ITER and BEYOND

Entering the fusion energy era

Joint ICTP-IAEA College on
Plasma Physics
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Atoms for Peace: The First Half Century
1957–2007

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Outlined

- Fusion Goal
- Fusion Challenges and Milestones
- Need and Strategy for Successful Development of a First of a Kind Fusion Plant

IAEA's Mission Statement

- assists its Member States, in the context of social and economic goals, in planning for and using nuclear science and technology for various peaceful purposes, including the generation of electricity, and facilitates the transfer of such technology and knowledge in a sustainable manner to developing Member States;
- develops nuclear safety standards and, based on these standards, promotes the achievement and maintenance of high levels of safety in applications of nuclear energy, as well as the protection of human health and the environment against ionizing radiation;
- verifies through its inspection system that States comply with their commitments, under the Non-Proliferation Treaty and other non-proliferation agreements, to use nuclear material and facilities only for peaceful purposes.

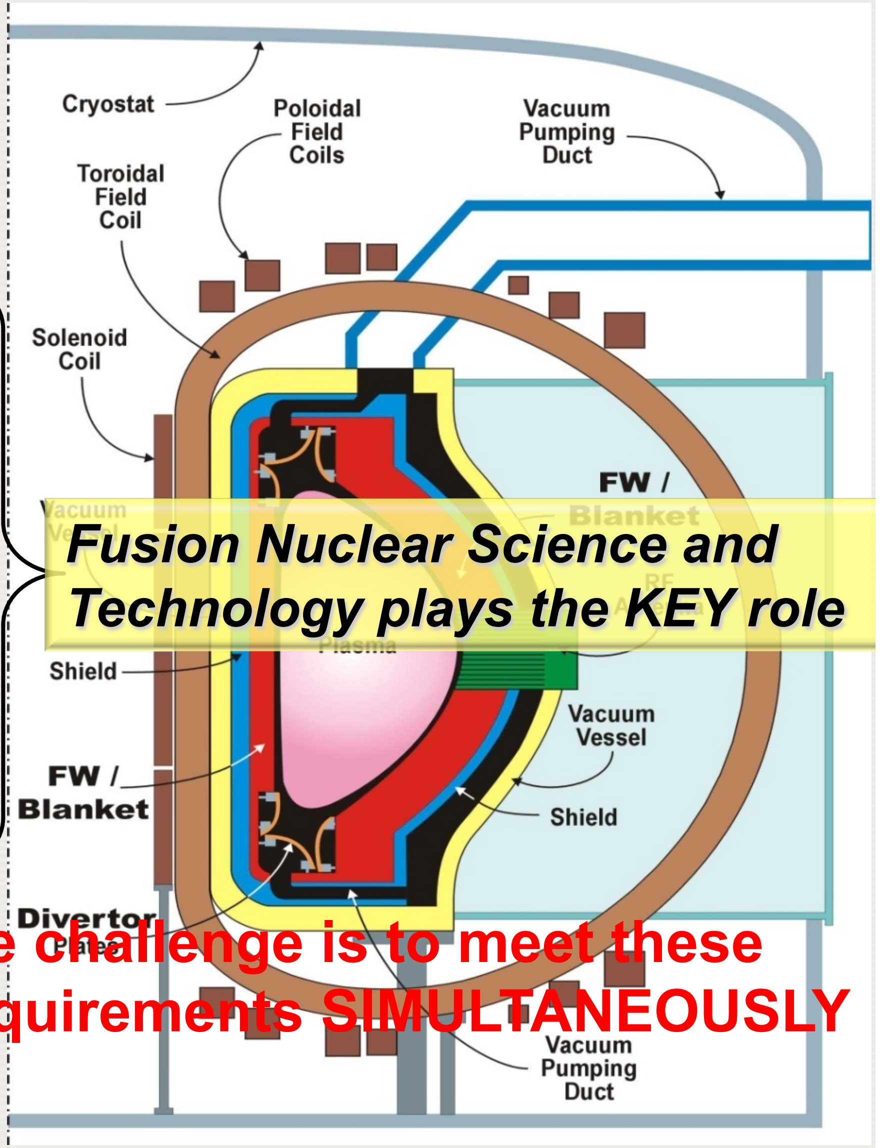
First-of-a-kind Fusion Power Plant

- Must competitively meet market requirements: cost of Electricity
- Must feature all the advantages known to fusion to generate interest from all the stakeholders including the public at large

Fusion Goal: Demonstrate that fusion energy can be produced, extracted, and converted under practical and attractive conditions

Requirements to realize fusion goal:

1. Confined and Controlled Burning Plasma (feasibility)
2. Tritium Fuel Self-Sufficiency (feasibility)
3. Efficient Heat Extraction and Conversion (feasibility)
4. Reliable/Maintainable System (feasibility/ attractiveness)
5. Safe and Environmentally Advantageous (feasibility/attractiveness)



Fusion Nuclear Science and Technology plays the KEY role

The challenge is to meet these Requirements SIMULTANEOUSLY

Fusion Nuclear Science and Technology (FNST)

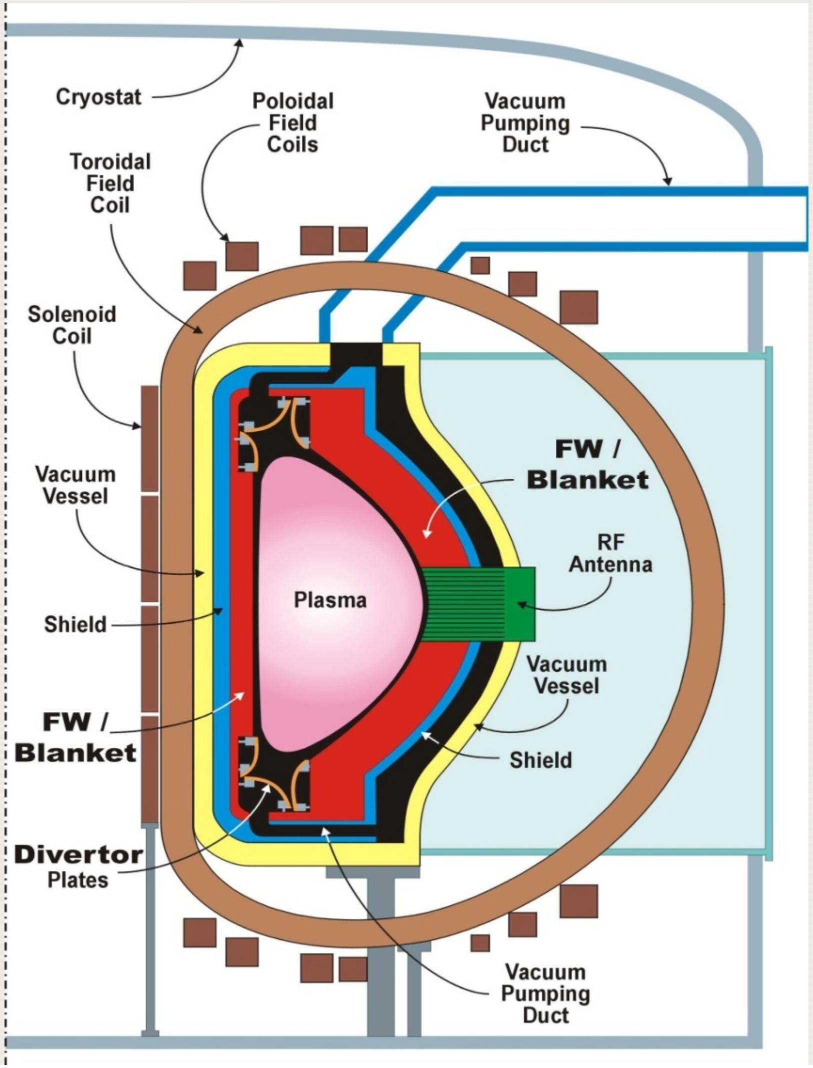
FNST is the **science**, **engineering**, **technology** and **materials** for the fusion nuclear components that generate, control and utilize neutrons, energetic particles & tritium.

