Mathematical Modelling of Engineering Problems
Vol. 11, No. 5, May, 2024, pp. 1273-1278
Journal homepage: http://iieta.org/journals/mmep

Investigating Xenon Aggregates Irradiated by Intense Attosecond Laser Pulses

Bariza Boudour[1,2]

[1] Laboratory of Elaboration Preparation and Analysis of Materials (L.E.A. M), Badji Mokhtar University, Annaba 07000, Algeria
[2] Department of Science of the Matter, Faculty of Exact Sciences Natural and Life Sciences, Mohamed Khider Biskra University, Biskra 23000, Algeria

Corresponding Author Email: bariza.boudour@univ-biskra.dz

https://doi.org/10.18280/mmep.110516

Received: 8 November 2023
Revised: 11 January 2024
Accepted: 20 January 2024
Available online: 30 May 2024

Keywords:
xenon aggregates, intense laser, attosecond pulses, nanoplasma model

ABSTRACT

Ultra-short and intense laser interactions with noble gas are used for accelerating or generating different particles such as electrons, protons or X-rays. Few works have addressed gases, particularly Xenon (Xe). Nevertheless, the analysis of attosecond electron pulses remains a major challenge. Thus, we study clusters of Xe, which leads to high excitation energy. To do this, we adopted the nanoplasma model. Thereby, we simulate the emission electron beam generated by laser absorption to optimize the electron energy and develop ultra-short pulse dense for the development of better detectors capable of resolving higher photon numbers and heat source length. From the simulation results, we found an important production of electrons, proportionally to the number of aggregates under the short and intense laser. In the first ionization, the minimum estimated energy absorbed agrees with the theory. These results enable real progress in different areas, for example, research in physics and chemistry, communication technology, surgery and medical treatment.

1. INTRODUCTION

In recent years, the interaction of an intense attosecond laser pulse with nanometric aggregates has been the subject of numerous research works. These aggregates can be obtained for example by spontaneous condensation of a rare gas during its expansion in a supersonic nozzle. These high intensities have been used to study the production of highly charged ions from multiphoton ionization of individual atoms [1-8], and the optical ionization of small molecules, in which the resulting coulomb explosion produces ions with the kinetic energy of up to 2 Kev. The irradiation of clusters by intense laser pulse may lead to the emission of high-energy (Kev) electrons, highly charged and very energetic ions and fragments as well as X-ray production [9-11]. The global response of the cluster is characterized by a heating of the electron cloud and electronic emission.

Several models have been developed to explain the experimental features observed in the interaction of high laser intensity with atomic clusters. In our work, we use the nanoplasma developed by Ditmire et al. [1]. This model offers a complete scenario of the interaction taking into account ionization, heating and explosion processes simultaneously.

The clusters are treated as spherical plasma when Plasmon resonance takes place. In this model, large electron temperatures are reached and highly charged ions are produced at resonance. The electron gas exerts a strong hydrodynamics pressure, which combined with the coulomb, leads to the final explosion of the clusters. These aggregates locally present a density close to that of a solid likely to induce a higher collisional absorption than a gaseous target. On the other hand, the quantity of material heated by the laser pulse being confined to the aggregates alone, the debris produced after the interaction is less numerous than a solid target. Several experiments have shown the potential of this target for the production of energetic particles (ions, electrons and photons), at high speed and without debris. The understanding of the mechanisms of the interaction involving laser aggregate xenon using the nanoplasma model proposed by Ditmire et al. [1] makes it possible to describe the dynamics leading to the explosion of large aggregates subjected to laser fields. The aggregate is considered a dielectric sphere (See the schematic diagram of the nano plasma model in Figure 1).

