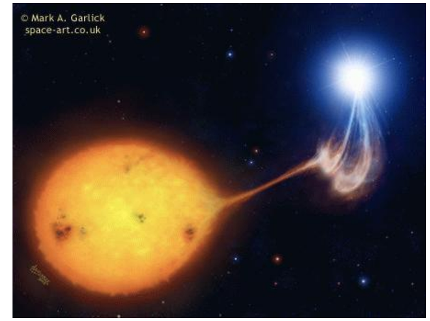


Magnetized laser produced plasmas: A way to reproduce astrophysical systems at LULI

Albertazzi Bruno

Magnetic meeting 23-24 April, Rochester

Outline

General context: laboratory astrophysics

1er Application: Collimation of Astrophysical Jets

- Context and motivation
- Results of ELFIE experiments
- Simulation platform: DUED + GORGON
- Comparison astrophysical simulations RAMSES vs astronomical observations

2eme Application: Dynamics and structure of magnetized reverse shock in POLAR

- Context and motivation
- Results of LULI experiments
- Simulation FLASH

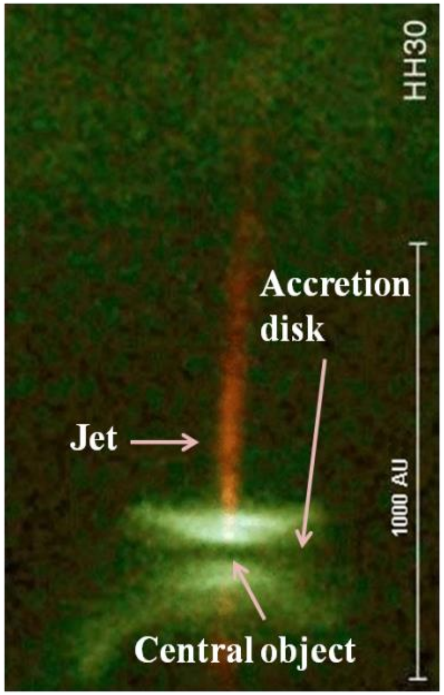
Modeling in the laboratory astrophysical plasmas

Simulate conditions relevant for astrophysical phenomenon study :

Magnetized laser produced plasmas

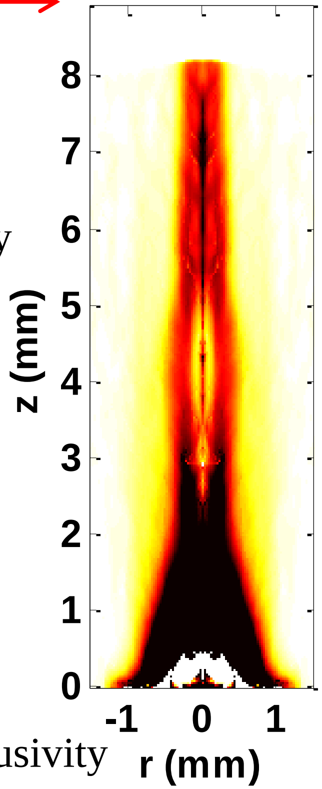
→ Scaling laws [Ryutov et al., ApJ 518, 821 (1999)] (Hydro)
[Ryutov et al., ApJSS 127, 465 (2000)] (MHD)

Universe



Dimensionless numbers

Experiment



Mach Number : $M = U_{jet}/c_s$

Peclet Number: $Pe = \frac{U_{jet}*R_{jet}}{\kappa}$ κ the thermal diffusivity

Reynolds Number: $Re = \frac{U_{jet}*R_{jet}}{\upsilon}$ υ the kinematic viscosity

$\sigma = P_{cin}/P_{mag}$ with $P_{cin} \sim \rho v^2$ and $P_{mag} = B^2/2\mu_0$

MHD: Magnetic Field lines frozen-in the plasma ?

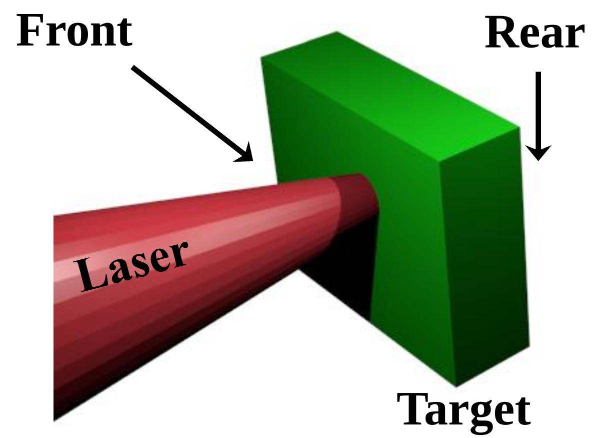
Magnetic Reynolds Number: $Rem = \frac{U_{jet}*R_{jet}}{\eta}$ η magnetic diffusivity

Possibility to reproduce relevant astrophysical conditions

Using High power laser coupled to high magnetic field

Possibility to produce differents plasma conditions :

- ➔ Front or rear surface of the target
- ➔ Laser parameters (intensity, focal spot, etc …)
- ➔ Targets
- ➔ Amplitude and orientation of the magnetic field

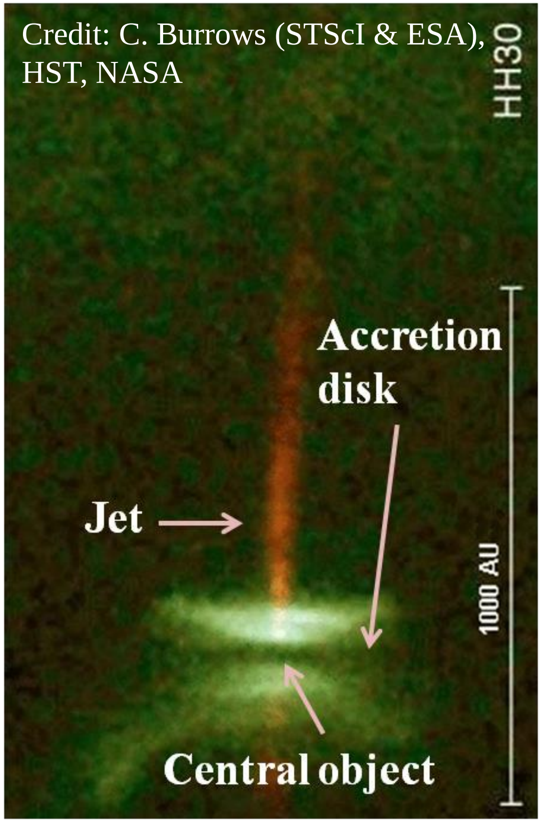


Parameters	Front surface of the target		YSO	Rear surface of the target	POLAR
	$I = 10^{12}$ W.cm^{-2}	$I = 10^{13}$ W.cm^{-2}		$I = 10^{14}$ W.cm^{-2}	
Peclet	3-5	6-9	1.10^{11}	< 1	
Reynolds	>> 100	>> 100	1.10^{13}	>> 100	1.10^{6}
Magnetic Reynolds	> 10	> 10	1.10^{15}	1 to 10	>> 100
Mach	1 to 6	1 to 8	10-50	7-10	> 10
σ	>> 1 close to the source, <<1 far	>> 1 close to the source, <<1 far	<< 1 at ~10s AU	>> 1 close to the source, < 1 far	

Magnetic field 20T **Magnetic field 15T**

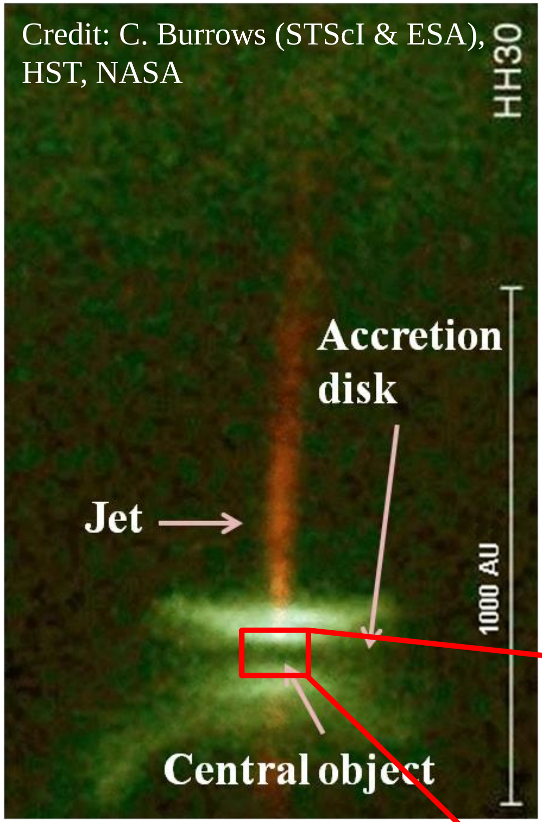
Collimation of Astrophysical Jets

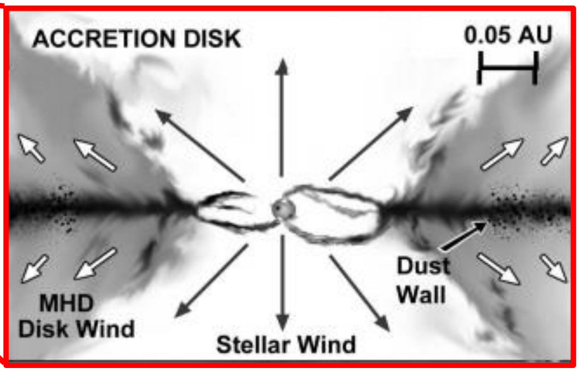
Context: collimation of Astrophysical jets



Credit: C. Burrows (STScI & ESA), HST, NASA

Context: collimation of Astrophysical jets



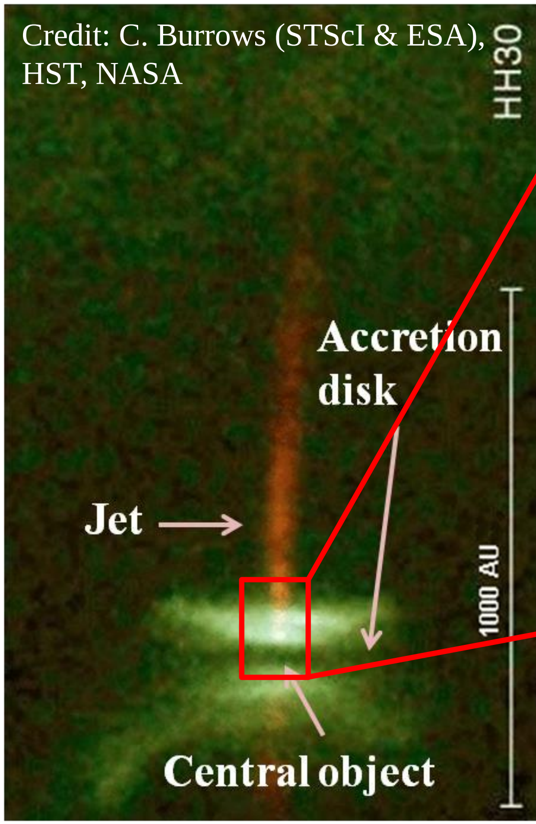


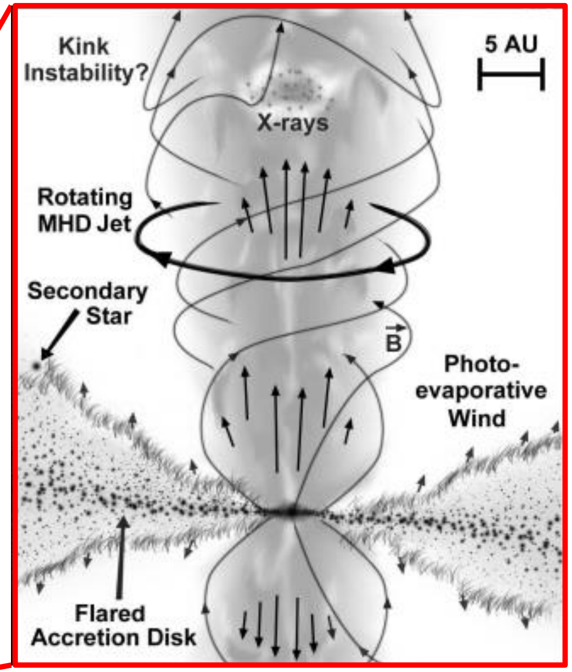
Mass ejection rate
10^{-7}-10^{-9} M_o/year

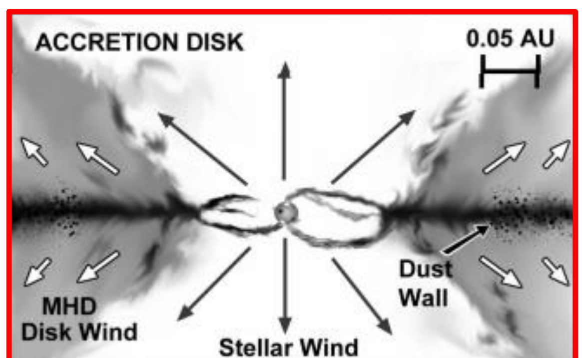
Velocity: 100-1000 km.s^{-1}

[A. Franck et al., Protostars and Planets, University of Arizona Press (2014)]
[R. D. Blandford et Payne, Mont. Not. R. Astron. Soc. 199, 883 (1982)]

Context: collimation of Astrophysical jets







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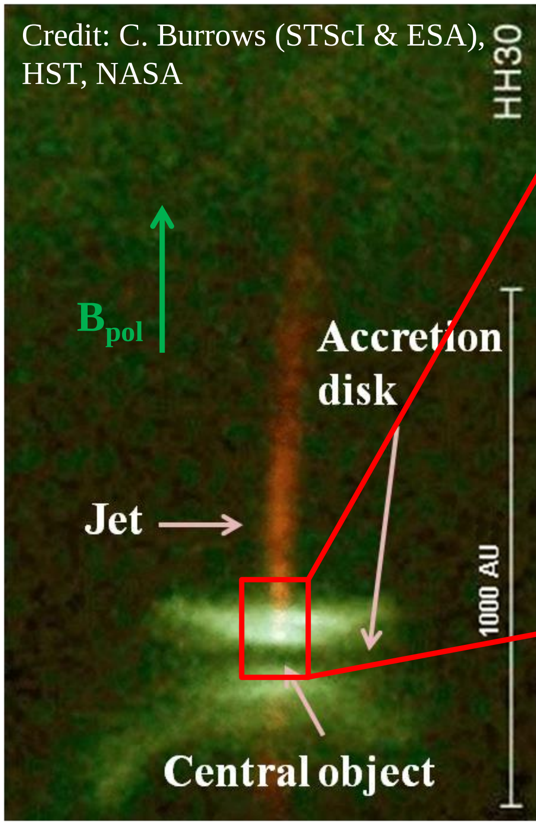
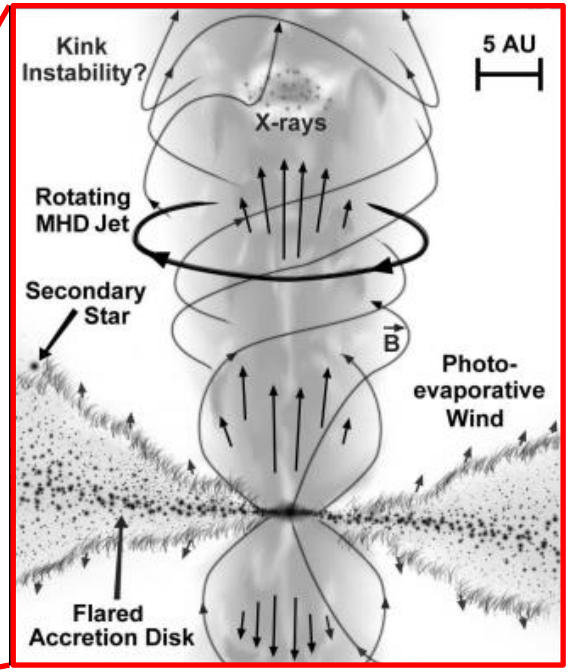
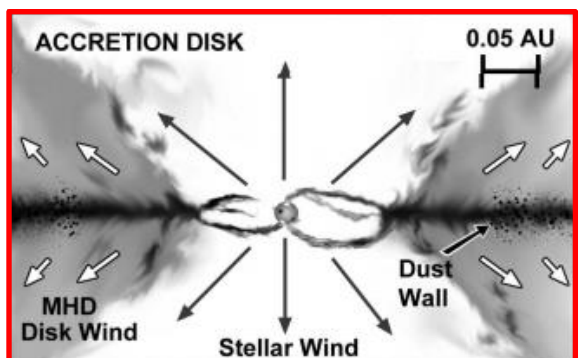
Context: collimation of Astrophysical jets







Collimation: toroidal B_θ et poloidal B_{pol}

[J. Ferreira A&A 319, 340 (1999)

$$F_\perp = -\underbrace{\frac{B_\theta}{\mu_0 r}\nabla_\perp(\mathrm{r}B_\theta)}_{} + \boxed{j_\theta B_{pol}}$$

Z pinch experiment:
Ciardi et al. 2009
In our case = 0

$\mathbf{B_{pol}}$ ~ **mG** (models + obs)

Influence of B_{pol} on the morphology and collimation of the jet ?

