Ultra-intense laser-plasma interaction toward collisionless shocks formation

Anna Grassi

17 October 2016

Shock waves

Relativistic jets from Active Galactic Nuclei

Supersonic aircraft

A shock wave is characterised by a nearly discontinuous change in pressure, temperature and density of the medium.

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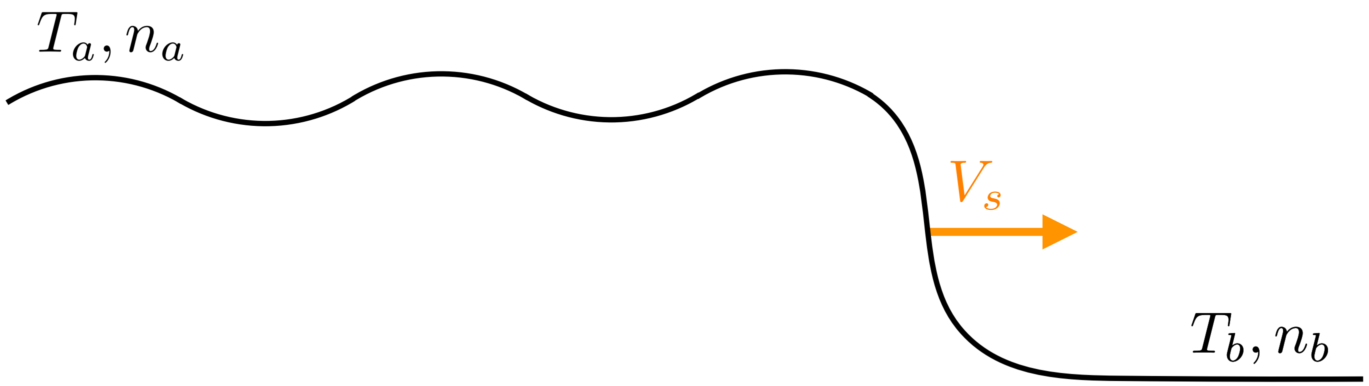

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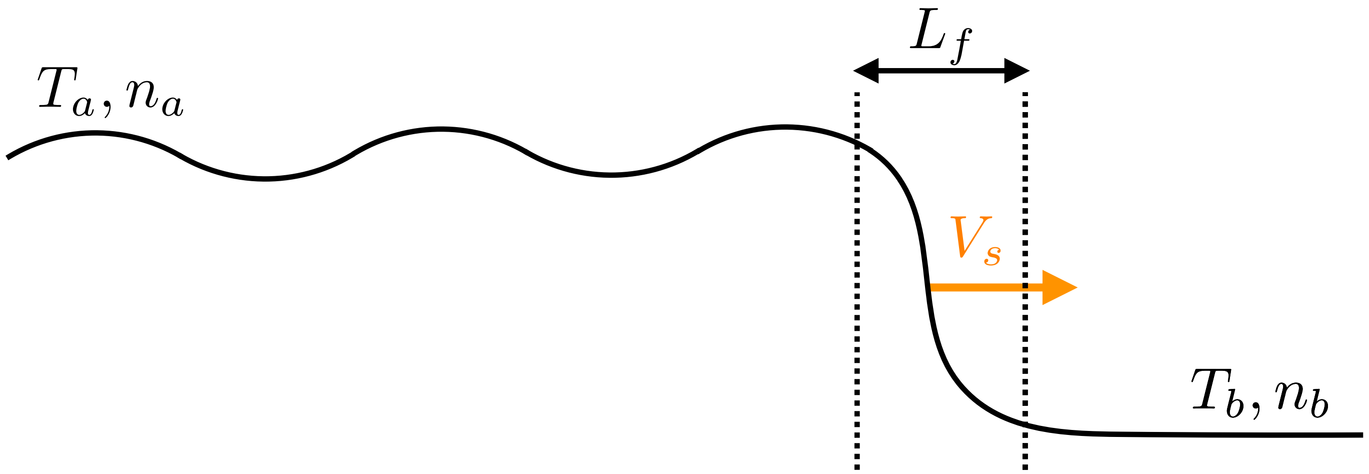

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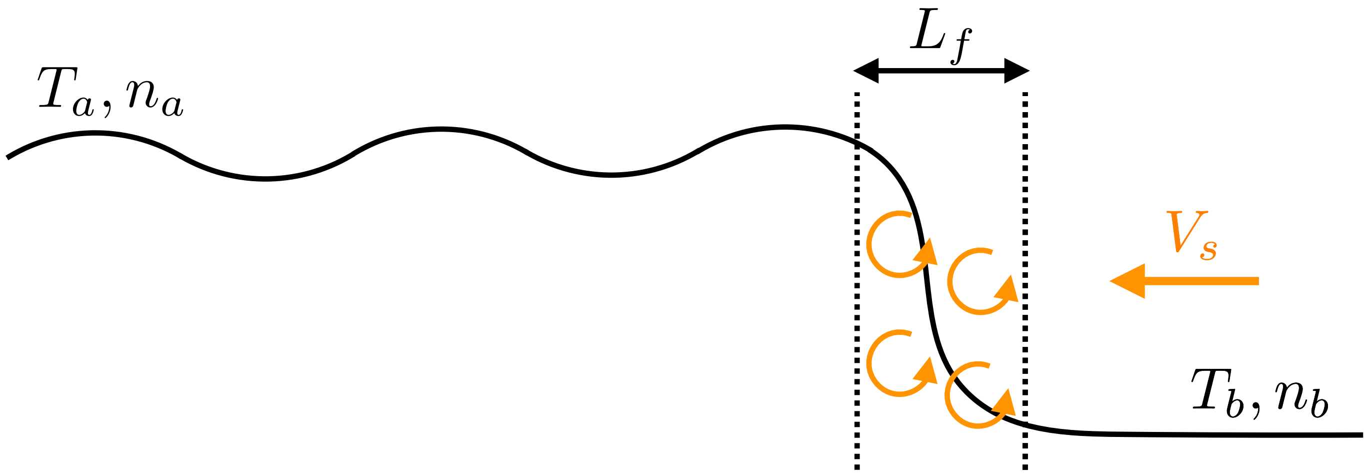

In the shock front frame

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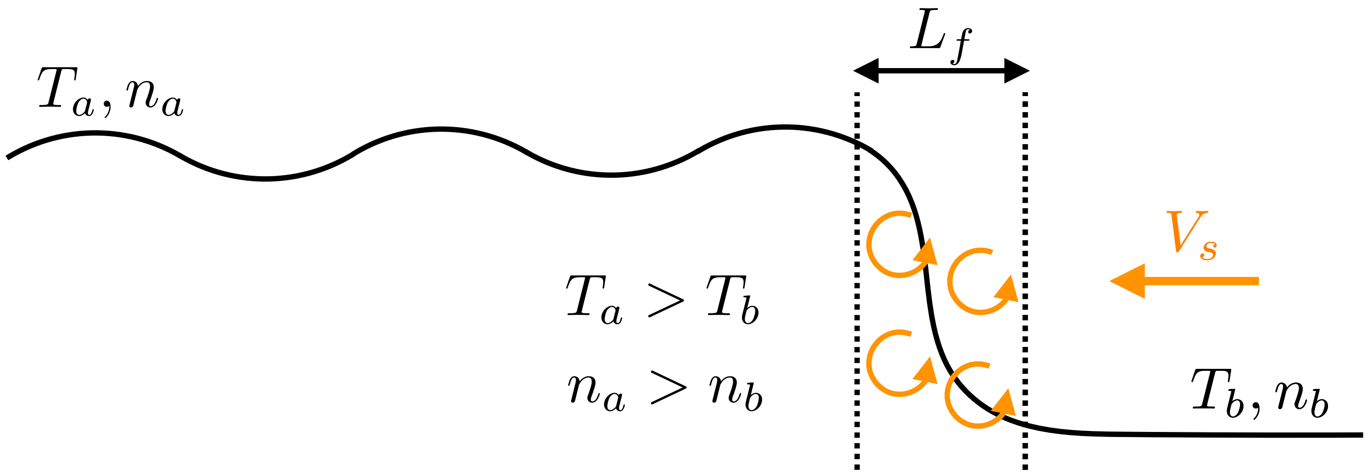

In the shock front frame

At the shock front
there is a fast isotropization
of the incoming flow

Shock waves

Relativistic jets from Active Galactic Nuclei

Supersonic aircraft

A shock wave is characterised by a nearly discontinuous change in pressure, temperature and density of the medium.

What is the main difference between these shocks ?

Mechanism acting at the shock front

What is the difference between these shocks ?

Supersonic aircraft

Relativistic jets from Active Galactic Nuclei

The shock front is mediated by :

	Collisions	Magnetic turbulence

Typical scale length of the shock front :

	$L_f \simeq \lambda_{mfp}$	$L_f \simeq c/\omega_p \ll \lambda_{mfp}$

What is the difference between these shocks ?

Relativistic jets from Active Galactic Nuclei

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Electromagnetic collisionless shock

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Astrophysical collisionless shocks

Shock waves are common in astrophysical environments.

- Relativistic jets from Active Galactic Nuclei

  composition: ~ pair plasma

  velocity: γ~45

- SuperNova Remnants

  composition: ~ electron-ion plasma

  velocity: v~0.1c

Astrophysical collisionless shocks

Shock waves are common in astrophysical environments.

Collisionless shocks are associated with extremely high energy particle production.

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How we approach the problem ?

- No in-situ measurements
- Reproduce the shock in laser-plasma experiments
- Simulate the shock with Particle-In-Cell code

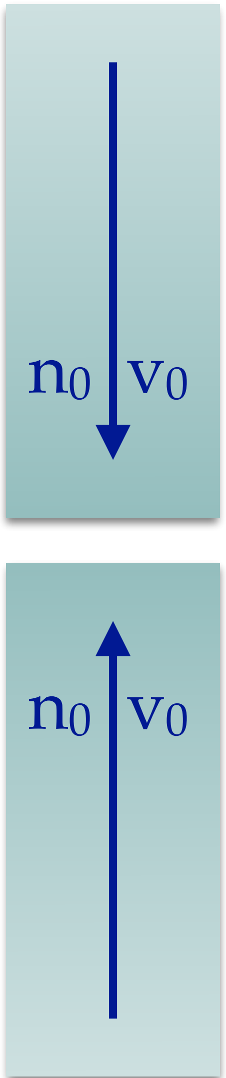
Outline

- What creates the magnetic turbulences ?
- How is the shock created ?

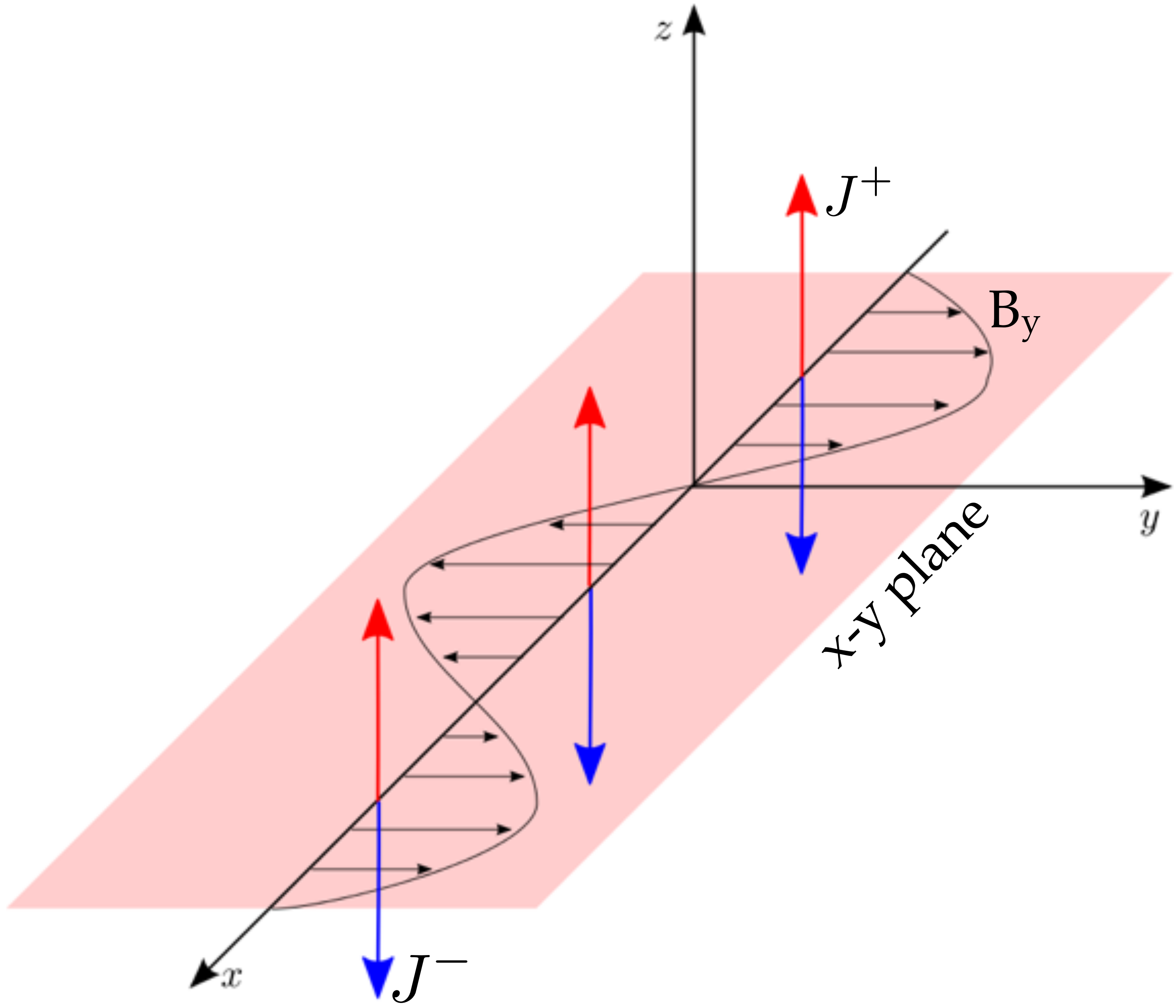
- Experiments currently investigated
- New proposal for future experiments

- Conclusion and perspective

Filamentation of current and magnetic field



- Instability driven by two relativistic counterstreaming beams.



