Divertor Design Considerations for China Engineering Experimental Fusion Reactors

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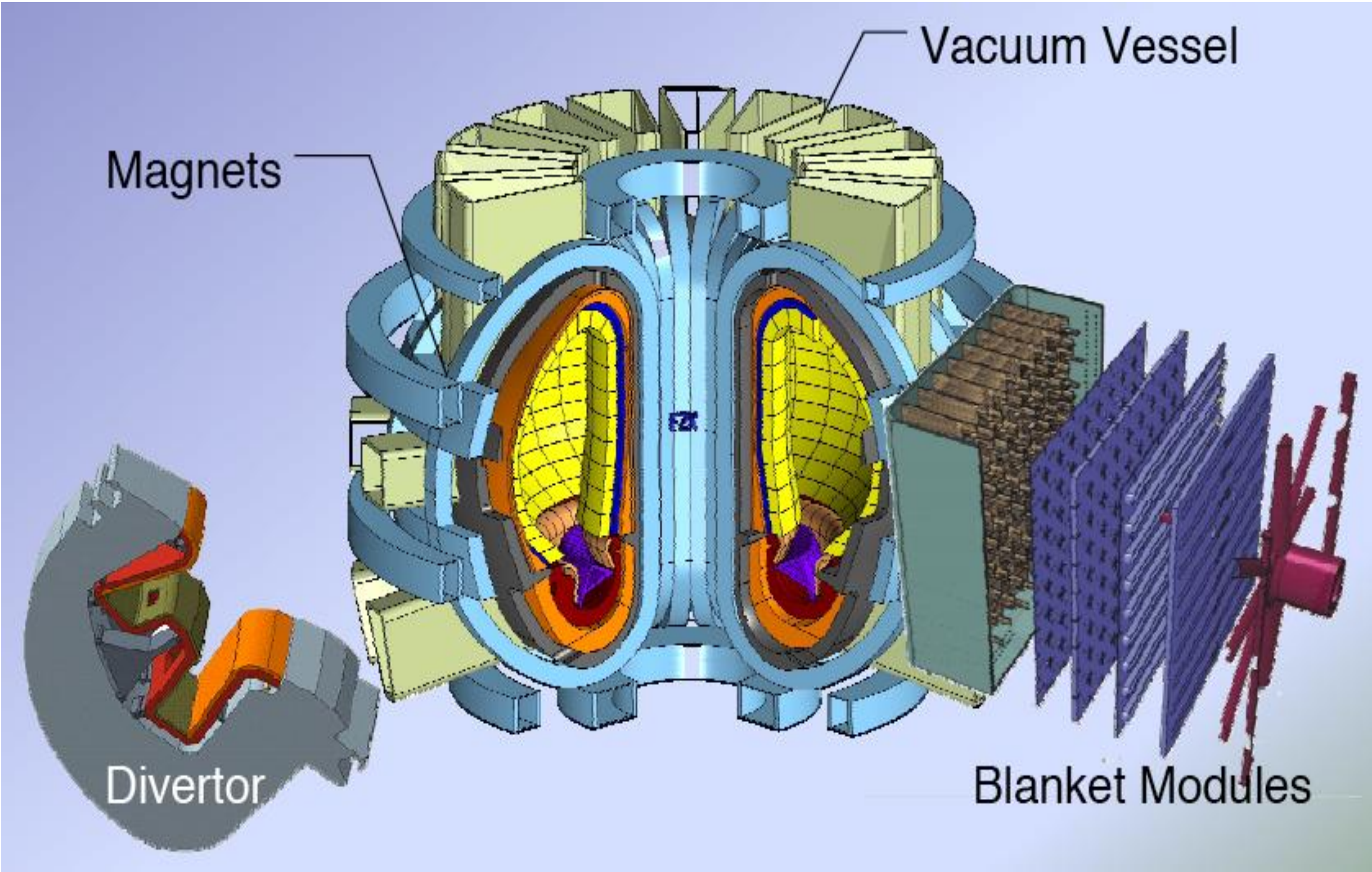
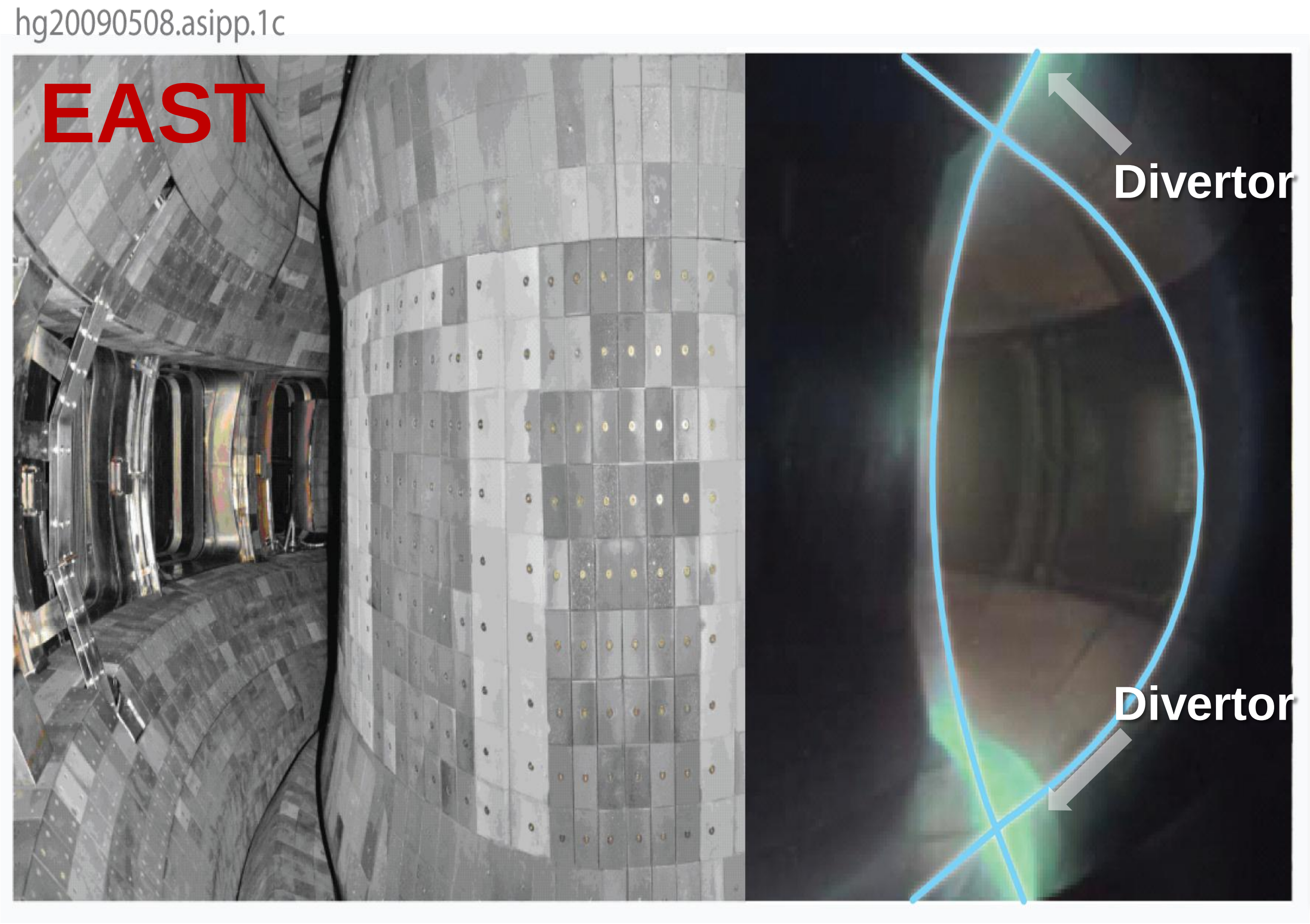
Divertor Is a Key Component of Fusion Reactors



