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LETTERS TO THE EDITORS

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Comments on the article "Collective ion acceleration in systems with a virtual cathode"

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The review article by A E Dubinov, I Yu Kornilova, and V D Selemir published in *Usp. Fiz. Nauk* **172** 1225 (2002) [*Phys. Usp.* **45** 1109 (2002)] is concerned with a modern investigation of the interesting phenomenon related to fast-ion generation on the basis of high-current electron beams. This effect was discovered almost forty years ago and, having been reproduced many times, holds considerable promise for diverse applications. The article contains useful information on the contemporary investigations of this problem but some conclusions about the mechanism of collective ion acceleration are not universally accepted. Furthermore, the interpretation of some experiments provokes objections. In what follows I would therefore like to set forth my viewpoint on the disputable questions of fast-ion production on the basis of high-current electron beams.

Beginning approximately in the 1930s, anomalously fast ions have occasionally been recorded in different beam-plasma systems. Various physical mechanisms were subsequently proposed to account for the observed phenomenon: plasma overheating; ion acceleration by ion-sound waves; acceleration by electrons during plasma expansion in a vacuum owing to the existence of external electric circuits in experimental facilities, which make up electric loops, and many others. The irreproducibility of results and the lack of reliable data hampered the unambiguous interpretation of the observed physical phenomenon. After the publication of the pioneering experimental paper [1] on ion acceleration in electron beams in 1967, whose results were repeatedly reproduced and borne out in the majority of world's research centers, a wealth of theoretical models have evolved, which have not led to new acceleration techniques reliant on collective fields. Despite the long period of time elapsed since Ref. [1] appeared, there is no clear concept of the physical mechanism of ion acceleration in electron beams. In pursuit of sensational results, many unintelligible and seemingly 'insignificant' experimental facts escaped notice. My 'comments' draw attention to some of them that are of significance for understanding the ion acceleration mechanism in systems without neutral gas filling, as well as to some inaccuracies inherent in the paper under consideration (hereinafter referred to merely as the paper).

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To account for the mechanism of ion acceleration in the electron beam, the authors of the paper resort to the concept of a virtual cathode. However, another group of authors (Adler et al., see p. 1122), based on experimental results, thrice change their conception of ion acceleration mechanism: abandoning the conception of ion acceleration in a stationary potential well, they adopted the conception of ion acceleration by the front of the electron beam, later arriving at a conclusion that the ion acceleration is likely to occur during the development of an electron – ion two-beam instability. The uncertainty in selecting the conception of the ion acceleration process stems from the lack of certain reliable experimental data, a rigorous theoretical model of the physical phenomenon, and some other reasons which are crucially important for the adequate interpretation of experimental results. We enlarge on some of these reasons. In particular, on page 1124 of the paper (left column, 4th line from the bottom) it is stated that "the highest ion energy is proportional to the ion charge multiplicity", according to the findings drawn in a series of investigations conducted employing a vacuum spark discharge [2 – 4]. This statement is fallacious, because in Ref. [3] (p. 420, right column, 11th line from the bottom) we read: "From the mass spectrograms it follows that the highest energies of the heavy ions are independent of their charge multiplicity". The independence of the highest energy of accelerated ions of equal mass on their charge multiplicity is also noted in another work of reference [1] on p. 540 (9th line from the bottom): "The highest energy is independent of the charge multiplicity". That is to say, the highest velocities of the ions of equal mass are independent of their charge multiplicity. Other authors also note the independence of the highest accelerated ion velocities from their charge multiplicity. For instance, in Ref. [5] it is noted that different ions are quite often observed in mass spectrographic investigations to have equal maximum velocities, and we add: irrespective of the charge multiplicity of the ions and their mass, which follows from Ref. [5, see Fig. 3b].

