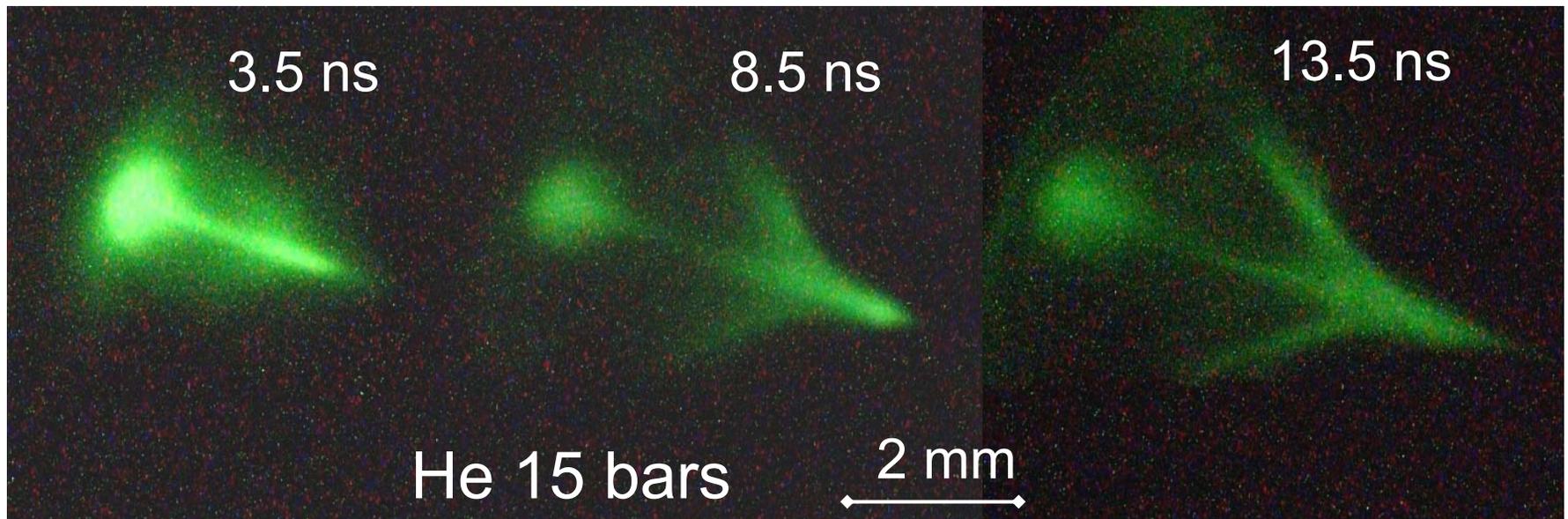


# *Laboratory modeling of supersonic jets propagation in plasmas and their scaling to astrophysical conditions*

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# Motivations

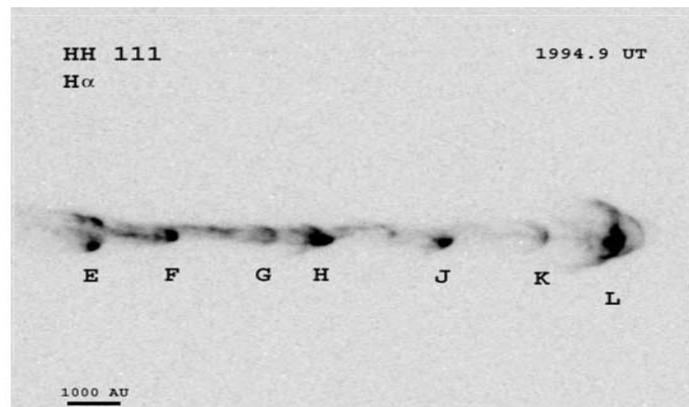
Issues relevant to astrophysical objects

- Collimation and propagation of jets over long distance
- Interaction of these jets with surrounding media
- X-ray emission of these jets

Issues relevant to the inertial fusion

- jets
- surface bumps
- fill tubes,...

Test for large multi D radiation hydrodynamic codes

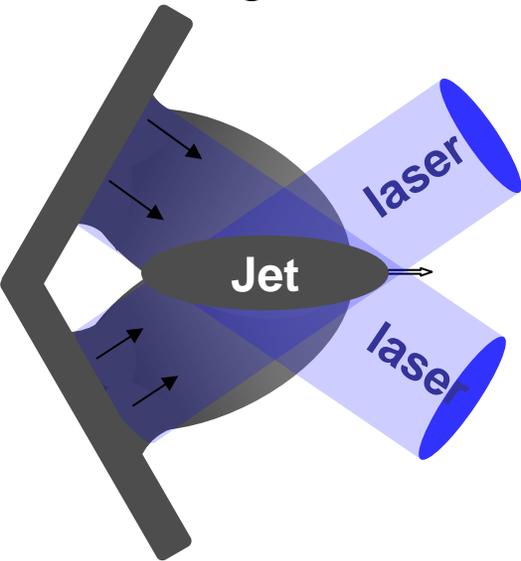


*Clumpy HH jet  
Hartigan 2006*

# Convergent plasma flows produce jets (radiative collapse)

Multi-beams

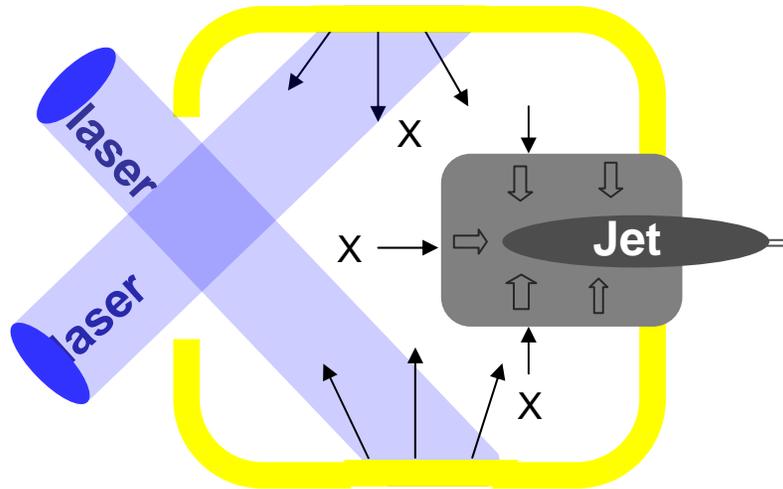
①



conical target

X-rays

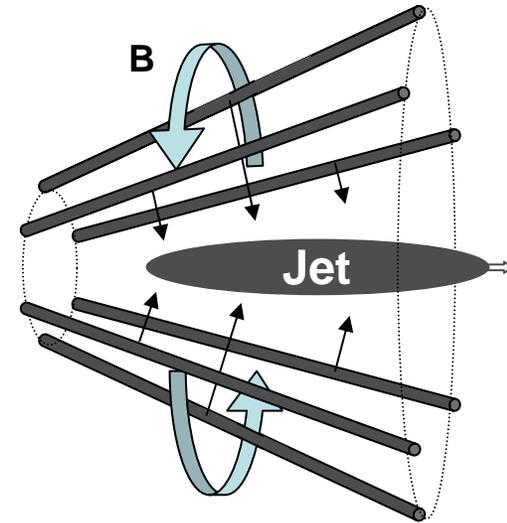
②



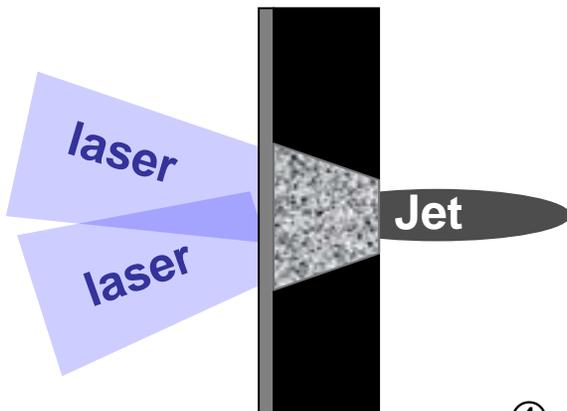
holraum

Z-pinch

③



wire array



Foam-filled cone target

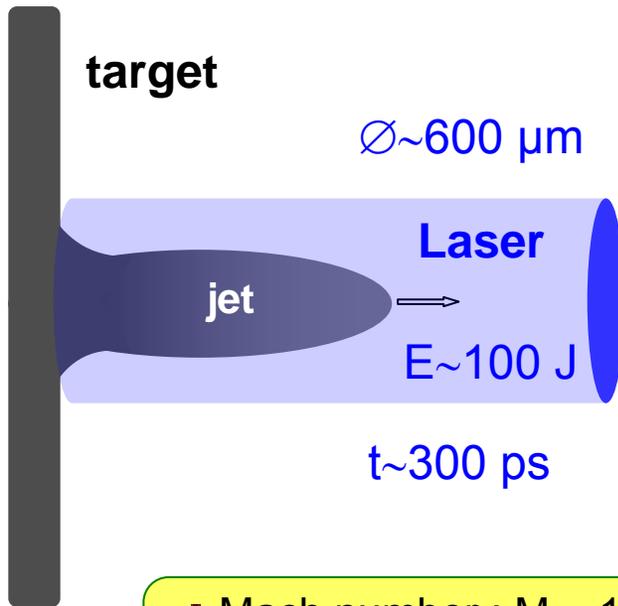
④

**These jets can be scaled to astrophysical conditions** ⑤

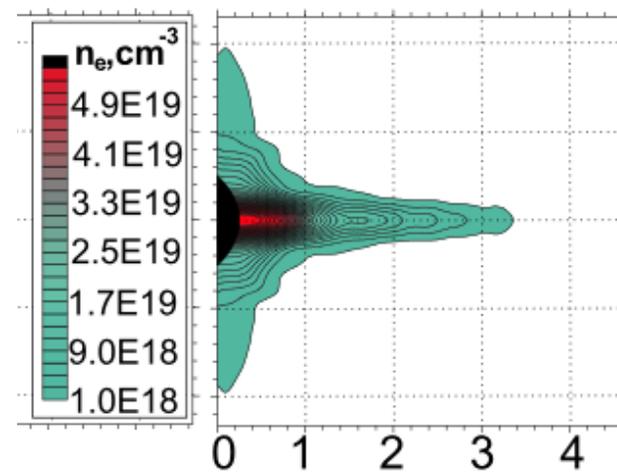
- ① D. Farley et al, Phys. Rev. Lett. 83, 1982 (1999)
- ② J Foster et al, Phys. Plasma 9, 2251 (2002)
- ③ S. Lebedev et al, Astrophys. J 564
- ④ B. Loupiau et al, Phys. Rev. Lett. (2007)
- ⑤ D. Ryutov et al, Astron. Astrophys. 518, 821 (1999)

