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14. ABSTRACT

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RPPR Final Report
as of 28-Apr-2020

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Major Goals: The overall goal of this research was to substantiate, through a series of basic laboratory experiments and corroborative numerical modeling, the fundamental physics of CME interaction with the solar wind flow in the Sun's outer corona. This research objective was to be accomplished in two ways. First, detailed laboratory experiments of the fundamental plasma physics were performed at U. New Mexico (UNM) using the existing Helicon-Cathode (HelCat) basic plasma science device, where CME-like structures moving into a flowing background plasma medium could be generated. Second, the U. Michigan state-of-the-art 3D BATS-R-US MHD numerical code was used to perform simulations of the propagation of plasma structures similar to those produced in the UNM experiments. The results of these two distinct approaches were to be compared in a systematic way to validate the numerical model, and to further our understanding of CME propagation through the solar wind.

The specific goals included

1. Performing ongoing laboratory experiments studying magnetic relaxation processes of a dense, magnetized plasma bubble generated by a coaxial plasma gun interacting with a less dense, magnetized background plasma. This laboratory experiment acted as a model for the interaction of coronal mass ejections with the background solar wind.

2. To upgrade the pulsed power and diagnostic systems for the laboratory experiments, in preparation for making more controlled and detailed comparisons with the results of numerical modeling.

3. To perform large scale computational modeling using the magnetohydrodynamic (MHD) BATS-R-US numerical code, modified to accurately model the laboratory experiment.

4. To make detailed experiment-model comparison in order to elucidate the underlying physics of CME-like structures interacting with background magnetized plasmas.

Accomplishments: Accomplishments on this project are briefly summarized here. Further details, including figures, are given in the uploaded attachment file, and in the publications and presentations listed in the "Results

Dissemination" section.

The first significant result is the observation of emergent stabilization of supersonic plasma jets injected into background magnetized plasma with transverse magnetic field (B-field). It was observed that when current-carrying plasma jets were launched into vacuum in the HelCat plasma device, they became unstable to the kink instability as their length reached approximately 1/3 of the 50 cm vacuum chamber diameter. This was expected, since the well-known Kruskal-Shafranov (KS) instability threshold [1] was exceeded at this jet length. However, when jets with the same parameters were launched into a background magnetized plasma with transverse B-field, they were found to be much more stable, typically propagating across the full diameter of the vacuum chamber. A detailed investigation showed that the kink instability was stabilized by axial velocity shear. As the jet propagates transverse to the B-field, it compresses magnetic flux in front of it, since the B-field cannot diffuse far into the conductive jet on microsecond time scales. This causes magnetic field lines to bend in the edge region of the jets, resulting in magnetic tension on these field lines. The magnetic tension on field lines frozen into the plasma then causes the axial jet velocity in the edge to reduce, resulting in a radial shearing (derivative) of the axial flow. This sheared flow is stabilizing to the kink mode, as previously predicted theoretically [2]. We have termed this behavior "emergent" since it simply evolves naturally in the presence of background transverse B-field. This velocity shear mechanism may be at work, at least partly, in stable jets observed on scales from solar surface phenomena to extragalactic jets, and may therefore be important in space weather dynamics.

The second significant result is that a rich and complex set of plasma dynamics have been observed and explored when magnetized plasma "bubbles" (gun-launched objects with closed magnetic field structures, i.e. spheromaks) are injected into background magnetized plasma in HelCat. These dynamics include a leading double shock structure, magneto-Rayleigh Taylor (MRT) instabilities at the bubble-background interface, and turbulence in the trailing bubble regions. These dynamics are also generally absent when bubbles are injected into background vacuum (no with background magnetic field), where they relax relatively smoothly into a structure that is consistent with a spheromak equilibrium. The double shock structure, which was predicted by previous numerical modeling [3], consists of a slightly super-Alfvenic shock font, followed by a supersonic shock. Basic hydrodynamic shock calculations predict that these shocks will accelerate ions to 50 - 80 eV energies, much higher than the bubble plasma temperature. Experiments are continuing to measure these fast ions via visible Doppler spectroscopy or energy analyzer probes.

The characteristics of the MRT instability are found to vary with position along the bubble-background interface. MRT growth maximizes where the interface total B-field is minimum, such that k•B is minimum, where k is the instability wavevector, consistent with basic theory. The growth rate estimated from experimental imaging data is ~ 1 – 3 x 10e-6 s, consistent with basic analytical estimates for MRT, but shows variation with background magnetic field and plasma (or neutral gas) density. This variation is not yet understood, but may be due to changes in viscosity at the bubble-background interface. Work is ongoing to better understand this. We note that, while viscosity is generally known to be stabilizing to interchange instabilities, such as MRT, there remain open questions as to the details of the viscosity in magnetized plasmas, which has bearing in both space and astrophysical plasmas. The observed trailing turbulence is also still under investigation via detailed electrostatic and B-dot probe array measurements.

The third significant result is that the BATS-R-US MHD space weather code from U. Michigan has been successfully adapted to model HelCat laboratory jet and bubble plasmas. It required significant effort to implement the physical boundaries of the coaxial plasma gun and vacuum chamber, as well as increased the effects of increased collisionality (modeled within the MHD framework through resistivity and viscosity via mass loading of magnetic field lines). Significant effort has also gone into implementing adaptive mesh refinement (AMR) of the computational grid in order to achieve sub-millimeter spatial resolution in critical positions in the simulation (e.g. in shock front regions) in simulations that can run in a reasonable time (e.g. < 1 week) on U. New Mexico parallel computing clusters. Plasma bubbles have been modeled as modified flux ropes, which are thought to be the form of solar structure that likely evolve into coronal mass ejections (CME's). BATS-R-US simulations now reproduce many features observed in experiments, such as leading shock fronts in bubbles, as well as boundary and trailing edge turbulence, although the model may still be overestimating turbulence levels due to insufficient mass loading of field lines (and therefore artificially reduced viscosity).

