Laboratory plasma experiments using merging supersonic plasma jets

Bringing Space Down to Earth Workshop, UCLA

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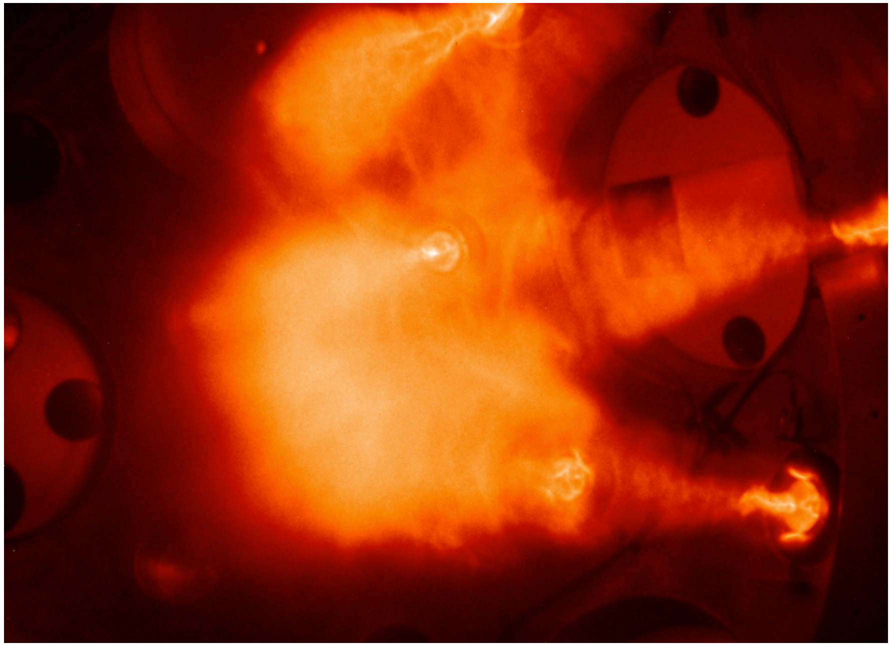


Six argon plasma jets merging (10-ns exposure, false color).

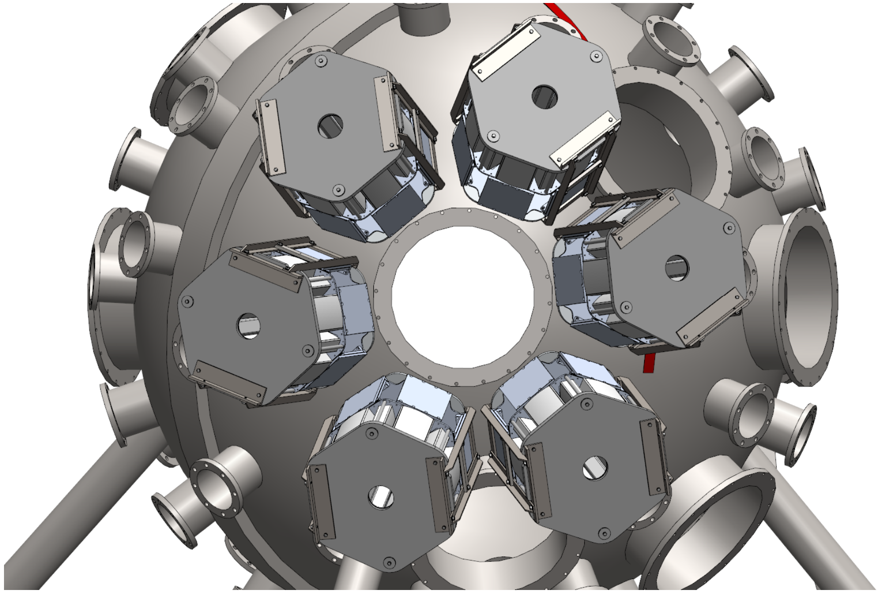
Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

Outline

- Experimental platform
- Configurations, parameter ranges, and physics studies enabled
- Sample results from colliding-jet experiments

