Formation of surface nano-structures by plasma expansion induced by highly charged ions

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Abstract

Contents

I. INTODUCTION

A. Definition of Plasma

The use of the term “PLASMA“ for an ionized gas was first coined in 1927 by Irving Langmuir (1881-1957), an American scientist [1]. The term was borrowed from the blood Plasma. The pioneer in this field was Hannes Alfvén, who around 1940 developed the theory of magnetohydrodyamics, or MHD, in which plasma is treated essentially as a conducting fluid. This theory has been both widely and successfully employed to investigate sunspots, solar flares, the solar wind, star formation, and a host of other topics in astrophysics. Any ionized gas cannot be called plasma, of course; there is always some small degree of ionization in any gas. Plasma is a special class of gases made up of a large number of electrons and ionized atoms and molecules, in addition to neutral atoms and molecules as are present in a normal (non-ionized) gas. The most important distinction between a plasma and a normal gas is the fact that mutual Coulomb interactions between charged particles are important in the dynamics of a plasma and cannot be disregarded. When a neutral gas is raised to a sufficiently high temperature, or when it is subjected to electric fields of sufficient intensity, the atoms and molecules of the gas may become ionized, electrons being stripped off by collisions as a result of the heightened thermal agitation of the particles.When a gas is ionized, even to a rather small degree, its dynamical behavior is typically dominated by the electromagnetic forces acting on the free ions and electrons, and it begins to conduct electricity. The charged particles in such an ionized gas interact with electromagnetic fields, and the organized motions of these charge carriers (e.g., electric currents, fluctuations in charge density) can in turn produce electromagnetic fields. The ability of an ionized gas to sustain electric current is particularly important in the presence of a magnetic field. The presence of mobile charged particles in a magnetic field yields a Lorentz force $qv \times B$.

A useful definition is as follows: A plasma is a quasineutral gas of charged and neutral particles which exhibits collective behavior. In Langmuir probe which is a device used to determine the electron temperature, electron density, and electric potential of a plasma Langmuir described his observations as:

(1) Except near the electrodes, where there are sheaths containing very few electrons, the ionized gas contains ions and electrons in about equal numbers so that the resultant space charge is very small. We shall use the name plasma to describe this region containing balanced charges of ions and electrons.

(2) Plasma is matter heated beyond its gaseous state, heated to a temperature so high that atoms are stripped of at least one electron in their outer shells, so that what remains are positive ions in a sea of free electrons.

(3) Not all the atoms have to be ionized: the cooler plasmas used in plasma processing are only 1-10% ionized, with the rest of the gas remaining as neutral atoms or molecules. At higher temperatures, such as those in nuclear fusion research, plasmas become fully ionized, meaning that all the particles are charged, not that the nuclei have been stripped of all their electrons [2].

We must now define "quasineutral" and "collective behavior." What is meant by "collective behavior" is as follows. Consider the forces acting on a molecule of, say, ordinary air. Since the molecule is neutral, there is no net electromagnetic force on it, and the force of gravity is negligible. The molecule moves undisturbed until it makes a collision with another molecule, and these collisions control the particle's motion. A macroscopic force applied to a neutral gas, such as from a loudspeaker generating sound waves, is transmitted to the individual atoms by collisions. The situation is totally different in plasma, which has charged particles. As these charges move around, they can generate local concentration of positive or negative charge, which give rise to electric fields. Motion of charges also generates currents, and hence magnetic fields. These fields affect the motion of other charged particles far away. By "collective behavior" we mean motions that depend not only on local conditions but on the state of the plasma in remote regions as well. Because of collective behavior, plasma does not tend to conform to external influences; rather, it often behaves as if it had a mind of its own.

All states of matter represent different degrees of organization, corresponding to certain values of binding energy. In order for matter to make the transition to its fourth state and exist as a plasma, the kinetic energy per plasma particle must exceed the ionizing potential of atoms (typically a few electron volts). Thus, the state of matter is basically determined by the average kinetic energy per particle. Although a plasma is often considered to be the fourth state of matter, it has many properties in common with the gaseous state. At the same time, the plasma is an ionized gas in which the long range of Coulomb forces gives rise to collective interaction effects, resembling a fluid with a density higher than that of a gas. In its most general sense, a plasma is any state of matter which contains enough free, charged particles for its dynamical behavior to be dominated by electromagnetic forces. Most applications of plasma physics are concerned with ionized gases. It turns out that a very low degree of ionization is sufficient for a gas to exhibit electromagnetic properties and behave as a plasma: a gas achieves an electrical conductivity of about half its possible maximum at about 0.1% ionization and has a conductivity nearly equal to that of a fully ionized gas at 1% ionization. The degree of ionization can be defined as the ratio $N_e/(N_e + N_n)$, where N_e is the electron density and N_n is the density of neutral molecules. (Since most plasmas are macroscopically neutral, the density of positive ions is equal to the density of electrons, i.e., $N_i = N_e$). As an example, the degree of ionization in a fluorescent tube is $\sim 10^{-5}$, with $N_n \simeq 10^{22} m^{-3}$ and $N_e \simeq 10^{17} m^{-3}$. Typically, a gas is considered to be a weakly (strongly) ionized gas if the degree of ionization is less than (greater than) 10^{-4}. The behavior of weakly ionized plasmas differs significantly from that of strongly ionized plasmas. In a plasma with a low density of charged particles (i.e., low value of N_e), the effect of the presence of neutral particles overshadows the Coulomb interactions between charged particles. The charged particles collide more often with neutrals than they interact (via the Coulomb repulsion force) with other charged particles, inhibiting collective plasma effects. As the degree of ionization increases, collisions with neutrals become less and less important and Coulomb interactions become increasingly important. In a fully ionized plasma, all particles are subject to Coulomb collisions. The Sun and the stars are hot enough to be almost completely ionized, with enormous densities ($N_e \simeq 10^{33} m^{-3}$).

One of the most important properties of a plasma is its tendency to remain electrically neutral, i.e., to balance positive and negative free charge ($N_e \simeq N_i$) in any given macroscopic volume element [3]. A slight imbalance in local charge densities gives rise to strong electrostatic forces that act in the direction of restoring neutrality. This property arises from the large charge-to-mass ratio (qe/me) of electrons, so that any significant imbalance of charge gives rise to an electric field of sufficient magnitude to drag a neutralizing cloud of electrons into the positively charged region. Consider a steady initial state in which there is a uniform number density $N_e = N_o$ of electrons, neutralized by an equal number of ions, i.e., $N_i = N_e = N_o$. We further assume that the plasma is "cold," meaning that the thermal motion of electrons and ions can be neglected. Since the electrons are much lighter than the ions, we make the safe assumption that the electrons move much faster and hence the motion of the ions can be neglected. The electric field E acts to reduce the charge separation by pulling the electrons back to their initial locations. In the absence of any damping (due, for example, to collisions of the electrons with ions or other electrons), this oscillatory motion would continue forever. In relatively tenuous (low-density) plasmas, collisional damping can be neglected, so any slight disturbance of the system leads to the oscillation process. Depending on the density of charged particles, a plasma behaves either as a fluid, with collective effects being dominant, or as a collection of individual particles.

B. Brief History

In the 1920's and 1930's a few isolated researchers, each motivated by a specific practical problem, began the study of what is now called plasma physics. This work was mainly directed towards understanding the effect of ionospheric plasma on long distance shortwave radio propagation and gaseous electron tubes. Since the 1960's an important effort has been directed towards using plasmas for space propulsion. Plasma thrusters have been developed ranging from small ion thrusters for spacecraft attitude correction to powerful magneto plasma dynamic thrusters that –given an adequate power supply – could be used for interplanetary missions. Plasma thrusters are now in use on some spacecraft and are under serious consideration for new and more ambitious spacecraft designs. Starting in the late 1980's a new application of plasma physics appeared – plasma processing – a critical aspect of the fabrication of the tiny, complex integrated circuits used in modern electronic devices. This application is now of great economic importance. In the 1990's studies began on dusty plasmas. Dust grains immersed in a plasma can become electrically charged and then act as an additional charged particle species. Because dust grains are massive compared to electrons or ions and can be charged to varying amounts, new physical behavior occurs that is sometimes an extension of what happens in a regular plasma and sometimes altogether new. In the 1980's and 90's there has also been investigation of non-neutral plasmas; these mimic the equations of incompressible hydrodynamics and so provide a compelling analog computer for problems in incompressible hydrodynamics. In addition to the above activities there have been continuing investigations of industrially relevant plasmas such as arcs, plasma torches, and laser plasmas. In particular, approximately 40% of the steel manufactured in the United States is recycled in huge electric arc furnaces capable of melting over 100 tons of scrap steel in a few minutes. Plasma displays are used for flat panel televisions and of course there are naturally-occurring such as lightning.

