Plasma Jet Drivers for Magneto-Inertial Fusion (PJMIF)

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Talk focuses on recent technical achievements that establish the foundation for a reactor-grade plasma gun driver.

**Talk Outline**

- Background/History
- Contoured gap coax guns (*A new approach*)
- Minirailgun injectors
- Minirailgun plasma guns
- Multi-jet technology demonstrations (*argon*)
- Mark2 Minirailgun performance achievement
- A reactor-grade coax gun system

Baseline use of plasma gun array.

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Pulsed plasma accelerator history

- Production of high velocity plasma jets motivated extensive research in pulsed coaxial plasma accelerators
- Bulk of research conducted in 1960’s
- Early emphasis on understanding acceleration mechanisms, particle velocity distribution, neutron production, and instabilities
- Applications in 1970’s-present
  - Fueling of magnetically confined plasmas
  - Propulsion
  - Dense plasma focus
  - Lethal intercept of missiles
- Various modes of operation identified and sensitive to initial conditions
  - Mass loading (gas puff, static prefill, preionization)
  - Charging voltage, current, capacitance
  - Electrode geometry (radius ratio, tapering, inner/outer electrode lengths)
Milestones Reached in Coaxial Gun Experiments

- Propulsion community placed emphasis on efficiency
  - >50% efficiency possible with carefully matched electrode geometry, propellant loading, and low inductance driver circuit (Gloresen et al 1966)
  - Mass per pulse $\sim 10 \mu g$ at 10 km/s
- Fusion and weapons communities focused on high velocities and particle densities
  - >200 km/s achievable with high currents (>100 kA)
  - Many experiments pursuing high density jets found tapered geometries desirable (Turchi 1988, Cheng 1971, Komel’kov 1977)
  - Mass up to 200 $\mu g$
  - Collimated jets possible with electrode tapering
- Tokamak fueling focuses on high dynamic pressure ($\rho v^2 \sim 100$ bar) and high velocities
  - >500 km/s velocities
  - Penetration of 5 T toroidal magnetic fields
HyperV Guns leverage 5 decades of research

- Total particle density and mass $\sim$ an order of magnitude above previous experiments in new collision dominated regime (Thio et al 2002)
  - Earlier research at lower densities shows higher prefill pressures lead to impermeable current sheet (Komel’kov et al 1977)
- Required velocity well within demonstrated capabilities (numerous sources)
- $>50\%$ efficiencies within reach with impedance matched electrodes and high utilization efficiency, and thruster staging or preionization (Gloresen et al 1966)
- Collimated, focused plasma jets produced with electrode taper (Turchi 1988, Chen 1971, Komel’kov et al 1977)
- Cassibry and Thio looked at ways to suppress the blowby instability using a contoured gap (Cassibry 2006)
A 2002 paper\cite{thio2002} by Thio proposed a new physics approach to overcome decades of stagnant progress in classical straight coax guns – thus providing the key to extremely high performance guns.

Core concepts of the new microphysics

- No prefill gas
- Inject high velocity dense plasma
- High density $\Rightarrow$ highly collisional
- Taper electrodes to improve flow control

\cite{thio2002}

The Blowby Instability limits performance of a classical straight coaxial accelerator

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

Mach2 mass density contour plots illustrate the blow-by instability in a straight coaxial accelerator.*
Electrode profile tailoring suppresses blow-by instability by matching local density with local JxB. Curvature forces density peaking along inner wall.

The forward tilting of the plasma increases in this region, further compressing the plasma towards the axis. The conical z-pincher 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 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.

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.

Injected plasma forms a fat z-pincher 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.

Angled injection works nicely.
Right angle turn is too sharp!
Combining Thio’s new physics approach with contoured gap electrodes allowed us to produce a small plasma gun that accelerates 1-2 orders of magnitude more mass to high velocity than straight classical coax guns of similar size.

Breakthrough performance achieved

- 90-100 km/s
- 100-350 µg
- $10^{15}$ cm$^{-3}$
- modest current (< 300 kA)
- 32 ablative capillaries (CH$_2$)

Low jitter


The TwoPi test fixtures taught us how to drive and trigger 64 capillaries with low jitter, in addition to early demonstrations of 2D imploding plasma liners.

