SAND2021-13972C

PUFFIN
puffin.mit.edu

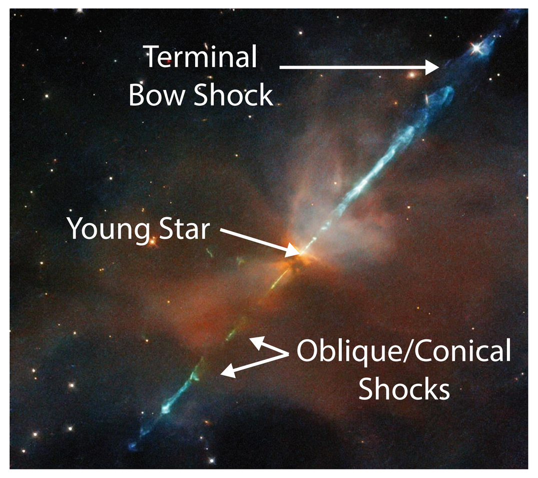
Magnetized Bow Shocks in Radiatively Cooled Collisional Plasma Flows

MIT | PSFC

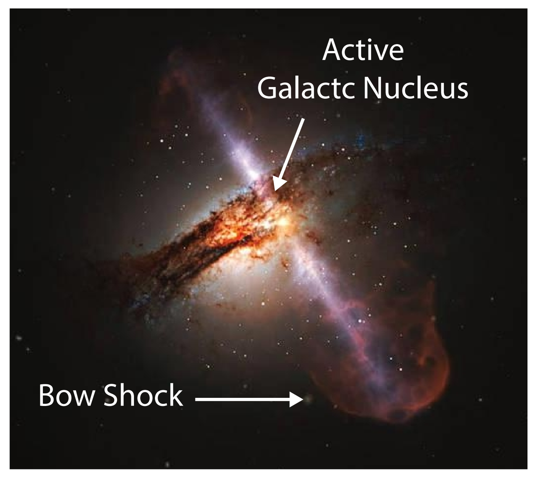
R Datta(rdatta@mit.edu)[1], J D Hare[1], C E Myers[2], D Ampleford[2], J P Chittenden[3], T Clayson[3], A Crilly[3], W Fox[4], J W D Halliday[3], C A Jennings[2], H Ji[4], C C Kuranz[5], S V Lebedev[3], R Melean[5], D R Russell[3], L G Suttle[3], I Tang[3] and D A Uzdensky[6]
[1]Plasma Science and Fusion Center, Massachusetts Institute of Technology, [2]Sandia National Laboratories, [3]Blackett Laboratory, Imperial College London, [4]Princeton Plasma Physics Laboratory, [5]University of Michigan, Ann Arbor, [6]University of Colorado, Boulder

Motivation

Supersonic magnetized plasma flows in astrophysical enviroments interact with obstacles to generate strongly radiating shocks.



