

Hydrodynamic Time Scale of Resonance in Intense Laser Irradiated Nano-Plasma of Different Geometries

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Abstract—Absorption of intense ultra-short laser pulse 10^{15} W/cm² $\ll I \ll 10^{18}$ W/cm² in hot dense plasmas is inefficient. At high temperatures plasma becomes collisionless and absorption could only be achieved by excitation of resonance. For realizing resonance nanostructures are used and for high absorption laser parameters like intensity and pulse duration should be judiciously chosen according to the shape of nanostructure. Intense laser heated hydro-dynamically expanding nanostructures undergo electron density dilution and their natural frequency of charge density oscillation meet the laser frequency for excitation of resonance. It is found that solid nano-particles like gas clusters and nano-rods, the hydrodynamic time scales to reach resonance is longer in comparison to hollow nanostructures like nano-tubes and nano-shells. It is also shown that due to polarization pressure solid nanostructure undergo expansion primarily along the incident laser polarization; this also leads to arrival of resonance condition earlier in time. It is desirable that the resonance occurs at high density for a significant radiation and particle flux. For this hollow nanostructures or higher laser intensity pulse is required for resonance condition to occur at higher density even for ultrashort pulses. This analytical analysis gives a handy recipe for choosing the laser Fluence/Intensity and pulse duration so that the resonance condition is met at the peak of the incident laser pulse. Also, the derived expressions for hydrodynamic time scales of resonance serve as a guide for choosing laser and target geometrical parameters for efficient laser energy coupling in nano-plasmas for efficient X-rays, electron and ion generation.

Keywords—Resonance, Nano-structures, Gas Clusters, Nano-rod, Nano-shell, Nano-tube, Elliptical Nano-cylinders, Hydrodynamics of plasma, Ultrashort Lasers, Collisionless plasmas

I. INTRODUCTION

Absorption of intense laser pulses in plasmas is a widely pursued challenging problem [1]. Coupling of laser energy in hot dense matter is paramount to efficient X-rays [2], Hot Ions [3], and Fast electron generation [4]. They have a widespread application in inertial confinement fusion [5], Radiation and particle radiography [6], Mammography [7], Cancer cure [8]. Various technological endeavours with futuristic progress and development promise, are undertaken from the interesting discoveries in the field of laser plasma interaction. However, absorption of intense ultra-short pulse in matter is a long standing problem [1,9]. Since at high intensities the temperature of the laser heated matter becomes > 1 keV the plasma becomes collisionless [9,10]. It is well known from the Poynting's theorem that absorption of light in matter should be accompanied by dephasing between the incident laser field E and resultant current density J [11]. Collisions cause a natural dephasing and hence are responsible for energy deposition in matter. However, in

absence of collisions a scenario that is encountered in intense laser matter interaction dephasing can be caused if resonance is excited [12]. It is also known that at resonance there is a polarizability reversal and occurrence of drastic phase change, therefore resonance is the key to laser energy coupling in matter in absence of collisions. Therefore it is not a surprise that a wide number of studies have been devoted to finding targets like nanostructures of various shape, size, morphology and geometry for efficient laser energy coupling [13]. For this purpose solid nanostructures like spherical gas clusters [14], metal clusters [15], nano-rods [16], nano-tubes [17], nano-shells etc. are used. The resonance supported by them depends on their shape and geometry [18]. Only little study has been done previously to analytically predict the time scales / laser pulse duration and intensity required for exciting resonance in nanostructures of different shapes and geometries. In this work we analytically predict the hydrodynamic time scales for occurrence of resonance in various nanostructures of different geometries. In addition to this the role of laser intensity in accelerating the density

