Outflow collimation by a poloidal magnetic field

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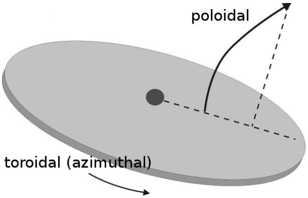
Magnetic collimation

"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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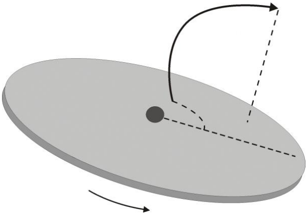

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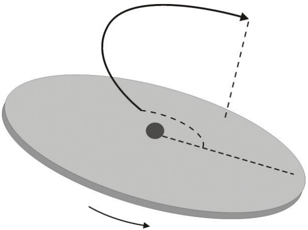

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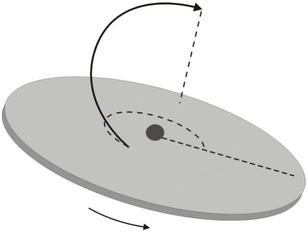

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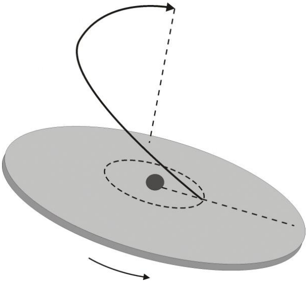


Magnetic collimation

"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):

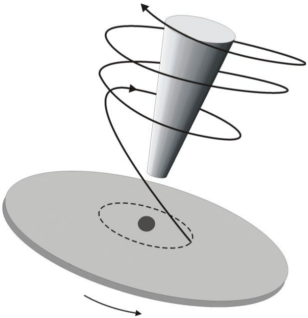
Azimuthal:

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

Poloidal:

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

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



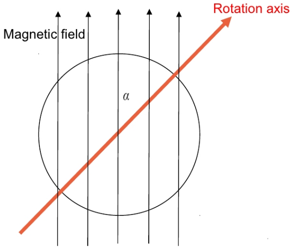
We are interested in $B_\phi = 0$ and the effects of B_{pol} only $\rightarrow j_\phi B_{pol}$

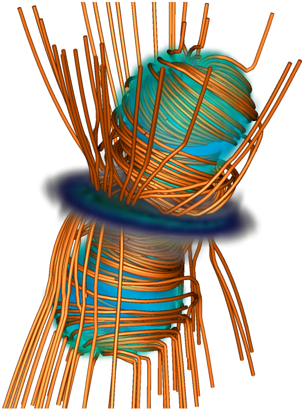
Collimation by the magnetic field

Outflows from collapsing pre-stellar cores[1]

Gravitationally collapsing dense core of 1 solar mass.

- $\rightarrow$ $R_{core} \sim 1000$ AU
- $\rightarrow$ $n \sim 10^6$ cm^{-3}
- $\rightarrow$ $T = 10$ K
- $\rightarrow$ $\mu = 5$ highly-magnetized, supercritical

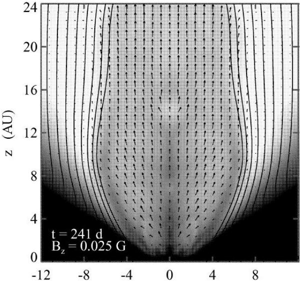




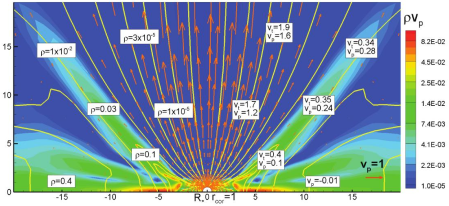
[1] *Hennebelle et al 2009, Ciardi et al 2010, Joos et al 2012*

Collimation by poloidal magnetic field

outflow collimation by disk field, star-disk interaction...[2]



