Theory and observation of hydrodynamic shocks in a plasma flowing across randomized ICF scale laser beams

J. Ludwig[2], S. Hüller[1], W. Rozmus[3], H.A. Rose[4], C. Bruulsema[1],
A. Milder[1], G. Swadling[2], C. A. Walsh[2], W.A. Farmer[2], B. B. Pollock[2], P. Michel[2]

[1]Centre de Physique Théorique (CPHT), CNRS,Ecole Polytechnique, Palaiseau, France
[2] Lawrence Livermore National Laboratory, Livermore, CA, USA 94550
[3]Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1
[4] Los Alamos National Laboratory, Los Alamos, New Mexico, USA 87545

Outline

- Deflection of a single laser beam by transverse flow in plasmas

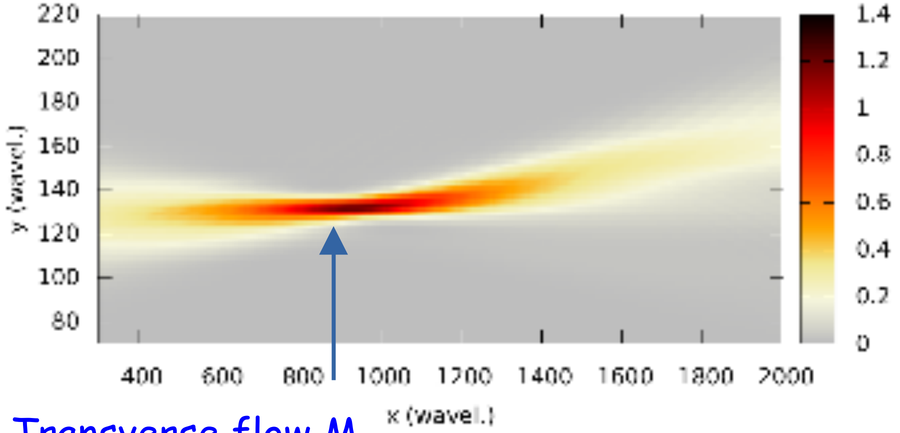
- Deflection of an optically smoothed laser beam by transverse flow
    - plasma response in the focal plane for slightly supersonic flow
    - case of CBET
    - supersonic flow: shock outbreak in the focal area
    - relations across the shock

- Experiments
    - campaign on OMEGA (2022)
    - future campaign on NIF (discovery science)
    - discussion

Beam deflection of a single laser beam
in presence of transverse flow

Theory of beam deflection due to plasma flow,
also in presence of self-focusing/filamentation

- Short/Bingham/Williams, Phys.Fluids 1982
- A. Schmitt, Phys. Fluids B 1989
- H. Rose, Phys. Plasmas 1996
- Ghosal/Rose, Phys. Plasmas 4, 2376 and 4189 (1997)
- Hinkel, Phys. Rev. Lett. 1998
- B. Bezzerides, Phys. Plasmas 5, 2712–2720 (1998).
- **our work (CBET):** S. Hüller et al, Phys. Plasmas 27, 022703 (2020)
- C. Ruyer et al. (CEA), Matter Radiat. Extremes **8**, 025901 (2023)



Transverse flow M

Plasma density modification :

- the ponderomotive force of the laser beam drives a density perturbation
- that is displaced downstream with transverse flow ;

Ponderomotive density perturbation $n_p(M=0) \sim \exp(-U_p/T)-1$ modified by flow

$$n_p(M) = n_p(M=0) / [\, 1 - M^2 + i\, \upsilon\, M \,]$$

with $M = (\mathbf{k}\ .\ \mathbf{v}) / (k_{perp}\, c_s)$ and damping υ

Laser beam deflection :

- M<1 subsonic flow : no efficient beam deflection, only close to M ~ 1

- M>1 supersonic flow : the laser beam is gradually deviated downstream

- M~1 sonic flow : beam bending (→CBET flat beams) over a resonance zone

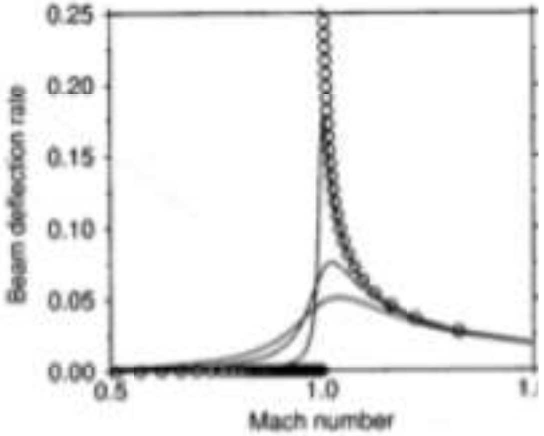
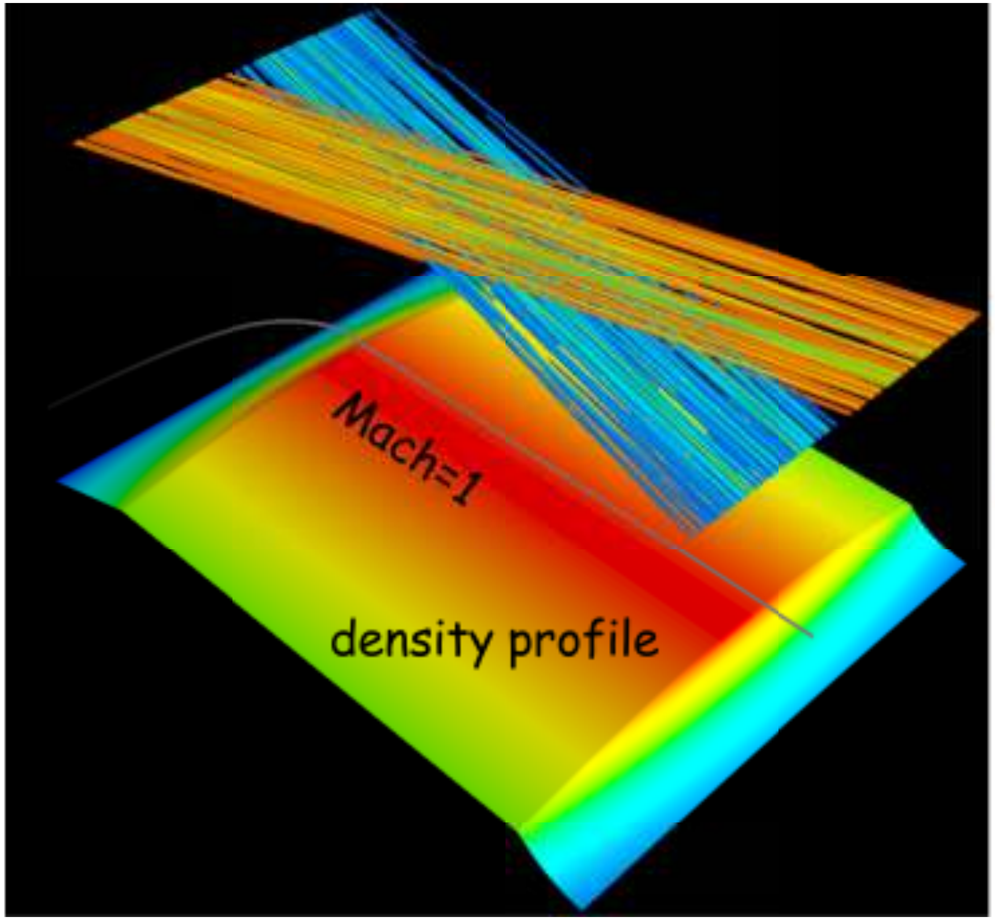


