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Dr. John Mandrekas
Mr. John Sauter
Dr. Darlene Markevich
U.S. Department of Energy
Office of Fusion Energy Sciences
19901 Germantown Road
Germantown, MD 20874-1290

Re: Final report on grant DE-FG02-07ER54931 titled "Hot Particle and Turbulent Transport Effects on Resistive Instabilities"

Dear Dr. Mandrekas, Mr. Sauter and Dr. Markevich,

After fully funding this project, this project completed its ultimate goal to form a foundation for continuing research in our team. A great deal of progress was made that in some cases extended beyond the original research goals. This research project included two main thrusts; energetic particle effects on resistive MHD modes in tokamaks, and turbulence interactions with tearing modes in simplified geometry. This grant funded a postdoctoral research scientist, summer months for myself as PI, graduate students, undergraduate research assistants, travel and other support to address this research. The grant was extended at no cost after the initial period 7/15/07-7/14/10, where work was completed on some remaining parts only recently. Below I have summed up the research progress that was made into a few relevant categories for your review.

Publications

The list of publications of work supported at least in part by this grant includes seven peer reviewed papers published up to this year. Four of these publications were authored primarily at Tulsa, while three were primarily authored at GA and PPPL.

- D.P. Brennan, C.C. Kim, and R.J. La Haye, "Kinetic effects of energetic particles on a 2/1 resistive MHD instability in a DIII-D discharge," Nucl. Fusion **52**, 033004 (2012).
- R.J. La Haye, D.P. Brennan, R.J. Buttery, and S.P. Gerhardt, "Islands in the Stream: The Effect of Plasma Flow on Tearing Stability," Phys. Plasmas **17**, 056110 (2010).
- D.P. Brennan, P.K. Browning, J. Gates, and R.A.M. Van der Linden, "Helicity Injected Current Drive and Open Flux Instabilities in Spherical Tokamaks," Plasma Phys. Control. Fusion **51**, 045004 (2009).
- R. Takahashi, D.P. Brennan, and C.C. Kim, "A Detailed Study of Kinetic Effects of Energetic Particles on Resistive MHD Linear Stability," Nucl. Fusion **49**, 065032 (2009).
- R. Takahashi, D.P. Brennan, and C.C. Kim, "Kinetic Effects of Energetic Particles on Resistive MHD Stability," Phys. Rev. Lett **102**, 135001 (2009).

- S.P. Gerhardt, D.P. Brennan, R. Buttery, R.J. La Haye, S. Sabbagh, E. Strait, M. Bell, R. Bell, E. Fredrickson, D. Gates, B. LeBlanc, J. Menard, D. Stutman, K. Tritz, and H. Yuh, "Relationship Between Onset Thresholds, Trigger Types and Rotation Shear for the m/n = 2/1 Neoclassical Tearing Mode in a High-β Spherical Torus," Nucl. Fusion **49**, 032003 (2009).
- R.J. La Haye, P.A. Politzer, and D.P. Brennan, "Beta Limit Due to m/n=2/1 Tearing Mode Onset in the DIII-D Hybrid Scenario," General Atomics Report 025707, Nucl. Fusion **48,** 015005 (2008).

The work in these publications mainly included a collaboration with Rob La Haye (GA) and Charlson Kim (Far-Tech) for computational analysis done at Tulsa, that also extended to experimental papers authored at GA and PPPL. This was the most successful research channel for publication. However, a number of other research projects were initiated as a result of the support from this grant, which broaden the scope of the research being conducted by our group, and will lead to publication in the near future.

Unpublished work in progress

Several other research projects were explored and developed with support from this grant, and continue to develop today. These projects include, but are not limited to:

- Accurate linear resistive stability calculations in high β, highly shaped AT discharges in DIII-D using PEST-III and NIMROD.
- Resistive stability of the m/n=2/1 mode in NSTX with equilibrium profiles similar to those in DIII-D hybrid discharges.
- Error field penetration and plasma response with a current gradient in slab geometry in extended MHD.
- Stability and control with both resistive walls and resistive plasmas, in simplified RFP and tokamak configurations, extending to accurate toroidal computations.
- A nonlinear five field model of ITG turbulence interaction with a tearing mode in simplified geometry.
- The effects of energetic particles on the nonlinear evolution of resistive MHD modes, including the non-resonant reversed shear mode observed in DIII-D, which is directly related to NSTX observations, and modeled in Nucl. Fusion **52**, 033004 (2012).

Each of these items has involved a collaborative effort that continues in some form today. Here is a summary of the status of each of these projects:

The first item, accurate linear resistive stability calculations, primarily involved a collaboration with Tim Luce and Francesca Turco at GA, to analyze the onset of NTMs in high β AT discharges. This work contributed directly to several conference presentations, and has broken significant ground on how to get accurate stability boundaries for the resistive mode and agreement between PEST-III and NIMROD for the most challenging cases in DIII-D. The results will likely lead to a publication in the near future, as well as contribute to any others using PEST-III, as the work is synergistic with current funding and research plans.

The second item, on error field penetration, stemmed from an extension of Cole and Fitzpatrick 2006, and contributed to a few conference presentations. The main idea is to include the effect of the stability of the equilibrium in the error field penetration threshold calculations. The project now has developed into a contribution to ongoing collaborative work with John Finn (LANL).