Finally, significant upgrades to the experimental infrastructure of the HelCat basic plasma science device have been made. Upgraded magnetic (B-dot) and electrostatic probe arrays and their associated electronics gave been built and fielded on HelCat. Fast 12 frame visible imaging using the Hadland Ultra 24 camera, with gate times down to ~ 1 ns, and interframe times down to ~ 5 ns, now operates routinely. Thirty-two channels of fast (100

Msample/sec) data acquisition based on a set of Gage digitizers from Dynamic Signals LLC is now also routinely available. Though this hardware was purchased with other grants, the manpower that allowed us to field functioning diagnostic systems was supported by this funding.

An important goal of this work was to make detailed experiment-model comparisons. While significant progress has been made on both the experimental and computational sides, experiment-model comparisons have, unfortunately, been limited to date. A primary reason for this is that the computational challenges of adapting the BATS-R-US code to the experiment were more significant than anticipated. Additionally, two key personnel left U. New Mexico before the project end date – Dr. Dustin Fisher, the PostDoc primarily responsible for computational work, and Mr. Ben Wallace, who was the primary experimentalist in year 2 of the grant. Mr. Wallace did complete his M.S. degree through coursework with support from this grant, but did not complete his M.S. thesis. Nevertheless, we are still working to complete the experiment-model comparisons and publish these results via other support.

[1] M Kruskal, and M Schwarzschild, 'Some Instabilities of a Completely Ionized Plasma', in Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences (The Royal Society, 1954), pp. 348-60.
[2] U Shumlak, and CW Hartman, 'Sheared Flow Stabilization of the M= 1 Kink Mode in Z Pinches', Physical review letters, 75 (1995), 3285.
[3] W. Liu, et al., “Ideal magnetohydrodynamic simulation of magnetic bubble expansion as a model for extragalactic radio lobes”, Physics of Plasmas 15, 072905 (2008)

Training Opportunities: One postdoctoral researcher, one Ph.D.student, one M.S. student, and two undergraduate student researchers worked on this project, and were all afforded significant training opportunities. All of these researchers had the opportunity to conduct research in a state of the art plasma science lab at U. New Mexico, and to attend several conferences and present their research. Conferences attended included the American Physical Society Division of Plasma Physics annual meeting, the SHINE solar physics annual workshop, the URSI (International Radio Science Union) USNC annual meeting, and the IEEE International Conference on Plasma Science (ICOPS) annual meeting.

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Results Dissemination: Results were disseminated in two journal publications, one refereed conference publication, one Ph.D. dissertation, one conference invited talk, and a number of contributed oral and poster presentations.

Journal Publications

1. Yue Zhang, Dustin M. Fisher, Mark Gilmore, Scott C. Hsu, and Alan G. Lynn (2018). “Experimental investigation of coaxial-gun-formed plasmas injected into a background transverse magnetic field or plasma”. Physics of Plasmas 25, 055709. https://doi.org/10.1063/1.5019727
2. Yue Zhang, Mark Gilmore, Scott C. Hsu, Dustin M. Fisher, and Alan G. Lynn (2017). “Emergent kink stability of a magnetized plasma jet injected into a transverse background magnetic field”, Phys Plasmas 24 110702.

Refereed Conference Publications
1. Y. Zhang, M. Gilmore, D.M. Fisher, and S.C. Hsu (2017). Laboratory Observation of the Stabilization of Supersonic Plasma Jets by Emergent Velocity Shear. Proceedings of the 2017 European Physical Society Conference on Plasma Physics Belfast, Northern Ireland, 26 – 30 June, 2017.

Ph.D. Dissertations
1. Yue Zhang, Experimental Investigation of Plasma Dynamics in Jets and Bubbles using a Compact Coaxial Plasma Gun in a Background Magnetized Plasma. Ph.D. Dissertation, University of New Mexico, December, 2016.

Invited Conference Talks
1. Y. Zhang, Mark Gilmore, Scott C. Hsu, Dustin M. Fisher. Dynamics of Plasma Jets and Bubbles Launched into a Transverse Background Magnetic Field. Invited oral presentation at the 59th Annual Meeting of the APS Division of Plasma Physics, Oct. 23–27, 2017; Milwaukee, WI, USA.

Contributed Conference Presentations
1. R.H. Dwyer, M. Gilmore, and N. Hines. Measurements of Global Dynamics and Shock Structures in Centimeter-Scale Plasma Jets and Bubbles. Contributed poster presentation at the 61st Annual Meeting of the APS Division of Plasma Physics, Oct. 21 - 25, 2019; Fort Lauderdale, FL, USA.

2. R. H. Dwyer, D. M. Fischer, and M. Gilmore. Measurements of the Magnetic Rayleigh Taylor Instability in Centimeter-Scale Magnetized Plasma Bubbles. Contributed poster presentation at the IEEE 2019 Pulsed Power and Plasma Sciences Meeting, June 22 – 28, 2019, Orlando, FL, USA.

3. M. Gilmore, R.H. Dwyer, and N. Hines. Observations and Modeling of Magnetized Plasma Jets and Bubbles Launched into a Magnetized Background Plasma. Contributed poster presentation at the 61st Annual Meeting of the APS Division of Plasma Physics, Oct. 21 - 25, 2019; Fort Lauderdale, FL, USA.

4. Robert H Dwyer, Dustin M Fisher, Mark Gilmore, Daniel F Puentes. Measurement and Modeling of Global Dynamics and Instabilities in Magnetized Plasma Bubbles and Jets in Background Plasma. Contributed poster presentation at the 60th Annual Meeting of the APS Division of Plasma Physics, Nov. 5 - 9, 2018; Portland, OR, USA.