C. Plasma Parameter

It has often been said that 99% of the matter in the universe is in the plasma state; that is, in the form of an electrified gas with the atoms dissociated into positive ions and negative electrons, This estimate may not be very accurate, but it is certainly a reasonable one in view of the fact that stellar interiors and atmospheres, gaseous nebulae, and much of the interstellar hydrogen are plasmas [4]. In our own neighborhood, as soon as one leaves the earth's atmosphere, one encounters the plasma comprising the Van Allen radiation belts and the solar wind [5]. On the other hand, in our everyday lives encounters with plasmas are limited to a few examples: the flash of lightning bolt, the soft glow of the Aurora Borealis, the conducting gas inside a fluorescent tube or neon sign, and the slight amount of ionization in a rocker exhaust, It would seem that we live in the 1% of the universe in which plasmas do not occur naturally [6]. The reason for this can be seen from the "Saha" equation, which tells us the amount of ionization to be expected in a gas in thermal equilibrium:

$$\frac{n_i}{n_n} \approx 2.4 \times 10^{21} \frac{T^{\frac{3}{2}}}{n_i} e^{-U_i/KT}$$

Here n_i and n_n are, respectively, the density (number per m^3) of ionized atoms and of neutral atoms, T is the gas temperature in $^\circ k$, K is Boltzmann's constant, and U_i is the ionization energy of the gas that is, the number of ergs required to remove the outermost electron from an atoms. (The mks or International System of units will be used in this essay.) For ordinary air at room temperature, we may take $n_n \approx 3 \times 10^{25} m^{-3}$, $T \approx 300^\circ k$, and $U_i = 14.5eV$ (for nitrogen), where $1eV = 1.6 \times 10^{-9} J$.

As the temperature is raised, the degree of ionization remains low until U_i is only a few times KT. Then n_i/n_n rises abruptly, and the gas is in plasma state. Further increase in temperature makes n_n less than n_i, and the plasma eventually becomes fully ionized. This is the reason Plasmas exist in astronomical bodies with temperatures of millions of degrees, but not on the earth. Life could not easily coexist with a plasma at least, plasma of the type we are talking about. The natural occurrence of plasma of the type we are talking about. The natural occurrence of plasmas at high temperatures is the reason for the designation "the fourth state of matter." Although we do not intend to emphasize the Saha equation, we should point out its physical meaning. Atoms in a gas have a spread of thermal energies, and as atoms is ionized when, by chance, it suffers a collision of high enough energy to knock out an electron. In a cold gas, such energetic collisions occur infrequently, since an atom must be accelerated to much higher than the average energy by a series of "favorable" collisions. The exponential factor in equation above expresses the fact that the number of fast atoms falls exponentially with U_i/KT. Once an atom is ionized, it remains charged until it meets an electron; it then very likely recombines with the electron to become neutral again. The recombination rate clearly depends on the density of electrons, which we can take as equal to n_i. The equilibrium ion density, therefore, should decrease with n_i; and this is the reason for the factor n_i^{-1} on the right-hand side of the equation. The plasma in the interstellar medium owes its existence to the low value of n_i (about 1 per cm^3), and hence the low recombination rate.

A fundamental characteristic of the behavior of plasma is its ability to shield out electric potential that are applied to it. If the plasma was cold and there were no thermal motions, the shielding would be perfect, and no electric field would be present in the body of the plasma outside of the clouds. On the other hand, if the temperature is finite, those particles that is at the edge of the cloud, where the electric field is weak, have enough thermal energy to escape from the electrostatic potential well. The "edge" of the cloud then occurs at the radius where the potential energy is approximately equal to the thermal energy KT of the particles, and the shielding is not complete. Potential of the order of KT/e can leak into the plasma and cause finite electric fields to exist there.

Let us compute the approximate thickness of such a charge cloud. Imagine that the potential ϕ on the plane $x = 0$ is held at a value $\phi_o$by a perfectly transparent grid (Fig.1. 1). We wish to compute $\phi(x)$. For simplicity, we assume that the ion-electron mass ration M/m is infinite, so that the ions do not move but form a uniform background of positive charge. To be more precise, we can say that M/m is large enough that the inertia of the ions prevents them from moving significantly on the time scale of the experiment.

Poisson's equation in one dimension is

$$\epsilon_o \frac{d^2\phi}{dx^2} = -e(n_i - n_e) \tag{1}$$

If the density far away is n_∞, we have $n_i = n_\infty$

If the presence of a potential energy $q\phi$, the electron distribution function is

$$f(u) = A\exp(-\frac{1}{2}mu^2/KT)$$

It would not be worthwhile to prove this here. What this equation says is intuitively obvious: There are fewer particles at places where the potential energy is large, since not all particles have enough energy to get there. Integrating $f(u)$ over u , setting $q = -e$, and noting that $n_e(\phi \to 0) = n_\infty$, we find

$$n_e = n_\infty \exp(e\phi/KT_e)$$

Substituting for n_i and n_e in Eq.(1), we have

$$\epsilon_o \frac{d^2\phi}{dx^2} = en_\infty \left[\exp(\frac{e\phi}{KT_e}) - 1\right].$$

In the region where $|e\phi/KT_e| \ll 1$, we can expand the exponential in a Taylor series:

$$\epsilon_o \frac{d^2\phi}{dx^2} = en_\infty \left[\frac{e\phi}{KT_e} + \frac{1}{2}(\frac{e\phi}{KT_e})^2 + ...\right]. \tag{2}$$

No simplification is possible for the region near the grid, where $|e\phi/KT_e|$ may be large. Fortunately, this region does not contribute much to the thickness of the cloud (called a sheath), because the potential falls very rapidly there keeping only the linear terms in Eq.(2), we have

$$\epsilon_o \frac{d^2\phi}{dx^2} = \frac{n_\infty e^2}{KT_e}\phi \tag{3}$$

Defining,[7]

$$\lambda_D \equiv \left(\frac{\epsilon_\text{o} KT_e}{e^2 n}\right)^{\frac{1}{2}}, \tag{4}$$

where n stand for n_∞, we can write the solution of Eq.(3) as

$$\phi = \phi_o \exp(-|x|/\lambda_D) \tag{5}$$

The quantity λ_D, called the Debye length, is a measure of the shielding distance or thickness of the sheath. Note that as the density is increased, λ_D decreases, as one would expect, since each layer of plasma contains more electrons. Furthermore, λ_D increases with increasing KT_e. Without thermal agitation, the charge cloud would collapse to an infinitely thin layer. Finally, it is the electron temperature which is used in the definition of λ_D because the electrons being more mobile than the ions, generally do the shielding by moving so as to create a surplus or deficit of negative charge. The following are useful forms of Eq.(4):

$$\lambda_D = 69(\frac{T}{n})^{\frac{1}{2}}m \ , \qquad T \text{ in k}$$
$$\lambda_D = 7430(KT/n)m \ , \qquad KT \text{ in eV} \tag{6}$$

We are now in a position to define "quasi-neutrality." If the dimensions L of a system are much larger than λ_D, then whenever local concentrations of charge arise or external potentials are introduced into the system, these are shielded out in a distance short compared with L, leaving the bulk of the plasma free of large electric potential or fields. Outside of the sheath on the wall o on an obstacle, $\nabla^2\phi$is very small, and n_i is equal to n_e, typically, to better than one part in 10^6. It takes only a small charge imbalance to give rise to potentials of the order of KT/e. The plasma is "quasi-neutral"; that is, neutral enough so that one can take $n_i \approx n_e \approx n$, where n is a common density called the plasma density, but not so neutral that all the interesting electromagnetic forces vanish. A criterion for an ionized gas to be a plasma is that it be dense enough the λ_D is much smaller than L.

