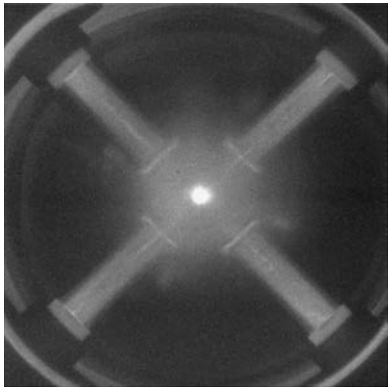
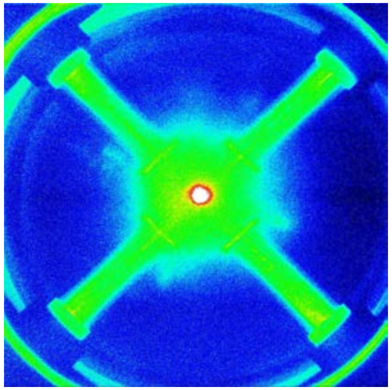




Plasma Jet Drivers for Magneto-Inertial Fusion (PJMIF)

F. Douglas Witherspoon
HyperV Technologies Corp., Chantilly, VA

with input from Jason Cassibry (*UAHuntsville*), Scott Hsu (*LANL*), Francis Thio (*DOE*)

ARPA-E Workshop
"Drivers For Low-Cost Development Towards Economical Fusion Power"
Berkeley, CA, October 29-30, 2013

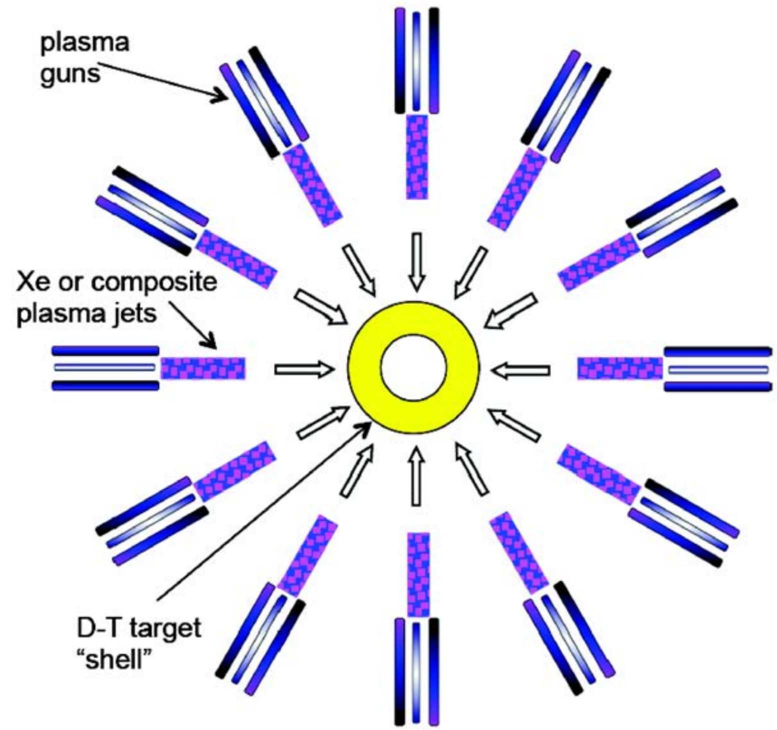
HYPERV TECHNOLOGIES CORP

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.



Thio, Y. C. F., C. E. Knapp, R. C. Kirkpatrick, R. E. Siemon, and P. J. Turchi, *"A physics exploratory experiment on plasma liner formation,"* Journal Fusion Energy, 20(1/2):111 (2001).

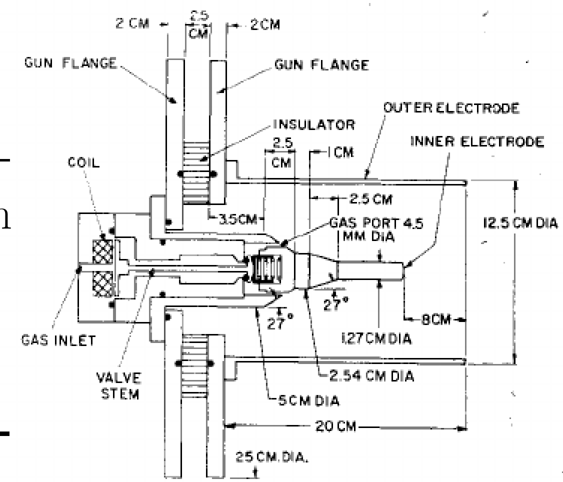
S. C. Hsu, T. J. Awe, S. Brockington, A. Case, J. T. Cassibry, G. Kagan, S. J. Messer, M. Stanic, X. Tang, D. R. Welch, and F. D. Witherspoon, *"Spherically Imploding Plasma Liners as a Standoff Driver for Magnetoinertial Fusion,"* IEEE Transactions On Plasma Science, Vol. 40, No. 5, May (2012).

HYPERV TECHNOLOGIES CORP

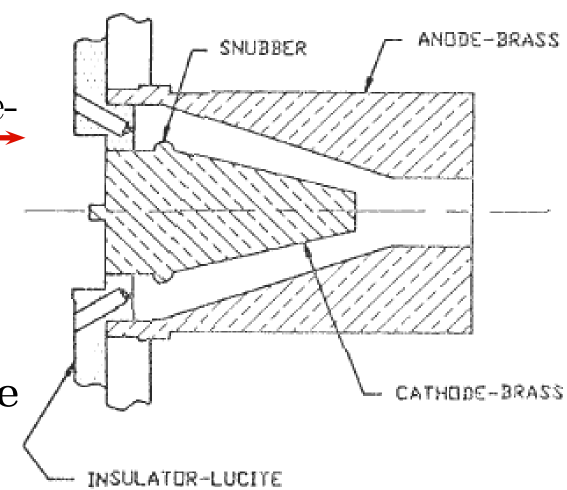
Pulsed plasma accelerator history

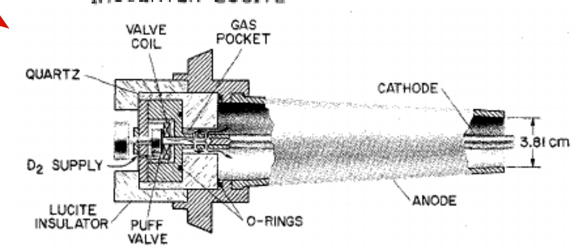
- **Production of high velocity plasma jets motivated extensive research in pulsed coaxial plasma accelerators**
- **Bulk of research conducted in 1960's**
- **Early emphasis on understanding acceleration mechanisms, particle velocity distribution, neutron production, and instabilities**
- **Applications 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 ∼10 μg 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 μg
  - Collimated jets possible with electrode tapering
- **Tokamak fueling focuses on high dynamic pressure (ρv^2 ∼100 bar) and high velocities**
  - >500 km/s velocities
  - Penetration of 5 T toroidal magnetic fields

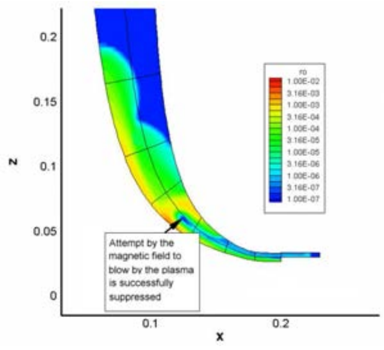




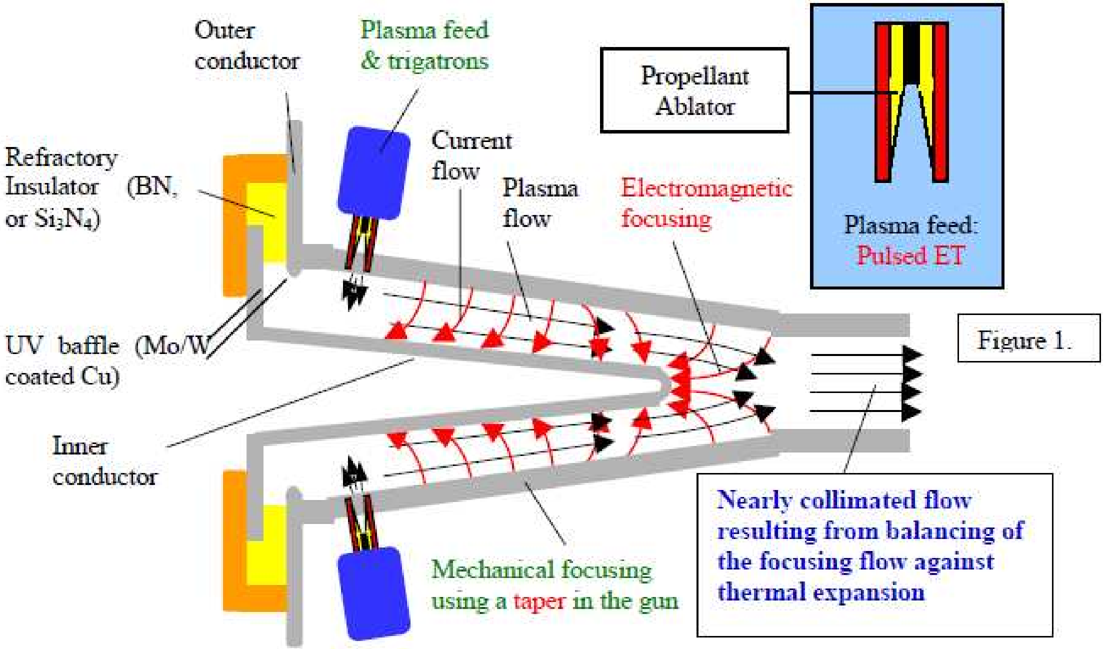
HYPERV TECHNOLOGIES CORP

HyperV Guns leverage 5 decades of research

- **Total particle density and mass ~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)**

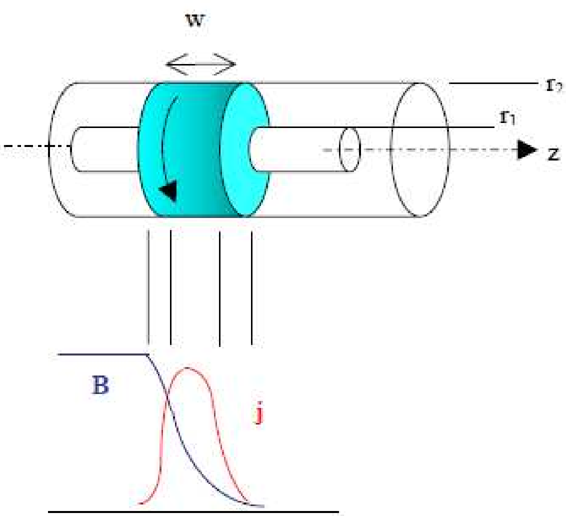


A 2002 paper* by Thio proposed a new physics approach to overcome decades of stagnant progress in classical straight coax guns – thus providing the key to extremely high performance guns.



