HELICITY SPACE

# Simulation of plectoneme formation

Final Report


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**Note: Report may be posted publicly. Do not include proprietary information.**

# 1 Technical Overview

## 1.1 Problem Statement

*Describe the company challenges this program is meant to address. Should be adapted from original application, noting any departures / evolutions from that original application.*

The challenge facing the company is developing some predictive capability for a key ingredient of the Helicity Drive fusion concept in a cost-effective and timely manner.

The key ingredient is a novel, magnetized, plasma configuration called a plectoneme for short.

A plectoneme is a non-axisymmetric $m$ = 1 Taylor state. It is a cousin of the spheromak which is the axisymmetric $m$ = 0 Taylor state. The name plectoneme is taken from the mathematics of twisted ribbons and frequently used in the description of DNA double-helix "supercoil" strands.

Open plectonemes can be thought of as cables or ropes that are sufficiently twisted to develop tight intertwined strands that emerge between the cable ends; and closed plectonemes can be thought of as tightly twisted rubber band loops inside a long closed cylinder. Magnetic plectoneme configurations were first predicted theoretically almost forty years ago [1, 2], and recently discovered in the SSX experiment with close-fitting flux conserving walls [3, 4] and in the MOCHI experiment within a stable magnetized jet without close-fitting walls [5-7].

The Helicity Drive fusion concept merges a number of these plectonemes, embedded inside stable jets like MOCHI, into a single one to pre-heat the plasma via magnetic reconnection prior to compression with an external peristaltic magnetic field.

The goal of the project was to answer three scientific questions. First, can the simulations reproduce the stability of the MOCHI jets? Does the specific MOCHI initial boundary conditions result in stabilizing helical shear flows as observed in the experiment? Does the plectoneme configuration form as it does in the experiment?

## 1.2 Work Scope

*Describe the approach used to achieve the project goals, including the capabilities at the national laboratory or partner facility, as well as the capabilities at the company and its subcontractors on this award. Can be informed / adapted from original application, noting departures / evolutions.*

The project used the LA-COMPASS 3D MHD code [8], with Dr. Hui Li, one of its creators, and Dr. Shengtai Li to perform these initial studies of plasma plectoneme formation. The reason for choosing this code is because Dr. Li has recently performed 3D simulations of the Caltech plasma jet experiment [9]. This experiment is closely related to the MOCHI experiment which itself is closely related to the Helicity Drive concept. In the Caltech experiment, a planar plasma gun forms plasma jets with interesting properties: the jets are dense, collimated, carry significant current, appear to be related to astrophysical jets [9, 10], and are precursors to spheromaks after these jets go kink unstable [11]. The LA-COMPASS code appears to have quantitative agreement with the Caltech experiment. This is impressive and remarkable because the experiment is deceptively simple. The specific experimental parameters require careful attention to the initial and boundary conditions of the simulation because they are difficult to replicate numerically: mass and magnetic flux injection at the boundaries; large density ratios between jet and vacuum environment; and 3D non-MHD behavior late in the jet evolution (magnetic reconnection and hierarchy of instabilities).

The MOCHI experiment [5] expands on the Caltech experiment in mainly two ways: a third planar electrode is placed around the planar plasma gun; and the gas source at the boundary is azimuthally symmetric instead of a discrete number of gas holes. The motivation for these two modifications is to allow more control on the interplay between magnetic forces, pressure, and flows. These two modifications have produced two very interesting new results [6, 7]: long-lived, tightly collimated, high aspect-ratio plasma jets with strong, sheared, helical flows (the Caltech jet would always be kink unstable at the Kruskal-Shafranov threshold); and the presence of a plectoneme magnetic configuration embedded inside the jet without the presence of tight-fitting, flux conserving, metal walls (the SSX experiment formed plectonemes using pairs of traditional plasma guns with flux conservers of differing aspect-ratios). It should be feasible to simulate the MOCHI and Helicity Drive configurations with modest effort since the LA-COMPASS code has succesfully simulated the configuration of the Caltech experiment. The code is now capable of performing simulations three times larger in each direction compared to the results reported in 2014. This has been very useful for the long plasma jets observed in MOCHI and expected in the Helicity Drive.

