Forced magnetic reconnection

J. Birn,[1] K. Galsgaard,[2] M. Hesse,[3] M. Hoshino,[4] J. Huba,[5] G. Lapenta,[1] P. L. Pritchett,[6] K. Schindler,[7] L. Yin,[1] J. Büchner,[8] T. Neukirch,[9] and E. R. Priest[9]

Received 22 November 2004; revised 2 February 2005; accepted 21 February 2005; published 25 March 2005.

[1] Using a multi-code approach, we investigate current sheet thinning and the onset and progress of fast magnetic reconnection, initiated by temporally limited, spatially varying, inflow of magnetic flux. The present study extends an earlier collaborative effort into the transition regime from thick to thin current sheets. Again we find that full particle, hybrid, and Hall-MHD simulations lead to the same fast reconnection rates, apparently independent of the dissipation mechanism. The reconnection rate in MHD simulations is considerably larger than in the earlier study, although still somewhat smaller than in the particle simulations. All simulations lead to surprisingly similar final states, despite differences in energy transfer and dissipation. These states are contrasted with equilibrium models derived for the same boundary perturbations. The similarity of the final states indicates that entropy conservation is satisfied similarly in fluid and kinetic approaches and that Joule dissipation plays only a minor role in the energy transfer. **Citation:** Birn, J., et al. (2005), Forced magnetic reconnection, *Geophys. Res. Lett.*, *32*, L06105, doi:10.1029/2004GL022058.

1. Introduction

[2] Magnetic reconnection is one of the most intriguing plasma processes, enabling the rapid conversion of excess magnetic energy into plasma heating, particle acceleration, and fast plasma flows, associated, for instance, with magnetospheric substorms and solar flares. A major challenge in investigating reconnection stems from the large discrepancy between the size of the energy release region (say, 100,000 km in the solar atmosphere as well as in the Earth's magnetosphere) and the small ion and even electron inertia or gyro scales involved in breaking the frozen-in field condition in highly conducting, collisionless, space and astrophysical plasmas (say, a few hundred km or less in the magnetosphere and 0.1 m in the solar atmosphere).

[3] Recently, a collaborative effort, termed the "Geospace Environment Modeling (GEM) Reconnection Challenge" [*Birn et al.*, 2001], investigated magnetic reconnection by a variety of simulation approaches, including resistive MHD, Hall-MHD, hybrid simulations (treating electrons as a fluid but ions as particles), and fully electromagnetic particle-in-cell (PIC) codes. All simulations addressed the same initial state, a plane current sheet separating antiparallel magnetic fields [*Harris*, 1962]. Reconnection was initiated by a finite initial magnetic field perturbation, creating magnetic islands and x-type neutral points. The surprising result of these simulations was that all approaches that included the Hall electric fields led to the same fast reconnection rates, independent of the dissipation mechanism. In contrast, resistive MHD simulations using typical (albeit ad hoc) resistivity values with Lundquist numbers $S \gg 1$ resulted in much slower reconnection rates, which depend on the resistivity. The MHD models achieved fast reconnection only when localized resistivity models with maximum values corresponding to Lundquist numbers of order unity were used. Since the Hall-term was the common factor in all simulations that achieved fast reconnection, the underlying mechanism was attributed to the dispersion properties of whistler waves, enabled by the Hall term.

[4] The GEM studies started from an initial current sheet with a half-thickness of 1/2 proton inertia length, and the initial perturbed state contained magnetic islands and x-points, without considering how this configuration was achieved. It seems quite obvious that the onset of fast magnetic reconnection requires a transition from a wider current sheet, which is either stable or undergoes considerably slower reconnection, to a thin one, driven by external or internal processes. The present study investigates this transition regime, where differences between fluid and kinetic approaches might become important. For comparison with the earlier results, we use again the one-dimensional initial Harris sheet. Current sheet thinning is forced by imposing a finite deformation of the field above and below the current sheet, resulting from plasma inflow over a limited time. This approach is motivated by simulations and equilibrium studies that demonstrate that thin current sheets can form in the magnetotail as a consequence of magnetopause boundary deformations as caused by solar wind interaction [e.g., *Schindler and Birn*, 1993; *Hesse et al.*, 1996].