Core concepts of the new microphysics

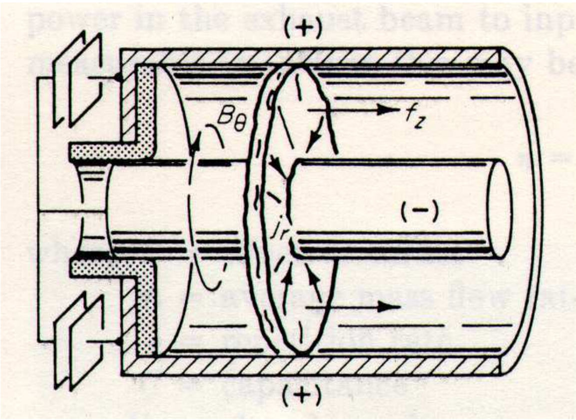
- No prefill gas
- Inject high velocity dense plasma
- High density $\Longrightarrow$ highly collisional
- Taper electrodes to improve flow control



*Y.C.F. Thio, J.T. Cassibry, and T.E. Markusic, "Pulsed Electromagnetic Acceleration of Plasmas," AIAA Joint Prop. Conf., Indianapolis, IN, Paper AIAA-2002-3803, July (2002).

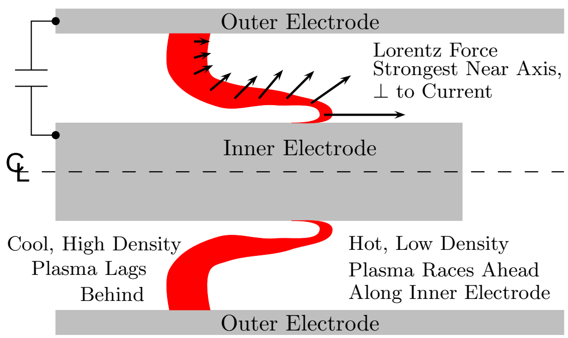
HYPERV TECHNOLOGIES CORP

The Blowby Instability limits performance of a classical straight coaxial accelerator

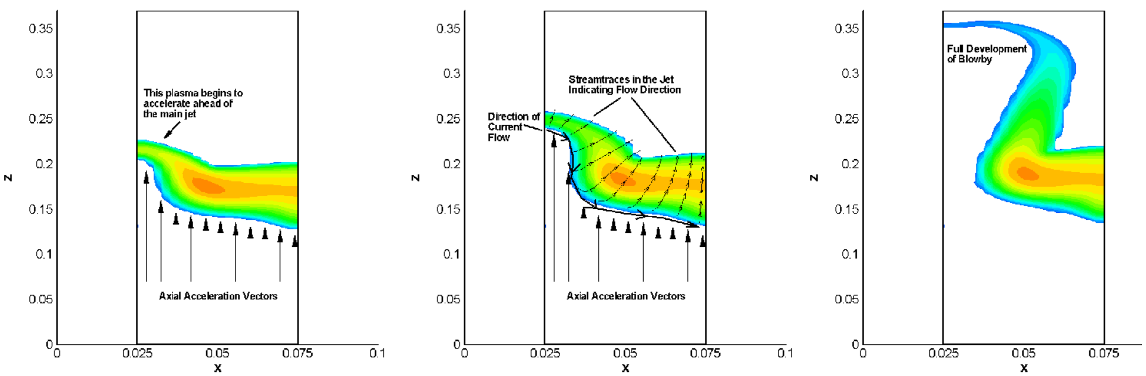


*From R.G. Jahn, *"Physics of Electric Propulsion,"* 1st ed., New York, McGraw-Hill, 1968.

- 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

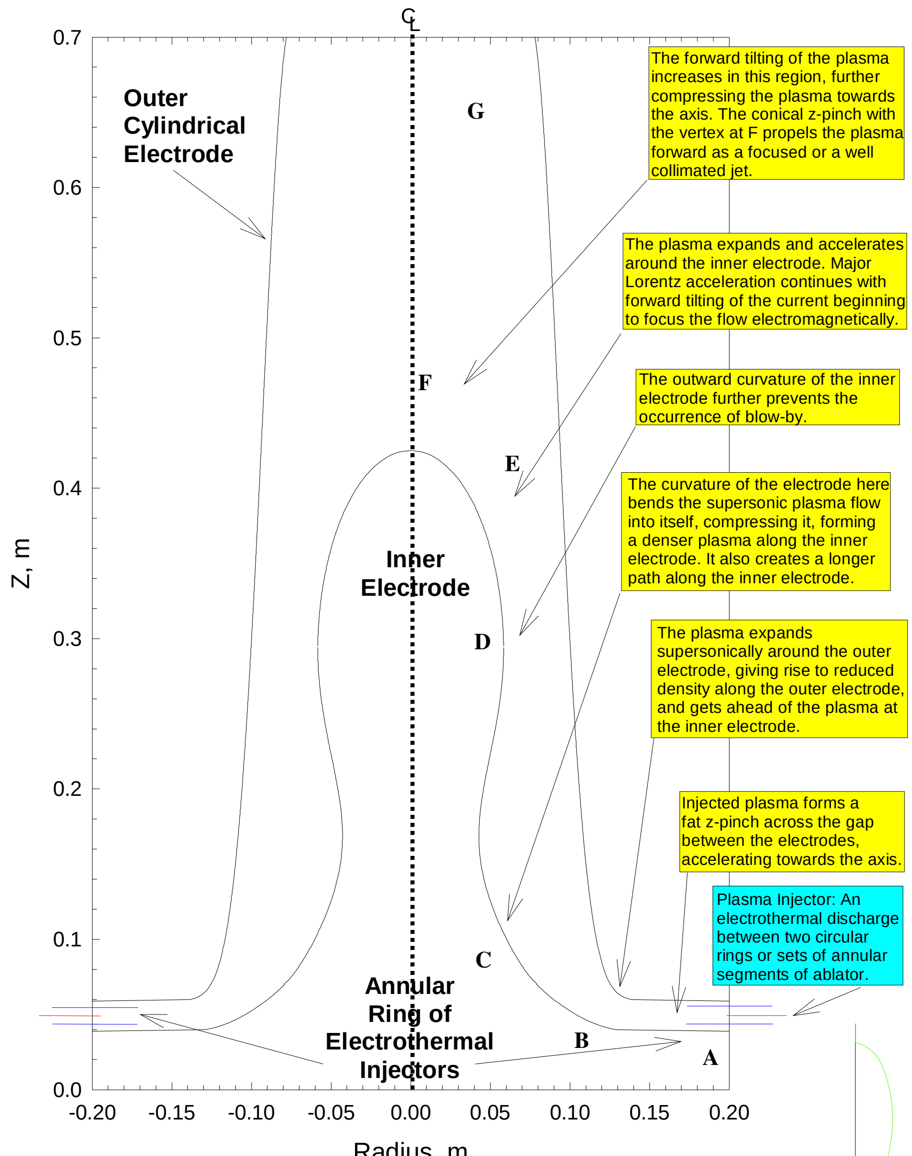


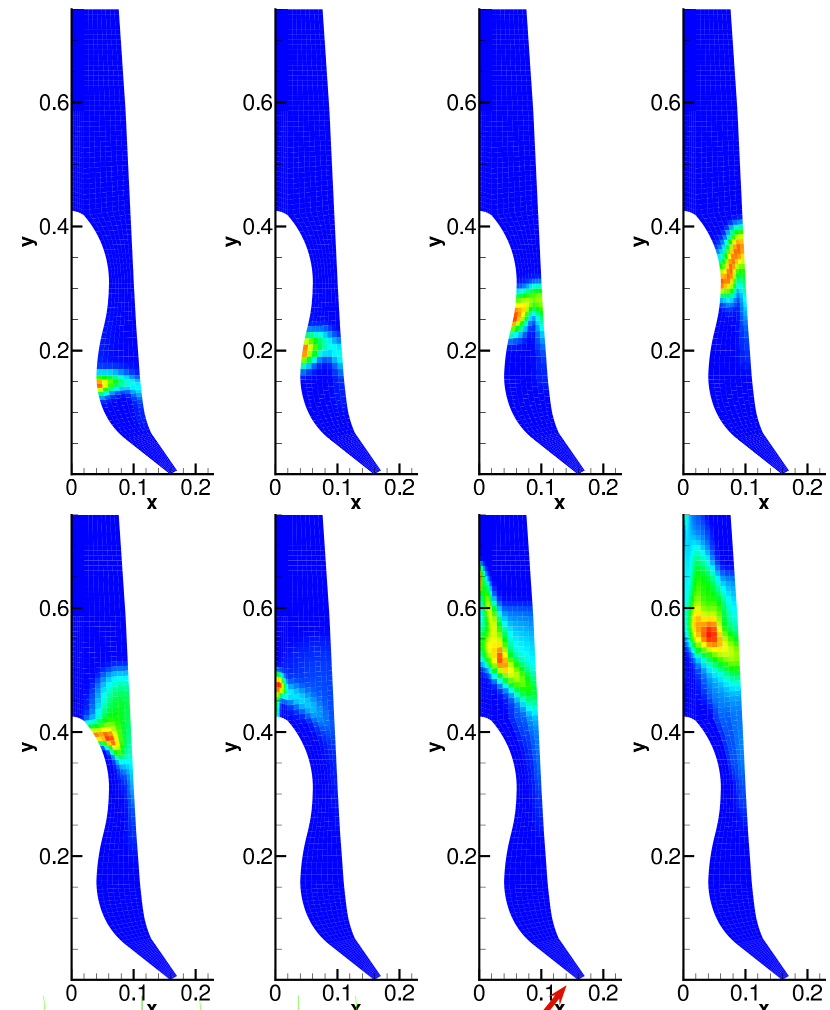
Mach2 mass density contour plots illustrate the blow-by instability in a straight coaxial accelerator.*

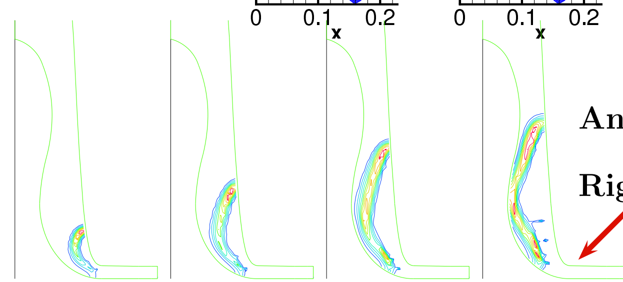


*Cassibry 2006

Electrode profile tailoring suppresses blow-by instability by matching local density with local JxB. Curvature forces density peaking along inner wall.



