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Annual Progress Report
USDOE Grant DE-FG03-98ER54461
"Determining How Magnetic Helicity Injection Really Works"

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1. Project Description

1.1 Goal

Magnetic helicity injection is the essential process underlying both spheromak formation and helicity injection toroidal current drive in tokamaks (e.g., HIT and NSTX). The dynamical details of the helicity injection process are poorly understood because existing models avoid a dynamic description. In particular, Taylor relaxation, the main model motivating helicity injection efforts, is an argument that predicts the state to which a turbulent magnetic configuration relaxes *after* all dynamics are over. The goal of the Caltech experiment is to investigate the actual dynamics and topological evolution associated with relaxation and so determine how helicity injection really works. Although the global relaxation model (i.e., Taylor model) typically invokes axisymmetry, simple physical arguments (Cowling's theorem) show that the detailed dynamics must involve topologically complex, non-axisymmetric processes.

1.2 Experimental setup

The experiment consists of a coaxial spheromak gun mounted on a large (1.4 m diameter) vacuum chamber which provides excellent viewing access of the plasma emerging from the spheromak gun. This gun has currents of 100-200 kA, maximum operating voltage of 12 kV, and a pulse length of approximately 10 microseconds. Since topological evolution is the key issue, special cameras have been developed which record the evolving topology of the plasma. Magnetic probes and other standard diagnostics are also used. The measurements reveal three dimensional aspects of the magnetic configuration and are compared to the prediction of theoretical models. There is no attempt at parameter pushing; the emphasis is to understand the physics underlying the complex, transient, 3D phenomena. This experiment has a synergism with another, similar experiment mounted on the same vacuum chamber and having the goal of simulating solar prominence eruption. The solar prominence simulation experiment shares many concepts, technologies, and diagnostics with the helicity injection experiment. This sharing of ideas and hardware provides substantial advantages for both experiments.

2. Activities during previous year

2.1 Diagnostic Improvements

2.1.1 Camera upgrade

Two Princeton Instrument gated, intensified CCD cameras have been made to work in tandem so as to provide high quality stereographic photographs of the emerging twisted plasma.

2.1.2 Magnetic probe array

A magnetic probe array was constructed by graduate student Jimmy Yee and used to scan a 3D volume of plasma. The measured magnetic fields were integrated in space to provide 3D field line trajectories. These field line trajectories were twisted in a manner reasonably consistent with the flux tubes photographed, but there were some minor discrepancies.

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2.1.3 Stark broadening measurement

An optical multichannel analyzer was used to search for broadening of H-alpha lines emitted by the spheromak plasma. At low densities (below 10^{14} cm^{-3}) broadening is expected to be mainly Doppler, but at high densities (10^{15} cm^{-3} and above) the broadening is expected to be mainly Stark. Significant broadening was observed (compared to a spectral reference lamp) and the preliminary interpretation is that this is Stark broadening. This project was done as a summer undergraduate research by Caltech undergraduate Celeste Yang.

2.1.4 Triple probe

A triple probe was constructed during the summer by undergraduate Jez Gaddoura from Hamilton College who was at Caltech on a DOE undergraduate fusion energy summer fellowship. A triple probe is a set of three adjacent Langmuir probes biased in such a way that plasma density and electron temperature can be determined without scanning bias voltage. Preliminary results (obtained during the summer) indicated a higher density than expected and work continues to see if the measurement is credible.

2.1.5 Laser Induced Fluorescence (LIF)

Efforts are underway to attempt LIF on a spheromak plasma. Our group has extensive LIF hardware which was originally designed for a quasi-cw research tokamak. Adapting this equipment to a spheromak measurement is a significant technical challenge, because of the different operating regime and also because of the single pulse nature of the spheromak. The electronics, CAMAC system and software have been reconfigured by grad student Steve Pracko for the spheromak experiment, and this reconfiguration will be tested on the research tokamak before being applied to the spheromak.

