Chapter 7

Enhancement of x-ray emission from nano-hole alumina.

As elaborated in the previous chapters, the inefficient deposition of the laser energy in solids can be improved by using nano-structure targets. The nano-structures offer a high absorption due to several reasons: 1) average mass density of a surface with nano-structure is lesser than a solid, implying a greater energy deposition depth ("Light trapping") [70] 2) greater surface to volume ratio also leads to enhanced interaction volume [71], 3) the protrusions of some nano-structures like, nano-wire, or metal nano-particles lead to efficient resonance absorption, because of the curvature of the structure, due to which the optimum angle for resonance absorption may be met locally [47]. Efficient absorption in nano-structured surface can also be achieved through excitation of surface plasma waves which are absent in planar solids [195]. Moreover, the electric field enhancement ("Lightning rod effect") [87] and linear [96-98] and nonlinear resonances [105-107] in nano-particles make them competitive as an efficient electron, ions and x-ray source [69-91]. They can be easily characterized by microscopic techniques, which gives them an edge over gas clusters whose characterization is difficult and indirect [92].

One can say that a nano-structured target should have the following characteristics for practical usability: i) it should be easy to produce in bulk quantity, ii) it should have a highly regular nano-structure, and iii) it should be cost effective. Nano-structured target like nano-hole alumina is a very promising laser-plasma x-ray source because of all the above mentioned characteristics present in it [196]. It consists of arrays of nano-holes which are perpendicular to the target surface. The target is easy to make with a large area, with a narrow hole size
distribution, by anodic oxidation of an aluminum plate. This target is also very useful to study the dynamics of ultra-short intense laser pulses with nano-structured targets owing to its regular arrangements of nano-holes.

The interaction of intense light with holes of few tens of nano-meters is also interesting for studying the electric field generated inside them after irradiation. Since, the nano-structured targets exhibit shape and size dependent field enhancement, which is evident from the hard x-ray emission from these targets, therefore nano-holes are also worth pursuing for study as target for the possibility of high fields in them. Nano-hole is a different type of structure. It is interesting to study the electric field inside the nano-holes, its hydrodynamic evolution, and its effect on x-ray emission. Although, nano-hole targets have been studied in the past for soft x-ray generation and the soft x-ray yield dependence on the nano-hole diameter [80,197], there is no study, on the hard x-ray emission and its dependence on laser pulse duration. Moreover, a clear understanding of the mechanism of x-ray enhancement in nano-holes is lacking.

In this chapter, we describe a comparative study of the laser energy absorption, soft x-ray emission (in the water window region : 2.3-4.4 nm), and hard x-ray emission (2-20 keV range) from planar aluminum and nano-hole alumina of various average diameters, when irradiated by Ti:sapphire laser pulses. The x-ray yield from the nano-holes was enhanced clearly showing an increased coupling of the laser energy to the target. The laser pulse duration was varied from 45 fs to 500 fs, and the focused intensity on the target ranged from \( \sim 3 \times 10^{16} \) W/cm\(^2\) to \( 3 \times 10^{17} \) W/cm\(^2\). The x-ray yield enhancement from the nano-holes shows an increased coupling of the laser energy to the target. The effect of laser pulse duration on the x-ray emission was also studied, where a resonance like phenomenon was observed. The laser energy absorption measurements in the nano-holes showed a marginal enhancement in absorption as compared to
planar Al. The integrated keV x-ray yield, from nano-hole alumina and planar Al, at an intensity of $3 \times 10^{17} \text{ W/cm}^2$, was 25 μJ and 3.5 μJ respectively. The results can be explained by considering the hydrodynamic expansion of the laser irradiated structure and field enhancement in the nano-holes.

