Laboratory Observation of the Stabilization of Supersonic Plasma Jets by Emergent Velocity Shear

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I. Introduction

Plasma jets occur on a wide variety of spatial and temporal scales, from microscopic jets in the laboratory to extragalactic astrophysical jets that span hundreds of thousands of light years. Although laboratory studies of plasma jets have been undertaken since at least the 1950's, and observations of astrophysical jets have been made since the 1980's, a number of fundamental physics questions remain regarding jet dynamics and stability [1]. For example, in the case of astrophysical jets, it is unclear why they are stable to kink modes over such large distances. Additionally, there have been a very limited number of laboratory experiments that investigate jet propagation into background media other than vacuum (e.g. magnetic field or magnetized plasma).

Here we report on a set of macroscopic (multi-centimeter in scale) basic plasma experiments that investigate the dynamics of supersonic plasma jet propagation into background magnetized plasma, or background transverse magnetic field (B-field). It is found that when the jets are launched into a background vacuum with no B-field, an $m = 1$ kink instability develops along the central current channel, consistent with the Kruskal-Shafranov (K-S) instability criterion, $q = q(a) = 2\pi a B_z/LB_\phi < 1$, where B_z and B_ϕ are the jet axial and azimuthal B-fields respectively, and a and L and the jet radius and length respectively [2]. However, when jets are launched into a background B-field (in vacuum) or a background magnetized plasma, the plasma is observed to be stable for significantly longer in time and space. Detailed magnetic measurements show that q remains < 1, so that the jet is still expected to be kink-unstable by the K-S criterion. However, detailed velocity profile measurements show that a shear develops in the axial velocity, v_z, when a background B-field is present, and the shear, dv_z/dr, is sufficient to stabilize the kink, consistent with the criterion $dv_z/dr > 0.1kv_A$, where k is the axial wavenumber, and v_A is the Alfvén speed [3].

II. Experimental Setup and Results

The jets are produced by a compact coaxial plasma gun [4], mounted on the side of the linear HelCat basic plasma science device [5], as shown in Fig. 1. The inner diameter of the

Table 1. Typical coaxial gun plasma parameters.

Parameter	Coaxial Gun Plasma
$n_e = n_i$ [m^{-3}]	10^{20}
T_i [eV]	10 - 15
T_e [eV]	10 - 15
B_z [mT]	100
β	0.1 - 0.2
R_m	10^2 - 10^5

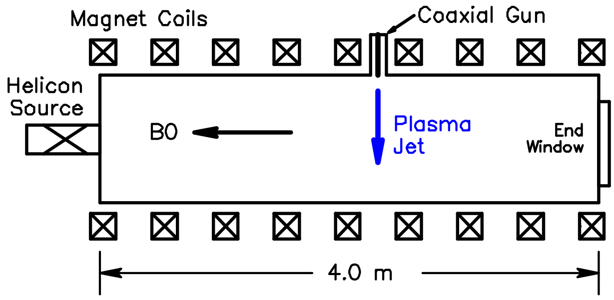

Fig. 1. Schematic of the HelCat plasma device with coaxial plasma gun and background B-field, B0. Fast CCD camera images are acquired through the end window, looking axially along the chamber. Probes are introduced radially from the port opposite the gun.

outer coaxial electrode is 5 cm. The HelCat vacuum chamber is 4 m long, 50 cm diameter, with uniform solenoidal magnetic field, B_0. B_0 ripple is < 1% on axis, and < 3% at the vacuum chamber wall. The gun is powered by an ignitron-switched 120 µF capacitor bank, and operates at I ~ 50 - 100 kA and V ~ 6 - 10 kV, with a ~ 10 µs rise time. A fast gas valve injects gas (typically Ar) at an initial fill pressure of ~ 0.25 Torr (33 Pa). The gun is surrounded by a solenoidal coil that produces an axial "bias" magnetic field. Depending on the relative bias field and gun current (which generates the azimuthal B-field, B_ϕ, via current flowing in the center electrode), the gun can produce either a jet or a spheromak-like plasma [1,4,5]. Here, we report only on experiments with jets. The $J_{radial} \times B_\phi$ force from radial gun current and azimuthal magnetic field ejects fully ionized plasma axially from the gun to form a plasma jet, with typical propagation speeds of $v_{jet} \approx 3 - 5 \times c_s$, where c_s is the ion sound speed. The ratio of the jet ram pressure, $\rho/2v_{jet}^2$, to the magnetic pressure of the background B-field, $B_0^2/2\mu_0$, is > 4 in the experiments, so that the jet easily penetrates the background field. The magnetic Reynolds number, $R_m = Lv_{jet}/\eta$, of the jet is > 100, so that magnetic diffusion into the jet plasma is small, and the jet displaces background magnetic flux, B_0, as it propagates. Here ρ is mass density and η is the plasma resistivity.

