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The Myths and the Truth about Langmuir-Wave-Caused "Dips" in Spectral Line Profiles

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ABSTRACT: The Langmuir-wave-caused highly-localized structures (later called "dips" for brevity), consisting of a local minimum of the intensity surrounded by two "bumps" (peaks), – is an *emergent phenomenon* that originates from *multifrequency nonlinear dynamic resonances.* The analytical predictions of the Langmuir-wave-caused "dips" were confirmed in a large number of experiments by various experimental groups working at different plasma machines (including the high-precision, benchmark experiments at the gas-liner pinch where plasma parameters were measured by the coherent Thomson scattering independently of the measurements of the line profiles), as well as in astrophysical observations. However, recently Alexiou published simulations (Atoms, 2023, 11, 29) where he totally ignored the actual nature of the Langmuir-wave-caused dips and thus was unable to reproduce them for the experimental spectral line profiles from two papers describing the collaborative (experiment plus theory) projects on spectroscopic diagnostics of the relativistic laser-plasma interactions. Since Alexiou got totally confused on this subject, perhaps others could also get confused. Therefore, the purpose of the present paper is to clarify the confusion for the entire research community. First, we describe afresh the gist of the emergent phenomenon of highly-localized structures in spectral line profiles (Langmuir "dips") caused by multifrequency nonlinear dynamic resonances. Then we point out severe flaws in Alexiou simulations resulting in his double-failure: the failure to capture the emergent phenomenon of the Langmuir "dips" and the failure to fit the experimental profiles from the above two papers. Therefore, his criticism, being based on his flawed simulations and the lack of understanding of the relevant physical processes, is without merit. It is just the mythology.

Key words: multifrequency nonlinear dynamic resonances; emergent phenomena; Langmuir-wave-caused dips; quasienergy states

1. INTRODUCTION

The Langmuir-wave-caused highly-localized structures (later called "dips" for brevity), consisting of a local minimum of the intensity surrounded by two "bumps" (peaks), – is an *emergent phenomenon* that originates from *multifrequency nonlinear dynamic resonances* (see, e.g., papers [1, 2] and books [3, 4]). The analytical predictions of the Langmuir-wave-caused "dips" were confirmed in a large number of experiments by various experimental groups working at different plasma machines, as well as in astrophysical observations. In these experiments and observations, that span the range of the electron densities about 10 orders of magnitude, the Langmuir-wave-caused dips were reliably detected, identified, and used for plasma diagnostics. This included, in particular, the high-precision, benchmark experiments at the gas-liner pinch [5, 6], where plasma parameters were measured by the coherent Thomson scattering independently of the measurements of the line profiles.

However, recently Alexiou [7] published simulations where he totally ignored the actual nature of the Langmuir-wave-caused dips and thus was unable to reproduce them for the experimental spectral line profiles from papers [8, 9]: the papers describing the projects on spectroscopic diagnostics of the relativistic laser-plasma interactions – the projects resulting from the collaboration of experimentalists and theorists from seven countries (Japan, the UK, France, Germany, Hungary, the USA, and Russia). Since Alexiou got totally confused on this subject, perhaps others could also get confused. Therefore, the purpose of the present paper is to clarify the confusion for the entire research community.

The paper is structured as follows. First, we describe afresh the gist of the emergent phenomenon of highly-localized structures in spectral line profiles (Langmuir "dips") caused by multifrequency nonlinear dynamic resonances. Then we point out severe flaws in Alexiou simulations [7] resulting in his failure to fit the experimental profiles from papers [8, 9].

2. WHAT THE LANGMUIR-WAVE-CAUSED "DIPS" ACTUALLY ARE

The emergent phenomenon of the Langmuir-wave-caused highly-localized structures ("dips" which are the bump-dip-bump structures) in spectral line profiles (that Alexiou code failed to capture) was predicted analytically in papers [1, 2] and later presented also in books [3, 4]. By the way, Alexiou [7] did not point out any error in those analytical calculations.