Inside the Vacuum Vessel "Reactor Core":

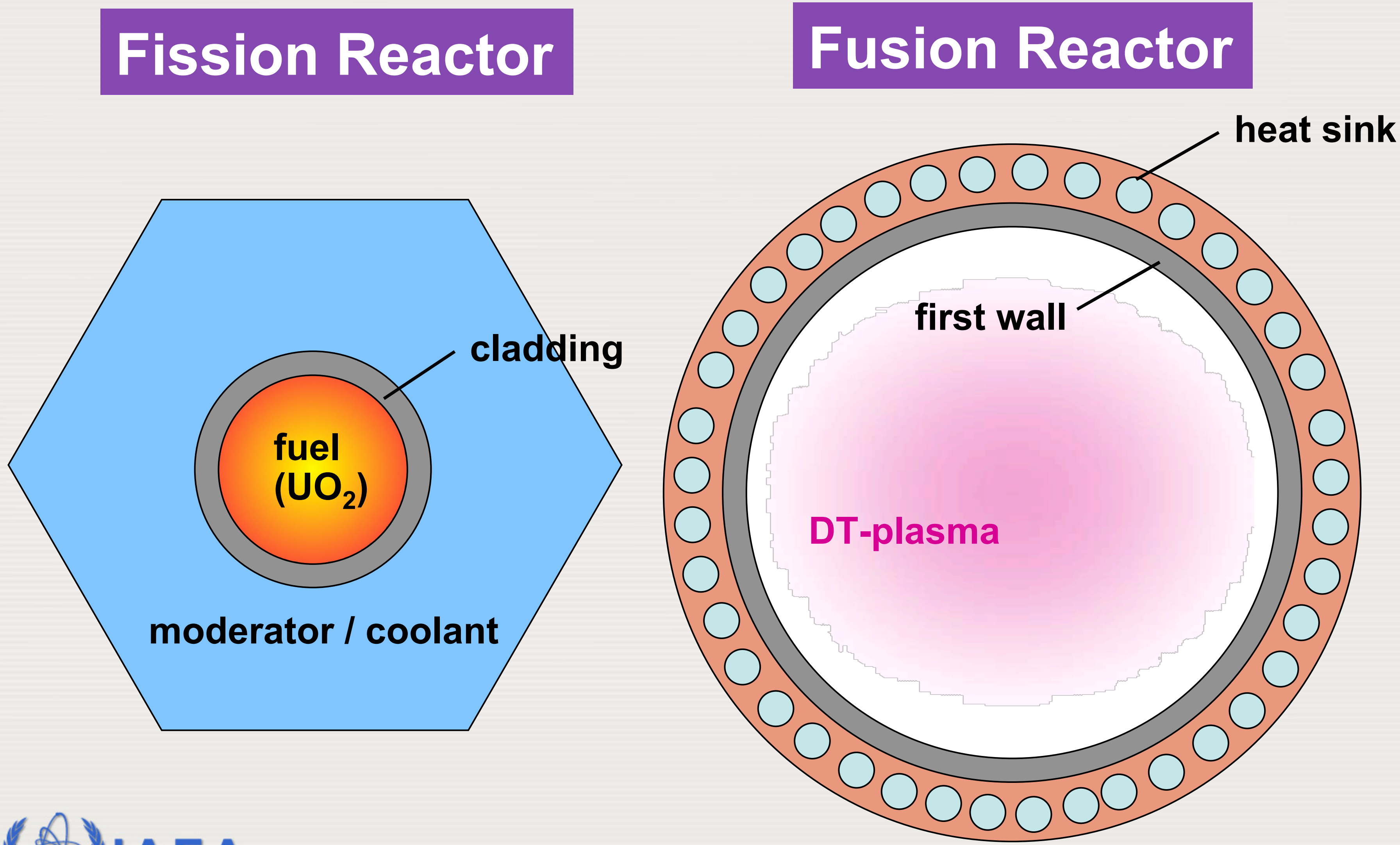
- **Plasma Facing Components**
  divertor, limiter and nuclear aspects of plasma heating/fueling
- **Blanket (with first wall)**
- **Vacuum Vessel & Shield**

Other Systems / Components affected by the Nuclear Environment:

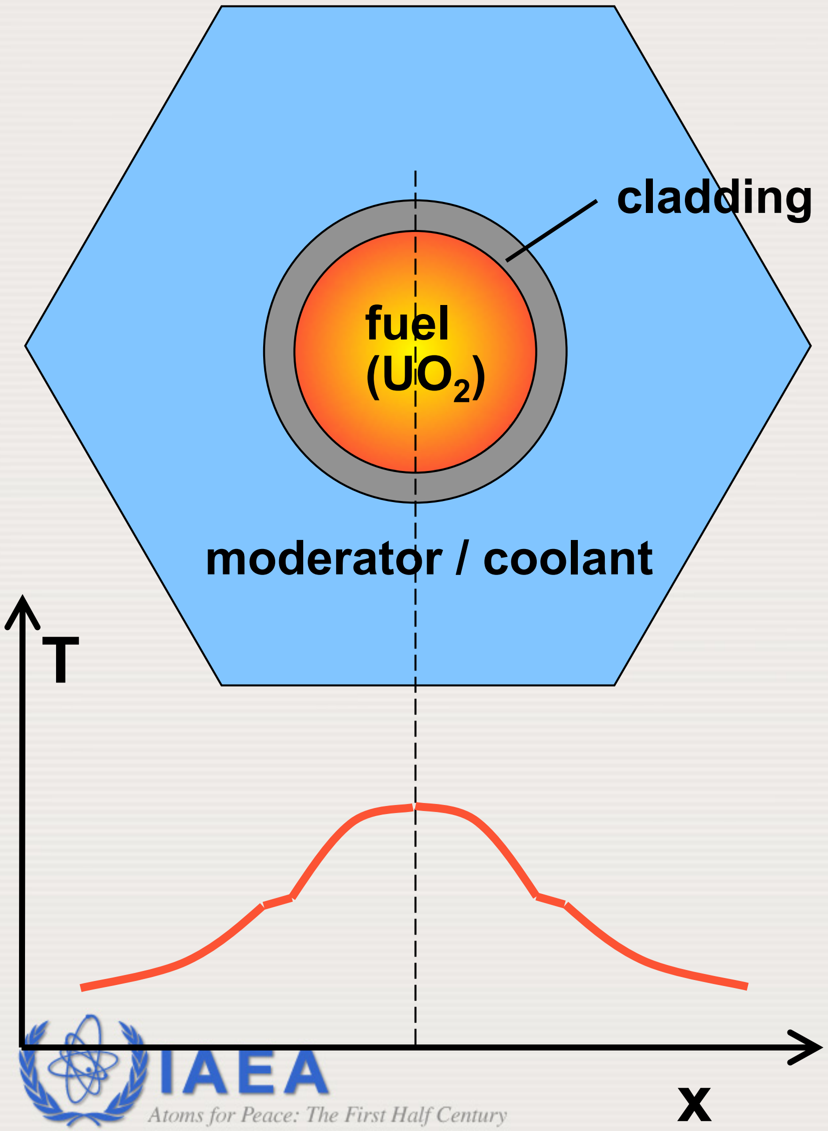
- Tritium Fuel Cycle
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems



