Overview of Plasma Guns for PLX

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Abstract

Plasma guns are being developed for use on the Plasma Liner Experiment (PLX) located at LANL. The collapsing plasma liner will be formed via merging of 30-60 dense, high Mach number plasma jets \( (n \sim 10^{16-17} \text{ cm}^{-3}, M \sim 10-35, v \sim 50-70 \text{ km/s}, r_{\text{jet}} \sim 5 \text{ cm}) \) in a spherically convergent geometry. Small parallel-plate railguns are being developed for this purpose. Each gun will operate at \( \sim 300-600 \text{ kA peak current} \), and launch up to \( \sim 8000 \mu g \) of high-Z plasma (Ar, Xe) using a \( \sim 50 \text{ kJ} \) pf\( n \). We are now successfully operating with very fast gas valve injection of Ar, and have already achieved good performance of 1200 \( \mu g \) at 42 km/s, and 4000 \( \mu g \) at 20-25 km/s at low current. Work is underway to increase both the mass and velocity using higher current. We describe experimental development of the minirailguns and their present and projected performance. We also discuss options for modest size coaxial guns that might achieve the same performance and provide additional control of the plasmoid structure.

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Related Posters

UP9.00108 Overview, Status, and Plans of the Plasma Liner Experiment (PLX)
UP9.00109 Diagnostics for the Plasma Liner Experiment (PLX)
UP9.00110 Pressure and Magnetics Measurements of Single and Merged Jets
UP9.00111 Overview of Plasma Guns for PLX
UP9.00112 High Current Systems for HyperV and PLX Plasma Railguns
UP9.00113 High Speed Jet Merging Studies In Support of PLX
UP9.00114 Modeling of plasma jet production from rail and coaxial guns for imploding plasma liner formation
UP9.00115 Numerical Studies of High-Z Plasma in the HyperV Plasma Guns
UP9.00116 One-dimensional numerical modeling of imploding plasma liners
UP9.00117 Idealized modeling of merging plasma jets in two dimensions using Nautilus
UP9.00118 Theory and Modeling of the Plasma Liner Experiment (PLX)
UP9.00119 Simulation of the Radiative Properties of Merging Plasma Jets in the Plasma Liner Experiment
UP9.00120 Simulation of Formation and Implosion of Plasma Liners for Magneto-Inertial Fusion
UP9.00121 Hybrid-PIC Algorithms for Simulation of Merging Plasma Jets in the Plasma Liner Experiment
UP9.00122 Plasma Jet Propagation and Stability Modeling for the Plasma Liner Experiment (PLX)
UP9.00123 Plasma-Jet Magneto-Inertial Fusion Burn Calculations
UP9.00124 Laser-driven Beat-Wave Current Drive in Dense Plasmas with Demo on CTIX
The PLX experiment at LANL will consist of 30 plasma guns mounted on a 9 foot diameter vacuum chamber.

See also Posters by Hsu (LANL), Merritt (UNM), and Cassibry (UAH).
PLX plans to merge 30 high Mach number plasma jets in spherically convergent geometry to create HED plasmas

**GOAL:**

Generate $\mu s/cm$-scale plasmas with 0.1-1.0 Mbar peak pressure using $\sim 1.5$ MJ of initial stored energy

Modeling by UAH and LANL indicate we will need the following to achieve that:

- 30 plasma guns
- 8000 $\mu g$
- 50 km/s
- $10^{16}$ cm$^{-3}$
- preferably short compact plasma blobs with fast rising density front

We are considering two plasma gun approaches to meet these requirements. The rest of this poster discusses the status and evaluation of those two approaches.

See also Posters by Hsu (LANL) and Cassibry (UAH).
Two plasma guns are being considered for the PLX experiment - Parallel-plate Minirailguns and Coaxial guns with contoured electrodes*

Both guns will be able to reach the desired performance in terms of mass and velocity.

The choice will be a compromise among several competing factors:
performance – cost – jet topology – growth potential – technical risk

Features in favor of each design are briefly summarized below.

