Outflow collimation by a poloidal magnetic field

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Collaboration LULI, LNCMI, CELIA: B. Albertazzi, J. Béard, J. Billette, S. Chen, T. Cowan, E. d'Humières, J. Fuchs, F. Kroll, M. Nakatsutsumi, O. Portugall, H. Pépin, C. Riconda, L. Romagnani, H-P. Schlenvoight, T. Vinci,

BASICS OF MAGNETIC COLLIMATION

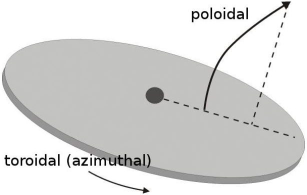
Magnetic collimation

“Main collimation mechanism” requires a toroidal (azimuthal) field component

From the (axisymmetric) induction equation:

$$\frac{\partial B_\phi}{\partial t} = -r\mathbf{B_{pol}} \cdot \nabla\omega(\mathbf{r}, \mathbf{z})$$

differential angular rotation, ω, along an initially poloidal field line, $\mathbf{B_{pol}}$, generates an azimuthal component B_ϕ.



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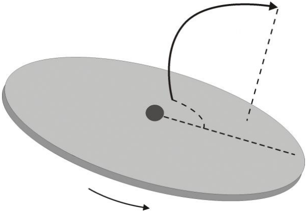

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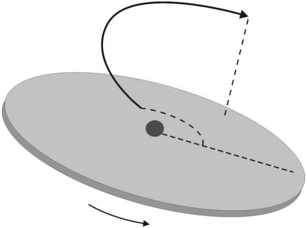

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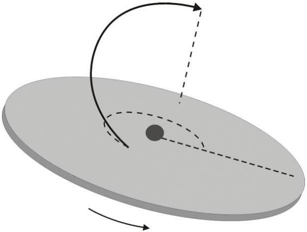

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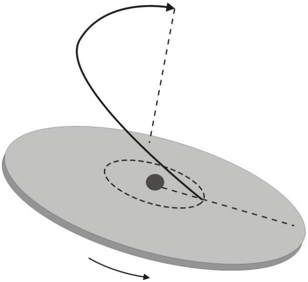


Magnetic collimation

“Main collimation mechanism” requires a toroidal (azimuthal) field component

Magnetic (Lorentz) force on the plasma $\mathbf{F} = \mathbf{j} \times \mathbf{B}$ can be written as (e.g. Ferreira 1997):

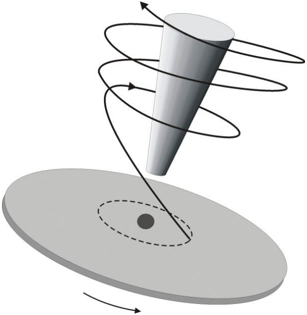
Azimuthal:

$$F_\phi = \frac{B_{pol}}{\mu_0 r} \nabla_\parallel (r B_\phi)$$

Poloidal:

$$F_\parallel = -\frac{B_\phi}{\mu_0 r} \nabla_\parallel (r B_\phi)$$

$$F_\perp = -\frac{B_\phi}{\mu_0 r} \nabla_\perp (r B_\phi) + j_\phi B_{pol}$$



We are interested in $B_\phi = 0$ and the effects of B_{pol} only $\rightarrow j_\phi B_{pol}$

COLLIMATION BY A POLOIDAL FIELD

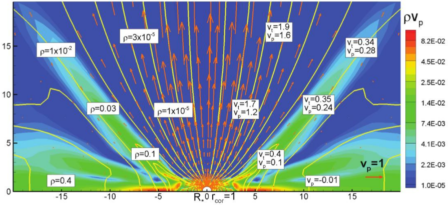
Collimation by a poloidal magnetic field

Magnetosphere-disc region[1]

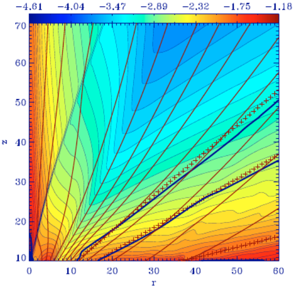
→ Two component magnetized outflows: stellar and disc winds