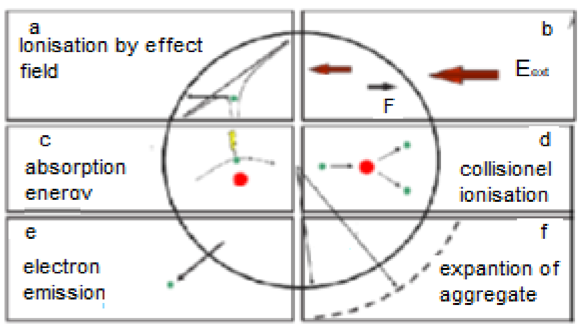

Figure 1. Diagram representing the process taken into account by the nanoplasma model

The interaction-laser aggregate is based on the following principle: the laser, which leads to the ionization of the atoms of the aggregate, so we will have the formation of an electronic cloud composed of electrons free, excites the parent atom. The overall response of the aggregate is defined by the heating of the electronic cloud. The final explosion of the cluster is caused by the global charge and the high energy acquired by the cluster.

In this context, we employ the nanoplasma model and simulation methods to study laser-irradiated nanoparticles, researchers aim to achieve specific outcomes related to electron dynamics, dense electron beam generation, and parameters and focus on, along with potential quantifications: Investigate the temporal evolution of electron density in laser-irradiated nanoparticles, offering a comprehensive view of the dynamic processes involved in nanoplasma formation.

The contribution is quantitative insights into optimized electron energy facilitating precise control over energy levels. The electrons become very energetic and have a speed of the order of 2.50×10^{6}m/s compared with light speed. Xe aggregates offer the possibility of reaching high energies greater than 10.58Kev.

We aim to study the different processes as well as the mechanisms of ionization and explosion inside the cluster. In this model, we consider a radius cluster of the order of a few nanometers in an intense linearly polarized laser field. This model can deal with all the processes of ionization, heating, electron emission and the process of expansion of the cluster. Thus, we will study the interaction of an intense attosecond laser with the xenon aggregate (3.10^{6} atoms) using the nanoplasma model to highlight the effect of wavelength and laser intensity on the different nanoplasma parameters [12-20].

The paper is organized as follows: After a brief introduction relating to the objective to be achieved, we describe in Section 2 some basic notions facilitating understanding.

Section 3 presents our simulation approach and Section 4 discusses some results obtained. We end this paper with a conclusion and future work.

2. PRELIMINARY CONCEPTS

We give below the structure of the nanoplasma model improved by Michaud 2, based on the idea of Ditmire et al. [1].

The aggregate is represented by a solid circle:

a. ionization by field effect
b. polarization and the field inside the aggregate
c. energy absorption
d. collisional ionization
e. electron emission
f. the expansion of the aggregate

2.1 Ionization by field effect

We also distinguish two types of ionization: multiphoton and tunnelling ionization.

2.1.1 Multiphoton ionization

It is a process by which an atomic level is ionized by the absorption of N photons from the laser.

2.1.2 Ionization by tunnel effect

It is a process during which the electron can be ejected from its atom due to the lowering of the potential barrier.

2.2 Collisional ionization

This mode of ionization requires the presence of free electrons in the medium and occurs later during the interaction. After the first electrons have been stripped by the laser field, these electrons have acquired certain energy by collisional heating. Depending on their energies, the collisions can lead to the excitation of the electronic procession of the target ion but also increase the state of ionization of the latter. Collisional ionization again depends on the electron-ion collision frequency (i.e. electron density and electron kinetic energy) [3-5].

2.3 Xenom aggregate model analogy

The nanoplasma model parameters describe how xenon aggregates respond to the conditions induced by the laser, affecting ionization, temperature, electron density, and other aspects of the aggregate's dynamics. The analogy helps in understanding the intricate processes occurring in xenon aggregates under intense laser irradiation. Here are these analogies for the parameters:

Aggregate Size: The size of the xenon aggregate refers to the number of xenon atoms forming the aggregate. A larger aggregate size implies a greater number of atoms participating in the plasma interactions.

Laser Intensity: Laser intensity indicates the power of the laser radiation. As intensity increases, more electrons are likely to be ejected from xenon atoms, leading to higher ionization levels and increased heating of the aggregate.

