Physics of Relativistic Shocks and Fermi Acceleration, and of Their Implementation Using PW Lasers

Gennady Shvets, Cornell University

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Outline of the Talk

- Collisionless shocks in astrophysical context
- Surprises from PIC simulations: classification of accelerated particles and energy bifurcations
- Modeling challenges and opportunities
- How to produce them in the lab? Challenges to producing dense, large, and relativistic plasmas using laser acceleration of structured targets
How does nature accelerate particles so easily: Astrophysical Accelerators!

Supernovae remnants stream against relativistic outflows from a rotating pulsar

A fireball drives collisionless shocks into interstellar medium

All these scenarios produce ultra-relativistic plasma flows via Fermi acceleration $\rightarrow 10^{20}$ eV (!!)
Three Pillars of the Project

Understanding and Analytic Interpretation of PIC Results

Using PIC Results to Develop Novel Efficient Codes

Laboratory Realization, or Why we still don’t know how to make large dense relativistic plasmas??
Colliding Plasma Shells $\rightarrow$ Collisionless Shocks via Weibel Instability

$e^{-}e^{+}$ plasma, $\gamma = 15$

$e^{-}e^{+}$ plasma, $\gamma_0 = 15$

Plasma shells co-penetrate, their currents neutralized by the return currents

Opposite currents are repelled $\rightarrow$ filaments formation and mutual interaction $\rightarrow$ energy extraction from the “beam”

Colliding Plasma Shells $\rightarrow$ Collisionless Shocks via Weibel Instability

$e^- e^+$ plasma, $\gamma = 15$

$e^- e^+$ plasma, $\gamma_0 = 15$

Contact surface

Hot thermalized plasma

downstream

$\langle \varepsilon_{Bz} \rangle$, $\langle \varepsilon_{Ex} \rangle$, $\langle \varepsilon_{Ey} \rangle$, $\langle n_e \rangle$

upstream

Cold streaming plasma, and more!
The structure of the shock and of the upstream: seeding the Weibel Instability

- Weibel instability requires counter-streaming $\Rightarrow$ small fraction of particles from downstream overtake the shock and penetrate the upstream

- The fraction of the counter-streaming particles $f_c \sim 10^{-2}$ for large $\gamma'$s of the shock, but increases for moderate relativistic factors
Structure of the extended shock: strong field exists ahead of the shock \( \rightarrow \) acceleration

- The relatively sharp density shock has extended electric fields into the upstream \( \rightarrow \) longitudinal momentum spread of the incoming upstream jet.

- The transverse energy spread is minimal \( \rightarrow \) necessary condition for Weibel instability.
Particle Acceleration in a Collisionless Pre-Shock: Fermi Acceleration?

Which Field Components Accelerate Particles $\rightarrow$ Energy Bifurcation?

**Emergence of several classes of accelerated particles:**

1. **Thermalized:** no energy gain $\rightarrow$ scattered by B-field in shock
2. **Reflected by shock** $\rightarrow$ small energy gain
3. **High energy gain** $\rightarrow$ Fermi acceleration

Transition to Fermi acceleration?
How do we see all this in the lab??

Challenge: hard to produce very long counter-propagating relativistic plasma shells!

Solution: an experiment in the upstream reference frame!

\[ v \quad v_1 \]

Short dense relativistic plasma

Long tenuous plasma
How do we see all this in the lab??

**Solution**: use laser-target acceleration $\rightarrow$ produce high-density relativistic plasma that can actually be called plasma $\rightarrow$ $\lambda_{pi} \sim c/\omega_{pi} < L_{x,y,z}$ $\rightarrow$ tough, especially for thick targets!

For $n_i \sim 10^{21} \text{cm}^{-3} \rightarrow \lambda_{pi} \sim 7\mu m$ $\rightarrow$ need to accelerate multi-micron thick target to relativistic energies $\rightarrow$ never been done!

The concept: **Laser-Ion Lensing & Acceleration (LILA)** $\rightarrow$ a shaped target is simultaneously focused and accelerated $\rightarrow$ compression in x-y directions, expansion in z-direction!
The LILA Concept: Thinner Portions of The Target Travel Longer Distance

The concept: Laser-Ion Lensing & Acceleration (LILA) → a shaped target is simultaneously focused and accelerated → compression in x-y directions, expansion in z-direction!

Target acceleration:
\[ g = \frac{E^2}{2\pi n_0 M_i d_0} \]

Target thickness:
\[ d(r) = d_0 \left(1 - \frac{r^2}{2R_c^2}\right) \]
The LILA Concept: A Hydrodynamic Model of Variable-Thickness Target

Parameters: $R_c = 6\mu m$, $d_0 = 300nm$, $n_0 = 100n_{\text{crit}}$

Wide target: $R_0 = R_c$

Narrow target: $R_0 = 2R_c/3$

Parabolic target thickness:

$$d(r) = d_0(1 - r^2/2R_c^2)$$

Target dynamics controlled by

$$\Gamma = gR_c/c^2$$
What can go wrong? RTI!

