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Development in the DIII-D Tokamak of Hybrid Operation Scenarios for Burning Plasma Experiments

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1. Introduction

The basic parameters of proposed burning plasma experiments such as ITER and FIRE have been chosen based on analysis of multi-machine databases of confinement, stability, and divertor operation [1–3]. Given these specifications, it is of interest to run discharges in present-day machines such as DIII-D to verify the design basis and evaluate the margin available to achieve the mission goals. It is especially important to operate discharges which are stationary with respect to the current relaxation time scale (τ_R) since it is well-known that higher performance can be achieved transiently [4].

Attention has been focused on validating the baseline scenario for diverted machines — ELMing H-mode discharges with $q_{95} = 3$ with sawteeth. However, there is also interest in the ITER program to assess the feasibility of operating the tokamak in a mode to maximize the neutron fluence for the purpose of testing the design of various components critical to the nuclear fuel cycle and energy conversion systems in a fusion power plant. It was originally envisioned that these discharges would be intermediate between an inductive burn (baseline) scenario and a fully noninductive (steady state) scenario; therefore, this type of discharge has become known as a "hybrid" scenario.

In the course of investigating these hybrid scenarios in DIII-D, two key results have been obtained. First, stationary discharges with $q_{95} > 4$ have been obtained which project to $Q_{fus} \sim 10$ in ITER. The projected duration of these discharges in ITER when using the full inductive flux capability is >4000 s. (The significant engineering issues of site heat capacity, activation, and tritium consumption are beyond the scope of this work.) Second, utilizing the same plasma initiation techniques as developed for the hybrid scenario, discharges at $q_{95} = 3.2$ project to near ignition in ITER, even with reduced parameters. This indicates the ITER design has significant performance margin and possesses the physics capability to carry out an extensive nuclear testing program. These same $q_{95} = 3.2$ discharges project to $Q_{fus} > 5$ in FIRE, even with pessimistic confinement scalings.

2. DIII-D Stationary Discharges

Stationary high performance discharges with $q_{95} > 4$, without sawteeth, but with $q_0 \sim 1$ were developed in DIII-D in 2000 [5,6]. The key element of the scenario appears to be reaching high β and triggering an m=3/n=2 tearing mode before the onset of sawteeth [7]. The tearing mode leads to a broader current profile which reaches a stationary state without sawteeth. Under these conditions, discharges were obtained which operated at the expected no-wall β limit without loss of stability [7].

Discussions within the steady-state operation and energetic particles and the transport and internal transport barrier topical groups of the ITPA led to a proposal to the large divertor tokamaks (ASDEX-Upgrade, DIII-D, JET, and JT-60U) to map the existence domain of this type of discharge as a function of q_{95} and density. Preliminary results from a q_{95} scan at fixed density are reported here. Results from JET and AUG will also be reported at this meeting [8].

A scan of q_{95} from 3.2 to 4.8 at $n = 5\times10^{19}$ m^3 indicated two classes of discharges. For $q_{95} \leq 4$, all discharges were robustly sawtoothing. However, even at q_{95} = 3.2 and with a significant m=3/n=2 tearing mode (~5 G at the wall), the fusion performance was very good (Fig. 1). The limit on β was given by the onset of an m=2/n=1 tearing mode which strongly degraded confinement. This mode appeared for $\beta_N > 2.8$ at both q_{95} = 3.2 and q_{95} = 4.0. As shown in Fig. 1, β_N = 2.8 was sustained by feedback control for ~4 s or >2 τ_R. A known weakness in the feedback scheme allows β_N to transiently rise to ~3 at 5700 ms leading to an m=2/n=1 tearing mode. Confinement remains quite good (H_{89} = 2.3) despite the m=3/n=2 tearing mode. After 3000 ms, the MSE signals in the plasma core have no net time evolution, indicating the current profile is completely relaxed. These discharges are prototypical of the ITER or FIRE baseline scenario.