2.1.6 X-ray camera

Efforts are underway to develop an x-ray camera which would provide soft x-ray imaging of the spheromak (and also the solar gun). This work is being done in collaboration with S. Zweben of PPPL. A first attempt was based on a pinhole camera illuminating a phosphor screen with a thin foil coating (to filter out visible light). This did not work and a second attempt is being planned which will replace the phosphor screen with a commercial micro-channel plate intensifier sensitive to x-rays but not visible light.

2.2 Machine improvements

2.2.1 Hinge for vacuum chamber end dome

A very large hinge was installed on one end dome of the vacuum chamber. This hinge allows the end dome to be opened, completely exposing the vacuum chamber interior. It is now possible to crawl into the vacuum chamber and access the interior. This allows repairs and modifications from the inside and also the installation of hardware too big to fit through existing ports.

2.2.2 New timing model

A twelve channel CAMAC timing module has been constructed by engineer Frank Cosso. This has optical fiber outputs and provides triggering signals for capacitor banks, cameras, and diagnostics.

2.2.3 Fiber Optic Analog Transceivers

Two 10 MHz transceivers have been acquired and are being installed for transmission of signals from noisy or high voltage locations. The transmitter can be battery operated and can

float at high voltages. The signal is transmitted via a long optical fiber cable and so there is complete immunity from noise and ground loops.

3. Publications, theory

3.1 Book on spheromaks

The PI is writing a book on spheromaks, to be published by Imperial College Press (UK). The book is intended to provide a good introduction to spheromak concepts for graduate students, postdocs, and established researchers from other backgrounds who are starting to work on spheromaks. It is also intended to serve as a useful handbook for scientists actively working on spheromaks. The book will be approximately 300 pages long and a first draft has been completed. It contains a mix of theory and practical experimental considerations. During the course of writing, new results on spheromak formation sequence and spheromak load impedance were obtained. These results predict a spheromak impedance from the combination of the Taylor relaxation model and helicity conservation. They also predict why spheromaks are sometimes observed to be flipped 180 degrees.

3.2 General Taylor Expansion Revisited

In the course of writing the spheromak book, the PI noticed an apparent paradox in an eigenfunction decomposition developed many years ago by Jensen and Chu and often cited. This paradox seemed important, because on the one hand a spheromak gun involves injection of current at the wall whereas the Jensen and Chu model involved summation of current eigenfunctions each vanishing at the wall. This concern was relayed to Jensen and Chu who reconsidered the expansion and realized that the paradox was due to a Gibb's phenomenon. A paper by Jensen, Chu, and the PI has been written resolving the paradox and will be submitted shortly.

3.3 Helicity and reconnection

The PI was asked to give an invited talk on helicity and reconnection at a July 1998 AGU Chapman workshop on Helicity in Lab and Space Plasmas. In conjunction with this talk, an invited paper will be published in an AGU monograph on helicity. This paper has been submitted.

3.4 Alfvén waves and magnetic reconnection

Magnetic reconnection is an essential aspect of magnetic helicity injection because helicity injection necessarily involves change of field line topology. The PI has proposed that localized reconnection will emit torsional Alfvén waves, because localized reconnection results in the creation of a localized twist on the newly reconnected field lines. Such a localized twist cannot be in equilibrium and equilibrates by propagating along the field line as a torsional Alfvén wave. The PI has proposed that, in certain situations, the radiation resistance associated with this emission can constitute the anomalous resistivity required for magnetic reconnection to proceed at observed rates. This work has just been published ["Collisionless Reconnection Via Alfvén Wave Radiation Resistance" by P. M. Bellan, *Phys. Plasmas* **5**, 3081(1998)].

3.5 Analysis of TEXT spheromak injection experiment

A paper analyzing our earlier experiment on TEXT was submitted and published ["Effects of CT injector acceleration electrode configuration on tokamak penetration", by J. Yee and P. M. Bellan, *Nucl. Fusion* **38**, 711(1998)]