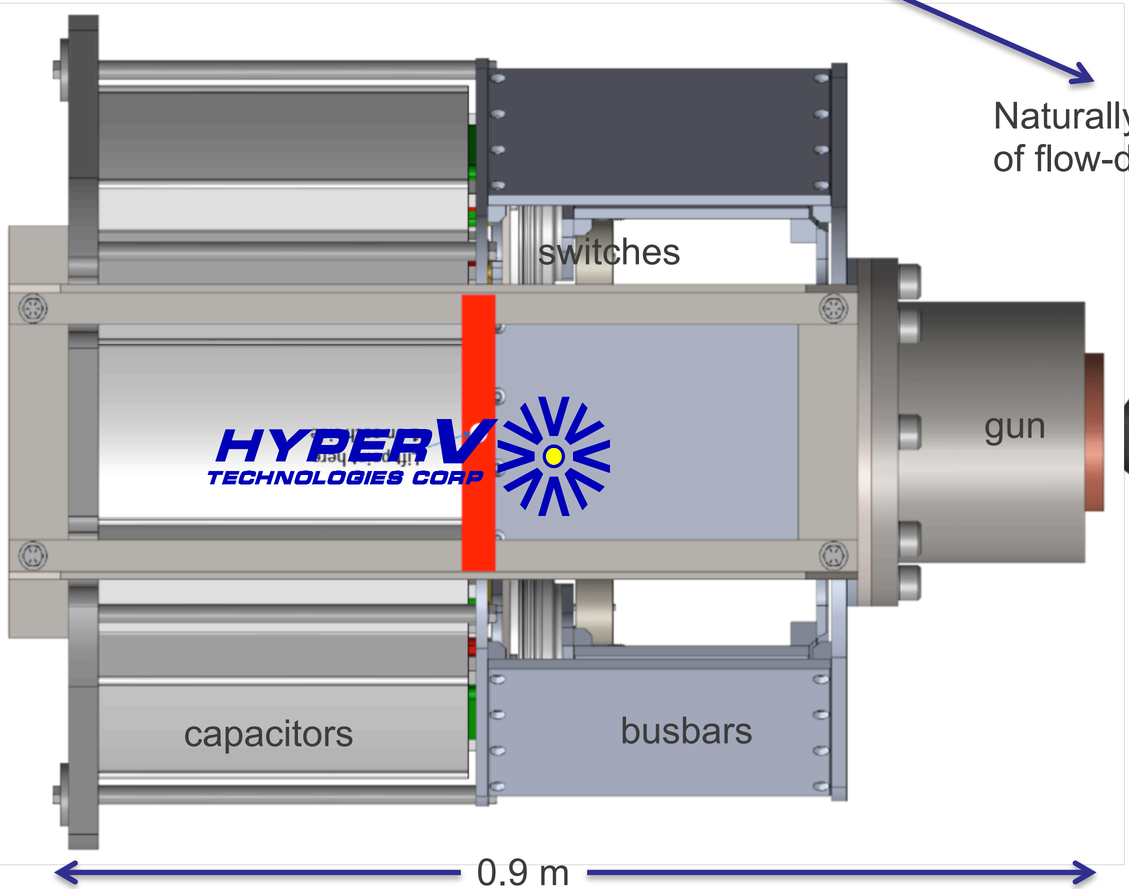
Existing experimental platform

Plasma Liner Experiment (PLX)



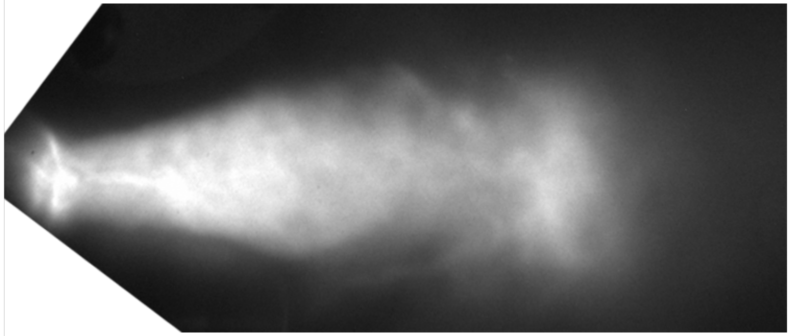
Six coaxial plasma guns mounted on a 9-ft.-diameter chamber.

Innovative coaxial plasma guns produce supersonic plasma jets of unprecedented combination of mass, density, and velocity



7.5-kJ capacitor stored energy per gun (5 kV, >600 kA)
1.5-kJ kinetic energy per jet

Naturally enables generation of a variety of flow-dominated plasma configurations