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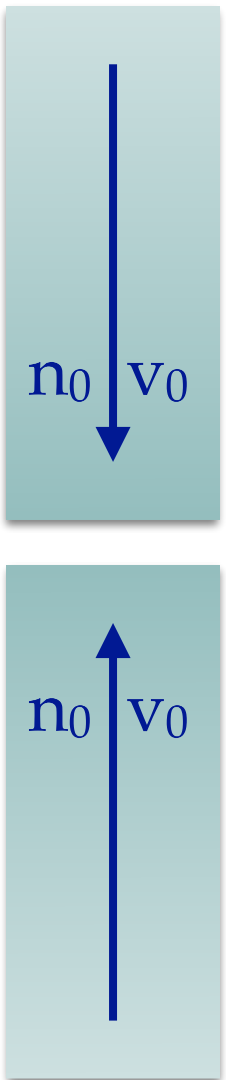

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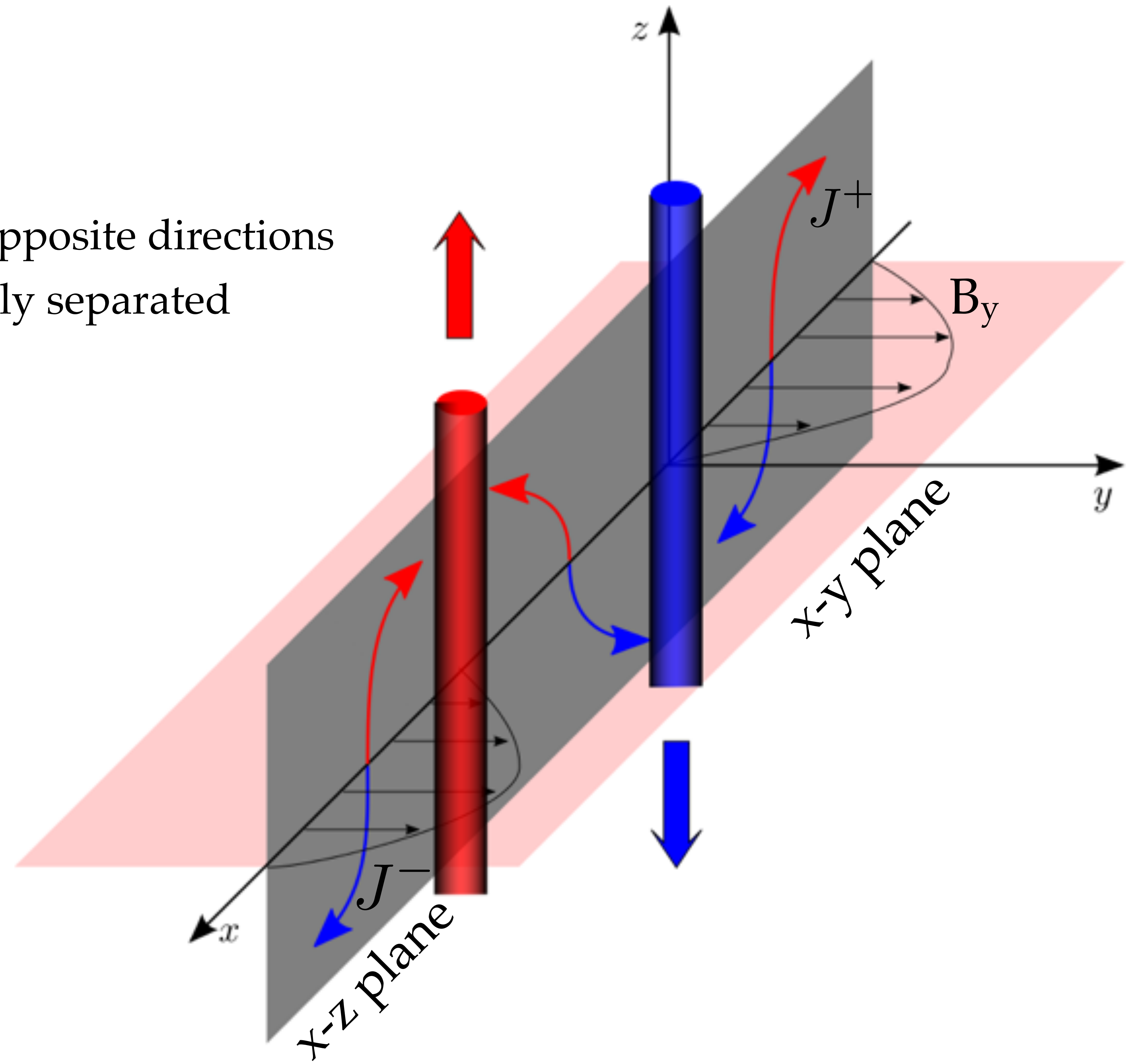
- Particles moving in opposite directions concentrate in spatially separated current filaments.



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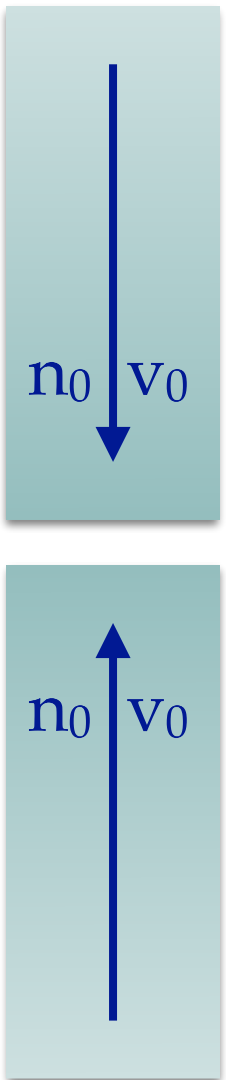
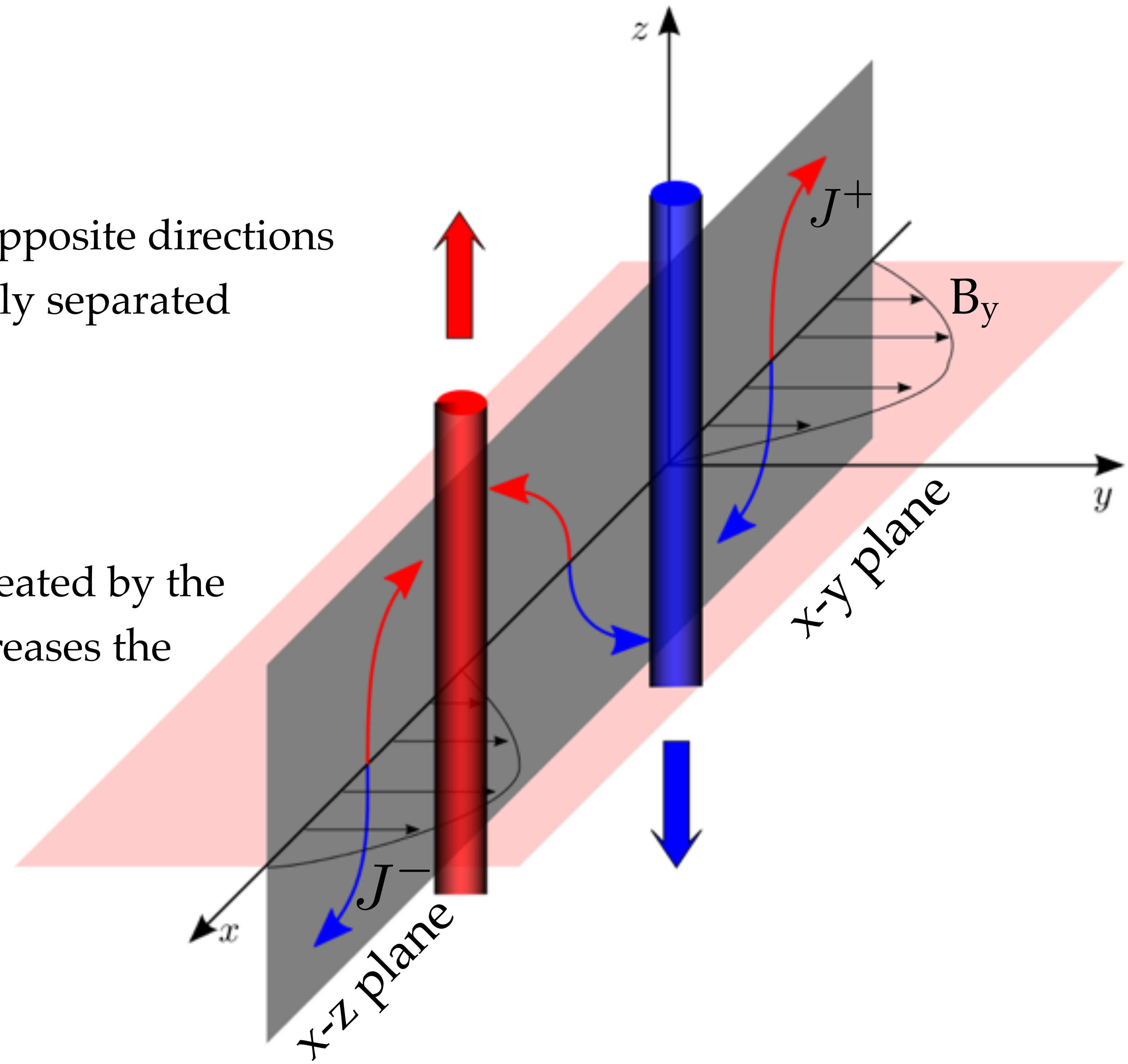
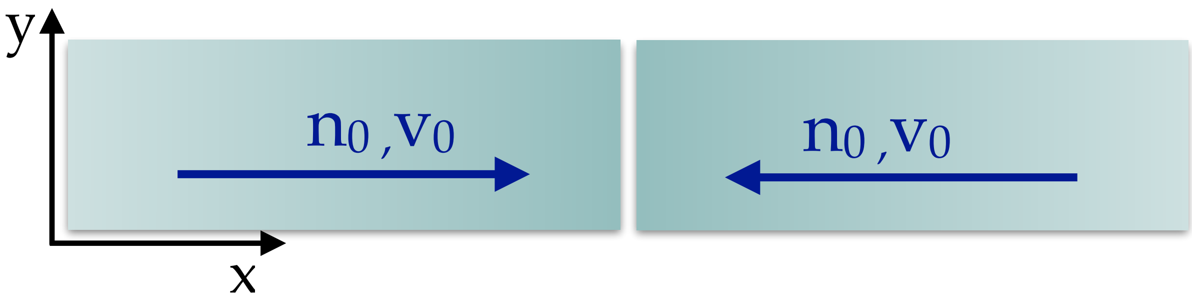


- Instability driven by two relativistic counterstreaming beams.
- Particles moving in opposite directions concentrate in spatially separated current filaments.
- The magnetic field created by the current filaments increases the initial perturbation.



From the turbulence to the shock formation

Counterstreaming beams



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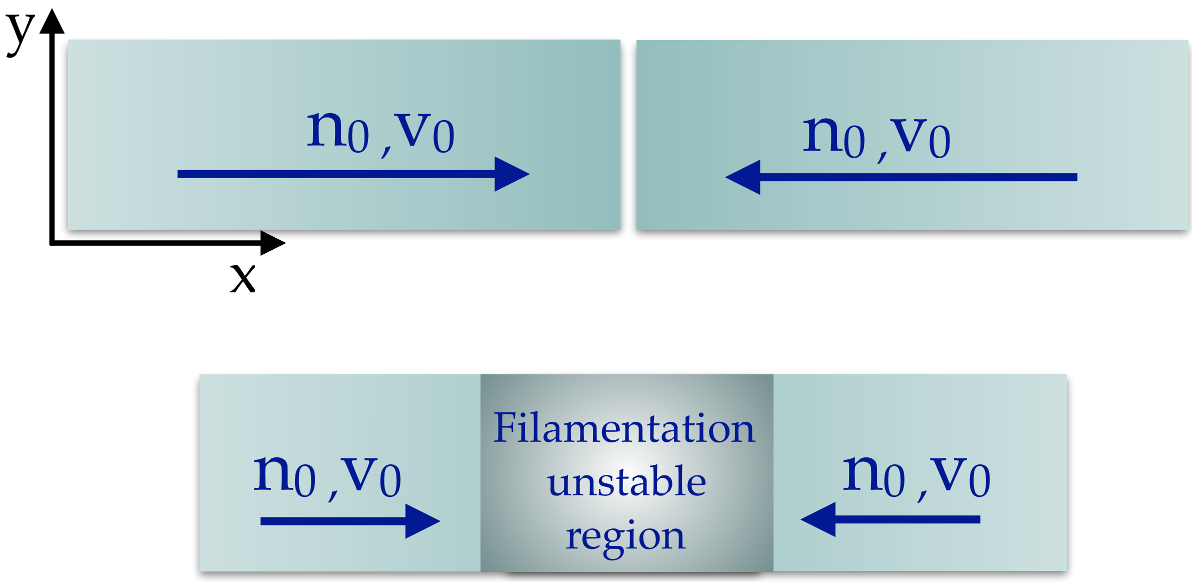