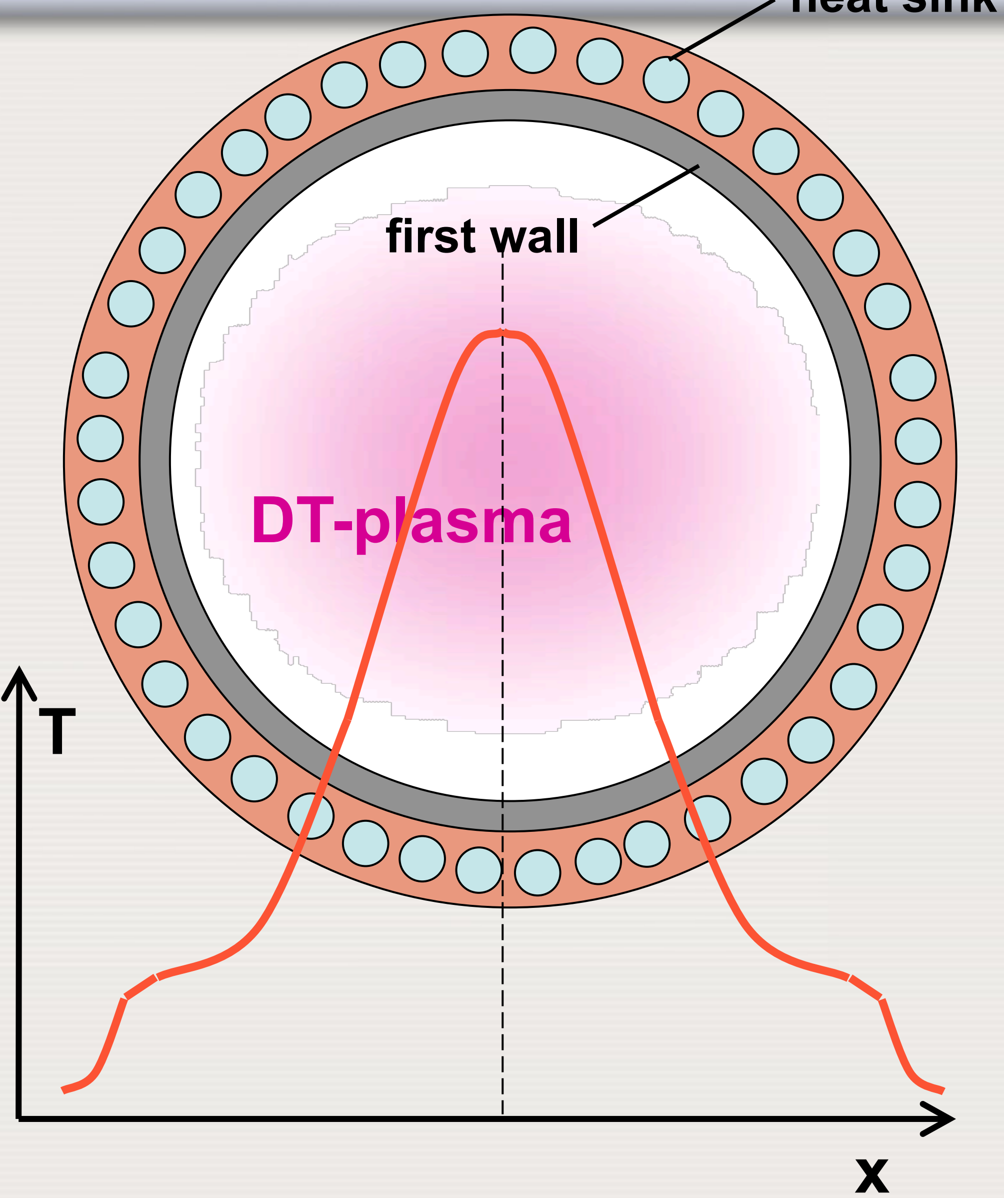
Material challenges in nuclear reactors



Fission Reactor

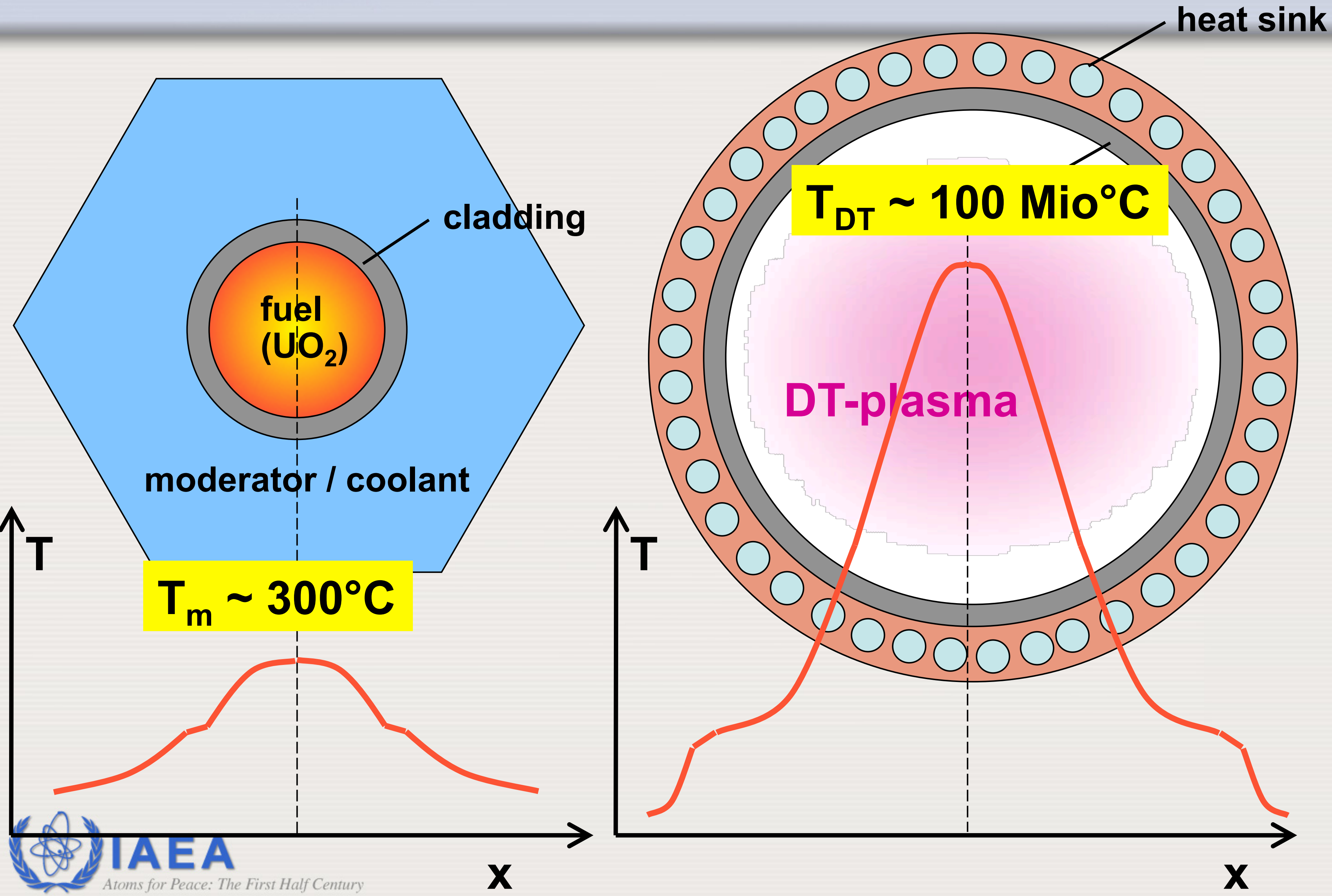


Fusion Reactor

