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Recent progress on modeling of ITER steady state scenarios by the ITPA Integrated Operation Scenario (IOS) Topical Group is reviewed. A new steady state scenario with weak magnetic shear has been derived using an efficient steady state solver and the theory-based transport model GLF23 with experimental boundary profiles scaled from present-day tokamak discharges. A second scenario with strongly reversed shear was derived using a prescribed transport model. Benchmarking activities have been undertaken by the ITPA IOS to validate the two reference scenarios. Finally, the steady-state solution method has been exploited to produce a large number of steady state scenarios with various mixes of heating and current drive (H&CD) to find upgrade options that fulfill the steady state objective.

One of the primary goals of the ITER program is to demonstrate reactor scale steady-state (SS) operation for future tokamak reactors. Specifically, long pulse (≥3000 s) operation with 100% noninductive current fraction (f_{NI}), high bootstrap current fraction, and fusion gain $Q \geq 5$ should be demonstrated. We present integrated modeling of such SS scenarios, using theory-based and semi-empirical transport models in conjunction with the heating and noninductive current drive sources projected for ITER. The simulations are carried out comparing several widely used transport codes, including ACCOME, ASTRA, CRONOS, ONETWO, PTRANSP, TASK, and TOPICS, and self-consistent calculation of the heating and current drive. Various constraints like beta limits and power loss to the divertor are taken into account. The modeling is validated by comparing the simulations with present-day experiments that have similar high noninductive fraction at high beta.

The new weak magnetic shear scenario was developed using GLF23 to model the core. To circumvent the difficulties of reproducing profiles near the pedestal with the theory-based model, an ELM-averaged edge profile scaled from an ITER SS demonstration discharge in DIII-D was adopted near the boundary (ρ=0.8–1.0). The edge scaling is based on the thermal profile $\beta_N^{th}(\rho)$, which has been shown to be relatively self-similar across tokamaks [Fig. 1(a)]. Iterative SS solutions were developed using a new fast transport solver FASTRAN with the ONETWO and

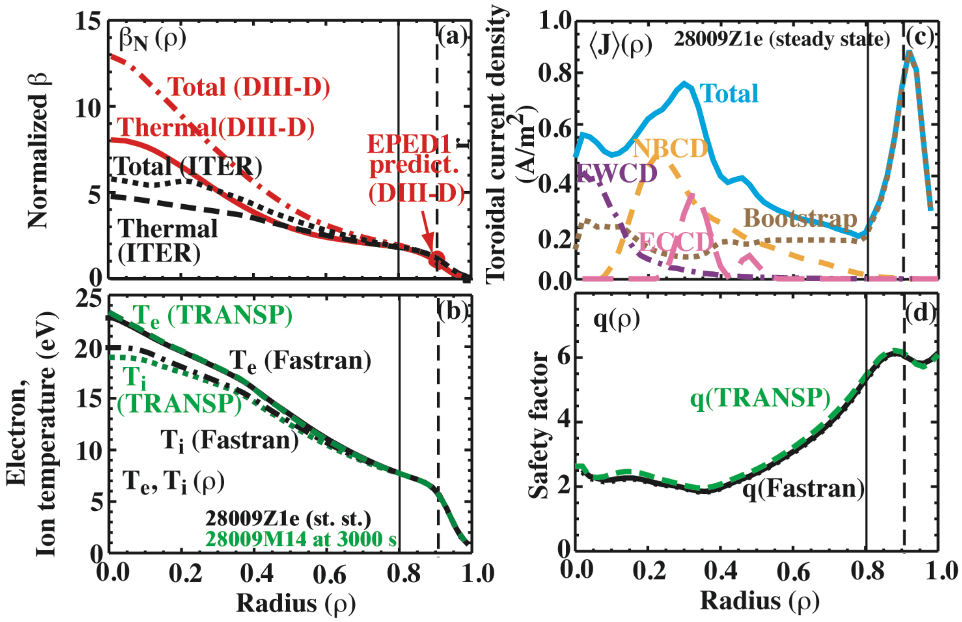

Fig. 1. ITER weak-shear steady-state profiles from the GLF23 model with the experimental boundary conditions at ρ = 0.8-1.0 from a DIII-D ITER Demo discharge (red). The theoretical pedestal model (EPED1) predicts β_{Nped} = 0.91 at ρ_{ped} = 0.905 (dashed line), while the experimental β_{Nped} is ≈10% higher at the same ρ_{ped}. The profile of the SS scenario agrees well with TRANSP profiles (t = 3000 s) (green).