dilution process during the hydrodynamic expansion is investigated. The paper is organised as follows. First in section II we give a basic introduction to light nano-structure interaction. In section III physics of resonance is discussed. Here we derive the resonance condition of solid spherical and nano-rods. This is followed by a brief overview on hollow nano-structures like nano-tubes and nano-shells in section IV. Interestingly hollow nanostructures exhibit two resonances and therefore have two instances when resonance condition is met during the hydrodynamic expansion. In section V the electric field and resonance density in elliptical nano-rod is shown. Section VI is devoted to finding the hydrodynamic time scales of resonance in solid, hollow and pointed nano-structures. The effect of polarisation pressure in making the expansion predominantly along the laser polarisation direction is elaborated in section VI. These results in the nano-rod shape modification to become nano-elliptical causing an increase of its resonance density. The derived expressions are used to produce various graphs in section VII. These graphs convey very easily the time scales of resonance in various nano-particles of different size and interacting at different laser intensities. It is shown that at high intensity the laser intensity is quite crucial for determining the time scales of occurrence of resonance. Resonance occurring at high density is important, and for this hollow and pointed nanostructures should be used. The need for exciting resonance at the peak of laser pulse demands that the pulse duration should be stretched, leading to lowering of intensity [10]. This can be avoided by using higher intensities to accelerate the expansion rate of nano-particles and resonance can occur at the peak of pulse with considerably low pulse stretching. Section VIII concludes the work and gives future perspective.

II. LIGHT NANO-STRUCTURE INTERACTION

First we outline the basic assumptions used to determine the hydrodynamic time scales of resonance in laser irradiated nano-structures. The incident laser light is linearly polarised and intensity $\gg 10^{15} \text{W/cm}^2$, pulse duration may be 100 fs -1 ps (ultra-short laser pulses). The incident laser wavelength is 800 nm Ti: Sa Laser and $\lambda \gg$ size of nano-particle. Under this assumption quasi-static approximation is used treating light matter interaction as dielectric kept in electric field [19]. For cylindrical nano-particles $\lambda \gg$ radius of the nano-cylinder [20]. The resonance density of different nanostructure is derived by solving the Laplace equation in proper coordinate system according to the nanostructure geometry. The normal component of electric displacement vector and tangential component of the electric field is continuous across the boundary. For hollow structures these boundary conditions are applied for both inner and outer surface [20]. Also the electric potential is continuous at the boundary. Another assumption which is also validated in other works is that laser ionizes the nano-structure at the foot of the pulse through tunnel and field ionisation and a solid

density nano-plasma is created [18, 19]. The heated nanostructure expands due to a combination of Hydrodynamic, Coulomb [19] and Polarisation pressure. Hydrodynamic pressure is predominant for large diameter nano-particle and polarisation pressure is dominant for pointed nano-structures. The energy decrease/cooling due to expansion is compensated by the incoming supply of laser pulse energy. Therefore the average temperature of the cluster during the hydrodynamic expansion does not strongly depend on laser pulse duration. But temperature is sensitive to the Fluence /Intensity of the pulse (Where intensity is varied by changing the laser energy). Moreover, ionisation produces more electrons as the laser instantaneous intensity increases, but the energy redistribution keeps the temperature almost constant. So the average temperature during the entire evolution dynamics determines the hydrodynamic expansion rate and is considered to depend only on laser Fluence or Intensity [21]. The polarization of the nano-particle dynamically varies with laser frequency and depends on the instantaneous electron density (n) and the geometry of the structure. Sufficient hydrodynamic expansion is needed for density dilution of the solid density nano-plasma (n_0); so that its natural instantaneous oscillation frequency becomes equal to the laser frequency ω (Resonance condition). This happens when the diluted instantaneous electron density (n) becomes equal to the resonance density [22].

III. RESONANCE IN SOLID NANO-STRUCTURES

The electric field inside a dielectric sphere (E_{in}) is well known and the resonance condition can be derived from it. At resonance polarisation reversal take place and electric field blows to a high magnitude. It may be noted that the field enhancement at resonance is instrumental in the efficient particle and radiation generation since the effective intensity of light also escalates to a very high value.