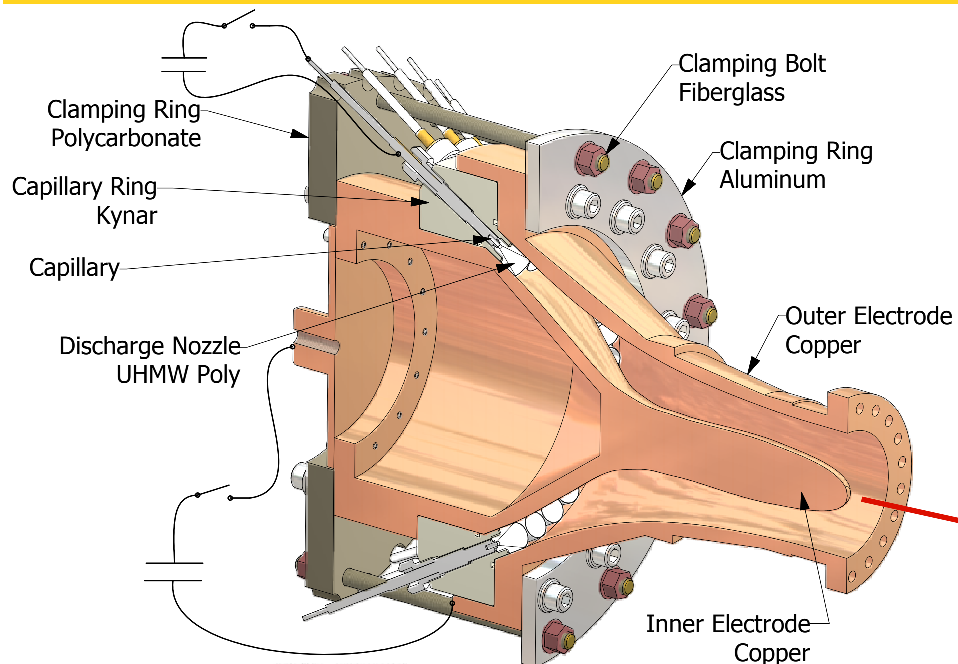




Angled injection works nicely.

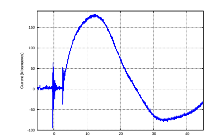
Right angle turn is too sharp!

Combining Thio's new physics approach with contoured gap elecrodes 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.



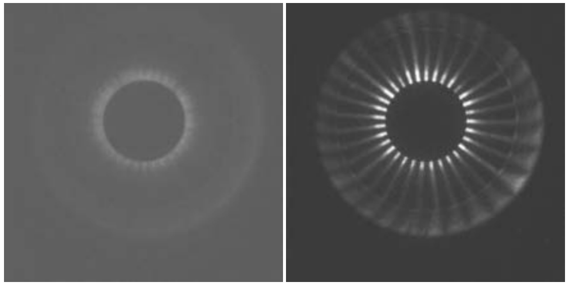
Breakthrough performance achieved

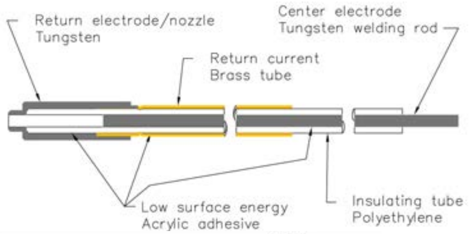
- 90-100 km/s
- 100-350 μg
- 10^{15} cm^{-3}
- modest current ($<$ 300 kA)
- 32 ablative capillaries (CH_2)

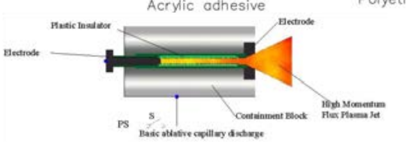


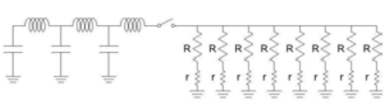
Low jitter

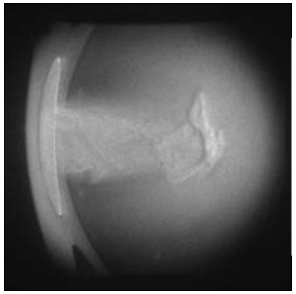
25 ns gate 1 μs gate

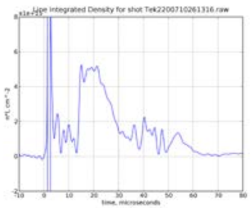


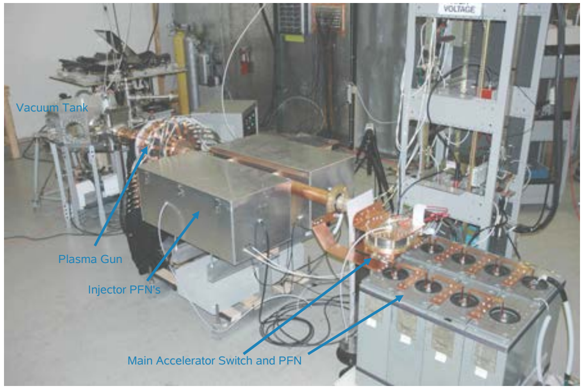












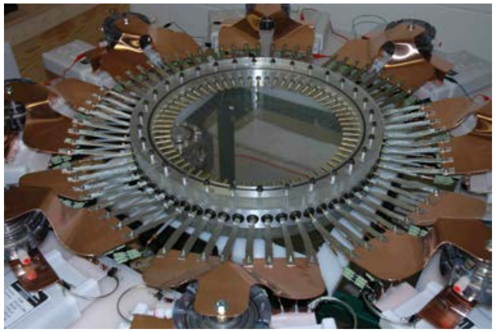
F.D. Witherspoon, A. Case, S. J. Messer, R. Bomgardner III, M. W. Phillips, S. Brockington, and R. Elton, *"A Contoured Gap Coaxial Plasma Gun with Injected Plasma Armature,"* *Rev. Sci. Inst.* 80, 083506 (2009).

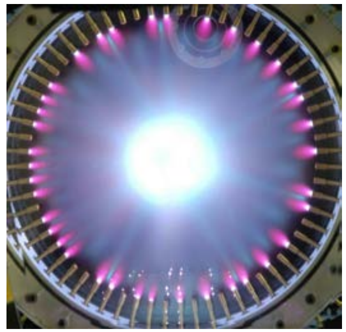
A. Case, S. Messer, R. Bomgardner, and F. D. Witherspoon, *"Interferometer density measurements of a high-velocity plasmoid,"* Physics of Plasmas 17, 053503 (2010).

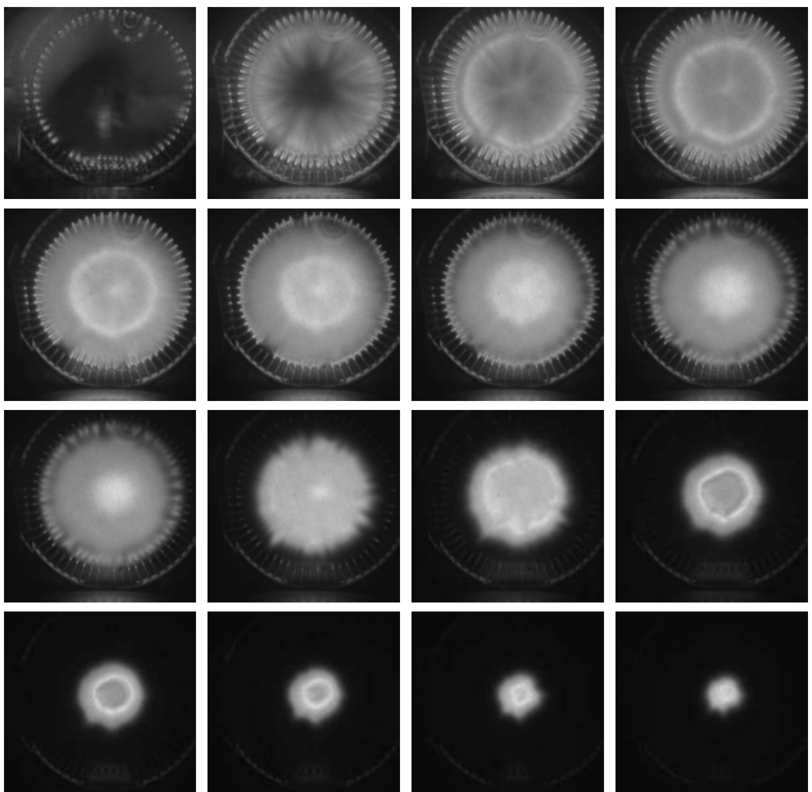
HYPERV TECHNOLOGIES CORP

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.

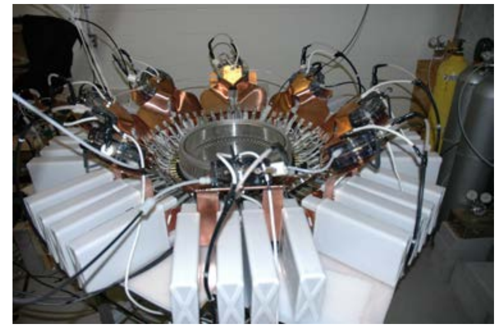
Original TwoPi

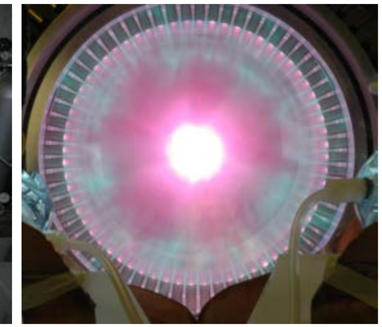


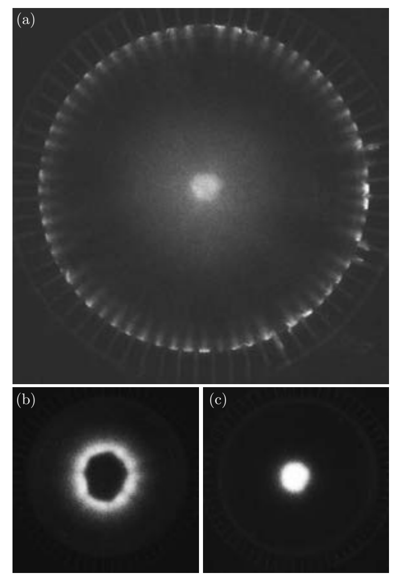




Upgraded TwoPi







- 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

Position	n_e (cm^{-3})	T_e (eV)
periphery	2.4×10^{14}	**2.4**
center	2.5×10^{15}	**4.0**
center*	1.1×10^{17}	**n/a**

$*$**vertically confined**

HYPERV TECHNOLOGIES CORP

Modeling for the PLX project, and PJMIF in general, showed it was more effective to use much larger masses but at only about ∼50-60 km/s to form the converging plasma liner.

- Want high-Z gases $\Longrightarrow$ 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.

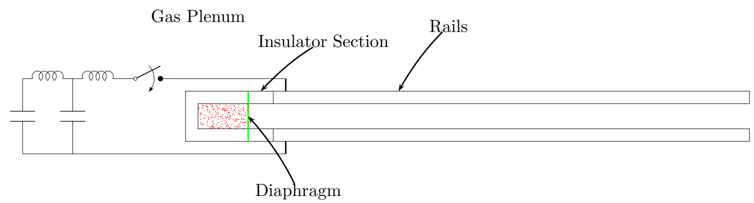
Modeling by UAH and LANL indicated we needed the following to achieve the 0.1Mbar PLX goal:

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

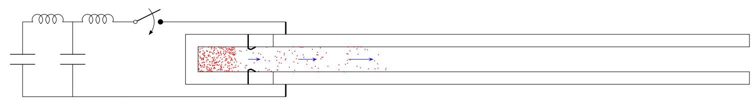
HYPERV TECHNOLOGIES CORP

A small parallel-plate "MiniRailgun" makes a good high-Z, high density plasma injector. Configurations include ablative and high density gas-fed.