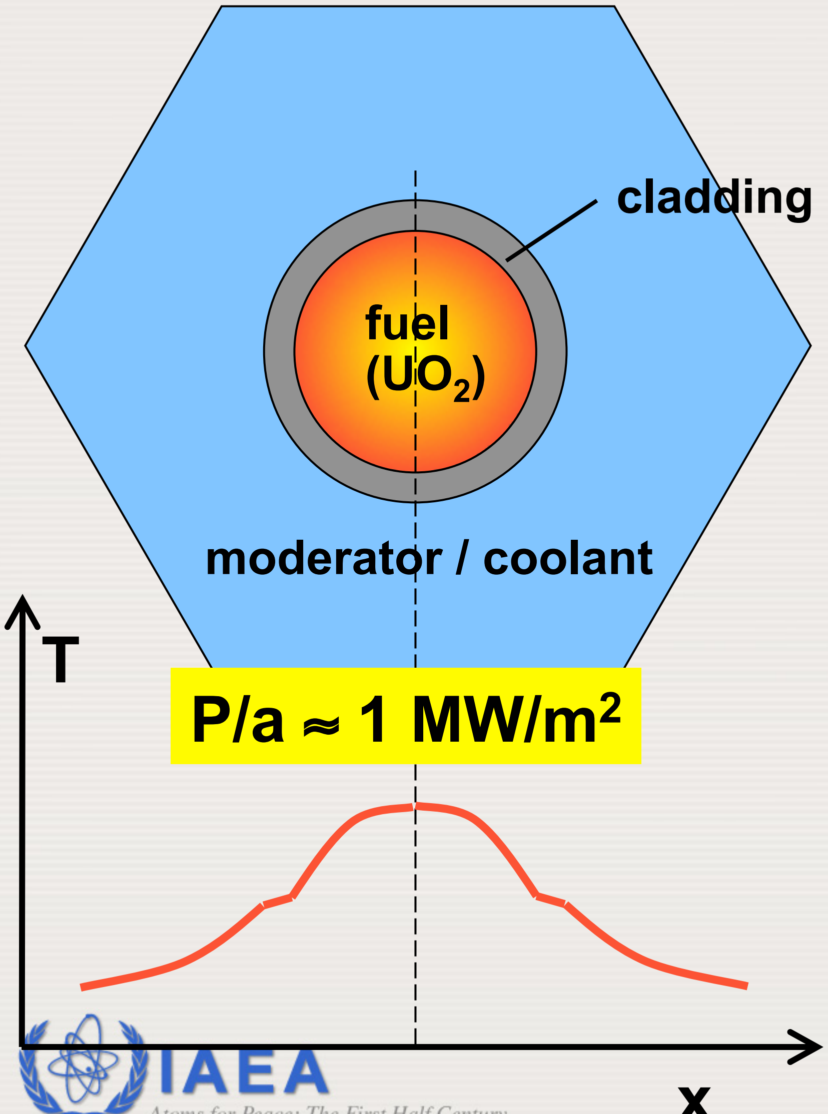


fission reactor

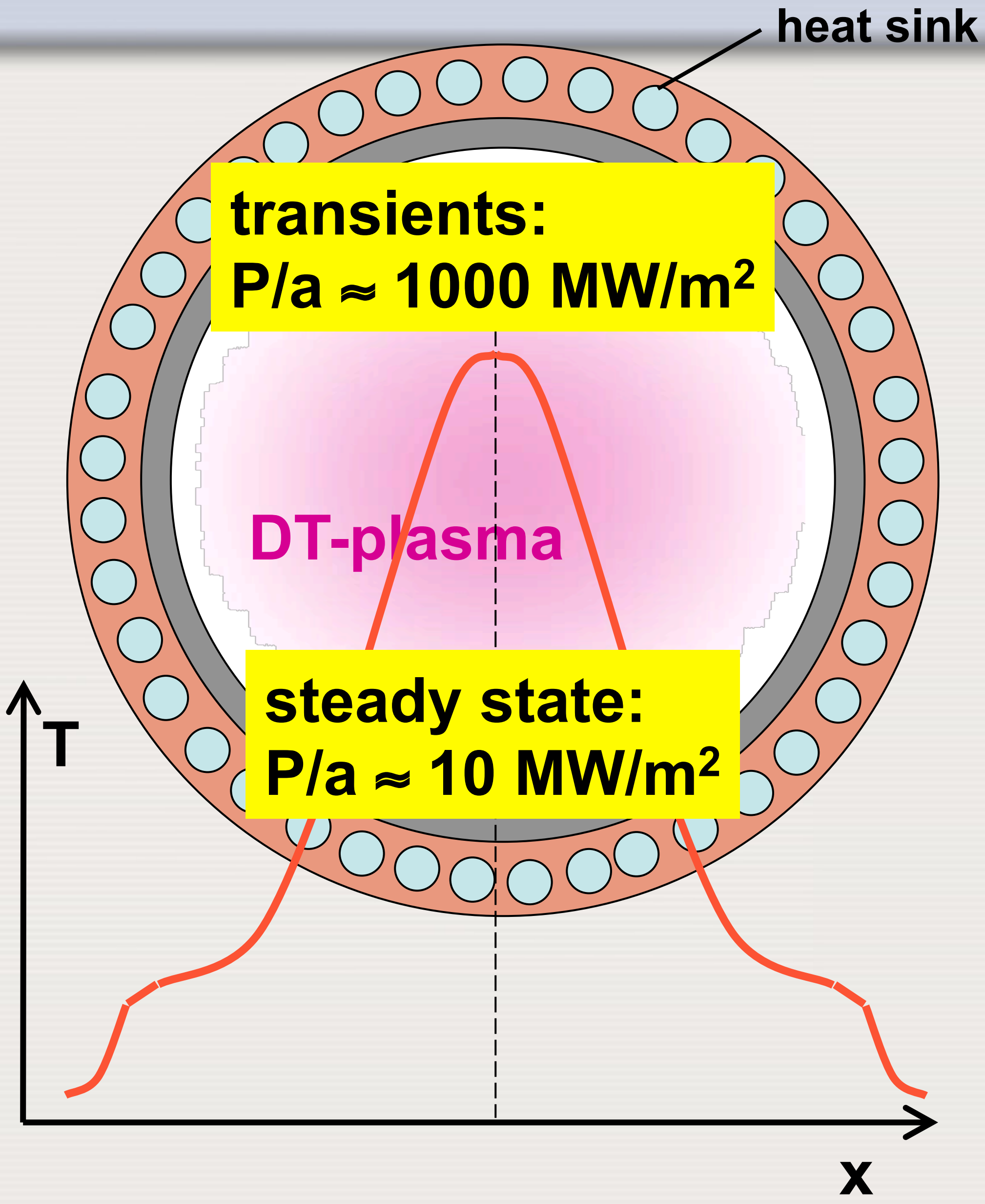
fusion reactor



Fission Reactor



Fusion Reactor