$$E_{in} = \frac{3E_0}{\epsilon + 2} \quad (1)$$

Here E_0 is the applied laser field. The dielectric constant ϵ of plasma is given by

$$\left(\epsilon = 1 - \frac{n_e / n_c}{(1 + i\nu / \omega)} \right) \quad (2)$$

It depends on electron density n_e , critical density n_c (which is $1.7 \times 10^{21} / \text{c.c.}$ for 800 nm light) and the collision frequency ν . The Spitzer collision frequency is given by eq.(3)

$$\nu_{e,i} \approx 3 \times 10^{-6} \ln \Lambda n_e \left(\frac{Z}{T_e^{3/2}} \right) \quad (3)$$

Where $\ln \Lambda$ is the Coulomb logarithm, T_e is the electron temperature and Z is the degree of ionization. At high intensity the collision frequency gets modified due to effective temperature of the electron moving in electric field. The modified value of temperature T_{eff} is put in eq.(3) using eq. (4). T_{eff} (eV) depends on $U_p=9.331_{14} (W/cm^2)\lambda(\mu m)^2$ which is the average oscillatory energy of electron in laser field. At high intensity $I \gg 10^{15} W/cm^2$ T_{eff} becomes > 1 keV and collision frequency becomes very low implying plasma becomes collisionless.

$$T_{eff} = \sqrt{T_e^2 + (U_p / k_B)^2} \quad (4)$$

For a collisionless plasma resonance density just depends on electron density. From eq.(1) resonance density is obtained by putting the denominator $(\epsilon+2)=0$. The inferences drawn using eq. (2), (3) and (4) yield the resonance density of spherical nano-particle as [19,21]

$$n_e = 3n_c \quad (5)$$

Similarly for plasma dielectric in the shape of solid nano-rod placed in the laser field, where the electric field is perpendicular to cylinder axis is given by [23]

$$E_{in} = \frac{2E_0}{\epsilon + 1} \quad (6)$$

And the resonance condition in solid nano-rod is

$$n_e = 2n_c \quad (7)$$

IV. RESONANCE IN HOLLOW NANO-STRUCTURES

The radial and angular averaged electric field inside a nano-tube (inner radius ‘a’ and outer radius ‘b’) like “carbon nano-tubes” (CNT) is given by (E_0 is perpendicular to the axis) [20]

$$\langle E_{in} \rangle = \sqrt{A_2^2 + \frac{B_2^2}{a^2 b^2}} \quad (8)$$

$$A_2 = \frac{-2E_0(\epsilon + 1)}{(\epsilon + 1)^2 - \left(\frac{a}{b}\right)^2 (\epsilon - 1)^2}; B_2 = \frac{-2E_0 a^2 (\epsilon - 1)}{(\epsilon + 1)^2 - \left(\frac{a}{b}\right)^2 (\epsilon - 1)^2} \quad (9)$$

The inspection of the above equations reveals that it has two resonance densities one is the high resonance and another is the low resonance density given by

$$n_H = \frac{2n_c}{1 - \left(\frac{a}{b}\right)} \quad (10)$$

$$n_L = \frac{2n_c}{1 + \left(\frac{a}{b}\right)} \quad (11)$$

It is easily seen that the resonance densities are tuneable depending on the instantaneous values of ‘a’ and ‘b’. Higher degree of hollowness means resonance density can be close to solid density.

Similar to nano-tubes the radial and angular averaged electric field inside a nano-shell (inner radius ‘a’ and outer radius ‘b’) like “fullerene” is given by

$$\langle E_{in} \rangle = \sqrt{C_1^2 + \frac{2D_1^2}{b^3 a^3}} \quad (12)$$

$$C_1 = \frac{-3E_0(2\epsilon + 1)}{D}, D_1 = \frac{-3E_0 a^3 (\epsilon - 1)}{D} \quad (13)$$

$$D = (\epsilon + 2)(2\epsilon + 1) - 2\alpha(\epsilon - 1)^2 \quad (14)$$

α is the degree of hollowness = a^3 / b^3

The inspection of the above equations again reveals that hollow nano-shells too has multiple resonance densities one is the high resonance and another is the low resonance density given by