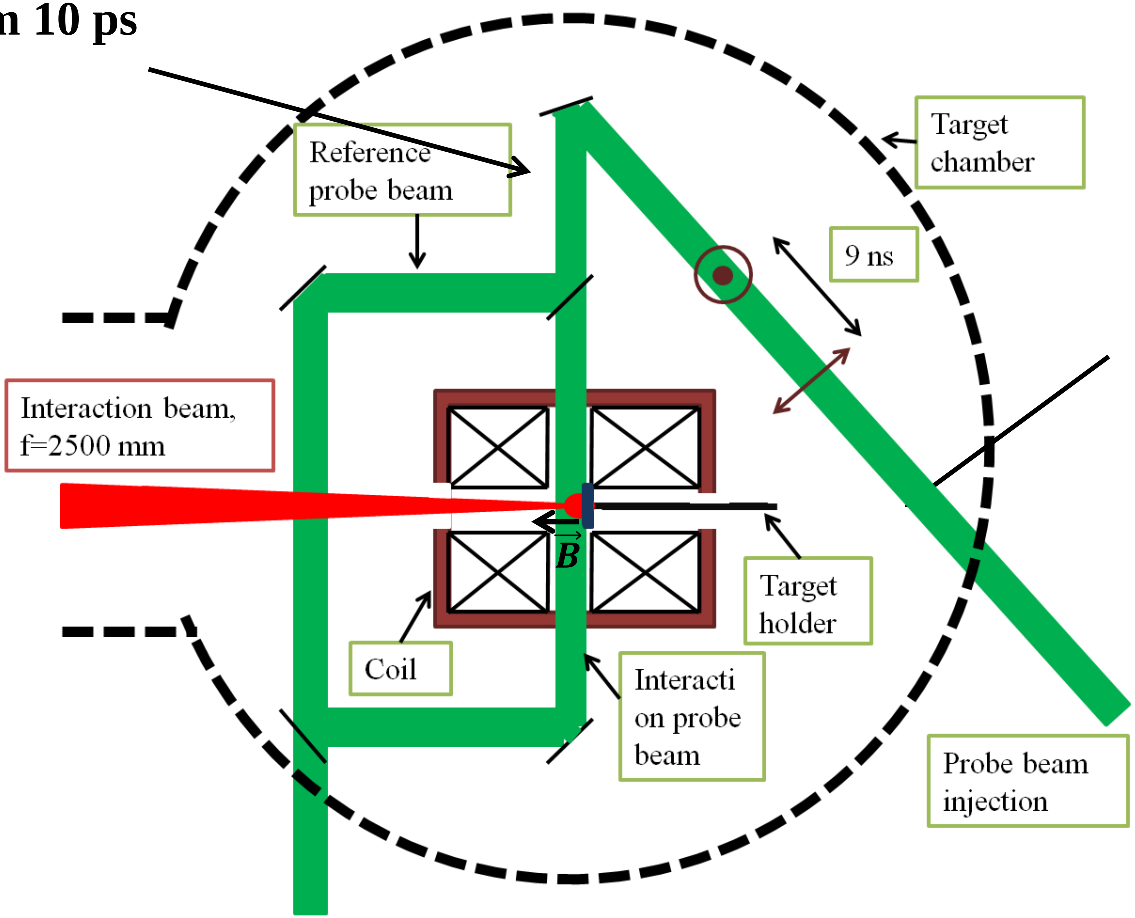
Mass ejection rate
10^{-7}-10^{-9} M_o/year

Velocity: 100-1000 $km.s^{-1}$

[A. Franck et al., Protostars and Planets, University of Arizona Press (2014)]
[R. D. Blandford et Payne, Mont. Not. R. Astron. Soc. 199, 883 (1982]

Experimental set-up

Probe beam 10 ps



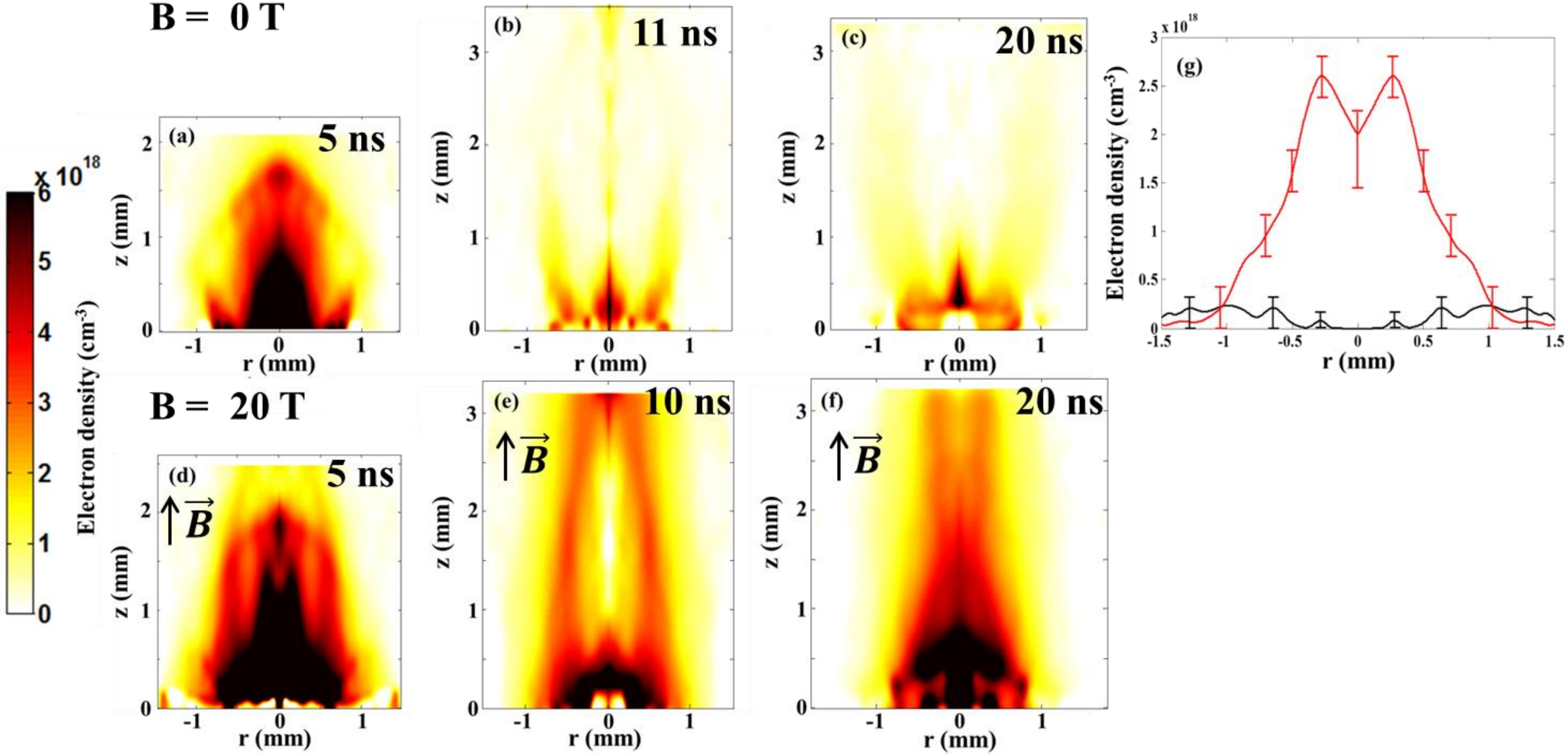
2 probing times using 2 polarisations S and P: delay of 9 ns between the 2

- **Magnetic Field of 20 T (6 kV)**
- **Measure of density through Mach Zehnder interferometer**

Magnetized Stellar Jets

Influence of an external magnetic field of 20 T on the dynamics of the plasma

Probe beam, 10 ps ➔ instantaneous: **density measurement**



CH target, I ~ 10^{12} W.cm^{-2}

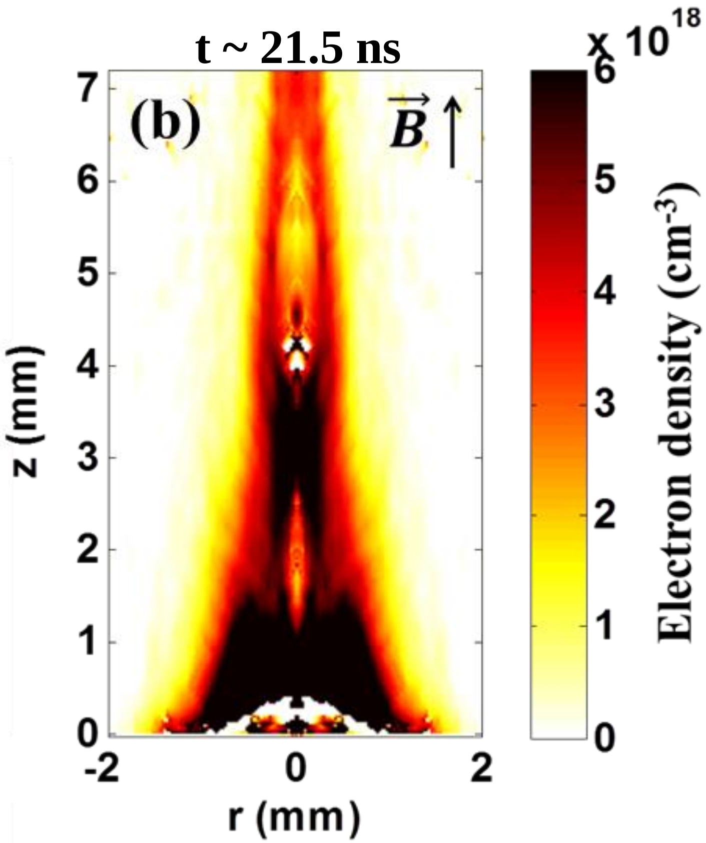
[B. Albertazzi et al., Science 346, 325 (2014)]

Magnetized Stellar Jets

Experimental observation of the formation of a conical shock

I ~ 10^{13} W.cm^{-2}

t ~ 21.5 ns

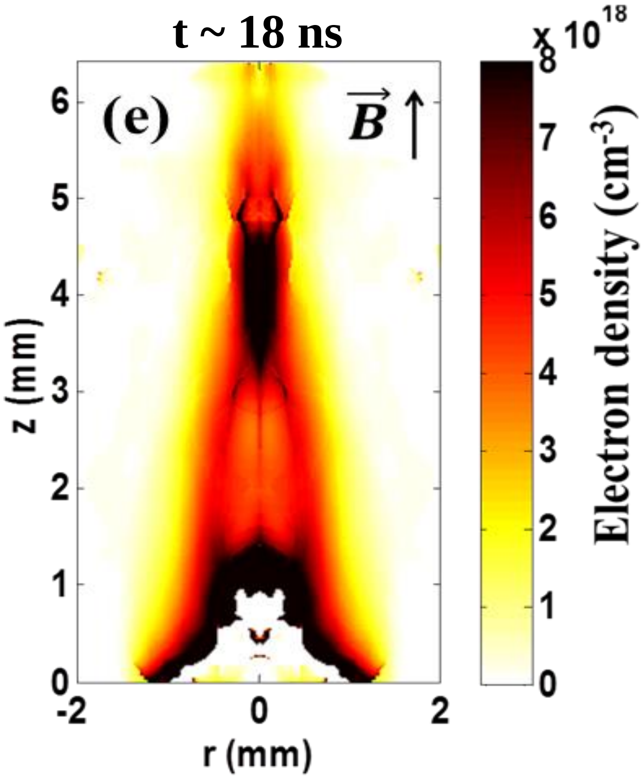


Processus of recollimation more than once

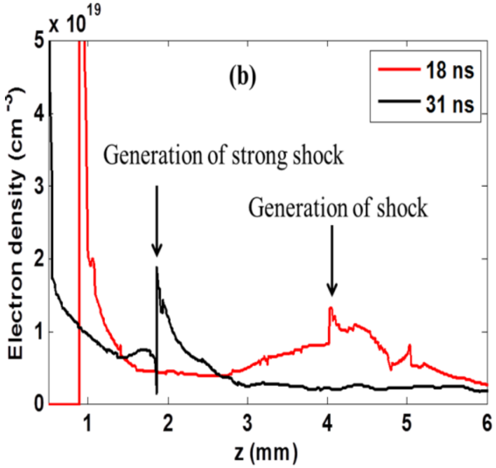
CH target

I ~ 2.10^{13} W.cm^{-2}

t ~ 18 ns



Formation of a conical shock



Comparisons
Simulations GORGON-Experiment

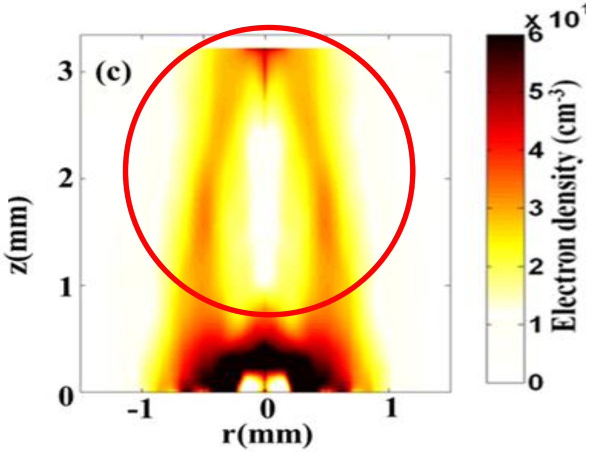
<u>Method of simulations :</u>

Interaction laser-solid target done by **DUED** (2D hydro-rad code) simulating interaction laser-solid