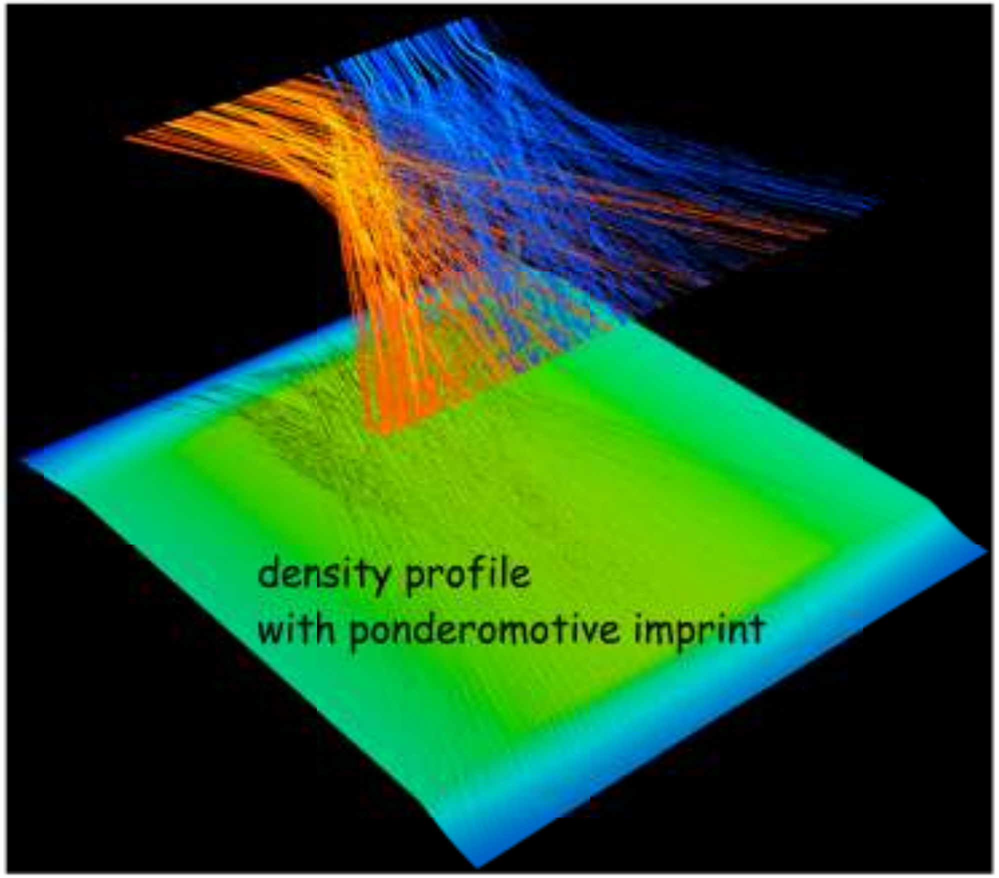
FIG. 5. The beam deflection for the Gaussian potential, D_{Gauss}, in the
ence (solid lines) of Landau damping (γ_L=0.01,0.05,0.1) and in the
sence (open circles) of Landau damping (β=0.1).

Deflection of optically smoothed laser beams:
case of inhomogeneous transverse flow with sonic layer:
Cross beam energy transfer CBET

early



late



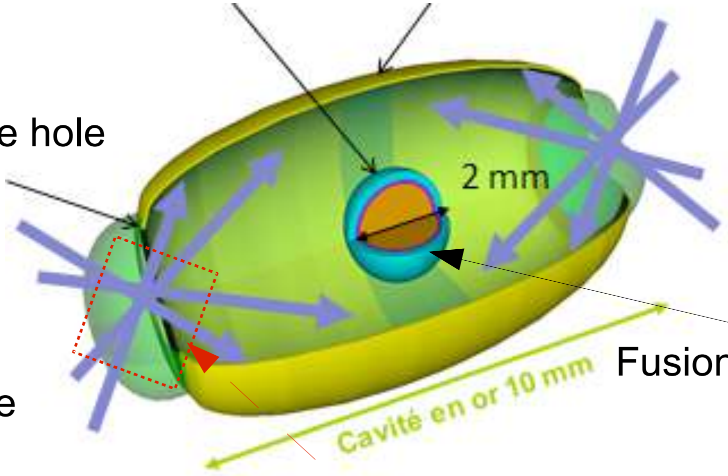
Inhomogeneous density- and flow profile, with flow u = (-.5 …. +1.5) x sound speed

Cross-beam energy transfer (CBET)

Crossed beam energy transfer appears in Laser fusion drive schemes:

- the underlying process is stimulated Brillouin scattering (in the plasma corona with flow at Mach=+/- 1)

Indirect drive
Several beams at the entrance holes, in cones, angles in between crossing beams are 20-60deg



Hohlraum entrance hole

Incident beams:
Each beam with
Speckle structure

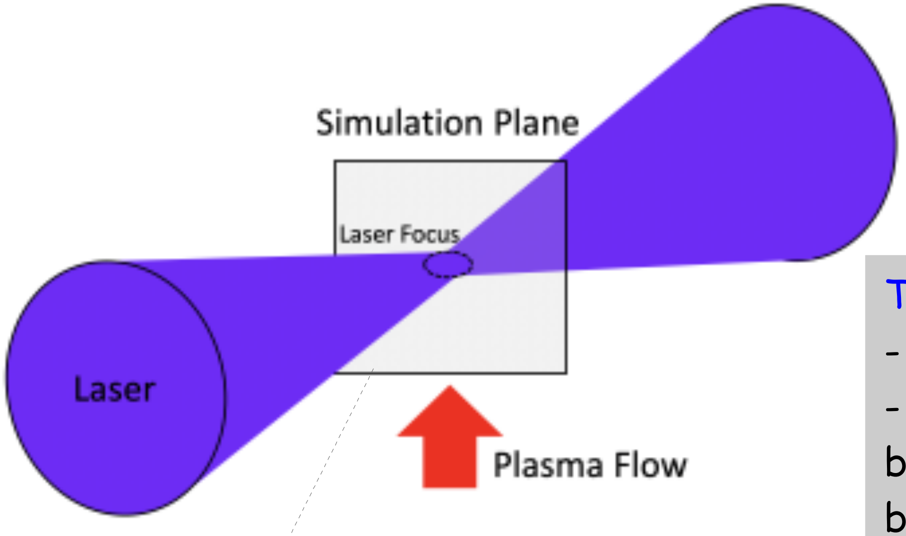
Fusion DT capsule

Crossing zone

Deflection of an optically smoothed laser beam by transverse flow; plasma response in the focal plane for slightly supersonic flow;

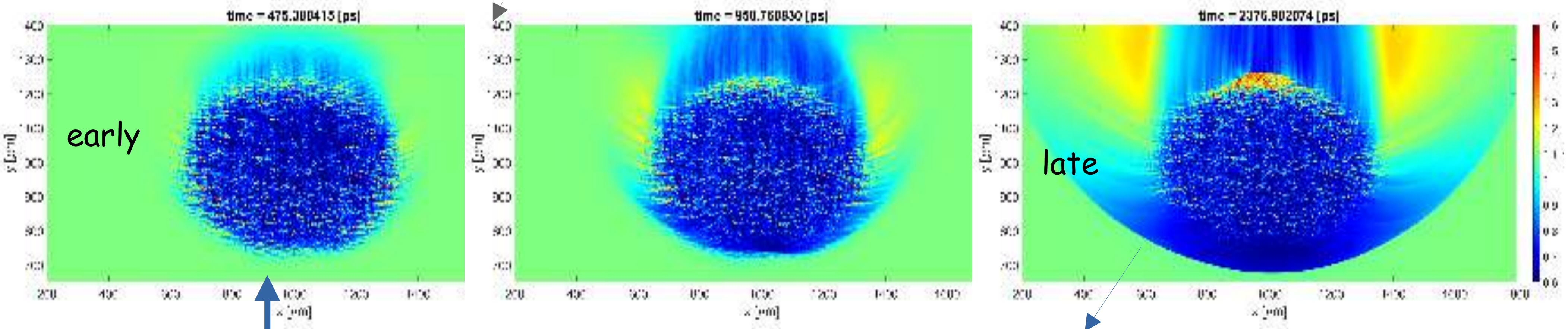
shock outbreak in the focal area

Crossing, smoothed Laser beams



Two aspects :

- laser beam deflection itself
- modification of the hydro motion by both ponderomotive drive and beam deflection



Incoming weakly supersonic flow (here M=1.1)

Shock outbreak

Deflection of an "optically smoothed" laser beam (with speckles) in presence of transverse flow

H.A. Rose, Phys. Plasmas **3**, 1709 (1996); S. Ghosal, H.A. Rose, Phys. Plasmas **4**, 4189 (1997); **4**, 2376 (1997).

