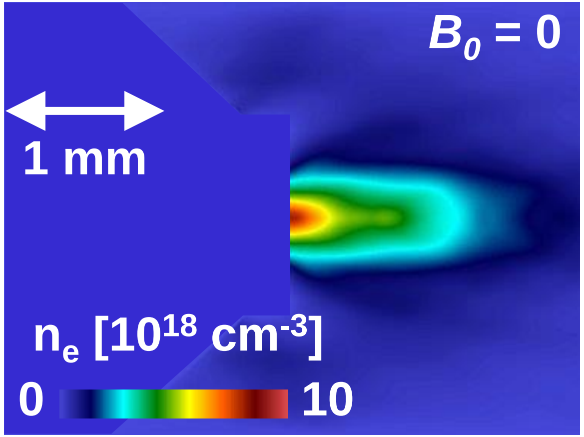
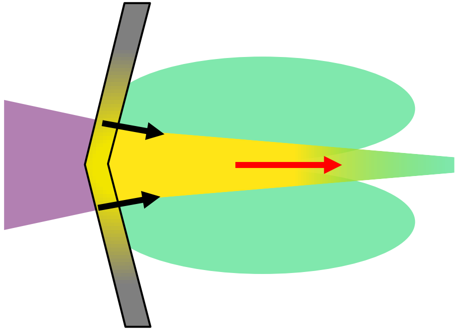
Magnetic Disruption of Inertially Collimated Flows on the Titan Laser Facility





Mario Manuel
Magnetic Meeting
University of Rochester
Laboratory for Laser Energetics

April 23rd, 2018

IFT\P2018-026

Manuel *et al.* HEDP 17 (2015)
Manuel *et al.* PRL (submitted)

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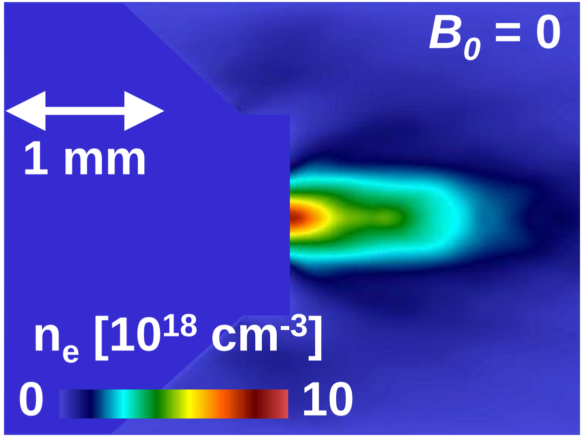

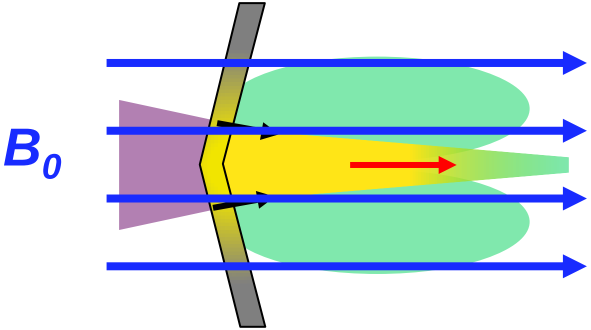

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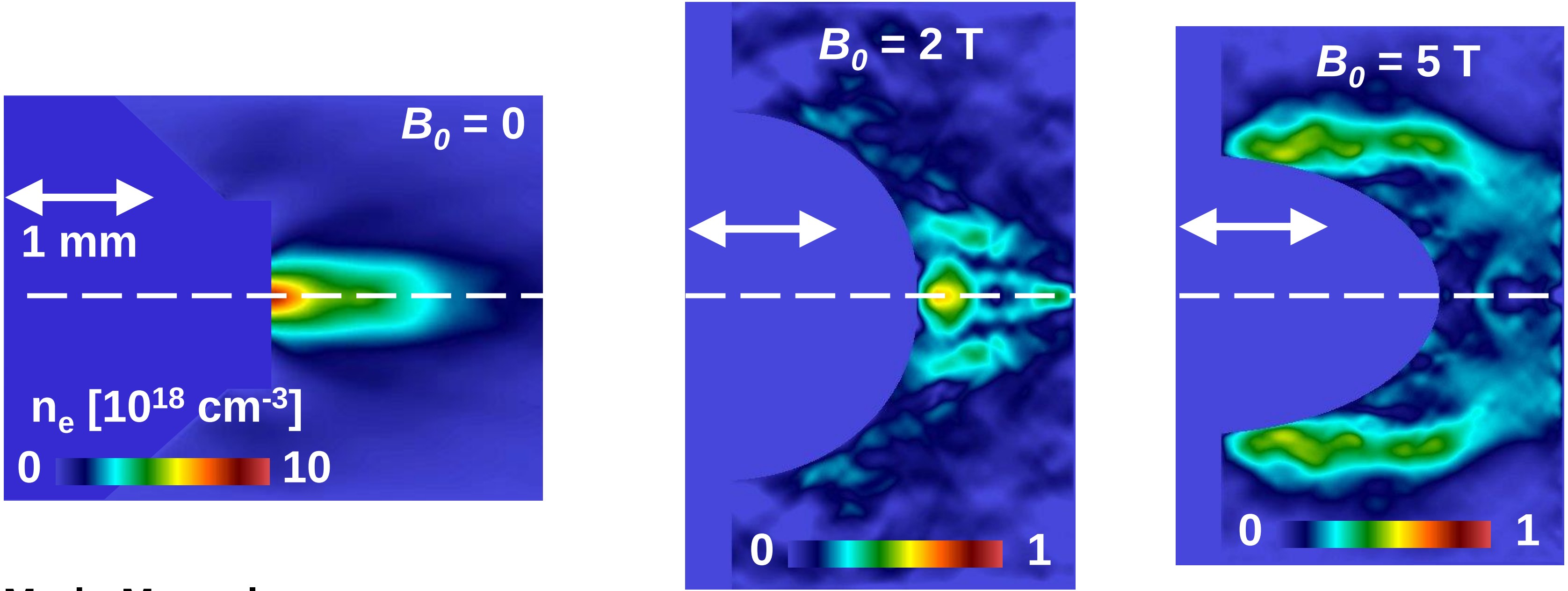

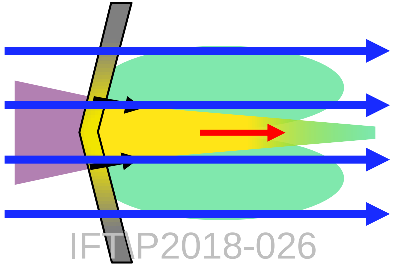

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Magnetized plasma jets are readily created in the lab for the study of plasmas relevant to astrophysical systems

- **Inertially collimated, supersonic plasmas may be magnetically disrupted by an axial B-field**

- **At high enough Re_m, inertia-dominant systems ($\rho v^2 \gg B^2/2\mu_0$) may disrupt due to amplification of even a weak axial B-field**

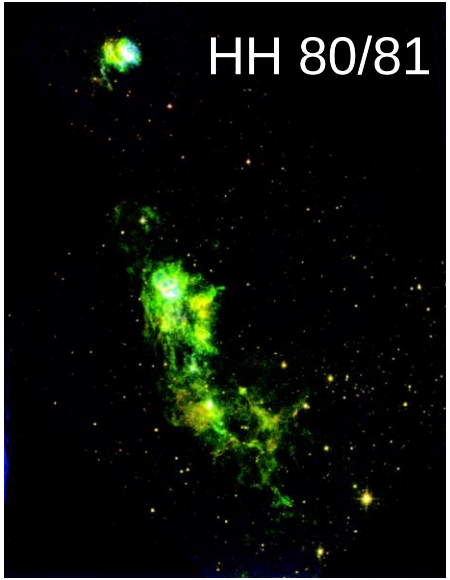
Collaborators

M. J.-E. Manuel, A. M. Rasmus, C. C. Kuranz, S. R. Klein, M. J. MacDonald, J. Davis, M. R. Trantham, J. R. Fein, P. X. Belancourt, R. P. Young, P. A. Keiter, R. P. Drake
University of Michigan

B. B. Pollock, J. Park, A. U. Hazi, G. J. Williams, H. Chen
Lawrence Livermore National Laboratory

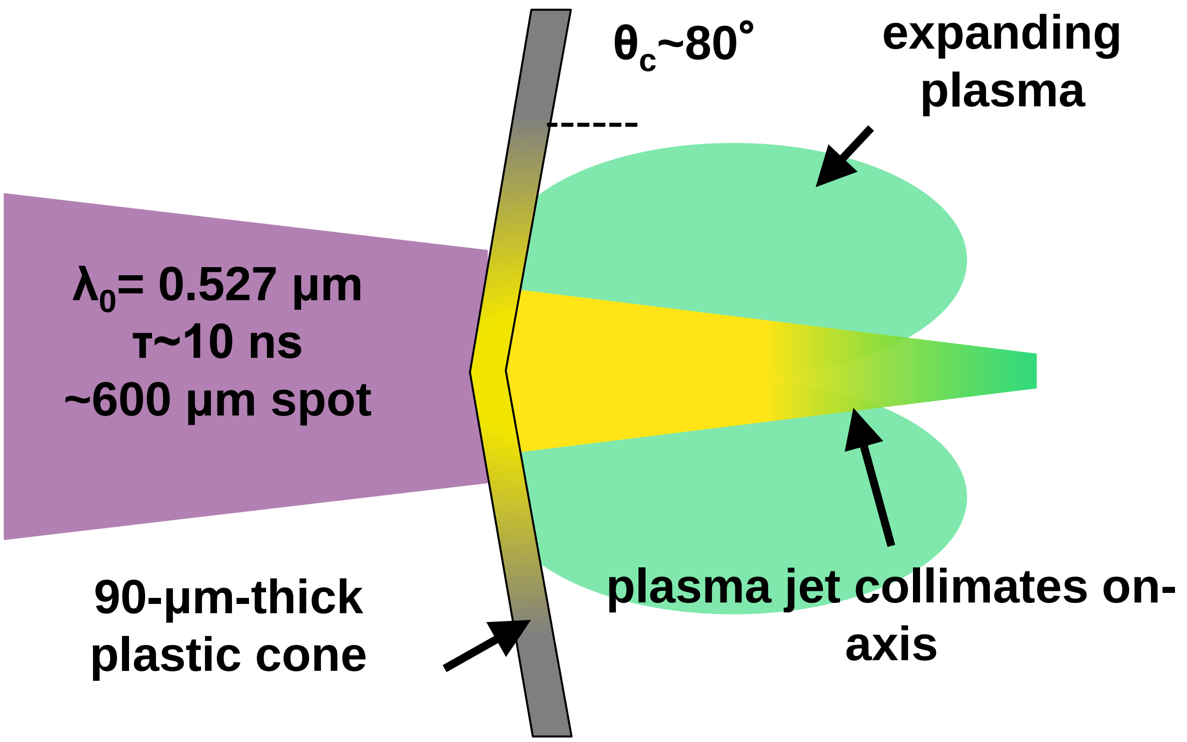
Support for this work was provided by NASA through Einstein Postdoctoral Fellowship grant number PF3-140111 awarded by the Chandra X-ray Center, which is operated by the Astrophysical Observatory for NASA under contract NAS8-03060, by the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-NA0001840 and by the Predictive Sciences Academic Alliances Program in NNSA-ASC via grant DEFC52-08NA28616. Work by LLNL was performed under the auspices of U.S. DOE under contract DE-AC52-07NA27344.