## Jet formation using a single laser beam

The experiment was carried out at the PALS iodine laser facility:  
**low energy, simple and reproducible conditions**



Experimental electron density distribution



- Mach number :  $M = 10 - 15$
- Velocity :  $U = 500 \text{ km/s}$
- Length :  $L = 3-4 \text{ mm}$
- duration  $\tau \geq 10 \text{ ns}$

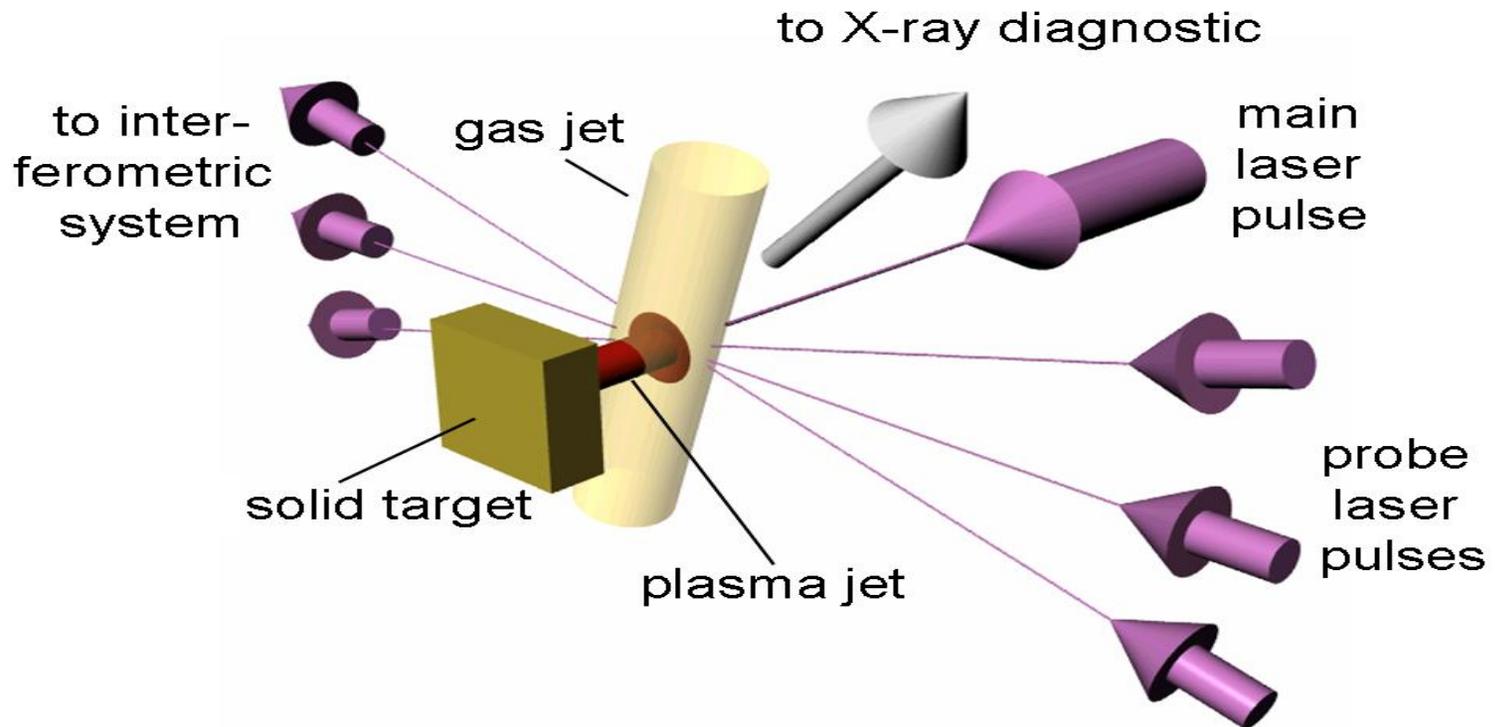
The jet is produced due to the radiative cooling of plasma  
 due to the laser focal spot shape (concave)

But jets are only observed from high atomic number targets

Competition between expansion time and radiation cooling time

# Experimental setup

The experiment was carried out at the PALS iodine laser facility



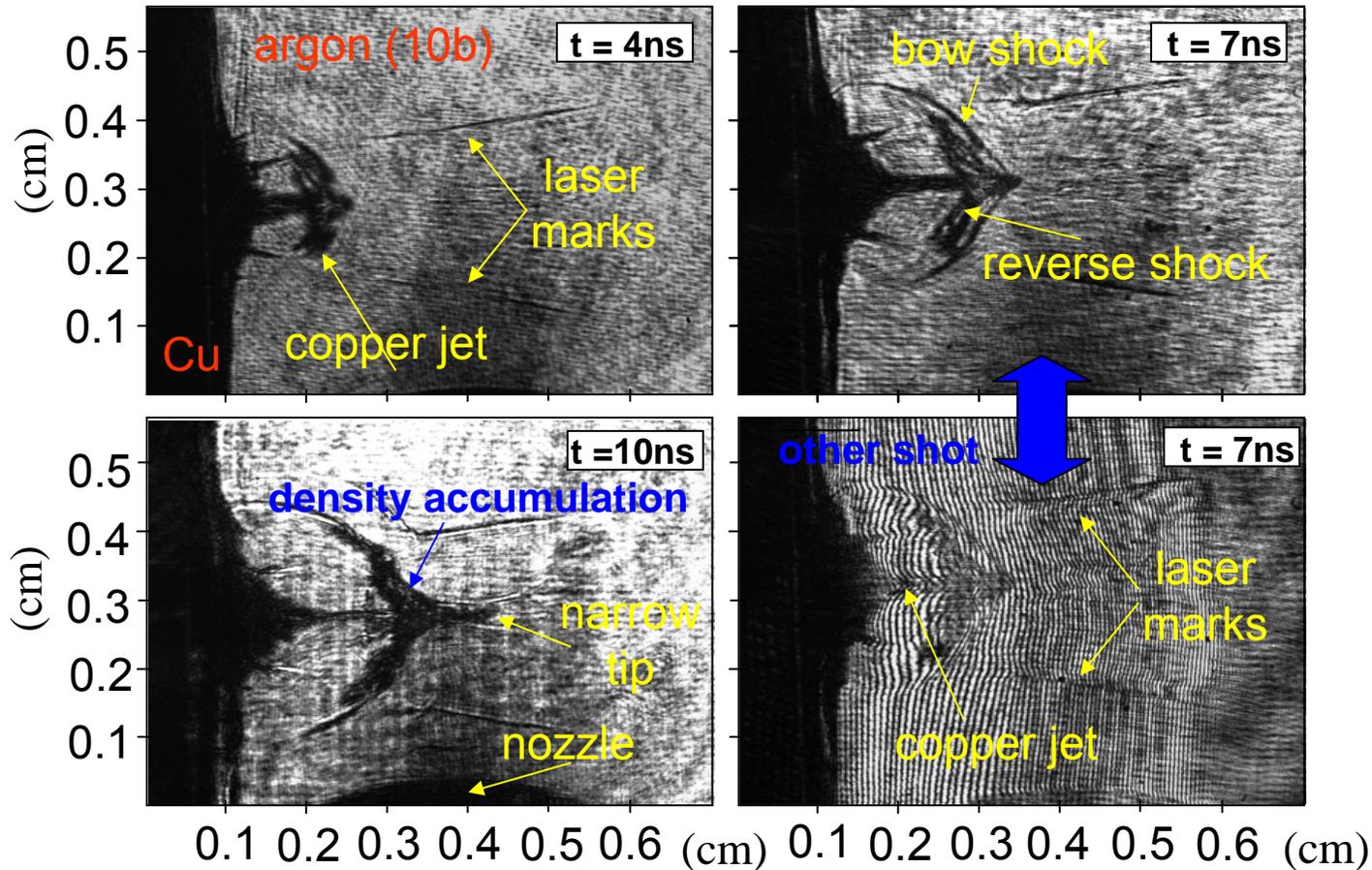
The laser beam:  $E_L \sim 30-100 \text{ J}$ ,  $\lambda_L = 0.438 \text{ } \mu\text{m}$ ,  $t_L = 300 \text{ ps}$ ,  $R_L = 300 \text{ } \mu\text{m}$

The gas puff : Argon or helium gas. Pressure  $\sim 2 - 40 \text{ bars}$

The plasma density profiles were obtained by means of a 3-frame interferometric system ( $3\omega$ )  
 The plasma X-ray emission were obtained by means of a 4-frame X-ray pinhole camera (.1-1keV)

