https://doi.org/10.1070/QEL16423

Merging of the waves produced by optical breakdowns in rarefied plasma with a magnetic field. Laboratory modelling

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Abstract. **In laboratory experiments using laser plasma, the criteria are confirmed in which periodic plasma bunches form simultaneously two types of quasi-stationary waves: torsional Alfven and slow magnetosonic waves propagating along the magnetic field tube.**

Keywords: *wave merging mechanism, laser plasma, magnetic field, torsional Alfven wave, slow magnetosonic wave.*

It has now been established that the mechanism of merging of the waves produced by periodic explosive plasma bunches, for example, optical breakdowns on a solid target, makes it possible to form low-frequency waves. In a gas, low-frequency sound and ultrasound are possible simultaneously [1, 2]. In a magnetic field in a vacuum, a train of bunches generates quasi-stationary waves: a torsional Alfven wave (AW) and a slow magnetosonic wave (MW), which propagate in a magnetic field tube filled with a source plasma [3]. It follows from the calculations that the wave merging mechanism (WMM) functions also in rarefied plasma with a magnetic field (hereinafter, background), where the source produces AWs and MWs, and the lengths of the plasma regions occupied by them (the AW and MW lengths) depend linearly on the number of bunches [4–6]. The waves propagate along the field tube, whose radius is determined by the energy of one bunch, and transfer the momentum (MW) and the angular momentum (plasma rotation in the AW), while, for example, in [7, 8], the waves transferred only energy. The possibility of laboratory modelling of AWs, formed by a flash on the Sun, was considered by Prokopov et al. [9]. Niemann et al. [10] studied AWs produced by a single bunch in plasma with a magnetic field. Fields and currents in laser plasma were investigated near the target [11].

In general, the source generates a sequence of AWs and MWs at a repetition rate of bunches. Quasi-stationary AWs and MWs are formed when the criteria obtained using the calculations [6] are fulfilled. The purpose of this paper is an experimental verification of the criteria for merging AWs and MWs in plasma with a magnetic field. The criteria allow ionospheric AWs and MWs to be simulated in laboratory conditions and the source parameters to be determined as functions of the background characteristics.

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Received 4 May 2017; revision received 26 June 2017
Kvantovaya Elektronika **47** (9) 849–852 (2017)
Translated by I.A. Ulitkin

We will list the main characteristics of AWs and MWs [3–6]. A magnetosonic wave is a compression wave (increasing the concentration n_0) of the background plasma, whose magnetic field is 'displaced' (reduced) by B_z, so that the total pressure of the plasma and the magnetic field in the MW is equal to the background pressure. The AW characteristics include the longitudinal current J_z, azimuthal magnetic (B_φ) and radial electric (E_r) fields and plasma rotation velocity V_φ. The values of n_0, B_z and J_z are maximal on the wave axis, and B_φ and E_r are maximal at a distance $r \approx 0.15R_d$ from the axis, where R_d is the dynamic radius characterising the expansion of the bunch in the background. The current J_z is closed at the AW periphery ($r \approx 0.5R_d$). Plasma regions with AWs and MWs merge in a space if the AW velocity (C_A) is equal to the MW velocity (C_M). When $C_A \gg C_M$ (conditions in the ionosphere), the AW and MW regions are partially combined at the stage of the source action, and then the AW separates and moves ahead of the MW.

Let us define the criteria for wave merging.

1. A single AW and a single MW are formed if the dimensionless repetition rates of bunches are close to the 'resonant' frequency $\omega_r \approx 0.25 - 0.5$:

$$f_A R_d / C_A \approx \omega_r, \quad f_M R_d / C_M \approx \omega_r. \tag{1}$$

