Cover Page

DOE Grant number: DE-SC0014528

Project Title: Turbulence Dynamics in the Presence of Flow Shear in a Collisional Plasma: Experiment-Model Cross-Validation

PD/PI Name: Mark Gilmore, Principal Investigator
Barrett N Rogers, Co-Principal Investigator

Recipient Organization: University of New Mexico, Dartmouth College

Project/Grant Period: 09/01/2015 - 08/31/2018

Reporting Period: 09/01/2017 - 08/31/2018

Submitting Official (if other than PD\PI): Mark Gilmore, Barrett Rogers, co-Principal Investigators

Submission Date: 03/18/2019

Accomplishments

What are the major goals of the project?
The goal of this proposed work was to validate, through controlled laboratory experiments and close experiment-theory/model coupling, a fully global, nonlinear two-fluid model appropriate for understanding turbulence and transport dynamics in a collisional laboratory plasma.

What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

Key outcomes or Other achievements:

Major Activities:

Numerical simulations, using a global, 3D, multi-fluid model (the GBS code), were carried out of controlled, well-diagnosed plasma experiments at the University of Mexico. Plasma experiments investigated plasma and neutral particle flow dynamics and their interaction, as well as the nonlinear dynamics of plasma fluctuations and particle transport in the presence of flows. The results of the model and experimental work are described in detail in our publications.

As stated above, the overarching goal was to make detailed model-experiment comparisons in order to validate the underlying physics basis of codes such as GBS. While both Dartmouth and UNM teams did independent numerical (Dartmouth) and experimental (UNM) work in support of this goal, significant effort was also made to compare experiment and model results. This work was led by Dr. Dustin Fisher, who completed his PhD at Dartmouth with Prof. Rogers on turbulence model of laboratory plasmas using the GBS code in 2015, and joined Prof. Gilmore's group at UNM as a post-doctoral fellow in January 2016. Dr. Fisher's work on this project was leveraged from a Department of Defense (DoD)-funded project (ARO award W911NF1510480) at no cost to this NSF-funded project. Dr. Fisher maintained regular contact with Prof. Rogers, and visited Dartmouth at least twice, in order to foster the experiment-model comparison collaboration.

While model-experiment comparisons do show general overall consistency between experiments and the paradigm of flow shear stabilization of turbulence, finding detailed agreement – or clear cut discrepancies – between GBS simulations and experiments has proven difficult. In particular, it has been difficult to match experimentally-observed azimuthal ion flow profiles in the simulations. In order to resolve this and other issues, Dr. Fisher has added a several new pieces of physics to the code. First, he has added a new model for the helicon source, which allows for axially-distributed, and radially off-center plasma generation, which are consistent with experimental observations. We note that this sourcing is significantly different than the GBS model of a hot cathode-sourced plasma. Second, a third fluid (neutrals) has been added to the code, including a full hydrodynamic description of neutral momentum, coupled to the ion and electron fluids via collisions. Third, an electron thermal force term, often assumed small and neglected in Braginskii models of laboratory plasmas, has been included in the code, and while not large, may not be negligible in HelCat helicon discharges. This thermal force term depends on the parallel electron temperature gradient, and is given by "RT" on page 37 of the NRL Plasma Formulary, for example.

These additions to the GBS code have resulted in improved simulation-experiment agreement. However, as of the end of this grant (August, 2018), this detailed comparison was, unfortunately, not sufficiently complete to merit journal publication. This work is ongoing (though unfunded), and we do hope to publish our findings in the 2019 calendar year.

Specific Objectives:

Most generally, the objective is to verify or challenge the idea that both the simulations and theory adhere to the paradigm that flow shear stabilizes turbulence.

Significant Results:

Generally, the simulations agreed well with the experiments. It was found that varying the level of flow shear clearly showed the expected trend on the turbulence in the simulations as well as in experiments. Understanding the underlying mechanisms that determine plasma flow proved more difficult, though some possible contributions to flow dynamics, such as momentum transfer from neutrals, were ruled out as significant contributors. Nevertheless, observed flows clearly affected turbulent fluctuations in ways consistent with the flow shear suppression paradigm.

Key outcomes or Other achievements:

The main hypothesis was confirmed, several articles were written, and a number of oral and poster presentation were given at relevant conferences.

What opportunities for training and professional development has the project provided?

On the experimental side (UNM), two graduate students (Tiffany Desjardins and Ralph Kelly) received PhD's working on this project (with full or partial financial support). Several undergraduate students also worked on the project, receiving significant training in experimental plasma physics. Three of these undergraduate students have gone on to pursue graduate degrees in plasma physics at UNM and elsewhere.

On the simulation side (Dartmouth), four graduate students - Dustin Fisher, Evan Miller, Ben Zhu and Mana Francisquez - received their PHD's while working on this project and the work of each touched upon the topic of the grant: the impact of ExB shear on turbulence.

