ADVANCED DESIGN OF A NOVEL STELLARATOR USING THE FREE BOUNDARY VMEC MAGNETIC EQUILIBRIUM CODE

Final Technical Report

For period March 1, 1999 – February 28, 2002

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June 2005

Prepared for
THE U.S. DEPARTMENT OF ENERGY
AWARD NO. DE-FG02-99ER45758
EPSCoR Laboratory Partnership Award

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Advanced design of a novel stellarator using the free boundary VMEC magnetic equilibrium code

1. Overview

This report describes the goals and accomplishments of a 3-year EPSCoR Laboratory Partnership award to design an advanced stellarator device for magnetic confinement of toroidal plasmas for fusion research. The project made use of the state-of-the-art Variational Moments Equilibrium Code (VMEC)[1] developed by Dr. Steven Hirshman and co-workers at Oak Ridge National Laboratory (ORNL) to design a novel stellarator as part of the Office of Fusion Energy Science's Compact Stellarator Program. While the experimental device that was ultimately designed was different than that envisioned at the start of this grant, the outcome was successful in that the construction and operation of a new stellarator at Auburn University, the Compact Toroidal Hybrid (CTH) has been approved and funded by the Office of Fusion Energy Sciences (OFES), and is now operational at Auburn University.

A further accomplishment of this award is the fostering of a specific linkage with ORNL and GA Technologies of San Diego to develop a versatile experimental tool to diagnose the magnetic configuration of stellarator plasmas from a finite set of measurements of the internal and external magnetic field. The VMEC code performs the MHD equilibrium calculation at the core of the V3FIT procedure. This technique to reconstruct the magnetic equilibrium of non-axisymmetric (three dimensional) plasmas from experimental data does not presently exist for stellarators, but is in growing demand by stellarator researchers around the world, and will be essential for the larger NCSX stellarator under construction at Princeton Plasma Physics Laboratory (PPPL) and ORNL. With our active participation in the development of this combined numerical and experimental technique (referred to as V3FIT), we plan to provide the first interactive test and validation of reconstruction of experimental stellarator plasma equilibria on the CTH device as a deliverable to the US fusion energy program. Moreover, our use and familiarity of the VMEC code has facilitated the successful grant proposal by Prof. J. Hanson of our department to OFES in response to DOE Office of Science Notice 02-20. Prof. Hanson is now a leading member of the V3FIT development team that also includes Drs. S. Hirshman and E. Lazarus of ORNL, Dr. L. Lao of GA, and myself.

The award has allowed us to train a post-doctoral fellow, Dr. Gregory Hartwell. Dr. Hartwell now serves as project scientist of the CTH project, fully funded by OFES. His experience that he has developed with VMEC continues to be invaluable. The V3FIT collaboration described in the previous paragraph is makes extensive use of the VMEC code, and engaged the efforts of Prof. James Hanson in working more closely with us. This EPSCoR award also partially supported one graduate student, who ultimately did not succeed in passing his Ph.D qualifying exams,and left our graduate program in late 2001. Fortunately, our research program has since attracted other, more promising candidates.

In summary, the accomplishments of this grant and its contribution to our overall research program are:

1. Fostered development of successful proposal for new long-term fusion experiment at Auburn University.
2. Initiated a specific collaboration with ORNL and industry in to develop technique to reconstruct (measure) experimental stellarator equilibria.
3. Successfully trained one post-doctoral researcher who is now a research assistant professor.
4. Publications, domestic and international conference proceedings and presentations (listed in Sec. 5).

2. Motivation of Work

The leading devices for magnetic containment of plasmas for fusion energy research are tokamaks and stellarators. Both are toroidal in configuration. The tokamak is axisymmetric (symmetric in the toroidal direction), and the requisite magnetic field for confining the plasma is created by currents in planar external coils as well as a large internal current flowing in the toroidal direction through the conducting plasma itself. The stellarator plasma is typically confined entirely by magnetic fields produced by currents flowing through generalized helical coils. No internal plasma current is required for confinement, although a significant "bootstrap" current can be generated in high-performance plasmas by the finite pressure of the plasma itself. Because of its helical configuration, the stellarator plasma is periodic but not symmetric in the toroidal direction; its geometry is said to be fully three-dimensional, and the description and implications of this geometry are more complex than those of the tokamak plasma.