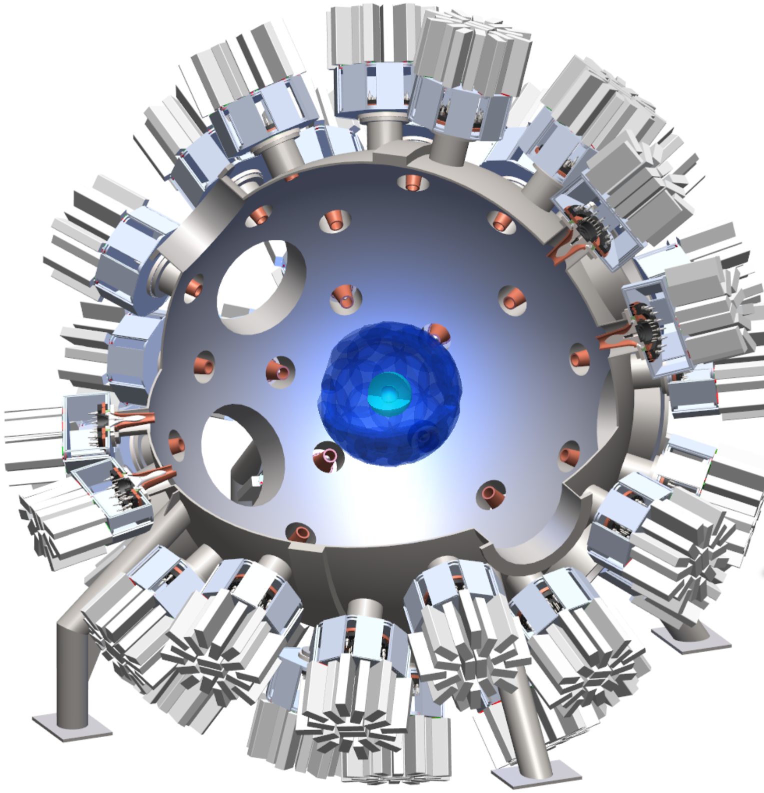


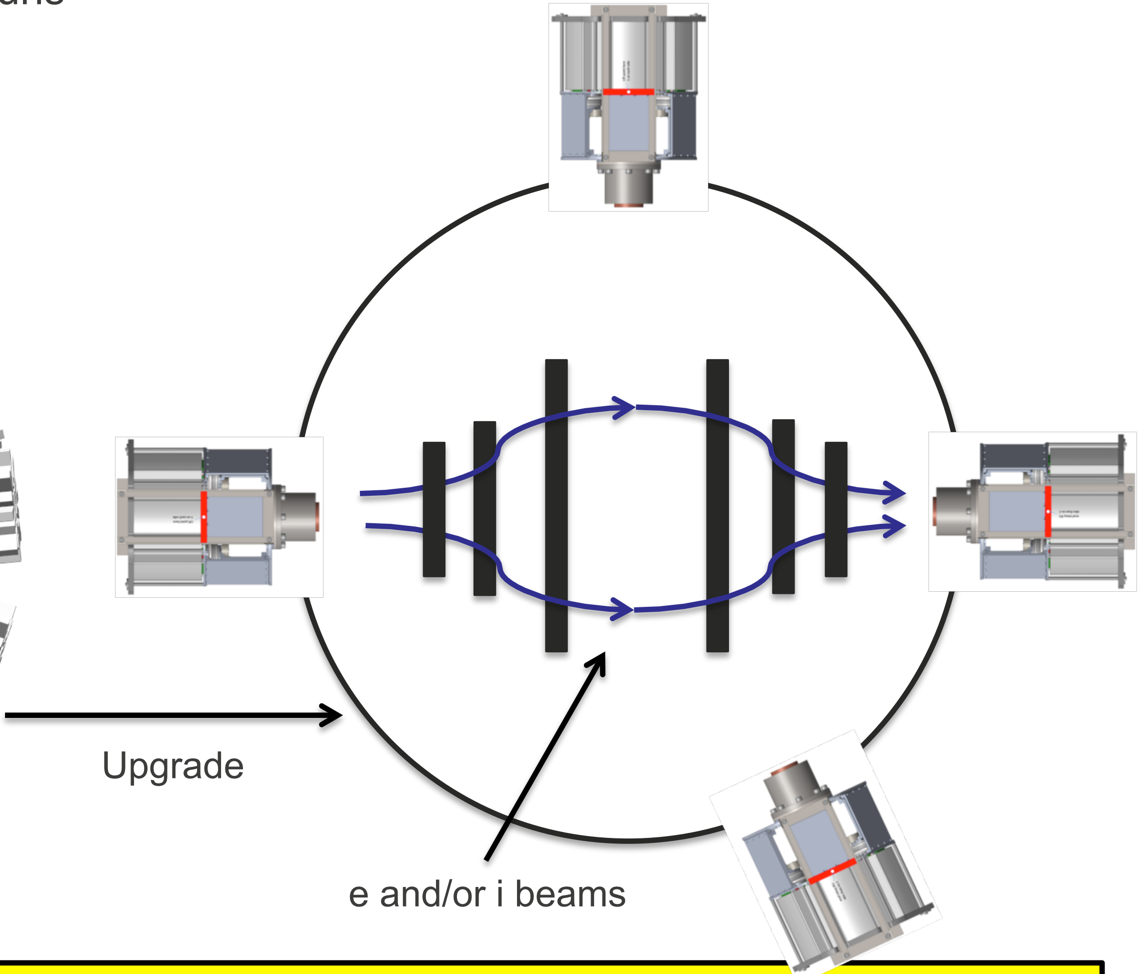
n_i ~ 10^{16} cm^{-3}
$T_e \approx T_i$ ~ 1.5 eV
V ≈ 50 km/s
mass ~ 1 mg
R ≈ 4 cm
L ≈ 25 cm
Any species/mixture from compressed-gas bottle

Planned and proposed experimental platforms

Planned (over next few years): 36–60 guns surrounding the chamber

Proposed: Add a mirror-like plasma "target," upon which other jets will impinge and drive flows





Enable space-physics-relevant experiments on fundamental plasma processes (e.g., dynamo, reconnection, shocks, turbulence, self-organization, etc.).

Space plasmas span a broad parameter range presenting a challenge to laboratory experiments

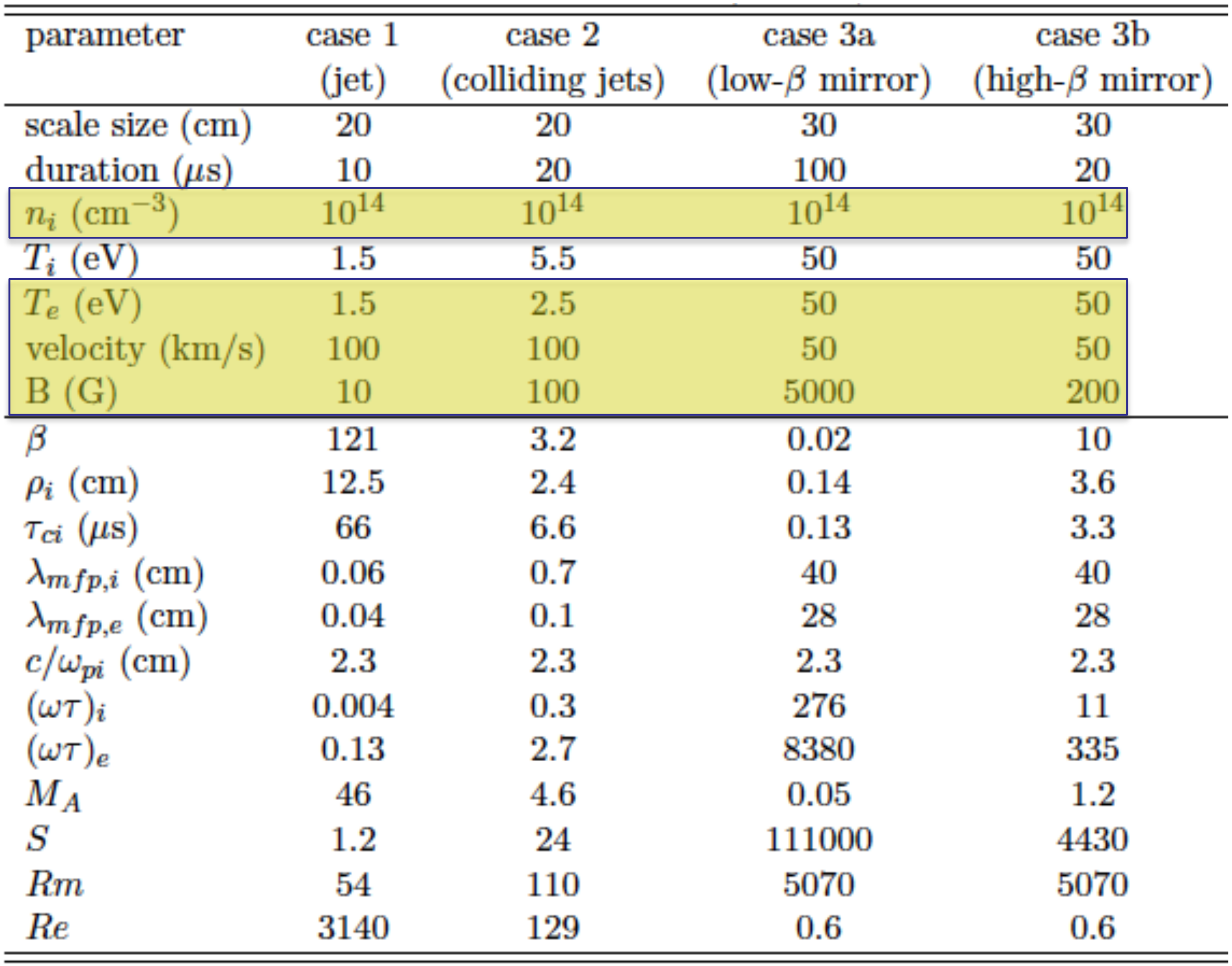
key parameters	**“traditional” lab plasma experiments**	**PLX achieved/ proposed**
β	< 1	0.01–10
$\rho v^2/(B^2/2\mu_0)$	$<< 1$	0.1–100
M, M_A	$<< 1$	$M>>1$, $M_A \geq 1$
T_e, T_i	<20 eV	>50 eV
R_m	<100	$\sim 5\times 10^3$
S	$<10^3$	$\sim 10^5$
λ_{ii}/L	~ 1	0.01–5