$$n_H = \frac{(9 + 3\sqrt{1 + 8\alpha})n_c}{4(1 - \alpha)} \quad (15)$$

$$n_L = \frac{(9 - 3\sqrt{1 + 8\alpha})n_c}{4(1 - \alpha)} \quad (16)$$

V. RESONANCE IN POINTED NANO-STRUCTURES

The case of nano-elliptical cylinder plasma dielectric kept in laser field with laser polarisation perpendicular to the axis is a little involved. Here the Laplace equation has to be solved in elliptical coordinates; for brevity we just provide the final expression of the inside electric field shown in eq. (17). Resonance condition is obtained from this and it clearly shows that more pointed elliptical cylinder $a \gg b$ has large resonance density.

$$E_m = \frac{(1 + a/b)E_0}{\epsilon + a/b} \quad (17)$$

The resonance density is given by

$$n_e = \left(1 + \frac{a}{b}\right)n_c \quad (18)$$

It should be mentioned here that nano-cylinder can become like a nano-elliptical cylinder due to polarisation pressure. This will be discussed later.

VI. HYDRODYNAMIC EXPANSION OF NANO-PLASMA

The laser heated matter is ionized to solid density n_0 at the foot of the intense pulse. At lower intensity there may be drastic variation in the maximum initial electron density, but at higher intensities $\gg 10^{15} \text{W/cm}^2$ the initial electron density n_0 is almost constant due to ionization saturation [21]. At high intensities due to the onset of hydrodynamic expansion the instantaneous electron density only depends majorly on the plasma expansion speed c_s . The net pressure that causes expansion is due to a sum total of Hydrodynamic, Coulomb and Polarization pressure

$$P = nk_B T_e + P_{coulomb} + P_{Polarisation} \quad (19)$$

Hydrodynamic pressure is predominant for large nanoparticles. The plasma expansion speed is given by

$$c_s = \left(\frac{Z k_B T_e}{M_i}\right)^{1/2} = 10^4 (T(\text{eV}))^{1/2} \left(\frac{Z^*}{Z}\right) \left(\frac{m}{s}\right) \quad (20)$$

Here Z^* is average degree of ionization and Z is the atomic number. The outward expansion of plasma means the radius changes as shown in eq.(21)

$$a = a_0 + c_s t ; b = a_0 + c_s t \quad (21)$$

Where ‘a’ and ‘b’ are time dependent quantities for hollow particles ‘a’ is inner and ‘b’ is outer radius. In elliptical cylinder ‘a’ is major axis along polarization and ‘b’ is minor axis perpendicular to laser polarization. T_e is shown to depend on laser intensity given by eq.(22) given by Riley et.al [24].

$$T(\text{eV}) = 9.05 \times 10^{-7} \left[I_{\text{abs}} (\text{W cm}^{-2}) \right]^{0.615} \quad (22)$$

c_s is assumed to be constant during the hydrodynamic expansion of nano-plasma as shown by R. Issac et.al. [25] They have done experiments where the laser pulse duration was varied from 60-2200 fs at Fluence of 8 kJ/cm^2 . They showed the electron temperature was nearly constant and varied from $\sim 1.5 \text{ keV}$ to 2 keV . In this temperature range the nano-plasma expansion velocity c_s varies from 270-320 nm/ps. It may be noted though variation of pulse duration has little impact on average temperature, but the fluence/intensity change (By varying the laser energy) cause a drastic change in T_e as shown in eq. (22). To find the effect of laser intensity c_s can be obtained using eq. (20) and (22) for evaluating the hydrodynamic time scales of resonance of nanostructures of different shapes and geometries. The conservation of the total number of electrons on hydrodynamic expansion, assuming no recombination in laser “on” condition helps in analytically estimating the resonance time scales.