Matt et al 2003



Romanova et al 2009

[2] *Stone et al 1992, Spruit et al 1997, Matt et al 2003, Fendt 2006, Romanova et al 2009*

Collimation by poloidal magnetic field

outflow collimation by disk field, star-disk interaction...[2]

Importance of magnetic field parametrized by

$$\sigma = \frac{B_z^2}{4\pi\rho v_{out}^2}$$

Observations

Table 1. Energy densities in AGB envelopes

		Photosphere	SiO	H_2O	OH
B	[G]	~ 50?	~ 3.5	~ 0.3	~ 0.003
R	[AU]	-	~ 3	~ 25	~ 500
		-	[2 – 4]	[5 – 50]	[100 – 10.000]
V_{exp}	[km s^{-1}]	~ 5	~ 5	~ 8	~ 10
n_{H_2}	[cm^{-3}]	$\sim 10^{14}$	$\sim 10^{10}$	$\sim 10^{8}$	$\sim 10^{6}$
T	[K]	~ 2500	~ 1300	~ 500	~ 300
$B^2/8\pi$	[dyne cm^{-2}]	$\mathbf{10^{+2.0}}$?	$\mathbf{10^{+0.1}}$	$\mathbf{10^{-2.4}}$	$10^{-6.4}$
nKT	[dyne cm^{-2}]	$10^{+1.5}$	$10^{-2.8}$	$10^{-5.2}$	$10^{-7.4}$
ρV_{exp}^2	[dyne cm^{-2}]	$10^{+1.5}$	$10^{-2.5}$	$10^{-4.1}$	$\mathbf{10^{-5.9}}$
V_A	[km s^{-1}]	~ 15	~ 100	~ 300	~ 8

Vlemmings 2011

Simulations $\sigma \sim 10^{-3} - 10^{-1}$

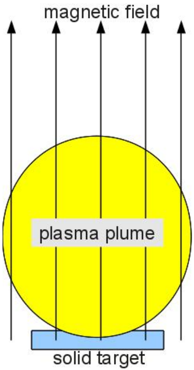
[2] *Stone et al 1992, Spruit et al 1997, Matt et al 2003, Fendt 2006, Romanova et al 2009*

Laser-driven, magnetically collimated jets

Experiments *recently* performed on the ELFIE 100 TW laser at the Ecole Polytechnique

Interaction of laser produced plasma plume with an *externally* generated magnetic field

- → current pulse $\sim 200\mu s \gg \tau_{laser}$
- → $B = 0 - 40$ Tesla
- → $\sigma = \frac{B_z^2}{4\pi\rho v_z^2} \sim 1 - 0.01$

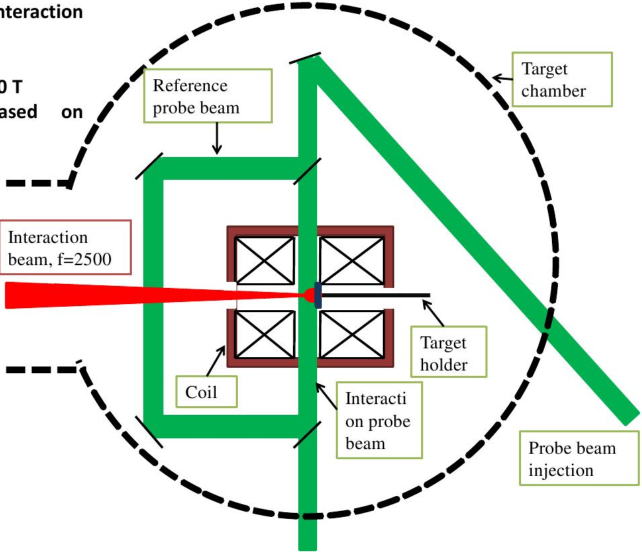


Laser: ELFIE 100 TW, 2 beams 30 TW (10 J, 300 fs), one long pulse (50 J, 500 ps), one probe beam (100 mJ, 300 fs).