Here, f_A and f_M are the frequencies corresponding to the merging of individual AWs and MWs into quasi-stationary AWs and MWs; $R_d = \{8\pi Q/[B_0^2(1+\beta)]\}^{1/3} \approx 630\{Q/[B_0^2(1+\beta)]\}^{1/3}$ (R_d is taken in cm); Q (in J) is the bunch energy; B_0 (in Gs) is the external magnetic field; $\beta = 8\pi k_B(1+Z_0)n_0T_0/B_0^2 = 4\times10^{-11}(1+Z_0)n_0T_0/B_0^2$ is the ratio of the plasma pressure to the magnetic field pressure in the background; and n_0 (in cm^{-3}), Z_0 and T_0 (in eV) are the concentration, ion charge, and background plasma temperature, respectively. The velocities (in cm s^{-1}) of AW and MW propagation along the field tube are $C_A = B_0/(4\pi n_0 m_0)^{1/2} = 2.18\times10^{11}B_0/(n_0m_0)^{1/2}$ and $C_M = C_A/\sqrt{1+2/(\gamma\beta)}$, where m_0 (in a.m.u) is the mass of background ions, and $\gamma \approx 1.6$ is the adiabatic index of the background. In the ionosphere, $\beta < 1$ and $C_A \gg C_M$. A source operating at a frequency f produces the following waves. At $f \geqslant f_A \approx \omega_r C_A/R_d \approx 3.46\times10^8\omega_r B_0^{5/3}\times(1+\beta)^{1/3}/[Q^{1/3}(n_0m_0)^{1/2}]$ (f is taken in Hz), a single AW and a single MW are generated. At $f \gg f_A$, the length of the AW depends weakly on the number of bunches (see below). In the range $f \leqslant f_M \approx \omega_p C_M/R_d \approx f_A/\sqrt{1+2/(\gamma\beta)}$, separate periodic AWs and MWs are formed, and in the range $f_M < f < f_A$, a single MW and individual AWs are produced.

2. The ratio $\alpha = r_L/l_{pi}$ of the Larmor radius of the source ions, r_L, to the ion-plasma length of the background, l_{pi}, satisfies the inequality:

$$\alpha \geqslant M_A m_2 Z_0/(m_0 Z_2) > 5, \quad (2)$$

where $M_A = V_2/C_A \approx 0.5 - 2$ [5]; V_2 is the initial velocity of expansion of the bunch plasma; and m_2 and Z_2 are the mass and charge of the bunch ions, respectively. In the region $\alpha < 5$, the Alfven wave is unstable and its amplitude (J_z and B_φ) is small. For $\alpha > 5$, the AW amplitude increases with increasing α.

3. The Alfven wave is most intense if the Larmor radius of the bunch ions, r_L, normalised to R_d, is close to unity:

$$R_L = r_L/R_d = 1.59\times10^{-7} V_2 m_2 (1+\beta)^{1/3}/[Z_2(B_0 Q)^{1/3}] \approx 1. \quad (3)$$

In the range $R_L \approx 0.5-2$, the AW amplitude is weakly dependent on R_L.

4. The Alfven wave is formed if the ion-plasma length l_{pi}, normalised to R_d, satisfies the condition

$$L_{pi} = l_{pi}/R_d = 3.66\times10^4 Z_0^{-1} \times\sqrt{m_0/n_0}\,\sqrt[3]{B_0^2(1+\beta)/Q} \leqslant 0.25. \quad (4)$$

As L_{pi} increases, the AW amplitude decreases and the role of whistlers increases [9, 12].

With the above expressions, we estimate the advantages of a train of N_p bunches used to produce waves of extended length in comparison with a single high-energy bunch. The length of the waves and their duration (the time of passage of waves through the observation point) with the simultaneous formation of AWs and MWs are as follows:

$$L_A \approx C_A N_p/f_A \approx N_p R_d/\omega_r,\ L_M \approx a C_M N_p/f_A = a N_p R_d/[\omega_r\sqrt{1+2/(\gamma\beta)}],\ t_A \approx L_A/C_A \approx N_p/f_A = N_p R_d/(\omega_r C_A),\ t_M \approx L_M/C_M = a N_p R_d/(\omega_r C_A).$$

In the expressions for L_M and t_M, the factor $a \approx 1$ at a large distance from the source and $\sim$1.5 for $z < 5R_d$, since in the near zone the front of the MW moves at a velocity of $\sim 1.5C_M$. The ratios of L_A and L_M to the lengths of the waves from one bunch with the energy equal to the total energy of the train $Q_s = N_p Q$ are $\sim N_p^{2/3}$. One bunch produces waves with the same length as that of N_p bunches if its energy is $\sim N_p^2$ times larger than Q_s. The main disadvantages of a single high-power bunch in terms of the generation of AWs and MWs are the small length of the waves and their attenuation at scales of hundreds of R_d, and also the limitation of the maximum energy of the bunch by condition (3) for the formation of intense AWs in the ionosphere.

