Development and Validation of a Boundary Plasma Model

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DEMO Heat flux control issues

The DEMO divertor must be designed to control the steady state heat flux to the target plates to a tolerable level, ≤ 10 MWm^{-2}. At the same time the edge pedestal must remain robust to maintain adequate confinement in the core plasma.

Divertor optimization techniques: for heat flux control include

1. **Magnetic Configuration:** Includes a choice between a single-null or double-null configuration, divertor volume through divertor leg length, locating the targets at large major radius and poloidal flux expansion. Large variations of these latter parameters can be achieved through utilization of the Super-X and Snowflake divertor geometries.

2. **Divertor surface geometry:** These options include tilting the divertor target with respect to the field line for more surface area and divertor baffling to keep radiating divertor conditions from degrading core confinement.

3. **Fuel and impurity particle control**: May be used for dissipating the divertor heat flux through radiation.

A boundary plasma model is required to optimize the divertor solution for DEMO utilizing the techniques outlined above. This model should be comprised of:

1. **Empirical scaling and fundamental theory:** varying degrees of each but it must be benchmarked and validated with experimental measurements.

2. **Plasma transport:** both parallel and perpendicular transport of particles and energy, not only the steady state average value but also the short time scale features.

3. **Kinetic effects and cross-field:** Important for plasma transport

4. **Atomic physics:** Radiation, ionization, recombination and charge-exchange processes

5. **All species:** Including electrons, ions, impurities and neutrals.

6. **Surface boundary conditions:** Including recycling, sputtering and redeposition. Though not part of the plasma, an important boundary condition.

7. **Compatibility with core plasma:** A robust pedestal which could be degraded by such factors as high separatrix and X-point density, MARFEs and low power flux across the separatrix. A boundary plasma solution should also be compatible with a number of characteristics associated with advanced tokamak operation including high beta and steady state non-inductive operation.

8. Comprehensive: The physics listed above is tightly coupled so it must be embodied in a single model, not a series of codes.

Boundary model development and validation requirements

Experimental facilities are required to develop the empirical scaling, test theory and validate the overall model performance. The experimental facilities will require flexible configuration and geometry, cover a wide range of experimental plasma parameters and most importantly employ an extensive diagnostic set.

Configuration flexibility The experimental facilities will need to access a wide range of configurations and parameters including:

1. Magnetic configuration Single and double null configurations as well as a wide range of divertor volume. These include the Super-X and Snowflake divertor configurations.

2. Divertor structure geometry Divertor baffling, from open to closed, along with variations of neutral particle pumping will need to be accessed. An open device that allows for easy access and installation of hardware would likely be the most appropriate for these kinds of configuration studies. The total variety of configuration and geometry could be addressed across several devices.

Access to a wide range of plasma parameters The underlying physics, or scaling, of the model must be tested over as wide a range as possible to provide confidence in scaling to DEMO.

1. Divertor and SOL parameters include density (and inversely temperature) of the divertor and SOL, neutral densities, power flow into the SOL and impurity levels (intrinsic and introduced) for radiation and detachment.

2. Core plasma parameters Access to advanced tokamak modes of operation are also needed, including a robust pedestal, ELM suppression, high beta and non-inductive current drive scenarios.

Extensive diagnostic set is required to examine the scaling laws and physics of the boundary model. Measurements beyond the diagnostic sets on current devices include:

1. Extensive implementation on a single device, in order to measure various effects that can obscure the physical process, or scaling, that is being examined.

2. 2D measurements. The boundary plasma constitutes a complex pattern of densities, temperatures, fluctuations and flows, that changes significantly with control parameters. Measurement in limited locations is insufficient to characterize the system. The 2D data can be acquired by scaling up existing diagnostic techniques to many measurement locations, or by developing innovative imaging techniques.

3. Ion temperature. Now only measured in the far SOL and needs to be extended throughout the boundary plasma. Non-Maxwellian features of the electron and ion distribution function may play an important role in boundary plasma.

4. Neutral density is a parameter that is important to the fundamental measurement of particle balance. Currently neutral density is measured by pressure gauges in the periphery or at a few localized points in the plasma. This needs to be extended to 2D.

5. Erosion rates are also not being adequately measured in current devices. Though not strictly a plasma parameter, erosion represents a boundary condition of impurity particle source that must be measured if a boundary plasma model is to be tested.

The requirements outlined above basically describe the experimental facilities and diagnostics that needed to validate boundary models. This effort presumes a parallel effort exists to incorporate the boundary physics and scaling into a quantitative code. There is considerable effort currently underway to develop such codes, but the effort will need to be intensified and closely coupled to experimental validation.

Research Thrust

The discussion above motivates the need and requirements for an experimental effort to contribute to the development and validation of a boundary plasma model adequate for design and operation of a future DEMO divertor. The experimental effort primarily requires an extensive diagnostic set with access to a wide range of divertor configurations, divertor surface geometry and boundary plasma parameters.

Parameter access. From the existing tokamaks in the US a wide range of conditions can be accessed. DIII-D and Alcator C-Mod are complementary for attaining a wide range of density, neutral opacity and heat flux density. For material surfaces the different US devices are also complimentary with DIII-D for carbon, Alcator C-Mod for high-Z molybdenum and NSTX for lithium.

Configuration and geometry. DIII-D can obtain a wide range of magnetic configurations with access to single-null and double-null divertor configurations as well as a wide range of separatrix shapes. Divertor configurations that increase the divertor volume, such as the Super-X and Snowflake divertors can also be explored. The open geometry of DIII-D also allows for installation of different divertor baffling surfaces and different pumping locations. Finally advanced modes of tokamak operation are also accessible in DIII-D to test their compatibility with divertor heat flux control techniques. These regimes include high beta operation as well as non-inductive steady state scenarios.

Diagnostics. DIII-D is an ideal facility for developing a comprehensive diagnostic set for testing boundary plasma models. The motivations for developing this diagnostic data set on DIII-D include; 1) extensive existing diagnostics that may only need upgrading instead of complete development, 2) open geometry for diagnostic deployment, including imaging for 2D profiles of all plasma and neutral profiles and 3) potential for eliminating 3D effects by use of toroidally symmetric surfaces for essentially all recycling surfaces.

By developing the resources outlined above an experimental program, in collaboration with a robust theory and modeling effort, has the potential to help develop and then validate a boundary plasma model(s) capable of design of the next generation of divertor hardware and operation for a DEMO reactor.