In more detail, the physics behind the Langmuir-wave-caused structures is the following. Let us consider the electric field

$$\mathbf{E}(t) = \mathbf{F} + \mathbf{E}_0 \cos(\omega t), \tag{1}$$

where $\mathbf{F}$ represents the quasistatic part of the electric field in the plasma. The field $\mathbf{F}$ could have not only the contribution from the quasistatic part of the ion microfield, but also of the contribution from the low-frequency electrostatic plasma turbulence (such as, e.g., the ion acoustic waves, or lower hybrid waves, or Bernstein modes). If $\mathbf{F}$ and $\mathbf{E}_0$ are not collinear (which is true for the overwhelming majority of possible mutual orientations of vectors $\mathbf{F}$ and $\mathbf{E}_0$), then the total field $\mathbf{E}(t)$ is *librating*. The frequency spectrum of this librating field consists not only of the frequency ω, but also of its *harmonics*: the frequency spectrum of the librating field is uω, where u = 1, 2, 3, … .

We denote by F_{eff} the absolute value of the total electric field averaged over the period of the libration:

$$F_{eff} = \langle |\mathbf{E}(t)| \rangle. \tag{2}$$

If the librating nature of the total electric field would be first disregarded, the energy levels of a radiating hydrogenic atom/ion (the radiator) of the nuclear charge Z_r would split into 2n – 1 Stark sublevels separated by (in the atomic units)

$$\Omega = 3nF_{eff}/(2Z_r), \tag{3}$$

where n is the principal quantum number. The Stark sublevels are distinguished by the electric quantum number

$$q = n_1 - n_2, \tag{4}$$

where n_1 and n_2 are the parabolic quantum numbers.

The combined system "radiator + field" can be described in terms of quasienergy states (introduced by Zeldovich [10] and Ritus [11]), whose quasienergies Q are as follows:

$$Q = \Omega + v\omega, \quad v = 0, \pm 1, \pm 2, \pm 3, \dots \tag{4}$$

Now we take into account the time-dependent component of the librating electric field. We remind that its frequency spectrum is uù, where u = 1, 2, 3, … . Here we come to the central point. In the situation, where

$$\Omega = u\omega, \qquad u = 1, 2, 3, \dots, \tag{5}$$

there occur multiple resonances between the harmonics of the librating field and *all* quasienergy states of the quasienergies Q = Ω + vω. In other words, the resonances are multiquantum (in terms of the quanta of the Langmuir field) and multifrequency. It causes the degeneracy of all quasienergy states: the quasienergy harmonics, resulting from each of the 2n – 1 atomic Stark substates, superimpose with each other

In this multiquantum multifrequency resonance, each degenerate quasienergy state is a superposition of several quasienergy harmonics originating from different Stark sublevels (sublevels of different values of the electric quantum number q). The Stark sublevel of some value of q is coupled by the dipole matrix element with the sublevels of q + 1 and q – 1. As a result of this coupling, there occurs an additional splitting of *all* quasienergy harmonics. This splitting has an analogy with the Rabi splitting, but it is its generalization for the case of the multiquantum multifrequency resonances. The additional splitting of *all* quasienergy harmonics is generally a *nonlinear* function of the Langmuir field amplitude E_0 (see, e.g, Eq. (9) from paper [2]).

The multiquantum multifrequency resonances corresponds to a set of specific locations in the profile of a hydrogenlike spectral line – because they correspond to specific resonance values of F_{eff} satisfying the condition (5). These locations are separated from the center of the spectral line by the well-defined amounts of the wavelength $\Delta\lambda^{dip}$ (ω), where $\Delta\lambda^{dip}$ (ω) are well-defined functions of the Langmuir wave frequency $\omega = (4\pi e^2N_e/m_e)^{1/2}$, so that (see, e.g., books [3, 4])

$$\Delta\lambda^{dip} = aN_e^{1/2} + bN_e^{3/4}, \tag{6}$$

where the coefficients a and b are controlled by quantum numbers and by the charges of the radiating and perturbing ions. The identification of these structures in the experimental line profile allows a very accurate determination of the electron density N_e from the locations of these structures.

