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THE INFLUENCE OF ION MASS IN PLASMA BUNCHES ON THE EFFICIENCY OF ALFVÉN WAVE GENERATION AND PROPAGATION IN PARTIALLY IONIZED PLASMA

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Abstract. This study employs numerical modeling to investigate the generation and propagation of Alfvén waves from a periodic sequence of plasma bunches in a partially ionized background plasma, operating in a sub-Alfvénic bunch expansion mode. We specifically examine the influence of plasma bunch ion mass on the amplitude and structure of the resulting Alfvén wave.

Introduction

The generation of intense magnetohydrodynamic (MHD) waves in laboratory plasma is of considerable interest for fundamental research and for modeling space processes. However, traditional methods, such as particle beam injection or RF excitation, often limit the amplitude and spatial extent of the generated disturbances. Researchers at the Institute of Laser Physics SB RAS are studying the wave merging mechanism (WMM), a method that generates MHD waves through the resonant interaction of periodic laser plasma bunches with magnetized background plasma [1-2]. This approach enables the creation of intense and extended wave disturbances, including Alfvén waves, slow magnetosonic waves, and whistlers. Previous work [1-4] has established optimal dimensionless relationships (criteria) for generating an extended Alfvén wave with an amplitude of $B\varphi/B_0 \sim 0.3$.

The main objective of this work is to apply the WMM to study the generation and propagation of Alfvén waves in plasma containing neutrals, using different masses of bunch ions at Alfvén-Mach numbers $M_A=0.2$. We employ a four-fluid EMHD model to simulate the generation and propagation of these Alfvén waves (for details, see [1,5]). Our simulation uses a cylindrical coordinate system (r,φ,z) with the external magnetic field oriented along the Z axis. The relative density fraction of the neutral component in the background plasma is $P_{na}=1$.

Problem Formulation

The expansion of plasma bunches displaces the external magnetic field and forms a cavern. This cavern formation generates an induction electric field, which sets background plasma ions in motion. Under conditions where the ion Larmor radius is of the same order of magnitude as the dynamic radius—a scenario typical for laboratory experiments and many geophysical phenomena—the Lorentz force mediates the interaction between the background plasma and the bunch plasma (the so-called magnetic-laminar interaction mechanism). This interaction nonlinearly twists the background plasma and compresses it along the magnetic field axis. This compression increases the pressure and drives a plasma outflow along the magnetic field lines. The periodic nature of this process generates an extended plasma flow that propagates along the magnetic field. This flow remains confined within a flux tube whose transverse size is close to that of the cavern near the bunch source. In addition to the plasma flow, the system excites two types of waves: a slow magnetosonic wave and a torsional Alfvén wave, which arises from the Larmor rotation of ions. These waves transfer energy, momentum, and angular momentum [3-4]. When we transition from a single bunch to a periodic sequence, the bunches resonantly interact with the magnetized background plasma at a specific frequency *f*. This resonant interaction, via the Wave Merging Mechanism (WMM), forms an extended and intense wave [1-4]. For this numerical study, we varied the mass of the plasma bunch ions m_1 as the main parameter, assigning it values from 207 to 22 in proton mass units. This range corresponds to ions of Pb^+, Ag^+, Ar^+, and Na^+. We held all other system parameters constant: the number of pulses N=10, the Alfvén-Mach number M_A=0.2, the dimensionless bunch pulsation frequency $\omega_r = 0.33$, the background plasma beta β=0.01, and the ion-inertial length $L_{pi} = c/(\omega_{pi} R_d) = 0.1$. The characteristic spatial radius of the problem, *Rd*, which determines the braking radius of individual plasma bunches by the magnetic field, also remained constant. The background ions have a mass of m_0=4. Neutral background particles possess zero charge and the same mass m_0 as the background ions.

