

Overlaps and Divergence
in Requirements for Fission and Fusion Systems

Fusion Power Co-ordinating Committee Meeting
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IAEA
Atoms for Peace: The First Half Century
1957–2007

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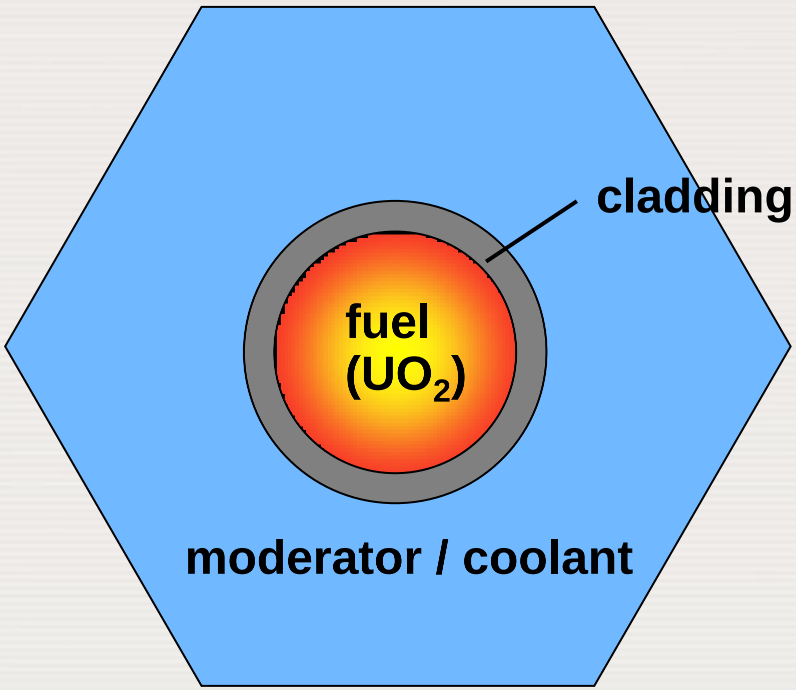
Outline

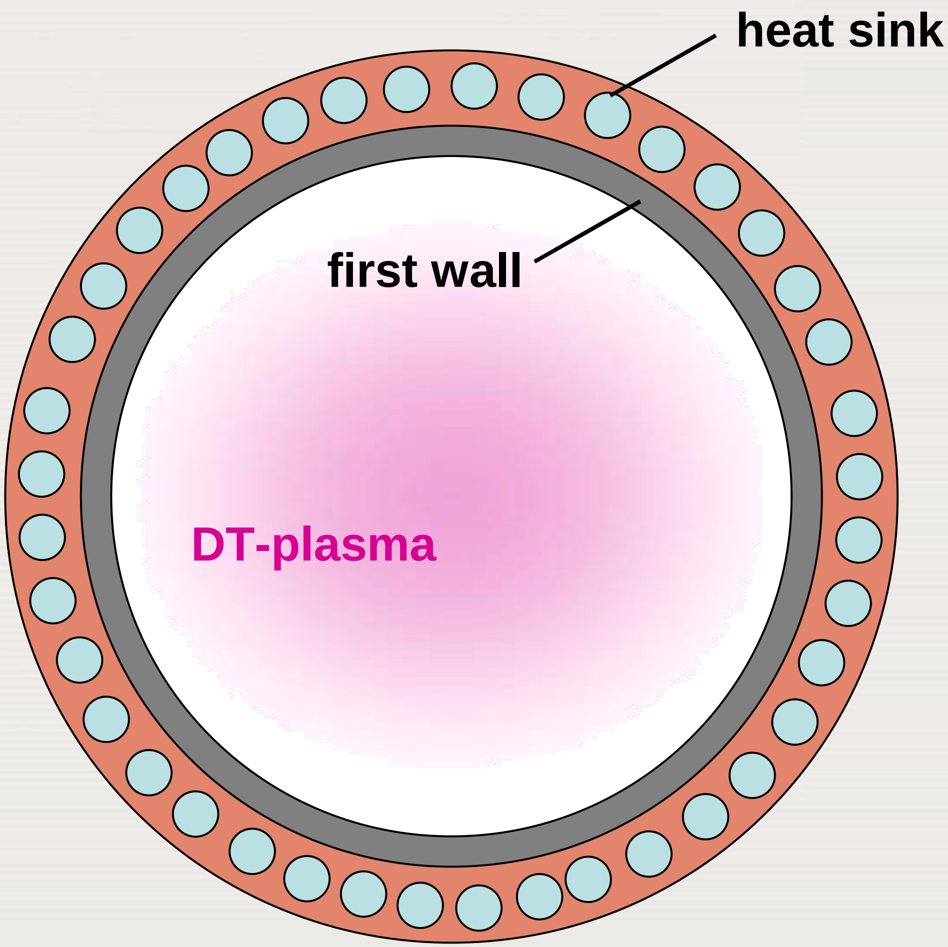
- Material Challenges in nuclear reactors
- Structural Materials in different reactor environments
- Operation conditions of DEMO & Sodium fast Reactor: Commonalities & Differences
- Discussion / Conclusions
- Key Facilities for Development of Fusion Materials