The goal of the project would be to answer the following scientific questions:

a. Does the numerical simulation qualitatively and/or quantitatively reproduce the MOCHI results, and therefore is able to simulate and predict (one of the steps in) the Helicity Drive operation?
b. Does the specific MOCHI configuration (triple electrode configuration and azimuthally symmetric mass sources) account for the helical flow shear observed in the experiment?
c. How does the plectoneme magnetic configuration observed in the experiment form exactly? How does the plectoneme parameters (e.g. magnetic field, flow field, plasma pressure) develop from the given initial and boundary conditions?

## 1.3 Results

*Describe the tasks accomplished, results obtained, key deliverables, lessons learned. Do not include proprietary information.*

The project has successfully answered the first two questions in the affirmative. The third question has not been fully answered. The following accomplished tasks describes these results.

Firstly, we revisited the 3D MHD code used specifically for the Zhai et al. (2014) jet results. It was written in the FORTRAN computer language and was difficult to adapt to other experimental setups and the accuracy of numerical scheme, which is of dimensional-split type, is only of second-order. We implemented a C-version of the code using the third-order dimensional-unsplit numerical scheme. The results compare well between the FORTRAN-version and C-version.

Next, we modified the code's initial and boundary conditions to mimic the MOCHI experimental setup: nested multiple electrodes, nested gas injection positions, a bias field, and time injection curves of mass, kinetic energy, and magnetic energy. Nested electrodes meant that the jet has a core and skin layer that can be driven independently by the nested electrodes. The rest of the volume has open boundaries. The simulation results show that we can observe a two-stage jet formed as observed in experiment: the first jet is formed and lasts only for a few nano-seconds and then disappears. Then the second jet is formed and lasts for a few nano-seconds and then becomes unstable. In the experiment, the second jet lasts much longer and is stable. Although this is similar qualitatively to the MOCHI experimental observations of a precursor, short-lived jet followed by a long-lived stable jet, the fundamental reason for this may be different for each case. In the experiment, the jet is formed in a vacuum (no background plasma) and the first jet becomes kink unstable after several microseconds at a length of a 10 cm approximately, detaches, and flies near-ballistically into the chamber (similar to the Caltech experiment and Zhai et al's numerical results). In MOCHI, the second jet forms into this background plasma on a longer time scale (tens of microseconds) which allows helical shear flows to form and stabilize the jet over 50-90 microseconds when the current runs out. In contrast, the simulation begins with a background plasma with a density several thousandths below the initial gas injection density. The short-lived nanosecond kink unstable jet in the simulation appears to be due to the formation of a jet with the low density background plasma evolving before the denser injection forms into a larger jet. The reason the second jet was also unstable (when the experiment's second jet was stable) became understood during the tasks in our next (third) phase.

In the third phase, we explored the MOCHI simulation setup and parameters space. After a number of numerical experiments, we have found a setup and a set of parameters that can produce a long stable jet similar to the jet observed in the MOCHI experiments. The key result is that the long stable jet only exists if three conditions are simultaneously satisfied: (1) a differential skin and core electrical current is driven in the jet, i.e. injection of shaped toroidal magnetic field; (2) an initial axial flow is driven at the footpoint in the jet, i.e. injection of poloidal flows; (3) plasma density is continuously added at the footpoint of the jet, i.e. injection of mass to prevent starvation. Removing any one of these conditions results in an unstable jet. These conditions were observed and satisfied in the MOCHI experiment. The related Caltech jet experiment and Zhai et al (2014) simulations did not have nested skin and core electrodes. The result of these three MOCHI conditions is that a helical shear flow is driven in the jet which stabilizes the jet to classical instabilities. This was observed on MOCHI and now confirmed with these numerical results. These numerical results also answered a critical question: can the stable jet be longer than the 1 m long MOCHI jet if the chamber walls were further away? The answer is yes, numerical results showed up to 3 m lengths and allowed HelicitySpace to design a new follow-on experiment with a larger vacuum chamber.

