Intense VUV–xenon-cluster interaction revisited

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During the inaugural experiment at FLASH, the first vacuum ultraviolet (VUV) free-electron laser facility, Wabnitz *et al.* [*Nature* **420**, 482 (2002)] irradiated xenon clusters and sparked a concerted theoretical and experimental effort to understand how dense, finite plasmas behave under intense irradiation. In this work, we revisit this experiment with a model that is based only on well-established atomic processes. We find that the experimental results can be explained by hybrid quantum-classical molecular-dynamics simulations if collisional excitation, recombination, and a sufficiently deep soft-core potential is used. Our recent theoretical model for inverse bremsstrahlung heating (IBH) is used to show that the measured energy absorbed by the cluster in the experiment is well predicted by our model.

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I. INTRODUCTION

In 2001, FLASH, at DESY, began a new era of exploration into vacuum ultraviolet (VUV) light-matter interactions in the nonlinear regime [1,2]. Small, condensed droplets of matter, clusters, were the first targets of these ultra-intense laser pulses. Clusters afford the ability to experimentally control their size distribution and, therefore, their properties, and they are simpler to model than other targets (biomolecules, solids). Thus, clusters allowed for the study of nonlinear light-matter interactions in dense, but finite, targets. Additionally, the shorter wavelength of the FLASH experiment allowed for direct access to the single-photon ionization channel in xenon. The first experiment investigated the interaction of xenon clusters with a pulse of sufficiently small wavelength ($\lambda \approx 100$ nm) to allow for single-photon ionization of xenon atoms, and with sufficient intensity to allow for inverse bremsstrahlung heating (IBH) [1]. Thus, a new regime of light-matter interaction, where the laser had both a particle (single-photon ionization) and wave (IBH) character, had been accessed.

The 2002 paper by Wabnitz *et al.* sparked a concerted theoretical and experimental effort to understand how clusters become highly ionized in the VUV regime [1]. The explanation that inner ionization of electrons was followed by the subsequent heating of those electrons via inverse bremsstrahlung was conceptually correct; however, the origin of the high charge states remained unexplained. Moreover, the theoretical predictions for the energy absorbed by the cluster were more than an order of magnitude smaller than what was measured experimentally. Updated pulse parameters, published one year

later in Wabnitz's thesis, indicated that the pulse was around 2.5 times *less* intense, and half the duration, with, therefore, roughly five times *less* energy than originally reported, deepening the mystery of the high charge states and cluster energy absorption [2,3]. Many attempts were made to explain the Wabnitz result theoretically using the original parameters of Ref. [1]. Even so, these models were only able to predict at best small populations of the highest charge state Xe^{8+} and did not see any higher charge states, even transiently.

The theoretical attempts fell into two broad categories: enhanced ionization mechanisms and enhanced absorption mechanisms. The enhanced ionization mechanisms were an augmentation of atomic theory descriptions of single-photon and collisional ionization [4,5]. This caused greater levels of ionization to be predicted than by atomic theory descriptions alone. The increased ionization, in turn, indirectly increased the predicted energy absorbed by the cluster. This additional energy absorption and ionization channel(s) increased the predicted charge states. However, much of this work was based on the originally reported laser parameters with five times more energy per pulse than the experiment.

The first enhanced ionization mechanism was proposed by Siedschlag *et al.* [4] and was improved over the years by others [6,7]. The mechanism described the change to the ionization potential (IP) by the plasma environment: the energy needed to photoionize an atom, or ion, is the energy needed to overcome the classical potential barrier of the neighboring ion, rather than the atomic IP. This reduced IP was restricted to photoionization and gave the system access to higher charge states by direct photoionization. A version of this model has been applied beyond the VUV into the extreme ultraviolet (XUV) [8,9], although subsequent direct quantum calculations suggest problems with the model [10]. Recent proposals have sought to test the existence of enhanced ionization mechanisms directly [11,12] since it was apparently absent in experiments where an aluminum foil was irradiated in the hard-x-ray regime [13,14]. Furthermore,

the mechanism is classically unstable, since the barrier can be energetically below the atomic IP which can become a runaway process [11]. In the VUV and XUV, the mechanism has been applied to photoionization, which has strict energy and angular-momentum transfer laws. Were it to be applied to collisional ionization, which can transfer arbitrary amounts of energy and angular momentum, and continue beyond the presence of the laser pulse, it may potentially exacerbate the runaway process.