# Structure and evolution of the working surface

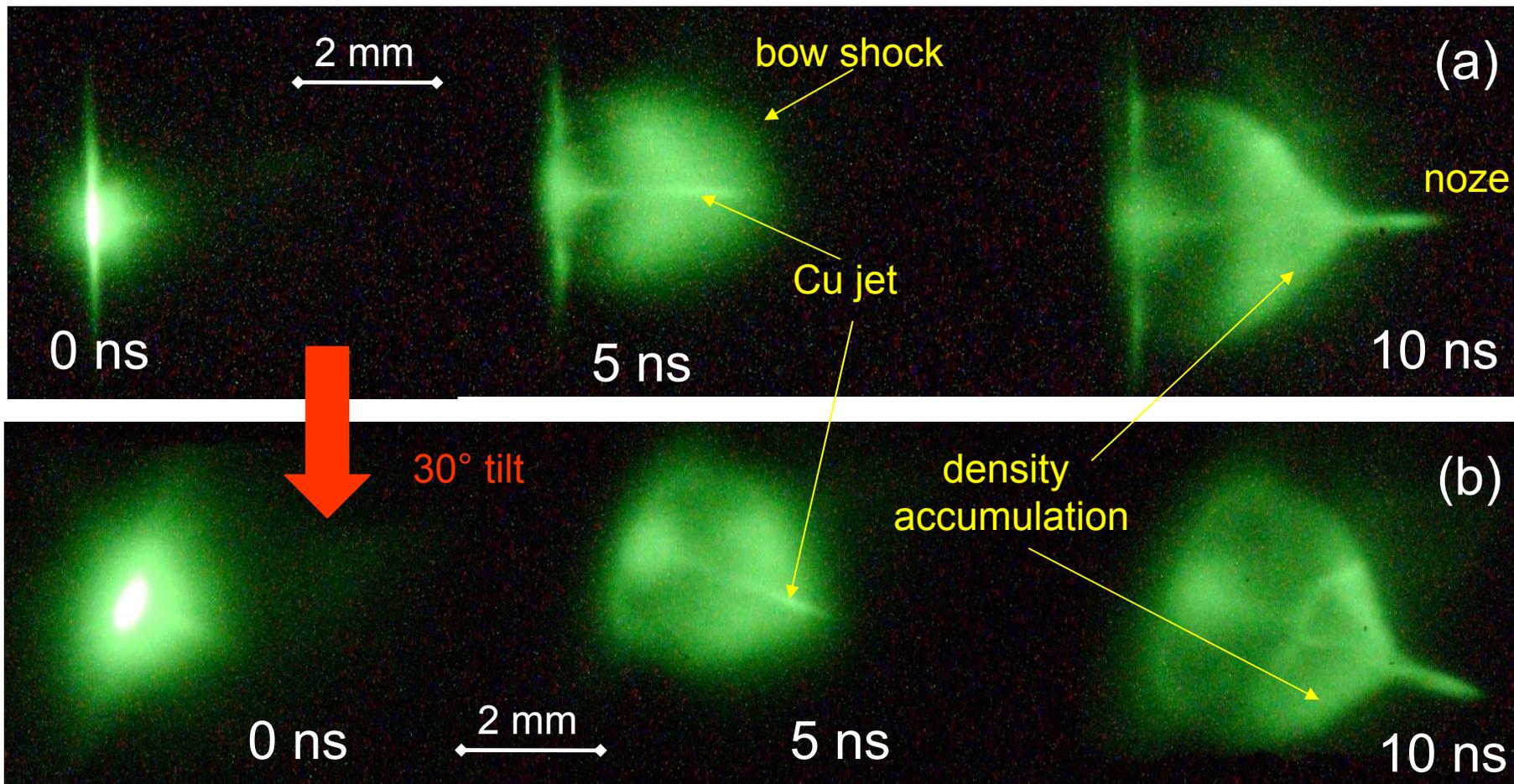
Shadowgraphic and interferometric images



- ✓ Detailed structure with three sequential snapshots
- ✓ Very good reproducibility shot after shot

# Structure and evolution of the working surface

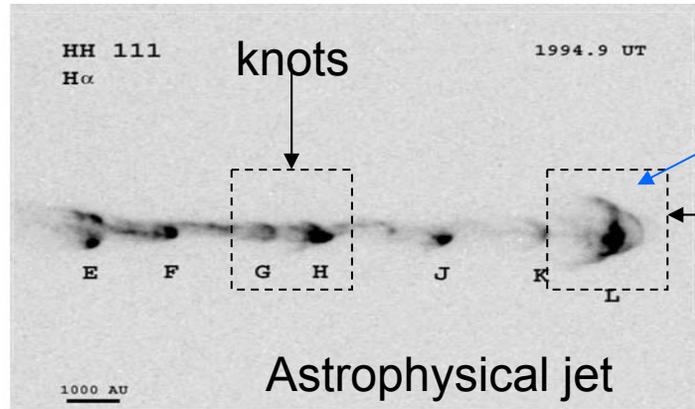
## X-ray images [100 eV – 1 keV]



Good correspondence between X-ray images and interferograms  
 bow shock, Cu jet, narrow tip and density accumulation

## Goals of the last campaign

During first campaigns one just « reproduced » in laboratory the jet head \* \*\* \*\*\*



Astrophysical jet

*P. Hartigan*

Bow shock in  
molecular gas

One has to increase the complexity of the jet structures to get closer to those of astrojets  
 One can observe knots in the astrojet body due to ? ...shock collisions? Instabilities?

How can we reproduce these structures in laboratory

\*Ph. Nicolai et al, Phys. Plasmas 15 082701 (2008),

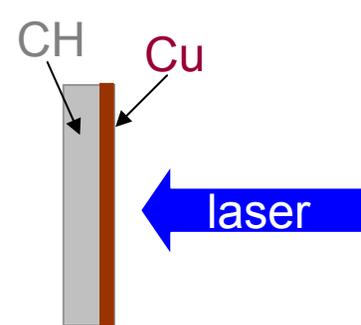
\*\*Bellan et al, Phys. Plasmas 16 041005 (2009)

\*\*\*V. Tikhonchuk et al, Plasma Phys. Contr. Fusion. 50 124056 (2008)

The shock velocity depends on the medium density and the radiation cooling strongly depends on the material used.

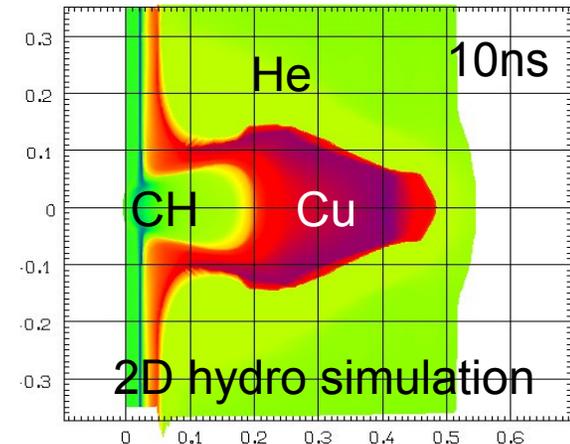
Different materials should modify the jet structure and the jet emission

A 100J energy, in a 300 microns focal spot radius, allows to ablate (500ps), using the third harmonic,  $\sim 200^*$  nm ( $250^{**}$ ) of Cu,  $650^*$  nm (730nm) of Al,  $1.6^*$   $\mu$ m ( $2\mu$ m) of CH



Suppose 200nm of Cu layer on a CH massive target.

After 10ns, the copper layer is ablated and 2mm of the jet is composed of CH material.



Due to the degradation of PALS laser performances, only 30J energy was available.

the ablated layer is thinner, the velocity is smaller, the jet length is shorter and so the second material more difficult to observe...

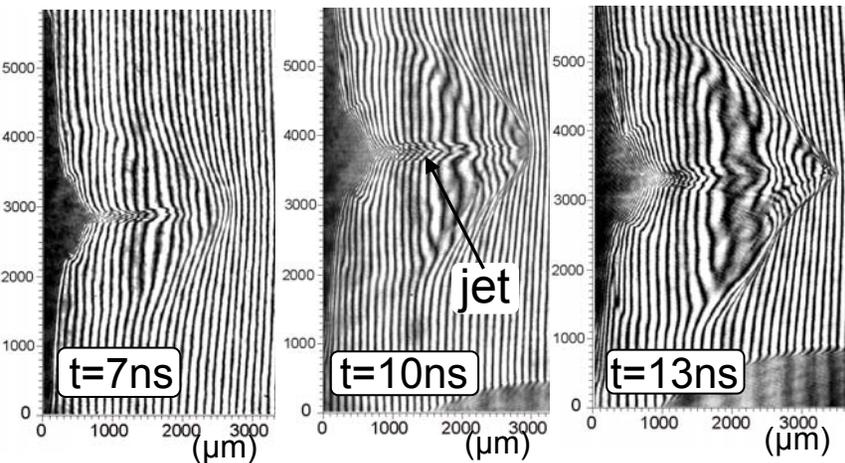
\* Scale law from Dautray et al, EYROLLES (1993)

\*\* Guskov calculations, private comm.

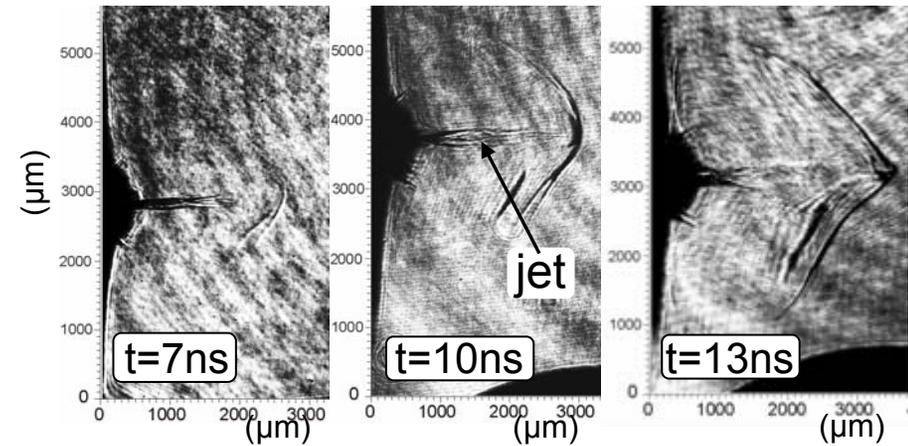
Cu solid target, helium gas puff at 15b, 31J laser energy

Jets are still present but less visible.

interferograms

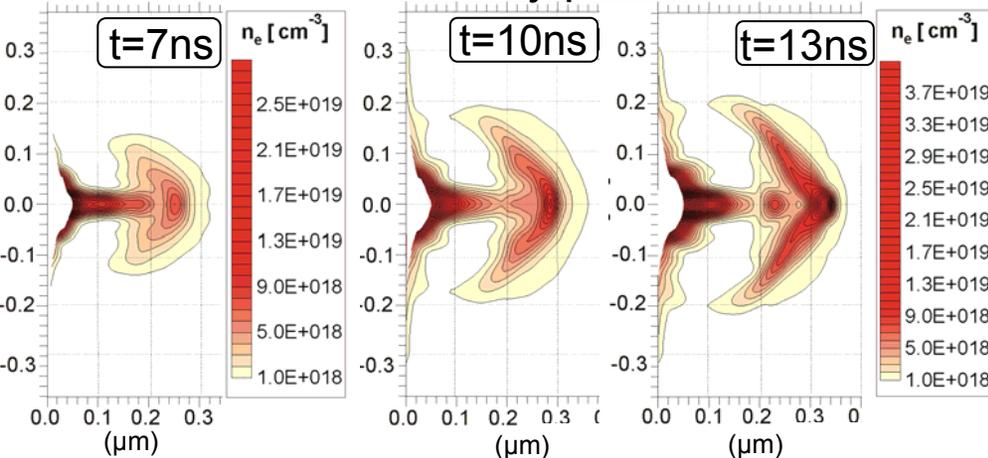


shadowgrams



Jets are less dense and gradients are smoother : shadowgram accuracy deteriorates