Laser Duration: The laser duration represents the period during which the xenon aggregate is exposed to laser radiation. A longer duration may result in more complex relaxation processes and changes in the aggregate's dynamics.

Laser Frequency: Laser frequency is the frequency of the electromagnetic radiation. Different frequencies can selectively interact with electrons in xenon atoms, influencing the photoionization process.

Photon Energy: Photon energy is the energy carried by each laser photon. Higher energy photons can lead to more significant ionization and intense heating of the xenon aggregate.

Electron Density: Electron density represents the number of free electrons in the xenon aggregate. A higher electron density can result in more frequent electron-electron interactions. Electron Temperature: Electron temperature reflects the average kinetic energy of electrons in the aggregate. A higher electron temperature indicates more vigorous electron motion.

Relaxation Dynamics: Relaxation dynamics describe how the xenon aggregate returns to an equilibrium state after exposure to the laser. This process may involve cooling, electron recombination, and other relaxation phenomena.

3. METHODOLOGY

Recent advances in the field of high-power laser sources from laser-cluster interactions make it possible to explore the dynamics of atoms under conditions of extreme illumination. When subjected to an intense and brief laser field, the aggregates have spectacular behaviour: They burst and disperse into various fragments formed of ions carrying several electrical charges, called multi-charged ions.

Laser sources are characterized by ultrashort pulses, lasting a few attoseconds. This brevity gives access to the timescale of the vibration movements of the atoms within the aggregates. Although the light energy per pulse is modest, these lasers deliver peak powers that can exceed one terawatt. By finely focusing such pulses, it is possible to achieve illumination corresponding to electric fields greater than those experienced by electrons within atoms, and thus explore the matter in extreme conditions.

To understand and decompose the laser-cluster interaction, we performed an adapted simulation of a model developed by Ditmire for noble gas clusters, in which the cluster is heated by the laser pulse and seen like a nanoplasma. This model takes into account the pressures that govern the dynamics of electrons and ions in the nanoplasma. Aggregates presenting plasma in the visible explode into ions of higher charges and energies. Electrons can absorb photons increasing the kinetic energy from the laser. This is the phenomenon of inverse bremsstrahlung collision absorption. It is a three-body process role of heating the medium by transferring energy from the laser to electrons as indicated by Eq. (1):

$$W_J^{TUN} = \sqrt{\frac{3}{2\pi}}\, W_S \left|C_{N*L*}{}^2\right| G_{LM} \left(\frac{4W_S}{W_S}\right)^{2n'-|M|-\frac{3}{2}} exp\frac{4W_S}{W} \quad (1)$$

where,

Jj: degree of ionization

N^*: $\frac{(Z)\sqrt{I_P^H}}{I_P}$

M: principal quantum number effective

$I_P\ et\ I_P^H$: ionization potential of the atom

$$W_S = \frac{I_P}{h}, W_{INT}/\sqrt{2M_E}I_P$$

The factors $G_M et\ \left|C_{N*L\mu}{}^2\right|$ are written as follows:

$$G_{LM} = \frac{(2L+1)(l+|M|!)(2^{-LM})}{(|M|)(l-|m|!)}$$

where, m is magnetic quantum number, L is orbital quantum number, N^*, increases for a large atomic number.

$$|C_{N*L}|^2 = \frac{\frac{4EXP(1)^2}{(N^*-L^{*2})^{N*}}(N^*L^*)}{(N^*-L^*)^{l+\frac{1}{2}(2\pi N^*)}}$$

The electron-ion collision frequency (i.e. electron density and electron kinetic energy) [3-5].