5. M. Gilmore, Y. Zhang, D.M. Fisher, and S.C. Hsu (2017). Laboratory Observation of the Stabilization of Supersonic Plasma Jets by Emergent Velocity Shear. Contributed oral presentation at the 2017 European Physical Society Conference on Plasma Physics Belfast, Northern Ireland, 26 – 30 June, 2017.

6. Mark Gilmore, Yue Zhang, Dustin M. Fisher, Ben Wallace, and Scott C. Hsu, Magnetohydrodynamic Instabilities in Jets and Bubbles Using a Compact Coaxial Plasma Gun in a Background Magnetized Plasma. Contributed oral presentation at the 2017 U.R.S.I. National Radio Science Meeting, Jan. 4 – 7, 2017, Boulder, CO, USA.

7. Dustin M. Fisher, Yue Zhang, Ben Wallace, Mark Gilmore, Ward B. Manchester IV, Bart van der Holst, Barrett N. Rogers, and Scott C. Hsu. Observations and modeling of magnetized plasma jets and bubbles launched into a transverse B-field Poster presentation at at the 59th Annual Meeting of the APS Division of Plasma Physics, Oct. 23–27, 2017; Milwaukee, WI, USA.

8. Y. Zhang, D.M. Fisher, B. Wallace, M. Gilmore, and S.C. Hsu. Investigation of MHD Instabilities in Jets and

Bubbles Using a Compact Coaxial Plasma Gun in a Background Magnetized Plasma, oral presentation at the 58th Annual Meeting of the American Physical Society Division of Plasma Physics, October 31–November 4, 2016; San Jose, California.

9. D.M. Fisher, Y. Zhang, B. Wallace, M. Gilmore, W. Manchester, and C.N. Arge. 3-D Flux Rope Modeling of CME-like Plasma Dynamics in the PBEX HelCat Experiment, poster presentation at SHINE (Solar, Heliosheric, and Interplanetary Environment(Workshop , July 11 – 15, 2016, Santa Fe, NM.

10. B. Wallace1, Y. Zhang, D. Fisher, M. Gilmore, C. N. Arge. Laboratory Simulations of CME-Solar Wind Interactions Using a Coaxial Plasma Gun and Background Plasma, , poster presentation at SHINE (Solar, Heliosheric, and Interplanetary Environment(Workshop , July 11 – 15, 2016, Santa Fe, NM

11. D.M. Fisher, Y. Zhang, B. Wallace, M. Gilmore, W. Manchester, and C.N. Arge. 3-D MHD modeling and stability analysis of jet and spheromak plasmas launched into a magnetized plasma, poster presentation at the 58th Annual Meeting of the American Physical Society Division of Plasma Physics, October 31–November 4 2016; San Jose, California.

12. B. Wallace, Y. Zhang, D.M, Fisher, and M. Gilmore. Dynamics of Magnetized Plasma Jets and Bubbles Launched into a Background Magnetized Plasma, poster presentation at the 58th Annual Meeting of the American Physical Society Division of Plasma Physics, October 31–November 4 2016; San Jose, California.

13. Y. Zhang, A. Lynn, M. A. Gilmore. Characterization of a Coaxial-Gun-Produced Magnetized Plasma, poster presentation at the 2015 Pulsed Power Conference, May 31 – June 4, 2015, Austin, TX, USA.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Mark Allen Gilmore
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Dustin Mark Fisher
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Ben Wallace
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:

National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Robert Dwyer
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Yue Zhang
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Karin Fulford
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Conference Name: 2017 European Physical Society Division of Plasma Physics Annual Meeting
Date Received: 25-Apr-2020 Conference Date: 19-Jun-2017 Date Published: 26-Jun-2017
Conference Location: Belfast, Northern Ireland, UK
Paper Title: Laboratory Observation of the Stabilization of Supersonic Plasma Jets by Emergent Velocity Shear
Authors: Y. Zhang, M. Gilmore, D.M. Fisher, S.C. Hsu
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: University of New Mexico
Date Received: 25-Apr-2020 Completion Date: 12/15/16 2:00PM
Title: EXPERIMENTAL INVESTIGATION OF PLASMA DYNAMICS IN JETS AND BUBBLES USING A COMPACT COAXIAL PLASMA GUN IN A BACKGROUND MAGNETIZED PLASMA
Authors: Yue Zhang
Acknowledged Federal Support: **Y**

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Final Report Addendum

Coupled Laboratory and Computational Investigation of Coronal Mass Ejection Dynamics

Award ARO W911NF1510480

I. Project Goals

The overall goal of this research was to substantiate, through a series of basic laboratory experiments and corroborative numerical modeling, the fundamental physics of CME interaction with the solar wind flow in the Sun's outer corona. This research objective was to be accomplished in two ways. First, detailed laboratory experiments of the fundamental plasma physics were performed at U. New Mexico (UNM) using the existing Helicon-Cathode (HelCat) basic plasma science device [1], where CME-like structures moving into a flowing background plasma medium could be generated. Second, the U. Michigan state-of-the-art 3D BATS-R-US MHD numerical code [2] was used to perform simulations of the propagation of plasma structures similar to those produced in the UNM experiments. Figures 1 and 2 show images of a CME event on the sun and a laboratory plasma jet produced in the HelCat device, respectively. There is an obvious visual similarity between the solar and laboratory cases, but more importantly, it is believed that there a substantial physics commonalities in the two cases, both of which involve hot, dense magnetized plasmas interacting with less dense, flowing magnetized plasmas.

The specific goals included

1. Performing ongoing laboratory experiments studying magnetic relaxation processes of a dense, magnetized plasma bubble generated by a coaxial plasma gun interacting with a less dense, magnetized background plasma. This laboratory experiment acted as a model for the interaction of coronal mass ejections with the background solar wind.
2. To upgrade the pulsed power and diagnostic systems for the laboratory experiments, in preparation for making more controlled and detailed comparisons with the results of numerical modeling.
3. To perform large scale computational modeling using the magnetohydrodynamic (MHD) BATS-R-US numerical code, modified to accurately model the laboratory experiment.

