Chapter 6

Soft x-ray emission from carbon nano-fibers

As mentioned in Chapter 5, point-like x-ray sources in the water-window spectral region (23-44 Å), emitting ultra-short pulses, are of particular interest for ultra-fast imaging of live biological samples with high contrast [108,171]. Plasma produced by intense ultra-short laser pulses from solid targets can serve as a compact and low-cost source for the above application [181-183]. As we have shown that the in situ formed targets are very attractive for overcoming the problem of low absorption of high-intensity, ultra-short laser pulses in plasma produced on solid targets. As mentioned in Chapters 1, 4 and 5, various other forms of solid targets like gratings, structured targets, metal clusters, nano-fibers etc. [69-86, 168,169] have been used by various experimental groups to enhance the laser energy absorption, production of energetic particles, and improving the x-ray conversion efficiency. In this and the following chapters, experiments on absorption and x-ray emission from intense laser irradiated nano-structures will be described. The aim is to study the effect of geometrical shape, size, fill fraction, and topography of the target on the absorption of intense ultra-short laser pulses. Another aspect is the dynamics of the laser irradiated nano-structures and resonances occurring in them, which can be manipulated for a higher absorption and the consequent x-ray conversion.

In this chapter, we describe an experimental study of the x-ray emission in the water-window region from carbon nano-fibers (CNFs) irradiated with ultra-short laser pulses. Since carbon also has intense resonance lines (from H-like and He-like ions) in the water-window region, graphite has been used as a target [184]. An increase in the x-ray emission may be expected by coupling intense short laser pulses to carbon based nano-structures [83,84,185-187]
instead of carbon-containing planar targets. CNFs, which can be produced easily in different sizes at low cost, are one such potential candidate.

We have observed that CNFs of different diameters show an order of magnitude enhancement of x-ray emission intensity over that for planar graphite target. The effect of laser pulse duration and the intensity scaling of the integrated x-ray yield are studied for CNFs of 60 nm and 160 nm diameters. The integrated x-ray yield of these carbon based targets is observed to scale with the laser intensity \(I_L\) as \(I_L^{-1.3-1.4}\) in the intensity range of \(4 \times 10^{16} - 4 \times 10^{17}\) W/cm\(^2\). The effect of the laser pulse duration on the x-ray emission from the CNFs has been also studied by varying the pulse duration from 45 fs up to 3 ps, at a constant fluence of \(2 \times 10^4\) J/cm\(^2\). The optimum laser pulse duration for maximum x-ray emission increases with the diameter of CNFs used. The results are explained from the physical considerations of heating and hydrodynamic expansion of the CNF plasma in which resonance field enhancement takes place while passing through two times the critical density. The results add to the efforts towards achieving an efficient low-cost water-window x-ray source for microscopy.

### 6.1 Description of the experiment

First a description of the processes used for CNF fabrication is given and also the characterization by a scanning electron microscope (SEM) is presented. The SEM is used to ascertain the CNF diameter and the inter fiber separation, as these factors determine the laser energy absorption.
6.1.1 Preparation and characterization of CNFs

CNFs of two different diameters were used. The 60 nm CNFs were prepared by spray pyrolysis of a mixture of ferrocene and benzene [188]. They had a size variation with a standard deviation of ~20 nm. The length distribution of the CNFs could not be determined because viewing the ends of the spaghetti-like CNFs turned out to be prohibitive. The thickness of the CNF deposition on the substrate was ~20-50 μm. Visual observation of a 5x7-μm² area of the sample suggested that about 30% of the area was free from CNFs in the deposited layer. The 160 nm CNFs were grown by thermal decomposition of a precursor mixture of acetylene and hydrogen (1:5). The growth was done on a strip of iron coated with its nitrite.

![SEM images of CNFs](image)

**FIG.6.1 :** SEM images of (a) 60 nm CNFs, (b) 160 nm CNFs and (c) graphite plate

Figure 6.1 shows the images of CNFs deposited on graphite plates, observed with an SEM (Philips XL30CP; ~3.5 nm instrumental resolution). It is noted from Fig. 6.1a that the
CNFs of 60 nm diameter have gaps between them of up to a few times their average diameter though the exact estimation of the intra-fiber spacing is difficult as it is non-uniform but it appears to be ~ 300-500 nm on an average. On the other hand, the larger diameter CNFs (see Fig.6.1b) are more closely packed and the average spacing between the fibers appears to be smaller than the intra-fiber spacing of the smaller nano-fiber target. The planar graphite target was porous in nature with many craters of nano-meter scale as seen from the SEM image shown in Fig.6.1c. Since porous targets are also efficient absorbers of ultra-short intense laser pulses, a planar polyethylene target free of porosity was also used for comparison.