Ionization of atoms or ions by collision their speed breaks down into a speed acquired by oscillation in the laser field and a thermal speed [1], due to the internal temperature of the electron gases according to Eq. (2):

$$V_E = V_{OSC} + V_{KT} \quad (2)$$

Approximate the probability W_{COLL} to ionize by the collision of another atom's velocities at two collision rates: W_J^{KT} and W_J^{LaS} , respectively associated with the velocities defined by Eq. (3).

$$W_J^{COLL} = W_J^{KT} + W_J^{LaS} \quad (3)$$

Each rate is calculated using an electron-ion collision cross-section ion depending on rate is calculated using an electron-ion collision cross-section ion following Eqs. (4) and (5).

$$W_J^{KT} = N_E(\sigma_j V_{KT})\ Distribution\ interne \quad (4)$$

$$W_J^{LaS} = N_E(\sigma_j V_{LaS})\ Periode\ optique \quad (5)$$

Subjecting aggregates to an intense laser field obtained thanks to the attosecond laser makes it possible to understand the dynamics of the interaction of rare gas "xenon" aggregates, analyzed by a simulation. Two steps were carried out one varying the pulse duration from 10 to 40 as by a constant illumination of 10^{18} w.cm^{-2} and the other consisted in varying the illumination intensities from 10^{18} to 10^{20} w.cm^{-2} for the constant duration and the same for numbers.

4. RESULTS

The nanoplasma model is a theoretical framework employed to describe the ultrafast dynamics of small clusters of atoms, particularly when exposed to intense laser pulses. It focuses on the formation and evolution of a highly excited electron-ion plasma, known as nanoplasma, within the cluster. The key processes include photoionization, plasma expansion, and subsequent relaxation.

Let us consider xenon rare gas clusters containing (3×10^6) atoms per cluster, irradiated by a short and intense laser field of intensity (I=$10^{21}\times$W.cm^{-2}), the wavelength at distance (τ=390nm) and duration (τ=150as). The interaction mechanisms considered are direct optical ionization through tunnelling ionization and electron-ion collisions. The temporal variation of the radius normalized by its initial value (R0) is illustrated in Figure 2.

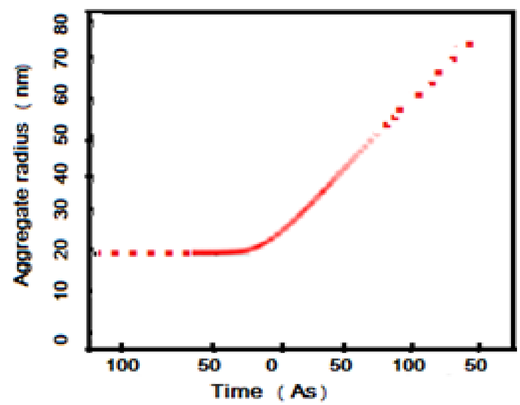

Figure 2. The temporal evolution of the aggregate radius Xe (3×10^6), I=$10^{21}\times$W.cm^{-2}, R0=22.25 nm, λ=390 nm and τ=150

In the beginning, we observe a very fast expansion of the Xe aggregate because of the rapid heating of the aggregate after absorption of the laser energy by the atoms and the ions of the aggregate, then the value of the radius tends towards values very large which indicates the final explosion of the aggregate. The Radius and speed of expansion, which agrees with the Eq. (6):

$$R = Vexpt \qquad (6)$$

where, R is the size of the aggregate, $Vexp$ is the speed of expansion, and t is the time.

Figure 3 represents the variation of the total energy of the electrons as a function of time. To compare with the metallic aggregates the energy of the order of 45Kev, the curve lets us deduce that the Xe aggregates offer the possibility of reaching high energies greater than 10.58Kev. The curve represents the variations of the total energy of the electrons as a function of time. Passing the point of the first resonance, the electrons absorb a lot of energy from the amplified laser field which justifies the rapid increase in the energy of the electrons until it reaches a maximum value of the order of 3.1010ev, λ=390 nm. So the wavelength of the laser has a great influence on the total energy of the electrons in the aggregate.

Figure 4 shows speed expansion evolution as a function radius of the 3×10^6 atoms aggregate. We see that at the beginning the speed increases very quickly, this is due to the high mobility of the electrons after having absorbed the applied laser energy.