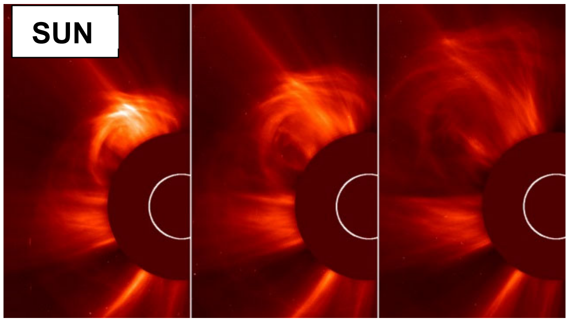


Fig. 1. Coronal Mass Ejection image from March 15, 2013 captured by the NASA Solar Heliospheric Observatory (SOHO). Taken from http://www.nasa.gov/images/content/734315main_20130315-LASCOC2-CME.jpg . Solar disk at right edge of image is blocked out.

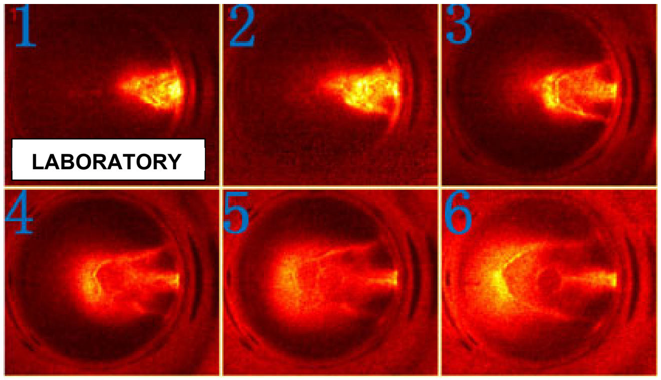


Fig. 2. Magnetized Plasma Jet ejected from a compact coaxial plasma gun (on the right) in the HelCat basic plasma science device. Unfiltered visible light image at 2 microseconds per frame.

4. To make detailed experiment-model comparison in order to elucidate the underlying physics of CME-like structures interacting with background magnetized plasmas.

II. Accomplishments

Emergent Sheared Flow Stabilization of Plasma Jets

An important result of this work is the observation of emergent stabilization of supersonic plasma jets injected into background magnetized plasma with transverse magnetic field (B-field). It was observed that when current-carrying plasma jets were launched into vacuum in the HelCat plasma device, they became unstable to the kink instability as their length reached approximately 1/3 of the way across the 50 cm vacuum chamber diameter. An example is shown in Fig. 3. This was expected, since the well-known Kruskal-Shafranov (KS) instability threshold [3] was exceeded at this jet length. However, when jets with the same parameters were launched into a background magnetized plasma with transverse B-field, they were found to be much more stable, typically propagating across the full diameter of the vacuum chamber. Fig. 4 shows an example case. A detailed investigation showed that the kink instability was stabilized by axial plasma velocity shear. As the jet propagates transverse to the B-field, it compresses magnetic flux in front of it, since the B-field cannot diffuse far into the conductive jet on microsecond time scales, as illustrated in Fig. 5. This causes magnetic field lines to bend in the edge region of the jets, resulting in magnetic tension on these field lines. The magnetic tension on field lines frozen into the plasma then causes the axial jet velocity in the edge to reduce, resulting in a radial shearing (radial derivative) of the axial flow. This sheared flow is stabilizing to the kink mode when the $dv_z/dr > 0.1kv_A$, as previously predicted theoretically [4]. Here v_z is the axial velocity, $k = \pi/L$, where L is the jet length, and v_A is the Alfvén speed. Figure 6 shows plots of example measured axial velocity and its radial shear for both stable and unstable jet cases. It can be seen that background B-field leads to stabilized jets, except at the longest jet lengths.

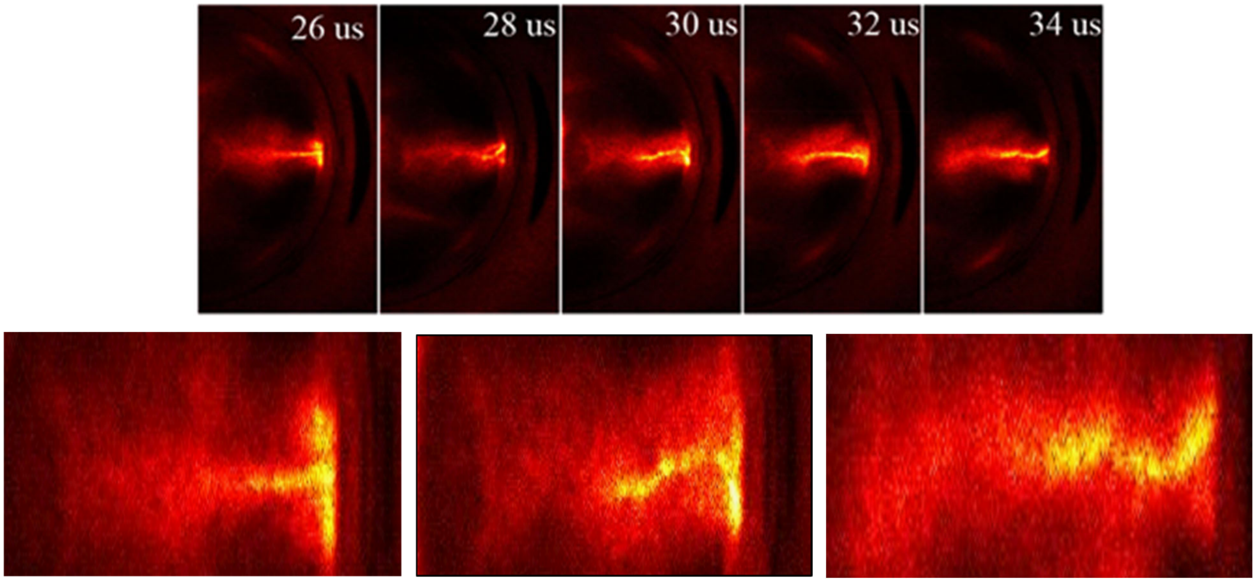


Fig. 3. Upper: unfiltered visible light images of an argon plasma jet propagating into background vacuum only ($B_0 = 0$). Lower: detail of light from the central current channel at several times, showing the evolution of a helical structure, consistent with an m = 1 kink instability. View is looking axially down HelCat vacuum chamber. Plasma gun is located on the right.