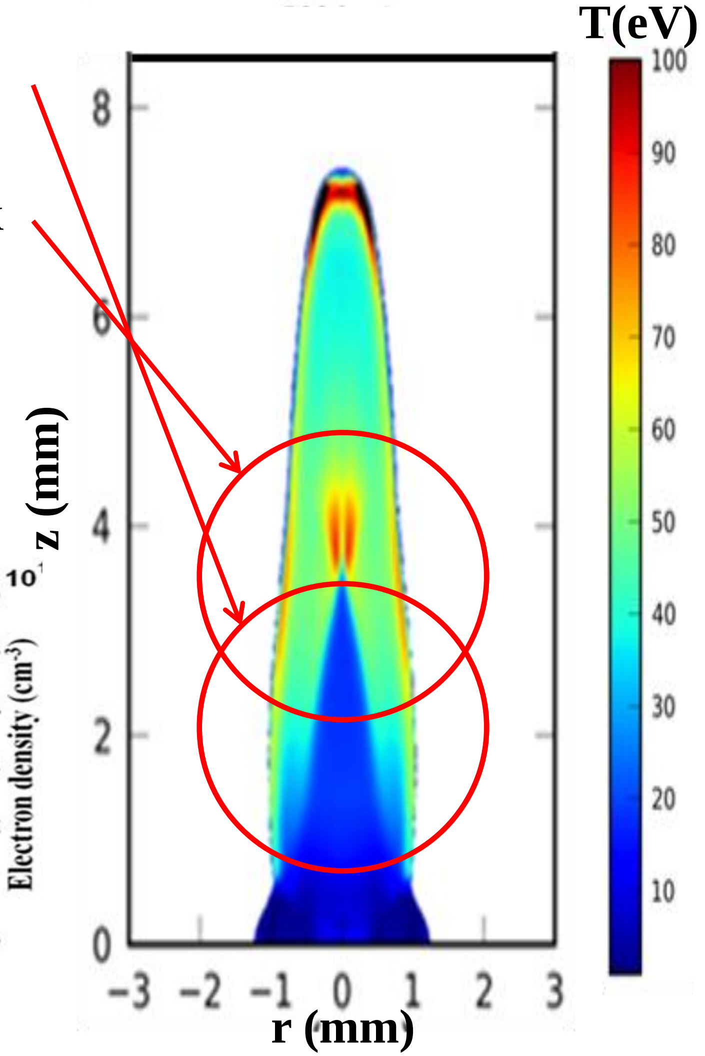
Injection of 3D maps of density, temperature and velocity as input in GORGON (3D MHD code)

A. Ciardi et al., Phys. Rev. Lett. **110**, 025002 (2013)

- Formation of a cavity
- Standing conical shock for recollimation of the jets
- **<u>Steady shock</u>**

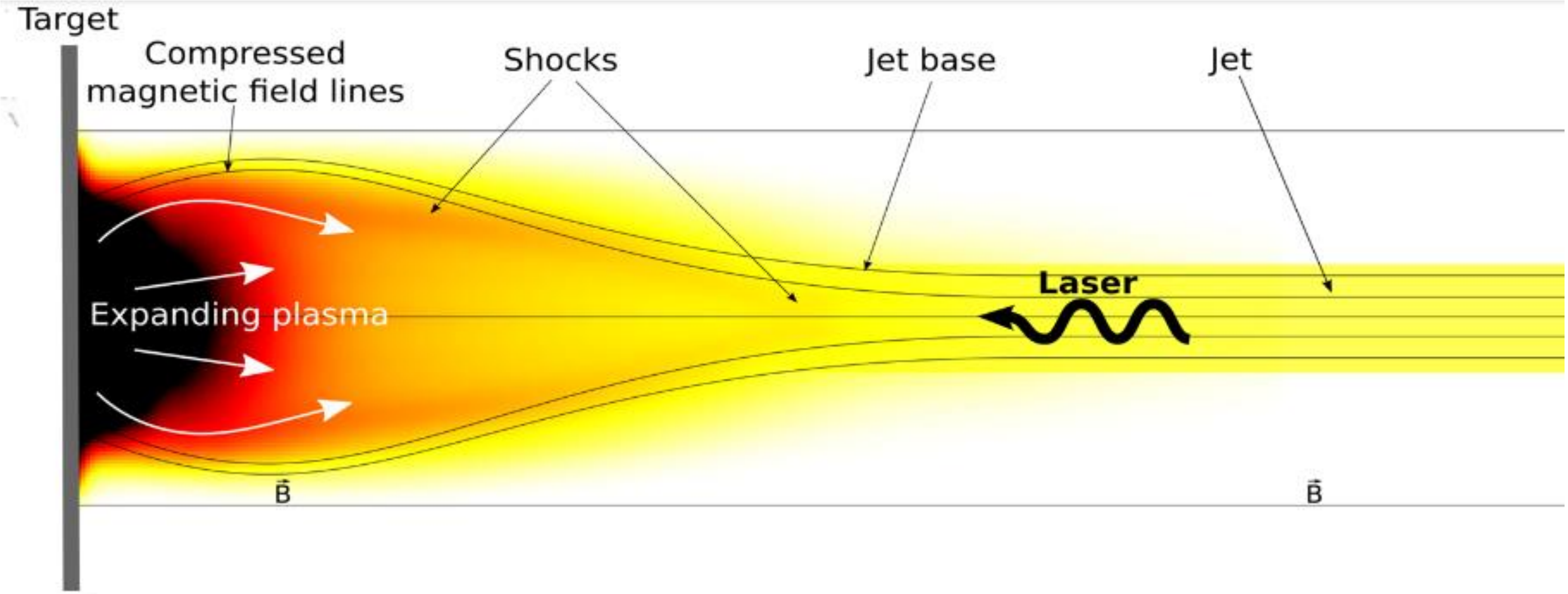


Experiment



Simulations GORGON

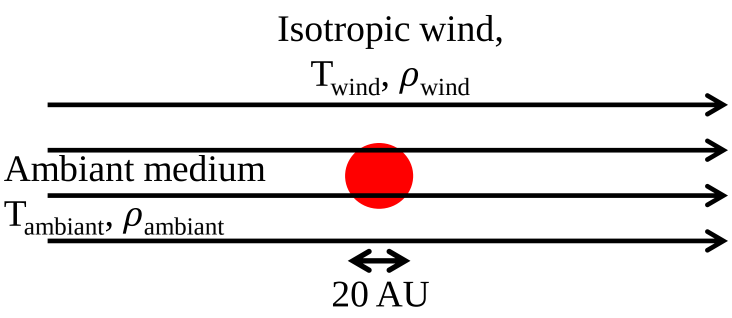
Physical mechanism

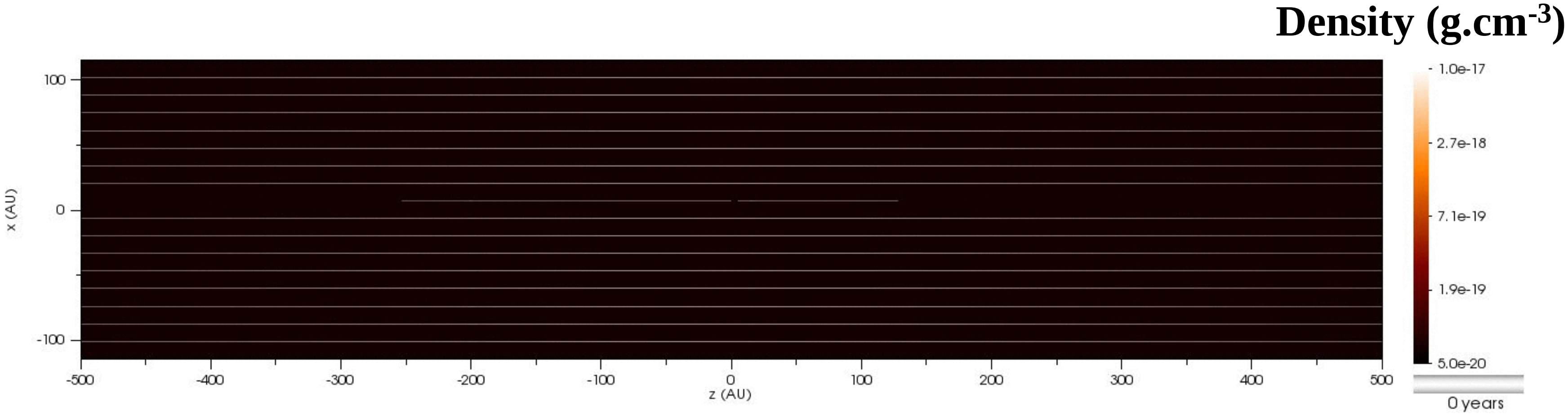


- Magnetic field lines are frozen in the plasma and they are swept laterally by the flow.
- B field lines are bent generating a radial component of B field which produce an additional radial forces and redirect the flow towards the axis.

[B. Albertazzi et al., Science 346, 325 (2014)]

Astrophysical simulations RAMSES

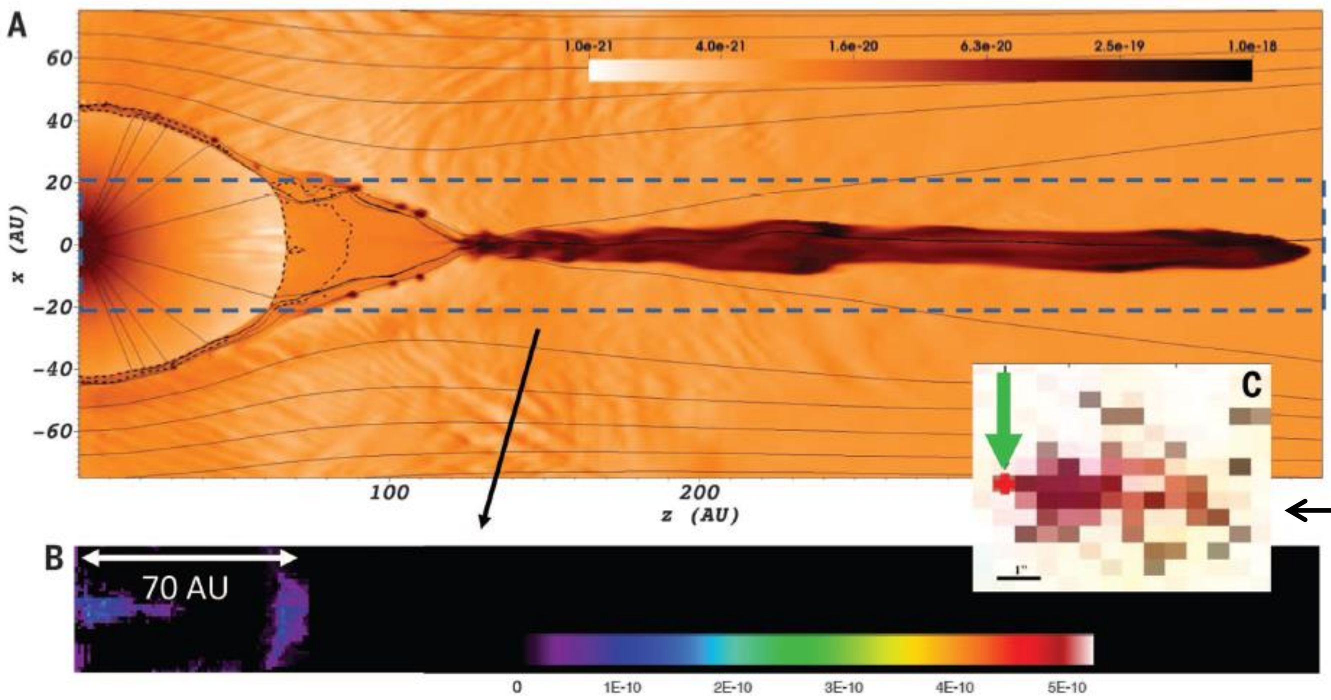




Important Parameters : B = 10 mG, Mass ejection rate ($M_{solaire}$/an) = 10^{-7}
Ejection velocity = 130 km.s^{-1}

Similarity between experiment and simulation : 20 ns ➔ 5.7 years

X-ray emission compatible with X-ray satellite measurements



Chandra observations of HH154

Same conclusion as the experiment:

- **B_{pol} can collimate a plasma flow by a recollimation shock**
- **X-ray emission compatible with recents astronomical observations**

[B. Albertazzi et al., Science 346, 325 (2014)]

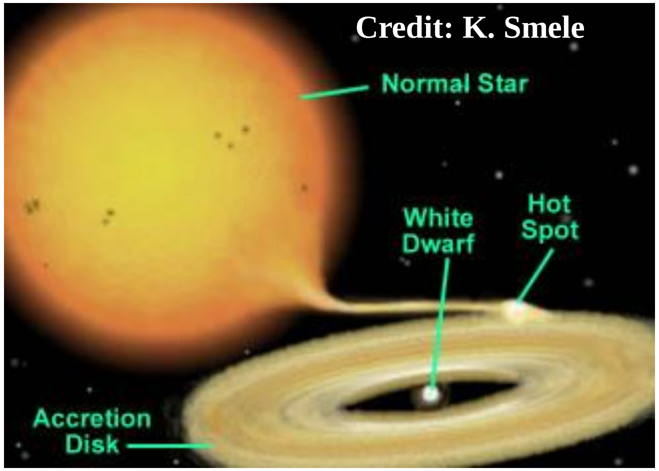
Dynamics and structure of magnetized reverse shock: POLAR

Context

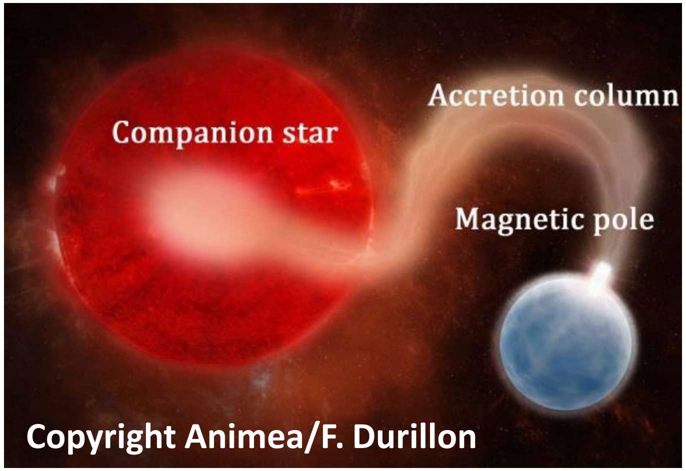
What is a cataclysmic variable POLAR ?

<u>Study of Cataclysmic variable:</u> Binary systems composed of a white dwarf accreting matter from a Sun-like star.

<u>Two type of CVs:</u>



B-field not sufficient: formation of an accretion disk



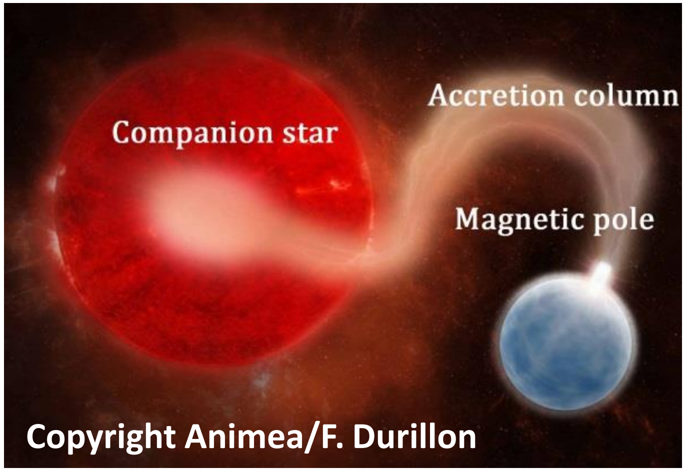
B-field extremly high: no formation of accretion disk

POLAR type: Example AM Herculis

Context

What is a cataclysmic variable POLAR ?