[5] The study grew out of a collaboration during a workshop on Magnetic Reconnection Theory, held in August 2004 at the Isaac Newton Institute, Cambridge, England, and was therefore dubbed the "Newton Challenge." The basic problem is also known as "Taylor's problem" and has been well studied by small-perturbation equilibrium

[1] Los Alamos National Laboratory, Los Alamos, New Mexico, USA.
[2] Niels Bohr Institute for Astronomy, Physics and Geophysics, Copenhagen, Denmark.
[3] NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[4] Department of Earth and Planetary Physics, University of Tokyo, Tokyo, Japan.
[5] Naval Research Laboratory, Washington, DC, USA.
[6] Department of Physics and Astronomy, University of California, Los Angeles, California, USA.
[7] Institut für Theoretische Physik, Ruhr-Universität Bochum, Bochum, Germany.
[8] Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany.
[9] School of Mathematics and Statistics, University of St. Andrews, UK.

0094-8276/05/2004GL022058

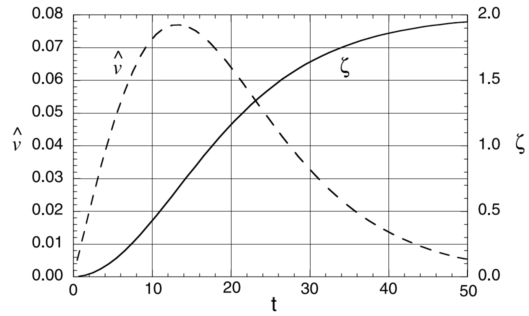

Figure 1. Time variation of the maximum boundary inflow speed $\hat{v}$ and the resulting inward displacement $\zeta(t) = \int \hat{v}(t)dt$.

theory as well as resistive MHD approaches [e.g., *Hahm and Kulsrud*, 1985; *Fitzpatrick*, 2003]. However, the present problem, defined in section 2, differs from these studies in several aspects. The most important one is the larger system size relative to the initial current sheet thickness. This has important consequences for the structure and accessibility of new equilibrium states (section 3) as well as for the stability and energy release driving reconnection (section 4).

2. Definition of the "Newton Challenge"

[6] The initial state is a Harris sheet [*Harris*, 1962], as in the GEM reconnection challenge, with magnetic field and plasma density given in magnetospheric coordinates by

$$B_x = B_0 \tanh(z/L) \tag{1}$$

$$n = n_0 / \cosh^2(z/L) + n_b \tag{2}$$

In contrast, however, the current sheet half-width L is larger by a factor of 4, that is $L = 2\ \lambda_i$, where $\lambda_i = c/\omega_{pi} = (m_i/\mu_0 n_0 e^2)^{1/2}$ is the ion inertia length. We include again a background density $n_b = n_0/5$ and assume a temperature ratio $T_i/T_e = 5$. The system size is slightly larger than in the GEM study, given by $-16 < x/\lambda_i < 16$, $-8 < z/\lambda_i < 8$.

[7] In the following we will use dimensionless quantities, based on the magnetic field strength B_0, the ion inertia length λ_i, the density n_0, and the ion cyclotron period $1/\omega_{ci} = m_i/eB_0$. The time dependent boundary conditions are characterized by a prescribed plasma inflow through the boundaries $|z| = z_{\max} = 8$, given by

$$v_z = \mp\hat{v}(t)\cos^2(\pi x/16) \qquad \text{for} \qquad z = \pm 8 \tag{3}$$

$$\hat{v}(t) = d\zeta/dt = 2a\omega\tanh(\omega t)/\cosh^2(\omega t) \tag{4}$$

$$\zeta(t) = a\tanh^2(\omega t) \tag{5}$$

The inflow velocity amplitude $\hat{v}$ and the corresponding displacement ζ are shown in Figure 1 as functions of time, for the parameters $a = 2$ and $\omega = 0.05$. The parameter a regulates the boundary deformation (or rather the deformation of a field line that initially forms the boundary at $z = z_{\max}$). The chosen value corresponds to an inward motion by a maximum of about 2 units, causing a magnetic field enhancement of about 25%. This is quite reasonable for the increase of the lobe field in the Earth's magnetotail during the substorm growth phase. (The actual displacement might be somewhat larger, mainly due to the onset of reconnection, which causes further inward flux transport.) In the PIC simulations the inflow condition was implemented by a prescribed boundary electric field E_y, rather than a flow speed.

