6

X-ray emission from ultrafast laser induced plasma in planar liquid jets

In this chapter we discuss plasma experiments conducted in thin planar liquid jets in ambient conditions. Results show that even in the absence of a vacuum, it is possible to get a substantial amount of soft x-rays from an ultrafast laser produced plasma. We also present a novel way of enhancing the x-ray emission yield and emission energy range by the incorporation of metal nanoparticles into the liquid used in the jet.

6.1 Introduction

Intense electromagnetic radiation is known to emanate from laser-produced plasmas (LPP). Soon after the invention of lasers, the possibility of LPP as a new radiation source was investigated. In particular, technologies such as Q-switching, mode locking, chirped pulse amplification etc., lead to shorter and more powerful laser pulses. Using intense lasers, it is possible to generate radiation pulses extending from TeraHertz frequencies ($\lambda = 100 \, \mu m$) to visible light, extreme ultraviolet light (EUV, $\lambda = 10 \, nm$), x-rays ($\lambda = 0.1-1 \, nm$) and γ-rays ($\lambda << 0.1 \, nm$). The emission of these radiations is controlled by optimizing laser-irradiation conditions and target materials {1}. An ultrafast radiation pulse is very useful to observe the dynamics of rapidly moving hot-dense materials such as laser-driven fusion pellets, live organisms, transient phenomena of shock-compressed
crystalline matter, and objects of nondestructive inspections {2-5}. LPP radiation is a compact pulse source, and it can be extended to a wide variety of industrial and scientific applications.

In this chapter, we discuss the spectroscopic study of x-ray emission from an ultrafast laser induced plasma generated in thin planar liquid jets of approximately 250 \( \mu \text{m} \) thickness. Laser pulses of 100 fs duration are focused to the jet to obtain intensity levels close to \( 10^{16} \, \text{W/cm}^2 \). Tunnel ionization is the dominant ionization mechanism at this intensity regime. X-rays in the range of 1.5 keV to 30 keV are recorded and analyzed. The directionality of the x-ray emission is measured and discussed.

6.2 Plasma production by ultrafast laser pulses

In the case of intense laser interactions with a liquid or solid target, the number of atoms exposed to the laser field becomes close to the solid density \( (10^{23} \, \text{atoms/cm}^3) \). Even though all the basic ionization mechanisms discussed in chapter one remain valid, there will be several other interactions between the electrons and ions due to the availability of a very large number of atoms. For intensities above \( 10^{14} \, \text{W/m}^2 \) the dominant ionization mechanisms will be tunnel ionization and over-the-barrier ionization \( (6) \). The free electrons produced by the ionization process are further accelerated by the electric field of the incident laser. In a solid density material, the electrons accelerated by the quiver motion will collide with the nearby neutral atoms inducing collisional ionization, unlike the less dense atomic systems where the acceleration is uninterrupted. Thus the ionization is much higher in the case of solid density materials. A dense cloud of electrons is formed even before the laser pulse reaches its peak. This electron cloud and the resultant positively charged ions constitute the 'plasma' [The word 'plasma' is used to describe a wide variety of macroscopically neutral substances containing many interacting free electrons and ionized atoms or molecules, which exhibit a collective behaviour due to long-range coloumb forces.]. The plasma gets heated up by energy transfer from the exciting electromagnetic wave through various absorption modes (described in detail in section 6.4). This results in further ionization leading to a denser plasma. A diagram
showing the various interactions \cite{7} in a laser-produced plasma is given as figure 6.1.

![Diagram showing various interactions in a laser-produced plasma.](image)

**Figure 6.1**: A diagram showing various interactions in a laser-produced plasma.

The properties of the plasma are markedly dependent upon particle interactions. The main feature that distinguishes plasma behavior from that of fluids and solids is the existence of collective effects. Due to the existence of long-range electromagnetic forces, each charged particle of the plasma interacts simultaneously with a considerable number of other charged particles, resulting in collective effects. A distinction can be made between weakly ionized and strongly ionized plasmas in terms of the nature of particle interactions. In a weakly ionized plasma, the charge-neutral interactions dominate over multiple Coulomb interactions (charge-charge interactions). On the other hand when the multiple Coulomb interactions dominate, the plasma can be termed strongly ionized. In fully ionized plasmas, all the particles will be subjected to multiple Coulomb interactions.
6.3 Basic properties of plasma

The fact that some or all the particles in a plasma are electrically charged, and can therefore interact with electromagnetic fields as well as create electromagnetic fields, gives rise to many novel phenomena that are not present in ordinary solids and fluids. Some important properties of the plasma are discussed in the following subsections.