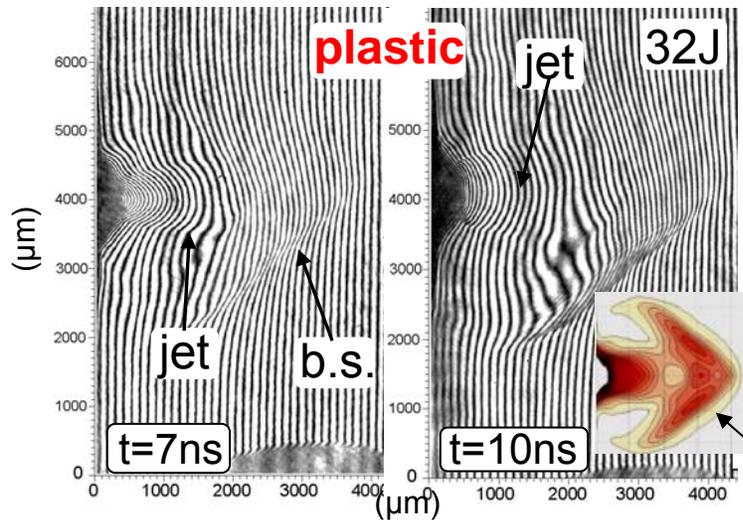
density profiles



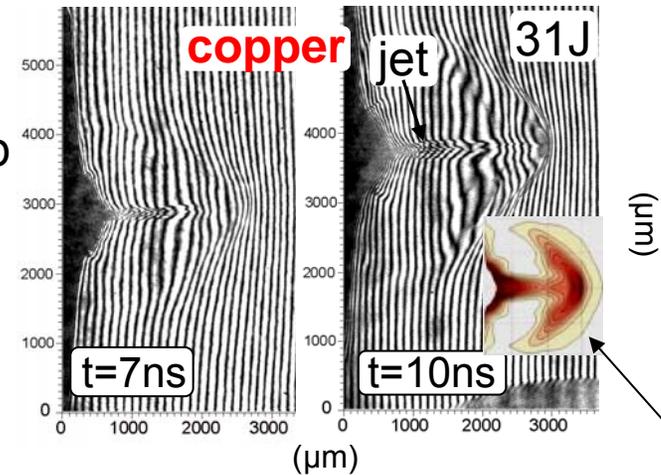
Spatial resolution is not good as in interferograms (smoothing introduced in the reconstruction procedure)

One can infer density, but for comparisons we will use interferograms

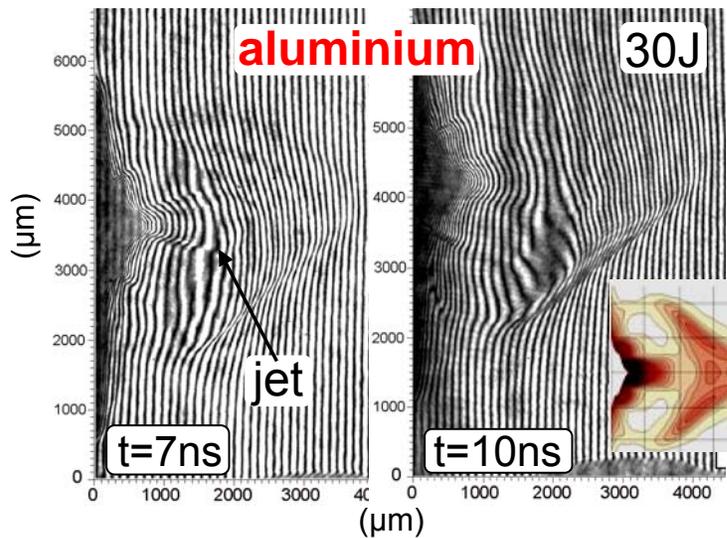
# Target composition effect on jet formation



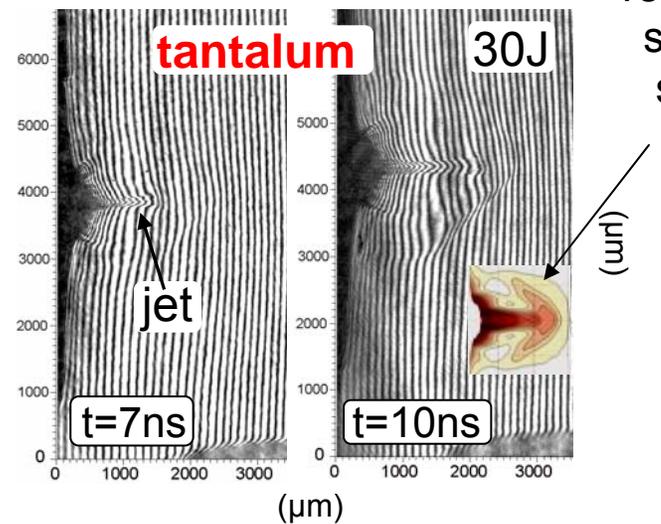
Helium  
at P=15b



reduced  
spatial  
scale  
(/2)



reduced  
spatial  
scale  
(/2)

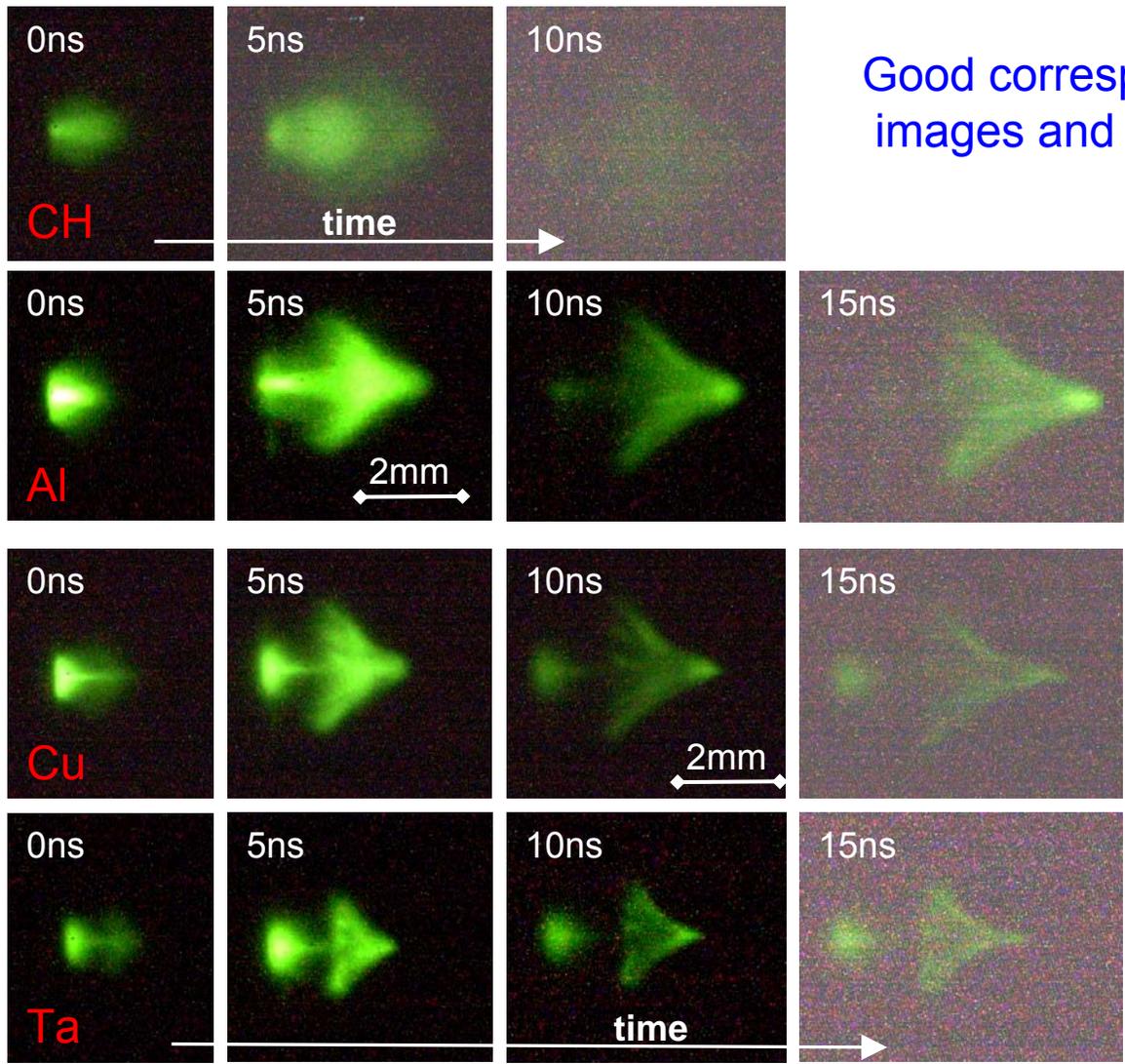
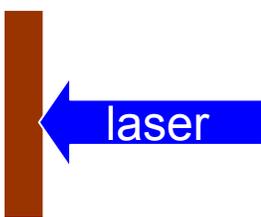


same laser focal spot

The jet becomes narrower as target atomic number increases

The jet propagation and bow shock velocities reduce as target atomic number increases

# Target composition effect on X-ray emission



Good correspondence between X-ray images and interferograms

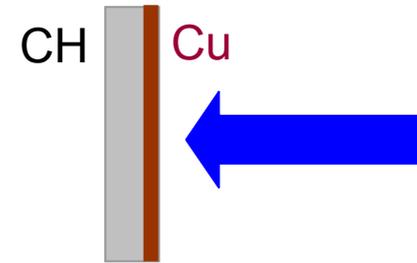
One just measures plasma jet emission. Helium gas does not emit X-rays.

same spatial scale  
not same luminosity scale

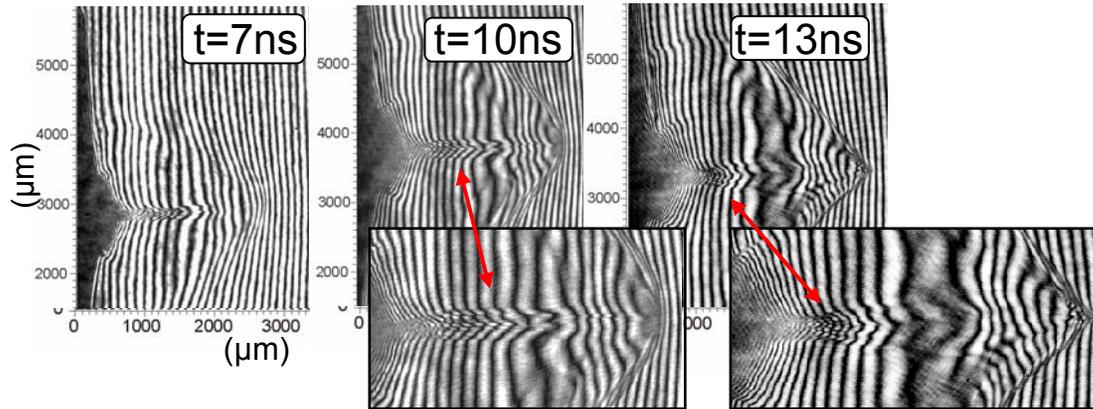
The jet width, jet length and interaction-zone size reduce as Z increases

