Poster TP9.00079

LA-UR 11-06554

Overview of the Plasma Liner Experiment (PLX)

Scott Hsu (LANL), Doug Witherspoon (HyperV), Jason Cassibry (UAHuntsville), Mark Gilmore (UNM) & The PLX Team

Collaborators: Voss Scientific, Far-Tech, Prism Computational Sciences, Tech-X Corp.

53rd Annual Meeting of the APS-DPP
Salt Lake City, UT
November 17, 2011

Operated by Los Alamos National Security, LLC for NNSA

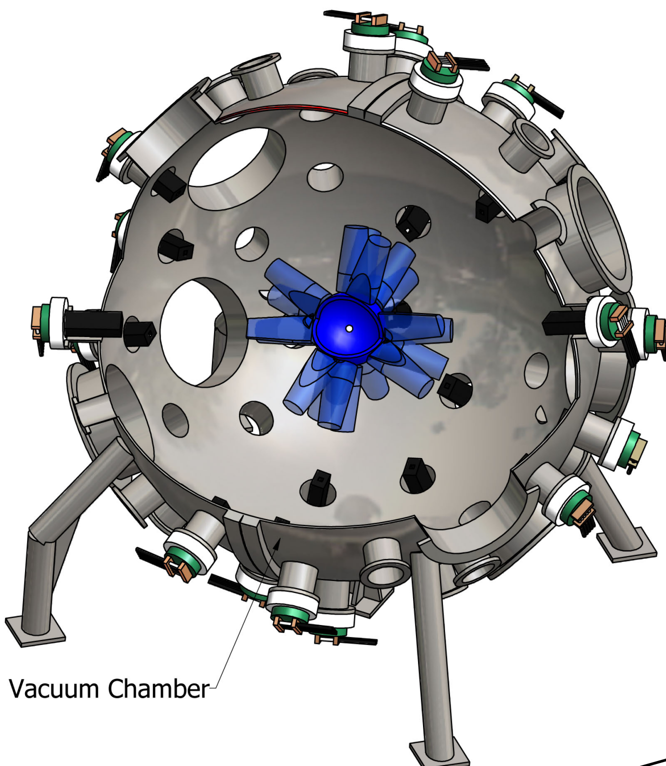
Funded by DOE-OFES as part of the SC/NNSA Joint Program in HEDLP

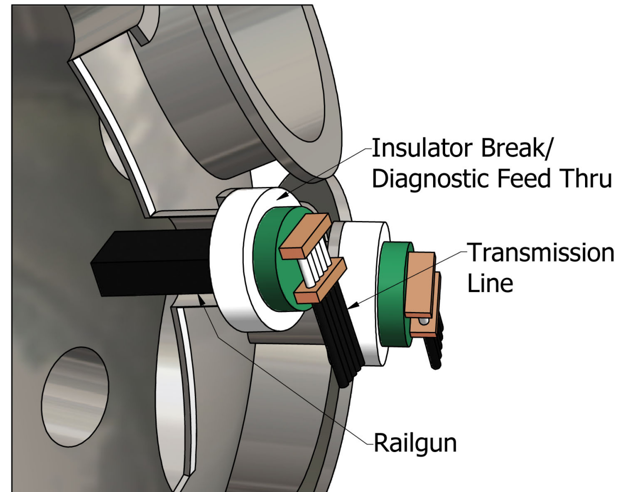
PLX is supported by a national collaboration

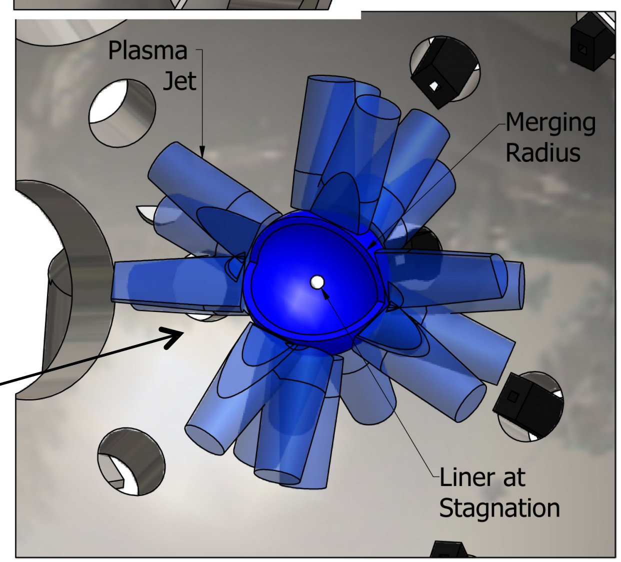
Overview of other PLX-related posters in this session

1. Plasma railguns for PLX, Doug Witherspoon (HyperV), TP9.00099
2. Single jet studies on PLX, Tom Awe (LANL), TP9.00086
3. 3D liner implosion modeling using SPHC, Jason Cassibry (UAH), TP9.00104
4. Interferometry results from initial experiments on PLX, Liz Merritt (UNM), TP9.00091
5. Plasma jet merging studies at HyperV, Andrew Case (HyperV), TP9.00083
6. Minirailgun pressure and magnetics measurements, Sarah Messer (HyperV), TP9.00093
7. Construction of PLX facility and schlieren conceptual design, Colin Adams (LANL/UNM), TP9.00084
8. Pulsed power systems for PLX minirailguns, Sam Brockington (HyperV), TP9.00098
9. 1D plasma jet propagation modeling using LSP, John Thompson (Far-Tech), TP9.00088
10. Ion kinetic effects in hybrid-PIC LSP simulations of merging jets, Carsten Thoma (Voss), TP09.00082
11. Simulated spectral and imaging diagnostics for PLX, Igor Golovkin (Prism), TP9.00078
12. 3D modeling of merging plasma jets using Nautilus, John Loverich (Tech-X), TP9.00096
13. Eulerian and Lagrangian plasma jet modeling, Richard Hatcher (UAH), TP9.00094
14. Numerical simulations of plasma jets for PLX, Linchun Wu (HyperV), TP9.00100
15. Hybrid algorithms for modeling plasma jets, Nicki Bruner (Voss), TP9.00080
16. Plasma jet modeling using ePLAS, Rod Mason (RAC), TP9.00097
17. Bounce-free spherical hydrodynamic implosion, Grisha Kagan (LANL), TP9.00103
18. Laser beat-wave current drive studies, Fei Liu (UC, Davis), TP9.00095

PLX plans to generate/study cm-, μs-, Mbar-scale plasmas formed by spherically imploding plasma liners







Plasma liner formed by 30 merging plasma jets

PLX will use ~1.5 MJ of initial stored energy to reach ~1 Mbar peak pressures

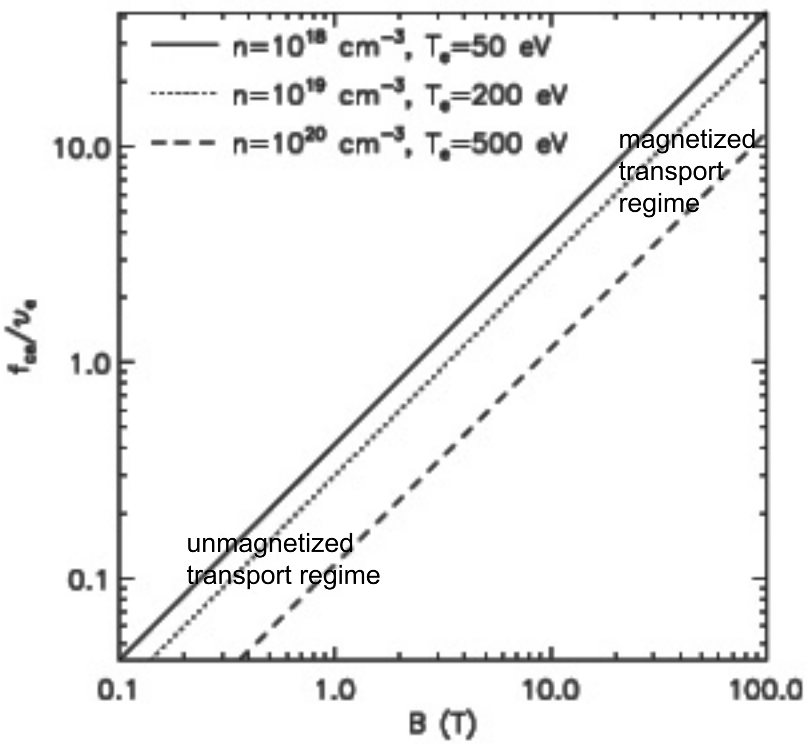
Drawing by David van Doren, HyperV

Motivation: PLX can provide a unique cost-effective platform for experimental HEDLP science

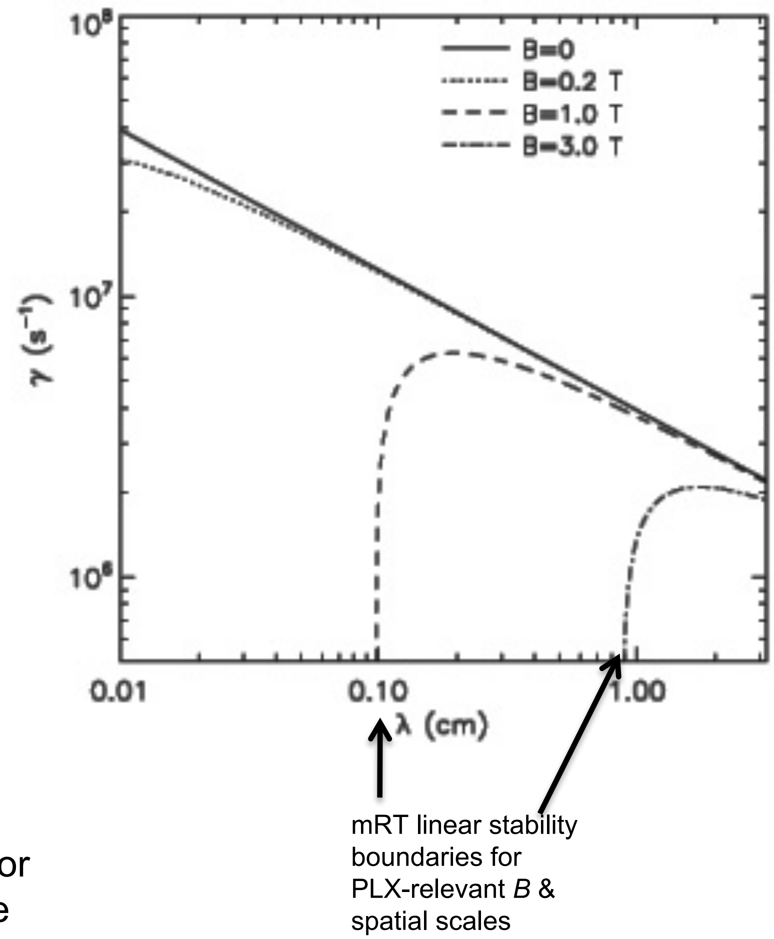
Facility	Shots/day (max)	Cost/shot
NIF	2	$250k
Omega	10	$12k
Shiva Star (AFRL)	2 per week	$150k
PLX	>50	<$1k (based on >2000 shots/yr @ $2M/year budget)