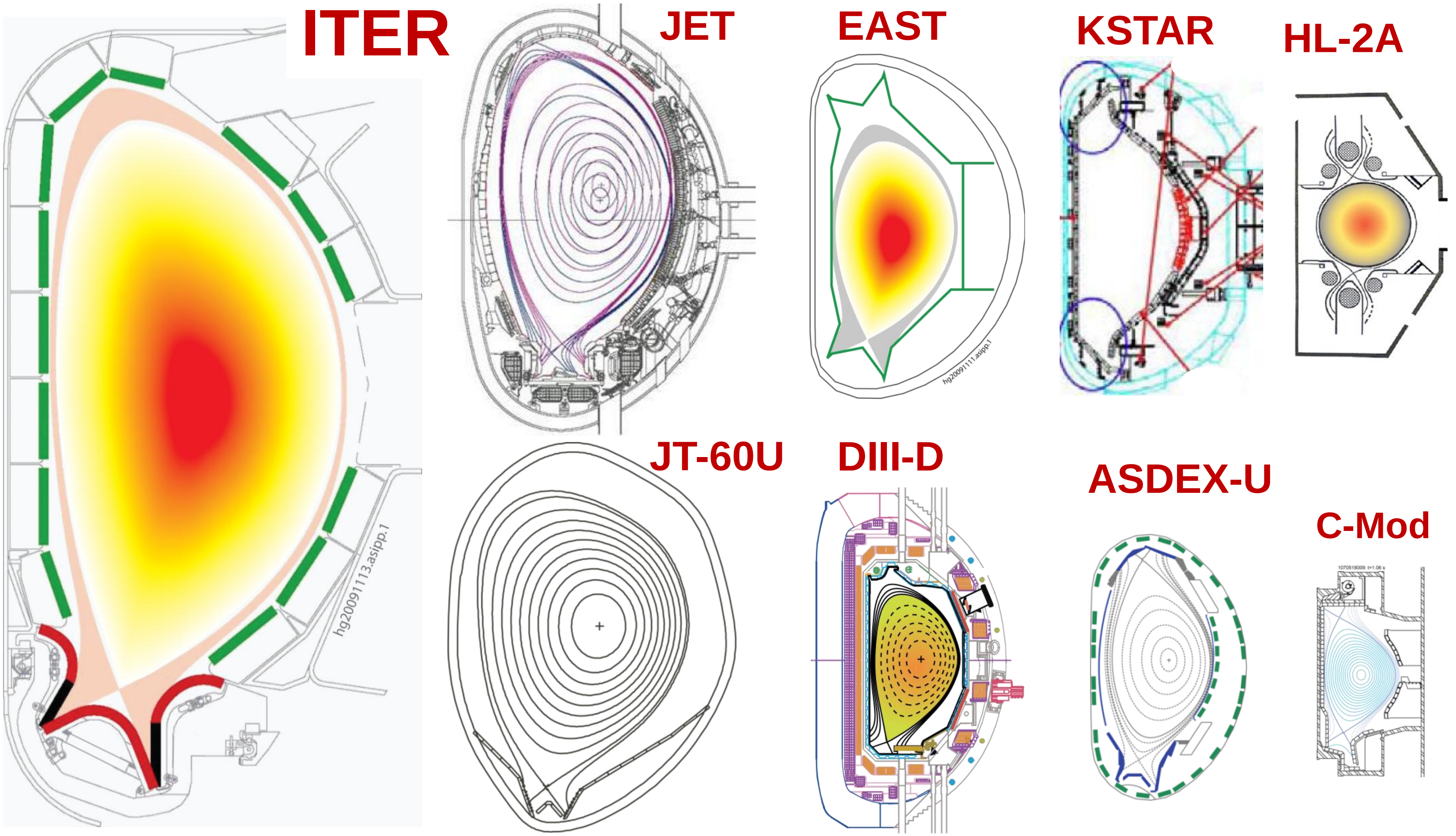
Principal Functions of Divertors



- Provide effective screening for impurities from plasma facing components
- Exhaust particle and energy fluxes from core plasma
- Remove He ash

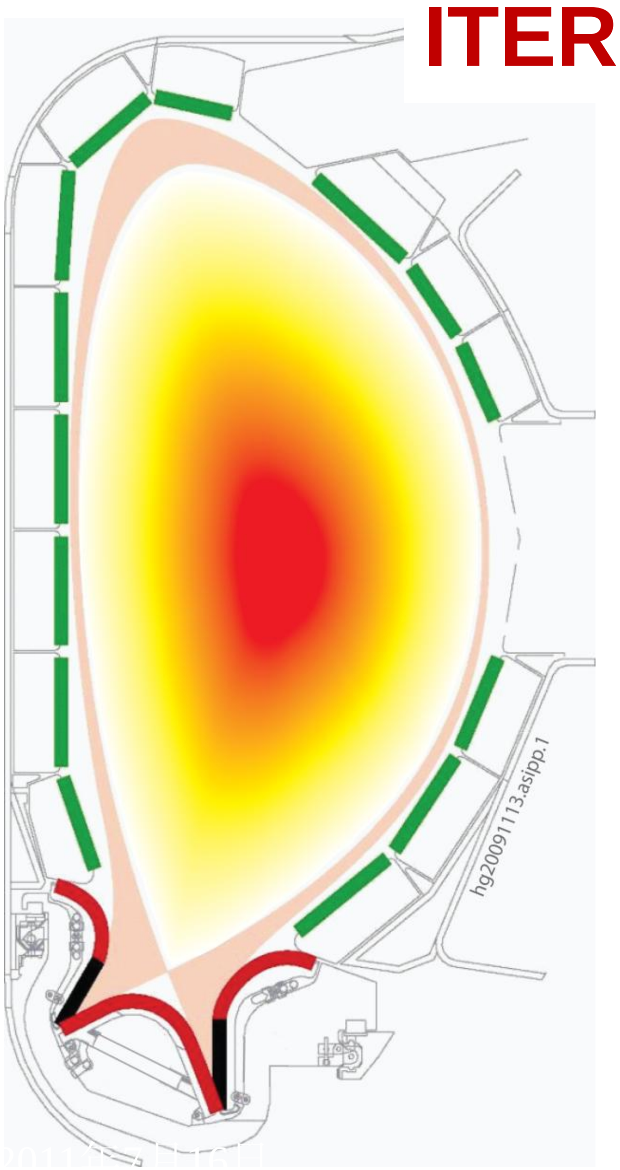
Divertor provides an intermediate boundary zone between hot plasma (>100 million °C) and solid materials.