The beam is deflected by averaging over the contributions from the laser speckles:

Average laser beam deflection rate for RPP, θ being the angle between beam direction and z axis
< > : averaging over laser speckle ensemble:

$$\frac{\partial}{\partial z}\left\langle \frac{k_\perp}{k_0}\right\rangle = \frac{\partial\langle\theta\rangle}{\partial z} = -\frac{1}{2}\frac{n_0}{n_c}\left\langle \vec{\nabla}_\perp \frac{\delta n}{n_0}\right\rangle$$

From linearized, isothermal hydrodynamics, under the influence of the pondermotive potential of the beam speckles:
$M = u/c_s$: Mach number

$$\frac{d\langle\theta\rangle}{dz} = \frac{128}{45}\frac{\langle n\rangle}{n_c}\frac{1}{F\lambda}\frac{\langle U\rangle}{T_e} f\left(M, \nu_{ia}\right)$$

magnitude of the
Ponderomotive pontential

$$\frac{U}{T_e} = 0.09\left(\frac{\lambda}{\mu m}\right)^2\left(\frac{I}{10^{15}W/cm^2}\right)\left(\frac{keV}{T_e}\right),$$

for example:

$I = 1\text{x}10^{16}\,W/cm^2$
$\lambda = 0.351\mu m$
$T_e = 5keV$

$$\frac{U}{T_e} \approx 0.02$$

Deflection of an "optically smoothed" laser beam (with speckles) in presence of transverse flow

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Average laser beam deflection rate for RPP:

$$\frac{d\langle\theta\rangle}{dz}=\frac{128}{45}\frac{\langle n\rangle}{n_c}\frac{1}{F\lambda}\frac{\langle U\rangle}{T_e}f(M,\nu_{ia})$$

$$f(M,\nu_{ia})=\frac{2}{\pi}\int_0^{\frac{\pi}{2}}\frac{M\,\nu_{ia}\cos(\theta)^2}{(1-M^2\cos(\theta)^2)^2+4M^2\nu_{ia}^2\cos(\theta)^2}\,d\theta$$

For small damping $\nu\to 0$:

subsonic M<1 : $f\to 0$

supersonic M>1 : $f\to 1/(2M(M^2-1)^{1/2})$

sonic M=1 (singular): f is integrable → CBET.

- Effect is enhanced with U/T and for small size speckles (as would appear with crossed beam reduction in F)

By momentum conservation : beam deflection by the collective action of many laser speckles slows down the flow velocity → shock formation

H.A. Rose, Phys. Plasmas **3**, 1709 (1996); S. Ghosal, H.A. Rose, Phys. Plasmas **4**, 4189 (1997); **4**, 2376 (1997).

Transition from supersonic flow, M>1, to subsonic, M<1, leads to shock formation

Isothermal hydrodynamic equations in 2D, in a plane transverse to the laser beam direction,

$$\frac{\partial \vec{p}_\perp}{\partial t} + \vec{\nabla}_\perp \cdot (\vec{v}_\perp \vec{p}_\perp) = -c_s^2 \vec{\nabla}_\perp \rho - c_s^2 \rho\, \nabla_\perp \left(\frac{U}{T_e}\right),$$

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}_\perp \cdot \vec{p}_\perp = 0,$$

Stationary solution to the hydro equations,

$$\frac{90}{256}\frac{d}{dy}\left(M+\frac{1}{M}\right) = -\frac{1}{f_\# \lambda}\left(\frac{\langle U\rangle}{T_e}\right)^2 \frac{1}{M^2\sqrt{M^2-1}}$$

yields the distance needed to slow down the flow from M>1 to subsonic flow inside the beam, i.e. where the ponderomotive potential Up >0

Sonic flow, $M = 1$ is reached at $y = y_{\text{sonic}}$

$$\frac{y_{sonic}}{y_p} = \frac{90}{256}\int_1^M (u^2-1)^{3/2} du$$

scaling length $y_p = f_\# \lambda / (\frac{\langle U\rangle}{T_e})^2$.

$$= \frac{90}{2048}\left(M(2M^2-5)\sqrt{M^2-1} + 3\ln\left[2(\sqrt{M^2-1}+M)\right]\right)$$

Beam deflection introduces fluctuations in the ponderomotive force term, that produces drag term ~ α in linearized hydro

$$\frac{\partial\langle\vec{p}_\perp\rangle}{\partial t} + \vec{\nabla}_\perp \cdot (\langle\vec{p}_\perp\rangle\langle\vec{v}_\perp\rangle) = -\alpha\langle\vec{p}_\perp\rangle - c_s^2\langle\rho\rangle\nabla_\perp\left(\ln\langle\rho\rangle + \frac{\langle U\rangle}{T_e}\right)$$

$$\frac{\partial\langle\rho\rangle}{\partial t} + \vec{\nabla}_\perp \cdot (\langle\rho\rangle\langle\vec{v}_\perp\rangle) = 0,$$