7.1  Description of the experiment

7.1.1  Experimental setup

![Experimental setup for absorption and x-ray measurements](image)

Fig.7.1:  Experimental setup for absorption and x-ray measurements

The experimental setup for the study of absorption and x-ray emission from planar Al and nano-hole alumina, is shown in the Fig.7.1. Ti:sapphire laser pulses, with 75 mJ energy and 45 fs pulse duration, were focused on the target to a spot of 20 μm diameter, using a convex lens having a focal length of 500 mm. The p-polarized laser beam, with nanosecond intensity contrast ~ $10^6$, was incident on the target at an angle of 45° with respect to the target normal. The intensity on the target surface was upto ~$3 \times 10^{17} \text{ W/cm}^2$. The laser energy absorption was studied
from the measurement of the reflected and scattered laser light energy as a percentage of the incident laser light energy. A convex lens was used to collect the reflected light onto an energy meter. The collection solid angle of the lens was kept large enough to ensure that any reflected light from the plasma was collected by the lens. Another convex lens (not shown in Fig.7.1), also kept at 45° to the laser beam axis, and was used to collect the side-scattered light, which was monitored using a sensitive calorimeter having sensitivity of 164 V/J. The scattering percentage was estimated by assuming isotropic scattering. The pulse duration was varied from 45 fs to 500 fs, by changing the grating pair separation, for studying its effect on the x-ray emission and absorption.

7.1.2 X-ray diagnostics

To estimate the x-ray yield in plasma produced by the planar and nano-structured targets, three diagnostics were used: 1) Transmission grating spectrograph (TGS), 2) Dispersion-less spectrograph (as shown in Fig 7.1) and 3) X-ray p-i-n diodes (not shown in Fig.7.1). These diagnostics were set up to measure the x-ray signal simultaneously from different ports of the diagnostics chamber along with the absorption measurements. In this setup, the TGS was mounted along the target surface. It was used for the measurement of the x-ray yield in the soft x-ray region, particularly in the water-window region (23Å - 44Å). The x-ray emission spectrum was recorded using an MCP with CCD camera-PC based on-line measurement system. To maintain the MCP at proper vacuum, an additional vacuum system was used.

An x-ray p-i-n diode (Quantrad) was used with a 75 μm Be filter to estimate the x-ray energy yield above 2 keV. It was kept in the plane containing the target normal and laser beam axis. A permanent magnet of 0.15 tesla field was also kept in front of the x-ray diode to prevent
the hot electrons, emitted normal to the target, from colliding with the filter foils of the p-i-n diode and generating x-rays, which can be misinterpreted as x-ray signal from the target.

The spectrum in the 2-20 keV region was recorded in single shot mode using the dispersion-less spectrograph. The spectrograph was mounted on the 22.5° port, below the x-ray p-i-n detectors, as shown in Fig.7.1 (p-i-n diodes not shown for clarity). The x-ray CCD camera of the dispersion-less spectrograph had 4x10⁶ pixels. A 25 μm thick Ni foil (cut-off at 7.9 keV) was put before the CCD for cutting off the low energy x-rays. Another magnet of 0.085 tesla field was kept in front of the x-ray CCD camera. This field was sufficient to deflect even the most energetic hot electrons, to avoid the x-ray contribution from the hot electrons striking the filter foil in front of the CCD camera.

![Fig.7.2: SEM image of nano-hole alumina showing hole size of ~ 40 nm.](image)

Figure 7.2 shows the SEM micrograph of nano-hole alumina. It shows that the nano-holes have a uniform size distribution of average diameter 40 nm.
7.2 Experimental Results

![X-ray spectra](image)