a) Solid Spherical nano/gas clusters

Conservation of electron number yield

$$\frac{4}{3} \pi a_0^3 n_0 = \frac{4}{3} \pi a_0^3 n(t) \quad (23)$$

From the resonance condition obtained in eq. (5) time scale of resonance τ_R is given by eq. (24) using eq.(21) and (23)

$$\tau_R = (a_0/c_s) \left(\sqrt[3]{\frac{n_0}{3n_c}} - 1 \right) \quad (24)$$

b) Solid Cylindrical nano/gas clusters

Conservation of electron number for nano-rod

$$\pi a_0^2 h n_0 = \pi a^2 h n(t) \quad (25)$$

‘h’ is height of nano-tube. From the resonance condition obtained in eq. (7) time scale of resonance τ_R is given by eq. (26) using eq.(21) and (25)

$$\tau_R = (a_0/c_s) \left(\sqrt{\frac{n_0}{2n_c}} - 1 \right) \quad (26)$$

c) *Hollow Cylindrical Nano-tube*

Conservation of electron number for nano-tube

$$\pi(b_0^2 - a_0^2)hn_0 = \pi(b^2 - a^2)hn(t) \quad (27)$$

'h' is height of nano-tube. From the two resonance condition obtained in eq. (10) and (11) the two time scale of resonance τ_H and τ_L is given by eq. (28) and (29) using eq.(21) and (27)

$$\tau_{RH} = \frac{-(\alpha + \beta) + \sqrt{(\alpha + \beta)^2 - 4\alpha\beta(1 - \gamma)}}{2\alpha\beta} \quad (28)$$

$$\alpha = \frac{2c_s}{a_0 + b_0}; \quad \beta = \frac{c_s}{b_0}; \quad \gamma = \frac{n_0}{2n_c} \left(1 - \frac{a_0}{b_0} \right)$$

In case degree of hollowness is high τ_{RH} can be approximated

$$\tau_{RH} = (b_0/c_s) \left(\sqrt{\frac{n_0}{2n_c} \left(1 - \frac{a_0^2}{b_0^2} \right)} - 1 \right) \quad (29)$$

The general hydrodynamic resonance time scale for low density resonance (without approximation) is given by

$$\tau_{RL} = \left(\frac{b_0}{c_s} \right) \left[\left(1 + \frac{a_0}{b_0} \right) \frac{n_0}{2n_c} - 1 \right] \quad (30)$$

d) *Hollow Nano-shell*

Conservation of electron number for nano-shell

$$\frac{4\pi}{3}(b_0^3 - a_0^3)n_0 = \frac{4\pi}{3}(b^3 - a^3)n(t) \quad (31)$$

From the two resonances condition obtained in eq. (15) and (16) the two time scale of resonance τ_H and τ_L is given by eq. (32) and (33). This calculated using eq.(15), (16), (21), (31). The general expression is quite complex so to have a simplistic inference the resonance times are calculated in the approximation of nano-shell having a high degree of hollowness.

$$\tau_{RH} = (b_0/c_s) \left(\left[\frac{n_0}{3n_c} \left(1 - \frac{a_0^3}{b_0^3} \right) \right]^{1/3} - 1 \right) \quad (32)$$

$$\tau_{LH} = (b_0/c_s) \left(\left[\frac{2n_0}{3n_c} \left(1 - \frac{a_0^3}{b_0^3} \right) \right]^{1/3} - 1 \right) \quad (33)$$

e) *Nano-elliptical cylinder*

Till now we considered that hydrodynamic pressure is the dominant contributor (see eq.(19)) in nano-plasma expansion dynamics. Now we will show that polarization pressure (eq.(34)) is also strong and causes the nano-particle to expand predominantly along the laser polarization. This leads to the structure becoming progressively more pointed. The nano-rod becomes nano-elliptical and nano-sphere becomes nano-ellipsoid. As the structure shape modifies and becomes pointed the polarization pressure increases further.

$$P_{pol} = \frac{1}{2} \text{Re}(\overline{\sigma \cdot E_{av}}) \quad \text{where } E_{av} = \frac{1}{2}(E_{in} + E_{out}) \quad (34)$$

$$P_{pol} = \frac{\epsilon_0 E_0^2}{4} \frac{3 - \epsilon}{\epsilon + 1} \cos^2 \theta \quad \text{for nano-rod} \quad (35)$$

