Experiments in Magnetic Flux Compression

Using Plasma Armatures

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A Cooperative Research Project between
UAH/PRC and NASA/MSFC

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Potential Space Thruster Applications

Pulsed Reactor
• Microfusion
• HEDM

Performance Attributes
• improved flux compression
• reduced seed field
• collimated thrust
• power generation

Design Attributes
• smaller
• more compact
• lower weight
Magnetic Flux Compression with Plasmas

Plasma Jet Characteristics

- conductivity → relatively low
- temperature → very high
- velocity → very high

Major Uncertainties

- achieving sufficiently high electrical conductivity
- suppression of Rayleigh-Taylor surface instabilities

Magnetic Reynolds Number

\[ R_m = \frac{B_i}{B_0} = \mu_0 \sigma u L \gg 1 \quad \Rightarrow \quad \text{low magnetic diffusivity} \]

\[ D_m = \frac{1}{\frac{1}{\sigma \mu_0}} \sim \frac{1}{R_m} \]

- micro fusion detonation → \( R_m \gg 1 \)
- pulsed plasma jet → \( R_m > 1 \)
- high explosive detonation → \( R_m > 1 \)
Fundamental Compression Experiments

Research goal is to investigate scientific and technological feasibility using non-nuclear detonations…

**Mark 1 Device**
Radial-mode, magnetic flux compression reactor

- Opposing HE charges
- Radially expanding plasma armature
- Moderate scale technology demonstrator
- Low cost expendable unit

... measurement of plasma electrical conductivity is a critical need
Measurement of Plasma Jet Conductivity

Inductive measurement technique provides a low cost direct measurement of plasma jet electrical conductivity …

**Principle of Inductive Measurement**

- magnetic field created by field coil
- conductive plasma jet displaces magnetic field lines
- magnetic field lines cut across search coil and induce an emf
- degree of field displacement (emf) is correlated with electrical conductivity
- apparatus calibrated by pre-firing a slug with known conductivity & velocity
- electrical conductivity determined by inversion of Fredholm Eqn. of 1st kind
**Lin Coil Design**

- **Field Coil**
  - 900-turn coil
  - No. 18 enameled wire

- **Search Coil**
  - 50-turn coil
  - No. 28 enameled wire

**Design Specifications**
- 0.5 – 1 Tesla excitation field
- 1-inch diameter working volume
- 60 A/300 V excitation power limit

All measurements in inches

Material: nylon
Search Coil Design Considerations

Search Coil Parameters

- 50-turns / No. 28 enamelled wire
- \( L = 8 \text{ mm} / D = 5.7 \text{ cm} \)
- dual 25-turn coil construction
  - standard option
  - push-pull option

Previous experience using inductive conductivity probes with shock layers has shown that a localized electrostatic charge can generate a signal in a standard configuration search coil due to finite capacitance between the coil and the ionized gas inside the tube.

**Push-Pull Configuration**

\[
\begin{align*}
\checkmark & \text{ cancels capacitive pick-up} \\
\checkmark & R_d \text{ is critical damping resistance (} \approx 1000 \Omega \text{)}
\end{align*}
\]
Lin Coil Calibration Apparatus

- light gas gun for slug acceleration (150 psig He)
- 1-inch i.d. plastic barrel with 6-inch long glass test section
- aluminum slug (D = 1-inch / L = 4-inch / ρ = 3(10)^{-8} Ω-m)
- direct optical measurement of slug velocity
- automated solenoid actuation with high speed data capture
Lin Coil Calibration – Timing Verification

- Current
- Velocity Response Function
- Current Response Function (push)
- Velocity
- Current Response Function (pull)
Probe Calibration – Algorithm Verification

Probe Response Function

- Data
- Gaussian fit ($\sigma = 1.8$ cm)

Algorithm Performance

- Constrained linear inversion
  ($H = I; \gamma = 10^{-3}$)
- Predicted
- Exact
Shape Charge Plasma Jet Conductivity