Motivation: magnetized* PLX plasmas could offer access to unique data on magnetized HED plasma transport and stability

PLX can potentially access both unmagnetized & magnetized HED regimes:

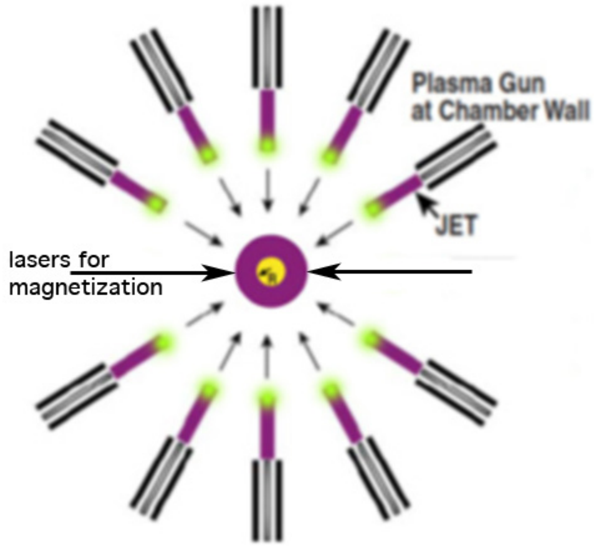


Instabilities such as magnetic Rayleigh-Taylor modes can be studied:



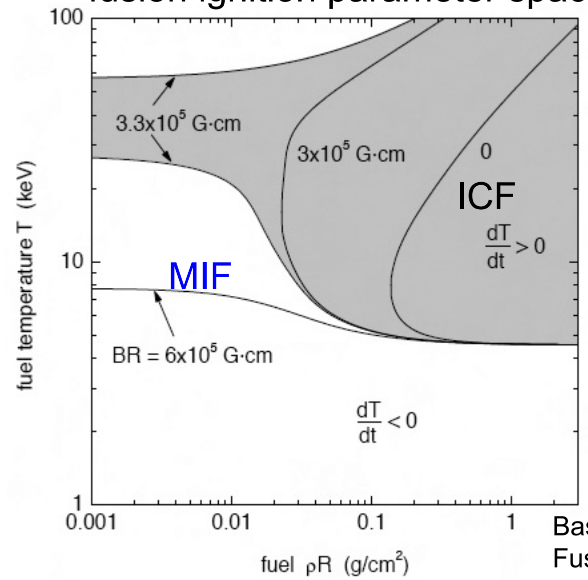
*See poster TP9.00095 by F. Liu for proposed magnetization technique

Motivation: Spherically imploding plasma liners formed by merging plasma jets could be an attractive standoff driver for magneto-inertial fusion

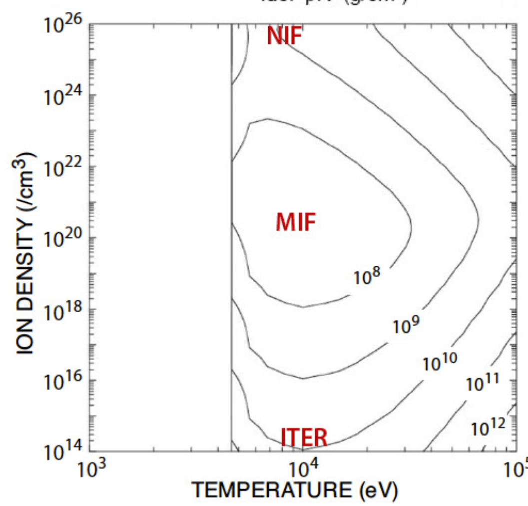


- Composite DT (yellow) and high-Z (purple) jets are imploded to ρr_{DT}~0.01 g/cm^2
- DT is magnetized just before peak compression (proposed method using laser generated beat-wave current drive)
- Implosion speed ~100 km/s
- Dwell time ~1 μs
- Batch burn with ~10% fuel burn-up
- Peak pressures ~100 Mbar

fusion ignition parameter space



Basko et al., Nucl. Fusion (2000)



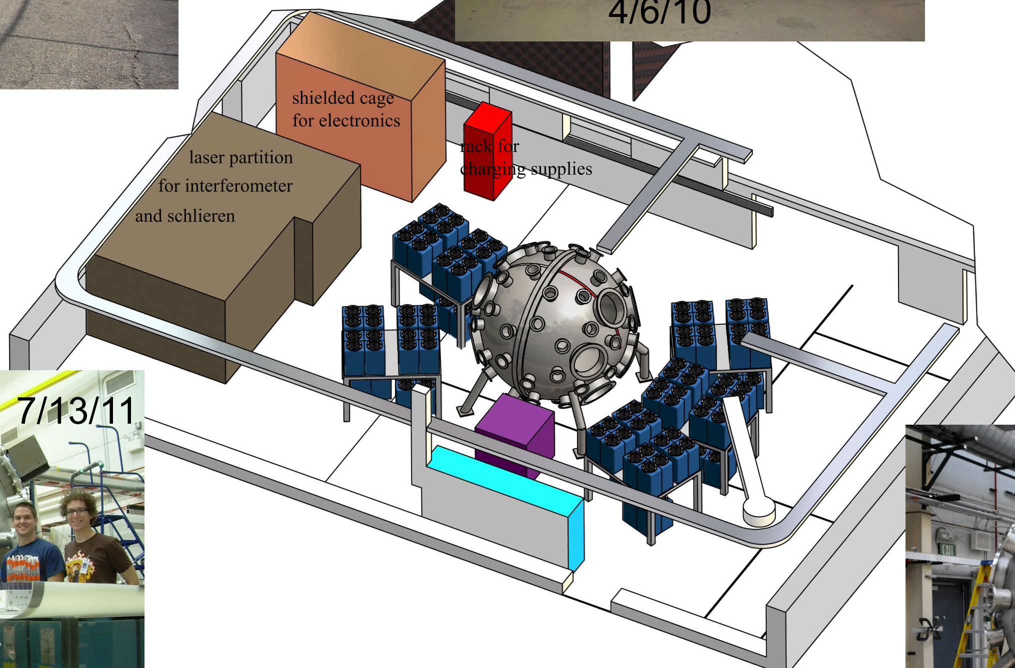
Intermediate density allows low cost fusion development path

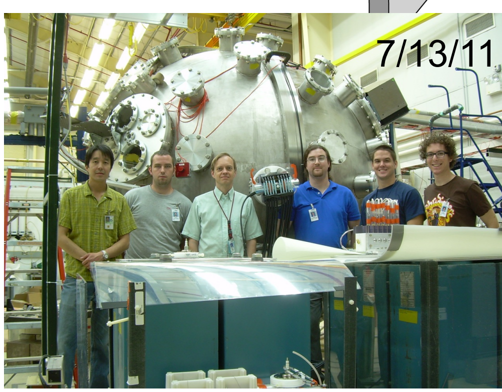
Lindemuth & Siemon, Amer. J. Phys. (2009)

PLX has three near-term science & technology objectives

1. **Form dense high Mach number, high Z (Ar, Xe) plasma jets with required density (~10^{17} cm^{-3}), mass (~few mg), and velocity (>50 km/s)**
2. **Demonstrate imploding plasma liner formation and predictive physics understanding of underlying steps:**
   - ***jet evolution from chamber wall to "merging" radius r_m***
   - ***liner formation via jet merging (jet inter-penetration, shock dynamics, uniformity)***
   - ***liner convergence (pressure amplification, atomic physics effects, convergent instabilities/mix)***
   - ***stagnation (peak pressure scaling, conversion of liner kinetic energy to thermal/radiation energy, confinement time)***
3. **Reach ~1 Mbar of peak pressure upon stagnation of spherically imploding plasma liner**

PLX construction photos & proposed 30 gun setup

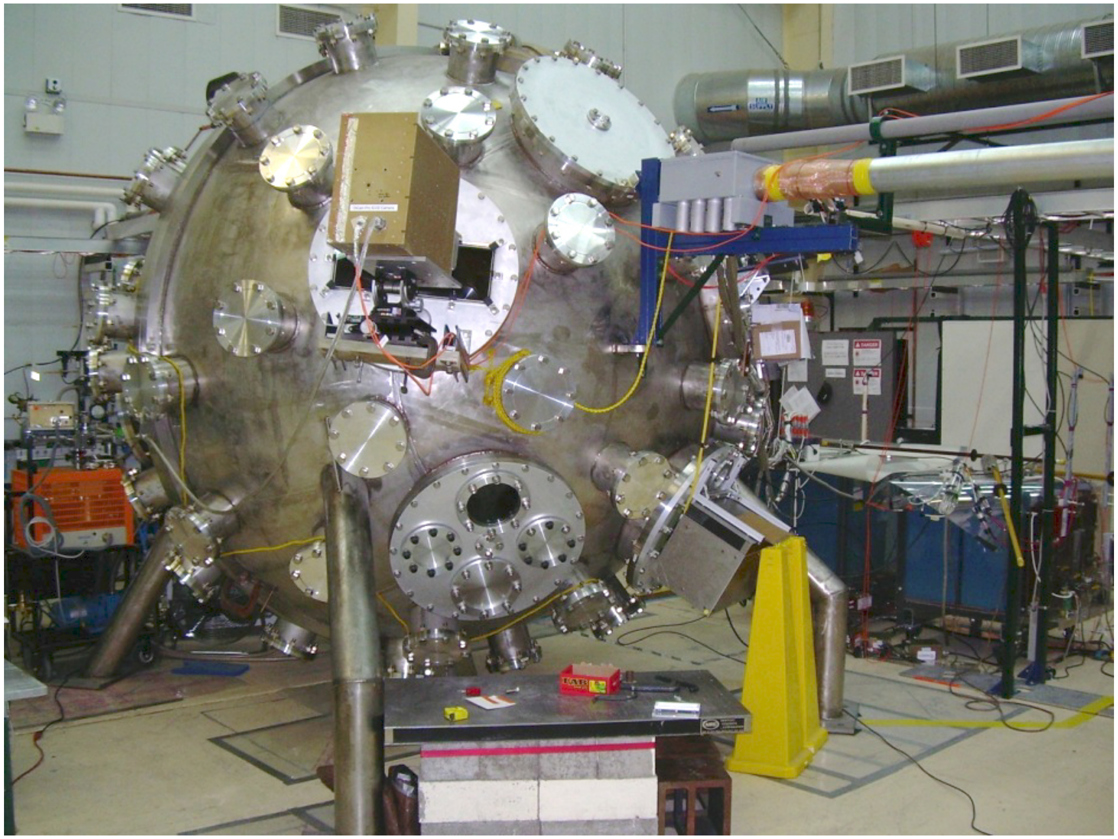




PLX is situated in a ~3000 ft.^{2} high-bay with a 10-ton overhead crane and shielded control room.

Drawing by David van Doren, HyperV

PLX phase 1 construction* complete with single jet experiments underway (first shot 9/13/11)



PLX 9’ diameter vacuum chamber in high-bay (9/14/11).

