Topic: EX

Scaling and Modeling Studies of High-Bootstrap-Fraction Tokamaks*

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A steady-state tokamak reactor must rely on the bootstrap current for nearly all of its toroidal current. This contrasts with many fully non-inductive discharges reported in the literature [1-7] where the bootstrap fraction lies near 50%–70%, with radio-frequency or directed neutral beam power providing the remainder of the plasma current. Indeed, since the current drive associated with auxiliary power heating is often comparable or greater than the bootstrap current, the bootstrap fraction must be less than unity by simple definition [5,6].

This paper addresses, via a simplified, circular-cross-section model, the transport scaling of bootstrap-only discharges for which the auxiliary power source has no direct current drive capability. Examples are thermonuclear reactions, perpendicular electron cyclotron heating , and fast wave heating with a balanced spectrum. For such power sources, bootstrap current is the only source for a steady-state poloidal field so the steady-state bootstrap fraction will be unity. These discharges require $\beta_\theta = 2.4(R/a)^{0.5}/C_{bs}$ where $C_{bs} \approx (0.8+4.0\eta)/(1+\eta)$ and $\eta=(T/n)(dn/dT)$ represent the role of the density gradient as a bootstrap current source. The key scaling results are

$$T_{keV}(0)^{3/2} = 1.3\ P_{MW}\left(\frac{R}{a}\right)^{1/2} C_{bs} \qquad I_{p,MA} = (0.23)\,(C_{bs})^{5/6}\,(n_{19})^{1/2}\,(P_{MW})^{1/3} a_m \left(\frac{a}{R}\right)^{1/12} \quad . (1)$$

Transport in high-bootstrap-fraction discharges involves strong coupling between slow, classical poloidal diffusion and rapid anomalous heat diffusion as illustrated in Fig. 1. The coupling lies in the poloidal field dependence of the anomalous heat diffusivity. Consequently, the pressure profile and bootstrap current density depend on poloidal field and magnetic shear.

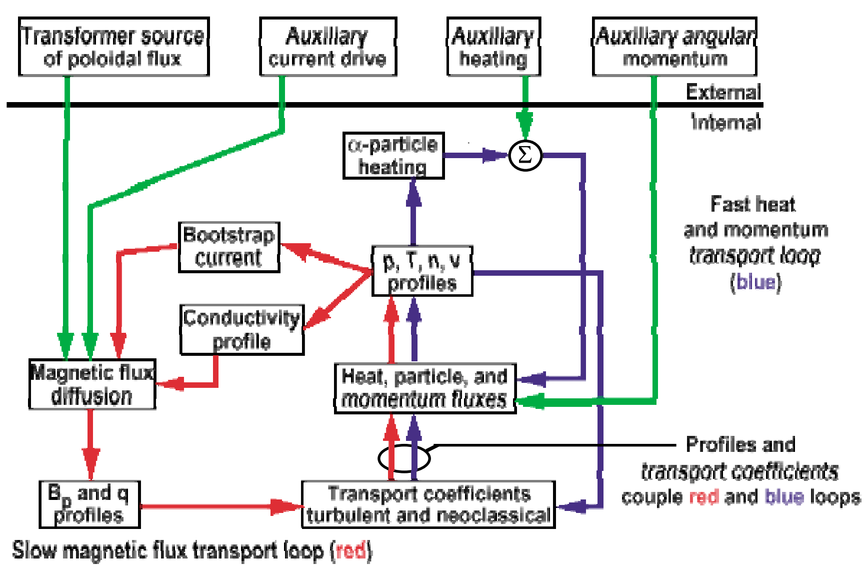

FIG. 1. Coupling of (fast) heat diffusion and (slow) magnetic diffusion processes.