- The magnetic field generated
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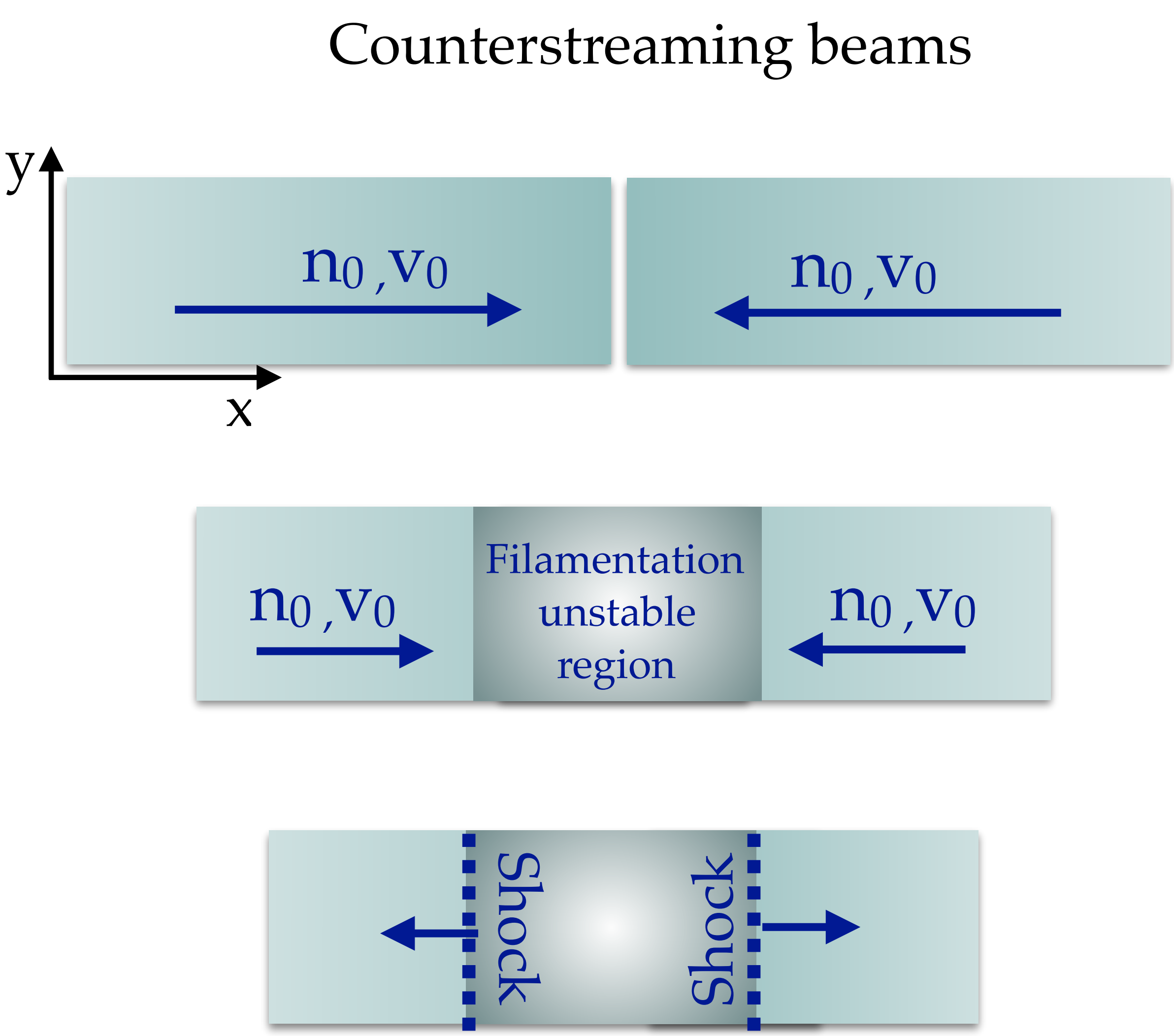
From the turbulence to the shock formation



- The magnetic field generated in the overlapping region stops the particles
- The density increases up to the Rankine-Hugoniot condition for a strong shock in 2D $\longrightarrow \frac{n_e}{n_0} = 3$

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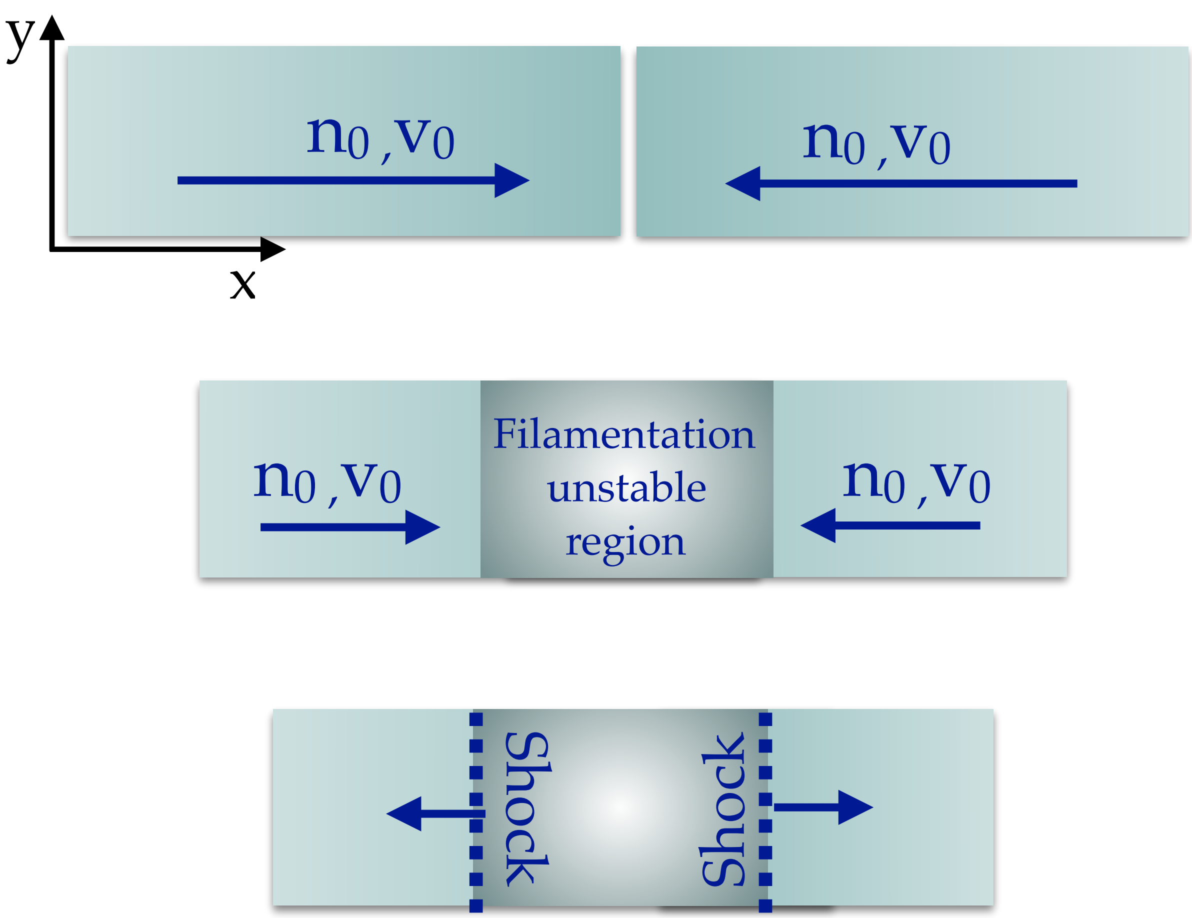
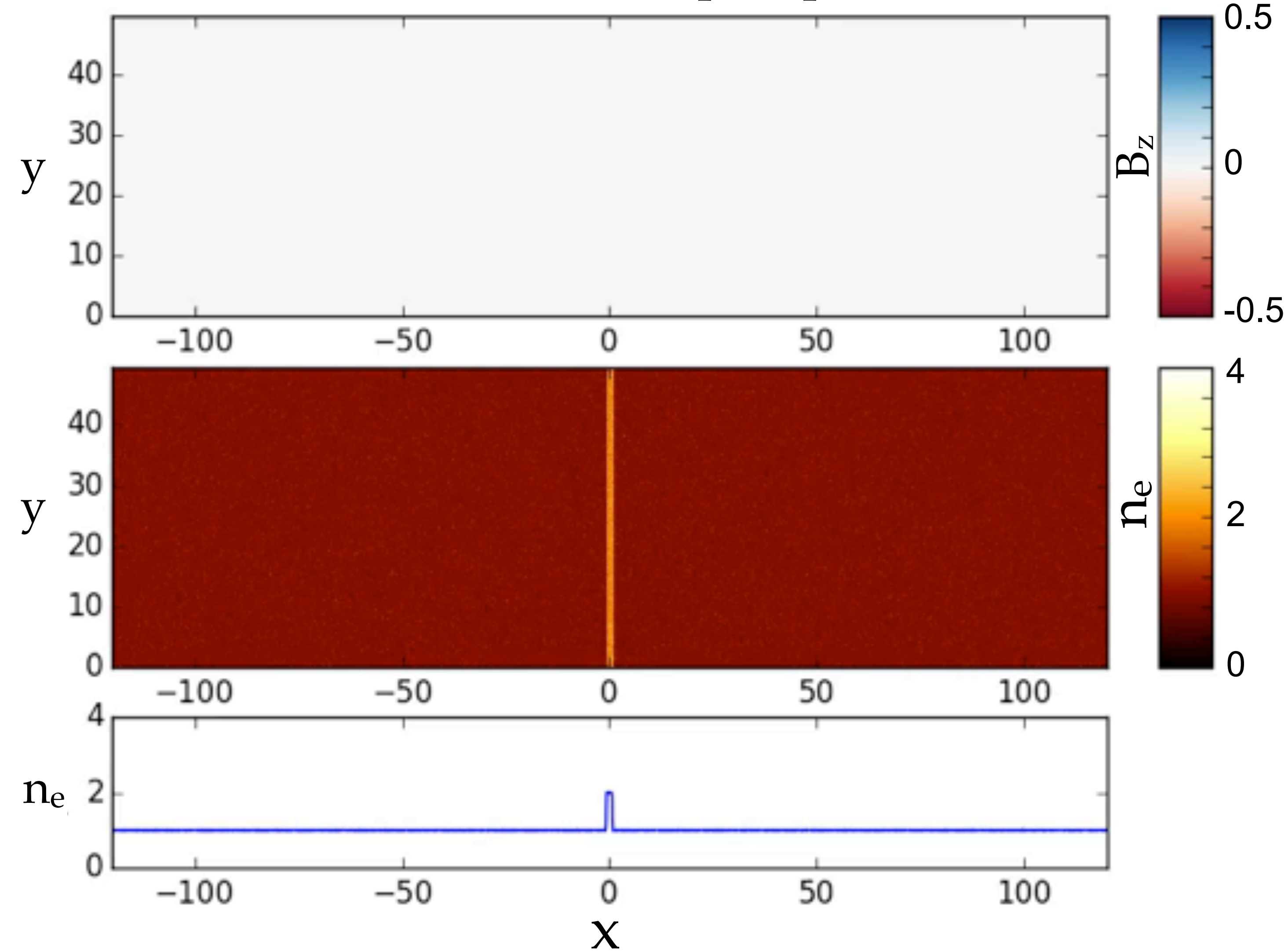


2D simulation with pair plasma



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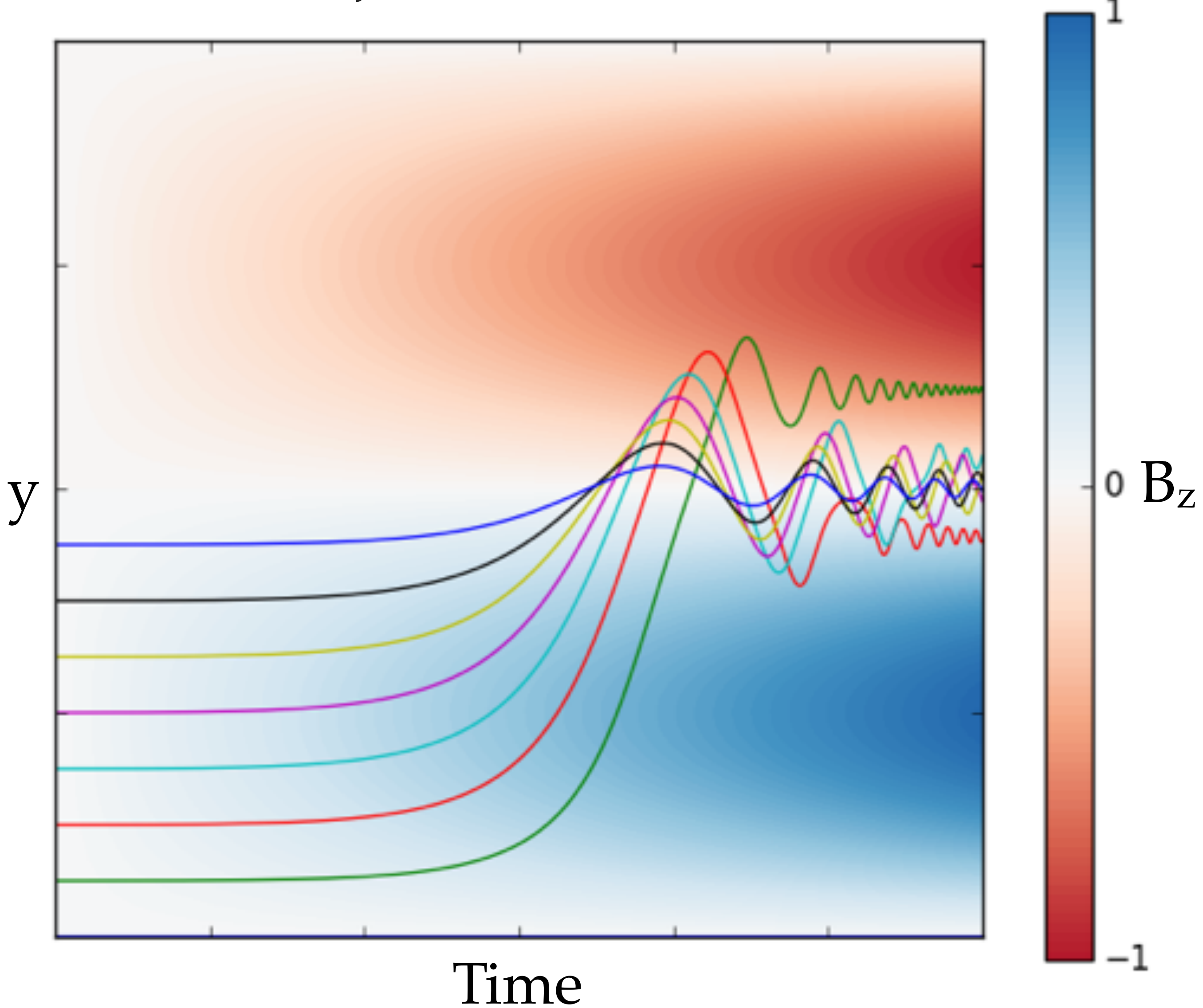
- The density increases up to the Rankine-Hugoniot condition for a strong shock in 2D $\longrightarrow \frac{n_e}{n_0} = 3$

How long is this phase ?