Divertor Configuration Is Essential for Advanced Tokamak Operations



Means to Control Plasma Boundary for ITER

Limiter	→	Star up ramp-down
Poloidal Div.	→	High power steady state
Ergodic Div.	→	ELM Control

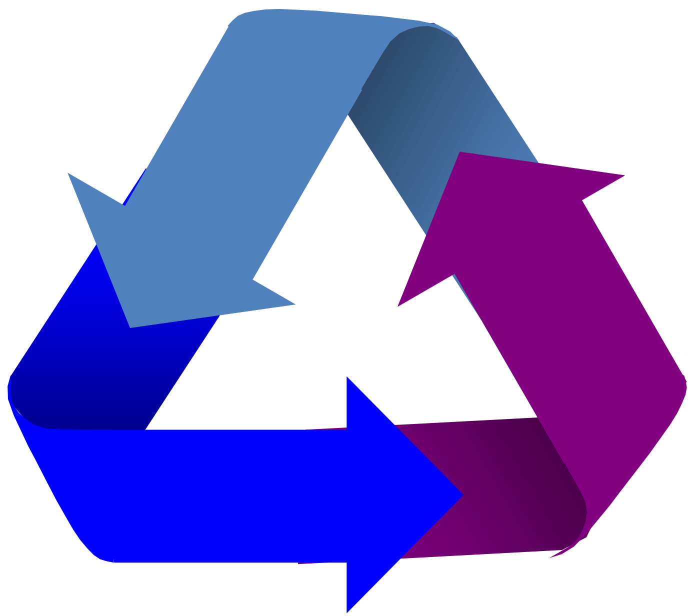


Present Status of Divertor/Edge Physics

- Significant progress has been made over the past decade in divertor and edge physics. Despite this progress, the basic processes that determine the local spatial scale lengths, and the heat and particle flow within the layer, are still not adequately understood.
- Hence, heat and particle loads on plasma facing components, impurity intrusion, and core fusion gain are difficult to predict, making **reactor design requirements and operational strategies uncertain.**