EFIT codes. Figure 1 shows profiles from the SS solution method for the ITER SS case at I_p = 8 MA. Full noninductive current is achieved with Q≈3.4 and β_N=2.8. The iterative SS solution method arrives at the same final operating points as the time-dependent transport codes [Fig. 1(d)], but much more efficiently. The main challenge concerning the scenarios is the extrapolability of the high performance operating point from the present database to different parameter regimes (e.g., reduced plasma rotation, T_e/T_i≈1, density peaking). Relevant experimental observations will be discussed.

The second SS scenario developed is the Internal Transport Barrier (ITB) strong reverse shear scenario. In this case the energy transport model is more difficult to prescribe since the models have deficiencies when applied to equilibria with reversed shear and high pressures (Shafranov shift). CRONOS simulations using a prescribed heat diffusivity model similar to that used in developing the official SS scenario have shown that ITB formation and sustainment requires current drive by FW and ECCD (rather than a broad current drive by NBCD as in the official scenaraio). The simulation using CRONOS will be tested against an ITB case in the DIII-D ECCD/NBCD experiments. The main challenge in this scenario is MHD stability with a large pressure gradient and strongly negative shear.

The optimum selection of H&CD sources is critical to the success of the ITER SS objectives. In particular, SS operation achieving simultaneously f_{NI}=1 and Q=5 may require an upgrade of the ITER Day-1 H&CD capabilities. A variation of the plasma current in the weak shear reference scenario with a fixed normalized density (n_{GW}=0.85) shows a trade-off between f_{NI} and Q (Fig. 2), indicating higher I_p operation (I_p = 9 MA) would be important to reach the Q=5 objective. However a missing current of 1–2 MA may have to be supplied with a new source. To explore ITER H&CD upgrade options, we have exploited the efficient SS solution methods to the operational space (f_{NI} vs Q) with different H&CD mixes. Electron cyclotron current drive (ECCD) calculations have been upgraded using a collision operator that preserves momentum in collisions between electrons. Monte-Carlo orbit following codes are used to calculate on- and off-axis NBCD correctly, taking into account the alignment of the NB injection with the magnetic pitch. Preliminary evaluation indicates that NBCD is necessary for off-axis current drive. Scenarios with LHCD will also be discussed.

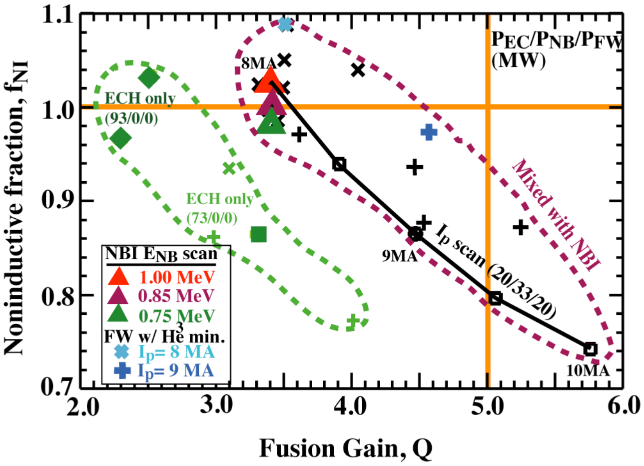

Fig. 2. Noninductive fraction (f_{NI}) vs fusion gain (Q) for various scenarios with different I_p and H&CD mixes in the weak shear regime. Higher Q values are obtained with high I_p and NBCD-mixed scenarios, but f_{NI} is 0.85-0.9 without NB upgrade.

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