Plasma Frequwncy is the most fundamental time-scale in plasma physics. Clearly, there is a different plasma frequency for each species. However, the relatively fast electron frequency is, by far, the most important, and references to "the plasma frequency" mean the electron plasma frequency. It is easily seen that ω_p corresponds to the typical electrostatic oscillation frequency of a given species in response to a small charge separation.

$$\omega_p^2 = \frac{e^2 n}{\epsilon_o m}$$

For instance, consider a one dimensional situation in which a slab consisting entirely of one charge species is displaced from its quasi-neutral position by an infinitesimal distance δx. The resulting charge density which develops on the leading face of the slab is $\sigma = en\delta x$. An equal and opposite charge density develops on the opposite face. The x-directed electric field generated inside the slab is of magnitude $E_x = -\sigma/\epsilon_\circ = -en\delta x/\epsilon_\circ$. Thus, Newton's law applied to an individual particle inside the slab yields giving $\delta x = (\delta x)_\circ \cos(\omega_p t)$.

$$m\frac{d^2\delta x}{dt^2} = eE_x = -m\omega_p^2 \delta x$$

Note that plasma oscillations will only be observed if the plasma system is studied over time periods τ longer than the plasma period $\tau_p \equiv 1/\omega_p$, and if external actions change the system at a rate no faster than ω_p. In the opposite case, one is clearly studying something other than plasma physics (e.g., nuclear reactions), and the system cannot not usefully be considered to be a plasma. Likewise, observations over length-scales L shorter than the distance $v\tau_p$ traveled by a typical plasma particle during a plasma period will also not detect plasma behavior. In this case, particles will exit the system before completing a plasma oscillation. This distance, which is the spatial equivalent to τ_p, is called the Debye length, and takes the form

$$\lambda_D \equiv \sqrt{T/m}\omega_p^{-1}.$$

Note that, $\lambda_D/L \ll 1$, is independent of mass, and therefore generally comparable for different species. Clearly, our idealized system can only usefully be considered to be a plasma provided that

$$\frac{\lambda_D}{L} \ll 1 \text{ and,}$$
$$\frac{\tau_p}{\tau} \ll 1.$$

Here, τ and L represent the typical time-scale and length-scale of the process under investigation. It should be noted that, despite the conventional requirement, plasma physics is capable of considering structures on the Debye scale. The most important example of this is the Debye sheath: i.e., the boundary layer which surrounds a plasma confined by a material surface.

The picture of Debye shielding that we have given above is valid only if there are enough particles in the charge cloud. Clearly, if there are only one or two particles in the sheath region, Debye shielding would not be a statistically valid concept. Using Eq.(6), we can compute the number N_D of particles in a "Debye sphere": [8]

$$N_D = \frac{4}{3}\pi n \lambda_D^3 = 1.38 \times 10^6 \times (T^{\frac{3}{2}}/n^{\frac{1}{2}}) \qquad (T \text{ in } {}^\circ K)$$

In addition to $\lambda_D \ll 1$, collective behavior requires $N_D \ggg 1$.

We have given two conditions that an ionized gas must satisfy to be called a plasma. A third condition has to do with collisions. The weakly ionized gas in a hest exhaust, for example, does not qualify as a plasma because the charged particles collide so frequently with neutral atoms that their motion is controlled by ordinary hydrodynamic forces rather than by electromagnetic forces. If ω is the frequency of typical plasma oscillations and τ is the mean time between collisions with neutral atoms, we require $\omega\tau > 1$ for the gas to behave like a plasma rather than a neutral gas. The three conditions a plasma must satisfy are therefore:

$$\lambda_D \ll 1,$$

$$N_D \ggg 1,$$

$$\omega\tau > 1.$$

D. Quantum Plasma Regime

Traditional plasma physics has mainly focused on regimes characterized by high temperatures and low densities, for which quantum mechanical effects have virtually no impact. However, recent technological advances (particularly on miniaturized semiconductor devices and nanoscale objects) have made it possible to envisage practical applications of plasma physics where the quantum nature of the particles plays a crucial role. Plasmas are characterized by regimes of high temperature and low density, for which quantum effects are totally negligible. However, physical systems where both plasma and quantum effects coexist do occur in nature. Quantum plasmas also occur in some astrophysical objects under extreme conditions of temperature and density, such as white dwarf stars, where the density is some ten order of magnitudes larger than that of ordinary solids. Because of such large densities, a white dwarf can be as hot as fusion plasma, but still behave quantum-mechanically. When quantum effects start playing a role, the above picture gets more complicated, as an additional length scale is introduced, namely the de Broglie wavelength of the charged particles,

$$\lambda_B = \hbar/mv$$

The de Broglie wavelength roughly represents the spatial extension of the particle wave function the larger it is, the more important quantum effects are. From the definition of λ_B, it is clear that quantum behavior will be reached much more easily for the electrons than for the ions, due to the large mass difference. Indeed, in all practical situations, even the most extreme, the ion dynamics is always classical, and only the electrons need to be treated quantum-mechanically.

Quantum effects can be measured by the thermal De Broglie wavelength of the particles composing the plasma, $\lambda_B = \hbar/mv_T$, which roughly represents the spatial extension of a particle's wave function due to quantum uncertainty. For classical regimes, the de Broglie wavelength is so small that particles can be considered as point like (except, as mentioned in the Introduction, when computing collision cross-sections), therefore there is no overlapping of the wave functions and no quantum interference. On this basis, it is reasonable to postulate that quantum effects start playing a significant role when the de Broglie wavelength is similar to or larger than the average inter particle distance $n^{\frac{-1}{3}}$, i.e. when $n\lambda_D^3 \geq 1$ [9].

On the other hand, it is well known from the statistical mechanics of ordinary gases that quantum effects become important when the temperature is lower than the so-called Fermi temperature T_F, defined as

$$K_B T_F \equiv E_F = \frac{\hbar^2}{2m}(3\pi^2)^{\frac{2}{3}} n^{\frac{2}{3}},$$

where we have also defined the Fermi energy E_F.When T approaches T_F, the relevant statistical distribution changes from Maxwell-Boltzmann to Fermi-Dirac. Now, it is easy to see that the ratio $\chi \equiv T/T_F$ is simply related to the dimensionless parameter $n\lambda_B^3$ discussed above:

$$\chi \equiv T/T_F = \frac{1}{2}(3\pi^2)^{\frac{2}{3}}(n\lambda_D^3)^{\frac{2}{3}}.$$

Thus, quantum effects become important when $\chi \geq 1$.

We now want to establish the typical space, time, and velocity scales for quantum plasma, as well as the relevant dimensionless parameters. First of all, we stress that simple expressions can be found only in the limiting cases $T \gg T_F$ (corresponding to the classical case) and $T \ll T_F$, which is the 'deeply quantum' (fully degenerate) regime that we are going to analyze. Of course, there will be a smooth transition between the two regimes, but this cannot be treated using straightforward dimensional arguments. Concerning the typical time scale for collective phenomena, this is still given by the inverse of the plasma frequency, even in the quantum regime. However, the thermal speed becomes meaningless in the very low temperature limit, and should be replaced by the typical velocity characterizing a Fermi-Dirac distribution. This is the Fermi velocity:

$$v_F = \left(\frac{2E_F}{m}\right)^{\frac{1}{2}} = \frac{\hbar}{m}(3\pi^2 n)^{\frac{1}{3}}.$$

With the plasma frequency and the Fermi velocity, we can define a typical length scale

$$\lambda_F = \frac{v_F}{\omega_p},$$

which is the quantum analog of the Debye length. Just like the Debye length, λ_B describes the scale length of electrostatic screening in quantum plasma. The quantum coupling parameter can be defined as the ratio of the interaction energy E_{int} to the average kinetic energy E_{kin}. The interaction energy is the same as in the classical case, whereas the kinetic energy is now given by the Fermi energy $E_{kin} = E_F$. With these assumptions, one can write the quantum coupling parameter as

$$g_Q \equiv \frac{E_{int}}{E_F} = \frac{2}{(3\pi^2)^{\frac{2}{3}}}\frac{e^2 m}{\hbar^2 \epsilon_\circ n^{\frac{1}{3}}} \approx \left(\frac{1}{n\lambda_D^3}\right)^{\frac{2}{3}} \approx \left(\frac{\hbar\omega_p}{E_F}\right)^2.$$

where we have left out proportionality constants for sake of clarity. The third expression of g_Q is completely analogous to the classical one when one substitutes $\lambda_F \to \lambda_D$. The last expression is more interesting, as it has no classical counterpart: it describes the coupling parameter as the ratio of the 'Plasmon energy' $\hbar\omega_p$(energy of an elementary excitation associated to an electron plasma wave) to the Fermi energy.

E. Dusty Plasma

Dusty plasmas are important in technological applications and in astrophysical situations. They can be formed under laboratory conditions (e.g., plasma processing reactors, laboratory experiments, rocket exhaust, and fusion experiments) with sizes of the dust cloud of a few millimeters to astrophysical systems (e.g., planetary rings, comet tails, nebula, interstellar medium and noctilucent clouds) with an enormous range of sizes. In the following, we mention briefly the presence of dusty plasmas in nature and in laboratory.

Dusty (complex) plasma is ubiquitous in different parts of our cosmic environment [10]; namely, in planetary rings, in circumsolar and phoboos dust ring, in the interplanetary medium, in cometary comae and tails, and in interstellar molecular clouds. In fact, the dark bands of dust, which are block parts of the Orion, Lagoon, Coalsack, Horsehead, and Eagle nebulae, indicate that dust must have abundant in the nebulae that coalesced to form the Sun, planets, and other stars. On the other hand, during the Voyager 1 and 2 flybys of the outer planets and the ICE flyby of comet Giaobini-Zinner, it has been demonstrated that the plasma wave instrument can detect small dust particles striking the space craft

wave instrument can detect small dust particles striking the space craft [11, 12]. Complex dusty plasmas also occur in the flame of a humble candle, in the zodiacal light, in cloud-to-ground lightening in thunderstorms containing smoke contaminated air over the United States, in volcanic cruptions, and in ball lightening.

