Plasma Jet Research at HyperV Technologies*

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Background

Applications

- Magneto-Inertial Fusion
- Magnetic Confinement Devices
- High Energy Density Laboratory Plasmas
- Simulating Astrophysical Jets
- Plasma Thrusters
- Materials Processing

Technical Goals

\[
\begin{align*}
\text{velocity} & > 200 \text{ km/s} \\
\text{mass} & \approx 100 - 200 \mu g \\
\text{density} & \approx 10^{16} - 10^{17} \text{ cm}^{-3} \\
\text{Mach} & \approx 10 - 20
\end{align*}
\]
Electrode Profile Tailoring Can Suppress Blow-By Instability by Matching Density with JxB

The forward tilting of the plasma increases in this region, further compressing the plasma towards the axis. The conical z-pinch with the vertex at F propels the plasma forward as a focused or a well collimated jet.

The plasma expands and accelerates around the inner electrode. Major Lorentz acceleration continues with forward tilting of the current beginning to focus the flow electromagnetically.

The outward curvature of the inner electrode further prevents the occurrence of blow-by.

The curvature of the electrode here bends the supersonic plasma flow into itself, compressing it, forming a denser plasma along the inner electrode. It also creates a longer path along the inner electrode.

The plasma expands supersonically around the outer electrode, giving rise to reduced density along the outer electrode, and gets ahead of the plasma at the inner electrode.

Injected plasma forms a fat z-pinch across the gap between the electrodes, accelerating towards the axis.

Plasma Injector: An electrothermal discharge between two circular rings or sets of annular segments of ablator.
Four Main Experimental Efforts at Present

**Wasp Profile**
*32 ablative capillary injectors, now on MCX*

**Circular Arc Profile**
*112 sparkgap tips*

**TwoPi**
*64 ablative capillary injectors*

**MiniRailgun Injector**
*Non-ablative pure gas injection*
Side Views Show Jet Structure

PLmax image
25 ns gate

Interferometer data

Nikon D70s image
2 sec exposure

Jet front impacts probe

Line integrated density

Pressure pulse coincides with line integrated density at left.
Sparkgap Approach Provides Better Injection Symmetry
More Energy Generates Increased Mass

- Circular Arc Profile vs. Wasp
- Vacuum tested to mid-$10^{-6}$ Torr

- 112 Tungsten electrodes provide “toroidal” capillaries
- Tips flush with polyethylene ablator surface
- Alternating polarity
- Provides “toroidal” capillaries
- Test circular arc profile
- Higher energy input → 360 $\mu g$
Plasma Jet Results to Date

- **Momentum/Mass**
  - $13 \text{ g-m/s (ballistic pendulum)}$
  - $160 \mu g \text{ at 85 km/s}$

- **Density**
  - $\text{mid} = 10^{15} \text{ cm}^{-3}$ (Stark broadening, before recent gun mods)
  - $\text{mid} = 10^{14} \text{ cm}^{-3}$ (interfer., Stark Broadening after recent gun mods)

- **Velocity**
  - Bulk, $\sim 75 - 90 \text{ km/s (Doppler, photodiodes, fast imaging)}$
  - Fast component H up to $145 \text{ km/s (Doppler, photodiodes, imaging)}$
  - Fast component C up to $110 \text{ km/s (Doppler, photodiodes, imaging)}$

- **Temperature**
  - $4 \text{ eV (spectroscopy)}$

- **Stagnation Pressure**
  - $90 \text{ kPa (piezoelectric transducer)}$

- **Velocity is reduced by**
  - Transverse B field
  - Long plastic tubes
  - Surrounding conducting loops
  - High base pressure
The Higher Energy TwoPi Injector Test Fixture

- Better vac - $10^{-5}$ Torr
- Better diagnostic access
- Smaller nozzle separation
- Tungsten electrodes
- More flexible
- Large vertical gap

![Image of the test fixture]

![Image of the test fixture in action]
A Fast Symmetric Implosion on Upgraded TwoPi

Precursor implosion at $v \sim 80 \text{ km/s}$
25 ns Plmax photo at 3.3 $\mu$s

<table>
<thead>
<tr>
<th></th>
<th>$n_e \text{ (cm}^{-3}\text{)}$</th>
<th>$T_e \text{ (eV)}$</th>
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</thead>
<tbody>
<tr>
<td>periphery</td>
<td>$2.4 \times 10^{14}$</td>
<td>2.4</td>
</tr>
<tr>
<td>center</td>
<td>$2.5 \times 10^{15}$</td>
<td>4.0</td>
</tr>
</tbody>
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Main plasma shell follows later
A MiniRailgun Can Provide a Pulsed High Mass Plasma Injector

Initial Conditions
*Pre-pressurized plenum, burst disk*

Diaphragm Bursts
*Energetic spark provides energy*

Main Armature Forms
*Gas/plasma fills bore*

Armature Sweeps up Plasma
*Delivers pulse at muzzle*

The pulse heated Plenum by itself may be sufficient!

- nonablative ceramic
- short plenum
- tungsten sparkgap, tantalum diaphragm
- very fast outflow \(2\ell/c_s\)
- pulse heat stored gas
- only works if jitter is small
Stages of Assembly of 1st Gen MiniRailgun

Initial copper rail busbar and acrylic insulator components.

First step of assembly.

Side view showing brass current feeds and sealing nose O-ring.

With one current feed in place.

Initial plenum components. White tee structure is the sparkgap electrode leads with insulation.

Closeup of the sparkgap tips barely protuding through surface of plenum back wall.

Side view of sparkgap tips.