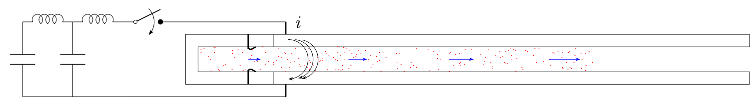
Heuristic model



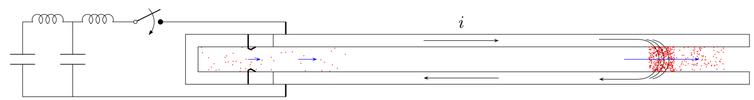
Pulse Heat Gas Stored in Plenum



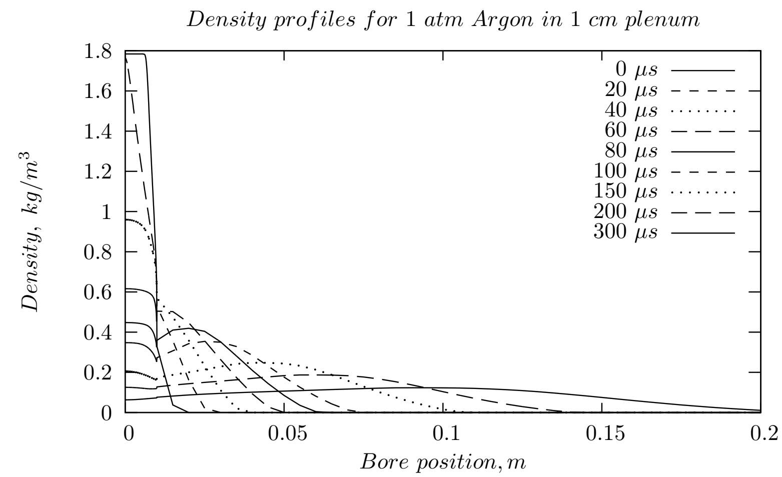
Restraining Diaphragm Bursts



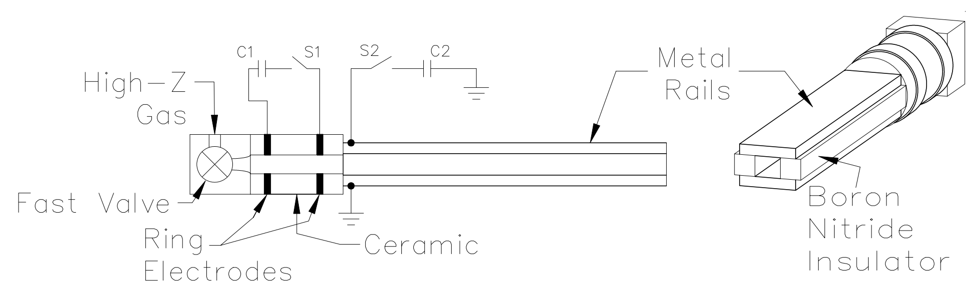
Initiate Arc after Short Delay

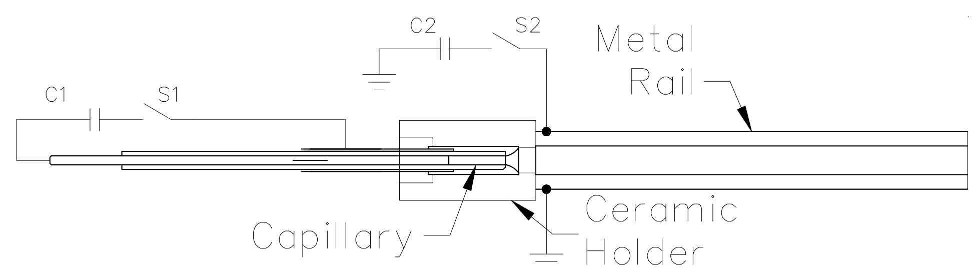


Armature Snowplows and Compresses



Two configurations:
Ablative and Gas-Fed

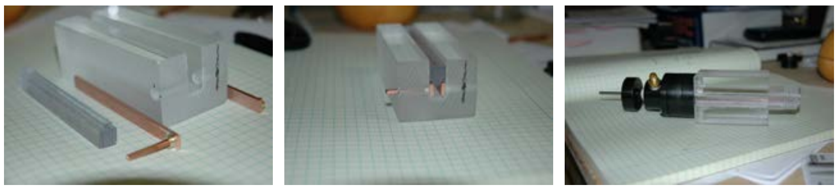




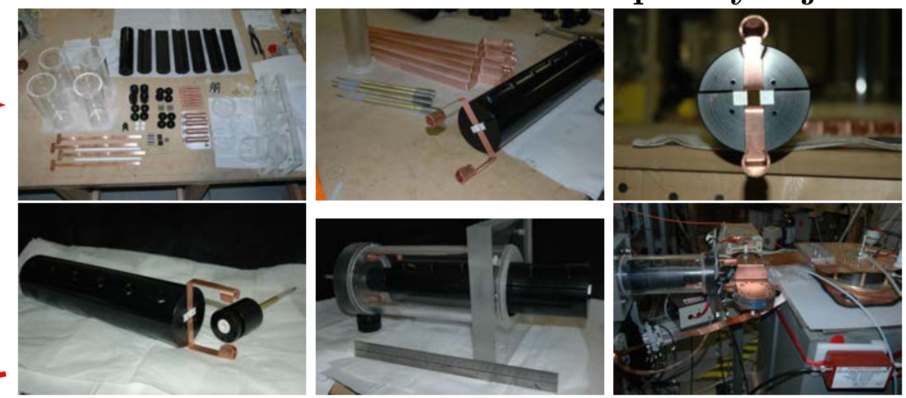
HYPERV TECHNOLOGIES CORP

The initial Minirailgun injector concept evolved into a full-fledged high performance plasma gun only 30 cm long chosen for the PLX experiment.

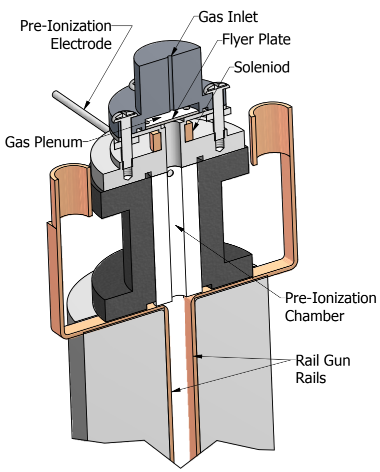
Initial few mm bore size

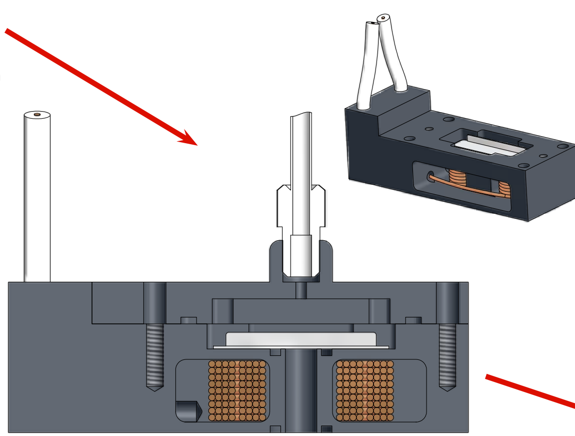


1cm bore size with ablative capillary injector



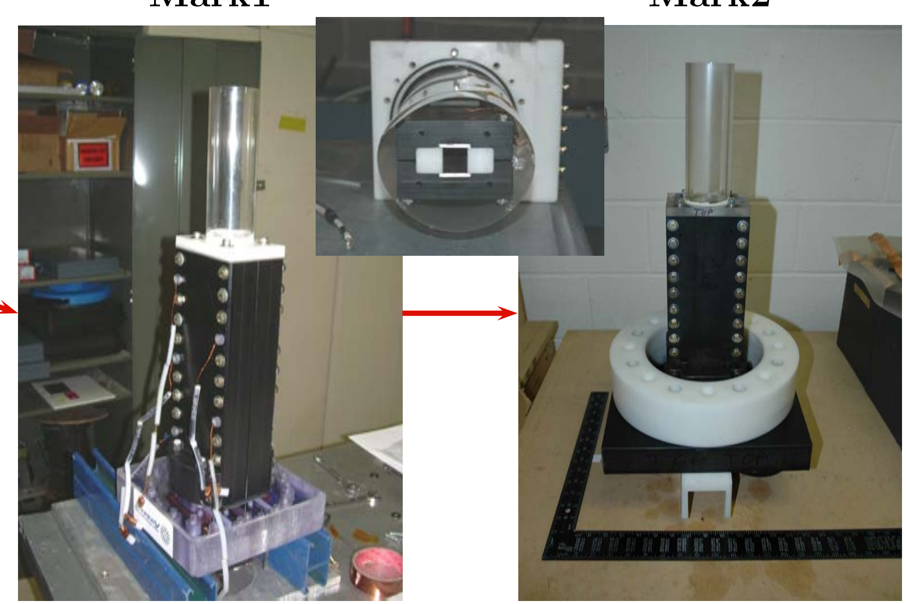
Fast gas valve development





- upgraded valve - more robust
- double coil
- lightweight Al flyer plate
- 60 psi
- $>$ 10 mg Ar