The dynamics and evolution of collimated plasma flows are important to astrophysical accretion systems

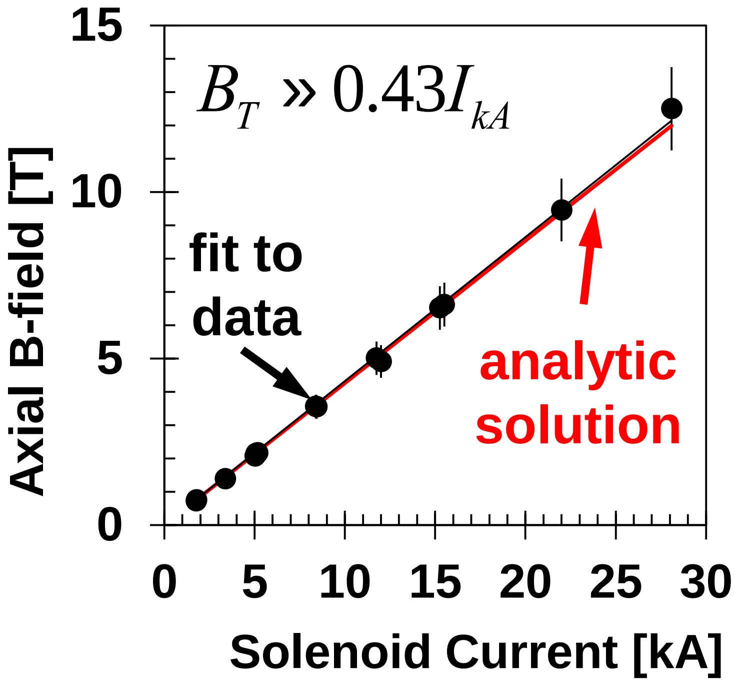


- YSOs, AGN, PNe, and pPNe
- Magnetic collimation (magnetic tower)
- Inertial collimation (shock-focused inertial confinement)

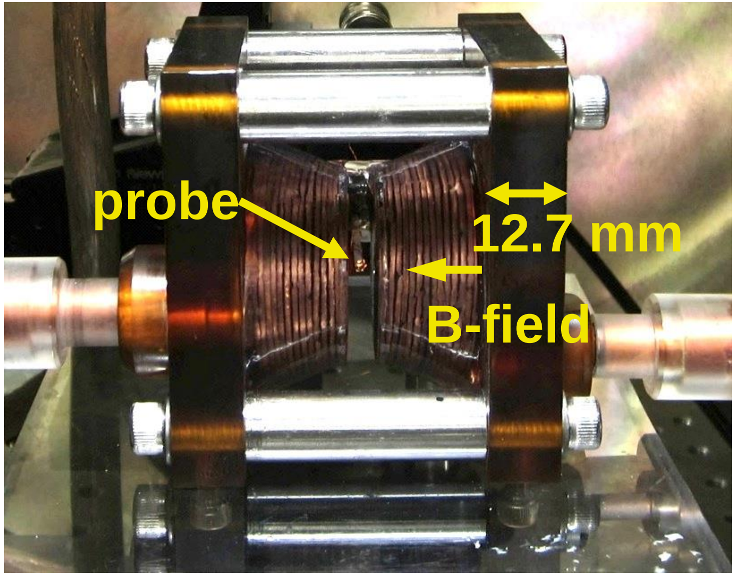
Jets are produced from laser-irradiated plastic targets



Plasma jets are magnetized externally using a custom-built, pulse-power solenoid

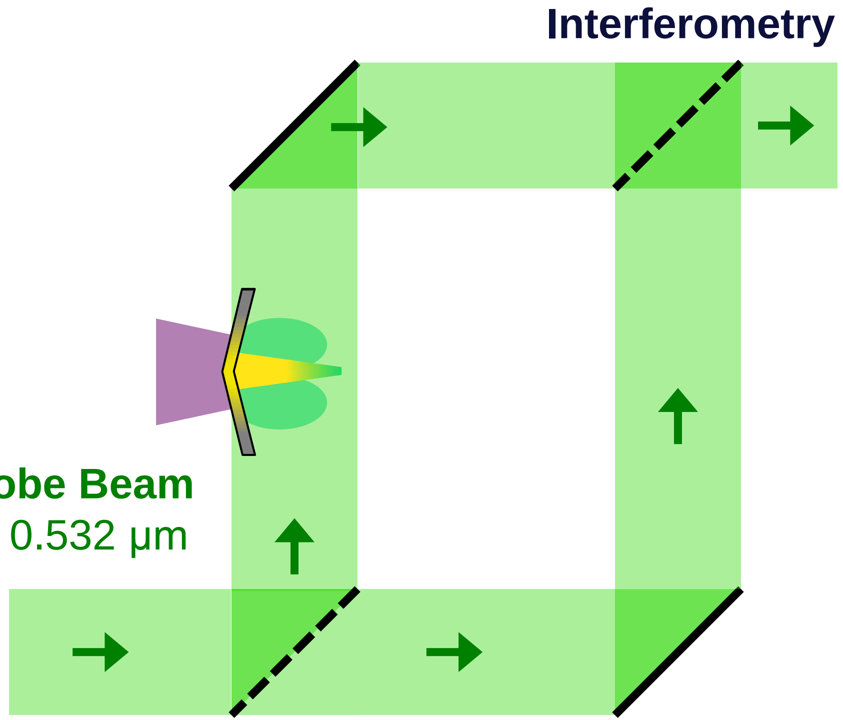


Side View



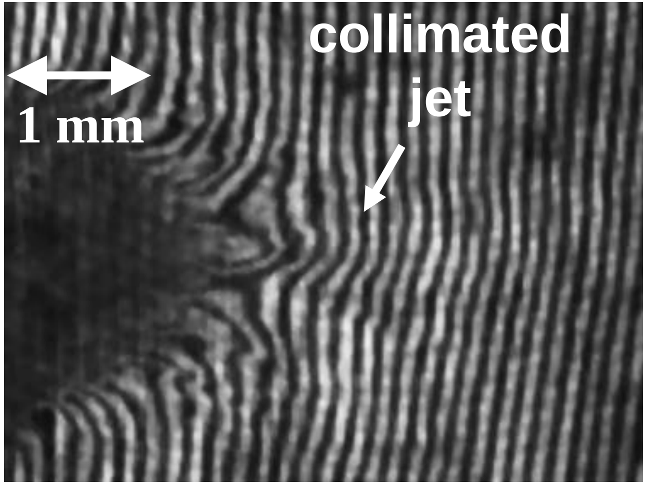
The axial B-field at the gap center is linearly proportional to the current and within 2% of the analytic solution.

Optical interferometry characterizes the spatial profile of inertially-confined plasma flows



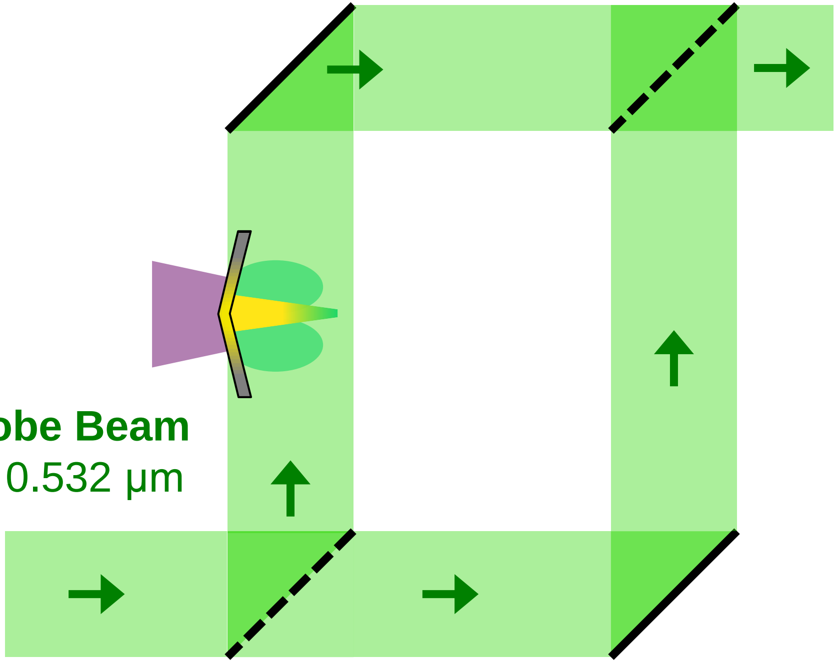
Optical interferometry characterizes the spatial profile of inertially-confined plasma flows

raw interferogram

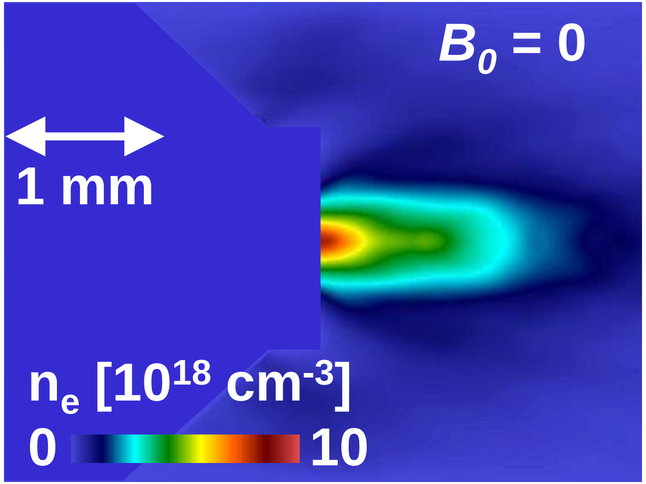


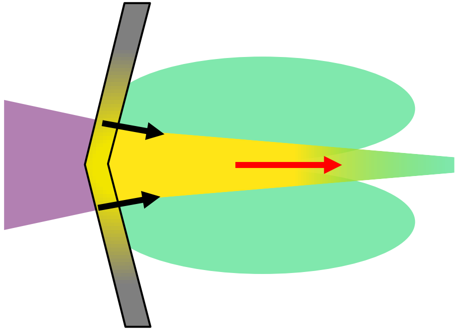
$$\mathrm{D}j_{\ free} \approx \int \left(- \frac{n_e}{2n_{cr}} \right) \frac{w}{c} dl$$