→ Collimation of stellar wind depends

- on the field anchored in disc
- disc wind



Romanova et al 2009



Matsakos et al 2009

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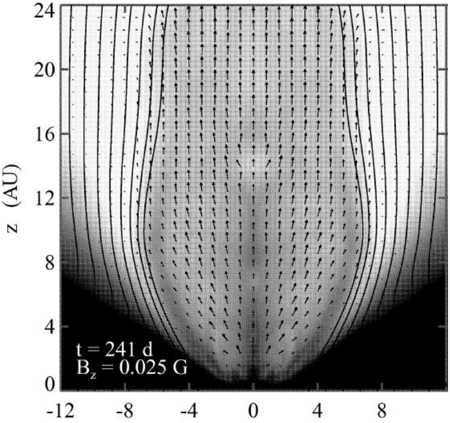
[1] *Stone et al 1992; Matt et al 2003*

Collimation by a poloidal magnetic field

Magnetosphere-disc region[2]

→ Collimation over a few ×10 AU of disc-stellar wind



Matt et al 2003

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[2] *Stone et al 1992; Matt et al 2003*

Collimation by a poloidal magnetic field

Outflows from collapsing pre-stellar cores[3]

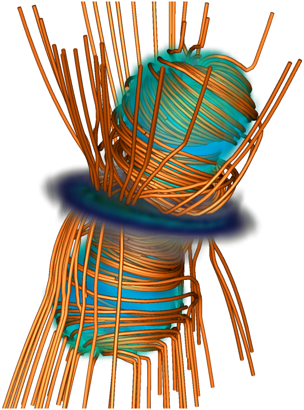
Gravitationally collapsing dense core of 1 solar mass.

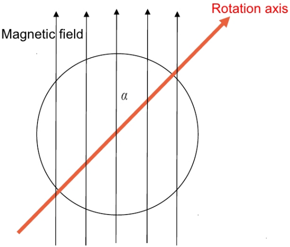
→ $R_{core} \sim 1000$ AU

→ $n \sim 10^6$ cm^{-3}

→ $T = 10$ K

→ $\mu = 5$ highly-magnetized, supercritical





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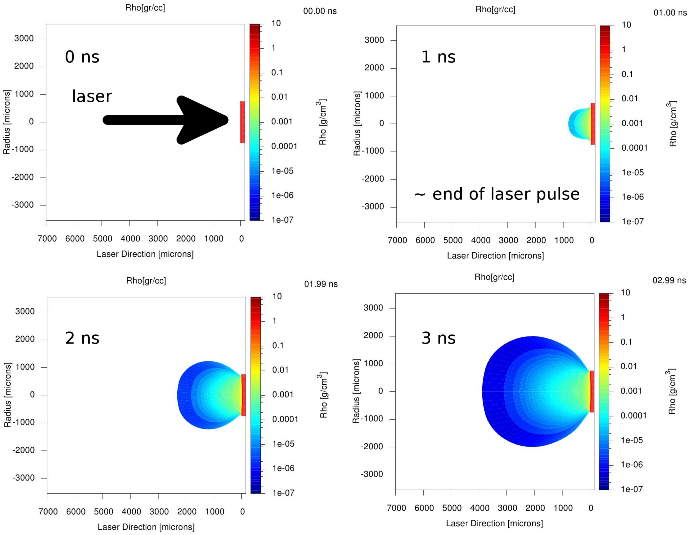
[3] *Hennebelle et al 2009, Ciardi et al 2010, Joos et al 2012*