The speed of the electrons always increases with the expansion of the rare gas cluster of Xe, then just after the explosion of the cluster the speed becomes constant and the electrons become very energetic and have a speed of the order of 2.50×10^6 m/s.

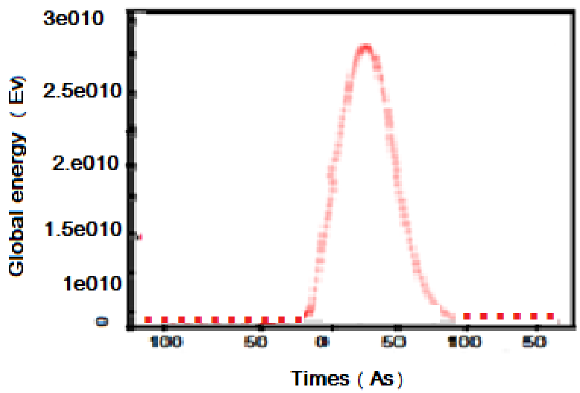

Figure 3. The time evolution of global energy Xe (3.10^6), $I=10^{21}$ W.cm^{-2}, ⅄=390 nm and τ =150

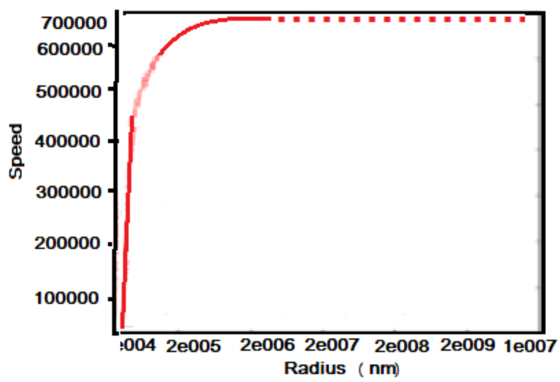

Figure 4. The expansion speed evolution of the aggregate Xe (3×10^6), as a function of the radius, $I=10^{21}\times$W.cm^{-2}, ⅄=390 nm and τ=150

The emission of electrons leads to a positive charge defect in the aggregate. This loss of neutrality of the nanoplasma produces an increase in the volume of the latter, therefore its expansion, as shown in Figures 5 and 6. In addition, the Coulomb pressure is caused by the forces of electrostatic repulsion between ions; the pressure due to the energy absorbed by the aggregate (hydrodynamic pressure) and the high electronic temperature make the nano plasma unstable (see Figure 7). The increase in the total charge of the aggregate leads to an increase in the value of the Coulomb pressure Xe ($Pc=1.5\times10^{10}$ Bar) compared with Coulomb pressure aggregate Na ($Pc=2.72\times10^9$ Bar), and hydrodynamics pressure value ($P_H=5\times10^{10}$ Bar). This value is very small compared to the maximum value of the kinetic pressure of hot electrons.

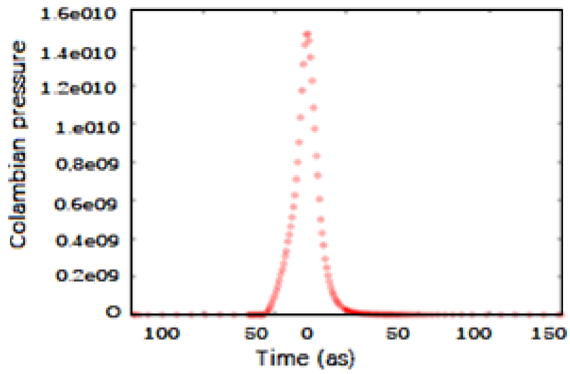

Figure 5. Temporal evolution Coulomb pressure Xe (3×10^6), $I=10^{21}\times$W.cm^{-2}, ⅄=390 nm and τ=150

