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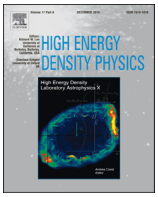

# Collisional–radiative simulations of a supersonic and radiatively cooled aluminum plasma jet

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ABSTRACT

A computational investigation based on collisional–radiative simulations of a supersonic and radiatively cooled aluminum plasma jet is presented. The jet, both in vacuum and in argon ambient gas, was produced on the MAGPIE (Mega Ampere Generator for Plasma Implosion Experiments) generator and is formed by ablation of an aluminum foil driven by a 1.4 MA, 250 ns current pulse in a radial foil Z-pinch configuration. In this work, population kinetics and radiative properties simulations of the jet in different theoretical approximations were performed. In particular, local thermodynamic equilibrium (LTE), non-LTE steady state (SS) and non-LTE time dependent (TD) models have been considered. This study allows us to make a convenient microscopic characterization of the aluminum plasma jet.

## 1. Introduction

High energy density laboratory astrophysics is a recent experimental research area that allows us to reproduce extreme astrophysical conditions in a laboratory. Nowadays, it is possible to emulate in laboratory astrophysical systems like stellar and planetary interiors, supernova explosions and supernova remnants, protostellar jets and other flows with a high Mach number, accretion disks around compact objects… [1], which represents a very important step forward in their study and understanding since the traditional analysis of these astrophysical objects was through theoretical study and numerical simulations. Two developments have contributed to the successful design of laboratory astrophysics experiments: on the one hand, the improvement of high-power laser systems and magnetic pinch facilities, that enable to generate plasmas in an astrophysical regime, and, on the other hand, the ability to scale astrophysical phenomena to laboratory experiments, although their length scales are clearly different [2,3]. This scaling method asserts that two physical systems of disparate length scales will behave identically if they are hydrodynamically similar.

Highly-collimated, supersonic jets and outflows are astrophysical phenomena of great interest since they are found in many objects throughout the universe, such as those ejected from galaxies or from stars in their formation stage [4] and their investigation is a topic of active interest. With that purpose, well-controlled and well-diagnosed laboratory experiments on high Mach number hydrodynamics jets are being carried out [1], either using high power lasers [5–7] or magnetic pinch facilities [8–12,4]. Many of these experimental works provide numerical simulations by means of hydrodynamics codes of the dynamic of the jets. However, in some cases the microscopic properties required in these simulations (such as the average ionization, plasma level populations or the radiative properties) are obtained with simplified population kinetic models (assuming, for example, local thermodynamic equilibrium (LTE) regime for all the plasma conditions under analysis) and, as far as we know, there are not available analysis of the influence of the kinetic model employed to calculate these plasma microscopic properties in the plasma conditions and for the elements of these experiments. This analysis is interesting for at least two reasons: first, this provides information about what issues affect the calculation

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of the plasma microscopic properties (such as for example, time dependence, influence of the plasma radiation self-absorption or the relative importance of the radiative driven atomic process); second, and as a consequence, the analysis also permits to determine which could be the most appropriate model or if a simplified model (such as, for example, steady-state non-LTE (NLTE) or LTE) can be used to obtain the microscopic properties required in the hydrodynamic simulation, which is a useful information since it reduces considerably the complexity and the computing time to calculate them.

This work has been designed in this context. Its main goal is to perform a qualitative analysis of the influence of the population kinetic models employed to calculate the plasma microscopic properties of a supersonic and radiatively cooled aluminum plasma jet, both in vacuum and in presence of an argon ambient gas. The jet (see F. Suzuki-Vidal et al. [13]) was produced on the MAGPIE generator and is formed by ablation of an aluminum foil driven by a 1.4 MA, 250 ns current pulse in a radial foil Z-pinch configuration. The aim of the authors were to reproduce in laboratory the jets launched from young stars, which are known as Herbig–Haro objects, and that are essential in the star formation. In this work the plasma population kinetic models considered have been LTE, steady-state NLTE (SS) and time-dependent NLTE (TD). Furthermore, for the last two models, we have considered either plasma radiation self-absorption or not in the calculation of the plasma level populations (i.e., assuming the plasma as optically thick or thin, respectively). The microscopic properties analyzed have been the average ionization, the radiative power loss (RPL) and the Planck mean opacity. Furthermore, we have also analyzed the influence of the population kinetic models in the calculation of the monochromatic opacities and emissivities and in the transverse specific intensities (with respect to the axis of the jet) emitted by the jet. The latter could be used to perform spectroscopic diagnostics of the electron density and temperature of the jet if the experiment is designed in such a way that the radiation is measured. Moreover, the transverse radiation could affect the ablation shock (a shock extending from the tip of the jet towards large radii [4]) that the jet generates when it propagates in an ambient gas, and, for this reason, its study is also interesting.