EXPERIMENTAL APPROACH

Laser-driven plasma plume → thermally-driven wind



Simple estimates

→ Spherical expansion halted when

$$\rho v^2 \sim B_0^2/8\pi$$

→ Collimation radius

$$R_{coll} \sim 0.8 \left(E_K/B_0^2\right)^{1/3} \quad \mathrm{cm}$$

→ Bulk kinetic energy

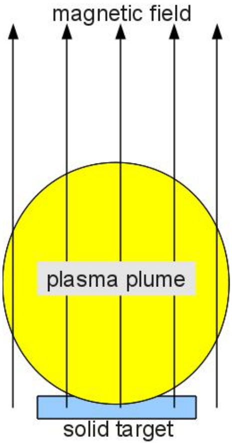
$$E_K = f\,E_L$$

with $f \sim 0.2 - 0.5$

→ Collimation time-scale

$$t_{coll} \sim R_{coll}/v_{exp}$$

where $v_{exp}(\mathrm{cm/s}) \sim 4.6 \times 10^7 I^{1/3} \lambda^{2/3}$



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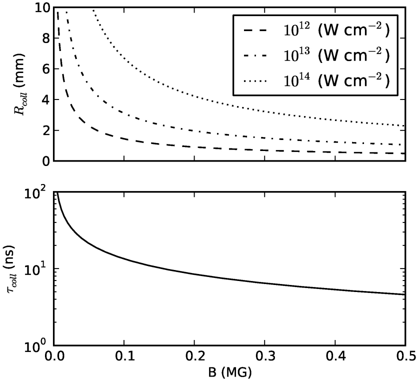

Nominal laser parameters:
$E_L = 50 - 500$ J ; $\tau_L = 1$ ns; $\lambda = 1.064\,\mu\mathrm{m}$;
$\phi = 750\,\mu\mathrm{m}$

Need $B_0 \gtrsim 0.1$ MG for several $t \gg 10$ ns

MODELLING THE EXPERIMENTS

Modelling tools

Laser-target interaction modelled with

→ DUED [4]

- 2D Lagrangian, radiation hydrodynamics
- 3 Temperatures
- Ray-tracing laser deposition
- Multi-group radiation transport
- Flux limited thermal diffusion (ion & electron)
- Tabulated EOS (SESAME)

Plasma-magnetic field interaction modelled with

→ GORGON[5]

- 3D Eulerian, resistive MHD with computational vacuum
- 2 Temperatures (ion & electron)
- Optically thin radiation losses with black-body limiter
- Flux limited thermal diffusion (ion & electron)
- Ions: perfect gas. Electrons: Thomas-Fermi LTE

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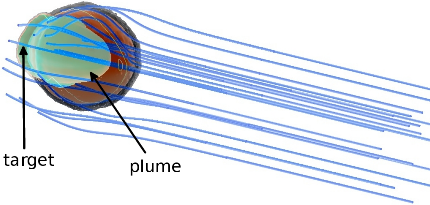
[4] *Atzeni et al 2005*

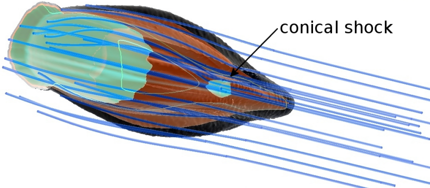
[5] *Chittenden et al 2004; Ciardi et al 2007*

Three main phases of evolution

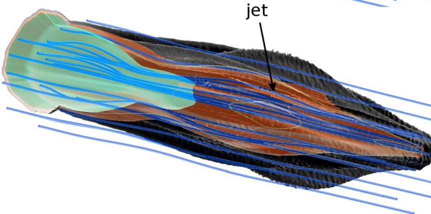
1. Cavity-shell formation
   - High-beta cavity
   - Formation of a shell of shocked material and compressed **B**
   - Re-direction of plasma along cavity walls



2. Jet formation
   - Re-directed flow converges towards the axis
   - Formation of a conical shock
   - Axial re-direction and jet formation

