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ORIGINAL ARTICLE

Generation of shear flow in conical wire arrays with a center wire

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Abstract At the Nevada Terawatt Facility we investigated the generation of a sheared plasma flow using conical wire arrays with an additional wire located on the axis of the pinch. The additional center wire generates axial current carrying plasma that serves as a target for the plasma accelerated from the outer wires, generating a sheared plasma flow which leads to the growth of the Kelvin-Helmholtz instability. These experiments were conducted on Zebra, a 2 TW pulse power device capable of delivering a 1 MA current in 100 ns. This paper will focus on the implosion dynamics that lead to shear flow and the development of the Kelvin Helmholtz instability.

Keywords Shear flow · Kelvin-Helmholtz instability · Conical wire array · Z-pinch

1 Introduction

Many astrophysical systems have transverse variations in velocity and these sheared flows are susceptible to the Kelvin-Helmholtz instability (Chandrasekhar 1961). Instability growth leads to energy, momentum, and particle transport (or fluid mixing) across the shear interface. This is of particular interest when magnetic fields are present, as in many natural systems. For example, the Kelvin-Helmholtz instability (KHI) is a prominent candidate for explaining the transport from the solar wind to the magnetosphere and its role in magnetic storms (Hasegawa et al. 2004). In certain settings, such as the expansion of the solar coronal plumes through the interplume plasma, the velocity shear triggers drift KHI, which do not produce plasma inhomogeneity over large scales (Andries and Goossens 2001). In the case of protostellar jets, KHI may be responsible for the formation of a mixing layer and internal shocks (Cantó and Raga 1991; Raymond et al. 1994), which may lead to jet deformation and breakup (Keppens and Tóth 1999). In all these examples, the shear layer forms in magnetized plasma and both observations and theory suggest that the field has a significant effect upon the development of the KHI and its consequences. The role of magnetic fields upon the stability of boundaries with sheared flows was further investigated by sophisticated three-dimensional simulations (Keppens and Tóth 1999; Ryu et al. 2000). Few laboratory experiments investigate the effects of sheared flows in magnetized plasma, for example Shumlak et al. (2001). Here we present a proof of principle experiment that demonstrates the excitation of the Kelvin-Helmholtz instability in magnetized plasma at a velocity shear layer created by a conical wire array with an additional central conductor.

2 Generation of shear flow

Conical wire arrays have been previously shown to produce axially flowing plasma (Lebedev et al. 2002; Ampleford et al. 2005; Lebedev et al. 2004). The conical wire array is a modified wire array Z-pinch, where the wires are ohmically heated and ablated to form a coronal plasma around each individual wire. The current then flows through this coronal plasma along each wire, continuing to heat it. The global magnetic field generated by all wires causes a Lorentz

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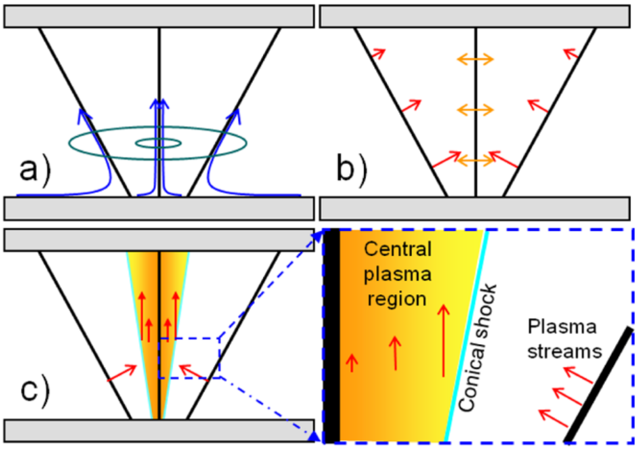

Fig. 1 (**a**) Current (*blue arrows*) flows through the wires, generating a local magnetic field around each wire and a global magnetic field (*green*) around the whole array. (**b**) Ohmic heating causes all wires to ablate. Plasma originating from the outer wires will be accelerated perpendicular to the wire surface toward the array axis (*red arrows*). The plasma from the center wire will expand (*orange*) and will be confined by its own magnetic field. (**c**) The interaction of the plasma streaming from the outer wires (*red*) with the center wire plasma (*orange yellow*) leads to the formation of a conical shock (*delineated* in *light blue*). Once it traverses the shock, the plasma originating from the outer wires will be redirected in axial direction, creating a sheared flow (*red*)