Laser-driven, magnetically collimated jets

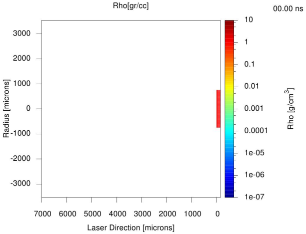
Experiments *recently* performed on the ELFIE 100 TW laser at the Ecole Polytechnique

-Long focal for interaction beam : f=2500
- 45 J, 600 ps FWHM
- Magnetic field of 20 T
- Interferometry based on Mach Zender

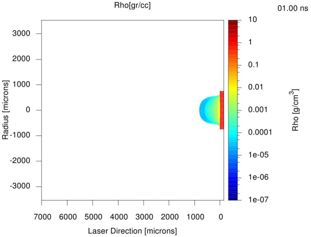


Laser-driven, magnetically collimated jets

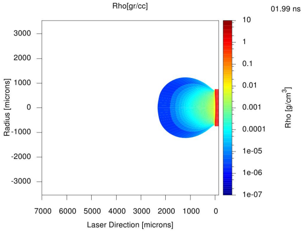
Laser-target interaction and initial hydrodynamic plasma evolution modelled with DUED[3]



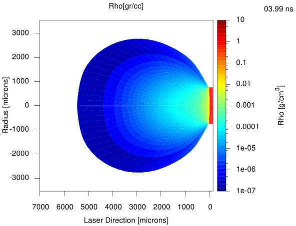
0 ns



1 ns



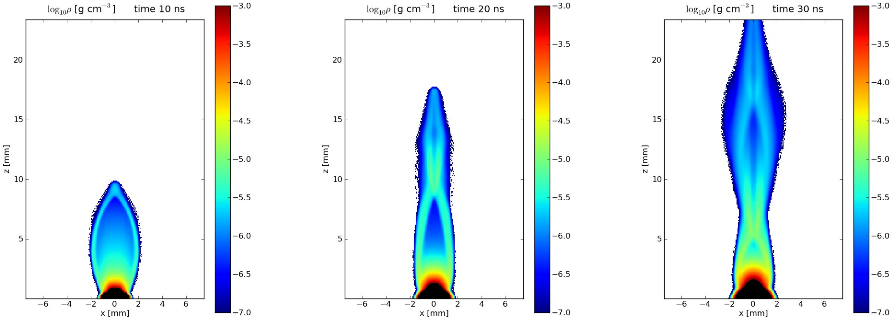
2 ns



4 ns

[3] *Atzeni 1986*

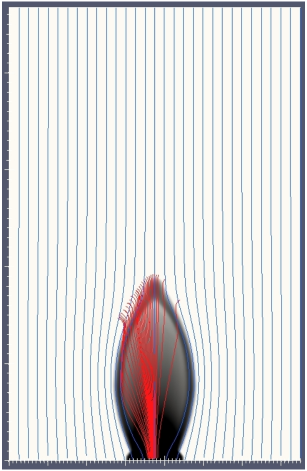
Three main phases of evolution



Aluminium, 10 Tesla, 50 Joules

Three main phases of evolution

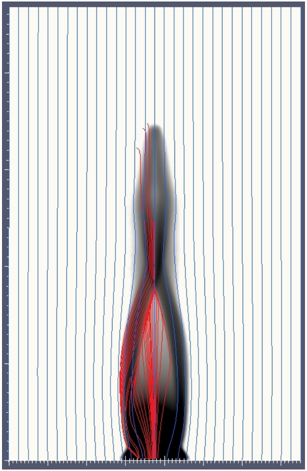
1. Cavity-shell formation
   - High-beta cavity
   - Formation of a shell of shocked material and compressed **B**
   - Re-direction of plasma along cavity walls