Interferometry

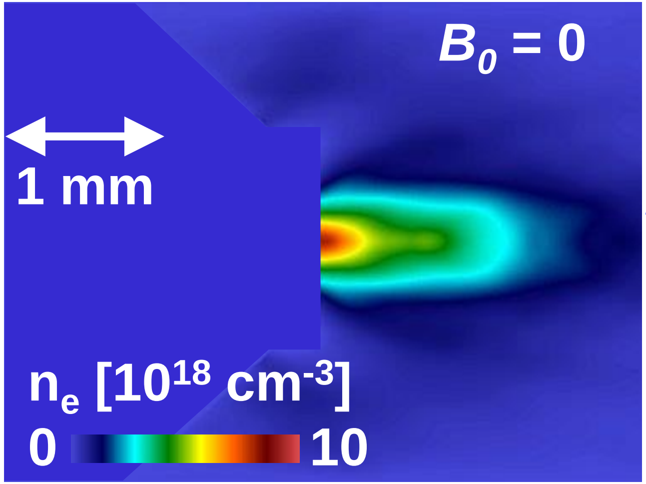


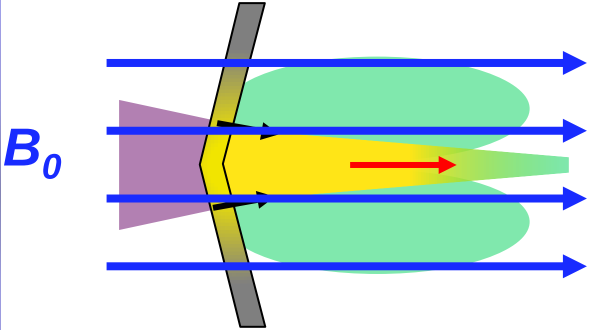
Processed interferograms show collimated flows when no axial B-field is applied

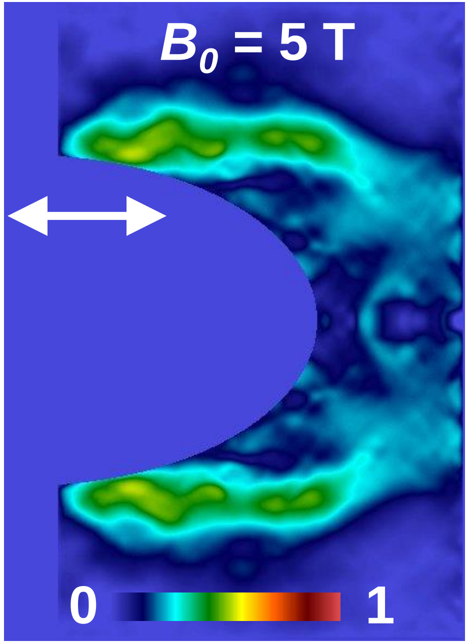




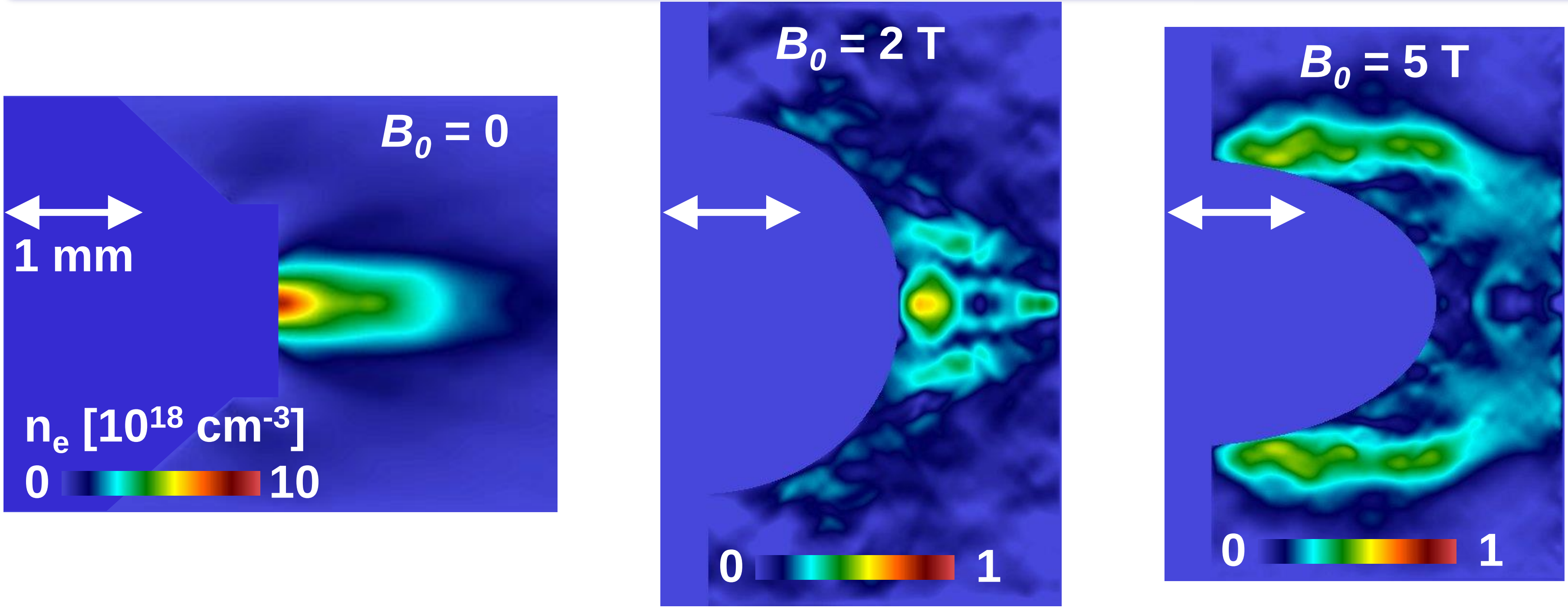
A 5-T B-field applied along the jet axis disrupts axial collimation







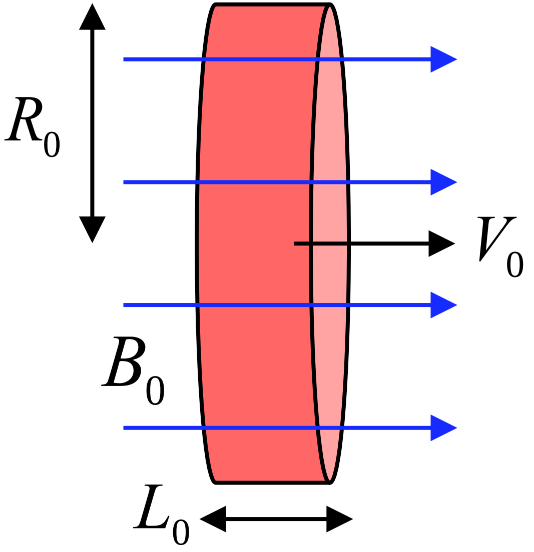
Jet-disruption effectiveness depends on the B-field strength



A 5-T axial B-field disrupts the inertially-collimated region of the flow, and magnetically collimates the radially expanding plasmas

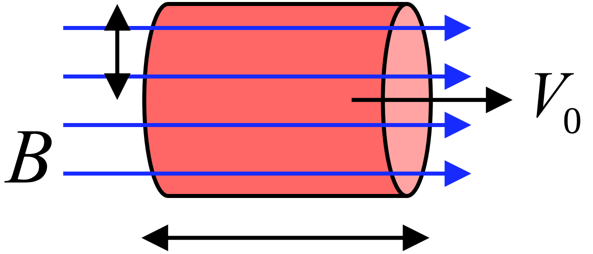
A Lagrangian model* analytically accounts for B-field advection and diffusion in a converging cylindrical plasma

initial condition



time *t* later

$$R = R_0/\sqrt{\tau}$$



$$L = L_0 + V_0 t$$

Dimensionless metric for time

$$\boxed{\tau \equiv L/L_0}$$

- **Uniform, incompressible, constant V_0**
- **Axial B-field B_0 penetrating the volume**
- **Elongation occurs in time due to collimation (dR/dt<0)**

***Fedorov CESW 41 (2005)**

A Lagrangian model* analytically accounts for B-field advection and diffusion in a converging cylindrical plasma

$$B(r,t) = B_0 t e^{-\frac{t^2 - 1}{2\,\mathrm{Re}_m}}$$

$$\mathrm{Re}_m = \left(\frac{R_0}{4L_0}\right)\frac{V_0 R_0}{h / m_0}$$

Ratio of B-field advection to diffusion

*Fedorov CESW 41 (2005)

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Linear amplification

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Linear amplification

Diffusion becomes more important with increasing τ (shrinking radius)

Ratio of B-field advection to diffusion

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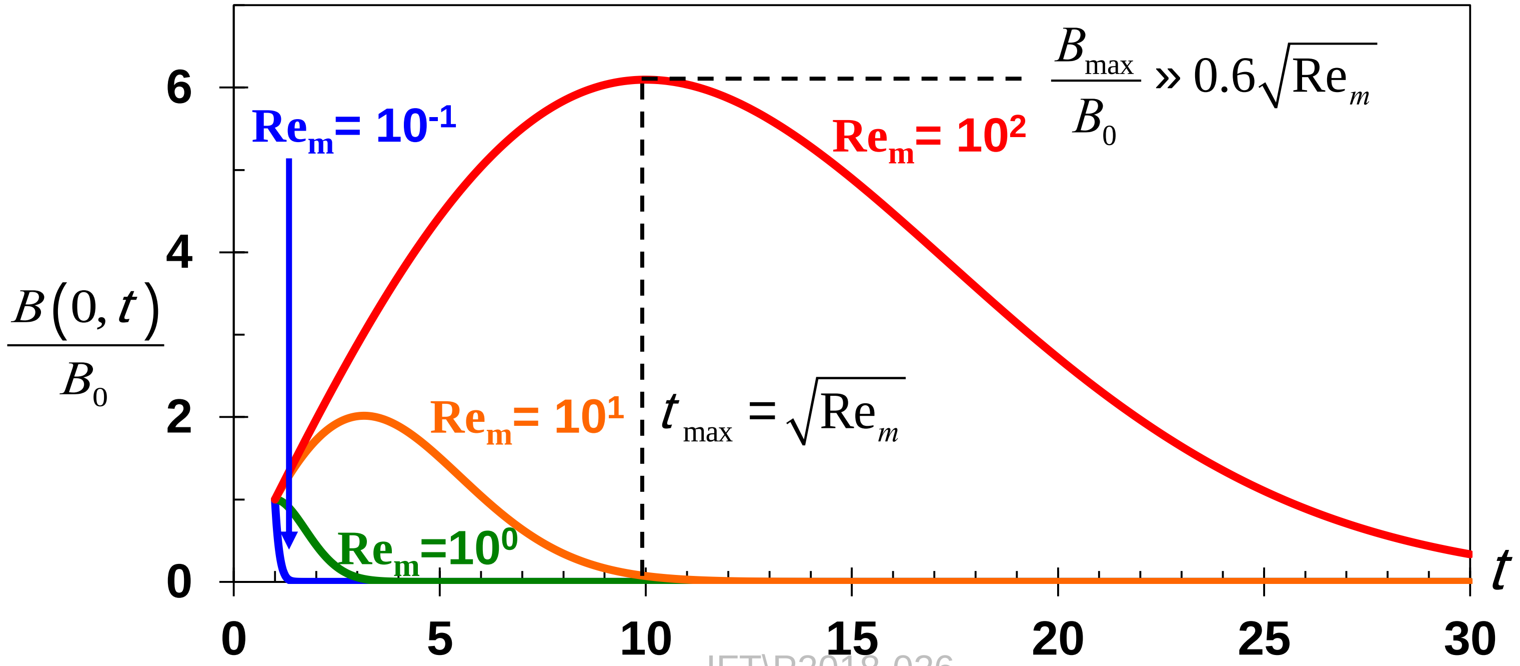