Experiments have been conducted where jets are launched into 1) background magnetic field (B_0) and vacuum, and 2) background magnetized plasma formed by a helicon source, expanded to fill the vacuum chamber radius. Thus far, no differences have been observed between these two cases (vacuum B-field vs. magnetized plasma). This is not unexpected, since the background helicon plasma is low beta, $\beta < 10^{-3}$, so that the dynamics of interactions of the jet with the background might be expected to be strongly dominated by

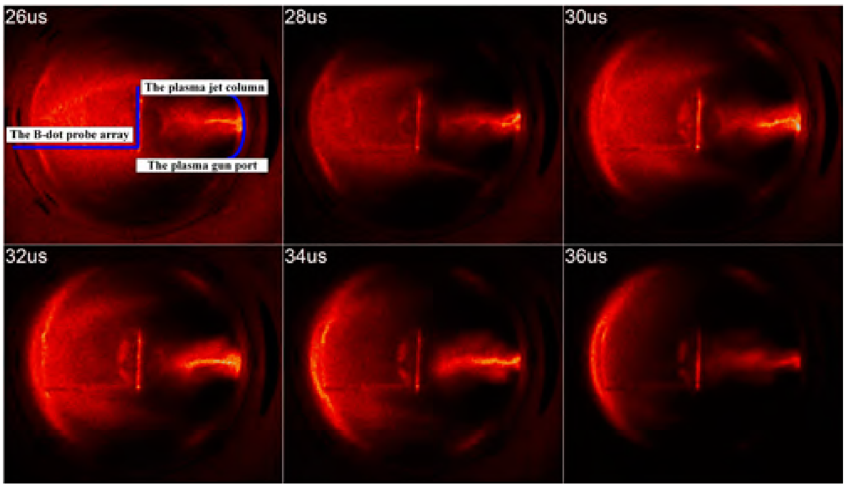

Fig. 2. Side-on unfiltered visible light image (false color), acquired with a Hadland Utlra UHSi 12/24 CCD camera, of an Ar plasma jet injected into vacuum only ($B_0 = 0$) showing kink instability growth on central current channel. Coaxial gun located on the right midplane.

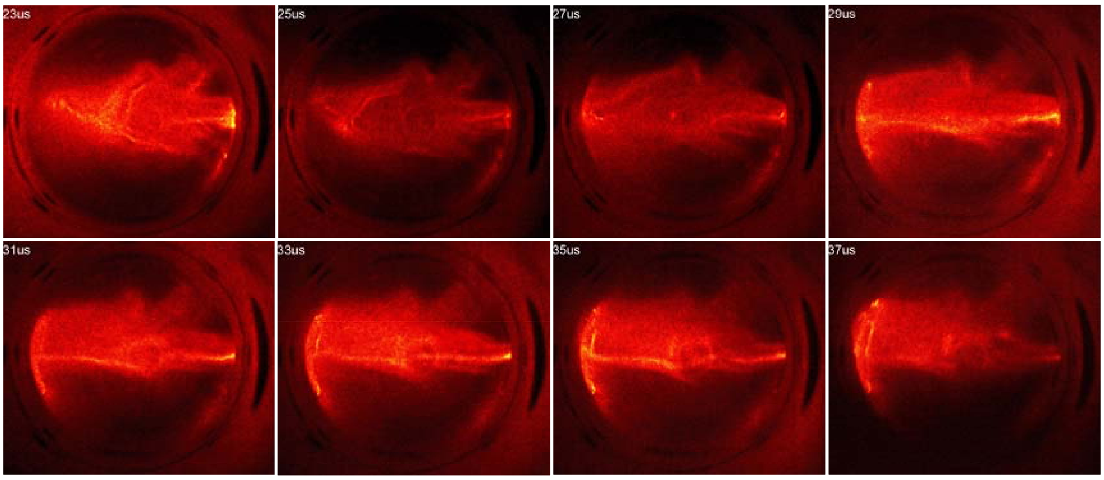

Fig. 3. Unfiltered visible light image (false color) of Ar plasma jet injected into vacuum with $B_0 = 50$ mT showing more kink-stable central current channel. View is identical to that of Fig. 2.

magnetic pressure over kinetic pressure. Here $\beta \approx nT_e/(B_0^2/2\mu_0)$, n is density, T_e is electron temperature ($T_e \gg T_i$ for the helicon plasma), and μ_0 is the permeability of free space.