Dust is thought to be present in the Earth's mesosphere at altitudes $\sim 85-95$ km . It has been conjectured that in the cold summer mesopause, ice particles possibly influencing the charge balance of the region [13, 14]. The role of charged dust in mesospheric electric fields is recognized by Zadorozhny [15]. The formation of an artificial dusty plasma in the ionosphere was also revealed during the Spacelab 2 mission when the space shuttle orbital maneuver system engines were fired [16]. The closest example of naturally occurring dusty plasmas in the Earth's environment are the Noctilucent clouds (NLC) which are formed in the arctic mesosphere ($\sim 80-110$ km altitude) in the summer. The term noctilucent comes from Latin and means luminous at night and therefore, these clouds are seen at night.

There are several dust formation mechanisms in laboratory plasmas [17, 18]. Dust can be produced by various plasma surface interaction mechanisms during the manufacturing of the tube or from electrodes or dielectric walls, or formed chemically from the gas due to polymerization or decomposition. Thermal fatiguing and thermal overloading of the wall components can be another source of dust in such plasmas, as both mechanisms lead to local evaporation of material. In the edge of fusion plasmas, the growth of small particles from atomic or molecular precursors can appear. They are released, afterwards, by physical or chemical erosion. Another possible mechanism is coagulation of metal atoms on tokomak walls due to the extremely high temperatures. Moreover, investigations have shown that the most particles will fall to bottom of the laboratory of fusion device, whereas lighter ones may be re-injected into the plasma either by magnetic or by electric forces and then levitated close to the wall. Dust particles are a sink or source for electrons and ions. For large concentrations, the balance between electrons and protons will thus be changed in the edge plasmas. This will result in a different sheath potential and heat transmission factor and in different dynamics of the edge plasma. This may even cause a plasma breakdown [19].

II. NANOTECHNOLOGY AND ITS APPLICATIONS

Nanoparticles are particles between 1 and 100 nanometers in size. In nanotechnology, a particle is defined as a small object that behaves as a whole unit with respect to its transport and properties. Particles are further classified according to diameter [20].Ultrafine particles are the same as nanoparticles and between 1 and 100 nanometers in size, fine particles are sized between 100 and 2,500 nanometers, and coarse particles cover a range between 2,500 and 10,000 nanometers. Nanoparticle research is currently an area of intense scientific interest due to a wide variety of potential applications in biomedical, optical and electronic fields. The National Nanotechnology Initiative has led to generous public funding for nanoparticle research in the United States .

A. Laser applications

The use of nanoparticles in laser dye-doped poly(methyl methacrylate) (PMMA) laser gain media was demonstrated in 2003 and it has been shown to improve conversion efficiencies and to decrease laser beam divergence [21]. Researchers attribute the reduction in beam divergence to improved dn/dT characteristics of the organic-inorganic dye-doped nanocomposite. The optimum composition reported by these researchers is 30% w/w of $SiO2$ (~ 12 nm) in dye-doped PMMA.

B. Medicinal applications

Nanomedicine is the medical application of nanotechnology [22]. Nanomedicine ranges from the medical applications of nanomaterials and biological devices, to nanoelectronic biosensors, and even possible future applications of molecular nanotechnology such as biological machines. Current problems for nanomedicine involve understanding the issues related to toxicity and environmental impact of nanoscale materials (materials whose structure is on the scale of nanometers, i.e. billionths of a meter).Functionalities can be added to nanomaterials by interfacing them with biological molecules or structures. The size of nanomaterials is similar to that of most biological molecules and structures; therefore, nanomaterials can be useful for both in vivo and in vitro biomedical research and applications. Thus far, the integration of nanomaterials with biology has led to the development of diagnostic devices, contrast agents, analytical tools, physical therapy applications, and drug delivery vehicles.

Iron oxide nanoparticles are iron oxide particles with diameters between about 1 and 100 nanometers. The two main forms are magnetite (Fe_3O_4) and its oxidized form maghemite (Fe_2O_3). They have attracted extensive interest due to their superparamagnetic properties and their potential applications in many fields (although Co and Ni are also highly magnetic materials, they are toxic and easily oxidized).

Applications of iron oxide nanoparticles include terabit magnetic storage devices, catalysis, sensors, and high-sensitivity biomolecular magnetic resonance imaging (MRI) for medical diagnosis and therapeutics. These applications require coating of the nanoparticles by agents such as long-chain fatty acids, alkyl-substituted amines and diols [23].

C. Surface nanostructure

Fabrication of extremely small surface nanostructures is a challenge for today's nanoelectronics and nanophotonics applications. Recently, many efforts have been devoted to study the creation of surface nanostructures by the bombardment with slow highly charged ions (HCI) as a promising nanotechnological tool[24, 25].

These studies showed that various surface nanostructures in different insulators (e.g., CaF_2[26, 27],BaF_2 [28, 29] ,PMMA[30], mica[31],SiO_2[32], $SrTiO_3$[33],$LiNbO_3$[34]), semiconductors (Si[35] , TiO_2[36]), and conductors (Au[37], HOPG[38]) can be created after irradiation with HCI of different charge states. A significant advantage of this method is that the structures are created without chemical treatment as used in the conventional optical lithographic methods. Moreover, structural modification occurs only in the topmost surface layers without modifying the bulk, which is not avoidable in case of high energetic ions. In fact, the interaction between HCI and the surface starts above the surface at certain critical distance, estimated by the classical over-barrier model,by Burgdeorfer, during the interaction a hollow atom[39] is formed by captures electrons above the surface into highly excited states of the ion. The shrinking and the decay of the hollow atom produce strong electronic excitations, via auto-ionisation and other Auger processes, in the surface within a few femtoseconds. The induced electrons will be then coupled to the lattice, in a picoseconds regime, producing restructuring in the impact region and consequently the creation of the permanent surface nanostructures. For the same material, the size and shape of the created nanostructures depends highly on the potential energy (sum of the ionization potentials) and kinetic energy of the used HCI. Despite the fact that kinetic energy for HCI (eV-keV) is much less than for swift ions (MeV-GeV), similar structures were observed in many materials, showing that a common mechanism occurs in both cases. In comparison to insulators, semiconductors were less studied regarding creation of surface nanostructures using slow highly charged ions. In this Letter, we show that the HCIs are able to create surface nanostructures in Zinc oxide (ZnO). This material is promising semiconducting oxide with a wide band gap of 3.37 eV and a large exciton binding energy of 60 meV in comparison to other semiconductors, e.g., ZnS and GaN.[40, 41]

Due to the excellent field emission, catalytic, and gas sensing properties of ZnO, the created ZnO nanostructures are of importance for various technological applications.[42, 43] Epi-polished ZnO single crystals (from MTI Corporation) ($0.5\times0.5\times0.2$ cm^3) were irradiated with isotope-pure$^{129}Xe^{q+}$ ions from the Electron Beam Ion Trap (EBIT) facility, Dresden-Germany. The irradiation was performed under normal incidence at room temperature. The charge states ($q = 28 - 36$) of the used ions were selected by adjusting the magnetic field from the 90° analyzing magnet. The ions were extracted at 4.5 kV. In order to obtain the ions with the same impact kinetic energy (126 keV), the ions of q $\succ$28+ were decelerated using the two-stage deceleration system. After exposure to fluences of 5×10^8 to 10^{10} ions/cm^2, the crystals were investigated using scanning force microscopy (SFM) (Nanoscope III, Digital Instruments) at contact mode under constant loading force (less than 10N) using nonconductive Si_3N_4 sensors of force constant $\sim$ 0.1 N/m.

Four SFM topographic images of ZnO surfaces irradiated with 126 keV Xe^{28+} , Xe^{32+} , Xe^{34+} , and Xe^{36+} are shown in Figs. 2. 1 (a) – (d), respectively. While no surface modifications observed after irradiations with Xe^{28+} and Xe^{32+} , the formation of nanohillocks was confirmed in case of Xe^{34+} and Xe^{36+}. The number of hillocks coincides with the utilized ion fluence. Due to the fact that the ion kinetic energy is kept constant (126 keV) for all ions, we can conclude that the creation of the hillocks is ascribed to the potential energy deposition. Furthermore, a potential energy threshold, E_p^{th} , [19.1 keV (Xe^{32+}) $\prec E_p^{th} \leq$ 23.3 keV (Xe^{34+})], should be surpassed for the formation of the ZnO nanostructures. The role of potential energy (E_p) for the hillocks creation was also seen by observing larger hillocks size by increasing E_p. This is demonstrated by observing an enlargement of hillocks from

(4.1±1.3) $\times 10^3$ to (13.6±3.4) $\times 10^3$ nm^3 by increasing E_p from 23.3 to 27.8 keV, as shown in Figs. 2. 1 (c) – (f).