6.1.2 Experimental setup

![Image of experimental setup]

*FIG.6.2: A schematic diagram of the experimental setup*

Figure 6.2 shows the schematic of experimental setup used in the current study. Plasma was produced by focusing 150 mJ, 45 fs (FWHM) Ti:sapphire laser pulses ($\lambda = 790$ nm) on a planar graphite target with / without pre-deposited carbon nano-fibers. The p-polarized laser
beam was made incident on the target at an angle of 45° with respect to the target normal, at a maximum intensity of \( \sim 4 \times 10^{17} \text{ W/cm}^2 \). The oblique incidence geometry was used so that the plasma produced from the planar targets was predominantly by the resonance absorption mechanism of laser light absorption [40,44]. The ns pre-pulse intensity contrast was better than \( 10^6 \). The x-ray emission spectra were recorded with a spectral resolution of \( \sim 1 \text{ Å} \), using a micro-channel plate - CCD camera based on-line transmission grating spectrograph [119]. The laser intensity was varied by using calibrated neutral density filters. To study the effect of the laser pulse duration on the x-ray yield, the former was varied by changing the grating pair separation in the optical compressor, from 45 fs to 3 ps, at a fixed fluence of \( \sim 2 \times 10^4 \text{ J/cm}^2 \). The stretching of the pulse duration by increasing the separation between the compressor gratings introduces negative chirp in the laser pulse i.e. the higher frequencies precede the lower frequencies temporally in the laser pulse.

6.2 Experimental Results

6.2.1 X-ray spectra from CNFs

Figure 6.3 shows the x-ray emission spectra from plasmas produced from polyethylene, graphite, and CNFs (60 nm and 160 nm) deposited on a graphite substrate. The x-ray emission in the water-window region has intense lines from carbon plasma, viz. C V \( 1s^2-1s2p \) (\( \lambda = 40.3 \text{ Å} \)) and C VI \( 1s-2p \) (\( \lambda = 33.7 \text{ Å} \)) riding over a strong continuum.
The x-ray intensity is much higher for 60 nm and 160 nm CNFs compared to that for graphite and polyethylene targets. It is also observed that the CNFs with the smaller diameter are more efficient x-ray emitters in the water window. The integrated x-ray intensity over the water-window spectral region for the 60 nm CNFs was ~ 18 times higher than that with planar graphite and ~45 times higher than that of the polyethylene target. The corresponding x-ray intensity enhancement for the 160 nm CNF target was ~2.5 and 7.5 times higher, respectively.

Although the enhancement of the x-ray emission from the CNFs over the planar graphite target was recorded along the target surface only, the x-ray intensity enhancement as compared to planar target is also expected at other angles. This is because the x-ray emission from plasma produced by the irradiation of a planar target with intense short laser pulses has a more isotropic distribution [15] than that generated through the irradiation with longer pulses of ps or ns duration. Since locally the carbon nano-fibers are at solid density, the x-ray emission from them is likely to show a behavior similar to that known from solids. In ref.13, the x-ray emission from

FIG.6.3: X-ray emission spectra from plasma produced from CNFs, graphite, and polyethylene targets.
carbon nano-tubes in the water window was studied under similar experimental conditions like us. They recorded the x-ray emission at 45° with respect to the target normal (instead of 90° in the present work). A higher x-ray emission from carbon nano-tubes as compared to planar carbon was observed by them in that direction. Therefore, it appears that x-ray enhancement will occur in other directions as well. We have measured the x-ray emission along the target surface since the plasma debris from the laser-irradiated target is minimal in this direction. Therefore, the x-ray enhancement in that direction is more important and desirable for applications (like microscopy, lithography etc).