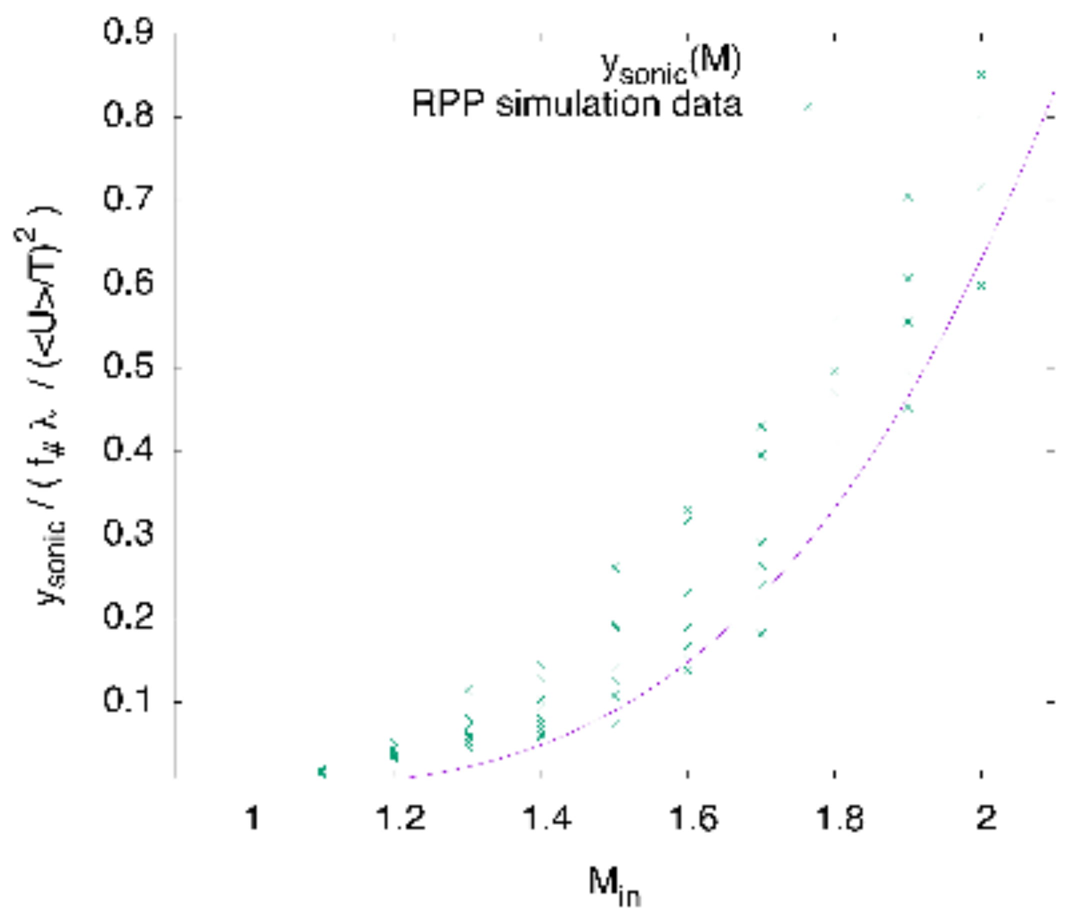
drag coefficient

$$\alpha = 2\frac{\langle U\rangle}{T_e}\frac{n_c}{\langle n\rangle}c_s\frac{1}{M}\frac{\partial\langle\theta\rangle}{\partial z} = \frac{256}{45}\left(\frac{\langle U\rangle}{T_e}\right)^2\frac{c_s}{F\lambda}\frac{f(M,\nu_{ia})}{M}$$

$$\frac{d\langle\theta\rangle}{dz} = \frac{128}{45}\frac{\langle n\rangle}{n_c}\frac{1}{F\lambda}\frac{\langle U\rangle}{T_e}f(M,\nu_{ia})$$

Distance y_{sonic} inside de the speckle pattern of an RPP beam at which the incoming flow is slowed down to M=1: comparison simulations vs. model from linear hydro

×



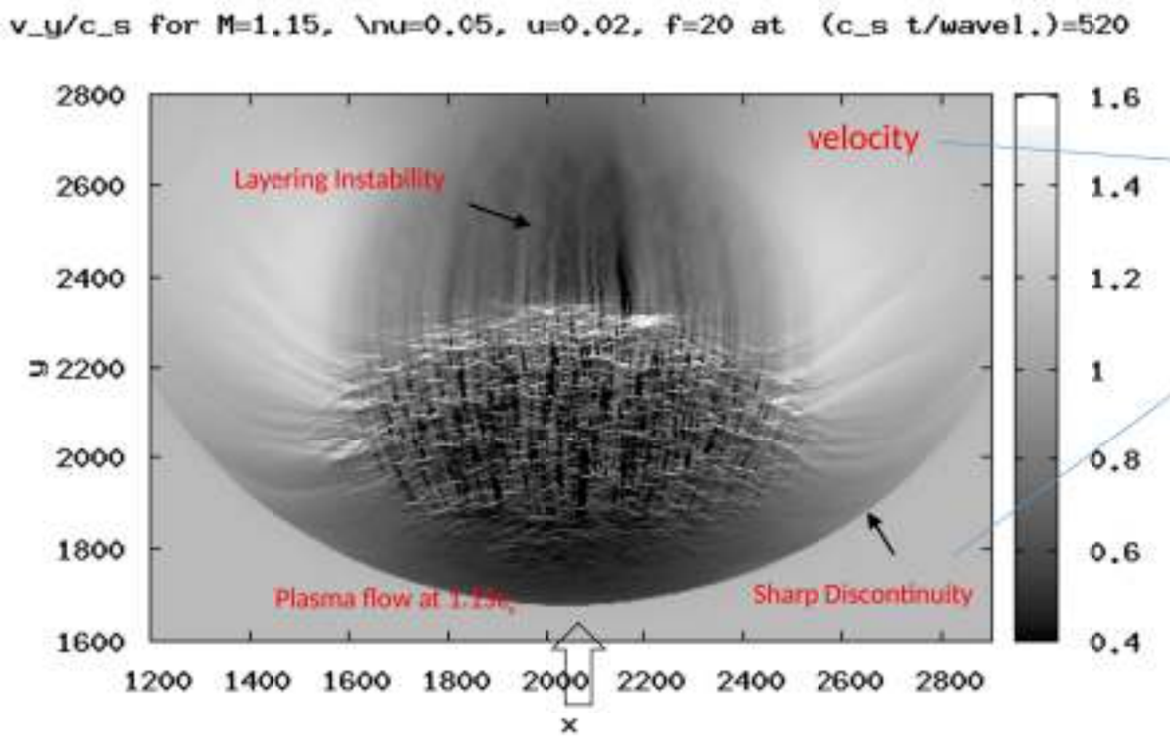
- RPP beam is effective in slowing down the transverse flow even for .
- y_{sonic} is a distance along the flow direction from the edge of a laser spot to plasma flow velocity: $v_y(y_{sonic})<c_s$ (M<1)

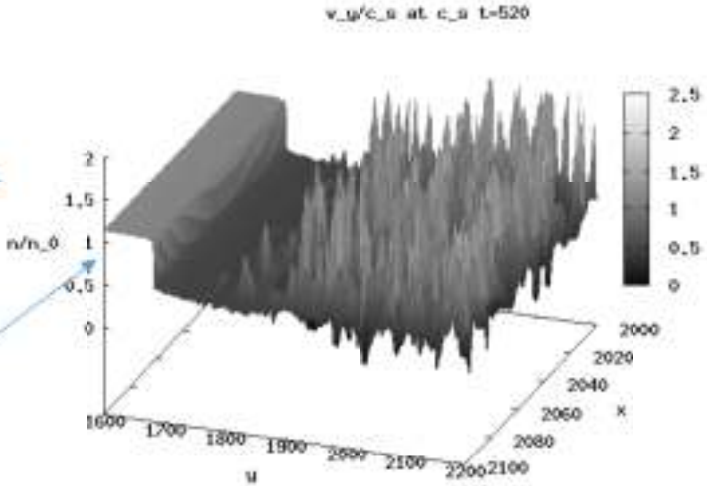
$I=2\ 10^{15}$ W/cm^2, T_e=3keV, n_0/n_c=0.1
c_s=5 10^7 cm/s
boundary layer: M_0 c_s/ M_0 1 mm (F/8)
time rate: =2 ns
e.g. normalized y_{sonic} = 0.1   y=F 0.64 mm

