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 and methodology

Magnetic helicity injection is the essential process underlying both spheromak formation and helicity injection toroidal current drive in tokamaks. 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, predicts the state to which a turbulent magnetic configuration relaxes *after* all dynamics are over. The goal of the Caltech program is to determine how helicity injection works by investigating the actual dynamics and topological evolution associated with relaxation. 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.

The philosophy of the Caltech research program is to develop clean, simple experiments that isolate the essence of magnetic helicity injection so that a meaningful comparison to models can be achieved and inspiration can be provided for developing new models.

1.2 New Planar Helicity Source

A new coaxial helicity injection source has been constructed and brought into operation. The key feature of this source is that it has maximum geometric simplicity. The purpose of this simplicity is to ensure that physical processes are not obscured by unnecessary geometrical complexity in the source. The source is called a 'planar helicity injector' and consists of a copper disk surrounded by a copper annulus with a bias coil located slightly behind the gap between the disk and the annulus. Gas injector ports are located on both the disk and the annulus. The injector is located in a large vacuum chamber that has superb viewing access via large windows.

The injector provides currents of ~150 kA and has produced some very interesting plasmas. These have been measured using high-speed photography, magnetic probes, soft x-ray detectors, triple probes, and current/voltage diagnostics.

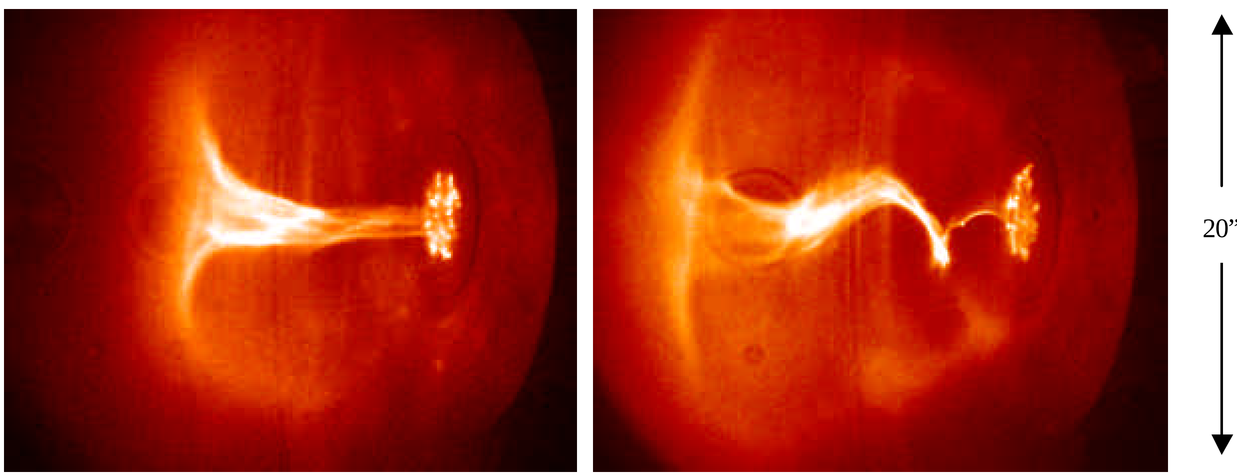
This experiment has a synergism with another, similar experiment mounted on the same vacuum chamber and having the goal of simulating solar prominence eruptions. The solar prominence simulation experiment shares many concepts, technologies, and diagnostics with the helicity injection experiment. This sharing of ideas and hardware provides substantial advantages for both experiments.

The planar helicity injector also has direct relevance to the astrophysical jets shooting out from the accretion disks surrounding black holes. In fact, the geometry of the planar helicity injector is essentially identical to the geometry of accretion disks, and the jet mechanism appears to be the same. Discussions have been held with Caltech astrophysicists on how the results of the planar helicity gun could help astrophysics research.

2. Activities during previous year

2.1 High quality framing photos of helicity injection, spheromak formation

Brief demonstrations of high-speed framing cameras were arranged (these cameras cost $180k-$250k) and as many configurations as possible were photographed during the brief demonstration period. These photos show remarkable features and in fact are being published in an upcoming special IEEE Transactions of Plasma Science issue on images of plasmas. These photos show a clear sequence of events in the formation process. In particular, they show initial merging/reconnection processes, jet-like expansion, kinking, and separation of the plasma from the source. Typical photos showing the jet-like expansion phase and the kink phase are shown below (the 8” diameter copper disk and the 20” o.d., 8.25” i.d. annulus are on the right; the bias coil is behind the disk).



Jet-like expansion　　　　　　　　　　Kink

2.2 Soft x-ray diodes

A system of filtered soft x-ray diodes has been constructed and used to observe x-ray emission from the plasma. The diode system uses high-speed AXUV diodes (<1 ns rise time), extreme electrical shielding (separate ground inside machine ground, semi-rigid coax, high-speed bias tee), and unlike our earlier attempts has provided credible signals.

2.3 Laser induced fluorescence

We are developing an LIF diagnostic for spheromak plasmas; this diagnostic uses an argon ion line. Very clean argon plasmas have been obtained using the new gas valves described in Sec. 2.4 below. LIF signals had been obtained from an earlier plasma source which had much less reproducibility than the present source and which produced a plasma which was much less regular in appearance. Ultra high-speed (1.3 GHz) digitizers have been obtained surplus from Sandia and have been used to capture the very short (10ns) LIF signal. This has been demonstrated on a test system having a high rep-rate plasma and is being implemented on the planar helicity source experiment.

