Kinetic simulations of weakly collisional shocks in space and in laboratory plasmas

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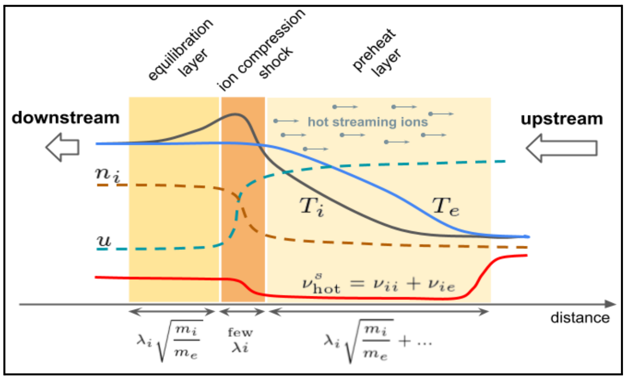
CONTEXT. The investigation of the structure of shock waves in a plasma has a rich history. The analysis of the Navier-Stokes type two-fluid equations, with transport coefficients drawn from plasma kinetic theory, has played a crucial role in establishing some of our fundamental understanding of **collisional** shocks. For example, *[Jaffrin and Probestein, 1964]* established that the basic collisional shock structure in plasma consists of three regions: the electron preheat layer where hot electrons have a high diffusivity, the ion compression shock where the ion viscosity is large, and the ion-electron thermal equilibration layer where electrons and ions tend to a common temperature. A schematic of the shock structure (in its reference frame) is shown in the figure. However, significant differences were found between the fluid and kinetic approaches *[Vidal+ 1993]*. At relatively high Mach numbers (*M = 5*), the shock transition was found to be wider than expected due to hot ions streaming into the cooler plasma. The development of potentially unstable double-humped ion velocity distributions in the transition region was particularly prominent during the shock formation. Energetic ions and plasma microinstabilities in collisional shocks have only been recently confirmed experimentally *[Rinderknecht+ 2018]*. The upstream heating due to the streaming hot ions leads to an expanded region that is influenced by viscosity, and blurs the shock front. However, the theoretical results were obtained for idealized shocks propagating in a relatively cold and dense medium (i.e. strongly collisional), and for relatively low Mach numbers. The more realistic picture, which includes magnetic fields and environments where collisions can be relatively scarce but non-negligible, is far more complicated. Although many astrophysical and laboratory plasmas are in this weakly collisional regime, there has been very little work in this area.



The **focus of this project** is to investigate the plasma physics of **weakly collisional shocks** from a kinetic point of view. Thanks to two complementary state-of-the-art codes, SMILEI and PHARE, and the support of laser experiments, we will be able to study for the first time the development and evolution of weakly collisional shocks, how the environment can lead to the transition from collisional to collisionless shocks (and vice versa), and the development of instabilities and energetic particles.

SCIENTIFIC PROJECT AND METHODOLOGY. Simulations will be performed with two complementary codes: the full PIC code **SMILEI** [*Derouillat+, 2018*] and the hybrid PIC code **PHARE** *[Aunai+ 2023]*. These codes are capable of exploring the physics of collisional and weakly collisional shocks, as well as the transition to collisionless shocks over the whole range of temporal and spatial scales. The PHARE code treats the ions kinetically as macro-particles, while the electrons are treated as a massless fluid. Coupled with its unique capability of **Adaptive Mesh Refinement** (AMR), this formalism can capture the large-scale physics of shocks without sacrificing ion kinetic effects. SMILEI is a full PIC code and it will be used to probe both electron and ion kinetic physics at the scale of the shock transition. The need to resolve electron physics limits these types of simulations to shorter times and length scales than PHARE.

The project is divided into three, partially overlapping main tasks. The first is dedicated to implementing a collision module in the hybrid code PHARE. The second is devoted to the simulation of weakly collisional shocks in plasmas. The third deals with the application of the results to laboratory and astrophysical plasmas.

Task 1.* Monte Carlo ion-ion and ion-electrons collisions. *Expected duration 6-9 months
The student will implement a Monte Carlo collision module in the PHARE code to handle ion-ion Coulomb collisions *[Takizuka & Abe, 1977]* and collisions between ion particles and fluid-electrons *[Sherlock 2008]*. We have ample experience in this type of code development and have already implemented it in another hybrid PIC code. The SMILEI code already has a collision module and the student will be able to run simulations with this code from the beginning of the thesis.

Task 2.* Investigating the weakly collisional shock regime. *Expected duration 12-18 months
First, the student will perform simulations with SMILEI taking into account the physics on small scales and short times, in particular the effects of (non-local) electron heat transport on the preheat region. Second, leveraging the unique AMR capability of PHARE, the student will explore the ion kinetic aspects of shock formation and evolution over long times and large spatial scales. The latter is necessary to investigate the wide class of electromagnetic and electrostatic ion instabilities that may develop ahead of the shock front due to ion streaming and/or temperature anisotropies. In particular, the PhD student will focus on the nature and level of

electromagnetic fluctuations and electrostatic fields generated around the shocks. In many astrophysical studies in the collisionless regime, such fields have been shown to be responsible for particle acceleration through different processes (shock surfing, shock drift, and eventually diffusive shock acceleration). This PhD work will highlight the impact that a weak collisionality has on the efficiency of non-thermal particle production.

