Final Report on Funding for DE-SC0013958 "Stability and Control of Burning Tokamak Plasmas with Resistive Walls" at the University of Tulsa

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Executive Summary

This document details the work accomplished during the period 07/01/2015-06/30/2017 at the University of Tulsa for the collaborative project, "Stability and Control of Burning Tokamak Plasmas with Resistive Walls," and serves as the final report on that project for Department of Energy Office of Science – Fusion Energy Sciences Grant No. DE-SC0013958. The overall collaborative project continues, though the portion of work conducted at the University of Tulsa is completed, and the associated grant has ended.

This project is focused on theoretical and computational development for quantitative prediction of the stability and control of the equilibrium state evolution in toroidal burning plasmas, including its interaction with the surrounding resistive wall. The stability of long pulse burning plasmas is highly sensitive to the physics of resonant layers in the plasma, sources of momentum and flow, kinetic effects of energetic particles, and boundary conditions at the wall, including feedback control and error fields. In ITER in particular, the low toroidal flow equilibrium state, sustained primarily by energetic alpha particles from fusion reactions, will require the consideration of all of these key elements to predict quantitatively the stability and evolution. The principal investigators on this project are leading experts in the relevant theoretical and computational areas, and aim to perform computations guided by analytic modeling, to address this physics in realistic configurations. The overall goal is to understand the key physics mechanisms that describe stable toroidal burning plasmas under active feedback control. With the physics of the resonant layers, resistive wall, and toroidal momentum transport included, this study will extend from recent publications in active feedback control to move toward predictive modeling for burning plasmas.

The original goals of the proposal are:

Year 1: Develop numerical representation of distribution function into NIMROD, study nonlinear simulations of energetic particle interaction with resistive MHD instabilities. Study resistive plasma – resistive wall mode stability in DIII-D and NSTX like configurations with PEST-III and NIMROD, including rotation and two fluid effects.

Year 2: Develop linear resistive wall and control model into PEST-III and extend cylindrical control studies to toroidal configurations. Develop Monte-Carlo collision operator into NIMROD.

Year 3: Include NTV torque in resistive plasma - resistive wall mode calculations in ITER, NSTX and DIII-D equilibria using PEST-III and NIMROD.

To a large extent the research effort has followed this plan, albeit with a reduced budget, with new discoveries engaging our efforts along the way.

The work plan and deliverables for this collaborative project stated in the "Revised Work Plan" dated March 9, 2015 are as follows:

Under a reduced budget which includes support for D.P. Brennan, A.J. Cole, three graduate students, and separate support for J.M. Finn, having originally included a postdoctoral researcher and additional student in the plan, it is anticipated that approximately 2/3 of the work originally proposed will be completed in the performance period of the project. The work plan is dominantly serial, in the sense that "production" computations in the final years will be dependent on completing technical developments in the previous years. Thus, the revised timetable reflects a reduction of the focus on applications, and instead a three year focus on the developments previously scheduled for the first two years. Production computations and analyses will be completed, albeit at a reduced pace from the original plan.

The different areas of focus of the PI's are made coherent by the fact that all three, Brennan, Cole and Finn, contribute to analytic and reduced modeling of the physics being investigated. Finn is predominantly focused on analytic work that directly guides the development, verification and validation of various aspects of the project. Cole also contributes advanced numerical resistive layer solutions, and kinetic physics analyses, which are applicable both to reduced modeling and computational experimental analyses. Brennan contributes extended MHD simulations and computational analyses of experiment, in addition to reduced modeling, which help validate the physics being addressed, and drive many of the questions being posed. Note that Finn has been funded from a source of funds in FES separate from this grant.

Progress Overview:

In brief, after two years of funding, the progress we have made on this collaborative project has progressed toward our goals, and unexpected new physics results have been achieved which have led to publication and invited talks. The work plan has slightly evolved over the first two years, and the plan for the third year has now become clear.

For brevity we list a few areas of active development and their status.

Energetic particle effects on resistive MHD modes

> Development of a numerical representation of the energetic ion distribution in MHD simulations has begun, which is synergistic with the reduced modeling of the energetic ions effects discussed above.

Development of NIMROD

> A spectrum of boundary field imposition has been coded into NIMROD, which has enabled simulations of extended MHD instabilities and error field penetration including energetic particle effects. Also a configuration with varying flow profiles and initial large saturated islands (3/2) which are unstable to the 2/1 mode have been established, simulating the condition entering into a disruption on DIII-D [See D.P. Brennan et al., APS-DPP 2015, 2016] and facilitating the study of torques and plasma response and the effect on the disruption mechanics.