The existed scenario for the mechanism responsible for hillocks creation by HCI in various surfaces is based mainly on the modified thermal spike model. Within the concept of this model, the formation of the observed hillocks is ascribed to the quenching of the ion-induced nano-sized molten material after exceeding certain potential energy threshold. Furthermore, another suggested mechanism for melting in ionic fluorides is what is called non-thermal melting, which is based on the change of the atom-interaction potential under high excitation density.[44, 45] Another model for explaining the ion-induced damage in inorganic solids is the ion explosion spike model,[46] where ionization followed by a strong repulsive force is created during the ion-solid interaction. These Coulomb repulsive forces within the ionized region can be sufficient to create significant lattice instability. This model was utilized for the description of nanostructures by laser induced plasma.[47, 48]

Here, we introduce plasma expansion approach for elucidating the formation mechanism of the created nano-structures by impinging of HCI on ZnO surface. It is based on the fact that the impinging ions is carrying high charge state, and therefore the deposited high potential energy will lead to strong electronic excitations in the ZnO surface and sub-surface regions creating dense plasma via thermal and/or non-thermal effect. The expansion of the created plasma can be briefly described as a rapid release of energy. Therefore, significant explosion will develop leading to expansion of the system perpendicular to the surface and directed in both directions inward and outward. Due to the rapid heating of a target in half-space, a steep temperature gradient happen causing a diffusion of heat into the interior of the target. Naturally, the electrons are easily stripped from the atoms, leaving them charged. Due to the light masses of the electrons, they escape from the created plasma bulk region, which creates ambipolar electrostatic field that accelerates the positive ions. Finally, the chemical bonds of the atoms are broken and a repulsive state is created leading to exploding of the material into a small plasma cloud of energetic ions with high velocity. Therefore, outward pressure is generated and consequently the expansion starts.[49]

The expansion of a plasma into empty surrounding space may result in the creation of nano-dust grains. These nanograins are formed due to the condensation process or bulk separation during plasma expansion. In addition, the dust can be created via ion-induced sputtering from the surface. This kind of sputtering is termed potential sputtering, where in case of HCIs is produced mainly by potential energy deposition.[50] This is different from what is called kinetic sputtering, which is caused by the electronic energy loss of swift heavy ions in matter.[51] The plasma particles (electrons and ions) are collected by the dust grains, and therefore they act as probes. Charging of the nano-dust grains would lead to the creation of either negative or positive charges on the dust surface.[52, 53] The presence of positive charged nano-dust grains increases the electron number density in the plasma, however negative nano-dust grains reduces the electrons from the system. Hence, the electron number density in the plasma changes due to the presence of nano-dust grains.

Within the scope of the plasma expansion approach, to create surface nano-hillocks, the deposited energy by the HCIs should be enough to produce a plasma in the ion impact region, which expands above the surface. For ZnO, the generated plasma consists of positive ions "Zn," negative ions "O," electrons, and a small amount of nano-dust particles. The density of the ZnO crystals is 5.61 g/cm^{-3}. So, the plasma number density is $\sim 8.9 \times 10^{22}$ cm^{-3}. Therefore, the electrons should be considered as degenerate Fermi gas, while the positive and negative ions can be treated as classical gas due to their high masses compared to the electrons. To describe the degenerated electrons, we used the pressure law $p_e \; \alpha \; n_e^{5/3}$, where p_e is the degenerate electron pressure and $p_e \; \alpha \; n_e^{5/3}$ the electron number density. The fluid theory was used to describe the plasma system, which is composed of positive ions, negative ions, degenerate electrons, and stationary nano-dust grains.

III. THEORETICAL MODEL

A. Plasma expansion

Plasma expansion is a common feature of the space environment , planetary rings , comet tails and solar wind , where plasma expands into the wake region of inert objects such as asteroids and the moon [54].

For a small volume , a rapid release of energy yields an explosion and the system expands into the surrounding medium (Fig. 3. 1).The resulting motion can be assumed to be held into vacuum if the density and pressure of the medium can be neglected [55]. Rapid heating of a solid in half-space sets up a steep temperature gradient, leading to the diffusion of heat into the interior of the body. In both cases, thermal pressure is generated and expansion starts. Lightweight particles escape the plasma bulk region first, and their motion creates an ambipolar electrostatic field that accelerates the other particles' motion [56–59] .The expansion process is often described under the assumption of Maxwellian electrons with velocities in local thermal equilibrium, known to be isotropically distributed around the average velocity. This assumption easily fails with very high density electrons since the electrons are considered as a degenerate Fermi gas. On the other hand, in some astrophysical systems,e.g. in white dwarf stars, the plasma number density could exceed $10^{29}\mathrm{cm}^{-3}$ [60, 61] .therefore the use of isothermal electron distribution lacks precision. Due to the very high density,the Pauli exclusion principle in quantum mechanics forbids electrons (and all fermions with half integer spin including neutron) occupying the same state. Basically, each electron must have different energy when they are packed together. The number of available low energy states is too small and many electrons are forced into high energy states.When this happens the electrons are said to be degenerate.These high energy electrons make a significant contribution to the pressure. Because this pressure arises from a quantum mechanical effect, it is insensitive to temperature, i.e. the pressure does not go down as the star cools. This pressure is known as electron degeneracy pressure and it is the force that supports white dwarf stars against their own gravity [62] .

B. Model Equations

We consider a collisionless, unmagnetized fourcomponent plasma composed of positive ions, negative ions, degenerate electrons, and stationary nano-dust particles. The expansion of such plasma is governed by the onedimensional fluid equations,

$$\frac{\partial n_+}{\partial t} + \frac{\partial}{\partial x}(n_+ u_+) = 0 \tag{1}$$

$$m_+ n_+ \left(\frac{\partial}{\partial t} + u_+ \frac{\partial}{\partial x}\right) u_+ + \frac{\partial p_+}{\partial x} + e z_{+n_+} \frac{\partial \phi}{\partial x} = 0 \tag{2}$$

$$\frac{\partial n_-}{\partial t} + \frac{\partial}{\partial x}(n_- u_-) = 0 \tag{3}$$

$$m_- n_- \left(\frac{\partial}{\partial t} + u_- \frac{\partial}{\partial x}\right) u_- + \frac{\partial p_-}{\partial x} - e z_{-n-} \frac{\partial \phi}{\partial x} = 0 \tag{4}$$

$$-e\frac{\partial \phi}{\partial x} + \frac{1}{n_e}\frac{\partial p_e}{\partial x} = 0 \tag{5}$$

$$Z_+ n_+ - Z_- n_- - n_e + \varepsilon z_d n_d = 0 \tag{6}$$

where $n_{\ +,-,e,d}$ is the positive ion/negative ion/electrons/dust number density, $u_{+,-}$ the ion fluid velocity, ϕ the electric potential, z_d the charge number, and $\varepsilon = +\ (-\ )$ for positive (negative) charged nano-dust particles. The variables appearing in Eqs. (1)–(6) have been appropriately normalized . Thus, $n_{+,-}$ is normalized by the unperturbed ion density $n^{(0)}_{+,-}$, $u_{+,-}$by the ion-acoustic speed $c_s = \left(\frac{K_B T_{Fe}}{m_+}\right)^{\frac{1}{2}}$, $p_{+,-}$ by $n^{(0)}_{+,-} K_{BT_{+,-}}$,and ϕ by $\frac{K_B T_{Fe}}{e}$.The ion pressure is assumed to be adiabatic since during this process the particles cool down, whereas using the isothermal pressure assume the system to be connected with a thermal reservoir, which is not the case at hand.The adiabatic ion pressure $p_{+,-}$ is proportional to the ion density $n_{+,-}$ by the relation $p_{+,-} \alpha n^3_{+,-}$.

The degenerated electron pressure $p_e = kn_e^{\frac{5}{3}}$,where $k \simeq \left(\frac{3}{4}\right)\hbar c$. Here, $T_{Fe} = \left(\frac{\hbar^2}{2m_eK_B}\right)\left(3\pi^2 n_e^{(0)}\right)^{\frac{2}{3}}$is the Fermi electron temperature, $T_{+,-}$is the positive (negative) thermal ion temperatures, $Z_{+,-}$is the positive (negative) ion charge number, $\hbar$ is the Planck constant divided by $2\pi, C$ is the speed of light in vacuum, K_B is the Boltzmann constant, $m_{+,-}$ is the positive (negative) ion mass, m_e is the electron mass, and e is the magnitude of the electron charge. In equilibrium, the neutrality condition of the plasma is satisfied, $Z_+n_+^{(0)} - Z_-n_-^{(0)} - n_e^{(0)} + \varepsilon z_d n_d = 0$.