Task 3. **Application to laboratory and astrophysical plasmas.** ***Expected duration: 9-12 months***
A crucial step in any theoretical investigation is the comparison to observations. While there exist extensive observations of collisionless shocks (mostly by spacecraft at the Earth bow shocks), such observations are much more indirect and incomplete for collisional and weakly collisional, far away astrophysical shocks. Using and **extending** the simulations of **Task 2** the student will apply the results to laboratory and astrophysical shock environments. Importantly, to develop a coherent approach to the subject, we have submitted a proposal for experiments on the LULI2000 laser facility. This work is in collaboration with the experimental group of Bruno Albertazzi (LULI). Given our previous success, we expect to have an accepted proposal in 2024 or 2025 at the latest. The PhD student will run simulations to support the interpretation of the experiment, and the design of follow up experimental campaigns. The student will use, and if needed further develop, the extensive set of existing tools to calibrate, post-process and analyze the experimental data.

PROFILE OF THE CANDIDATE. The candidate should have a solid background in plasma physics, and be at ease with C++ and Python programming. Experience with HPC computing is an advantage but not necessary. The PhD student will be based in the LERMA/LPP/LULI offices on the Jussieu Campus of Sorbonne Université.

EXPECTED OUTCOMES AND RELEVANCE FOR THE IPI. This transverse project involves three laboratories of Sorbonne Université and it is at the interface between laser-produced plasmas and astrophysical plasmas. The expected outcomes are:
→ The first coherent study of the microphysics of shocks from collisional to collisionless, with particular focus on the intermediate weakly collisional regime.
→ An improved understanding of the interplay of collisions and kinetic effects in weakly collisional shocks.
→ First simulations to explore the conditions for particle acceleration in weakly collisional shocks.
→ A state-of-the-art collision operator for the PHARE code which can be used for a variety of applications beyond those of the project.

ROLE OF THE PI AND CO-PI. The supervision of the student will be equally shared by the three applicants. The PI and co-PI have an internationally recognised expertise in plasma astrophysics and high-energy density laboratory astrophysics, with over 100 published articles in the field. Lately, they have developed a series of novel and unique studies of astrophysically relevant phenomena using magnetized laser-produced plasmas (shocks, accretion-ejection in stars, reconnection, particle acceleration...). The applicants are recognised experts in code development and numerical modeling: A. Ciardi and R. Smets are core developers of PHARE and A. Grassi has extensively used SMILEI and other PIC codes. They also have a demonstrated track record of access to national and international laser facilities as **principal investigators**, and have extensive experience in the supervision of PhD students..

SELECTED PUBLICATION BY THE APPLICANTS
→ Marret, A. Ciardi A, Smets, R., et al, "Enhancement of the non-resonant streaming instability by particle collisions", Phys. Rev. Lett. 128, 115101 (2022)
→ Tranchant et al. "New Class of Laboratory Astrophysics Experiments: Application to Radiative Accretion Processes around Neutron Stars", The Astrophysical Journal, 936, 14 (2022)
→ Yao, W. et al, "Laboratory evidence for proton energization by collisionless shock surfing", Nature Physics (2021).
→ Smets, R., Aunai, N, Ciardi A, et al, "A new method to dispatch split particles in Particle-In-Cell codes", Computer Physics Communications, Volume 261, 107666 (2021)
→ Fiuza F. Swadling GF, Grassi, A et al, "Electron acceleration in laboratory-produced turbulent collisionless shocks" Nature physics 16 (9), 916-920, (2020)
→ Albertazzi, B. et al., "Experimental characterization of the interaction zone between counter propagating Taylor Sedov blast waves", Physics of Plasmas 27, 022111 (2020)
→ Khiar, B. et al. "Laser-produced magnetic-Rayleigh-Taylor unstable plasma slabs in a 20 T magnetic field", Physical Review Letters 123, 205001 (2019)
→ Van Box Som, L., et al, "Numerical simulations of high-energy flows in accreting magnetic white dwarfs", Monthly Notices of the Royal Astronomical Society, Volume 473, Issue 3, Pages 3158–3168 (2018)
→ Revet et al, "Laboratory unravelling of matter accretion in young stars", Science Advances, Vol. 3, no. 11, e1700982 (2017)
→ Suzuki-Vidal, F, et al, "Bow shock fragmentation driven by a thermal instability in laboratory-astrophysics experiments", 2015, The Astrophysical Journal, Volume 815, pp. 96

SMILEI and PHARE codes
→ Derouillat, J.,…Grassi A.,...et al, "SMILEI: collaborative, open-source, multi-purpose particle-in-cell code for plasma simulation" Computer Physics Communications 222, 351 (2018).
→ Aunai, N, Smets, R, Ciardi, A. et al, "PHARE : Parallel hybrid particle-in-cell code with patch-based adaptive mesh refinement", under review in Computer Physics Communications.