Development of PEST-III

> We resolved issues with the PEST-III code which made it difficult to computationally resolve the stability of shaped DIII-D cases with structured profiles. The resistive wall version of the VACUUM has been coupled to PEST-III, as have layer models with differential rotation between layers. Further benchmarking with Resistive DCON has lead to improvement and verification of both codes. Advanced models of layer responses are now being developed by Cole and Brennan for use in PEST-III based analyses. We have also collaborated significantly with Z. Wang (PPPL) and F. Turco (GA) on PEST-III development in comparison to Resistive DCON, to verify the solutions in both codes and validate against experimental cases.

Also, a new effort has been initiated in collaboration with Carlos Paz-Soldan (GA) to use many of the tools and analyses we have been working on in this project to understand and predict upcoming D3D experiments on rotation limits and tearing mode stability (DIII-D MP 2017-26-05). Brennan and Cole have generated a preliminary analysis using reduced modeling, which is helping to steer the experimental planning, and will continue to analyze the experimental outcomes.

We are confident that the collaborative interaction we have established, including frequent in-person visits, teleconferencing, and conference co-attendance, will enable us to complete the research funded in this work plan over the coming year.

Several collaborative visits and numerous teleconference meetings have occurred between Princeton, Columbia, Tibbar/LANL and Tulsa.

Below we review the number of conference presentations and collaborative visits, journal publications, and progress in a few areas of research that are highlighted.

Key Results Obtained During the Performance Period

Selected publications associated with this project:

Over the first two years, four papers have been published (three appear on ArXiv, two are published in PoP, one in PoP review), and two PhD theses have been produced, one submitted and defended (D. Rhodes, Columbia U) and the other in preparation and being submitted in Dec 2017. One additional journal paper is in draft for imminent submission. We list them here and briefly describe the results, starting with the published refereed journal papers, Arxiv submissions and PhD theses, followed by the paper in preparation.

M.R. Halfmoon and D.P. Brennan "A Model of Energetic Ion Effects on Pressure Driven Tearing Modes in Tokamaks" arXiv:1702.06837v2, Phys. Plasmas **24**, 062501 (2017).

- In this paper, the effects that high energy trapped ions have on linear resistive instabilities are studied in a reduced analytic model to explain results found in DIII-D simulations where the ions drive or damp the modes [1- 2]. The results show that the outer region energetic ions damp and stabilize the mode, while in the core the energetic ions can drive the mode unstable given weak or reversed shear.

J.M. Finn, A. J. Cole and D.P. Brennan "Real frequency tearing modes with parallel dynamics and their effect on resistive wall modes and locking," arXiv:1708.04700, to be submitted Phys. Plasmas (2017).

This paper focuses on tearing modes with real frequencies in the plasma frame, which is typically the case. Extending from Ref. [3] we derive the tearing mode dispersion relation in two simple models involving real frequencies, and show that in both regimes the existence of tearing modes with complex frequencies is related to interaction with nearby electrostatic resistive interchange modes with complex frequencies.

J.M. Finn, A.J. Cole, and D.P. Brennan, "Error field penetration and locking to the backward propagating wave", arXiv:1507.04012v2, Phys. Plasmas (Letters) **22**, 120701 (2015).

- Two invited talks on this subject have resulted from this paper, one at the 2015 Theory and Simulation of Disruptions Workshop by J. Finn, and the other at the 2016 Sherwood Theory Conference by A. Cole.· This paper focuses on error field penetration, or locking, behavior in plasmas having stable tearing modes with finite real frequencies ω_r in the plasma frame. In particular, we address the fact that locking can drive a significant equilibrium flow. We show that this interaction with a backward propagating tearing mode in the plasma frame is applicable to a wide range of tearing mode regimes, indeed any regime where real frequencies occur.

Dov J. Rhodes, A. J. Cole, D. P. Brennan, J. M. Finn, R. Fitzpatrick, M. E. Mauel, and G. A. Navratil, "Shaping effects on the rotational stabilizability of magnetohydrodynamic modes in the presence of plasma and wall resistivity," submitted and under review, Phys. Plasmas (2017).

- This study explores the effects of plasma shaping on MHD mode stability and rotational stabilizability in a tokamak, including both plasma and wall resistivity. Depending upon the plasma shape, safety factor and distance from the wall, the β-limit for rotational stabilizability is given by either the resistive-plasma ideal-wall (tearing mode) limit or the ideal-plasma resistive-wall (resistive wall mode) limit. In order to explore this broad parameter space, a sharp-boundary model is developed with realistic geometry, resonant tearing surfaces and a resistive wall.

Two PhD theses have been produced, each expanding in detail on the material in the related journal publications listed above:

D. Rhodes "Shaping Effects on Resistive Instabilities in a Tokamak Plasma Surrounded by a Resistive Wall," PhD Thesis, Columbia University, New York, New York (Completed 4/20/2017).

M.R. Halfmoon "The Effects of Energetic Ions on Tearing Instabilities in Tokamak Experiments," PhD Thesis, University of Tulsa, Tulsa, Oklahoma (to be submitted 12/2017).