Evolution in time of the magnetic field amplitude

+

Trajectories of electrons



- The magnetic field amplitude to trap electrons and positrons is the same.

How long is this phase ?

Evolution in time of the magnetic field amplitude
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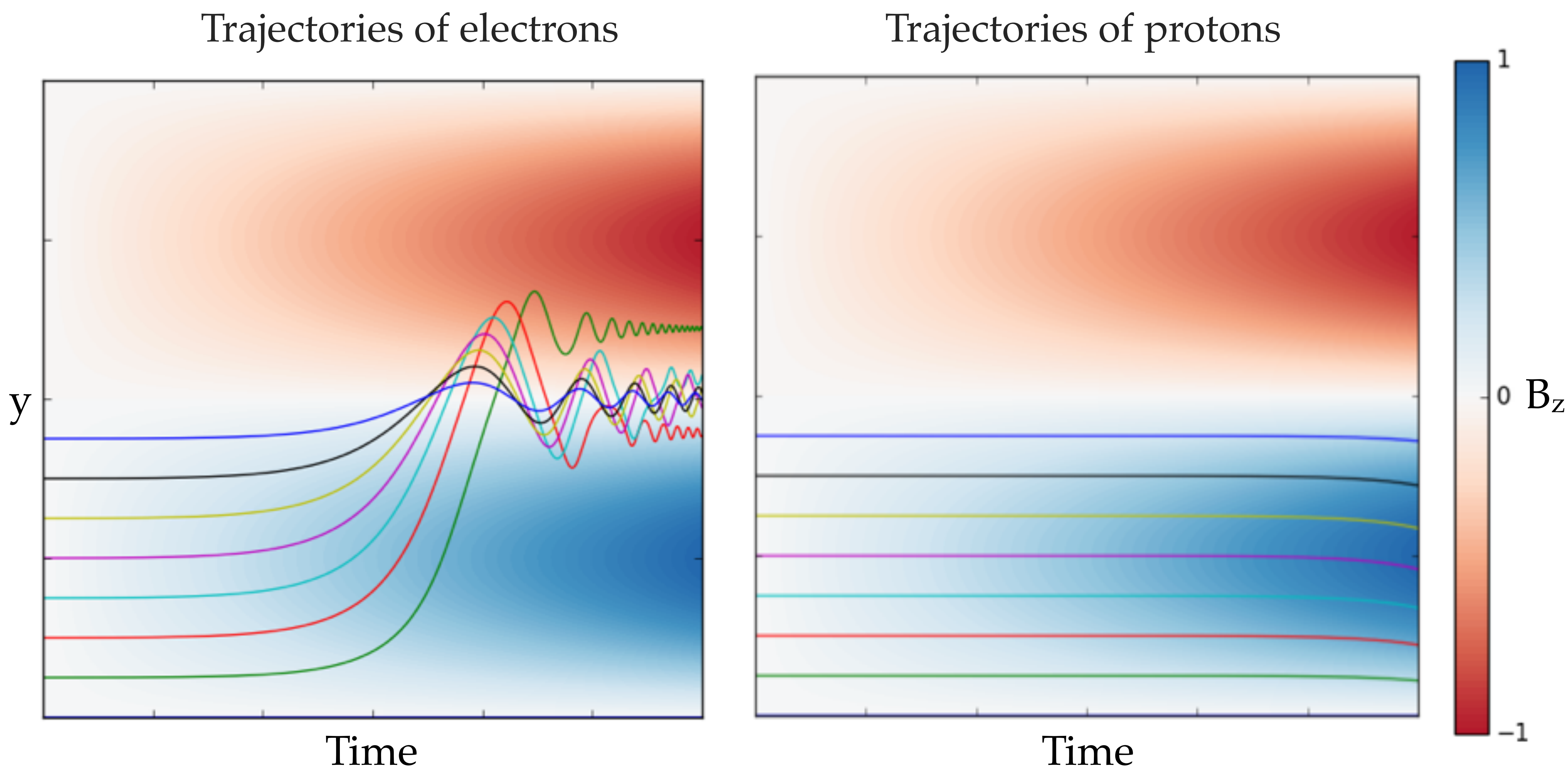

- The magnetic field amplitude to trap electrons and positrons is the same.
- Ions are not deflected efficiently. Additional time is required to develop ion filaments.

Experiment of e^-/ion counterstreaming plasma

Configuration already tested at OMEGA and NIF

new generation of high-energy (~kJ)

high intensity (~PW) lasers

Experiment of e⁻/ion counterstreaming plasma

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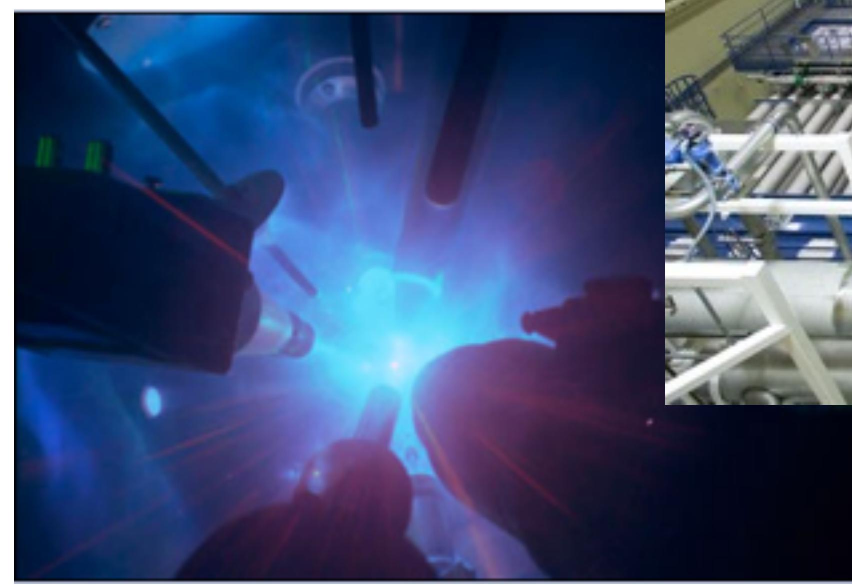

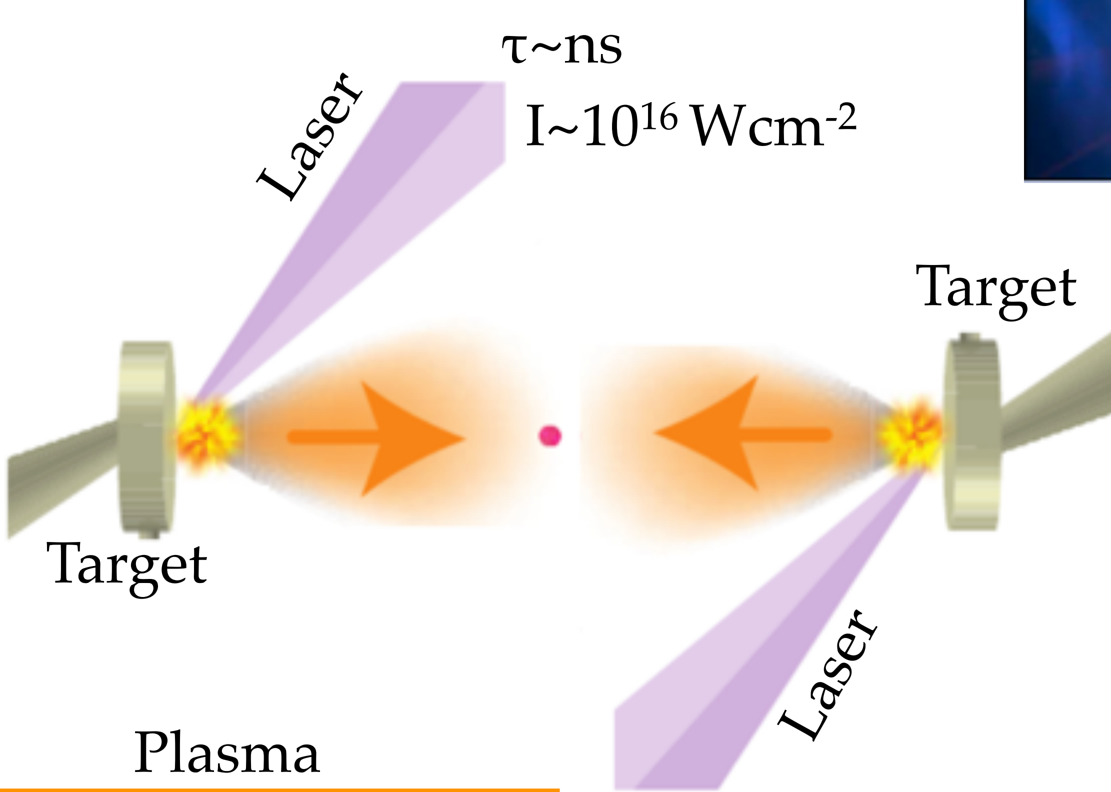

Plasma

Velocity ~ 10^3 km/s

Density ~ 10^{19} cm^{-3}

Park, HEDP 8 (2012).
Kugland, Nature Physics 8 (2012).
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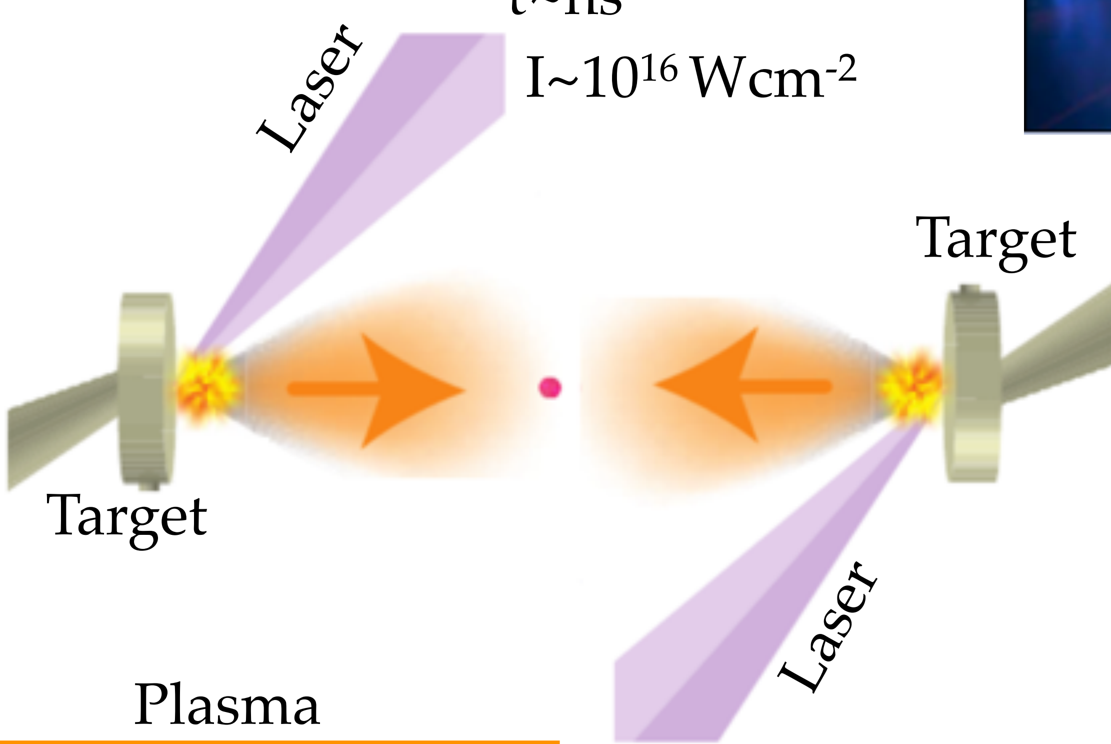

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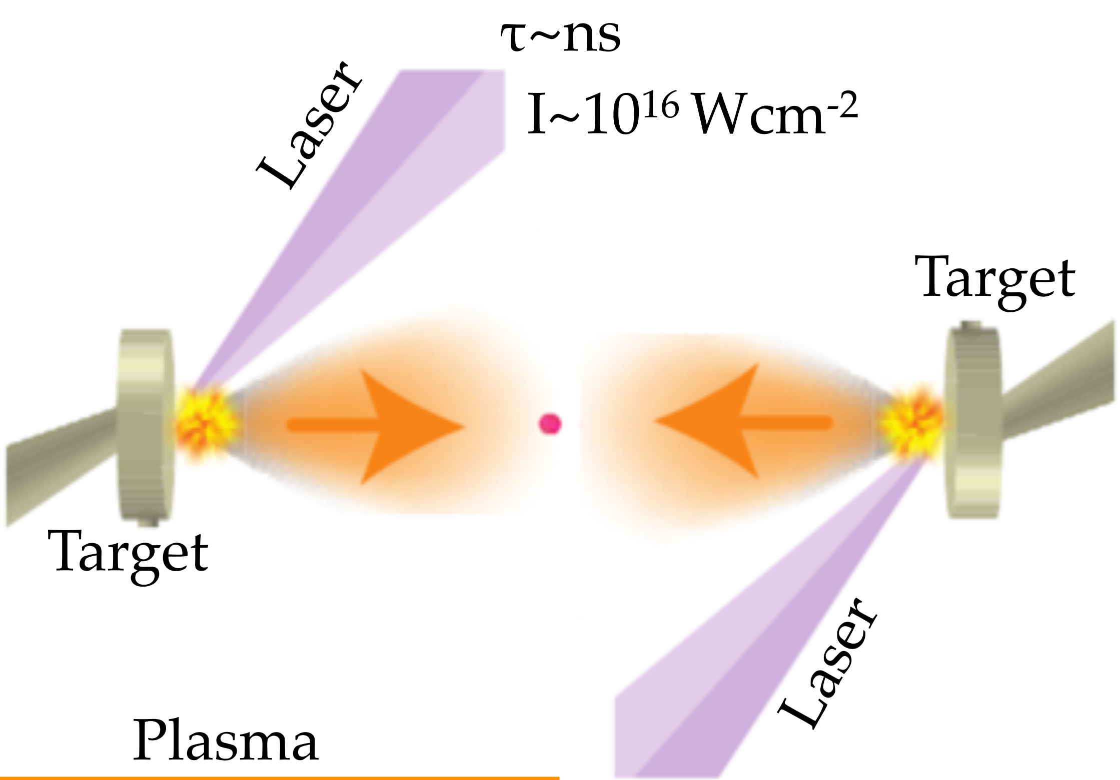
Theoretical and numerical model