The creation of the observed nano-hillocks was assumed to be correlated to the nonlinear perturbation of the plasma particles in the form of ion-acoustic waves that transport the energy in the half space with certain velocity. In other words, the plasma is supposed to fill the half space $x \succ 0$ and the front is moving with ion-acoustic speed C_S which is matching the ion motion time scale. The expansion front is formed by part of the ions that are subsequently accelerated, and is associated with density depletion. The region of decreasing density moves into the ambient plasma with the ion-acoustic speed. Employing the dimensionless self-similar variable $\xi = \frac{x}{C_s t}$ into Eqs. (1)–(6) and solve the system of equations numerically, we obtain the density and velocity profiles through the expansion process. Typical experimental data are used such as the unperturbed electron number density $n_e^{(0)} = 8.9 \times 10^{22}$ cm^{-3}, the nano-hillock height is $\sim 4 - 7 \times 10^{-7}$cm, and the time of hillock formation is $\sim 10^{-12}$ s. Therefore, the self-similar variable is $\xi \sim 1$ [63] .

Using the dimensionless self-similar variable $\xi = x/C_S t$, we obtain the following set of normalized ordinary differential equations:

where : $\frac{\partial}{\partial t} = \frac{-\xi}{t}\frac{\partial}{\partial \xi}$ and $\frac{\partial}{\partial x} = \frac{1}{C_s t}\frac{\partial}{\partial \xi}$.

Employing the dimensionless self-similar variable $\xi = x/C_S t$ into Eq (1) :

$$\frac{-\xi}{t}\frac{dn_+}{d\xi} + \frac{1}{C_s t}\frac{d}{d\xi}(n_+u_+) = 0, \tag{7}$$

$$\begin{aligned} \frac{-\xi}{t}\frac{dn_+}{d\xi} + \frac{1}{C_s t}n_+\frac{du_+}{d\xi} + \frac{1}{C_s t}u_+\frac{dn_+}{d\xi} = 0, \\ -\xi\frac{dn_+}{d\xi} + \frac{1}{C_s}n_+\frac{du_+}{d\xi} + \frac{1}{C_s}u_+\frac{dn_+}{d\xi} = 0, \end{aligned} \tag{8}$$

simplifying last equation we get :

$$\left(\frac{u_+}{C_s}-\xi\right)\frac{dn_+}{d\xi}+\frac{n_+}{C_s}\frac{du_+}{d\xi}=0, \tag{9}$$

normalizing this equation as : $u_+ = C_s\ \widetilde{u}_+$, $n_+ = n_+^{(0)}\widetilde{n}_+$.

$$\left(\widetilde{u}_+-\xi\right)n_+^{(0)}\frac{d\widetilde{n}_+}{d\xi}+\frac{n_+^{(0)}\widetilde{n}_+}{C_s}C_s\frac{d\widetilde{u}_+}{d\xi}=0, \tag{10}$$

Finally we get :

$$\left(\widetilde{u}_+-\xi\right)\frac{d\widetilde{n}_+}{d\xi}+\widetilde{n}_+\frac{d\widetilde{u}_+}{d\xi}=0. \tag{11}$$

Using the self-similar variable $\xi = x/C_st$ into Eq in the equation (2):

$$m_+n_+\left(\frac{-\xi}{t}\frac{du_+}{d\xi}+u_+\frac{1}{C_st}\frac{du_+}{d\xi}\right)+\frac{1}{C_st}\frac{dp_+}{d\xi}+ez_{+n_+}\frac{1}{C_st}\frac{d\phi}{d\xi}=0, \tag{12}$$

simplifying this equation we get :

$$m_+n_+\left(-\xi\frac{du_+}{d\xi}+u_+\frac{1}{C_s}\frac{du_+}{d\xi}\right)+\frac{1}{C_s}\frac{dp_+}{d\xi}+ez_{+n_+}\frac{1}{C_s}\frac{d\phi}{d\xi}=0, \tag{13}$$

divided equation by m_+n_+ :

$$-\xi\frac{du_+}{d\xi}+u_+\frac{1}{C_s}\frac{du_+}{d\xi}+\frac{1}{C_sm_+n_+}\frac{dp_+}{d\xi}+ez_+\frac{1}{C_sm_+}\frac{d\phi}{d\xi}=0, \tag{14}$$

then we obtain :

$$\left(\frac{u_+}{C_s}-\xi\right)\frac{du_+}{d\xi}+\frac{1}{C_sm_+n_+}\frac{dp_+}{d\xi}+ez_+\frac{1}{C_sm_+}\frac{d\phi}{d\xi}=0, \tag{15}$$

normalizing this equation :

where : $p_+ = n_0K_BT_+\widetilde{p}_+$, $\phi = \dfrac{K_BT_{Fe}}{e}\widetilde{\phi}$ and $c_s = \left(\dfrac{K_BT_{Fe}}{m_+}\right)^{\frac{1}{2}}$.

$$\left(\widetilde{u}_+-\xi\right)C_s\frac{d\widetilde{u}_+}{d\xi}+\frac{1}{C_sm_+n_+^{(0)}\widetilde{n}_+}n_0K_BT_+\frac{d\widetilde{p}_+}{d\xi}+ez_+\frac{1}{C_sm_+}\frac{K_BT_{Fe}}{e}\frac{d\widetilde{\phi}}{d\xi}=0, \tag{16}$$

$$\left(\widetilde{u}_+-\xi\right)C_s\frac{d\widetilde{u}_+}{d\xi}+\frac{1}{C_sm_+\widetilde{n}_+}K_BT_+\frac{d\widetilde{p}_+}{d\xi}+z_+\frac{1}{C_sm_+}K_BT_{Fe}\frac{d\widetilde{\phi}}{d\xi}=0,$$

multiplying the term $\frac{1}{C_s m_+ \widetilde{n}_+} K_B T_+ \frac{\partial \widetilde{p}_+}{\partial \xi}$ by $\frac{T_{Fe}}{T_{Fe}}$we get :

$$\left(\widetilde{u}_+ - \xi\right) C_s \frac{d\widetilde{u}_+}{d\xi} + \frac{1}{C_s m_+ \widetilde{n}_+} K_B T_+ \frac{T_{Fe}}{T_{Fe}} \frac{d\widetilde{p}_+}{d\xi} + z_+ \frac{C_s^2}{C_s} \frac{d\widetilde{\phi}}{d\xi} = 0, \tag{17}$$

where : $c_s^2 = \left(\frac{K_B T_{Fe}}{m_+}\right)$.

$$\left(\widetilde{u}_+ - \xi\right) C_s \frac{d\widetilde{u}_+}{d\xi} + \frac{T_+ C_s^2}{C_s \widetilde{n}_+ T_{Fe}} \frac{d\widetilde{p}_+}{d\xi} + z_+ C_s \frac{d\widetilde{\phi}}{d\xi} = 0, \tag{18}$$
$$\left(\widetilde{u}_+ - \xi\right) \frac{d\widetilde{u}_+}{d\xi} + \frac{T_+}{\widetilde{n}_+ T_{Fe}} \frac{d\widetilde{p}_+}{d\xi} + z_+ \frac{d\widetilde{\phi}}{d\xi} = 0,$$

when $\widetilde{p}_+ \alpha\ \widetilde{n}_+^3$ so we have :

$$\left(\widetilde{u}_+ - \xi\right) \frac{d\widetilde{u}_+}{d\xi} + 3\widetilde{n}_+^2 \frac{T_+}{\widetilde{n}_+ T_{Fe}} \frac{d\widetilde{n}_+}{d\xi} + z_+ \frac{d\widetilde{\phi}}{d\xi} = 0, \tag{19}$$
$$\left(\widetilde{u}_+ - \xi\right) \frac{d\widetilde{u}_+}{d\xi} + 3\widetilde{n}_+ \frac{T_+}{T_{Fe}} \frac{d\widetilde{n}_+}{d\xi} + z_+ \frac{d\widetilde{\phi}}{d\xi} = 0,$$

we assume that $\sigma_+ = \frac{3T_+}{T_{Fe}}$ so we get :

$$\left(\widetilde{u}_+ - \xi\right) \frac{d\widetilde{u}_+}{d\xi} + \sigma_+ \widetilde{n}_+ \frac{d\widetilde{p}_+}{d\xi} + z_+ \frac{d\widetilde{\phi}}{d\xi} = 0. \tag{20}$$