One additional paper is in preparation:

D.P. Brennan, M.R. Halfmoon, D.J. Rhodes, A.J. Cole and J.M. Finn, "Simulations and reduced modeling of coupled modes in flow with resonant field penetration" to be submitted Phys. Plasmas 2017.

- This study presents a comparison of simulations of DIII-D configurations and a reduced analytic framework to study two coupled mode components of a single mode resonant at surfaces with safety factor q=m/n and (m+1)/n, where m is the poloidal and n the axial wavenumber. The models are used to interpret calculations using the PEST-III and NIMROD codes and compare with experiment. The results highlight discrepancies between the theory, simulation and experimental observations. Presentations at conferences, workshops and DIII-D experimental science meetings have been given in preparation or this paper.

Selected conference presentations and invited seminars associated with this project:

Since funding began in July 2015, 21 conference papers have been presented that are either fully or partially funded by this grant. These presentations have included 2 invited presentations by the PI's, 1 student invited presentation and 8 student posters. These conferences have included the APS-DPP, Sherwood Fusion Theory, Theory and Simulation of Disruptions Workshops, and MHD Stability and Control Workshop meetings. Also, 3 invited seminars were given, overviewing some of the collaborative results from the project. We list these presentations here for reference.

Conference Presentations:

D.P. Brennan, M.R. Halfmoon, A.J. Cole, D.J. Rhodes, J.M. Finn "Energetic ion effects on resistive instabilities with plasma rotation and a resistive wall," International Sherwood Fusion Theory Conference, Annapolis, Maryland, May, 2017.
Dov J. Rhodes, A.J. Cole, D.P. Brennan, J.M. Finn, R. Fitzpatrick, M.E. Mauel, G.A. Navratil "Shaping effects on the rotational stabilizability of resistive-plasma resistive-wall modes in a tokamak," International Sherwood Fusion Theory Conference, Annapolis, Maryland, May, 2017.

D. Rhodes, A.J. Cole, G.A. Navratil, M.E. Mauel D.P. Brennan, J.M. Finn and R. Fitzpatrick "Shaping effects on stability limits and control of resistive-plasma resistive-wall modes," MHD Stability and Control Workshop, General Atomics, San Diego, California, November, 2016.

Andrew Cole, J.M. Finn and D.P. Brennan "Real frequency tearing modes with parallel dynamics and their effect on locking and resistive wall modes," 58th Annual Meeting of the American Physical Society Division of Plasma Physics, San Jose, California, November, 2016.

Dov Rhodes, A.J. Cole, G.A. Navratil, J.P. Levesque, M.E. Mauel, D.P. Brennan, J.M. Finn and R. Fitzpatrick, "Shaping Effects on Resistive-Plasma Resistive-Wall Mode Stability in a Tokamak," 58th Annual Meeting of the American Physical Society Division of Plasma Physics, San Jose, California, November, 2016.

Dylan Brennan, Michael Halfmoon, Dov Rhodes, Andrew Cole, Michio Okabayashi, Carlos Paz-Soldan and John Finn, "The effects of differential flow between rational surfaces on toroidal resistive MHD modes," 58th Annual Meeting of the American Physical Society Division of Plasma Physics, San Jose, California, November, 2016.

A. H. Glasser, Z. R. Wang, J.-K. Park and D. P. Brennan, "Recent Progress on the DCON Code," 58th Annual Meeting of the American Physical Society Division of Plasma Physics, San Jose, California, November, 2016.

M.R. Halfmoon and D.P. Brennan, "A model of energetic ion effects on pressure driven tearing modes in tokamaks," 58th Annual Meeting of the American Physical Society Division of Plasma Physics, San Jose, California, November, 2016.

M. Okabayashi, B Budny, D Brennan et al., "Neoclassical Tearing Mode Locking Avoidance by 3D Fields and Recovery of High Confinement," 58th Annual Meeting of the American Physical Society Division of Plasma Physics, San Jose, California, November, 2016.

Dov J. Rhodes, A.J. Cole, D.P. Brennan, J.M. Finn, R. Fitzpatrick, M. Halfmoon, M.E. Mauel, G.A. Navratil, "Exploring Alternate Ordering of the MHD Stability Limits for Coupled Tearing-Wall Modes," International Sherwood Fusion Theory Conference, Madison, Wisconsin, April, 2016.

D.P. Brennan, A.J. Cole, M.R. Halfmoon, D.J. Rhodes and J.M. Finn, "A reduced model of differential flow effects on stability and penetration of coupled toroidal modes," International Sherwood Fusion Theory Conference, Madison, Wisconsin, April, 2016.

John Finn, D. Rhodes, M. Halfmoon, D. Brennan, A. Cole, "Simple model for toroidal coupling of tearing modes, including the presence of rotation shear," International Sherwood Fusion Theory Conference, Madison, Wisconsin, April, 2016.