Study of Cataclysmic variable: Binary systems composed of a white dwarf accreting matter from a Sun-like star.



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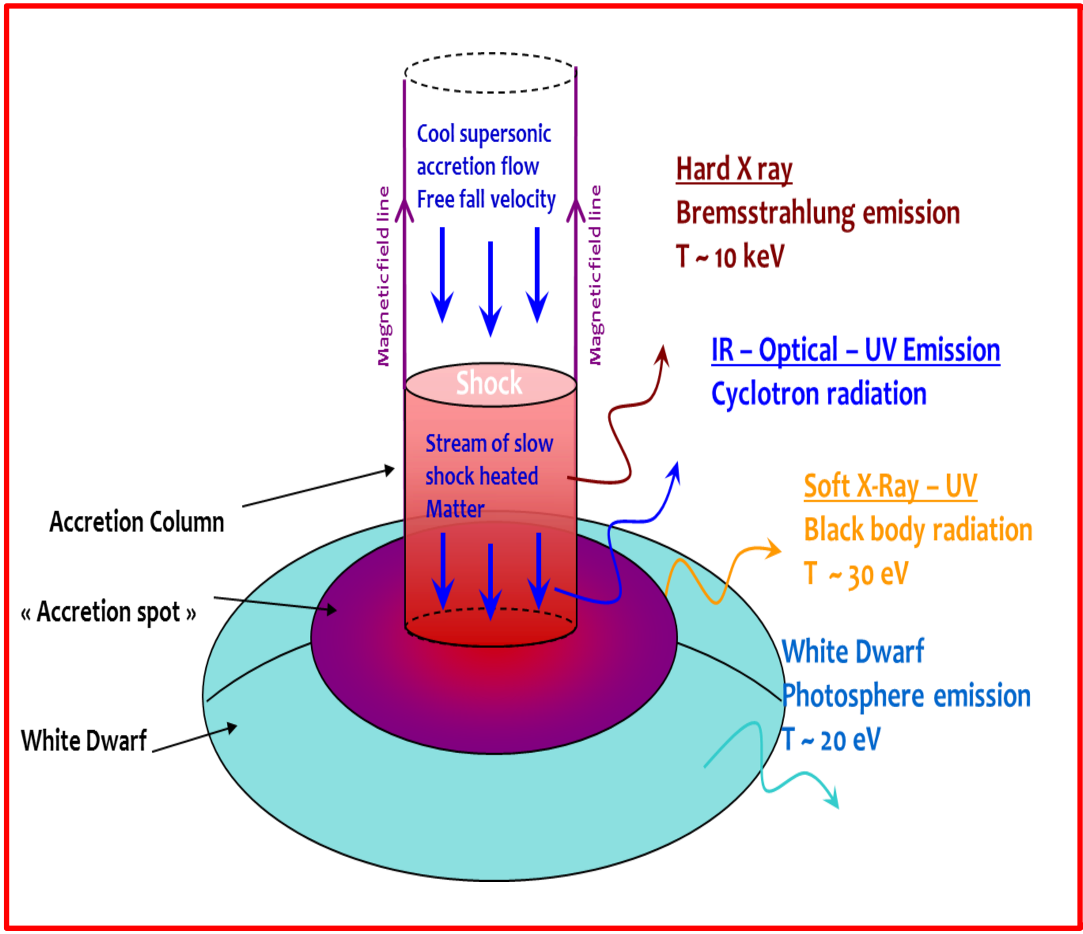
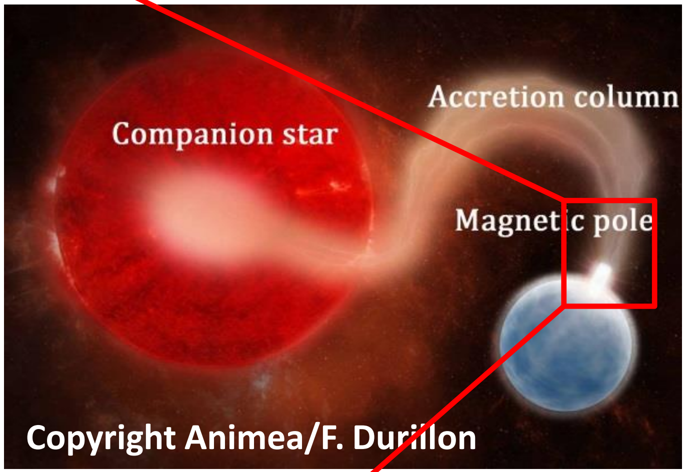




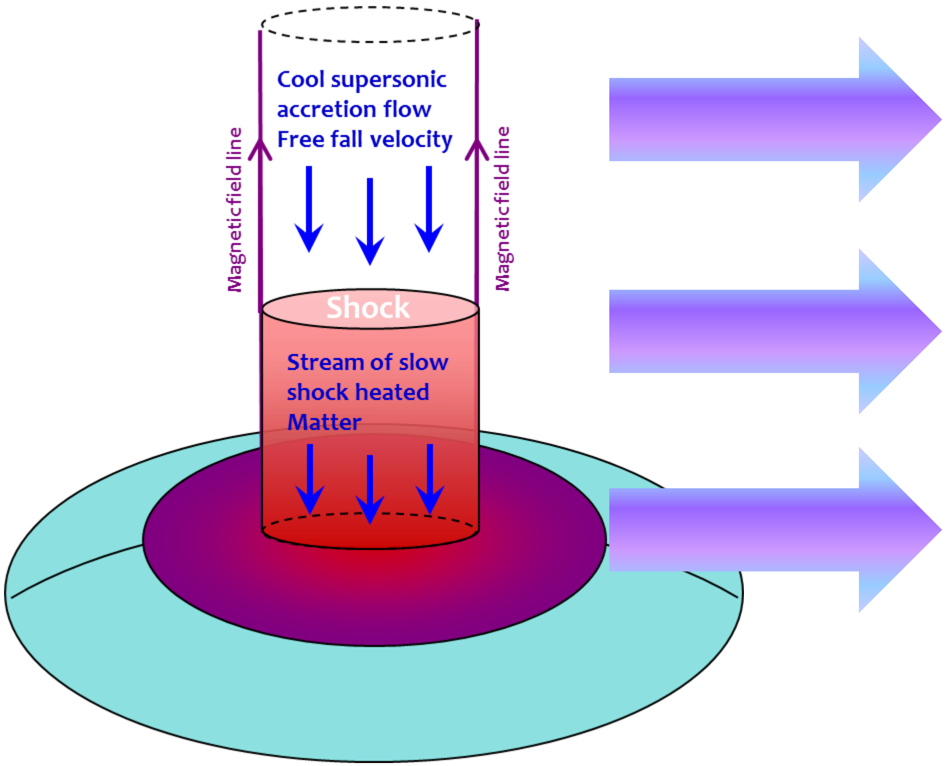
B-field extremly high: no formation of accretion disk

POLAR type: Example AM Herculis

Context

How to reproduce experimentally Polar system in the laboratory ?

POLAR



Experiment

Reproduce a plasma flow: irradiation of a target with a laser

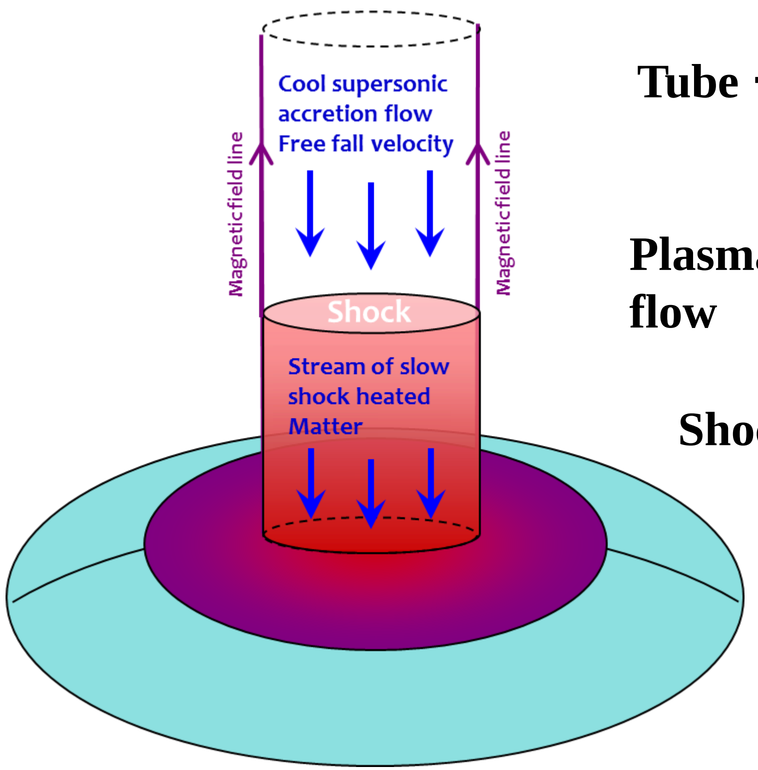
Collimation of the plasma flow by **a tube or a magnetic field**

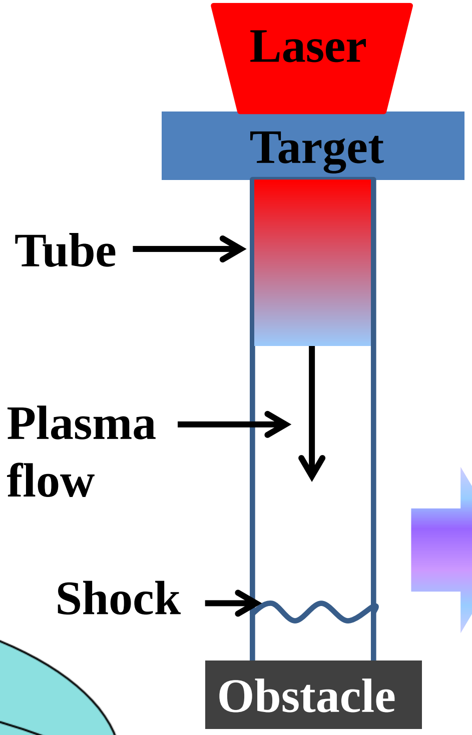
Simulate the photosphere of the WD by an obstacle

Previous work

How to reproduce experimentally Polar system in the laboratory ?

POLAR





1. **Tube can modify the dynamics of the reverse shock**
2. **Not possible to study MHD instabilities**

Collimation with a tube Experiment on LULI2000, GEKKO, OMEGA, ORION

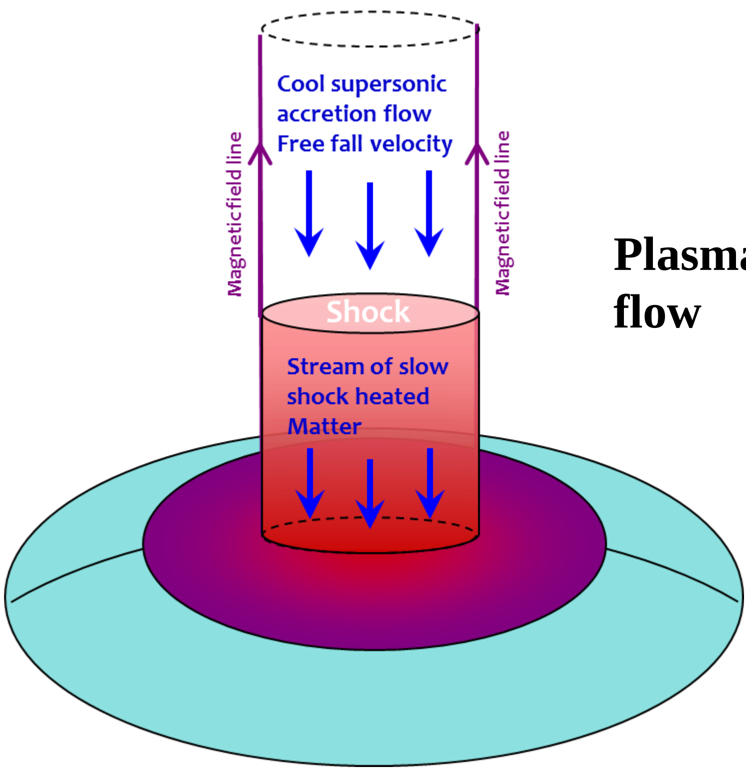
Example of target:

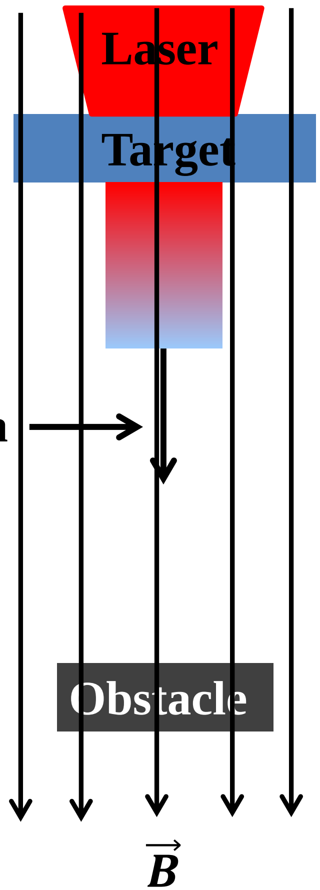
E. Falize et al. ApSS (2009)
E. Falize et al. HEDP (2012)
B. Loupias HEDLA (2012)
C. Busschaert et al. NJP (2013)
J. Cross et al., Nat. Comm (2016)
C. Busschaert PhD (2013)

