SIMULATION OF ALPHA POWER DYNAMICS IN DIII-D

[1]F. TURCO, [1]G.A. NAVRATIL, [1]J.M. HANSON, [2]C.M. GREENFIELD, [3]T. ODSTRCIL, [4]A. MCLEAN, [5]W. BOYES

[1]Columbia U, [2]ORNL, [3]GA, [4]LLNL, [5]ORAU

1. BACKGROUND AND MAIN RESULTS

The key power balance building blocks of a burning plasma have been simulated in DIII-D using Xenon and Krypton for Tungsten (W)-like core radiation, NBI and/or ECH for α-heating (P_α), and independently controlled plasma β_N using NBI. Under these conditions, DIII-D experiments have uncovered non-linear oscillations coupling density, temperature and radiation. These oscillations have been reproduced with a new coupled model that includes radiation and input power feedback consistent with the experiment. To apply this model in reactor-relevant experiments, a new algorithm was demonstrated, capable of simulating any desired fraction of P_α, using real-time measurements of core T_i and density, and a temperature-shifted fusion reactivity to reproduce the cross-section dependence on T_i at DIII-D levels. The resulting simulated P_α was then added to either or both NBI and ECH power commands. At DIII-D's ITER Baseline's discharges core T_e≈2-3 keV, Kr and Xe radiate at equivalent rates to W at the expected ITER and FPP reactors T_e≈20 keV. In these experiments, the Baseline scenario has also been demonstrated in a sawtooth-free state, which originates from the higher core radiation typical of metal or metal-equivalent environments, where the core T_e profile is flattened, the local Ohmic current decreases and q_{min} increases to q~1. At that point a self-organised state with a 1/1 quasi-interchange (QI) mode (AKA a helical core, also reported in Negative Triangularity plasmas [1]) is observed, which is postulated to maintain the sawtooth-free state for several current relaxation times (τ_R~1 s in these plasmas). With the addition of the self-heating ingredient that will dominate ITER and other fusion reactors and has the dependence $P_\alpha \sim n_e^2 T_i^2$, the non-linearity in P_{rad}-n_e-T of the DIII-D experiments is expected to be enhanced compared to present experiments, calling for viable control solutions. The new model reproduces the oscillations, as well as the interplay of the P_α with the background plasma, showing an increase in the oscillation frequency and amplitude proportional to the magnitude of P_α when this term is turned on. In the experimental application, the interplay between the W-like core radiated power, the simulated P_α, and the β_N feedback shows a significant impact of the added uncontrolled power to the temperature, density and impurity accumulation. New experiments have demonstrated the alpha power dynamics both in the flattop and in the ramp-down of IBS plasmas, at various self-heating fractions, showing both stationary and oscillating output.

2. NON-LINEAR OSCILLATIONS AND HELICAL CORES

In DIII-D experiments reproducing the ITER Baseline scenario, where the plasma shape is matched to a scaled ITER shape (including the aspect ratio), the normalised current I_N=*I/aB*=1.415 and β_N=1.8-2, q_{95}=3 and T=0 Nm are matched to the design ITER values, fidelity to ITER and reactor conditions has been further increased by adding the element of core W-like radiation. This is achieved in a carbon-wall machine by using elements such as Kr and Xe, which have the same radiative loss rate (L_z) at 2-3 keV that W has at 15-20 keV [2]. In a series of experiments, injection of Kr and Xe was scanned over the flattop portion of IBS discharges, to study the limits of operability in ITER-like radiative regimes. These obtained stationary plasmas with up to core radiated fraction values of f_{rad}~0.3, consistent with expected ITER values. Across this range of f_{rad}, the variation of the radiative loss rate L_z with the core T_e, and the presence of β_N feedback, cause the scenario to bifurcate to a non-stationary oscillatory regime, where the plasma is cooled by excessive radiation, T_e decreases while the feedback tries to increase it again with a delay, the radiation decreases, and so forth (Fig. 1). The database shows that benign saturated n>1 tearing modes can enhance the oscillatory behaviour, without causing a disruption or triggering m=1/n=1 tearing modes. In comparison experiments without Kr or Xe, but containing various levels of intrinsic metals such as W from W-coated tiles, or Molybdenum, Ni and Fe (from in vessel RF antennas), the same oscillatory behaviour is observed, when the high-Z impurity concentration values are low enough to lead to comparable f_{rad}~0.3. In all these plasmas, when the core radiation reduces the central electron temperature enough to change the balance between the Ohmic current in the core and the bootstrap current in the pedestal (with the total plasma current being held fixed by the central solenoid, CS), the oscillatory regime is often replaced by a sawtooth-free state caused by the reduction of core Ohmic current. After the safety factor rises naturally above the 1/1 rational surface, a stationary QI mode keeps the current from relaxing back to a peaked profile driven by the CS. This

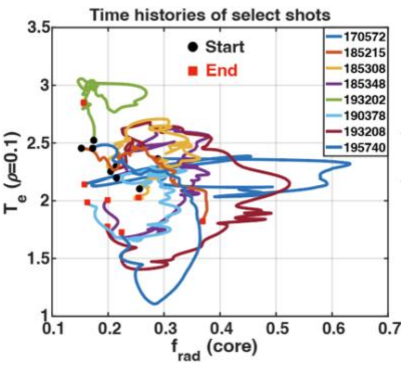

Figure 1: Oscillation cycles of f_{rad} and core T_e in a series of IBS plasmas.

state is hence maintained stationarily for >3 τ_R, while the QI mode forms a helical core, shown by 2D SXR analysis to be rotating in the poloidal plane within ρ~0.05-0.3. The IBS discharges in this sawtooth-free state lie in a portion of the database with higher core density and lower core temperature, and do not exhibit better 2/1 TM stability, or reduced performance.

