Final Report

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DoE Award No. DE-FG02-04ER54791

Project Title: *Experimental Investigation of Active Feedback Control of
Turbulent Transport in a Magnetized Plasma*

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I. Overview

DoE Award No. DE-FG02-04ER54791 was a Department of Energy Office of Fusion Energy Sciences (OFES) Junior Faculty grant, whose stated goals were 1) to build a new basic plasma science laboratory device suitable for basic plasma science studies of relevance to the DoE OFES mission, and 2) to begin a research program investigating the active feedback control of turbulent transport in a laboratory environment. Both of these goals have been achieved, and investigation of transport control is ongoing under the support of follow-on DoE/National Science Foundation grant funding.

II. The HelCat Basic Plasma Science Device and Infrastructure

The Helcat Device

The HelCat (Helicon-Cathode) device, shown in Figs. 1 and 2, is a linear plasma device with a 4 m long, 50 cm diameter vacuum chamber. Water-cooled magnetic field coils generate an axial magnetic field $B_0 \leq 2.2$ kG. The device utilizes two different plasma sources – an RF helicon source and a thermionic cathode source – one at each end of the device. These two sources can be operated independently, or simultaneously. In 2007, HelCat began full operation with both RF helicon and thermionic cathode sources, at full magnetic field.

The helicon source operates between 10 – 30 MHz at RF powers up to 5 kW. It can produce plasma columns 2 – 4 m long, ~ 15 cm diameter (Full Width, Half Max, FWHM), with peak electron densities, n_e , up to 10^{20} m^{-3} . The cathode source can produce up to 2.5 kA of discharge current at up to 100 V discharge voltage (anode-cathode, A-K, voltage), and can produce plasma columns 2 – 4 m long, 15 – 20 cm FWHM, with peak electron densities up to $8 \times 10^{18} \text{ m}^{-3}$. The electron temperature, T_e , of plasmas produced by both sources is ~ 5 eV. Radial density profiles of the helicon and cathode source plasmas, measured by a double Langmuir probe, are shown in Fig. 3.

The HelCat vacuum chamber provides excellent access for diagnostic measurements and other systems through a large number of conflate (CF) vacuum ports ranging in diameter from 2-3/4 to 10 inches. Additionally, a large vacuum “port box” has been fabricated and installed, to allow the insertion and retraction of objects as large as the full vacuum chamber cross section (50 cm), such as concentric ring electrodes used to bias the plasma and impose azimuthal $E \times B$ flow (see Fig. 1).

The two plasma sources make HELCAT an extremely flexible laboratory plasma device that can operate over a wide range of plasma parameters in density, collisionality, background magnetic field, and turbulence characteristics. Thus, HELCAT is well-suited to a wide range of laboratory plasma physics experiments in areas such as turbulence, Alfvén waves, magnetic reconnection, and diagnostic development for MFE. For example, the helicon source typically operates with peak electron $n_e \sim 10^{13} - 10^{14} \text{ cm}^{-3}$ and neutral fill pressure, $P_n \sim 1 - 5$ mTorr. This plasma typically has high collisionality (ion-neutral collisions). On the other hand, the cathode produces plasmas with peak electron $n_e \sim 10^{12} \text{ cm}^{-3}$ and neutral fill pressure, $P_n \sim 10^{-5} - 10^{-4}$ Torr. In this case, drift waves are more collisionless. Furthermore, operating both sources simultaneously allows access to new parameter regimes. For example, if the gas is preionized by the cathode source, helicon discharges may be able to be obtained at much lower fill pressures, which could give high density plasmas ($n_e \sim 10^{13} - 10^{14} \text{ cm}^{-3}$) with lower collisionality. As far as we are aware, such a dual device utilizing both helicon and cathode sources has not been reported elsewhere.

Power Systems/Infrastructure

Power systems (magnet coil power supplies, cathode discharge supply, cathode heater supply, Helicon RF source) and other infrastructure such as cooling water, vacuum pumping, mechanical support, gas feed, and machine safety/control are now all in place and functioning.

Figure 1. Schematic view of the active turbulent transport control experiment in the HELCAT (HELicon-CAThode) device.

Figure 2. HELCAT (HELicon-CAThode) plasma device. Left: device from helicon source end. Below left: hot cathode assembly at the north end. Below right: helicon RF matching network and antennas at the south end.