Phase 1 complete (late-FY11):

- **Spherical vacuum chamber mid-10^{-7} T base pressure**
- **One plasma gun operational, with second operational by Jan. 2012**
- **Multi-chord interferometry, visible spectroscopy, photodiode array, and CCD camera imaging operational**
- **Schlieren being bench-tested**

Proposed phase 2 (by FY13), pending HEDLP renewal:

- **Increase to 30 guns and ~1.5 MJ capacitor banks**
- **Add VUV spectroscopy, soft x-ray bolometry**
- **Full liner implosion studies**

*See poster TP9.00084 by C. Adams for details on facility construction/hardware

Plasma guns by HyperV Technologies Corp.* have achieved nearly the required performance for PLX

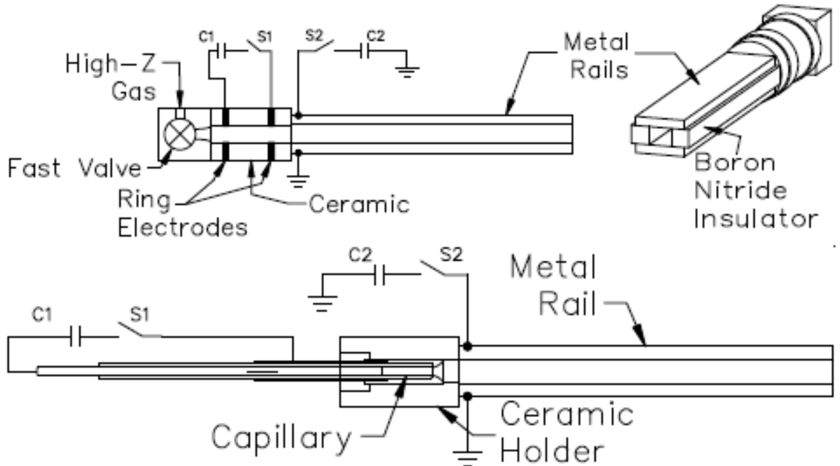


Figure 12 *Railgun with two versions of plasma injector, (top) ceramic capillary with fast valve gas injection, (bottom) polyethylene ablative capillary. The dimensions of the railgun relative to the injectors are not quite to scale here.*

Latest results @ ~400 kA: 5-6 mg mass, 10^{16} cm^{-3}, 44 km/s (peak currents expected to be >600 kA)

Projected Parameters

Bore size	2-5 cm square or rectangular
Length	~30 cm
L'	~ 0.5-0.9 μH/m (augmented)
Rails	Cu, W, Ta, GlidCop
Insulator	BN, Si_3N_4
Current	$\leq$500 kA
Pulsewidth	10-15 μs
Circuit type	probably simple RLC
Capacitance	~40 μF (total)
Bank energy	~50 kJ
Voltage	~40 kV (goal)
Armature mass	8000 μg of Ar or Xe
$V_{injection}$	~ 1-2 km/s for xenon
	~ 2-3 km/s for argon
V_{jet}	50 km/s

Some potential issues:

pfn constrained by available capacitors
Current sheet canting
Leakage through current sheet
High collisionality may help

*See poster TP9.00099 by Doug Witherspoon for details on gun development and status

Diagnostics effort led by University of New Mexico* is being implemented in two phases

Experiment Stage	*Quantity*	*Diagnostic*
2-5 Jets Merging	n_e	**Interferometer** **Schlieren Imaging** **Stark Broadening** **Visible Imaging**
	T_e	**Spectral Line Intensity Ratios**
	Mach #	**Doppler Broadening**
Imploded Plasma Liner	n_e	**Interferometer** **Schlieren Imaging** **Stark Broadening** **Visible Imaging**
Region I **(Outer Liner at Stagnation)**	T_e	**Spectral Line Intensity Ratios**
Region II **(Inner Liner at Stagnation)**	n_e	**Stark Broadening**
	T_e	**Spectral Line Intensity Ratios**
	$P(n_e, n_i, T_e)$	**Bolometry**

*A. G. Lynn et al., *Rev. Sci. Instrum.* **81**, 10E115 (2010)

Theory/modeling including generation of synthetic diagnostic data coordinates efforts of many institutions using many different codes

Problem	Institution	Code	Type
jet merging, liner formation/implosion, peak pressure scaling	UAHuntsville	SPHC	3D smooth particle hydrodynamics (meshless Lagrangian)
liner implosion	LANL, Tech X	RAVEN, HELIOS, Nautilus	1D rad-hydro (RAVEN, HELIOS) & 2D two-fluid MHD (Nautilus)
jet propagation/merging	Far-Tech, Voss, Tech-X, UAHuntsville	LSP, Nautilus, SPHC	PIC w/atomic physics, two-fluid MHD, 3D smooth particle hydrodynamics
jet formation/acceleration	HyperV, Voss, UAHuntsville, RAC	MACH2, LSP, ePLAS	Rad-MHD (MACH2), PIC w/atomic physics (LSP), hybrid-PIC
effects of atomic physics on jet propagation and liner convergence	Prism, Far-Tech, Voss, LANL, UAHuntsville, Tech X	PrismSpect, LSP, HELIOS, Nautilus	DCA atomic physics (PrismSpect), others given above
predictions of spectral lines for diagnostics	Prism, UNR, LANL	PrismSpect, Spect3D	DCA atomic physics
laser beat wave generation	Voss, LANL	LSP	PIC

1D rad-hydro simulation study* using RAVEN revealed evolution of imploding spherical plasma liner and peak pressure scaling

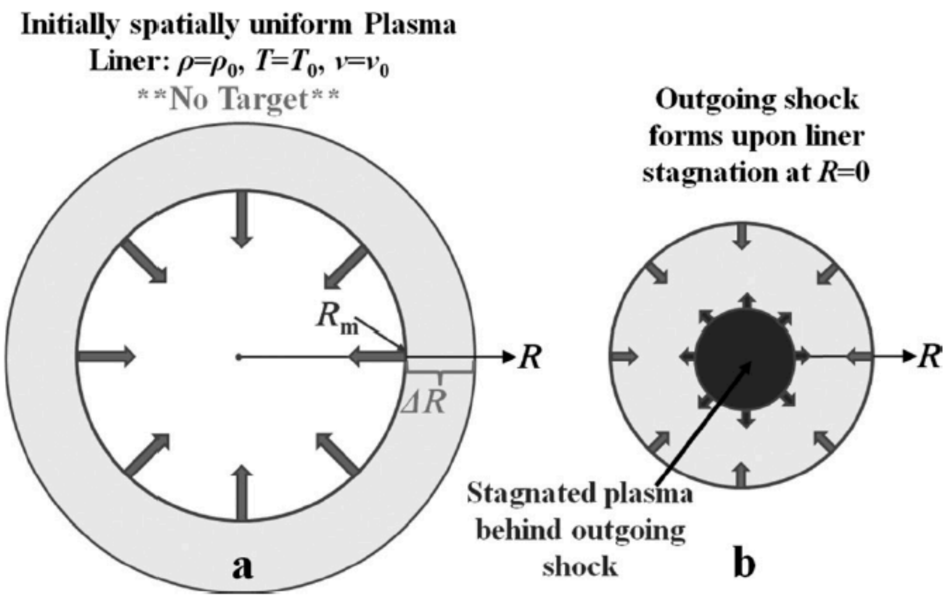


FIG. 1. (a) Initial configuration used in 1D plasma liner simulations. Plasma with constant density, temperature, and fluid velocity extends from $r_{in} = R_m$ to $r_{out} = R_m + \Delta R$. Simulations contain no target plasma. (b) The plasma configuration after collapse upon the origin. A spherical shock wave propagates outward into the remaining incoming liner plasma. Behind the shock front, high-pressure stagnated plasma persists until the shock front and outer edge of the liner meet.

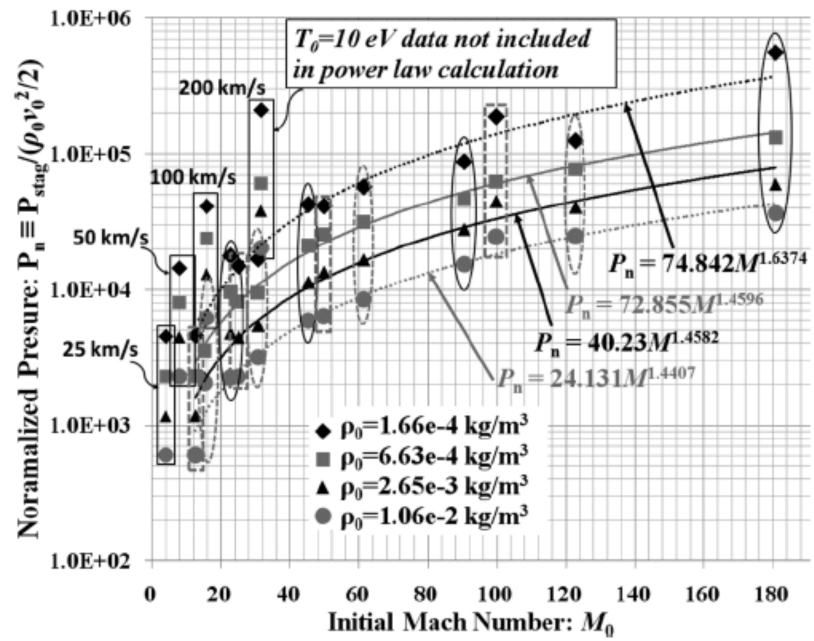
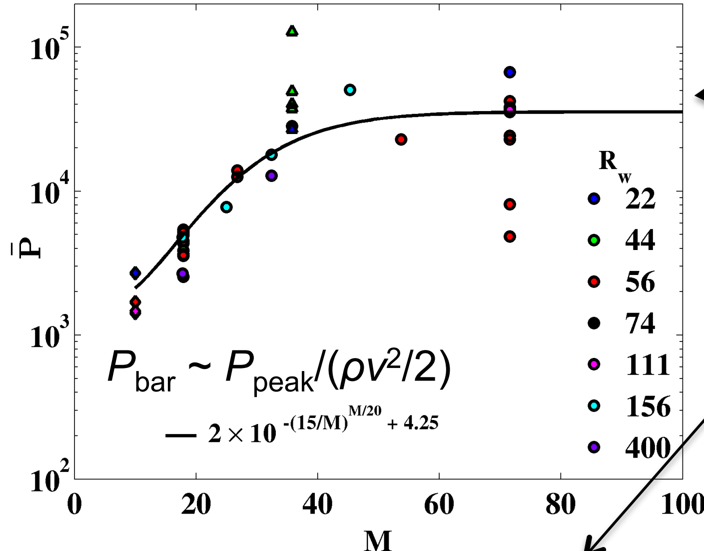


FIG. 11. RAVEN calculated normalized pressure $\{P_n = P_{stag}/(\rho_0 v_0^2/2)\}$ versus initial Mach number (M_0) for 4 different sets of the 16 simulations defined in Table II. Data are grouped according to the simulation atomic species, γ, and T_0 by the dashed rectangles (Ar, $\gamma = 5/3$, $T_0 = 1.0$ eV), solid ovals (Xe, $\gamma = 5/3$, $T_0 = 1.0$ eV), solid rectangles (Ar, $\gamma = 5/3$, $T_0 = 10$ eV), and dashed ovals (Ar, $\gamma = 1.1$, $T_0 = 1.0$ eV). Separate scaling laws have been fit to the $T_0 = 1.0$ eV data for each initial density. Power law scaling functions are best fit to the data and given by $P_n \propto M_0^{1.64}$, $P_n \propto M_0^{1.46}$, $P_n \propto M_0^{1.46}$, and $P_n \propto M_0^{1.44}$, for $\rho_0 = 1.66 \times 10^{-4}, 6.63 \times 10^{-4}, 2.65 \times 10^{-3}$, and 1.06×10^{-2} kg/m^3, respectively.