' σ ' is surface charge density. The polarization pressure of nano-rod is given by eq. (35). It has strong dependence on electric field of laser and has a $\cos\theta$ dependence, which means the pressure is maximum along laser polarization and is zero perpendicular to it. As seen from eq.(18) larger is the value of 'a' (semi major axis) larger is the resonance density. This naturally implies that the resonance density can be achieved for shorter pulse duration if the asymmetric expansion due to polarization pressure is included. The resonance time scale for nano-elliptical cylinder can be obtained as follows. Conservation of electron number for nano-elliptical cylinder assuming expansion along E_0

$$\pi(a_0^2)hn_0 = \pi a_0(a_0 + c_s t)hn(t) \quad (36)$$

From eq. (18), (21) and (36) the time scale of resonance is

$$\tau_{RH} = \frac{-3 + \sqrt{1 + 4\xi}}{2\kappa} \quad (37)$$

$$\xi = \frac{n_0}{n_c}; \quad \kappa = \frac{c_s}{a_0}$$

VII. RESULTS AND DISCUSSION

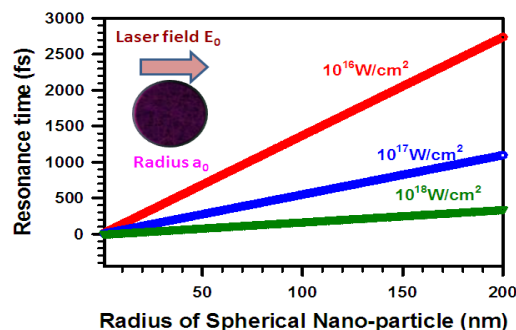


Figure 1. Resonance time in solid spherical cluster as a function of initial size (radius) and intensity of laser irradiation

Based on the derivation of hydrodynamic time scales of resonance in nano-structures of different geometries as done in the previous section, we now present the typical time scale of resonance in different nano-particles as a function of their geometry and incident laser intensity. The initial electron density close to solid density plasma $n_0/n_c=40$ [20,23]. Intensity dependence of c_s is obtained from eq.(20) and (22) is in agreement with predictions of R. Issac et.al[25].

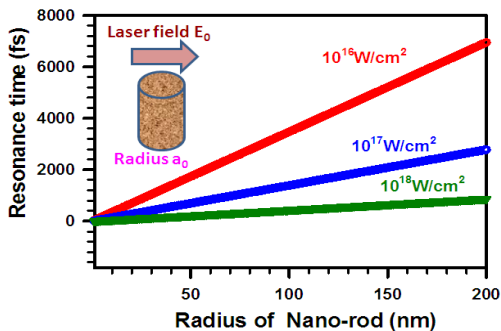


Figure 2. Resonance time in solid nano-rod as a function of initial size (radius) and intensity of laser irradiation

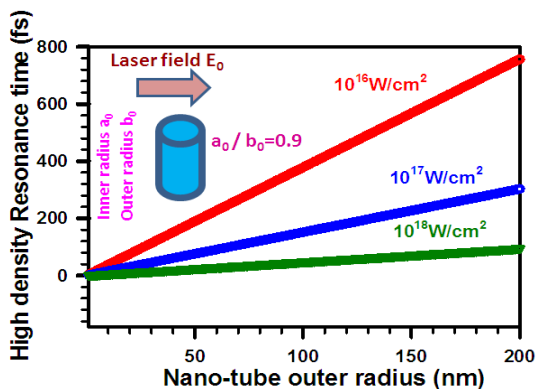


Figure 3. High density resonance time in hollow nano-tube as a function of initial size (outer radius b_0) and intensity of laser irradiation for $a_0/b_0=0.9$