The second category of theoretical models sparked by the FLASH experiment involved introducing direct mechanisms of enhanced energy absorption [15]. The additional energy creates a warmer nanoplasma and increases the amount of collisional ionization. Two enhanced absorption methods were separately proposed. Santra *et al.* used self-consistent potentials for the inverse bremsstrahlung heating (IBH) rate calculation which resulted in a significant increase in the IBH cross section [15,16]. The second mechanism is called many-body recombination (MBR) [5]. It relies on the fact that the nanoplasma is highly collisional, allowing the electrons to thermalize very quickly. Due to the high density of the cluster, the cold electrons recombine with ions during the laser pulse, giving their energy to other electrons in the process. These newly recombined electrons can then be re-ionized by standard photoionization. Thus, the self-consistent potentials and MBR mechanisms increase the amount of energy absorbed by the cluster, increasing the electron plasma temperature and driving additional collisional ionization.

In 2009, Ziaja *et al.* combined these models and followed the energetics of the system by using a nonequilibrium Boltzmann solver with the updated experimental pulse duration and intensity [17]. One of their main findings was the strong role recombination played in lowering the charge states of the ions in the core of the cluster. They also found, by using self-consistent potentials, that the IBH cross section increased; this was the primary mechanism to reach higher charge states.

In this paper, we revisit the intense VUV-xenon-cluster experiment using a model that only relies on well-accepted atomic processes and find that this is sufficient to explain the experimental results, even with the updated pulse parameters. We extend our model developed for x-ray and XUV laser-cluster interactions to the VUV and simulate the interaction during and after the laser pulse and, indeed, all the way to the time-of-flight (TOF) detector in order to compare with the experimental signals. Our calculated TOF signal agrees well with the experiment and we are able to see both transient and TOF-detectable states above Xe^{8+} . We use our recent IBH theoretical model to reexamine the amount of energy absorbed by the cluster and find that it is not anomalous as previously reported [1,3]. The key to both approaches is ensuring that the Coulomb potential is adequately represented; it cannot be cut off at too shallow a value, or IBH is significantly underestimated. Furthermore, by including collisional excitation, the energy absorbed by IBH is efficiently used for ionization. It is known that the radiation intensity fluctuates from pulse to pulse in self-amplified spontaneous emission (SASE) free-electron laser (FEL) pulses and it may be possible to assume that the highest charge states are the result of frequent, high intensity pulse variations well beyond the reported peak intensity. However, we take a conservative

approach, using the updated intensity from Refs. [2,3], which is the lower of the two reported values. Thus, a full picture of both the energetics and ionization of the Wabnitz experiment is presented showing that the energy absorption is dominated by IBH and ionization is dominated by collisional processes without the need for additional ionization mechanisms, nor the need for non-Coulombic potentials.

II. THEORY OF CLUSTER ENERGY ABSORPTION

A significant difference between theory and experiment [1] was that the energy absorbed per electron, based on the standard inverse bremsstrahlung theoretical model and the plasmon absorption model, were orders of magnitude lower than the values obtained experimentally [1,3]. This discrepancy is often cited as the motivation to extend the standard laser absorption or ionization channels. In the following, the theoretical model used in Ref. [18] will be reviewed, followed by a calculation using our recent model based on scattering theory, to find a prediction for the energy absorbed by the cluster.

A. Model 1: Kinetic equation

In the original FLASH experiment publication [1] and follow-up work in Wabnitz's thesis [3], the inverse bremsstrahlung model was obtained from Silin [19] and used the kinetic equation for a plasma in a strong, uniform electric field. They found its solution in zeroth and first-order approximations and developed the rate of change in current density to model the electron-ion collision frequency [19]. Ditmire *et al.* [18], Wabnitz *et al.* [1], and Wabnitz in his thesis work [3] used this electron-ion collision frequency ν to determine the rate of energy absorption per electron, $\frac{\partial \epsilon}{\partial t}$, by multiplying ν by the ponderomotive potential U , giving

$$\frac{\partial \epsilon}{\partial t} = \nu U. \quad (1)$$

The electron-ion collision frequency was taken to be [1,18–20]

$$\nu = \frac{4}{3} \sqrt{2\pi} \frac{e^4 Z^2 n_i}{m^{1/2} (kT)^{3/2}} \ln \Lambda, \quad (2)$$