Twin jets from young stellar object HH111. *Image: ESA/Hubble & NASA, B. Nisini*

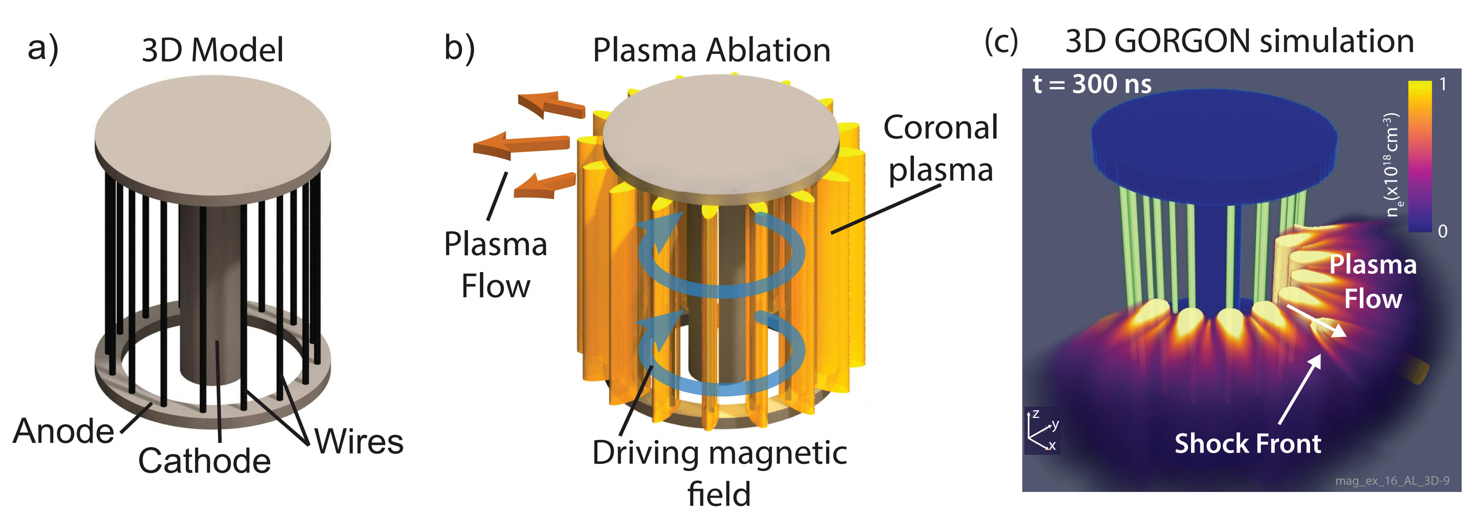


Relativistic jets from a supermassive blackhole. *Image: NASA/ESA/STScl*

Research goals:

(1) Generate astrophysically relevant magnetized bow shocks on ~1 MA facilities.
(2) Characterize shock morphology and post-shock magnetic field.
(3) Benchmark 3D resistive MHD simulations against experimental results.
(4) Use simulations to predict dynamics of strongly-radiatively cooled shocks on the ~10 MA generator at the Z HEDP facility for MARZ experiments.