6.2.2 X-ray yield study with intensity and pulse duration.

![Graph showing x-ray yield vs laser intensity](image)

**FIG.6.4 : Dependence of the integrated x-ray intensity from CNFs and graphite target plasma on laser intensity (45 fs pulse duration).**

Figure 6.4 shows the dependence of the integrated x-ray yield (in the 23-44 Å water window range) from graphite and CNF targets on the laser intensity $I_L$. The x-ray yield increases as $I_L^{-1.3}$-
for the two CNFs and the graphite as well. Fig. 6.4 also reveals that the enhancement factor for the CNF targets does not vary much with $I_L$. The emission from the 60 nm CNF target was highest in the entire range of laser intensities used in the experiment.

**FIG.6.5**: Integrated x-ray intensity from plasma produced from CNFs and graphite targets as a function of laser pulse duration, at a constant laser fluence of $2 \times 10^4$ J/cm$^2$.

Figure 6.5 shows the dependence of the integrated x-ray yield in the water-window spectral region on the laser pulse duration, at a constant fluence of $2 \times 10^4$ J/cm$^2$ for the graphite and the 60 nm and 160 nm diameter CNFs as well. While the x-ray intensity from the graphite target shows a small monotonic increase with the laser pulse duration, the 60 nm and 160 nm diameter CNFs exhibit a peak. The emission from the 60 nm CNF target is highest in the entire range of laser pulse duration used in the experiment. The x-ray yield for the 60 nm diameter CNF is maximal at 300 fs and thereafter gradually decreases till 3 ps. For 160 nm CNFs, the peak behavior is more pronounced, a distinct peak occurs at the laser pulse duration of 700 fs.
The x-ray intensity enhancement factor for the two CNFs of different diameters with respect to the graphite target, as a function of the laser pulse duration, is shown in Fig. 6.6. The enhancement factor increases from 18 to 27 when the laser pulse duration is changed from 45 to 300 fs. For larger pulse durations, the enhancement factor decreases gradually. However, even for irradiation of the 60 nm CNFs with 3 ps laser pulses, there is a considerable enhancement factor of ~10. In the case of the 160 nm CNFs, a similar behavior is observed, where the enhancement first gradually increases, peaks at 700 fs (peak value ~ 10), and then smoothly declines when the laser pulse duration increases.

FIG. 6.6: Enhancement of water-window x-ray yield from CNFs w.r.t. graphite target as a function of laser pulse duration, at a constant fluence of 2x10^4 J/cm^2.

It is important to mention here that for applications like contact microscopy of biological specimen, the x-ray pulse duration should be sub-ns, so that image blurring due to hydrodynamic motion is negligible. Since we did not measure the x-ray pulse duration of the emission from graphite and CNFs, we refer in this context to the work of Nishikawa et al. [13] who measured
the pulse duration of the x-rays (in the water window region) from laser-irradiated carbon nano-tubes using a streak camera with 3 ps time resolution. The x-ray pulse durations for planar solid carbon and carbon nano-tubes were 8 and 26 ps, respectively. Thus, even though the x-ray pulse duration from the CNFs is likely to be larger than the laser pulse duration, the CNF-based source is still attractive for many applications.

### 6.3 Application of the nano-plasma model for x-ray enhancement

The x-ray intensity enhancement observed for CNF targets is basically due to higher laser energy absorption in the CNF plasma compared to that occurring in plasma from planar solid targets. The absorption of a high-intensity ($I\lambda^2 > 10^{17}$ W/cm$^2$) p-polarized laser pulse obliquely incident on a planar solid surface is mostly by resonance absorption, vacuum heating, and $\vec{j} \times \vec{B}$ heating, whereas at lower laser intensities ($I\lambda^2 < 10^{17}$ W/cm$^2$), inverse bremsstrahlung absorption is more dominant [52]. A major difference in the absorption by a bulk target and a nano-size target (like gas clusters or CNF) is that the laser field gets strongly enhanced inside a nano-particle for certain values of the dielectric constant and this forms the basis of the nano-plasma model [96-98]. We have applied this model to explain our results since the model successfully explains various experimental results with clusters concerning laser energy absorption [88,96-99], x-ray emission [101], electron emission [75] and ion emission [95].