where m (e) is electron mass (charge), n_i is the ion density, Z is the ion charge state, $\ln \Lambda$ is the standard Coulomb logarithm, k is the Boltzmann constant, and T is the temperature of the electrons. The heating rate per unit volume, $\frac{\partial \xi}{\partial t}$, in the cluster is [3,18]

$$\frac{\partial \xi}{\partial t} = \frac{9\omega^2 \omega_p^2 \nu}{8\pi} \frac{1}{9\omega^2(\omega^2 + \nu^2) + \omega_p^2(\omega_p^2 - 6\omega^2)} |E_0|^2, \quad (3)$$

where $E_0 = \sqrt{2c\mu_0 I}$ is the electric-field strength of the laser in vacuum, ω is the frequency of the laser, and ω_p is the plasma frequency.

Using the updated parameters taken from Wabnitz's thesis [3] and the above equations, this model predicts that each cluster absorbs about 15 eV per electron for a 50 fs, $\lambda = 98$ nm pulse [21]. The average charge state from Ref. [3] of $\bar{Z} = 3$ is then used to obtain the energy absorption estimate of 45 eV/atom. However, analysis of the experimental results

from the TOF signal estimated the average energy absorbed to be 640 eV/atom [3]. Even if the additional effect of ions being accelerated by the cluster's global charge buildup is included and taking into account the transmission characteristics of the skimmer (the so-called space-charge effect), the experimental value is still 550 eV/atom [3], more than an order of magnitude larger than predicted by Eq. (3). In part, it was this discrepancy that led to the intense theoretical effort to reconcile theory and experiment.

B. Model 2: Scattering theory

The discrepancy in the previous section motivated us to develop a model for the electron-ion collision frequency and ultimately find the rate of energy absorption by using scattering theory [22]. In this model, we derived the cross section by using scattering theory with the Coulomb potential and then derived the electron-ion collision frequency ν by using this cross section. Finally, we used ν to derive the rate of energy absorption. Thus, the model is atomistic and well suited for noncontinuum plasmas.

Our model [22] estimates the rate of energy absorption per electron:

$$\frac{d\epsilon}{dt} = \frac{e^2 |E_0|^2}{2m\omega^2} \nu n_i \left(\frac{4\pi \mu^2 Z e^4}{\hbar^2 k_0 k} \right) \left(\frac{1}{Q_{\min}^2} - \frac{1}{Q_{\max}^2} \right). \quad (4)$$

Here, n_i is the ion density, μ is the reduced mass of the ion and electron, $\hbar k_0$ is the linear momentum of the incident electron, $\hbar k$ is the linear momentum of the scattered electron, v is the velocity of the electron, and $Q_{\max}$ and $Q_{\min}$ are maximum and minimum values of the momentum transfer. The values of $Q_{\max}$ and $Q_{\min}$ are

$$Q_{\min} = \frac{2\hbar\omega}{v}, \quad (5)$$

$$Q_{\max} = \frac{2}{v} (\sqrt{E} + \sqrt{E + \hbar\omega})^2. \quad (6)$$

By using the same parameters as in Wabnitz's thesis [3], our model gives 139 eV per electron energy absorption for a 50 fs, $\lambda = 98$ nm pulse and, thus, 417 eV/atom. This is much closer to the experimentally estimated value of 550 eV/atom [3]. If one also considers the cumulative ionization energy, which is the energy needed to ionize Xe to Xe^{3+} by three single-photon ionization events (≈ 65 eV to ionize Xe to Xe^{1+} , then Xe^{1+} to Xe^{2+} , and finally Xe^{2+} to Xe^{3+}), the energy absorption predicted by using scattering theory is around 482 eV/atom.

III. NUMERICAL MODEL OF THE COMPLETE INTERACTION

In this section, we present a dynamical simulation of the intense VUV-cluster interaction via a molecular-dynamics approach wherein atomistic models for ionization are incorporated into the code. We track the particles from their initial neutral atom configuration until the cluster's disintegration. The initial neutral configuration is obtained via molecular dynamics by using a van der Waals potential from an initial fcc icosahedral configuration [5]. Upon disintegration, the motion of the ions to the time-of-flight (TOF) detector is solved and

the simulated TOF signal is obtained. There are several ionization channels that are implemented into the code, including single and multiphoton ionization, collisional excitation, and ionization using the augmented collisional ionization (ACI) [23]. ACI is a process wherein an electron can be excited from the electronic ground state to one of the lowest eight excited states by a colliding electron and then subsequently ionized from the excited state to the continuum by another colliding electron. The excitation and ionization cross sections are taken from gas experimental results when available and theoretical calculations otherwise [23]. The local ionization threshold model is used to extend the gas ionization model into the cluster environment [10].