Divertor Design Must Satisfy Both Core Performance and Engineering Constraints

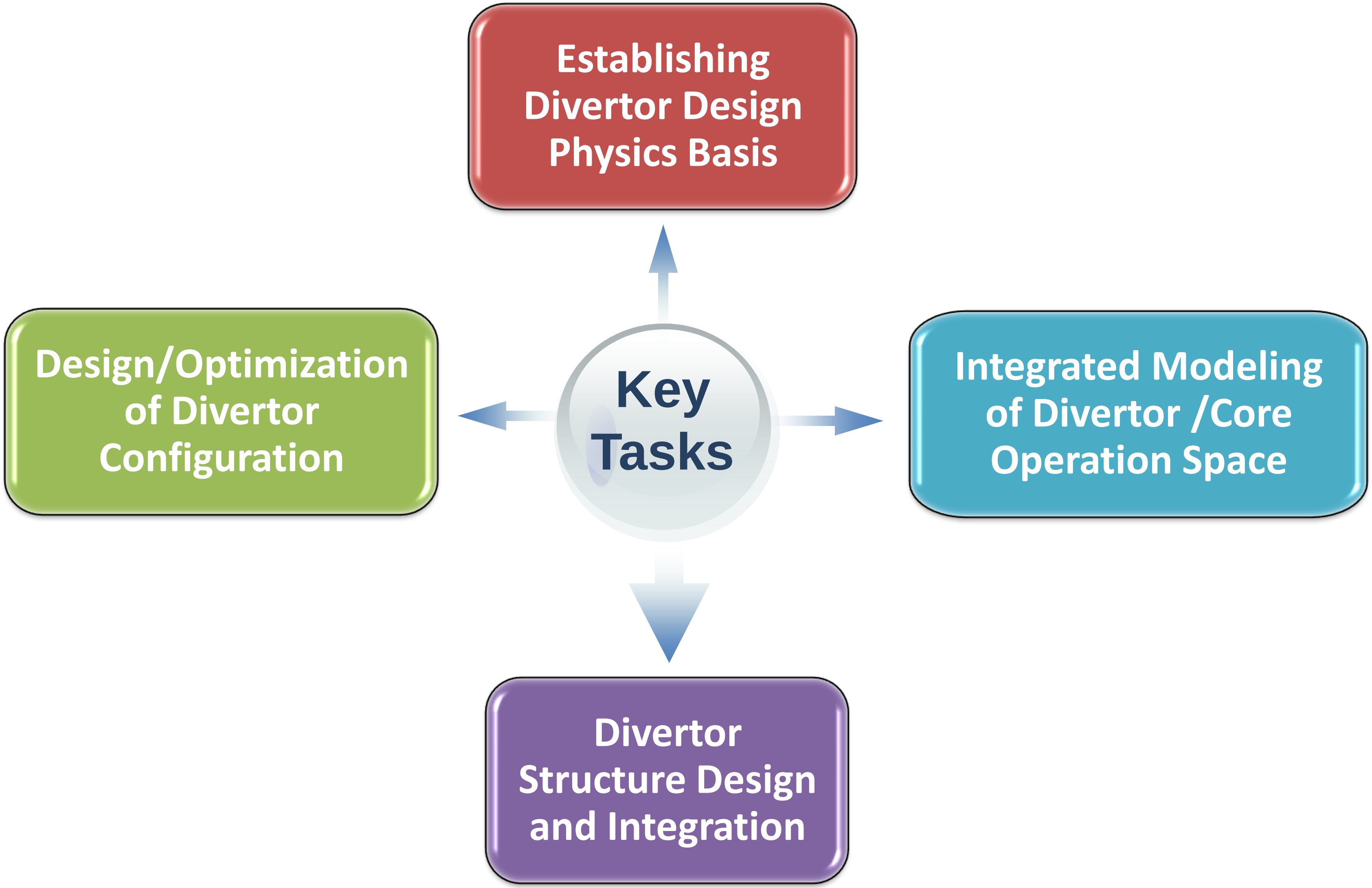
Exhaust Most Alpha Energy



Remove He Ash

Control Impurity Content

Approaches to Reactor Divertor Design



Task 1: Establish Divertor Design Physics Basis

- **Understand and absorb ITER physics and engineering design basis.**
- **Divertor design must be compatible with core plasma conditions ensuring necessary reactor performance. It must tolerate high heat loads while at the same time providing neutron shielding for vacuum vessel and magnets in the vicinity of the divertor.**
- **Although good progress has been made in the understanding of divertor and edge plasma physics, only a part of the physics controlling the boundary layer has yet been identified.**
- **The existing ITER design is predicted to have little margin for managing the plasma heat load, and higher-power devices will require substantially increased power exhaust requirements. ITER divertor allows only ~ 40% energy from core plasma。**

Thus, it is urgently needed to extend the current ITER design physics basis for the next-step China engineering experimental fusion reactor.

Need Effective Means for Controlling ELMs & Disruption to Ensure Reactor Lifetime & Integrity

- **ELMs are nearly ubiquitous in H-modes, driven by peeling-ballooning modes, acting to expel periodically particles and energy that build up in the pedestal region during the improved confinement phase between the ELMs.**

- **Disruptions occur less frequently than ELMs, but generate even greater peak power fluxes onto PFCs, typically one order of magnitude higher than ELMs.**

- **For steady-state operation, heat load is limited to ~10 MW/m^2 (up to 20 MW/m^2 during transients) for both CFC and W due to the technological feasibility for actively cooled structures.**

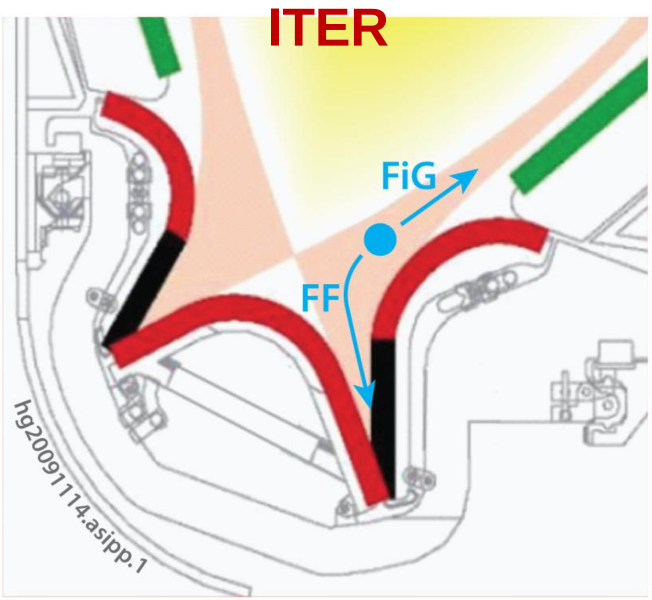
- **In addition, maximum energy due to ELMs cannot exceed ~0.5 MJ/m^2 in ~250 μs, due to surface damage by**
  - **Micro-cracking for tungsten**
  - **Fiber erosion for carbon fiber composites**