[8] The parameter ω governs the time scale of the applied inflow. The chosen value leads to a maximum inflow speed of 0.08 (in units of the typical Alfvén speed) at $t \approx 13$, and the inflow subsides after $t \approx 60$. This characteristic time scale is sufficiently large compared to the characteristic Alfvén time, so that wave fluctuations remain relatively small, but, as it turns out, shorter than the typical system response time. It also keeps the length of particle simulations within reasonable time limits. Periodic boundary conditions were employed at $x = 0$ and $x = x_{\max}$. MHD runs using line-tying solid wall boundary conditions instead, and a PIC run with open outflow boundaries showed little effect on the dynamic evolution.

3. Neighboring Equilibria and Final State

[9] Before considering the dynamic evolution it is instructive to follow the procedure of *Hahm and Kulsrud* [1985] for Taylor's problem in looking for equilibrium solutions for a perturbed boundary satisfying the Grad-Shafranov equation

$$-\nabla^2 A = dp(A)/dA \tag{6}$$

Here A is the flux function (y component of the vector potential), defining the magnetic field $\mathbf{B} = \nabla \times [A(x, z)\mathbf{e}_y]$, and $\mathbf{e}_y$ is the unit vector in the y direction. It is easy to verify that Hahm and Kulsrud's solution corresponds to the case where $p(A)$ remains unchanged from the unperturbed case. We note here that the dynamic approaches described in section 4 do not satisfy this condition; a more appropriate equilibrium approach should impose conservation of entropy rather than of the pressure distribution. However, this approach has not been developed far enough yet. We therefore studied the equilibrium problem under the conservation of the function $p(A)$, which nevertheless provides insights into the differences from the Hahm and Kulsrud studies.

[10] Figure 2 shows equilibrium configurations obtained for the same pressure function $p(A)$ as the initial Harris sheet but using a perturbed flux distribution at the boundaries $z = \pm 8$, which would result for $t \to \infty$ from the inflow given by (3). Configurations (a) and (b) are equivalent to the two solutions obtained by *Hahm and Kulsrud* [1985] for small perturbations. Configuration (a) has the same topology as the original Harris sheet but contains a surface current at $z = 0$. Configuration (b) is characterized by a continuous current distribution but changed topology. This configuration differs from the

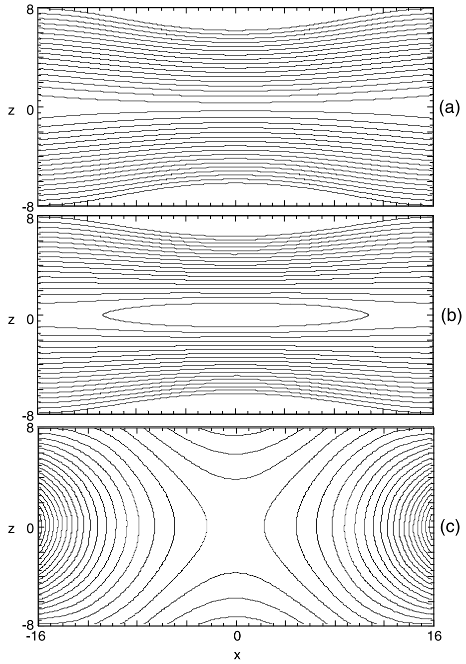

Figure 2. Equilibrium configurations for the same pressure function $p(A)$ as the initial Harris sheet but perturbed flux at $|z| = z_{\max}$, which is the same for all cases. (a) This configuration has the same topology as the initial Harris sheet but contains a surface current at $z = 0$. (b) This configuration is characterized by continuous current distribution but changed topology. (c) This is the lowest energy configuration under the given constraints.

corresponding one obtained by Hahm and Kulsrud as it contains a magnetic island in the region of strongest compression rather than an x-point.

[11] This is due to the fact that our system width in z is large compared to the current sheet width, whereas Hahm and Kulsrud considered a system with an initially uniform current distribution. If we also take into account that our characteristic scale in the x direction is much larger than the initial current sheet width, a configuration as shown in Figure 2b should satisfy approximate pressure balance in the z direction [*Birn et al.*, 1975]. This means that enhanced magnetic pressure outside the current sheet, resulting from flux addition, is balanced by enhanced plasma pressure inside the current sheet. Since the flux addition is largest at $x = 0$, the pressure should assume a local maximum at $x = 0$, $z = 0$. For a monotonic pressure function $p(A)$, such as the exponential $p = p_0 \exp(-2A)$ defining the Harris sheet, this implies that the flux variable A also should have a local maximum or minimum, that is, an o-type neutral point. Obviously, this configuration, which is a valid solution under the given boundary conditions, is nevertheless not accessible, as it requires the generation of new flux within the magnetic island.