The third item, on Stability and Control, is the main collaborative effort with John Finn, which eventually was funded on a new grant. However, the initial stages of this ongoing collaboration were funded by this grant. The work involves calculations of resistive wall mode and tearing mode stability under feedback control from coils and sensors. A publication on RFP mode control from our group is imminent. Our initial efforts favored cylindrical geometry with direct relevance to RFX, whereas the overall direction is to study tokamak configurations with relevant developments in PEST-III and NIMROD.

The fourth item, turbulent field interaction with tearing modes, contributed to conference presentations and was also ultimately funded on a subsequent grant with Chris Holland (UCSD). The computational and theoretical approaches by Chris Holland and myself involve the use of a wave kinetic approach to derive a turbulent resistivity and viscosity, which scale as powers of the turbulent wavevectors, and should affect the reconnection rates. Conversely the stability of the background equilibrium and the presence of a nonlinear island both affect the turbulence. Computational analysis with a five field initial value code currently in development at Tulsa will be compared to analytic models.

Last, following on from three of the publications in the list above, in collaboration with Charlson Kim and Rob La Haye, we intend to move forward with studies of energetic particle interaction with resistive MHD instabilities. The future focus in this area is with the nonlinear evolution of the modes we have addressed linearly. The most important physical aspect under investigation is to determine if nonlinear simulations reproduce an expected 2/1 mode growing from beneath a saturated non-resonant core mode in DIII-D hybrid and NSTX discharges, and if this compares well with experimental observations for the 2/1 onset.

<u>The most significant results</u>

The two most significant published results from this research came in the energetic particle effects on resistive MHD. In one study, R. Takahashi, Phys. Rev. Lett **102**, 135001 (2009), the m/n=2/1 beta driven tearing mode in model DIII-D equilibria was shown to be damped and eventually stabilized by a slowing down energetic particle population, emulating neutral beam heating. This case study included positive magnetic shear throughout the minor radius. In a subsequent study, D.P. Brennan, Nucl. Fusion **52**, 033004 (2012), using weakly reversed magnetic shear in the core, several MHD instabilities, including the 2/1 mode, are instead driven unstable by the energetic particles. Experimental comparisons strongly support the latter result, where experimental equilibrium reconstructions were used. Experimental comparisons of the former result are not available as model equilibria were used. This damping may in fact occur in relevant experimental configurations with positive magnetic shear throughout the minor radius and high q_min~1.5, such as the DIII-D AT discharges being investigated as described above.

The Team: Postdoctoral Research Scientists and Students

A large part of the funding supported Dr. Ryoji Takahashi as a postdoc, and Michael Halfmoon as a graduate student on this grant. Dr. Takahashi has now moved on to conduct research in Spain. Dr. Karl Sassenberg has now joined our team form Asdex-Upgrade and UC Cork, Ireland, and is currently funded by a new grant. Michael Halfmoon and Spencer James are current graduate students, both currently funded on separate grants. However, because of the collaborative nature of the work being conducted by the graduate student and postdoctoral members of our team, and the travel and undergraduate support, two postdoctoral scientists, three graduate students, and several undergraduate students were supported, at least in some small part, by this grant. In summary, this grant both provided substantial opportunity to explore new ideas, and significant positive exposure of the work in our field to scientists who will take that knowledge forward in their careers.

RESEARCH ADVISEES 2006-2011

	POSTDOCTORAL	GRADUATE	UNDERGRADUATE
CURRENT	K. Sassenberg (TU)	S. James (TU) M. Halfmoon (TU)	N. Willy (TU)
FORMER	R. Takahashi (BSC)	H. Mohammadi (U Miami)	M. Behlmann (MIT) J. Gates (CSM) B. Bennett (UT) D. Flanagan (Wash U) A. Preston (UNT)

Highlights:

- The main funded postdoctoral scientist (Takahashi) published two first author papers, including a PRL on energetic particle effects on resistive MHD mode in tokamaks, using NIMROD in a collaboration with Charlson Kim (Far-Tech).
- The main funded graduate student (Halfmoon) is currently working with energetic particle effects on resistive MHD modes, including work with PEST-III and NIMROD, and is now funded on a new grant.
- The other current graduate student (James) took up the second subject on this grant, turbulence interaction with tearing modes, and is developing a new code in a collaboration with Chris Holland (UCSD) to study this subject, being funded by university scholarship in addition to a new grant.
- One graduate student (Mohammadi) completed a masters thesis on neoclassical transport effects on Rutherford island evolution, ala S. Guenter. These results could directly lead to publication.
- Three undergraduate students (Preston, Willy and Bennett) worked on basic plasma physics theses.
- Two undergraduate students (Flanagan and Behlmann) completed undergraduate theses on error field penetration.
- Two undergraduate students (Gates and Behlmann) completed undergraduate theses including NIMROD simulations.

Travel support to APS, Sherwood, EPS and other meetings went to Dylan Brennan, Ryoji Takahashi, Karl Sassenberg, Michael Halfmoon, Hadi Mohammadi, and Spencer James.

Additional related travel funds have been provided on other grants by OFES and by the university.