*T. J. Awe et al., *Phys. Plasmas* **18**, 072705 (2011)

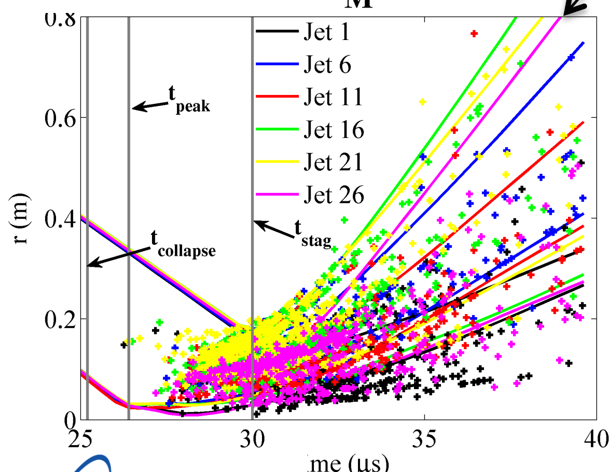
Smooth particle hydrodynamic simulations are exploring pressure scaling, mix, and 3D effects with very encouraging early results!

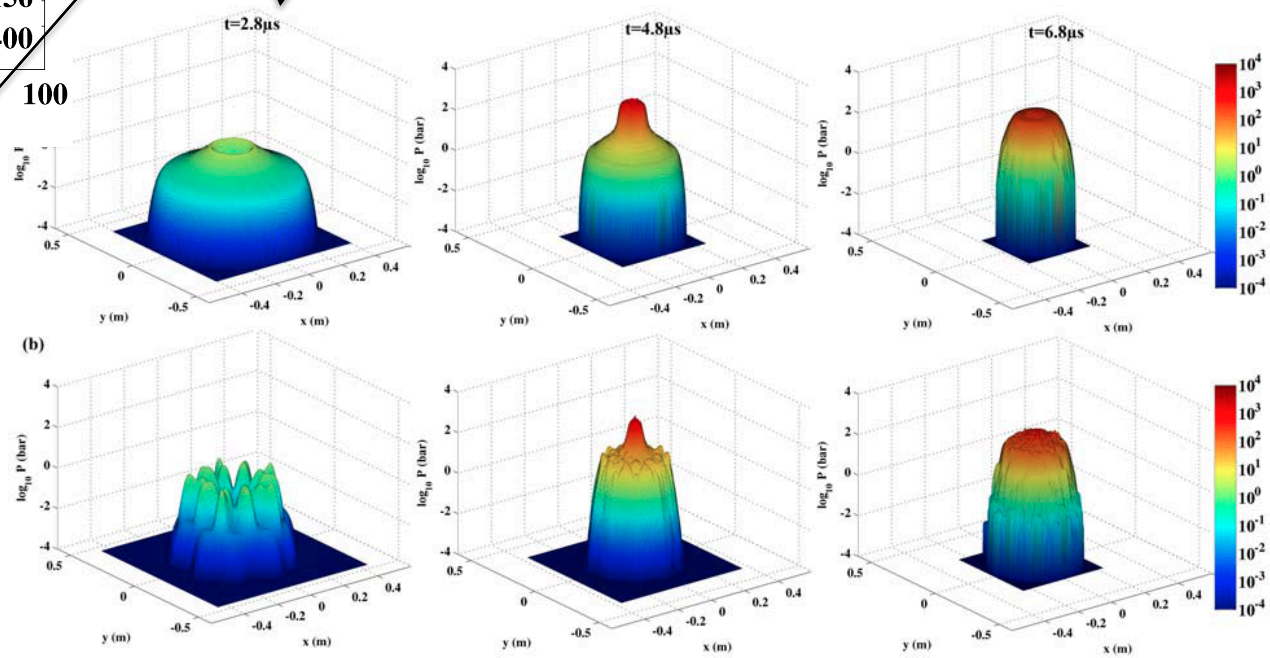


(a) Pressure scaling

(b) Mix events occur mostly after stagnation

(c) initial liner non-uniformity is smeared out by stagnation





*See poster TP9.00104 by J. Cassibry (UAHuntsville)

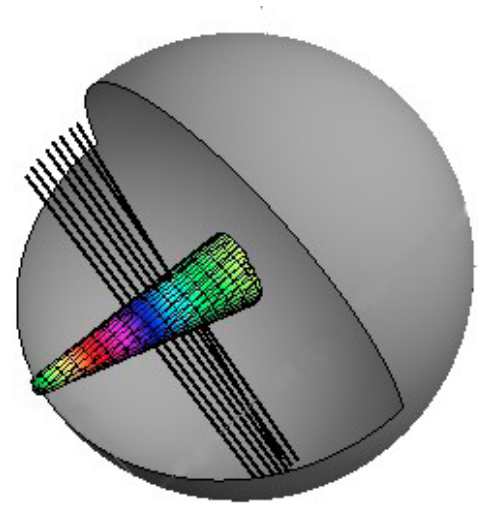
Experimental campaigns in 2011 & 2012 are addressing jet propagation and 2 jet merging physics issues

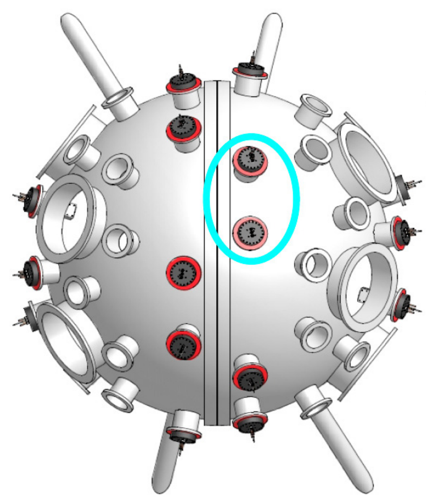
Single jet propagation/evolution:

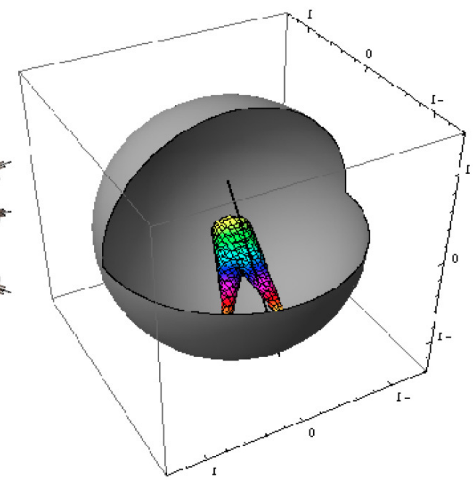
- Developing a predictive capability for evolution of jet n, T, v, B, Z_{eff} during propagation
- Jet profiles and their effects
- Impurity effects
- Effects of unforeseen phenomena such as filamentation or other jet structure/dynamics

Two jet merging:

- Jet inter-penetration and mixing length
- Shock formation/dynamics and heating
- Post-merge plasma properties



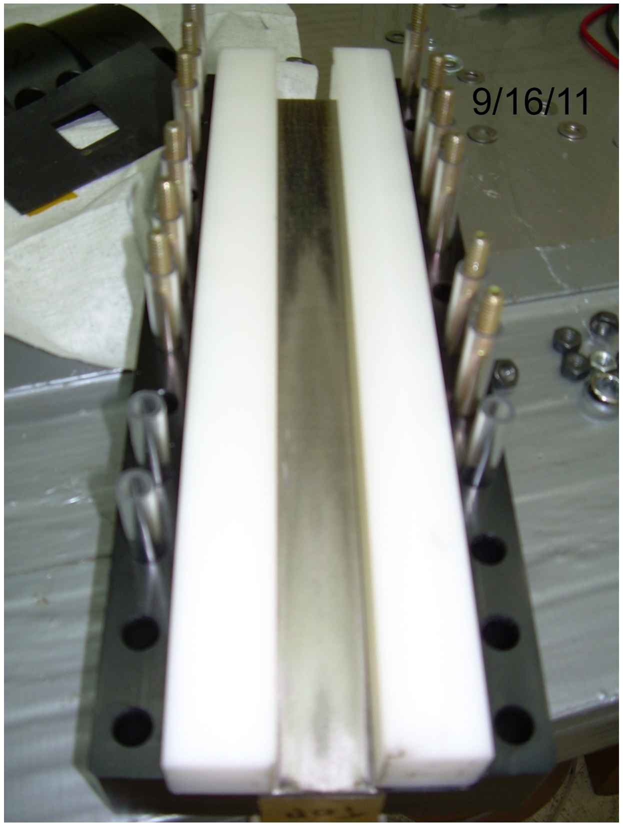




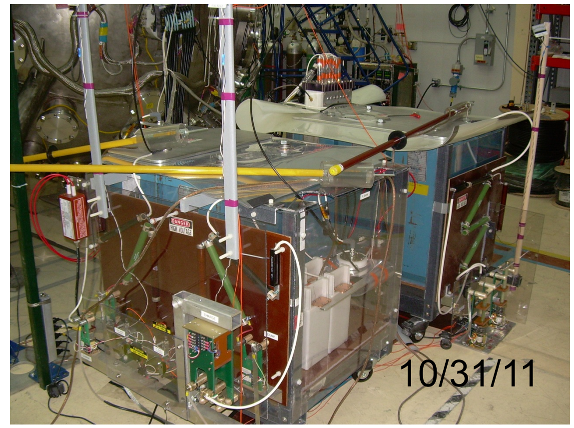
Figures by Elizabeth Merritt (UNM) and David Van Doren (HyperV)

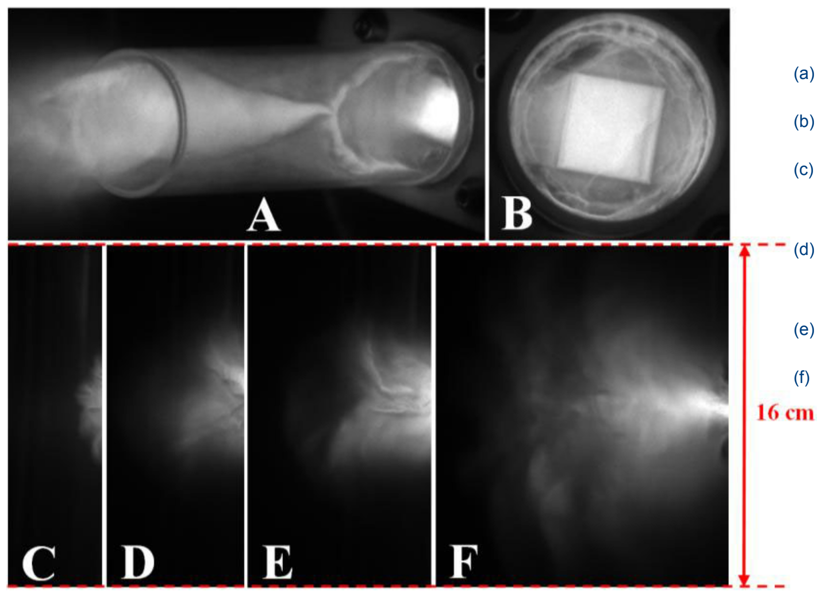
Plasma gun with a Delrin insulator is being fired for PLX facility and diagnostic shakedown at <300 kA gun current

