Application of pulsed power driven plasmas to study astrophysical jets and supersonic outflows

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Introduction

- Mass ablation rate described by Rocket model (S.Ledebev, Phys Plasmas, 8, p3734, (2001))

\[ V_{abl} \frac{dm}{dt} = -\frac{\mu_0 I^2}{4\pi R_0} \]

- Mass ablated determined by \( I_{max} \)
- Timescale determined by \( \tau \)

<table>
<thead>
<tr>
<th>Generator</th>
<th>Location</th>
<th>( I_{max} )</th>
<th>( \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAGPIE</td>
<td>Imperial College</td>
<td>1MA (2MA)</td>
<td>250ns</td>
</tr>
<tr>
<td>GenASIS</td>
<td>UCSD</td>
<td>0.25 MA</td>
<td>150ns</td>
</tr>
<tr>
<td>X-Pinch Driver</td>
<td>UCSD</td>
<td>0.08 MA</td>
<td>50ns</td>
</tr>
</tbody>
</table>


[Diagram of ablation process]
Supersonic Plasma Flow

Flow Parameters

- Plasma density ($N_{\text{ion}}$): $1 \times 10^{14} - 5 \times 10^{17} \text{ cm}^{-3}$
- Plasma Velocity: $1.5 \times 10^5 \text{ ms}^{-1}$
- $T_e = 5 - 15 \text{ eV}$
- Mach number: 3-5
- $R_m < 1$ (experimental)

Collisionality

$$\lambda_{\text{perp}} = \frac{m_{\text{ion}}^2 v_{\text{abl}}^4}{8\pi Z^4 e^4 n_{\text{ion}} \ln \Lambda \sqrt{\pi} / 2}$$

**MAGPIE**

Al : typically <1mm
W : >8mm for ~140ns

**UCSD:**

Some collisionless flow even for Al

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Time-slice from 3D Resistive MHD Gorgon Code
(J.Chittenden, Plasma Phys Control Fusion 46, B457 (2004))

Gated axial XUV self-emission images from 16 wire arrays on MAGPIE
Shock formation in supersonic plasma flow

Collisional systems:

• e.g. Nested Wire Arrays at >1MA
Shock formation in supersonic plasma flow

Collisional systems:

• e.g. Nested Wire Arrays at >1MA
• Data from 32 outer and 16 inner Al wires on MAGPIE
• Bow shocks formed around inner wires
• Secondary shocking also observed
• D.J.Amplford at HEDLA

Axial gated XUV self-emission imaging of nested Al arrays on MAGPIE
(D.J.Amplford in prep. PRL)
**Shock formation in supersonic plasma flow**

**Collisional systems:**
- e.g. Nested Wire Arrays at >1MA
- Data from 32 outer and 16 inner Al wires on MAGPIE
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**Collisionless systems:**
- UCSD experiments will provide collisionless flow,
- Good diagnostic access and shot rate
Inertially Confined plasma column formed

Precursor Column parameters

- $N_{\text{ion}} : 10^{18} - 10^{22} \text{ cm}^{-3} (0.1 - 1 \text{ kg/m}^3)$
- $Z: (\text{Al}) \sim 7, (\text{W}) \sim 14$
- $T_e \sim 60\text{ eV} - 100 \text{ eV}$
- Diameter: 0.5-3 mm

Dense precursor condensation on axis

Axial (lineouts right) and radial gated XUV self-emission images, along with column density with time for MAGPIE and COBRA W experiments (Bott et al, Phys Rev E, 74 046403 (2006))

Radiatively cooled and steady state (several shock transit times)
Hydrodynamic Jet formation

Typical Parameters scale well to astrophysical jets

General flow variables
- Length (cm): 2
- Width (cm): 0.1
- Dynamical time Scale: 100 ns
- Electron temperature (eV): 10
- Jet tip velocity (km/s): ~200
- Jet density, $\rho \sim 10^{-4}$ (g/cm$^3$)
- Localisation parameter: $10^{-4}$
- Reynolds Number ($R_e$): $10^5 \sim 10^8$
- Peclet number ($P_e$): $2 \sim 2 \times 10^3$

Jet scaling
- Mach number, $M > 20$
- Density Contrast, $100/ \sim 1$
- Cooling Parameter, 1