[12] In contrast to Figure 2b, the configuration in Figure 2c, obtained by a numerical continuation method [*Neukirch and Hesse*, 1993], has the same x-type topology as the second solution derived by Hahm and Kulsrud. However, it is no longer a neighboring solution but deviates considerably from the initial state. It is fairly close to the current-free configuration for the same boundary distribution of A and represents the lowest energy configuration under the given constraints.

4. Dynamic Evolution

[13] The reconnection problem outlined in section 2 was studied dynamically by a variety of codes: MHD codes, using a resistivity model based on flow convergence [*Galsgaard*, 2000], or spatially localized but fixed resistivity (with maximum values $\eta_1 = 0.02$, and $\eta_1 = 0.005$) [*Birn et al.*, 1996], a Hall MHD code without explicit dissipation term [*Huba*, 2003], three different fully electromagnetic particle-in-cell codes [*Pritchett*, 2001; *Hesse et al.*, 2001; *Hoshino et al.*, 2001], an implicit particle code [*Lapenta and Brackbill*, 2000], and a hybrid code with dissipation associated with electron anisotropy [*Hesse et al.*, 1996; *Yin et al.*, 2001]. All particle simulations results shown here are obtained using an ion/electron mass ratio of $m_i/m_e = 25$.

[14] Figure 3 summarizes results from these simulations, showing the reconnected flux, defined as the integral over B_z between x- and o-point, as function of time. Obviously, all particle studies, as well as the Hall-MHD study show very similar reconnection rates, although the onset times differ, not only between different codes, but also for similar codes. All studies also show nearly the same final amount of reconnected flux. Three of the studies (Hesse, Pritchett, and Yin) show an interesting two-stage behavior with a weak increase following the initial strong increase. This needs further exploration.

[15] In contrast to the particle studies, the MHD simulations show reduced reconnection rates, which depend on the resistivity. The final amount of reconnected flux, however, is the same as in the particle and Hall simulations. Also the final configurations are surprisingly similar to the particle results. Figure 4 shows the magnetic field (contour lines) and current distributions (color coded) for late stages of three simulations indicated in the figure caption. (Others, not shown here, are similar.) They all show a current concentration in a ring around the o-point inside the

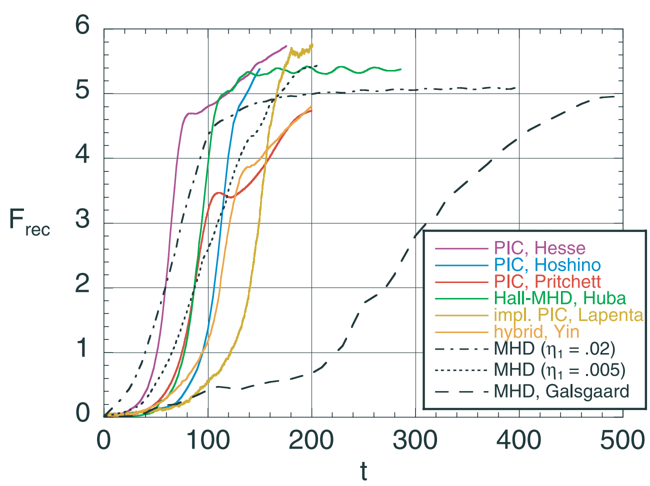

Figure 3. Time variation of the reconnected flux for various simulations of forced reconnection, as indicated.