The jet foot disappears for Al and CH targets

# multi-layer target : plastic-copper case

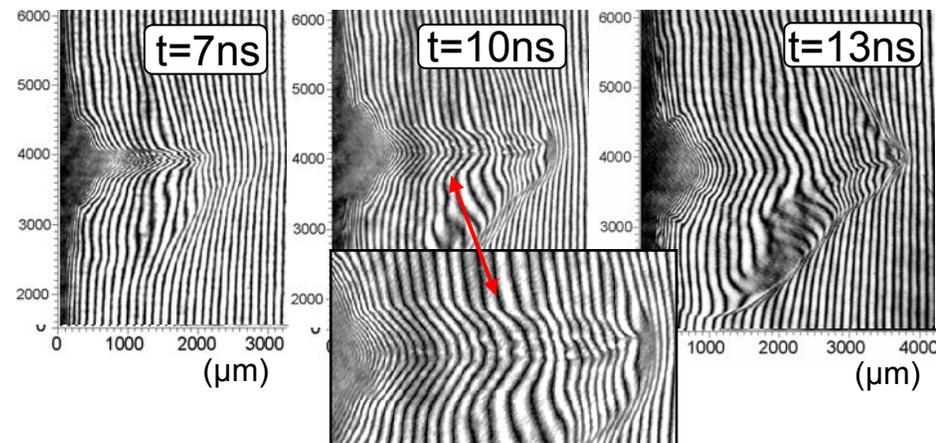
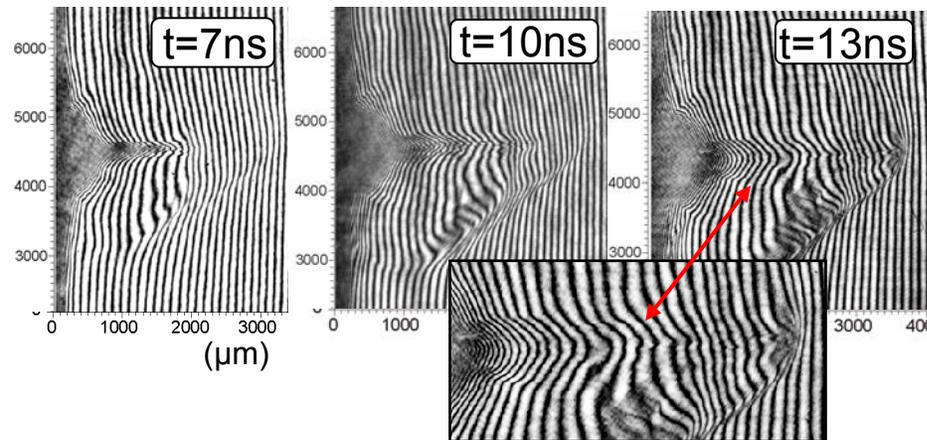


reference case : copper only 31J



CH-Cu(50nm) 31J

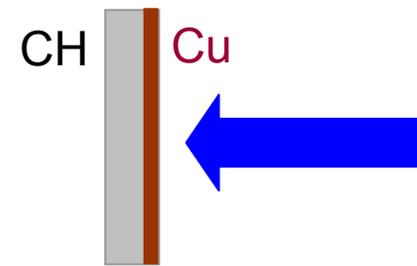
CH-Cu(30nm) 27J



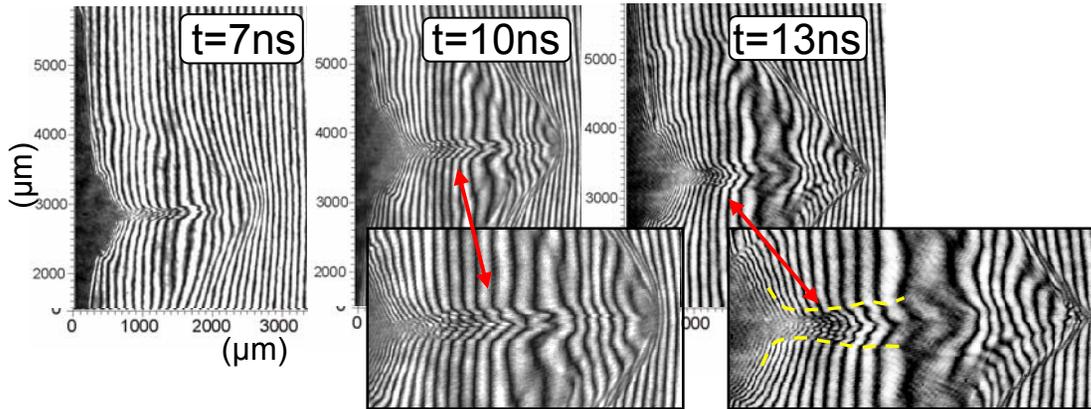
Obvious effects of plastic material on jet formation and jet composition (radiation eff.)

Jet modification arises earlier for thinner copper layer

# multi-layer target : plastic-copper case

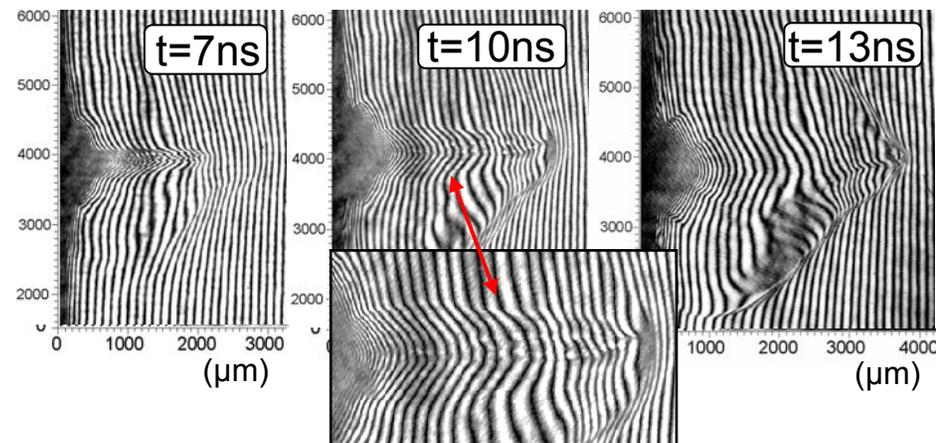
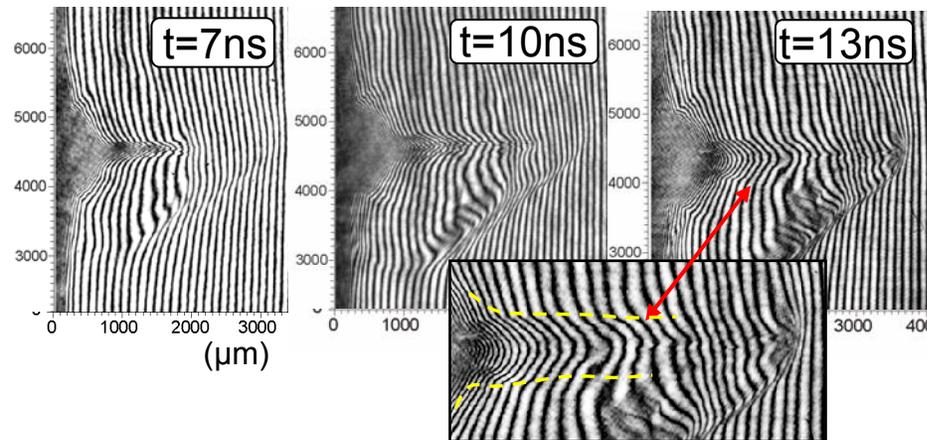


reference case : copper only 31J



CH-Cu(50nm) 31J

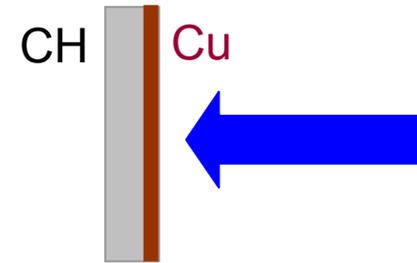
CH-Cu(30nm) 27J



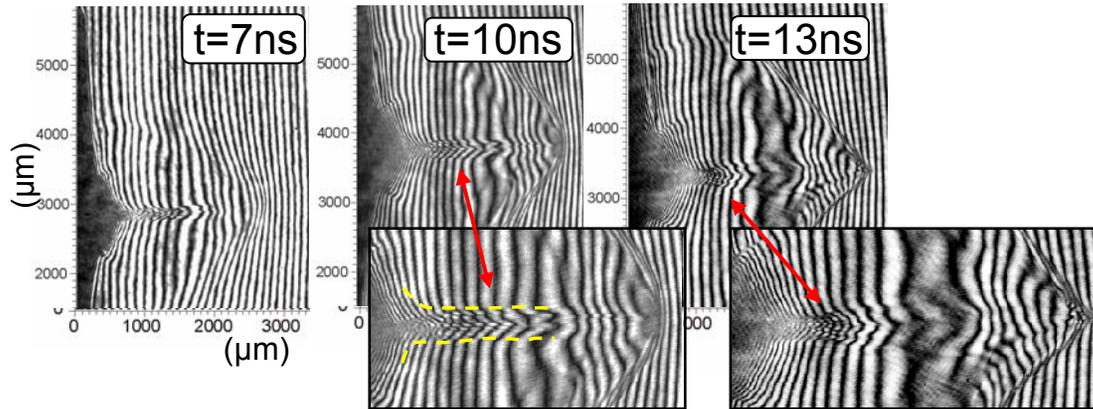
Obvious effects of plastic material on jet formation and jet composition (radiation eff.)

