

**Kleva and Guzdar Reply:** In our Letter on  $\beta$  limit disruptions in tokamaks [1], we presented nonlinear MHD tokamak simulations in which confinement is destroyed by fingers of hot plasma (Fig. 1 of [1]) driven by coherent vortex flows [Fig. 2(c) of [1]]. In contrast, Park *et al.* [2] claim that in their simulations there is a “fragmentation of pressure contours . . . due to fast thermal conduction along the stochastic magnetic field lines” (Ref. [2], p. 1764 and Fig. 4). The hot fingers in our simulations jet across the field lines, as we stated in Ref. [1]. As the fingers grow, the gradients steepen nonlinearly over a short scale length. Over these short scales the resistivity is effective in decoupling the fluid and the magnetic field. In fact, the size of the scale length is determined by the dissipation: the gradients steepen until the diffusion becomes large enough to balance the nonlinear steepening. This process does not require magnetic reconnection or a change in magnetic topology. Since the scale length is set by the dissipation, nonideal effects (including the electron mass) cannot be ignored. In Fig. 4 of [1] we showed that the growth rate of the fingers in our simulations does not decrease as the dissipation is reduced. Although the scenario of flux surface destruction and stochasticity proposed in Ref. [2] depends on the resistivity, and the reconnection rate decreases as the resistivity is reduced, the magnitude of the resistivity used in the simulation is not disclosed in Ref. [2].

In our simulation (Ref. [1], Fig. 1), it takes approximately 20  $\mu\text{sec}$  for the hot plasma fingers convecting from the center to first reach the wall. It takes somewhat longer for all the energy at the center to be convected to the wall. The time scale in our simulations is consistent with the experimental observation that “the thermal quench takes from one to several hundred  $\mu\text{s}$ ” (Ref. [3], p. 4218). Our simulations are the first in which the loss of energy is as rapid as is observed experimentally during disruptions. In contrast, the time scale in the simulation of Park *et al.* is not disclosed in Ref. [2].

The results presented in Figs. 1 and 2 of our Letter [1] show that confinement is destroyed by coherent vortex flows. These results were obtained from the MHD equations, which do not include the physics of parallel energy transport. Therefore, energy transport down stochastic field lines cannot possibly be the cause of the loss of confinement. Furthermore, when we include the physics of parallel transport in our simulations, we find that the convective loss of confinement is so fast that parallel energy transport cannot counteract it (Ref. [1], Fig. 5). Although Park *et al.* [2] claim that the thermal quench is caused by stochastic field lines, they do not present a Poincaré plot that demonstrates that all the flux surfaces are destroyed. The magnitude of the magnetic field perturbations in their simulation is also not disclosed in Ref. [3].

As we discussed in Ref. [1], the electron-ion (and electron-electron) collision time  $\tau_{ei} \approx 250 \mu\text{sec}$  in an

8 keV plasma. In hotter plasmas  $\tau_{ei}$  is even longer. The slowest thermal quench time reported in Ref. [3] is 400  $\mu\text{sec}$ ; all other disruptions had shorter quench times. Thus, central energy confinement is completely lost in one collision time or less. Most of the thermal energy in high- $\beta$  tokamaks resides in the ions and travels down the field lines at the ion thermal speed. On the short collisionless time scale of the quench, the electron energy cannot leave the plasma at the hot electron thermal speed because the plasma must remain quasineutral. As a hot central electron tries to move away from the more massive ions down a field line, an electric field is generated which slows down the electron and reduces its energy. Any other electron which tries to move up the field line to replace this electron is accelerated and gains energy. Thus, energy from the first electron is transferred to the electron that replaces it, and this energy remains in the center. A slow collisional diffusion of energy down a field line takes many collision times and cannot play a role in the thermal quench which is completed within one collision time. Experimental observations during  $\beta$  limit disruptions contradict the stochastic magnetic field model of Ref. [2]: “there is no evidence that islands or stochastic regions form” and “it does not appear that there is a flux reconnection at the time of the thermal quench” (Ref. [3], p. 4224).

The spectrum of growing ballooning modes of moderate toroidal mode number  $n$  in our simulations does indeed produce toroidally localized structures: The localization in toroidal angle is inversely proportional to the spectral width. The claim in Ref. [2] that the higher  $n$  modes are driven unstable by an  $n = 1$  mode is contradicted by the experimental observations. Prior to disruptions there are sometimes growing moderate  $n$  ballooning mode precursors with “no visible  $n = 1$  mode” (Ref. [3], p. 4224). Even when there are also  $n = 1$  precursors in addition to higher  $n$  modes, “there is no obvious correlation between the amplitude of the  $n = 1$  kink and the experimental growth rate of the ballooning mode” (Ref. [4], p. 2624).

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