At each exact location in the line profile, corresponding to the resonance (5), (for brevity, the "resonance location") due to the generalized Rabi splitting of the quasienergies, there occurs a partial transfer of the intensity from the wavelength of the exact resonance location to adjacent wavelengths on each side of the exact resonance location. As a result, there can appear a structure consisting of the local depression of the intensity surrounded by two relatively small "bumps", as illustrated in Fig. 1.

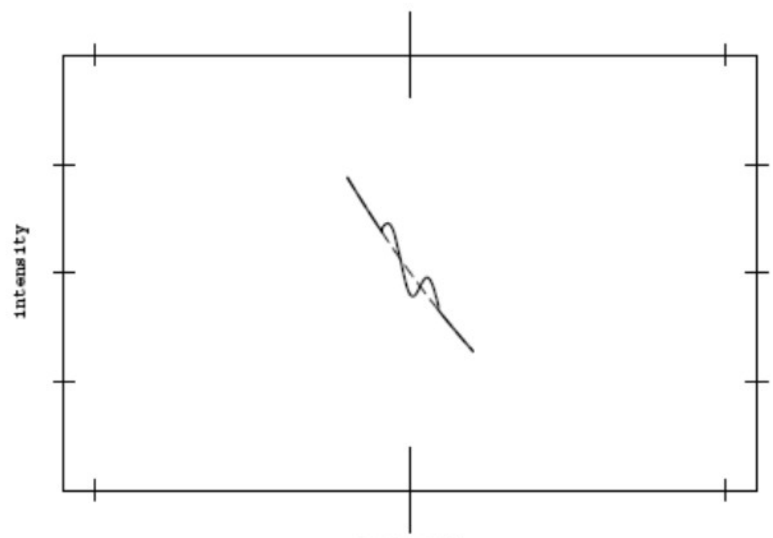

Fig. 1. Calculated "bump-dip-bump" structure, caused by the multifrequency nonlinear dynamic resonance (5), superimposed with an inclined "unperturbed" spectral line profile.

Being superimposed with an inclined "unperturbed" spectral profile, *each bump-dip-bump structure can be responsible for two local minima of the intensity* – as shown in Fig. 1 - rather than just for one local minimum of the intensity. The secondary minimum located at the higher intensity than the primary minimum is of no physical significance. Sometimes one of the two bumps and/or the secondary local minimum manifests only as a small "shoulder".

The analytically predicted Langmuir-wave-caused "dips" were then revealed in a large number of various experiments around the world [5, 6, 8, 12-20] and in astrophysical observations [21]. In these experiments and observations, the Langmuir-wave-caused "dips" were reliably detected, identified, and used for plasma diagnostics in plasmas of the electron density ranging from 10^{13} cm^{-3} to $3x10^{22}$ cm^{-3}.

For example, in the high-precision, benchmark experiments by the Kunze group at the gas-liner pinch [5, 6], where plasma parameters were measured by the coherent Thomson scattering independently of the measurements of the line profiles, first, it was reliably established the existence of the Langmuir-wave-caused "dips", the evolution of their positions as the electron density varied being consistent with the theory. Second, detailed bump-dip-bump structure in the was revealed experimentally for the first time – see Fig. 2.

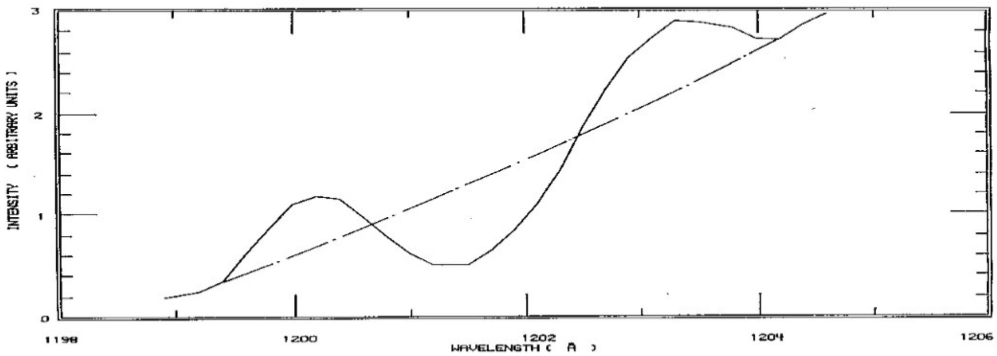

Fig. 2. A magnified part of the profile of the Ly-alpha line, obtained in the high-precision, benchmark experiment at the gas-liner pinch [6], showing the observed bump-dip-bump structure.