Figure 1 shows the scheme of the experiment on the KI-1 bench at the ILP SB RAS. The space background was simulated in a 5-m-long vacuum chamber ($\sim 2\times10^{-6}$ Torr) with a diameter of 1.2 m, where an axial magnetic field $B_0 \approx$ 175–350 Gs and a hydrogen plasma flow were formed (concentration $n_0 \approx 10^{13}$ cm^{-3}, velocity $\sim 3\times10^6$ cm s^{-1}). Laser plasma bunches were produced as a result of sequential irradiation of a polyethylene target (a disk with a diameter of 2.5 cm and a thickness of 0.5 cm) by radiation of two CO_2 lasers. The energy of the pulses was 150–200 J, their duration was about 1 μs and the energy density at the target was about 40 J cm^{-2}. Each of the laser beams was preliminarily split into two parts, which simultaneously created a plasma. Varying the delay time τ of the second laser pulse ($\tau \approx 0-100$ μs) made it possible to determine the frequency range ω_r, in which the bunches form a single AW and a single MW.

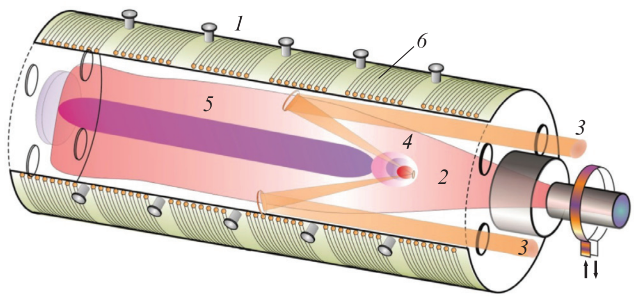

Figure 1. Scheme for modelling AWs and MWs on the KI-1 bench: (*1*) vacuum chamber; (*2*) plasma flow; (*3*) radiation from a CO_2 laser; (*4*) plasma bunches on the irradiated target; (*5*) AW and MW; (*6*) solenoid producing an axial magnetic field.

The following parameters were measured: for a MW, the longitudinal component of the magnetic field B_z, the plasma concentration $n(t)$ and the value of nV_z, where V_z is the longitudinal velocity of the plasma in the wave; for an AW – the azimuthal component of the magnetic field B_φ, the electric field E_r and the longitudinal current J_z (with the help of a Rogowski coil). Thus, we measured the space–time structure of the plasma glow using an electron-optical converter, as well as the energy and shape of laser pulses. The measurements were made in several cross sections of the chamber at distances of $\sim$1–2.5 m from the target. The temperatures of the background plasmas ($T_0 \approx 10$ eV) and MW ($T_2 \approx 30$ eV) were determined from the current–voltage characteristics of the sensors. Using this data, the energy of the bunch, $Q \approx$ 25 J, was found.

In the experiment, the background characteristics and the delay of the pulses τ were chosen taking into account conditions (1)–(4) and the bench capabilities that determine the energy of bunches, the initial velocity of their spread, the chamber radius, etc. The minimum background plasma concentration was obtained from (2) using formulas for C_A:

$$n_0 \geqslant 4.75\times10^{22} m_0[\alpha B_0 Z_2/(V_2 Z_0 m_2)]^2. \quad (5)$$

The results of calculating n_0 and other experimental parameters are shown in Fig. 2. The following values are used: $\alpha = 5$, $m_0 = 1$ a.m.u., $Z_0 = 1$, $T_0 \approx 10$ eV, $m_2 = 7$ a.m.u., $Z_2 = 2$ and $V_2 = 2\times10^7$ cm s^{-1}. The values of n_0 are bounded from above by the condition $\beta < 1$. The Larmor radius is found from formula (3), and the ion-plasma length $L_{pi} = 1.68\times10^{-7} V_2 m_2 \times (1+\beta)^{1/3}[\alpha Z_2(QB_0)^{1/3}]^{-1} \approx 0.8/B_0^{1/3}$ – from formulas (4) and (5). The ratio of the background plasma pressure to the magnetic field pressure is $\beta = 1.9\times10^{12}(1+Z_0)T_0 m_0 \alpha^2[Z_2/(V_2 Z_0 \times m_2)]^2 \approx 0.2$. Expressions (2) and (5) make it possible to find the velocities of the waves $C_A = V_2 Z_0 m_2 \times (\alpha m_0 Z_2)^{-1} \approx 1.4\times10^7$ cm s^{-1} and $C_M = C_A/[\sqrt{1+2/(\gamma\beta)}] \approx 5.2\times10^6$ cm s^{-1} and maximum delay of laser pulses $\tau = 132/(\omega_r B_0^{2/3})$, bounding from above the range of τ values at which a single AW is formed. The calculated value of $\tau(B_0)$ corresponds to the optimal frequency $\omega_r \approx 0.25$. In this case, a single MW is formed,

