Exploring Astrophysical Magnetohydrodynamics Using High-power Laser Facilities

- Collimation and propagation dynamics in magnetized flows
- Radiative and reverse-radiative shock systems
- Collisionless shock interactions
- Instabilities in plasma – RT, RM, KH, MRI, MTI
- Equation of state – planetary and stellar interiors
- Relativistic electron-positron plasmas
- Nucleosynthesis - relevant Gamow energies in a 'thermal' plasma

Mario Manuel

Einstein Fellows Symposium

Harvard-Smithsonian Center for Astrophysics

October 28th, 2014

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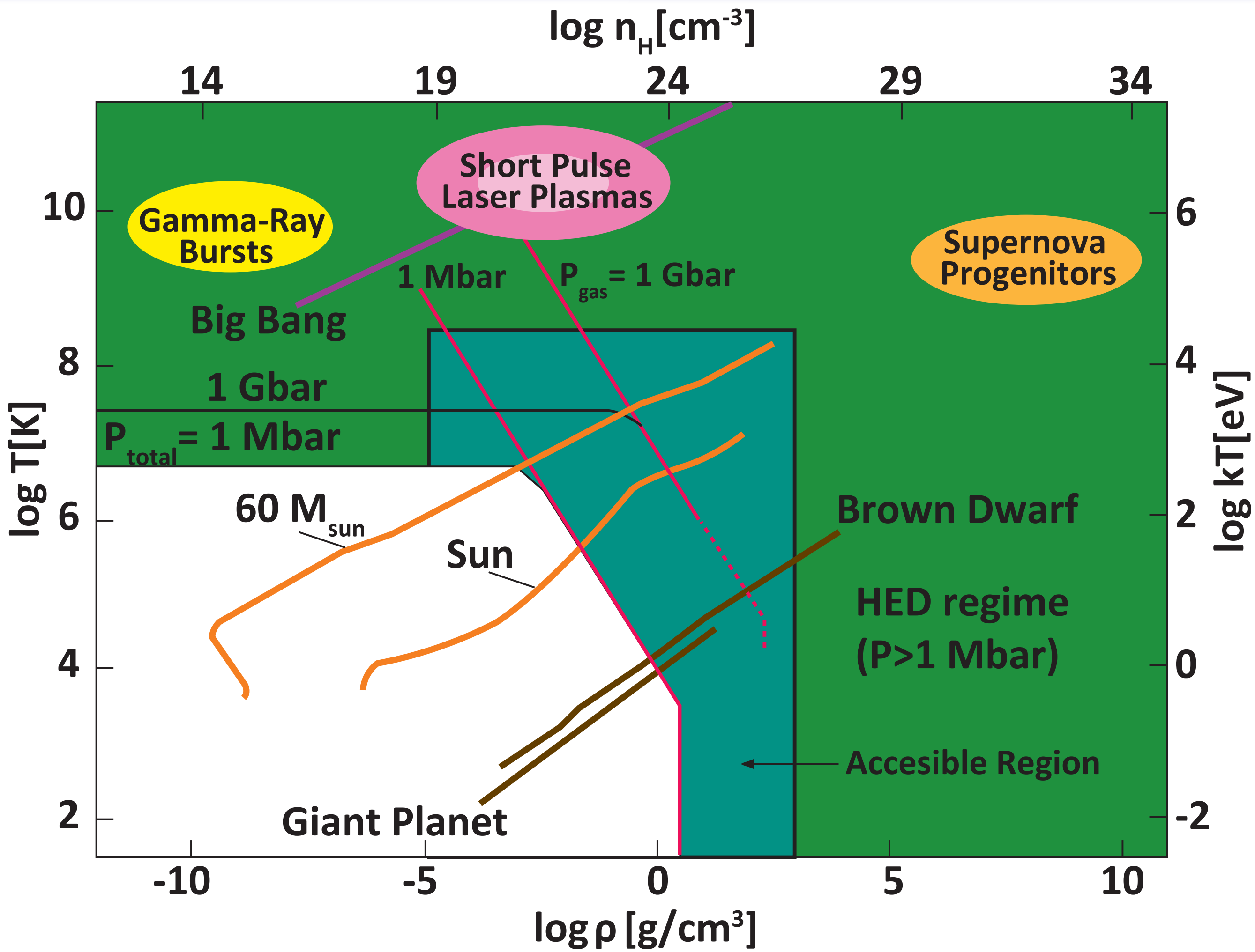

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*Adapted from NRC committee on HEDP (2003)

Scaled experiments provide a complimentary technique to investigate the dynamics in some astrophysical systems

- High-power laser facilities provide a unique opportunity to generate physical conditions similar to those in various astrophysical systems

- Laboratory results are directly scalable when similarity and geometric conditions hold between the two systems

- Experiments also allow for detailed benchmark comparisons with numerical calculations in relevant dynamic regimes