**Fig.7.3: X-ray spectra of carbon, planar aluminum, and nano-hole alumina, in the water window region.**

The soft x-ray emission spectrum was recorded using the TGS, from targets irradiated by Ti:sapphire laser beam at an intensity of \( \sim 3 \times 10^{17} \text{ W/cm}^2 \). Figure 7.3 shows the x-ray spectra obtained from carbon, aluminum and nano-hole alumina. The carbon spectrum shows two peaks corresponding to He-\( \alpha \) and Ly-\( \alpha \) at wavelength \( \lambda = 40.7 \text{ Å} \) and 33.7 Å. These intense lines were used as reference for the x-ray emission spectra of Al and nano-hole alumina targets. Fig.7.3 also shows that in the soft x-ray region, the x-ray yield is \( \sim 4 \) times higher for nano-hole alumina compared to that for planar aluminum target. Due to the poor resolution of this spectrograph, Al lines from the targets were not seen. A nano-hole target offers a larger surface area that interacts with the fs-laser pulses leading to whole volume heating of the material by the laser. This observation is similar to that of Nishikawa et al [80,197] showing nano-hole alumina as a good soft x-ray source.
Figure 7.4 shows the x-ray spectra recorded using the x-ray CCD working as a spectrograph in the single photon counting regime (i.e. as a dispersion-less spectrograph). It clearly shows a high enhancement in the 1-10 keV range. Beyond 10 keV, the increase was not significant. The value of the enhancement varied between 6 to 8 in the above spectral range. More error is likely in the higher energy range than in lower energy range due to poor signal to noise ratio.

![Fig.7.4 X-ray spectra for planar aluminum (lower) and nano-hole alumina (upper)](image)

7.2.1 Effect of pulse duration

Figure 7.5 shows the pulse duration dependence of integrated yield of x-ray emission in the energy range of 2.2 keV to 20 keV region, recorded using the dispersion less spectrograph. Planar Al and nano-hole alumina targets were irradiated by laser pulses with variable pulse duration, at a fixed fluence of $\sim 10^4$ J/cm$^2$. The pulse duration was varied by changing the grating pair separation in the laser pulse compressor.
It was observed that for the planar aluminum, the x-ray yield (denoted by circles) decreased monotonically with increasing the pulse duration, but for the case of nano-hole alumina, the x-ray yield (denoted by inverted triangles) increased with pulse duration, reaching a maximum at ~100 fs, and then decreased with increasing pulse duration. The enhancement of the x-ray yield in the above mentioned range for the shortest pulse duration (45 fs) was 7 times. The maximum x-ray yield (at 100 fs) was 12 times higher than that for planar Al target, followed by a gradual decrease at higher pulse duration. At an intensity of $3 \times 10^{17}$ W/cm$^2$ for 45 fs pulses, the integrated x-ray yield above 2 keV from planar Al was 3.5 µJ and that from nano-hole alumina was 25 µJ measured using the p-i-n diode. The x-ray yield from nano-hole target was somewhat higher than the x-ray yield reported using Al coated grating target, where 20 µJ yield was achieved under similar conditions [161]. On stretching the pulse to 100 fs, the intensity was
~1.5×10^{17} \text{ W/cm}^2, \text{ and the x-ray yield above 2 keV from nano-hole alumina was 43 \mu J, whereas from planar Al it was 3.2 \mu J.}

### 7.2.2 Absorption studies

![Graph showing absorption, reflectivity, and scattering vs. pulse duration for planar aluminum and nano-hole alumina targets.]

**Fig. 7.6:** Percentage of absorption, reflectivity and scattering vs. pulse duration, for: a) planar aluminum, and b) nano-hole alumina

The laser energy absorption in both the targets was also studied and estimated by monitoring the specularly reflected light along with the scattering measurement at 45\(^\circ\) angle of incidence. Figures 7.6a and 7.6b show the variation of the percentage of absorption, reflectivity, and scattering, as a function of the pulse duration, for planar Al and nano-hole alumina targets,
respectively. The absorption measurements were made simultaneously with the x-ray measurements at a fixed fluence of $\sim 10^4$ J/cm$^2$. The data of scattering and reflectivity was averaged over 3 shots. Comparing the two graphs, one can see a nominal increase of absorption in nano-hole targets compared to the planar Al. Quantitatively, for the nano-hole alumina, the absorption was about 10-15% higher in comparison to that in planar Al. It is also observed that, for the nano-hole alumina target, scattering is less than that for planar Al, perhaps due to light trapping in the holes. Planar Al had absorption between 38 to 53%, whereas for nano-hole alumina, it was between 52 to 69%.