<table>
<thead>
<tr>
<th>MiniRail Gun</th>
<th>MiniCoax Gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>• higher $L' \Rightarrow$ lower peak current</td>
<td>• higher ultimate performance (high V)</td>
</tr>
<tr>
<td>• augmentation possible</td>
<td>• better overall symmetry</td>
</tr>
<tr>
<td>• closer to required mass and velocity</td>
<td>• axisymmetry reduces consequences of current sheet canting</td>
</tr>
<tr>
<td>• simpler plasma injection</td>
<td>• superior jet topology</td>
</tr>
<tr>
<td>• lower overall cost</td>
<td>• easier vacuum and mounting design</td>
</tr>
<tr>
<td>• can easily use refractory alloy rails</td>
<td>• possibly overall simpler structure</td>
</tr>
<tr>
<td>• more forgiving of external circuit inductance</td>
<td>• no armature interaction with an insulator</td>
</tr>
<tr>
<td>• lower demands on switch</td>
<td>• possibly more effective use of nozzles</td>
</tr>
<tr>
<td>• nozzle and high density may alleviate canting</td>
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</tbody>
</table>

The HyperV Technologies plasma jet development laboratory
The octagon facility has provided a flexible testing site for plasma guns

Minirail Nozzle study experimental set-up. Foreground are the $56 \mu F$ minirail bank and crowbar switch, fast gas valve bank and crowbar switch. The octagon vacuum vessel (46 cm diameter by 30 cm tall) is in the center. The diagnostic suite of fiber coupled optics on top plate, pressure probe on far side of octagon and the Heterodyne Laser Interferometer (large sideways tuning fork structure) are shown.
A small parallel-plate “MiniRailgun” makes a good high-Z injector

Preionization may be Important

Pulse Heat Gas Stored in Plenum

Restraining Diaphragm Bursts

Initiate Arc after Short Delay

Armature Snowplows and Compresses

Could even work with low-Z if MiniRailgun is long enough!
MiniRailgun configurations include both ablative and high density gas-feed

Plasma Source

Fast Gas Valve (H, He, Ne, Ar, Xe, ...)

Ablative (CH₂)
1cm bore MiniRailgun hardware shows basic construction approach

Components for 4 guns
Delrin body with nylon bolts

30 cm long
Copper rails

1 cm square bore
Boron Nitride insulators

Capillary injector
Boron Nitride cup

Vacuum assembly good to
$10^{-6}$ Torr range

HV pulse forming circuits, 0.44 $\mu F$
injector, 6 $\mu F$ rail bank, with crowbar
The Minirailgun has developed into a compact high performance gun

Cut away view of Minirailgun with fast gas valve mounted on left.

Photo of the assembled Minirailgun on its mounting flange. The two copper electrode attachments can be seen on the left, and a nozzle attached on the right. The tubing feeds high pressure argon into the gas valve.
Interferometer reveals a compact plasma blob

Line integrated density measurement of the plasmoid from the HyperV Technologies 1 cm bore railgun with a straight acrylic Nozzle. The nozzle is a Plexiglas cylinder 7.5 cm long, 3.3 cm internal diameter. The velocity inferred from photodiode time-of-flight measurements for this test is 32 km/s, so the full width at half maximum for the largest peak (3.2 $\mu$s) corresponds to a length of 10 cm.

Line integrated density measurement of the plasmoid from the HyperV Technologies 1 cm bore railgun with a straight quartz Nozzle. The nozzle is a quartz cylinder 7.5 cm long, 3.3 cm internal diameter. The velocity inferred from photodiode time-of-flight measurements for this test is 35 km/s, so the full width at half maximum for the largest peak (1.2 $\mu$s) corresponds to a length of 4 cm.
Some typical traces from a Minirail test

Inside view of octagon vacuum tank with 1cm x 15cm Minirail with 30° (half angle) x 4.5cm long Acrylic Nozzle mounted on left side port.

Typical fast gas valve and Minirail current profile. -12kV, 130kA rails. Valve and rail circuits are both crowbarred at current zero.

Typical Magnetic Field profile traveling from breech to muzzle. $B_{max} \sim 5$ Tesla. $V_{max} \sim 42$ km/s.