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# multi-layer target : plastic-copper case

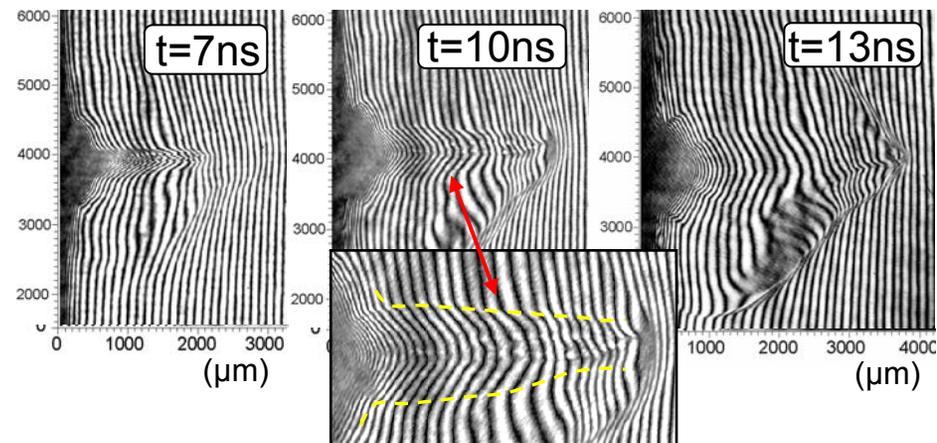
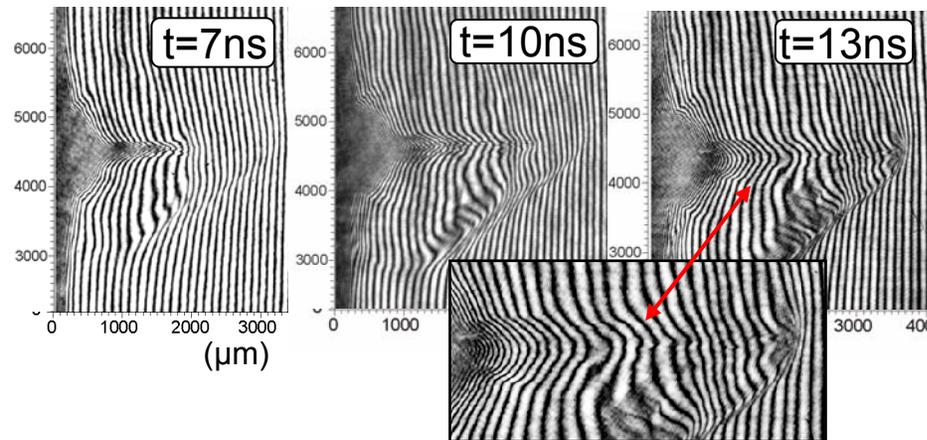


reference case : copper only 31J



CH-Cu(50nm) 31J

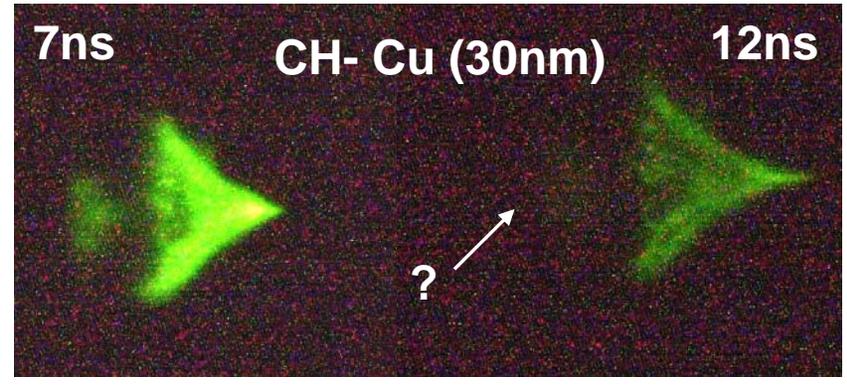
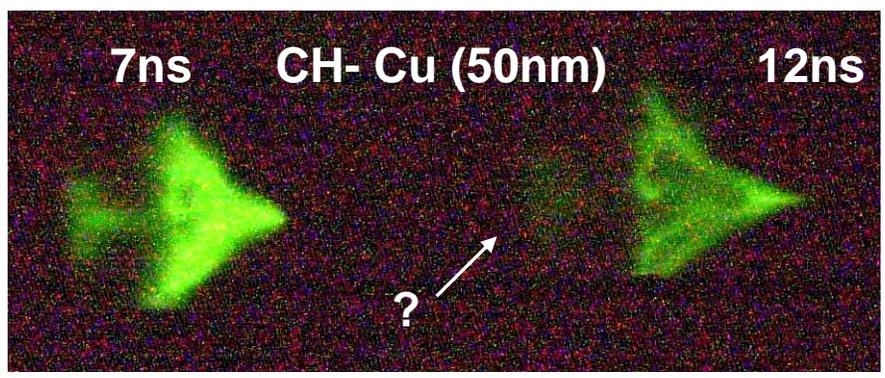
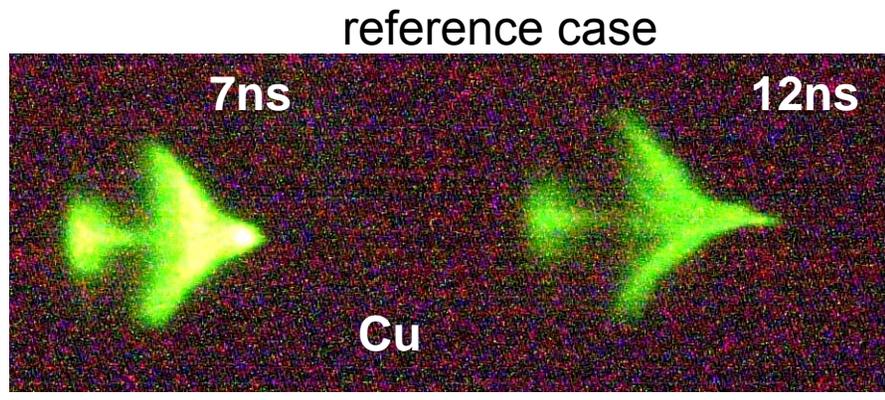
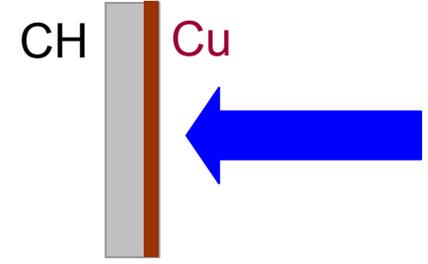
CH-Cu(30nm) 27J



Obvious effects of plastic material on jet formation and jet composition (radiation eff.)

Jet modification arises earlier for thinner copper layer

plastic-copper target: X-ray emission



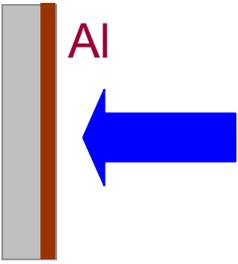
The jet head, composed of copper, remains identical

The jet is less visible and jet foot (basis) disappears at late time.

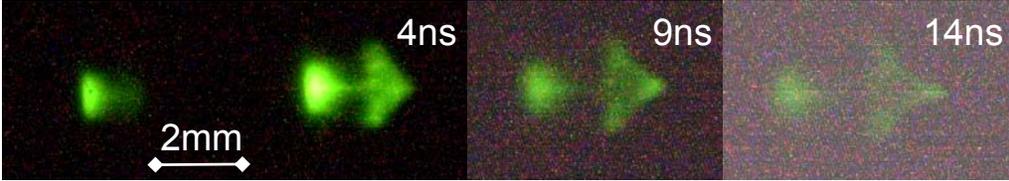
From massive target, one knows plastic emission is very low

# Tantalum–aluminium target : X-ray emission

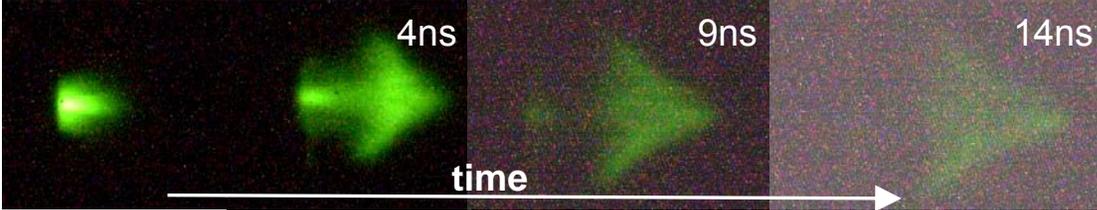
Ta



tantalum

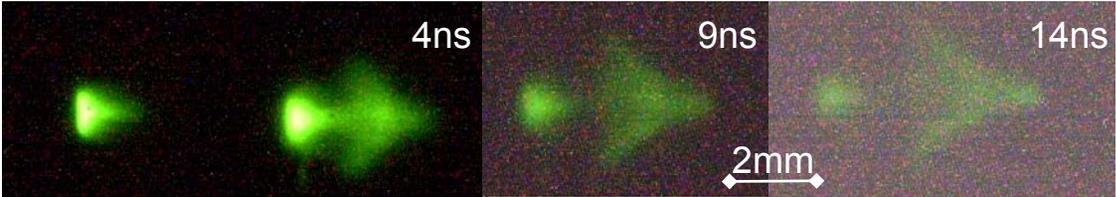


aluminium



same spatial scale

tantalum–aluminium



Jets launched from multi-layer targets combine characteristics of both tantalum and aluminium jets.