Fig. 3. Left: HelCat helicon source full density profile and half profiles of density fluctuations, δn , and normalized density fluctuations. Right: Cathode source ion saturation current, I_{is} , profile. $I_{\text{is}} \propto n$, density. Peak density, at $R = 0$ cm is $n \approx 5 \times 10^{18} \text{ m}^{-3}$.

Plasma Diagnostics

A number of diagnostics are in place and operating routinely. These include: electrostatic probes, magnetic probes, two radially viewing microwave interferometers operating at 40 GHz and 94 GHz, and optical survey (Ocean Optics USB 4000) and high resolution spectroscopy (Spex 1 m visible/IR spectrometer).

Data Acquisition/Turbulence Control System

The data acquisition/turbulence control feedback system is now functioning. The system is fully operational for performing data acquisition, and the feedback control mode is operating in a shot-to-shot mode, that is, control outputs can now be delivered on the next discharge, using input data from the previous shot. (The discharge repetition rate is 1 shot/second.) Work is continuing to complete implementing fully real time feedback control within a single 250 ms long discharge.

The feedback control actuator, which consists of a set of concentric ring electrodes that terminate the plasma column in order to actively affect the plasma $E_r \times B_z$ flow profile, and a set of high current, high slew rate operation amplifiers/power supplies, is shown in Fig. 4. Hardware for the feedback system consists a 14 bit I/O board (32 input, 32 output channels) built by D-TACQ Inc (model ACQ196C) in a compact PCI rack, a PC running Linux, and a set of Kepco power operational amplifiers to drive the bias rings. This system is also shown in Fig. 4. This hardware is very similar to the plasma control system hardware used by Alcator C-Mod and DIII-D tokamaks. This D-TACQ board has a unique “real time” control mode where inputs can be read and outputs written within 100 μs , which is obtained via a custom software driver developed at General Atomics.

Unfortunately, this system does not have high enough throughput to accomplish any necessary signal processing within the control loop on the Linux-based computer, such as cross correlation of density and potential fluctuation data from probes to obtain radial particle flux ($\Gamma_r = \langle \tilde{n} \tilde{\phi} \rangle$). External signal processing hardware will therefore be required (as it is at Alcator C-Mod and DIII-D) to complete the control loop. This processing will reside between the probes and the digitizer inputs. Designs using either a dedicated DSP processor, such as one of the Texas Instruments TMS 3200 series chips, or analog processing, are now being considered.

Fig. 4. Left: Feedback control actuators: concentric bias rings for imposing controlled $E \times B$ flow profiles (above). Rings are copper, mounted on an alumina substrate. Outer ring is 15 cm diameter. Kepco power op amps used to drive the rings (± 20 V, ± 20 A, 20 A/100 μ s slew rate (below). Right: Data acquisition/feedback control system, including Linux-based PC, and D-TACQ ACQ196C system.

III. Initial Turbulence and Transport Experiments

Initial studies of the electrostatic turbulence and transport, and the interaction with controlled $E \times B$ flows using the helicon source are now underway. Additionally, some data were obtained using the hot cathode. Figures 5 and 6 show example data. In figure 5, a typical power spectrum of ion saturation data from a double Langmuir probe in an Argon helicon discharge is plotted. A low frequency spectrum in the range below 10 kHz that we interpret as electrostatic drift wave fluctuations is clearly present, as expected. As can be seen, a higher frequency feature, in the 40 – 50 kHz range, is also present. Though pickup has not been conclusively ruled out, this feature appears to be a higher

frequency plasma fluctuations, and may be a Kelvin-Helmholtz (KH) instability, driven by velocity shear.

Fig. 6 shows a phase lag plot of ion saturation fluctuation data from HELCAT, i.e. a phase space plot. The “ball of fuzz” plot indicates that there is not a low-dimensional (e.g. 2 or 3 dimension) attractor present. This, in turn, means that the fluctuations cannot be characterized by a low dimensional chaos. While this may not be surprising for turbulence, it should be noted that these are fluctuations in a relatively simple laboratory plasma, which on an oscilloscope appear to consist of just a few coupled modes. The upshot of this observation is that chaotic control, which was one potential nonlinear control method discussed in the original grant proposal, does not appear to be suitable for this application.