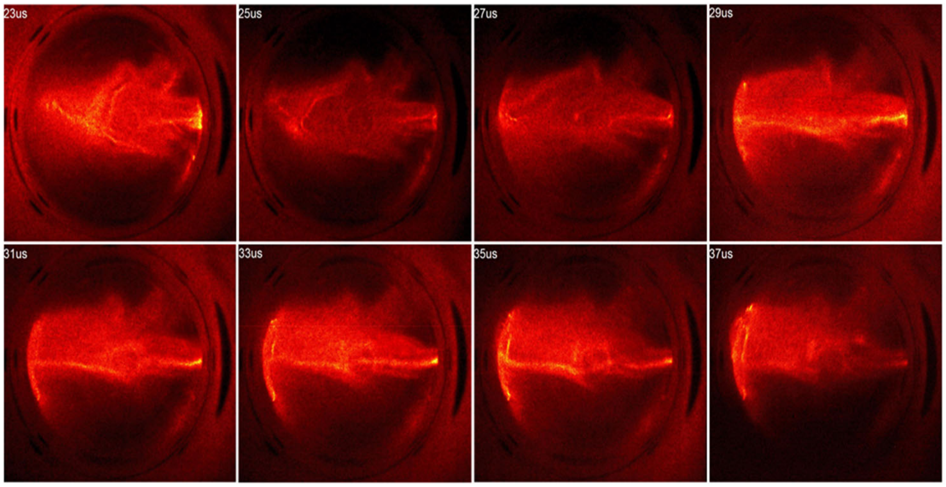


Fig. 4. Unfiltered visible light images of an Ar plasma jet injected transverse to a background magnetic field, B_0 = 500 G (vacuum background). It can be seen that the jet extends all the way across the vacuum chamber, L = 50 cm. Experimental parameters are identical to those of Fig. 3, except for the background B-field.

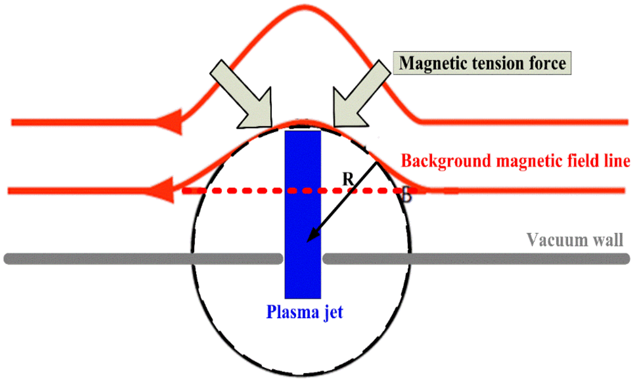
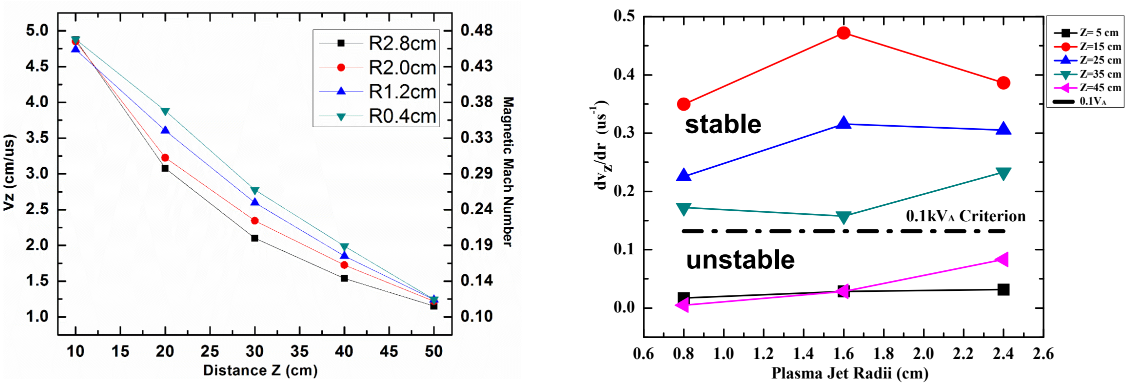


Fig. 5. Schematic of plasma jet displacing background magnetic flux as it propagates transverse to B_0. Field line bending results in magnetic tension, which slows the jet at its radial edge, resulting in emergent axial velocity shear, dv_z/dr.



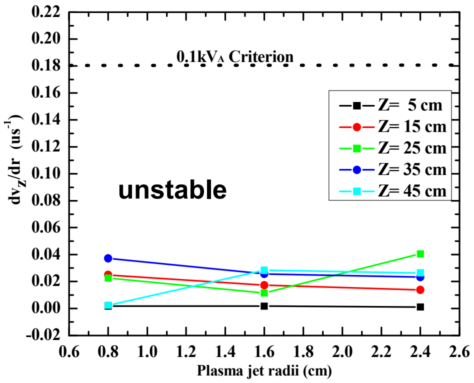


Fig. 6. Upper left: axial velocity vs. axial distance from the gun at various jet radii, estimated from Langmuir and B-dot probe array measurements. B_0 = 500 G. Upper right: radial shearing rate of axial velocity, dv_z/dr, at various axial distances, with B_0 = 500 G. $dv_z/dr > 0.1kv_A$, except at the longest distances, indicating sufficient velocity shear for kink mode stabilization. Lower left: dv_z/dr, at various axial distances, with no background B-field, B_0 = 0 G. Velocity shear is insufficient for kink stabilization in these cases, as expected.