Material challenges in nuclear reactors

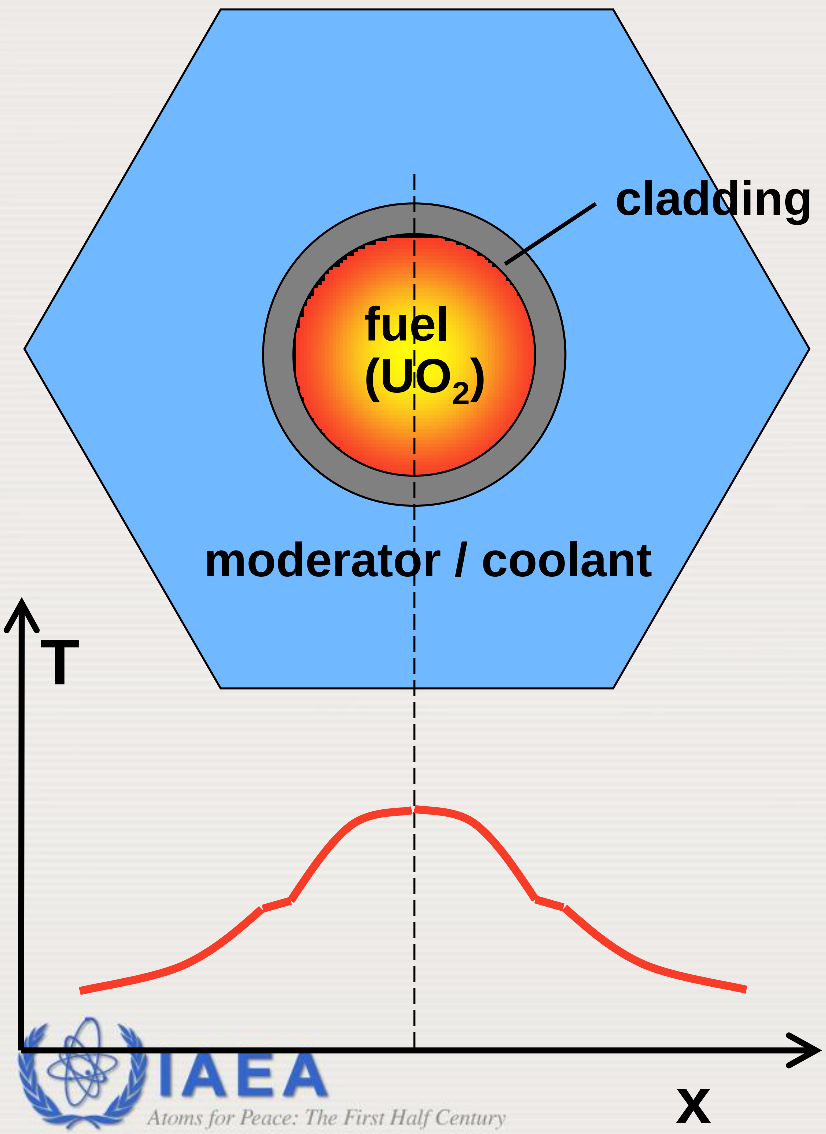
Fission Reactor



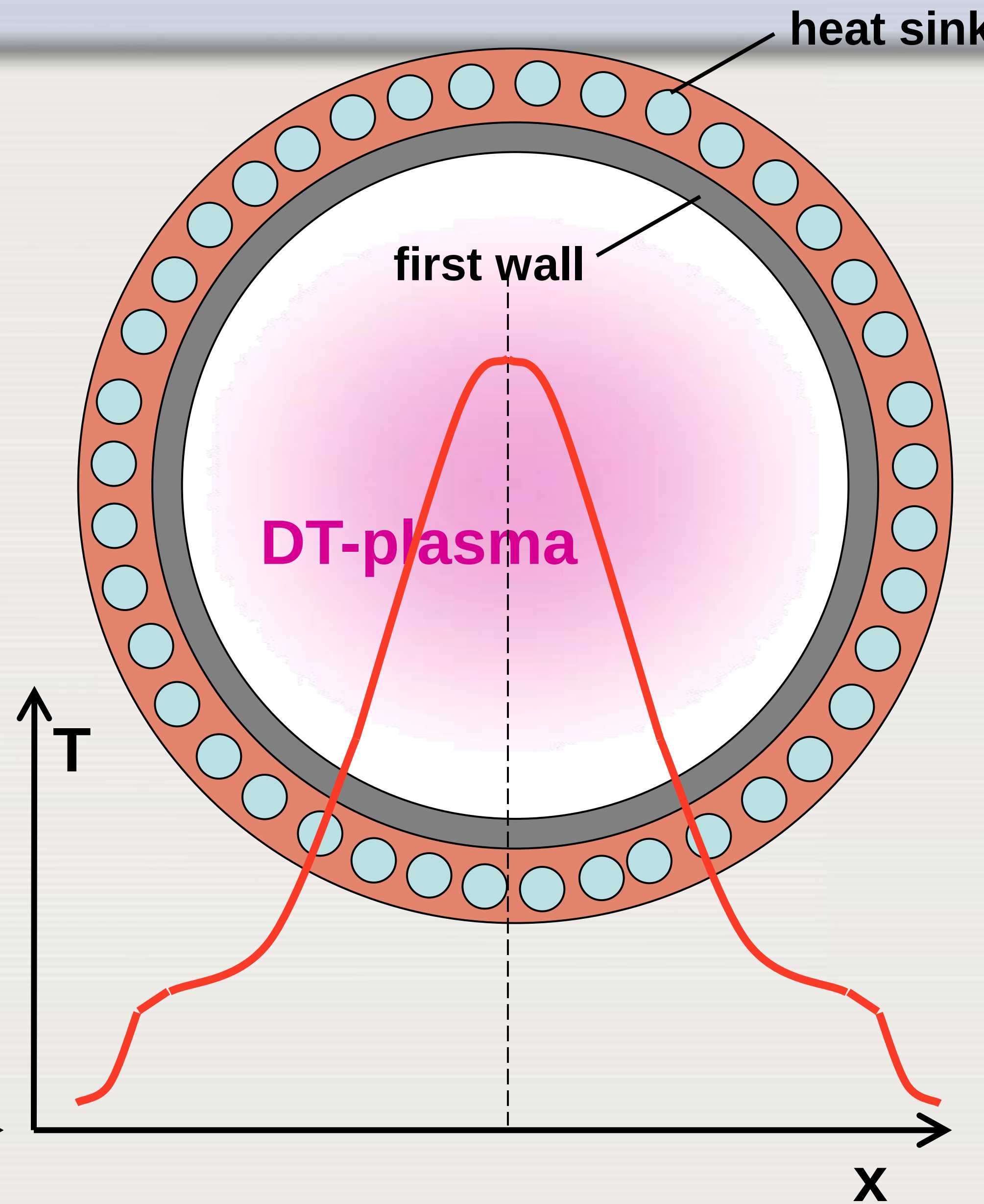
Fusion Reactor



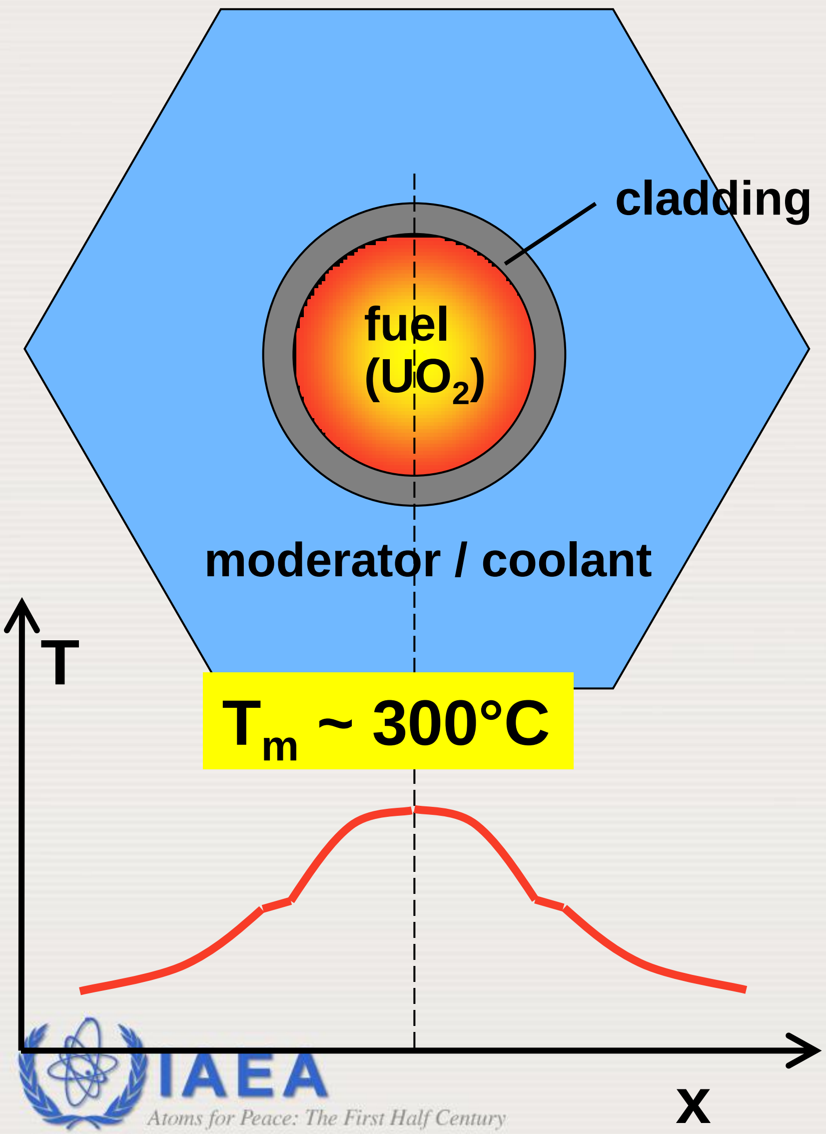
