October 6, 2016

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U. S. Department of Energy
1000 Independence Avenue, SW
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RE: DE-SC0006103

Dr. Barish,

The following is the final report for the grant Targeted Optimization of Quasisymmetric Stellarators, SC0006103. The timescale of this report includes the the five year period May 15, 2011 to May 14, 2016. Let me know if you need any further information.

Sincerely

Chris Hegna
Harvey D. Spangler Professor
Department of Engineering Physics
University of Wisconsin

Final Report for DOE Grant

Targeted Optimization of Quasi-Symmetric Stellarators

Principle Investigator: C. C. Hegna, University of Wisconsin
Co-Principle Investigators: D. T. Anderson, J. N. Talmadge, University of Wisconsin
Grant Period: May 15, 2011 - May 14, 2016

This is the final report for the grant "Targeted Optimization of Quasi-Symmetric Stellarators," DE-SC0006103. This report summarizes research activities from the five year period May 15, 2011 to May 15, 2016. This grant was originally funded as a three-year grant starting in May, 2011 and subsequently renewed twice for one additional year each time. The funding level for the first year was $300,016. The funding level for year two was $250,000. The funding level for the final three years was $236,000 per year. The participating personnel with an approximate degree of involvement during this period were C. C. Hegna (Professor, $\sim$ 1 month/year), D. T. Anderson (Professor, $\sim$ 1 month/year), J. N. Talmadge (Associate Scientist, $\sim$ 1 month/year). Aaron Bader (post-doc 1/12-12/14, Assistant Scientist 1/15-5/16, 12 months/year), M. J. Pueschel (Assistant Scientist, $\sim$ 4 months/year starting 9/15) and graduate students Mordechai Rorvig, Ben Faber, and Carson Cook who were all funded in part by this grant during the course of their graduate careers. Rorvig and Cook have completed their graduate studies. We anticipate Ben Faber will complete his PhD in the near future.

Broadly, there were four areas of stellarator related research that were carried out over the past five years: 1) divertor and edge physics modeling, 2) magnetic island physics (including collaborations with LHD) 3) microinstabilities in 3D configurations and 4) energetic ion confinement. The funded research lead to 15 Journal Publications, the completion of 2 graduate theses, 7 conference reports, 13 invited talks and 49 poster and contributed oral presentations. Of note, the PI and Co-PI were both asked to give a number of overview presentations articulating research needs for the stellarator program. During the course of carrying out this research, a significant number of collaborations with colleagues, both foreign and domestic, were established in an effort to draw on their expertise, learn state-of-the-art computational tools and complement existing research programs. Additionally, issues of mutual interest to the HSX and LHD experimental programs and this grant were pursued in the areas of edge physics, turbulent transport and island physics. Moreover, this funded activity also enabled advances in the broad of area of 3D plasma science where the results of this grant were found to impact the tokamak and RFP magnetic confinement communities. In the following, a brief summary of the major results from this grant are provided.

1. Divertor and edge physics modeling

During the course of this research, our group performed a number of numerical simulations of stellarator edge physics using EMC3-EIRENE. Support from this grant has enabled us to become incorporated into the global stellarator edge community [5,7]. There are coordinated efforts to understand the role of 3D fields on edge physics in a variety of configurations. EMC3-EIRENE predictions are being compared with experimental results from LHD, HSX and Wendelstein [5,7]. One of the primary interests of the stellarator community is to understand the role of edge localized magnetic islands. We studied a variety of configurations available to the HSX configurations that have a range of island sizes. These include a configuration with large 4/4 islands, the standard QHS configuration which contains smaller 8/7 islands outside the confinement region and a configuration with small islands in the edge. Extensive parameter scans have been performed for these configurations.

EMC3 calculations predict a prominent counter-streaming flow structure associated with the islands. The effects of these flows and cross-field transport are predicted to impact the ability for stellarators to obtain high recycling regimes. The simulations indicate that transitions to high recycling regimes are more easily obtained in the configurations with large islands [4]. This transition is also more easily obtained with double-sized HSX configurations are simulated. These trends are similar to the results of prior calculations by Feng who compared the W7-AS (which had difficulty obtaining a high recycling regime) and W7-X configurations. Additionally, the role of cross-field transport is monitored. When smaller diffusion coefficients are used, the heat flux on the wall and flow structures have much sharper features than the equivalent calculations with larger diffusion coefficients.