Conical Wire Array


Gated XUV Emission

Laser Shadowgram


HH502

100 years 300 years
Variation of jet parameters: Jets at UCSD

- Range of jet parameters possible using different currents (e.g. 2 Generators at UCSD & MAGPIE)
- First free propagating jets from x-pinches recently measured at UCSD at 80 kA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>80 kA X-pinch measured</th>
<th>250 kA Conical Expected (HEDLA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{jet}$</td>
<td>$3.3 \times 10^4$ ms$^{-1}$</td>
<td>$1 \times 10^5$ ms$^{-1}$ (100 km/s)</td>
</tr>
<tr>
<td>$c_s$ (radial exp)</td>
<td>$5.5 \times 10^3$ ms$^{-1}$</td>
<td>$M &gt; 10$</td>
</tr>
<tr>
<td>$M$</td>
<td>4-8</td>
<td>$\sim 10^{18} - 10^{19}$</td>
</tr>
<tr>
<td>$\rho_e$ (cm$^{-3}$)</td>
<td>few $\times 10^{17}$</td>
<td>$\sim 15$</td>
</tr>
<tr>
<td>$T$ (eV)</td>
<td>$\sim 15$</td>
<td>$\sim 5$</td>
</tr>
<tr>
<td>$Z$</td>
<td>$\sim 5$</td>
<td></td>
</tr>
</tbody>
</table>
Magnetically Driven Jets

Radial Wire Arrays

- Wires show magnetic bubble structure and jet formation (Lebedev AIP Conf. 2006)
- Foils loads show repeat formation of this structure during one current pulse
- Recently foils performed with and without a gas fill (see F. Suzuki-Vidal at upcoming HEDLA conference)

Ciardi et al, Phys. Plasmas 14, 056501 2007
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FIGURE 2a. XZ TAU. Credits: John Krist (STScI) et al. WPFC2, HST, NASA
Future Studies at UCSD

**UCSD Drivers**
- Good diagnostic access, high shot rate
- 2 generators to give plasma source, and independent B-field or second plasma

**Parameter space accessible**

*Can adjust*  
Plasma $\rho : n_{\text{ion}} \sim 10^{14} \text{– } 10^{17} \text{ cm}^{-3}$  
B-field: Variable up to $\sim 50T$ (200 kA)

*Difficult to adjust:*  
Plasma velocity (ablation physics)  
T: 10eV in flow, 60-100 eV in column  
Material At No. below 6(C) (typ. 13, Al)

**Physical Conditions:** Collisionality of flow  
Magnetization of ions  
Low T limits plasma to low $\beta$  
*Need to investigate application to cosmic shocks (Drake PoP 2000)*

**Modelling**
- GORGON for hydro and magnetic jets (J. Chittenden & A.Ciardi)  
- Also use of LSP, h2d, and ePlas at UCSD
**Imperial College / UCSD Collaborative Studies**

**Imperial College**: High current drive, extensive diagnostics, experienced team

**UCSD**: 2 drivers, high shot rate in simplified set-ups

**Compression of targets using ablated plasma flow**

Pressures: 1 – 100 kbar
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**Compression of targets using ablated plasma flow**

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Magnetic field in precursor column

Twisted Arrays
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**Compression of targets using ablated plasma flow**

- Pressures: 1 – 100 kbar
- Magnetic field in precursor column
- Twisted Arrays
  - Inductive split from main current
  - Additional generator

**Diagram:**
- Current Drive: Marx or inductive split
- $I_{array}$
- $J \times B$ force
- Ablated plasma flow $P_{flow} = \rho v^2$
- $B_{global}$
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**Thin-Walled Metal tube**  
**JxB force**  
**ANODE**  
**B**  
**CATHODE**  
**I_{array}**  
**B_{global}**  
**WIREs**  

**Compression of targets using ablated plasma flow**

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**B-field flux compression**
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Jet Interaction Experiments

Use of radial / conical arrays for interaction with

- Precursor plasma column
- Magnetised precursor
- Counter-propagating jet
Jets and outflows from pulsed power driven plasmas

Well characterised…….

• Generation and deflection of hydrodynamic jets
• Generation of magnetically driven jets

Systems developing…..

• Multi-stage magnetically driven jets
• Low jet/ambient medium density ratio experiments
• Hydro Jet work at UCSD
• Jets with angular momentum (Ampleford, PRL 100, p035001, 2008)

To come…….

• Compression of magnetised plasmas
• Propagation of plasma into B-field / magnetised targets
• Collisionless shock systems