How have the results been disseminated to communities of interest?

Several oral and poster presentations, including one invited conference talk, have been given at national and international meetings about the results of this project.

Products

Journals or Juried Conference Papers

A. Stegmeir, A. Ross, T. Body, M. Francisquez, W. Zholobenko, D. Coster, O. Maj, P. Manz, F. Jenko, B.N. Rogers,K.S. Kang (2019). Global edge/scrape-off layer turbulence simulations with GRILLIX. *Phys. Plasmas*.
Status = SUBMITTED; Acknowledgment of Federal Support = No ; Peer Reviewed = Yes

B. Rogers, B. Zhu and M. Francisquez (2018). Gyrokinetic theory of slab universal modes and the non existence of the Gradient Drift Coupling (GDC) instability. *Physics of Plasmas*. 25 052115.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes

B. Zhu, M. Francisquez and B. Rogers (2017). Global 3D two-fluid simulations of the tokamak edge region: Turbulence, transport, profile evolution, and spontaneous ExB rotation. *Physics of Plasmas*. 24 055903.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

B. Zhu, M. Francisquez and B. Rogers (2018). GDB: a global 3D two-fluid code for plasma turbulence and transport at tokamak edge region. *Computer Physics Communication*. 232 46.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

B. Zhu, M. Francisquez and B. Rogers (2018). Up-down symmetry breaking in global tokamak edge simulations. *Nuclear Fusion*. 58 116049.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

B. Zhu, M. Francisquez, B. Zhu, B. N. Rogers (2019). Multigrid treatment of implicit continuum diffusion. *Computer Physics Communications*. 236 104.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

D. Fisher and B. N. Rogers (2017). Two-fluid biasing simulations of the large plasma device. *Physics of Plasmas*. 24 022303.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

D. Fisher, B. N. Rogers, G. Rossi, D. Guice and T. Carter (2015). 3D Turbulence Simulations of the Large Plasma Device. *Phys. Plasmas*. 22 (092121).
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

E. D. Miller and B. N. Rogers (2016). Relativistic thermal electron scale instabilities in sheared flow plasma. *J. of Plasma Physics*. 82 (2), 905820205.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

M. Francisquez, B. Zhu and B. Rogers (2018). Global 3D Braginskii simulations of the tokamak edge region of IWL discharges. *Nuclear Fusion*. 57 055903.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

O. Gurcan, S. Kobayshi, B. Rogers (2016). The Interaction Mechanism between Zonal Flows and Turbulence Close to the Stability Threshold. *J. Plasma Fusion Res.*. 92 (3).
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

R. E. Denton, L. Ofman, Y. Y. Shprits, C. L. da Silva, J. Bortnik, B. N. Rogers, M. K. Hudson, R. M. Millan, K. Min, A. Glocer, and C. Komar, C. J. Rodger (2019). Pitch angle scattering of relatively low energy relativistic electrons by electromagnetic ion cyclotron waves. *Journal of Geophys. Res. Space Phys.*.
Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

R. F. Kelly, K. D. Meaney, M. Gilmore,a) T. R. Desjardins, and Y. Zhang (2016). ArI/ArII laser induced fluorescence system for measurement of neutral and ion dynamics in a large scale helicon plasma. *Review of Scientific Instruments*. 87, 11E560.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: http://dx.doi.org/10.1063/1.4959157

T.R. Desjardins and M. Gilmore (2016). Dynamics of flows, fluctuations, and global instability under electrode biasing in a linear plasma device. *Physics of Plasmas*. 23 055710.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes

T.R. Desjardins and M. Gilmore (2018). The potential relaxation instability in a helicon plasma. *Physics of Plasmas*. 25 062117.
Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: https://doi.org/10.1063/1.5030430

Thesis/Dissertations

Ralph F. Kelly. *DENSITY AND VELOCITY MEASUREMENT OF ARI AND ARII USING LASER INDUCED FLUORESCENCE (LIF) IN A LARGE-SCALE HELICON PLASMA*. (2018). University of New Mexico.
Acknowledgement of Federal Support = Yes

Tiffany Renea Desjardins. *Dynamics of Turbulence and Flows in a Helicon Plasma Under Electrode Biasing*. (2016). University of New Mexico.
Acknowledgement of Federal Support = Yes

What individuals have worked on the project?
(Name Most Senior Project Role Nearest Person Month Worked)

Gilmore, Mark PD/PI, person months: 9
Rogers, Barrett Co PD/PI, person months: 2
Fisher, Dustin Postdoctoral (scholar, fellow or other postdoctoral position) , person months: 12
Kelly, Ralph Graduate Student (research assistant), person months: 6
Fullford, Karin Undergraduate Student, person months: 7
Hatch, Maren Undergraduate Student, person months: 7
Meek, Hanna Undergraduate Student, person months: 4
Dwyer, Robert High School Student, person months: 5

