Fusion Research Progress and Plans on DIII-D

R.J. Buttery and the DIII-D Team

General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA

Abstract. The DIII-D tokamak continues to address key issues of preparation for ITER, while also exploring the longer-range path to steady state fusion energy through the Advanced Tokamak (AT) concept. Substantial progress has been made in understanding tools and behaviors for the ITER baseline scenario with techniques to mitigate ELMs, probe stability, understand transport, and safely quench the plasma. But an overall integrated solution for Q=10 remains elusive, as scenarios become challenged to sustain stability and ELM suppression at low rotation. Planned upgrades in 3-D capability and electron cyclotron heating (ECH) will help elucidate solutions further. On the AT path, DIII-D flexible heating and current drive systems have identified several promising candidate regimes for steady state fusion energy, with recent progress in control of instabilities and ELMs, and new understanding of transport and energetic particle behavior, as well as divertor flows and detachment. This leaves DIII-D well positioned for a major upgrade next year to raise heating and current drive power to access reactor relevant regimes and develop a projectable understanding of the AT path to fusion energy.

I. Preparation for ITER

Research on DIII-D is focused on ensuring the successful operation of ITER. This work benefits from DIII-D's ability to access ITER relevant low torque and low collisionality regimes, as well as a strong diagnostic set, perturbative and control tools. Significant progress has been made in developing and understanding some of the key tools ITER will need to use to control its plasmas. For example, it is found that shattered pellets provide promising potential to safely quench ITER plasmas, where control of the impurity content of the pellets enables the thermal and current quench properties to be optimized to better meet ITER's needs (Fig. 1) [1]. Disruptions can also lead to formation of a runaway electron beam which must also be dissipated. A new gamma ray imaging camera validates runaway electron generation and dissipation models at high energies, but identifies increased dissipation at low energy compared to theoretical models [2]. Studies are exploring this further.

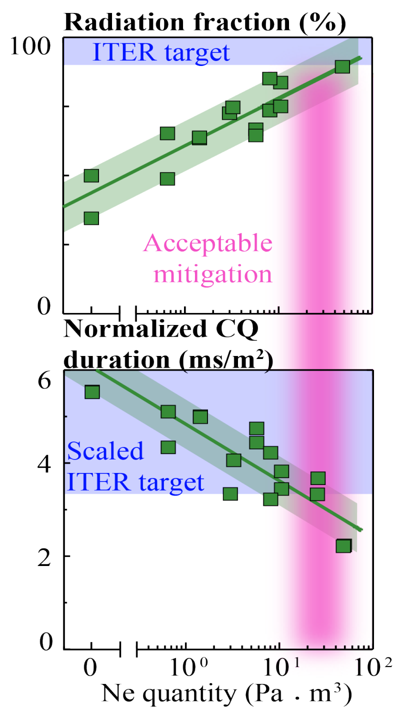

Fig 1: Adjusting the impurity mix of shattered pellets can tune disruption quench properties.

ITER must also suppress, or greatly mitigate ELMs. The physics of 'RMP' ELM suppression by 3D fields is found to be associated with excitement of an edge current driven mode. The technique has been extended to the metal walled ASDEX Upgrade with good performance and impurity flushing, in joint work with DIII-D that identifies the crucial role played by plasma triangularity in the plasma response to the 3D fields [3]. A new six current source '3D' power supply has also been used to demonstrate improved access to suppression with combined n=2 & 3 fields (vs pure n=3 fields). Alternative ELM suppression techniques are also being explored with the Quiescent H-mode making significant progress towards high density and low rotation in recent years. In this Q-H regime, the ELMs are replaced by edge MHD modes, that act to regulate particles and impurities. It is found that as rotation is lowered a broadband turbulence MHD emerges which regulates pedestal gradients more strongly [4]. This leads to wider and higher pedestal pressures. Non-linear simulations [5] with the NIMROD code may explain this, predicting a sea of low m/n modes that interact to reach a saturated state (Fig. 2).

