Lehigh University
Rossin College of Engineering & Applied Science
Mechanical Engineering & Mechanics
Nuclear-Fusion Plasma Control Laboratory

Control-Oriented Core-SOL-Divertor Model for Integrated Burn and Divertor Control in ITER

Vincent Graber and Eugenio Schuster

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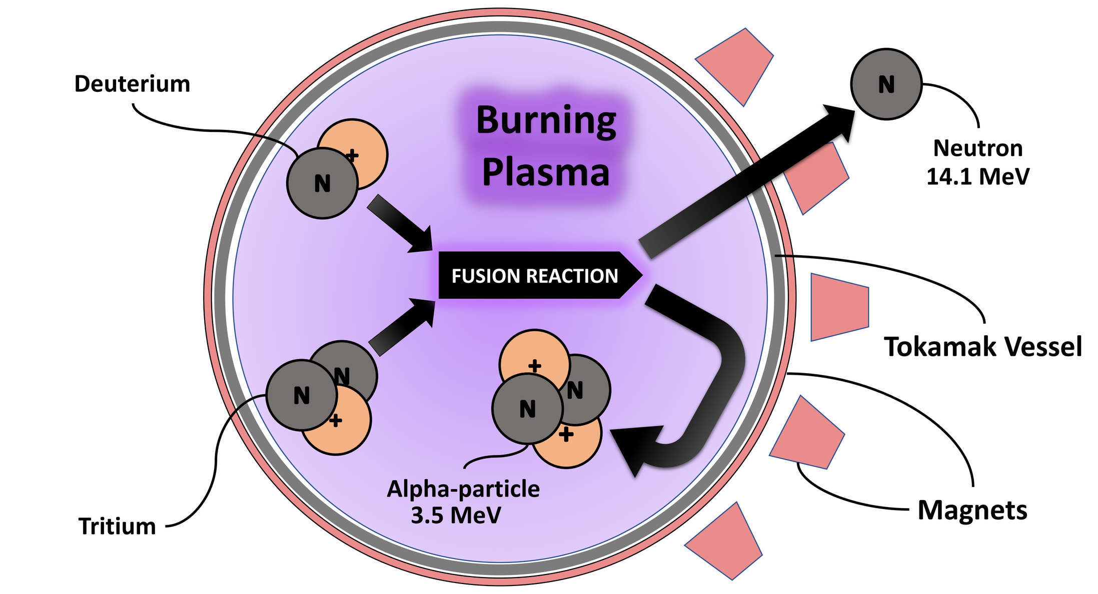
Background on Nuclear Fusion and Burn Control

A tokamak is a toroidally-shaped device that magnetically confines a plasma (hot gas of ions) and brings it to 100 million degrees where fusion reactions can occur. In a DT fusion reaction, deuterium (D) and tritium (T) combine into an energetic alpha-particle (α). Due to the alpha-particle's charge, it is magnetically confined inside the plasma and its kinetic energy heats the plasma. A neutron is also a product of the DT fusion reaction. This chargeless particle escapes the tokamak's magnetic confinement, and its kinetic energy can be harnessed to generate electricity. ITER will be the first tokamak designed to operate fusion-producing plasmas (known as burning plasmas) that output ten times more power than the power put into it.



The objective of burn control is to regulate a burning plasma's temperature and density. The plasma can be controlled using various auxiliary heating systems (e.g., neutral beam heating) and fueling systems (e.g., pellet injection). Controlling the core plasma is made more challenging due to its sensitivity to conditions in the edge plasma. The edge plasma begins with a region called the scrape-off-layer (SOL) that surrounds the core. Lots of heat and particles from the core flow through the SOL into the target plates inside the divertor. Mitigating the heat load delivered to the target plates in order to prevent melting is an important divertor control objective. Gas puffing and particle pumping can add or remove particles in the plasma region near the divertor (called the divertor plasma). This work presents a coupled model of the core, SOL and divertor plasmas that is used to study the operational limits in ITER through Plasma Operation CONtour (POPCON) analysis.

Introduction to The Core-SOL-Divertor Model

Core Chamber:

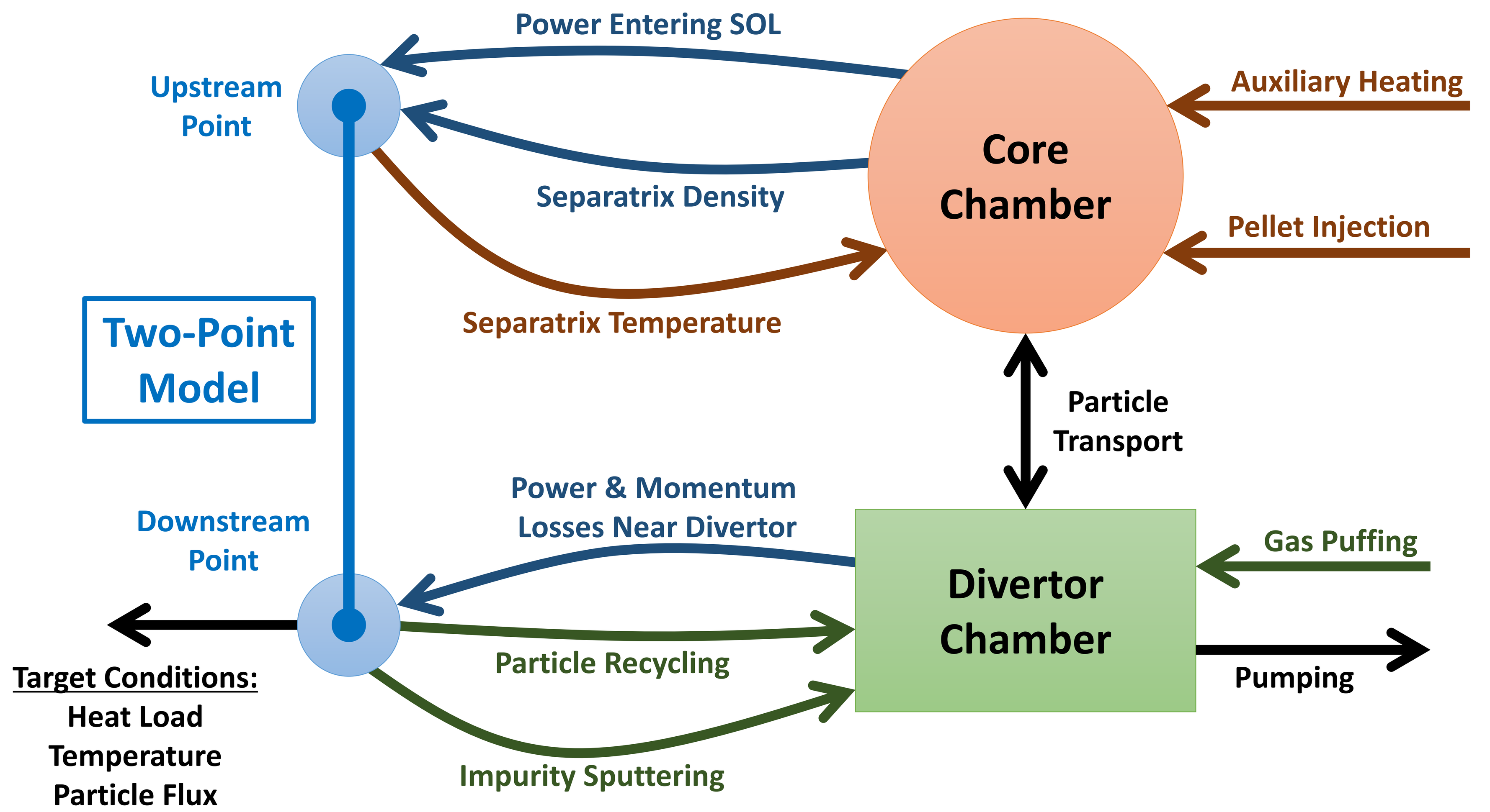
- Responsible for DT fusion power production
- Particle outflow to the Divertor Chamber
- Actuators: Pellet Injection and Auxiliary Heating

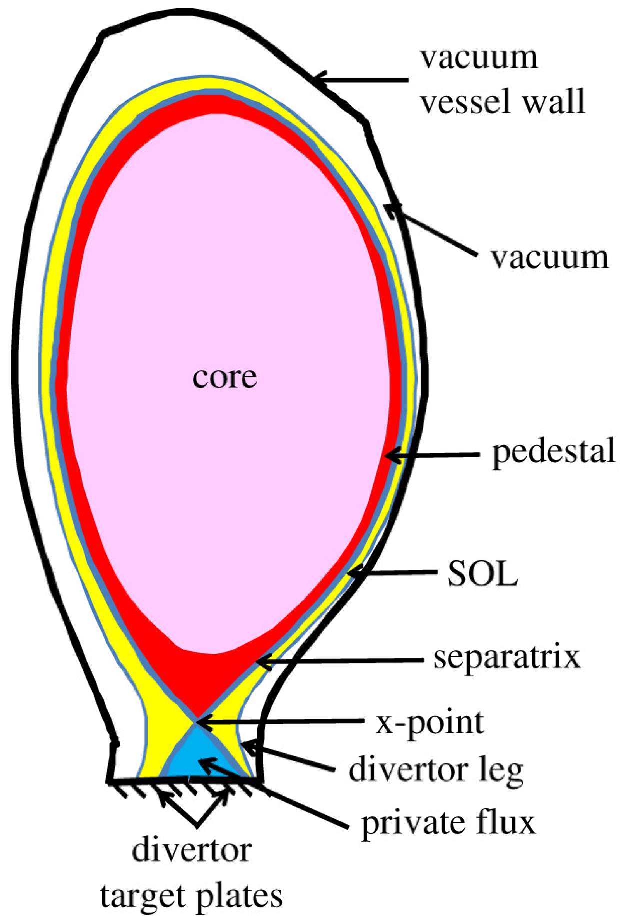
Divertor Chamber:

- Divertor neutral-particle balance equations
- Particle outflow to the Core Chamber
- Actuators: Gas Puffing and Particle Pumping

Two-Point Model:

- Describes SOL by connecting upstream conditions (near core plasma) with downstream conditions (near divertor targets)
- Plasma-wall interactions, such as DT recycling and impurity sputtering, send particles to Divertor Chamber which can leak into Core Chamber
- Regulated by Core Chamber's density & power





Source for Illustration of Plasma Regions: H. Wilson, *The Impact of Plasma Physics on the Timescale to a Tokamak Fusion Power Plant*. Phil. Trans. R. Soc., 2019.

Core & Divertor Chambers

Energy equation governing Core Chamber:

$$\frac{d}{dt}\left[\frac{3}{2}n\langle T\rangle\right] = -\frac{3n\langle T\rangle}{2\tau_E} + \sum P_j$$

Temperature profiles ($\langle T\rangle$ is volume average) depends on central T_0 & edge T_u temperatures:

$$T(t,\psi) = (T_0 - T_u)(1-\psi/\psi_0)^2 + T_u$$

ψ : radial coordinate, n : plasma density
P_j : power sources/sinks, τ_E : confinement time

Particle Balances in Core & Divertor Chambers:

$$\dot{n}_{core} = -\phi_+ + \gamma\phi_D + \phi_{pell} \pm \phi_\alpha$$
$$\dot{n}_{div} = \phi_+ - \gamma\phi_D - \phi_{pump} + \phi_{puff} + \phi_{wall}$$

ϕ_+ is ionic outflow from core to SOL/divertor
$\gamma\phi_D$ is fueling rate from divertor to core plasma
ϕ_{pell} is the core fueling from pellet injection
ϕ_α is fusion source/sink for DT/alpha-particles
ϕ_{pump} is the pumping exhaust sink in divertor
ϕ_{puff} is the edge fueling from gas puffing
ϕ_{wall} is the recycling/sputtering source

Two-Point Model (SOL)

The Two-Point Model of the SOL relates upstream conditions (u) near to the core to downstream conditions (t) at the target. Particle, pressure and power balances along the SOL give:

$$2n_t T_t = f_{mom} n_u T_u,$$
$$T_u^{7/2} = T_t^{7/2} + \frac{7}{2}\frac{f_{cond} q_\parallel L}{\kappa_0},$$
$$(1-f_{pow})q_\parallel = \gamma_s n_t T_t c_{st},$$

where n_t and T_t are the downstream density and temperature, $q_\parallel$ is the parallel power flux density, and f_{cond}, f_{mom} and f_{pow} are correction factors for conduction, momentum and power losses. The two-point model can be written in terms of $n_u = n_{core}$ and P_{SOL}. The power entering the SOL, P_{SOL}, is equivalent to total power in the core. The DT recycling and impurity sputtering sources from wall effects ϕ_{wall} can be computed. Finally, the heat load on the divertor can be determined for divertor control [1].

[1] P. Stangeby, *The Plasma Boundary of Magnetic Fusion Devices*. Bristol: IOP, 2000.

POPCON Analysis for ITER Operation

The presented Core-SOL-Divertor Model can be used to study the steady-state operational space of ITER through the creation of Plasma Operation CONtour (POPCON) plots. POPCONs are generated by solving the system of dynamic equations for the core plasma in steady-state simultaneously with the static two-point model equations*. The results are plotted in density(n_e)-temperature(T_e) space (for the electrons specifically). In the POPCON below, the black contour lines show the fusion power output (MW) of a plasma with a certain set of conditions.

Listed in the legend below, the operational constraints for ITER are maximum auxiliary power injection, the maximum fueling rate from the two pellet injectors (one with 10%D-90%T pellets and the other with 100%D pellets), the H-mode power threshold (H-mode is a plasma regime with improved energy and particle confinement), the maximum allowable divertor heat load, and the maintenance of divertor detachment (attaining this "divertor regime" helps reduce power and ion fluxes on the target plates).

The light green area of the POPCON defines the ITER operational zone where all of the aforementioned operational constraints are met. The POPCON shows that fusion powers exceeding 700 MW are accessible.

*For brevity, not all of the equations used to generate the POPCON were included in this poster.