Magnetohydrodynamic (MHD) equations describe both laboratory and astrophysical systems

Continuity $$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0$$

Momentum $$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = -\nabla p + \frac{1}{\mu_0}(\nabla \times \mathbf{B}) \times \mathbf{B}$$

Energy $$\frac{\partial p}{\partial t} - \gamma \frac{p}{\rho}\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla p - \gamma \frac{p}{\rho} \mathbf{v} \cdot \nabla \rho = 0$$

Field Evolution $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

[1] Ryutov, ApJ 518 (1999)
[2] Ryutov, POP 8 (2001)
[3] Drake, High-energy-density physics (2006), ch 10
[4] Remington, RMP 78 (2006)
[5] Falize, ApJ 730 (2011)

Multiple dimensionless parameters determine the validity of using the MHD equations to describe system dynamics

- **The system exhibits fluid-like behavior** $l_{mfp}/L << 1$
- **Energy flow by particle heat conduction is negligible** $\mathrm{Pe} >> 1$
- **Energy flow by radiation flux is negligible** $\mathrm{Pe}_{\gamma} >> 1$
- **Viscous dissipation is negligible** $\mathrm{Re} >> 1$
- **Magnetic field diffusion is negligible** $\mathrm{Re}_{m} >> 1$

Astrophysical systems are large and fulfill these criteria in many cases!

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Two MHD systems evolve similarly when the Euler number (Eu) and magnetization (μ) are similar.

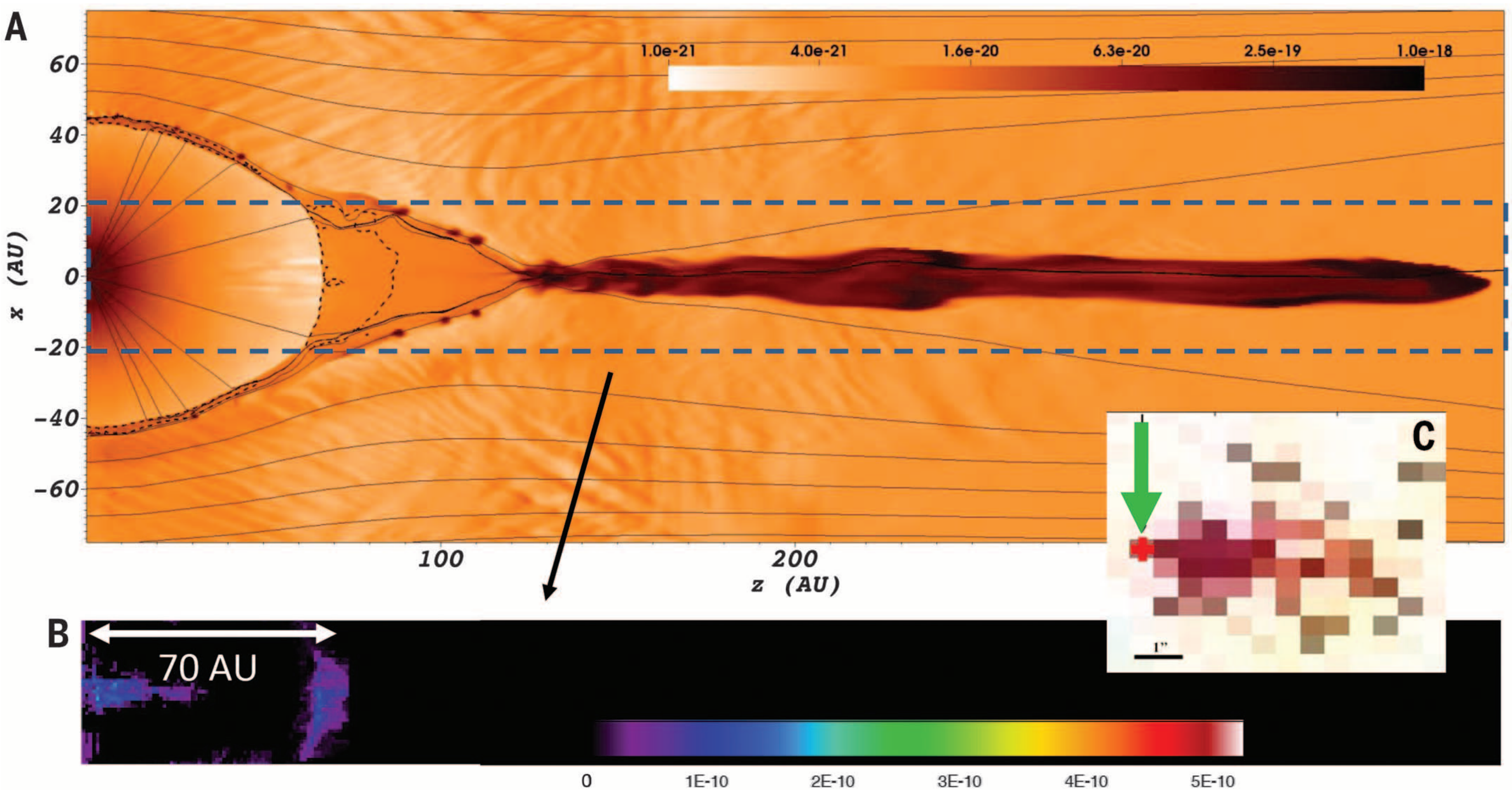
$$\mathrm{Eu} \equiv \frac{v^*}{\sqrt{p^*/\rho^*}} \qquad \beta \equiv \frac{1}{\mu} \equiv \frac{p^*}{\left(B^*\right)^2}$$