The multiphoton ionization rates are taken from Ref. [24], which are linked to measurements in xenon and argon gas conducted by Wabnitz *et al.* [25]. Although the theory does not produce exact agreement with the experiment, they provide reasonable estimates sufficient for our purposes here, where multiphoton ionization events are rare. The model treats each particle as a Gaussian charge distribution. It uses the soft-core potential energy

$$U_p(r) = \frac{Z_1 Z_2 e^2}{r} \text{erf}\left(\frac{D\sqrt{\pi}}{2Z_1} r\right), \quad (7)$$

where Z_1 and Z_2 are the charge states of the particle and its partner respectively, e is the electron charge, erf is the error function, and

$$D = \frac{z_1}{w} \sqrt{\frac{2}{\pi}}, \quad (8)$$

where D is the potential depth per charge, w is the width parameter (similar to the standard deviation of a normal distribution), and $z_1 = Z_1 e$ is the charge of the particle. See the Supplemental Material for a plot of the soft-core potentials [26].

The value of the potential depth determines the minimum potential energy. For instance, with $D = 2$ (blue, long-dashed), $U_p(r = 0) = -2$ hartree, and $U_p(r = 0) = -6$ hartree if the ion has a charge state of $Z_1 = 3$ (not shown).

Including the process of electron-ion recombination in our code allows us to consider a value of D that is deeper than the ionization potential (IP) of the lowest unoccupied state of an ion. In our implementation, the total energy of an electron is (in atomic units)

$$E_{\text{total}} = \frac{1}{2} v^2 - \sum_{n=0}^N \left(\frac{Z}{r_n} \right), \quad (9)$$

where N is the number of particles excluding the electron, r_n is the distance to the n th particle, Z is the charge of the n th particle, and $V(r \rightarrow \infty) = 0$. The total energy of the electron will be negative, unless the electron is not bound to the cluster.

When an electron is in the vicinity (1 bohr = 0.529 Å) of an ion its total energy is compared with the energy of the ion's lowest unoccupied state. The latter is determined by first calculating the potential energy at the ion's location due to all cluster particles excluding itself and the impacting electron, then subtracting from this the IP of the lowest unoccupied state using the value as determined from usual atomic theory. An electron with a total energy less than the energy of the

lowest unoccupied state is recombined to the ion, meaning that the electron is removed from the cluster particle list, and the ion's charge state is decreased by one [10,27]. Electrons with higher total energies that would not be recombined upon a close encounter with an ion can still sample the deeper potential, significantly increasing the energy absorbed by IBH [22].

The model includes many-body recombination (MBR) implicitly since electrons may lose energy to the plasma through many-body collisions and become classically bound to an ion [5]. We determine this to have occurred when the total energy of the electron is less than the energy of the lowest unoccupied state of the closest ion. If an electron is classically bound, then this would trigger a recombination event in our code as described above. This ion can then subsequently emit an electron via ionization events at a lower IP than if the recombination had not occurred, resulting in an overall enhanced heating. The effect can be significant. For example, for $\lambda = 100$ nm even at low intensity the probability of single-photon ionization from neutral xenon is large, whereas single-photon ionization from Xe^{1+} can occur, albeit with much reduced probability.

The predicted energy absorbed from the laser via IBH has recently been shown to be a function of the maximum potential depth D , although we found previously that the amount of energy absorbed saturates when D is large enough and reaches the value expected by the true Coulomb potential [22]. A potential depth of $D = 3$ hartree (around 82 eV) was found to give convergent results. In molecular-dynamics simulations, this required a time step of 150 zeptoseconds (1.5×10^{-19} s) in order to minimize numerical heating. Self-consistent potentials would be expected to even further increase the energy absorbed [15,16], but these were not used in our model for reasons discussed in the results section.

In the following, we show that this numerical model agrees well with the experimental results, allowing us to illuminate some of the underlying ionization behavior of the system during its transient state.