Fission Reactor



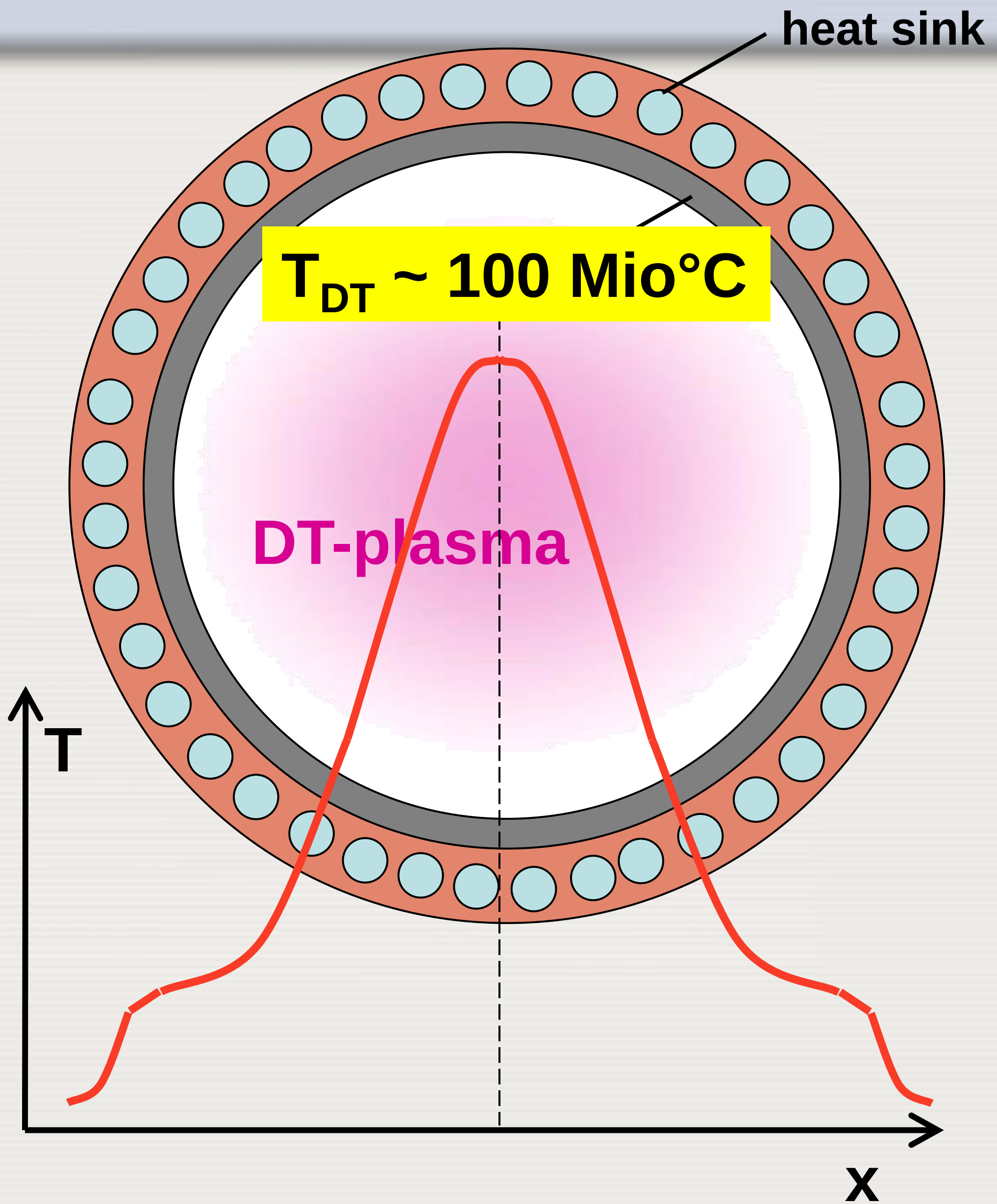
Fusion Reactor



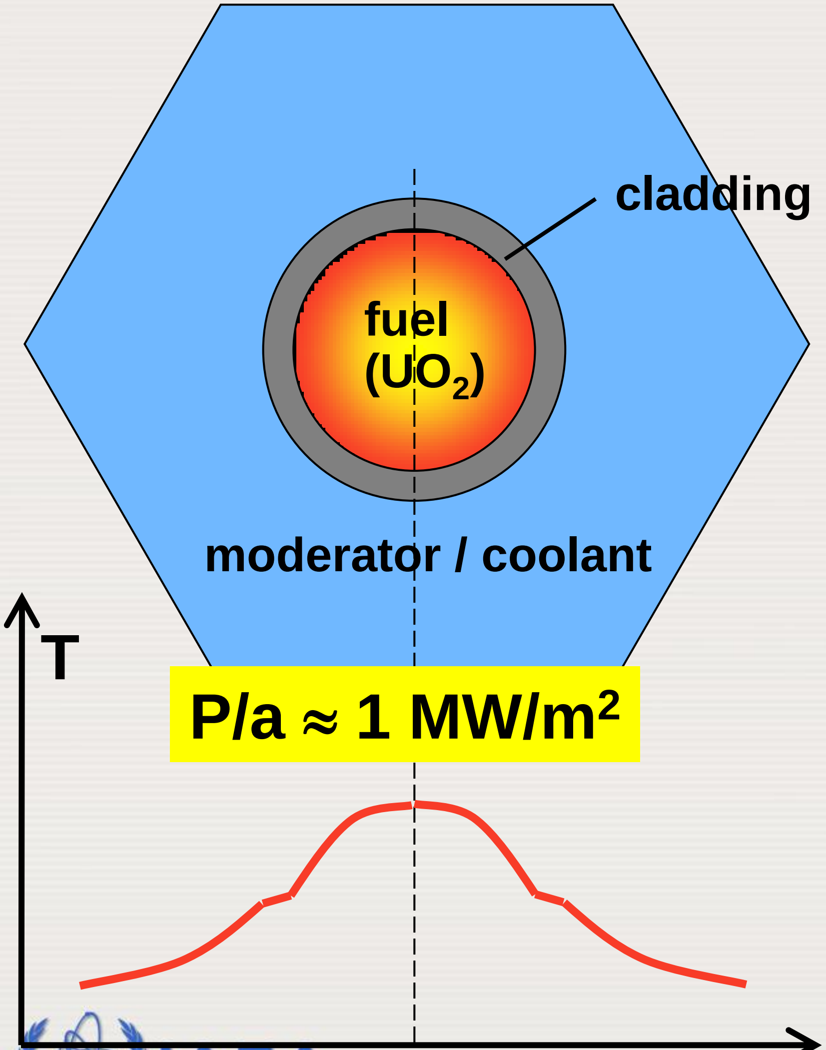
fission reactor



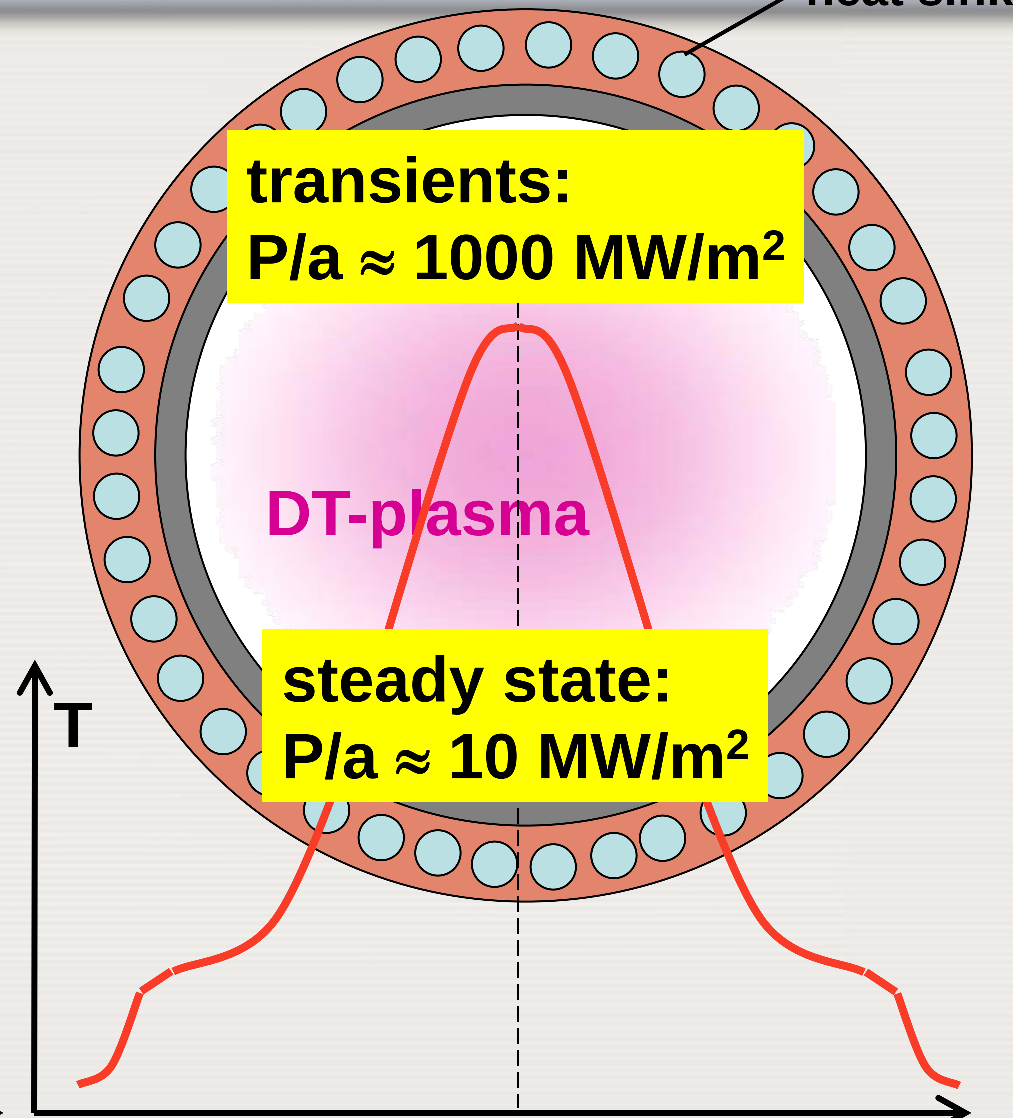
fusion reactor



Fission Reactor



