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Intense EM filamentation in relativistic hot plasmas

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ABSTRACT

Through 2D particle-in-cell (PIC) simulations, we demonstrate that the nature of filamentation of a high intensity electromagnetic (EM) pulse propagating in an underdense plasma, is profoundly affected at relativistically high temperatures. The "relativistic" filaments are sharper, are dramatically extended (along the direction of propagation), and live much longer than their lower temperature counterparts. The thermally boosted electron inertia is invoked to understand this very interesting and powerful phenomenon.

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1. Introduction

Laser filamentation is one of the rather profound expressions of nonlinear processes unleashed during the interaction of a high amplitude laser pulse with a plasma (laser created or otherwise). The phenomenon has been vigorously investigated, both experimentally and theoretically [1–6] because of its intrinsic scientific challenges, and because of its immense relevance to astrophysics [7,8] and other areas of physics [9–11].

The basic physics of filamentation, originating in the density dependence of the refractive/dispersive properties of the plasma, is quite simple. When a propagating intense laser beam encounters a density perturbation in the plasma, it is, preferentially, refracted to lower density regions (more transparent to the electromagnetic wave) boosting up the local energy density. The ponderomotive force resulting from the differential (inhomogeneous) local electromagnetic (EM) energy density, by pushing the plasma particles from the low to the high density regions, sets in the positive feed back instability that piles up more and more electromagnetic energy into the density troughs. Eventually, the laser beam filaments and begins to flow in narrow plasma channels that are characterized by high EM intensity simultaneous with low plasma density [12].

It is natural to expect that the basic laser/plasma parameters (laser power, frequency, energy distribution, plasma density and temperature [12,13]), that determine the linear and nonlinear refraction coefficient and the ponderomotive force, will also control the dynamics of filamentation. There are several physical observables that may be invoked to characterize filamentation: the onset time, the extension of the filament along the direction of propagation (to be called the filament length, L_F), and the persistence time before the filaments begin to diffuse by new nonlinear processes. Both the spatial extension and longevity of the filaments can serve as characteristic measures of the filament "quality". The primary determinants of L_F, for example, must be the basic laser/plasma parameters. It is found, however, that additional factors, like the wave polarization might also influence the filaments length; the temperature T and the effective mass, measured in energy units, tend to be smaller for linear polarization as compared to circular polarization due to a higher nonlinear coefficient [14,15].

Although we did list plasma temperature as a possible parameter that influences the filamentation dynamics, there is very little theoretical or experimental effort to chart out what the variation of temperature actually does. The goal of this paper, therefore, is to investigate the temperature dependence of filamentation dynamics through Particle-in-cell (PIC) simulations of the fate of a high intensity EM pulse propagating in a hot under dense plasma. Bulk relativistic electrons and ions with temperatures of multi-MeV have been achieved in laboratory [16,17] and observed in astrophysical systems [18]. Multiple MeV plasma will be routinely created in the class of experiment called "laboratory astrophysics" [19]. Thus in our simulations, the plasma is allowed to be fully relativistic both kinematically and thermally, i.e., T/m can be greater than 1. In this paper, the temperature T is measured in energy units, m is the electron rest mass, and the speed of light, $c = 1$.

We find that, although the filamentation dynamics is relatively insensitive to temperature variation in the nonrelativistic regime

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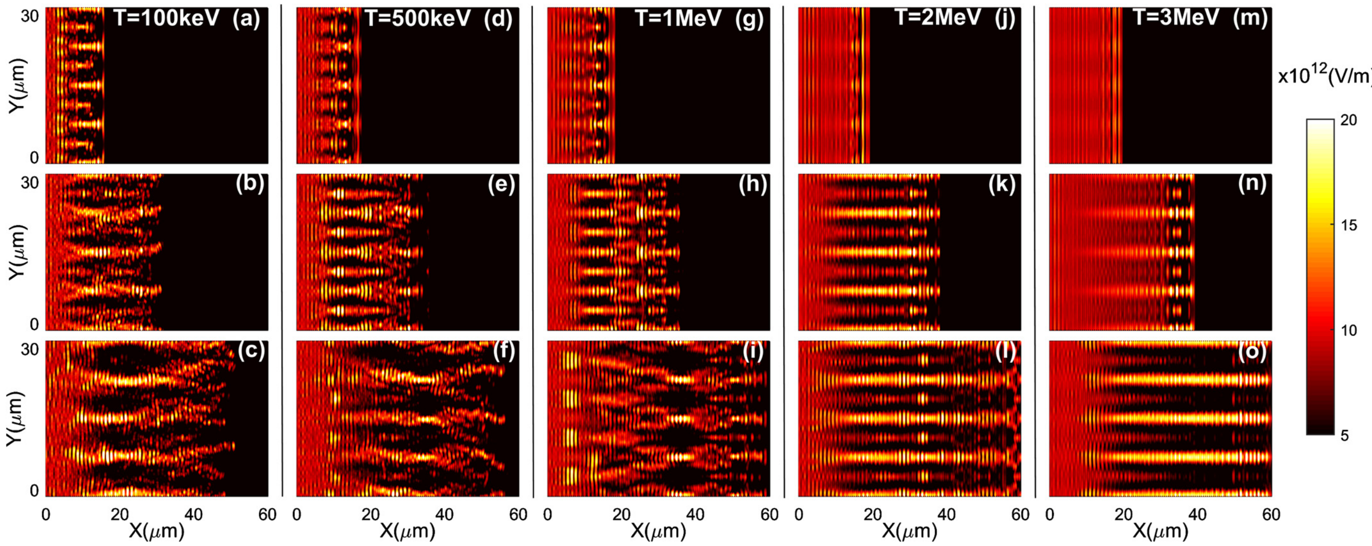