A collimation parameter (ψ) is derived from the on-axis pressure normalized to the magnetic pressure

$$b_{dyn} = \frac{r V_0^2}{B_0^2 / 2m_0} \qquad y = \underbrace{\frac{1}{4}\left(\frac{R_0}{L_0}\right)^2 \frac{b_{dyn}}{t^3}}_{\textbf{Inertial Collimation}}$$

A collimation parameter (ψ) is derived from the on-axis pressure normalized to the magnetic pressure

$$\beta_{dyn} = \frac{\rho V_0^2}{B_0^2 / 2\mu_0}$$

$$\psi = \underbrace{\frac{1}{4}\left(\frac{R_0}{L_0}\right)^2 \frac{\beta_{dyn}}{t^3}}_{\text{Inertial Collimation}} - \underbrace{\frac{\beta_{th}}{\sqrt{t}}}_{\text{Thermal Expansion}}$$

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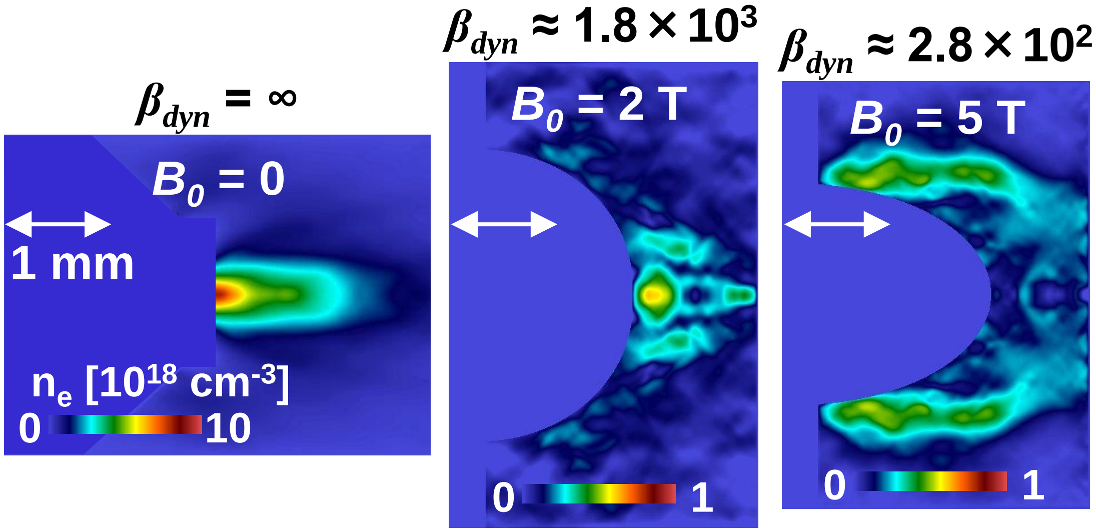
$$\mathrm{Re}_m = \left(\frac{R_0}{4L_0}\right)\frac{V_0 R_0}{\eta / \mu_0}$$

$$\boxed{\begin{array}{l} \psi < 0 : \text{Jet Disruption} \\ \psi > 0 : \text{Jet Formation} \end{array}}$$

The Lagrangian-cylinder model describes observations well in a semi-quantitative manner at 50 ns (τ~25)



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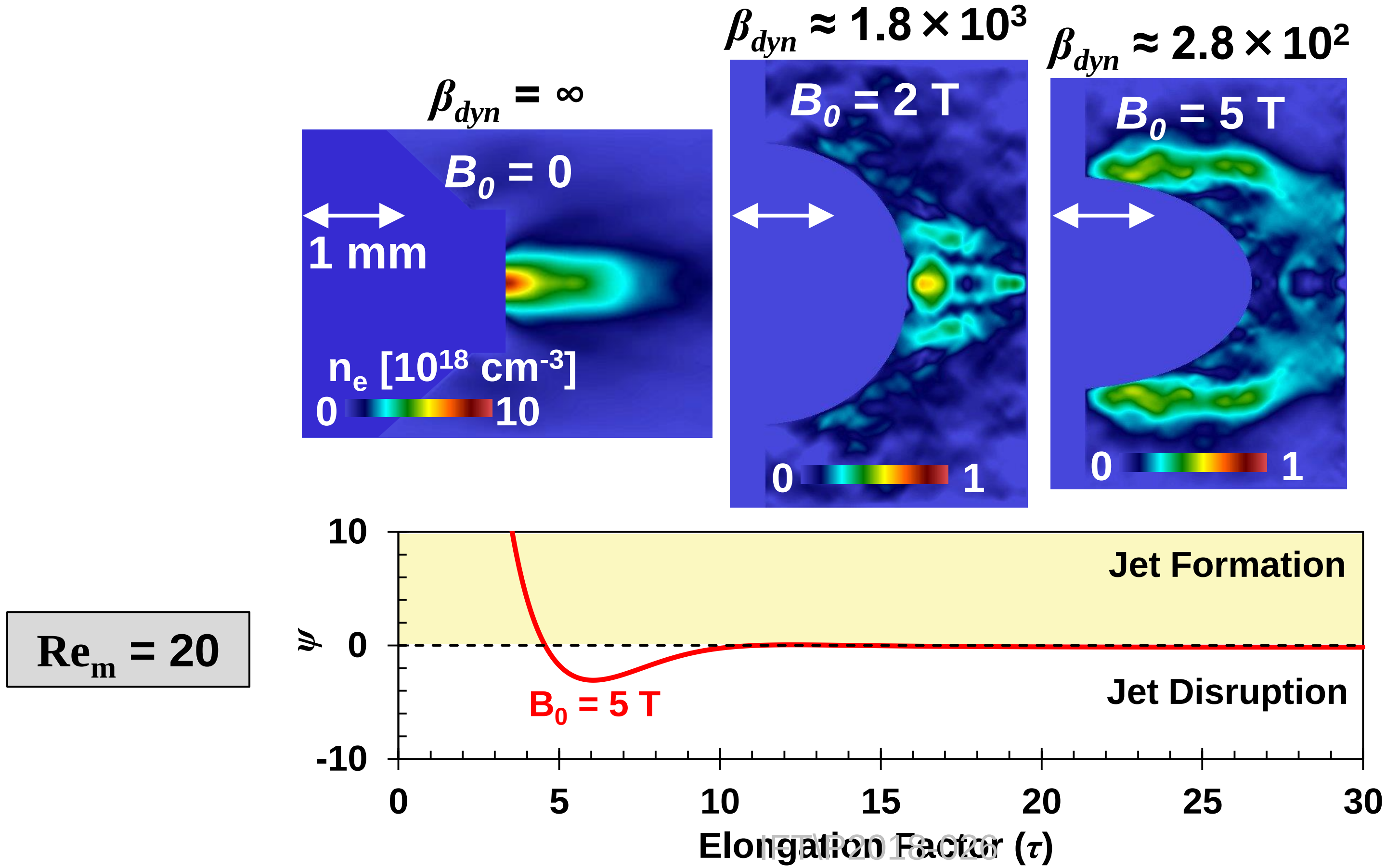

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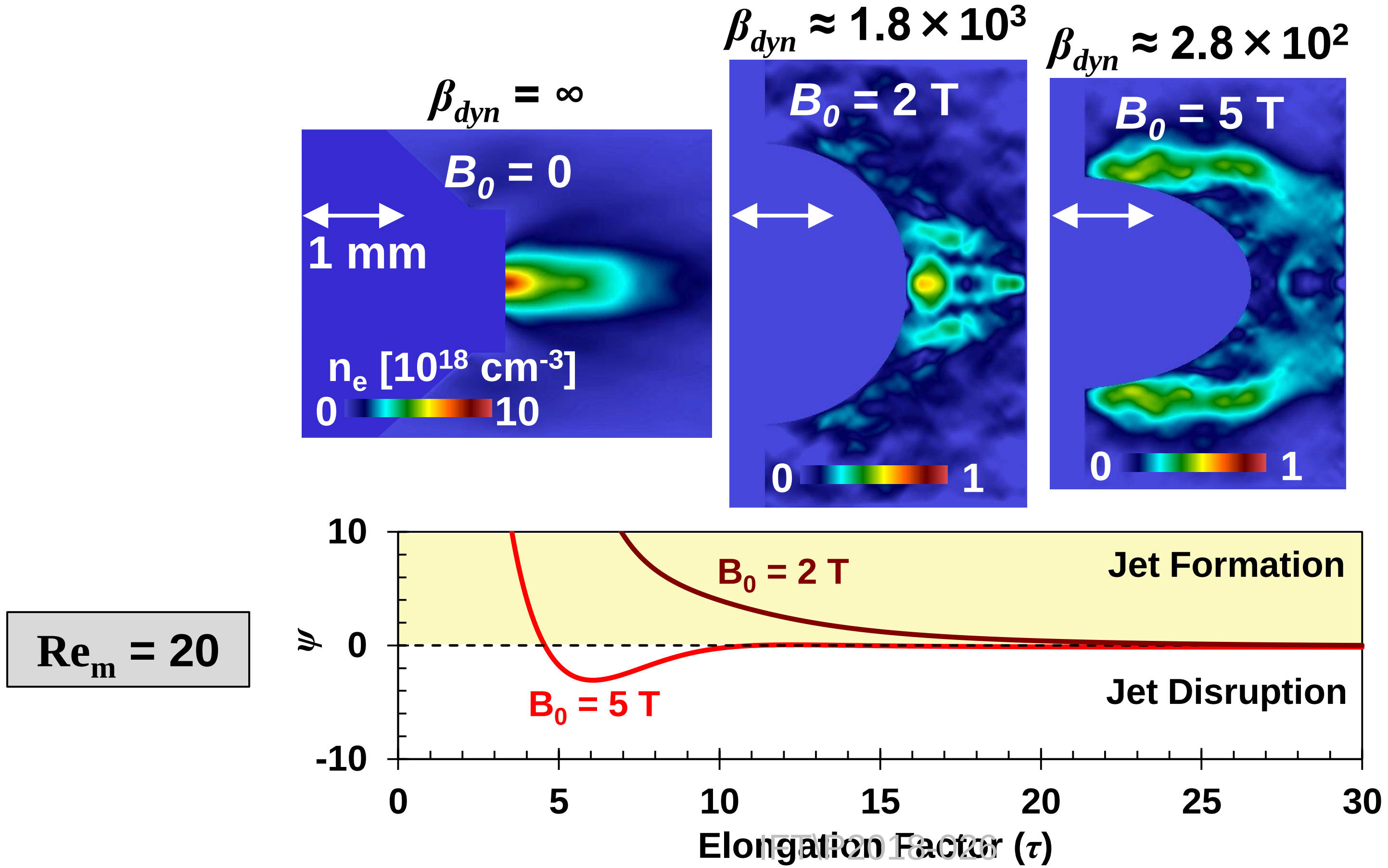
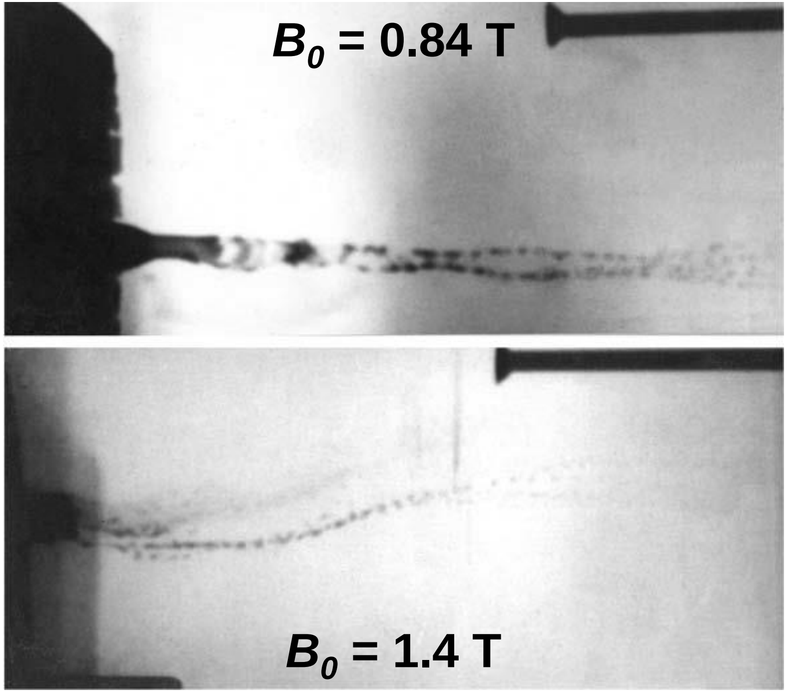