Collimation of the outflow by a magnetic field

LULI2000 Experiment

POLAR





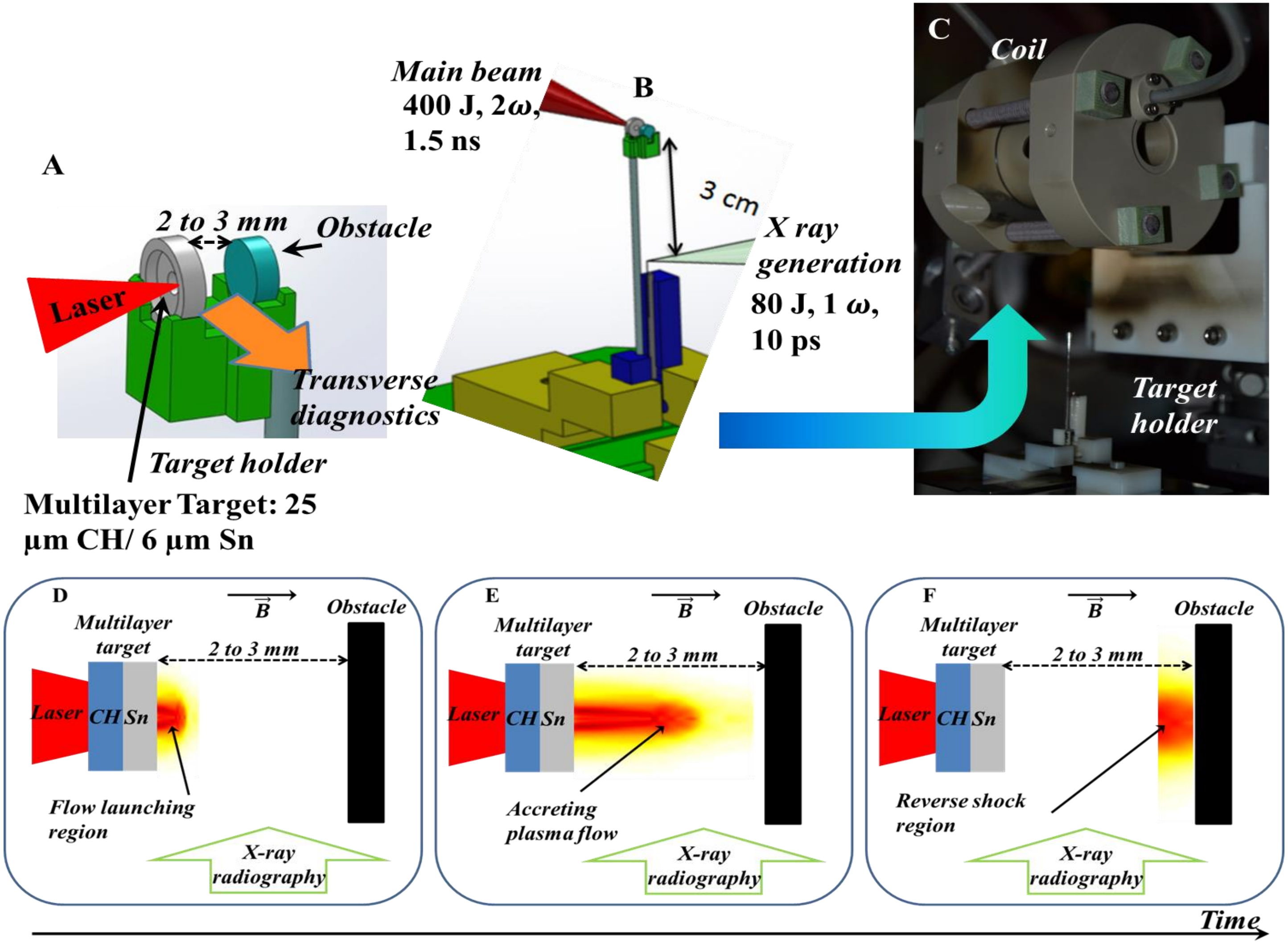
Similarity:

	POLAR	Lab perfect	LULI2000 Exp
Velocity (km/s)	1000	300	80
Density (g/cm3)	10^{-8}	10	5.10^{-3}
Magnetic field (MG)	10	625	0.1
Temperature (eV)	10^{5}	350	25
Mach Number	> 10	> 10	7-8

Collimation with an external magnetic field of 10-15 T

[B. Albertazzi et al., submitted]

Experimental set-up @ LULI 2000



Magnetic Field up to 15 T

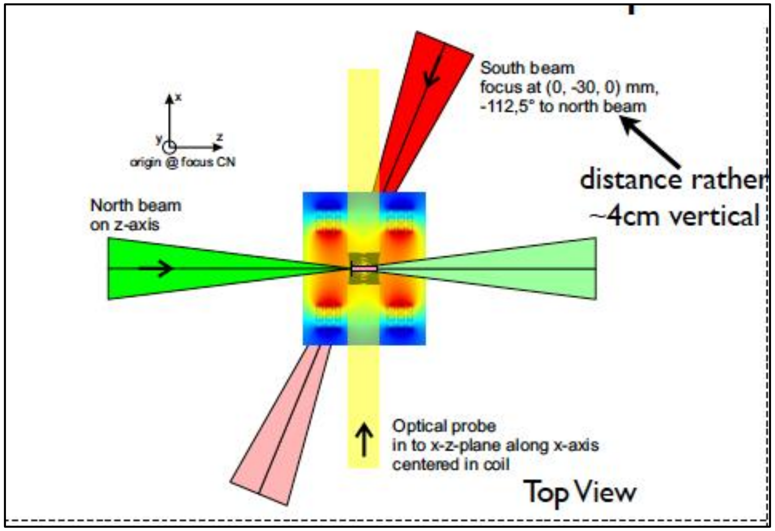
[B. Albertazzi et al., submitted]

Diagnostics

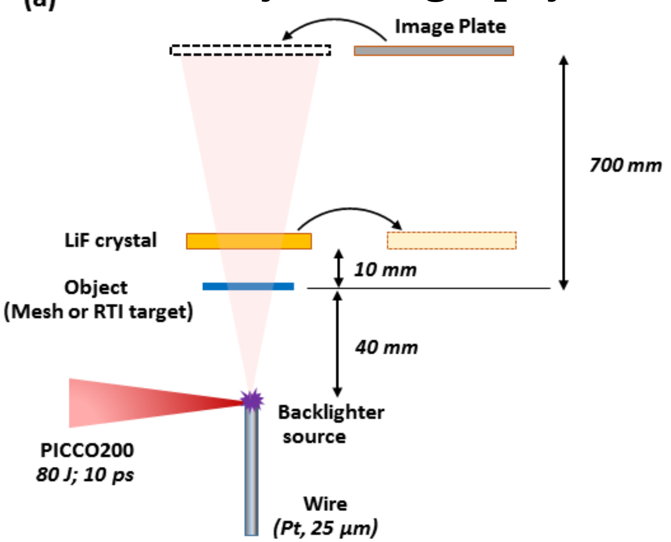
Diagnostics

- X ray radiography to probe the dense part of the plasma ($n_e > 5.10^{19}$ cm^{-3})
- SOP 1D transverse to get velocity of the plasma: constraint the simulation
- 2D shadowgraphy (integrated over 200 ps) or SOP 2D transverse
- Interferometry (integrated over 200 ps) to get the density of the plasma (~ 5.10^{17}-1.10^{20} cm^{-3})

Optical Diagnostics



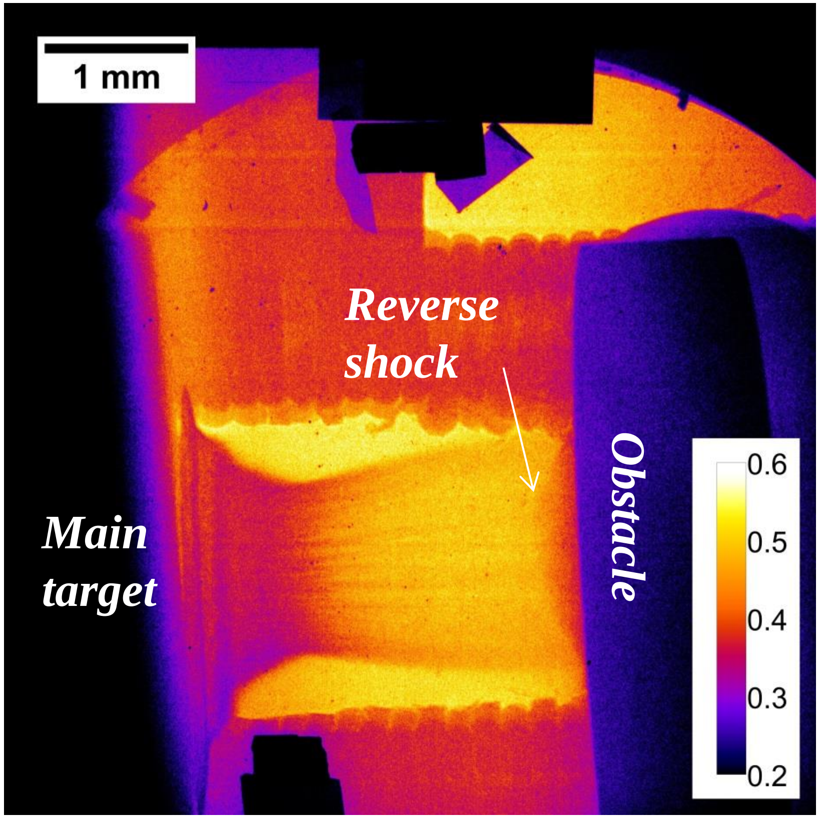
X-rays radiography



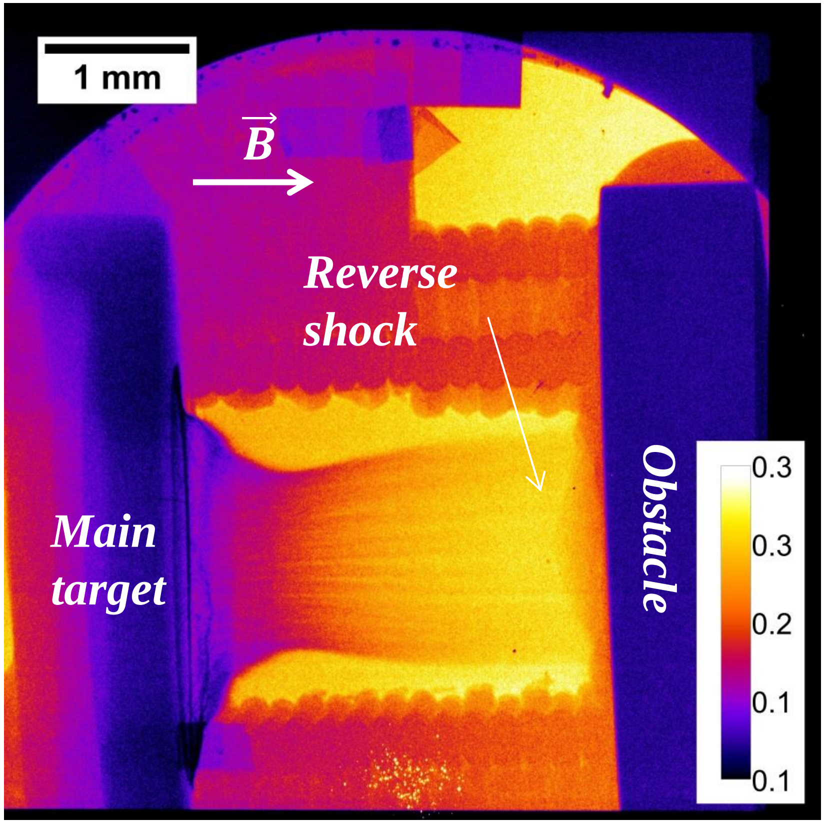
Collimation of the outflow by a magnetic field

X-ray radiography (120 ns)

Without B-field



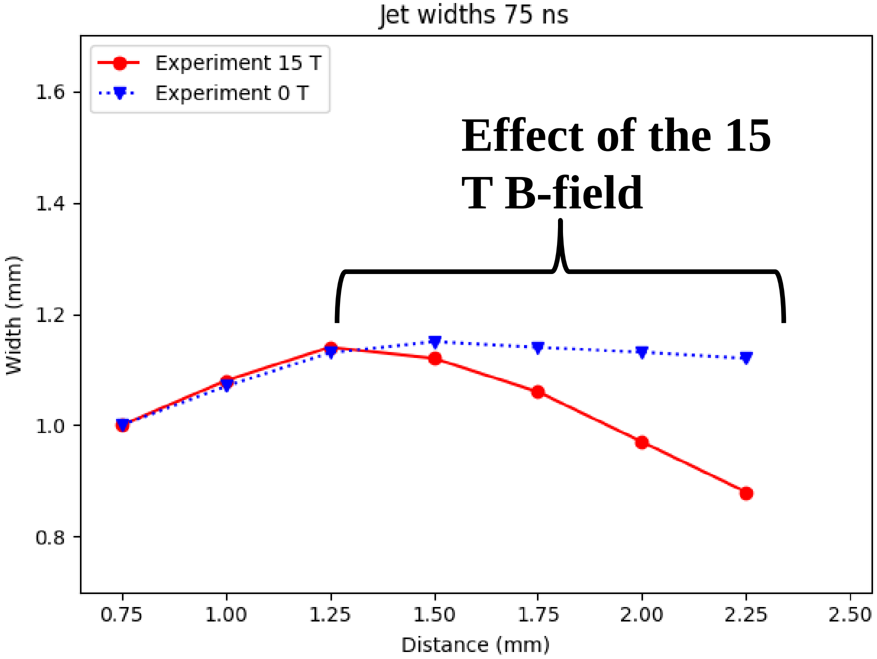
With a 15 T B-field

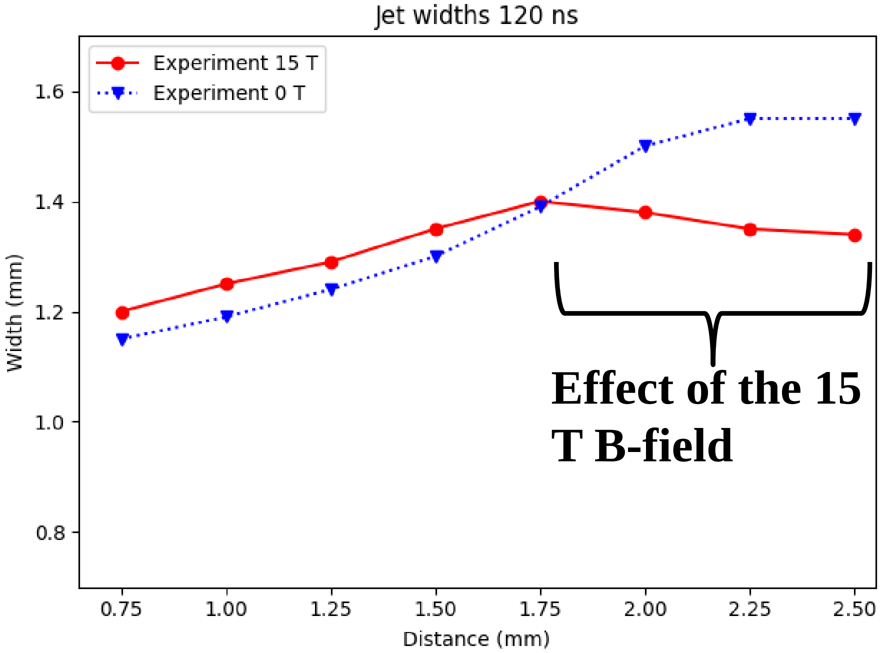


[P. Mabey et al., in preparation]