The remainder of the paper is organized as follows: in Section 2 a brief description of the main characteristics experimentally observed of the dynamics of the jet both in vacuum and argon ambient gas is presented. A brief description of the main theoretical considerations of the collisional–radiative and radiative properties models is made in Section 3. Also, in this section, we describe how was discretized the jet in cells in order to perform the collisional–radiative simulations. In Section 4 the study of the influence of the kinetic population model in the calculation of the average properties, the monochromatic radiative properties and the intensity of the radiation emitted by the jet, both when it is propagating in vacuum or in argon as an ambient gas, is presented. And finally, in Section 5 main conclusions and general remarks are presented.

## 2. Dynamics of the jet

Jets are produced on the MAGPIE generator by the ablation of plasma from surface of aluminum foil driven by the 1.4 MA, 250 ns current pulse in a radial foil Z-pinch configuration. The experimental setup, plasma diagnostic, dynamics of plasma formation and magneto-hydrodynamics (MHD) simulations were described in detail in previous works [13–17] and we give a brief description here. An example of the structure and evolution of the plasma jet in the absence of ambient medium as well as in the presence of ambient gas (argon) is illustrated by XUV images in Fig. 1 [13].

In vacuum, the figure reveals that the jet is highly collimated, with an aspect ratio 20 (jet length to jet radius). The flow is sustained to at least 470 ns and the tip of the jet reaches at least a height of 35 mm above the foil. The jet has a well-define smooth boundary, a very high degree of azimuthal (and radial) symmetry, an electron density profile that decreases with height (along the axial direction) and it has no noticeable perturbation in its shape or in the intensity of the emission. One important parameter is the velocity of the jet. It has been observed that the jet is supersonic with velocities of the tip of the jet greater than 100 km/s and Mach numbers 3–5. In the case where argon is present above the foil (as an ambient gas) the gas does not disrupt the formation of a well-defined collimated jet, but leads to the appearance of a number of new features. As time passes, the ablation from aluminum foil extends radially. Consequently, a shock (or ablation shock) is launched which moves vertically upwards and expands radially. This shock starts converging onto the axis, eventually forming a plasma column (or jet), following a zippering implosion. Both the central jet and the ablation shock remain well-defined throughout the entire experiment. At 240 ns (near peak current) the jet reaches its minimum diameter (1 mm), which then gradually increases with time. From 300 ns appears a secondary shock (or bow shock) propagating on axis ahead of the ablation shock (see Fig. 1). This bow shock is driven by re-direction and acceleration of the flow produced by a nozzle-like structure formed at the tip of the ablation shock. In a previous work [13], numerical simulations of the experiments were performed with the GORGON code [18], an explicit, parallel code designed to solve the resistive MHD equations on 3-D Cartesian grid employing a Van Leer type algorithm. Fig. 2 shows a comparison between mass density and electron temperature profiles on the axis of the jet with and without the presence or argon at

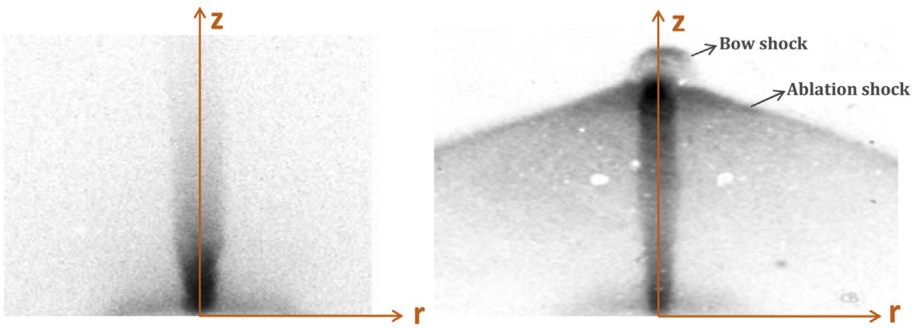

**Fig. 1.** XUV self-emission images of a jet from a radial foil propagating in the absence of ambient medium (left) and in the presence of argon ambient gas (right) [13] at 320 and 330 ns, respectively.