The three conditions are fulfilled self-consistently in the experiment. The electrical current in a flared poloidal magnetic field “gobbles” up frozen-in plasma up the flare resulting in a collimated jet with axial flows (Bellan, 2003). The nested nature of the electrical current in MOCHI does the same, with the addition of differential azimuthal flows from the radial electric field, resulting in helical shear flows. In the numerical simulation, we have not set up the boundary conditions to be self-consistent between magnetic, kinetic, and mass injection rates because we have to formulate the “gobble” equations (Bellan, 2003) into a form suitable for MOCHI experimental boundaries and the numerical simulation boundaries. It is currently unclear if it is possible. So we impose the three conditions with a simple linear injection rate for each and the resulting plasma flows can be intermittent or pile-up. Yet, the resulting stability, timescale, flow rates are close to the experimental observations. This suggests that the stability of the jet is quite robust to the details of the magnetic, kinetic and mass injection process.

One of the goals of the project was to evaluate the formation of a plectonemic Taylor state that was observed in the MOCHI experiment (Lavine & You, 2021)). While the simulations showed interesting lambda profiles and values appropriate to Taylor solutions, no plectoneme was observed. We think this is due to the fact that ideal MHD could not resolve non-ideal physics that are critical to plasma relaxing from an axisymmetric poloidal field into a spheromak or a plectoneme. Prior plectonemic Taylor state simulations (Brown et al, 2020) have imposed a spheromak initial condition to observe the tilting and reconfiguration into a plectoneme.

Another interesting preliminary result is that the simulations appear to show helicity conversion from helical magnetic fields near the footpoint of the jet into helical flows further up the jet. This has been theoretically predicted in prior work on canonical helicity conservation (You, 2012; You 2014; You 2016; Lavine & You, 2017).

In the fourth phase, armed with these results, we performed a short run of initial simulations of the interaction of two parallel or two inclined jets. This task is to help the design of a new fusion confinement concept experiment at HelicitySpace. The main question to answer is whether the merging of multiple jets is feasible and remains stable.

# 2 Impact

## 2.1 Use of Projected Results

*Describe how the results obtained contributes to the company's roadmap. Include a timeline slide pointing out relationships to other DOE programs and company milestones.*

The CRADA work resulted in a successful new network and collaboration between Contractor LANL scientific investigators and the Participant HelicitySpace scientific investigators. This enabled a new project between the two collaborating entities, now including Caltech as a third collaborator, within a larger simulation project funded privately by the company and with the support of a new INFUSE partnership. The results of the simulation particularly in the form of a video animations served in successful pitch presentations to private investors to explain the plasma source for the new experiment.