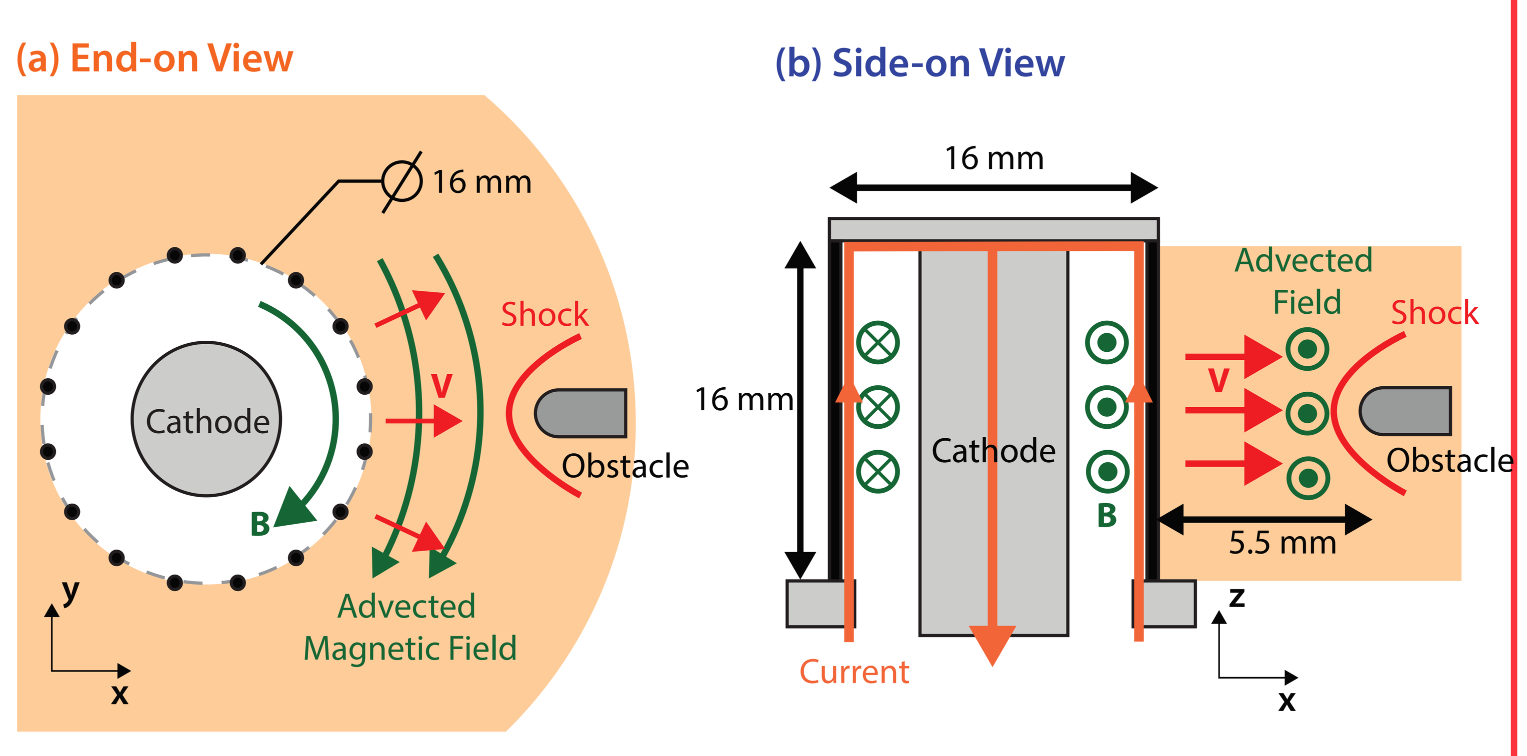
Pulsed-Power Driven Laboratory Plasma



An exploding wire array generates radially diverging plasma flows when a high-amplitude fast-rising current pulse is applied.

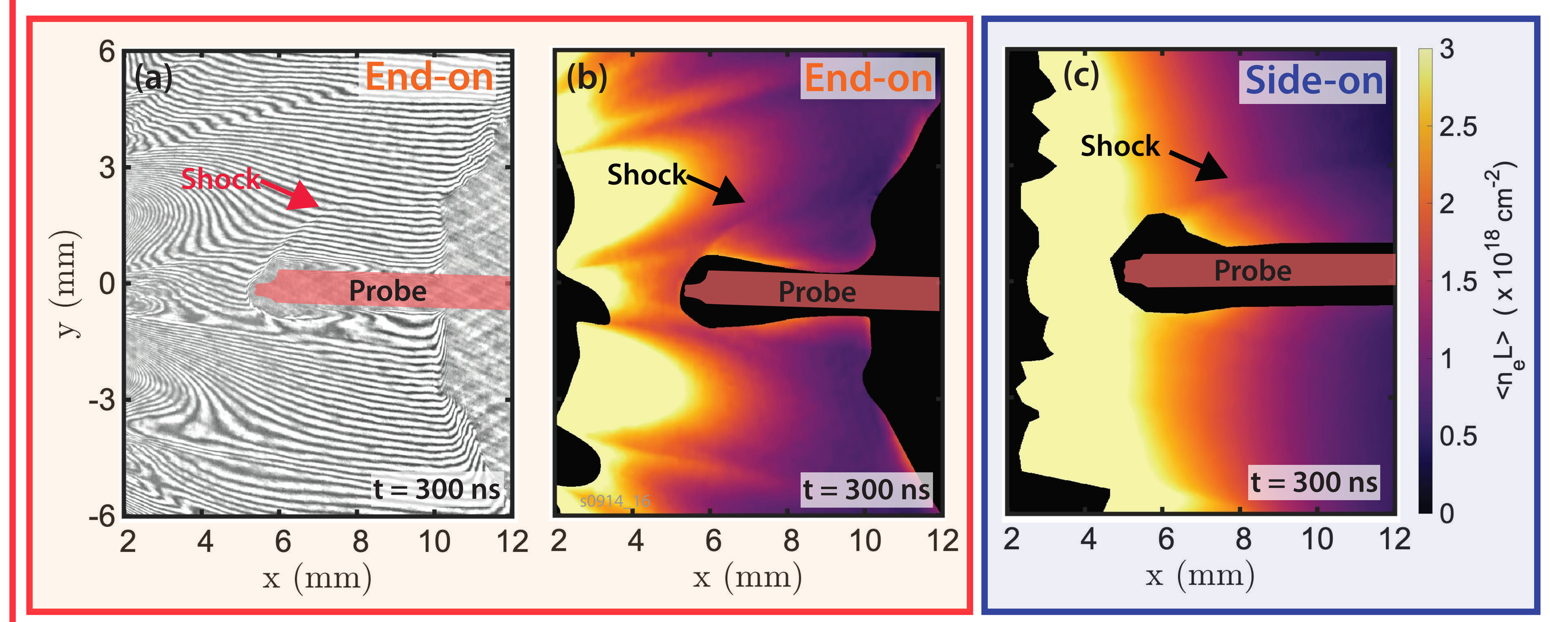
On MAGPIE, we use a 1.4 MA peak current with a 250 ns rise time, generating plasma flows of $n_e \sim 1 \times 10^{18}$ cm^{-3}, V ~100 km/s, B ~10 T, and $T_e \sim T_i \sim 10$ eV.