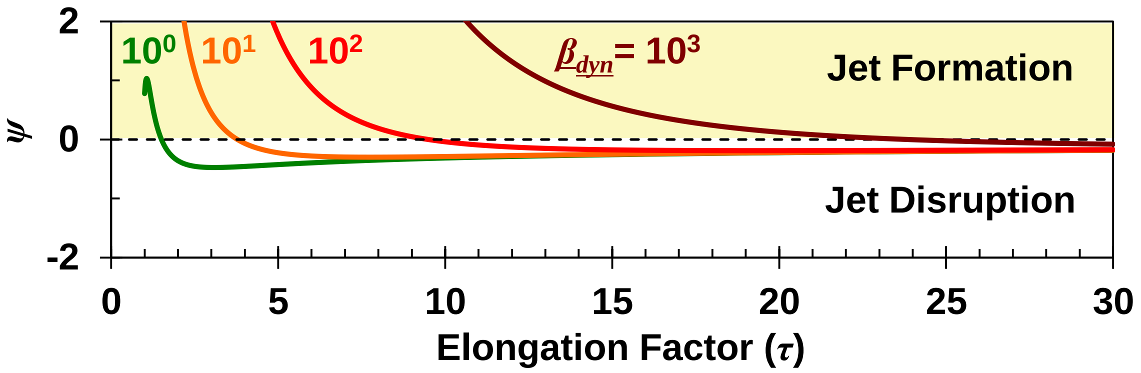
Similar behavior is observed* in magnetized shaped charges



*Fedorov JAMTP 48 (2007)

B-field amplification can quickly cause jet disruption at high enough magnetic Reynolds numbers

$Re_m = 10^{-1}$



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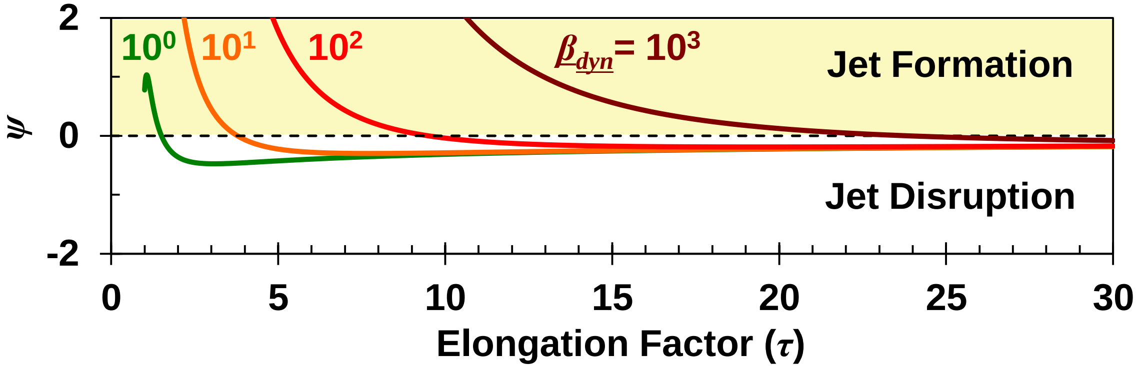
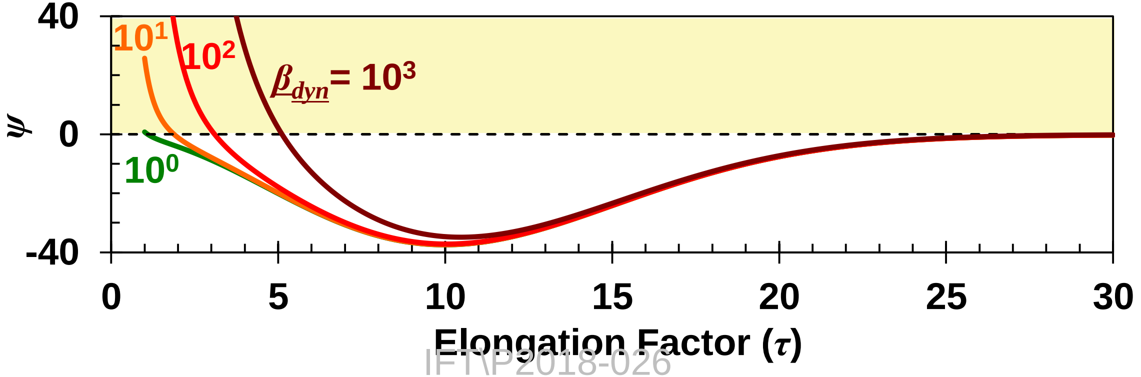


Higher $\mathrm{Re_m}$ pushes $\psi < 0$ at earlier τ

$\mathrm{Re_m} = 10^2$

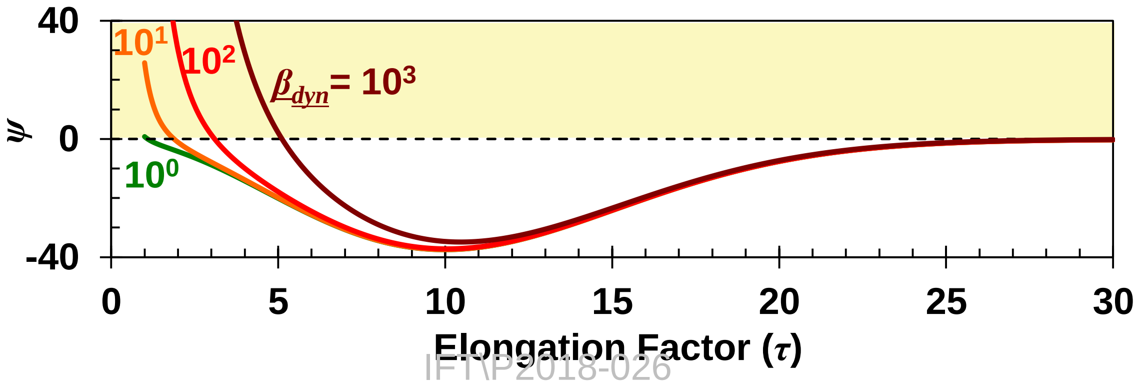


B-field amplification can quickly cause jet disruption at high enough magnetic Reynolds numbers

- The presence of even a weak axial B-field in a hydrodynamically converging system will disrupt collimation at high enough Re_m

- In astrophysical accretion systems $Re_m > 10^{10}$, observations of a weak B-field parallel to the outflow* precludes inertial-collimation as a source

$Re_m = 10^2$



* Targon ApJ 743 (2011)

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- At high enough Re_m, inertia-dominant systems ($\rho v^2 \gg B^2/2\mu_0$) may disrupt due to amplification of even a weak axial B-field

Backup Slides

B-field diffusion may be estimated using the magnetic Reynolds number

$$\tau_d \approx \frac{L^2}{D_m} \qquad Re_m = {}^{VL}/_{D_m} \qquad \tau_d \approx \left(\frac{L}{V}\right) Re_m$$

- **For experimental parameters, L~1 mm and V~50 km/s,**

$$\tau_d \approx 20 Re_m \text{ [ns]}$$

- **Magnetic Reynolds numbers of ~20 suggest diffusion times of order 400 ns, significantly longer than the experimental time scale**

Radial pressure balance determines if the plasma cylinder continues to collimate

Radial Pressure Balance

$$r\frac{dv_r}{dt} = -\frac{\P p}{\P r} + j_f B_z$$

Central Axis Pressure $(r/R)^2 \ll 1$

$$p_c = \frac{1}{4}\left(\frac{R_0}{L_0}\right)^2 \frac{r V_0^2}{t^3} - \frac{p_{th,0}}{\sqrt{t}} - \frac{B_0^2}{2m_0} t^2 e^{-\frac{t^2-1}{\mathrm{Re}_m}}$$

Collimation Parameter

Normalize to Magnetic Pressure

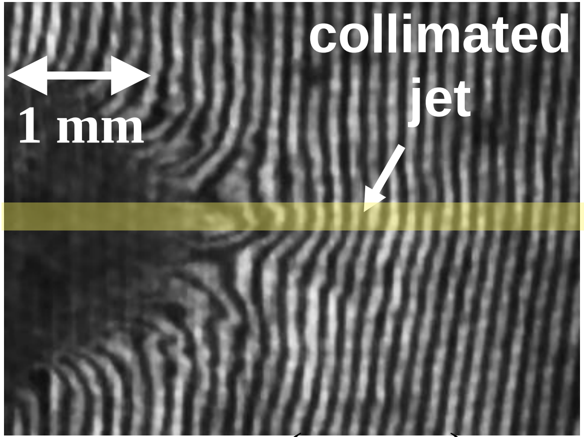
$$y = \underbrace{\frac{1}{4}\left(\frac{R_0}{L_0}\right)^2 \frac{b_{dyn}}{t^3}}_{\text{Inertial Collimation}} - \underbrace{\frac{b_{th}}{\sqrt{t}}}_{\text{Thermal Expansion}} - \underbrace{t^2 e^{-\frac{t^2-1}{\mathrm{Re}_m}}}_{\text{Magnetic Expansion}}$$