Plasma Jet Conductivity Measurement
Preliminary HE Testing

- Octol (75% HMX/25% TNT)
- Potassium-Carbonate Seeding
  - 0%, 1%, 2% by mass
- 15 gram shape charges
  - 1.25 inch diameter
  - 44° cone angle
Preliminary Test Results

Time-of-flight

Response Fnc (push)

Response Fnc (pull)
**HE Testing – Results**

**Time-of-Flight Output**

Plasma velocity: \[ u = \frac{dx}{dt} = \frac{10^{-1} m}{11(10)^{-6} \text{ sec}} = 9.1 \text{ km/sec} \]
HE Testing – Results

Search Coil Response Function

0% KCO₃

push coil

test 2-10 (0% seed)

pull coil

2% KCO₃

push coil

test 2-12 (2% seed)

pull coil
HE Testing – Analysis

Step Function ↔ Gaussian Curve

\[
\frac{\sigma^*}{\sigma_c} = \frac{u_c^2 I_c V_p}{U^2 I V_{cp}} \Psi_1 = \frac{u_c^2 I_c \Phi}{U^2 I \Phi_c} \Psi_2
\]

For a Gaussian function:

\[
\Psi_1 = \Psi_2 = 1
\]
HE Testing – Analysis

Integral Method Calculation: \[ \frac{\sigma^*}{\sigma_c} = \frac{u_c^2 I_c \Phi}{U^2 I \Phi_c} \Psi^2 \]

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<th>Test</th>
<th>2-4</th>
<th>2-10</th>
<th>2-6</th>
<th>2-12</th>
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<tr>
<td>Seed (%)</td>
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<td>0</td>
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<td>0</td>
<td>2</td>
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<tr>
<td>( \frac{\sigma^*}{\sigma_c} \times 10^{-5} )</td>
<td>5.9</td>
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<tr>
<td>( \frac{\sigma^* u}{\sigma_c u_c} \times 10^{-2} )</td>
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<td>5.1</td>
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<td>24</td>
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<tr>
<td>( \sigma^* (kS / m) )</td>
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<td>3.6</td>
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<td>( \mu_0 \sigma^* u (m^{-1}) )</td>
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Fundamental Research on Rayleigh Taylor Instabilities

Tapered Pulse Plasma Gun

Plasma Jet Characteristics

\[ u \sim 10^4 \text{ m/s} \quad T_e \sim 10 \text{ eV} \]

Diagnostics:

- High speed imaging
- Time-resolved interferometry
- Time-resolved spectroscopy
- dB/dt probes
Development of Pulsed Plasma Experiment

- Triggered spark gap
- High voltage feedthrough
- Diffusion pump
- Lin Coil System
- Vacuum chamber
- Pulse plasma gun
- Optical window
Pulsed Plasma Gun Design
Experimental Set-Up

Design

• four 2-\mu F capacitors (ONR surplus)
• configurable power bus (1, 2, 3, or 4 capacitors in parallel)
• capacitor bank and discharge circuit mounted on cart for portability
Conclusions

- An electrode-less inductive probe for measuring plasma jet electrical conductivity was designed, calibrated, and tested
- Calibrated with slug of known conductivity
  Inversion algorithm marginally successful
  Assumed conductivity distribution with known solutions
- Laboratory experiments using seeded and unseeded shape charge explosives
  Average jet velocity = 9-10 km/sec
  Measured conductivities: 4 kS/m (unseeded)
  26 kS/m (2% seed)
- Magnetic Reynolds numbers > 1 (for fractions of a meter scale)
  Mark 1 device has a good chance of being successful
- Inductive probing technique represents a very successful and reliable tool for investigating plasma jet characteristics
- High explosive plasma sources capable of producing high $Re_m$
Future Plans

1. Pulsed plasma gun / discharge circuit completed
   - tapered plasma gun designed, fabricated, and tested
   - high voltage discharge circuit operational
   - vacuum chamber, pump, feedthroughs assembled
   - high-purity aluminum magnet on its way
   - testing to begin very soon

2. Mark 1 Device, radial-mode magnetic flux compression reactor using high explosive shaped charges