Third, it was also demonstrated that the experimental dip positions yielded the values of the electron density just as accurate as the electron density measured by the coherent Thomson scattering – see Fig. 3.

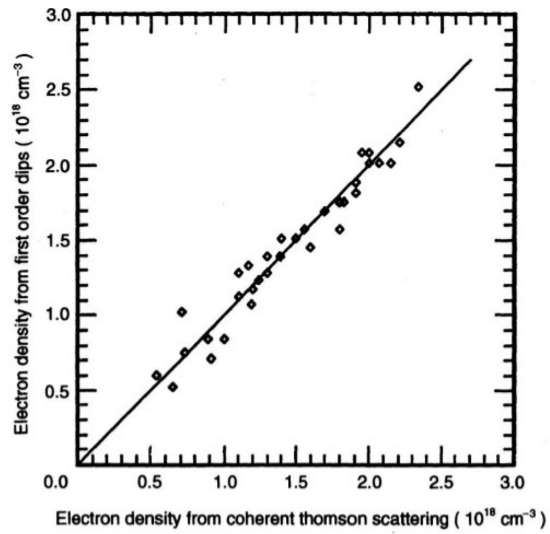

Fig. 3. Electron densities, obtained from the experimental positions of the Langmuir-wave-caused bump-dip-bump structures versus the electron densities measured by the coherent Thomson scattering. The comparison is shown at many electron densities in the experiments at the gas-liner pinch [6].

Thus, all theoretical predictions from papers [1, 2] (as well as from subsequent works covered in books [3, 4]), concerning the multifrequency nonlinear dynamic resonances and the resulting bump-dip-bump structures in spectral line profiles, have been confirmed and used for plasma diagnostics at numerous experiments around the world.

3. SEVERE FLAWS OF ALEXIOU PAPER

1. The primary flaw of Alexiou simulations is the following: he does not seem to understand the nature of the *emergent phenomenon* of Langmuir-wave-caused "dips" as stemming from the *multifrequency nonlinear dynamic resonance*. This kind of the resonance effects is beyond his code. From the outset, his code is tied to Blochinzew satellites (theoretically predicted by Blochinzew in 1933 [22]). What Alexiou calls "dips" are just *troughs between the peaks*, where the peaks are (shifted) Blochinzew satellites. Alexiou's definition of

the “dips” has absolutely nothing to do with the highly-localized structures in spectral line profiles caused by the multifrequency nonlinear dynamic resonances.

For a given hydrogenic spectral line, a given nuclear charge of the radiator, and a given charge of the perturbing ions, the locations of these structures (the Langmuir wave-caused “dips”) are controlled by the electron density N_e (which is why from the experimental locations of these structures one can deduce N_e with the same accuracy as if N_e would be measured by the Thomson scattering). In distinction, the locations of Alexiou’s troughs between the Blochinzew peaks (the troughs that he confused with the above structures manifesting the multifrequency nonlinear dynamic resonances) result from the interplay of many plasma parameters and practically cannot be used for determining the electron density. Just this primary flaw of Alexiou simulations would be the sufficient cause of his failure to fit the experimental data (that he attempted to fit).

By the way, it should be also clarified that under the condition $E_0 << F_{eff}$ (where F_{eff} is given by Eq. (2)) typical for all experiments in plasmas containing Langmuir waves, the observed local structures in the profiles can be only the Langmuir-wave-caused “dips”, rather than Blochinzew satellites, as explained in detail in section 7.1 of book [3]. Blochinzew satellites could be observed in the “underdense” regions of laser-produced plasmas where these satellites would be caused by the laser field, rather than by the field of the Langmuir waves. These are the regions below the critical electron density where the laser radiation can propagate inside the plasma and cause the situation where the laser amplitude significantly exceeds the quasistatic electric field in the plasma.