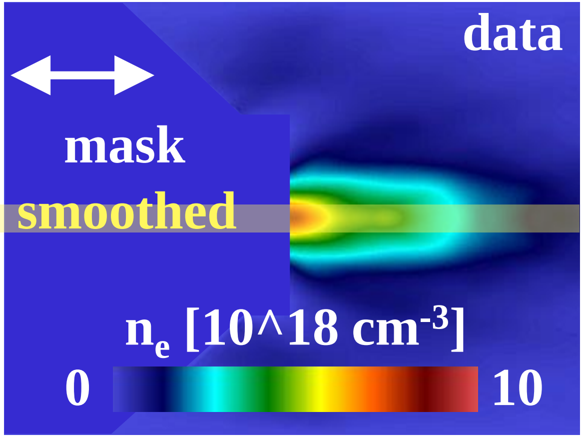
$y < 0$: Jet Disruption

$y > 0$: Jet Formation

Interferometry is used to measure the free-electron density and diagnose the evolution of the plasma jet

raw interferogram





$$\Delta\varphi_{free} \approx \int \left(-\frac{n_e}{2n_{cr}} \right) \frac{\omega}{c} dl$$

- **Abel-transformed data of the top and bottom are averaged to create a symmetric image ($\Delta_{err} < 30\%$)**

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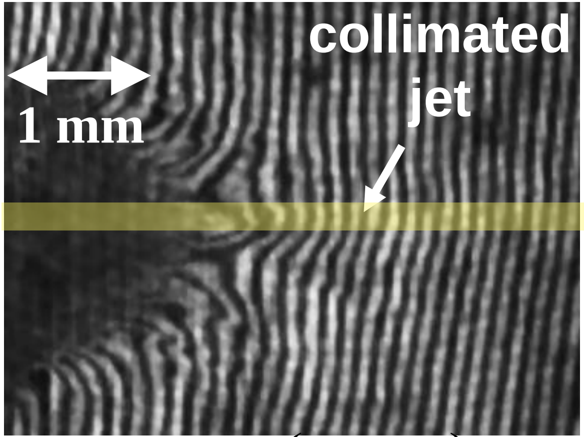

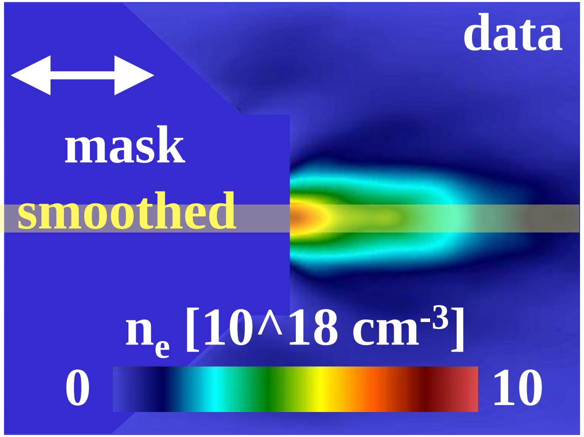

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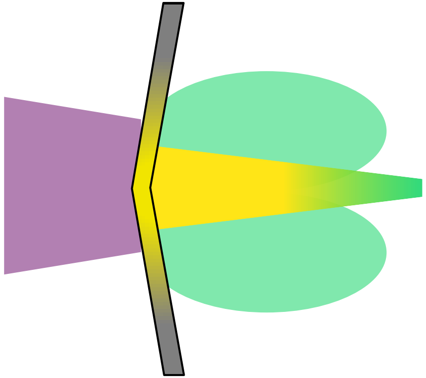
- **Abel-transformed data of the top and bottom are averaged to create a symmetric image (Δ_{err} < 30%)**

$$\Delta\varphi_{meas} < \Delta\varphi_{free}$$

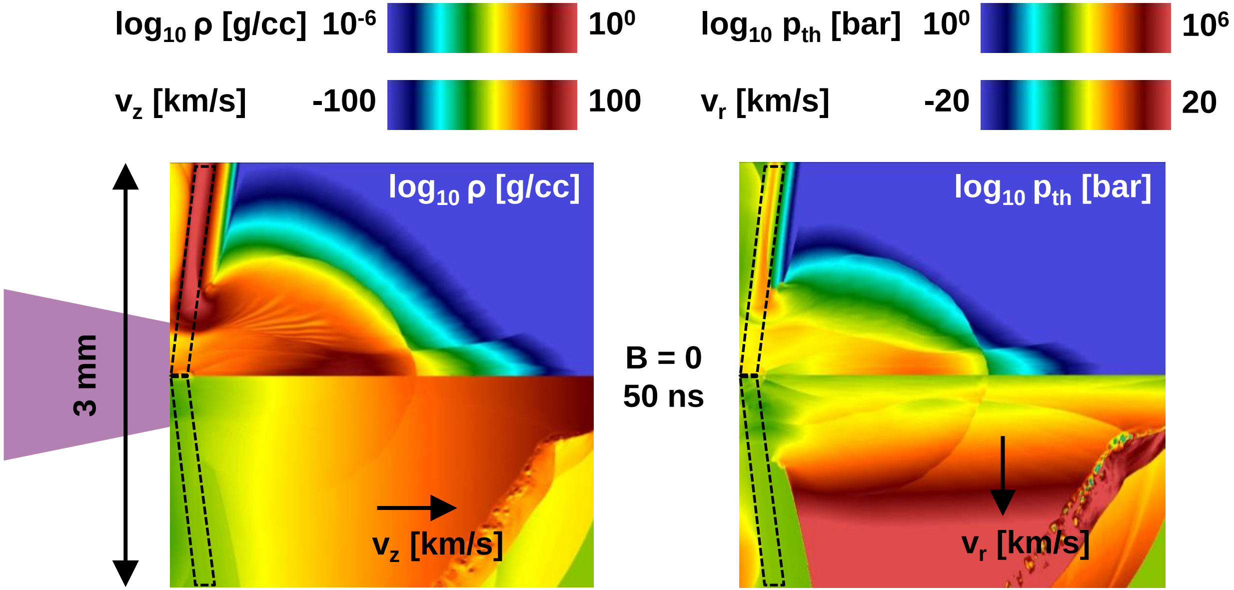
Abel Transform

$$n_e > n_{cr} \frac{1}{\pi} \int_r^{\infty} \frac{d(\Delta\varphi_{meas})}{dy} \frac{dy}{\sqrt{y^2 - r^2}}$$

Radiation-hydrodynamic calculations predict inertial collimation in the breakout plasma of conical targets

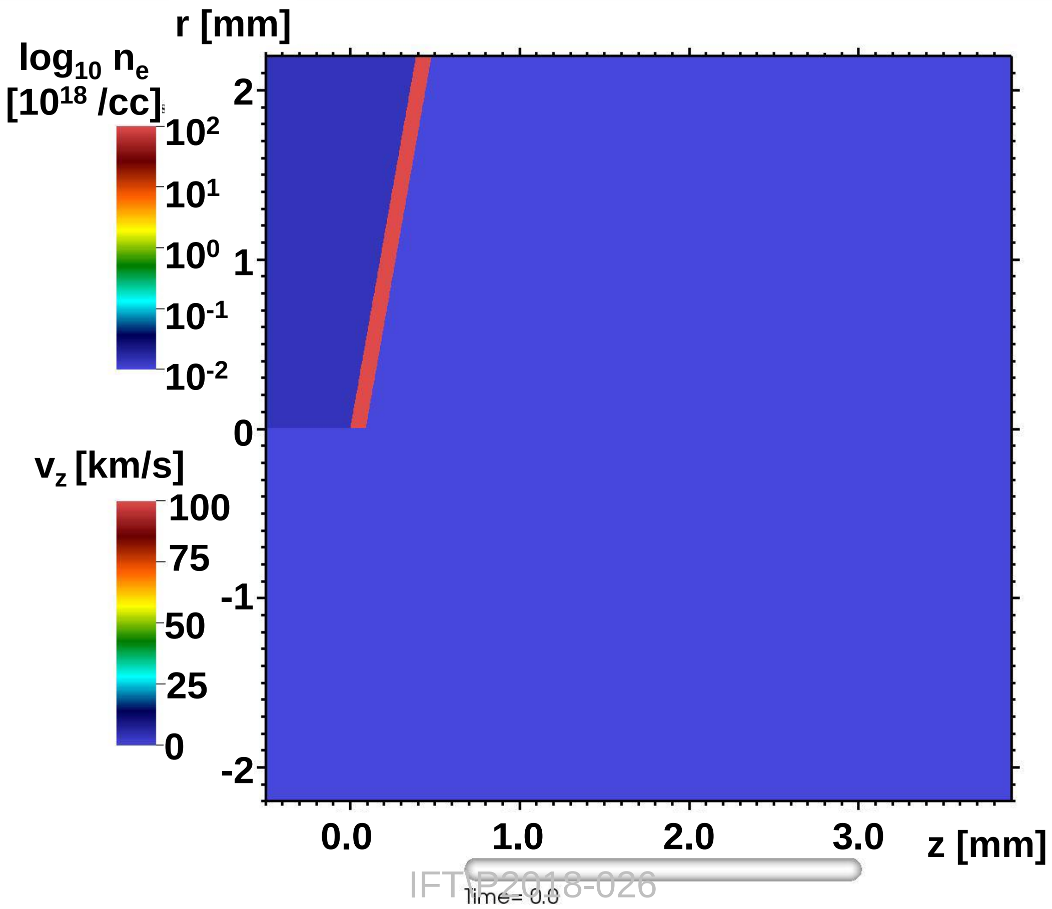


Schematic

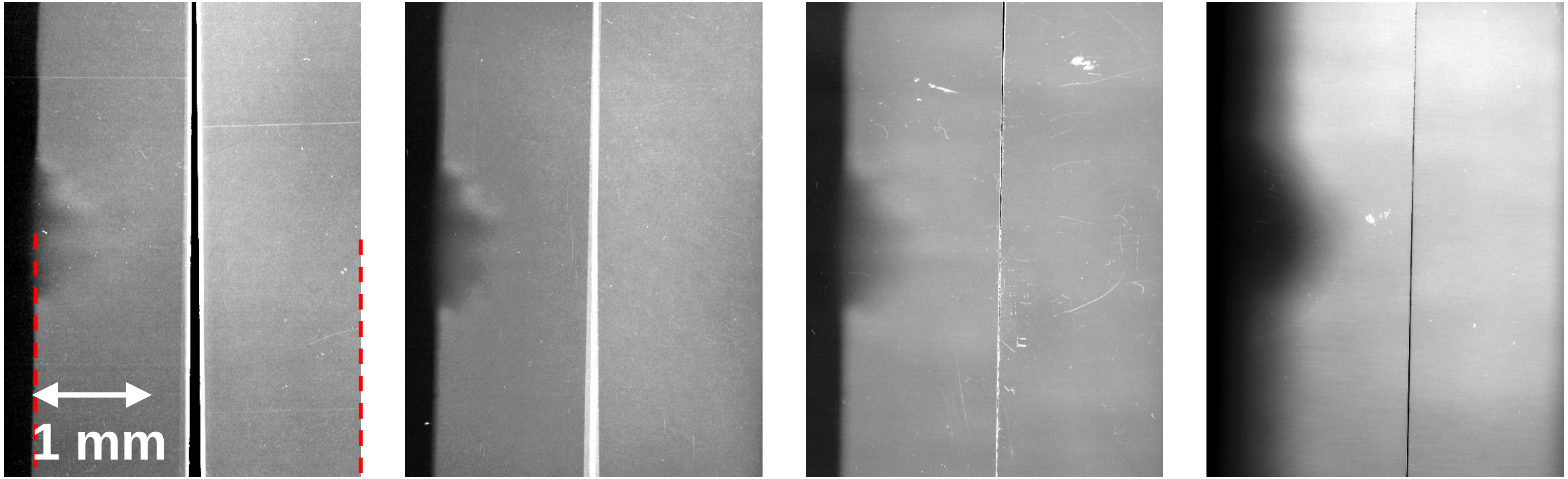


FLASH Results

Pinching in this geometry is proposed as a mechanism that can form astrophysical jets from isotropic, stellar outflows