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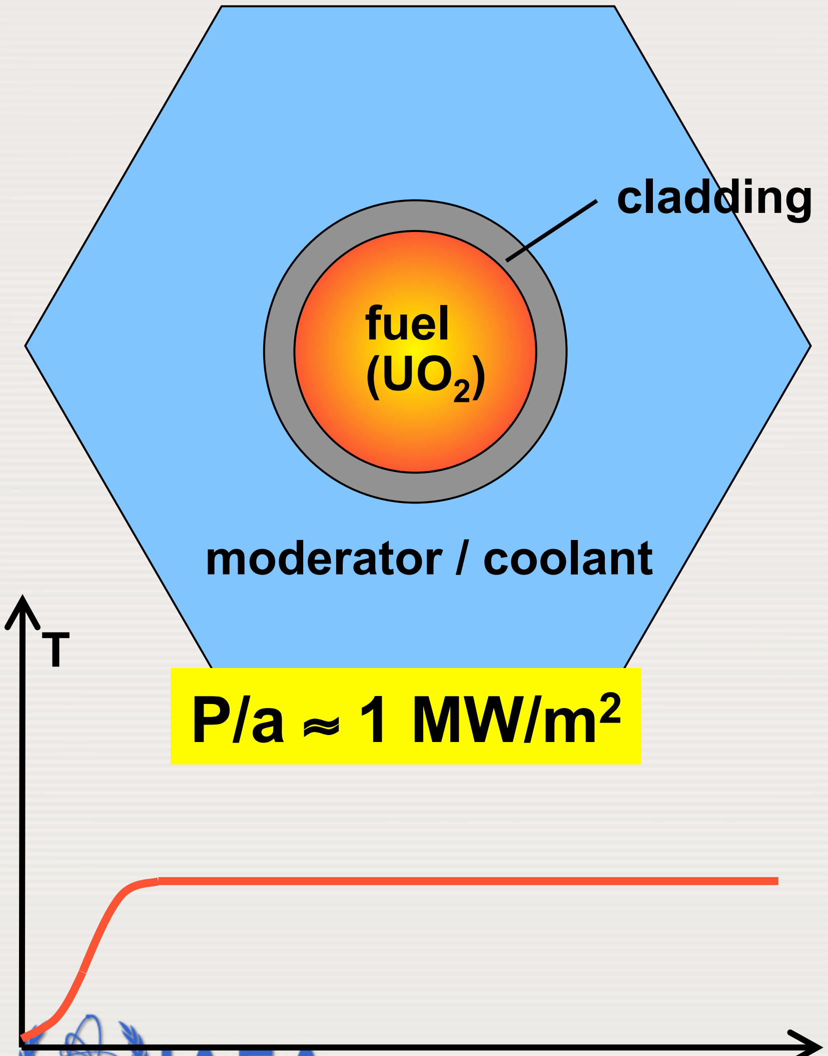
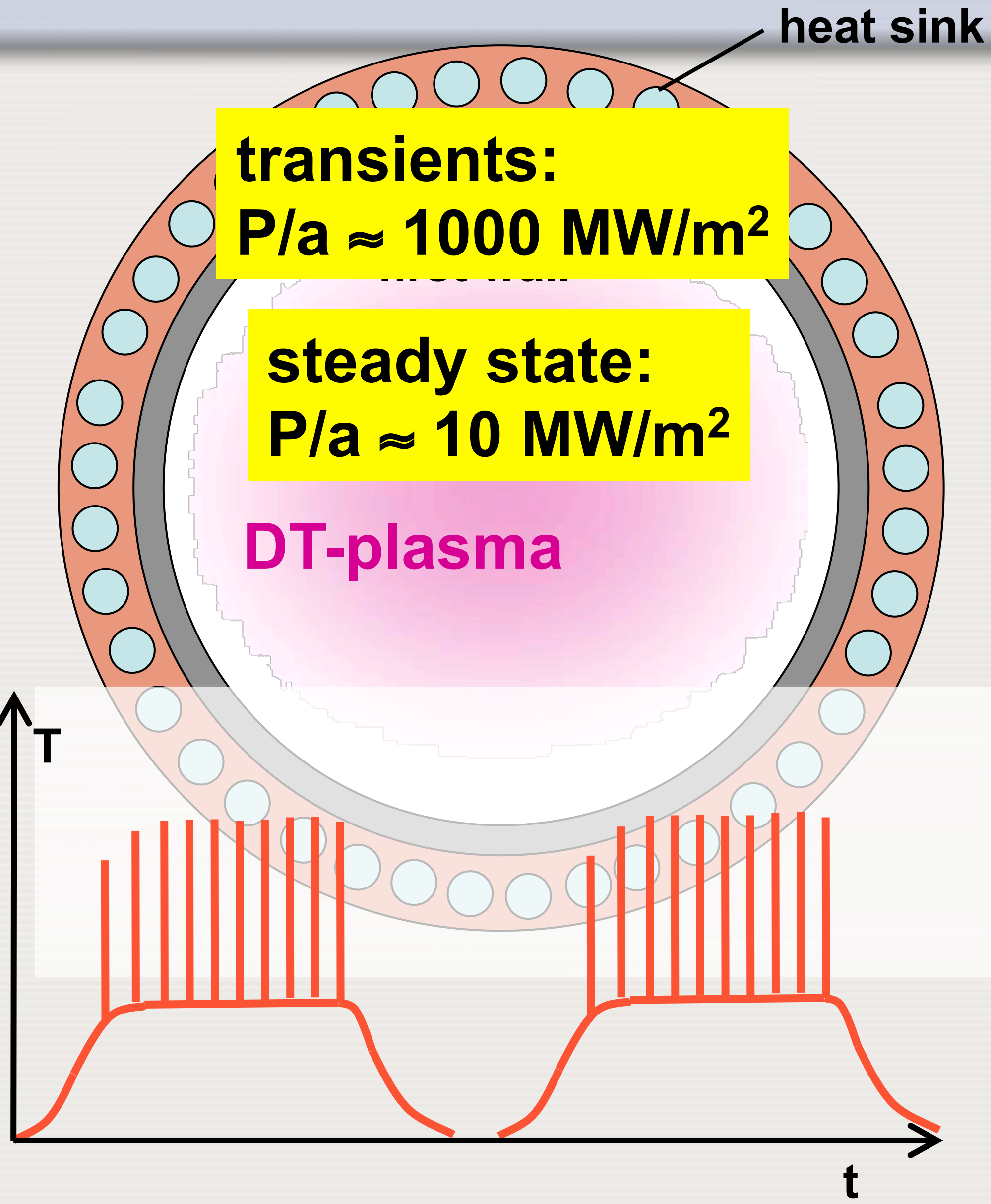
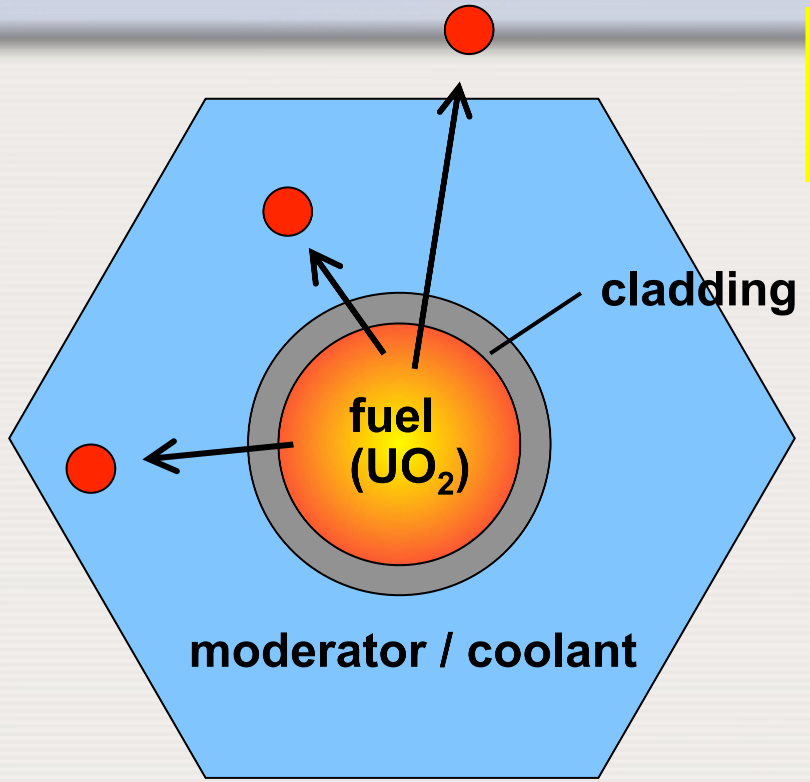
Fission Reactor