Results

We obtain a simulated time-of-flight (TOF) signal for $N = 2057$ xenon clusters by using the updated parameters from Ref. [3] with $I = 2.8 \times 10^{13}$ W/cm², $\lambda = 98$ nm, and a full-width-at-half-max pulse duration of 50 fs. We perform the calculation for 14 different intensities (four runs for each intensity for better statistics) in order to integrate over the pulse's spatial distribution [27]. Our model's calculated TOF signal is in good agreement with those detected by the experiment (Fig. 1). The experiment detected charge states up to Xe^{8+} [Fig. 1(b)] as does our model [Fig. 1(a)]. The relative intensity of the signal also matches well for the higher charge states. The discrepancies in the lower charge states are expected and likely due to cluster size impurities in the experiment, including the presence of xenon gas, which we do not consider here. The cluster size distribution is only expected to broaden the peaks [28].

Another comparison with the experiment is made through the ion ejection energy. Using the TOF data, Wabnitz *et al.* calculated the average ion ejection energy per charge state

FIG. 1. The (a) theoretical and (b) experimental time-of-flight (TOF) signals for Xe_{2057} irradiated by a 50 fs, $\lambda = 98$ nm laser pulse with a peak intensity of 2.8×10^{13} W/cm². Panel (b) was created from the data given in Ref. [3].

(crosses in Fig. 2) and found the trend was quadratic [3]. This is indicative of a Coulomb explosion [3] and the line in Fig. 2 is a quadratic best fit of the experimental data. Our model's result agrees well with the experimental results and deviates only for the highest charged states experimentally detected (stars with error bars in Fig. 2). This is likely due to a combination of many other sized clusters being present in the experimental signal and the difficulty of determining the kinetic energy for such small TOF peaks. The very highest charge state, Xe^{11+} , was not clearly detected in the experiment and only a small number were present in the numerical results and thus do not necessarily constitute a departure from the Coulomb explosion model.

A detailed analysis of our simulation data reveals that the dominant ionization mechanism for ions is collisional ionization, primarily through augmented collisional ionization (ACI) [23]. At peak intensity, over 90% of the charge states above Xe^{8+} are ionized by ACI. Multiphoton ionization accounts for less than 1% of the ionization of any charge state, while single-photon ionization occurs only for neutral atoms and accounts for just under 50% of their ionization.

1. Energy absorption dynamics

Insight into how the energy is absorbed by the cluster is obtained by separating the energy contained within the electron and ionic plasmas. In this section we show that the primary energy absorption channel from the laser is through inverse bremsstrahlung heating (IBH) to the electron plasma, in agreement with previous results [16,17]. This can be deduced from the average energy per electron in the electron plasma, and the ion average kinetic energy, as a function of time (red solid line and blue-dashed line in Fig. 3, respectively) for a cluster irradiated at the focus of the laser pulse. The peak average energy of the electrons occurs at the end of the laser pulse, illustrated in yellow. The average charge state of the ions (not shown) is around 7 at the peak of the electron's average kinetic energy at $t = 80$ fs. The electron plasma thus contains a total kinetic energy of about 490 eV/atom (70 eV/electron with an average of 7 electrons ionized per atom), while the ions have about 85 eV/atom of kinetic energy (as read directly from

FIG. 2. The theoretical (star error bars) and experimental (crosses) average ion kinetic energy per charge state. A quadratic fit of the experimental data is given as the solid line. The experimental data (crosses) were obtained from the data given in Ref. [3].

Fig. 3). The cumulative ionization energy (see section II B) of Xe^{7+} is 430 eV and, thus, most of the energy (49%) in the system is in the electron plasma early on. The kinetic energy immediately after the pulse is around 1 keV/atom.

Following the laser pulse, the electrons transfer their energy to the ions. The average charge state soon after the laser pulse is around 7. By 800 fs, it has been reduced to around 5 and those recombining electrons must transfer their energy. The electron-ion recombination heats the electron plasma by 230 eV/atom, the cumulative ionization energy of Xe^{5+} to Xe^{7+} . However, the electron plasma at 800 fs is much colder (6.8 eV/electron $\times$ 5 electrons/atom = 34 eV/atom) than after the laser pulse (72 eV/electron $\times$ 7 electrons/atom = 504 eV/atom). Thus, all this energy is efficiently transferred to the ions and only 3% (34 eV/1.1 keV) of the energy per atom is with the electrons, and the majority of the energy (76%) is now in the ion plasma out of the total 1.1 keV/atom (the

FIG. 3. The average electron (red, solid line) and ion (blue, dashed line) kinetic energy as a function of time for a Xe_{2057} cluster irradiated at the peak intensity of $2.8 \times 10^{13} \text{ W/cm}^2$, $\lambda = 98 \text{ nm}$ for a Gaussian-shaped 50 fs pulse (yellow shaded region).

additional 100 eV is due to the conversion of potential energy to kinetic energy as the cluster disintegrates). This is higher than the average value reported in the experiment [1,3], as expected since this is for the peak irradiation (the experimental value is averaged over a range of lower intensities due to the spatial distribution of the pulse). Thus, the picture of the cluster's energy absorption is as follows: The laser pulse primarily infuses electrons with kinetic energy and, consequently, ions with potential energy. As the cluster disintegrates without the influence of the laser, the electrons' kinetic energy and ion potential energy are converted into the ions' kinetic energy.