2.4 Puffed gas valve

Our laser induced fluorescence experiments requires argon plasma instead of the usual hydrogen plasma. There were serious problems with blowback arcs destroying the gas injection lines when using argon. It was therefore necessary to redesign the gas injection system to avoid this. The new design has floating capacitor banks to power the gas valves connected to the high voltage electrode (disk) and grounded capactor banks to power the valves connected to the ground electrode (annulus). This necessitated building a new version of gas puff valve with a larger plenum. These valves were designed to be very consistent from one unit to another and easy to assemble. An interesting new effect was observed when calibrating the new valves and, because of the potential practical applications of this effect, a provisional patent has been applied for. It was discovered that the gas puff, being supersonic, ionizes some of the injected gas so that an electrical signal can be measured on an unbiased cold probe placed in the flight path of the gas puff. Gas puffs have traditionally been diagnosed using ionization gauges which require a hot filament to emit ionizing electrons. Here, there is no need for a hot filament since the gas is weakly auto-ionized. Measurement of the auto-ionization gives information on gas valve timing, reproducibility, gas velocity, and surface vacuum condition.

2.5 Magnetic probe development

A scheme has been developed for using miniature ceramic inductors as the coils in a magnetic probe array. These inductors are mounted on a stalk with pockets machined to match the inductor dimensions. The machining is done by a CNC mill and provides a way for easily mounting 60 coils on a stalk. This system has been tested on the planar helicity injector experiment, but there were problems with some connections breaking. A new version with more robust connectors is under construction.

2.6 High speed camera for SSPX

An optical system has been designed and tested at Caltech to allow placing a high-speed camera on the Sustained Spheromak Physics Experiment (SSPX) at Livermore. This system involves a screen (or optional relay lens) system for relaying the image viewed through a narrow slot in the flux conserver to the camera located about 0.5 meter away. Demonstrations of cameras were arranged (at both Caltech and LLNL), a camera was selected (Cooke DiCam Pro) and ordered. There has been much interaction with the SSPX group (visits, email, phone, etc.) and it is anticipated that the camera system will be ready shortly.

3. Publications, talks, theory, etc.

3.1 DPP Distinguished Lecture Talks

Paul Bellan has given DPP Distinguished Lecture talks during the last year on how experimental plasma methods can help understand solar physics at Utah State University, Loyola Marymount University, Florida Institute of Technology, University of Calgary, University of Lethbridge, and Sacramento State University. A talk will also be given at Montana State University later this month. A more technical version of the talk was given at Lockheed Martin Space and Astrophysics Lab (the developers of the TRACE spacecraft that has provided the most exciting recent photos of the solar corona). An invited talk was presented at the ISSS-6 conference in Garching, Germany.

3.2 IPELS

Scott Hsu presented a paper on the planar helicity injector at the Interrelationship between Plasma Experiments in Lab and in Space (IPELS) meeting in Japan in June, 2001.

3.3 Astrophysics Conference Invitation

Freddy Hansen has been asked to give an invited talk on the solar prominence simulation experiments at an upcoming astrophysics conference. The conference is titled "Black Holes: Theory Confronts Reality, 3 Years Later" and will be held February 2002 at the Institute for Theoretical Physics, Santa Barbara.

3.4 Award

The Solar Physics Division of the American Astronomical Society awarded Paul Bellan the '2001 Award for Popular Writing on Solar Physics' by a professional scientist for the article "Simulating Solar Prominences in the Laboratory" which appeared in the March-April 2000 issue of American Scientist.

3.5 Publications

1. Bellan P. M., Yee J., and Hansen J. F., *Spheromaks, solar prominences, and Alfven instability of current sheets*, Earth Planets Space **53**, 495 (2001).
2. Bellan, P. M., *Alfven wave instability of current sheets in force-free plasmas: comparison to ion acoustic instability*, Advances in Space Research (accepted for publication).
3. Hsu, S. and Bellan, P. M., "*Studies of magnetic helicity injection via plasma imaging using a high speed digital camera*", IEEE Transactions on Plasma Science Special Issue on 'Images in Plasma Science', (to appear Feb. 2002).
4. Tokman, M. and Bellan, P.M., *Three-dimensional model of the structure and evolution of coronal mass ejections*, submitted to Astrophysical Journal.
5. Hansen, J. F. and Bellan, P. M., *Experimental demonstration of how strapping fields can inhibit solar prominence eruptions*, submitted to Astrophysical Journal Letters, tentatively accepted subject to a few revisions.
6. Bellan, P. M., *Why coronal flux tubes have axially invariant cross-section*, submitted to Physical Review Letters.

3.6 PhD's completed in 2001

1. Larry Sverdrup (experiments on lower hybrid wave propagation, work was completed in 1987, but thesis not submitted until 2001).
2. J. Freddy Hansen (solar prominence simulation experiments)
3. Mayya Tokman (3D numerical MHD simulations of dynamic solar coronal structures having some similarities to spheromaks, co-advisor: D. Meiron, Applied Math Dept).