Fusion Reactor

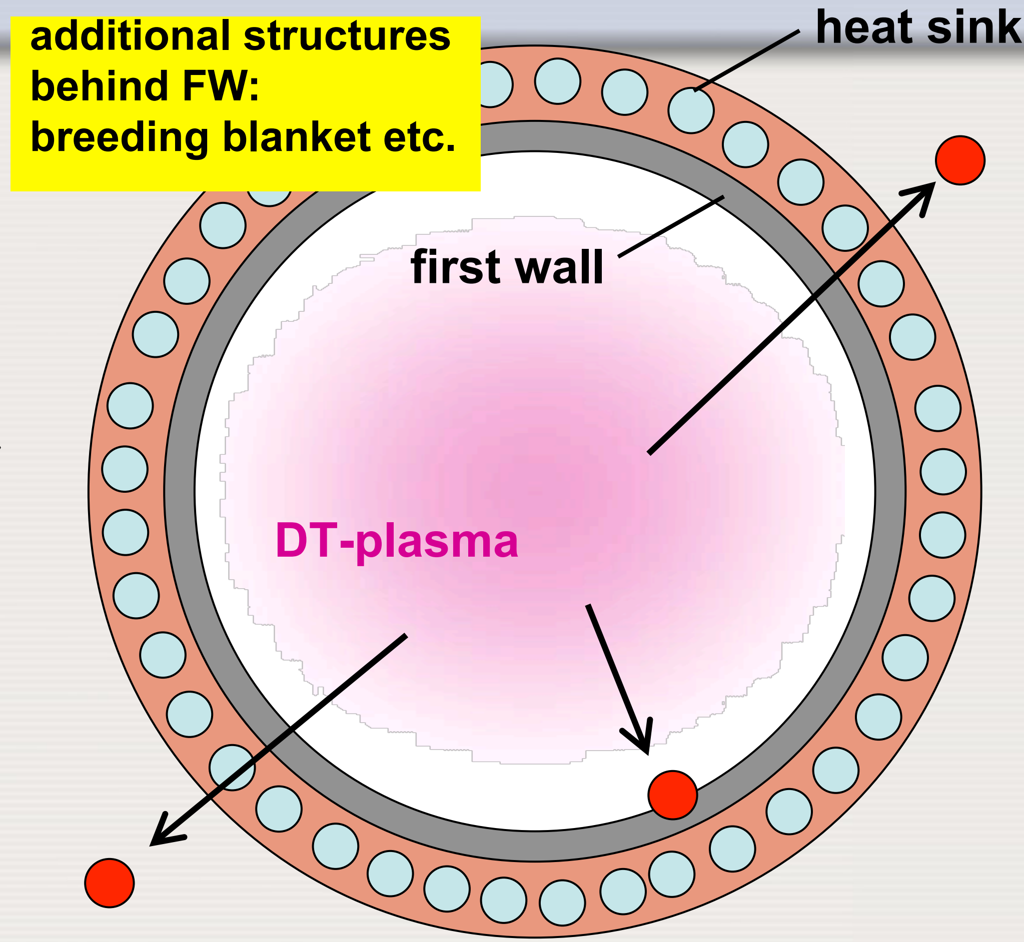


Fission Reactor



$\langle E_n \rangle = 2$ MeV

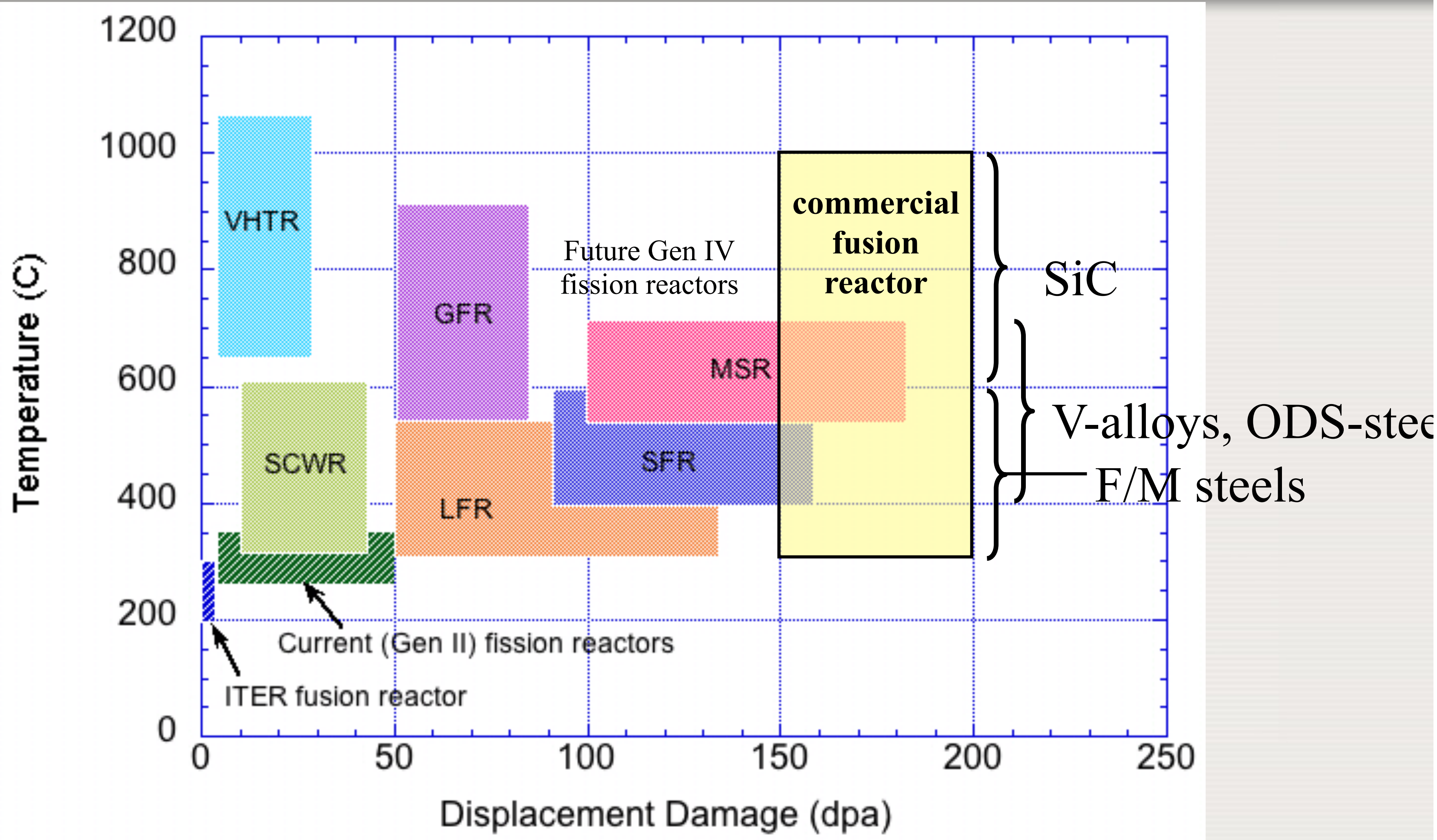
Fusion Reactor



$E_n = 14.1$ MeV

Material activation and degradation by energetic neutrons

Structural materials in different reactor environments



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

ITER Will Not Make Significant Contributions in a Number of Key Areas(1)

- Tritium breeding and fuel cycle, including steady state pumping and tritium residence time