Proton radiography suggests that jet collimation is not aided by self-generated B-fields



E~10.1 MeV
T_0+450 ps

E~7.6 MeV
T_0+520 ps

E~5.0 MeV
T_0+650 ps

E~2.3 MeV
T_0+950 ps

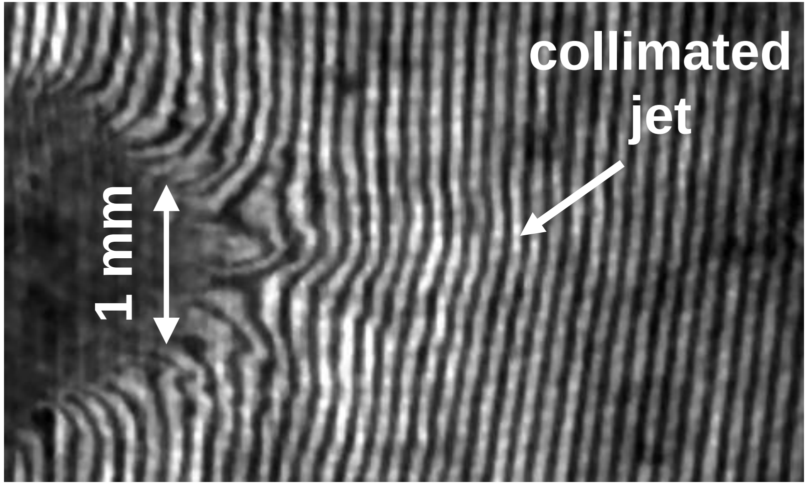
Proton Fluence

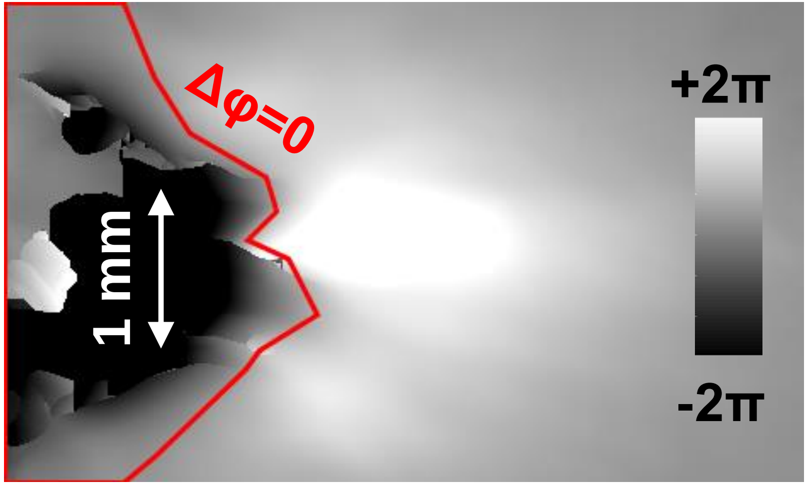
high

low

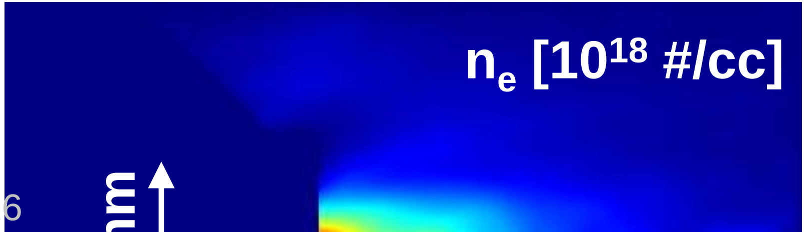
Lack of proton deflections at the jet location indicate hydrodynamic collimation.

Processed interferograms indicate collimated jet formation



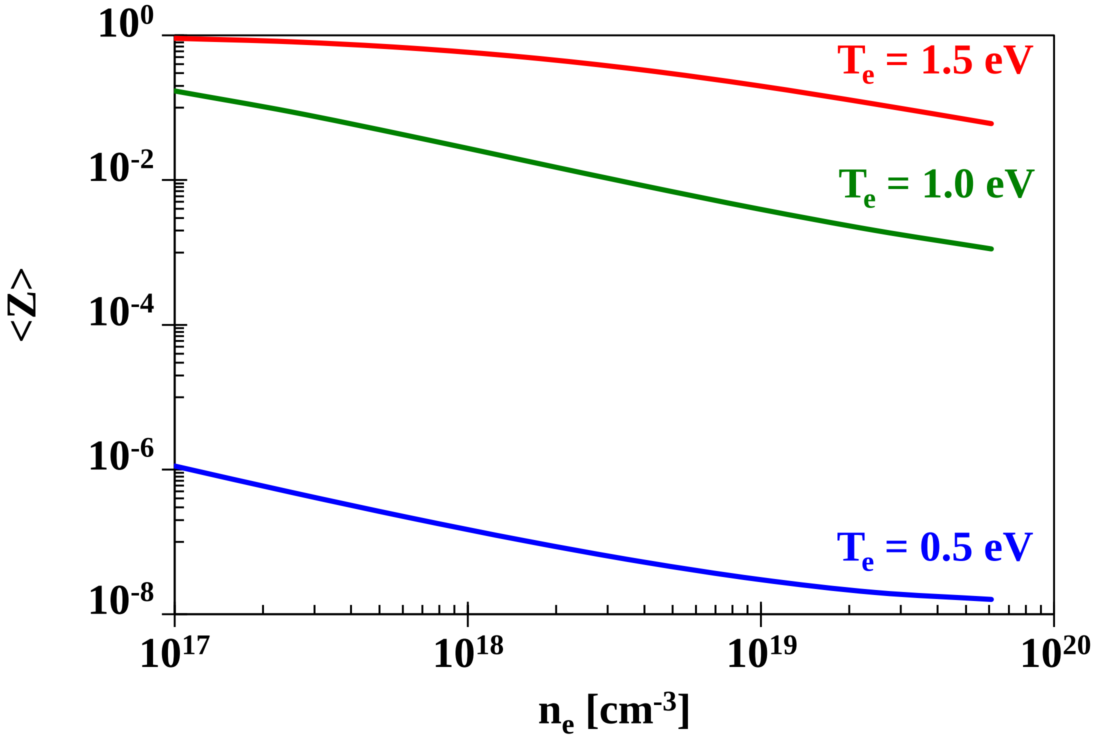


- Interferograms show fringe shifts
- Wavelet analysis reveals the phase change distribution



FLYCHK Results

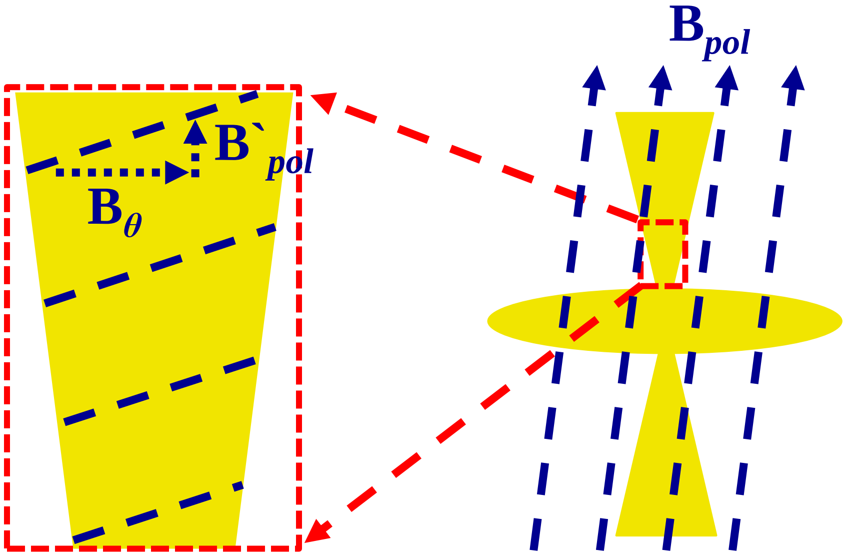
Atomic Composition of the Cone:
$C_5H_8O_2$ – Trace $Sb_{0.03}$
<A> = 6.7
<Z> = 3.6
(essentially acrylic)

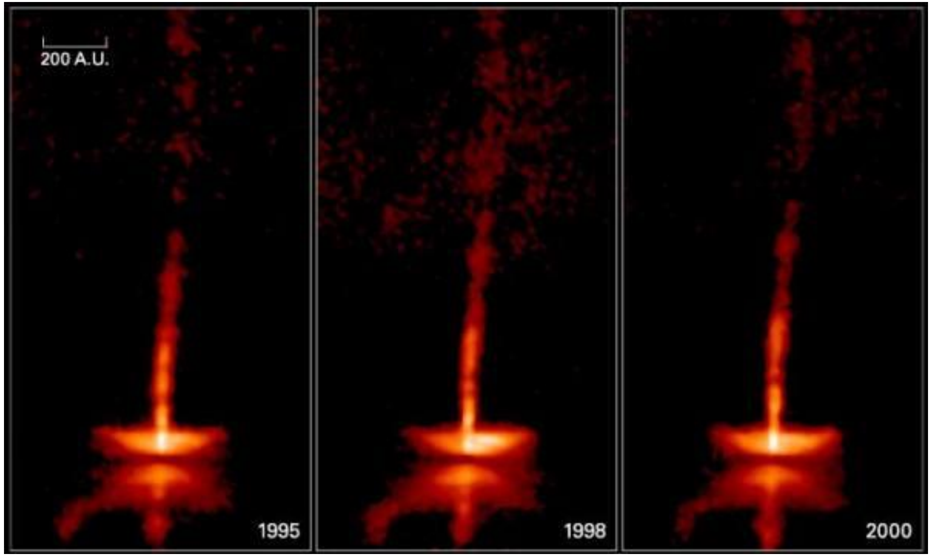


At low ionization states maybe coulomb interactions with neutrals becomes important. Quick calculations indicate that at Z~.01, Te=1eV and ne=1e18, that CM x-section is ~1000 times less than plasma x-section.