Results

Figure 1 illustrates the spatial structure of the azimuthal magnetic field of Alfvén wave generated by N = 10 plasma bunches, propagating in a fully ionized plasma (top) and in a plasma with neutrals P_{na}=1 (bottom). The boundary of the computational domain along the axis is Z = 0 ÷ 102 and along the R axis is 0 ÷ 8.

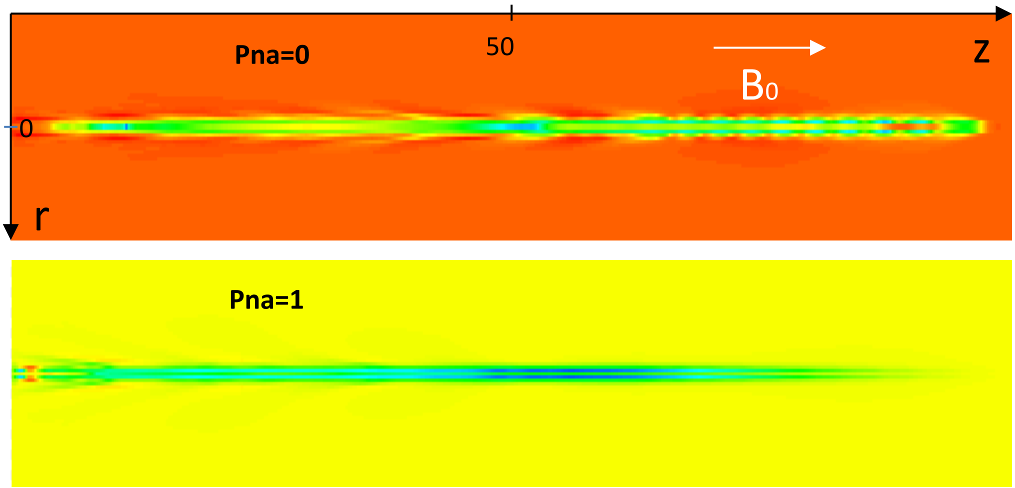

Figure 1. Spatial structure of the azimuthal magnetic field (Bφ) of the Alfvén wave generated by N=10 plasma clots. Left: Bφ propagates in plasma without neutrals (Pna=0); right, in plasma with neutrals (P_{na}=1). Time t=100. Source ion mass m_1=207, background ion mass m_0=4.

Figure 2 presents the profiles of the longitudinal current and the Alfvén wave. Figure 2A displays the distribution of the current that a train of N=10 bunches generates in a plasma for different bunch ion masses. For comparison, Figure 2B shows data for a single bunch (N=1) in two limiting cases: without neutrals (P_{na}=0) and with them present (P_{na}=1). As earlier work demonstrated [6], the Alfvén wave in the pre-Alfvénic bunch expansion regime consists of two parts: a front part, which the plasma clumps create, and an extended "tail" that forms after the bunches cease acting, resulting from the radial collapse of the plasma cloud. Our analysis of Figure 2A reveals that the wave amplitude changes with the mass of the bunch ions. The different efficiency of attenuation due to ion-neutral collisions serves as the main mechanism for this amplitude change. Although the drag force acting per unit plasma volume is proportional to the bunch mass density, the key factor is the difference in the inertial properties of the system. Lighter bunches (e.g., Ar^+, Na^+) easily transfer momentum to the neutral component and quickly achieve kinematic velocity matching. This process leads to efficient dissipation of the wave energy and strong damping. In contrast, bunches with heavier ions possess significant inertia, which allows them to maintain a high relative velocity between ions and neutrals. Consequently, energy lost in collisions accounts for a smaller fraction of the total oscillation energy. This inertial superiority reduces the damping efficiency and enables the wave to maintain a higher amplitude, as higher-mass bunches lose energy more slowly. Figure 3 illustrates the maximum amplitude of the wave's azimuthal magnetic field as a function of the bunch ion masses.