Experimental configuration



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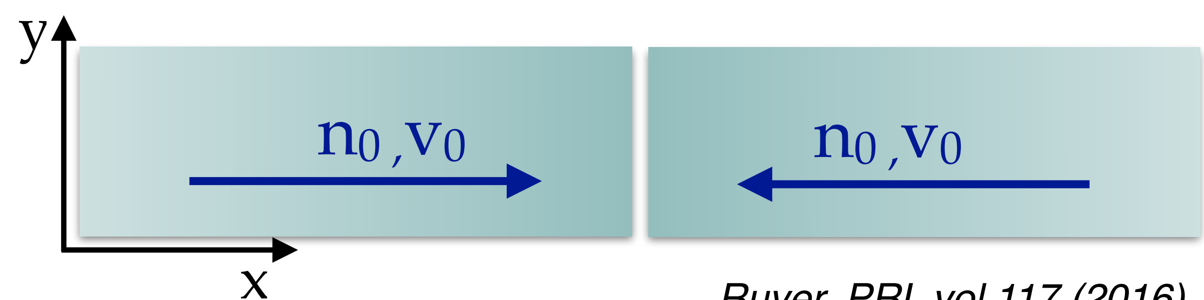

Ruyer, PRL vol.117 (2016).

The model suggests that the distance between the targets should be ~7 times larger.

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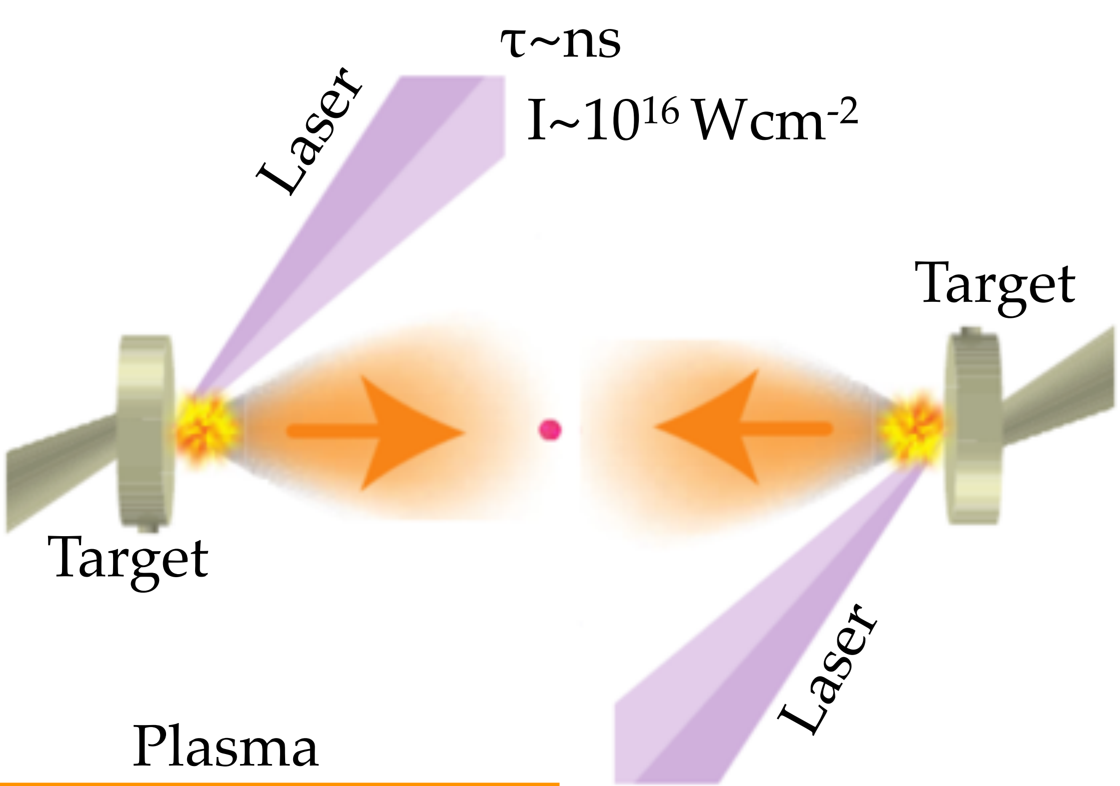

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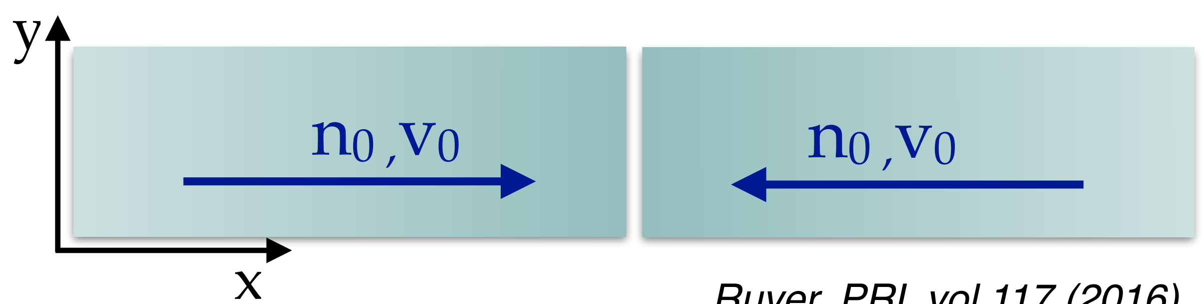

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The model suggests that the distance between the targets should be ~7 times larger.

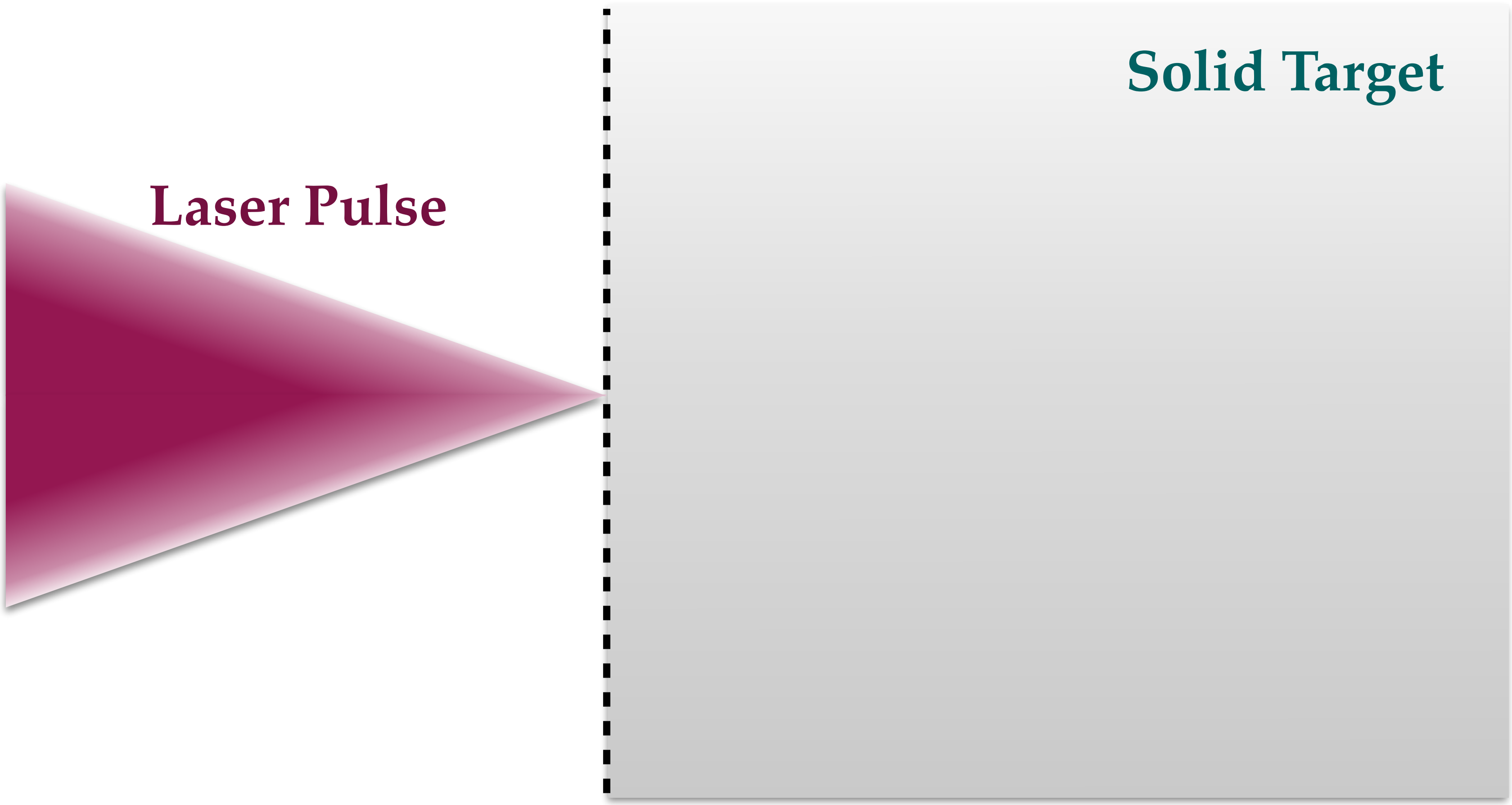
We performed simulations with a realistic density and velocity profile

Filaments formation is drastically slowed down.

No evidence of shock formation.

New suggested configuration

An intense laser pulse interacting with a solid target



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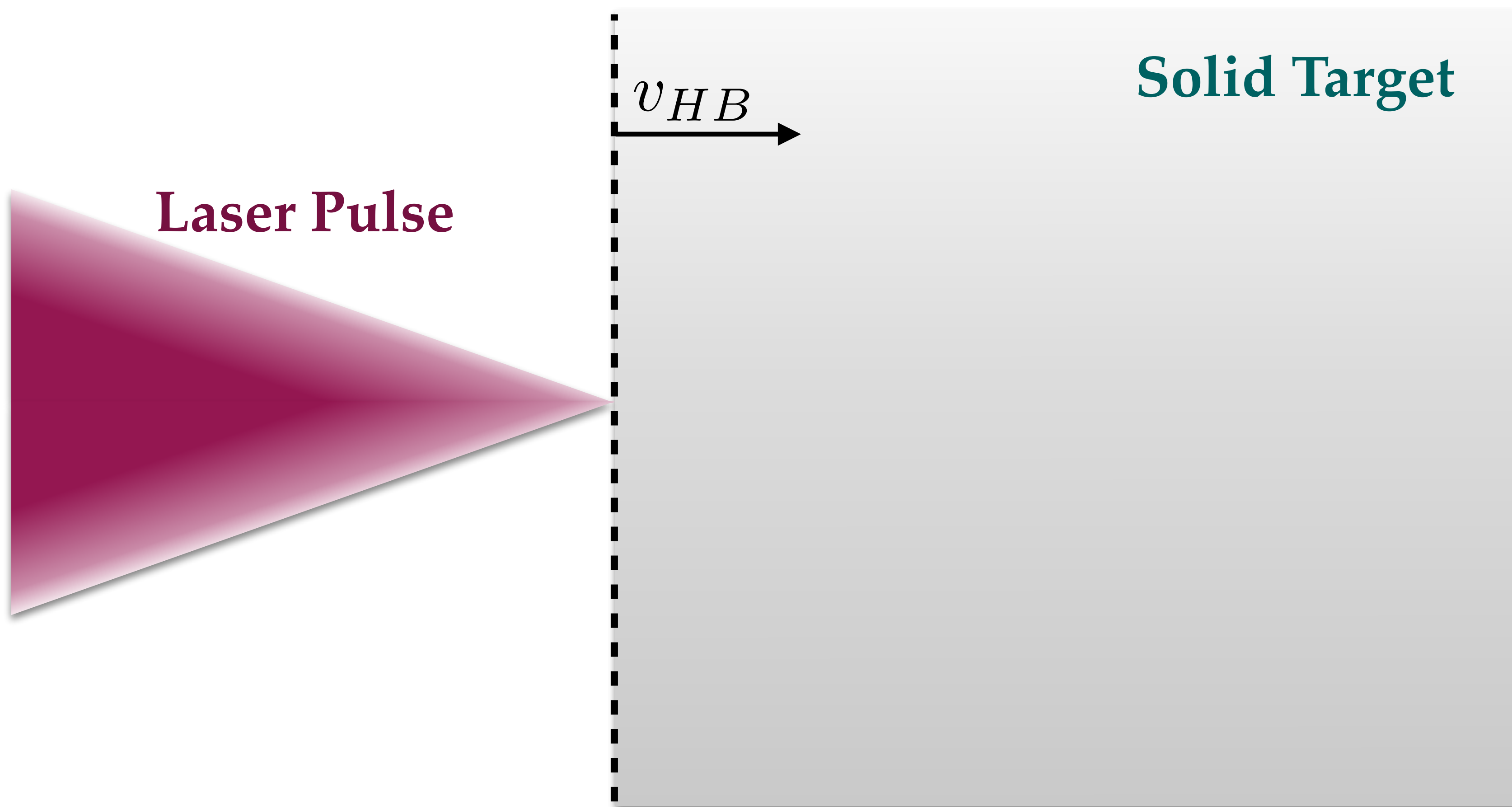

$$v_{HB} \simeq \sqrt{\frac{I}{M_i n_i c}}$$

The laser pulse acts as a piston, pushing surface of the plasma.