3. SELF-HEATING DYNAMICS

With the new high-Z impurities, ITER Baseline Scenario plasmas have now been also demonstrated with the complete power balance including the tungsten-equivalent core radiation, stationary and varying input power and simulated alpha power with the correct temperature, density and cross section dependence in the ITER range, in a significant step to increase the fidelity of DIII-D plasmas to the IBS conditions. A new coupled model reproduces the experimental amplitude and frequency of the oscillations and a term representing self-heating P_α has been added to study its impact on the system. The model is adapted to present machines by expressing the fusion reactivity σ with a polynomial shifted in T_i by an arbitrary number (15 keV in our case), to recover the T_i dependence of σ(T) at ITER's temperatures. The interplay of P_a with the background plasma shows an increase in the oscillations frequency and amplitude depending on the timing and magnitude of the alpha power, which indicates the potential issues that ITER will encounter and needs to be prepared for in its burn control methods. In order to include the "uncontrolled" self-heating ingredient also in experiments, a new algorithm was designed and demonstrated in the DIII-D Plasma Control System, capable of simulating any desired fraction of alpha power, using RT measurements of T_i and density, the same modelled σ(T) expression to reproduce the cross-section dependence on T_i at DIII-D levels, and the output to either or both NBI and ECH power, which can be mixed independently. The P_α algorithm was demonstrated in a variety of conditions, obtaining self-heating cases with fixed auxiliary power (P_{aux}, representing the external "controlled" power) and low core radiation, which leads to slow oscillations in P_α, β_T (which is proportional to P_{fusion}) and T_e, T_i (Fig 2, left-hand column). When the feedback system is turned on (Fig 2, right-hand column), to study the requirements for fixed P_{fusion}~β_T under higher core radiation conditions, it becomes clear how the non-linearity between P_{rad} and T_i (which in these experiments is coupled to T_e just like in ITER) makes the system unstable, with P_α dropping faster than P_{aux} can react if the D ion density is not increased.

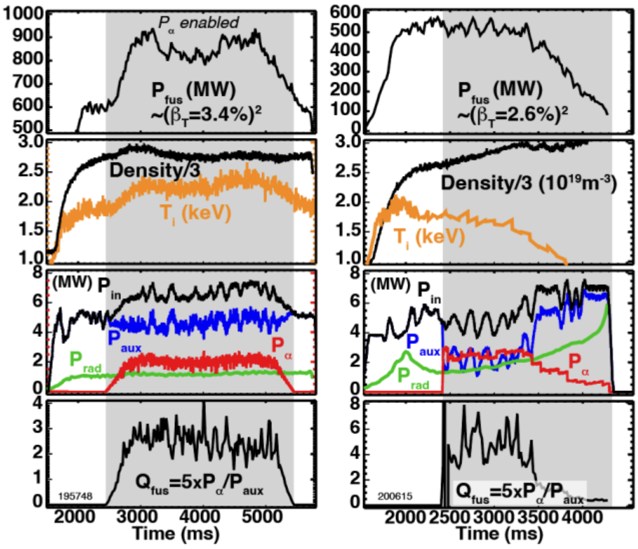

Figure 2: Relevant quantities for two IBS shots with P_α with fixed P_{aux} (left) and feedback P_{aux} on β_N (right).

4. CONCLUSIONS

As fusion researchers turn their focus to producing and controlling a burning plasma, it is imperative that techniques for burn control in ITER and other forthcoming devices be developed. Fusion power will respond nonlinearly to even small changes to heating power, which is supplied by both external (controllable) sources and self-heating by energetic alpha particles produced by the fusion reactions themselves. Burn control is a grand challenge for fusion research but experiments to simulate it in present-day devices are difficult and have only rarely been attempted. The experiments we report on were carried out under conditions of increasing fidelity to future burning plasmas, with T_e/T_i, input torque, and core impurity radiation simulating the expected behaviour of plasmas in ITER. These experiments are foundational to establishing a test-bed for simulating fusion burn dynamics and testing burn control techniques needed for long pulse high fusion gain experiments in ITER and reactors where the fusion gain will be much higher than Q=10, with very small margins to control it.

REFERENCES

[1] W. Boyes *et al* 2024 *Nucl. Fusion* 64 124005
[2] F. Turco et al 2024 Nucl. Fusion 64 076063

ACKNOWLEDGEMENTS

This work was supported by the US Department of Energy under DE-FG02-04ER54761, DE-AC05-00OR22725, DE-FC02-04ER54698, DE-AC52-07NA27344.