The nano-plasma model considers the irradiation of a cluster by an intense short pulse laser which results in the initial ionization of the cluster by the optical field. The free electrons thus produced oscillate under the laser electric field and collide with the surrounding ions (at near solid density) and transfer their energy collisionally to the ions. This raises the temperature of the nano-plasma cluster ball which subsequently expands due to a combined Coulomb and
hydrodynamic pressure. Although such a simple model successfully explains the numerous experimental observations, the notion of hydrodynamic expansion of a cluster on 100 fs time scale is debatable, as the typical time scale for energy transfer from electron to ion is few ps. Hence, the efficient absorption of ultra-short laser pulse (< 100 fs) by clusters has been attributed to the non-collisional process [105-107]. Nevertheless, as the laser irradiated clusters have locally solid density and are highly ionized, the plasma is highly collisional [96]. Invoking this aspect, the nano-plasma model justifies efficient absorption even for ultra-short pulses ∼ 100 fs where the hydrodynamic motion may be negligible. Several authors have carried out numerical simulations on the clusters hydrodynamic expansion in the nano-plasma [96,102,189]. The simulations show the time evolution of the electric field, the plasma temperature, and the hydrodynamic pressure inside the cluster, which causes cluster expansion and density dilution. Subsequently the electron density starts approaching 3n_c near the peak of the laser pulse [94-99,189]. Therefore, although the cluster does not expand sufficiently to arrive at the resonance condition at the peak of laser pulse, still high electric field, temperature and pressure are attained. The simulations further show that the cluster electrons density eventually becomes 3n_c on a time scale of few 100 fs away from the peak of the ultra-short laser pulse (∼ 100 fs) [94-99]. This implies that there is further scope for even higher absorption if the laser pulse is stretched to be > 100 fs, so that the cluster density passes through 3n_c at the peak of the pulse [97]. It has been experimentally verified that stretched pulses lead to the best x-ray output because for a cluster of given size there exists an optimum pulse duration for maximum absorption which may vary from ∼ 100 fs to ∼ 1 ps [97,101].

In the present context, the nano-fiber target used in our experiments has a resemblance with the generally used spherical metal and gas clusters, and the major difference is that it has a
cylindrical shape due to which they show resonance at $2n_c$ [190] instead of $3n_c$. The CNFs are like cylindrical nano-particles (nano-rod) and to study their interaction with intense laser pulses it can be considered as a cylindrical dielectric placed in the laser field, in a treatment similar to clusters. The experimental observations can be explained by extending the nano-plasma model from a spherical to a cylindrical geometry.

When an external electric field $E_0$ is applied perpendicular to the axis of a cylindrical nano-particle (having a very large length in comparison to its diameter), the inside field $E_{in}$ is given by the relation [190]

$$E_{in} = \frac{2}{\varepsilon + 1} E_0.$$ ....6.1

The inside field becomes very large when the dielectric constant $\varepsilon$ approaches -1. For heated nano-fiber plasma, $\varepsilon$ shows a transient behavior because the rapid heating is followed by a density reduction due to hydrodynamic expansion. For plasma the dependence of $\varepsilon$ on density has the form

$$\varepsilon = 1 - \frac{n_e}{n_c}$$ ....6.2

where $n_e$ is the electron density and $n_c$ is the critical density. It follows from Eqns.6.1 and 6.2 that the inside field becomes very large in the vicinity of $n_e = 2n_c$. However, when the applied field is parallel to the axis of a nano-cylinder, due to the long extent of the cylinder (compared to the laser wavelength), there will be no field enhancement. An electric field applied to an unaligned CNF will have field components perpendicular and parallel to the fibre axis. When the plasma density approaches $2n_c$, there will be a large enhancement of the radial component of the electric field, leading to strong inverse bremsstrahlung absorption of the laser light. The time $\tau_R$ taken for reaching this condition depends on the initial radius $r_o$, the initial density $n_o$, and the
expansion speed $c_s$. The expression for $\tau_R$ of CNFs is similar to that for clusters [97] and is given by

$$\tau_R = \left( \frac{r_0}{c_s} \right) \left( \sqrt{\frac{n_0}{2n_c}} - 1 \right).$$

As seen from Eq.6.3, the resonance condition for larger diameter nano-fibers is attained later in time, in comparison to the smaller diameter nano-fibers. Since the diameters of the CNFs vary in a given target sample and the hydrodynamic expansion may also be non-uniform, and hence the resonance condition is expected to occur over a period of time. It may also be noted that for spherical nano-plasma, due to 3-D expansion, the resonance condition is reached earlier in time than for cylindrical nano-plasma which undergoes 2-D expansion.