In general, computational simulations (codes), being only a model of nature, not nature itself, usually fail to capture emergent phenomena (and lack the physical insight) – see, e.g., [23, 24]. The primary advantage of analytical calculations over codes is that the former can capture emergent phenomena while the latter usually cannot.

Two leading experts in computational science, Post and Votta [23] emphasized the difference between the verification and validation of codes. They wrote: “By verification we mean the determination that the code solves the chosen model correctly. Validation, on the other hand, is the determination that the model itself captures the essential physical phenomena with adequate fidelity.” Further, they quoted the theorist Robert Laughlin: “One generally can’t get the right answer with the wrong equations.” In other words, if any simulation settings do not include the ability to model the specific phenomenon, such as the multifrequency nonlinear dynamic resonances, the simulation results would be inadequate to the corresponding physical reality. This is why Alexiou’s code failed to capture the emergent phenomenon of highly-localized structures in spectral line profiles originating from multifrequency nonlinear dynamic resonances.

2. Alexiou qualified the experimental spectra presented in parts A, B, and C of Fig. 3 from paper [8] as “noisy”. This indicates again that he does not seem to understand that the Langmuir-wave-caused “dip” is the structure consisting of the local minimum of the intensity (at the location controlled by the electron density) surrounding by two local maxima (“bumps”) plus the secondary minimum. With the understanding of this structure of each “dip”, all local minima and maxima of the intensity in parts A, B, and C of Fig. 3 from paper [8] have been identified, accounted for, and clearly indicated. Besides, the bump-to-dip ratio of the intensities was up to 45%, thus exceeding the noise level by at least one order of magnitude. No wonder that the experimental spectra, obtained with a high spectral resolution (l/dl ~ 3000), easily allowed the reliable and the only one possible identification of the above structures.
3. Another flaw of Alexiou paper is the following. He does not seem to understand that regardless of the specific distribution of the quasistatic field **F** over its magnitude and its direction, there is always a small group of radiators in the ensemble, for which the Stark splitting by the field **F** is in the multiquantum/ multifrequency resonance with the frequency of the Langmuir field $\mathbf{E}_0$ cos(ùt) and its harmonics. Therefore, the locations of the resulting highly-localized structures in the spectral line profiles do not depend on the specific distribution of the quasistatic field **F** – in distinction to the locations of the troughs between (shifted) Blochinzew satellites, calculated by Alexiou.
4. Alexiou also claims that distribution functions of the turbulent fields are not known. However, in reality the distribution functions of the quasistatic turbulent fields had been derived analytically in paper [25] already in

1976. One should study the literature instead of making false claims.

5. Besides, Alexiou claims to be the first to reveal that in plasmas containing Langmuir waves, the spectral line profiles exhibit directional/polarization effects. However, already in 1977, in paper [26] it was shown analytically that the highly-localized structures in spectral line profiles, emitted from such plasmas due to the above dynamical resonances, exhibit directional/polarization effects. Moreover, in the same year 1977, these polarization effects have been confirmed experimentally and used for plasma diagnostics in paper [12]. So, Alexiou is late by 45 years to qualify as the pioneer in this regard.

6. Alexiou is known by having numerous flaws in his codes. For example, in papers [27, 28], Alexiou used his code to simulate how the fact that in strongly-magnetized plasmas, perturbing electron move in helical (rather then rectilinear) trajectories, affects the width of hydrogen spectral line. He found that the width decreases compared to calculations using rectilinear trajectories.

However, in paper [29] it was shown analytically that actually the allowance for helical trajectories of perturbing electrons could lead to two different outcomes: to either decreasing or increasing the width of hydrogen lines – depending on the electron density and temperature, as well as on the quantum numbers of the energy levels involved in the radiative transition. For example, at some values of the electron density and temperature, the effect of the helical trajectories can decrease the width of the Balmer-alpha and Balmer-beta lines, but increase the width of the Balmer-delta and higher Balmer lines.