$\boldsymbol{j} \times \boldsymbol{B}$ force on the plasma coronas, which accelerates them towards the axis of the array. The acceleration is perpendicular to each wire, creating plasma streams that have radial and axial momentum. For a cylindrical wire array, the kinetic energy of the radial motion is thermalized at stagnation on the axis of the array, creating a hot precursor plasma column. This precursor column is modified for the conical array configuration, as described in Lebedev et al. (2002), Ampleford et al. (2007), to create a conical shock (Cantó et al. 1988). For the estimated values of the plasma parameters at the time of the conical shock development, the ion mean free path is of the order of 10 μm, thus the shocked material is redirected to the axial direction producing an axially flowing plasma. When introducing a wire on axis, it is ablated (Fig. 1a) due to heating by the current it carries. In this case, the plasma flow interacts with a central plasma stationary in axial direction. Assuming a no-slip boundary condition on the surface of the center plasma, a quasi-parabolic velocity profile results (Wanex 2005)

$$v_z(r) = V \frac{\ln(r_w) r^2 - r_w^2 \ln(r)}{R^2 \ln(r_w) - r_w^2 \ln(R)}, \tag{1}$$

where v_z is the axial velocity, r_w is the radius of the axial plasma, R is the flow radius, and V is the flow velocity at the edge.

For the laboratory experiments presented here, the conical wire arrays (Fig. 1) consisted of eight 15 μm Al wires, equally spaced and had a cathode (bottom) diameter of 6 mm and an anode (top) diameter of 18 mm, giving the array an opening angle of 16.7°, measured from the z axis to the outer wires (this array configuration is identical to the Zebra experiments described in Ampleford et al. 2007 and Presura et al. 2001). The center wire was a 10 μm diameter Al wire. Both the conical array and the center wire use the alloy Al 5056 (95% Al, 5% Mg) such that a small amount of magnesium is present for spectroscopic analysis. These arrays were imploded using the Zebra Z-pinch generator, which is capable of delivering 1 MA of current to a load in 90 ns (Shlachter 1990).

Considering a cylindrical wire array with 12 mm diameter as a proxy for the conical wire arrays used in experiment, the current through the center wire I_{in} can be estimated by using Velikovich et al. (2002)

$$\frac{I_{in}}{I} = \frac{\omega(L_{out} - M) + R_{out}}{\omega(L_{in} + L_{out} - 2M) + R_{in} + R_{out}}, \tag{2}$$

where I is the total array current, ω is the frequency of the current pulse, L_{in} is the inductance of the center wire, L_{out} is the inductance of the outer array, M is the mutual inductance between the center wire and the outer array, R_{in} is the resistance of the center wire, and R_{out} is the resistance of the outer array. This equation predicts that the center wire will carry about 6% of the total current while the wires remain cold.

The plasma dynamics were observed using multi-frame shadow imaging (Ivanov et al. 2006) with a 532 nm wavelength, 150 ps diagnostic laser. In addition, Faraday rotation images were also taken to qualitatively assess the presence of an azimuthal magnetic field inside the wire array. Time-gated X-ray pinhole images were used to obtain the phase velocity of the zippering pinch. Time-integrated spectroscopy was used to obtain estimates of the electron temperature and density.

3 Evidence of shear flow

Shadow images show evidence of a conical shock formed between the center wire and the outer wires Fig. 2a. At this shock, the streams from the outer wires change direction from a conical converging flow to an axially flowing plasma. The velocity of the material ablated from the outer wires can be estimated based on work by Ampleford et al. (2007). Measuring the time dependence of the stagnated pinch height in the time-gated X-ray pinhole images, indicates a "zippering" velocity of about 400 km/s. Using a purely geometrical analysis and considering that the delay between the plasma arrival at the array center and the X-ray emission is short compared with the characteristic time for plasma motion, the ablation velocity can be estimated as