Using the dimensionless self-similar variable $\xi = x/C_S t$ in the equation(3):

$$\frac{-\xi}{t} \frac{dn_-}{d\xi} + \frac{1}{C_s t} \frac{d}{d\xi} \left(n_- u_-\right) = 0, \tag{21}$$

$$\frac{-\xi}{t} \frac{dn_-}{d\xi} + \frac{1}{C_s t} n_- \frac{du_-}{d\xi} + \frac{1}{C_s t} u_- \frac{dn_-}{d\xi} = 0, \tag{22}$$
$$-\xi \frac{dn_-}{d\xi} + \frac{1}{C_s} n_- \frac{du_-}{d\xi} + \frac{1}{C_s} u_- \frac{dn_-}{d\xi} = 0,$$

simplifying last equation we get :

$$\left(\frac{u_-}{C_s} - \xi\right) \frac{dn_-}{d\xi} + \frac{n_-}{C_s} \frac{du_-}{d\xi} = 0, \tag{23}$$

normalizing this equation as : $u_- = C_s\ \widetilde{u}_-$, $n_- = n_-^{(0)}\widetilde{n}_-$.

$$(\widetilde{u}_- - \xi)\, n_-^{(0)} \frac{d\widetilde{n}_-}{d\xi} + \frac{n_-^{(0)}\widetilde{n}_-}{C_s} C_s \frac{d\widetilde{u}_-}{d\xi} = 0, \tag{24}$$

Finally we get :

$$(\widetilde{u}_- - \xi)\, \frac{d\widetilde{n}_-}{d\xi} + \widetilde{n}_- \frac{d\widetilde{u}_-}{d\xi} = 0. \tag{25}$$

Employing the dimensionless self-similar variable $\xi = x/C_s t$ into Eq (4):

$$m_- n_- \left(\frac{-\xi}{t} \frac{du_-}{d\xi} + u_- \frac{1}{C_s t} \frac{du_-}{d\xi} \right) + \frac{1}{C_s t} \frac{dp_-}{d\xi} - e z_- n_- \frac{1}{C_s t} \frac{d\phi}{d\xi} = 0, \tag{26}$$

simplifying this equation we get :

$$m_- n_- \left(-\xi \frac{du_-}{d\xi} + u_- \frac{1}{C_s} \frac{du_-}{d\xi} \right) + \frac{1}{C_s} \frac{dp_-}{d\xi} - e z_- n_- \frac{1}{C_s} \frac{d\phi}{d\xi} = 0, \tag{27}$$

divided equation by $m_- n_-$:

$$-\xi \frac{du_-}{d\xi} + u_- \frac{1}{C_s} \frac{du_-}{d\xi} + \frac{1}{C_s m_- n_-} \frac{dp_-}{d\xi} - e z_- \frac{1}{C_s m_-} \frac{d\phi}{d\xi} = 0, \tag{28}$$

we obtain that:

$$\left(\frac{u_-}{C_s} - \xi \right) \frac{du_-}{d\xi} + \frac{1}{C_s m_- n_-} \frac{dp_-}{d\xi} - e z_- \frac{1}{C_s m_-} \frac{d\phi}{d\xi} = 0, \tag{29}$$

normalizing this equation :

where : $p_- = n_0 K_B T_- \widetilde{p}_-$, $\phi = \dfrac{K_B T_{Fe}}{e}\ \widetilde{\phi}$ and $c_s = \left(\dfrac{K_B T_{Fe}}{m_+} \right)^{\frac{1}{2}}$.

$$(\widetilde{u}_- - \xi)\, C_s \frac{d\widetilde{u}_-}{d\xi} + \frac{1}{C_s m_- n_-^{(0)} \widetilde{n}_-} n_0 K_B T_- \frac{d\widetilde{p}_-}{d\xi} - e z_- \frac{1}{C_s m_-} \frac{K_B T_{Fe}}{e} \frac{d\widetilde{\phi}}{d\xi} = 0, \tag{30}$$

$$(\widetilde{u}_- - \xi)\, C_s \frac{d\widetilde{u}_-}{d\xi} + \frac{1}{C_s m_{-} {}_{-} \widetilde{n}_-} K_B T_- \frac{d\widetilde{p}_-}{d\xi} - z_- \frac{1}{C_s m_-} K_B T_{Fe} \frac{d\widetilde{\phi}}{d\xi} = 0,$$

multiplying the term $\dfrac{1}{C_s m_- \widetilde{n}_-} K_B T_- \dfrac{\partial \widetilde{p}_-}{\partial \xi}$ by $\dfrac{m_+}{m_+}.\dfrac{T_{Fe}}{T_{Fe}}$and the term $-z_- \dfrac{1}{C_s m_-} K_B T_{Fe} \dfrac{\partial \widetilde{\phi}}{\partial \xi}$ by$\dfrac{m_+}{m_+}$ we get :

$$\left(\widetilde{u}_{-}-\xi\right)C_s\frac{d\widetilde{u}_{-}}{d\xi}+\frac{m_+}{m_+}\frac{T_{Fe}}{T_{Fe}}\frac{1}{C_s m_-\widetilde{n}_-}K_BT_-\frac{d\widetilde{p}_-}{d\xi}-z_-\frac{1}{C_s m_-}\frac{m_+}{m_+}K_BT_{Fe}\frac{d\widetilde{\phi}}{d\xi}=0, \quad (31)$$

$$\left(\widetilde{u}_{-}-\xi\right)C_s\frac{d\widetilde{u}_{-}}{d\xi}+\frac{C_s m_+ T_-}{m_-\widetilde{n}_- T_{Fe}}\frac{d\widetilde{p}_-}{d\xi}-\frac{z_- C_s m_+}{m_-}\frac{d\widetilde{\phi}}{d\xi}=0,$$

$$\left(\widetilde{u}_{-}-\xi\right)\frac{d\widetilde{u}_{-}}{d\xi}+\frac{m_+ T_-}{m_- n\tilde{_-} T_{Fe}}\frac{d\widetilde{p}_-}{d\xi}-\frac{z_- m_+}{m_-}\frac{d\widetilde{\phi}}{d\xi}=0,$$

we assume that : $Q_-=\frac{m_+}{m_-}$.

$$\left(\widetilde{u}_{-}-\xi\right)\frac{d\widetilde{u}_{-}}{d\xi}+\frac{T_-}{\widetilde{n}_- T_{Fe}}Q_-\frac{d\widetilde{p}_-}{d\xi}-z_-Q_-\frac{d\widetilde{\phi}}{d\xi}=0, \quad (32)$$

when$\widetilde{p}_-\alpha\ \widetilde{n}_-^3$ so we have :

$$\left(\widetilde{u}_{-}-\xi\right)\frac{d\widetilde{u}_{-}}{d\xi}+3\widetilde{n}_-^2\frac{T_-}{\widetilde{n}_- T_{Fe}}Q_-\frac{d\widetilde{n}_-}{d\xi}-z_-Q_-\frac{d\widetilde{\phi}}{d\xi}=0, \quad (33)$$

$$\left(\widetilde{u}_{-}-\xi\right)\frac{d\widetilde{u}_{-}}{d\xi}+3\widetilde{n}_-\frac{T_-}{T_{Fe}}Q_-\frac{d\widetilde{n}_-}{d\xi}-z_-Q_-\frac{d\widetilde{\phi}}{d\xi}=0,$$

Using: $\sigma_-=\frac{3T_-}{T_{Fe}}$.

$$\left(\widetilde{u}_{-}-\xi\right)\frac{d\widetilde{u}_{-}}{d\xi}+\widetilde{n}_-\sigma_-Q_-\frac{d\widetilde{n}_-}{d\xi}-z_-Q_-\frac{d\widetilde{\phi}}{d\xi}=0. \quad (34)$$

Employing the dimensionless self-similar variable $\xi=x/C_St$ into Eq (5):

$$-\frac{e}{C_s t}\frac{d\phi}{d\xi}+\frac{1}{C_s n_e t}\frac{dp_e}{d\xi}=0, \quad (35)$$

$$-e\frac{d\phi}{d\xi}+\frac{1}{n_e}\frac{dp_e}{d\xi}=0,$$

normalizing this equation where : $\phi=\frac{K_BT_{Fe}}{e}\ \widetilde{\phi}$.

$$-e\frac{K_BT_{Fe}}{e}\frac{d\widetilde{\phi}}{d\xi}+\frac{1}{n_e}\frac{dp_e}{d\xi}=0, \quad (36)$$

$$-K_BT_{Fe}\frac{d\widetilde{\phi}}{d\xi}+\frac{1}{n_e}\frac{dp_e}{d\xi}=0,$$

using the degenerated electron pressure $p_e = kn_e^{5/3}$.