Key challenges for PLX include having sufficient plasma lifetime (need $\tau >> \tau_{ci}$) and spatial size (need $L >> c/\omega_{pi}$)

Three fundamental plasma configurations

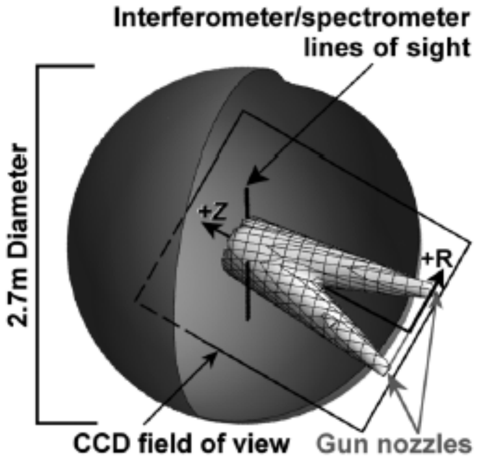
Configuration	Attributes	Physics studies enabled	Relevant space environments or problems
Colliding jets with or w/o B field	High counter-streaming velocities to access magnetized, collisionless regimes	Shock structure and particle acceleration, collisionless-shock dissipation mechanisms	Magnetopause, heliopause
Jets colliding with mirror-like target (low or high β)	Both high temperature and flow-dominated, inherently 3D/ dynamic	Flow-driven dynamo, 3D reconnection, collisionless shocks, possibly low- or high-β turbulence	Solar corona, solar wind, magnetotail
Single-jet propagation	Simple, diagnosable	EOS, non-LTE atomic physics, basic heat/ momentum transport, turbulent flow	Ionosphere or other with $Z>1$

Parameters for plasma configurations

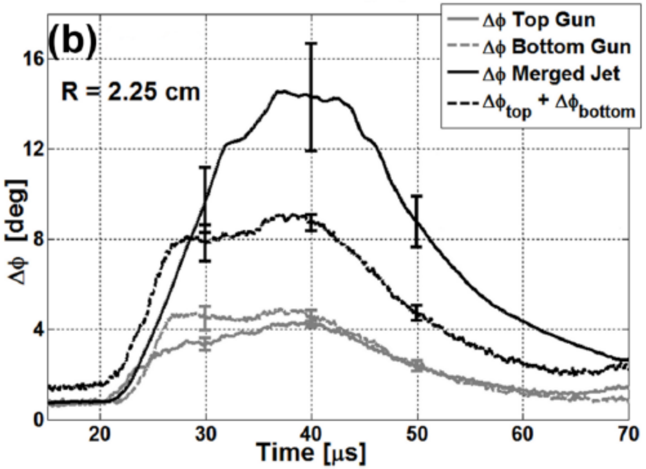


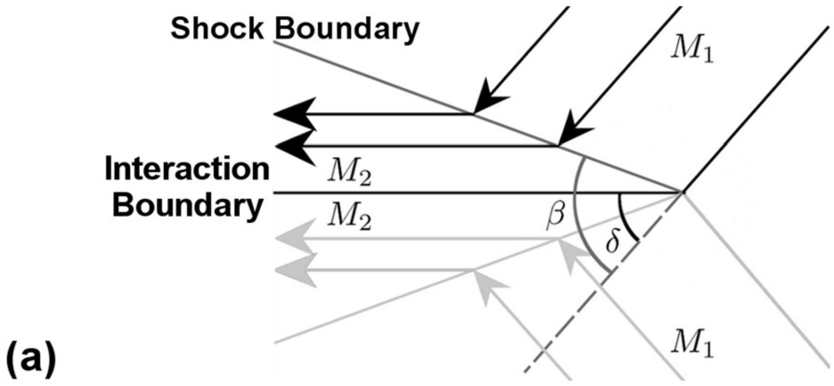
parameter	case 1 (jet)	case 2 (colliding jets)	case 3a (low-β mirror)	case 3b (high-β mirror)
scale size (cm)	20	20	30	30
duration (μs)	10	20	100	20
n_i (cm^{-3})	10^{14}	10^{14}	10^{14}	10^{14}
T_i (eV)	1.5	5.5	50	50
T_e (eV)	1.5	2.5	50	50
velocity (km/s)	100	100	50	50
B (G)	10	100	5000	200
β	121	3.2	0.02	10
ρ_i (cm)	12.5	2.4	0.14	3.6
τ_{ci} (μs)	66	6.6	0.13	3.3
$\lambda_{mfp,i}$ (cm)	0.06	0.7	40	40
$\lambda_{mfp,e}$ (cm)	0.04	0.1	28	28
c/ω_{pi} (cm)	2.3	2.3	2.3	2.3
$(\omega\tau)_i$	0.004	0.3	276	11
$(\omega\tau)_e$	0.13	2.7	8380	335
M_A	46	4.6	0.05	1.2
S	1.2	24	111000	4430
Rm	54	110	5070	5070
Re	3140	129	0.6	0.6