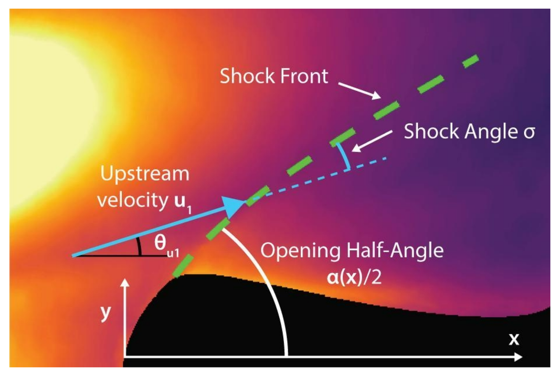
Experimental Setup



Exploding wire array with 16 equally-spaced 30 µm Φ Aluminum wires.
Obstacles are inductive probes that measure magnetic field.

Shock Geometry Measurements





Shock Angle:

$$\sigma = \alpha(x)/2 - \theta_{u1}$$

Mach Angle:

$$\mu = \sigma(x \to \infty) \approx \sin^{-1}(1/M_1)$$

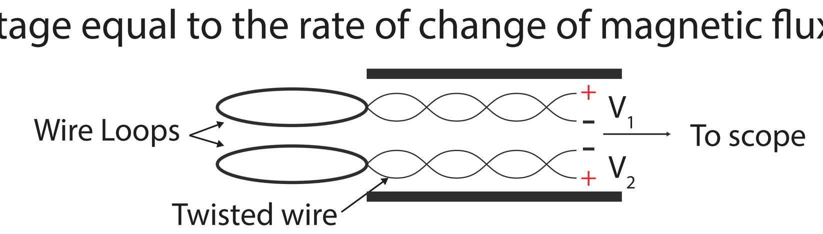
(1) Shock opening angle is larger in end-on plane ($\alpha(\infty)/2 \approx 30^\circ$) than in side-on plane ($\alpha(\infty)/2 \approx 7^\circ$).
(2) Mach angles are ~11° (end-on) and ~7° (side-on).
Expected upstream Mach numbers are 5.2±0.3 (end-on), and 8.2 ±0.6 (side-on).