- Irradiation of materials with a neutron spectrum corresponding to the first wall to damage levels relevant to FOAK (or DEMOs)
- Demonstration of required reliability and availability of the various subsystems, in particular HCD, pellet fueling and remote maintenance
- Demonstration of FOAK conditions for plasma facing components (first wall, limiters and divertor), especially under off normal events such as disruptions and ELMs

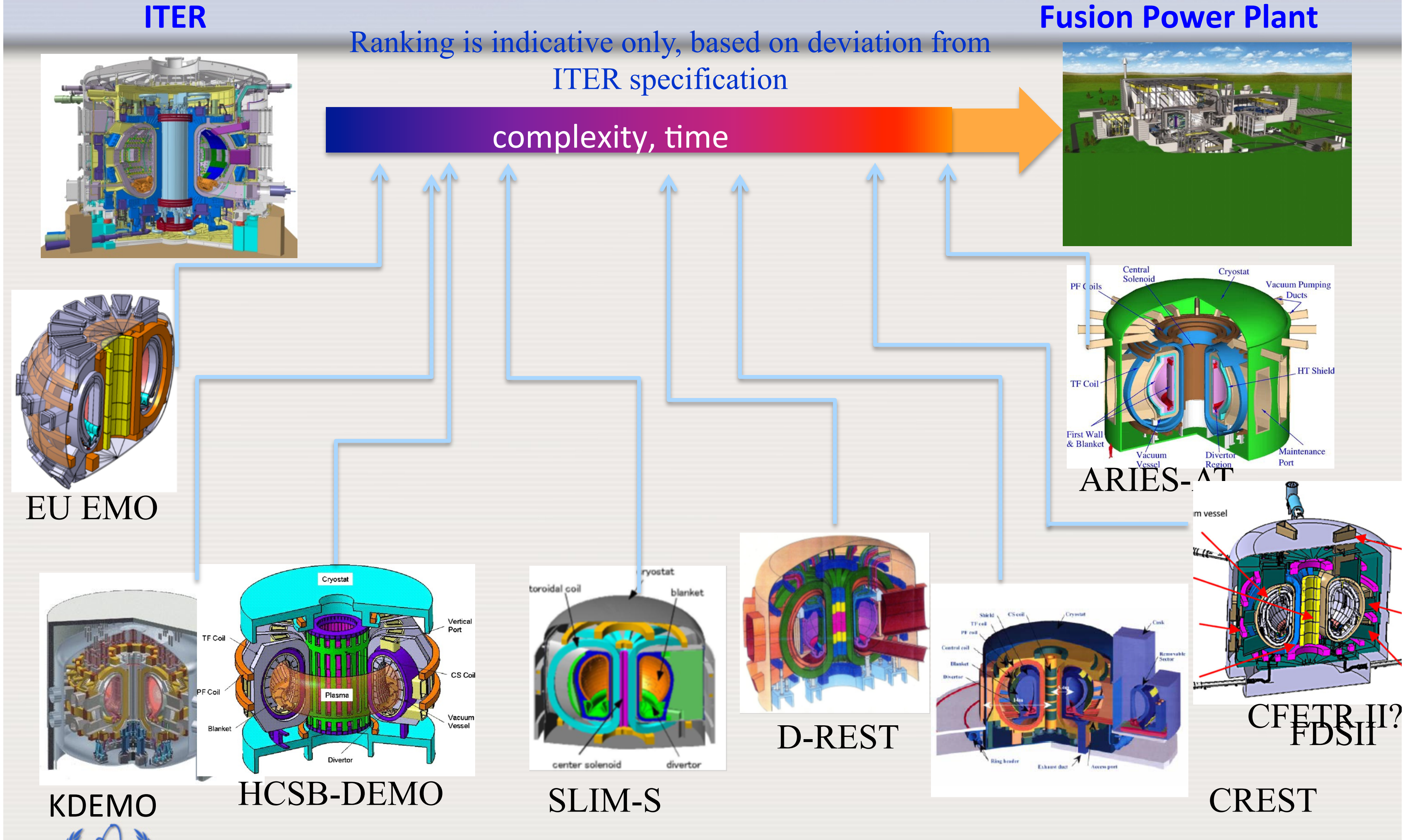
ITER Will Not Make Significant Contributions in a Number of Key Areas (2)