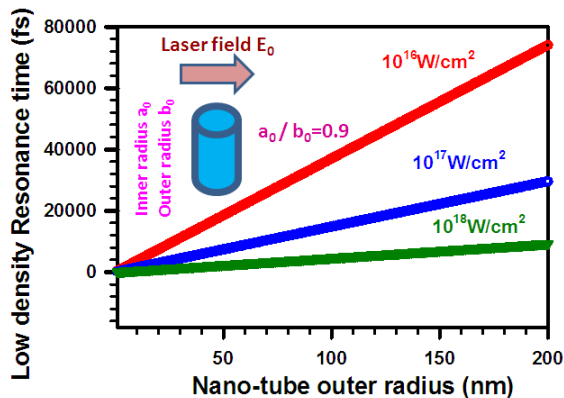


Figure 4. Low density resonance time in hollow nano-tube as a function of initial size (outer radius b_0) and intensity of laser irradiation for $a_0/b_0=0.9$

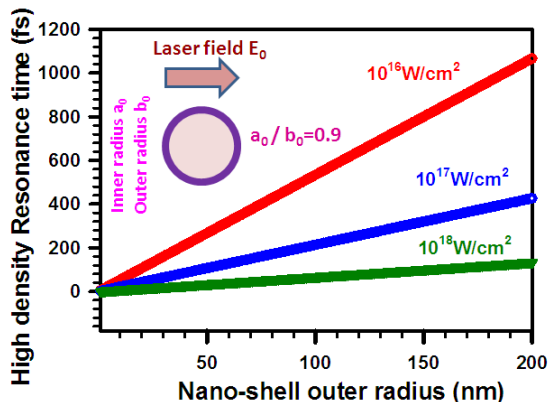


Figure 5. High density resonance time in hollow nano-shell as a function of initial size (outer radius b_0) and intensity of laser irradiation for $a_0/b_0=0.9$

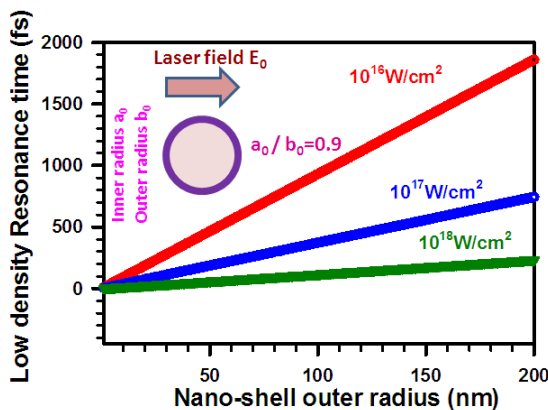


Figure 6. Low density resonance time in hollow nano-shell as a function of initial size (outer radius b_0) and intensity of laser irradiation for $a_0/b_0=0.9$

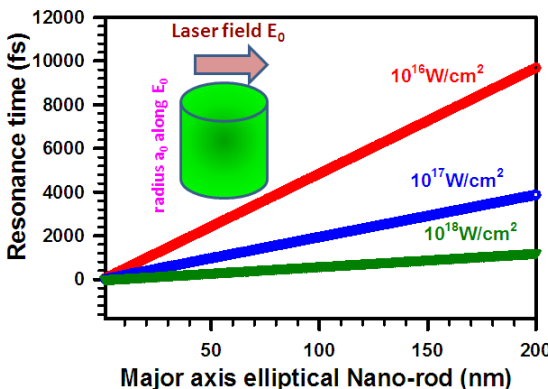


Figure 7. Resonance time in elliptical nanorod as a function of initial size (major axis that is parallel to laser polarisation) and intensity of laser irradiation

After plotting the graphs of hydrodynamic time scales of resonance in nano-structures we now point out and discuss the most noteworthy points. Fig. (1) and (2) shows Resonance time as a function of size (radius) and intensity of laser

