White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	July 23rd, 2015

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column.

Plasma Atomic physics and the interface with chemistry and biology	
Turbulence and transport	S
Interactions of plasmas and waves	S
Plasma self-organization	P
Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

Oral	
Poster	
Either Oral or Poster	
Will not attend	X

Title:	Advancements In Guide Field Reconnection Through Gyrokinetics
Corresponding Author:	M.J. Pueschel
Institution:	University of Wisconsin-Madison
email:	`mjp@physics.wisc.edu`
Co-Authors:	W. Dorland, F. Jenko, R. Numata, B.N. Rogers, P.W. Terry, D. Told

Frontier: kinetic physics in guide field reconnection

Reconnection of magnetic field lines in plasma is a ubiquitous phenomenon, affecting systems on vastly separated scales, from laboratory fusion experiments to the solar corona. Field line tearing can strongly influence plasma energetics and dynamics, and a thorough theoretical understanding of this process is of the utmost importance for both the fusion and space plasma communities.
Past research on reconnection has mostly focused on either reduced modeling[1–4] – MHD and two-fluid theories – or kinetic approaches with weak or no guide fields[5–7]. While this latter scenario is of great interest, the case where the background magnetic field dominates its fluctuations is of equal importance. However, fully kinetic simulations are limited by the scale separation between reconnection physics and cyclotron motion: as the magnetic guide field is increased beyond the reconnecting field, calculations soon become intractable, and gyrokinetics becomes the tool of choice.
Arguably, the most important physical systems where reconnection is being investigated are those where the guide field far exceeds any other magnetic fields:

1. **The solar corona heating problem**. For decades, the process by which the solar corona is able to maintain temperatures far above those on the surface of the sun has eluded researchers.

A primary candidate is magnetic reconnection, with kinetic-theory-based research requiring a multi-scale approach covering length scales bridging approximately eight orders of magnitude as well as time scales strongly separated due to a guide field larger than the reconnecting fields by a factor of about twenty.

2. **Tearing modes in fusion experiments**. Sawtooth oscillations and other reconnection-related events are known to have mostly deleterious effects on plasma confinement. A more encompassing approach will couple fluid and kinetic scales to study how such negative effects may be mitigated.

Other examples of astrophysical applications include magnetotail and bow shock reconnection or coronal mass ejections.
It is therefore essential – if these systems are to be fully understood – that research based on the gyrokinetic framework be allowed to build on recent advances and successes.

Next Steps Using Gyrokinetics

Devised specifically for the strong guide fields in fusion devices, gyrokinetics can be derived from the kinetic equations by a phase space average eliminating the fast gyromotion. For strong guide fields, speed-ups of many orders of magnitude are typically observed relative to kinetic approaches. In recent years, a growing number of gyrokinetic space- and astrophysical applications has been observed[8–18], among which reconnection-related research has been a central topic. It has been determined that gyrokinetic and kinetic codes produce results in good agreement given that the appropriate limits are fulfilled[17]. Contrary to fluid-theory-based expectations, reconnection can be enhanced in the presence of pressure gradients[15,18]. And a gyrokinetic study of turbulent reconnection in the solar corona suggests that this approach may be of central importance in solving the coronal heating problem[16].
Gyrokinetic research into reconnection physics is likely to produce much-needed answers in both areas outlined above:

1. After taking an intermediate step in answering questions related to the role of pressure gradients, geometry, and boundary conditions, gyrokinetic research will likely soon advance to the point where **direct simulation of the solar corona** with very little need for approximation will be possible. Thus, significant progress can be expected in understanding quantitatively to what degree magnetic reconnection contributes to coronal heating.

2. A full-physics description of tearing in fusion devices is a goal for the next decade of research. In the case of reversed-field pinches, multi-scale investigations will determine to what degree energy injected into small scales via a cascade of tearing mode energy is able to affect transport and profile evolution – for instance, via effects on zonal flows[19] – and thus have an impact on the original tearing mode.

Summary

The study of **magnetic reconnection in strong guide fields** promises to answer important questions related to fusion and space plasma behavior: a **multi-scale description of tearing modes** and a clear route to determining how much **reconnection-based heating occurs in the solar corona**. These questions can be addressed with the ideal tool for this task: gyrokinetics, a framework designed for retaining all relevant physical effects and extremely efficient when compared with fully kinetic approaches.

Furthermore, combining fusion and space applications provides great interdisciplinary potential: demonstrating that gyrokinetics is able to capture corona-relevant physics will lend additional credence to its predictions for future fusion reactors; and new post-processing diagnostics for space plasma investigations can simultaneously be used for fusion theory.

References

[1] A. Bhattacharjee, Y.-M. Huang, H. Yang, and B. Rogers, Phys. Plasmas **16**, 112102 (2009)

[2] D. Del Sarto, C. Marchetto, F. Pegoraro, and F. Califano, Plasma Phys. Control. Fusion **53** 035008 (2011)

[3] S. Servidio, A. Greco, W.H. Matthaeus, K.T. Osman, and P. Dmitruk, J. Geophys. Res. **116**, A09102

[4] E.G. Zweibel, E. Lawrence, J. Yoo, H. Ji, M. Yamada, and L.M. Malyshkin, Phys. Plasmas **18**, 111211 (2011)

[5] M. Swisdak, B.N. Rogers, J.F. Drake, and M.A. Shay, J. Geophys. Res. **103**, 1218 (2003)

[6] J.F. Drake, M. Swisdak, K.M. Schoeffler, B.N. Rogers, and S. Kobayashi, Geophys. Res. Lett. **33**, L13105 (2006)

[7] W. Daughton, V. Roytershteyn, H. Karimabadi, L. Yin, B.J. Albright, B. Bergen, and K.J. Bowers, Nat. Phys. **7**, 539 (2011)

[8] B.N. Rogers, S. Kobayashi, P. Ricci, W. Dorland, J. Drake, and T. Tatsuno, Phys. Plasmas **14**, 092110 (2007)

[9] R. Numata et al., Phys. Plasmas **18**, 112106 (2011)

[10] M.J. Pueschel, F. Jenko, D. Told, and J. Büchner, Phys. Plasmas **18**, 112102 (2011)

[11] O. Zacharias, R. Kleiber, and R. Hatzky, J. Phys. Conf. Series **401**, 012026 (2012)

[12] A. Ishizawa and T.-H. Watanabe, Phys. Plasmas **20**, 102116 (2013)

[13] N.F. Loureiro, A.A. Schekochihin, and A. Zocco, Phys. Rev. Lett. **111**, 025002 (2013)

[14] J.M. TenBarge and G.G. Howes, Astrophys. J. Lett. **771**, L27 (2013)

[15] S. Kobayashi, B.N. Rogers, and R. Numata, Phys. Plasmas **21**, 040704 (2014)

[16] M.J. Pueschel, D. Told, P.W. Terry, F. Jenko, E.G. Zweibel, V. Zhdankin, and H. Lesch, Astrophys. J. Suppl. Ser. **213**, 30 (2014)

[17] J.M. TenBarge, W. Daughton, H. Karimabadi, G.G. Howes, and W. Dorland, Phys. Plasmas **21**, 020708 (2014)

[18] M.J. Pueschel, P.W. Terry, D. Told, and F. Jenko, Phys. Plasmas **22**, 062105 (2015)

[19] D. Carmody, M.J. Pueschel, J.K. Anderson, and P.W. Terry, Phys. Plasmas **22**, 012504 (2015)