The velocity is estimated from the momentum conservation.

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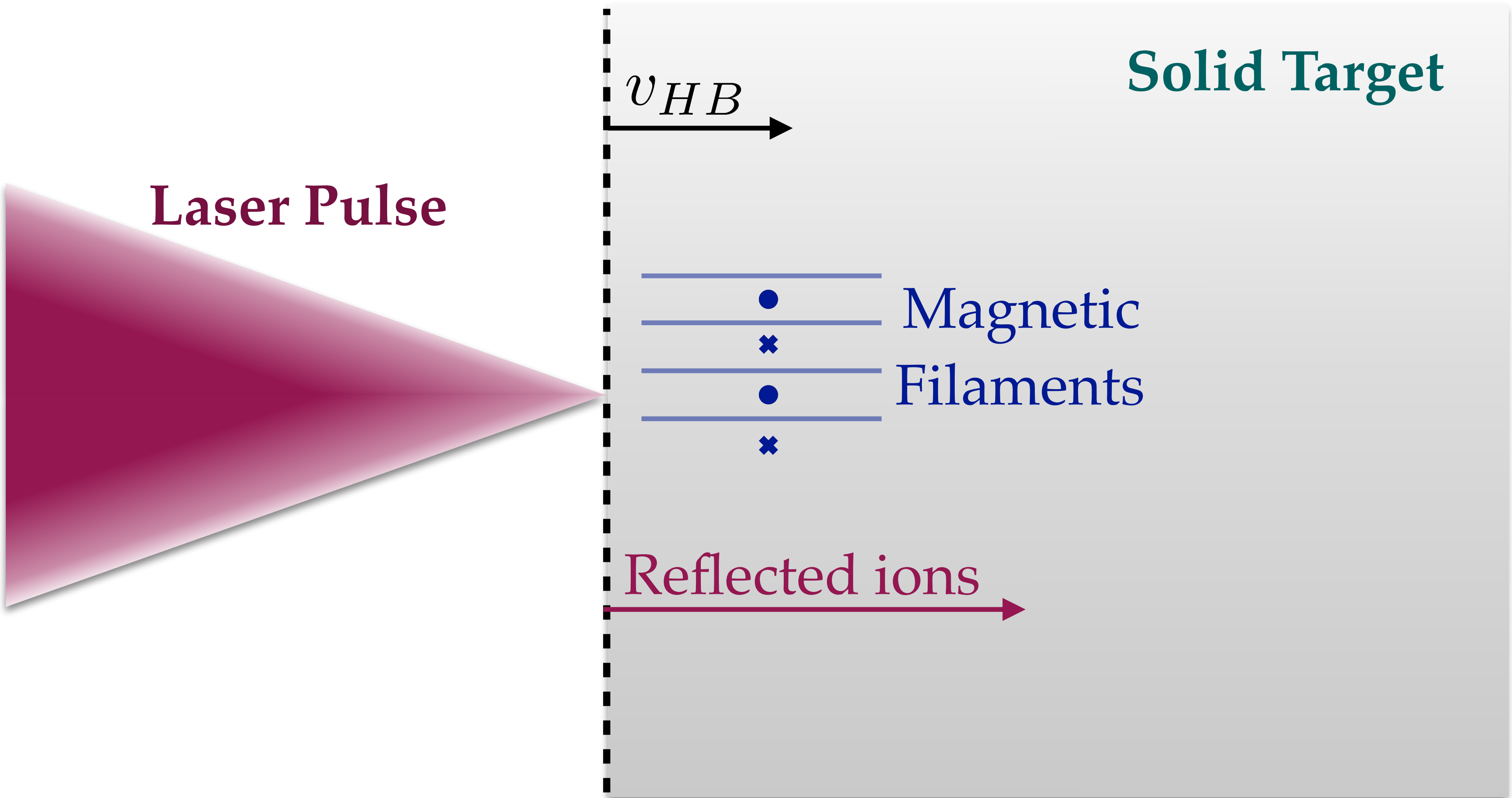

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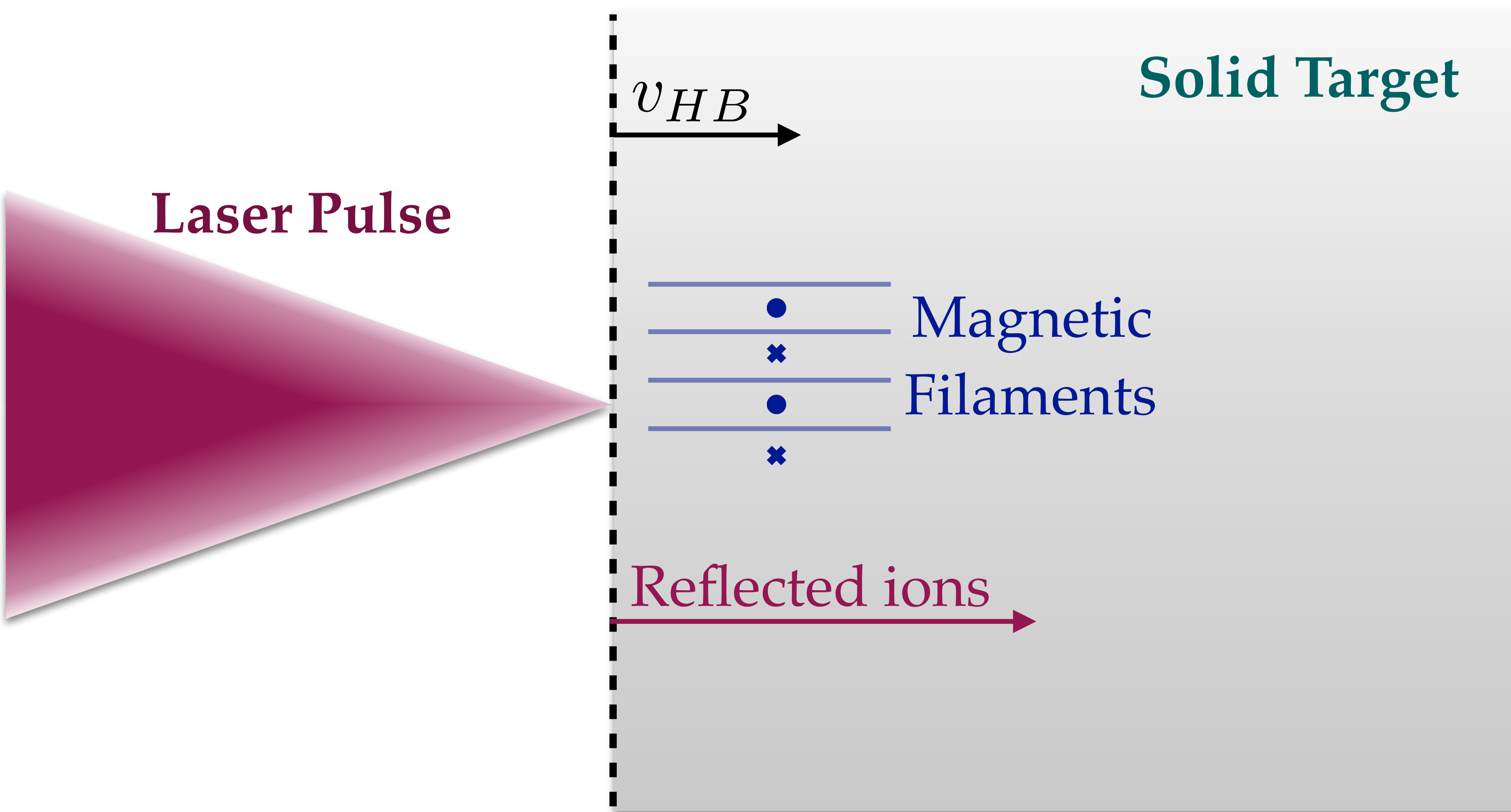

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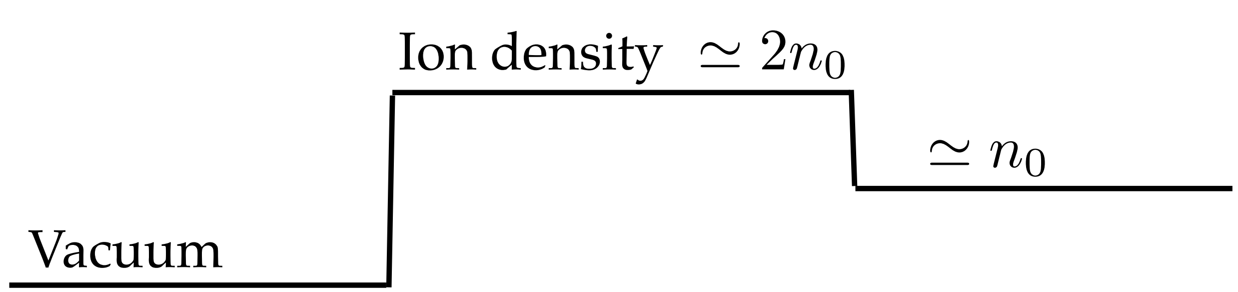

To evolve in a shock, the density should increase up to ~$3n_0$.

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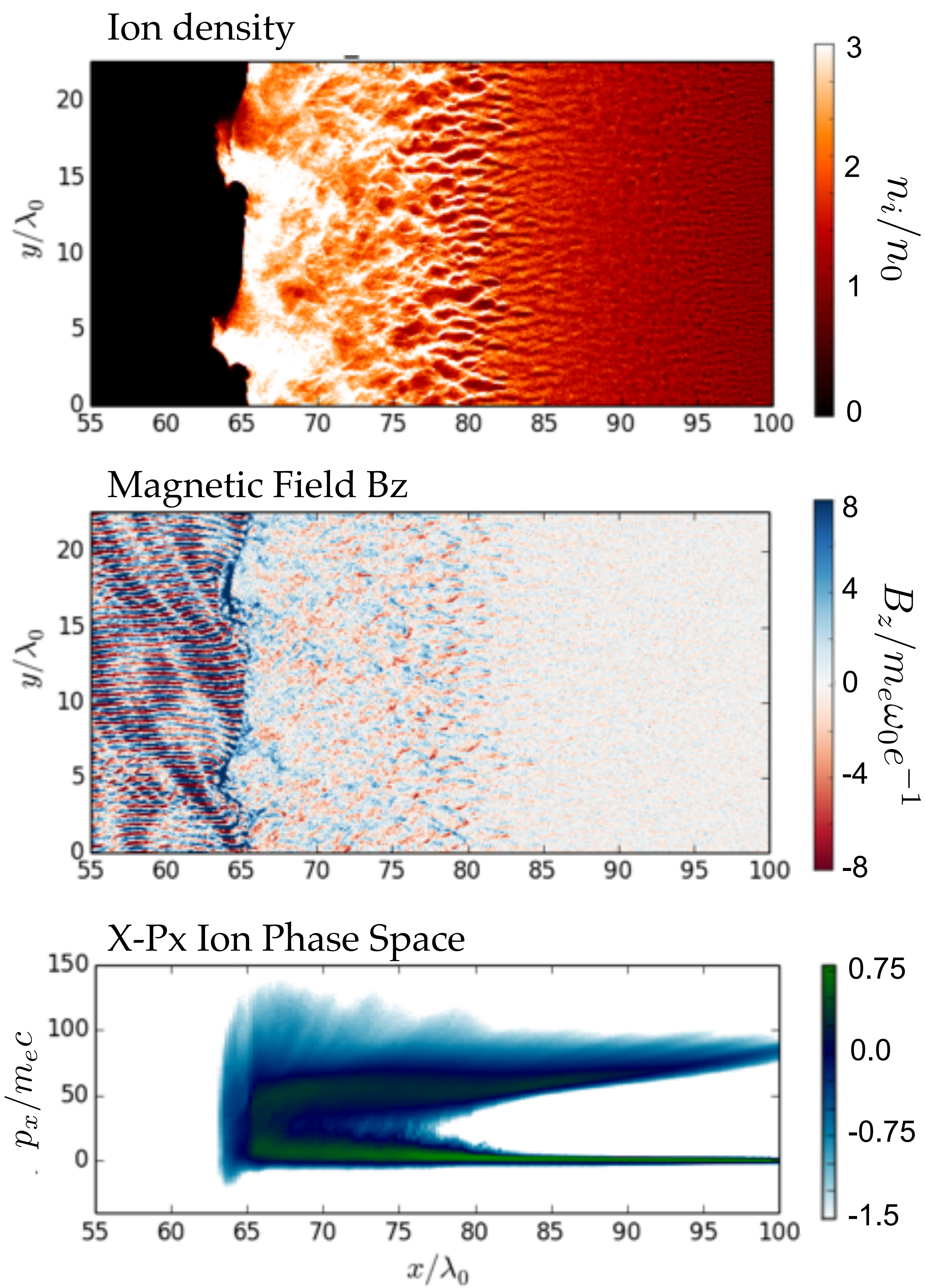