**Challenge:** Rayleigh-Taylor Instability during acceleration of planar targets

**Opportunity:** bending target appears to be less susceptible to RTI

\[ \gamma = \sqrt{gk} \]

RTI in planar and shaped targets

Flat target

Laser: $P = 35\, PW$, $\sigma = 8\, \mu m$

Variable thickness target

VTT: high energy, low emittance
3D PIC (VLPL) Simulations of LILA

Intensity: $I = 1.8 \times 10^{22} \text{W/cm}^2$
Power over target: $P \approx 35 \text{PW}$
Laser duration: $\tau \approx 50 \text{fs}$
Laser energy: $U \approx 1.6 \text{kJ}$

Target thickness: $d_0 = 300 \text{nm}$, density: $n_0 = 100n_{\text{crit}}$, radius: $R_0 = 8 \mu m$

Conversion efficiency: 20% $\Rightarrow$ 300 Joules of relativistic energy packed into a $10 \mu m^3$ volume $\Rightarrow$ energy density $\sim 10^{13} \text{J/cm}^3 = 10^7 \text{TPa}$

Definition of HEDP: $10^5 \text{J/cm}^3 = 0.1 \text{TPa}$
Thermonuclear explosion: $400 \text{TPa}$

Lesson: we need much bigger lasers!!
Moderate Laser Pulses Possible (2D)

Power: $P \approx 1.5\text{PW}$
Laser duration: $\tau \approx 60\text{fs}$
Laser energy: $U \approx 90\text{J}$

This could be done on OMEGA: cut out 60fs out of the existing ps pulse!
Applications of Focused Relativistic Quasi-Neutral Plasmas

Shock generation in stationary plasmas ("inter-stellar medium")
Proton radiography (pRAD, CMU/DOE,...) → small proton source provides high spatial resolution
Proton radiology of tumor
Generation of warm dense matter (WDM)
Achieving power densities exceeding those in nuclear explosions
Things to Do: From Shocks to Dense Ultra-Relativistic Plasmas

Understanding and Analytic Interpretation of PIC Results

Using PIC Results to Develop Novel Efficient Hybrid Codes

Laser Ion Lensing & Acceleration:

1. Realistic target (multi-ions)
2. Understanding the physics of RTI suppression in rapidly converging plasma targets
3. Lower power laser (<10PW) for near-horizon experiments (ELI, LLE, Korea)
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Shocks in three dimensions

Smallest magnetic field: $B_x \rightarrow$ all fields can be described in terms of $(A_x, \phi) \rightarrow$ simplified numerical codes (e.g., fluid electrons and kinetic ions)
Reduced Physics Codes Model
Collisionless Shocks in 3D

\[ V_\perp^2 A_x + \frac{4\pi}{c} J_x = \frac{1}{c} \frac{\partial^2 \phi}{\partial x \partial t} + \frac{1}{c^2} \frac{\partial^2 A_x}{\partial t^2} \]

Smallest magnetic field: \( B_x \rightarrow \) all fields can be described in terms of \((A_x, \phi)\)

\[ V_\perp^2 \phi + 4\pi \rho = -\frac{1}{c} \frac{\partial^2 A_x}{\partial x \partial t} - \frac{\partial^2 \phi}{\partial x^2} \]

Equation of motion for electrons/ions:

\[
\frac{d}{dt} \left( \gamma_j \vec{v}_j \right) = -\frac{q_j}{M_j} \left( \vec{V}_\perp \phi + \frac{v_{xj}}{c} \vec{V}_\perp A_x \right) \\
\frac{d}{dt} \left( \gamma_j v_{xj} + \frac{q_j}{M_j} A_x \right) = -\frac{q_j}{M_j} \frac{\partial}{\partial x} \left( \frac{v_{xj}}{c} A_x + \phi \right)
\]
Reduced Physics Codes Model
Collisionless Shocks in 3D

Smallest magnetic field: $B_x \rightarrow$ all fields can be described in terms of $(A_x, \phi) \rightarrow$ simplified numerical codes (e.g., fluid electrons and kinetic ions)

Filaments can be very tilted $\rightarrow$ can we really ignore the $\text{d}/\text{d}x$ derivatives??
Particle Acceleration in a Collisionless Shock: Fermi Acceleration?

What happens to a particle in a shock?

Low energy particles ($\gamma < 20$)

Upstream
What happens to a particle in a shock?

Low energy particles ($\gamma < 20$)

High energy particles ($\gamma \approx 20$)