Mark1 Mark2

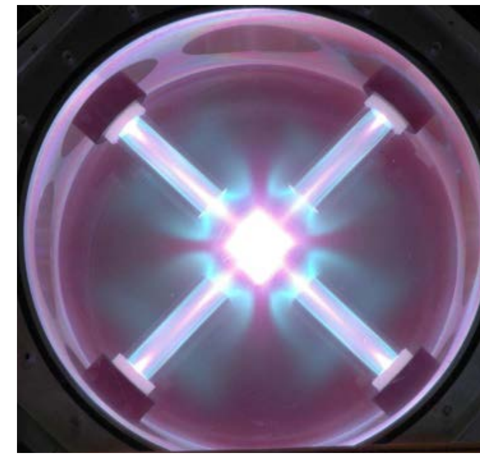


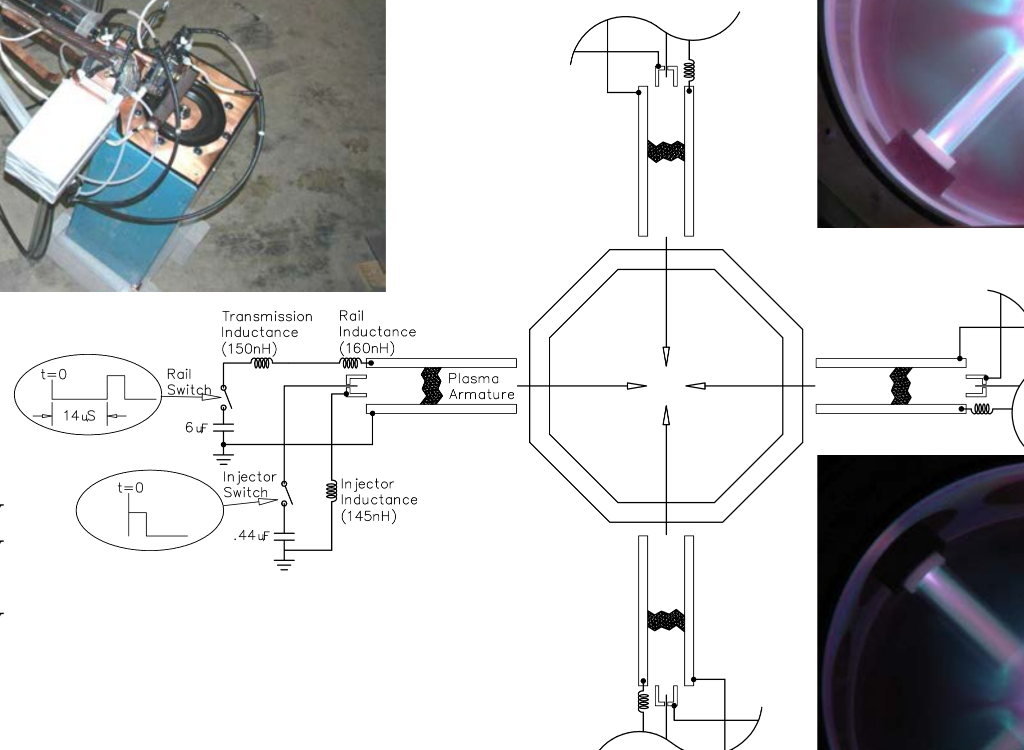
HYPERV TECHNOLOGIES CORP

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

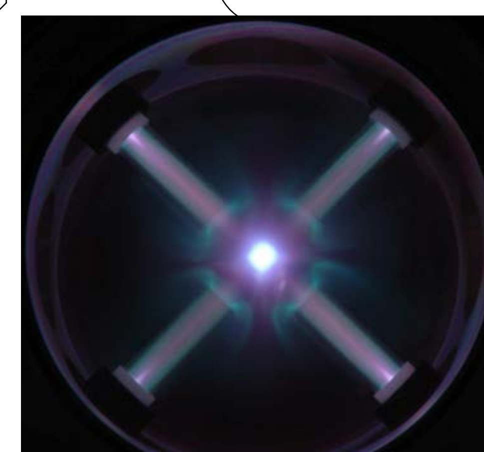
Nikon D70s open shutter photos (f/29)





Single MiniRail	Stark Density	T_e
in bore	$8\cdot10^{18}$-$2\cdot10^{19}$	6eV
at muzzle exit	$1\cdot10^{17}$	4eV
at nozzle exit	$2\cdot10^{16}$	–
at center	$5\cdot10^{15}$	3eV
4 MiniRails		
Converged		
at center	$1\cdot10^{17}$	5eV

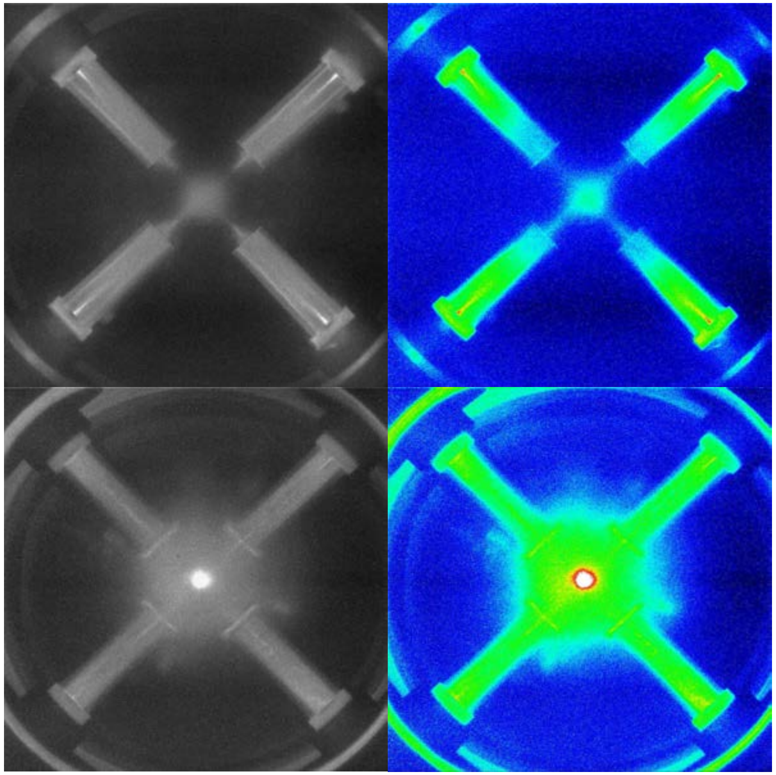
With 0.9 Neutral Density Filter



HYPERV TECHNOLOGIES CORP

Top and side views reveal “spherical” structure despite only 4 jets

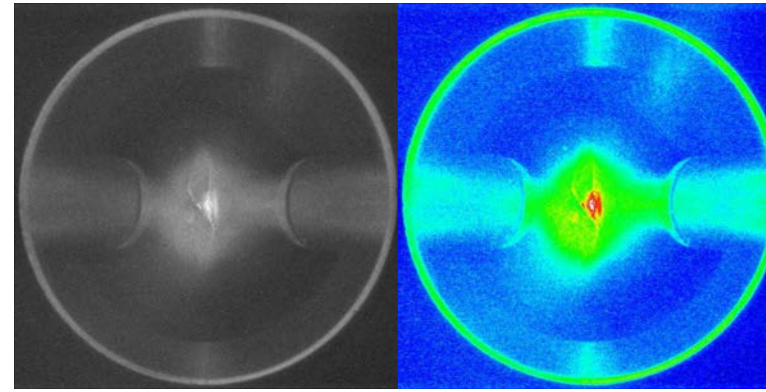
Top view



6 μs after rail trig
85 km/s

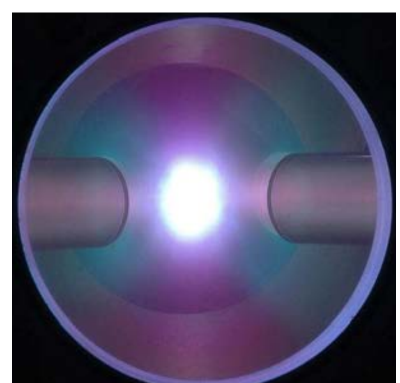
10 μs after rail trig
85 km/s

Side view

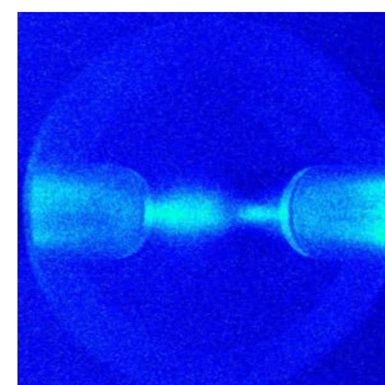


All PImax photos, 25 ns gate (f/16)

Vertical “polar” jets
(Nikon open shutter)

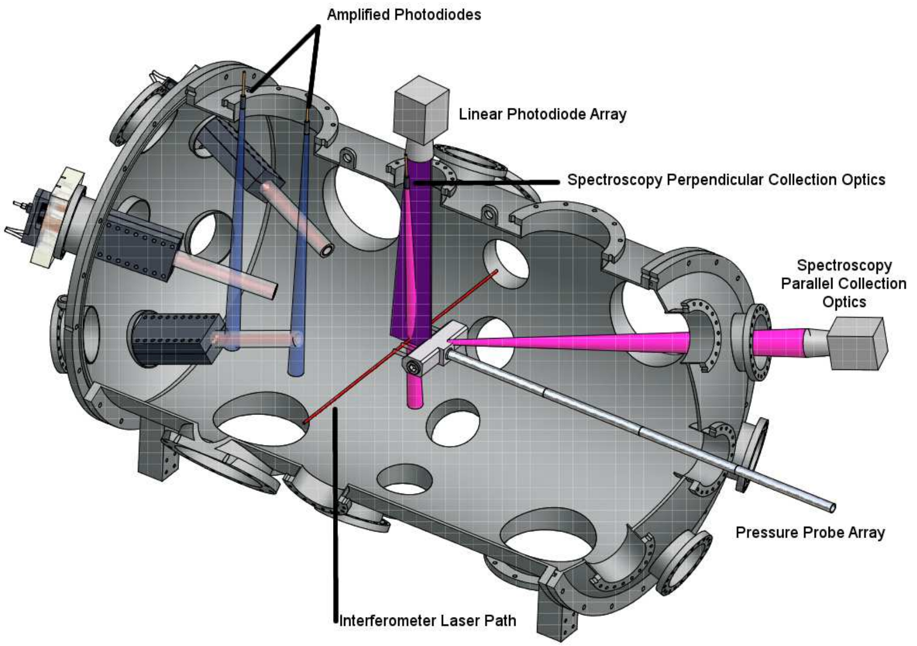


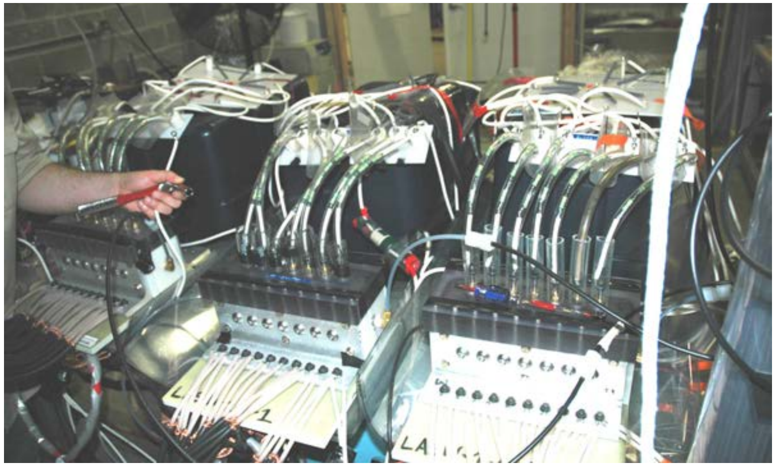
Just before
initial collision



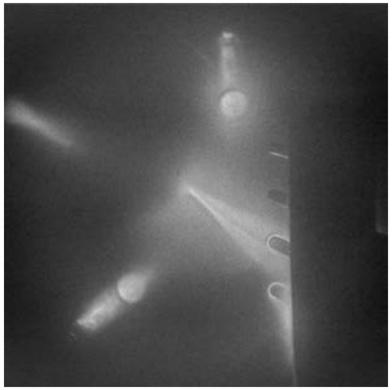
HYPERV TECHNOLOGIES CORP

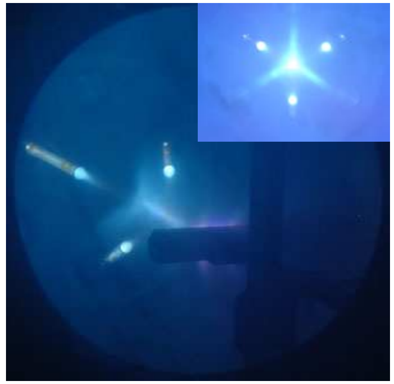
The three jet and six jet merge testing at HyperV using argon injected 1 cm guns provided a testbed for demonstrating all required functionality for a 6-gun grouping for PLX.