Fig. 5. Power spectrum of ion saturation fluctuations from an Argon helicon discharge in HELCAT.

Fig. 6. Phase space plot (via phase lag) of ion saturation data from an Argon helicon discharge in HELCAT. A low dimensional attractor cannot be identified in these data.

IV. Theory and Modeling Support and Collaborations

Collaborations in theory and modeling for these experiments have been initiated in two areas. In the turbulence and transport modeling area, we have begun a collaboration with Prof. Andrew Ware of the University of Montana. Prof. Ware spent a week visiting UNM in January, 2006, and has provided us with a copy of a 1D transport code. This code was originally developed at Oak Ridge National Laboratory, and has since been upgraded by Prof. Ware and his students [1]. With Dr. Ware’s assistance, this code is being modified appropriately to model transport in the HELCAT device, in the presence of sheared $E \times B$ flows imposed by concentric biased rings. The goal of this work is to embed this plasma transport code (as the “nonlinear system”) within a feedback loop simulation using standard MATLAB-based control engineering tools (SIMULINK) in order to investigate feedback control via numerical simulation. The intent here is to guide the lab experiments and development of control algorithms, similar to what has been done with the VALEN MHD code for controlling global MHD modes in the HBT device at Columbia University [2], for example.

In the turbulence control algorithm area, we have established a collaboration with Prof. Luca Zaccarian of the University Roma Tor Vergata, Rome, Italy, who has worked on plasma control at

DIII-D, JET, and the Frascati tokamak (FTU). This connection has been established by our local control systems collaborator, Prof. Chaouki Abdallah of UNM. One of Prof. Zaccarian's Ph.D. students, Mr. Luigi Pangione, visited our laboratory from August 2005 until Feb 2006 (at no cost to us), where he worked developing real time control system hardware and software for this project, as well as on running Prof. Ware's transport code. Additionally, Prof. Zaccarian visited UNM for two weeks beginning May 1, 2006.

V. Post-Doctoral, Graduate and Undergraduate Student Researchers Supported

The following students and post-doctoral researchers are or have been involved in the project, some of whom are funded directly by this grant, with others being funded by the UNM ECE Dept., and as visitors from the EU.

Dr. Alan Lynn, Post-Doctoral Researcher, plasma physics (part time)
 Mr. Steven Will, M.S. student, Electrical Engineering (plasma physics)
 Mr. Luigi Pangione, visiting Ph.D. student, Universita' di Roma, Tor Vergata, Roma, Italy, control systems
 Mr. Shuangwei Xei, Ph.D. student, Electrical Engineering (plasma physics, control systems)
 Ms. Priyanka Ram, M.S. student, Electrical Engineering (control systems)
 Ms. Janus Herrera, M.S. student, Manufacturing Engineering
 Mr. Marco Cueto, undergraduate, Electrical Engineering
 Mr. Micheal Curry, undergraduate, Pre-Engineering
 Ms. Laurel Roberson, undergraduate, Electrical Engineering
 Ms. Emilie Steihhoff, undergraduate, Chemical Engineering

Mr. Steven Will completed his M.S. Thesis, "Design, Construction, and Characterization of a Laboratory Plasma Device for the Investigation of Active Control of Turbulent Transport - the ACTT Device" and graduated with the M.S. in Electrical Engineering in December, 2005. Steve is now working in the plasma physics field at Novellus Inc. in Portland, Or, a manufacturer of plasma processing tools.

VI. Publications and Presentations

Publications in preparation:

1. A. G. Lynn, M. Gilmore, C. Watts, J. Harerra, R. Kelly, S. Xie, L. Yan and Y. Zhang. "The HelCat Dual Source Plasma Device," to be submitted to *Rev Sci Instrumen*.

The following conference presentations related to this project have been made in the last year.

1. *Observation of Chaos in a Magnetized Laboratory Plasma under the Influence of Variable Biasing.* S. Xie, C. Watts, M. Gilmore, and L. Yan. Poster presentation at the 49th Annual Meeting of the American Physical Society Division of Plasma Physics, Nov. 12 - 16, 2007, Orlando, FL, USA.
2. *Nonlinear Dynamics of Fluctuations and Convective Blobs in the Presence of Sheared Flows in a Magnetized Laboratory Plasma.* L. Yan, M. Gilmore, S. Xie, and C. Watts. Poster presentation at the 49th Annual Meeting of the American Physical Society Division of Plasma Physics, Nov. 12 - 16, 2007, Orlando, FL, USA.