irradiation in solid spherical cluster and nano-rod respectively. They are plotted using eq. (24) and (26). First and foremost large sized nano-particle reaches resonance later. Therefore longer pulse duration are required to hit resonance at the laser peak. The time scale of resonance in spherical clusters is much larger in cylindrical target of same size. The reason behind is simple that spherical cluster undergoes faster density dilution rate proportional to $1/r^4$ as compared to cylinder whose density varies as $1/r^3$. Intensity plays a crucial role in deciding the resonance time and if the available laser pulse is short then a high intensity should be used so that the resonance condition is met at the peak of the laser pulse. Fig.(3) and (5) show that the high density resonance time in hollow nanostructures like nano-tube and nano-shell is drastically small plotted using eq. (29) and (32). This means if the laser pulse duration is ultrashort hollow nanostructure must be used. In comparison to solid nano-particle hollow ones have multiple resonance feature. Fig.(4) and (6) shows Low density resonance time in hollow nano-tube as a function of initial size (outer radius b_0) and intensity of laser irradiation for $a_0/b_0=0.9$. They are plotted using eq. (30) and (33). The low density resonance is almost inconsequential for ultrashort pulses as these resonances occur in the ps time scales. However on increasing the laser intensity this resonance may occur during the laser pulse due to an accelerated expansion. Fig. (7) shows the resonance time in elliptical nanorod as a function of initial size (major axis that is parallel to laser polarisation) and intensity of laser irradiation. The plot is obtained from eq.(37). Here polarisation pressure is assumed to cause expansion at the similar rates as other structures. Only expansion along laser electric field is considered. This one directional expansion causes slower expansion. But if both hydrodynamic and polarisation pressure are included then expansion will occur perpendicular to laser field as well. Though this expansion speed will be less than the expansion along the major axis of elliptical cylinder. Nevertheless a simplistic estimate of the resonance time scale seen from Fig. (7) tell that in elliptical nan-rod a higher intensity is required so that polarisation pressure determine the quick arrival of resonance. The analysis given in the paper is a simplistic and comprehensive overview with some major assumptions based on certain experimental and theoretical reports available [9,10,19,21,25]. Detailed computer simulations will give further insight. Though the derived expression for resonance time scale is quite handy for target design and choice of laser intensity and pulse duration.

VIII. CONCLUSION AND FUTURE SCOPE

In conclusion the following remarks can be made regarding the hydrodynamic time scales of resonance of different nanostructures.

1) Resonance is the key to efficient energy coupling in nano-plasmas and nanostructure geometry decide the density at which resonance will occur and also the field strength.

2) Solid nanostructures like spherical gas clusters ($3n_c$) and nanorod ($2n_c$) have lower resonance densities and therefore longer time is required for sufficient density dilution on hydrodynamic expansion for achieving the resonance condition.

3) Hollow nanostructures (nano-tubes and shells like CNT and fullerenes) have multiple resonance densities. One is higher resonance density (n_H) and another lower density (n_L). Higher resonance density is achieved for shorter pulse duration and lower resonance density is achieved in longer time. For ultrashort pulses targets of higher degree of hollowness are ideal, since hydrodynamic expansion for density dilution is not a strong pre-requisite.

4) Polarisation pressure causes asymmetric expansion and leads to an accelerated expansion predominantly along the laser polarisation. The case of asymmetric expansion is shown for nano-cylinder though further studies are needed for dynamics of nano-particle evolution by including Hydrodynamic, Polarization and Coulomb pressure simultaneously.

5) Laser fluence / Intensity also play a dominant role in determining the hydrodynamic time scales for resonance due to faster expansion at higher intensities. Higher intensity causes resonance to be achieved earlier in time and therefore stretching of pulse to meet resonance at laser peak is precluded. Hollow and pointed nanostructures resonance can be excited at lower intensity since they have already high resonance density and therefore high intensity requirement for resonance excitation is not too strong.

Generally laser gas cluster [14,21] and nano-rod [16,23] interaction with intense pulses has been studied experimentally and analytically in various Laboratories but hollow nanostructures like nano-tube, nano-shells and pointed nanostructures studies are rather rare. Using them can lead to significant advancement in overcoming the challenge of inefficient coupling of high intensity light in solid density matter. This work and the derived expressions for hydrodynamic time scales of resonance will serve as a guide for choosing laser and target geometrical parameters for efficient laser energy coupling in nano-plasmas for efficient X-rays, electron and ion generation. Also the analytical solutions of fields and resonance densities are useful for plasma and nano-science community [26, 27].

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