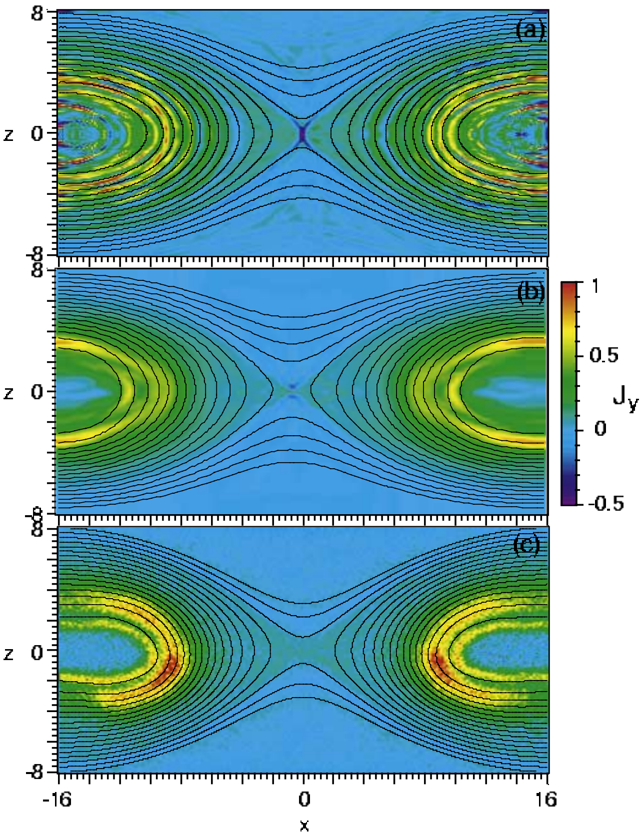

Figure 4. Late stages of the magnetic field (contour lines) and current distribution (color coded) for various simulations: (a) MHD simulations using spatially localized resistivity (J. Birn), (b) Hall-MHD simulation without explicit dissipation term (J. Huba), (c) PIC simulation (M. Hesse).

magnetic islands, although local details differ. The overall magnetic structure is similar to the lowest-energy equilibrium in Figure 2c.

5. Summary and Conclusions

[16] We have extended a multi-code approach akin to the GEM reconnection challenge [*Birn et al.*, 2001] to explore the initiation of fast reconnection by thinning of a relatively thick current sheet, four times as thick as in the GEM study. The thinning is forced by the application of spatially varying and temporally limited inflow from outside the current sheet, which causes local magnetic field enhancement of ~20–40%. The basic problem is known as Taylor's problem and has been studied extensively by equilibrium and resistive MHD approaches [e.g., *Hahm and Kulsrud*, 1985; *Fitzpatrick*, 2003].

[17] However, the present problem differs from those studies particularly by the larger system size, which permits the growth of unstable tearing modes and the release of free energy. Furthermore, our equilibrium studies indicate, that for small perturbations, neighboring equilibria with magnetic x-points at the location of strongest compression do not exist; the corresponding x-type, lowest-energy configuration deviates strongly from the initial state.

[18] Hence the configurations undergo drastic changes with fast reconnection rates, which are similar for all studies that include the Hall term, ~20–50% smaller than those in the GEM studies. Similar to that study, resistive MHD simulations show reduced reconnection rates that depend on the magnitude of the resistivity. However, significant reconnection rates were obtained also for MHD models with moderate, localized resistivity, smaller than those needed in the GEM studies.

[19] For similar compression, the final configurations are surprisingly similar for various methods, including MHD as well as PIC simulations. This indicates that entropy conservation operates similarly despite the fact that kinetic approaches include anisotropy, a different dissipation mechanism, and different waves not included in MHD and that Joule dissipation $\mathbf{E}' \cdot \mathbf{j}$ (where $\mathbf{E}'$ is the electric field in the plasma rest frame) is strongly localized and hence less significant than the adiabatic transport for the pressure distribution in the final state.

[20] **Acknowledgments.** The present work grew out of a collaboration during a workshop on Magnetic Reconnection Theory, held in August 2004 at the Isaac Newton Institute, Cambridge, England, organized by E. R. Priest, T. G. Forbes, and J. Birn and funded by the Isaac Newton Institute. The authors are particularly grateful to the Institute's Director, Sir John Kingman, the main organizer, Eric Priest, and the following participants, who provided very helpful discussions: A. Bhattacharjee, J. Dorelli, J. Drake, T. Forbes, M. Scholer, M. Shay, and G. Vekstein. This research was also supported by the US Department of Energy's Office of Basic Energy Sciences, by the National Science Foundation, and by NASA's Sun-Earth Connection Theory and Supporting Research and Technology Programs.

References

Birn, J., R. Sommer, and K. Schindler (1975), Open and closed magnetospheric tail configurations and their stability, *Astrophys. Space Sci.*, *35*, 389.