Fusion Reactor



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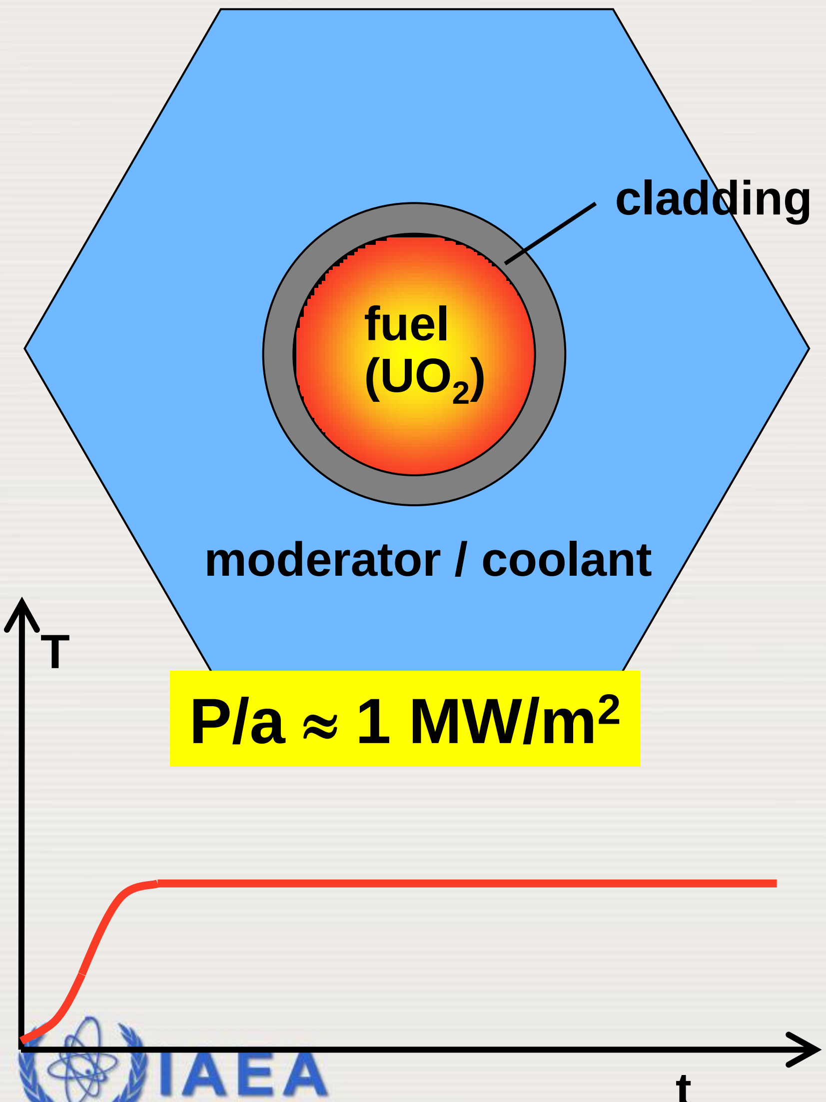
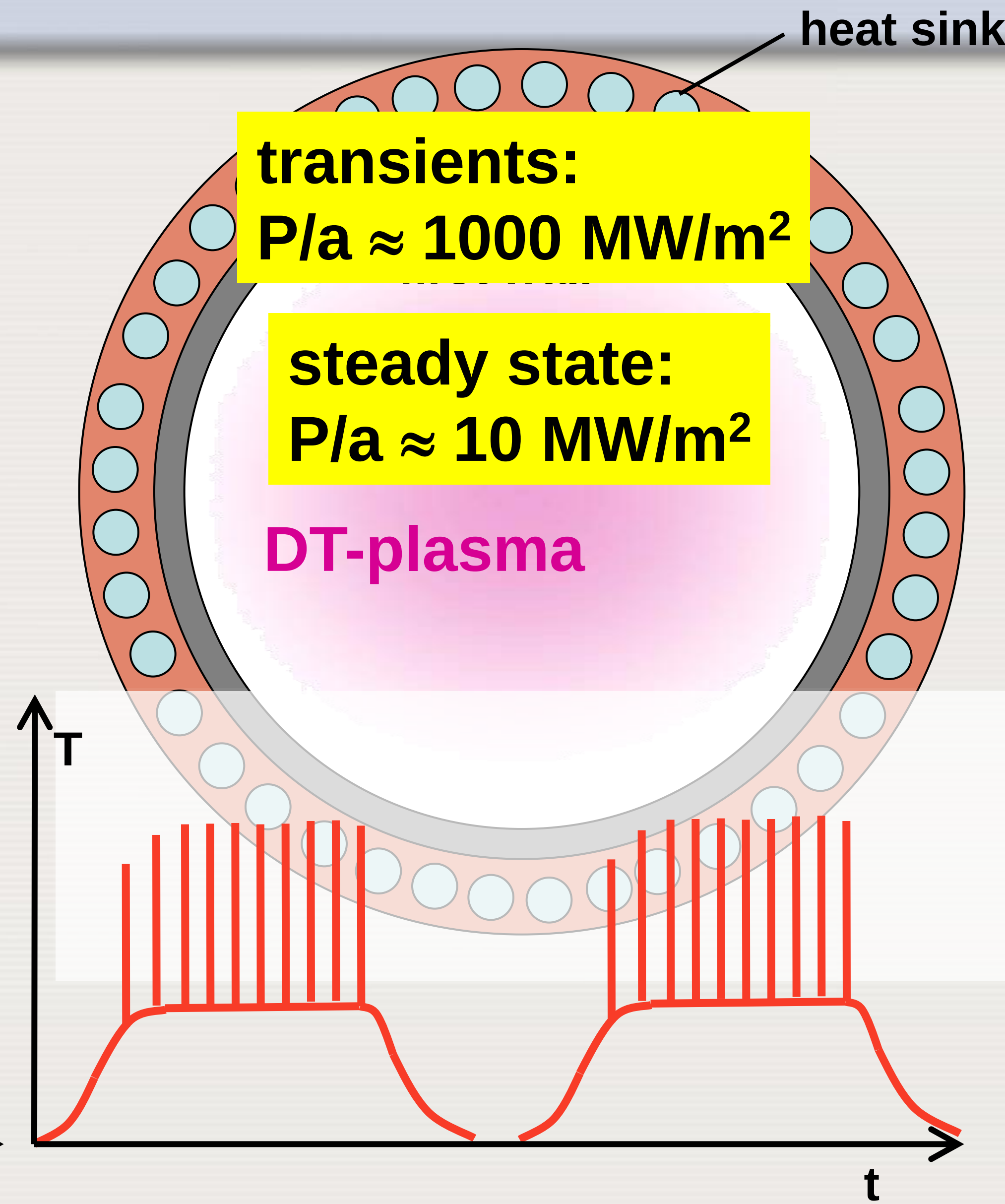
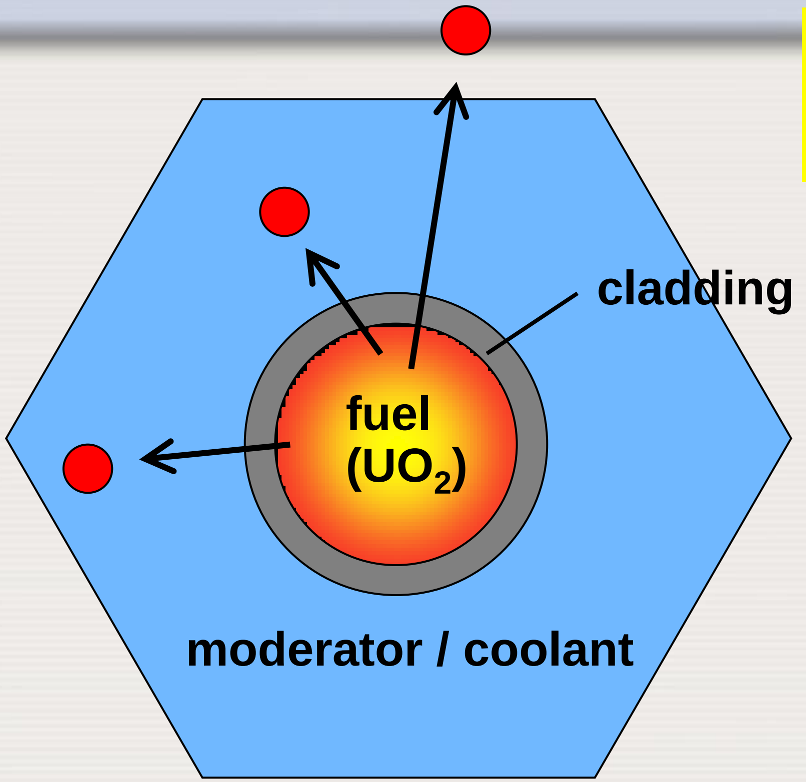