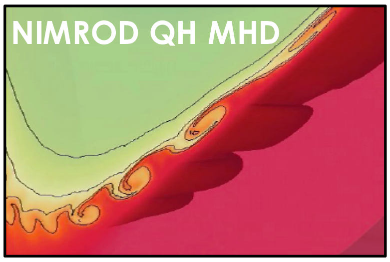

Fig 2: Simulation of broadband MHD turbulence in QH mode.

Despite this progress, a fully integrated solution for the ITER baseline (IBS) remains elusive. ELM suppression remains to be demonstrated at ITER relevant rotation and q_{95}, while 2/1 tearing instabilities often occur, particularly if RMP-ELM suppression is attempted. Probing ITER baseline-like scenarios with external 3D fields identifies increased plasma response prior to tearing mode onset at low rotation (Fig. 3) [6]. This suggests ideal MHD may influence tearing stability, and provide useful sensing tool. It is interesting to note that this behavior is only partially captured by ideal+kinetic MHD simulations with MARS-K. Further work is investigating how to optimize stability by tuning the current profile in the vicinity of the q=2. Studies are also exploring how to combine favorable properties of pedestal optimization (such as QH mode) with improved stability and higher safety factor regimes (such as hybrid scenarios). Future work will benefit from increases in ECH and additional power supplies to further tune profiles and stability, while proposed in-vessel outer midplane coils are predicted to aid access to RMP-ELM suppression, and mimic ITER's coil set to understand the optimization for ITER.

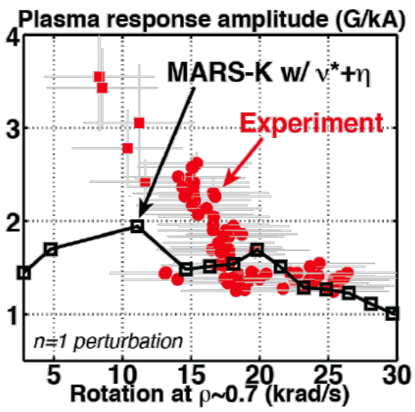

Fig 3: Plasma response to 3D field vs rotation compared MARS-K.

DIII-D is also identifying key trends and validating models for transport, energetic particles, pedestal optimization and H-mode access to predict behavior in ITER. Beam fueling is found to play a role in density peaking at low collisionality, suggesting care must be taken in projecting to ITER, where beams will not fuel significantly. At low power, H-mode access is facilitated by the occurrence of dual band turbulence associated with increased velocity shear. Observations of core rotation reversal in torque-free ECH H-mode are matched by gyro-kinetic simulations (Fig. 4, upper) [7,8]; combining simulation with measured intrinsic torque scaling projects significant rotation in ITER (lower panel) that increases density peaking and thus fusion performance. Finally, a first principles core-pedestal transport model formed by integrating the TGYRO and EPED codes was validated using IBS plasmas on DIII-D and found to predict Q=10 in ITER [9].

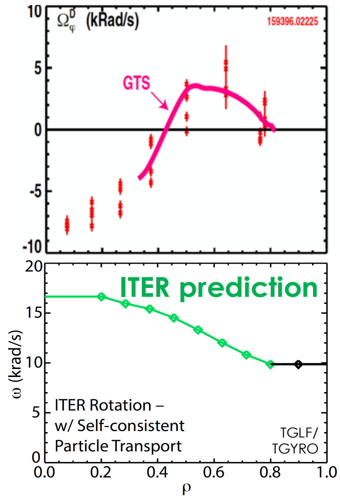

Fig. 4: Comparison of rotation reversal with GTS code (upper) and use of simulation to predict ITER rotation (lower).

II. The Advanced Tokamak Path to Steady State Fusion

DIII-D is using its flexible heating and current drive tools to explore the path toward a steady state advanced tokamak reactor with an integrated core-edge solution. In fully non-inductive steady state 'hybrid' plasmas, robust ELM control induced by 3D field is found compatible with high confinement (Fig. 5) [10]. This benefits from increased plasma response to the 3D fields at high β_N. Separate studies show compatibility of hybrid scenarios with a radiative edge. With broader profiles from off-axis beams and ECCD, reversed magnetic shear plasmas are found with good MHD stability. In these scenarios, energetic particle transport is explained by multiple overlapping Alfvén eigenmodes (RSAEs) which can be avoided by modifying current profile, neutral beam properties or possibly deploying electron heating, understood to act on RSAEs through changes to the GAM frequency (Fig. 6) [11]. The beneficial properties of a broader current profile are confirmed by observations of reduced rise in turbulence with electron heating in reverse vs positive shear. This work sets the groundwork for a major development in heating capability for 2018, with neutral beams