Argon cold gas pressure in 2cm x 15cm minirail bore. Blue is pressure at 7.7cm in bore and red is pressure at muzzle. Note gas pulse rise times <20 $\mu$s, Gas front velocity $\approx 1000$ m/s. Valve starts moving at $t \approx 100$ $\mu$s, 3.3cm back from the breech.
Views of the 15cm long Minirailgun

Tungsten rails brazed to copper connectors for the 1cm MiniRailgun.

1cm square bore by 15cm Minirail HD-17 rails, Boron Nitride insulators.

The plastic structural components will be replaced in future with ceramic to be more vacuum compatible.

2cm square bore by 15cm Minirail. Copper rails, Boron Nitride insulators.
Minirailgun jet data

5 ns gate, 17 μs delay. Plasma forms compact 5 cm long jet (see photodiode to right).

5 cm long jet. 1.2 μs photodiode half width signal at 42 km/s.

Pressure probe trace, 133 bar, 17 cm from muzzle with the 2.6 cm diameter, 11 cm long straight nozzle.

Stark broadening of Hβ (486.1 nm) at 10 cm (FWHM=4.46 nm) and 30 cm (FWHM=0.42 nm) from muzzle. 2.6 cm x 11 cm straight nozzle. 

\[ n_{\text{ion}}(\text{at } 10 \text{ cm}) = 1.2 \times 10^{17} \text{ cm}^{-3}. \]

\[ n_{\text{ion}}(\text{at } 30 \text{ cm}) = 3.4 \times 10^{15} \text{ cm}^{-3}. \]
Some tungsten impurities are seen in the main plasma blob, but are not expected to be an issue for PLX.

Photodiode traces showing plasma jet profile at 10cm from muzzle. No nozzle (red), Quartz Nozzle (green, saturated), and Acrylic Nozzle (blue). Action high resolution spectroscopy analysis of peak one and larger peak two on blue plot revealed Argon as the predominant species in peak one while hydrogen and carbon are the predominant species in peak two.

Spectral intensity plot of W I with respect to time. Plot shows trace amounts of W I around peak current and after plasma jet passes optics. The bulk jet has ~2% tungsten.
Long propagation test

Octagon with 10in diameter extension tube x 37in long. This tube extends the distance from MiniRail muzzle to wall to 1.4 meters of travel. Long Nozzles were made to deliver plasma through narrow adapter flange plate.

Nikon open shutter photo of 1200 µg of argon through a straight quartz nozzle impinging onto pressure probe over 1 meter downstream. Plasma jet travels from left to right.

Photodiodes at 0.1 meter (red) and 1.0 meter (green) from minirail muzzle with 3.3cm dia. x 7.5cm Quartz nozzle. Photodiode half widths are 1.2 µs and 4.5 µs respectively. Average velocity over 1 meter = 36 km/s, corresponding to a 5cm long jet at 10cm and a 16cm long jet at 1 meter.

By mounting the 10 inch diameter 3 foot long acrylic vacuum chamber on the opposite port from the minirailgun on the octagon, we have managed to propagate a plasma jet a full 1.37 m (the same as needed in PLX). The photodiode signals show that the jet expands axially but maintains its compact structure during flight.
MiniRail gun performance at low currents is very encouraging. Next step is to jump to 600-700 kA range with 3cm bore and ET current sheet ignitor.

New performance records:
- 1200 µg at 42 k/s
- 4000 µg at 20 k/s

(at less than 200 kA)

See table below
Summary of gun performance at modest currents

11 bar plasma jet pressure (blue) at 23cm from muzzle, 10cm from nozzle. Pressure pulse timing and width correlates to photodiode pulse. Pressure pulse half width ~3us or a 13 cm plasma jet. Arrival times at various locations confirm 42 km/s velocity for about 1200 µg. (Red trace saturated the photodiode digitizer.)

Nikon open shutter photo of 1200 µg of argon through quartz nozzle impinging on pressure probe.

Brief summary of MiniRailgun performance data showing first observations of stagnation pressures nearing 150 bar from a single gun. Pressure probes are used to observe stagnation pressure.