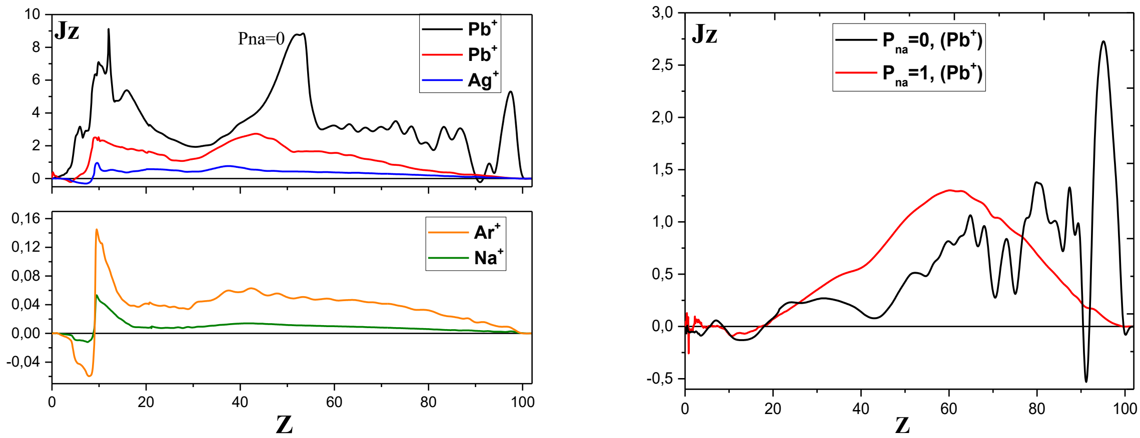

Figure 2. Longitudinal current Jz generated by N=10 plasma bunches with different bunch ion masses (A). Current Jz generated by one bunch with an initial background neutral density Pna=0 and 1 (B) at time t=100.

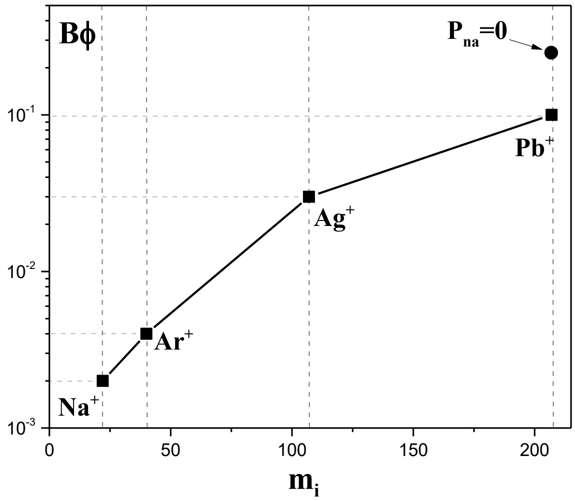

Figure 3. Dependence of the amplitude of the azimuthal magnetic field on the mass of the bunch ions at time t=100. The symbol (●) illustrates the maximum amplitude Bφ in the case of a fully ionized background plasma.

Figure 4 shows the time dependences of the efficiency of plasma bunch energy conversion into Alfvén wave energy for different bunch ion masses. Over time t = 20 ÷ 75, the efficiency of bunches with ion masses $m_I \leq 107$ decreases linearly, reaching values of η = 0.1 (Ag+), 0.01 (Ar+), and 0.008 (Na+). The maximum efficiency η ~ 0.3 is achieved when using ions with a mass m_I = 207.

