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TRANSPORT SIMULATION OF ITER STARTUP*

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Abstract

The present International Thermonuclear Engineering Reactor (ITER) reference configurations are the "Technology Phase," in which the plasma current is maintained noninductively at a subignition density, and the "Physics Phase," which is ignited but requires inductive maintenance of the current. The WHIST 1.5-D transport code is used to evaluate the volt-second requirements of both configurations. A slow current ramp (60–80 s) is required for fixed-radius startup in ITER to avoid hollow current density profiles. To reach the operating point requires about 203 V·s for the Technology Phase (18 MA) and about 270 V·s for the Physics Phase (22 MA). The resistive losses can be reduced with expanding-radius startup.

Introduction

The poloidal magnetic flux available to establish the plasma toroidal current and to maintain it against resistive and disruptive losses is limited by engineering constraints. At steady state, the number of volt-seconds of magnetic flux stored in the poloidal magnetic field is directly proportional to the inductively maintained toroidal current, with the proportionality constant being determined by the plasma current profile. Since experimental evidence shows that higher currents give better energy confinement, it is desirable to minimize volt-second losses.

The primary volt-second loss mechanisms are resistive current decay and direct volt-second dissipation via flux surface reconnection during sawtooth disruptions.[1] The resistive dissipation rate becomes smaller as the plasma temperature increases; therefore, it is particularly helpful to ramp the current quickly at low temperatures. If sawteeth are present, the increased ramp rate also reduces the total volt-seconds dissipated by sawteeth during startup. However, if the current is ramped too quickly in a fixed-radius startup, the plasma is likely to form an unstable hollow current density profile, resulting in a major disruption. An expanding-radius startup, an option not discussed in this paper, could relax this limit.[2]

The volt-second startup requirements tend to be reduced by current drive from neutral beam injection and other auxiliary sources. The magnitude of this effect is evaluated.

The flat-top current in the Physics Phase of ITER[3] is fully inductive since no auxiliary heating is required at ignition. However, it would be possible to add a small amount of noninductive current drive for profile-shaping purposes, provided it does not cause beta to exceed the critical value for stability. It may be possible to use noninductive current drive to tailor the current profile in order to reduce or avoid sawteeth. (Certainly it is possible to *increase* sawtooth activity by driving a narrow spike of current density at the magnetic axis.) It may also be possible to directly influence the energy confinement time by tailoring the current profile, although the physical relations involved are not fully understood. The two ITER phases represent the end points of a range of potentially interesting devices, from no auxiliary sources to full maintenance of plasma current by noninductive sources. Designing ITER to accommodate those end points permits future consideration of intermediate designs, tailored to new physical models as they become available.

The present work focuses on a quantitative estimate of the volt-seconds required for startup for both phases of the ITER device. The WHIST 1.5-D transport code is used to simulate the time-dependent behavior of the plasma, including beam-driven and bootstrap currents. No rf or lower hybrid current drive is assumed. Sawtooth disruptions are the only magnetohydrodynamic activity simulated, although a simple condition for ballooning stability is monitored. At each time step the profiles of toroidal current, electron and ion temperature, and deuterium and tritium densities are computed. The electron energy confinement is assumed to be governed by anomalous Goldston scaling with Chang-Hinton neoclassical ion conductivity. The flux surface equilibrium is updated periodically and the beam deposition solved in a fully three-dimensional geometry. A more extensive description of the models was published previously.[1,4]

Technology Phase

The following scenario for startup of the ITER Techology Phase device ($R = 5.5$ m, $a = 1.8$ m, $\kappa = 1.68$, $B = 5.3$ T, $I = 18$ MA) is intended to reduce volt-second consumption by reaching the operating point as quickly as possible with a full-radius startup while avoiding significant skin currents. The startup consists of a 50-s inductive current ramp followed by 10 s of combined inductive and noninductive current ramp. The current ramp rate is held at 0.2 MA/s over the whole interval. Figure 1(a) shows the average and peak electron and ion temperatures during the startup and the initial part of the burn. The average electron density [Fig. 1(b)] is ramped by gas puffing slowly enough to avoid thermal collapse due to line radiation but quickly enough to reduce the edge plasma temperature and increase the plasma resistivity, avoiding a buildup of skin current. At 50 s, the current reaches 14.5 of the required 18 MA, and there is no longer much advantage in keeping the temperature low. At this point, 90 MW of 1-MeV beams are turned on and the density ramp rate is increased sharply for the next 10 s. At 60 s, the operating point is reached, and the current is then maintained noninductively by the beams for the duration of the simulation.