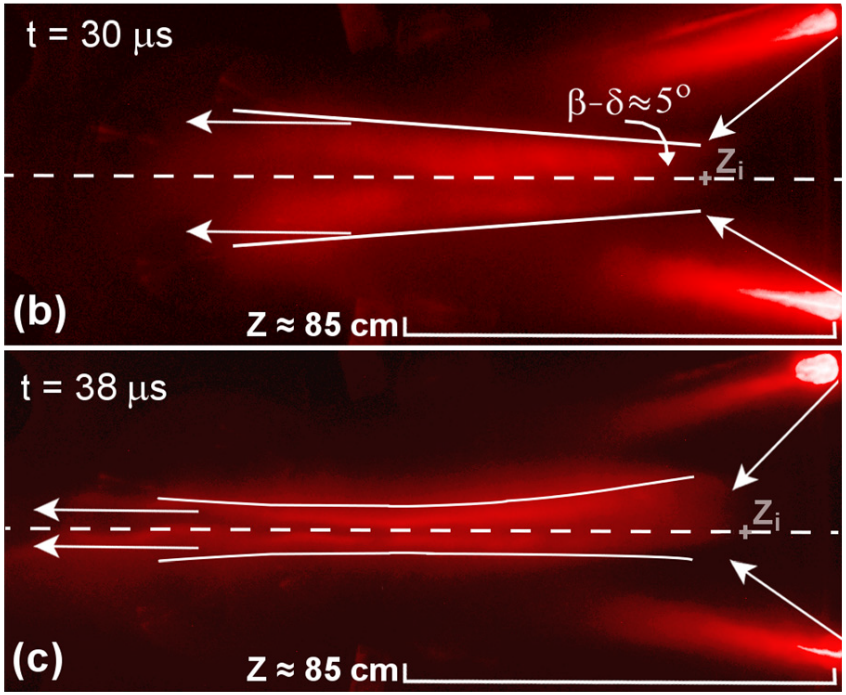
Collisional shock formation by obliquely merging plasma jets → confirming the hydrodynamic limit



$$\frac{n_2}{n_1} = \frac{(M_1 \sin \beta)^2(\gamma + 1)}{(M_1 \sin \beta)^2(\gamma - 1) + 2}$$

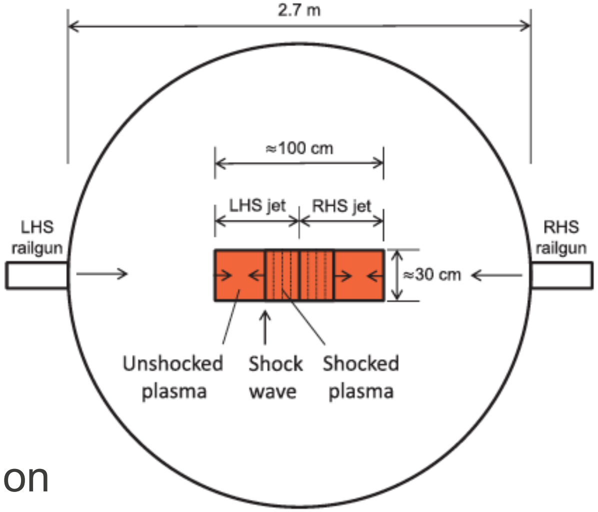






E. C. Merritt et al., *Phys. Rev. Lett.* **111**, 085003 (2013); *Phys. Plasmas* **21**, 055703 (2014).

First attempt to generate a collisionless shock; we were thwarted by an interesting effect



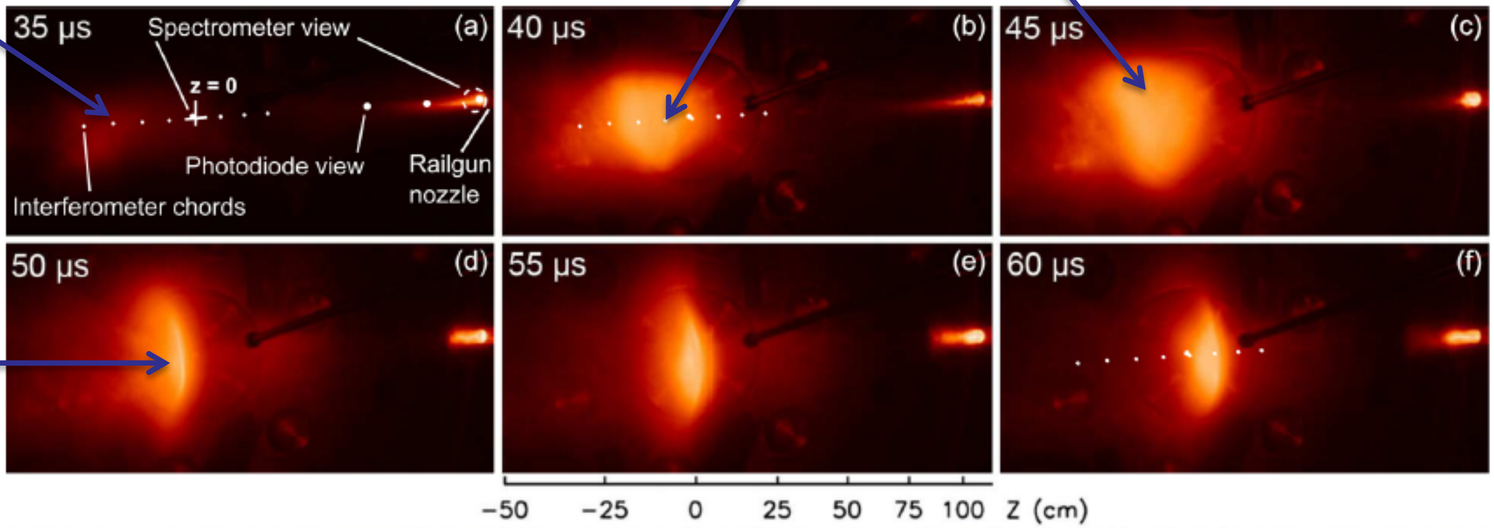
Interjet ion-ion mean free path $\lambda_{ii} \sim Z^{-4}$, where Z is mean ionization level.