$$v_{abl} = v_{zip} \sin(\alpha), \tag{3}$$

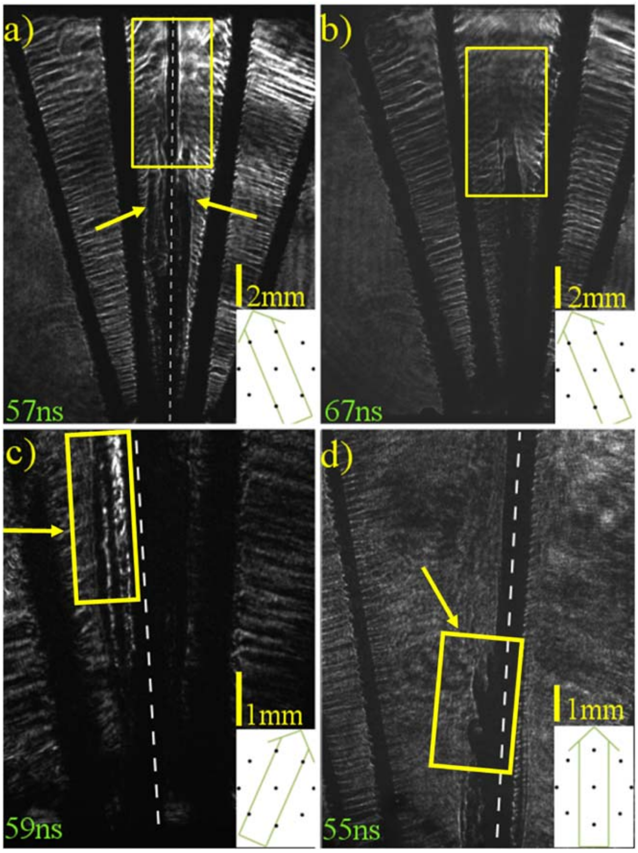

Fig. 2 Plasma images obtained with laser diagnostics. (**a**) Shadow image of a conical wire array with a center wire. In this image we see the development of the conical shock (*arrows*). The center wire is seen to expand uniformly, even above the conical shock. (**b**) Conical wire array without a center wire shows a lack of dense plasma above the conical shock in contrast to Fig. 2a. (**c**) Faraday image indicating that a magnetic field is present near the center of the array. (**d**) Shadow image showing the nonlinear stage of the Kelvin-Helmholtz instability. Time labels are zeroed to 10% current peak. The orientation of the probing laser beam through the wire array is shown in each image. The location of the center wire is denoted with a *dashed line*

where α is the opening angle of the array, v_{zip} is the observed zippering velocity and v_{abl} is the ablation velocity. For the measured value of the zippering velocity, (4) gives an ablation velocity of about 110 km/s. Assuming that the axial momentum is conserved in the pinching process, the resulting axial plasma velocity is about 33 km/s. However if any accelerating mechanism is active, the axial plasma velocity would exceed this estimate. In fact, in several shots, the axial velocity of features in the central plasma column could be measured, giving values around 100 km/s, which are in good agreement with theoretical results of Cantó et al. (1988) for strong adiabatic shocks.

This plasma flow interacts with an axially stationary center plasma produced by ablation of the center wire. For the case of a conical wire array with a center wire, a uniform column of dense plasma forms on axis along the full height of the array, even above the top of the conical shock Fig. 2a, in contrast with the case of conical wire arrays without a central wire Fig. 2b. The Faraday rotation images show brightening of the left side of the array and darkening of the right Fig. 2c compared with a reference image, indicating the presence of an azimuthal magnetic field and supporting the hypothesis that the center wire is carrying sufficient current to ablate the wire. The interaction of the axial plasma flow with this axially stationary plasma produces a radial dependence of the axial velocity.

4 Development of vortices

As described in the previous section, when the plasma streams from the outer wires cross the conical shock, they change direction from a conical converging flow to an axially flowing plasma. Across the boundary, the axial velocity may increase (in the case of an adiabatic flow) or remain unchanged (if the axial momentum is conserved). In the former case, the resulting shear layer would be too narrow for the diagnostics to detect. However, in both cases, a shear layer with continuously variable velocity forms when the axial flow interacts with the axially static center plasma and this layer is prone to the Kelvin-Helmholtz instability. The shadow images indicate development of vortices characteristic of the nonlinear stage of the KHI Fig. 2d close to the dense center plasma column, in the interior of the conical shock.