7.3 Analysis of the results

To investigate the reason for a large enhancement in the x-ray yield despite just a marginal increase in the absorption, the electric field inside these nano-holes was calculated. The details of the calculation are given below and the results of the calculations of electric field for nano-holes and nano-wires are shown in Fig.7.7. It shows that the field inside a nano-cylindrical hole can be very high (i.e. holes inside a dielectric medium can be very effective for field enhancement). The calculation is done for the electric field inside a solid nano-cylinder (nano-wire or nano-rod) and compared with a cylindrical hole in a dielectric (nano-hole), to study the interaction of these targets with intense short pulses. Although we have not done experiments with aluminum based nano-wires, for the sake of completeness, the case of solid nano-wire is also discussed along with other targets. It may be noted that in some other experiment on studying x-ray emission (not reported here) from planar zinc and zinc oxide nano-wires, the hard x-ray enhancement was only moderate (2-3 times), although a very high absorption of 90% was recorded in the ZnO nano-wire target. The strikingly less efficient x-ray generation from nano-
wire in comparison to a nano-hole structure brings out the importance of spatial feature of nano-structure for field enhancement in them.

For the case of a nano-cylinder, when the laser light having electric field $E_0$ is incident on it, two cases arise:

In the first case, when the applied electric field is parallel to the cylindrical axis, the electric field inside the cylinder is given by $E_{in} = E_0$ [190]. This is because the length of the cylinder in this direction is much longer than the light wavelength, and there is no enhancement of the field.

In the second case, when the electric field is perpendicular to cylindrical axis, the electric field magnitude inside the cylinder is given by the relation [190]

$$E_{in} = \frac{2}{\varepsilon + 1} E_0 \quad \ldots(7.1)$$

where the dielectric constant of plasma is given by

$$\varepsilon = 1 - \frac{n_e}{n_i(1 + iv/\omega)} \quad \ldots(7.2)$$

where $n_e$ is the critical density corresponding to the laser wavelength ($v/\omega$ is the ratio of collision frequency and the laser frequency). Equation 7.1 gives enhancement in the field inside the nano-cylinder at a density $n_e = 2n_c$, after ignoring the collision term [190]. This is similar to the enhancement observed at $3n_e$ in gas clusters ($E_{in} = \frac{3}{\varepsilon + 2} E_0$ in spherical geometry) and $n_e$ in planar solid ($E_{in} = \frac{1}{\varepsilon} E_0$ in slab geometry) [190].

In general, for the laser electric field applied at some angle with the cylinder axis, the electric field will have two component, one along the cylindrical axis and the other perpendicular
to it. This perpendicular component is the one which gives the enhancement in electric field inside cylinder as per Eq. 7.1.

For the case of a nano-hole of radius “a” inside a dielectric medium, the expression for electric field inside the hole can be easily calculated by replacing ε by 1/ε in Eq. 7.1 (similar to the treatment for uniform density nano-plasma model for the case of nano-sphere for spherical cavity in a dielectric). Therefore, the magnitude of the field inside the nano-hole can be found by replacing ε by 1/ε in equation 7.1 as [198]

\[ E_m = \frac{2\varepsilon}{\varepsilon + 1} E_0 \] 

.....(7.3)

As seen from this equation, the magnitude of the internal field is independent of \( r \) and \( \theta \), and the direction is along the applied field. However, the electric field outside the hole, i.e. at \( r >a \), has a radial field component \( (E_{r_{\text{out}}}) \) given by

\[ E_{r_{\text{out}}} = \left( \frac{a^2}{r^2} \frac{1 - \varepsilon}{\varepsilon + 1} + 1 \right) E_0 \cos \theta \] 