At T_e~1eV in the density regimes of interest <Z>~10^{-1} – 10^{-3}

Plasma flows in transverse B-fields are relevant to a variety of astrophysical plasmas

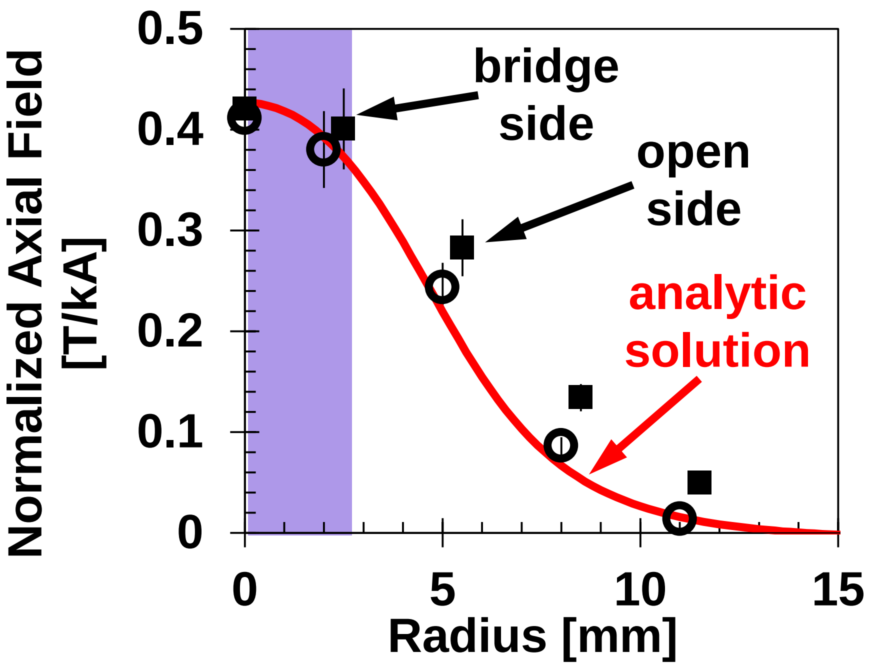




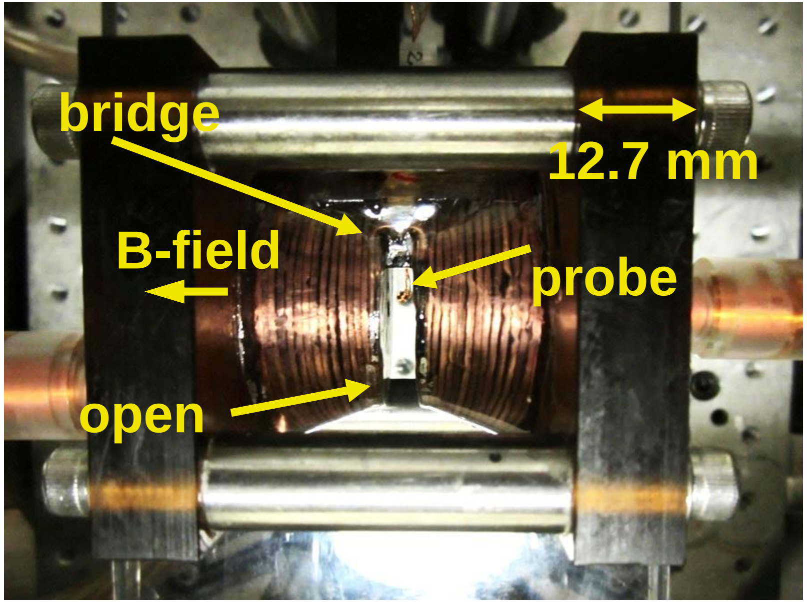
Herbig-Haro Object HH30

Collimating Force $$F_{\perp} = \underbrace{-\frac{B_{\theta}}{\mu_0 r}\nabla_{\perp}\left(rB_{\theta}\right)}_{\text{self-collimation}} + \underbrace{j_{\theta}B_{pol}}_{\text{pinching}}$$

A custom-designed ~1-mm^3 B-dot probe spatially resolved the axial magnetic-field strength in the solenoid gap

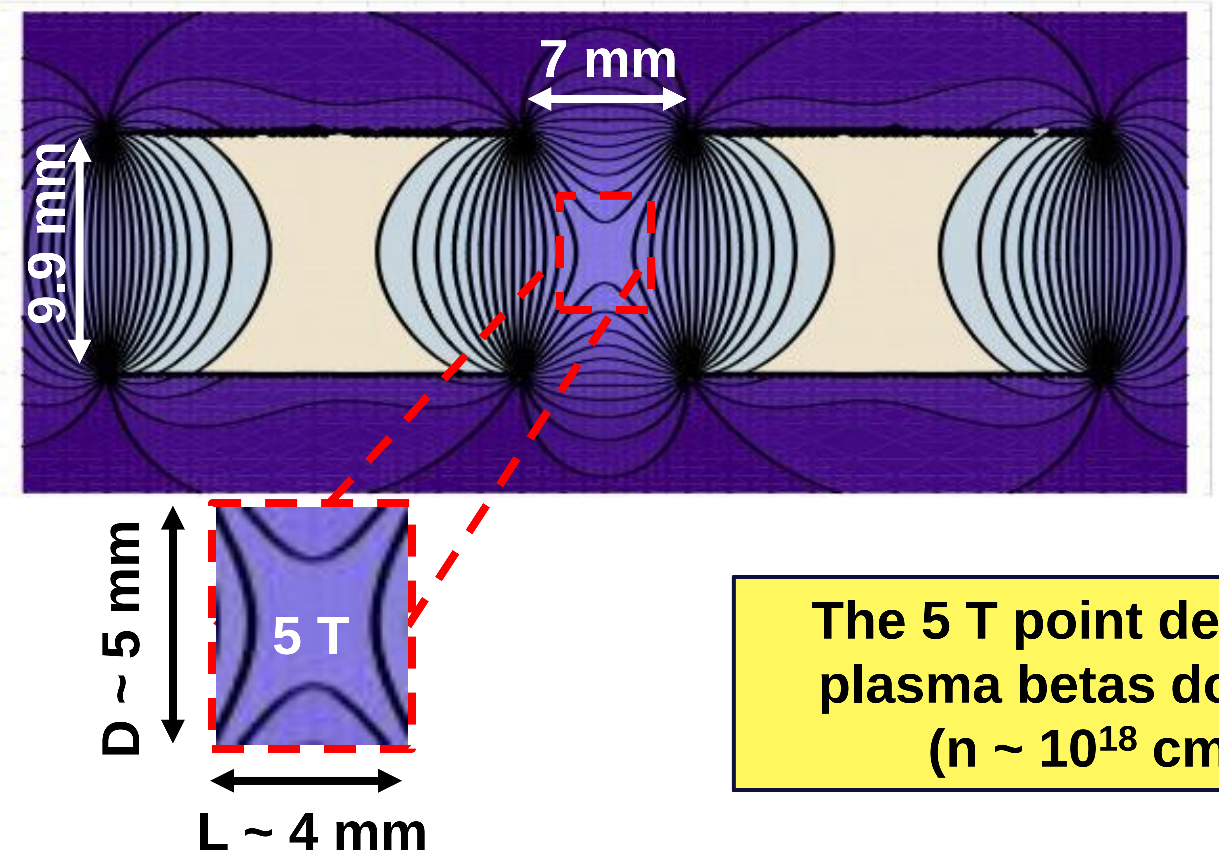


Top View



B-field measurements demonstrate a <5% spatial variation within a 2.5 mm radius of the gap center.

A custom-designed solenoid provided a constant field while still allowing diagnostic access



The 5 T point design generates plasma betas down to β_{th}~0.02 (n ~ 10^{18} cm^{-3}, T~1 eV)

Magnetohydrodynamic (MHD) equations describe both laboratory and astrophysical systems

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

Momentum $$r\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \frac{1}{m_0}\left(\nabla\times\mathbf{B}\right)\text{´ }\mathbf{B}$$

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

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

Ryutov, ApJ 518 (1999); Ryutov, POP 8 (2001); Drake, High-energy-density physics (2006), ch 10; Remington, RMP 78 (2006)

Magnetohydrodynamic (MHD) equations describe both laboratory and astrophysical systems

Combine the Electron Momentum Equation and Faraday's Law:

$$\underbrace{\frac{\partial}{\partial t}\left(\vec{B} - m_e \nabla \times \vec{v}_e\right)}_{\text{Conservation of Generalized Vorticity}} = \underbrace{\nabla \times \left(\vec{v}_e \times \vec{B}\right)}_{\text{Electron B-field Convection}} + \underbrace{\nabla \times \left(\frac{\nabla p_e}{n_e e_0}\right)}_{\text{Thermo-electric Field Generation}} - \underbrace{\nabla \times \frac{\left(\nabla \times \vec{B}\right) \times \vec{B}}{\mu_0 n_e e_0}}_{\text{j X B Force Term}} + \underbrace{\nabla \times \frac{\nabla \cdot \vec{\vec{P}}}{n_e e_0}}_{\text{Pressure Tensor Term}} - \underbrace{\nabla \times \frac{\vec{R}_T + \vec{R}_U}{n_e e_0}}_{\text{Thermal and Frictional Forces}}$$

- Most terms describe B-field evolution in time and space
- Pressure Tensor is typically small relative to other terms
- **Thermoelectric term typically dominates field generation**

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

- The system exhibits fluid-like behavior $l_{mfp}/L \ll 1$
- Energy flow by particle heat conduction is negligible $\mathrm{Pe} \gg 1$
- Energy flow by radiation flux is negligible $\mathrm{Pe}_g \gg 1$
- Viscous dissipation is negligible $\mathrm{Re} \gg 1$

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 beta (β) are similar.

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

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

Physical condition	Constraint	YSO 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	$\sim 10^{1} - 10^{2}$	$\sim 10^{0} - 10^{1}$
Thermal compared to magnetic pressure	Thermal plasma β_{th}	$\sim 10^{-3} - 10^{1}$	$\sim 10^{0} - 10^{5}$
Dynamic compared to magnetic pressure	Dynamic plasma β_{dyn}	$\sim 10^{-3} - 10^{1}$	$\sim 10^{-3} - 10^{5}$

Curran et al., MNRAS 382 (2007); Carrasco-Gonzalez et al., Science 330 (2010); Ferreira AA 452 (2006); Reipurth ARAA 39 (2001)