The results of the proposed technical assistance have significantly advanced and accelerated the development of our fusion concept. Our Helicity Drive fusion concept forms, then merges, several such plectonemes into one, with fast magnetic reconnection efficiently converting magnetic energy into high ion temperatures with cool electrons. The hot plectoneme then travels through a constant-energy compression magnetic nozzle to modestly compress the plasma and raise the triple product. The exhaust plasma can then generate thrust or electricity via thermal or direct-electric conversion methods. We currently have detailed calculations for each of the steps in this magnetic four-stroke engine that provide a reasonable estimate of the scaling of plasma parameters and scaling of triple product with physics and engineering input parameters. But the input parameters are based on the PI's experience with the MOCHI, Caltech, and Univ. Tokyo experiments. The completed project has provided detailed quantitative insight into the interplay of plasma flows, magnetic forces and pressure in the stable jet configuration (even if the plectoneme itself wihtin the jet is still elusive), uniquely surrounded by vacuum far from walls, from initial and boundary conditions beyond the PI's practical experience. This strengthens the assumptions behind input values; it helps solidify the confidence in the triple product scaling calculations; and provide feedback to the Helicity Drive prototype laboratory experiments. In the business market, our Helicity Drive IP has significant physics and engineering advantages over the competition in terms of compactness, efficiency, and scalability. The IP should be able to produce net fusion energy gain in short pulses with the minimum hardware. There is no need for inefficient, massive, external heating systems nor complex, difficult, dynamic compression liners. Choosing the number of initial plectonemes to merge—like choosing the number of cylinders in a car engine—provides scalability and the unique ability to independently control plasma parameters during the short pulse. Independent control of the plasma density, temperature, and magnetic energy content allows us to compensate for uncertainties in the confinement time

## 2.2 Fusion Energy Impact

*Describe how this project will contribute to advancing fusion energy development more generally.*

This project, even in its mostly succesful completion, significantly contributes to advancing fusion energy development by providing a much more detailed understanding of the stability, aspect-ratio and formation of the fundamental plasma jet surrounding the plectoneme configuration. This acts as dynamic boundary conditions, beyond the static flux conserving chamber walls, and sets the foundation for the larger simulation effort to replicate the Helicity Drive fusion concept, in support of the new Concept Exploration experiment currently under construction. The plectoneme configuration resembles a tilted, twisted spheromak squeezed into an elongated flux-conserving cylinder. The SSX experiment reported that the confinement time of the plectoneme was "unexpectedly good despite its non-axisymmetric structure" and its lifetime "was better than the lifetime of axisymmetric plasmas" [3]. Furthermore, the MOCHI experiment produced plectonemes inside long, stable plasma jets with helical flows and without close-fitting metallic walls. These experimental observations of remarkable stability, lifetime, and robustness— from relatively simple hardware—has potential as a fusion energy confinement scheme, especially as an ideal plasma target for magneto-inertial concepts like the Helicity Drive.

## 2.3 Intellectual Property, Publications and Conferences

*Identify new IP, publications and conference presentations generated from this project.*

A manuscript for a submission to a peer-reviewed journal is in preparation.
The results were presented at the APS DPP 2021, and the INFUSE workshop 2021.

# 3 References


1. J. M. Finn, W. Manheimer, E. Ott, Phys. Fluids, 24, 1336 (1981)
2. A. Bondeson, G. Marklin, Z. G. An, H. H. Chen, Y. C. Lee, C. S. Liu, Phys. Fluids, 24, 1682 (1981)
3. C. D. Cothran, M. R. Brown, T. Gray, M. J. Schaffer, G. Marklin, Phys. Rev. Lett., 103, 215002 (2009)
4. C. D. Cothran, M. R. Brown, T. Gray, M. J. Schaffer, G. Marklin, V. S. Lukin, Phys. Plasmas, 17, 055705 (2010)
5. S. You, J. von der Linden, E. S. Lavine, et al, Astrophys. J. Suppl., 236, 29 (2018)
6. E. S. Lavine, The evolution and dynamics of magnetized plasma jets in the MOCHI experiment, PhD Thesis, University of Washington (2018)
7. E. S. Lavine, S. You, Observations of a plectonemic configuration in a stable magnetized plasma jet, Phys. Plasmas, 28, 040703 (2021)
8. S. Li., H. Li., Los Alamos National Lab. Tech. Rep. LA-UR-03-8935 (2003)
9. X. Zhai, H. Li, P. M. Bellan, S. Li, Astrophys. J., 791, 40 (2014)
10. P. M. Bellan, S. You, S. C. Hsu, Astrophys. Space Sci., 298, 203 (2005)
11. S. C. Hsu, P. M. Bellan, Phys. Rev. Lett., 90, 21 (2003)