......(7.4)

and an azimuthal component \( (E_{\theta_{\text{out}}}) \) given by

\[ E_{\theta_{\text{out}}} = \left( \frac{a^2}{r^2} \frac{1 - \varepsilon}{\varepsilon + 1} - 1 \right) E_0 \sin \theta . \] 

......(7.5)

The magnitude of this external field \( (E_{\text{out}}) \) is given by \( \sqrt{E_r^2 + E_{\theta}^2} \) and it is a function of both \( r \) and \( \theta \). The electric field value just at the hole-boundary (i.e. at \( r = a \)) is given by

\[ E_{\text{out}} = \frac{2\sqrt{\cos^2 \theta + \varepsilon^2 \sin^2 \theta}}{1 + \varepsilon} E_0 . \] 

......(7.6)

The spatial average of the electric field magnitude taken over \( 2\pi \) is given by the expression

\[ E_{\text{rms, out}} = \frac{2\sqrt{1 + \varepsilon^2}}{1 + \varepsilon} \frac{E_0}{\sqrt{4\pi}} \] 

......(7.7)
Equations 7.1, 7.3-7.7 show that resonant enhancement occurs in the field inside the nano-hole as well as outside it, at $2n_c$.

In a practical situation, when an intense ultra-short pulse irradiates a nano-wire or a nano-hole, the foot of the intense laser pulse ionizes the matter and the subsequent pulse interacts with the plasma electrons which oscillate under the applied field and collide with the ions to deposit their energy. The initial density of the electrons in both cases (nano-wire or nano-hole) will be equal to solid density, which is $\sim 100 \ n_c$ in the beginning. The energy deposition leads to the enhancement of the temperature and this causes the density of the electrons in the nano-particle to evolve hydrodynamically, i.e. the nano-hole will decrease its radius (ultimately leading to void closure) and the nano-wire will increase its radius. In both the cases, the electron density will decrease because of the volume expansion. However, there is a difference in the electric field value inside the nano-wire and the nano-hole as shown in Fig.7.7a which summarizes the field enhancement factor in planar solid, solid nano-wire, outside nano-hole, and inside nano-hole (using equations 7.1, 7.3, 7.7).

The field enhancement factor mentioned here is defined as the magnitude of the ratio of the electric field inside the nano-structure to the applied laser electric field strength, that is $|E/E_o|$. Initially the electron density is $\sim 100 \ n_c$ which keeps decreasing with time. The maximum field enhancement take place at $2n_c$ for both the cylindrical targets (nano-wire and nano-hole), and at $n_c$ for planar solid. When the electron density surrounding the nano-hole is high ($n_e > 2n_c$), Fig.7.7a shows that the field inside the nano-hole is twice high as compared to the applied field. As the heated nano-holes expand, the density reduces and there is further field enhancement. When the density reduces to two times of critical density, the electric field inside the nano-hole
is resonantly enhanced compared to the applied field. The enhancement value remains above a factor of 2 till the density falls to less than 1.5 $n_c$.

Fig. 7.7: a) Electric field evolution with density for inside and outside nano-holes, solid nano-wires, and planar solid for comparison. b) Rate of deposition of energy in planar solid, nano-wire, and region outside the nano-hole. $\nu/\omega$ is taken as 0.1 for all the plots.

As explained in the next section, this field enhancement in the nano-hole exists over a very large range of densities, and results in higher x-ray emission, as seen in Figs. 7.3, 7.4, and 7.5. In comparison, the resonant field enhancement in the case of a planar target occurs only at the critical density, and therefore the x-ray emission in this case remains much below that in the
case of the nano-holes. In addition, the field outside the nano-hole is also high as compared to the planar solid and solid nano-wire for most of the range of electron density. The electric field inside a nano-structure governs the ionization and energy deposition processes in the plasma. The laser primarily deposits its energy into the free electrons through inverse bremsstrahlung. The rate of deposition of energy in the target is the heating rate \( \frac{\partial U}{\partial t} \) and it can be found by considering dielectric constant (\( \varepsilon \)) of plasma and the electric field inside the irradiated nano-structure. The energy deposited per unit volume in the plasma is given by [199]

\[
\frac{\partial U}{\partial t} = \frac{1}{4\pi} E \cdot \frac{\partial D}{\partial t}
\]