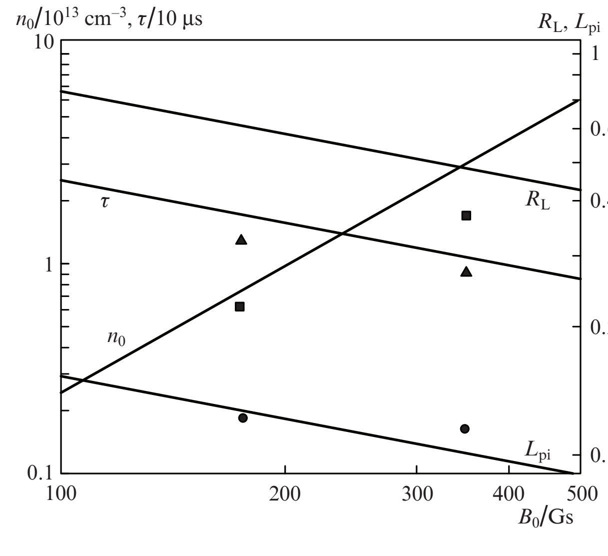

Figure 2. Dependence of experimental parameters on the magnetic field. Solid lines show the calculation, points – the experiment.

because the maximum delay for it is $\sqrt{1 + 2/(\gamma\beta)} \approx 2$ times greater than for an AW.

In the experiment, background plasma with a concentration $n_0 \approx (0.5-3)\times10^{13}$ cm^{-3}, close to the calculated one, was produced. The maximum energy of the bunches and the minimum field $B_0 \approx 175$ Ga are limited by the chamber radius of ~60 cm. The maximum length of the AW ($L_A \approx 2$ m) does not exceed the longitudinal size of the chamber. It is seen from Fig. 2 that the concentration n_0 measured in the experiment, as well as the Larmor radius and the ion-plasma length, normalised to the dynamic radius of the bunch, are close to the optimum values from (2)–(5). The value of τ corresponds to the maximum delay of the second laser pulse, in which the formation of a single AW and a single MW was observed in the experiment.

The merging of AWs and MWs, generated by plasma bunches when the target is irradiated with two laser pulses, is shown in Fig. 3. The time $t = 0$ corresponds to the arrival of the background plasma flux (Figs 3a, 3b) or waves (Fig. 3c) to the receiver. For a MW, the plasma concentration n and the change in the external field B_z in the MW are shown, and for an AW – the longitudinal current J_z and the azimuthal magnetic field B_φ. The pulse delay τ was varied, which made it possible to determine its maximum value and, thereby, the minimum frequency ω_r at which the WMM is realised.

Figure 3a shows the concentration of the background plasma at $B_0 = 175$ Gs in the absence of laser plasma, and also the plasma concentration when the target is irradiated with laser pulses simultaneously ($\tau = 0$) and with a delay $\tau = 8.5$ μs. Two bunches produce a more extended wave than one bunch with doubled energy. A good fit of the measured wavelengths of ~20 and 35 μs (at FWHM) with the calculated values of ~17 μs (one bunch) and 30 μs (two bunches) indicates the WMM efficiency for generating extended waves. Figure 3b illustrates the case when the merging condition is partially satisfied for the MW [$f_M R_d/C_M \approx 0.37$, see (1)], but not for the AW ($f_A R_d/C_A \approx 0.15$). As a result, a quasi-unified MW (see curves for n and B_z) and individual AW (curves for B_φ) are formed. The amplitude modulation of the MW decreases as the wave propagates. The AW moves ahead of the MW due to the difference in their velocities.