Fusion Reactor

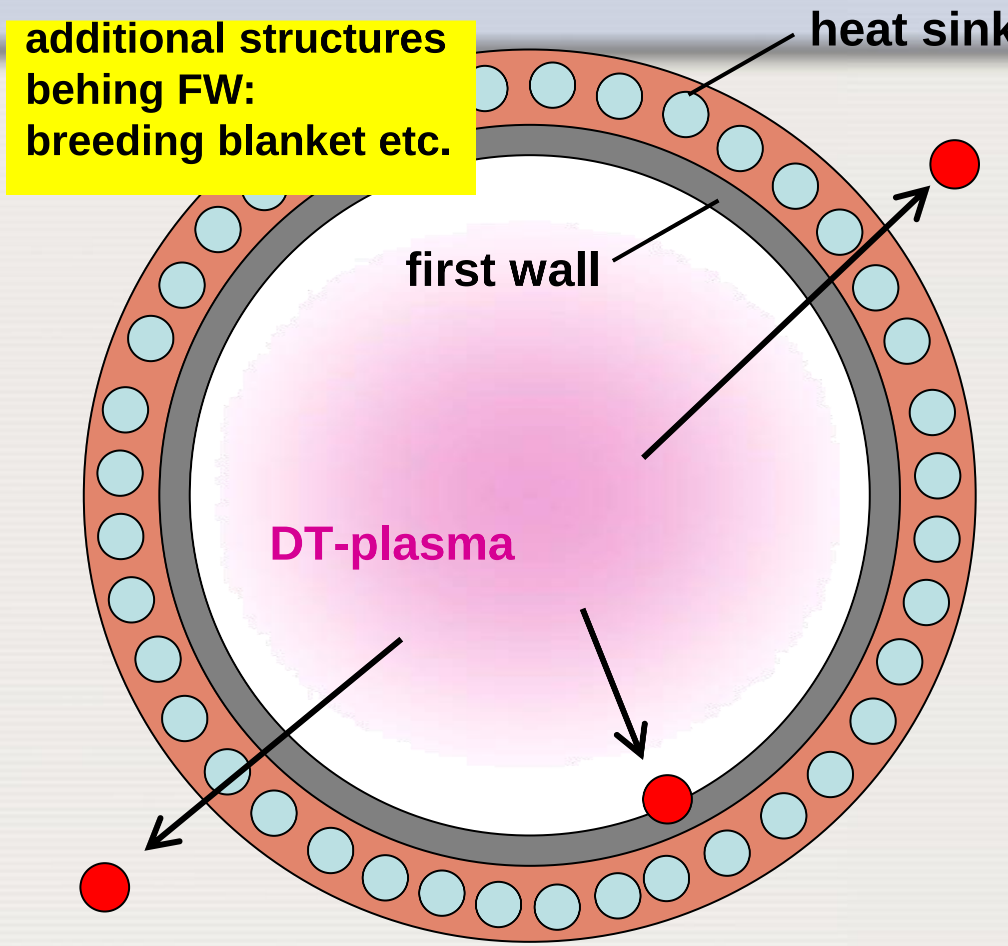


Fission Reactor



$\langle E_n \rangle = 2$ MeV

Fusion Reactor



$E_n = 14.1$ MeV

Material activation and degradation by energetic neutrons

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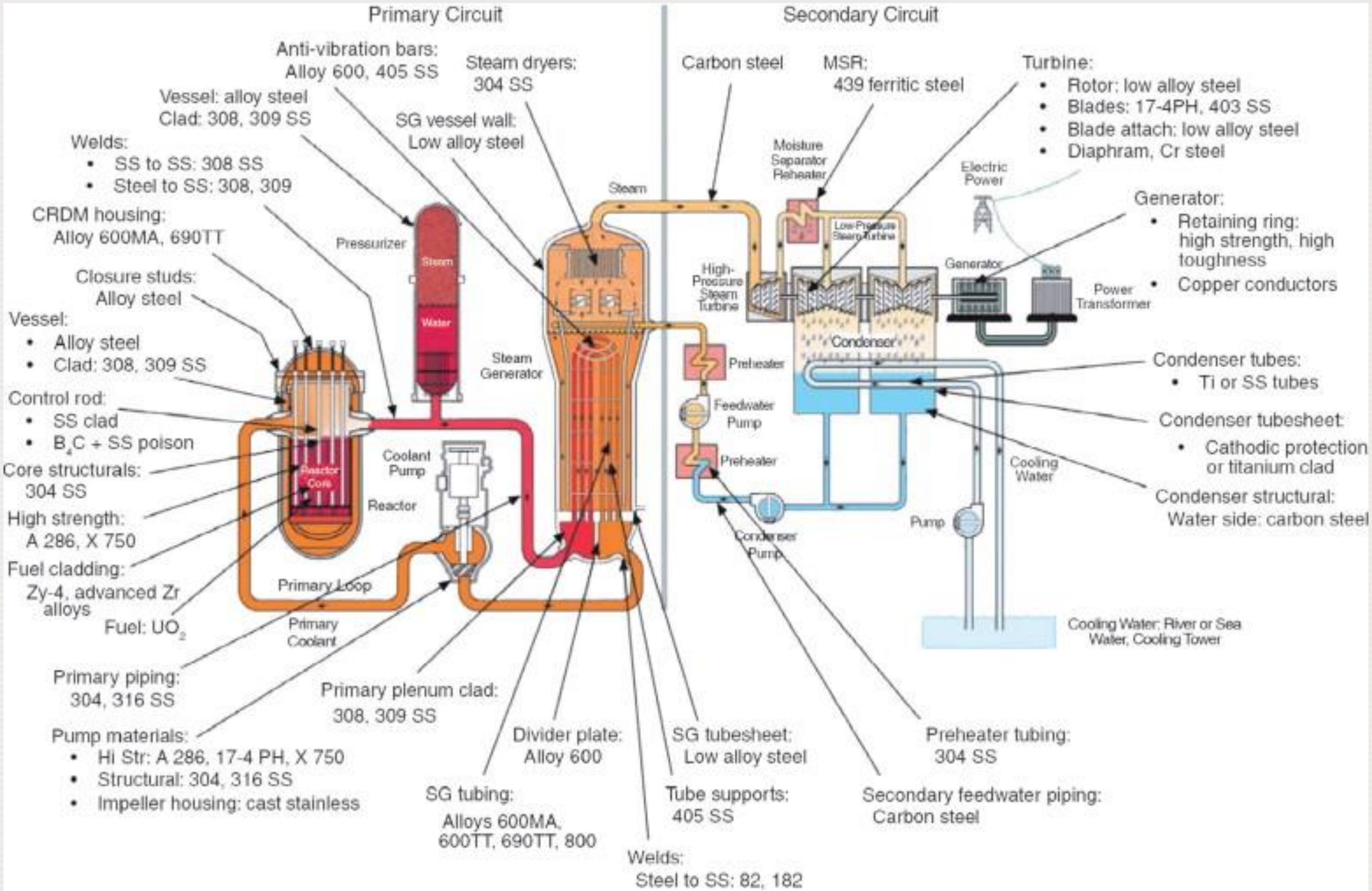
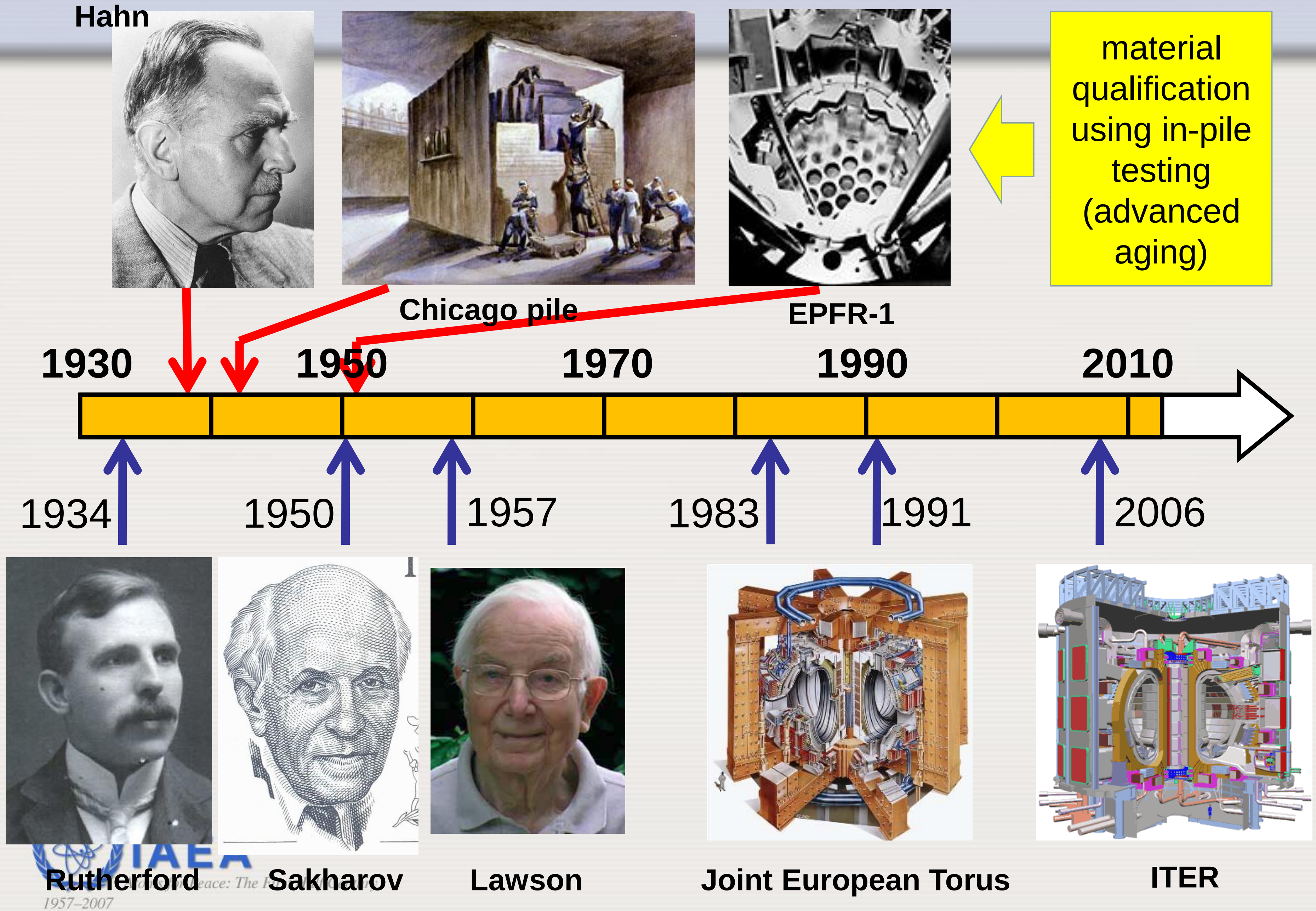
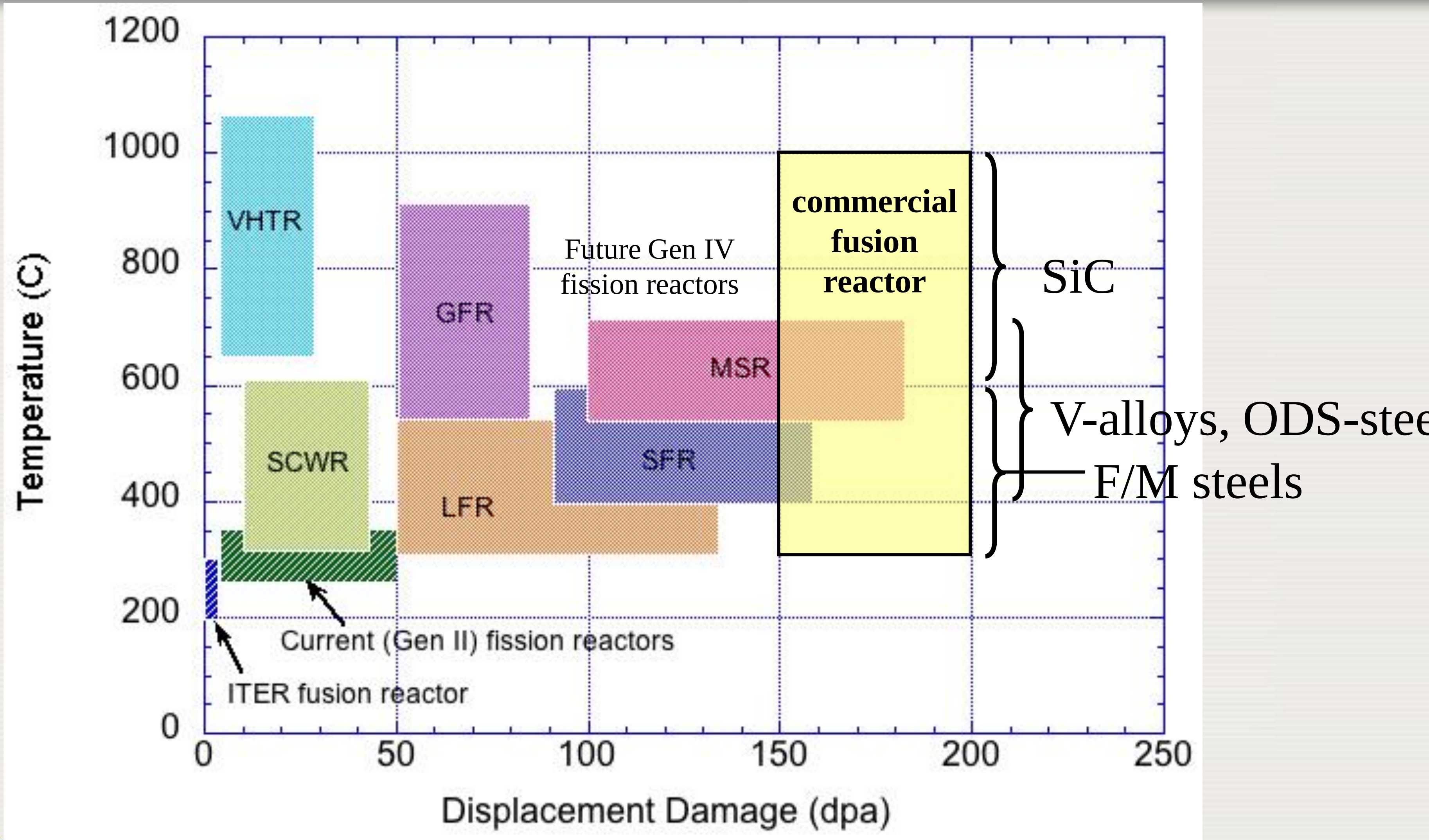