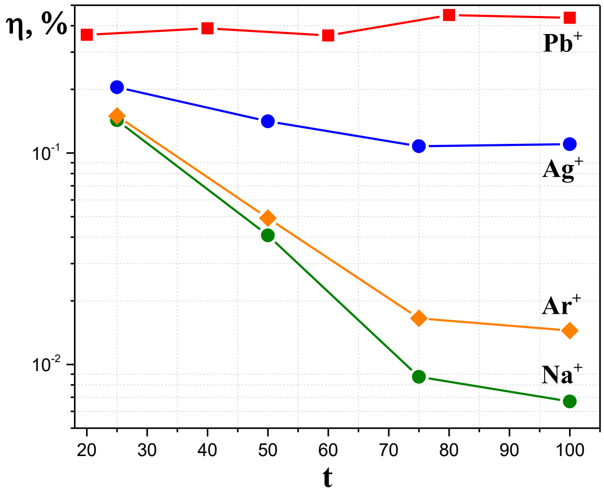

Figure 4. Time dependence of the energy conversion efficiency of bunches into Alfvén waves for different bunch ion masses. The computational domain for calculating the efficiency was ΔZ = 0 ÷ 100, ΔR = 0 ÷ 2 at time t=100.

Discussions

This paper presents the results of a numerical simulation on the generation of low-frequency Alfvén waves by periodic laser plasma bunches in partially ionized plasma under sub-Alfvénic expansion conditions. Our results demonstrate that the inertial properties of the ions significantly affect both the amplitude of the generated wave and the efficiency of converting bunch energy into wave energy. The efficiency of wave attenuation through ion-neutral collisions primarily governs this dependence. Lighter ions (e.g., Na^+, Ar^+) rapidly achieve kinematic matching with the neutral component. This process leads to intense energy dissipation, resulting in strong wave attenuation and low efficiency (η ~ 0.008–0.01). In contrast, heavy ions (e.g., with a mass of m_I=207) possess significant inertia, which enables them to maintain a high relative velocity with respect to neutrals for a longer duration. This inertia reduces the share of energy lost through collisions from the total oscillation energy, thereby decreasing damping. Consequently, heavy bunches generate Alfvén waves with a larger amplitude and achieve a maximum efficiency of η ~ 0.3.

Acknowledgments

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References

1. Tishchenko, V.N., & Shaikhislamov, I.F. (2014). Wave merging mechanism: formation of low-frequency Alfven and magnetosonic waves in cosmic plasmas. Quantum Electronics, 44(2), 98. DOI: 10.1070/QE2014v044n02ABEH015326
2. Tishchenko, V.N., Zakharov, Y.P., Shaikhislamov, I.F., Berezutskii, A.G., Boyarintsev, E.L., Melekhov, A.V., Ponomarenko, A.G., Posukh, V.G., Prokopov, P.A. (2016). Torsional Alfvén and slow magnetoacoustic waves generated by a plasma in a magnetic field. JETP letters, 104, 293-296. https://doi.org/10.1134/S0021364016170136
3. Tishchenko, V.N., Berezutskiy, A.G., Boyarintsev, E.L., Zakharov, Y.P., Melekhov, A.V., Miroshnichenko, I.B., Ponomarenko, A.G., Posukh, V.G., Shaikhislamov, I.D. (2017). Merging of the waves produced by optical breakdowns in rarefied plasma with a magnetic field. Laboratory modelling. Quantum Electronics, 47(9), 849. DOI: 10.1070/QEL16423
4. Berezutsky, A.G., Tishchenko, V.N., Zakharov, Y.P., Miroshnichenko, I.B., Shaikhislamov, I.F. (2019). Generation of torsional Alfvén and slow magnetosonic waves by periodic bunches of laser plasma in a magnetised background. Quantum Electronics, 49(2), 178. DOI: 10.1070/QEL16873
5. Berezutskiy, A.G., Tishchenko, V.N., Sharipov, S.S., Chibranov, A.A., Miroshnichenko, I.B., Shaikhislamov, I.F. (2025). Influence of neutral particles in plasma on the efficient generation and propagation of Alfvén waves created by periodic bunches of laser plasma. Quantum Electronics, 55(5), 280.
6. Tishchenko, V.N., Dmitrieva, L.R., Miroshnichenko, I.B., Shaikhislamov, I.F. (2022). Generation of Alfvén waves in magnetized plasma by laser plasma bunches at Mach numbers much less than unity. Solar-Terrestrial Physics, 8(2), 91-97. DOI: 10.12737/stp-82202214