Collimation of the outflow by a magnetic field

X-ray radiography

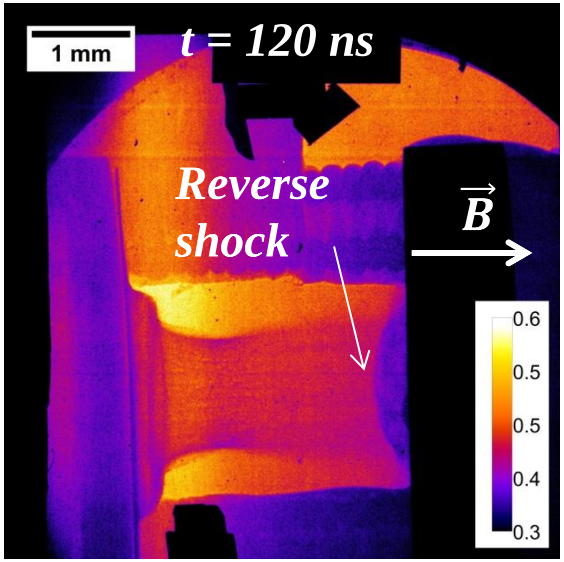


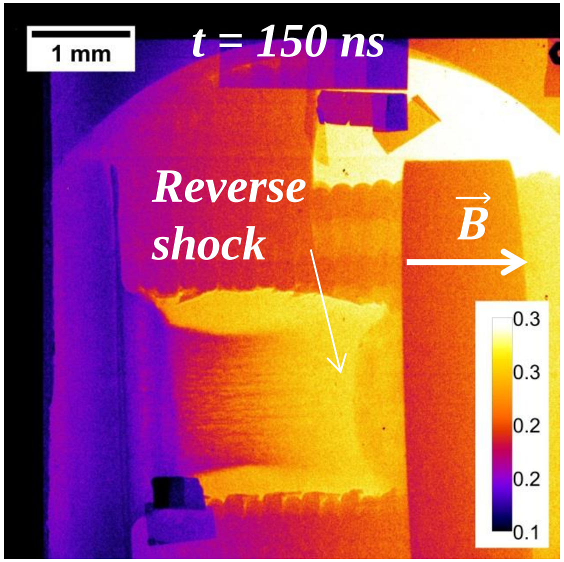


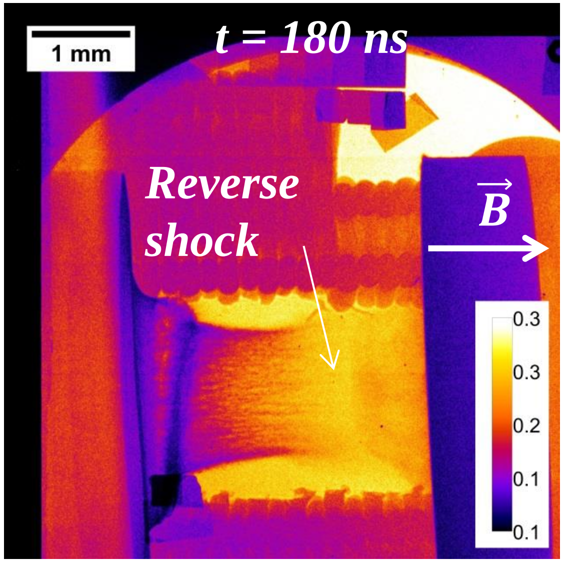
Collimation of the plasma flow leading to a higher mass flux coming on the obstacle and the formation of a more visible reverse shock with higher optical emission

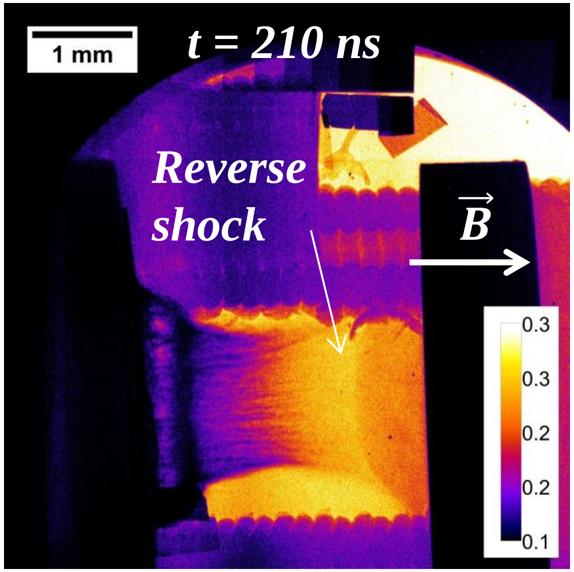
Collimation of the outflow by a magnetic field

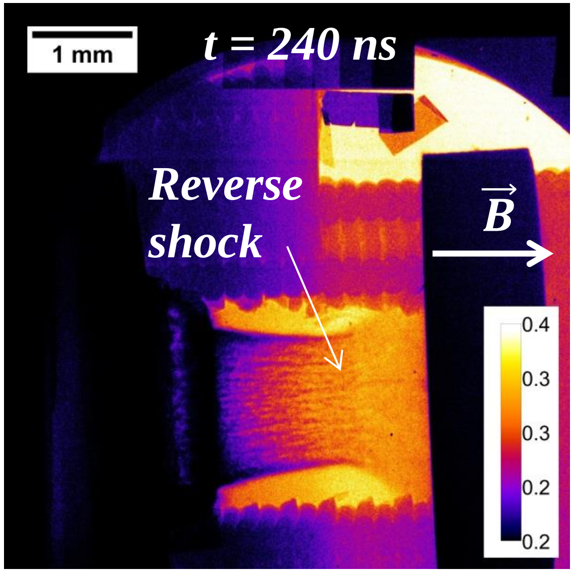
X-ray radiography: reverse shock dynamics











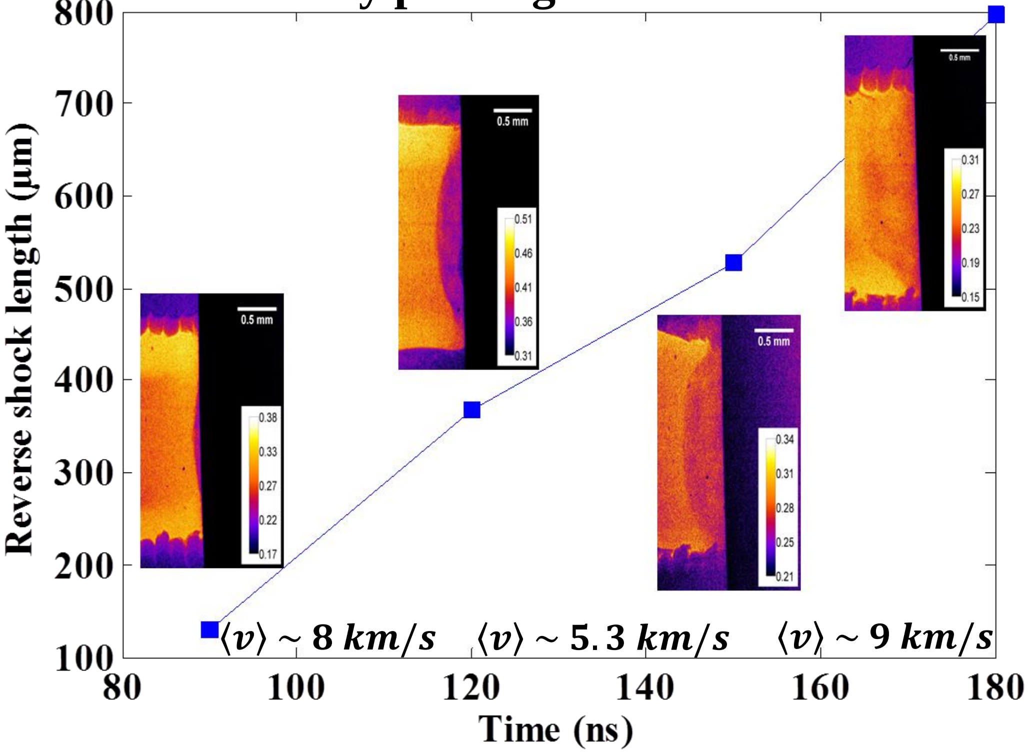
Reverse shock dynamics

Evolution of an instability ? Or due to the holder ?

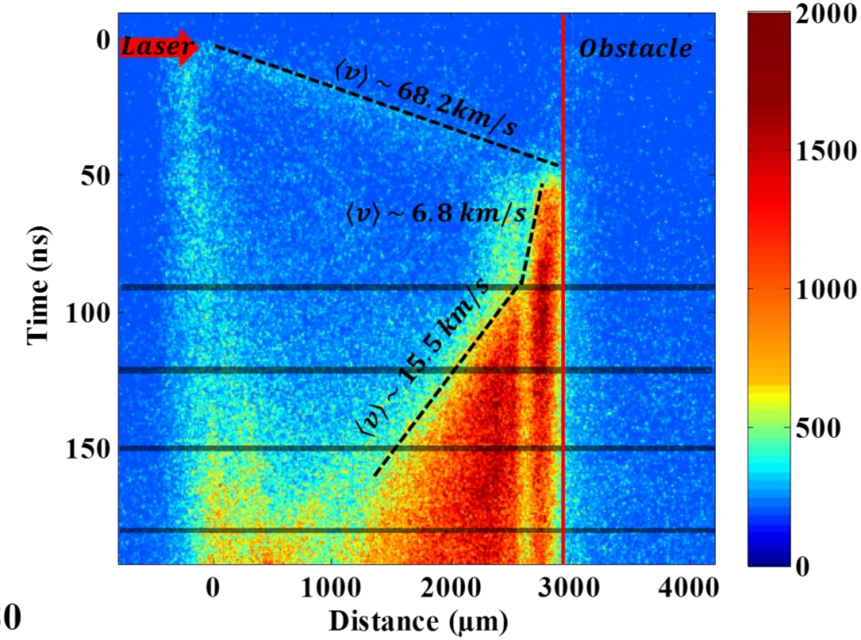
Experimental results/Preliminary analysis

Reverse shock dynamics and structure

X-ray probing at 4.5 keV



Optical emission at 450 ± 40 nm



Observations of two distincts regimes:

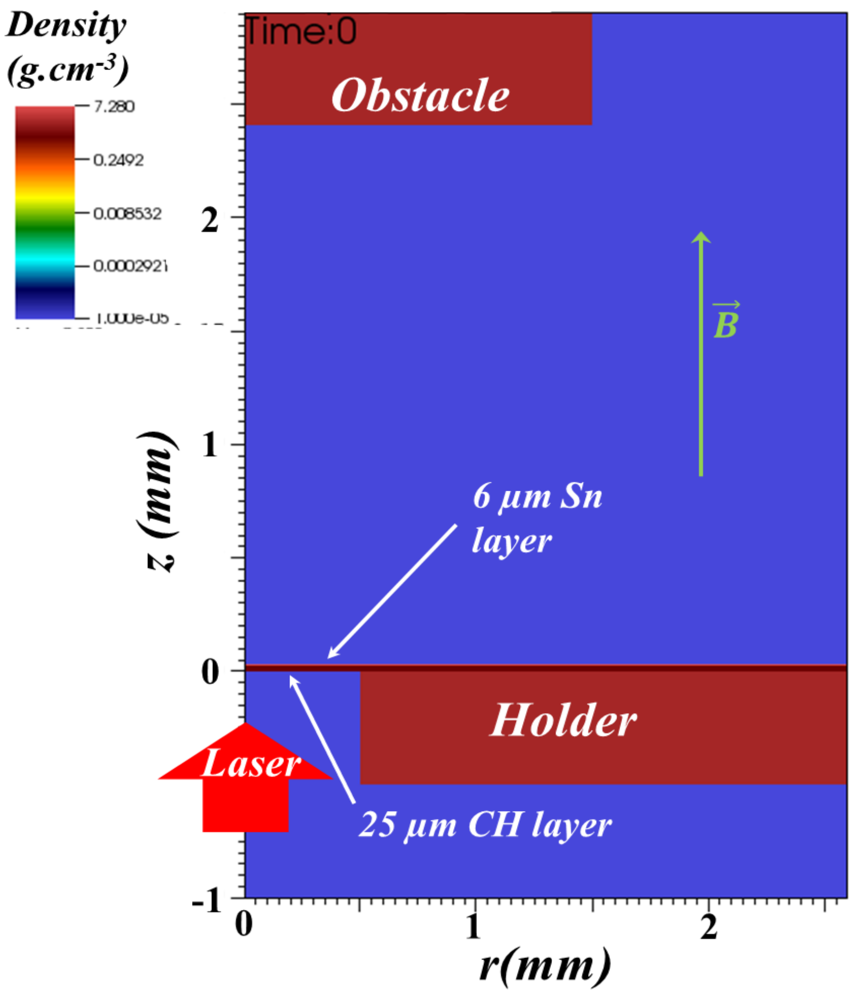
- A slow (~ 7 km/s) one due to plasma stagnation at the obstacle
- A fast one (~ 15-17 km/s) observed only on optical emission

Optical emission does not match with X-ray radiography ➔ Structure of the shock

FLASH simulation (U. Chicago)

Initial conditions

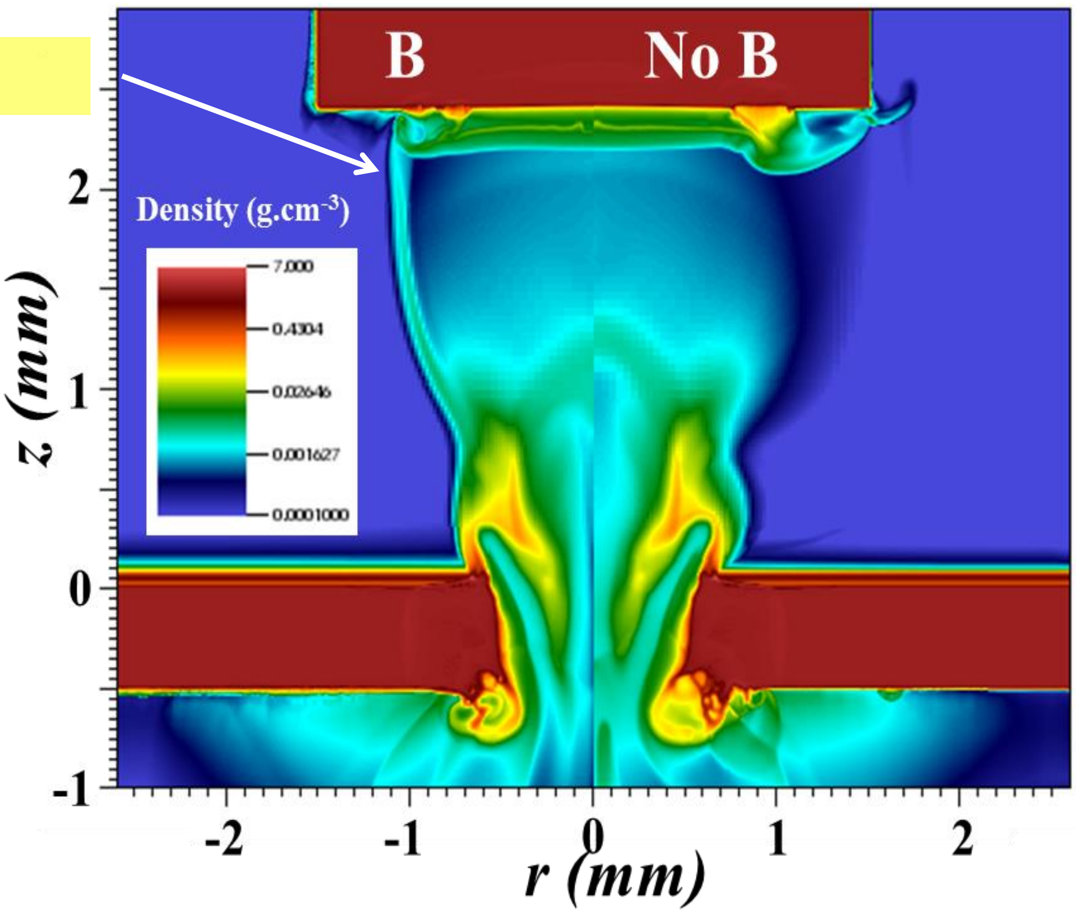
- 2D Axis symmetric
- SESAME EOS
- Multi-group diffusion approximation using 40 radiation groups
- Effective resolution 5.08 µm