→

Bow shock formation seen in nonlinear hydro simulations

Transition from supersonic flow, M>1, to subsonic, M<1, leads to shock formation



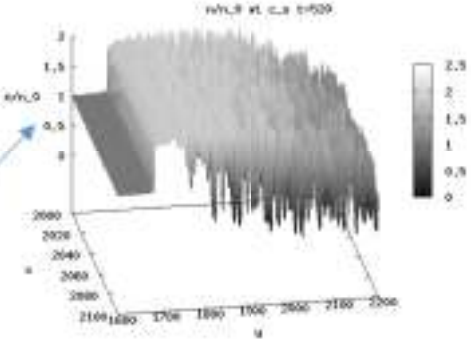


U/T_e=0.02

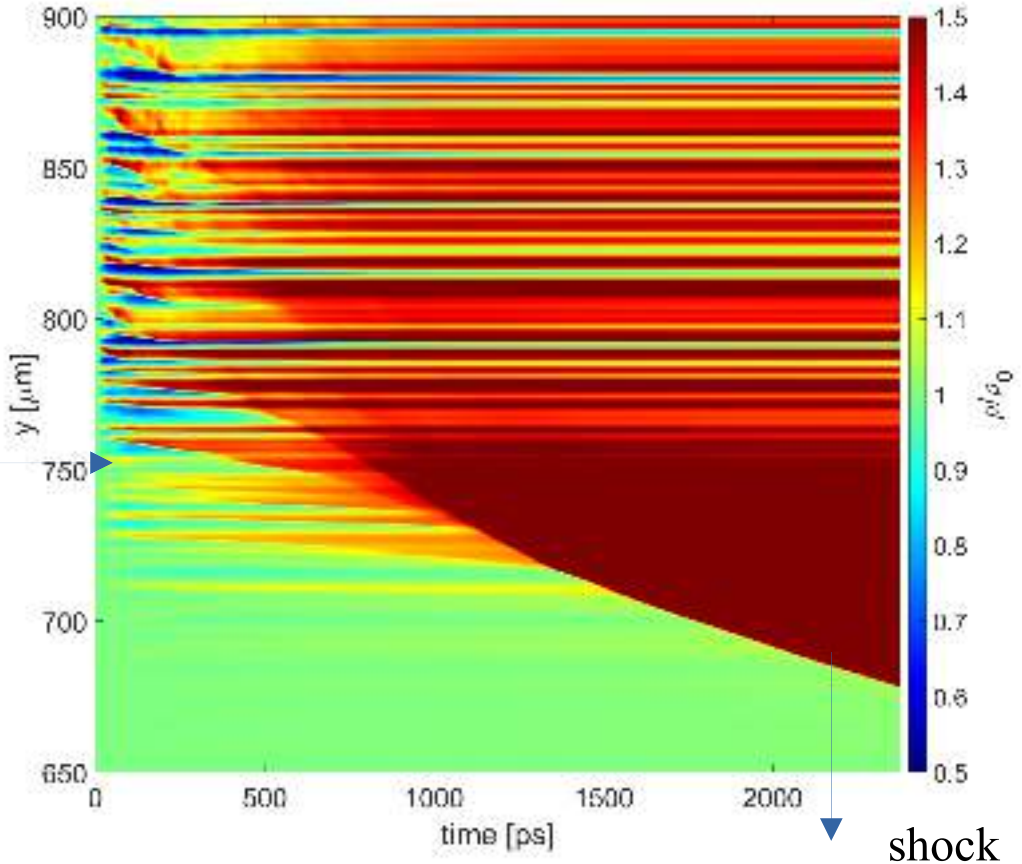
v_y/c_s=1.15

Fλ=7.02

free propagating shock in density perturbation:



Temporal dynamics of the shock outbreak seen in the central cut of the beam cross section



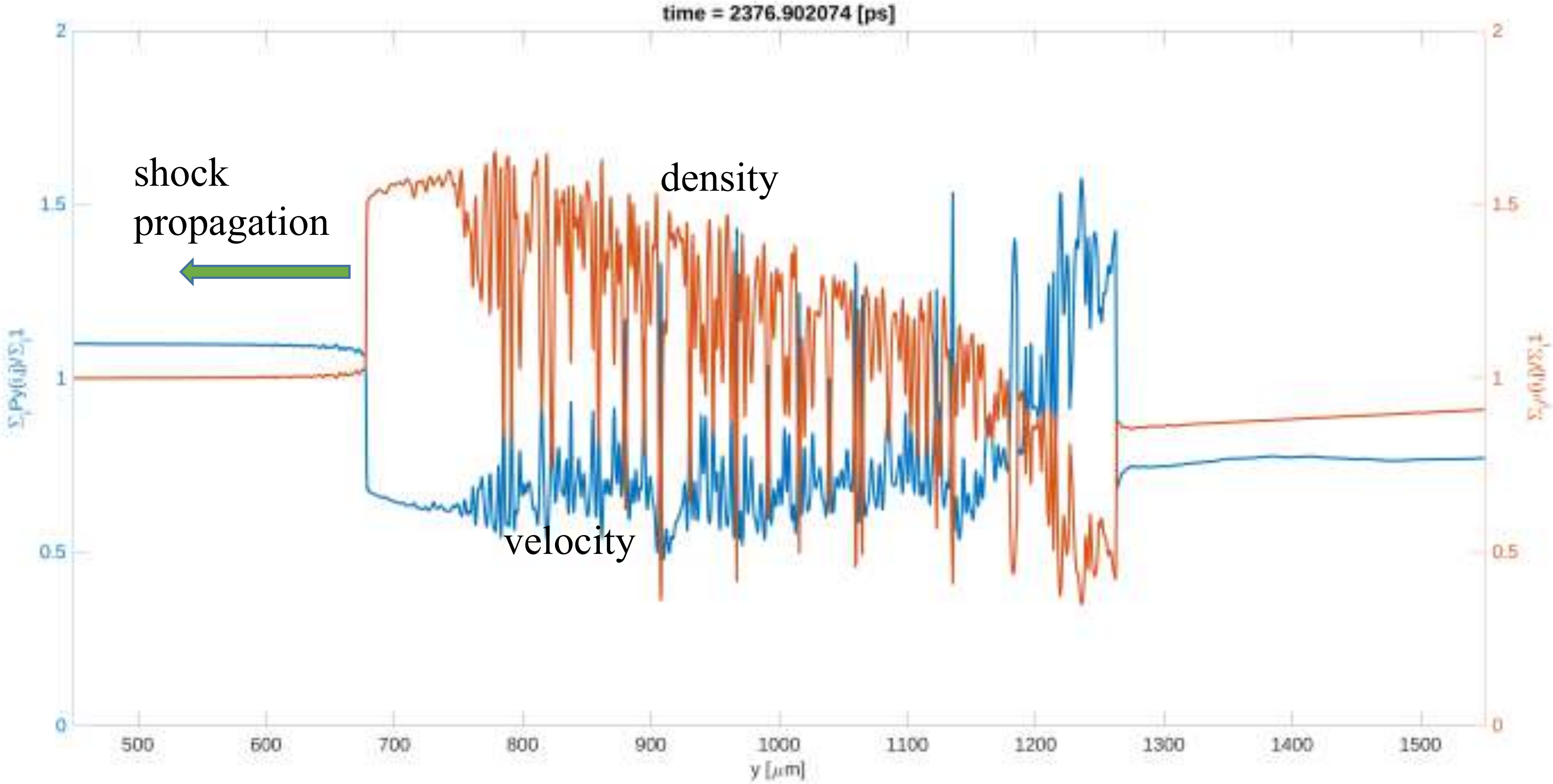
y_{sonic}

Incoming supersonic flow

shock propagation

Shock outbreak:
central cut of the beam cross section from nonlinear hydro simulations

- (U/T_e=0.13, M=1.1, F/6)