Birn, J., F. Iinoya, J. U. Brackbill, and M. Hesse (1996), A comparison of MHD simulations of magnetotail dynamics, *Geophys. Res. Lett.*, *23*, 323.

Birn, J., et al. (2001), Geospace environment modeling (GEM) magnetic reconnection challenge, *J. Geophys. Res.*, *106*, 3715.

Fitzpatrick, R. (2003), A numerical study of forced magnetic reconnection in the viscous Taylor problem, *Phys. Plasmas*, *10*, 2304.

Galsgaard, K. (2000), Dynamical investigation of three-dimensional reconnection in quasi-separatrix layers in a boundary-driven magnetic field, *J. Geophys. Res.*, *105*, 5119.

Hahm, T., and R. Kulsrud (1985), Forced magnetic reconnection, *Phys. Fluids*, *28*, 2412.

Harris, E. G. (1962), On a plasma sheath separating regions of oppositely directed fields, *Nuovo Cimento*, *23*, 115.

Hesse, M., D. Winske, M. Kuznetsova, J. Birn, and K. Schindler (1996), Hybrid modeling of the formation of thin current sheets in magnetotail configurations, *J. Geomagn. Geoelectr.*, *48*, 749.

Hesse, M., J. Birn, and M. Kuznetsova (2001), Collisionless magnetic reconnection: Electron processes and transport modeling, *J. Geophys. Res.*, *106*, 3721.

Hoshino, M., K. Hiraide, and T. Mukai (2001), Strong electron heating and non-Maxwellian behavior in magnetic reconnection, *Earth Planets Space*, *53*, 627.

Huba, J. D. (2003), A tutorial on Hall magnetohydrodynamics, in *Space Plasma Simulations*, edited by J. Büchner, C. T. Dum, and M. Scholer, p. 170, Springer, New York.

Lapenta, G., and J. U. Brackbill (2000), 3d reconnection due to oblique modes: A simulation of Harris current sheets, *Nonlinear Processes Geophys.*, *7*, 151.

Neukirch, T., and M. Hesse (1993), Bifurcation analysis of a simple analytical model of self-propagating star formation, *Astrophys. J.*, *411*, 840.

Pritchett, P. L. (2001), Geospace Environment Modeling magnetic reconnection challenge: Simulations with a full particle electromagnetic code, *J. Geophys. Res.*, *106*, 3783.

Schindler, K., and J. Birn (1993), On the cause of thin current sheets in the near-Earth magnetotail and their possible significance for magnetospheric substorms, *J. Geophys. Res.*, *98*, 15,477.

Yin, L., D. Winske, S. P. Gary, and J. Birn (2001), Hybrid and Hall-MHD simulations of collisionless reconnection: Dynamics of the electron pressure tensor, *J. Geophys. Res.*, *106*, 10,761.

J. Birn, G. Lapenta, and L. Yin, Space and Atmospheric Sciences Group, Los Alamos National Laboratory, Los Alamos, NM 87545, USA. (jbirn@lanl.gov; lapenta@lanl.gov; lyin@lanl.gov)

J. Büchner, Max-Planck-Institut für Sonnensystemforschung, Max Planck Str 2, Katlenburg-Lindau D-37191, Germany. (buechner@mps.mpg.de)

K. Galsgaard, Niels Bohr Institute for Astronomy, Physics and Geophysics, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark. (kg@astro.ku.dk)

M. Hesse, NASA Goddard Space Flight Center, Code 696, Greenbelt, MD 20771, USA. (hesse@gsfc.nasa.gov)

M. Hoshino, Department of Earth and Planetary Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku Tokyo, 113 0033, Japan. (hoshino@eps.s.u-tokyo.ac.jp)

J. Huba, Naval Research Laboratory, MC 4780, 4555 Overlook Ave SW, Washington, DC 20375-5000, USA. (huba@ppd.nrl.navy.mil)

T. Neukirch and E. R. Priest, School of Mathematics and Statistics, University of St. Andrews, St. Andrews, KY16 9SS, UK. (thomas@mcs.st-and.ac.uk; eric@mcs.st-and.ac.uk)

P. L. Pritchett, Department of Physics and Astronomy, University of California, 405 Hilgard Ave, Los Angeles, CA 90095-1547, USA. (pritchet@physics.ucla.edu)

K. Schindler, Institut für Theoretische Physik, Ruhr-Universität Bochum, Bochum D-44780, Germany. (kschindler1@aol.com)