Magnetized plasma jets are prominent in young stellar objects with a wide range of parameters

Physical condition	Constraint	Stellar Jets	Experiment
Viscosity plays minor role	Reynolds	$\sim 10^{3}$ - 10^{7}	$\sim 10^{3}$ - 10^{5}
Magnetic diffusion plays minor role	Magnetic Reynolds	$\sim 10^{13}$ - 10^{17}	$\sim 10^{-1}$ - 10^{2}
Supersonic flow	Mach number	$\sim 10^{1}$ - 10^{2}	$\sim 10^{0}$
Thermal compared to magnetic pressure	Thermal plasma β_{th}	$\sim 10^{-3}$ - 10^{1}	$\sim 10^{0}$ - 10^{5}
Ram compared to magnetic pressure	Ram plasma β_{ram}	$\sim 10^{-3}$ - 10^{1}	$\sim 10^{-3}$ - 10^{5}

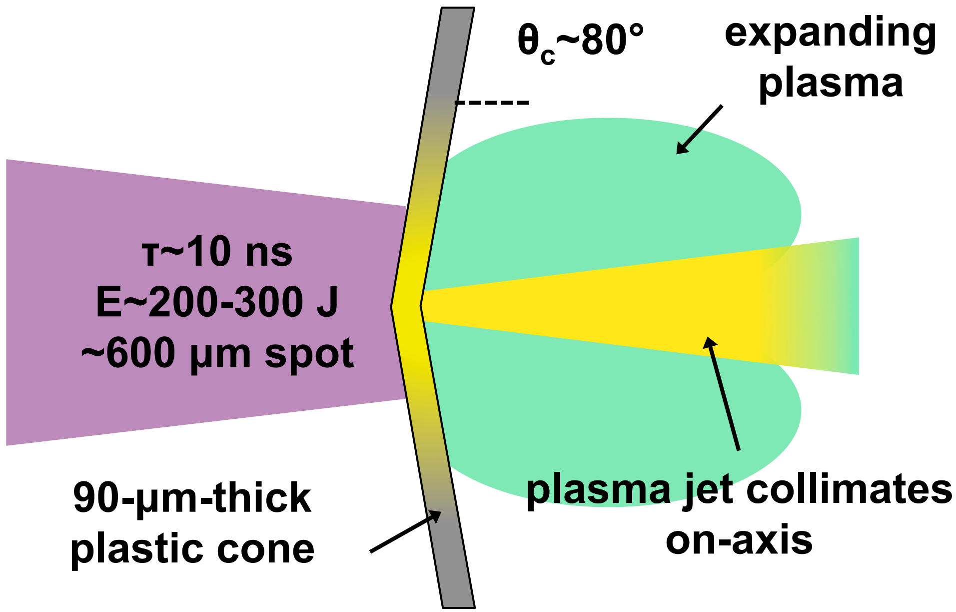
Curran et al., Mon. Not. R. Astron. Soc. 382 (2007); Carrasco-Gonzalez et al., Science 330 (2010); Ferreira AA 452 (2006); Reipurth ARAA 39 (2001)

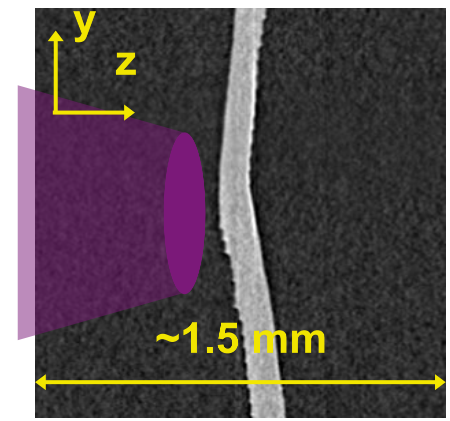
Recent work by colleagues investigated astrophysical jets under similar laboratory-created environments