S.J. Zinkle, Materials today, Vol. 12, No. 11, Nov. 2009

History of Fission and Fusion



Structural materials in different reactor environments



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Materials choices for fusion applications

Operating temperature windows for fusion reactor structural materials

S.J. Zinkle [a,*], N.M. Ghoniem [b]

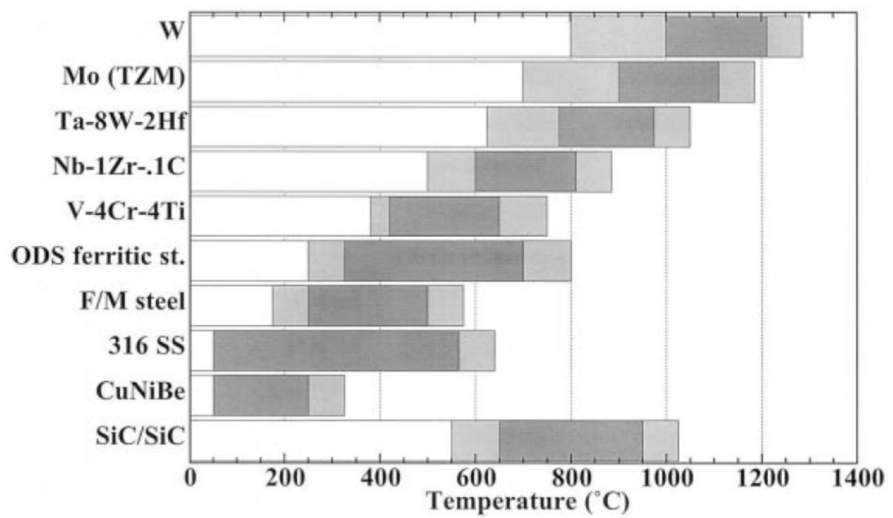

Fig. 6. Operating temperature windows (based on radiation damage and thermal creep considerations) for refractory alloys, Fe–(8–9%)Cr ferritic-martensitic steel, Fe–13%Cr oxide dispersion strengthened ferritic steel, Type 316 austenitic stainless steel, solutionized and aged Cu–2%Ni–0.3%Be, and SiC/SiC composites. The light shaded bands on either side of the dark bands represent the uncertainties in the minimum and maximum temperature limits.