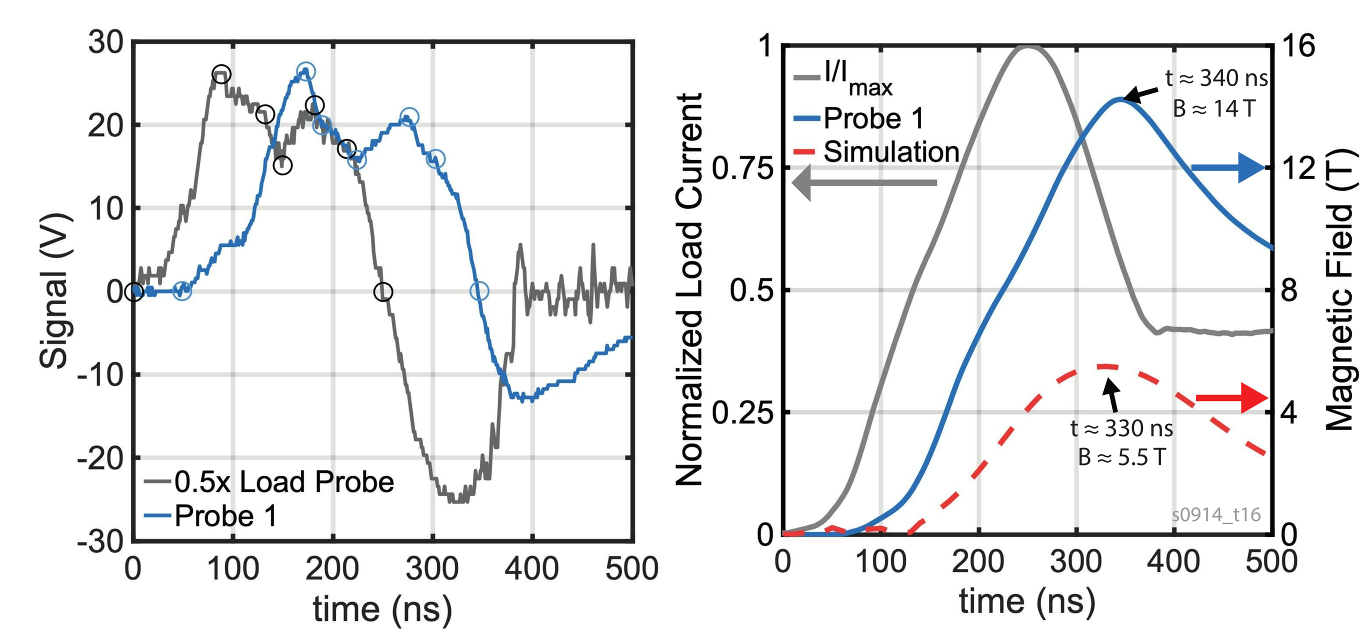
Magnetic Field and Velocity Measurements

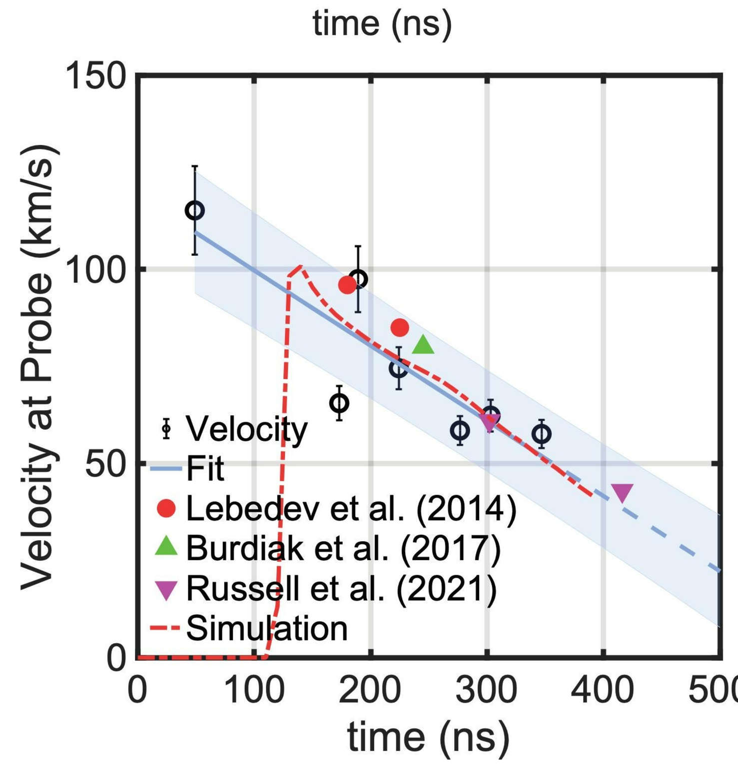
Inductive probes generate a voltage equal to the rate of change of magnetic flux.