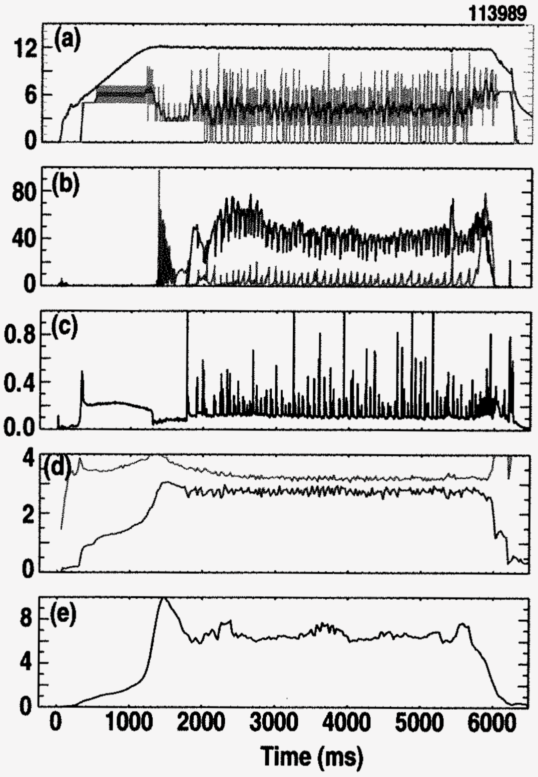

Fig. 1. Time histories of various quantities for a sawtoothing q_{95} = 3.2 discharge (B = 1.24 T). (a) Plasma current (MA) x10 (red), neutral beam power (MW) (grey), time-averaged neutral beam power (MW) (magenta); (b) even dB/dt (t/s) (red) (m=3/n=2 tearing mode), odd dB/dt (T/s) (green) (sawteeth); (c) upper divertor D_α (a.u.); (d) internal inductance (ℓ_i) x4 (green), normalized β (β_N) (red); (e) $\beta_N H_{89}$ (H_{89} is the ratio of the total energy confinement time to the ITER89P scaling).

The second class of discharges, found when $q_{95} > 4$, reaches a stationary state without sawteeth. As shown in Fig. 2, these discharges can be maintained by feedback at β_N = 3.2 without loss of stability for >2 s. Again, β is limited by an m=2/n=1 tearing mode which spoils confinement. This level of β is at the estimated no-wall β limit for this configuration (~4 ℓ_i). Confinement is still good (H_{89} = 2.5) with the m=3/n=2 tearing mode at ~4 G at the wall. The current profile is somewhat less stationary than in the previously reported discharges at lower density and the same q_{95} [5–7]. Longer pulses should be obtained to verify this level of performance can be maintained. These discharges are prototypical of the ITER hybrid scenario.

3. Projections to Burning Plasmas

A very simple methodology has been adopted here to project the DIII-D results to FIRE and ITER. The methodology and projections will be discussed first, then some comments on the physics issues will be given.

Despite the difference in aspect ratio between the DIII-D discharges and the ITER and FIRE designs, it is assumed that the same β_N can be achieved with the same poloidal cross section and q_{95}. To calculate the fusion power, the electron density and temperature profiles from the DIII-D discharges are used and the ions are taken to be equilibrated to the electrons. Choosing the electron temperature profile for the projection assumes that the electron energy transport will dominate in burning plasmas. The auxiliary power required is determined by assuming a confinement scaling relation with fixed enhancement factor. Three scalings are used in this paper — the L-mode ITER89P scaling [9], the recommended ITER H mode scaling (IPB98y2) [1], and an electrostatic gyroBohm scaling [10]. The deficit in the power balance between the loss power and the α heating power is then supplied by auxiliary heating. This heating is assumed to be thermal so there is no fast ion enhancement of the reactivity. Bremsstrahlung losses for the given profiles are computed and included in the energy balance. The pressure split between density and temperature is determined by specifying a given ratio of line-averaged density to the Greenwald density limit estimate. Note that the DIII-D discharges are not a one-parameter similarity extrapolation to either machine.