The independence of the highest accelerated ion velocities on the ion charge, which is of significance for the understanding of the physical phenomenon, reflects the salient feature (anomality) of collective ion acceleration in electron beams. Ideally, when the process energetics is high enough, anomalous ion acceleration in electron beams has the result that the maximum velocities of different ions are equal, regardless of their mass and charge multiplicity. This is also borne out by the results of experiments whereby ions with higher masses $m_{\rm n}$ possess higher energies $W_{\rm n\,max}$ than those of lower-mass ions, $W_{\rm i\,max}$, for instance, by Refs [1, 3, 5], namely

$$W_{\rm n\,max} \leqslant \frac{m_{\rm n}}{m_{\rm i}}\; W_{\rm i\,max} \quad (m_{\rm n} > m_{\rm i})\,.$$

The inequality sign corresponds to the case of nonideal acceleration conditions. The above-listed features show up not only for a specific ratio $I_e/I_{e\,lim} > 1$ between the electron beam current and the limiting current in spark or other high-current beam-electron systems, but in low-current stationary discharge systems as well [1, p. 540, 7th line from the bottom]. The low-current systems revealed under controllable conditions, apart from the above features, several other characteristics of the acceleration process. In Ref. [6], for instance, the highest value of anomalous acceleration coefficient defined as the ratio between the highest accelerated ion energy $W_{i\,max}$ and the electron beam energy $W_e \approx eU_0$ ($k_i = W_{i\,max}/W_e$) was shown to be achieved in the range of low electron currents $I_e \leqslant 1$ A and low accelerating voltages $U_0 \leqslant 1$ kV for an independent plasma source. Attention is drawn to the fact that the anomalous ion acceleration in the electron beam for an independent plasma source takes place throughout the entire range of unstable states of the electron beam formed by the plasma diode [7] (for a given average value $\bar{I}_e$ of the electron current it is unstable in a broad range of voltages φ across the diode: $\varphi_a < \varphi < \varphi_v$, $\varphi_v/\varphi_a \geqslant 10^3$, where φ_v is on the order of the average ion energy in the source plasma, and φ_v is defined by the plasma nonuniformity as well as by the size and geometry of the emission opening).

It is well known [8] that the condition $I_e/I_{e\,lim} > 1$ is sufficient for the emergence of a virtual cathode in the transportation of the electron beam bounded by a longitudinal magnetic field in the transverse direction, but it is insufficient for the acceleration of the resultant potential well of the virtual cathode, as well as for the capture and confinement of the ions of different mass and charge even for a deep potential well being accelerated. The situation whereby the highest velocities of the ions of different mass and charge are observed to be equal and their currents are high can be realized only when the acceleration of the field of the virtual cathode proceeds at resonance with the stable motion of a bunch of charged particles captured by this field. And so, while the conception of a virtual cathode provides a rather clear description of the physics of high-power positive-ion pulse production in reflex systems (diodes, triodes, etc.), the validity of applying this conception to account for the anomalously accelerated high-powered flux of different ions in electron beams is not evident.

The paper emphasizes the work [9] of a group of scientists supervised by J Luce from the Lawrence Livermore National Laboratory (LLNL), who repeated the experiment of the Sukhumi Physicotechnical Institute (SPTI) of the 1960s employing modern high-power experimental facilities of the Febatron and FX-75 types. This scientific group believes that the modification they made, which consists of the insulation of the diode anode with a dielectric insertion, brought about a fundamental change in the diode system. Therefore, they set their facility apart with a special structure, which underlay the high experimental results. We consider this question in greater detail.

In the experimental facilities of the SPTI, the plasma was produced by an independent source and was delivered to the diode prior to the voltage application to the diode or with a time delay. Owing to the plasma instability in the electric field of the diode [7] it drifted into the anode region from where it arrived at the vacuum drift region and was scattered at the walls of the experimental facility, like the ions accelerated by the electron beam. Therefore, the electron beam – plasma interaction region in the SPTI facilities comprised the diode gap, the anode region, and the vacuum drift space. In the experimental facilities of the LLNL, the existence of the dielectric insertion in the diode anode made it possible to produce (under the action of electrons and the breakdown of the insertion) the anode plasma from the ions of the insertion material. The anode plasma entered the diode gap and the vacuum drift space. Hence, the electron beam – plasma interaction region in the LLNL facilities comprised the diode gap adjacent to the anode, the anode region, and the vacuum drift space. Consequently, the conditions for the electron beam – plasma interaction and the ion acceleration are not radically different in the SPTI and the LLNL experiments. That is why, despite the distinction in designs, the acceleration physics in the two cases under discussion is supposedly similar and the LLNL diode should not be placed into a special category.