- Highly symmetric implosion at 80 km/s
- Small well defined central ‘sphere’ of high density plasma
- Slower more massive shell follows later
- Finally collapses/implodes
- Images contrast enhanced to show detail

<table>
<thead>
<tr>
<th>Position</th>
<th>$n_e \ (cm^{-3})$</th>
<th>$T_e \ (eV)$</th>
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<tr>
<td>periphery</td>
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<td>2.4</td>
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<tr>
<td>center</td>
<td>$2.5 \times 10^{15}$</td>
<td>4.0</td>
</tr>
<tr>
<td>center*</td>
<td>$1.1 \times 10^{17}$</td>
<td>n/a</td>
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*vertically confined
Modeling for the PLX project, and PJMIF in general, showed it was more effective to use much larger masses but at only about $\sim 50-60$ km/s to form the converging plasma liner.

- Want high-Z gases $\Rightarrow$ high Mach numbers
- Need high density injection
- Want independent control of mass, velocity, temperature, size
- Need high total mass
- Need straightforward repetitive operation
- Need compact armature injection into coax gun breech
- Small parallel-plate railguns (Minirailguns) can provide the needed injector functionality.

Modeling by UAH and LANL indicated we needed the following to achieve the 0.1Mbar PLX goal:

- 30 plasma guns
- 8000 $\mu$g
- 50 km/s
- $10^{16}$ cm$^{-3}$
- preferably short compact plasma blobs with fast rising density front
A small parallel-plate “MiniRailgun” makes a good high-Z, high density plasma injector. Configurations include ablative and high density gas-fed.

Heuristic model

Pulse Heat Gas Stored in Plenum

Restraining Diaphragm Bursts

Initiate Arc after Short Delay

Armature Snowplows and Compresses

Two configurations:
Ablative and Gas-Fed
The initial Minirailgun injector concept evolved into a full-fledged high performance plasma gun only 30 cm long chosen for the PLX experiment.

- Initial few mm bore size
- 1 cm bore size with ablative capillary injector

Fast gas valve development

- Mark 1
- Mark 2

- upgraded valve - more robust
- double coil
- lightweight Al flyer plate
- 60 psi
- > 10 mg Ar
QuadJet experiment first demonstrated higher energy merging of 4 MiniRail-guns with low jitter. Densities 10-100 times higher than previous TwoPi.

Ablative capillary injection into 1cm Minirailguns

<table>
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<tr>
<th>Single MiniRail</th>
<th>Stark Density</th>
<th>$T_e$</th>
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<tr>
<td>in bore</td>
<td>$8 \cdot 10^{18} - 2 \cdot 10^{19}$</td>
<td>6eV</td>
</tr>
<tr>
<td>at muzzle exit</td>
<td>$1 \cdot 10^{17}$</td>
<td>4eV</td>
</tr>
<tr>
<td>at nozzle exit</td>
<td>$2 \cdot 10^{16}$</td>
<td>–</td>
</tr>
<tr>
<td>at center</td>
<td>$5 \cdot 10^{15}$</td>
<td>3eV</td>
</tr>
</tbody>
</table>

4 MiniRails
Converged
at center
$1 \cdot 10^{17}$ 5eV

Nikon D70s open shutter photos (f/29)

With 0.9 Neutral Density Filter
Top and side views reveal “spherical” structure despite only 4 jets

- Top view
- Side view

6 $\mu$s after rail trig
85 km/s

10 $\mu$s after rail trig
85 km/s

All PImax photos, 25 ns gate (f/16)

Vertical “polar” jets
(Nikon open shutter)

Just before initial collision
The three jet and six jet merge testing at HyperV using argon injected 1 cm guns provided a testbed for demonstrating all required functionality for a 6-gun grouping for PLX.
Fast and open shutter imaging of three and six jets merging shows the symmetry of convergence and a much denser combined jet.

PI-Max image (5 ns gate) of three merging jets, showing formation of a secondary jet as the plasma flows past the point of convergence, where it impinges on the pressure probe array. [Case 2013]

Six jets merging three from each end.
Mark1 guns increased energy and mass over the 1cm. Two Mark1’s were installed on PLX while a higher performing Mark2 version was being developed at HyperV.
The Mark2 substantially exceeded the PLX plasma gun performance goal of 8000 $\mu$g at 50 km/s (achieved with $\sim$500 kA).