Full details of individuals who have worked on the project:

Mark Gilmore
Email: gilmore@ece.unm.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 9
Contribution to the Project: Project PI
Funding Support: 9 month academic salary
International Collaboration: No
International Travel: Yes, Switzerland - 0 years, 0 months, 7 days

Barrett Rogers
Email: Barrett.N.Rogers@Dartmouth.EDU
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 2
Contribution to the Project: Simulations and Analysis of theory and experimental results
Funding Support: NSF, DOE
International Collaboration: Yes, Switzerland
International Travel: Yes, Switzerland - 0 years, 2 months, 0 days

Dustin Fisher
Email: dufisher@unm.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 12
Contribution to the Project: Primary responsibility for numerical modeling using GBS code.
Funding Support: Dr. Fisher's support was leveraged from a similar project funded by the Army Research Office.
International Collaboration: No
International Travel: No

Ralph Kelly
Email: ralphkelly0000@gmail.com
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6
Contribution to the Project: Graduate student researcher.
Funding Support: Supported 100% by UNM Electrical and Computer Engineering Dept.
International Collaboration: No
International Travel: No

Karin Fullford
Email: kfulford@unm.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 7
Contribution to the Project: Assisted with conducting experiments and building experimental apparatus.
Funding Support: This NSF grant.
International Collaboration: No
International Travel: No

Maren Hatch
Email: mwhatch@unm.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 7
Contribution to the Project: Conducted and assisted with experiments, and build experimental apparatus.
Funding Support: This NSF grant.
International Collaboration: No
International Travel: No

Hanna Meek
Email: hmeek2@uw.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 4
Contribution to the Project: Assisted with experiments, and built experimental apparatus.
Funding Support: This NSF grant.
International Collaboration: No
International Travel: No

Robert Dwyer
Email: rdwyer@unm.edu
Most Senior Project Role: High School Student
Nearest Person Month Worked: 5
Contribution to the Project: Assisted with experiments and built experimental apparatus.
Funding Support: NSF grant.
International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name Type of Partner Organization Location
Ecole Polytechnique de Lausanne Academic Institution Switzerland

Max Plank Institute for Plasma Physique Academic Institution Germany

Full details of organizations that have been involved as partners:

Ecole Polytechnique de Lausanne
Organization Type: Academic Institution
Organization Location: Switzerland
Partner's Contribution to the Project:
In-Kind Support
Facilities
Collaborative Research
Personnel Exchanges

More Detail on Partner and Contribution:

Max Plank Institute for Plasma Physique
Organization Type: Academic Institution
Organization Location: Germany
Partner's Contribution to the Project:
In-Kind Support
Facilities
Collaborative Research
Personnel Exchanges

More Detail on Partner and Contribution:

What other collaborators or contacts have been involved?
Nothing to report

Impacts

What is the impact on the development of the principal discipline(s) of the project?
This study adds further, more quntitative and experiental evidence to the role of flow shear on turbulence. It also helps to elucidate the role of neutral dynamics in linear laboratory plasmas, especially helicon plasmas.

What is the impact on other disciplines?
The results have been tested across a range of several devices (to fusion machione, basic plasma devices such as LAPD) and found to be consistent and similar.

What is the impact on the development of human resources?
This grant contributed to the PhD's of 4 graduate students at Dartmouth, 2 PhD's at UNM, and the training of several undergraduate and high school students (some of whom are now pursing graduate or undergraduate studies in plasma physics and fusion).

What is the impact on physical resources that form infrastructure?
At Dartmouth, new numerical methods - in particular parallel multi-grip methods of solve boundary value problems – were developed. At UNM, significant enhacements to the HelCat basic plasma science facility have resulted from this grant, such as the implementation of a laser induced fluorescence (LIF) system that now operates routinely.

What is the impact on institutional resources that form infrastructure?
At Dartmouth, the project extended the capabilitities of the campus supercomputer, the Discovery cluster. At UNM - please see the "physical resources" section above.

What is the impact on information resources that form infrastructure?
see above

What is the impact on technology transfer?
The numerical techniques developed as part of this project have applicability across all areas of computational applications. LIF of ArII on a new spectral line at approx. 694 nm was demonstrated, and a description of this technique was published in Rev. Sci. Instrumen.

What is the impact on society beyond science and technology?
Stronger collaborations were formed between institutions in Germany and Switzerland.

Changes/Problems

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them
Nothing to report.

Changes that have a significant impact on expenditures
Prof. Mark Gilmore was paid less summer salary than budgeted (7.4% of the budgeted salary). Since Prof. Gilmore's 9 month academic salary is sufficient to cover an entire year, these unpaid funds were used instead to pay undergraduate and high school student laboratory assistants.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.

Special Requirements

Responses to any special reporting requirements specified in the award terms and conditions, as well as any award specific reporting requirements.
Nothing to report.