HyperV Mark-1-H railgun with HD-17 rails and Delrin insulators



Capacitor banks: (front) PI (40 kV, 0.8 μF) & gas valve (20 kV, 24 μF); (back) gun (40 kV, 36 μF)





(a) t=38.7μs; 20ns gate

(b) t=16.5μs; 3ns gate

(c) t=29μs; 20ns gate; v~11km/s

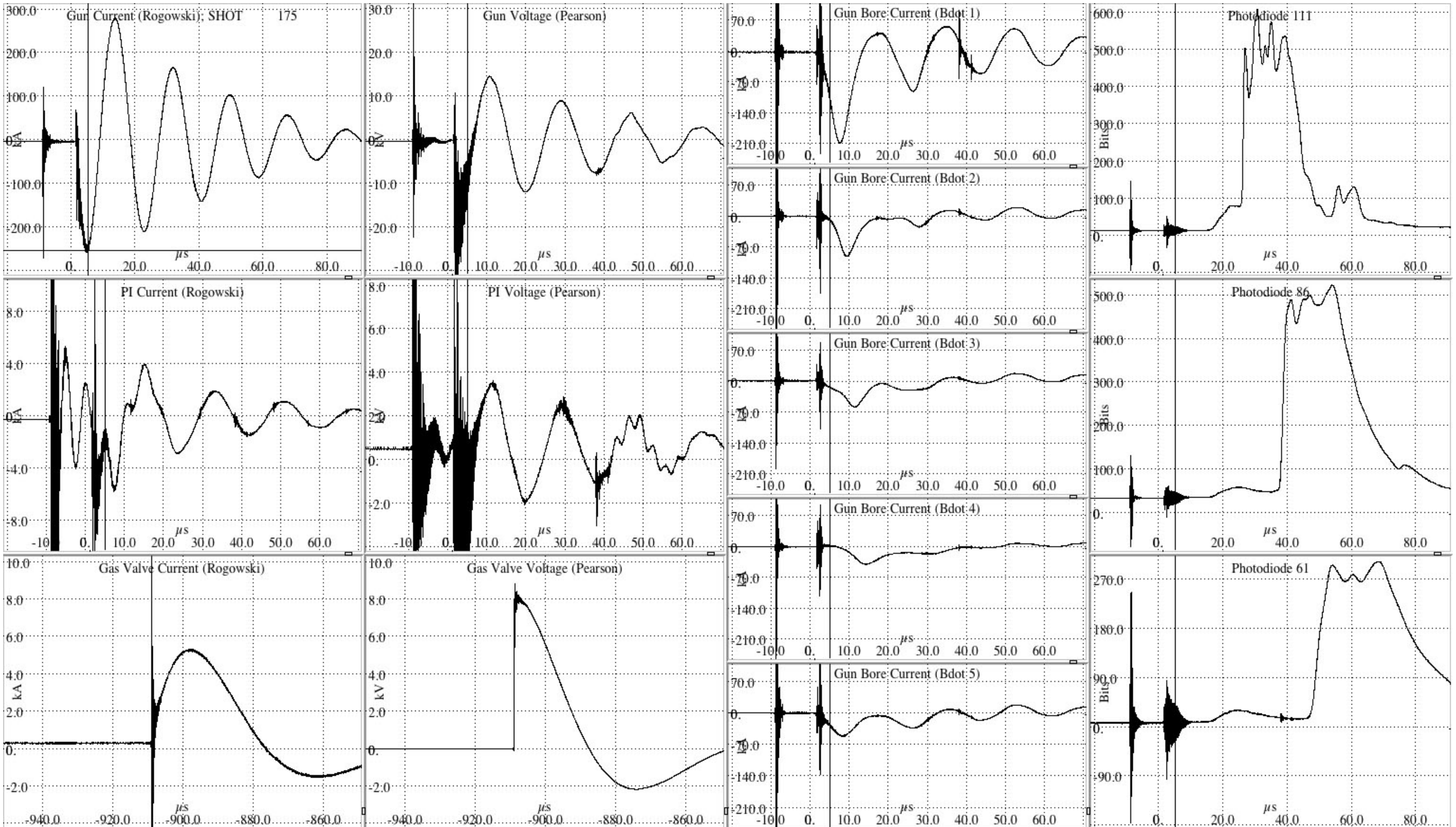
(d) t=29μs; 20ns gate; v~19km/s

(e) t=28.7μs; v~21km/s

(f) T=39μs; v~11km/s

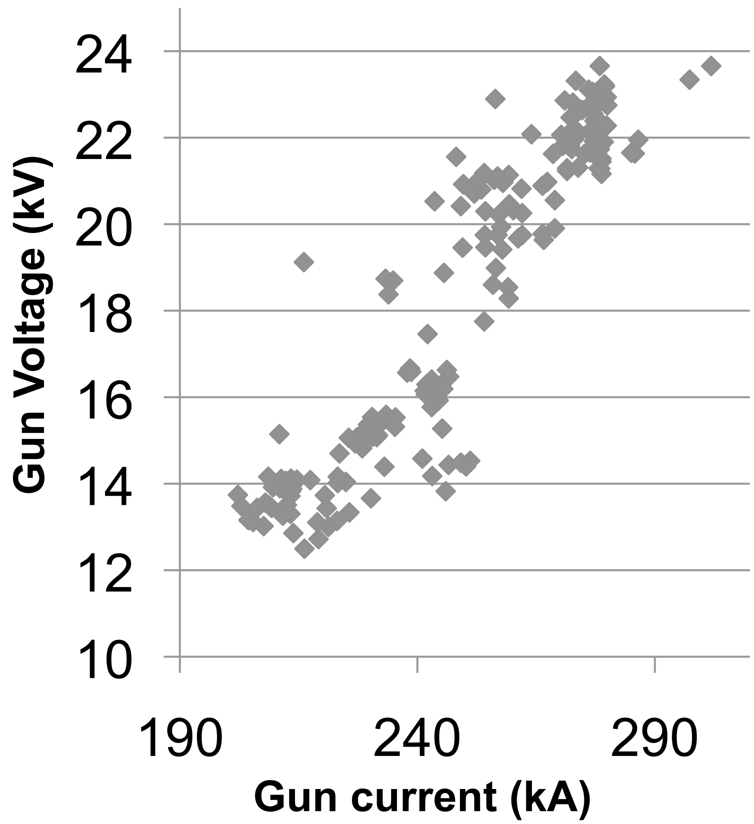
CCD images by Tom Awe (LANL)

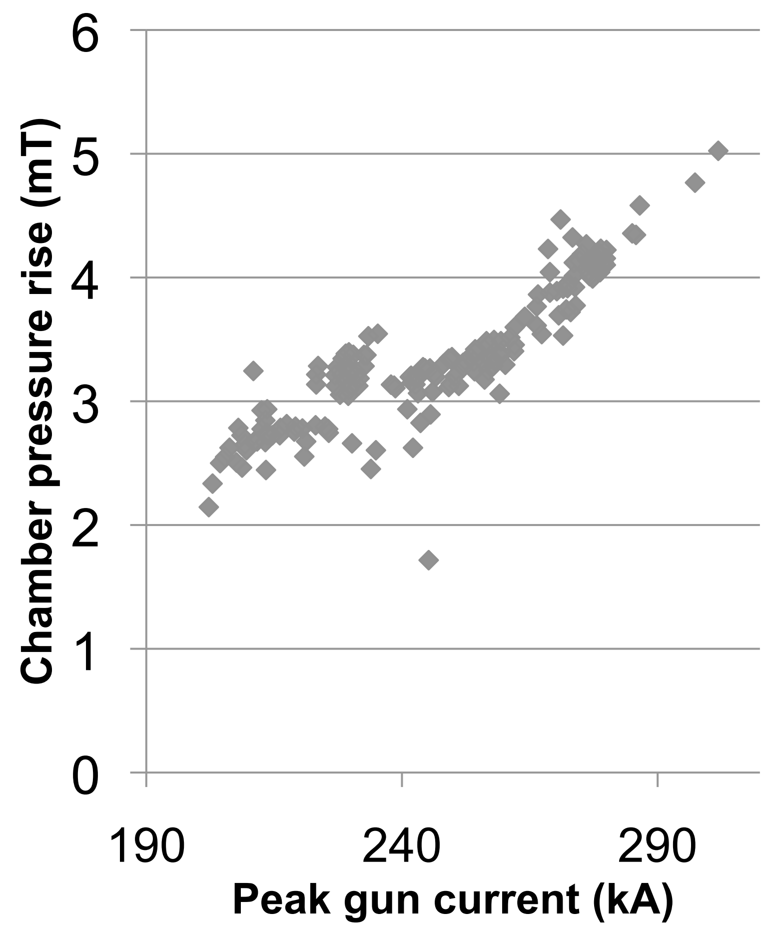
Shot data including gun current/voltage and photodiode signals are evaluated immediately after every shot – over 250 shots so far



MDSplus jScope screenshot

Gun operating characteristics are mostly as expected (but most of chamber pressure rise likely due to Delrin ablation instead of argon)