jet head (interaction zone) and jet length correspond to aluminium jet features

Jet basis is clearly characteristic of tantalium presence

## The numerical tool

We use the 2 D radiative magneto-hydrodynamic code, CHIC\*

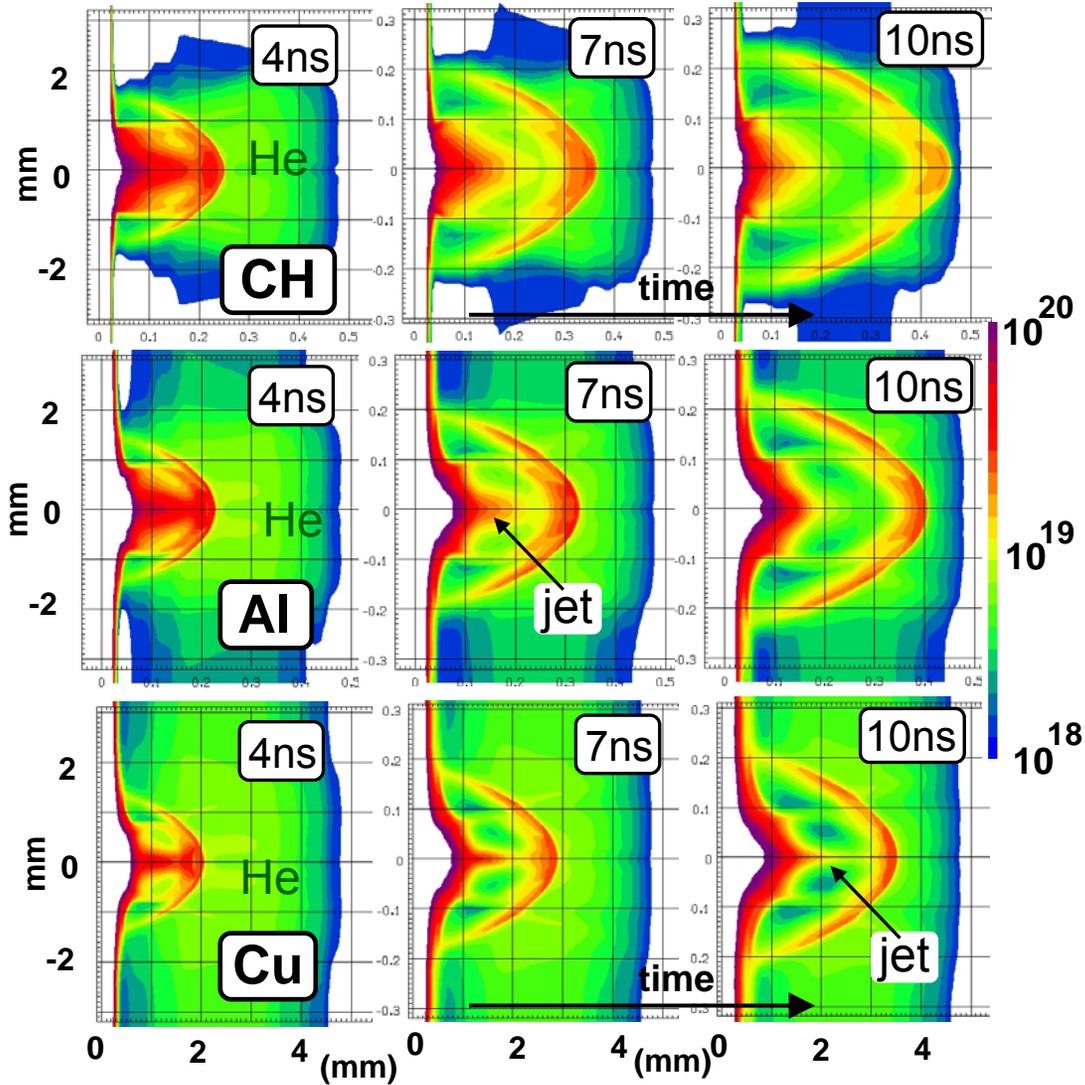
- ✓ second order cell centered Lagrangian scheme
- ✓ ALE scheme
- ✓ unstructured meshes
- ✓ classical or nonlocal thermal conduction
- ✓ nine points scheme
- ✓ thermal coupling
- ✓ detailed radiation transport
- ✓ LTE or NLTE opacities
- ✓ real Equation of State (QEOS and Sesame)
- ✓ 3D ray tracing for laser propagation
- ✓ self-generated magnetic fields
- ✓ thermonuclear burn

\*PH Maire et al, SIAM JSC 29, 1781 (2007),

\*J. Breil et al, J. Comp. Phys. 224, 785 (2007)

# Structure and evolution of the jets

solid target, helium gas puff at 15b, 30J laser energy



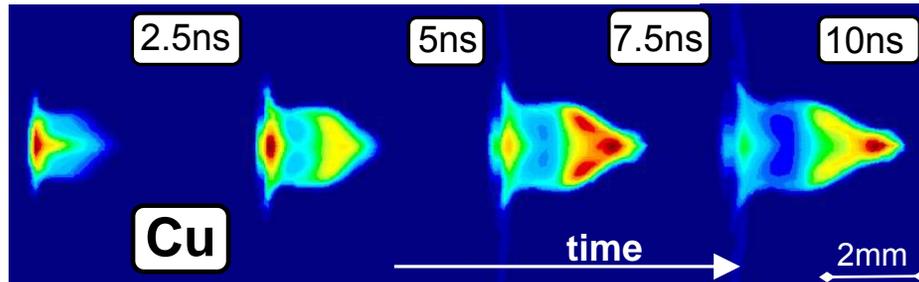
Simulations correctly reproduce target material change

The jet becomes narrower as target atomic number increases

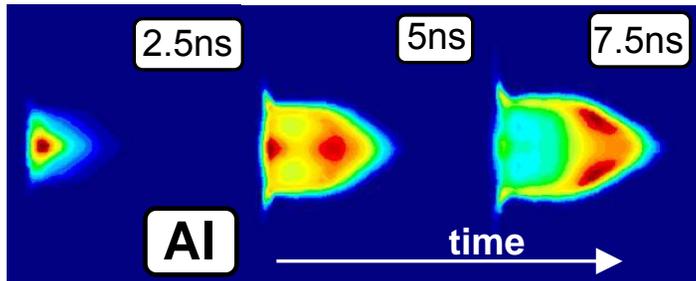
The jet propagation and bow shock velocities reduce as target atomic number increases

At late time, jet structure disappears for all materials

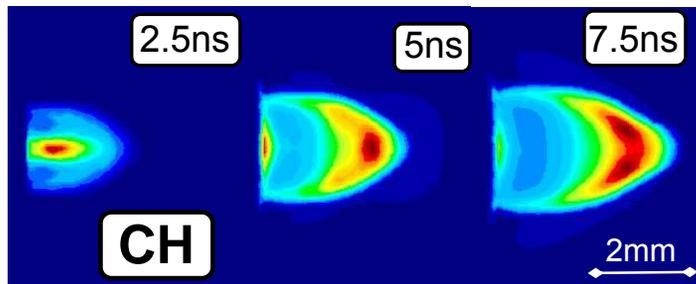
Main features of X-ray emissions are reproduced



same spatial scale  
not same luminosity scale

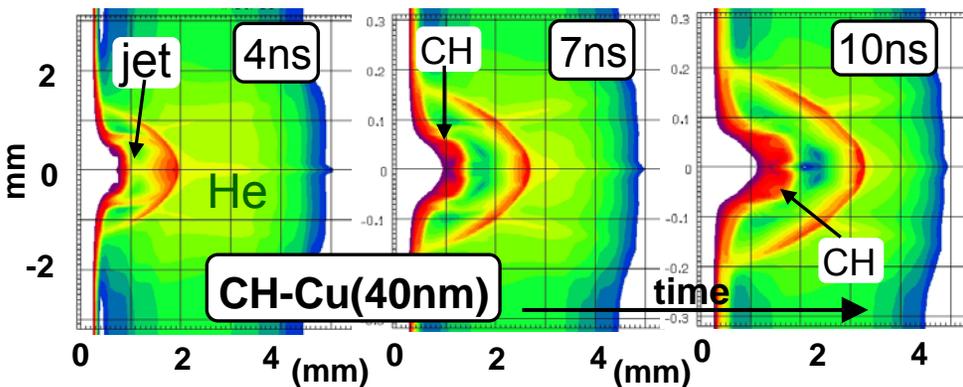
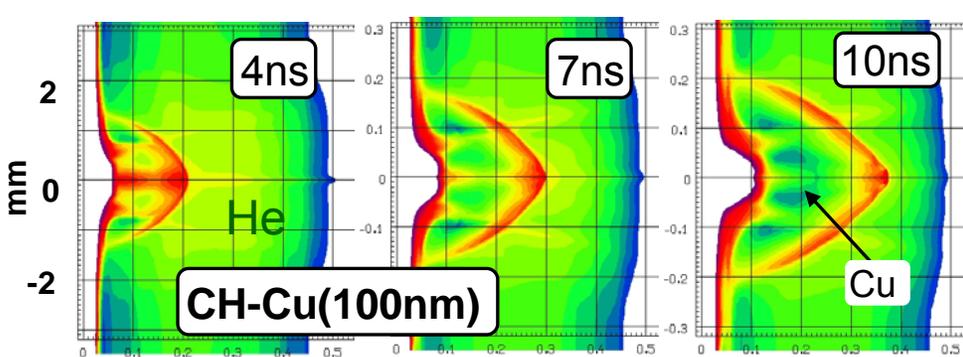
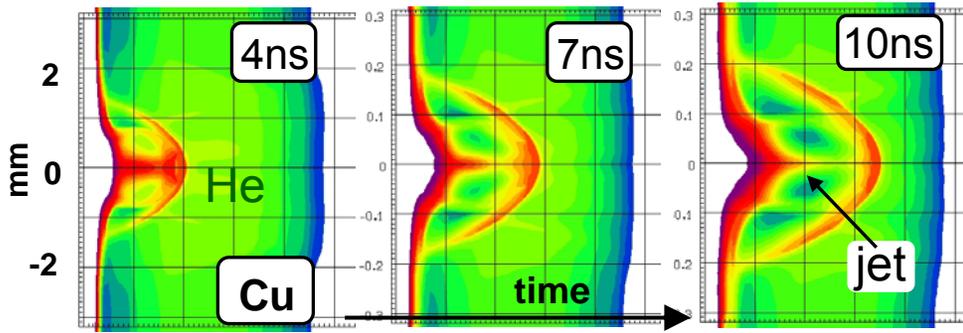
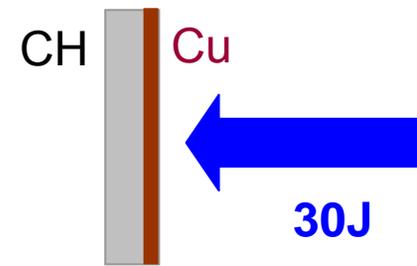