2. Numerical inverse bremsstrahlung heating

The theoretical results of Sec. II B agree well with the experimental results when the potential is Coulombic. Numerical models of the laser-cluster interaction which use molecular dynamics to solve Newton's equations of motion cannot use the exact Coulomb potential due to the singularity at $r = 0$. The use of so-called soft-core potentials, as we presented above, is thus common among these models, and we now examine the effect of this approximation.

Soft-core potentials have a parameter which determines the maximum potential energy a particle can experience (which is related to the maximum acceleration the particle can feel). This is sometimes called the potential depth D (cf. Sec. II B). Common practice before the inclusion of electron-ion recombination in these models was to set the potential depth to be above the actual ionization potential in order to avoid the classical electron having more potential energy than a bound electron would have. For xenon, this was often chosen to be $D = 0.44 \text{ hartree}$ (12 eV) which is just above xenon's first-ionization potential of 0.444 hartree (12.1 eV). Recently, by using the scattering approach to inverse bremsstrahlung heating (IBH) of Sec. II B, from Ref. [22], it was found

FIG. 4. The charge state distribution fraction (as a percentage) for Xe_{2057} clusters calculated by integrating over the spatial distribution of the laser pulse with a peak intensity of $2.8 \times 10^{13} \text{ W/cm}^2$, $\lambda = 98 \text{ nm}$ and a Gaussian-shaped 50 fs full width at half maximum [3]. For each charge state, the results for different potential depths are shown, where 0.44 hartree (12 eV) was the value primarily used in previous work to disallow electrons from having an energy below xenon's ionization potential (0.444 hartree or 12.1 eV).

that the potential-depth parameter has a large influence on the scattering cross section and thus the energy absorbed. However, it was found that the cross section saturates for large potential depths, but this value occurs at a potential depth that is typically larger than the ionization potential by an order of magnitude [22,29].

The effect of the potential depth on the energy absorbed by the cluster was examined in our simulations and is considered in the context of the charge state distribution. Figure 4 shows the charge state distribution for five different potential depths, where the results have been integrated over the spatial distribution of the laser pulse using 14 different intensities. The charge states above Xe^{8+} are visible when the potential depth is greater than 0.44 hartree. There is a trend that the deeper the potential depth is, the more abundant the higher charge states are with a rapid saturation as the potential depth increases. It was determined in the theoretical work that the cross section of IBH saturates for soft-core potentials, such as Eq. (7), around 3 hartree. This agrees well with the results shown in Fig. 4.

The success of our model at matching the experimental signals by using a soft-core potential of sufficient depth makes the inclusion of the self-consistent potentials of Refs. [16,17] unnecessary. Furthermore, the implementation of self-consistent potentials is difficult in molecular dynamics due to the singularities of the potentials and the nonreciprocal shape with the electrons. Smoothing out the singularities would still likely present much larger forces on the particles and thus require a much smaller time step to resolve (and reduce numerical heating). However, the results of including

these potentials would be interesting. We speculate that their role may be to increase the highest charge states, but not significantly since the experimental TOF showed only Xe^{8+} as did our model. If including self-consistent potentials significantly increased the charge states, then the predicted TOF signal would contain clear peaks beyond Xe^{8+} and deviate from what the experiment detected.

IV. SUMMARY

We presented a theoretical and computational investigation of intense VUV-cluster interaction and found that we could reproduce experimental results by using only well-established atomic processes. We first applied our theoretical approach using scattering theory to explain the results of Wabnitz *et al.* Additionally, we have shown that a hybrid quantum-classical model of the laser-cluster interaction is able to reproduce the dominant features of the experiment and give detailed insight into the transient dynamics of the laser-cluster interaction. The observed high charge states in the experiment were found to be primarily due to the collisional excitation and ionization channel which is driven by the IBH of the nanoplasma.

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