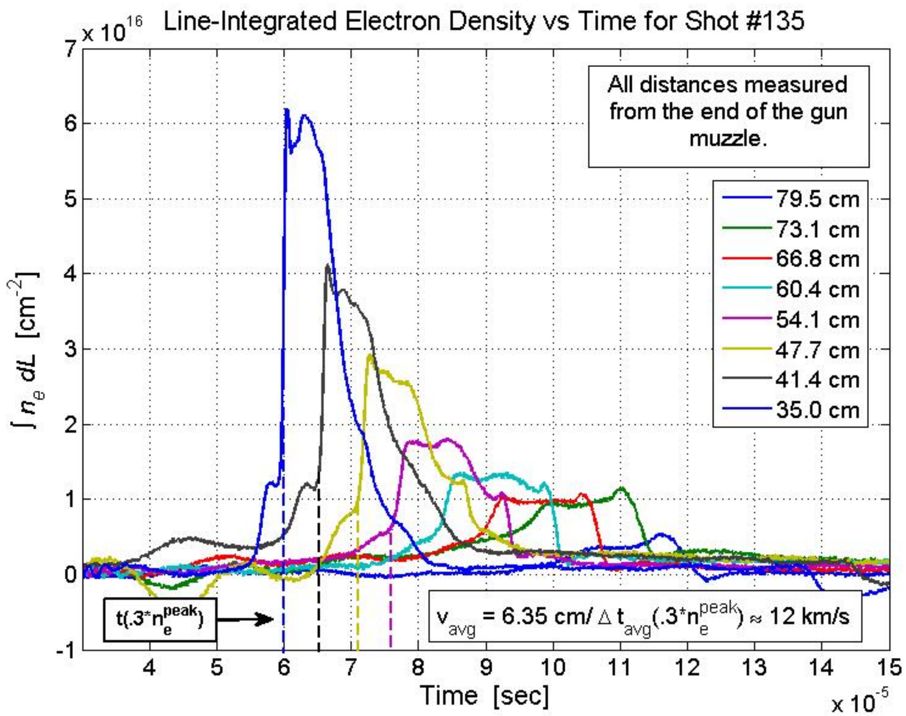


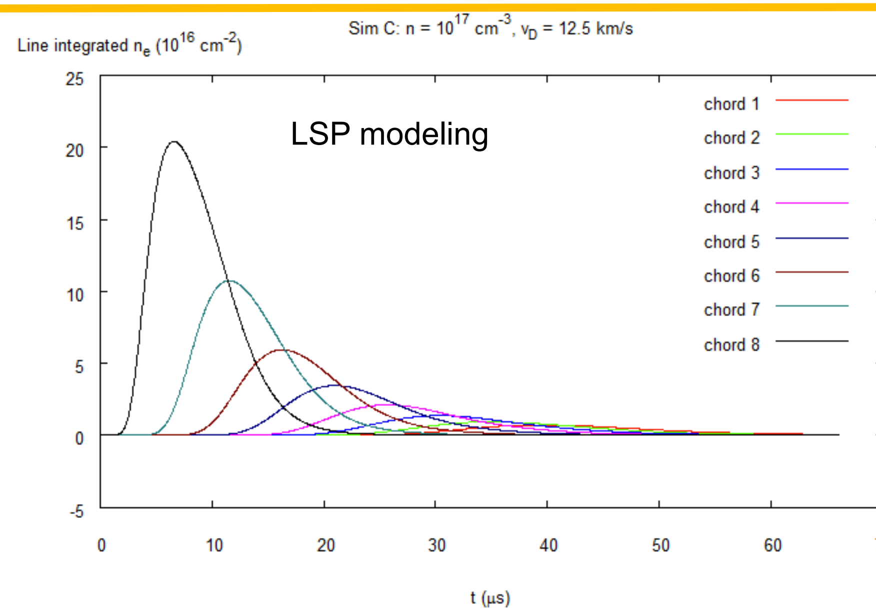


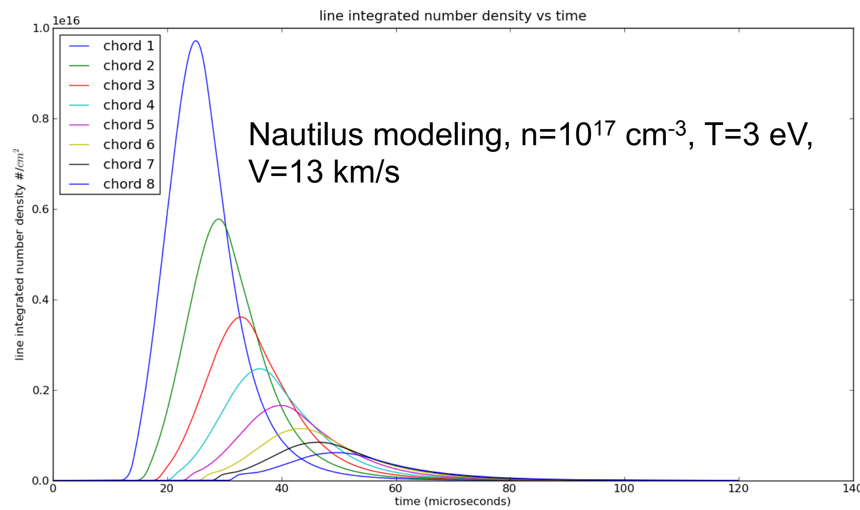
In our chamber p=1 mT ➔ $N \approx 3.5 \times 10^{20}$ atoms or molecules at T=298 K

Plots by Josh Davis (LANL)

Multi-chord interferometry* confirms expected jet density (~10^{16} cm^{-3}) & velocity (10–20 km/s) ranges, and a sharper leading edge profile than modeling predictions



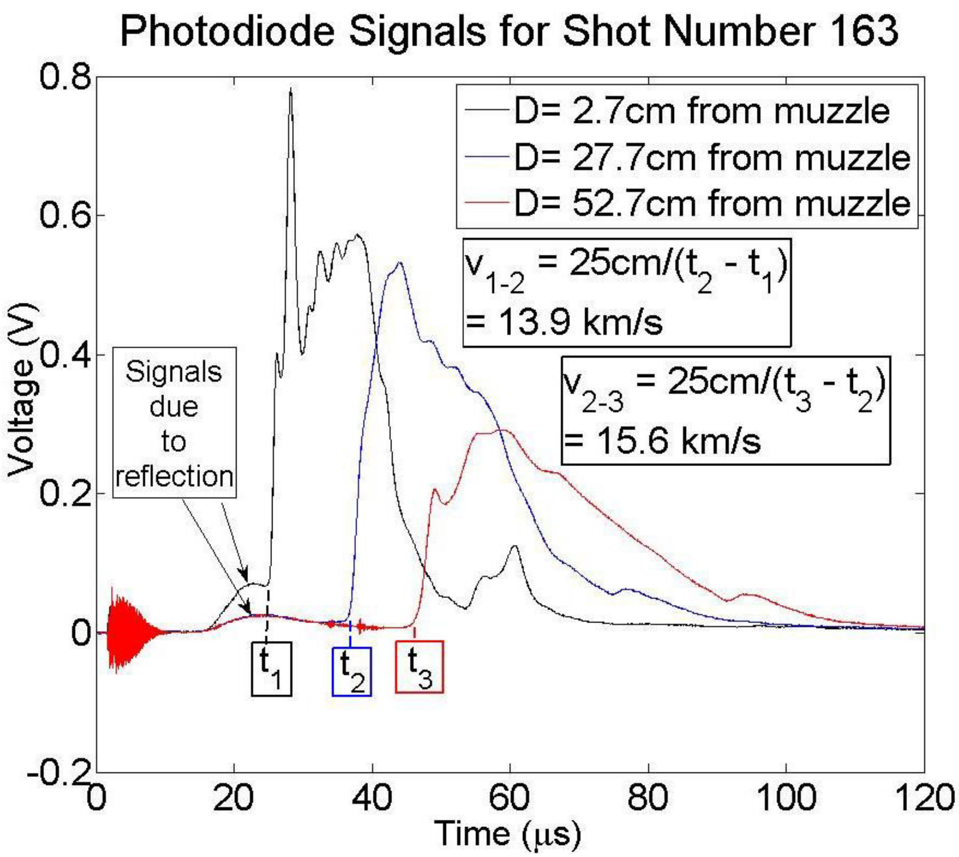


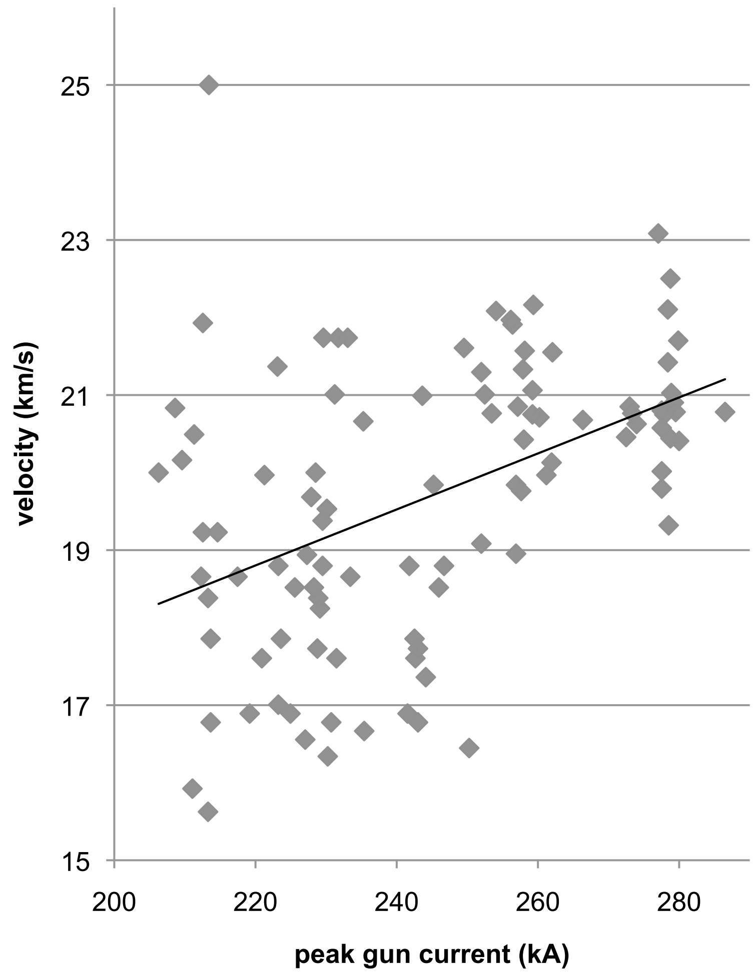


*Interferometry data by Liz Merritt (UNM); see poster TP9.00091 for details

LSP modeling by Carsten Thoma (Voss Scientific)

Photodiode array gives plasma jet velocity which goes up roughly linearly with peak gun current