As the parameters required for fusion-grade plasmas have been most closely approached in tokamak plasmas, pressure and current-driven hydrodynamic instabilities of the fluid plasma are providing severe challenges to the reliable operation of tokamaks. The stability of the plasma is directly related to the shape of the magnetic flux surfaces in which the plasma is embedded; specifically, the local and global curvature of the magnetic field lines, the shear of the magnetic field, and the free energy in the plasma current and pressure. There is good reason to believe that the stellarator configuration, with its minimal plasma current and comparative freedom to tailor the 3-D design of the magnetic field configuration, can be made considerably more resistant and even immune to the most virulent of magnetohydrodynamic (MHD) instabilities at the plasma pressure levels required for efficient fusion power production. Nevertheless, advanced stellarators will operate with some level of internal current, and the presence, and need, of internal currents has been incorporated into the design of the NCSX and QPS stellarator devices. The program at Auburn University accordingly centers on (1) developing tools for diagnosing the 3-D equilibrium of stellarator plasmas in which the vacuum magnetic congfiguration is strongly modified by internal currents; and (2) developing a more comprehensive understanding of the potential for suppression of current-driven MHD instabilities in stellarator plasmas. This EPSCoR award appropriately laid the groundwork for the design and construction of new Compact Toroidal Hybrid that addresses these areas.

The design of a magnetic configuration in which a stable plasma can be held in equilibrium generally increases with the complexity of the configuration. In brief, while the design of 2-D symmetric plasma configurations, e.g. tokamaks, can benefit from simplified analysis, the design of the fully 3-D stellarator configuration generally requires a sophisticated computer code to iteratively solve the pressure balance to obtain a predicted equilibrium of nested magnetic flux surfaces. The VMEC code is widely used for this purpose, and it was essential that our group develop the expertise to use this code effectively in designing a new stellarator experiment in which the relationship of plasma stability to the underlying magnetic configuration would be studied.

In addition to the design of the desired magnetic configuration, it is also critical to measure the magnetic equilibrium that is actually achieved in the experiment in order to compare with MHD stability theory. Again, in 2-D configurations such as the tokamak, the challenge of "re-constructing" the plasma equilibrium from measurements of local magnetic fields and fluxes is simplified by the existence of the Grad-Shafranov equilibrium equation that relates the shape of the magnetic flux surfaces to only two free parameters. An efficient technique that makes use of this approach is the EFIT code[2] which is widely used in similar work on tokamaks. Because of the lack of symmetry, no simplifying relation exists for stellarators, but the need for a 3-D equilibrium reconstruction technique is becoming more pressing as (1) plasma pressures (and achieved MHD stability values) in advanced stellarator devices around the world are approaching comparable values achieved in tokamaks; and (2) new stellarator configurations now being planned at PPPL and ORNL are predicted to benefit from using a small level of plasma current, thus acting as stellarator/tokamak hybrids. Consequently, a collaborative effort between S. Hirshman of ORNL, L. Lao and E. Lazarus of GA Technologies, and J. Hanson and S. Knowlton of Auburn has been initiated during the last year to develop and test a reconstruction method for stellarator equilibria. (The ORNL and GA team members receive funding from OFES.) The technique being developed is based on the VMEC code; therefore a practical, working knowledge of VMEC is essential for our participation in this project. This background has effectively been provided by this award.

3. Accomplishments

When the EPSCoR proposal for this work was originally prepared, our group was planning an experimental device with quasi-toroidal symmetry, based on the conceptual design of Prof. P. Garabedian of New York University, called the Quasi-Toroidal Stellarator (QUATOS). We submitted a 3-year proposal for the design and construction of this device to the Office of Fusion Energy Sciences. While the three-year construction proposal was not accepted, the group was awarded a two-year contract to continue the design work. During this period, the Auburn team participated in an *ad hoc* group of university and national laboratory scientists to develop a collaborative national research plan for advanced stellarator research. What ultimately emerged from this planning effort was the US Compact Stellarator Program, in which PPPL would propose to construct a large, proof-of-principle scale quasi-toroidally symmetric stellarator (now referred to as the National Compact Stellarator Experiment, or NCSX), ORNL would propose a quasi-poloidally symmetric stellarator (QPS), the University of Wisconsin would continue its HSX experiment, and Auburn would design and build a low-aspect ratio (compact) stellarator that would operate with plasma current. Its role within this integrated program was to explore aspects of current-driven (MHD) instabilities in stellarators that were expected to have significant consequences for the research plans of NCSX and QPS, as well as finite-β stellarators in the international fusion research program. These included the investigation of current-driven disruptions in stellarators and their avoidance through external control of the rotational transform profile as well as the testing and validation of novel 3-D equilibrium reconstruction techniques.

Because of PPPL's intent to proceed with the design of a large quasi-toroidal stellarator with the support of OFES, the task of our two-year grant evolved away from the design of an exploratory quasi-toroidal stellarator to the planning of studies that would address some of the major physics issues that stellarators with quasi-toroidal symmetry would face, including some of the same challenges considered in our original proposed experiment. We published a paper on the design of QUATOS, and after initially considering an upgrade of our existing Compact Auburn Torsatron (CAT), we designed a new stellarator device called the Compact Toroidal Hybrid (CTH), and in Feb. 2000, submitted a proposal entitled "MHD Stability Studies of Current-Carrying Plasmas in the Compact Toroidal Hybrid " to OFES in response to a competitive call for proposals. The use of the VMEC code was instrumental in carrying out the design of the CTH experiment. That proposal was accepted, and a new contract, DE-FG02-00ER54610 was issued to Auburn University to carry out this important element of the US Compact Stellarator Program. The construction of CTH is now essentially complete, and the first plasma in CTH was obtained in Feb. 2005.