An important role of these simulations is to provide testable information for the HSX experimental group. A program to characterize the edge properties of HSX was a major emphasis of recent HSX PhD thesis. By making comparisons with EMC3-EIRENE, cross-field transport coefficients of the HSX were deduced. Additionally, evidence for the predicted counter-propagating flows were seen [14]. However, features not present in the simulations were also observed. Namely, large potential structures associated with island remnants were measured.

Additionally, our group provided theoretical support for a set of experiments carried out by our UW colleague Oliver Schmitz on LHD. The goal of these experiments was to understand the role of edge magnetic islands on helium transport. Experiments indicate that edge islands can provide a partial screening effect on helium that prevents their proliferation into the plasma core region. Our simulations provided detailed predictions to be corroborated with spectroscopy measurements [15]. One of the important results of this comparison was to understand the details of the helium fueling.

Recent activities from our group have focused on the possibility of improved stellarator divertor design. Working with Allen Boozer of Columbia University we have been pursuing the notion of a 'resilient' divertor whereby the configuration has robust heat flux strike point patterns that are insensitive to the details of the plasma profiles and configuration [82]. HSX appears to be a device with resilient divertor possibilities. As long as no prominent island feature is present near the plasma-wall interface, the heat flux pattern on the wall is largely the same. Indeed, efforts to stochasticize the edge with divertor coils made only minor changes to strike points and deposition profiles [51,63]. Attempts to implement advanced tokamak concepts from the tokamak community (snowflake and X-divertor) into HSX configurations have not been found to date. In part, these results are due to the close proximity of the existing HSX coils to the plasma but also reflective of resilient divertor possibilities.

2. Magnetic Island Physics

During the period of this grant, a significant research result was achieved in the area of magnetic island physics. An analytic model was developed to explain the observed healing of imposed vacuum magnetic islands [2] on the Large Helical Device (LHD) operating at the National Institute for Fusion Studies (NIFS) in Toki, Japan. The model accounts for the competition between electromagnetic torques, the neoclassical flow damping properties of conventional stellarators and cross-field viscous forces. The model was constructed in an effort to explain a long standing issue concerning LHD island studies where neither 3-D MHD equilibrium codes or previous analytic island models were able to explain the experimental observations. An important element in the theory is the proper accounting of flow physics. In particular, the new theory is able to accurately describe the LHD phenomenology and provides a theoretical prediction for the observed critical beta for healing as a function of plasma collisionality. A second paper extended these studies by accounting for transitions from the $1/\nu$ to plateau collisionality regimes of stellarator neoclassical transport [3]. This extension of the theory was employed in order to accommodate further data from LHD that has a broad range of collisionalities. The theory correctly predicts a hysteresis between island healing and field error penetration. This prediction has inspired further experiments on LHD in the past number of year that have further corraborated the theory [19,21] . These studies are part of a continuing collaboration between our group and the LHD team. This work received considerable attention in the community as evidenced by invited talks at NIFS as part of the International Stellarator Working Group Meeting, Oak Ridge National Laboratory [25], the ICC Meeting [26], the APS-DPP meeting in Salt Lake City [27] and the 18th International Stellarator Workshop in Australia [28].

Additionally, our group collaborated with colleagues developing the new 3-D MHD equilibrium code SIESTA [1]. This collaboration is primarily carried through interactions with University of Wisconsin graduate student Carson Cook. Carson regularly interacted with Steve Hirshman and Raul Sanchez of ORNL and has already made substantial contributions to the development of SIESTA.

In 2015, Carson Cook completed his PhD studies on the effect of magnetic islands on the Alfvén spectrum of toroidal plasmas [17]. This work used a combination of analytic theory [8], computational development using novel application of stellarator MHD equilibrium tools and coordination with experimental colleagues to test key aspects of the theory [13]. This work grew out of Carson working with the SIESTA code. Following a suggestion from Don Spong, we recognized that SIESTA could be used to deduce the effects of magnetic islands on the linear ideal MHD spectrum. Subsequently, we became aware of results from MST where Alfvénic activity in the presence of an energetic ion population was unexplained by convention tools to calculate the Alfvén spectrum that assume the existence of axisymmetric magnetic surfaces.

Analytic techniques were employed to describe the Alfvénic spectrum in the vicinity of and inside the separatrix of a magnetic island [8]. The theory predicts that an equilibrium magnetic island causes an upshift in the accumulation point frequency and that the minimum of the frequency spectrum is shifted from the rational surface to the island separatrix. For quantitative predictions of the Alfvénic spectrum, we developed a new computation tool, SIESTAlfvén. The SIESTAlfvén results come from 3-D MHD equilibria with magnetic islands as computed by SIESTA. The Alfvén modes are computed by solving the generalized eigenvalue problem obtained from the Hessian matrix of SIESTA's potential energy along with inertia matrix obtained from the SIESTA equilibrium.