Fig. 2 shows a series of unfiltered visible light images of an Ar jet injected into vacuum with no background field. The bright central chord corresponds to the central current channel, where a kink-like structure can be seen. Indeed, detailed magnetic measurements and comparison with the K-S criterion show that this is consistent with an m = 1 kink mode. The kink appears when the jet length, L, is large enough that q drops below 1, which occurs at times $t \sim t_{Alfvén} = L/v_{Alfvén}$. In contrast, Fig. 3 shows a corresponding set of images when the jet is launched into a 50 mT background B-field (in vacuum). It can be seen that the jet is longer - reaching the far side of the vacuum chamber, and is stable for a longer time, $t \sim 4\text{-}6\times t_{Alfvén}$. Magnetic measurements show that in this case q is still < 1, and is actually lower

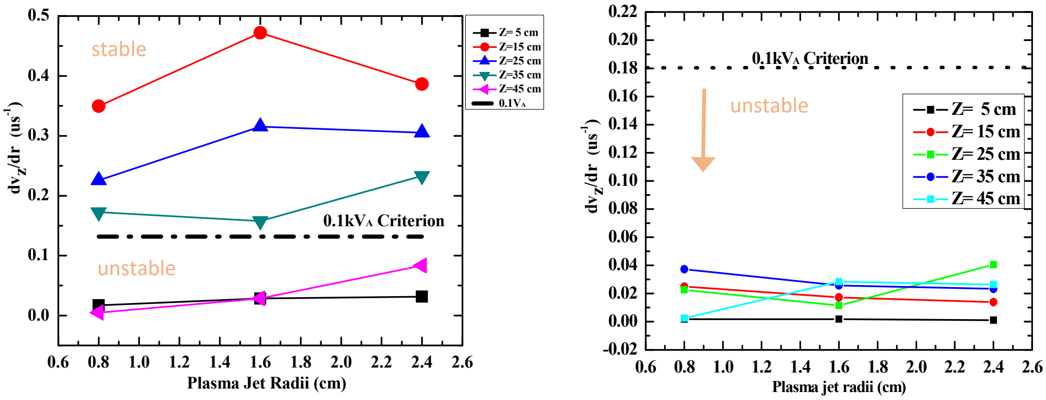

Fig. 4. Axial velocity shear, dv_z/dr, vs. plasma jet radius at various axial positions of the jet leading edge as it propagates. Left: $B_0 = 50$ mT. Right: $B_0 = 0$. $0.1kv_A$ criterion line indicates the kink mode velocity shear stabilization threshold [3]. In the $B_0 = 0$ case (right), velocity shear is insufficient for stabilization.

than the $B_0 = 0$ case, indicating that the increased kink stability is not explained by an increase in q. However, measurements of v_z vs. jet radius, determined by time of arrival of leading edge features seen on both B-dot and Langmuir probes, indicate that there is an increased velocity shear, dv_z/dr, when background B-field is present, as compared to the $B_0 = 0$ case. In cases with increased stability, it is found that $dv_z/dr > 0.1kv_A$, consistent with the theoretical criterion for sheared flow stabilization of the kink mode derived in ref. [3]. Here k is taken as $k = 2\pi/L$. Fig. 4 plots dv_z/dr at various jet lengths for the $B_0 = 0$ and $B_0 \neq 0$ cases. It can be seen that in the $B_0 \neq 0$ case, $dv_z/dr > 0.1kv_A$, at least for shorter jet lengths, while this is not true when $B_0 = 0$. These data are consistent with the mechanism of shear flow stabilization of the kink mode when a background B-field is present. We hypothesize that magnetic tension, which results from field line bending as the background B-field is displaced by the jet, reduces v_z at the jet edge, resulting in a radial shear. Since the magnetic Reynolds number of the jet is > 100, magnetic field diffusion of B_0 into the jet is expected to be small - likely just into the outer edge. Detailed MHD (magnetohydrodynamic) modelling is now underway to test this hypothesis.

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