We inferred that Z rose from 1.2 to 1.7 between 35 and 40 μs (due to presence of impurities), leading to drop in λ_{ii} from hundreds of cm to ~30 cm.

Collisionless interpenetration

Transition to collisional stagnation

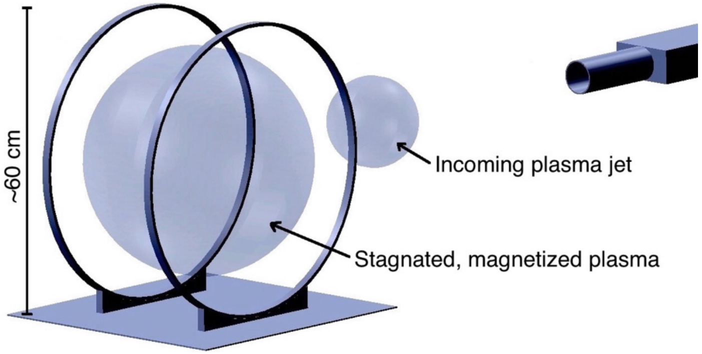
Shock formation



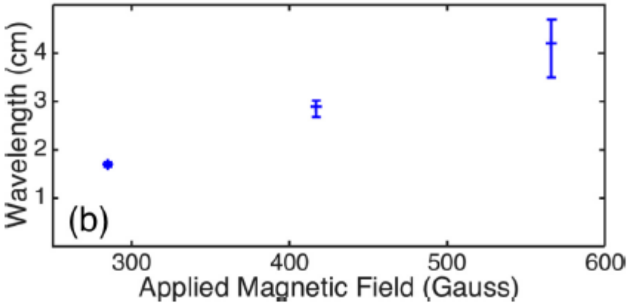
Our new plasma guns have much-lower impurity levels → interaction expected to remain collisionless

A. L. Moser and S. C. Hsu, *Phys. Plasmas* **22**, 055707 (2015).

Precursor to a "mirror target": studies of Rayleigh-Taylor instability at a decelerating plasma interface