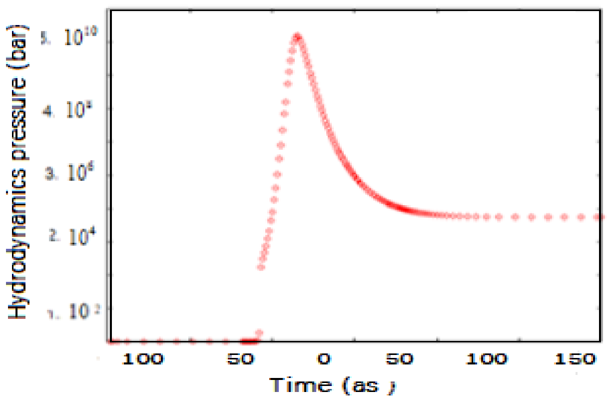

Figure 6. Aggregate Xe (3×10^6), $I=10^{21}\times$W.cm^{-2}, ⅄=390 nm and τ=150 as temporal evolution hydrodynamics pressure

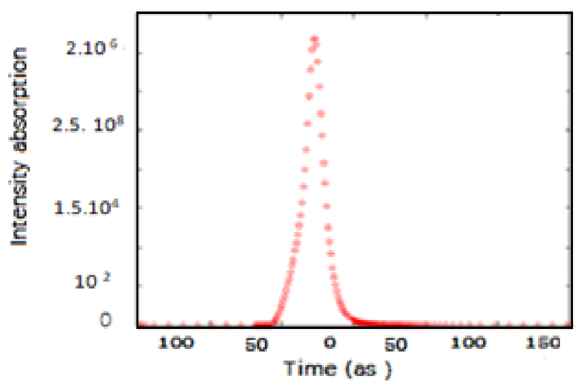

Figure 7. Aggregate Xe (3×10^6), $I=10^{21}\times$W.cm^{-2}, ⅄=390 nm and τ=150 as temporal evolution absorption intensity

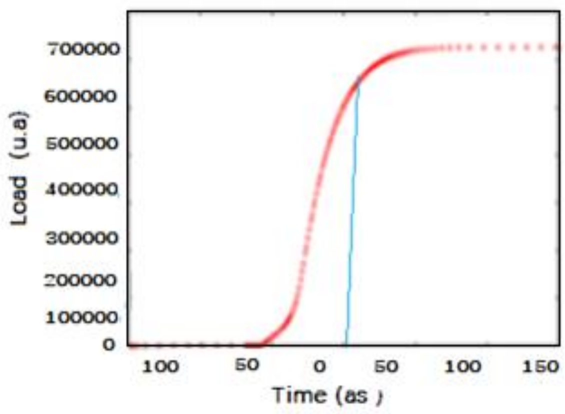

Figure 8. The temporal evolution of the aggregate Xe (3×10^6), $I=10^{21}\times W.cm^{-2}$, $\lambda=390$ nm and $\tau=150$

The variation of the electronic density is described in Figure 8, at the beginning of the formation of the nanoplasma after ionization of the parent atoms, the electronic density increases when the system passes through the resonance, and there is a strong amplification of the laser field from where the almost total ionization, this is justified by the increase in the electron density until reaching maximum values for 390 nm. The high mobility of the electrons after absorbing the applied laser energy, the energy of the electrons always increases with the expansion of the aggregate after its explosion, the speed becomes constant and the electrons become very energetic and have an approximate maximum energy of 3,61 10^8ev.

We find electrons emitted increase rapidly from ($I=10^{17}$-10^{19}) $W.cm^{-2}$ and reach the total emission of electrons stagnates at ($I=10^{20}$-10^{21} at $W.cm^{-2}$) with a large number of emitted electrons (75 000). This means a dependence between the laser intensity, the size and the maximum energy emitted is estimated at 90 168.75 ev, which agrees with the theory). The increase in the total charge of the aggregate leads to an increase in the value of the Coulomb pressure Xe ($Pc=1.5\times10^{10}$ Bar) compared with Coulomb pressure aggregate Na ($P_C=2.72\times10^9$ Bar), and hydrodynamics pressure value ($P_H=5\times10^{10}$ Bar). This value is very small compared to the maximum value of the kinetic pressure of hot electrons. A way to produce energetic multiply charged ions which could have diverse applications.

