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Comment on "Fluid modeling of a high-voltage nanosecond pulsed xenon microdischarge" [Phys. Plasmas 23, 073513 (2016)]

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Simulations of sparks in 10 atmosphere Xenon gas by Levko and Raja [Phys. Plasmas **23**, 073513 (2016)] are unable to reproduce the experimental fact of their opacity to visible light [Bataller *et al.*, Appl. Phys. Lett. **105**, 223501 (2014)]. Levko and Raja have argued the discrepancy is due to enhanced ionization from the probing laser radiation and/or cathode field emission. Having observed comparable opacity in similar systems without probing lasers and without electrodes, we instead argue that the enhanced ionization is a thermodynamic result of dense plasma screening effects that lower the effective ionization potential. Levko and Raja do not adequately address these density effects in their spark discharge simulations. *Published by AIP Publishing.*
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We appreciate Levko and Raja's effort[1] to simulate spark breakdown under conditions more appropriate for comparison to our experiments[2] than they had done previously.[3] Our experiments[2] demonstrate that microdischarges in 10 atm of xenon (Xe) gas are opaque to visible light, which requires an electron density of $\sim 10^{27}/\mathrm{m}^3$. As they paraphrase in Ref. 1, Levko and Raja's conclusion in Ref. 3 was that "the microdischarge by itself cannot generate fully ionized plasma" as is necessary to explain the opacity. Their simulation—in 1 atm Xe—results in a plasma of only $\sim$0.01% ionization, and so they suggest that additional "plasma is generated when the electromagnetic radiation [from the laser probe] further increases the plasma density."[3] In Ref. 4, we emphasize that the microdischarge remains opaque in the zero-laser-power limit, and so the laser radiation cannot account for the high electron density. Their more recent simulations[1]—in 10 atm Xe—show less than $\sim$1% ionization and a peak plasma density of $\sim 10^{24}/\mathrm{m}^3$, still far too low to explain the opacity, and so they offer the alternative explanation that "field emission is another mechanism [that] can be responsible for the generation of a denser plasma."[1]

We agree with Levko and Raja that the high electron density must be due to physics that is not included in their software package, but we do not believe it is attributed to field emission. Our group has observed high-opacity phenomena in similar systems that do not have electrodes. For example, a collapsing bubble generates an 11 000 K Xe plasma of collapse density equivalent to 16 bar ($4 \times 10^{26}/\mathrm{m}^3$)[5] that is also opaque to visible light. In addition, laser breakdown in 5 bar Xe gas generates a plasma that emits a 13 000 K blackbody spectrum, with emissivity equal to 1 (Ref. 6)—which implies opacity through Kirchoff's Law.

The universality of this high-electron-density state suggests that it has a thermodynamic origin. We believe the explanation is ionization potential lowering due to screening beyond the realm of validity of the perturbative Debye model at these high densities. Our measurements of potential lowering in sonoluminescence plasma,[7] and more recently in dense Xe sparks[8] have shown it is substantial, and an approximate thermodynamic theory taking into account such effects leads to runaway ionization,[9] which parallels phase transitions from weak to strong in electrolytes.[10]

To our knowledge, density dependent screening effects are not included in the VizGlow software developed by Raja's group and used by Levko and Raja in Ref. 1, whose own brochure[11] states it has been "used for applications involving pressures ranging from a few mTorr to several Torr," and for which no published experimental benchmarks exist at such high pressures. Simulations of Refs. 3 and 1 cannot reasonably be expected to match reality because the physics of this warm, dense regime remains unknown. In the framework of Ref. 1, screening effects would manifest as a reduced, density dependent, electron-ion recombination rate (to single out only one of the many density-independent rate equations input to the model and listed in Table 1 of Ref. 1), which is exactly what Levko and Raja claim limits the peak plasma density in their simulation.[1] However, even in the dilute limit, Saha's equation predicts >50% ionization for the conditions in Ref. 1–10 atm Xe at 2.5 eV (29 000 K)—and first order screening corrections are known to increase the degree of ionization.[12,13] We therefore find the <1% ionization claimed in Ref. 1 to be surprising, and wonder what the physics behind the reduced electron density in their simulation might be.

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[1]D. Levko and L. Raja, "Fluid modeling of a high-voltage nanosecond pulsed xenon microdischarge," Phys. Plasmas **23**, 073513 (2016).
[2]A. Bataller, J. Koulakis, S. Pree, and S. Putterman, "Nanosecond high-power dense microplasma switch for visible light," Appl. Phys. Lett. **105**, 223501 (2014).

[3]D. Levko and L. Raja, "Early stage time evolution of a dense nanosecond microdischarge used in fast optical switching applications," Phys. Plasmas **22**, 123518 (2015).
[4]A. Bataller, J. Koulakis, S. Pree, and S. Putterman, "Comment on 'Early state time evolution of a dense nanosecond microdischarge used in fast optical switching applications' [Phys. Plasmas **22**, 123518 (2015)]," Phys. Plasmas **23**, 034705 (2016).
[5]S. Khalid, B. Kappus, K. Weninger, and S. Putterman, "Opacity and transport measurements reveal that dilute plasma models of sonoluminescence are not valid," Phys. Rev. Lett. **108**, 104302 (2012).
[6]A. Bataller, G. R. Plateau, B. Kappus, and S. Putterman, "Blackbody emission from laser breakdown in high-pressure gases," Phys. Rev. Lett. **113**, 075001 (2014).
[7]B. Kappus, A. Bataller, and S. J. Putterman, "Energy balance for a sonoluminescence bubble yields a measure of ionization potential lowering," Phys. Rev. Lett. **111**, 234301 (2013).
[8]A. Bataller, S. Putterman, S. Pree, and J. Koulakis, "Observation of shell structure, electronic screening, and energetic limiting in sparks," Phys. Rev. Lett. **117**, 085001 (2016).
[9]B. Kappus, S. Khalid, A. Chakravarty, and S. Putterman, "Phase transition to an opaque plasma in a sonoluminescing bubble," Phys. Rev. Lett. **106**, 234302 (2011).
[10]V. A. Kozlov, S. V. Sokolova, and N. A. Trufanov, "Phase transitions in electrolyte solutions," Sov. Phys. JETP **71**(6), 1224 (1990).
[11]Esgee Technologies, Inc., http://esgeetech.com/wp-content/uploads/Why_VizGlow.pdf for Why VizGlow for Plasma Modeling and Simulation.
[12]L. D. Landau and E. M. Lifshitz, *Statistical Physics, Part I* (Oxford, Pergamon, 1976).
[13]J. C. Stewart and K. D. Pyatt, "Lowering of ionization potentials in plasmas," Astrophys. J. **144**, 1203 (1966).