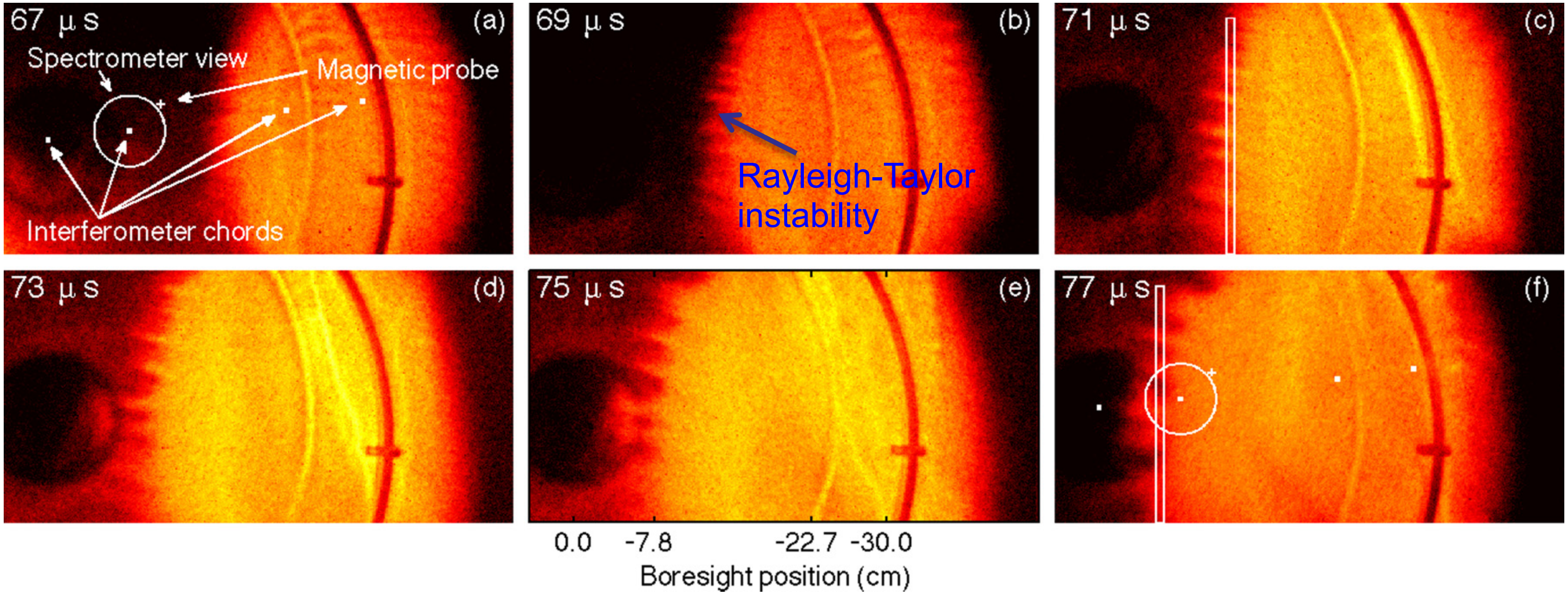


Magnetic stabilization



Viscous stabilization

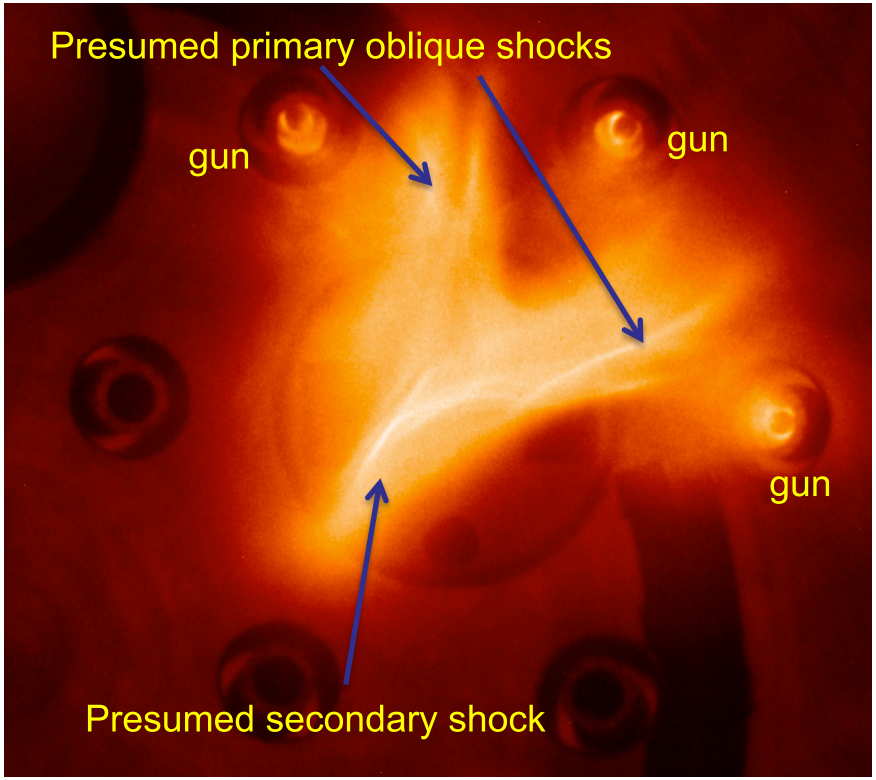
$\lambda_{cutoff} \sim 4\pi[v^2/(gA)]^{1/3} \sim T_i^{5/3} Z^{-8/3} \approx 2$ cm



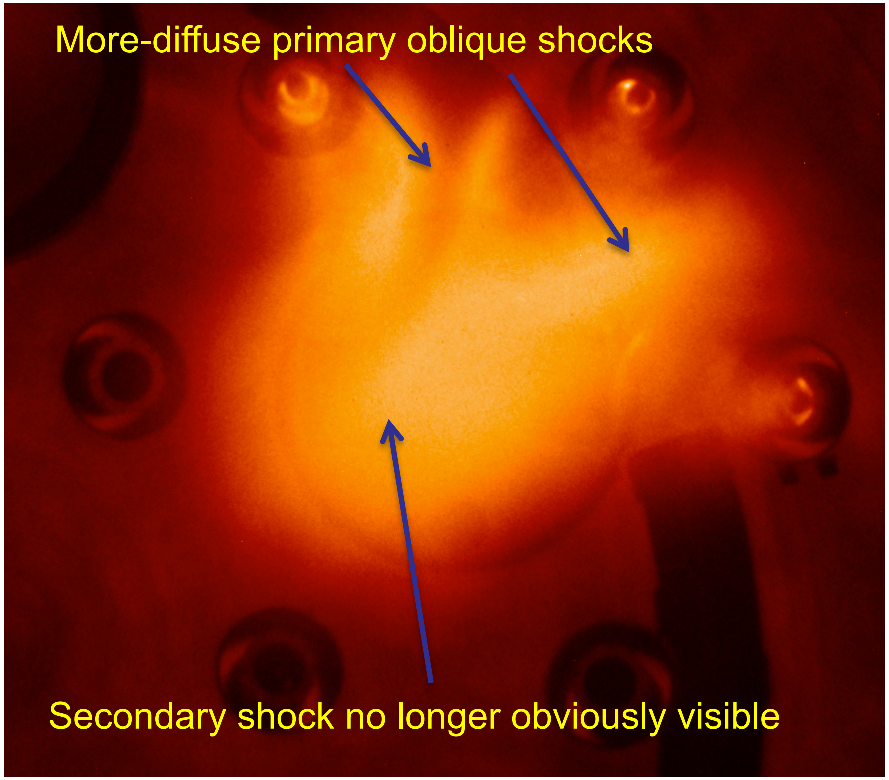
C. S. Adams, A. L. Moser, and S. C. Hsu, *Phys. Rev. E* **92**, 051101(R) (2015).

Possible effects of impurities and radiation cooling on shock formation (using new plasma guns)

3-gun shots; end-on view; *t*=27 μs after guns fire; 10-ns exposure
(log intensity plotted in false color)



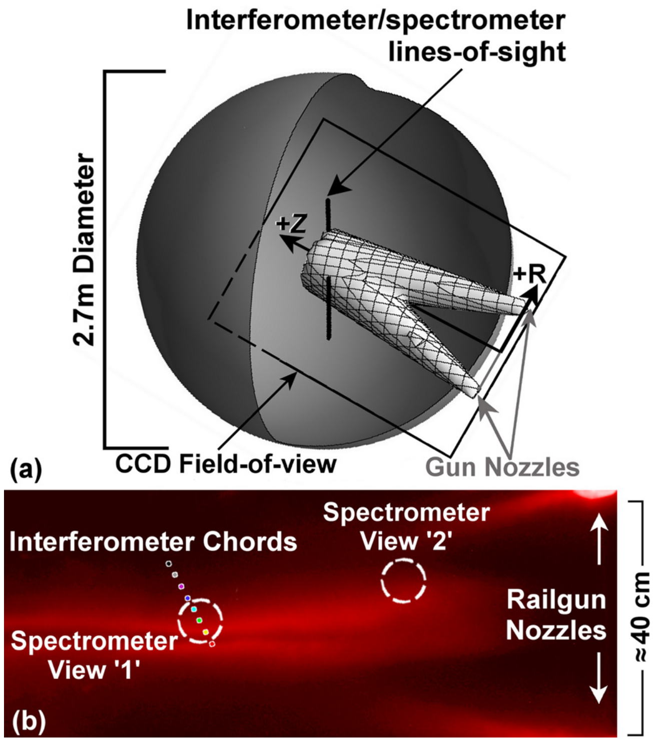
Early shot after gun install, up to 50% higher impurity level compare to right-hand image