The jet width, jet length and interaction-zone size  
reduce as Z increases



The jet foot emission reduces at late times  
for Al and CH targets

# multi-layer target : plastic-copper case



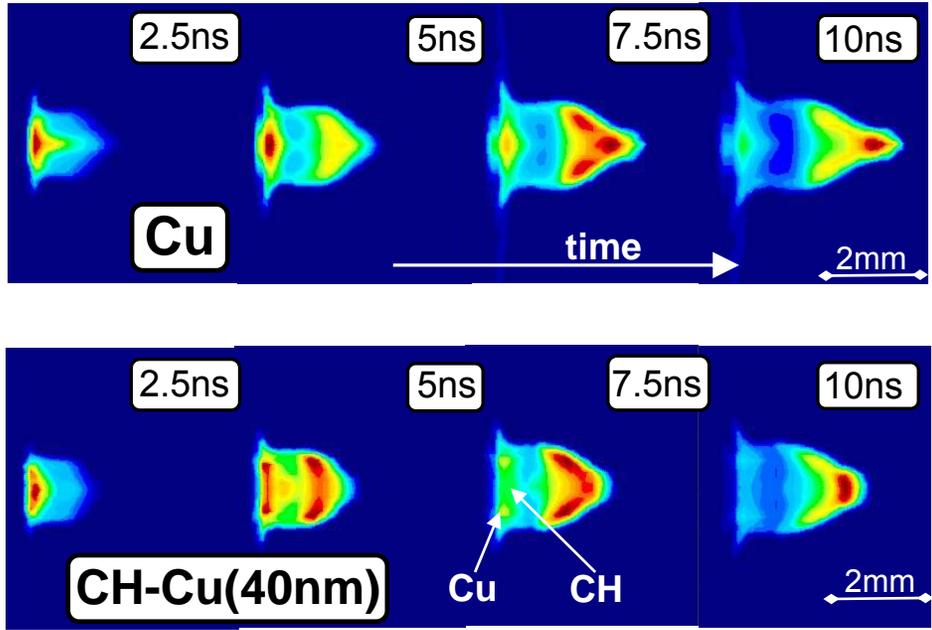
From multilayer target, jet body is composed of copper and of plastic

Jet launching and collimation depend on the radiative cooling of plasma

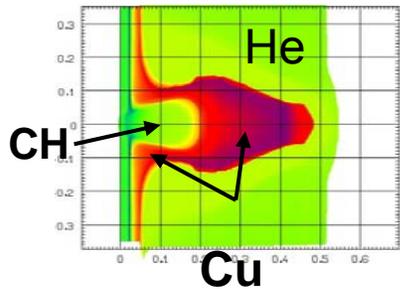
Plastic presence damages copper jet

At late time, copper material is mainly present in the interaction zone

# plastic-copper case : X-ray emission



same spatial scale  
not same luminosity scale



For thin copper layer

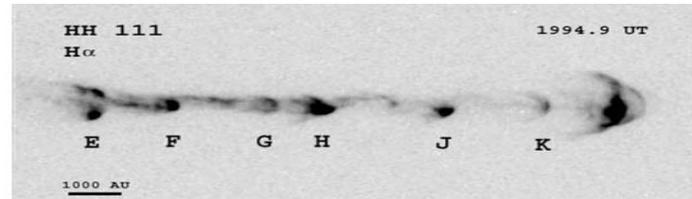
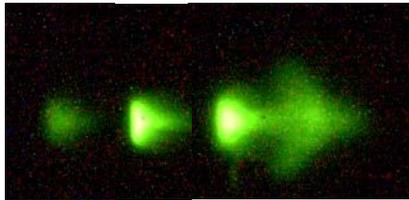
after 5ns, jet head emission and jet foot emission have the same intensity.

after a 7ns delay , the jet foot emission switches off due to CH presence.

Supersonic, multi-material jets have been produced at PALS laser facility

These jets verify the similarity criteria and apply to astroφ conditions

Next step could consist in increasing the laser energy and the layer number



P. Hartigan

Induce variable flow velocities in the jet body to produce a shock series

LULI proposal (J. Fuchs et al) has been registered in order to reproduce PALS jet experiments and to study the influence of external magnetic fields.

- Nicolai, P et al, *Experimental evidence of multi-material jet formation with lasers*, **submitted to Phys. Plasmas**
- Ribeyre, X. et al, *Simulations of the supersonic radiative jet propagation in plasmas*, **Astrophys. Space Sci.** 322, 85 (2009)
- Nicolai, P et al ; *Supersonic plasma jet interaction with gases and plasmas*, **Astrophys. Space Sci.** 322, 11 (2009)
- Bellan, P. et al, *Astrophysical jets: Observations, numerical simulations, and laboratory experiments*, **Phys. Plasmas** 16, 041005 (2009)
- Kasperczuk, A. et al, *Investigations of plasma jet interaction with ambient gases by multi-frame interferometric and X-ray pinhole camera systems*, **Laser Part. Beams** 27, 115 (2009)
- Tikhonchuk, V. et al, *Laboratory modeling of supersonic radiative jets propagation in plasmas and their scaling to astrophysical conditions*, **Plasma Phys. Cont. Fusion** 50, 124056 (2008)
- Nicolai, P. et al, *Studies of supersonic, radiative plasma jet interaction with gases at the Prague Asterix Laser System facility*, **Phys. Plasmas** 15, 082701 (2008)
- Pisarczyk, T. al, *The PALS iodine laser-driven jets*, **Plasma Phys. Cont. Fusion** 49, B611 (2008)
- Nicolai, P. et al, *How Produce a Plasma Jet Using a Single and Low Energy Laser Beam*, **Astrophys. Space Sci.** 307, 87 (2007)
- Kasperczuk, A et al, *Stable dense plasma jets produced at laser power densities around  $10^{14}$  W/cm<sup>2</sup>* **Phys. Plasmas** 13, 062701 (2006)
- Nicolai, P. et al, *Plasma jets produced in a single laser beam interaction with a planar target*, **Phys. Plasmas** 13, 062704 (2006)

Can the experiment be scaled to an astrophysical jet ?

|                        | Symbol                            | Herbig -Haro object                          | laser experiment                     |
|------------------------|-----------------------------------|--|--------------------------------------|
| Jet radius, Jet length | $r_j, L_j$                        | $7.5 \times 10^{13}$ m, $3 \times 10^{15}$ m | 0.3 mm, 5 mm                         |
| Jet velocity           | $v_j$                             | 100 km/s                                     | 400 km/s                             |
| Ion density            | $n$                               | $20 \text{ cm}^{-3}$                         | $1.5 \times 10^{18} \text{ cm}^{-3}$ |
| Density                | $\rho$                            | $10^{-22} \text{ g/cm}^3$                    | $10^{-4} \text{ g/cm}^3$             |
| Temperature            | T                                 | 1 eV   | 100 eV                               |
| Pressure               | P                                 | $10^{-16}$ bars                              | $2.5 \times 10^3$ bars               |
| Sound speed            | $c_s = \sqrt{\gamma P / \rho}$    | 10 km/s                                      | 70 km/s                              |
| Time scale             | $t_s = r_j \sqrt{\rho / P}$       | 280 yrs                                      | 6 ns                                 |
| Mach number            | $M = v_j / c_s$                   | 9  | 6                                    |
| Euler number           | $\text{Eu} = v_j \sqrt{\rho / P}$ | 12   | 8                                    |
| Peclet number          | Pe                                | $2.5 \times 10^4$                            | 5                                    |
| Reynolds number        | Re                                | $1.5 \times 10^7$                            | $3 \times 10^5$                      |
| cooling time           | $t_{cool}$                        | 170 yrs                                      | 2 ns                                 |
| cooling parameter      | $t_s / t_{cool}$                  | 1.5  | 3                                    |

# Estimate of Radiation losses

For a plane slab of thickness  $d$ , the cooling time writes  $\square$  :

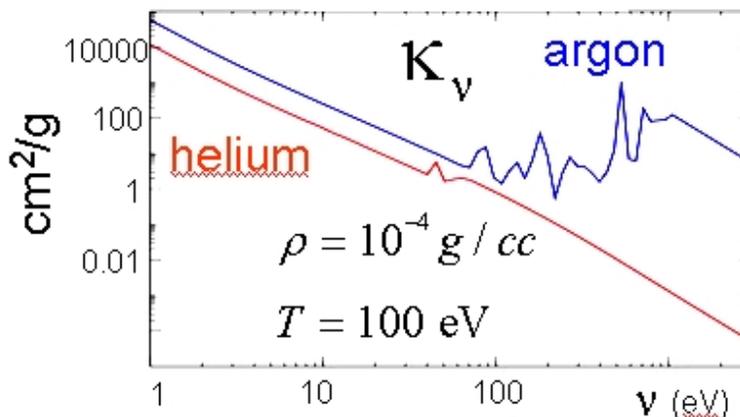
$$\tau_c = \frac{\text{Energy density} * d}{\text{radiation flux}} = \frac{\rho d C_v T}{2F_R} = f(\tau) \frac{Z+1}{A} T^{-3} \kappa_m^{-1}$$

where  $f(\tau)$  is a function of the optical depth  $\tau = d\rho\kappa_m$

$\kappa_m$  = mean Planck opacity

$$= \frac{15}{\pi^4} \int_0^\infty \kappa_\nu u^3 e^{-u} du$$

with  $u = \frac{h\nu}{T}$



Ar :  $\kappa_m = 79 \text{ cm}^2 / \text{g} \Rightarrow \tau_c \approx 2 \text{ ns}$   
 He :  $\kappa_m = .089 \text{ cm}^2 / \text{g} \Rightarrow \tau_c \approx 2 \mu\text{s}$

from bremsstrahlung emission Ar :  $\tau_c \approx 450 \text{ ns}$   
 He :  $\tau_c \approx 3 \mu\text{s}$

to be compared with the jet propagation time  $\sim 5 \text{ ns}$

## The use Conditions of hydrocode

One has to verify that the mean free paths are shorter than the dimensions of structures observed in experiment

Fast copper ions are slowed down in collisions with the ions and e- of ambient gas

By using the NRL plasma formulary<sup>①</sup>, the collision frequencies read

$$\nu_{Cu-a} = 9.10^{-8} n_i^a Z_a^2 Z_{Cu}^2 \Lambda_{Cu-a} (A_{Cu}^{-1} + A_a^{-1}) A_{Cu}^{1/2} \epsilon_{Cu}^{-3/2} s^{-1}$$

$$\nu_{Cu-e} \approx 1.610^{-9} n_e Z_{Cu}^2 \Lambda_{Cu-e} A_{Cu}^{-1} T_e^{-3/2} s^{-1}$$

For our parameters; kinetic energy of Cu ion  $\epsilon \sim 50$  keV,  $T \sim 100$  eV,  $\rho \sim 10^{-4}$  g/cc

$$\nu_{Cu-a} \approx \nu_{Cu-e} \approx 4.10^9 s^{-1}$$

Given the jet velocity  $v_{Cu} = 400$  km/s, the m.f.p;  $\lambda_{Cu} = v_{Cu} / (\nu_{Cu-a} + \nu_{Cu-e}) \approx 50 \mu m$

The gas is not motionless (bow shock), and the relative velocity should be smaller.

$$\text{As } \lambda_{Cu} \propto v^4 \text{ if } v \rightarrow v/2 \Rightarrow \lambda_{Cu} \rightarrow \lambda_{Cu} / 16$$

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