Using high-power laser for plasmas studies and applications: examples of collaborative work within Plas@Par

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High-power lasers produce EXTREME matter and fields

LASER = The highest achievable concentration of power, on a small surface

Laser beam
GW – PW (10⁹-10¹² W)

Target heated to MK (10⁶ K)

Intense transverse & longitudinal fields
10¹² V/m - 10⁵ T (10⁹ G)

Intensities 10¹³ - 10²⁰ W/cm²

Focal spot 1 mm to 1 μm
The lasers of the LULI lab at Ecole Polytechnique

Present

LULI 2000 facility
kJ/ns + 40 J/ps

ELFIE laser facility (30 J / 300 fs)

Future (2016) - Apollon /CILEX

F1: 150 J max, 15 fs – 5 ps
F2: 15 J, 15 – 200 fs
F3: Long Pulse: 200 J
F4: Probe: 0.25 J, < 20 fs
There are two main branches of applications

1-We produce a LOT of photons = maximum energy → “thermal” plasma

2-We produce the highest power = maximum E-field associated to the laser pulse → “kinetic plasma”
Example 1: Impact of magnetic fields on plasma flows relevant to astrophysical jets (with LERMA: A. Ciardi, et al.)

Impact of jets:
• Jets extract lots of power & angular momentum
• Affect the inner regions of disks (< few AU)
• Remove mass → limit final mass?
• Inject energy into ISM → sustain turbulence

cloud
Where are astrophysical jets coming from?

Accretion disk with toroidal motion (azimuthal)

Wide-angle wind

µG galactic « poloidal » B-field

Central object

mG disk « poloidal » B-field
Q: what is really the effect of $B_{pol}$? → experiment

Plasma length: cm

Plasma diameter: 1-2 mm

ns laser

B field: 20 T

Density: $\sim 5 \times 10^{18} \text{ cm}^{-3}$
A crucial component: coupling of large-scale homogeneous B-field to a high-power laser
What we found: Typical experimental full jet morphology at 20 ns

Technique to reconstruct jet

B. Albertazzi et al., Science (2014)
Mechanism: shock-focusing & collimation

Simulations performed by A. Ciardi

Formation of a shell of shocked material and compressed $B$

Axial re-direction and jet formation

Re-collimation, conical shock and jet

Parameters:
- target Al
- intensity: $1.5 \times 10^{13}$ W.cm$^{-2}$
- $B = 10$ T

3D MHD Gorgon code

The same morphology is found in a full-scale astrophysical simulation.

Simulations performed by A. Ciardi (code RAMSES)

<table>
<thead>
<tr>
<th>Objet</th>
<th>cas 1</th>
<th>cas 2</th>
<th>cas 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Champ magnétique (mG)</td>
<td>5</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Taux de masse éjecté (Mₘ₀/solar/anneau)</td>
<td>$10^{-8}$</td>
<td>$5.10^{-7}$</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>T_{ambient} (K)</td>
<td>100</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>T_{vent} (K)</td>
<td>10000</td>
<td>500</td>
<td>10000</td>
</tr>
<tr>
<td>$\rho_{vent}$ (part.cm⁻³)</td>
<td>$10^5$</td>
<td>$10^7$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>$\rho_{ambient}$ (part.cm⁻³)</td>
<td>$4.10^3$</td>
<td>$4.10^5$</td>
<td>$4.10^4$</td>
</tr>
<tr>
<td>R_{éjection} (U.A)</td>
<td>8</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>vitesse d'éjection (km.s⁻¹)</td>
<td>200</td>
<td>70</td>
<td>130</td>
</tr>
<tr>
<td>Perturbation en vitesse (°o)</td>
<td>5</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

5-10 mG typical
Next step: study of magnetized accretion shock
Example 2: study of magnetic reconnection using lasers
(with LPP: R. Smets, et al., and CEA-DAM)

- Compressed flow, strong density currents, no more “ideal”
- Many other effects, e.g. turbulence / Hall effect (electrons decouple from ions, electrons can be accelerated)
How can lasers be used for such study?
Reconnection is also a process at play which could influence laser fusion targets dynamics.

\[ D + T \rightarrow ^4\text{He} (3.5\text{MeV}) + n (14.1\text{MeV}) \]
Some potentially important questions for laser fusion

Q:
- a “significant” fraction of the energy goes into B field in fusion targets → Enough to affect the interaction in the event of a brutal released?
- In fusion targets, the geometry is complex → can this affect reconnection?
A first step is to well understand the B-field geometry in laser targets.

\[
\frac{\partial B}{\partial t} \approx \text{Convection} + \text{Diffusion}
\]

\[
- \frac{1}{en_e} \nabla n_e \times \nabla T_e
\]

Source

C.K. Li et al., PRL 99, 015001 (2007)
Which is quite different from what we found...

L. Lancia et al., PRL 113, 235001 (2014)
Next step: quantitative study of reconnection using the “LULI2000” lasers (June 2015)
Conclusion

- High-power lasers can generate very varied plasmas, from thermal, compressed, kinetic, magnetized or not
- Significant external magnetic fields can be applied, allowing to study varied configuration of guide fields
- More areas of collaborative work with other Plas@Par teams:
  - Ion-matter interactions (INSP, D. Vernhet et al.)
  - « Plasma optics » (LULI, C. Riconda et al.)
- Soon-to-come Apollon facility will allow exploring high-field, QED, etc physics