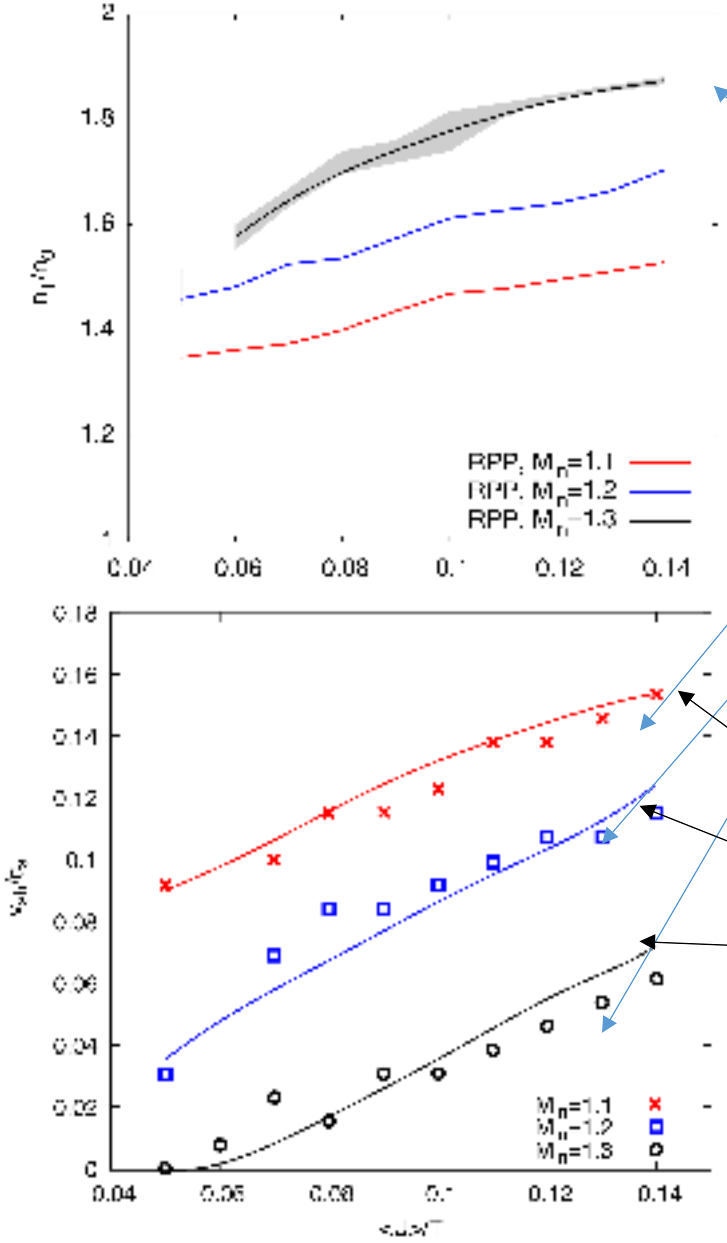


shock
propagation

density

velocity

Density jump and Shock velocity across the shock: summary of simulation series compared to semi-analytical theory



Results of nonlinear hydrodynamic simulations for freely propagating shocks, i.e. outside the laser beam cross section.

Simulation data for density and flow across the shock front fulfill the Rankine-Hugoniot relations:

- the density jump across the shock and
- the shock speed (lab frame) increase with <U>/T

For higher incoming, supersonic flow M_{in}

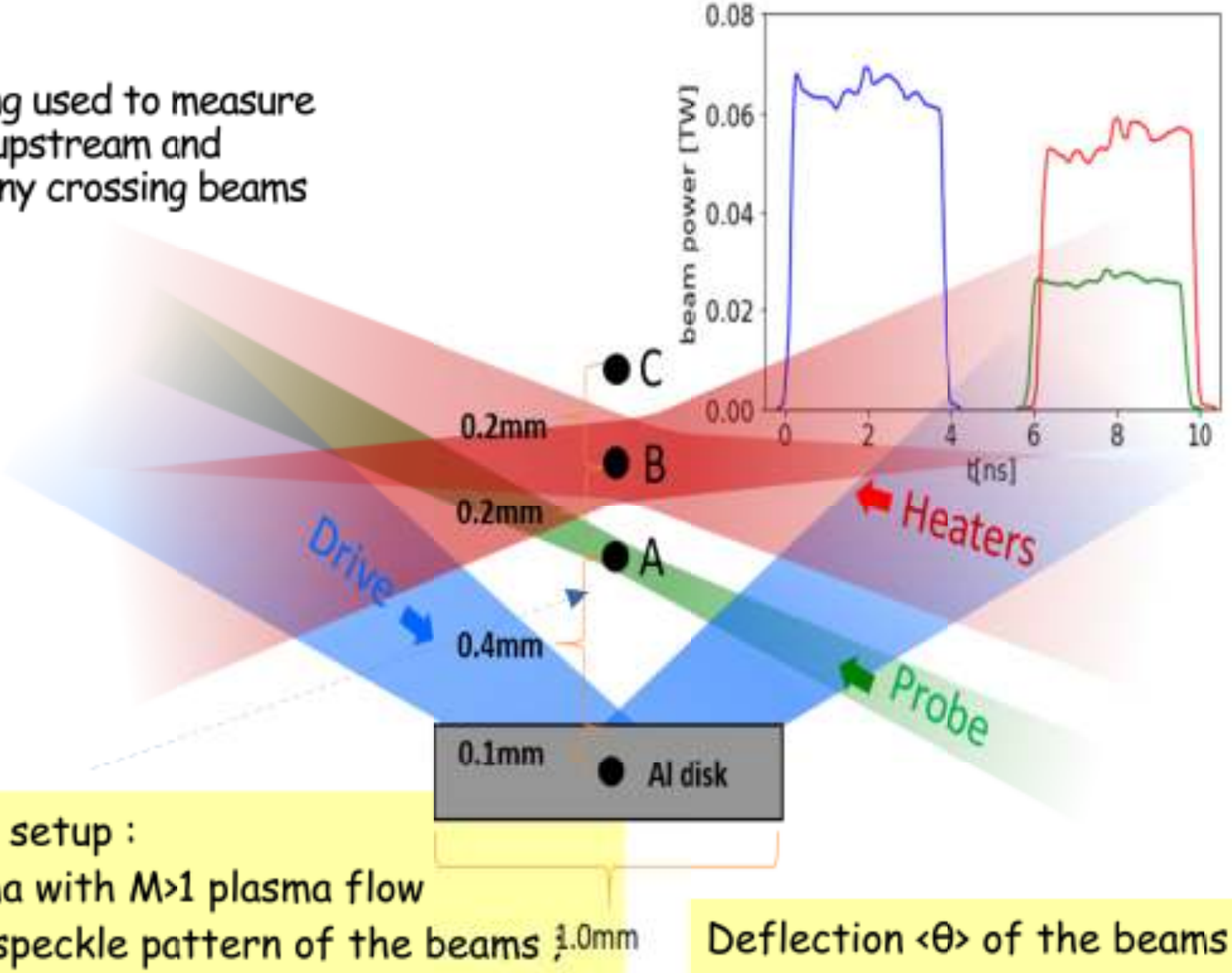
- the density jump is stronger but
- the shock speed tends to smaller values,
- eventually inhibiting shock outbreak for too high M_{in}

Analytic expression linking Hugoniot relations to the ponderomotive potential

$$\frac{v_{sh}}{c_s} = M_{in} - \frac{u_0}{c_c} = M_{in} - \frac{\ln\left(\frac{n_1}{n_0}\right)^2 + \frac{2\,\Delta\langle U\rangle}{T_e}}{1-\left(\frac{n_0}{n_1}\right)^2}$$

Experimental setup on the Omega laser facility
LLE, University of Rochester

Thomson scattering used to measure plasma conditions upstream and downstream of many crossing beams