Fig. 1. Snapshots of the laser electric field strength inside the plasma. From left to right, the columns correspond, respectively, to plasma temperatures: $T = 100$ keV, 500 keV, 1 MeV, 2 MeV and 3 MeV. The first, 2nd and 3rd rows show snapshots at time $t = 75$ fs, 150 fs and 250 fs respectively.

($T \ll m \approx 500$ keV), it is profoundly affected in the regime of relativistic temperatures. As T/m becomes bigger than unity, the onset of filamentation is delayed, but once formed, the filaments are sharp, are spectacularly extended (larger L_F), and persist for a longer time. Later, we will proffer a theoretical explanation for the simulation results that we now describe.

2. Simulation – results

To elicit the essential features of EM filamentation in high temperature plasmas, we carried out 2D simulations using a fully relativistic PIC code (EPOCH) [20,21]. We study a neutral proton–electron plasma and a simulation box of size 60 μm × 30 μm containing 900 × 450 cells. Initially, the ions and electrons have the designated temperature and a number density $n = n_c/2$ (n_c is the critical density) or 8000 particles per cell. A laser, linearly polarized in the z-direction, propagating in the x-direction, with intensity

$$I = I_0 \left[1 + \delta \cos\left(k_y y\right)\right] \cos^2 \left(k_x x - \omega t\right) \tag{1}$$

is normally incident from the left ($x = 0$ μm). In our simulations, the main part of the beam has an intensity $I_0 = 1.24 \times 10^{23}$ W/m^2 and its wavelength $\lambda = 1.06$ μm. The perturbation $\delta \cos\left(k_y y\right)$ has an amplitude $\delta = 0.02$, and a wave vector $k_y = 8\pi/30$ μm^{-1} in the y-direction. Simulations invoke periodic boundary conditions in the y-direction.

The most important of our results are displayed in a set of snapshots shown in Fig. 1, showing, for different initial temperatures, the filamented structure of the laser beam at three different times: $t = 75, 150$ and 250 fs (evolving from an initial ($t = 0$) y profile that is essentially uniform with a small $\delta = 0.02$ modulation). We note:

1) For higher temperatures, the filamentation begins at later times; in the 75 fs row, for example, the filamentation is clearly manifest at 100 and 500 keV, it is barely discernible at 1 MeV, is about to begin at 2 MeV, and is absent at 3 MeV. At a later time, $t = 150$ fs, the filaments are beginning to diffuse for lower temperatures, while sharp, well-formed distinctive filamented structures emerge at higher T; the trend continues in the 250 fs frames; filamentation is sharpest at 3 MeV.

2) Though the filamentation has a delayed onset at high temperatures, it is at relativistic temperatures where the filamentation dynamics is most spectacular; the spatial extension L_F of the stable filaments increases rapidly with temperature as is reflected clearly in the frames displayed in the last row of Fig. 1. From the L_F versus T curve in Fig. 2, we deduce; i) in the entire non relativistic range (unto $T \approx 300$ keV), L_F is essentially unchanged, ii) as we enter and go deeper into the relativistic regime, the filaments live longer and become very extended in the direction of propagation; in, fact, L_F shows an "explosive" increase after T/m crosses unity.

3) In all cases, the peak electric field strength in the established filamentation is about 3 times the incident wave amplitude (9.66×10^{12} V/m).

4) The filamentation dynamics is rather complex and multiply structured; in addition to the main filaments (large concentration of EM energy) formed about the crests of the δ perturbation, second order filaments, with somewhat weaker energy concentration, are seen to grow in between the main filaments (Fig. 1). Although it is the very sharp main filaments that represent the principle nonlinear reorganization of the plasma-laser system (instead of the leaser beam propagating with a uniform y profile, it flows through low density plasma channels), the nonlinear physics of the formation (and then weakening) of the secondary filaments is highly interesting and very involved.

5) To demonstrate that the basic characteristics of the filamentation phenomena are independent of the magnitude of the perturbation, we carried out simulations with several values of δ (0.01, 0.02 and 0.04) and found no qualitative difference. The temperature dependence of the filamentation length, L_F (one of the key results), was nearly the same for all values of δ.

3. Theoretical explanation – discussion

In order to understand and properly interpret the remarkable change in dynamics brought about by relativistic temperatures, let us review, in some detail, the basic determinants of the nonlinear processes that lead to filamentation.

It was mentioned earlier that the density dependent refractive properties of the plasma, in conjunction with the ponderomotive force, may be the root cause of filament formation. That statement, however, is only partially correct. Although for non-relativistic temperatures, the refractive properties do, indeed, remain essentially independent of thermal energy, they are strongly affected in the regime of relativistic temperatures. Let us exam-

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