Although this performance is already in the ballpark for that needed for a reactor-grade plasma gun driver, i.e. 10-20 mg at 50-70 km/s, we want more than just mass and velocity!
We also need plasma jet shape control for a reactor driver

- The coax geometry along with nozzles gives better control of jet topology
- Want a jet structure more like a pancake/hockey puck instead of a fat cigar
- Lower current density of coax gun reduces electrode erosion and impurities
Simulations show that contoured-gap coaxial plasma guns can indeed accelerate the required masses to the required velocities. The task is to minimize their size and cost and increase efficiency.

Mach2 Simulations Predict High Mass/Density Capability

- 200-400 $\mu$g at 200 km/s for 800 kA
- 8000 $\mu$g at 50 km/s for 800 kA
Contoured gap coax + Minirailgun injectors $\Rightarrow$ Reactor-grade driver

- Eliminates linear insulator - reduces high velocity plasma/wall interactions
- Lower current density reduces impurities and electrode erosion
- Better shaping of plasma jet/blob - better symmetry, superior jet topology (and easier to control)
- Easier to implement a structured armature
- Lower lead inductance (matched pfn $\Rightarrow$ high efficiency, no ringing)
- Electrodes act as own vacuum containment – much simpler vacuum and mounting design
A reactor-grade plasma gun uses an array of small gas-fed Minirailgun injectors and an integrated well-matched pulse forming network.

- 50 kJ per gun
- 0.5m length
- 5-7 cm jet radius
- 10-20 mg at 50-60 km/s
- 1 Hz repeate

Minirailgun Injector Array

- Refractory materials
- Switchless - if possible
- 50-80% efficiency
- $10-20K per gun module in production quantities
- 30M shot lifetime
- $0.02/MJ over lifetime

Symmetrical low inductance current feeds

Integrated Pulse Forming Network

Early example of an integrated gun/RLC package.

Injectors not to scale!

qty \sim 24
A Pulse Forming Network can be matched to a low impedance coax gun by arranging the pfn wave speed to match the armature velocity profile.

Assume constant acceleration

$$a = \frac{v^2}{2x} = \frac{(60 \text{ k}/\text{s})^2}{2(0.5 \text{ m})} = 3.6 \cdot 10^9 \text{m/s}^2$$  \hspace{1cm} (1)

For a railgun,

$$F = ma = \frac{1}{2} L'_g I^2$$  \hspace{1cm} (2)

so that for $m= 10 \text{ mg}$ and $L'_g = 0.138 \text{ } \mu\text{H/m}$

$$I = \left(\frac{2ma}{L'_g}\right)^{1/2} = 722 \text{ kA}$$  \hspace{1cm} (3)

and the acceleration time is

$$t_{\text{accel}} = \left(\frac{2x}{a}\right)^{1/2} = 16.7 \mu\text{s.}$$  \hspace{1cm} (4)

The pulse width of a pfn is given by

$$\tau = 2CZ \simeq 2CL'_g \langle v \rangle$$  \hspace{1cm} (5)

where we have matched the impedance of the pfn to that of the gun.

$$Z \simeq L'_g \langle v \rangle \simeq 0.004$$  \hspace{1cm} (6)

Thus,

$$C = \frac{\tau}{2L'_g \langle v \rangle} = 0.002 \text{ F}$$  \hspace{1cm} (7)

$$Z = \sqrt{\frac{L'}{C'}} = \sqrt{\frac{L}{C}}$$  \hspace{1cm} (8)

$$L = CZ^2 = 32 \text{nH}$$  \hspace{1cm} (9)

A quick circuit simulation of only a four section pfn with each $C=500 \text{ } \mu\text{F}$ and each $L = 8 \text{ nH}$. Charge voltage is 5 kV. This pfn needs tweaking but shows a fairly well matched pfn to the load. A real system might have 9 or more sections.

A matched gun and pfn should allow electrical efficiencies of 50-80%.
Issues and Challenges

- Determining proper electrode contour gap. Parameter space is very large. We need to characterize parameter space and identify those regions best suited for the required performance.
- Developing robust injector system – fast gas valves with long life
- Demonstrating high efficiency, >50%
- Repetitive pulsed power systems
- Demonstrating compact structured jets with proper topology
- Integrated PFN-plasma gun driver
- Switchless operation (fallback is solid-state)
- Maintaining low jitter over hundreds of guns
- Achieving projected costs
- Low cost manufacturing guns in mass produced quantities
- Robust - must survive fusion blast