$$V_{1,2} = \pm\dot{B}A_p + V_s$$

$$V = \frac{1}{2}(V_1 - V_2)$$







At t = 300 ns,

V = 62 ± 12 km/s

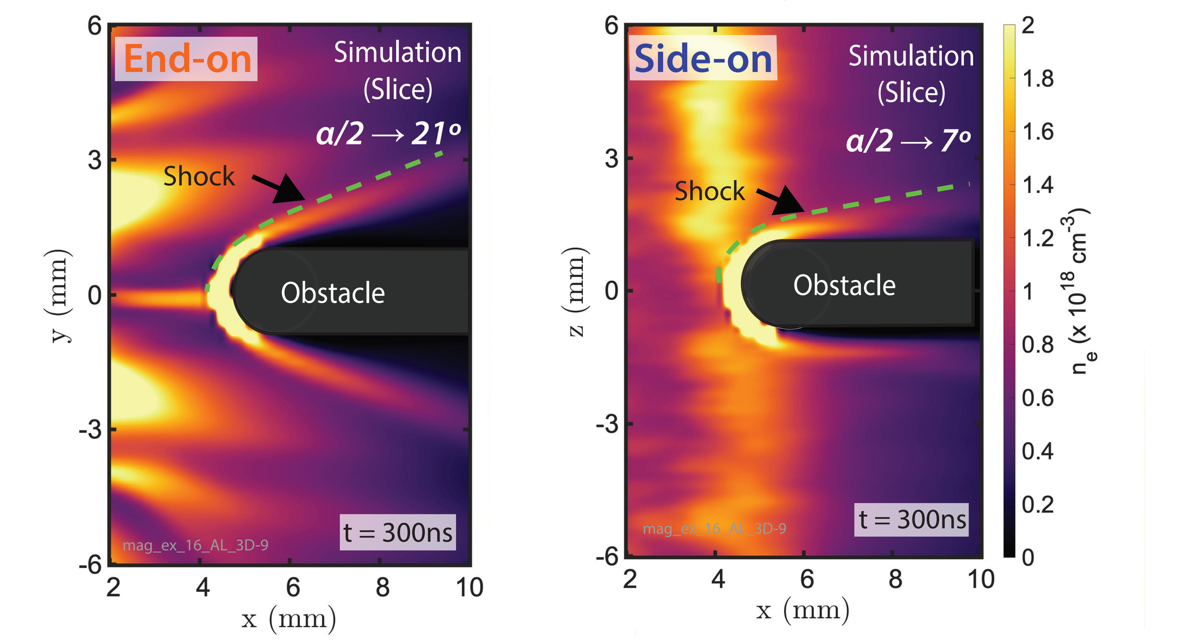
For side-on (hydrodynamic) shock
$M_s = 8.2 \pm 0.6$

So electron temperature:
$ZT_e = 14 \pm 6$ eV

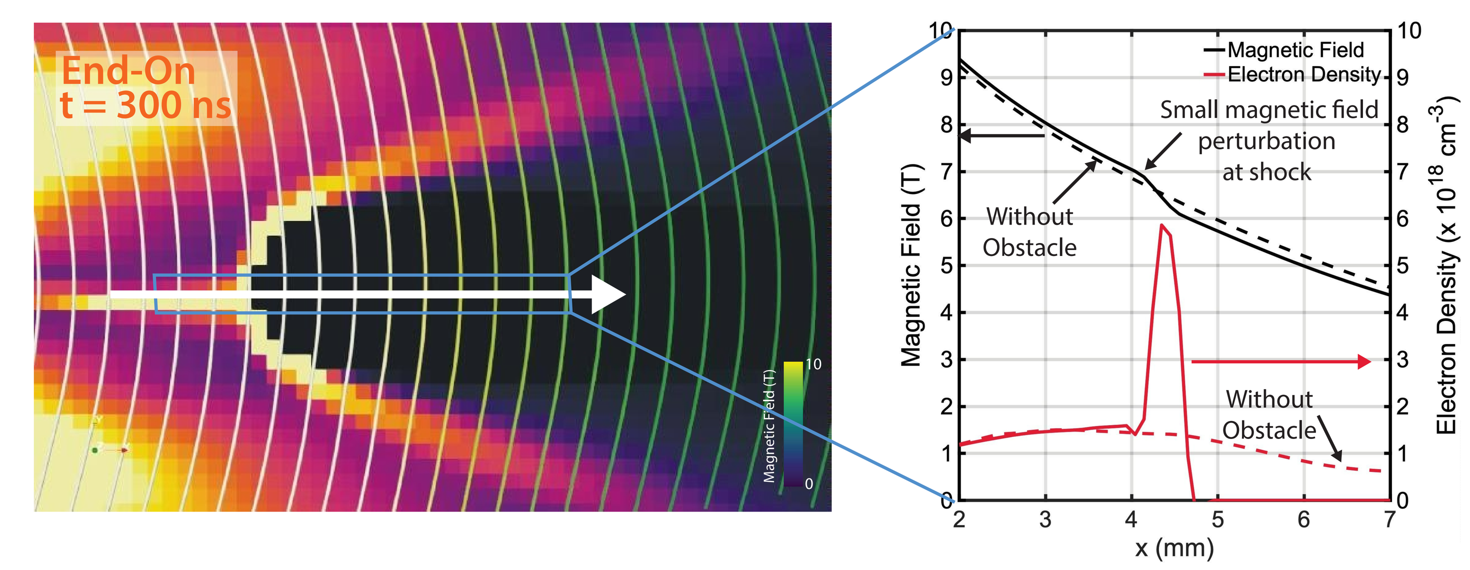
(1) Signal shape at the load matches that at the probes. Magnetic field is frozen into the flow and advected by the plasma.
(2) Combining measured velocity with estimated Mach number (from shock geometry) gives us an estimate of the plasma temperature.