The distinction in the designs of the experimental facilities underlies the difference in the way of changing the accelerated ions. Changing the accelerated ions in the SPTI experimental facilities requires replacing the independent plasma source, and the possibility thereby exists of producing the beams of anomalously accelerated ions of practically all the elements of the Periodic Table. Replacing the accelerated ions in the LLNL facilities requires changing the composition of the solid dielectric for the diode anode insertion. In this case, the composition of the anomalously accelerated ion beam is a mixture of the ions of the anode insertion dielectric material [10]. Therefore, if the diodes are to be personified, which is done in the paper, the Luce diode of the LLNL is nothing more nor less than a modification of the Plyutto diode employed in the SPTI at least six years earlier [1].

The authors of the paper note the record-high energies and high currents of accelerated ions obtained on the LLNL facilities and attribute them to the properties of the diode in use, which is referred to as 'the Luce diode'. We will discuss this issue.

In the mid 1970s to 1980s, Mr. H Sahlin, a staff member of the LLNL and a co-author of Luce's papers, visited the SPTI (when this took place, the author of the present 'Comments' was absent). From the first paper [10] of their group on the subject being discussed and the information on the results obtained, which Mr. Sahlin passed to SPTI staff members, one can conclude that the high energies of accelerated ions were secured primarily by the energy potential of the experimental facilities. In particular, when the nuclear reaction yield of the Febatron with the parameters $U_0 = 2.1$ MV, $I_e = 5$ kA, a current pulse duration $\tau_u = 50$ ns, and a Lawson parameter (in the paper, the Lawson parameter [11] is termed the Budker parameter) $v/\gamma = 0.1$ attained saturation, the Luce group went over to a higher-power FX-75 type facility with the parameters $U_0 = 4$ MV (2.5 MV), $I_e = 30$ kA, $\tau_u = 30$ ns, and $v/\gamma = 0.3$ with retention of the diode design. The increased energy parameters of the system made it possible to additionally conduct several nuclear reactions up to the reactions on natural uranium, which was bombarded by protons and carbon ions. The accelerated proton energy exceeded 15 MeV. After Ref. [10] was submitted for publication, it was possible to produce protons with an energy of 180 MeV with the attainment of californium (Sahlin's private communication). The newly opened energy capabilities enabled them to conduct nuclear reactions with carbon, fluorine, silicon, chlorine, and other ions contained in the material of the dielectric anode insertion (Sahlin's private communication). The parameters of the facilities and the

Table 1

Experiment site	U_0, MV	I_e, kA	τ_u, nc	$k_i = W_{i\,max}/W_e$	v/γ	Protons per pulse	$W_{i\,max}$, MeV	W_{max}, MeV	References
SPTI	0.2–0.3	0.2–1.0	≈ 100	10–100	≈ 0.05	$10^{11}-10^{12}$	5 (H^+)	20 ($C^{+1,2,3,4}$)	[1, 3]
LLNL	4 (2.5)	30	30	≈ 4 (7)	0.3	$> 10^{14}$	15 (H^+)		[10]

results obtained in the SPTI and the LLNL are collected for comparison in Table 1. One can see that, despite the simple design and the primitiveness of equipment employed in the SPTI facilities (by the early 1960s, high-power impulse technology based on distributed parameter pulse-forming lines had not yet been developed), the pioneering results on ion acceleration in electron beams are rather high and correspond to the energy characteristics of diode feeding.

Along with the inaccuracies noted above we direct the reader's attention to an inaccuracy of another kind. On p. 1123 (left column, 4th line from the top) it is stated that "the acceleration in the A–C gap was originally discovered in work [12]", i.e., by foreign scientists, in 1974. This statement is incorrect, because Ref. [1], which had been published seven years earlier (1967), underscores (p. 540, 17th line from the bottom) that "the acceleration is effected in gap 1 and ...", i.e., in the anode–cathode (A–C) gap.

I believe that the fair comment presented will be useful for the contemporary understanding of the problem of ion acceleration in high-power electron beams, as well as for the future advancement of this problem.

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[1] The figures in square brackets at the end of a reference correspond to the number of reference to this paper in the review by A E Dubinov, I Yu Kornilova, and V D Selemir published in *Usp. Fiz. Nauk* **172** 1225 (2002) [*Phys. Usp.* **45** 1109 (2002)].