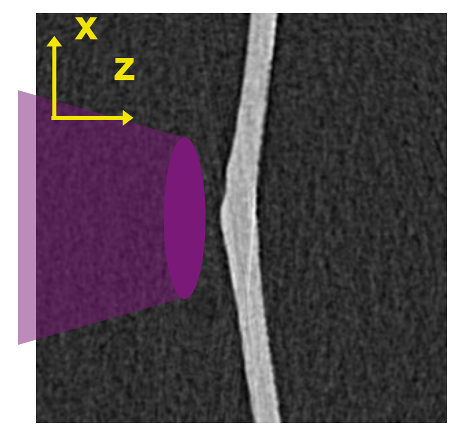


Ciardi et al., PRL 110 (2013); Albertazzi et al., Science 346 (2014)

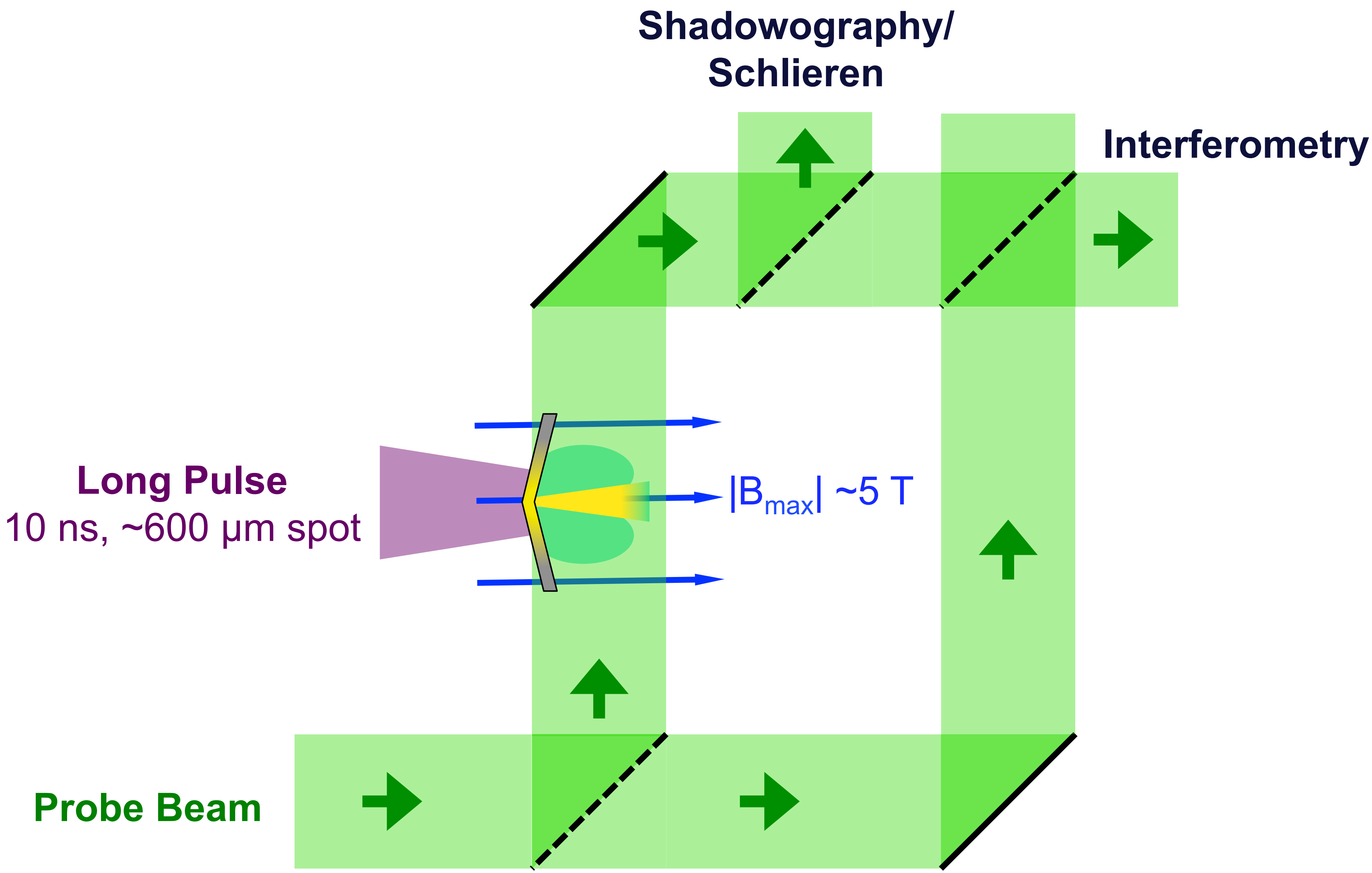
Laser-irradiated cones create collimated plasma flows