<table>
<thead>
<tr>
<th>Minirail size</th>
<th>Peak Current (kA)</th>
<th>Pulse width (µs)</th>
<th>Bank Energy (kJ)</th>
<th>Capacitance Voltage (µF, kV)</th>
<th>Momentum (gm·m/s)</th>
<th>Pressure (17cm) bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1x1x15</td>
<td>140</td>
<td>6</td>
<td>7.4</td>
<td>12, 35</td>
<td>16-19</td>
<td>8</td>
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<tr>
<td>1x1x15</td>
<td>140</td>
<td>12</td>
<td>4</td>
<td>56, 12</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>1x1x15</td>
<td>160</td>
<td>20</td>
<td>6</td>
<td>84, 12</td>
<td>70</td>
<td>73</td>
</tr>
<tr>
<td>1x1x15</td>
<td>190</td>
<td>20</td>
<td>9.5</td>
<td>84, 15</td>
<td>80</td>
<td>105</td>
</tr>
<tr>
<td>1x1x15</td>
<td>210</td>
<td>23</td>
<td>12.6</td>
<td>112, 15</td>
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<td>145</td>
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<tr>
<td>1x1x15</td>
<td>80</td>
<td>23</td>
<td>12.6</td>
<td>112, 15</td>
<td>72</td>
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<td>1x1x30</td>
<td>140</td>
<td>12</td>
<td>4</td>
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<td>30</td>
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<tr>
<td>1x1x30</td>
<td>140</td>
<td>12</td>
<td>4</td>
<td>56, 12</td>
<td>52</td>
<td>11</td>
</tr>
<tr>
<td>2x2x15</td>
<td>170</td>
<td>6</td>
<td>4</td>
<td>18, 21</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td>2x2x15</td>
<td>330</td>
<td>9</td>
<td>14.7</td>
<td>24, 35</td>
<td>42</td>
<td>120</td>
</tr>
<tr>
<td>5x5x30</td>
<td>165</td>
<td>13</td>
<td>7.2</td>
<td>36, 20</td>
<td>54</td>
<td>1.5</td>
</tr>
<tr>
<td>5x5x30</td>
<td>165</td>
<td>13</td>
<td>7.2</td>
<td>36, 20</td>
<td>74</td>
<td>1.5</td>
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<tr>
<td>5x5x30</td>
<td>165</td>
<td>13</td>
<td>7.2</td>
<td>36, 20</td>
<td>80</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Momentum measured using a ballistic pendulum.
MACH2 simulations show MiniRailgun can reach desired performance using available capacitors. Lowering external inductance pays big dividends.

Adding augmentation would reduce the peak current by perhaps 30%, but would increase cost and complexity and may not be worth it or even needed.
MACH2 simulations are in rough agreement with railgun test at 1200 $\mu g$ at 42 k/s

See test shot marked in blue at left.
The full-scale coax gun can achieve the desired performance but is too big. Can a half-scale or a quarter-scale coax gun do the job? Yes, but it entails higher current and more complexity in an annular gas feed.

AFRL Mach2 Simulations Predict High Mass/Density Capability for Full-scale Gun
200-400 \( \mu g \) at 200 km/s for 800 kA
8000 \( \mu g \) at 50 km/s for 800 kA

The “wasp” shaped electrode profile helps prevent the occurrence of blowby instability as illustrated in the density contour plots above.
How do coaxial and minirailgun performance compare?

For constant acceleration $a$ and gun length $x$, velocity is given by

$$v^2 = 2ax$$  \hspace{1cm} (1)$$

Railgun acceleration $a$ is given by

$$ma = 1/2L'I^2,$$  \hspace{1cm} (2)$$

where $L'$ is the inductance gradient of the rails. For a straight coaxial gun

$$L' = 2 \cdot 10^{-7} \log \left( \frac{R_{out}}{R_{in}} \right).$$  \hspace{1cm} (3)$$