The theory is used to explain previously unresolved Alfvénic activity observed on MST during NBI [13]. What is new in the present analysis is the recognition that a sizable $n = 5$ island exists in the plasma core. The presence of the island was not accounted for in previous simulations of MST's Alfvén spectrum. The theoretical Alfvén continua in the core of the island provides a gap in which the observed $n = 4$ Alfvénic bursts reside. Numerical simulations using SIESTAlfvén have identified the bursts as Island-induced Alfvén Eigenmodes (IAE). The IAE arises from a helical coupling of mode numbers, similar to the helicity induced Alfvén eigenmode, but occurs on helical surfaces residing inside the magnetic island separatrix.

3. Microinstability studies in 3D configurations

Microinstability studies in stellarator configurations are a relatively new research thrust in our group. The broad goal of this work is to find appropriate means to optimize turbulent transport through 3-D shaping. In these studies, both analytic theory and GENE simulations are employed to study ITG and TEM turbulence. We developed a simplified analytic theory as a proxy for ITG linear instability in quasi-helically symmetric configurations [16]. Since flux tube calculations are employed, only local 3-D equilibrium is required. Following the prescriptions for local 3-D MHD equilibrium theory, important geometric properties can be easily manipulated. Using a test function approach, analytic estimates for the linear growth rate can be constructed as a function of various 3-D shaping parameters. These calculations identify a competition between destabilizing drift frequency effects (which are influenced by normal and geodesic curvature and local shear) and stabilizing $k_\perp^2 \rho_s^2$.

Proxy function estimates are compared to GENE simulations for a variety of 2-D and 3-D configurations. These studies show that the contribution to the drift frequency drive from the product of the geodesic curvature and the integrated local shear can play an important role. While the normal curvature largely defines the depth of the bad curvature, this additional term controls the extent of the bad curvature along the field line. These results are also consist with optimization work carried out by Mynick et al for NCSX configurations.

We published the first results of linear and nonlinear gyrokinetic simulations of trapped electron mode (TEM) turbulence in quasi-symmetric stellarators [11]. These results were highly motivated by results from HSX who have definitively shown that successful optimization using the quasi-symmetric principle can reduce the level of collisional neoclassical electron heat transport so that turbulent transport processes dominate. The results of the simulations coupled with perturbative transport studies on HSX using ECRH indicate that collisionless trapped electron modes are the likely candidate to explain the dominant anomalous transport losses.

Linear simulations show that growth-rates peak at $k_y \rho_s \sim 1$ as anticipated by similar studies in tokamak geometry. Nonlinear simulations show that the dominant contribution to the heat flux is due to modes with $k_y \rho_s < 1$. However, as the density gradient drive increases, there is a significant contribution to the heat flux at long wavelength ($k_y \rho_s \sim 0.1$). This low-k_y transport peak emanates from linearly stable eigenmodes [37] that are generated by robust nonlinearly generated coherent structures. This long wavelength structure is a major contributor to the transport on the most unstable flux tube and is far larger than the quasilinear predictions for the transport at low k_y.

Nonlinear gyrokinetic simulations of ion temperature gradient (ITG) turbulence have been carried out in HSX geometry. What these simulations show is that due to the complex geometry and relatively low averaged magnetic shear, there are a large number of subdominant unstable eigenmodes [12]. Turbulent spectra are broadband as a consequence. Additionally, it is shown that successful quasi-linear mixing length transport modeling is possible, however it is essential to account for all subdominant unstable modes.

Finally, efforts continue to try to understand how improvements to stellarator design might be accomplished by incorporating turbulent transport metrics in optimization schemes. Our initial attempts at this emphasized understanding of how 3-D shaping can influence linear ITG instabilities. We employed a simplified analytic fluid model to provide a proxy for the eigenvalue. This produced crude predictions for the linear growth rate based on the relative roles of a destabilizing curvature drive and the stabilizing effect of the local shear for the "toroidal" ITG. However, it has been noted that because of the relatively short connection length present in quasi-helically symmetric (QHS) configurations, the "slab" ITG root is predominant [52] and a different optimization approach may be needed. Additionally, efforts were employed to understand the properties of linear TEM instability. Analytic machinery was developed using local 3-D MHD equilibrium theoryto describe the role of 3-D shaping on trapped particle precessional drifts. This calculation was applied to tokamak cases in the presence of weak 3-D magnetic fields [9]. More recently, we have embarked on a program to understand nonlinear turbulent saturation processes in stellarators. This work is carried out in collaboration with Prof. Paul Terry who has been developing a program for understanding turbulent saturation through the paradigm of zonal flow-mediated nonlinear energy transfer from unstable to damped eigenmodes as the dominant process.