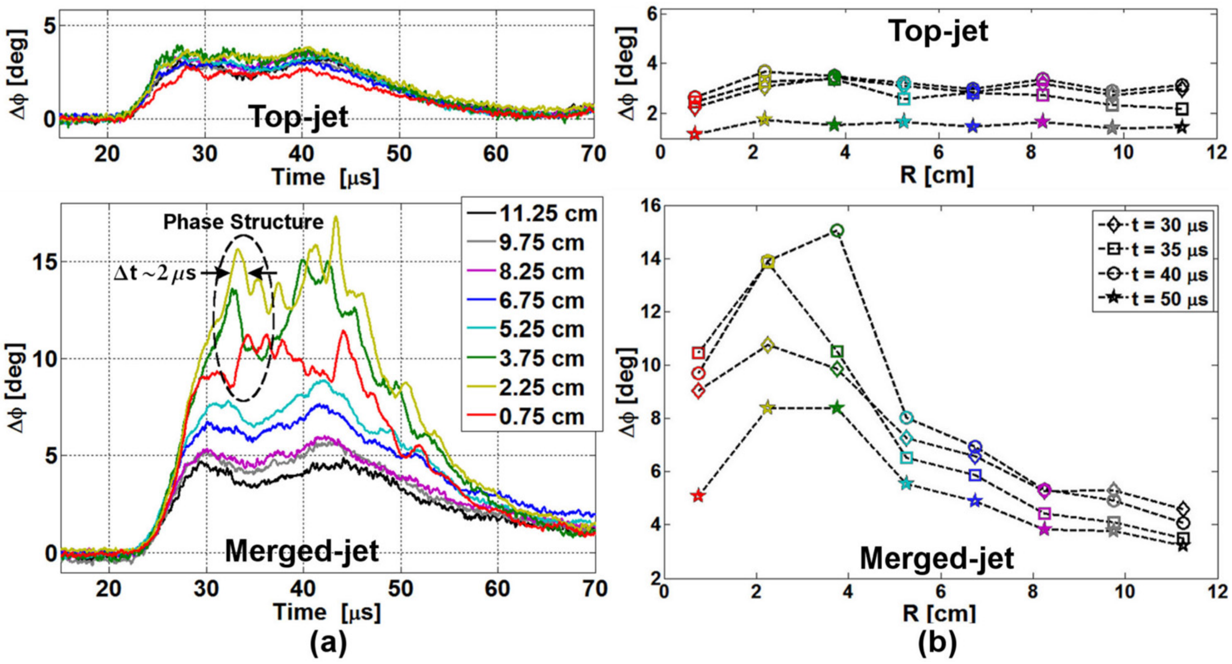


20 shots later (same settings), up to 50% lower impurity level compared to left-hand image

Discussion and questions

Sample interferometry data





E. C. Merritt et al., *Phys. Rev. Lett.* **111**, 085003 (2013); *Phys. Plasmas* **21**, 055703 (2014).

Sample spectroscopy data

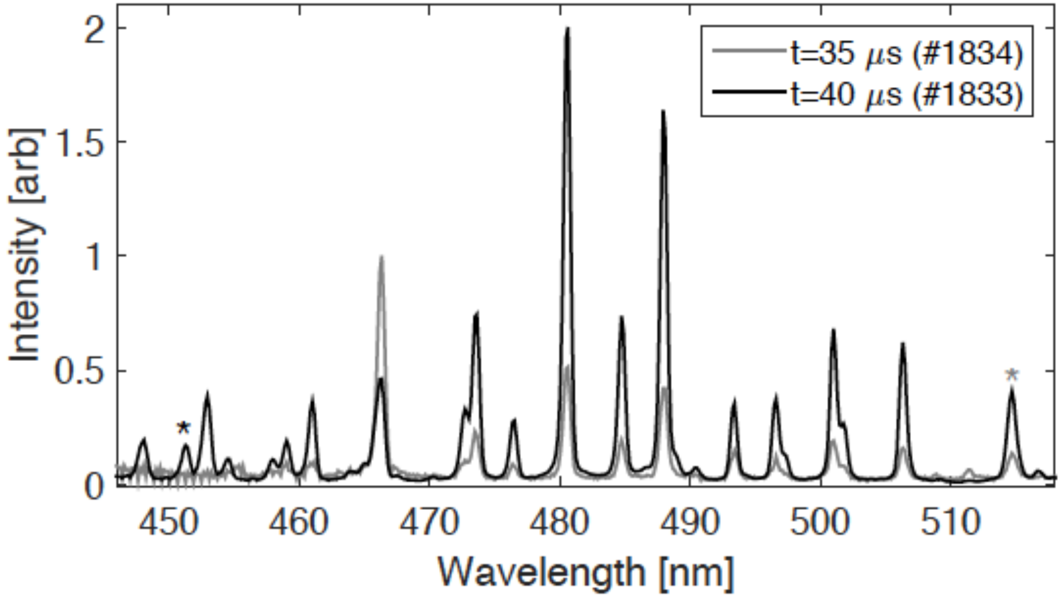


Figure 2: Spectroscopic measurements of argon experiments for $t = 35\ \mu s$ (shot #1834) and $t = 40\ \mu s$ (shot #1833), near $z = 0$ cm [see Fig. 2(a) of the paper for spectrometer chord position]. Lines used to determine T_e, 514.7 nm (Ar II) for the $t = 35\ \mu s$ case and 451.4 nm (Al III) for the $t = 40\ \mu s$ case, are indicated with an asterisk.

A. L. Moser and S. C. Hsu, *Phys. Plasmas* **22**, 055707 (2015).