Operating points and feedback control of plasma characteristics in tokamaks with full current drive*

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Tokamak operation using advanced tokamak modes with steady-state current drive may provide better performance, thereby improving the prospects of power-producing fusion reactors. Scenarios for such operation in TPX and in an ITER-like scale-up of TPX are modeled. Results indicate that the heating and current drive power and feedback control requirements may be achievable.

1. INTRODUCTION

One of the most promising avenues for using a tokamak as an economical fusion reactor is the possibility of operating it as a steady-state machine, with the majority of the plasma current being driven by bootstrap current and a modest "seed" current from external current drive sources (e.g., radio frequency current drive, neutral beams). Advanced physics (AP) operating modes with improved confinement times make the operation appear even more attractive.

To achieve these operating regimes, careful control of the heating and current drive (H&CD) sources must be achieved. Simulations of operating scenarios for TPX [1] and an ITER-scale, TPX-like reactor that should access the AP regimes have been done.

Analysis of these simulations yields the requirements on the H&CD systems: power needed from each system; time response; and ability to change the driven current and current profile during operation [e.g., by changing the phasing of ion cyclotron fast-

wave (FW) or lower hybrid (LH) systems]. The results indicate that the degree of control and the reliability of the systems must be very high. These requirements will be drivers in H&CD system development over the next several years.

This sequence of steps is used to generate scenarios of interest:

1. Identification of desirable end states, using time-independent equations to define a 0-D equilibrium that satisfies power balance and current drive constraints.

2. More detailed modeling of the power and current drive, using the ACCOME code [2], which contains a calculation of current drive sources (FW, LH, bootstrap...) in noncircular geometry.

3. Time-dependent modeling with 0- or 1/2-D power balance (profiles specified) and a time-dependent model of the feedback-controlled current drive system.

4. Fully integrated 1-D modeling of all heating, power and particle transport, and current drive with the WHIST code [3]. In addition, the MHD stability of the profiles

* This research was sponsored by the Office of Fusion Energy, U. S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc., and under Contract DE-AC02-76-CHO3073 with Princeton Plasma Physics Laboratory.

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obtained can be checked.

The sophistication (and the resulting amount of effort required) increases as one moves through the sequence. Iteration of this sequence is an ongoing task.

2. ACCOME CODE RESULTS FOR TPX

Figure 1 shows current density profiles from the ACCOME code for a particular TPX scenario. For this case, the device is operating in a reverse-shear mode with $B_0=3$ T, $I_p=1.5$ MA, and power inputs of 1.5 MW of LH, 8 MW of neutral beam (NB), and 8 MW of FW heating (but no FW current drive). VH-mode confinement is assumed, with a confinement enhancement (H factor) of 3 over ITER89-P scaling [4].

Figure 1. Top: Current density from different sources vs. normalized radius. Bottom: q profile.

The ACCOME code does a calculation of LH and NB current drive with the bootstrap current, iterating on both the 2-D equilibrium and on the current drive sources until a self-consistent solution is obtained. In this case, a particularly high bootstrap fraction ($f_{bs} \approx 0.9$) is obtained.

3. TIME-DEPENDENT SCENARIO FOR TPX

A significant issue is how to get to a desired final state when one starts from an L-mode plasma with a "conventional" q -profile. Of particular interest is the requirement for time-dependent control of both the amount of auxiliary heating power going to the plasma, and the amount and profile of the current driven by the H&CD system. To evaluate the control requirements for the TPX NB, FW, and LH systems, a simple model has been derived that uses 0-D confinement scaling (ITER89-P) with specified density and temperature profile shapes and specified current drive profile shapes for the different sources of current.

Figure 2 shows the results of a time-dependent simulation of access to a VH mode with reversed shear and high bootstrap fraction. The average density was specified at $0.4 \times 10^{20} \text{ m}^{-3}$, and the temperature was determined from power balance. The demand signals (Figs. 2a and 2b) are the normalized beta β_N , total plasma current I_p , and q on axis q_0 (set to change from 1.5 initially to 2.9 to achieve a reverse-shear region). The H factor changes from 1 to 2 as the power is raised initially, and from 2 to 3 shortly after the reverse-shear state is achieved. To simulate an AP mode, we assume that a value of β_N of 4.5 can be sustained in the reverse-shear state with VH-mode confinement.

