Collisionless magnetized plasma interaction in the context of astrophysical experiments

Ph. Korneev[1,2], E. d'Humières[1], D. P. Higginson[3], J. Fuchs[3], R. Riquier[3],
H. Pepin[4], J. Beard[5], B. Pollock[6] and V. Tikhonchuk[1]
[1] *Univ. Bordeaux, CNRS, CELIA, France ;* [2] *NRNU MEPhI, Russian Federation ;*
[3] *LULI, Paris, France ;* [4] *INRS, Canada ;*
[5] *LNCMI, Toulouse, France ;* [6] *LLNL, Livermore, United States*

Introduction

Laboratory studies of a magnetized plasmas interaction now allow to approach astrophysical conditions, at least in terms of dimensionless ruling parameters. The usage of terawatt-class lasers in a combination with efficient magnetic pulsers allows to study physics, related to such astrophysical objects, as collisionless shocks [1] in supernovae remnants (SNRs), micro-quasars, Gamma-ray bursts (GRBs) [2], pulsars, blazers, Cosmic Rays (CR) [3] etc. One of the most evident experimental possibility is a magnetized plasma flows collision [4]. Such studies may give a better understanding of the formation of collisionless shocks, their structure, dependence on plasma parameters, i.e. flow velocity and magnetization, which is demanded by modern astrophysics.

Among certain questions in the modelling of astrophysical collisionless shocks in laboratory conditions, one of the most important is the initialization of the shock. Experiments, conducted recently, which deals with the counter-streaming plasma-plasma flows interaction, show an increasing of electron density in the interpenetration region in the presence of an ambient magnetic field compared to the case of its absence. Our theoretical studies, including numerical simulations, are performed to understand the experimental results. We show the highly nonlinear behaviour of plasma, due to the presence of the magnetic field. Several important features of an interaction in such a geomentry are distinguished, but at the same time we do not try to cover all the possible effects, intrinsic for experimental modelling of astrophysical effects. This means, that our palsmas are collisionless [5], we simplify the problem to a 2D3V in simulations and analytical models, and we do not take into account the composition of plasmas, it is supposed to be electron-proton plasma throughout the paper.

Two main features of experimental study of our interest are an accumulation of an external magnetic field during TNSA plasma expansion [6] and its compression when flows collide. In astrophysical context the collision of plasma flows in an external magnetic field seems irrele-