The Kelvin-Helmholtz instability grows from the same perturbations of the dense center plasma that would produce the $m = 0$ current-driven instability or the Rayleigh-Taylor instability in the absence of an axial flow, as observed in cylindrical wire arrays. As shown in Fig. 2d, the instability produces roll-up structures, in contrast to the bubble and spike structure expected for typical Z-pinch instabilities (Peterson et al. 1996).

Assuming that the shear layer is an infinitely thin step boundary, the linear growth rate can be calculated from (Chandrasekhar 1961)

$$\gamma = \frac{k\sqrt{\rho_1\rho_2}|U_1 - U_2|}{\rho_1 + \rho_2}, \tag{4}$$

where k is the wave number of the mode considered, and ρ_i and U_i are the density and velocity of the i-th fluid, respectively. The wavelength is measured on the shadowgram to be $\sim$1 mm. Assuming that the central wire plasma is one order of magnitude denser than the plasma streaming from the outer wires, such that $\rho_1 \approx 10\rho_2$, and using the flow velocity of 100 km/s as $|U_1 - U_2|$, a KHI growth time of about 5 ns results. If the actual density ratio is higher, the growth time increases approximately linearly with the square root of the ratio. The pinch evolution time includes several instability growth times, thus allowing the KHI to reach the non-linear stage. It is important to note that the KHI has been observed in a relatively small number of shots and never with azimuthal symmetry. The latter may be due to the low number of wires of the conical array, which leads the formation of a corrugated conical shock. In this case, the individual oblique shocks formed for each outer wire may have different parameters, so that not all of them meet the correct criteria for exciting the instability. Alternately, as the instability grows the fastest when the density ratio is one, the density-sensitive laser diagnostics used here may not always detect it.

5 Scaling

Values of dimensionless parameters can be used to assess the relevance of this experiment to astrophysical and space physics phenomena. Order of magnitude values of the Peclet, Reynolds and magnetic Reynolds numbers (Ryutov et al. 1999; Ryutov et al. 2001) were obtained from approximate plasma parameters. Time integrated Mg line spectra (Vainshtein et al. 1980; Vinogradov et al. 1975) were used to estimate the plasma temperature around 100 eV and the plasma density about 10^{19} cm^{-3}. A charge state $Z = 5$, a flow velocity of 100 km/s, and a plasma column radius of 0.5 mm were considered. Assuming that 10% of the array current halfway through the rise time flows through the center plasma, the magnetic field is of the order of 20 T. With these values, the dimensionless parameters can be calculated: $Pe \sim 10$, $Re \sim 10^3$, and $Re_M \sim 10$. Based on the accuracy of the plasma parameters used, these values are correct within a factor of 2. Although these numbers are by many orders of magnitude smaller than in those characteristic to the solar wind or protostellar jets, they are significantly larger than one, indicating that the same transport processes dominate.

6 Conclusions and future work

This proof of principle experiment demonstrated that a conical wire array with a center wire is capable of generating a sheared flow, as evidenced by laser imaging of the plasma. This shear flow can excite the Kelvin-Helmholtz instability, as indicated by the formation of vortices, which are characteristic of the nonlinear stage of the KHI. A simple hydrodynamic analysis of the instability growth rate indicates that the vortices seen can indeed be generated by the KHI. However, the appearance of the KHI is non-periodic and does not present cylindrical symmetry, which requires further investigation.

In future experiments, the configuration will be optimized to investigate the details of the KHI growth in magnetized plasma shear layers. The flow velocity, which determines the growth rate, can be varied by changing the conical wire array opening angle. In addition, this type of experiment presents the advantage that using wires with different atomic numbers changes the amount of energy lost by radiation. This radiative cooling process (Ampleford et al. 2005) can be used to modify plasma density and flow velocity. To investigate the effect of the magnetic field upon the instability growth, the intensity of the current flowing through the center wire can be varied by changing the number of wires in the wire array or changing the central wire thickness. Adding an external axial magnetic field will enable the study of its stabilizing effect upon KHI.

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