10 ns

Three main phases of evolution

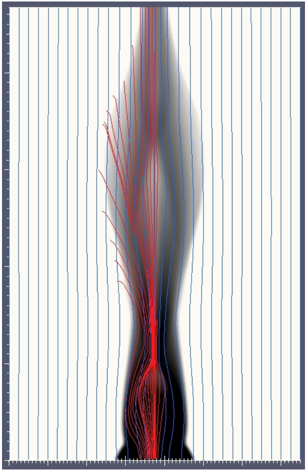
1. Cavity-shell formation
    - High-beta cavity
    - Formation of a shell of shocked material and compressed **B**
    - Re-direction of plasma along cavity walls
2. Jet formation
    - Re-directed flow converges towards the axis
    - Formation of a conical shock
    - Axial re-direction and jet formation



20 ns

Three main phases of evolution

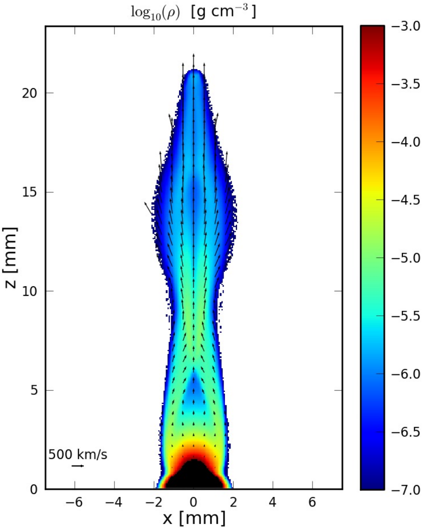
1. Cavity-shell formation
   - High-beta cavity
   - Formation of a shell of shocked material and compressed **B**
   - Re-direction of plasma along cavity walls
2. Jet formation
   - Re-directed flow converges towards the axis
   - Formation of a conical shock
   - Axial re-direction and jet formation
3. Re-collimation
   - Secondary cavity
   - Re-collimation, conical shock and jet



30 ns

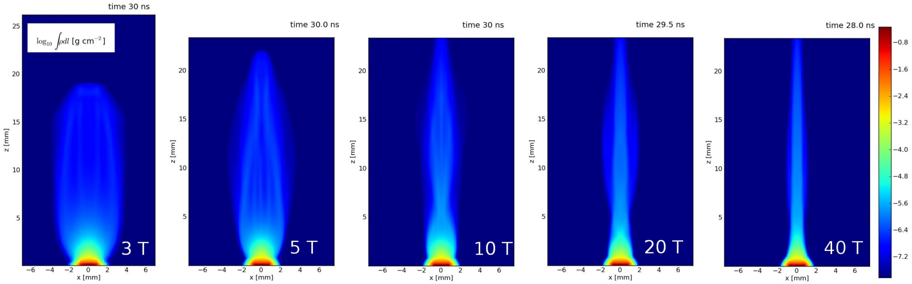
Characteristic flow parameters

- → $v_{flow} \sim 100 - 500$ km/s
- → Mach number ~ 5
- → Alfvenic Mach number $\sim 3 - 5$

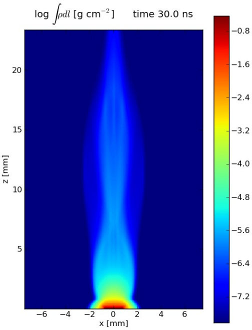


Effects of the magnetic field strength

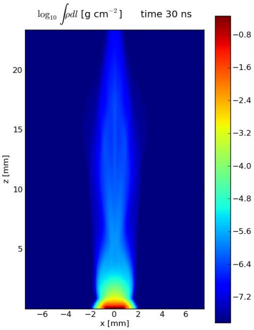
Collimated jet formation suppressed at low field strength