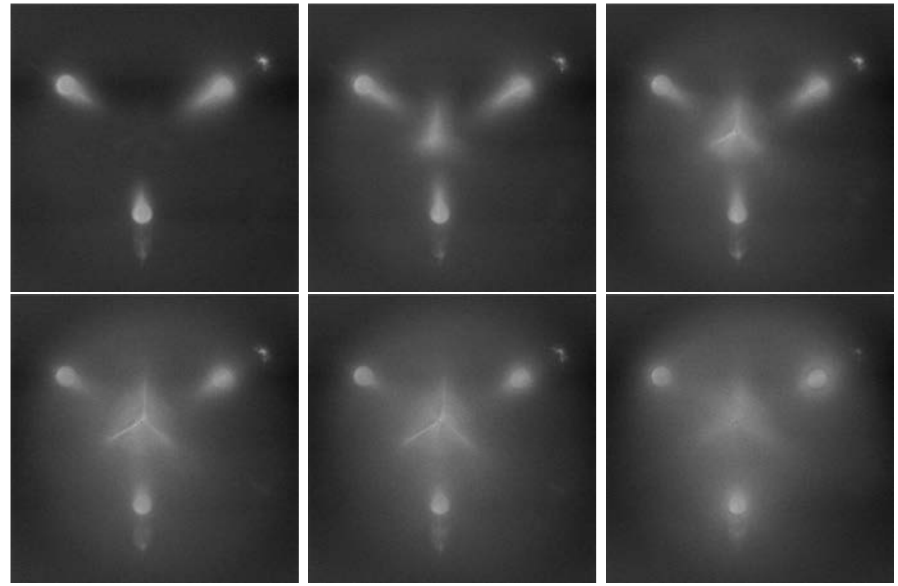




Fast and open shutter imaging of three and six jets merging shows the symmetry of convergence and a much denser combined jet.

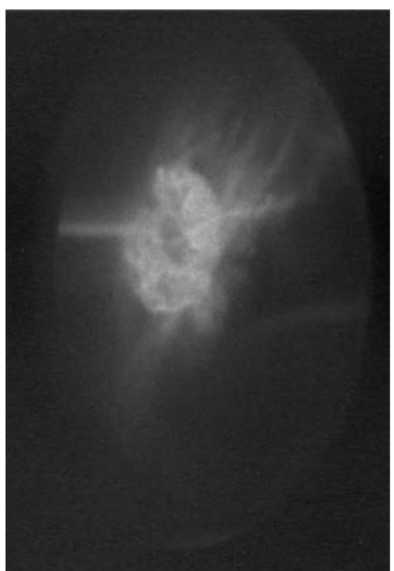






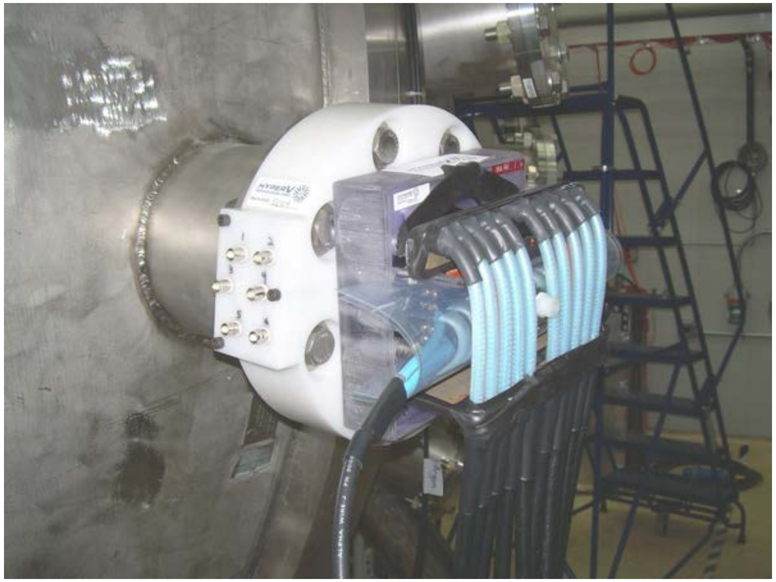
PI-Max image (5 ns gate) of three merging jets, showng formation of a secondary jet as the plasma flows past the point of convergence, where it impinges on the pressure probe array. [Case 2013]

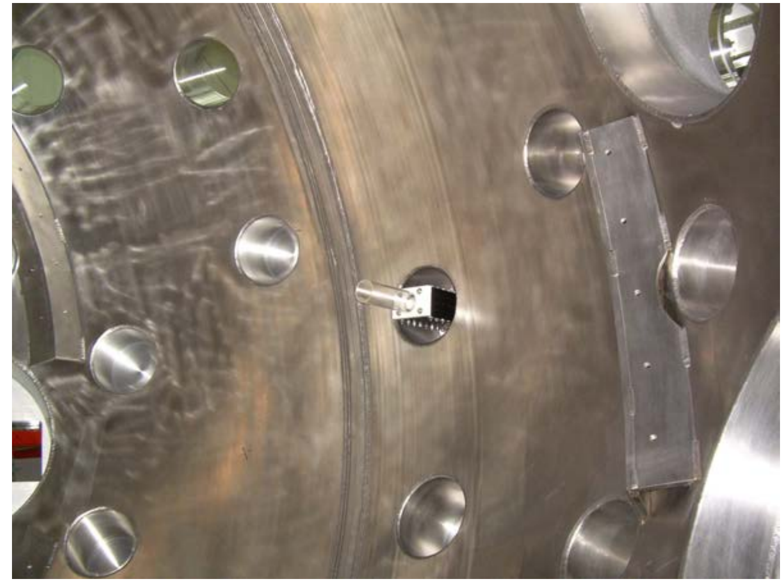
Six jets merging three from each end.

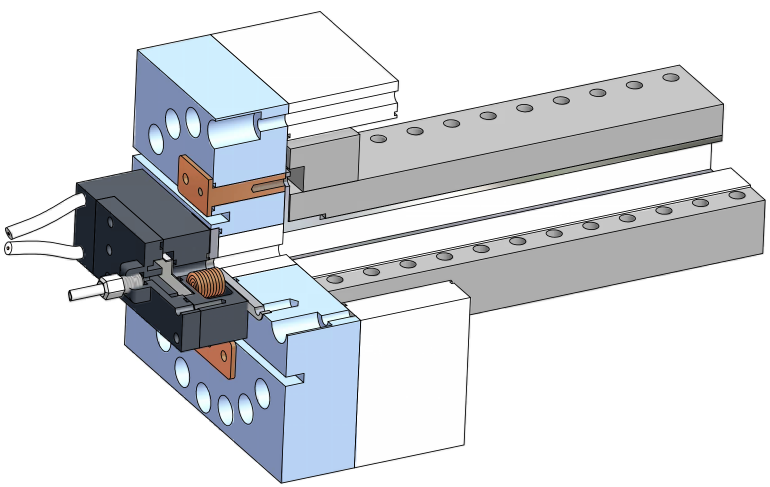


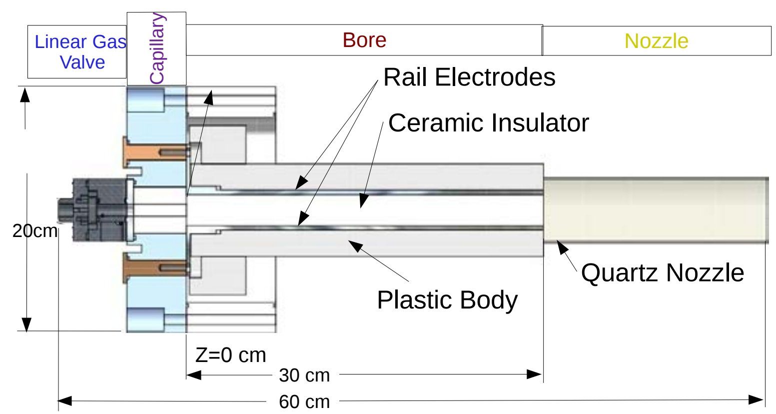
HYPERV TECHNOLOGIES CORP

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.



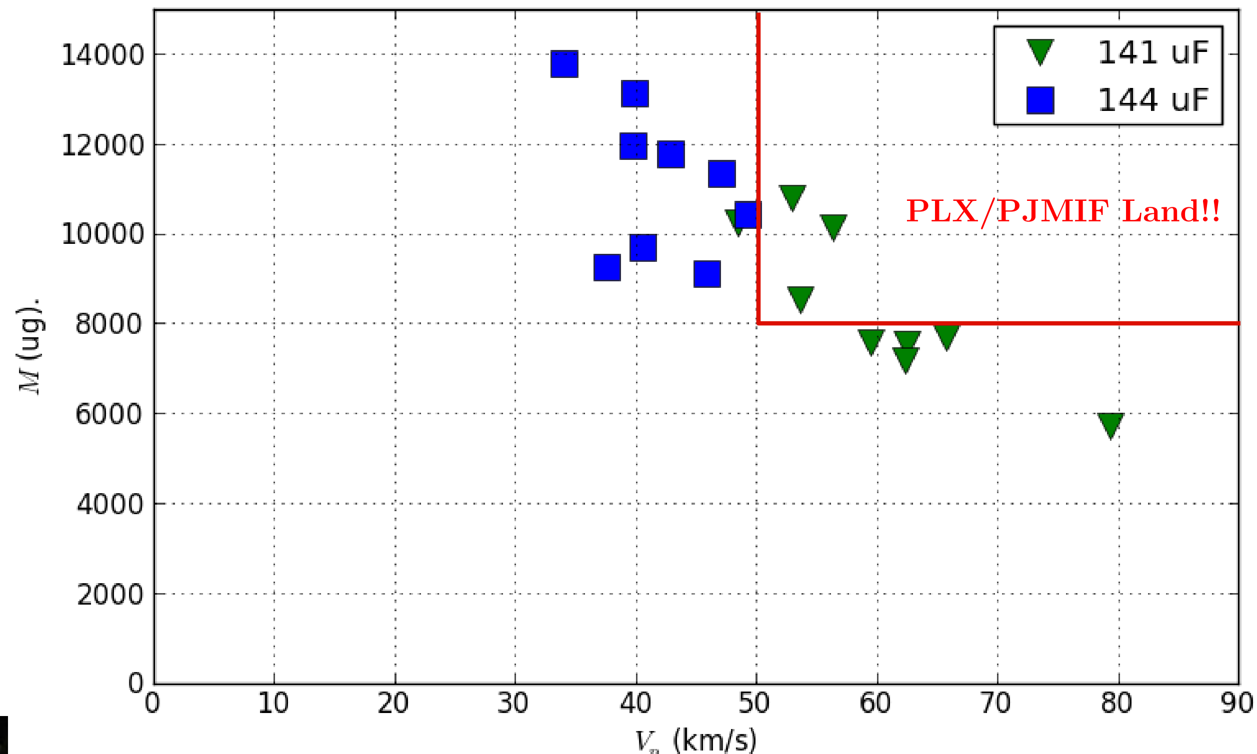






The Mark2 substantially exceeded the PLX plasma gun performance goal of 8000 μg at 50 km/s (achieved with ~500 kA).