$$-K_B T_{Fe}\frac{d\widetilde{\phi}}{d\xi} + \frac{5}{3}kn_e^{2/3}\frac{1}{n_e}\frac{dn_e}{d\xi} = 0,$$
$$-K_B T_{Fe}\frac{d\widetilde{\phi}}{d\xi} + \frac{5}{3}kn_e^{-1/3}\frac{dn_e}{d\xi} = 0, \tag{37}$$

Take :$n_e = n_e^{(0)}\widetilde{n}_e$.

$$-K_B T_{Fe}\frac{d\widetilde{\phi}}{d\xi} + \frac{5}{3}kn_e^{(0)-1/3}\widetilde{n}_e^{-1/3}n_e^{(0)}\frac{d\widetilde{n}_e}{d\xi} = 0,$$
$$-\frac{d\widetilde{\phi}}{d\xi} + \frac{\frac{5}{3}kn_e^{(0)2/3}}{K_B T_{Fe}}\widetilde{n}_e^{-1/3}\frac{d\widetilde{n}_e}{d\xi} = 0, \tag{38}$$

assume that : $\beta = \frac{5}{3}kn_e^{(0)2/3}/K_B T_{Fe}$.

$$\frac{d\widetilde{\phi}}{d\xi} - \beta\ \widetilde{n}_e^{-1/3}\frac{d\widetilde{n}_e}{d\xi} = 0. \tag{39}$$

normalizing equation (6) as : $n_+ = n_+^{(0)}\widetilde{n}_+$, $n_- = n_-^{(0)}\widetilde{n}_-$ and $n_e = n_e^{(0)}\ \widetilde{n}_e$.

$$z_+ n_+^{(0)}\widetilde{n}_+ - z_- n_-^{(0)}\widetilde{n}_- - n_e^{(0)}\widetilde{n}_e = 0, \tag{40}$$

so we get :

$$z_+\widetilde{n}_+ - z_-\frac{n_-^{(0)}}{n_+^{(0)}}\widetilde{n}_- - \frac{n_e^{(0)}}{n_+^{(0)}}\widetilde{n}_e = 0, \tag{41}$$

assume that : $\alpha = \dfrac{n_-^{(0)}}{n_+^{(0)}}$ and $\gamma = \dfrac{n_e^{(0)}}{n_+^{(0)}}$.

$$z_+\widetilde{n}_+ - z_-\alpha\widetilde{n}_- - \gamma\widetilde{n}_e = 0. \tag{42}$$

The basic set of fluid equations (11) , (20) , (25) , (34) , (39) , (42) are then transformed to ordinary . To have a nontrivial solution of these equations the following determent should be vanish .

$$
\text{Deter} = \begin{vmatrix} \left(u_+^{\sim} - \xi\right) & n_+^{\sim} & 0 & 0 & 0 & 0 \\ \sigma_+ n_+^{\sim} & \left(u_+^{\sim} - \xi\right) & 0 & 0 & z_+ & 0 \\ 0 & 0 & \left(u_-^{\sim} - \xi\right) & n_-^{\sim} & 0 & 0 \\ 0 & 0 & \sigma_- Q_- n_-^{\sim} & \left(u_-^{\sim} - \xi\right) & -z_- Q_- & 0 \\ 0 & 0 & 0 & 0 & 1 & -\beta n_e^{\sim \frac{-1}{3}} \\ z_+ & 0 & -z_-\alpha & 0 & 0 & -\gamma \end{vmatrix} = 0 \ .
$$

Solving the last determent we obtain an expression of, using it along with basic equaions (11) , (20) , (25) , (34) , (39) , (42) and solving them numerically with the aid of Mathematica code we can determine the properties of created plasma .

IV. DISCUSSION

The numerical solutions of the fluid equations showed the profile changes of both the normalized ion density "n_+ " and velocity "u_+" with the ion temperature, see Figs. (3. 2) (a) and (b). Here after , we shall omitt "n_+ " , "u_+" from the dependent parameters for simplicity . Using $T_+ \approx T_- = 7000$, 9000, and 11000 K, we have observed that the increase of the ion temperature would lead to the rise of the rate of the ion density depletion, as shown in Fig. (3. 2) . This behavior is expected due to the high potential energy deposited by highly charged ions into a localized region. This will lead to strong electronic excitations in the ZnO surface and sub-surface regions that increase the temperature via electron-phonon coupling. The increase in the temperature in the impact region would lead to the creation of plasma. Furthermore, the energy gain for the electrons and consequently move faster by depositing higher energy. These fast electrons create more charge separation between the electrons and positive ions.

In fact, the positive ions are much heavier than the electrons, so they move behind the electrons to maintain the quasi-neutrality condition. Therefore, the self-similar solution validity domain (i,e, ξ) increases with the potential energy of the highly charged xenon ions. On the other hand, the surface nano-hillocks became taller by increasing the ion potential energy. The size control of the created nanostructures by tuning the potential energy is of vital importance in future application. It should be emphasized that within the created plasma region, the surface nano-hillocks can be only formed if the potential energy of the used HCIs is above a threshold value, which is required for maintaining the creation of plasma in the nano-scale size. During the earlier stage of the expansion, an am-bipolar electrostatic potential rises due to the local charge separation. Depending on the temperature, there are mainly two profiles. The first corresponds to low temperature regime and it is almost linear (solid line). In this case, the electrostatic interaction is stronger than the thermal excitation, allowing particles to keep constant distance and creates constant electrostatic field. The second when the particles kinetic energy overcome the electrostatic barrier, the distance between the electrons and the positive charges increases. During the expansion, the particles cool down as shown in the velocity plot in Fig. 3. 2 (b), where the velocity starts to have a constant profile beyond a critical value of ξ.

Due to the fact that the high energy density delivered by HCIs, can lead to the formation of negative/positive charged nano-dust grains, we studied their effects of the created plasma and its expansion. Indeed, both types of polarity changes for nano-dust grains are possible to exist. Recalling that the charging of the nano-dust grains by either negative or positive charges would lead to decrease or increase the electron number density in the system. Therefore, the electron number density in the plasma system changes with the presence of nano-dust grains. Figure (3. 3) shows the normalized ion density and velocity profiles for negative and positive nano-dust grains. For negative nano-dust particles, both the self-similar solution validity domain and the velocity of the ions increase. Thus, the nano-hillocks height becomes taller. However, the positive nano-dust particles play an opposite rule, *i.e.*, the self-similar solution validity domain and the velocity of the ions shrinks. So, the nanohillocks height is stumpy. One can attribute this behavior to the fact that if there are excess of electrons (positive dust case) then the energy of HCI is distributed over many electrons that would lead to significant reduction of the exchange energy. This energy will be maximum in case of negative dust due to a limited number of electrons, so the electrons gain more energy and acquire high speed that increases the expansion and consequently the hillocks become taller.

For positively charged dust (dashed line), the electrons are attracted. So, they cannot be pushed away for long distance that reduce the expansion of both the electrons and ions. This effect is depicted through the reduction of the self-similar expansion domain. However, negative dust acts on the electrons via Coulomb interaction giving rise to a repulsive force. This propulsion for the electrons leads to an increase of the ion front expansion (dotted line).

In conclusion, we have shown that single highly charged ions are able to create surface nanostructures in zinc oxide (ZnO). Using ions of constant kinetic energy, the significant role of potential energy for the creation of nano-hillocks was demonstrated. Furthermore, controlling the size of the observed nanostructures was done by tuning the potential energy. To explain the formation of the created nanostructures, we used plasma expansion approach along with suitable fluid equations. Solving the basic equations numerically, we found that the surface nano-hillocks became taller with the increase of the ion temperature. This increase in the temperature in the impact region would lead to energy gain for the electrons that drag the ions and consequently create taller nano-hillocks. Furthermore, the effect of nano-dust particles polarity was invoked, showing that the presence of positive and negative dust particles make the nano-structures shorter and taller, respectively [63] .

V. SUMMARY

To summarize, we have introduced a new approach for explaining the creation mechanism of HCIs induced surface nano-structures on Zinc Oxide. We have used the plasma expansion approach with suitable hydrodynamic equations for the positive ions, negative ions, electrons and nano-dust particles. By using a self-similar transformation, the governing nonlinear equations are numerically solved for typical values of nano-scale experiment. The potential energy deposited by the HCIs leads to strong electronic excitations in the Zinc Oxide surface and sub-surface regions that increases the temperature via electron-phonon coupling. The increase of the induced HCIs energy would lead to enhance the surface temperature to break the bonds that hold solids together and a small amount of solid (nano-dust particles) explodes into a plasma of ionized atomic particles. Within the nano-scale created plasma region, the increase of the temperature causes an increase of the self-similar solution validity domain and consequently the surface nano-hillocks become taller. Furthermore, the effect of nano-dust particles polarity has been studied. Finally, creation and size control of the HCIs induced surface nanostructures, by tuning potential energy, are of importance for future nanotechnological applications.

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