Our simplified model consists of a nested circular flux surface tokamak in a time-asymptotic limit where both diffusion loops have reached a steady solution. The source for the poloidal field is the bootstrap current. Motivated by experiment, the anomalous radial heat diffusivity χ is constructed to have the following properties, 1) gyroBohm scaling, 2) dependence only on the poloidal field and 3) a characteristic gradient scale length of L_T. Power deposition is centralized to a region of radius $\Delta << a$, and a normalization constant $C_\chi \approx 0.05$ adjusted to fit the confinement time of recent high-β_p discharges on DIII-D exemplified by Fig. 2. In physics units, the model system is

$$\frac{\partial}{r\partial r}\left(rB_\theta\right) = \mu_o j \qquad\qquad j = \left(\frac{r}{R}\right)^{1/2} C_{bs}\,\frac{n_e}{B_\theta}\left(\frac{dT}{dr}\right) \tag{2}$$

$$\frac{\partial}{r\partial r}\left(r\,n\,\chi\,\frac{\partial T}{\partial r}\right) = Q = \frac{P}{2\pi^2 R\Delta^2}\left\{\frac{\Delta^2}{\Delta^2 + r^2}\right\}^2 \qquad\qquad \chi = C_\chi\,\frac{T^{3/2} r^2 M^{1/2}}{e^2 B_\theta^{\,2} R^2}\left\{\frac{1}{T}\left(\frac{\partial T}{\partial r}\right)\right\} \tag{3}$$

Casting these equations into nondimensional form reduces the problem to a second-order differential eigenvalue equation for relative profiles and the scaling relations of Eq.(1). It is interesting that the central temperature depends only on the driving power level, and not on density, device size, or applied toroidal field. For the model diffusivity of Eq. (3), The relative q profile is quite flat with $q(a)/q(0) \approx 2$. The pressure profile is triangular. Also note that $\beta_{tor} \propto \beta_p\,(a/qR)^2$.

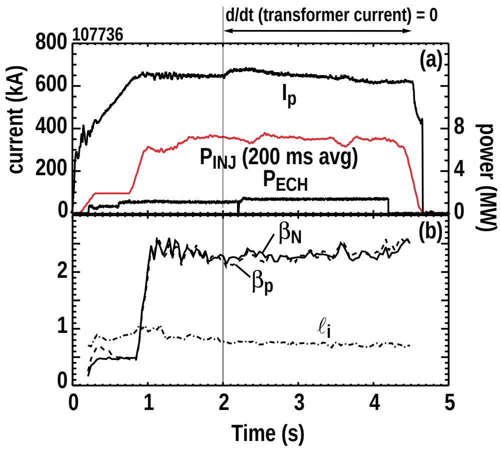

FIG 2.. Nearly stationary discharge for over 2 s at high beta (107736). (a) Plasma current, NB power (200 ms average; the power is modulated to maintain constant stored energy), and EC power. The transformer current is fixed from 2.0 s onward. (b) β_N, β_p, and l_i. β_N is held constant by the NB feedback control. There is a very slow broadening of the current profile indicated by the decreasing l_i.

Tokamak discharges with bootstrap-only current are planned for the near future, using ECH for DIII-D and ICRF for C-Mod. Data displayed in Fig. 2 and other discharges in the literature [4,6,7] indicate that such discharges should be stable at the β_θ value ($\beta_\theta = 2.4(R/a)^{0.5}/C_{bs}$) required for a bootstrap-only discharge.

Conclusion. Performance of a high-bootstrap-fraction tokamak reactor will be governed by the scaling relations (1) and will have profiles determined by nondimensional equations. Additional investigations will generalize to shaped discharges in full toroidal geometry, assess the effect of critical temperature gradients and magnetic shear on diffusivity and profiles, and determine β limits for these profiles and their generalizations. These generalizations will not affect the fundamental scaling properties of Eq. (1). Plans call for comparison with ECH/DIII-D and ICRF/C-Mod data where auxiliary power has no direct current drive. Estimates based on Eq. (1) are T(0) = 2.5 keV and I_p = 0.2 MA.

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