18 crossing beams
6.0 to 9.7 ns

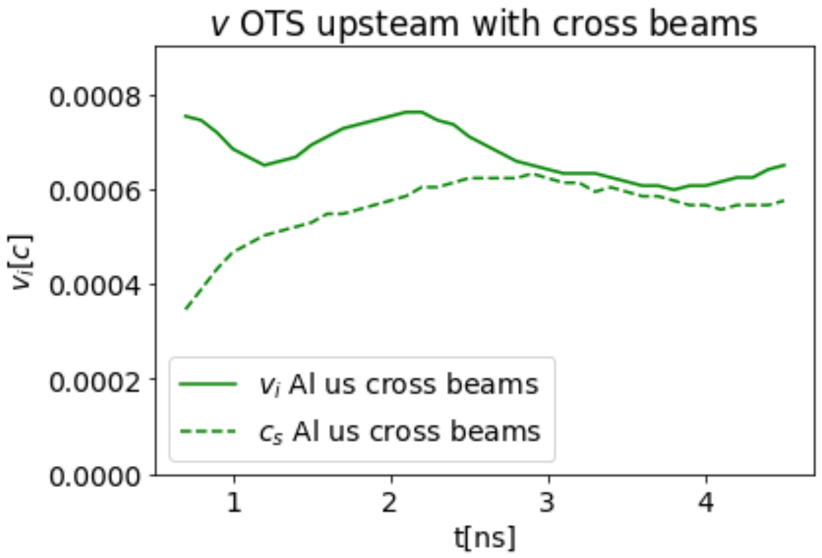
OTS probe
5.8 to 9.5 ns

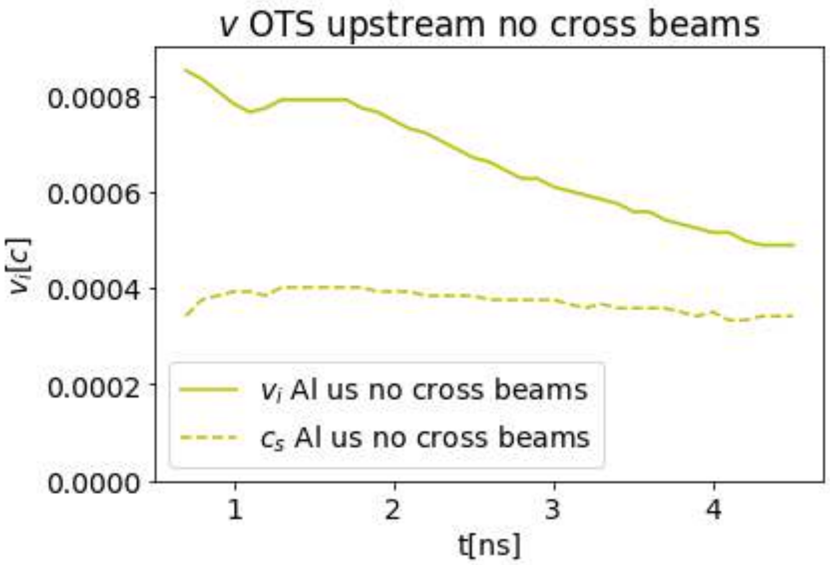
Objective of the setup :
Generate a plasma with M>1 plasma flow running into the speckle pattern of the beams ;
The ponderomotively driven shock should run into the upstream region.

Deflection <θ> of the beams due to the collective Effect to which speckles contribute should be measurable behind

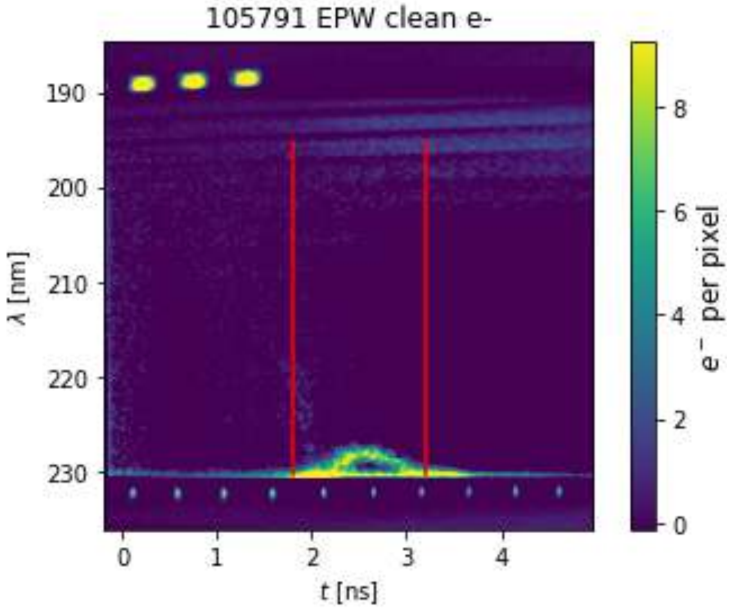
Preliminary results from experiments on the Omega laser facility

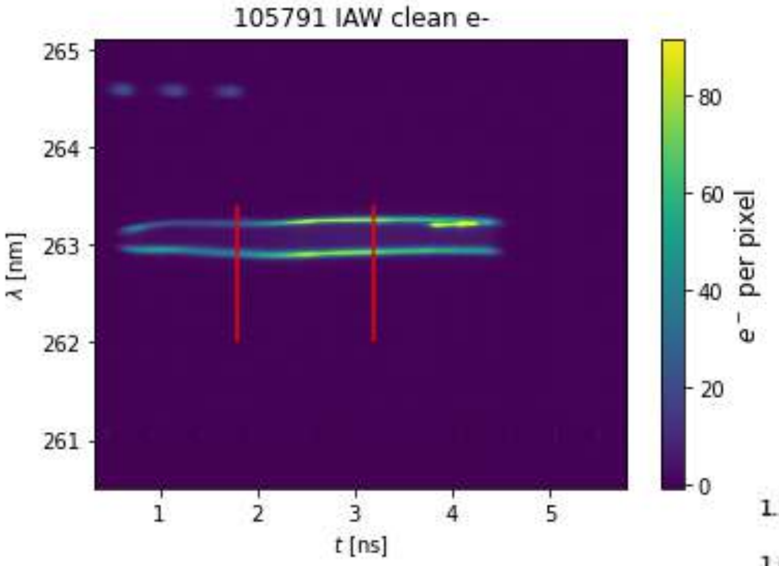
Summary of flow velocities in Al shots





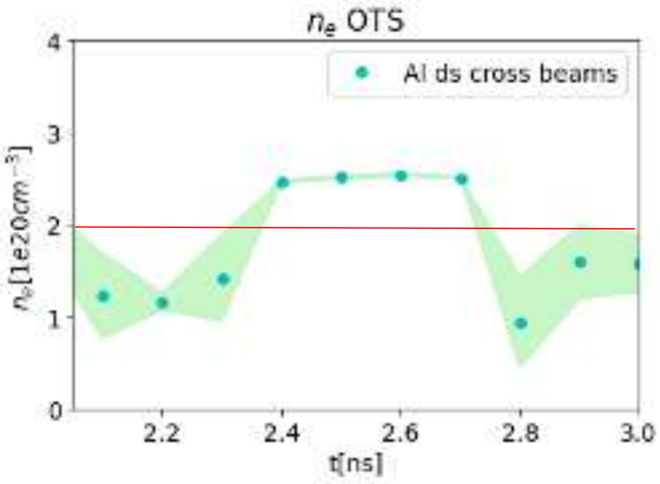
Preliminary results from experiments on the Omega laser facility
Upstream OTS measurements – shock signatures

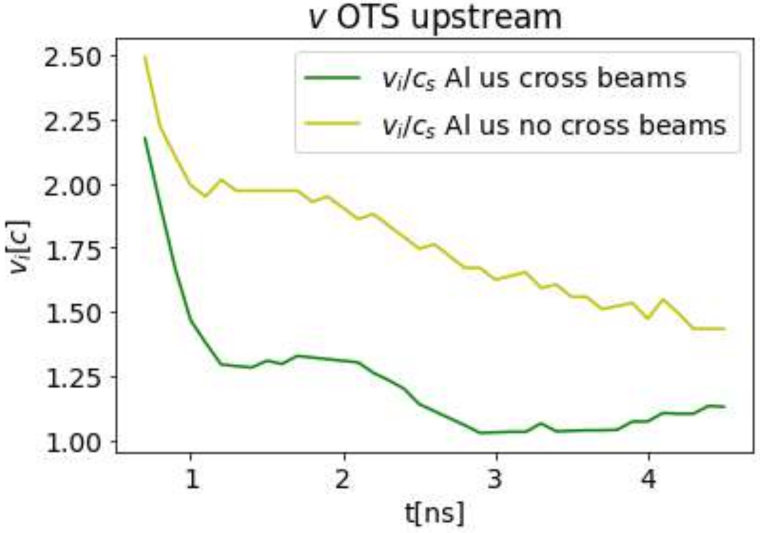




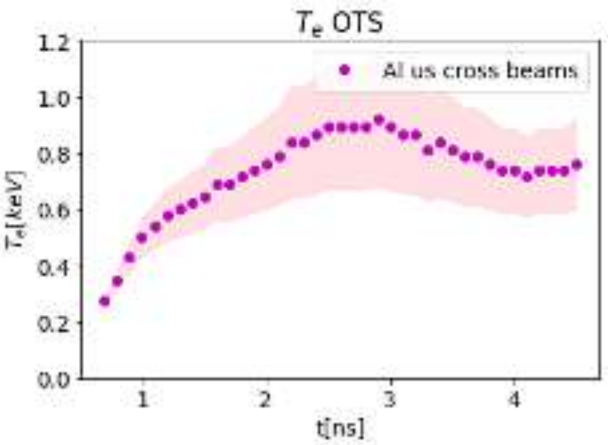
IAW spectra allow on the accurate flow velocity and T_e measurements. Note enhancement of the signal consistent with the density jump.