700 kA sparkgap switch

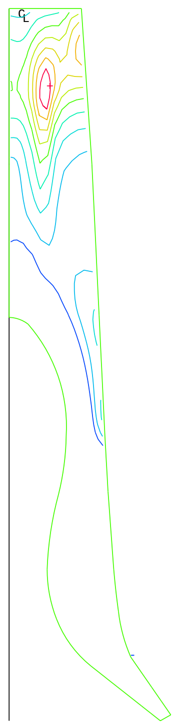


Although this performance is already in the ballpark for that needed for a reactor-grade plasma gun driver, i.e. 10-20 mg at 50-70 km/s, we want more than just mass and velocity!

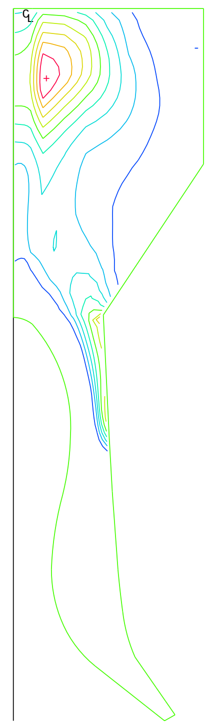
HYPERV TECHNOLOGIES CORP

We also need plasma jet shape control for a reactor driver

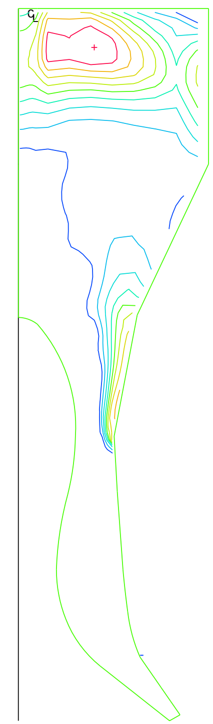
- The coax geometry along with nozzles gives better control of jet topology
- Want a jet structure more like a pancake/hocky puck instead of a fat cigar
- Lower current density of coax gun reduces electrode erosion and impurities



7.8 μs
4.3$\times$**10**^{16} cm^{-3}
190 k/s



7.8 μs
2.15$\times$**10**^{16} cm^{-3}
195 k/s



7.8 μs
1.11$\times$**10**^{16} cm^{-3}
205 k/s

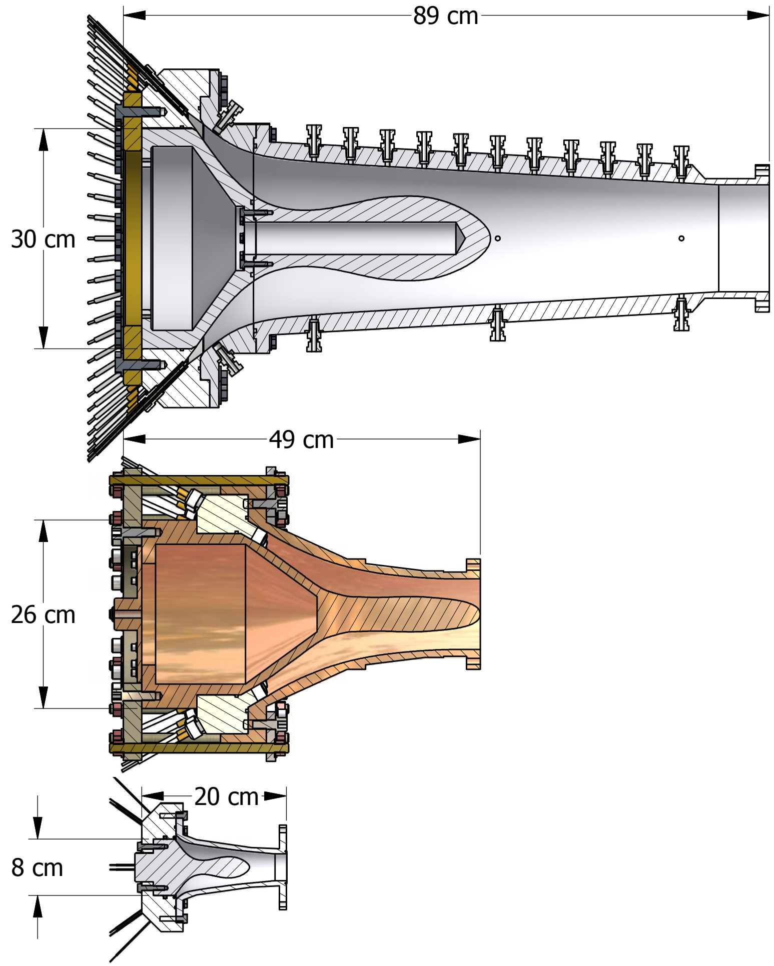
HYPERV TECHNOLOGIES CORP

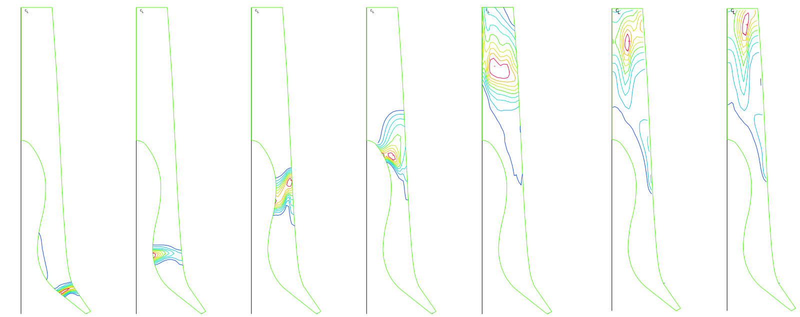
Simulations show that contoured-gap coaxial plasma guns can indeed accelerate the required masses to the required velocities. The task is to minimize their size and cost and increase efficiency.

Scale

Full

Half

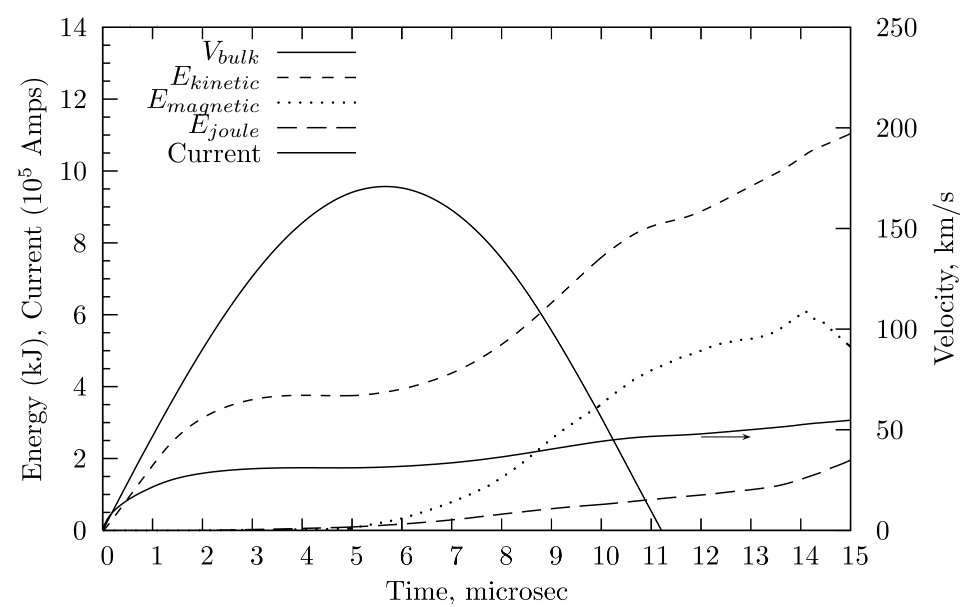




Mach2 Simulations Predict High Mass/Density Capability

200-400 μg at 200 km/s for 800 kA

8000 μg at 50 km/s for 800 kA



HYPERV TECHNOLOGIES CORP

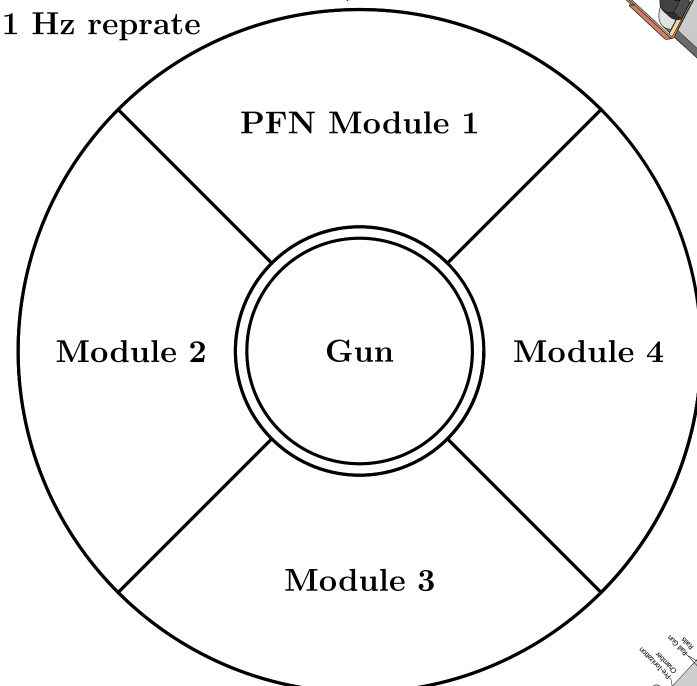
Contoured gap coax + Minirailgun injectors ⇒ Reactor-grade driver

- **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 ⇒ high efficiency, no ringing)**
- **Electrodes act as own vacuum containment – much simpler vacuum and mounting design**