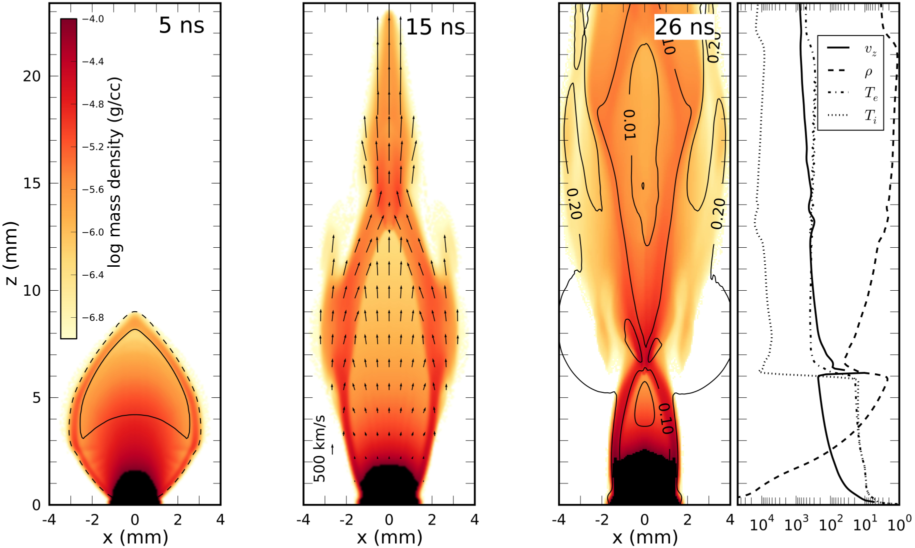


3. Re-collimation
   - Secondary cavity
   - Re-collimation, conical shock and jet



Three main phases of evolution

Dynamics at $I \sim 10^{14}\,\mathrm{W\,cm^{-2}}$ and $B_0 \sim 0.2\,\mathrm{MG}$



Flow instabilities

Rayleigh-Taylor type filamentation instability[6]

Configuration similar to a θ-pinch

→ Growth rate

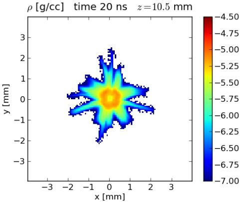
$$\gamma \sim \sqrt{g k_\theta}$$

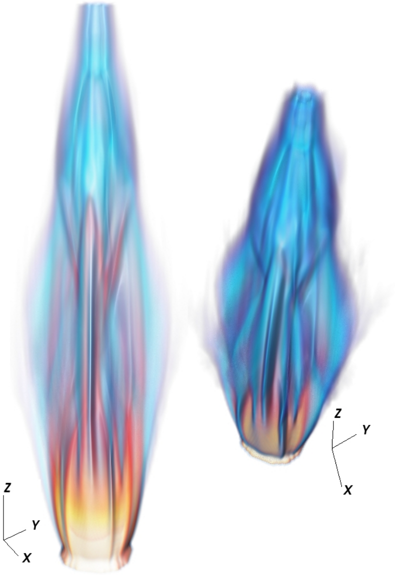
$$k_\theta = m / R_{jet}$$

$$g \sim v^2 / R_C$$

→ Growth time-scale is short

$$\tau_I \sim \frac{\tau_{coll}}{\sqrt{m}} \sim \text{few ns}$$





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[6] *Kleev & Velikovich 1990*

Flow instabilities

Firehose[7]

Jet may be susceptible to firehose instability

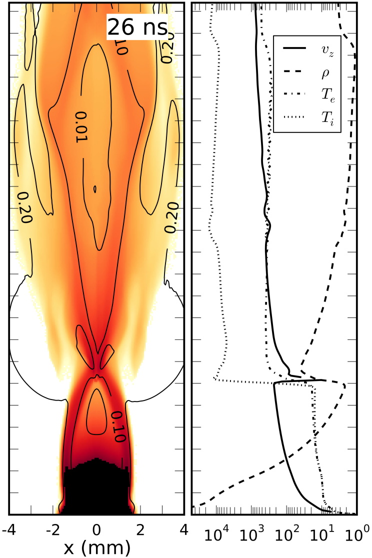
$$P_{\parallel} - P_{\perp} > \frac{B^2}{4\pi}$$

$$P_{\parallel} \sim \rho v^2$$

$$M_A^2 - \frac{\beta}{3} > 1$$

Marginally stable for some combination of laser intensity and magnetic field

- → Possible Kelvin-Helmoltz
- → Electrons may are highly-magnetized → possible anisotropic thermal pressure
- → Possible stabilization by the surrounding dense, magnetized plasma



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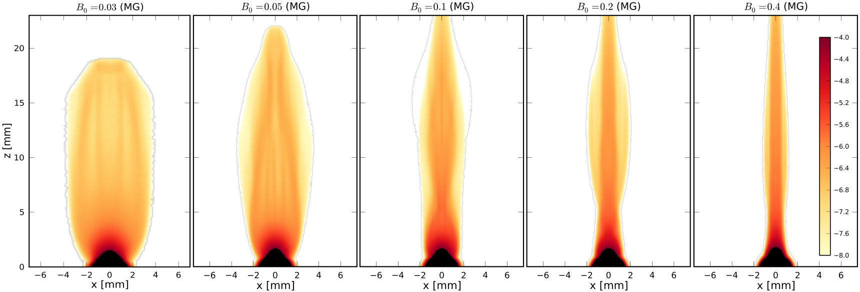
[7] *e.g. Benford 1981*

