

Montgomery expresses concern about the theoretical basis for predicting the performance of ITER, the planned international magnetic fusion energy experiment. He focuses specifically on the use of ideal (nondissipative) magnetohydrodynamics (MHD) as the zeroth-order description of equilibrium in magnetically confined plasmas. He correctly points out that such an ordering is not generally possible in the mechanics of neutral fluids.

Although in principle that concern could be legitimate, in practice a wide range of experiments has confirmed that the ideal MHD model excellently describes the equilibrium of high-temperature magnetically confined plasmas. Global and detailed local measurements of plasma equilibrium show excellent agreement with ideal theory. Fast instabilities are also well described by ideal theory; slower, dissipative instabilities require more elaborate description, but under the usual operating conditions, the basic ordering that starts from ideal equilibrium is not violated. Ideal MHD calculations are routinely used in major magnetic confinement experiments to assemble and interpret measurements of magnetic fields, pressure gradients, and flow speeds, and to predict stability boundaries. Those MHD codes track experimental behavior consistently and in detail.

Why does ideal MHD provide a legitimate zeroth-order description of magnetically confined plasmas? The answer is tied to researchers' broad success in using magnetic fields to confine plasmas in relatively quiescent states free of large-scale MHD instability. By contrast, the evolution of globally turbulent *neutral* fluids depends on a dynamic balance between ideal forces, acceleration, and dissipation. In magnetically confined plasmas, the ideal equilibrium forces— $\mathbf{j} \times \mathbf{B}$, ∇p , and to a lesser degree $\rho(\mathbf{v} \cdot \nabla)\mathbf{v}$ —are measured to balance each other and dominate strongly over acceleration and nonideal dissipation terms, confirming experimentally the ordering procedure that Montgomery questions. Violation of that ordering corresponds to global acceleration on an ideal MHD time scale, and so to rapid plasma loss, which is observed only under circumstances in which ideal MHD stability is compromised. Even Montgomery's model calculations support the use of an ordering that starts from ideal equilibrium MHD, since the results he displays show a very low flow speed, in the range of 1 m/s.

One of the most exciting developments in fusion-energy research over the past decade has been the increasing agreement between magnetized plasma

theory and confinement experiments. Recent progress in achieving predictive understanding of confined plasma behavior seems to us, an experimentalist and a theorist, truly remarkable. Theory—including MHD theory, more elaborate fluid models, and fully kinetic plasma descriptions—does not play a “decorative” role today in high-temperature plasma physics; such tools provide an essential guide in the design and execution of experiments. Theory and advanced computing, particularly through the US Department of Energy's Scientific Discovery Through Advanced Computing and Leadership-Class Computing initiatives, are key elements of US preparations for ITER operation.

Robert J. Goldston

(rgoldston@pppl.gov)
Princeton Plasma Physics Laboratory
Princeton, New Jersey

Richard D. Hazeltine

(rdh@physics.utexas.edu)
Institute for Fusion Studies
University of Texas at Austin

Montgomery replies: It isn't easy to reply to citation-free claims about physics projects that assert “broad successes,” but that is apparently what has to be done when tweaking the controlled fusion program. A first point to be made is that fundamental properties of differential equations are not trivially changed by “ordering” the terms, particularly when the ordering involves dropping those terms with the highest numbers of derivatives. Then even the boundary conditions necessary to determine a solution change. One way to see this would be to try to re-derive the results of our nonideal toroidal steady-state calculation¹ from a perturbation series that starts with ideal MHD.

As far as the alleged differences between MHD and fluid dynamics go, the mechanics of rotating fluids (as in oceans and atmospheres) are actually not that much different. The role of MHD Lorentz forces gets taken over to a large degree by the Coriolis force. The principal results that emerge in geostrophic flow, Ekman circulation, thermal convection, and so on would all be impossible without the inclusion of dissipation coefficients at crucial places in the essential nonideal aspects of the phenomena.²

I would say that whether flows of meters per second amount to a serious threat for ITER likely depends on the geometry of the flow in a cross section of the toroid. A simple poloidal rotation of that magnitude might be no problem; but a dipolar flow pattern whose streamlines connect the hot geometrical center with the cool perimeter could be a disaster. In our article for the *Journal of Plasma*

Physics, Leon Kamp and I found a transition from the second behavior to the first as the shape of the cross-sectional boundary and the Hartmann number were varied.¹ Is that result in dispute?

References

1. L. P. J. Kamp, D. C. Montgomery, *J. Plasma Phys.* **70**, 113 (2004).
2. See, for example, H. P. Greenspan, *The Theory of Rotating Fluids*, Cambridge U. Press, Cambridge, UK (1968); J. Pedlosky, *Geophysical Fluid Dynamics*, Springer-Verlag, New York (1979).

David Montgomery

Dartmouth College
Hanover, New Hampshire

Wilczek responds on absolute units

In my essay “On Absolute Units, II: Challenges and Responses” (PHYSICS TODAY, January 2006, page 10), in the first column, the ratio between the fundamental mass scales in strong and Planck units should read $M_{\text{strong}}/M_{\text{Planck}} \equiv \sqrt{m_p^2 G/\hbar c}$.

In the second column, the ratio between the fundamental mass scales in atomic and Planck units should read $M_{\text{atomic}}/M_{\text{Planck}} \equiv \sqrt{m_e^2 G/\hbar c}$.

Frank Wilczek

Massachusetts Institute of Technology
Cambridge

Correction

April 2006, page 84—Nicholas A. Peppas, Fletcher S. Pratt Chair of Chemical and Biomedical Engineering; director of the Laboratory for Biomaterials, Drug Delivery, Bionanotechnology, and Molecular Recognition; and director of the NSF program on cellular and molecular imaging for diagnostics and therapeutics, all at the University of Texas at Austin, is among the new members elected this year to the National Academy of Engineering. ■

Rights & Permissions

You may make single copies of articles or departments for private use or for research. Authorization does not extend to systematic or multiple reproduction, to copying for promotional purposes, to electronic storage or distribution (including on the Web), or to republication in any form. In all such cases, you must obtain specific, written permission from the American Institute of Physics.

Contact the

AIP Rights and Permissions Office,
Suite 1N01,

2 Huntington Quadrangle,
Melville, NY 11747-4502

Fax: 516-575-2450

Telephone: 516-576-2268

E-mail: rights@aip.org