The poloidal flux required during the startup and initial burn is shown in Fig. 1(c). The individual terms are derived from a Faraday's law representation in which

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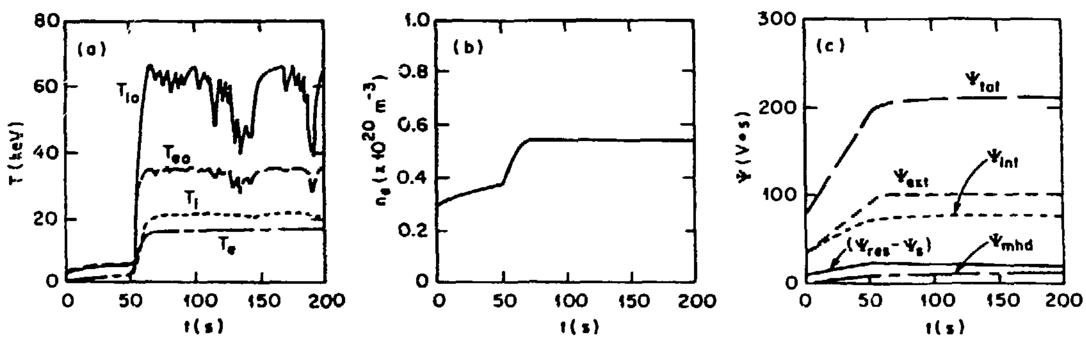

Fig. 1. Technology Phase startup evolution of (a) temperature, (b) average electron density, and (c) volt-second requirements.

$$\Psi_{tot} = \Psi_{int} + \Psi_{ext} + \Psi_{mhd} + \Psi_{res} - \Psi_s ,$$

where Ψ_{tot} is the total magnetic flux supplied by the transformer core, Ψ_{int} is the poloidal flux in the plasma, Ψ_{ext} is the external flux, Ψ_{mhd} is the flux dissipated as a consequence of sawteeth, Ψ_{res} is the resistive flux loss, and Ψ_s is the current source term. About 203 V·s is required to reach the operating point, of which about 31 V·s is dissipated by plasma resistivity and sawteeth. The flux savings due to turning on the beam prior to the end of the current ramp were on the order of 3.1 V·s. This is due primarily to reduced resistance from heating and not to beam-driven current.

Figures 2(a) and 2(b) show the evolution of the profiles of electron temperature and density, respectively. Sawtooth activity begins to be visible at about 25 s, when the current is around 11 MA. The electron density is centrally peaked because of deuterium from the beams after they are turned on at 50 s.

The total toroidal current density profile is limited in the core by the sawtooth model, as shown in Fig. 2(c). The current ramp is slow enough to avoid skin currents. Note that the source current density from beam injection [Fig. 2(d)] is more peaked than the total current density and actually is much larger than the total current density on axis. Such a case results in a negative emf in the plasma core,

$$E = \eta \, (J_{total} - J_{source}) .$$

The total current density tries to respond on a resistive time scale by becoming more peaked, but sawteeth prevent the central current density from increasing for very long. The whole picture is complicated by bootstrap currents, which contribute to the source term in a way that depends on the local density and temperature gradients.

The volt-second consumption by sawteeth could be reduced if the source current density could be flattened sufficiently, perhaps by aiming the beams a little farther away from the axis. In the present cases, the beam is injected at a 4.6° angle to the horizontal midplane, and it crosses the midplane 0.8 m inboard of the major radius. For these simulations, no effort was made to eliminate sawteeth by varying the injection geometry, although we have demonstrated elsewhere that this is possible to some degree.[5] In general, the optimum injection geometry depends on the plasma density; one must consider whether the shinethrough during startup is too large, as well as whether the current source profile is too peaked. The addition of lower hybrid or other current-broadening sources would permit an optimal current source profile to be achieved more easily.

At steady state, beta is near the critical value (4.7%), and $Q \cong 5$. The bootstrap effect provides about 10% of the total current, and the current drive efficiency is around 0.2 A/W.