In Figure 9, we observe the emission of the electrons.

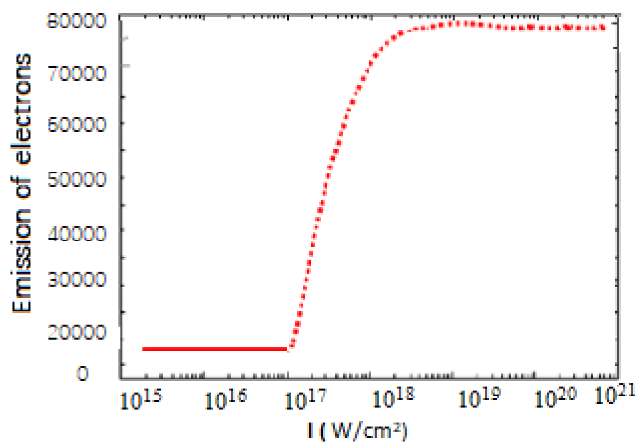

Figure 9. The emission of electrons depends on laser intensity aggregate Xe (3×10^6), $\lambda=390$ nm and $\tau=150$

In a few words, we studied clusters of Xe containing 3.10^6 atoms, a radius is 22.25 nm, a wavelength is 390 nm and a pulse duration is 150 as, subjected to an intense laser ($I=10^{21}$ $W.cm^{-2}$), which leads to high excitation energy. Hence, we simulate the emission electron beam generated by laser absorption with regards to the parameters model to optimize the electron energy and develop ultra-short pulse dense applied in areas such as telecommunication. We found an important production of electrons which can result from the effect of the resonance according to the electron density increasing the radius of the aggregates during this interaction. For all ionization, the maximum energy absorbed is estimated at $3,61.10^8$ ev and the maximum energy emitted is estimated at 90,168.75 ev which agrees with the theory. The production of the electron depends not only on the collisions but also on the evolution of the volume, proportionally to the number of aggregates under the short and intense laser compared to previous researches [16, 18].

5. CONCLUSION

This paper focused on the description of the laser interaction in a wide range of illumination from 10^{21} $W.cm^{-2}$ with large aggregates, from several thousand atoms.

The main results showed the maximum energy absorbed estimated at $3,61.10^8$ and the maximum energy emitted is estimated at 90,168.75 ev. The irradiation by an intense laser produces a rapid heating of the cluster by the different processes of collisions, the coulomb and hydrodynamic pressures were established to be responsible for the explosion, the ratio of the electronic density and the critical density depends on the wavelength. The hydrodynamic pressure was found to be greater than the Coulomb pressure, so the application of an intense laser influences the total energy of emission electrons.

The significance of findings related to laser interactions with xenon aggregates lies in their contribution to fundamental science, materials science, technological applications, and the advancement of laser technology. The knowledge gained from such studies not only deepens our understanding of fundamental physical processes but also has the potential to inspire innovations with practical applications in various fields.

Investigating the ultrafast dynamics of xenon aggregates and nanoplasmas remains a key area of interest. Researchers may focus on studying the timescales and mechanisms involved in the formation, evolution, and eventual disintegration of nanoplasmas induced by intense laser pulses.

Ultimately, in addition to simulating other aspects of this attosecond physics, the final step is experimentation. Devices are required to generate ultra-short and intense pulses in the UV field and even efforts for the development of better detectors capable of resolving higher photon numbers.

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NOMENCLATURE

I Intensity, $W.cm^{-2}$

Greek symbols

λ Heat source length, nm
τ Pulse rate, as