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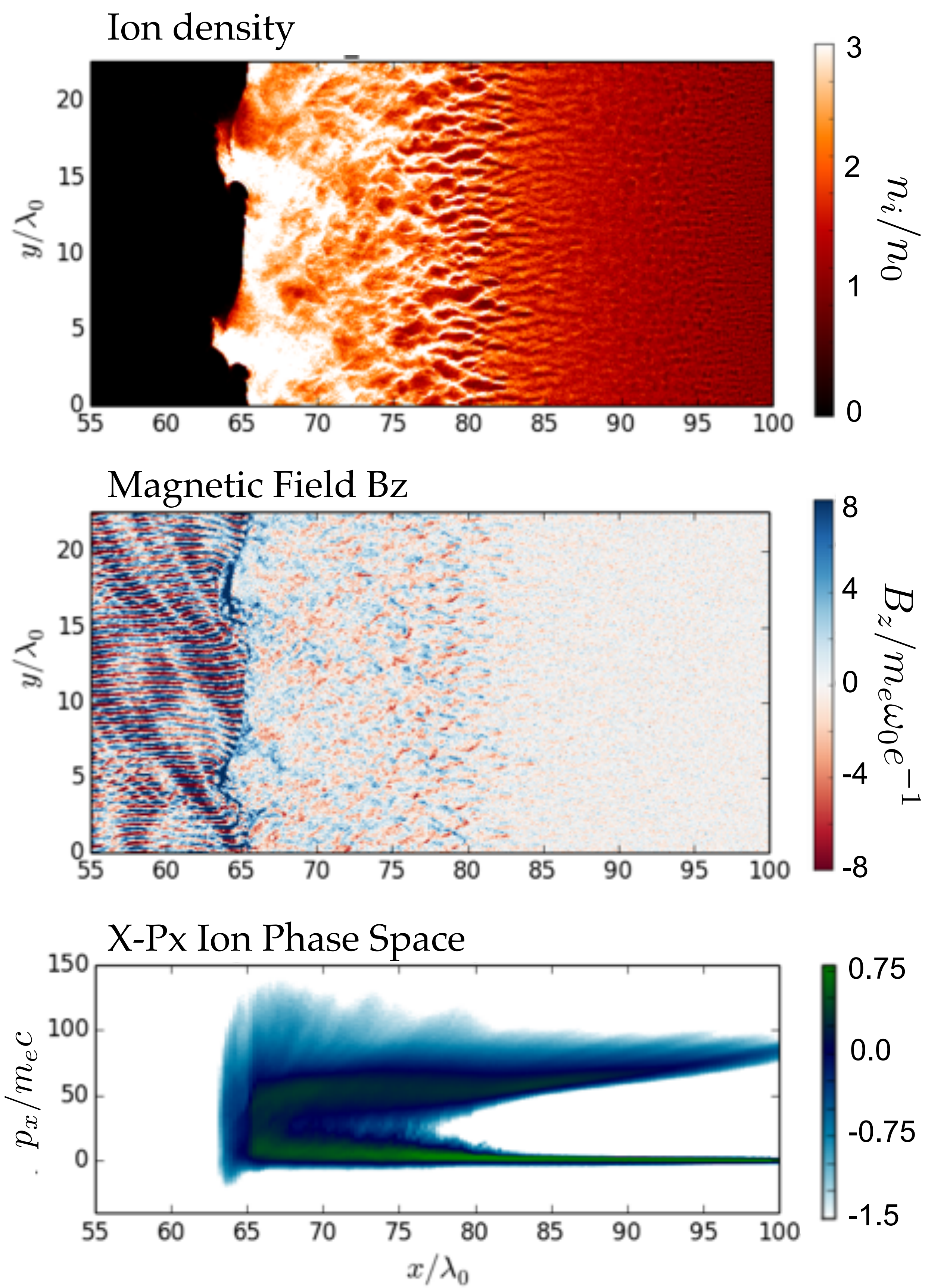


Simulation Parameters

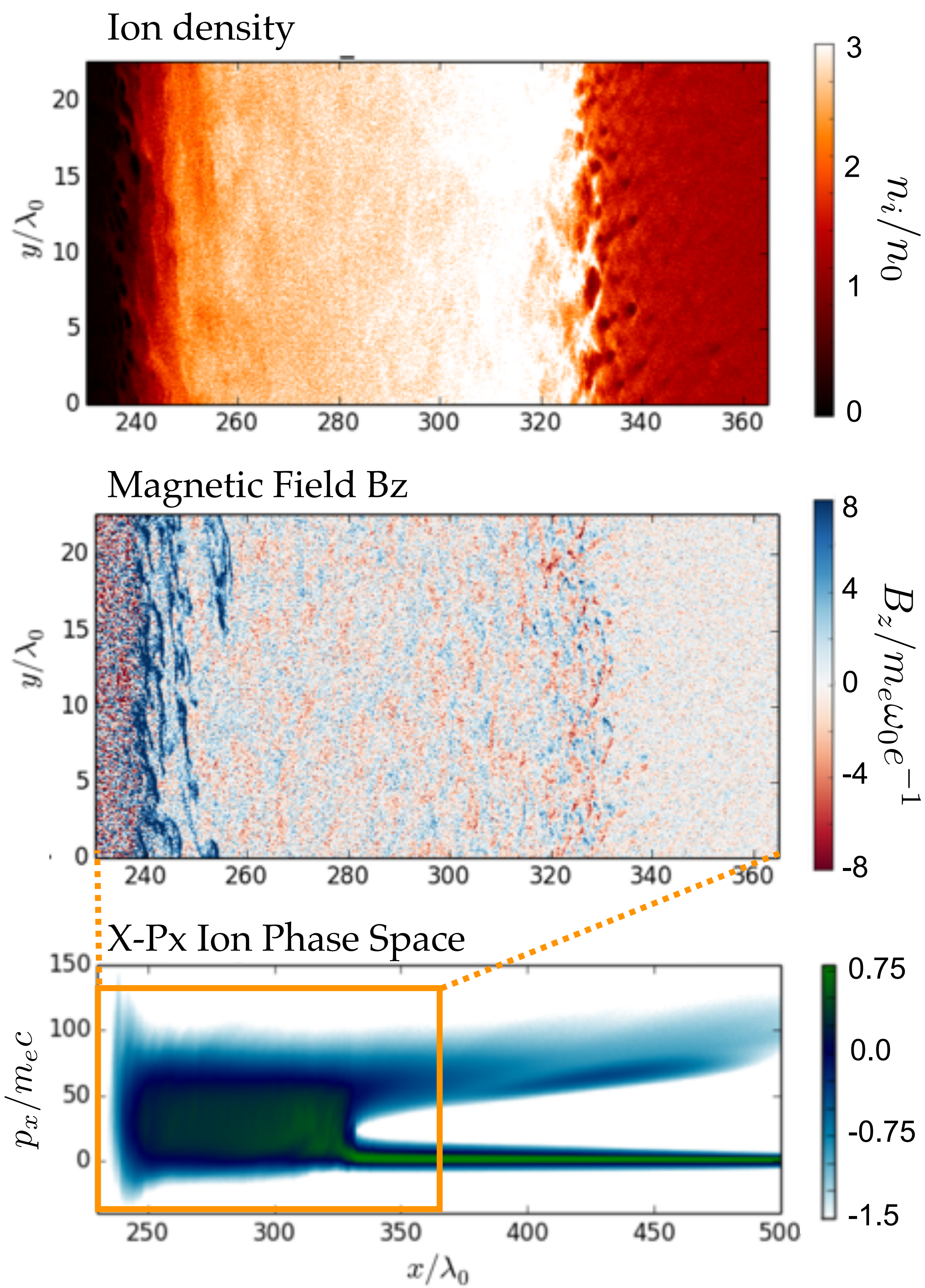
$$I \simeq 5 \times 10^{21} W cm^{-2}$$

$$M_i = 100 m_e$$

$$v_{HB} \simeq 0.38c$$

To carry out the simulation
the ion mass in artificially reduced !

Collisionless shock formation



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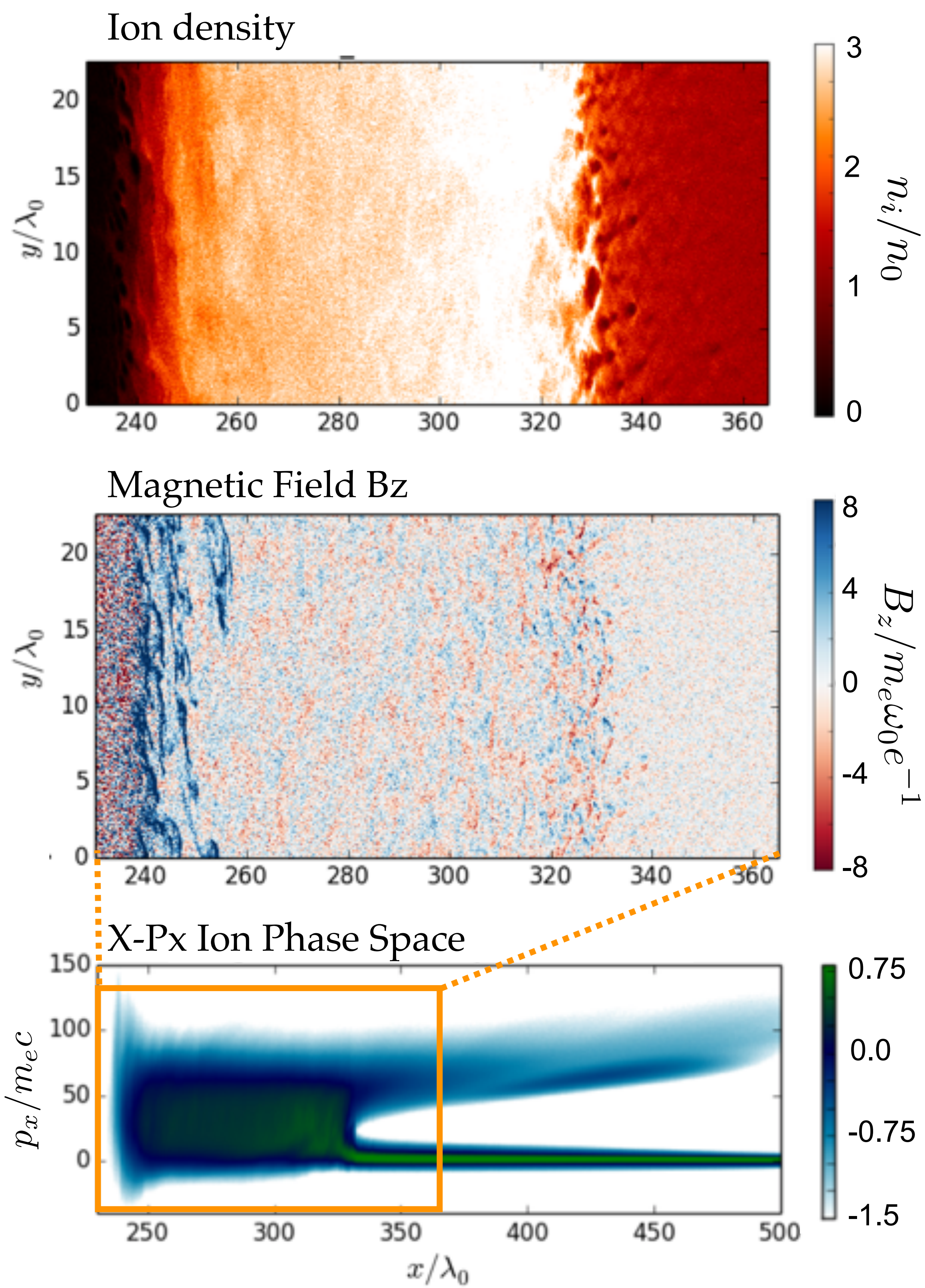
Shock Formation

$t_f \simeq 2$ ps

$L_f \simeq 80\ \mu$m

Collisionless shock formation



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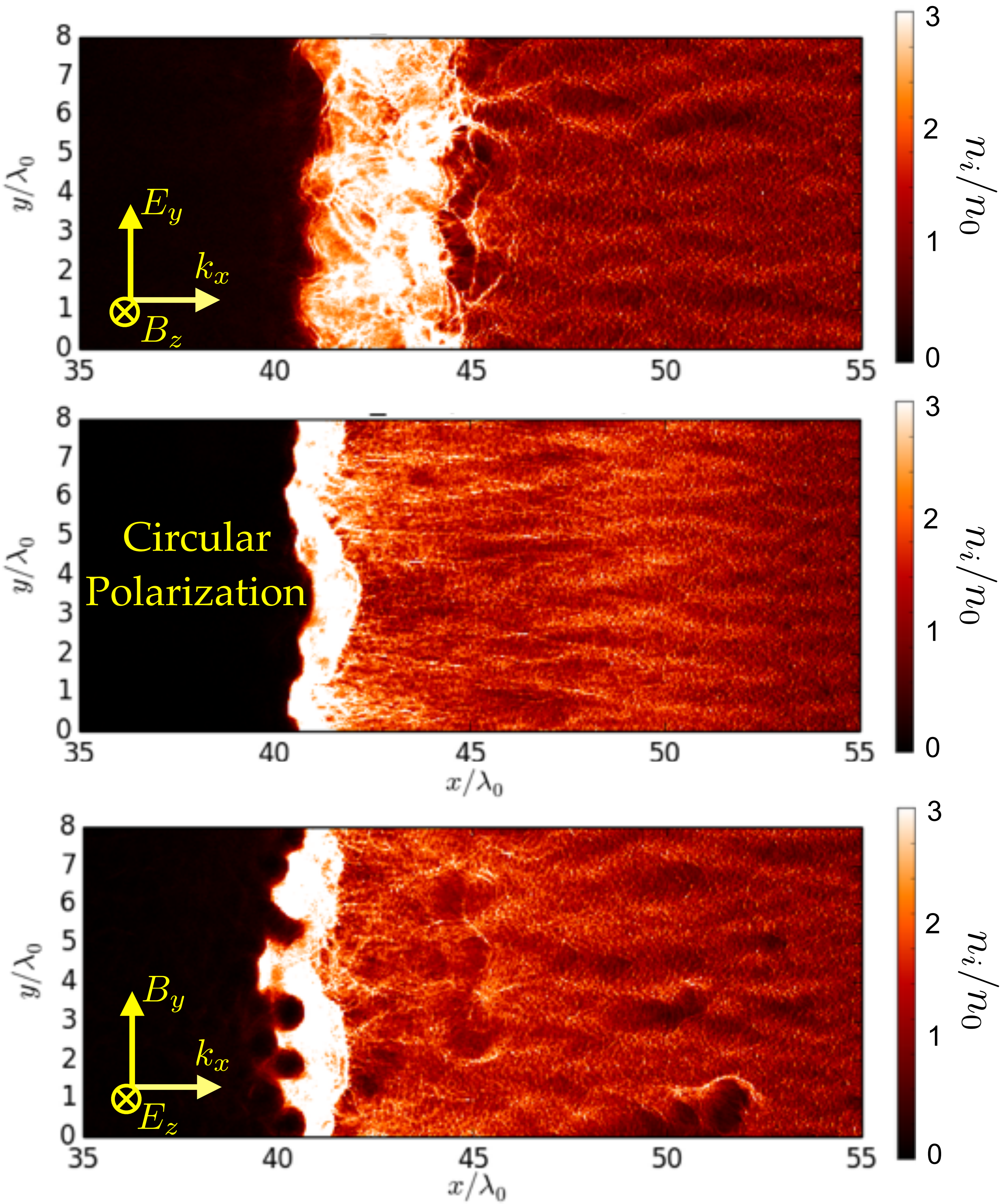
Formation time
with the real ion mass

$$t_f \simeq 30 \text{ ps}$$

This laser facility
is not yet available!