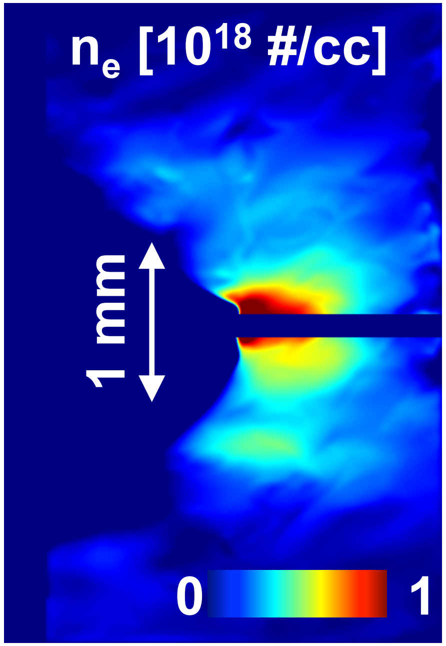


Optical diagnostics and proton radiography characterized plasma flows

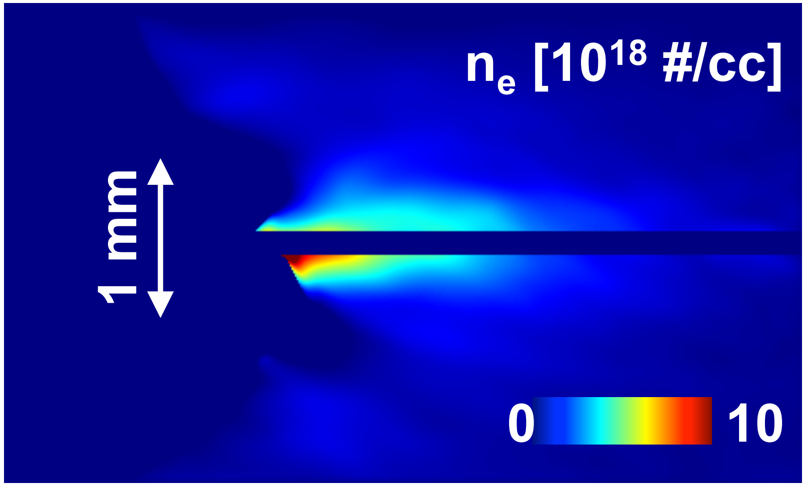


Collimated jets formed at varying drive energies

E ≈ 180 J



E ≈ 330 J

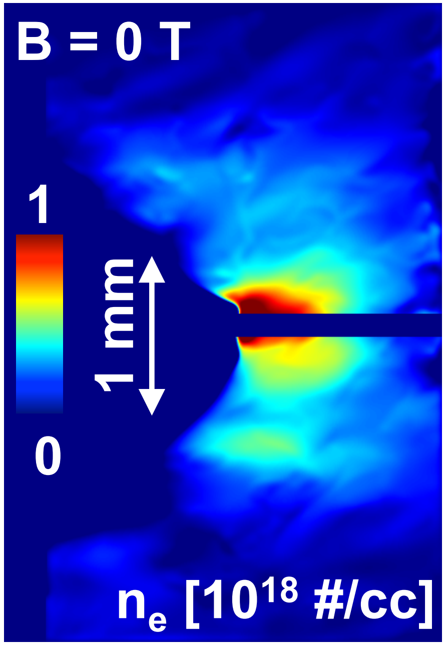


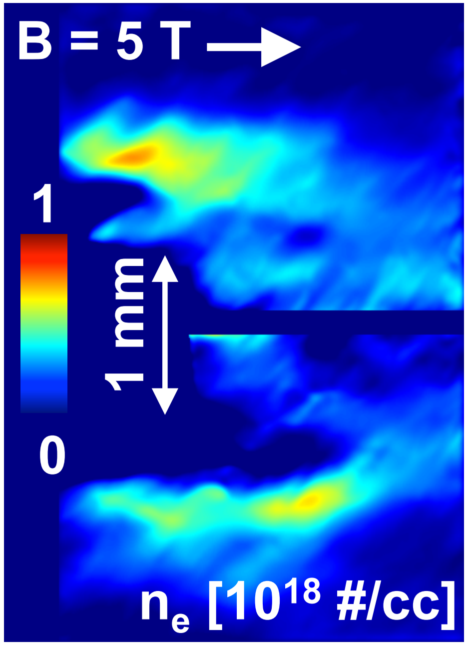
Free electron density is reduced at lower energies, but bulk jet characteristics are roughly constant:

- collimated diameter is ~500 μm

- average axial velocity is ~45 μm/ns

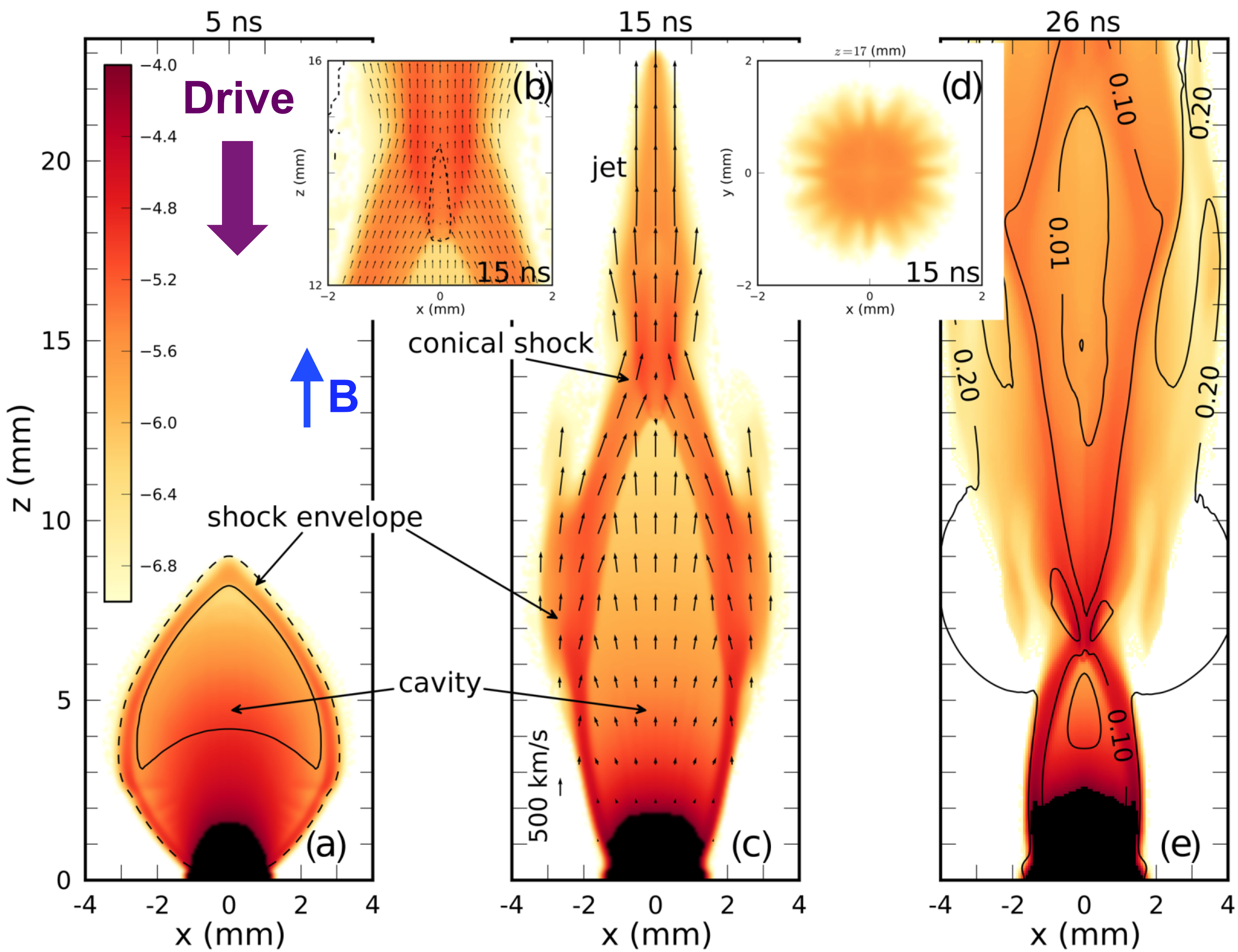
Complete disruption of the collimated jet was observed with an applied 5-T B-field along the jet axis





- **A tapered hollow cavity is observed in processed interferograms**
- **The cavity wall is ~300 μm thick and tapers from ~3 mm to ~2 mm in diameter**

Simulations* of similar systems predict cavity formation prior to magnetized jet collimation



*Ciardi *et al.* PRL 110 (2013)