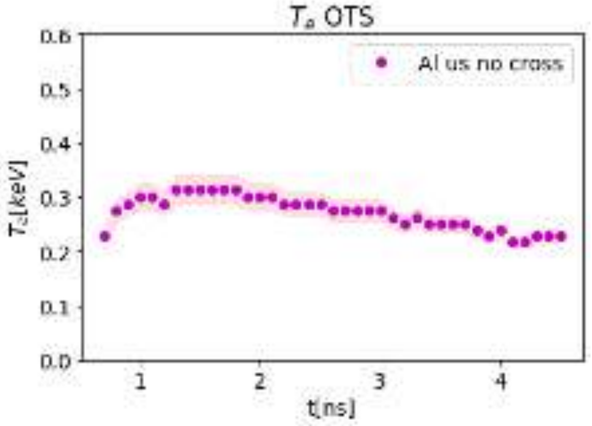
Instrumental limits on the spectral range of the EPW measurement restricts density enhancement (above red line)





Flow velocity normalized to sound speed includes heating due crossing beams.



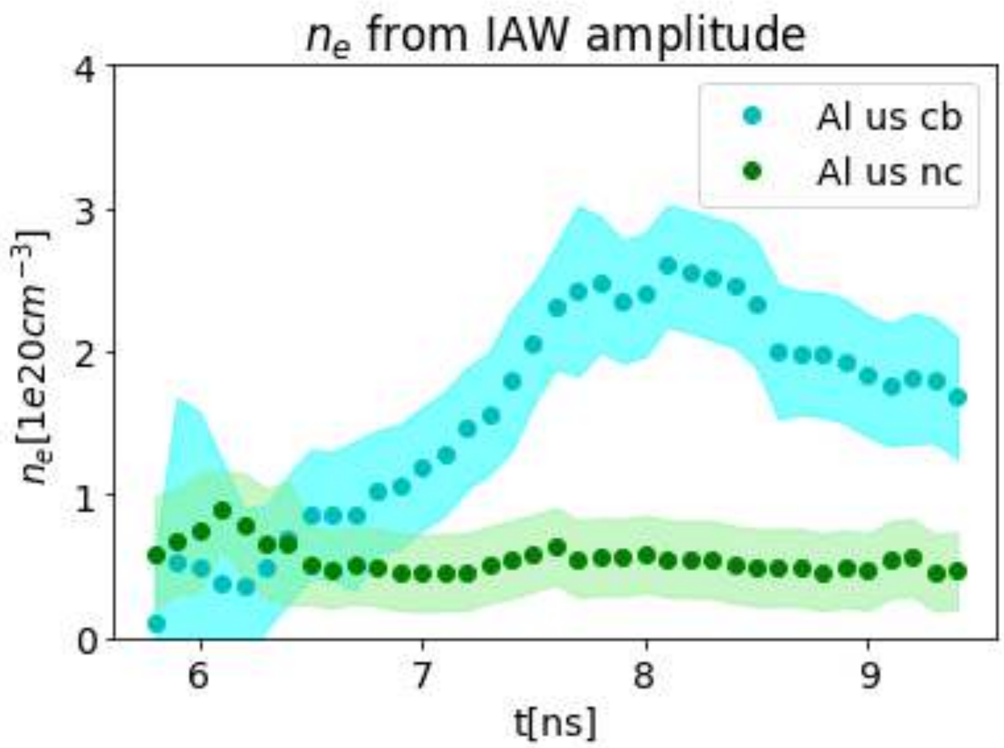


Preliminary results from experiments on the Omega laser facility

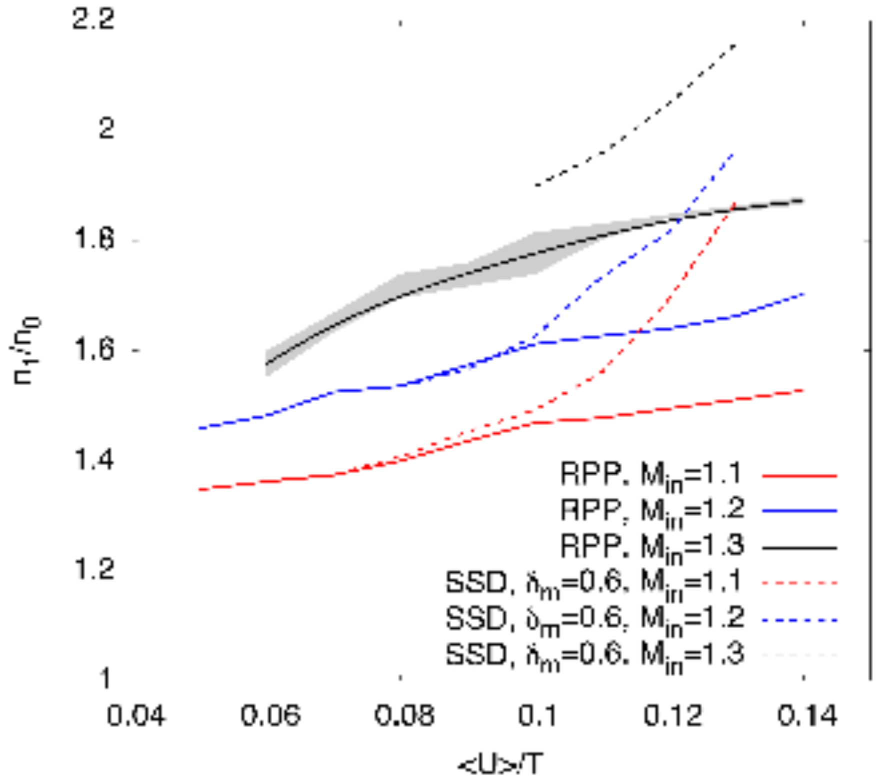
Upstream optical Thomson scatt. (OTS) measurements : density enhancement seen in presence of crossing beams

Careful analysis of the IAW spectrum confirms:

- density enhancement is consistent with the upstream shock propagation.
- no such enhancement is seen in the reference shot without crossing beams.
- the ion acoustic wave spectrum can be used for a density measurement, based on the intensity of the scattered light ~ n_e.



Impact of spatio-temporal smoothing (SSD) in comparison with RPP only: density jump and Shock velocity across the shock



Density jump, n_1/n_0 over the shock as a function of the average value of the ponderomotive potential $\langle U \rangle / T_e$

Summary and outlook

Ponderomotively driven shock waves running against transverse supersonic flow should arise from the central region of optically smoothed crossing beams

The beams are progressively deflected by the collective ponderomotive action of the beam speckles

The effect increases with the average ponderomotive potential <U>/T of the beam overlap, but shock outbreak may be inhibited for too high M_{in} values

With spatio-temporal smoothing (SSD) the effects persist

First experiments on OMEGA (LLE Rochester), via OTS, have evidenced the density enhancement in the upstream region

A campaign on NIF with similar setup, but higher beam intensity is scheduled for this summer