The current and acceleration time are then given by

$$I = \left( \frac{m}{L'x} \right)^{1/2} v$$  \hspace{1cm} (4)$$

$$t = \frac{4x}{L'I^2}$$  \hspace{1cm} (5)$$

<table>
<thead>
<tr>
<th>Representative Scaling for Constant Current Drive</th>
<th>Coax</th>
<th>Coax</th>
<th>Coax</th>
<th>Coax</th>
<th>Coax</th>
<th>Coax</th>
<th>MiniRail</th>
<th>Augmented</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{out}$</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
<td>3.0</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
<td>cm</td>
</tr>
<tr>
<td>$R_{in}$</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>cm</td>
</tr>
<tr>
<td>$R_{ratio}$</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
<td>1.5</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Bore</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>2.0</td>
<td>-</td>
<td>cm</td>
</tr>
<tr>
<td>$L'$</td>
<td>0.060</td>
<td>0.095</td>
<td>0.120</td>
<td>0.035</td>
<td>0.060</td>
<td>0.500</td>
<td>0.900</td>
<td>$\mu$H/m</td>
</tr>
<tr>
<td>Current (30cm)</td>
<td>1052</td>
<td>836</td>
<td>744</td>
<td>1376</td>
<td>1052</td>
<td>365</td>
<td>272</td>
<td>kA</td>
</tr>
<tr>
<td>Current (20cm)</td>
<td>1488</td>
<td>1182</td>
<td>1052</td>
<td>1946</td>
<td>1488</td>
<td>516</td>
<td>385</td>
<td>kA</td>
</tr>
</tbody>
</table>
A nozzle can help optimize jet shape and performance in a natural way for coax guns. This provides a better topology for the jet than MiniRail can achieve.
MACH2 simulations of the 1/2-scale coax gun show need for large currents.

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**Ar, 36 \( \mu F \), 60 kV, 50 nH, 1/2 scale**

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**Ar, 48 \( \mu F \), 60 kV, 50 nH, 1/2 scale**

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**Ar, 60 \( \mu F \), 60 kV, 50 nH, 1/2 scale**
Of more interest are 1/4 scale coax guns which are less expensive to fabricate. MACH2 simulations still show they can reach the performance, but need more capacitance or less inductance, and large currents.

We are still exploring parameter space for the 1/4 scale guns in an attempt to find geometries that significantly reduce the current. It may be possible to stretch out the pulse over longer time to reduce the peak current, and also to make some improvement in the $L'$ by going to larger radius ratios, but these changes must be consistent with avoiding plasma blowby, which the tailored electrode profile tries to avoid.
A number of major tasks still need to be accomplished for either gun to achieve the desired performance.

**MiniRail Gun**

- build 3 cm square bore gun to handle full mass (8000\(\mu g\)) and current (600-700kA) - 1st prototype of PLX gun. Low inductance and stronger current leads.
- implement ET current sheet preionizer at breech
- redesign for good vacuum compatibility (i.e. replace plastics with ceramics)
- examine jet leading edge for canting, if any
- longer life gas valve

**MiniCoax Gun**

- develop and test annular gas valve
- implement annular current sheet preionizer at breech
- identify the electrode profile(s) that leads to lowest possible current
- develop even higher current switches - probably >1.5 MA
- demonstrate high mass operation
Summary

- Gun performance has improved dramatically in the past year. Now routinely accelerating 1000’s µg of Argon plasma to 10’s km/s.

- Ready to build 1st prototype PLX gun for testing (before end of December) which should get 8000µg to 50 km/s

- Gained extensive operational experience with fast gas valve fed MiniRail (but needs longer life components)

- Moving to good vacuum compatibility materials - i.e. ceramics

- Evaluation of MiniRail vs MiniCoax underway

- Mach2 modeling shows both MiniRail and MiniCoax can achieve desired performance. MiniCoax has edge for long term performance and jet structure, but MiniRail has edge for near term performance and cost. Final choice may be strongly affected by affordability. Plan to make a decision within next 2 months.

- Full-scale coax gun now under testing at >700 kA with extensive diagnostic suite. Will be used to help benchmark Mach2 code for coax geometry.

- Upgraded pulsed power capability
  - Demonstrated 1 MA level switches
  - Transmission lines
  - HyperV recently acquired 97 17µF, 45kV caps courtesy of MIT
  - HyperV will soon acquire 200 more from Utron, Inc. with mix of 10, 20, and 30 kV