Despite the fact that the irradiation of the nano-fibers with ultra-short duration pulses (~45 fs) will not cause expansion sufficient enough to reach the resonance condition, a significant absorption of the ultra-short pulses is still observed in nano-particles. This has been explained by various models which consider the collective electron dynamics and nonlinear resonances [104-107]. Moreover, due to the collisions present within a cluster, the resonance gets broadened over a larger range of densities and pulse duration [96]. In addition to this, the collision frequency of large sized cluster is known to be inversely related to its size [191]. This explains the observed higher x-ray enhancement in the case of the smaller diameter nano-fibers (60 nm) as compared to the larger 160 nm fibers because of the higher collisionality in the former. Hence, even for the smallest pulse duration, the x-ray yield is not negligible compared to the peak value at some higher pulse duration. Moreover, the 60 nm CNF absorbs more laser energy than the 160 nm CNF, as the density of the former approaches $2n_c$ earlier in time [148,
as the rate of decrease of electron density with the instantaneous radius \( r \) is inversely proportional to the cube of \( r \) i.e. \( \frac{dn}{dr} \propto \frac{1}{r^3} \) (as for cylindrical nano-fibers \( n \propto \frac{1}{r^2} \)).

On the basis of the above physical picture, one can explain the results shown in Figs. 6.3-6.6. As stated earlier, the resonance field enhancement in nano-fiber plasma in the vicinity of \( 2n_c \) will result in strong absorption of laser energy to increase the nano-plasma temperature. This is responsible for the large enhancement factor in the x-ray yield for CNF plasma as compared to the carbon-containing planar solid targets. First, we discuss the dependence of the integrated x-ray yield on laser intensity for CNF and graphite targets. All three targets showed almost the same scaling \( I_L^{-1.3-1.4} \). The spaghetti-like structure of the nano-fibers (Fig.6.1) has nano-meter sized spaces (voids). Due to these voids, the incident laser light gets multiply reflected from one fiber to another and thus gets better absorbed (by being trapped in the voids). This would also enhance the x-ray emission compared to a planar target. The SEM image of the graphite target (Fig.6.1c) clearly shows nano-sized pits on its surface, which, due to multiple reflections, may lead to a better absorption of laser energy. This is also consistent with the observation of a much smaller x-ray yield from the polyethylene target which had no porosity.

### 6.4 Resonance in nano-fibers

Now we come to the variation of the x-ray yield with the laser pulse duration. As observed from Fig.6.5, the x-ray yield for CNF targets first increases with laser pulse duration, reaches a peak at a certain value and then decreases. As the laser pulse duration is increased, plasma of a longer scale length is produced, leading to an increase in the collisional absorption. Secondly, the increase in x-ray emission can also be due to a larger volume of the expanded
plasma and longer emission time. Also, there is a slower decrease of the electron temperature with time due to larger density scale length. Thus the plasma emission time is also longer, which can explain the increase in x-ray yield [184 ] with increase in laser pulse duration. However, as the laser pulse duration is further increased, the resonance condition would progressively occur in the initial part of the laser pulse. Due to the continued plasma expansion during the remaining laser pulse, the laser energy absorption would occur at lower plasma density (away from $2n_c$). This would result in less effective heating of the plasma and thereby providing a lower x-ray yield.

The above qualitative picture is also consistent with the observation of different values of laser pulse duration for peak enhancement for the two different diameters of CNFs used (Fig. 6.6). As the smaller diameter nano-fibers (60 nm) will reach resonance earlier than the larger ones (160 nm ), the x-ray yield in the former case peaks at a smaller pulse duration of ~300 fs while the latter showed a maximum at a laser pulse duration of ~700 fs (since $\tau_R$ is proportional to $r_0$ as seen from Eq. 6.3).