FLASH simulation

Influence of the B-field

$\sigma \sim 1$ and $R_m > 1$

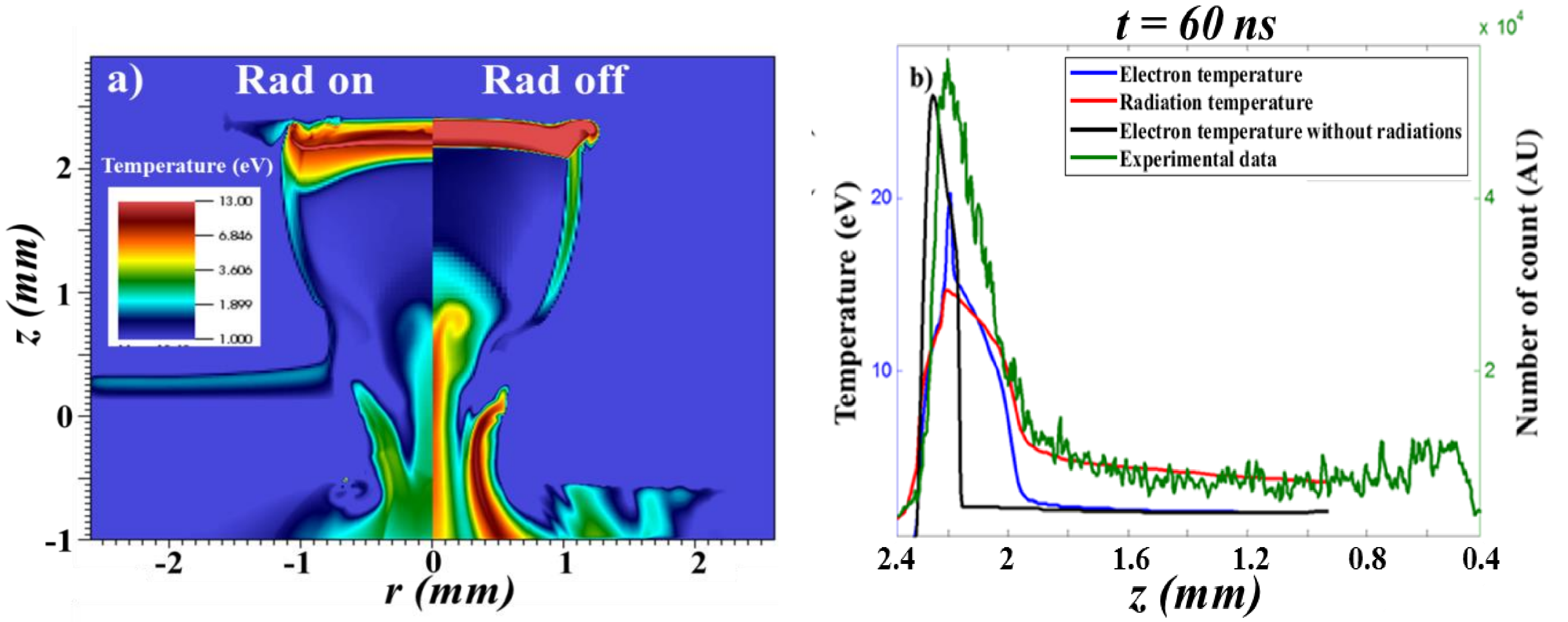


Collimation of the plasma flow by the magnetic field

Reverse shock constraint by the magnetic field

FLASH simulation

Influence of radiation



To reproduce the data, radiation module should be on
Structure of the shock seems to be similar to a radiative shock

Conclusion

Coupling between magnetic field and laser produced plasmas can produce plasmas relevant for astrophysical investigation (or magnetized FCI)

Take into account all the physics
Compressible, radiative MHD

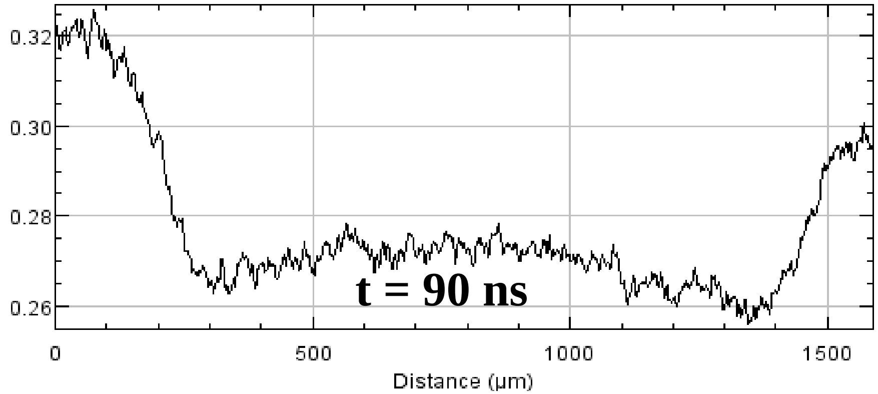
Acknowledgements

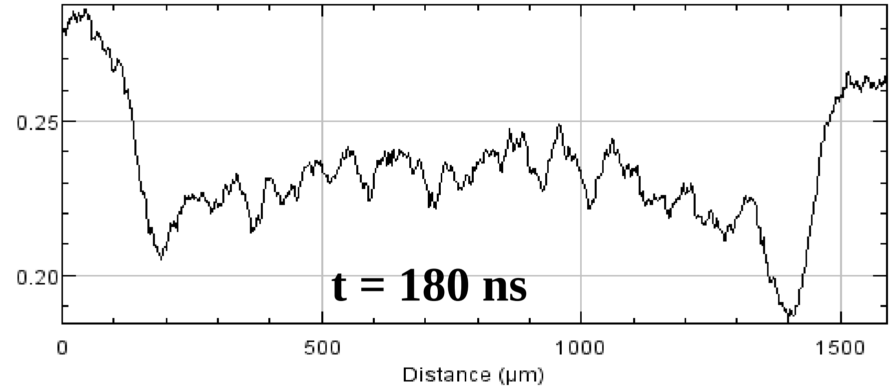
A. Ciardi[3,4], M. Nakatsutsumi[1], T. Vinci[1], J. Béard[5], S. Bonito[6,7], J. Billette[5], M. Borghesi[8,9], Z. Burkley[1], S.N. Chen[1], T. E. Cowan[10,11], T. Herrmannsdörfer[7], D. P. Higginson[1], F. Kroll[10,11], S. A. Pikuz[12,13], K. Naughton[8], L. Romagnagni[1], C.Riconda[1], G. Revet[1], R. Riquier[1,15], H-P. Schlenvoigt[11], I. Yu. Skobelev[12], A. Ya. Faenov[12,16], A. Soloviev[17], M. Huarte-Espinosa[18,19], A. Franck[18], O. Portugall[5], H. Pépin[2], J. Fuchs[1,17]

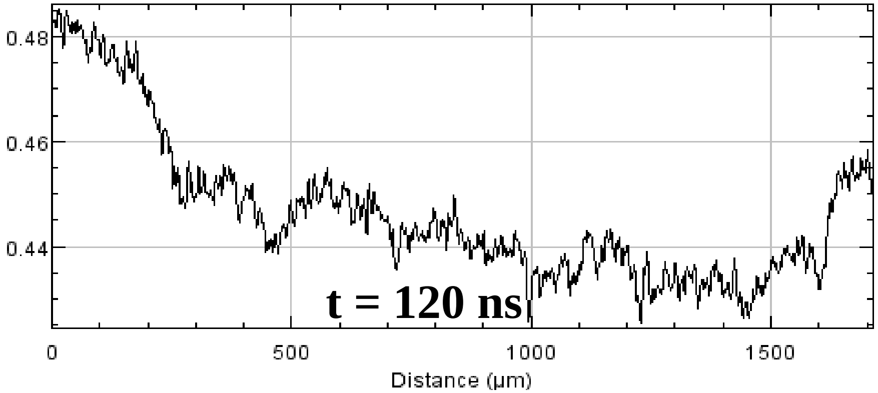
E. Falize[2,3], A. Pelka[4], F. Brack[4], F. Kroll[4], R. Yurchak[1] , E. Brambrink[1], P. Mabey[1], N. Ozaki[6], S. Pikuz[7,8], L Van Box Som[2,3], J. M. Bonnet-Bidaud[3], J. E. Cross[9], E. Filippov[7,8], G. Gregori[9], R. Kodama[10], M. Mouchet[11], T. Morita[12], Y. Sakawa[10], R.P. Drake,[5], C. C. Kuranz[5], M. J.-E. Manuel[13], C. Li[14], P. Tzeferacos[15], D. Lamb[15], U. Schramm[4] and M. Koenig[1,6]

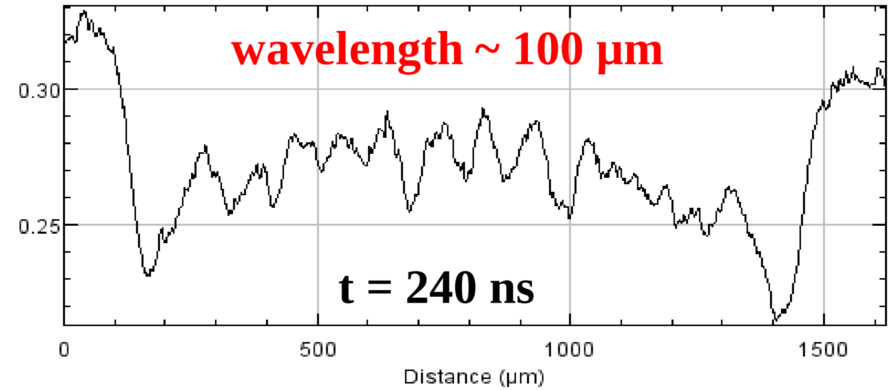
Experimental results/Preliminary analysis

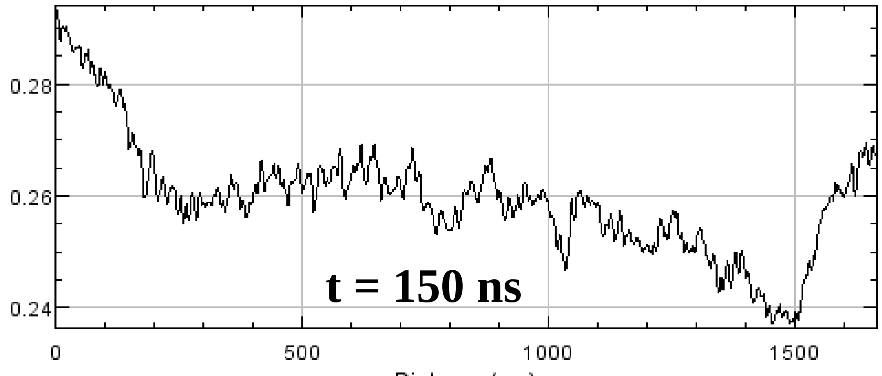
Experimental observations of filamentation instability











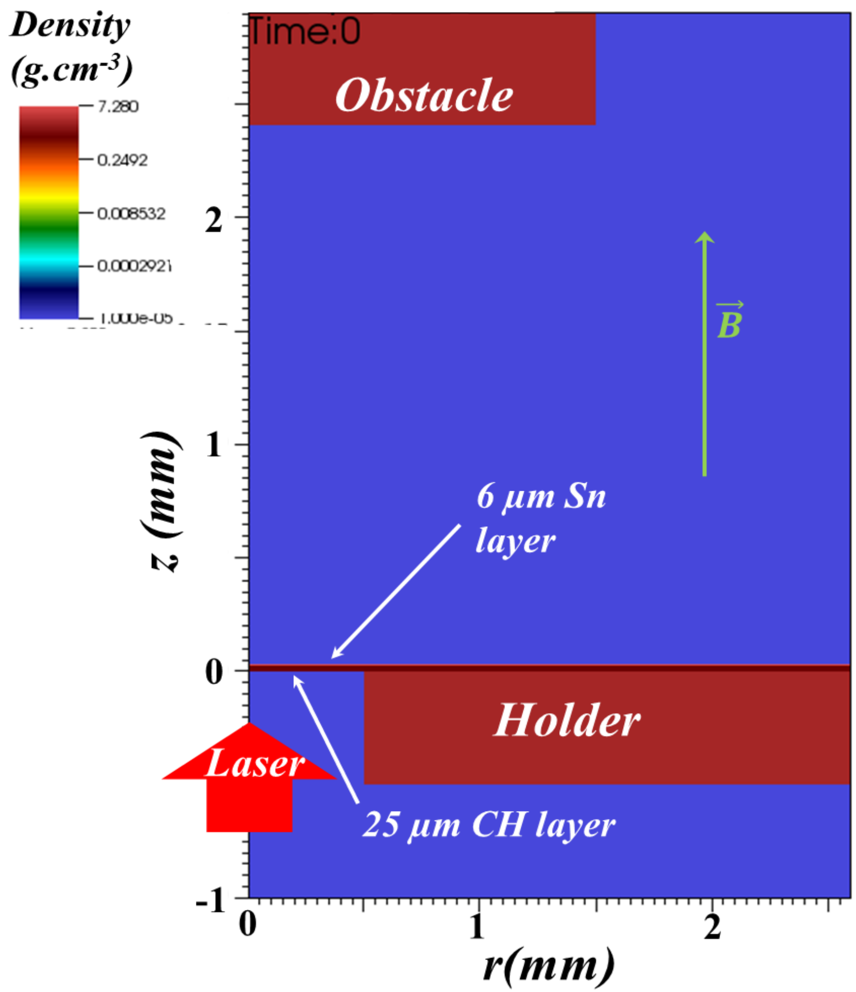
Instability due to multilayer target ?

If not, it is really interesting …

FLASH simulation

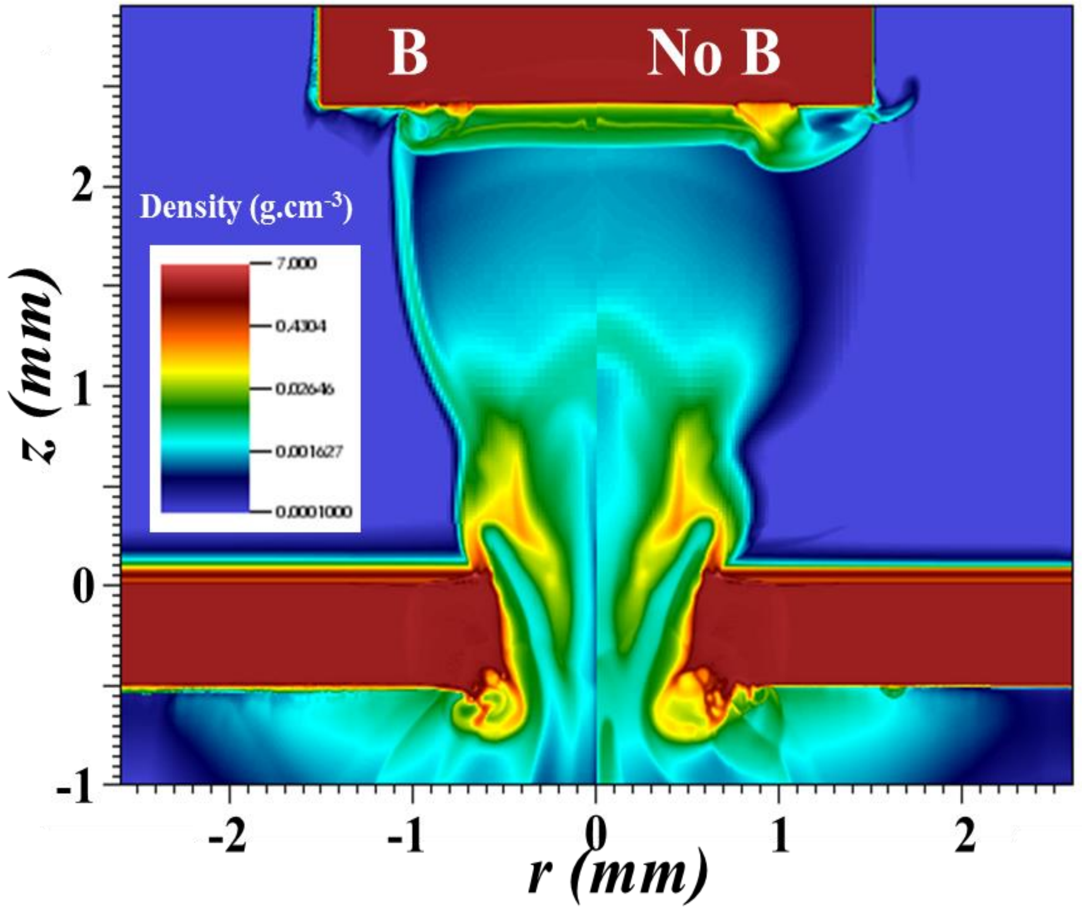
Initial conditions

- 2D Axis symetric
- SESAME EOS
- Multi-group diffusion approximation using 40 radiation groups
- Effective resolution 5.08 µm