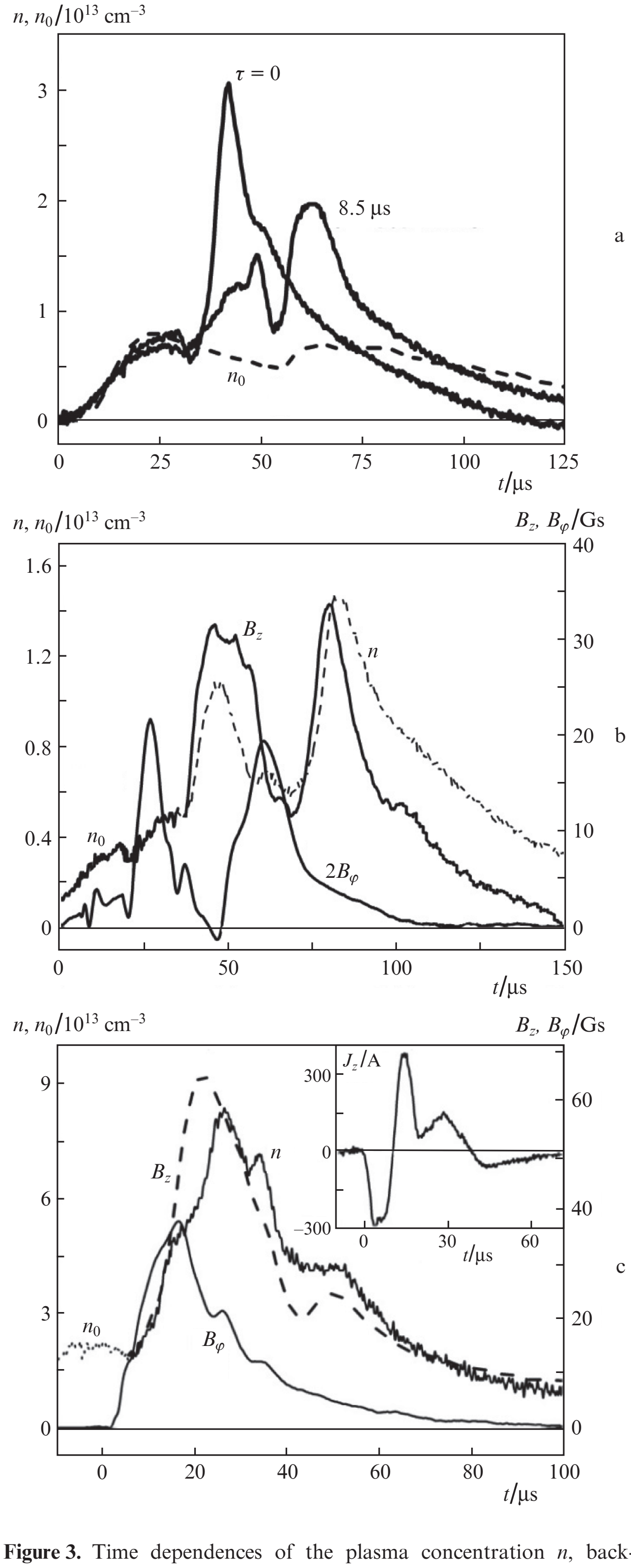

Figure 3. Time dependences of the plasma concentration n, background plasma concentration n_0 and magnetic field B_z in a slow MW, and also the azimuthal magnetic field B_φ and longitudinal current J_z (on the inset) in a torsional AW at B_0 = (a, b) 175 and (c) 350 Gs. The plasma concentration in the MW was determined for (a) $\tau = 0$ and 8.5 μs at a distance $z = 120$ cm from the target, (b) $\tau = 20$ μs, $z = 190$ cm and (c) $\tau = 7.5$ μs, $z = 150$ cm.

Figure 3c shows an example of the simultaneous formation of a single AW and a single MW, produced by bunches in a magnetic field $B_0 = 350$ Gs. The background plasma concentration is $n_0 \approx 2\times10^{13}$ cm^{-3}, and the delay between laser pulses, τ = 7.5 μs, corresponds to the frequencies satisfying the manifestation of the WMM for the AW and MW simultaneously. Other parameters are close to optimal ($\alpha \approx 7$, β = 0.27, L_{pi} = 0.12, R_L = 0.35); as a result, an intense AW is formed (the longitudinal current is $J_z \approx 300$ A, the plasma rotation velocity is $V_\varphi \approx C_A B_\varphi / B_0 = 1.6\times10^6$ cm s^{-1} and reaches $\sim0.25C_M$). Consequently, the MW and AW transfer not only the momentum, but also a large angular momentum.

Thus, when the conditions for wave merging are satisfied, a train of bunches forms extended waves – a slow MW and a strong torsional AW, the lengths of which depend linearly on the number of bunches.

Acknowledgements. This work was supported by the Presidium of the Russian Academy of Sciences ('Basic Foundations of Dual-Use Technologies in the Interests of National Security' Programme No. 31).

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