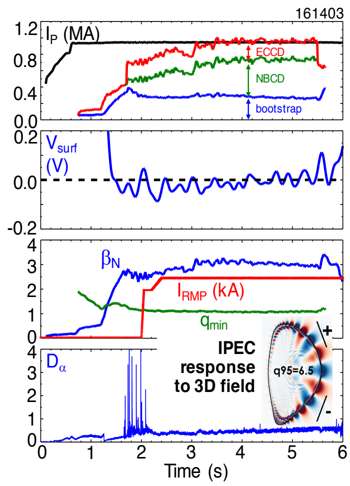

Fig 5: Fully non-inductive hybrid scenario compatible with RMP-ELM control.

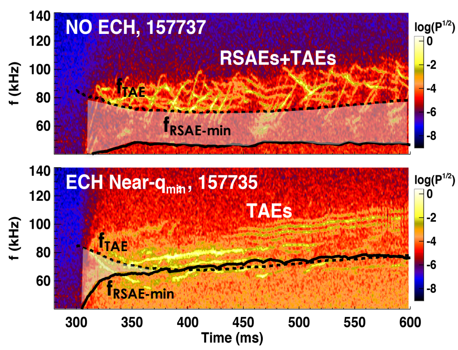

Fig 6: Absence of RSAEs explained by change in stability with electron heating.

becoming toroidally steerable and a doubling of off-axis injectors, coupled with a rise in ECCD power to provide access to broader profiles and much higher β_N to enable more reactor relevant studies across the program.

III. Reactor Relevant Boundary Solution

A critical issue for steady state fusion is to develop a compatible divertor configuration to handle the hot plasma exhaust in steady state conditions (i.e. virtually no erosion). This likely requires highly detached operation, and DIII-D research is targeted at understanding the physics basis to achieve this and optimize the design of a reactor divertor. Experiments have identified the critical role of drifts in H mode plasma (Fig. 7), with poloidal drifts responsible for strong HFS/LFS asymmetries in heat load, while radial drifts influence the density profiles [12]. Separate studies using Helium plasmas have helped isolate discrepancies in divertor simulation models, pointing to the need for improved molecular radiation models and better accounting of midplane-to-divertor transport to accurately predict detachment [13]. Studies are also exploring the role of divertor closure, with a new small angle slot (SAS) divertor installed giving encouraging indications in the validation of predictions of improved access to more completely detached regimes at lower upstream density. Tests with novel tungsten-isotope rings have also helped isolate impurity migration sources and trajectories [14]. These elements represent the start of a major focus going forward to develop the physics basis for divertor optimization, through increasing diagnostics and simulation, implementation of main upper and then lower divertor configuration changes, and progressive exploration and installation of reactor relevant materials.

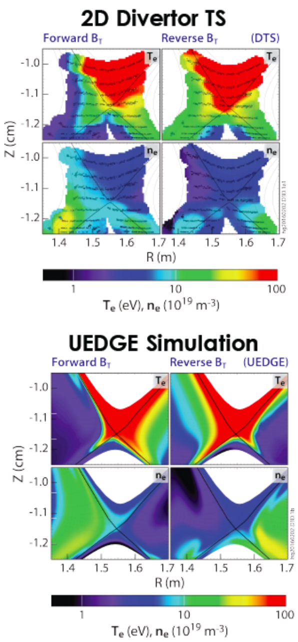

Fig 7: Comparison of 2D divertor density and temperature with UEDGE simulations.

These developments represent significant progress in understanding the path to fusion energy, while the exciting facility upgrades represent key opportunities for DIII-D to address critical outstanding research questions to accelerate the path to fusion energy.

This work was supported by the US Dept. of Energy under DE-FC02-04ER54698.

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