Physics Phase

For the ITER Physics Phase ($R = 5.8$ m, $a = 2.2$ m, $\kappa = 1.88$, $B = 5.0$ T, $I = 22$ MA), the current is ramped at the same rate as for the Technology Phase but is continued out to 80 s to achieve the operating current of 22 MA. After full current is achieved, 50 MW of 1-MeV beams is turned on for 20 s. Figure 3(a) shows the average and peak electron and ion temperatures during the startup and the initial part of the burn. The average electron density [Fig. 3(b)] is ramped to encourage current penetration without causing a thermal collapse, as described in the preceding section. At 100 s, the ignited operating point is reached and no further beam heating is required.

The poloidal flux required during the startup and initial burn is shown in Fig. 3(c). About 270 V·s is required to reach the operating point, of which about 58.7 V·s was dissipated by plasma resistivity and sawteeth. The sawtooth contribution is larger than that for the Technology Phase because of the higher current, which tends to decrease q on axis. During the burn, flux is dissipated at about 0.06 (V·s)/s, which must be supplied inductively. This should be regarded as an estimate; evaluating accurately the rate of flux dissipation over many hundreds of sawtooth periods while incorporating the slow relaxation of the current profile is a numerically difficult problem that is sensitive to the physical details of the sawtooth model.

Figures 4(a) and 4(b) show the evolution of the profiles of electron temperature and density, respectively. Sawtooth activity is clearly visible by about 40 s, corresponding to a plasma current of about 14 MA. Since the beam power is lower than that for the Technology Phase, the fueling by the beam is less. This lower beam fueling, together with the broader sawtooth region due to the higher operating current, prevents peaking of the density profile.

The total toroidal current density profile [Fig. 4(c)] shows no significant effect from the source due to beam heating [Fig. 4(d)]. The source is much smaller than that for the Technology Phase because of the reduced beam power and the higher target plasma density.

At the operating point, beta is near the critical value (6%), and the bootstrap effect provides about 14% of the total current.

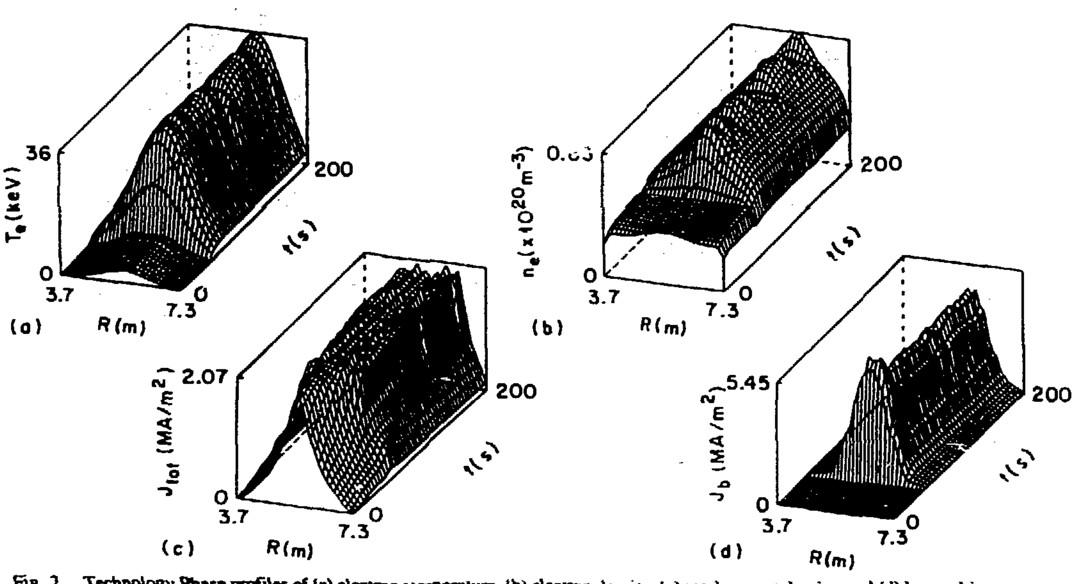

Fig. 2. Technology Phase profiles of (a) electron temperature, (b) electron density, (c) total current density, and (d) beam-driven current density vs time.