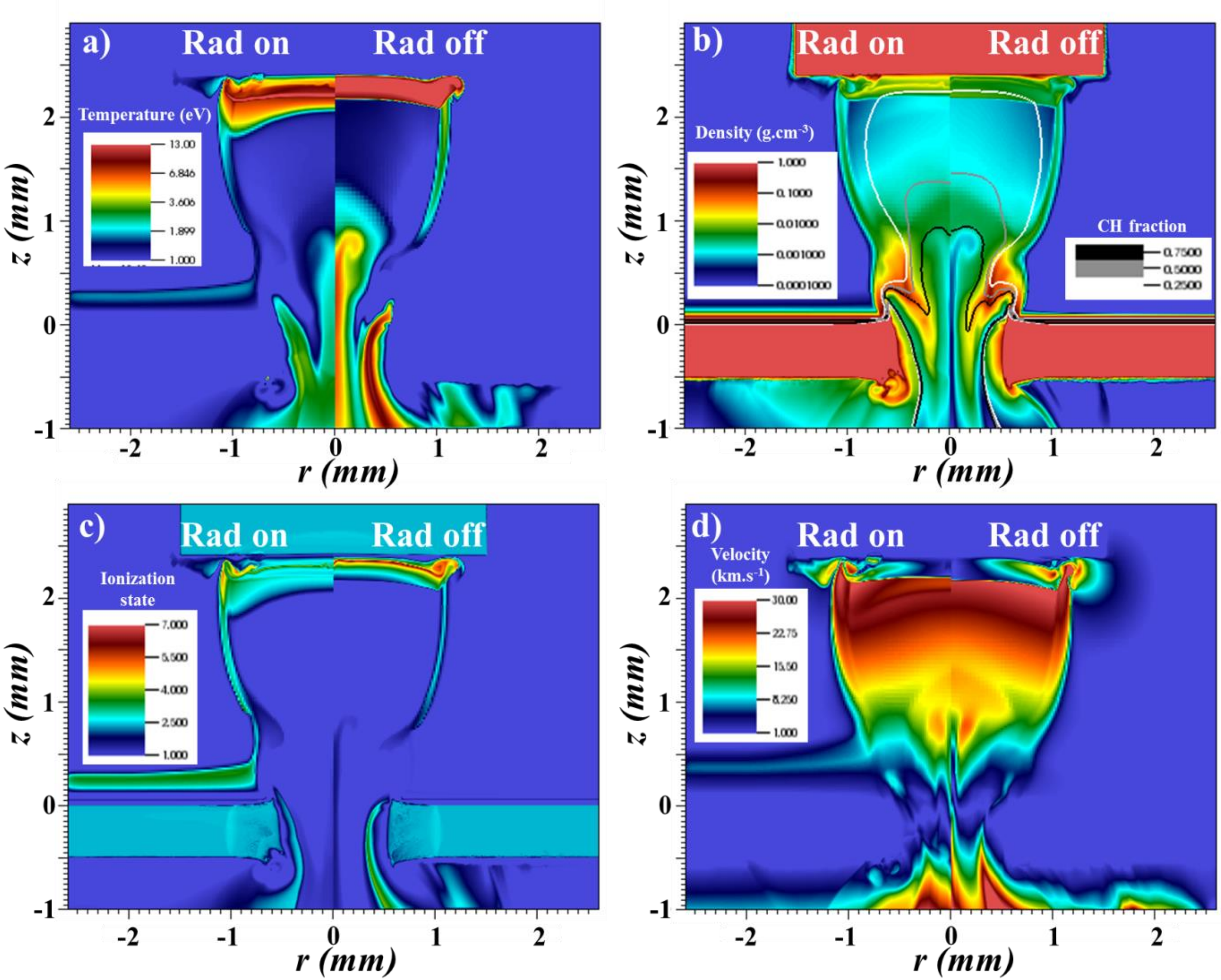
FLASH simulation

Influence of the B-field

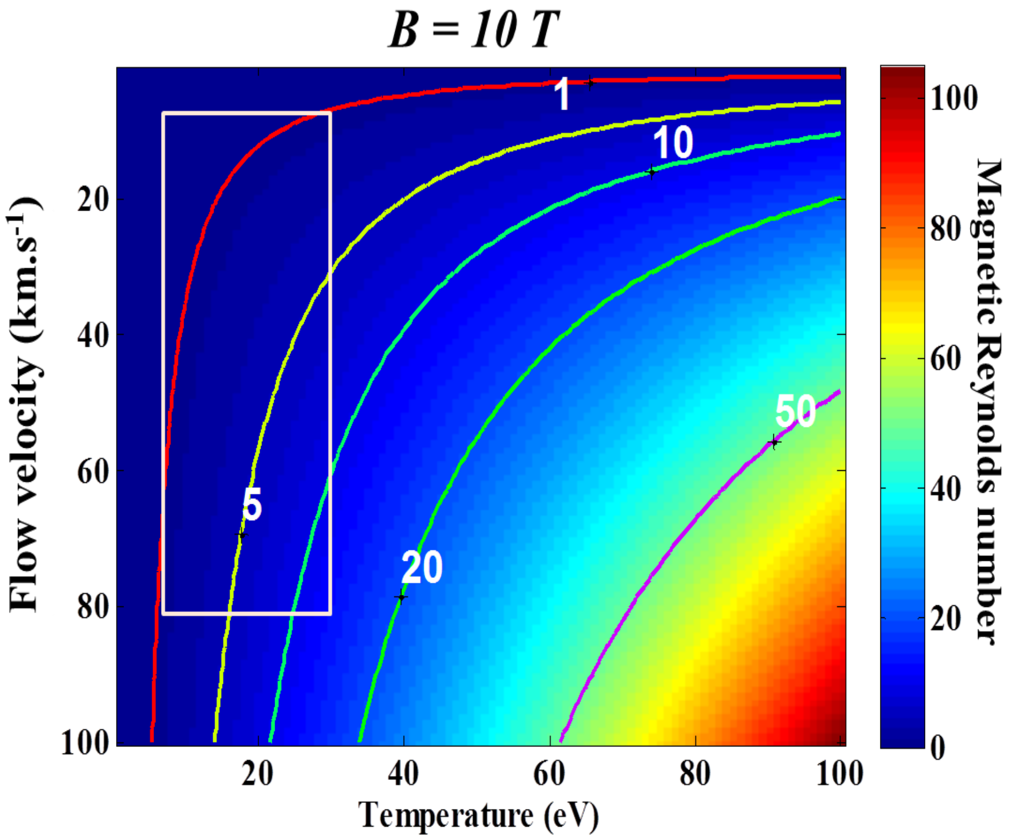


FLASH simulation

Influence of radiation

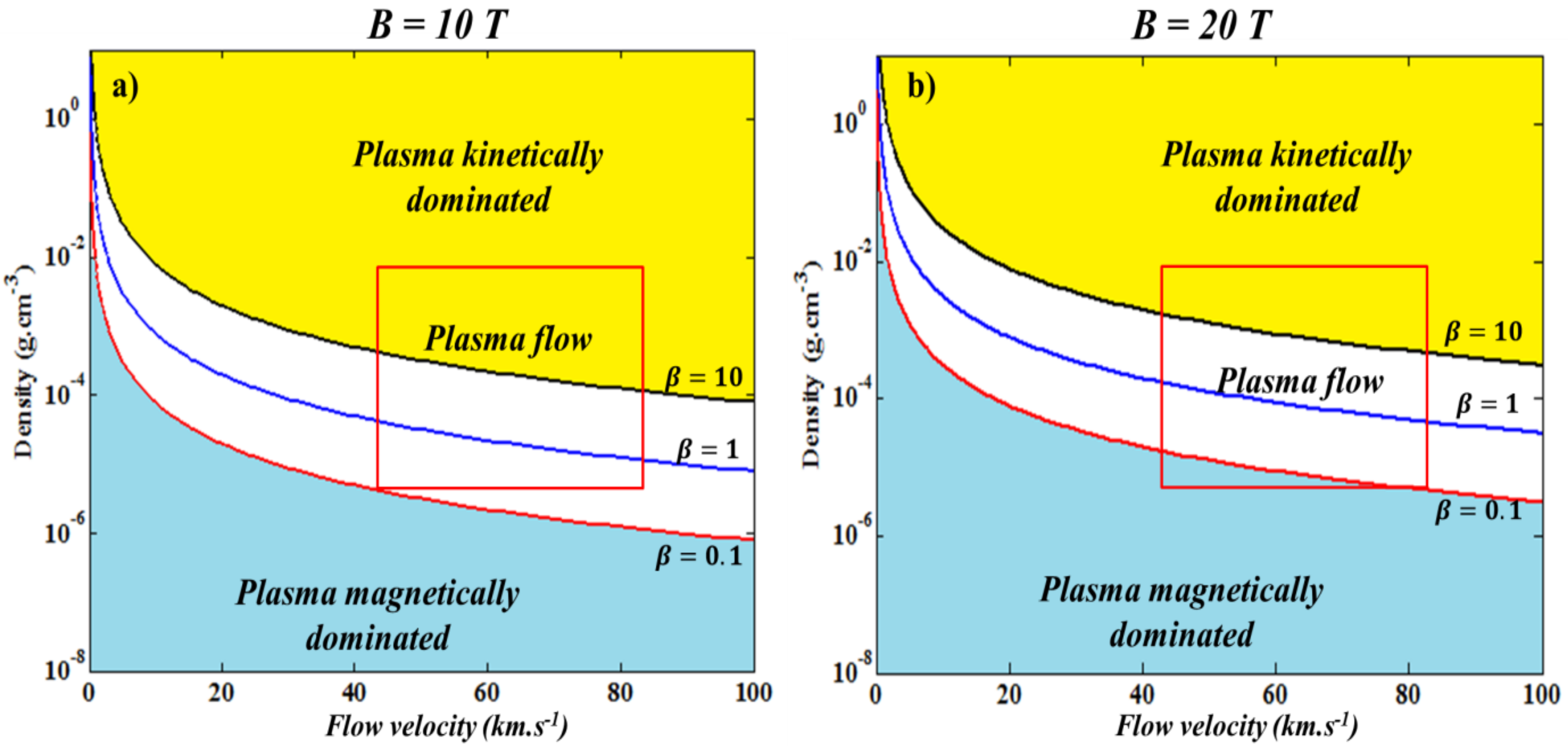


σ and R_{em}

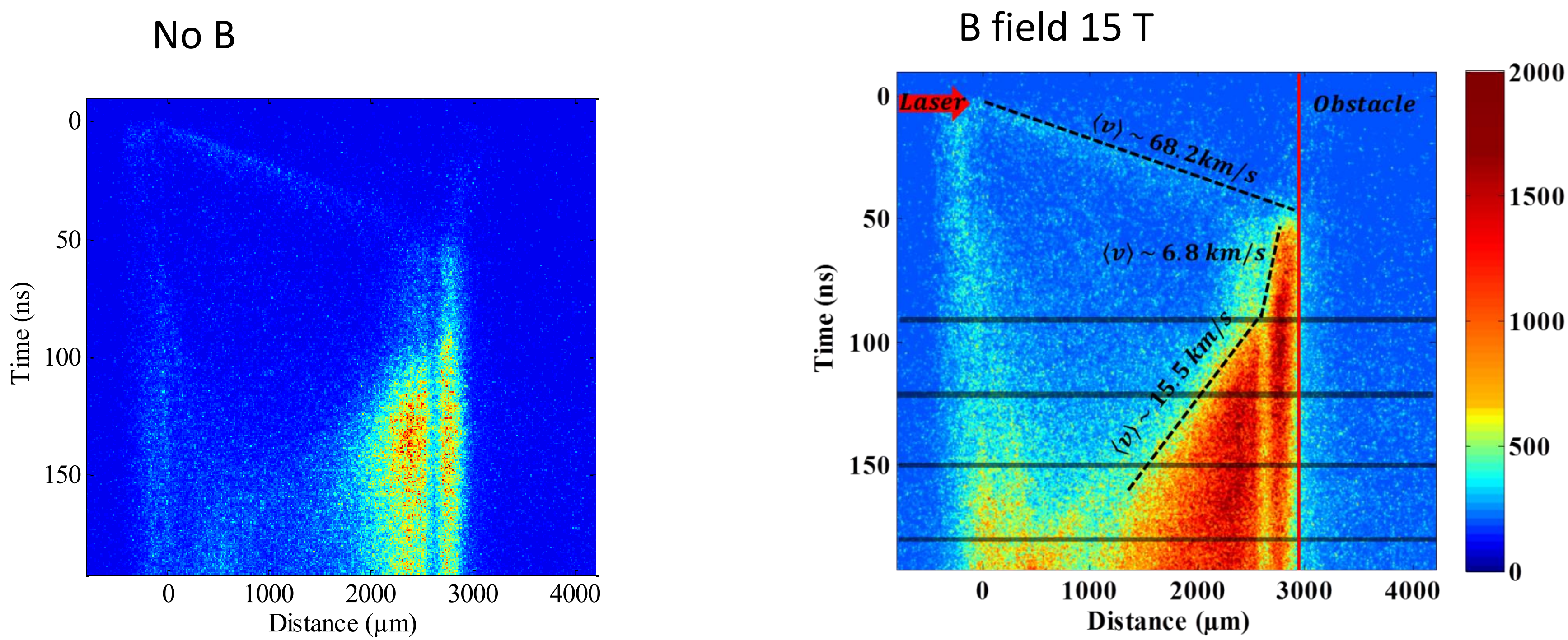


B = 10 T
1
10
50
5
20
Flow velocity (km.s-1)
20
40
60
80
100
Temperature (eV)
20
40
60
80
100
Magnetic Reynolds number
100
80
60
40
20
0

σ and R_{em}



B = 10 T
a)
Plasma kinetically dominated
Plasma flow
β = 10
β = 1
β = 0.1
Plasma magnetically dominated
Density (g.cm-3)
10^0
10^-2
10^-4
10^-6
10^-8
0
20
40
60
80
100
Flow velocity (km.s-1)
B = 20 T
b)
Plasma kinetically dominated
Plasma flow
β = 10
β = 1
β = 0.1
Plasma magnetically dominated
Density (g.cm-3)
10^0
10^-2
10^-4
10^-6
10^-8
0
20
40
60
80
100
Flow velocity (km.s-1)


No B
Time (ns)
Distance (µm)
B field 15 T
Laser
Obstacle
⟨v⟩ ~ 68.2km/s
⟨v⟩ ~ 6.8 km/s
⟨v⟩ ~ 15.5 km/s
Time (ns)
Distance (µm)