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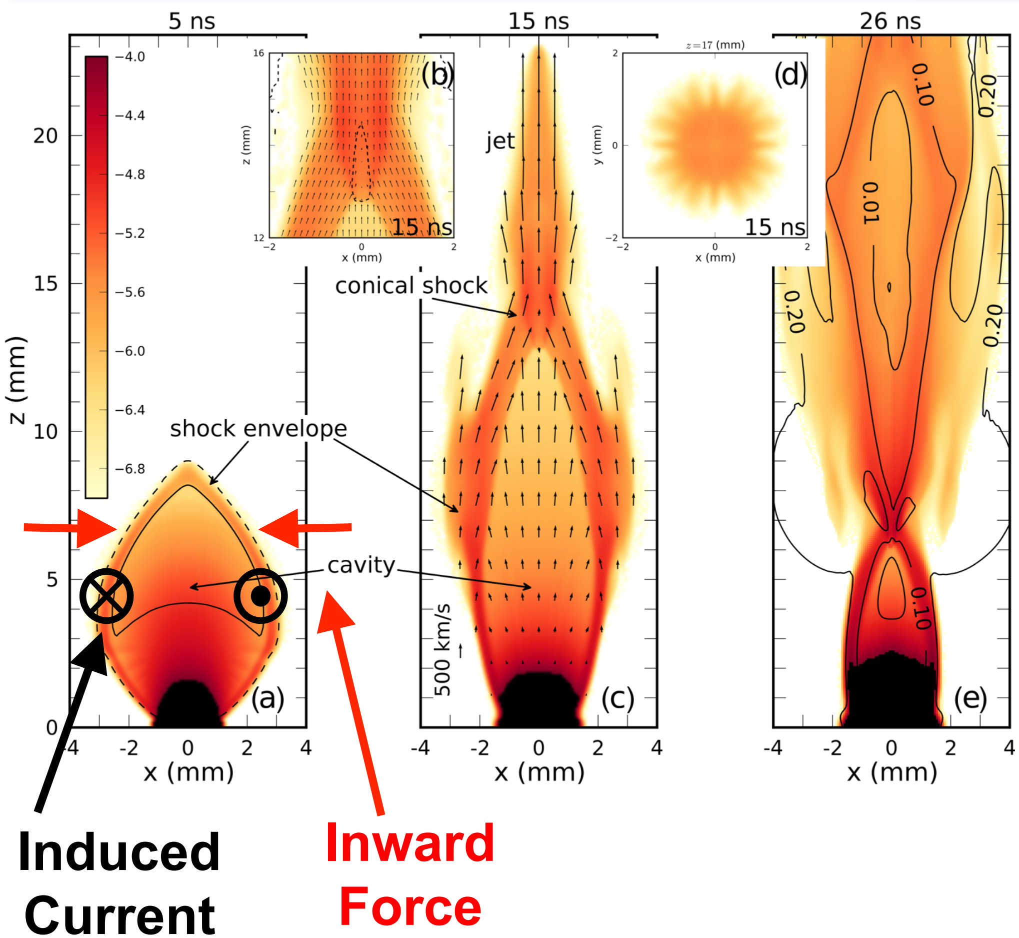


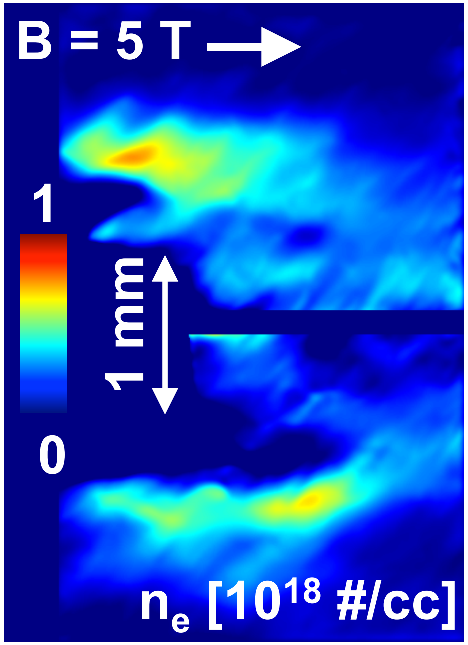
$$F_r \approx j_\theta B_z$$

- **Purely expanding plasma**
- **Cavity bounded by shock envelope**
- **Radial collimation (pinching)**
- **"frozen-in" magnetic field compresses at the shock**
- **Standing conical shock collimates a jet beam**

*Ciardi *et al.* PRL 110 (2013)

Cavity formation in our experiments appears similar to previous predictions

	Cone Target	Flat Target
T [eV]	~1	~400
V [μm/ns]	~50	~100
Re_m	~1	~100
β	~1	~1



- ~~Purely expanding plasma~~
- ✓ Cavity bounded by shock envelope
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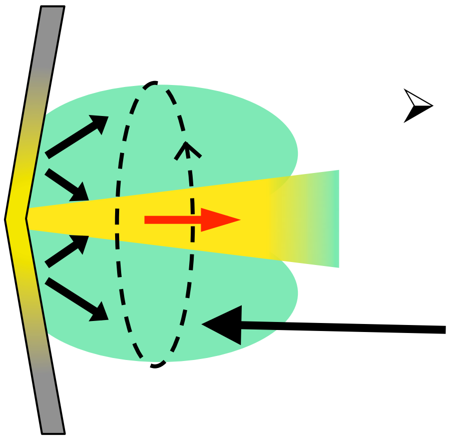
- ? Standing conical shock collimates a jet beam

Different plasma parameters and initial conditions yielded similar behavior.