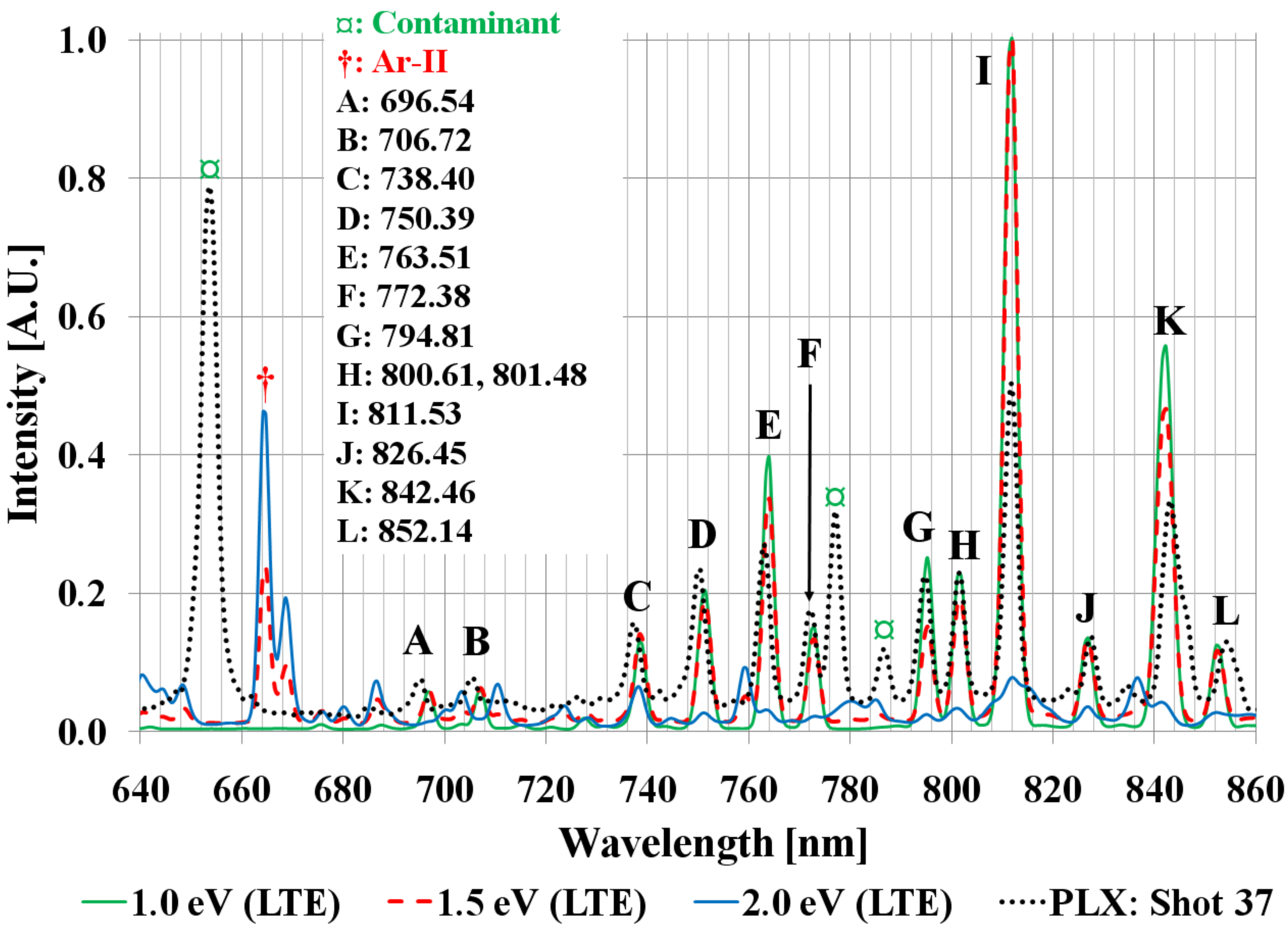




We see clear evidence for jet acceleration during propagation, and do not yet understand it…

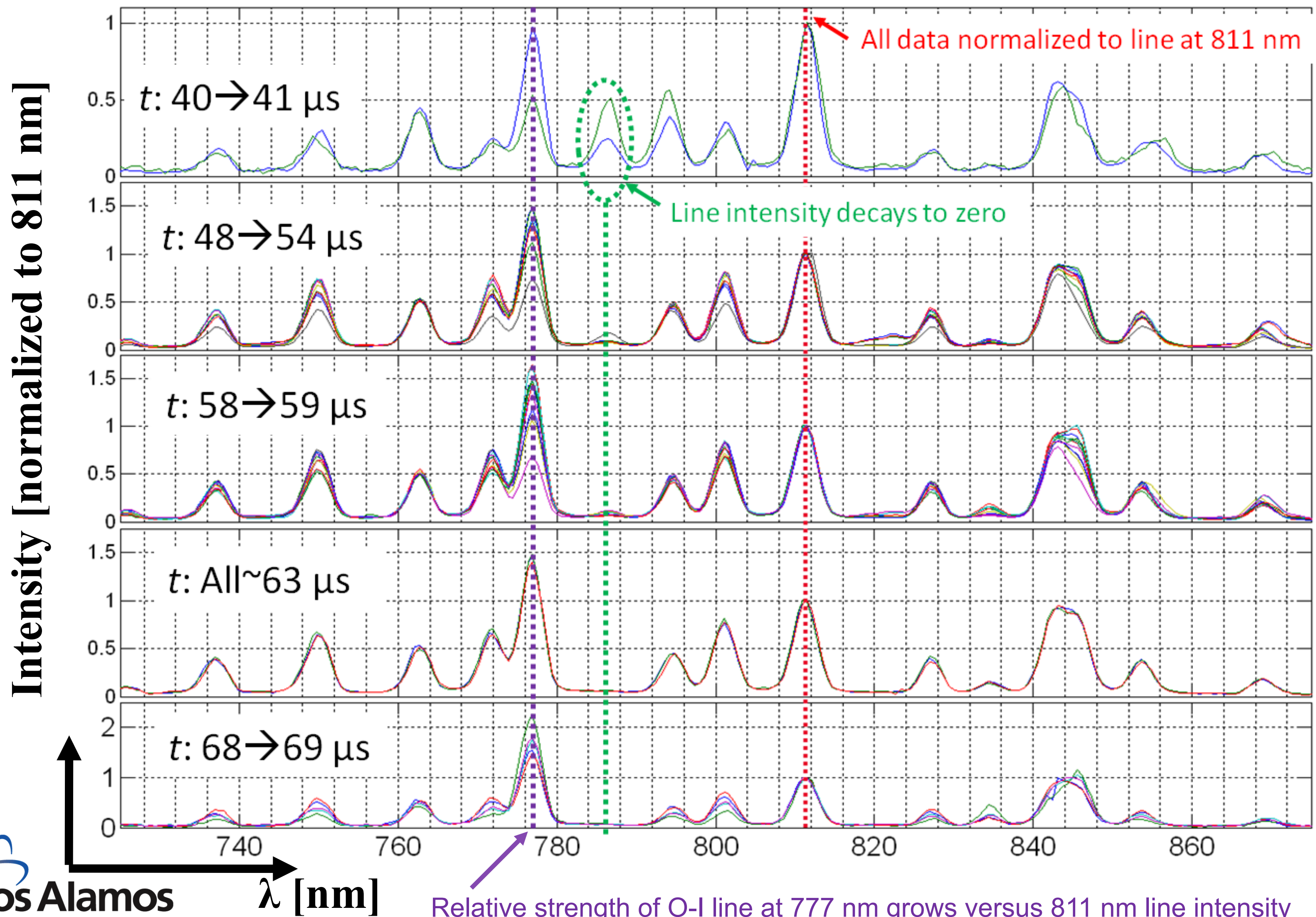
Photodiode data by Josh Davis (LANL)

Survey spectroscopy indicates the presence of Ar I and impurity lines – Absence of Ar II suggests T_e<1.5 eV



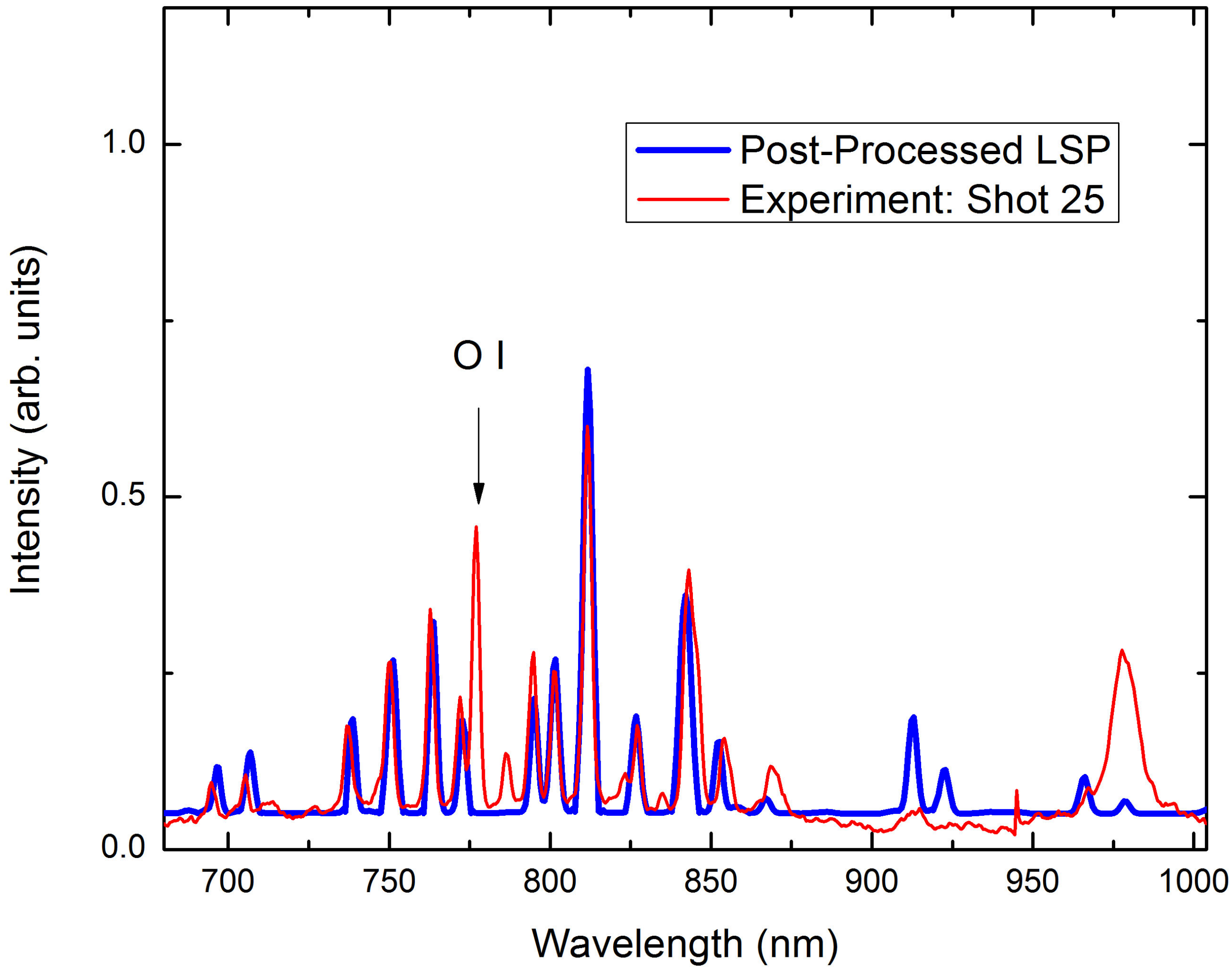
Plot by Tom Awe

Spectrum obtained 25 cm from gun nozzle shows systematic changes across jet's axial extent



Plot by Tom Awe

Detailed comparisons between survey spectroscopy data and numerical modeling is underway



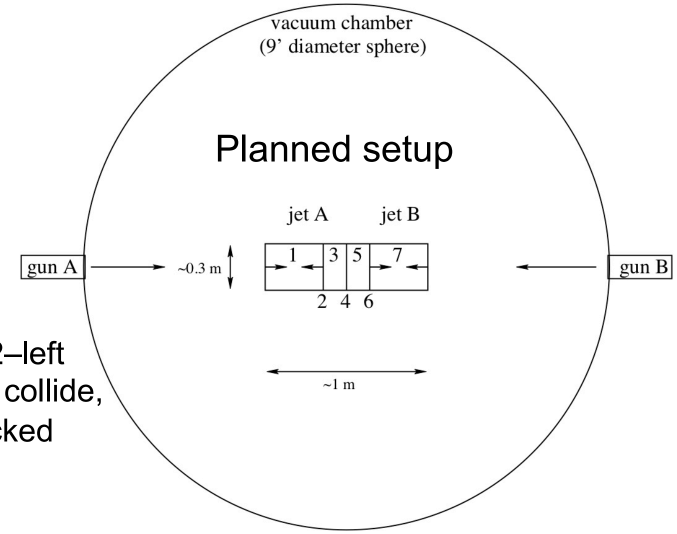
Plot courtesy of MacFarlane, Golovkin, Awe, Thoma

A cosmically-relevant collisionless shock experiment will be fielded by colliding two plasma jets head-on*

Table 1 *Proposed reference experimental values, and evaluation of the resultant physics criteria against Drake's [Drake, 2000] criteria for a cosmically-relevant collisionless shock experiment. All speeds are for the laboratory frame of reference.* R. P. Drake, Phys. Plasmas **7**, 2690 (2000)

parameter	jets at collision	jets initial
species	H^+	H^+
density (cm^{-3})	3×10^{14}	$\sim 5 \times 10^{15}$
temperature (eV)	1	2.5
speed (km/s)	100	100
magnetic field (G)	1000 (applied)	50 (decays quickly)
length L (cm)	50	35
radius R (cm)	15	5
background vacuum pressure (Torr)	10^{-6}	10^{-6}
shock speed V_s (km/s)	167	N/A
post-shock T_i (eV)	139	N/A
criterion (see Sec. 3.2)	**estimate for proposed experiment**	
$2R/\rho_i \gg 1$	25	
post-shock $\beta > 1$	1.7	
$M_A > 1$	2.1	
$\lambda_i/\rho_i \gg 1$	~ 10 (quasi-$\perp$) and 2–3 (quasi-$\|$)	
$R_M \gg 1$	~ 100	
$\lambda_{in} > L$	> 2 (1% neutrals in jet)	
$\omega_{ci}\tau_{exp} \gg 1$	20	
$L/(c/\omega_{pi}) \gg 1$	40	

Bow shock around young star LL Ori (image credit: Hubble Institute).