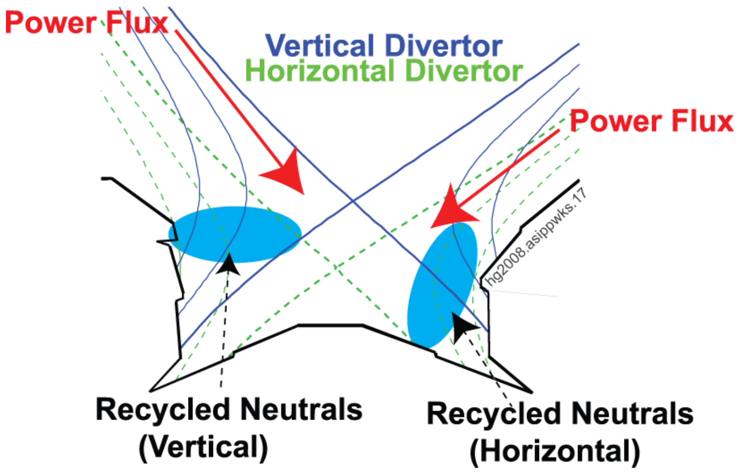
Possible Means for Controlling Steady-State and Transient Heat Fluxes

- **Steady-state power control**
  - **Radiative divertor：** effective at controlling steady-state energy deposition, but not transient heat fluxes from ELMs or disruptions.
- **ELM control**
  - **Pellet pacing:** Injecting H/D pellets to increase frequency, reduce size of Type-I ELMs.
  - **Resonant magnetic perturbation (RMP):** Distorting, and to a large extent ergodizing the edge magnetic field to suppress ELMs.
- **Disruption control**
  - **Disruption prediction:** Accurate prediction of an impending disruption is a key element of both avoidance and mitigation of disruptions and has not been demonstrated to date.
  - **Disruption mitigation by massive gas injection:** Removing plasma energy by radiation, and raising particle density to the level needed for collisional suppression of a runaway electron avalanche which is a remaining challenge.

Task 2: Design and Optimize Divertor Configuration

- **Use SOLPS-B2/Eriene, which was used as a basic tool for ITER divertor design.**
- **Adopt ITER-like vertical target structure, which exhibits the following key features:**
  - ✓ *Improve divertor pumping efficiency* due to intrinsically enhanced divertor closure for neutrals.
  - ✓ *Reduce peak heat load on the divertor target plates* due to preferential ionization of neutrals near strike points, hence
  - ✓ *Promote partial detachment near the strike points.*