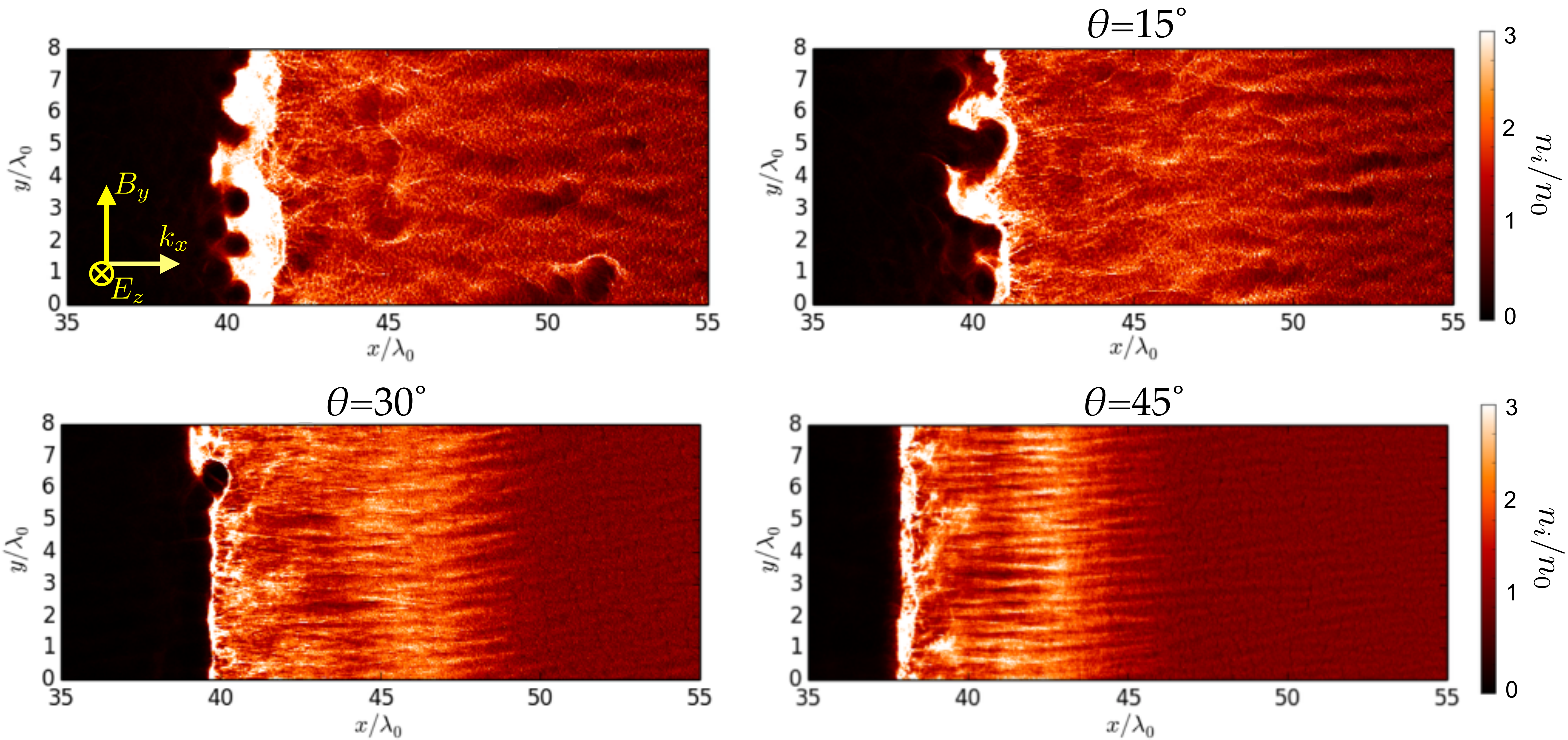
Different laser polarizations



- Varying the laser polarisation, we can control the rippling at the surface.

Angle of incidence

For experimental purpose is important to have non-normal incidence.



- Increasing the angle of incidence
  the surface remains flat for longer time.

Conclusion and Future Works

- Increasing interest in the study of this kind of shock
- Great challenge from both numerical and experimental points of view
- What can we do to make our configuration reproducible in the lab ?

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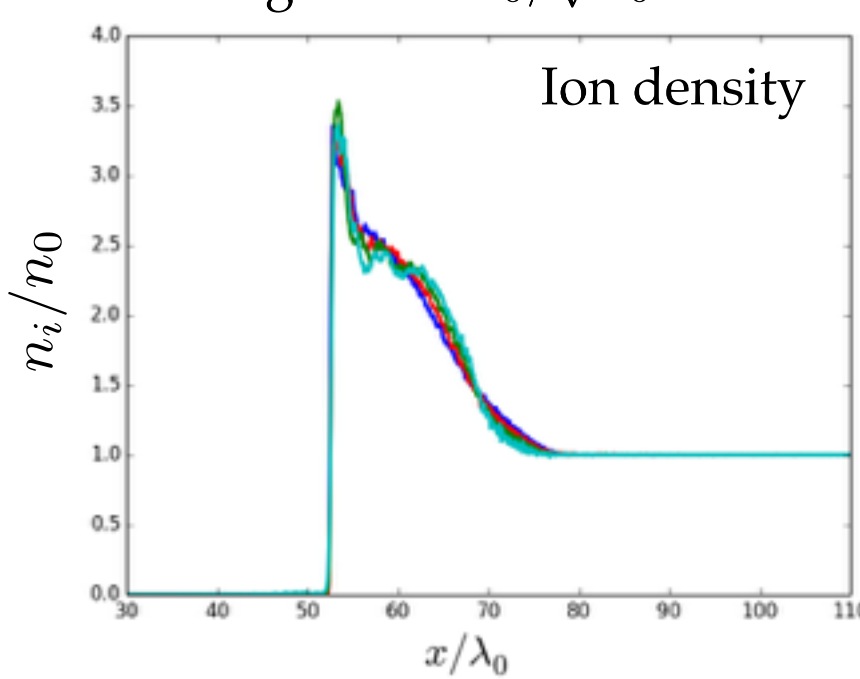
Scaling Factor $a_0/\sqrt{n_0} = const$



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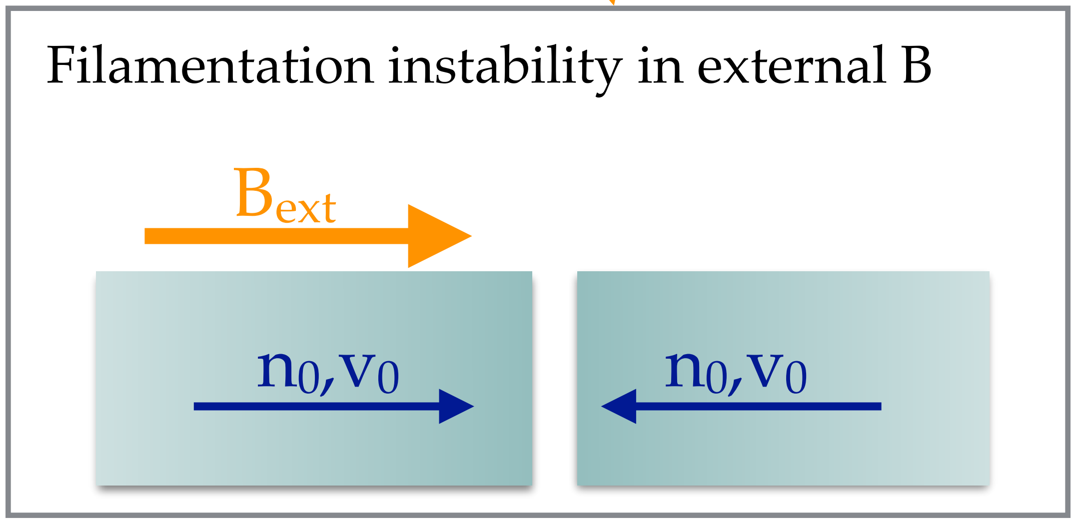

to be submitted.

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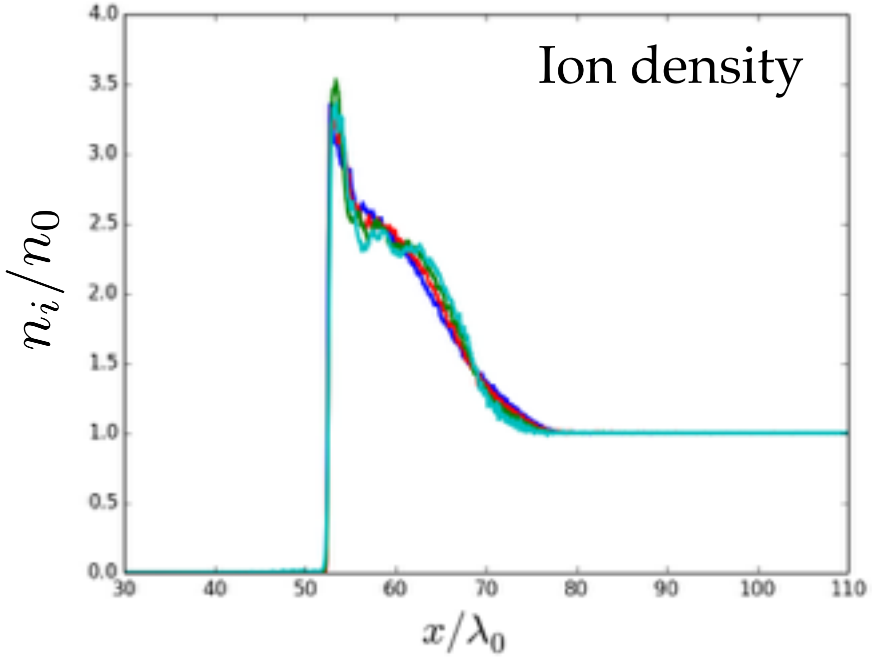

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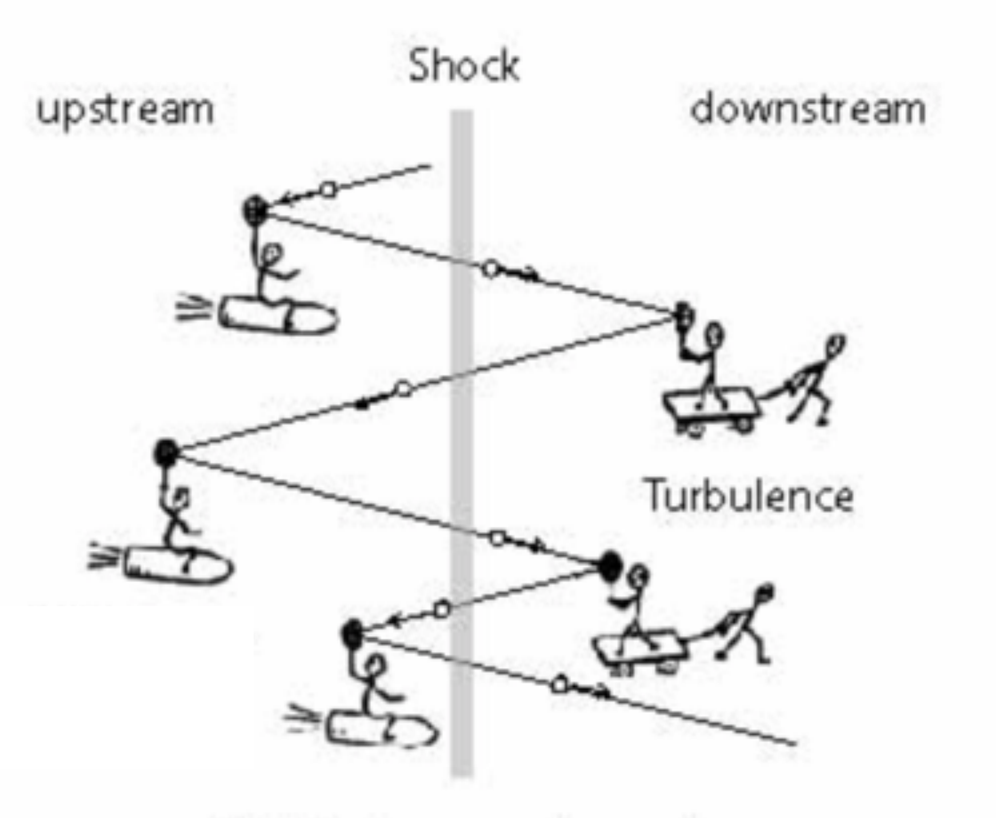
Thanks for the attention !

Why are these shocks interesting ?

Collisionless shocks are associated with extremely high energy particle production.

Cosmic ray acceleration via Fermi mechanism



Kinetic energy up to

$$E_k \simeq 10^{10}\text{GeV}$$

We would like to investigate

the first phase of the shock formation
&
the injection mechanism

Particle-In-Cell code

SMILEI (Simulating Matter Irradiated by Light at Extreme Intensities)

Open-source Particle-In-Cell code developed in C++

1D3V and 2D3V cartesian geometry

Resolution of a system of differential equations to compute the trajectories of the macro-particles

$$\frac{dx_n}{dt} = \frac{p_{x,n}}{m\gamma_n}$$

$$\frac{d\vec{p}_n}{dt} = q(\vec{E} + \frac{\vec{v}_n}{c} \times \vec{B})$$

Resolution of the Maxwell's equations to compute the e.m. fields (external fields + self-consistent fields)