We have termed this velocity shear behavior "emergent" since it simply evolves naturally in the presence of background transverse B-field. This shear mechanism may be at work, at least partly, in stable jets observed in space on scales from solar surface phenomena to extragalactic jets, and may therefore be important in space weather dynamics.

Enhanced Dynamics of Plasma Bubbles Interacting with Background Magnetized Plasma

When the coaxial plasma gun on HelCat is operated with its coaxial magnet coil on, structures with closed magnetic field topology (plasma "bubbles") are produced instead of plasma jets [5]. When such bubbles are launched into unmagnetized vacuum in HelCat, they are found to relax relatively smoothly to a structure consistent with spheromak equilibrium. Spheromaks are well-known MHD equilibrium states that occur in laboratory fusion experiments, and are possible configurations of detached CME's [6]. An image of such a case in HelCat is shown in Fig. 7a, where the plasma appears to smoothly expand to fill the vacuum chamber.

In contrast, when a bubble is launched into background magnetized plasma, a rich set of dynamics is observed as the bubble expands, which is not seen in the unmagnetized vacuum case. An example is shown in Fig. 7b, where a number of new structures can be identified. These structures include a double shock structure at the leading edge of the expanding bubble (the double bright "lines" on the left edge of the bubble in the image), an interchange instability, identified as Magneto-Rayleigh Taylor (MRT) mode (bright "fingers" protruding toward the vacuum chamber at the upper right of the bubble), and trailing edge turbulence (light intensity variations in the center/center right of the bubble).

Velocity measurements via electrostatic probes and image analysis show that the double shock structure consists of a slightly super-Alfvénic shock front followed by a supersonic shock front. Analytical calculations using basic hydrodynamic shock theory indicate that these shocks would be expected to accelerate ions to 50 – 80 eV (as compared to the bubble thermal ion temperature

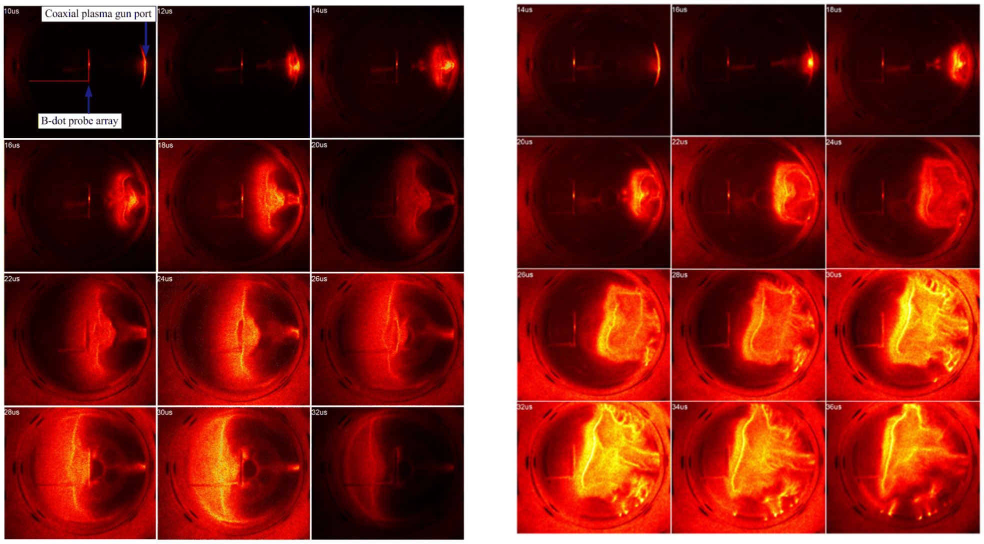


Fig. 7. Argon plasma bubble injected into a) (left) vacuum with no background magnetic field, $B_0 = 0$, and b) (right) vacuum with transverse $B_0 = 500$ G. Images are (false color) unfiltered visible light from a high speed multiframe camera (2 μs between frames). Axial view along vacuum chamber. Plasma gun is on the right. Time advances from upper left frame to lower right. View is looking axially down the cylindrical vacuum chamber (50 cm diameter).

of 10 – 15 eV). In space weather, of course, fast ions are of significant concern due to their potential for causing damage to satellites. Work is ongoing in HelCat to measure such energetic ions via visible Doppler spectroscopy and energy analyzer probes.

The characteristics of the finger-like structures shown in Fig. 7b have been studied via fast visible imaging and electrostatic probe arrays, and are found to be consistent with an interchange instability. In particular, these structures appear to be a type of interchange mode known as Magneto-Rayleigh Taylor (MRT). The characteristics of the MRT instability are found to vary with position along the bubble-background interface. MRT growth maximizes where the interface total B-field is minimum, such that $\underline{k}\bullet\underline{B}$ is minimum, where $\underline{k}$ is the instability wavevector, consistent with basic theory. Thus, the fingers appear at a consistent, predictable position (upper right in Fig. 7b) on the bubble, depending on experimental parameters such as background and bubble B-field magnitude and direction and background gas pressure or plasma density. The growth rate estimated from experimental imaging data is ~ $1–3\times10^{-6}$ s, consistent with basic analytical estimates for MRT, but shows variation with experimental parameters. This variation is not yet fully understood, but may be due to changes in viscosity at the bubble-background interface. Work is ongoing to better understand this. We note that, while viscosity is generally known to be stabilizing to interchange instabilities, such as MRT, there remain open questions as to the details of the viscosity in magnetized plasmas, which has bearing in both space and astrophysical plasmas. The observed trailing turbulence is also still under investigation via detailed electrostatic and B-dot probe array measurements.