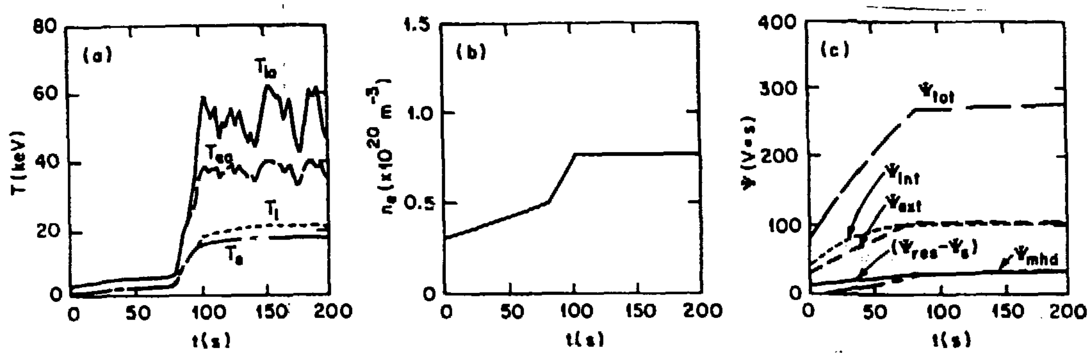

Fig. 3. Physics Phase startup evolution of (a) temperature, (b) average electron density, and (c) volt-second requirements.

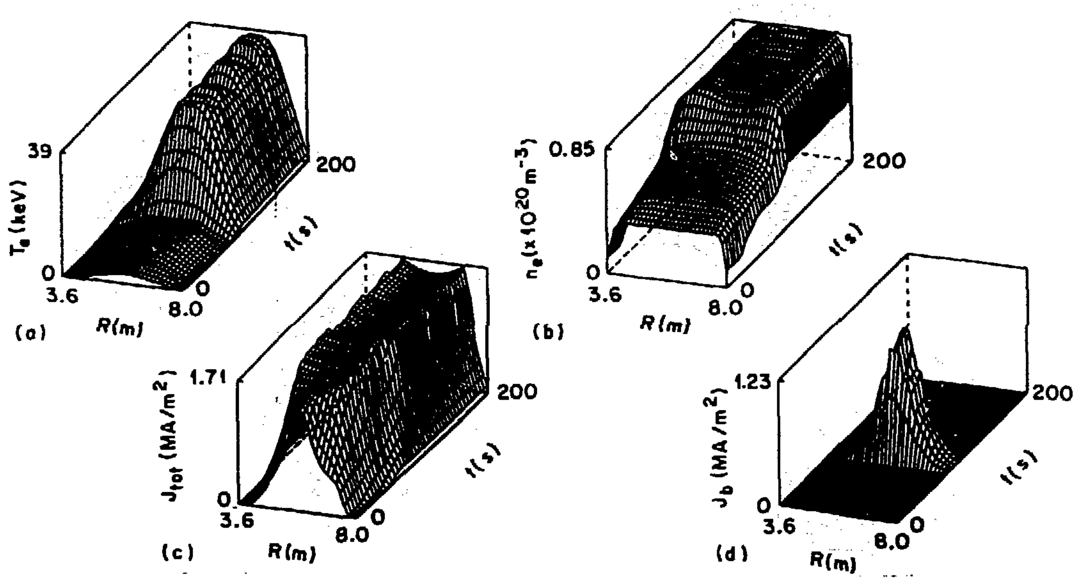

Fig. 4. Physics Phase profiles of (a) electron temperature, (b) electron density, (c) total current density, and (d) beam-driven current density vs time.

Conclusions

The two ITER phases represent the end points of a range of potentially interesting devices, from no auxiliary sources to full maintenance of plasma current by noninductive sources. Designing ITER to accommodate these end points permits future consideration of intermediate designs, tailored to new physical models as they become available.

The leading candidates for current drive—neutral beams and lower hybrid—are inefficient at low plasma temperature. The efficiencies of all known noninductive schemes are much less than the efficiency of inductive current drive, which is around 19 A/W for the Technology Phase operating point.[4] Therefore, a predominantly inductive startup seems to be necessary. In such a startup, most of the volt-seconds needed to establish the operating point are retained in the poloidal magnetic field and represent an irreducible minimum investment of flux.

Assuming a fixed-radius startup, the current must be ramped slowly in order to avoid hollow current density profiles. This results in dissipation of about 15 or 20% of the volt-seconds invested.

Neutral beams have not been observed to significantly reduce the volt-seconds required to reach the operating point. For this reason, the volt-second requirements for startup of both ITER phases are similar, except that the Physics (ignited) Phase operates at a higher current with proportionately higher volt-second requirements.

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