Fusion Engineering and Design 51–52 (2000) 55–71

- Candidate fusion structural materials have to comply with mandate for reduced activation and high performance
- Most developed fusion candidate structural material is FM steel: **EUROFER97** (EU), **F82H** (Japan), **CLAM** (China)

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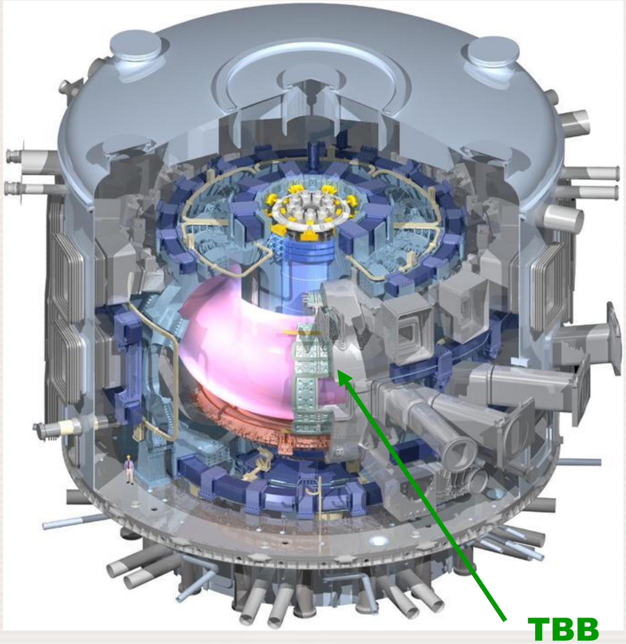
Fusion & Fission Reactors

Tokamak Reactor

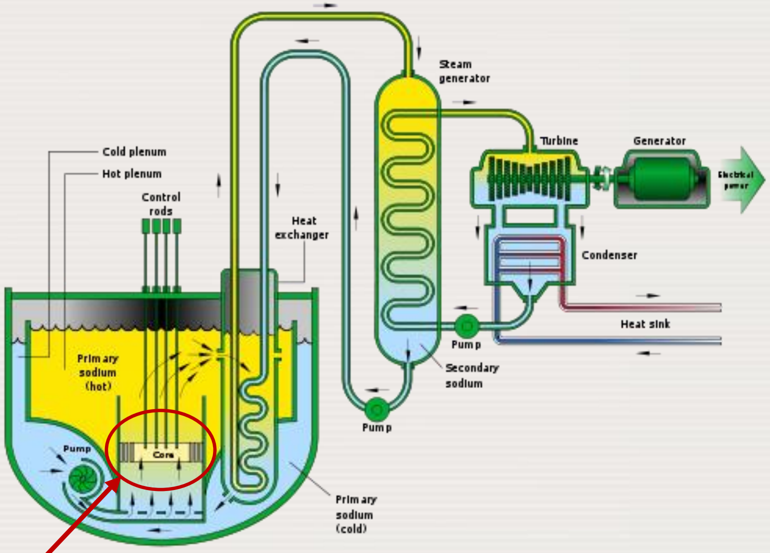


TBB

Tritium Breeding Blankets

- 14 MeV neutrons
- 30-100 dpa
- He production ~10 appm/dpa (close to FW)
- H production ~ 45 appm/ dpa (close to FW)
- Peak heat flux ~ 0.5 MW/m^2 (close to FW)

Sodium cooled Fast Reactor (SFR)

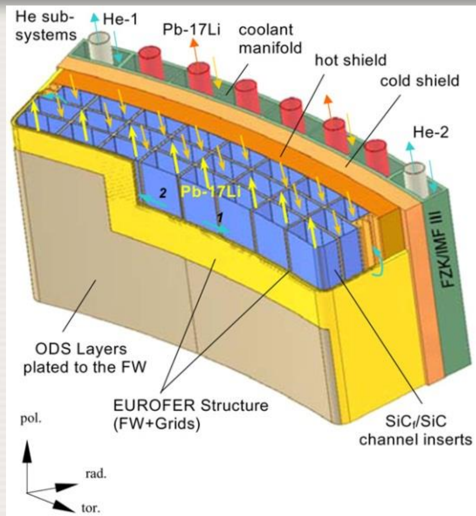


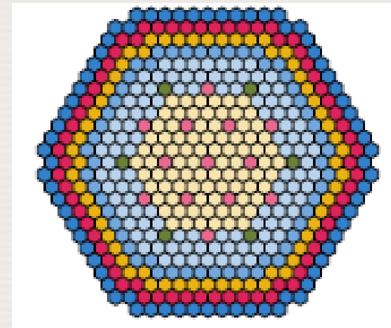
Fissile Core

Fissile core

- Neutron energy in the range of a few MeV
- Up to 200 dpa (cladding)

Fusion & Fission: Commonalities, Differences





- **High levels of damage → up to hundreds of dpa**
- **High operating temperature → up to 700-750 °C**

Fusion Power Reactor Dual – Coolant T – Blanket	
He 80 bars	$Pb\text{-}^{17}Li$ ~ bar
Structural materials **F-M steels EUROFER (upper T ~550 °C)** **ODS Ferritic steels (upper T ~750 °C)** **SiC$_f$/SiC thermal & elect. Insulator**	
FW: T_{max} = 625 °C **Channel: T_{max} = 500°C** **Insert: T_{max} ~1000 °C**	
Dose: 30-100 dpa	

	GFR	**SFR**
Coolant	He 70 bars	Liquid Na, a few bars
Core Structure	SiC composite	ODS Ferritic steels (cladding) F/M steels (hexagonal tube)
Temperature	600-1200°C →1650°C	350 – 700°C (cladding) 350 -550 °C (hexagonal tube)
Dose	60/90 dpa	200 dpa
Vessel	9Cr martensitic steels (T91) or improved version	316L Austenitic steels

BUT : different operating conditions!

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Materials for Fusion Blanket / Gen IV

Fusion:

(9Cr-) FM Steels, ODS F steels, SiC/SiC composites

Fission:

FM steels, ODS F, *SS, Ni-alloys, Graphite, Ceramics* (**SiC/SiC**) …

→ **Overlap in material choice**

However, for fusion:

- *materials are a "subgroup" (e.g. due to the low activation requirement)*
- *Different development OBJECTIVES (driven by mission and requirement on loading conditions and component life time)*
- *Whole set of well balanced properties (HT strength, fracture, ..)*
- *Complex geometry in breeding blankets (not in fission claddings) -> Many (critical) joints. Workability/Fabrication*

Conclusion

- New high performance materials are mandatory to build and to operate future fission and fusion reactors.
- Structural materials, i.e. highly radiation resistant steels operating at very high temperatures are urgently needed in both systems:

  → **ODS FS**

- In addition, a wide variety of functional materials (cladding, plasma facing materials, superconducting magnets, insulators etc.) have to be developed and tested under operational conditions. In this area synergies between fission and fusion are scarce.

OPERATING CONDITIONS in FUSION and FISSION are not the same

REQUIREMENTS ARE DIFFERENT

COMMONALITIES

Production of ODS FS

Modelling of neutron damage

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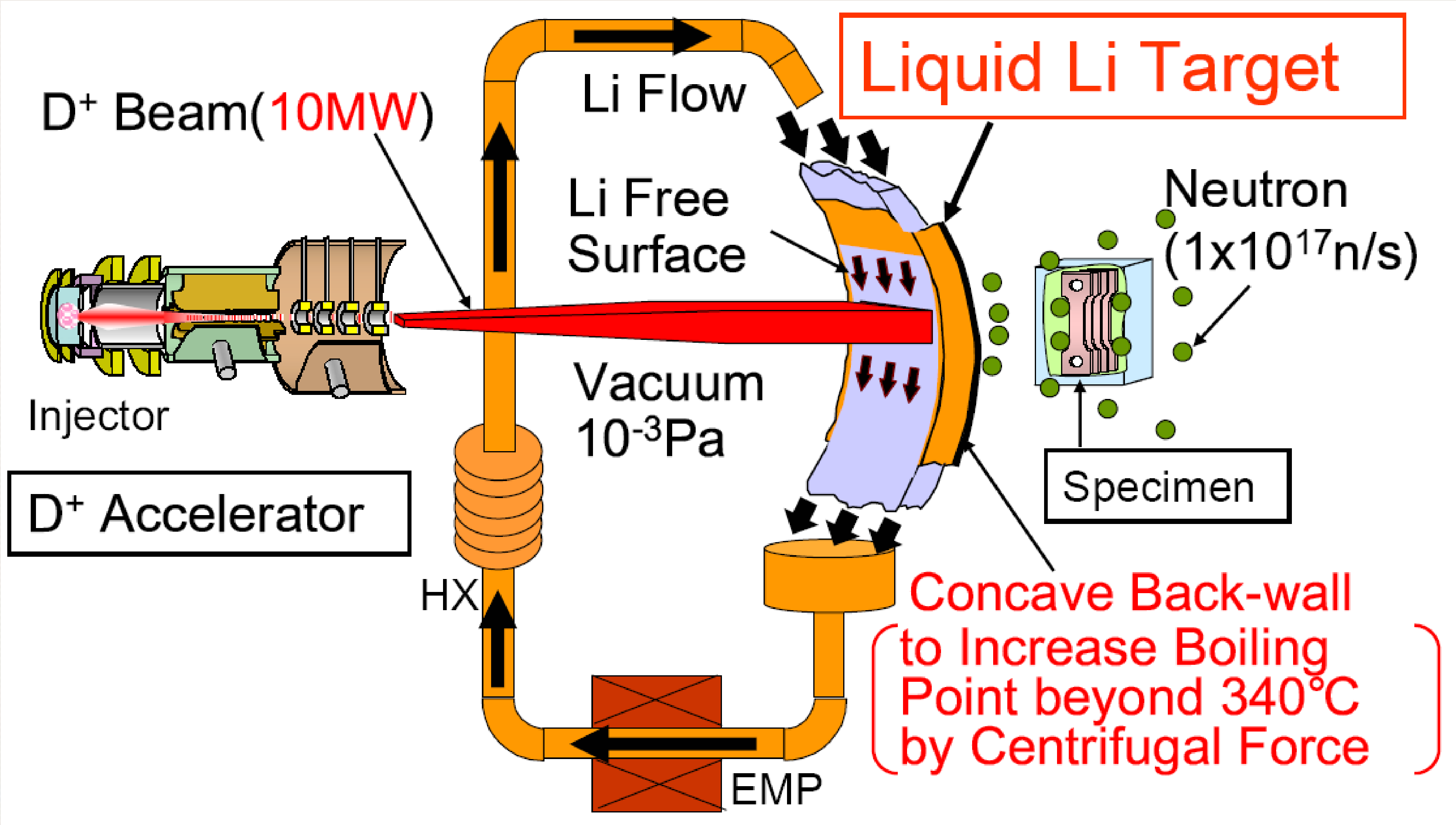
International Fusion Materials Irradiation Facility (IFMIF)