Comparison With 3D MHD Simulations

3D resistive two-temperature MHD simulations using GORGON (Δx ≈ 180 µm).



Simulated electron density slices



Simulated electron density with overlaid magnetic field lines.

Line-outs of magnetic field and electron denisty along obstacle axis.

Magnetic field is not compressed and diffuses through the obstacle due to large L_η. Simulation predicts hydrodynamic-like shock.

Conclusions & Future Work

		Mach Angle (degrees)	Mach Number (from geometry)	Mach Number (from fluid parameters)	Temperature ZT_e (eV)	Velocity (km/s)
Experiment	End-On	11 +/- 0.5	5.2 +/- 0.3	-	-	62 +/- 12
	Side-on	7 +/- 0.5	8.2 +/- 0.6	-	14 +/- 6	
Simulation	End-On	8	7.2	5.5-8	~25	60
	Side-on	7	8.2	5.4-8.2		

(1) The upstream Mach number predicted from shock geometry is $5 < M_1 < 8$.
(2) Measured magnetic field (~10 T) is higher than simulated (~6 T).
(3) Simulated Mach angle is similar in both planes, but the end-on Mach angle (11°) is higher than the side-on Mach angle (7°)
(4) Simultaneous measurement of shock geometry and inductive probe signal provides an inexpensive measurement of temperature.

Next Steps:

(1) Better measure shock geometry using Schlieren / Shadowgraphy imaging.
(2) Measure flow profile and fluid Mach number using Thompson Scattering.
(3) Visualize magnetic field using Faraday Polarimetry.

Validating GORGON simulations with MAGPIE (~1 MA) experiments allows us to predict shock dynamics on the Z facility (~10 MA) for MARZ experiments.

References

[1] Nisini B. (2021)Hubble Snaps Speedy Star Jets. ESA/Hubble & NASA.
[2] Chiaberge M. (2015) Merging galaxies break radio silence. NASA, ESA, STScl.
[3] Lebedev, S. V., Suttle, L., Swadling, et al. (2014). The formation of reverse shocks in magnetized high energy density supersonic plasma flows. Physics of Plasmas, 21(5).
[4] Burdiak, G. C., Lebedev, S. V., Bland, S. N., et al. (2017). The structure of bow shocks formed by the interaction of pulsed-power driven magnetised plasma flows with conducting obstacles. Phys ics of Plasmas, 24(7).
[5] L G Suttle, G C Burdiak, C L Cheung, et al (2019). Interactions of magnetized plasma flows in pulsed-power driven experiments. Plasma Physics and Controlled Fusion.

Acknowledgements

Simulations were performed on the MIT-PSFC partition of the Engaging cluster at the MGHPCC facility (www.mghpcc.org) funded by DoE grant number DE-FG02-91-ER54109.

Experiments were performed at the MAGPIE facility at Imperial College London.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.