- The use of HTS magnets to reduce the size of the TF coils and/or to allow coolants other than LHe to be used, offering cost savings. In addition, it may be possible to create demountable magnets using HTS that would revolutionize RM and construction protocols.
- Demonstration of remote handling in highly active environments
- Development of material recycling and waste reduction technologies
- Operation at high β_N and density above N_G to identify stability limits and confinement scaling laws.
- Transport of fuelling pellets through the hot breeding blanket i.e. thermal isolation of the pellet flight tube

Mission and Performance Goals of Planned Next-Step Integrated Fusion Devices

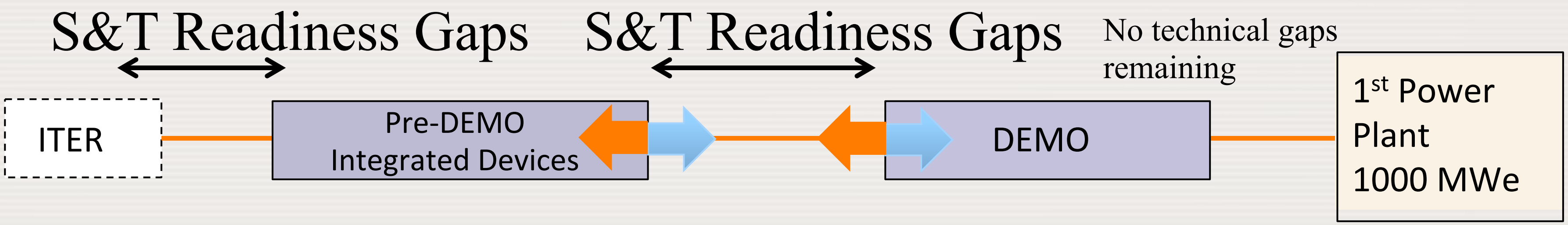
	EU DEMO	JA DEMO	K-DEMO	CFETR (Phase I)
Mission	Net electricity (Q_{eng} > 1) Tritium self-sufficiency	Net electricity (Q_{eng} > 1) Tritium self-sufficiency	Net electricity (Q_{eng} > 1) Tritium self-sufficiency Materials & component testing in fusion environment	Materials & component testing in fusion environment Full tritium fuel cycle
P_{fus}	2000 MW	1500 MW	≥ 300 MW	50-200 MW
TBR	> 1.0	> 1.05	> 1.0	≥ 1.0
Pulse length	2 hrs	2 hrs to Steady State	Steady State	1000 s to Steady State
Duty factor	~ 70%			30-50%
P_{elec}	500 MW	200-300 MW (net)	≥ 150 MW (net)	N/A
Tritium breeding	To be determined – solid and LiPb breeder under consideration	Solid breeder, PWR technology	Solid breeder, PWR technology	Solid breeder, PWR technology, close tritium cycle at ~ 1/10 DEMO scale
Magnetic configuration	Tokamak	Tokamak	Tokamak	Tokamak
Maintenance	Remote handling	Remote handling	Remote handling	Remote handling

DEMO Specification



Current National Plans Beyond ITER

- The set of DEMO machines now being considered world-wide* span an interesting range in technical readiness, risks, mission goals, and envisioned schedules.
  *Includes CFETR, K-DEMO, EU DEMO, U.S. FNSF,…



The Need for International Collaboration

Some widely acknowledged facts:

- for early fission power plants multiple versions of multiple designs were developed
- most of these were not economic power plants
- national government support ($) and public acceptance

Fusion will have to:

- demonstrate large societal benefits to gain public acceptance
- demonstrate better long term economics than rivals to gain national support of larger capital costs

Why should fusion achieve this in a smaller number of steps than fission given that the plant is inherently more complex, the power source less stable and predictable and the engineering problems greater?

It is unlikely that a single nation will repeat the fission experience for fusion,
so how can fusion power be achieved?

How can magnetic fusion be achieved?

- To formulate a strategy that will answer this question, it is first necessary to establish the **technical gaps** that exist now and that will remain following the operation of the ITER experiment
- Anticipated timescales for developing the technologies to fill these gaps can then be used to formulate a **technical roadmap** giving a possible **duration** and **structure** to the FOAK programme
    - Duration => Elapsed time relationships
    - Structure => Programmatic relationships

Why a Technical Roadmap Independent of Existing National Programmes?

- To inform understanding of the programme requirements for commercial D-T fusion power, based on magnetically confined devices, to become a reality
- To identify programmatic and elapsed time relationships between individual elements
- To enable analysis of critical external influences such as world tritium supply
- To provide **sound basis for a coordinated approach** from the whole fusion community

Roadmap Characteristics

- The Roadmap attempts to capture the processes necessary to develop a FOAK and is not related to any particular design
- Hence it represents a generalised view of the R&D programme
- For this reason the Roadmap shows only elapsed time, it is not fixed to a particular national programme or proposed development schedule
- It indicates the shortest time for realisation of a FOAK that might reasonably be anticipated

Roadmap timescales

- At present the critical path to a FOAK appears finely balanced between engineering validation of irradiated materials and operational understanding of the burning plasma
- The elapsed timescale has been evaluated from the known time to irradiate, test and qualify structural materials based on some assumptions.

Opportunity For a Strategy Towards FOAK

- There are a range of proposed DEMO designs of varying complexity
- At first approach, it seems they can be ordered in a consistent manner in terms of development and enabling requirements
- Can this be exploited by the international fusion community to solve the multiple development machine problem?

Some caveats that have to be considered:

- the electricity generating performance of a given machine is largely determined by the engineering design – operating temperature, BoP, heating systems, magnets, etc.
- it is feasible to change blanket & divertor design in a phased approach but probably not BoP
- no single machine will solve all the problems simultaneously

Rationale For a Strategy towards FOAK

- The Roadmap is expressed in terms of elapsed time as it is dependent upon the availability of a relevant neutron irradiation source
- At present this is an unknown but assuming such a facility is available in the 2020 decade the Roadmap shows that there is a coincidence between the timescales of proposed DEMO programmes in China, Korea and EU and the phase for testing of tritium breeding blankets and divertors under combined nuclear loads for the FOAK.
- Thus if the FOAK programme were to be an international effort, an opportunity may exist for these DEMO programmes to represent the testing facilities necessary. Coordination would be needed to avoid unnecessary duplication and sufficient variety of designs could be tested

Thank you for your attention

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