This failure of Alexiou's code stems from the general inferiority of simulations compared to the analytical theory: simulations are not able to yield the functional dependence of the effect under consideration on various input parameters (in important distinction to the analytical theory). Therefore, simulations in general and simulations by Alexiou in particular frequently miss the big picture.

Another example: compared to the widths of the Balmer-alpha line, measured in the benchmark experiment in the Kunze's group [30], Alexiou's simulations [31] dramatically underestimated the measured width – by 30% for the lowest density. (Again: in the benchmark experiment [30], plasma parameters were measured by the Thomson scattering independently of the measurements of the line profiles.) Instead of trying to find out what is wrong with his simulations, Alexiou suggested that this benchmark experiment is incorrect – the statement typical for him. However, physics is first and foremost the experimental science, rather than the "simulational" science – especially regarding precise, benchmark experiments performed in rigorously controlled conditions (such as, e.g., the experiment [30]). Typically, the benchmark experiments, rather than simulations, move physics to new horizons.

4. CONCLUSIONS

Highly-localized bump-dip-bump structures in spectral line profiles are an *emergent phenomenon* that springs from *multifrequency nonlinear dynamic resonances*. The central point of the physics behind the formation of these structures is that in the combined system "radiator + oscillating field" (more rigorously, "radiator + librating field"), the resonances cause the degeneracy of the quasienergy states – the degeneracy partially eliminated by the generalized Rabi splitting.

The analytical predictions of the emergent phenomenon of the Langmuir-wave-caused "dips" were confirmed in a large number of experiments by various experimental groups working at different plasma machines, as well as in astrophysical observations. In these experiments and observations, that span the range of the electron densities about 10 orders of magnitude, the Langmuir-wave-caused highly-localized structures were reliably detected, identified, and used for plasma diagnostics. This included, in particular, the high-precision, benchmark experiments at the gas-liner pinch [5, 6], where plasma parameters were measured by the coherent Thomson scattering independently of the measurements of the line profiles.

These multifrequency nonlinear dynamic resonances are beyond Alexiou's code. From the outset, his code is tied to Blochinzew satellites. What Alexiou calls "dips" are just *troughs between the peaks*, where the peaks are (shifted) Blochinzew satellites. Alexiou's definition of the "dips" has absolutely nothing to do with the highly-localized structures in spectral line profiles caused by the multifrequency nonlinear dynamic resonances.

The locations of Alexiou’s troughs between peaks (the troughs that he confused with the above structures manifesting the multifrequency nonlinear dynamic resonances) result from the interplay of many plasma parameters and practically cannot be used for determining the electron density. This is a clear distinction to the highly-localized structures, caused by the multifrequency nonlinear dynamic resonances, whose locations have one-to-one correspondence with the electron density N_e and were used for very accurate determination of N_e in numerous plasma experiments.

Just this *primary flaw* of Alexiou simulations would be the sufficient cause of his failure to fit the experimental data (that he attempted to fit) and is the reason why his criticism is pointless. Alexiou simulation settings did not include the ability to model the multifrequency nonlinear dynamic resonances, which is why he was unable to fit the experimental data from papers [8, 9].

Besides, Alexiou codes are known to have numerous flaws, as it was clearly indicated by the past experience specified above. Just as Alexiou code failed to explain the experimental results of the benchmark experiment [30], his code failed to explain the results of the experiments [2, 3].

We also note in passing that Alexiou wrote that in his code “all physics is included”. “All physics” is an interesting choice of words because it can be understood as including, e.g., the string theory, the general relativity, the quantum entanglement, or at least the plasma polarization shift (though of course none of these parts of “all physics” were included). But he did not include the part of physics most relevant to the subject: the multifrequency nonlinear dynamic resonances that can cause the highly-localized bump-dip-bump structures in spectral line profiles.

Thus, Alexiou criticism of papers [8, 9] – the criticism based on his flawed simulations and the lack of understanding of the relevant physical processes – is without merit. It is just the mythology.

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