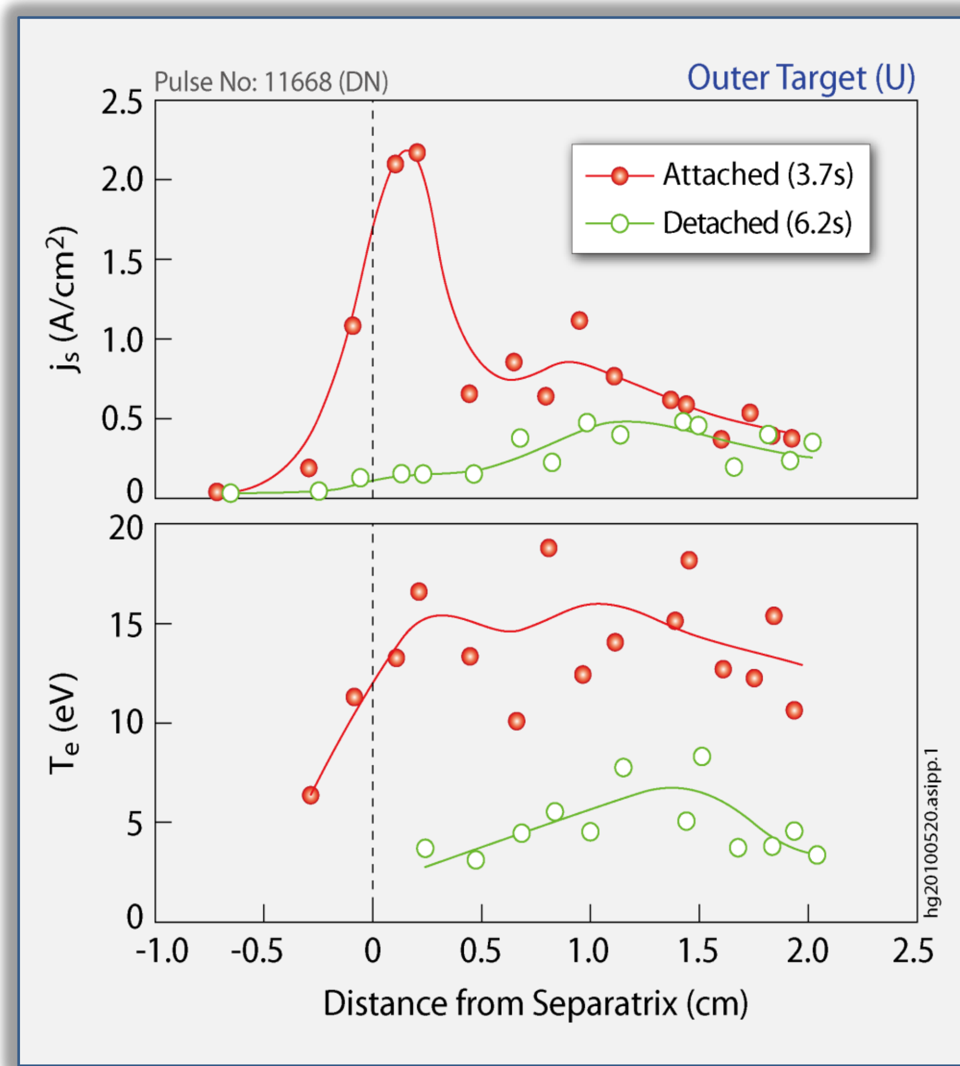


Most Significant Advantage of Vertical Target:
Preferential Detachment at Strike Point

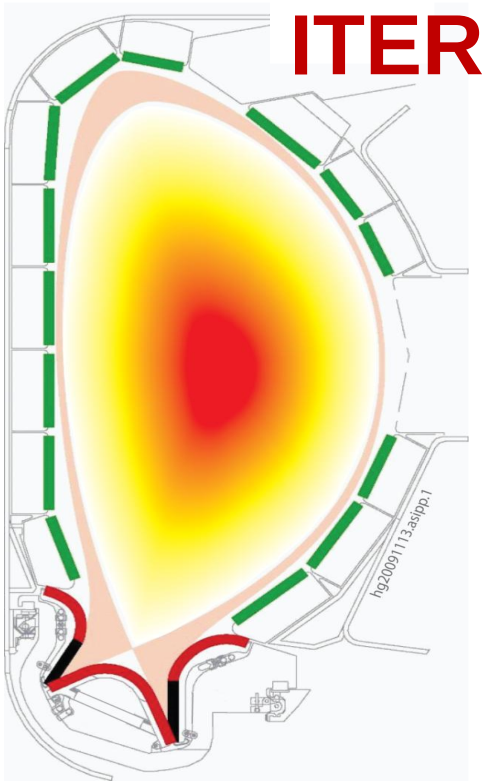
- **Detachment occurs near separatrix, with far SOL still attached to reduce peak heat flux and ensure adequate pumping.**
- **In contrast, horizontal target operation leads to preferential detachment in the far SOL.**
- **Thus, vertical target configuration addresses the issue with target heat load, also facilitates He ash removal.**