Legend for figure on right: 1–unshocked plasma of jet A, 2–left going shock, 3–shocked plasma of jet A, 4–where jets A/B collide, 5–shocked plasma of jet B, 6–right going shock, 7–unshocked plasma of jet B.

*Funded by LANL LDRD FY12–FY14

Collisionless shock research issues we hope to address

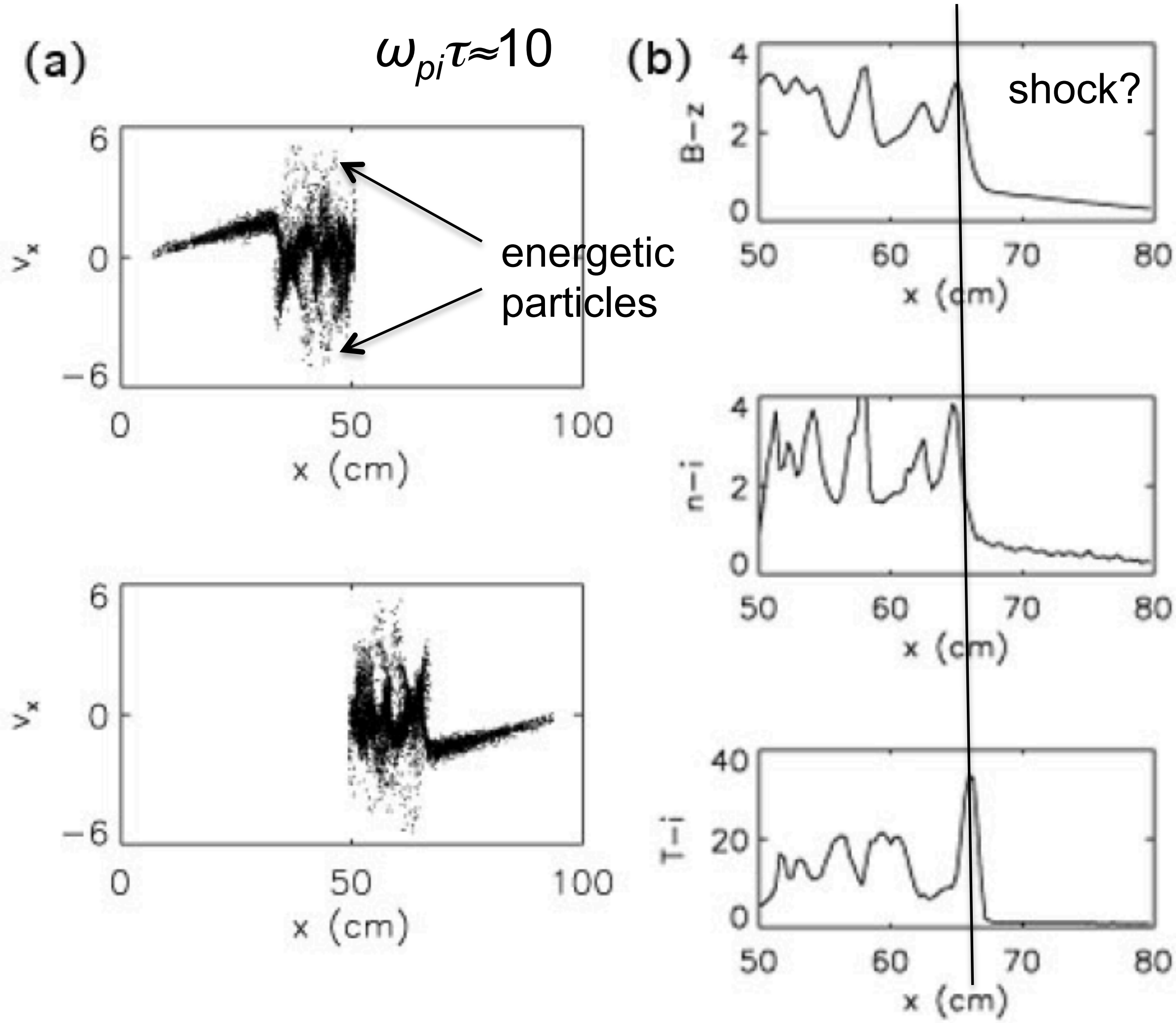
Issues	Yes	Stretch goal	Probably not
Shock structure	x		
Particle acceleration	x (above thermal)		x (>> thermal)
B-field generation	x		
Formation time		x	
Formation mechanism (filamentation, Weibel?)		x	
Ion vs. electron heating		x	
Particle injection		x	
Role of B-field on above	x	x	

Collisionless 1D hybrid-PIC simulations of colliding jets using planned parameters reveal complex interaction

(a) v_x normalized to V_A=120 km/s; x normalized to c/ω_{pi}

(b) B_z normalized to 1 kG; n_i normalized to 3×10^{14} cm^{-3}; T_i normalized to 10 eV

As B-field varies to parallel, there is more penetration and longer time for shock formation.

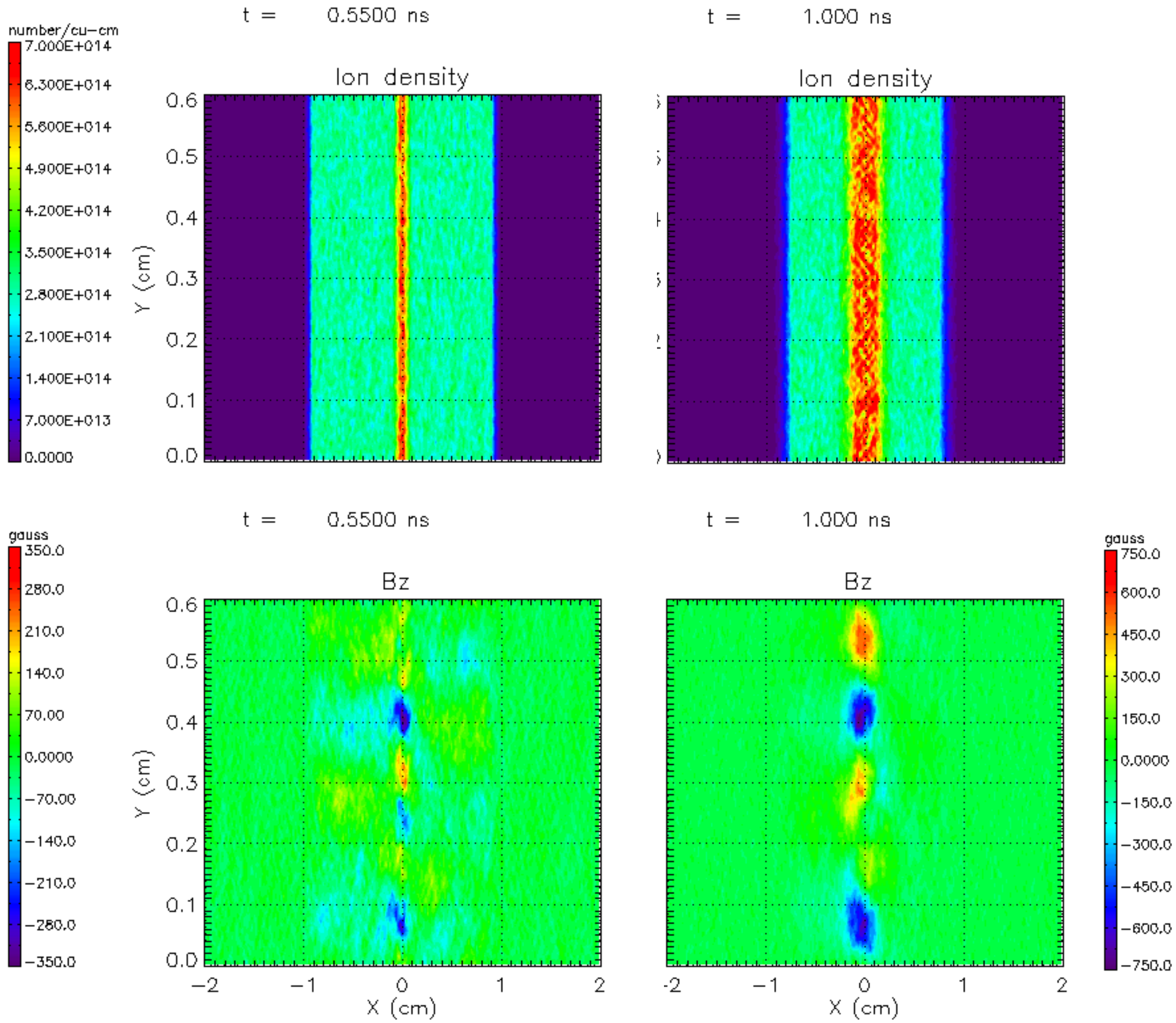


Simulation/plots courtesy of D. Winske (LANL)

We are setting up 2D hybrid-PIC simulations to determine requirements on initial plasma jet parameters

Sample 2D collisionless hybrid-PIC simulation with reduced mass ratio

This code (LSP) has collision package and atomic physics and EOS models for accurate plasma jet simulations



Simulation/plots courtesy of C. Thoma (Voss Scientific)

Summary

- **Merging plasma jets and imploding plasma liners have many applications**
  - Assembling repetitive cm-, μs-, Mbar-scale plasmas for HEDLP scientific studies
  - Collisionless shock and other plasma astrophysics experiments
  - Innovative standoff driver for magneto-inertial fusion (MIF)
- **PLX plans to explore/demonstrate formation of imploding plasma liners to ~1 Mbar peak pressure using 1.5 MJ of initial stored energy**
- **Focus will be on predictive physics understanding of:**
  - Plasma jet propagation, expansion, merging
  - Liner formation and convergence
  - Stagnation dynamics determining peak pressure and dwell time
- **There is a coordinated multi-institutional theory/modeling effort using many different codes**
- **First plasma fired on PLX 9/13/11, with single jet propagation experiments underway and two jet experiments planned Jan–May 2012**

Sign up for copies (email only please)