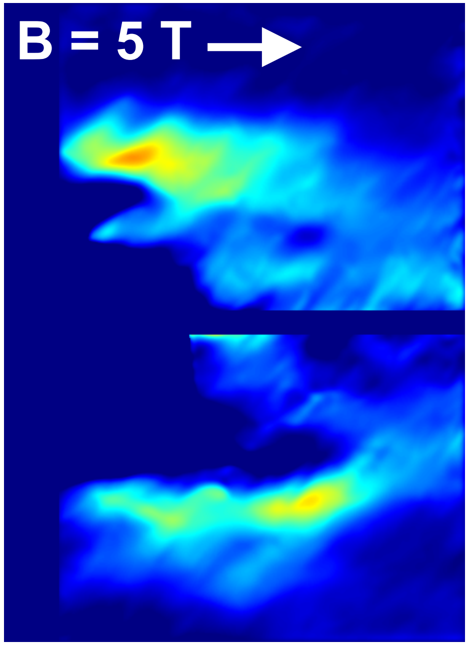
Central jet disruption and shock envelope formation may be simply caused by induction



- **Induced toroidal current acts to oppose the change in flux**
- **Direction of radial velocity sets the direction of toroidal current**

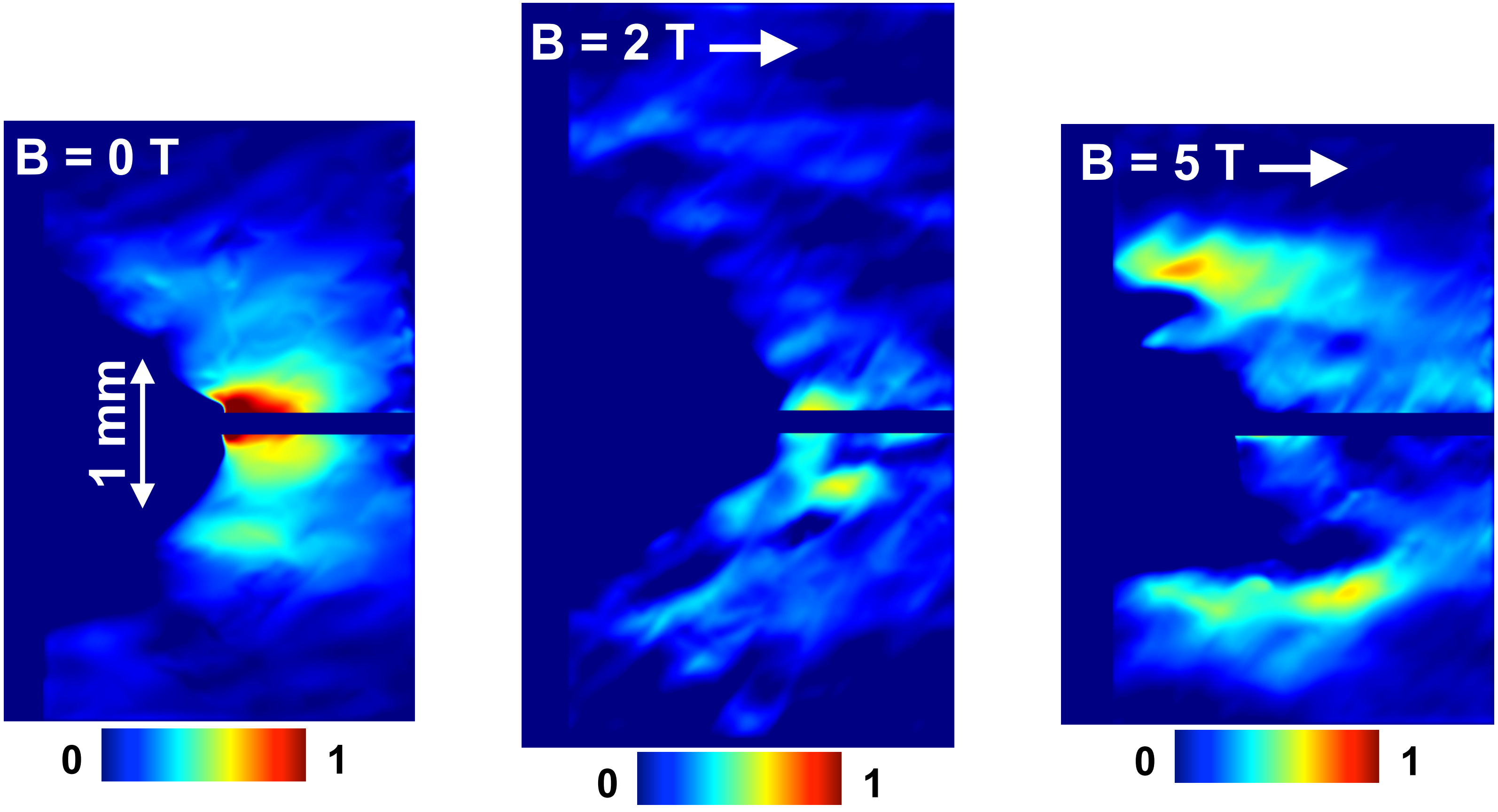
$$j_\theta(r) = -\frac{2\pi}{\eta}\int B_z v_r dr$$

$$F_r \approx j_\theta B_z$$



The J×B force did not permit axial collimation but still formed an envelope from the radially expanding plasma

Cavity formation is very sensitive to the plasma-β



In the stellar analog to these systems, collimated outflows from the star may be disrupted by the background field.

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