To substantiate the time scales for the resonance ($\tau_R$), we estimate the expected $\tau_R$ for the nano-fibers taking the typical laser parameters, plasma temperature and density and the targets geometrical parameter $r_0$. To estimate $\tau_R$, we first estimate the plasma expansion speed $c_s = \sqrt{\frac{ZkT_e}{M_i}}$ where $M_i$ is the ion mass. Since $c_s$ is temperature dependent, we take temperature value from the work of Issac et al [192] who have done experiments using very similar laser parameters, with the shortest pulse duration of 60 fs and worked at a fluence of 8 kJ/cm$^2$, which in our experiments was 20 kJ/cm$^2$. They have estimated the electron temperature at various pulse durations from 60 fs to 2.2 ps which is again very similar to pulse duration range covered in our
experiments, while keeping the fluence unchanged. Their electron temperature varied from \(~1.5\) keV to 2 keV. In this temperature range \(c_s\) varies from \(2.7-3.2 \times 10^7\) cm/s. The value of \(n_0/n_c\) for carbon nano-fiber irradiated with Ti:sapphire laser at 800 nm is taken to be 40. The time for occurrence of resonance \(\tau_R\) can be found using Eq.6.3. For a 60 nm fiber, the resonance would occur at 320-380 fs (considering the range of speed of expansion). Similarly, the resonance is expected to occur between 850 fs- 1ps for the 160 nm fiber. The observed resonance for smaller diameter nano-fibers (60 nm) \(~300\) fs and the observed peak for larger diameter nano-fibers (160 nm) \(~700\) are in close agreement with the predicted values and hence substantiate the claim of resonance absorption occurring in the nano-fibers.

Void closure may also be a factor in governing laser energy absorption in the nano-fiber targets. For the 60 nm CNFs, the void closure can occur over a 1-2 ps time scale. This is because, considering the intra-fiber distance to be 300-500 nm and the plasma of \(~1.5-2\) keV temperature expanding at the rate of \(~2-3 \times 10^7\) cm/s will take about a picosecond time for void closure, which is also similar to the time scales reported by Gibbon \textit{et al} [193]. Thus, in the case of the smaller diameter fibers, the void closure will occur after the resonance is reached. However, for the 160 nm CNFs, the average intra-fiber spacing is of smaller magnitude compared to that for the 60 nm diameter nano-fibers. In this case, there is a possibility that void closure may occur on a sub-ps time scale, even before reaching resonance. Thus, smaller laser energy absorption may occur for the larger diameter (160 nm) CNFs in comparison to the 60 nm diameter CNFs.

Lastly, we consider the effect of pre-pulse associated with the laser pulse which can damage the nano-structure prior to the arrival of the main pulse. The pre-pulse can form a pre-plasma making the geometrical shape of the nano-structure not effective. In addition to this, the
field enhancement occurring in the nano-fiber will make the effective intensity of the pre-pulse interacting with the nano-fiber further higher. However, we believe that the pre-pulse did not contribute in the present experiment due to the following reasons. The contrast ratio of the pre-pulse before 8 ns (replica contrast) was better than $10^{-6}$ and the contrast ratio of ns-pedestal due to amplified spontaneous emission (ASE contrast) was also about $10^{-6}$. Therefore, the pre-pulse intensity is less than $4 \times 10^{11}$ W/cm$^2$. As for the replica pre-pulse (the one 8 ns before the main pulse), its duration being short (same as that of the main pulse), it has a large threshold to produce plasma. Rajeev et al [194] have experimentally measured the plasma formation threshold intensity for solid copper and copper nano-particles containing target using 100 fs laser pulses. The threshold intensity for plasma formation was found to be about $10^{14}$ W/cm$^2$ for both the targets. Since the highest intensity of the pre-pulse in our experiments ($4 \times 10^{11}$ W/cm$^2$) is much smaller than the value of plasma formation threshold by more than two orders of magnitude, one can assume that even the effect of field enhancement facilitated by the nano-fiber will not lead to any pre-plasma formation due to the replica pre-pulse. This argument is strengthened by the observation of Dorchies et al [101] who conclude that the pre-pulse contrast should be better than $2 \times 10^{-6}$ so as to prevent the cluster from any modification prior to the arrival of main pulse. As for the ASE foot, the focused intensity is much smaller due to its larger divergence to cause any significant heating. Moreover, the ASE intensity does not vary with change of laser pulse duration, and hence had ASE been the dominant factor, one would not see any variation with the laser pulse duration observed in the experiment (Fig. 6.5).

Thus, we have demonstrated that CNFs irradiated with ultra-short laser pulses show more than one order of magnitude enhancement in x-ray yield in the water-window x-ray emission from for 60 nm diameter CNF compared to graphite and polyethylene targets. The higher x-ray
yield, the scaling of the x-ray yield with laser intensity, and the dependence of the x-ray yield enhancement on laser pulse duration are explained by higher absorption due to the occurrence of resonance field enhancement at two times the critical density in nano-fiber plasma during its hydrodynamic evolution. The results may be helpful in determining the optimum parameters of nano-fiber targets and laser pulses to achieve high x-ray yield in the water-window spectral region for x-ray microscopy.