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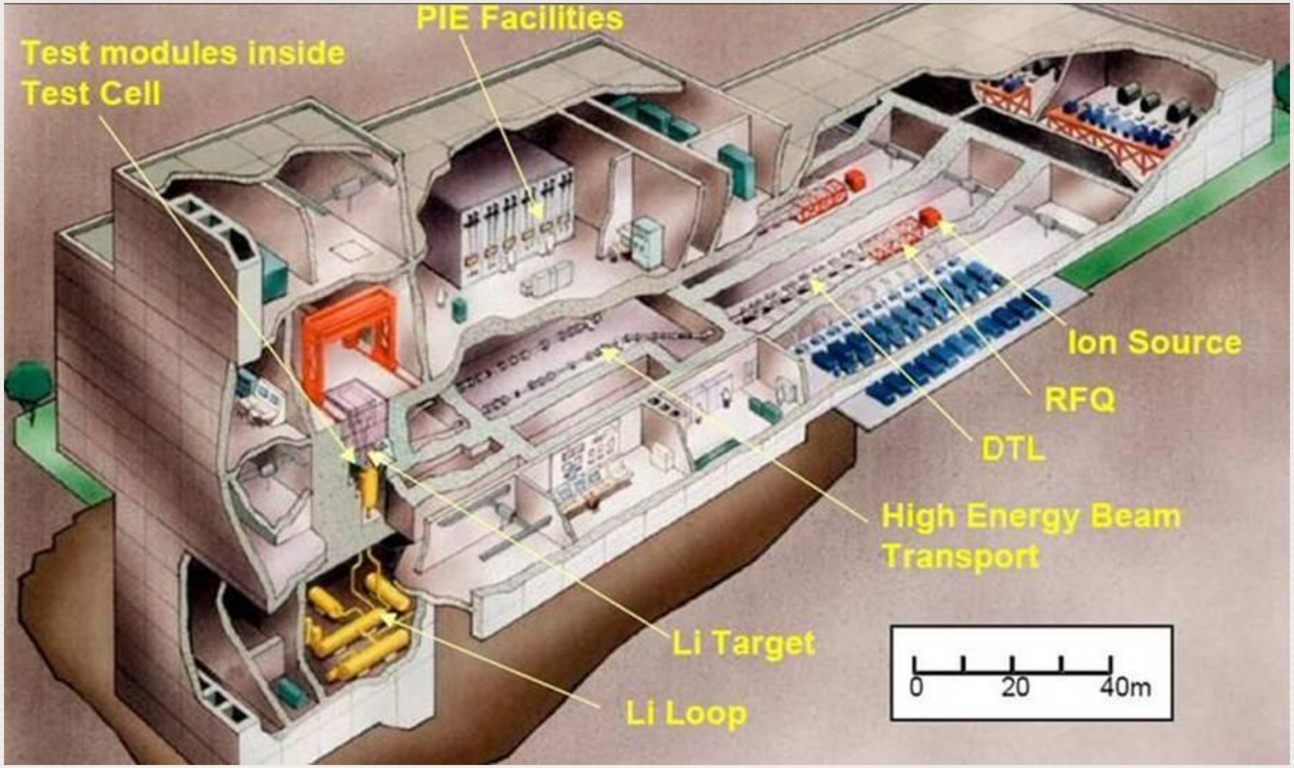
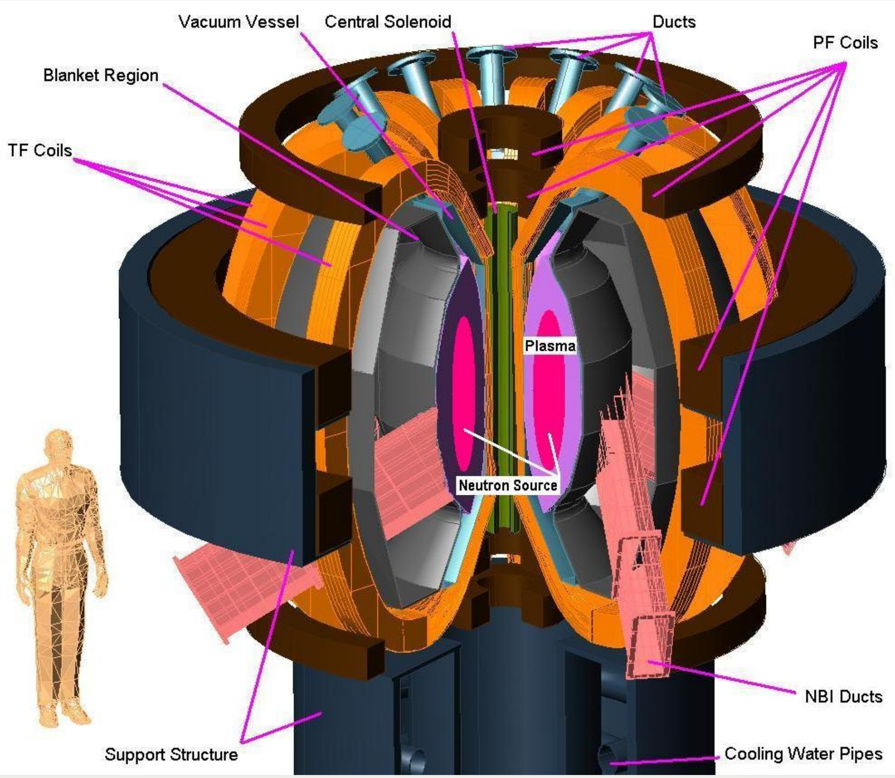


High Flux (> 20 dpa/fpy)	0.5 liter
Medium Flux (1.0 to 20 dpa/fpy)	6 liter
Low Flux (0.1 to 1.0 dpa/fpy)	7.5 liter
Very Low Flux (0.01 to 0.1 dpa/fpy)	>100 liter

Volumetric Fusion Neutron Sources / CTFs

- Testing of material systems and components in an integrated environment
- Comprehensive investigation of multiple effects/multiple interactions



Thank you for your attention

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Fusion/Fission overlap areas

Requirements for structural materials to be used in TBB and fissile core:

- **Withstand high levels of damage generated by fast neutrons (MeV) up to hundreds of dpa**
- **High operation temperature up to 700-750 °C**
- **High thermal loads, MW/m^2**

ODS ferritic steels provide high creep strength at higher temperatures and higher resistance to swelling

Modelling provides guidance to the understanding of mechanisms responsible for the degradation of mechanical and physical properties under neutron irradiation

Comparison Fusion & Fission

	ITER	DEMO	*Reactor*
Heat flux (FW) [MW/m^2]	~0.5 (Peak)	0.5	*0.5*
Neutron Wall Load (FW) [MW/m^2]	<0.8	~2	*~2*
Integrated Wall Load (FW) [MW.year/m^2]	< 0.1	8	*10 - 15*
Displacement per atom (dpa) (in Iron)	< 1	~ 80	*100 - 150*

REQUIREMENT: Need 10-20 dpa / fpy
Preferably a factor of two accelerated testing !

For comparison	*Fission Gen I*	DEMO	*Fission Gen IV*
Displacement per atom [dpa]	*~ 1*	80 (50-100)	*order: ~100*
Transmutation (He) [appm]	*~ 0.1 - 0,2*	~800 (Fe) ~5000 (SiC)	*order: -10 /20*

Factor of 40 difference in He/dpa ratio

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