

# Response to “Comment on ‘Magnetohydrodynamic simulations of direct current helicity injection for current drive in tokamaks’ ” [Phys. Plasmas 3, 1038 (1996)]

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In Ref. 1 we investigated dc helicity injection current drive by solving a set of resistive magnetohydrodynamic (MHD) equations in a circular, cylindrical configuration. Two of our results are that (1) current penetration is incomplete, and (2) penetration is accompanied by magnetic fluctuations with amplitude of order 1%. We believe the chosen MHD equations are highly relevant for two reasons. First, the resistive MHD equations are the basis for the Taylor relaxation and helicity balance arguments that underlie the proposals for a dc helicity injected tokamak.<sup>2,3</sup> Second, the equations and code that we employ have provided enormous insight into current profile relaxation and fluctuations in related situations, such as the reversed field pinch. The comment by Jarboe *et al.*<sup>4</sup> reports no error in the computation or any of our physics results. Their comment is devoted to a speculation that additional effects (toroidicity, Hall and rotamak effects, and Lundquist number scaling) will greatly and positively alter the two physics results cited above. Although they present neither experimental nor theoretical results to support their claims, we have no quarrel with their speculations since they are outside the scope of our work. Nonetheless, we respond to their comments below and clarify some misconceptions therein. Many of these points can only be settled by further research, such as that being carried out in the Helicity Injected Tokamak (HIT) experiment conducted by the authors of the comment.

(1) Jarboe *et al.* remark on toroidal effects. They note that in tokamaks with strong poloidal asymmetry (such as at a small aspect ratio) a hollow current profile can yield a hollow  $q$  profile, and that HIT data are consistent with such profiles. We are aware of this fact and agree with the implication that hollow, partly penetrated profiles can then be of fusion relevance. While it is interesting that HIT results are consistent with hollow current profiles, as observed in our computation, determining the influence of toroidicity on mode coupling and overall dynamics will require further computation.

(2) Jarboe *et al.* are misleading in their assertion of the importance of the Hall term relative to other terms in Ohm’s law. They mistakenly judge its importance by comparing it to the resistive term, which is important for the parallel component and permits magnetic reconnection. They also overlook the dominant fluctuation-induced  $\mathbf{V} \times \mathbf{B}$  term in Ohm’s law, which, indeed, is also large and competitive with the Hall term. The influence of the Hall term is a well-known,

unsolved issue. Computational results have shown that it can become large as viscosity is increased.<sup>5</sup> The only experimental input of which we are aware is a direct measurement of the Hall dynamo in the Madison Symmetric Torus (MST) reversed-field pinch, wherein the Hall dynamo ( $\mathbf{J} \times \mathbf{B}$  term) can account for no more than 25% of the fluctuation-driven current in the plasma edge.<sup>6</sup>

Jarboe *et al.* invoke the rotamak concept<sup>7</sup> to buttress their anticipation that the Hall term is significant. In the rotamak concept, externally driven waves produce current through the Hall effect associated with the wave fields. This has little to do with dc helicity injection, in which the fluctuations spontaneously arise from the current density gradient. Interestingly, the observed  $n = 1$  magnetic fluctuations in HIT with amplitudes between 1% and 10% appear to be consistent with our calculations.

The statement that “the lack of Hall terms has been used to explain differences between the fluctuations predicted by the code and those observed in quiescent reversed-field pinch (RFP) confinement experiments which have  $\Theta < 1.5$ ” refers to speculation following a very rough Lundquist number scaling inferred from computation.<sup>8</sup> Improvement in  $S$  scaling studies in both computation<sup>9,10</sup> and experiment has eliminated the discrepancy within the context of resistive MHD, although the issue of  $S$  scaling remains open.

(3) We agree that the scaling of helicity injection physics with  $S$  is an important issue, as we stress in our paper. Unfortunately, in both computation and present experiments, such as HIT, the  $S$  values are many orders of magnitude less than that of a reactor. In our paper we report a limited  $S$  scaling study, which implies that our results might not be greatly altered as  $S$  increases. In addition, extensive studies in the RFP indicate that the  $S$  values of the computation are sufficiently large that the fluctuations and relaxation are not resistively quenched. Nonetheless, resolution of this issue awaits further research.

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