Side view of assembled unit.
MiniRailgun Armature and Plume Imaging

A 1 sec exposure with Nikon D70s in the 10cm MiniRailgun.

Fast Plmax image of armature halfway down the bore. 25 ns gate width, 5 $\mu$s after trigger.

Fast Plmax image of arc at end of rails and plasma jet plume extending into the vacuum chamber. 25 ns gate width, 20 $\mu$s after trigger.
Experimental setup for dual railgun tests to investigate diaphragm burst jitter.

Signals on two separate pressure probes just downstream of the railgun muzzles. The base pressure here was about 1 Torr.

Light emission from the burst diaphragm appears within less than $1 \mu s$ from each plenum.

Fast Plmax image of armature halfway down the bore. 25 ns gate width, $5 \mu s$ after trigger.

A 25 ns gate at 10 $\mu s$. 
Summary

- Demonstrated Plasma Injection into Coaxial Plasma Gun
  - Ablative Capillaries
  - Good Jitter
  - Achieved 160 \( \mu g \) at 85 km/s
  - Needs more energy
- Suite of Diagnostics Developed
- Performed Initial Jet Merging Experiments
- Pulsed MiniRailgun Injector under Development
HyperV Plasma Jet Internal Structure

Cross-section of shaped main electrodes with 32 capillary discharge injectors.

Jitter is well in hand - less than 25 ns at 35 kV
Capillary driver:
0.6\( \mu F \), 35\( kV \), \( R_{ballast} = 0 \rightarrow 8 \Omega \), 5\( kA \)

Coaxial driver:
112\( \mu F \), 18\( kV \), \( R_{ballast} \sim 40 \)\( m\Omega \), 180\( kA \)

Switch:
Trigatron, 250\( kA \), 30\( kV \)

Triggering:
Fiber optic, 1 – 4 \( \mu s \) adj. delay
The TwoPi Injector Test Fixture
Injector Development and Jet Merging Expts

- 64 capillary jets
- 24 inch diameter
- 2 inch vertical gap
- Base pressure $6 \times 10^{-4}$ Torr
- Brass nozzles
- Tungsten center electrode
- 0.15 $\mu F$ Maxwell cap per 4 capillaries at 35 kV
- $R_{ballast} = 1.3 \, \Omega$
Density and Velocity Spectra

Hydrogen Balmer-β spectrum

- \( n_e \) increases as \( R_{ballast} \) decreases
- \( H_\beta \) and \( H_\gamma \) stark broadening are in close agreement
- Stark broadening tends to overestimate density slightly due to radial expansion

\[ \text{Stark Broadening: } N_e = 4.7 \times 10^{14} \text{ cm}^{-3} \]

Carbon II spectra

- 1.0 meter focal length f/8 high resolution monochrometer
- PImax camera detector
- simultaneous axial and radial views
- \( H_\alpha \) shifts \( \Rightarrow 75 \text{ km/s} \)
- Carbon II \( \Rightarrow 82 \text{ km/s} \)
- Carbon III \( \Rightarrow 71 \text{ km/s} \) with significant stationary component
- Carbon IV \( \Rightarrow 63 \text{ km/s} \) no detectable stationary component
- Photodiodes provide cross-check

\[ \Delta \lambda = 0.18 \text{ nm } \Rightarrow v_e = 82 \text{ km/sec} \]
Merging of High Mach Number Plasma Jets to Form Dense Imploding Plasma Liners

An approximately spherical distribution of plasma jets are launched towards a common center. The jets merge to form a spherical shell (liner), imploding towards the center.

Slide courtesy of F. Thio
Use Plasma Jet to Inject Momentum and Drive Rotation in the Maryland Centrifugal eXperiment (MCX)

Plasma Gun Mounted on MCX

Simulation*

*Courtesy of I. Shamim, A. B. Hassam, and R. F. Ellis - University of Maryland.
The Blowby Instability Limits Performance of a Classical Straight Coaxial Accelerator

- $B \sim 1/r$
- higher $\vec{j} \times \vec{B}$ near inner electrode
- current distribution is unstable
- $J(r, z)$ ”runs away” leaving most mass behind
- must peak density profile near inner electrode

Mass density contour plots illustrate the blow-by instability in a straight coaxial accelerator.*

* From J. Cassibry’s PhD Dissertation
Ballistic Pendulum Tests

- Pendulum mass = 12.75 gm
- Recoil velocity \(\simeq 0.86\) m/s
- Plasma velocity from Doppler shift \(\simeq 70\) km/s
- Calculated plasma mass \(\simeq 157\) \(\mu g\)
- 11.4 g-m/s

Five 8 \(\mu s\) exposures, 100 ms apart, 25 ms delay.

Stagnation on bottom inside of cup. 50 ns exposure at 18.5 \(\mu s\).

Expansion back to right after impact at 28.5\(\mu s\).
Imaging of Bore Reveals Complex Behavior

Diffuse plasma structure

Plasma current envelopes tip

Plmax 25 ns images reveal diffuse structure during main current discharge during earlier tests.

2 sec exposures with Nikon D70s (f/29) on recent tests indicate an asymmetry.

Current pinched on tip

Current fills only left half (contrast enhanced)
Inductive Damping Observed

Plasma slug travels down 1 m long by 10 cm diameter acrylic tube. Visible plasma front is diffuse and bullet shaped.

Passing through one turn of awg14 wire slows, flattens, and compresses the luminous front.

False color images from Plmax camera. Lower image also shows photodiodes used to view luminous front. Many other conducting rings have been tested with similar results. No velocity damping is observed if conducting loop is broken.