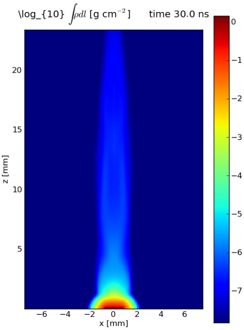
Effects of target material (radiative losses)



Carbon

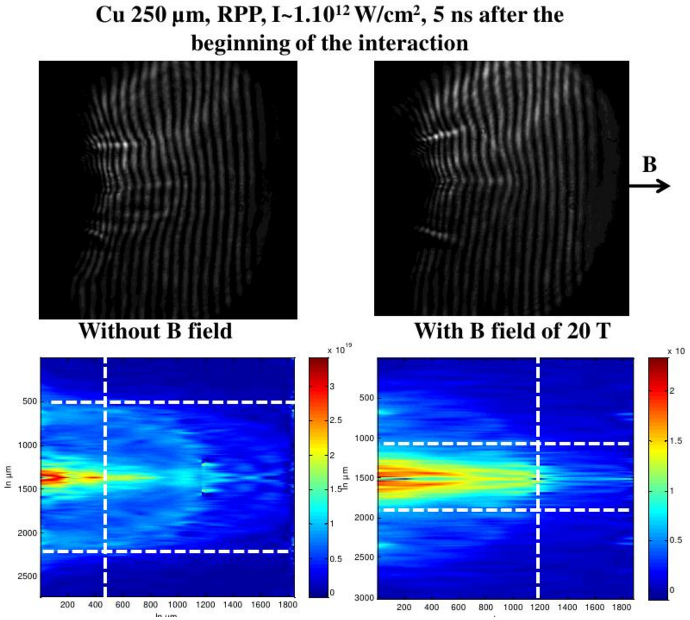


Aluminium



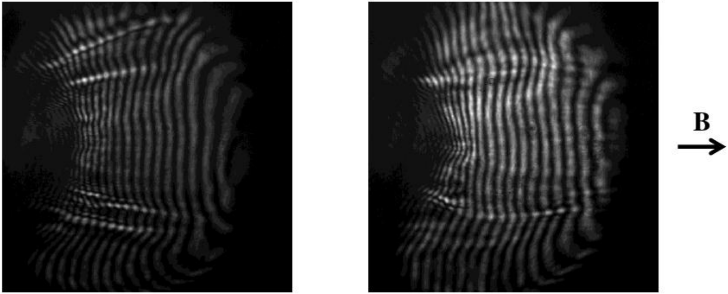
Copper

Preliminary analysis of experimental results



Preliminary analysis of experimental results

Cu 250 µm, RPP, I~1.10^{13} W/cm^2, 11 ns after the beginning of the interaction



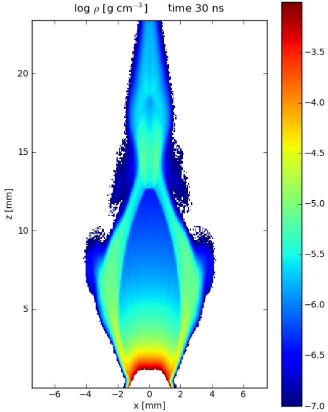
Without B field | **With B field of 20 T**

Summary and future directions

Coupling laser and external magnetic field has potential to studv:

→ outflow collimation mechanism by a poloidal field

- jet formation by re-converging flows



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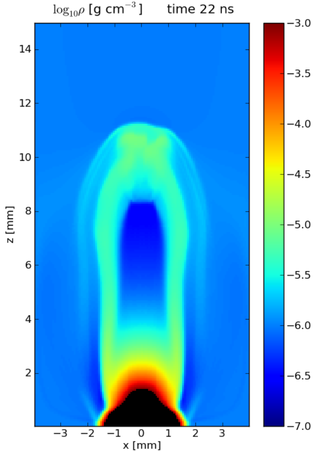
→ jet interaction with ambient medium



Summary and future directions

Coupling laser and external magnetic field has potential to study:

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