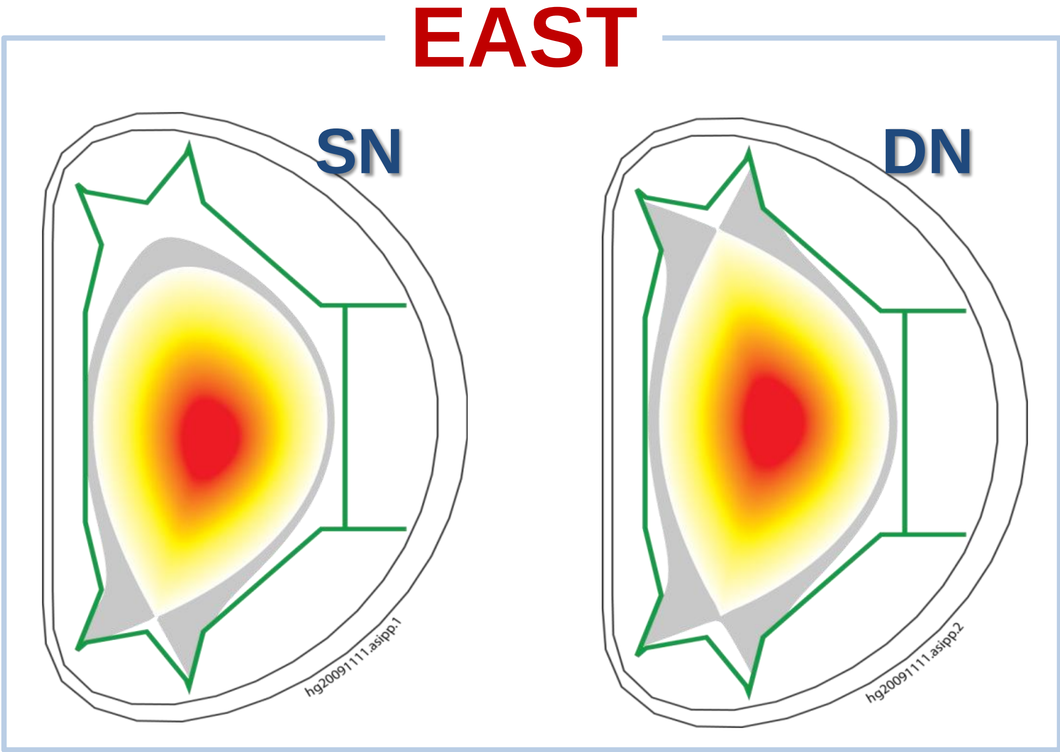
This is what a fusion reactor needs!

EAST



Other Considerations





- **Single null (SN) or double null (DN)?**
  - **SN makes better use of vessel volume, mitigates in-out divertor asymmetry.**
  - **DN allows naturally high triangularity, facilitating advanced operation.**
- **Other configurations?**
  - **e.g., snowflake configuration, to further reduce divertor heat load.**

Task 3: Explore Overall Divertor Operation Space

- **Use SOLPS, coupled with impurity transport code DIVIMP and PSI codes EDDY/ERO , to investigate material migration, erosion/redeposition, heat load etc., and their effects on reactor lifetime.**

- **Couple with core transport code ONETWO, to explore overall operation space, and look into**
  - **Absorption of LHW in the SOL**
  - **Scattering of RFW by blob-filaments**
  - **Interaction of SOL with MHD instabilities (tearing mode, RWM), etc.**

- **Use BOUT (3D fluid turbulence code) to further investigate edge turbulence transport and its effect on divertor operation space.**

Also Need to Look into Core Physics and Engineering Constraints

- Divertor plasma must be compatible with core plasma conditions to ensure the necessary reactor performance:
  - Edge and core densities are highly related; core density is limited by Greenwald limit. Edge fuelling must be sufficient to maintain density pedestal without affecting core confinement.
  - He content in core plasma, limited by fuel dilution.
  - Zeff, limited by the acceptable impurity radiation and fuel dilution.
- Divertor plasma must be compatible with various technological requirements:
  - Peak heat load, limited by the PFC thermodynamic proporties (20 MW/m^2 is the maximum limit and 10 MW/m^2 or less is desirable).
  - DT exhaust capability, limited by the capacity of the pumping and tritium processing facility and tritium inventory considerations.
  - Reactor lifetime, limited by wall and target erosion, etc.

Task 4: Divertor Structure Design and Integration

- **Divertor Target：** **Strong interactions with plasma, directly affecting reactor lifetime.**
- **Divertor Cassette：** **Provide a mechanical support for plasma interface components, and neutron shielding for magnetics and cooling system.**
- **Divertor puming system：** **Exhaust He ash, control density and core impurity content, essential for steady-state operation.**
- **Fuelling system：** **Sustain plasma density, also useful for heat flux control, e.g., by divertor puffing.**
- **Cooling system：** **Remove peak heat load. Hot wall operation with gas cooling seems to be vital to fusion's success, for**
  - **Tritium recovery, suppression of retention in codeposits.**
  - **Walls and particles in equilibrium**
  - **Annealing of neutron damage**

However, no one, including ITER, is pursing this.

Summary

Make use of ITER physics and engineering design basis, and new relevant resources, both domestic and international, to complete, in three years, the design of the divertor systems of two engineering fusion reactors, which satisfy both the core fusion performance requirements, and also divertor target heat load and material thermodynamic constraints.