3. L. Yan, M. Gilmore, S.W. Xie, and C. Watts, “Nonlinear Dynamics of Turbulent Fluctuations in a Linear Magnetized Plasma with Controlled Flow Shear.” Talk to be presented June 18, 2007 at the IEEE International Conference on Plasma Science, June 18 – 22, 2007, Albuquerque, NM.
4. L. Yan, M. Gilmore, N. Crocker, T.A. Carter and W.A. Peebles, “Investigation of Intermittent Transport and Turbulent Structures in the Presence of Controlled Sheared Flows.” Poster presented at the 48th annual meeting of the APS DPP, Oct. 30 – Nov. 3, 2006, Philadelphia, PA.
5. S.W. Xie, M. Gilmore, C. Watts, L. Yan, A. Lynn, C.T. Abdallah, and A.S. Ware, “Investigation of Active Feedback Control of Turbulent Transport in a Magnetized Laboratory Plasma.” Poster presented at the 48th annual meeting of the APS DPP, Oct. 30 – Nov. 3, 2006, Philadelphia, PA.
6. S.W. Xie, M. Gilmore, C. Watts, S.W. Will, A. Lynn, P. Ram, L. Pangione, and C.T. Abdallah, “Experimental Investigation of Active Feedback Control of Turbulent Transport in a Magnetized Laboratory Plasma.” Presented at the 47th annual meeting of the APS DPP, Oct. 24 – 28, 2005, Denver, CO.
7. S.W. Will, M. Gilmore, C. Watts, S. Xie, J. Herrera, and A. Lynn. “Construction of the HELCAT dual Helicon/Cathode Linear Plasma Device.” Presented at the 47th annual meeting of the APS DPP, Oct. 24 – 28, 2005, Denver, CO.
8. S.W. Xie, M. Gilmore, C. Watts, A. Lynn, P. Ram, L. Pangione, A.S. Ware, and C.T. Abdallah, “Investigation of Active Feedback Control of Turbulent Transport in a Magnetized Laboratory Plasma.” To be presented at the “Mathematical Modeling and Control of Plasmas in Magnetic Fusion” NSF-sponsored workshop, May 11 – 12, 2006, at General Atomics, San Diego, CA.

VII. Patents and Copyrights

No patents or copyrights have resulted from this work.

VIII. Summary

In summary, the main conclusions of this work are as follows.

1. Construction of the HelCat basic plasma science device has been completed, and it is now operating routinely. HelCat is a unique basic plasma device with two different plasma sources that can produce plasmas with a range of densities from $\sim 10^{18} - 20^{20} \text{ m}^{-3}$, radii, and turbulence characteristics – from coherent to fully developed turbulence. HelCat is suitable for a wide range of basic plasma physics studies. An extensive set of diagnostics and now in place, including electrostatic and magnetic probes, mm-wave interferometry, and visible spectroscopy – both survey and high resolution. The data acquisition system, which also functions as a real time feedback controller for investigation of feedback control of turbulent transport, is also operational.
2. Experimental and numerical work is now underway on the understanding and active feedback control of turbulent transport. Initial experimental work is focusing on 1) basic characterization of the turbulent fluctuations with both the helicon and cathode sources, and 2) implementation of hardware (biased electrode actuators and computer controllers) for control experiments. Numerical

work includes adaptation of a 1D transport code to model HelCat plasmas, and integration of this model into the MATLAB SIMULINK control tool.

References

- [1] B. Fetscher, N.D. Daniels, A.S. Ware, D.E. Newman, B.A. Carreras, and c. Hidalgo. “Hysteresis effects in edge poloidal flow generation.” LP1.034. Proceedings of the 47th annual meeting of the APS DPP, Oct. 24 – 28, 2005, Denver, CO.
- [2] G.A. Navratil, *et al.* “HBT-EP Active Mode Control Research.” BP1.002. Proceedings of the 47th annual meeting of the APS DPP, Oct. 24 – 28, 2005, Denver, CO.