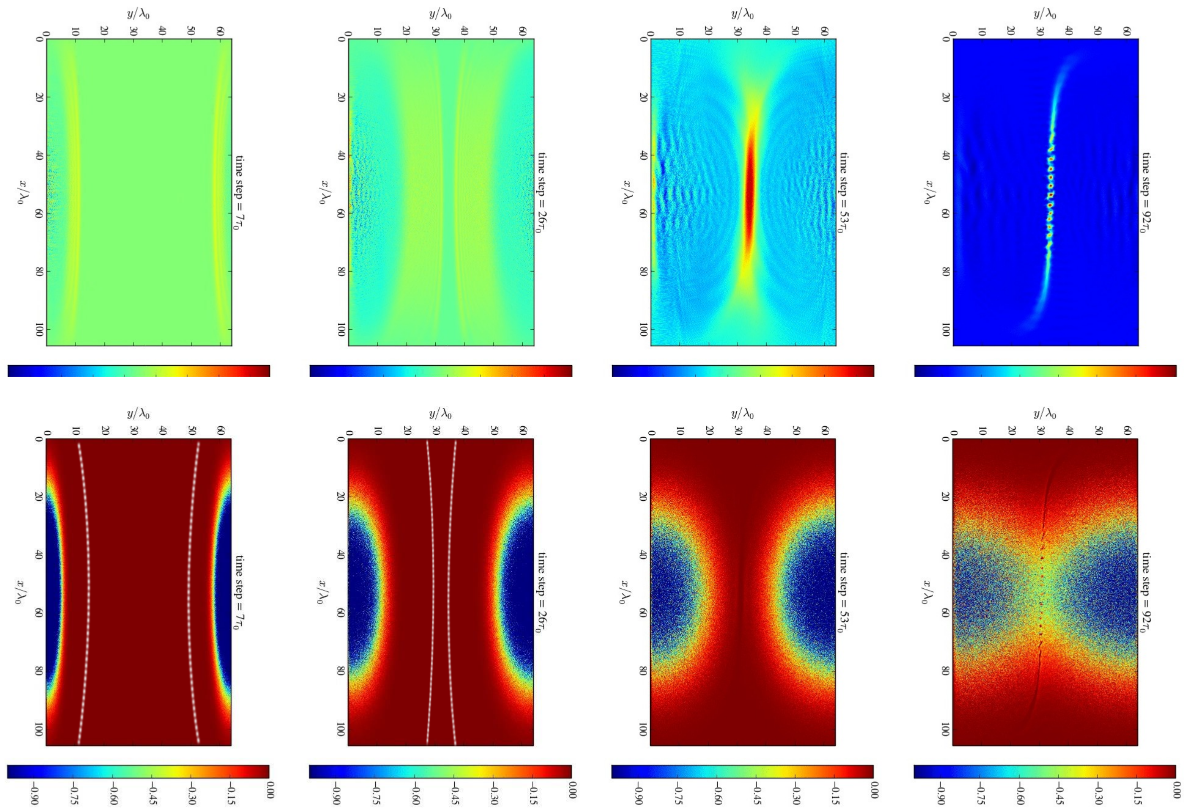

Figure 1: *Magnetic field (upper sequence of images) and electron density (lower sequence of images), from 2D3V PIC simulations, corresponding to the expansion of TNSA-like plasma profile in an ambient magnetic field. White dashed lines on density plots show the plasma cutoffs, so that in between white dashed lines it is vacuum. From left to right time moments:* $7\tau_0$, $26\tau_0$, $53\tau_0$, $92\tau_0$.

vant, since plasma is a carrier of a magnetic field in space. Then the interaction scheme, used in some previous studies, without vacuum separation, can better serve for a description of a developed shock structure, which has an astrophysical origin.

TNSA plasma expansion in an ambient magnetic field

For production of a relativistic plasma flow, one of the possibilities is a TNSA mechanism [7]. However, this process is not yet well understood when it occurs in an ambient magnetic field. From the simulations results presented here we may conclude, that, if plasma expansion is not ultrarelativistic, magnetic field around it in vacuum has a constant initial value. During plasma expansion, magnetic field is expelled [8], as we see also in our PIC simulations on figure 1. However, there is an intermediate region between plasma and vacuum field, which behavior brings a non-triviality to the process. On the time $7\tau_0$ on figure 1, it is already seen, that on the edge of the expanding plasma, where its density is several orders less, than in the main flow,