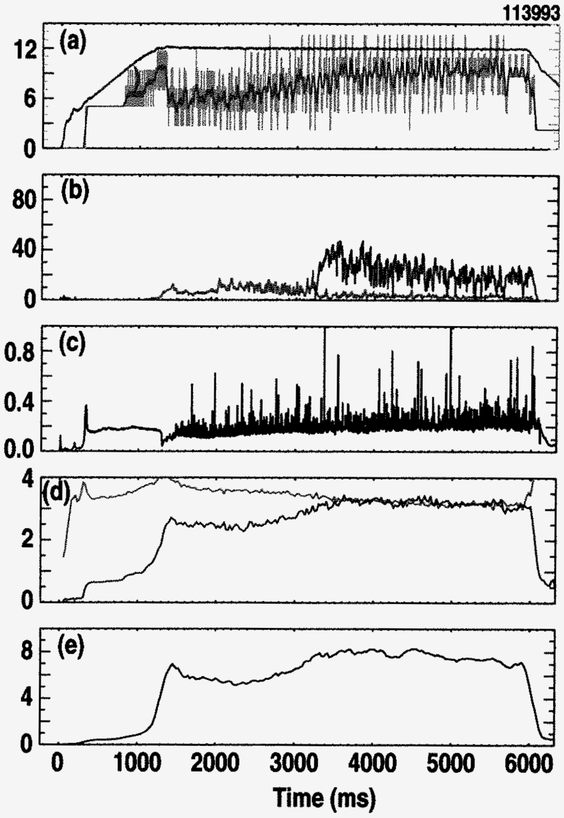

Fig. 2. Time histories of various quantities for a q_{95} = 4.4 discharge (B = 1.7 T). (a) I_p x 10 (MA) (red), P_{NB} (MW) (grey), $\langle P_{NBI} \rangle$ (MW) (magenta); (b) even dB/dt (T/s) (red) (m=3/n=2 tearing mode), odd dB/dt (T/s) (green) (n=3 tearing mode); (c) upper divertor D_α (a.u.); (d) 4 ℓ_i (green), β_N (red); (e) $\beta_N H_{89}$.

Table 1
Projections of a q_{95} = 4.4 discharge to ITER. The ITER parameters used are B = 5.3 T, R = 6.2 m, a = 2.0 m, 2% Be, 1.2% C, n/n_G = 1. For the DIII-D cross section and q_{95}, I = 10.3 MA. The number in parentheses is the DIII-D H factor. A lower H is required to achieve energy balance.

	H	P_{fus} (MW)	P_{aux} (MW)	Q_{fus}
ITER89P	2.2	670	165	4.1
IPB98y2	1.58	650	64	10.2
Pure gB	1.45 (1.61)	630	0	∞

The projections to a "hybrid" scenario for ITER from the q_{95} = 4.4 DIII-D case shown in Table I indicate that the Q=10 goal can be achieved at less than full current, if the ρ_* scaling from DIII-D is nearly gyroBohm. Given the inductive capability of ITER (275 Vs), these discharges could be sustained for >4000 s. Projection of the DIII-D q_{95} = 3.2 discharge to ITER indicates nearly ignited conditions even with Bohm-like ρ_* scaling. For the gyroBohm scalings, ignition is predicted with significant margins. Even these discharges could be inductively sustained for nearly 2000 s. The fusion power in both cases is significantly above the nominal design point of ITER (400 MW). In principle, the fusion power can be reduced by lowering the density, the current, or both the current and field at fixed q. The consequences of these options on the fusion gain have not yet been assessed.

FIRE does not propose a nuclear testing mission so only the DIII-D q_{95} = 3.2 case has been evaluated. Table 3 shows that the FIRE baseline performance goal of $Q_{fus} > 5$ could be obtained even with Bohm scaling, while the pure gyroBohm scaling would indicate approach to ignition.

Table 2
Projections of a q_{95} = 3.2 discharge to ITER. The same parameters listed in the caption of Table 1 are used. The current in ITER is 13.9 MA. Again, the numbers in parentheses are the DIII-D H factors which must be reduced to achieve energy balance.

	H	P_{fus} (MW)	P_{aux} (MW)	Q_{fus}
ITER89P	2.4	950	31	31
IPB98y2	1.34 (1.47)	940	0	∞
Pure gB	0.99 (1.63)	940	0	∞

Table 3
Projections of a q_{95} = 3.2 discharge to FIRE. The FIRE parameters used are B = 10 T, R = 2.14 m, a = 0.595 m, Z_{eff} = 1.4 (Be), n/n_G = 0.7. For the DIII-D cross section and q_{95}, I = 6.6 MA for FIRE. The number in parentheses is the DIII-D H factor for that scaling, which must be reduced to achieve energy balance.

	H	P_{fus} (MW)	P_{aux} (MW)	Q_{fus}
ITER89P	2.4	280	48	5.8
IPB98y2	1.47	280	35	8.0
Pure gB	1.55 (1.63)	270	0	820

4. Discussion

The results of these studies are uniformly positive for ITER and FIRE performance. However, significant uncertainties remain. The variation of the projections with the confinement scalings is partially due to the sensitivity of Q_{fus} at high values, but also due to the large distance in ρ_* from DIII-D to ITER and FIRE (factor of 6–7). Results from JET and JT–60U will add significantly to the assessment of these projections. To date, all of the DIII-D discharges have $T_i/T_e > 1$ which is known to enhance confinement. Density scans indicate the enhancement is not a strong function of T_e/T_i [7], but further studies are needed. Note that this affects the H factor, not the scaling relation, so strong corrections to these projections are not expected. Finally, operation at lower current implies lower density, if the Greenwald limit applies. Lower density may place greater strain on the divertor, but there is qualitative evidence from the DIII-D discharges that the ELM effects are reduced at higher q_{95}. In spite of these uncertainties, the ability of DIII-D and other devices to operate under stationary conditions, without active stabilization of instabilities, at parameters which project to fusion performance well above the baseline designs of ITER and FIRE provides confidence that these machines would achieve their goals.

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