……..(7.8)

where \( E \) and \( D \) are the electric field and the electric displacement vector inside the plasma dielectric material, and \( \varepsilon \) is the dielectric constant of plasma given by Eq. 7.2. The heating rate time averaged over a cycle becomes [96]

\[
\frac{\partial U}{\partial t} = \frac{\omega}{8\pi} \text{Im} \varepsilon |E^2|
\]

……..(7.9)

The rate of heating described in equation 7.9 has a resonant phase when the electric field maximizes while the electron density passes through \( 2n_c \), for cylindrical geometry targets. It is important to note here that the expression of electric field ‘E’ inside the plasma from equations 7.1, 7.3-7.7 is dependent on the dielectric constant ‘\( \varepsilon \)’ which also contains the term \( \nu/\omega \) (which is the ratio of collision frequency and the laser frequency). The relative height and width of this resonance is dependent on the collision frequency \( \nu \). The collision frequency in turn depends on the electron density of the plasma and the temperature of the plasma as \( \nu = 2.91 \times 10^{-6} Z n_e T_e^{-3/2} \)
\ln \Lambda, \text{ where } Z \text{ is number of free electrons per atom, } n_e \text{ is the electron density in cm}^{-3}, T_e \text{ is electron temperature of the plasma in eV, and } \ln\Lambda \text{ is the Coulomb logarithm. Assuming } Z=5 \text{ and } T_e=1 \text{ keV and } \ln\Lambda=10, \text{ the value of } v/\omega \text{ varies from 0.004 to 0.4 in the density range from } n_e \text{ to } 100n_e. \text{ We assume an intermediate fixed value of the term } v/\omega \text{ to be equal to 0.1 to bring out qualitatively the difference of the energy deposition rate in planar solid, nano-wire and region around nano-hole. Taking this collision frequency parameter into account, and using equations 7.1, 7.2, 7.7 and 7.9, the rate of heating, which is proportional to } \text{Im}(\varepsilon)|E|^2 \text{ [96], is shown for various targets in Fig.7.7b. It is clearly seen that the rate of energy deposition is higher in a nano-hole structure as compared to planar solid or a nano-wire as seen from Fig.7.7b. This leads to an efficient heating of the nano-hole alumina material and results in enhanced temperature of the hot plasma and hence efficient x-ray emission is observed from them.}

The question that remains is how the electric field enhancement inside the nano-holes, where there are no ions to absorb the laser energy, helps in x-ray emission enhancement. As mentioned earlier, the absorption of laser energy in 40 nm nano-holes alumina was slightly higher (by 10-15\%) than that in planar Al target. However, although the ions are absent in the nano-holes, the electrons oscillating in the applied electric field will still be present. For example, at an intensity of 3x10^{17}/W/cm^{2}, the excursion peak amplitude of the electrons (eE_0/m\omega_0^2) will be \sim 60 nm, which is of the order of the diameter of the nano-holes. With enhanced field, the excursion length is going to be even higher. This will force the electrons ejected from one side of the nano-hole penetrate into the other side of the nano-hole. These energetic electrons colliding with the ions can give rise to enhanced x-ray emission, as observed experimentally.
The increase of x-ray emission in nano-hole targets on stretching the laser pulse (as seen in Fig.7.5) is perhaps because a longer laser pulse will see higher field enhancement. Assuming that the density reduction due to expansion takes place at a certain rate, a longer pulse will reach closer to $2n_e$ before it dies out, than a shorter laser pulse. As a result, the x-ray emission will show increase with pulse duration. However, as the laser pulse duration is increased, the electric field of the laser reduces. Moreover, as the plasma expands, the nano-holes will get filled up (void closure). Once this happens, one has almost uniform density plasma all over, like in a planar target, and there is no field enhancement. As a result of both these effects, the x-ray emission will start decreasing to reach the value for a planar target, at large pulse widths. Thus, there will be a maximum at some pulse duration. Experimentally, for 40 nm nano-holes, the optimum pulse duration is observed to be about 100 fs (Fig.7.5).