The second major accomplishment fostered by this EPSCoR project was the participation of the Auburn experimental fusion research group in the development of the V3FIT equilibrium reconstruction code for stellarators. This work maintains the linkage with ORNL initiated by the EPSCoR award. The development effort in still ongoing, and has resulted in a publication and several conference proceedings.

4. Conclusion

The VMEC code was applied not only to the QUATOS project as originally planned in the EPSCoR grant planned, but was also crucial to the design of the CTH stellarator at Auburn, a device that was actually built. Moreover, the facility developed in using the VMEC code was also leveraged into Auburn's successful and ongoing participation in the state-of-the-art V3FIT 3D equilibrium reconstruction effort. The grant substantially aided in the development of a younger scientist into a research professor. Overall, it was quite successful in achieving the EPSCoR mission goals of improved competitiveness and human resource development.

5. Publications and Presentations

Publications supported by this grant (including subsequent related work)

Steven P. Hirshman, Edward A. Lazarus, James D. Hanson, Stephen F. Knowlton, and Lang L. Lao, "Magnetic diagnostic responses for compact stellarators", Physics of Plasmas 11, 595 (2004).

C. Watts, R. F. Gandy, J. Hanson, G. J. Hartwell, S. F. Knowlton, P. Garabedian, A. Carnevali, "QUATOS: A University-Scale Test of the Quasi-Toroidal Stellarator Concept", Fusion Technol. 37, 211 (2000).

S. Knowlton, R. Gandy, P. Garabedian, C. Watts, A. Carnevali, J, Cooney, C. Doloc, J. Hanson, G. Hartwell, and Y. Yuan, "Design of a Toroidally Symmetric Stellarator", Journal of Plasma and Fusion Research, 1 (1998)

Conference presentations directly supported by this grant

G.J. Hartwell, S.F. Knowlton, C. Watts, J.D. Hanson, and T. Brown, "Design and Construction Progress on the Compact Toroidal Hybrid, paper presented at the 15th Int. Stellarator Workshop, Canberra, Australia, Feb. 2002.

S. F. Knowlton, "Theory & Computation for the Compact Toroidal Hybrid (CTH) CE Program" invited talk given at 3-D Plasma Theory Workshop, Oak Ridge National Laboratory, Jan 2002.

S.F. Knowlton, G.J. Hartwell, J.D. Hanson, "MHD Stability Studies of Current-Carrying Plasmas in the Compact Toroidal Hybrid", Bull. Am. Phys. Soc., 46, 74 (2001).

S.F. Knowlton, G.J. Hartwell, J.D. Hanson, "Planned MHD Stability Studies of Current-Carrying Plasmas in the Compact Toroidal Hybrid", paper presented at Innovative Confinement Concepts for Fusion Workshop, College Park, MD, Jan. 2001.

S.F. Knowlton, "Innovation in the Stellarator Concept: An Overview of new US Stellarator Experiments", invited talk given at Innovative Confinement Concepts for Fusion Workshop, College Park, MD., Jan. 2001.

S.F. Knowlton, G.J. Hartwell, C. Watts & J.D. Hanson, "MHD Stability Studies of Current-Driven Plasmas in the Compact Toroidal Hybrid", Bull. Am. Phys, Soc. 45 (2001) 170.

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S. F. Knowlton, G. J. Hartwell, R. F. Gandy, J. D. Hanson, T. A. Schneider, C. Watts, W. A. Cooper, "MHD Stability and Disruption Studies of Current-Carrying Plasmas in the Upgraded Compact Auburn Torsatron", presented at 12th International Stellarator Conference, Madison, WI (Oct. 1999).

S. Knowlton, R. Gandy, J. Hanson, G. Hartwell, C. Watts, "Planned MHD Stability Studies in the Upgraded Compact Auburn Torsatron (CAT), presented at US/Japan Workshop for Helical System Improvement, Oak Ridge TN (Sept. 1999)

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G. Hartwell, R.Gandy, S.F. Knowlton, C. Watts, T.A. Schneider, A. Carnevali, Design of the Compact Auburn Torsatron Upgrade", Bull. Am. Phys. Soc., 1680 (1998).

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[1] S. P. Hirshman, W. I. van Rij, and P. Merkel, Comp. Phys. Comm. **43**, 143 (1986)

[2] L.L. Lao, H. St. John, R. D. Stambaugh, A. G. Kellman, and W. Pfeiffer, Nucl. Fusion **25**, 1611 (1985)

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PATENT CERTIFICATION

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