Since Coronal Mass Ejections interact with the background corona and solar wind plasma and not simply vacuum, it is conceivable that the dynamics as they leave the sun are more akin to those in Fig. 7b (background magnetized plasma in HelCat) than those in Fig. 7a (unmagnetized vacuum in HelCat). Having a well-verified numerical model of CME's, through experiments such as these is surely important for improving understanding and moving to predictive modelling of space weather events such as CME's.

MHD Numerical Modeling with the BATS-R-US Code

The BATS-R-US MHD space weather code from U. Michigan has been successfully adapted to model HelCat laboratory jet and bubble plasmas. It required significant effort to implement the physical boundaries of the coaxial plasma gun and vacuum chamber, as well as increased the effects of increased collisionality (modeled within the MHD framework through resistivity and viscosity via mass loading of magnetic field lines). Significant effort has also gone into implementing adaptive mesh refinement (AMR) of the computational grid in order to achieve sub-millimeter spatial resolution in critical positions in the simulation (e.g. in shock front regions) in simulations that can run in a reasonable time (e.g. < 1 week) on U. New Mexico parallel computing clusters. Plasma bubbles have been modeled as a pair of counter-propagating flux ropes, which are thought to be the form of solar structure that likely evolve into coronal mass ejections (CME's).

Figure 8 shows a zoomed-in view of the current density and magnetic field strength of an expanding set of flux-ropes. These code runs have a much higher (sub-millimeter) resolution and are able to capture the expansion of the flux ropes with less diffusion than earlier runs. It is also important to point out that the grid scaling (which acts to mimic that seen in the bubble experiment) allows for a more realistic injection from the gun into a background magnetic field. This injection can be seen more clearly in a top-down view of the simulation domain shown in Figure 9.

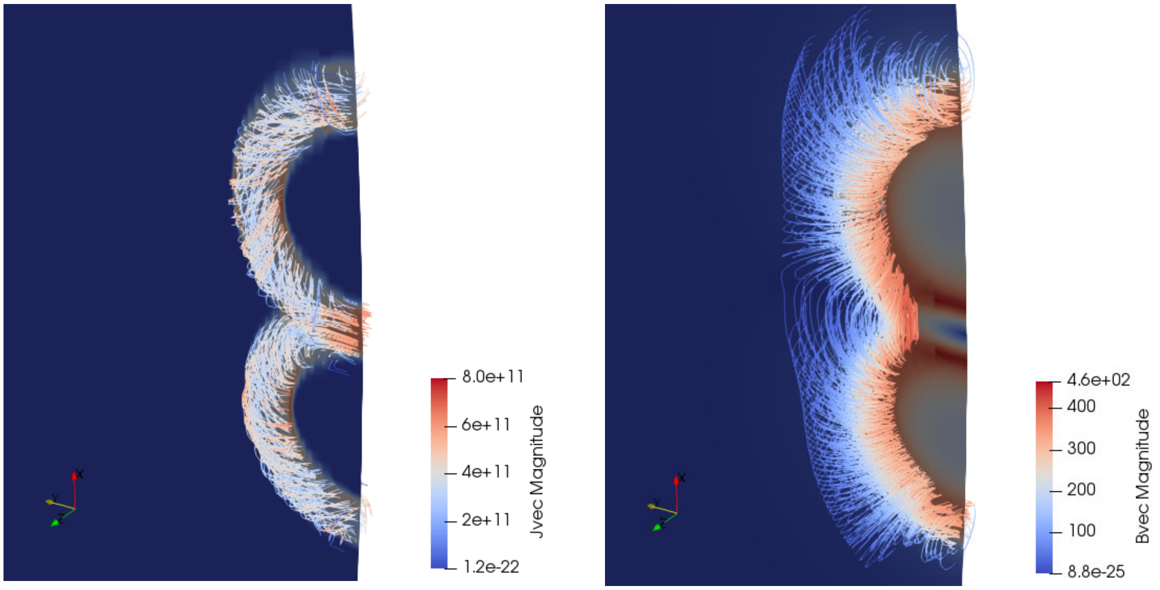


Fig. 8. (Left) Highly resolved current density at the initialization of the flux-rope; (Right) Corresponding magnetic field lines and magnetic flux density.

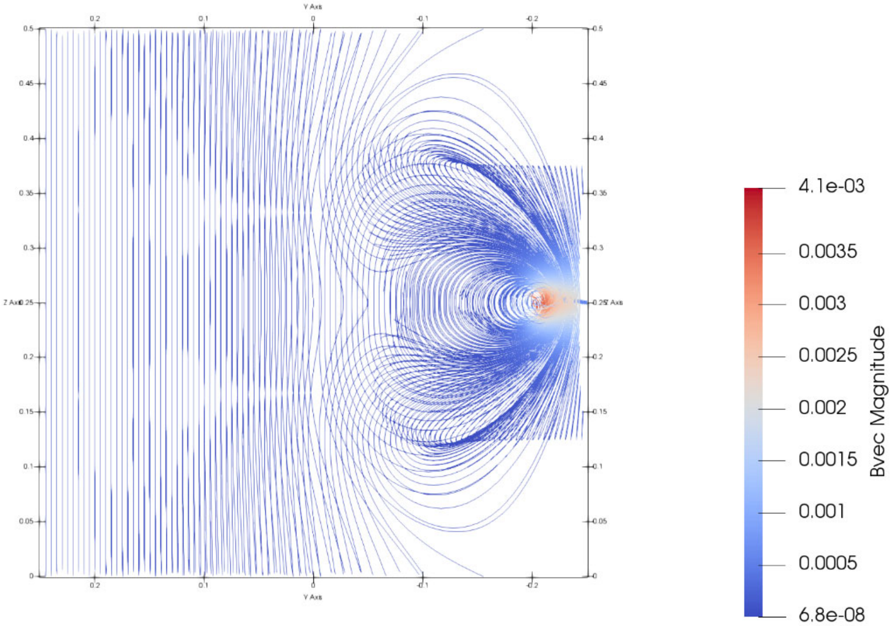


Fig. 9. Top-down view of the BATS-R-US simulation domain showing the magnetic field lines of an emerging flux-rope from the right-side of the cylinder. Selected streamlines of the background field can be seen towards the left of the simulation with the flux-ropes field structure impacting it near the midplane.