HYPERV TECHNOLOGIES CORP

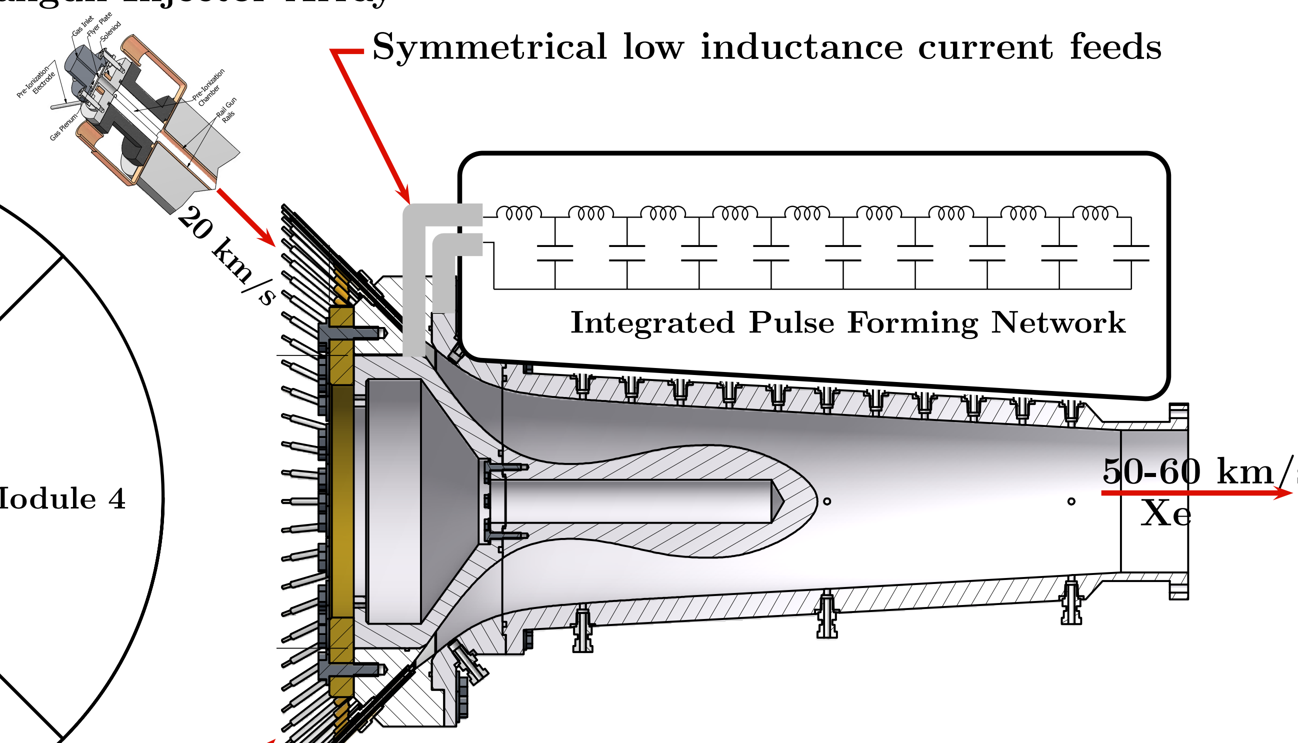
A reactor-grade plasma gun uses an array of small gas-fed Minirailgun injectors and an integrated well-matched pulse forming network.

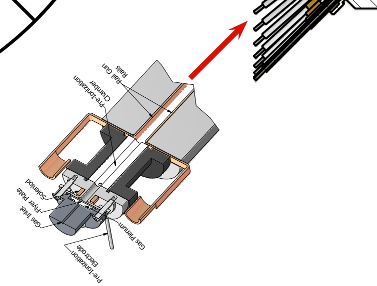
- 50 kJ per gun
- 0.5m length
- 5-7 cm jet radius
- 10-20 mg at 50-60 km/s
- 1 Hz reprate



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

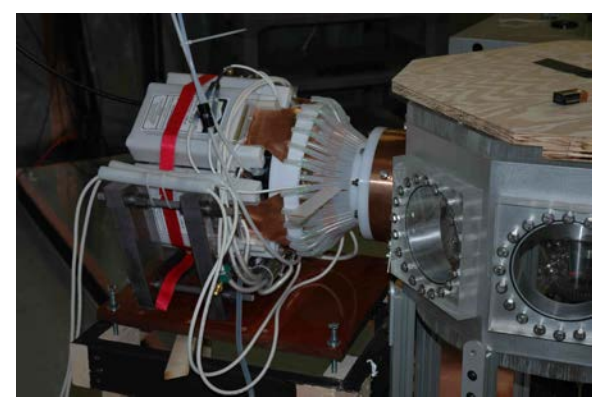
Minirailgun Injector Array





Injectors not to scale!
qty ~ 24

Early example of an integrated gun/RLC package.



HYPERV TECHNOLOGIES CORP

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

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

For a railgun,

$$F = ma = \frac{1}{2} L'_g I^2 \tag{2}$$

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

$$I = (\frac{2ma}{L'_g})^{1/2} = 722\ kA \tag{3}$$

and the acceleration time is

$$t_{accel} = (\frac{2x}{a})^{1/2} = 16.7\ \mu s. \tag{4}$$

The pulse width of a pfn is given by

$$\tau = 2CZ \simeq 2CL'_g\langle v\rangle \tag{5}$$

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

$$Z \simeq L'_g\langle v\rangle \simeq 0.004 \tag{6}$$

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

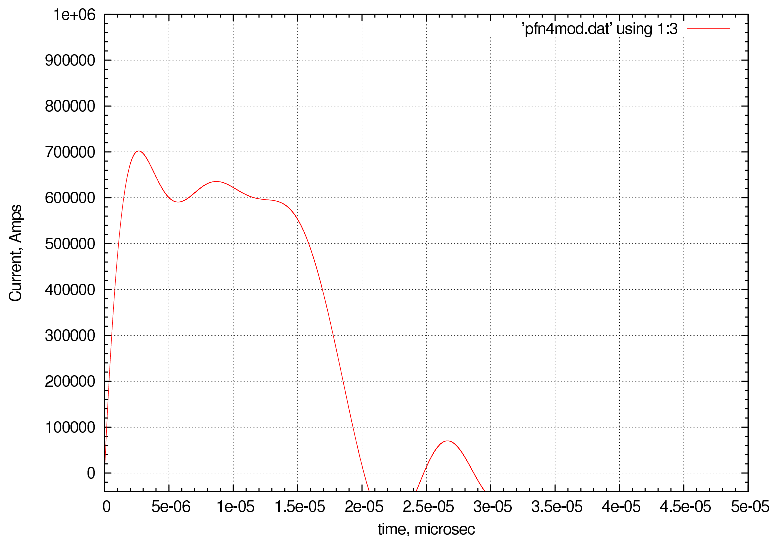
Thus,

$$C = \frac{\tau}{2L'_g\langle v\rangle} = 0.002\ F \tag{7}$$

$$Z = \sqrt{\frac{L'}{C'}} = \sqrt{\frac{L}{C}} \tag{8}$$

$$L = CZ^2 = 32nH \tag{9}$$

A quick circuit simulation of only a four section pfn with each C=500 μF and each L = 8 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.



HYPERV TECHNOLOGIES CORP

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

HYPERV TECHNOLOGIES CORP

References

- Burton, R. L. and P. J. Turchi, *"Pulsed plasma thruster,"* Journal of Propulsion and Power, 14(5):716735 (1998).
- Case, A., S. Messer, S. Brockington, L. Wu, F.D. Witherspoon, R. Elton, *"Merging of high speed argon plasma jets,"* Physics of Plasmas 20, 012704 (2013).
- A. Case, S. Messer, R. Bomgardner, and F. D. Witherspoon, *"Interferometer density measurements of a high-velocity plasmoid,"* Physics of Plasmas 17, 053503 (2010).
- Cassibry, J., F. Thio, T. E Markusic, and S. T Wu, *"Numerical Modeling of a Pulsed Electromagnetic Plasma Thruster Experiment,"* Journal of Propulsion and Power 22 (2): 628636 (2006).
- Cassibry, J., F. Thio, and S. T Wu, *"2-D Axisymmetric Magnetohydrodynamic Analysis of Blowby in a Coaxial Plasma Accelerator,"* Physics of Plasmas 13 (5) (2006).
- Cassibry, J., M. Stanic, and S. Hsu, *"Ideal hydrodynamic scaling relations for a stagnated imploding spherical plasma liner formed by an array of merging plasma jets,"* Physics of Plasmas 20, 032706 (2013).
- Cheng, D. Y., *"Plasma deflagration and the properties of a coaxial plasma deflagration gun,"* Nuclear Fusion, (10):305317 (1970).
- Cheng, D. Y. *"Application of a Deflagration Plasma Gun as a Space Propulsion Thruster,"* AIAA Journal 9 (9): 16811685 (1971).
- A. Dattner and J. Eninger, *"Studies of a coaxial plasma gun,"* Physics of Fluids Supplement, 7(11):S41S44 (1964).
- Degnan, J. H., W. L. Baker, M. Cowan, J. D. Graham, J. H. Holmes, E. A. Lopez, D. W. Price, D. Ralph, and N. F. Roderick, *"Operation of Cylindrical Array of Plasma Guns,"* Fusion Technology 35: 354360 (1999).
- Gloersen, P., B. Gorowitz, and J. T Kenney, *"Energy Efficiency Trends in a Coaxial Gun Plasma Engine System,"* AIAA Journal 4 (3): 436441 (1966).

References - cont'd

- D.C. Hagerman and J. E. Osher, *"Two high velocity plasma guns,"* The Review of Scientific Instruments, 34(1):5660 (1963).
- R.G. Jahn, *"Physics of Electric Propulsion,"* 1st ed., New York, McGraw-Hill (1968).
- Kirkpatrick R. C., C.E. Knapp, Y. C. F. Thio, *"Progress in magnetized target fusion driven by plasma liners,"* In E. Panarella, editor, Current Trends in International Fusion Research. Proc. of the 4th Symposium. Physics Essay, Ottawa, Canada (2002).
- Komelkov, V.S., and V.I. Modzolevskii, *"Coaxial Accelerator for Dense Plasmas,"* Soviet Journal of Plasma Physics 3 (5): 533538 (1977).
- Lee, J.H., D.R. McFarland, and F. Hohl, *"Production of dense plasmas in a hypocycloidal pinch apparatus,"* Physics of Fluids, 20(2):313321 (1977).
- John Marshall, *"Performance of a hydromagnetic plasma gun,"* Physics of Fluids:Letters to the Editor, 3(1):134135 (1960).
- J. W. Mather, *"Investigation of the high-energy acceleration mode in the coaxial gun,"* The Physics of Fluids Supplement, 7(11):S28S34 (1964).
- Merritt, E.C., A.L. Moser, S.C. Hsu, J. Loverich, and M. Gilmore, *"Experimental Characterization of the Stagnation Layer between Two Obliquely Merging Supersonic Plasma Jets,"* Phys. Rev. Lett. 111, 085003 (2013).
- Thio, Y. C. F., C. E. Knapp, R. C. Kirkpatrick, R. E. Siemon, and P. J. Turchi, *"A physics exploratory experiment on plasma liner formation,"* Journal Fusion Energy, 20(1/2):111 (2001).
- Thio, Y. C., *"Status of the U. S. Program in Magneto-inertial Fusion,"* Journal of Physics: Conference Series 112 (042084) (1978).
- Thio, Y. C. F, J. T. Cassibry, and T. E. Markusic, *"Pulsed Electromagnetic Acceleration of Plasmas,"* In 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. Indianapolis, Indiana (2002).

References - cont'd

- **Y. C. F. Thio, E. Panarella, R. C. Kirkpatrick, C. E. Knapp, and F. Wysocki, *"Magnetized target fusion in a spheroidal geometry with standoff drivers,"* In E. Panarella, editor, Current Trends in International Fusion Research Proceedings of the Second Symposium, Ottawa, Canada, NRC Research Press (1999).**

- **Turchi, P. J, and J. F. Davis, *"Propagation of Dense Plasma Jets,"* In SPIE Microwave and Particle Beam Sources and Propagation. Vol. 873. Los Angeles, California (1988).**

- **Witherspoon, F. D. A. Case, S. J. Messer, R. Bomgardner III, M. W. Phillips, S. Brockington, and R. Elton, *"A Contoured Gap Coaxial Plasma Gun with Injected Plasma Armature," Rev. Sci. Inst.* 80, 083506 (2009).**

- **J. K. Ziemer, *"Performance Scaling of Gas-Fed Pulsed Plasma Thrusters,"* Phd dissertation, Princeton University, 2001.**

HYPERV TECHNOLOGIES CORP