Andrew J. Cole, J.M. Finn, and D.P. Brennan, "Error field penetration and locking to the backward wave," International Sherwood Fusion Theory Conference, Madison, Wisconsin, April, 2016.

Spencer D. James, D.P. Brennan, O. Izacard, and C. Holland, "Self-consistent interactions of the tearing mode and drift-wave microturbulence," International Sherwood Fusion Theory Conference, Madison, Wisconsin, April, 2016.

Michael R Halfmoon and D.P. Brennan, "Effects of Shear on Energetic Ion Interactions with Tearing Modes," International Sherwood Fusion Theory Conference, Madison, Wisconsin, April, 2016.

Dov Rhodes, A.J. Cole, G.A. Navratil, J.P. Levesque, M.E. Mauel, and R. Fitzpatrick, "Non-Ideal Error-Field Response Model with a Ferritic and Resistive Wall," 57th Annual Meeting of the American Physical Society Division of Plasma Physics, Savannah, Georgia, November, 2015.

John Finn, Andrew Cole, and Dylan Brennan, "Error field penetration and locking to the backward propagating wave," 57th Annual Meeting of the American Physical Society Division of Plasma Physics, Savannah, Georgia, November, 2015.

Michael Halfmoon and Dylan Brennan, "Energetic Ion Interactions with Tearing Mode Stability," 57th Annual Meeting of the American Physical Society Division of Plasma Physics, Savannah, Georgia, November, 2015.

S.D. James, D.P. Brennan, O. Izacard, and C. Holland, "Simulating the coupled evolution of drift-wave turbulence and the tearing mode," 57th Annual Meeting of the American Physical Society Division of Plasma Physics, Savannah, Georgia, November, 2015.

D.P. Brennan, A.J. Cole and J.M. Finn, "Error field penetration and beta limits in two fluid toroidal plasmas," 57th Annual Meeting of the American Physical Society Division of Plasma Physics, Savannah, Georgia, November, 2015.

J.M. Finn, A.J. Cole, and D.P. Brennan, "Error field penetration and locking to the backward wave," Theory and Simulation of Disruptions Workshop, Princeton Plasma Physics Laboratory, Princeton, New Jersey, July, 2015.

Invited Seminars :

D.P. Brennan, M.R. Halfmoon, D.J. Rhodes, A.J. Cole, J.M. Finn "Energetic ion effects on disruptive resistive instabilities in tokamaks," DIII-D Science Meeting Seminar Series, General Atomics, San Diego, California, August, 2017

D.P. Brennan, "Simulations of disruptive 2/1 tearing modes in DIII-D with differential rotation between surfaces," DIII-D Science Meeting Seminar Series, General Atomics, San Diego, California, September, 2016

D.P. Brennan, A.J. Cole, J.M. Finn, M.R. Halfmoon, D.J. Rhodes, "Modeling Stability and Control of Tokamaks with Resistive Walls," Research and Review Seminar Series, Princeton Plasma Physics Laboratory, Princeton, New Jersey, April, 2016.

Summary

In short all of the scheduled items in Timeline and Evaluation Phases have been addressed to some extent. The research plan will continue to completion within the three-year plan in addition to new physics investigations that have been identified during this work.

The forward looking research is focused on finishing papers in progress. This technical areas of focus can be summarized as:

- Nonlinear simulations of extended MHD modes in DIII-D and NSTX equilibria.
- PEST-III benchmark and development, resolving the most challenging cases.
- Analytic and computational analysis of drift MHD description of error field penetration, resistive wall modes and control.
- Theoretical analyses of controlled avoidance of disruptive instabilities in burning plasmas.

There have been three PhD students funded on this grant: M. Halfmoon (U. Tulsa), S. James (U. Tulsa) and D. Rhodes (Columbia), in addition to partial support for PI's D. Brennan and A. Cole. Rhodes has defended on April 20, 2017. Halfmoon is expected to submit by Dec 2017, and James is expected to submit shortly after. The collaboration with J. Finn at LANL (funded separately through the FWP process) has been fruitful and will continue. PI G. Miller is continuing to oversee the Tulsa students' progress in their degree programs. Each of the three students have attended multiple conferences in the course of the first two years of the project, in addition to the collaborative visits. Overall, the opportunities for training and professional development for these three students have been excellent.

References

[1] R. Takahashi, D.P. Brennan, and C.C. Kim, Phys. Rev. Lett 102, 135001 (2009).

[2] D.P. Brennan, C.C. Kim, and R.J. La Haye, Nucl. Fusion 52, 033004 (2012).

[3] J.M. Finn, A.J. Cole, and D.P. Brennan, Phys. Plasmas (Letters) 22, 120701 (2015).