Figures 10 and 11 show the current density of two different long-time-evolved simulations. Fig. 10 shows a launch into vacuum, while Fig. 11 shows a side view into a background magnetic field. Turbulent dynamics can be seen in Fig. 10 (most likely due to under-loading the flux-ropes with ArII ions) and Fig. 11 shows an interesting tail structure beginning to form in the wake of the shock that may be similar to dynamics seen in the bubble experiment from CCD images.

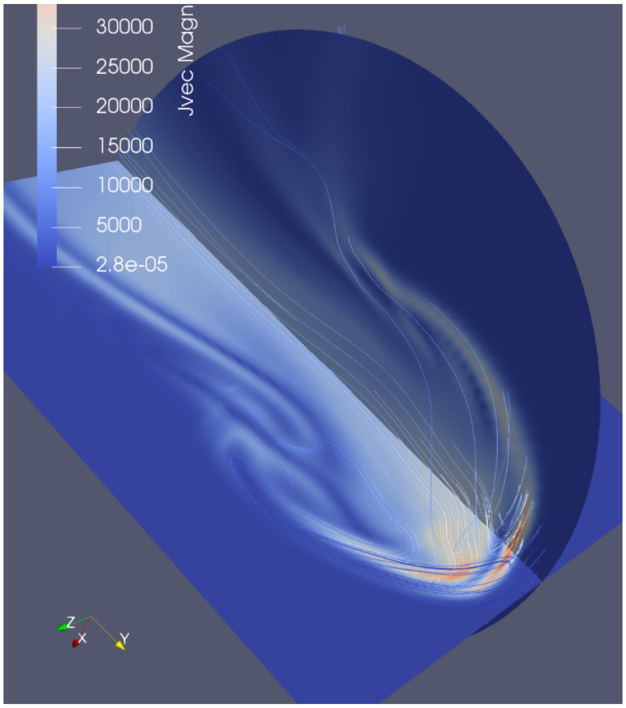


Fig. 10. Current density of a long-time-evolved flux-rope structure. Turbulent structures can be seen in the wake of the shock front, most likely due to low ram pressure.

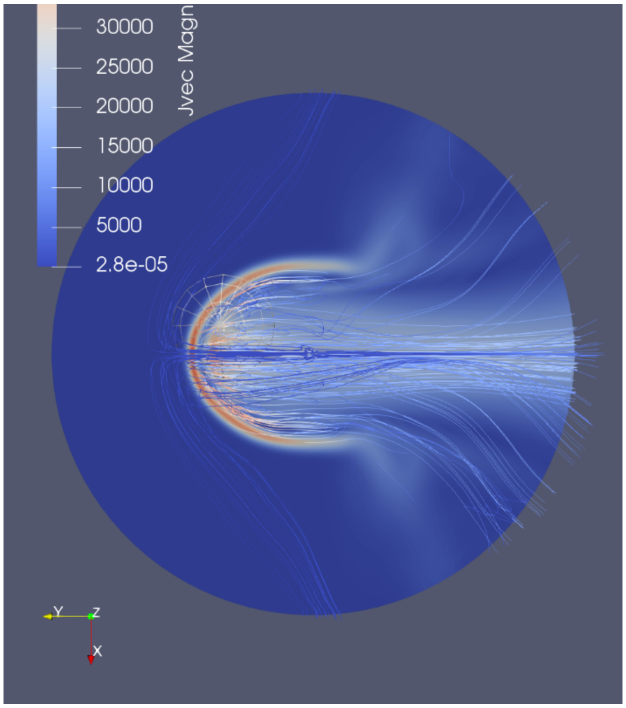


Fig. 11. Current density of a flux-rope launched bubble into background magnetic field. Ongoing adjustments to the mass-loading and MHD physics parameters aim to match the shock-front observed

BATS-R-US simulations now reproduce many features observed in experiments, such as leading shock fronts in bubbles, as well as boundary and trailing edge turbulence, although the model may still be overestimating turbulence levels due to insufficient mass loading of field lines (and therefore artificially reduced viscosity).

HelCat Infrastructure Upgrades

Significant upgrades to the experimental infrastructure of the HelCat basic plasma science device have been made. Upgraded magnetic (B-dot) and electrostatic probe arrays and their associated electronics gave been built and fielded on HelCat. Fast 12 frame visible imaging using the Hadland Ultra 24 camera, with gate times down to ~ 1 ns, and interframe times down to ~ 5 ns, now operates routinely. Thirty-two channels of fast (100 Msample/sec) data acquisition based on a set of Gage digitizers from Dynamic Signals LLC is now also routinely available. Though this hardware was purchased with other grants, the manpower that allowed us to field functioning diagnostic systems was supported by this funding.

Ongoing Research

An important goal of this work was to make detailed experiment-model comparisons. While significant progress has been made on both the experimental and computational sides, experiment-model comparisons have, unfortunately, been limited to date. A primary reason for this is that the computational challenges of adapting the BATS-R-US code to the experiment were more significant than anticipated. However, the groundwork has now been laid, and work is continuing to complete the experiment-model comparisons and publish these results via other funding support.

IV. References

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