4. Energetic ion confinement

A collaboration was initiated with V.V. Nemov of the Institute of Plasma Physics, Kharkov, Ukraine and W. Kernbichler of the Institut für Theoretische Physik, Graz, Austria on a study of energetic particle confinement in HSX and HSX-like fusion reactors. The goal was to investigate and improve the confinement properties of the quasihelically symmetric configuration. The HSX configuration was scaled up to $a = 1.6m$ and $B = 5T$ and the collisionless orbit of $3.5MeV$ alpha particles was followed. It was found that alpha particle confinement in an HSX reactor was degraded because of the modular ripple (the $n = 48, m = 0$ term in the magnetic field spectrum) due to the discrete coils and their finite radial width. Doubling the number of coils decreased the ripple and substantially improved the alpha particle confinement. A faster method to categorize energetic particle confinement is the parameter defined by Nemov as Γ_v, the surface average of the collisionless bounce-averaged ∇B drift velocity. This parameter was used as the target function of an optimization code that varied the currents in the auxiliary coil set to see if Γ_v could be decreased in the plasma core of the HSX experiment. The results indicated that the enhanced losses due to the coil ripple could not be compensated by the auxiliary coils, although it was very easy to degrade the energetic particle confinement even further. Furthermore, it was shown that while Γ_v decreased with doubling of the number of coils in HSX, the effective ripple for this new device actually increased. The effective ripple, which is often used as a measure of stellarator confinement, but is explicitly related to confinement in the $1/\nu$ regime, is an inadequate measure of alpha particle confinement. This work highlighted the importance of making sure the coils in a stellarator reactor need to be optimized explicitly for alpha particle confinement.

Grant Related Publications and Presentations

Publications

[1] S. P. Hirshman, R. Sanchez and C. Cook, *Phys. Plasmas* **18** 062504 (2011).

[2] C. C. Hegna, "Healing of magnetic islands in stellarators by plasma flow," *Nuclear Fusion* **51**, 113017 (2011).

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Graduate Theses

[16] M. N. Rorvig, "Principles of toroidal geometry optimization for ITG modes," UW CPTC Report 14-02, August, 2014, Masters Thesis.

[17] C. R. Cook, "Shear Alfven continua and discrete modes in the present of a magnetic island," UW CPTC 15-03, June 2015, PhD Thesis.

Conference Reports

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Feng, H. Funaba, M. Goto, C. C. Hegna, O. Mitarai, T.Morisaki, G. Motojima, Y. Narushima, D. Nicolai, U. Samm, G. Spizzo, H. Tanaka, M. Yoshinuma, and Y. Xu, "Enhancement of helium exhaust by resonant magnetic perturbation fields," to be presented at the 26th IAEA Fusion Energy Conference, paper ID number 230.

[23] J. S. Sarff, J. K. Anderson, P. Brunsell, D. Brower, ... C. C. Hegna, ... "Overview of MST Reversed Field Pinch Resarch in Advancing Fusion Science," to be presented at the 26th IAEA Fusion Energy Conference, paper ID number 236.

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Invited Talks

[25] C. C. Hegna "Healing of magnetic islands in stellarators with plasma flow," Oak Ridge National Laboratory, June 23, 2011.

[26] C. C. Hegna "Healing of magnetic islands by plasma flow," Innovative Confinement Concepts and US-Japan Compact Torus Plasma Workshop, Seattle, WA, August 16, 2011.

[27] C. C. Hegna "Healing of magnetic islands in stellarators with plasma flow," 2011 APS-DPP Meeting, Salt Lake CIty, UT, November 17, 2011. *Bull. Am. Phys. Soc.* **56**(16) VI3.00004 (2011).

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[29] D. T. Anderson "Progress and prospects in stellarator physics and 3D plasma confinement," Workshop on Exploratory Topics in Plasma and Fusion Research, Fort Worth, TX, February 14, 2013.

[30] C. C. Hegna, "Differences and similarities in the 3-D physics of stellarator/ heliotrons and reversed field pinches," to be given at the Joint 19th ISHW and 16th IEA-RFP workshop Padova, Italy, September 16-20, 2013.

[31] C. C. Hegna "The effects of weakly 3-D equilibria on the MHD stability of tokamak pedestals," Columbia University Plasma Physics Colloquium, New York, NY, May 2, 2014.

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Poster presentations

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