Finally, it is necessary to mention here that the observed x-ray enhancement from a nano-hole target has been explained invoking basic electromagnetic theory in a very idealized geometry. In reality, the length of the cylinder (hole depth) in the direction parallel to the cylindrical axis is finite and in some cases may not be much longer than the light wavelength. For example, the SEM image of the cross-section of the nano-hole alumina target used in our experiments shows the depth of the nano-hole target was ~2 μm, which is not large enough to be considered as much larger than the light wavelength. Consequently, such a structure should be considered as a cone-shape cavity rather than a cylinder. Then, certain resonant electromagnetic modes other than the mode located in the density $n_e=2n_e$ may be excited, as evident in detailed numerical simulations available on such cavity structures. For example, Huang et al [200] have shown through simulations that surface-plasmon-related electromagnetic modes can be excited in the cavity nano-structures irradiated by intense ultra-short pulse laser, which would induce
strong localized field enhancement in the cavity. Excitation of these surface plasmons need free electrons which are readily available in metallic medium. When the nano-hole alumina surface is irradiated by an intense ultra-short pulse, free electrons are generated instantaneously and therefore the dielectric constant of nano-hole alumina transforms from being dielectric to metallic, and the plasmonic effect can be activated [201]. Thus for a complete understanding of the observed experimental results, such detailed simulations [200,201] would be very important. Nevertheless, the simple analytical analysis described in this paper broadly helps in understanding the x-ray enhancement from nano-hole target.

7.4 Hole size effect

Fig.7.8: SEM image of a) Planar aluminium, rest are nano-hole alumina showing hole size b) ~ 40 nm, b) ~60 nm, d) 90 nm.

We also studied the hard x-ray emission (in the 2-20 keV range) from planar aluminium and nano-hole alumina of various hole diameters. Figure 7.8 shows the SEM micrograph of a) Planar aluminum, rest are nano-hole alumina showing hole size b) ~ 40 nm, b) ~60 nm, d) 90 nm.
The effect of laser pulse duration on the x-ray emission was also studied, where the x-rays showed a peak behavior in all the cases for nano-hole targets. The pulse duration was varied by changing the compressor grating separation. Both positive and negative chirped pulses were used and chirp had no effect on the x-ray peak and x-ray yield, as the yield was similar in both cases of the chirp. The peaking time was observed to be proportional to the hole diameter. For instance, nano-holes of hole diameter 40 nm (see Fig. 7.5), 60 nm and 90 nm exhibit peaks in x-ray yield at 100 fs, 200 fs and 300 fs respectively as seen from Fig. 7.9. The results can be explained by considering the hydrodynamic expansion of the laser irradiated structure and field enhancement in the nano-holes.

The nano-hole target plasma does not possibly reach the resonance \(2n_c\) before the void closure. The x-ray peak is therefore observed due to absence of field enhancement on void
closure. Void closure time is observed to be proportional to the hole diameter. The nano-holes of diameter 40 nm, 60 nm and 90 nm exhibit peaks in x-ray yield at 100 fs, 200 fs and 300 fs respectively. From the void closure time, it is concluded that for the 40, 60 and 90 nm sized holes $Cs= 200 \text{ nm/ps}$ (for 40 nm nano-holes) and $Cs= 150 \text{ nm/ps}$ for the others. In summary, the nano-hole alumina target exhibit enhancement in the water window region and the hard x-ray (2-20 keV region) over planar aluminum. The observations of higher x-ray yield in the nano-hole targets (c/f planar target) and peaking of the x-ray yield in nano-hole targets is explained considering the electric field enhancement and void closure during hydrodynamic expansion.