The closed-loop feedback control system changes the powers of the different H&CD sources including the loop voltage (Fig. 2c) in response to the demand signals. In addition, the feedback system changes the relative current drive efficiencies f_{fw} and f_{lh} of the FW and LH systems (Fig. 2d), where (for example) $I_{fw} = \gamma_{fw}(T) f_{fw} P_{fw} n / R$, and f_{fw} is allowed to

Figure 2. Time-dependent simulation of feedback-controlled, high- β_N , VH-mode case for TPX.

- a- Demand value of β_N (squares) and response (solid); H- factor (dashed).
- b- q_0 demand (squares) and response (solid); I_p demand (Δ 's) and response (dashed).
- c- FW, LH, NB power in response to demand signals.
- d- Relative CD efficiency of fast wave (f_{fw}) and lower hybrid (f_{lh}), and loop volts (V_{loop}), all of which are feedback controlled in response to the demand signals.
- e- Total CD-system-driven current (solid), bootstrap current (dashed), and ohmic current (Δ 's).
- f- q profiles vs. normalized radius at $t=0, 5, 10, 20$ s.

vary between -1 and 1 . The NB power is also controlled, but as there is only one NB on TPX initially, there is no independent control of its current drive capability.

The resulting currents vs time from all sources (H&CD system, bootstrap current, and ohmic current) are shown in Fig. 2e. The q profiles at selected times are in Fig. 2f. A q profile is obtained with the desired reversed shear.

The results of simulations of time-dependent cases with feedback control of the current profile depend on the parameters of the feedback control system. For this case, emphasis was placed on responding to the β_N , I_p , and q_0 demands, so the other necessary

requirement for long-pulse operation of zero average loop voltage was not met. In this case, the loop voltage is slightly positive. For a specified density, the requirement that the average value of V_{loop} be zero can also be included as a constraint in the feedback control system, at the expense of maintaining the total current, q_0 , and/or β_N at exactly their desired values.

4. REACTOR SIMULATION

The reactor potential of some AP operating modes proposed for TPX has been examined [5]. A moderate aspect ratio ($A = 4.5$ as in TPX) 2-GW reactor (i.e., ITER-like performance) with

the potential for steady-state, noninductive operation with high bootstrap current fraction was analyzed using the WHIST code. Parameters of the machine are: $B_0=6.6$ T, $R_0=7.28$ m, $a=1.62$ m, $\kappa=2.0$, $I_p=9.4$ MA.

For an H-mode factor of 2, the bootstrap current typically provides 80 to 90% of the total current. FW current drive at the plasma center provides the central seed current, and feedback-controlled LH current drive is used to control the total plasma current.

Figure 3 illustrates the change in H&CD system power requirements as the density in a power-producing, fully current-driven (i.e., $V_{loop}=0$) reactor is varied. Feedback control of the FW power was used to maintain $q_0 < 2.5$,

Figure 3. FW and LH system powers needed and fusion power output (top), and current fractions (bottom) vs density.

and feedback on the LH power kept $I_p=9.4$ MA. As the density is increased, the fusion power increases and the CD requirements are reduced because of the increasing bootstrap current contribution.

Sensitivity of the current profile to the FW and LH power deposition profiles has also been studied; see Ref. 5 for details. One (and sometimes two) reverse-shear regions exist in the plasma: one near the plasma center governed by the bootstrap current profile, and another just inside the peak of the LH power deposition. Between these two regions is a region of very low shear. Thus even in reactor-level plasmas, application of moderate amounts of H&CD power can result in reverse-shear scenarios.

5. CONCLUSIONS

A number of codes have been used to model reverse-shear and other advanced, steady-state operating modes that typically have more than 50% of the total plasma current carried by the bootstrap current. These appear readily achievable with moderate heating and current drive powers. Feedback control of both the heating power and the current drive efficiency appears necessary to achieve and maintain these modes of operation.

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