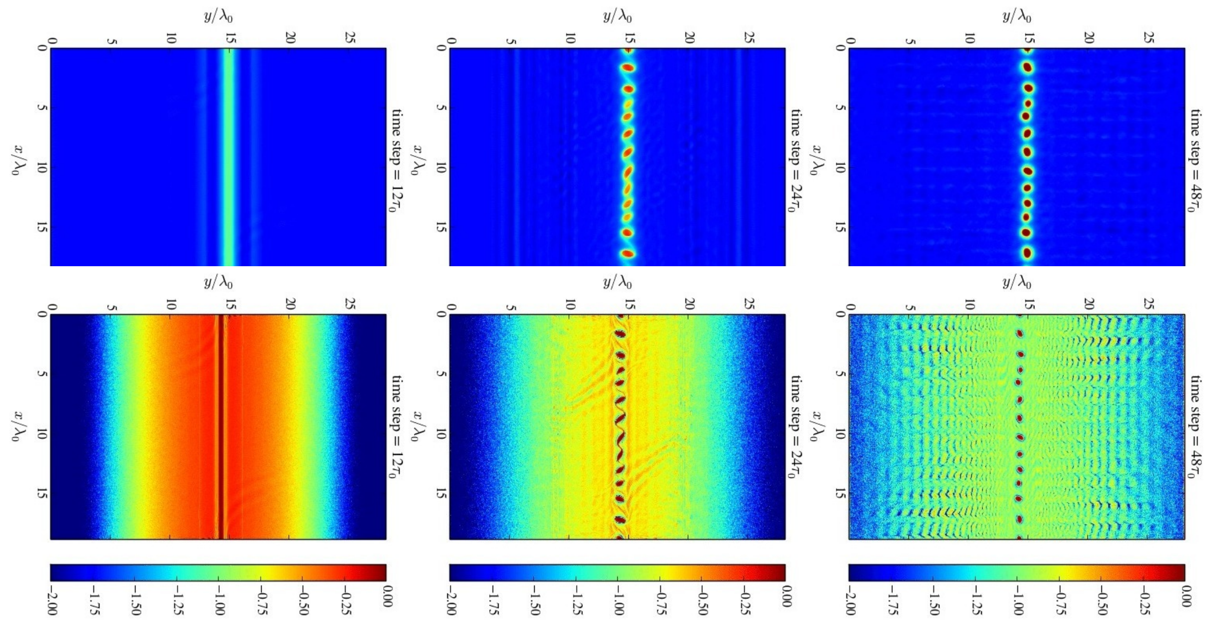

Figure 2: *A closer look (a different 2D3V PIC simulations, corresponding to the expansion of transversely homogeneous TNSA-like plasma profile in an ambient magnetic field) on the interaction region between plasma flows. Magnetic field (upper sequence of images) and density (lower sequence of images). From left to right time moments:* $12\tau_0$, $24\tau_0$, $48\tau_0$.

magnetic field increases. On the time step $26\tau_0$ on figure 1, almost just before plasmas begin to interpenetrate, the magnetized plasma region is wider, and its magnetization is higher. Later on, during the collision of main flows, this low-density plasma layer is compressed with the carried magnetic field, which is seen on the time step $53\tau_0$ on figure 1.

A very important issue turns out to be the fact, that available magnetic field, of the order of several tenth of Teslas in pulsers, can affect the TNSA plasma interaction. It is well understood, that with relativistic laser intensities one inevitably produces magnetic fields during TNSA, which are of the order of relativistic values, much higher, than an applied ambient field. However, during the expansion, plasma shovels up a great part of the magnetic flux on its way. As a result, the final stage of interaction of main flows is preceeded by the stage of a compression of *magnetized* low-density plasmas.

Instability between plasma flows.

The initial stage of the interaction between the compressed magnetic field and main parts of TNSA flows are shown in more detail on figure 2. The scenario reminds results from [9], where a model problem of interaction of two plasmas with a constant density profile and a constant velocity was considered. In [9], a stability analysis was presented for this stage. The TNSA plasma profile considered here brings certain changes to the preceeding analysis. The main difference is that the region between dense plasmas is partially neutralized by electrons which were magnetized during the expansion stage. However, the density of these electrons is still much less, than the density of the main flows, even after the compression. It is clear from the density (lower) row of images on figure 2.

An observed on figure 2 magnetic structure plays an important role in later evolution. The pronounced effect is an amplification of electrostatic instability, seen at the time moment $48\tau_0$ on figure 2, as a density modulation in a direction normal to plasma flows propagation. This effect is caused by an average electrostatic field modulation because of a charge separation near magnetic islands. It serves as a seed of an instability developed in the passing electron fluxes. For later times this modulation is supressed and Weibel instability starts to dominate.

Conclusions

In conclusion, we have shown a set of effects, intrinsic to a TNSA-like plasma expansion and plasma flows interaction in an ambient magnetic field. The most pronounced effect of an ambient magnetic field, is its accumulation and compression up to values, which exceeds even relativistic fields, generated by a TNSA process itself. The considered effects are to be taken into account when planning this type of experiments in a context of laboratory astrophysics.

References

[1] L. Sironi and A. Spitkovsky, *The Astrophysical Journal*, vol. 726, no. 2, p. 75, 2011.

[2] T. Piran, *Rev. Mod. Phys.*, vol. 76, pp. 1143–1210, Jan 2005.

[3] V. S. Ptuskin, *Physics-Uspekhi*, vol. 50, no. 5, pp. 534–540, 2007.

[4] J. S. Ross et.al., *Physics of Plasmas*, vol. 19, no. 5, p. 056501, 2012.

[5] D. D. Ryutov et.al., *Physics of Plasmas (1994-present)*, vol. 21, no. 3, pp. –, 2014.

[6] S. C. Wilks et.al., *Physics of Plasmas (1994-present)*, vol. 8, no. 2, 2001.

[7] P. Mora, *Phys. Rev. Lett.*, vol. 90, p. 185002, May 2003.

[8] D. Anderson, M. Bonnedal, and M. Lisak, *Physica Scripta*, vol. 22, no. 5, p. 507, 1980.

[9] P. Korneev, E. d'Humières, and V. Tikhonchuk, *Physics of Plasmas (1994-present)*, vol. 21, no. 2, 2014.