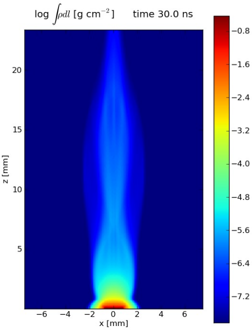
EXPERIMENTAL FLEXIBILITY

Effects of the magnetic field strength

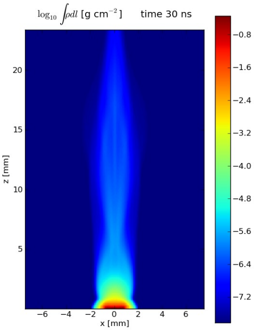
Jet formation by a conical shock suppressed at low field strength



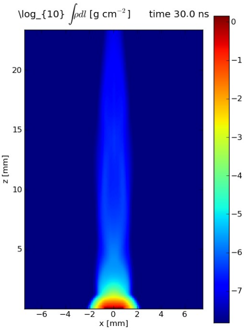
Effects of target material (radiative losses)



Carbon

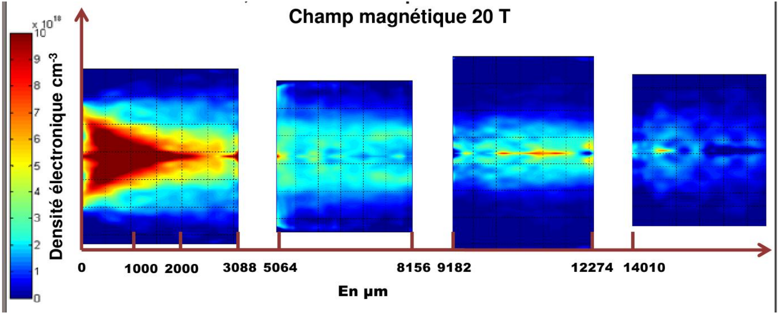


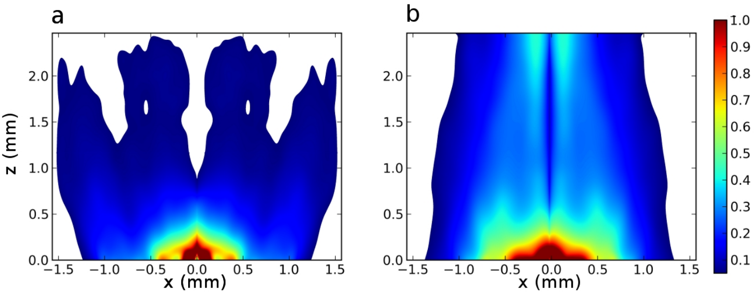
Aluminium



Copper

Preliminary experimental results



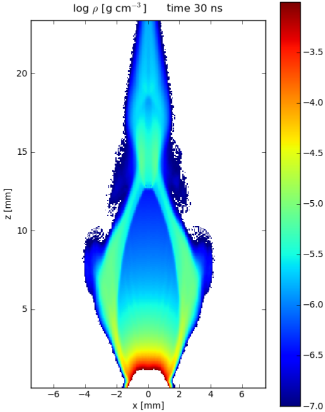


Summary and future directions

Potential studies with coupled laser-driven plasmas and external magnetic field.

→ outflow collimation mechanism by a poloidal field

  - jet formation by re-converging flows



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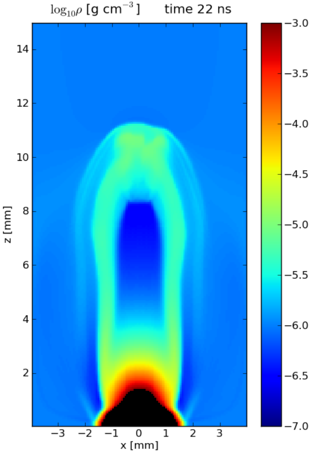
- → jet interaction with ambient medium



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- → outflow collimation mechanism by a poloidal field
  - ▸ jet formation by re-converging flows
- → jet interaction with ambient medium
- → magnetized accretion shocks