6.3.1 Macroscopic neutrality (Quasi-neutrality)

A plasma is macroscopically neutral in the absence of external forces. This means that under equilibrium conditions with no external forces present, in a volume of the plasma sufficiently large to contain a large amount of particles and yet sufficiently small compared to the characteristic lengths for variation of macroscopic parameters such as density and temperature, the net resulting electric charge is zero. The existence of a very small amount of charge separation over a very short spatial scale for a very small time interval is known as the quasi-neutrality of plasma {8}. In the interior of the plasma the microscopic space charge fields cancel each other, and no net space charge exists over a macroscopic region.

If this macroscopic neutrality was not maintained, the potential energy associated with the resulting Coulomb forces could be enormous compared to the thermal particle kinetic energy. Departures from macroscopic electrical neutrality can naturally occur only over distances in which a balance is obtained between the thermal particle energy, which tends to disturb the electrical neutrality, and the electrostatic potential energy resulting from any charge separation, which tends to restore the electrical neutrality. This distance is of the order of a characteristic length parameter of the plasma, called the Debye length. In the absence of external forces, the plasma cannot support departures from macroscopic neutrality over larger distances than this, since the charged particles are able to move freely to neutralize any regions of excess space charge in response to the large Coulomb forces that appear.
6.3.2 Debye Shielding

The Debye length is an important physical parameter for the description of a plasma. It provides a measure of the distance over which the influence of the electric field of an individual charged particle (or of a surface at some nonzero potential) is felt by the other charged particle inside the plasma. The charged particles arrange themselves in such a way as to effectively shield any electrostatic fields within a distance of the order of Debye length. A calculation of the shielding distance was first performed by Debye for an electrolyte and is given by

\[ \lambda_D = \left( \frac{\varepsilon_0 k T}{n_e e^2} \right)^{\frac{1}{2}} \]  

- (6.1)

It is convenient to define a Debye sphere as a sphere inside the plasma of radius \( \lambda_D \). Any electrostatic fields originated outside a Debye sphere are effectively screened by the charged particles and do not contribute significantly to the electric field inside the sphere. Consequently, each charge in the plasma interacts collectively only with the charges that lie inside its Debye sphere, its effect on the other charges being negligibly small. The first criterion for the existence of the plasma is that its characteristic dimensions of the plasma should be greater than \( \lambda_D \). Otherwise, there is just not sufficient space for the collective shielding effect to take place, and the collection of the charged particles will not exhibit plasma behavior. The second criterion is that the number of electrons inside the Debye sphere should be very high, i.e. \( n_e \lambda_D^3 \gg 1 \). This means that the average distance between the electrons, given by \( n_e^{-\frac{1}{3}} \), must be very small compared to \( \lambda_D \). The quantity defined by \( g = \frac{1}{n_e \lambda_D^3} \) is known as the plasma parameter and the condition \( g \ll 1 \) is called the plasma approximation. This parameter is also a measure of the ratio of the mean inter-particle potential energy to the mean plasma kinetic energy. The number of electrons \( N_D \), inside a Debye sphere can be calculated as

\[ N_D = \frac{4}{3} \pi \lambda_D^3 n_e = \frac{4}{3} \pi \left( \frac{\varepsilon_0 k T}{n_e^3 e^2} \right)^{\frac{1}{2}} \]  

- (6.2)
6.3.3 The plasma frequency

An important plasma property is the stability of its macroscopic space charge neutrality. This is sometimes considered as the third criterion for the existence of a plasma. When a plasma is instantaneously disturbed from the equilibrium condition, the resulting internal space charge fields give rise to collective particle motions that tend to restore the original charge neutrality. These collective motions are characterized by a natural frequency of oscillation known as the plasma frequency. Since these are high-frequency oscillations, the ions, because of their heavy mass, are to a certain extent unable to follow the motion of the electrons. The electrons oscillate collectively about the heavy ions, the necessary collective restoring force being provided by the ion-electron Coulomb attraction. The period of this natural oscillation constitutes a meaningful time scale against which can be compared the dissipative mechanisms tending to destroy the collective electron motion.

Consider a plasma initially uniform and at rest, and suppose that by some external means a small charge separation is produced inside it. If the external force is removed instantaneously, the internal electric field resulting from charge separation collectively accelerates the electrons in an attempt to restore the charge neutrality. However, because of their inertia, the electrons move beyond the equilibrium position, and an electric field is produced in the opposite direction. This sequence of movements repeats itself periodically with a continuous transformation of kinetic energy into potential energy and vice-versa, resulting in fast collective oscillations of the electrons about the more massive ions. On the average, the plasma maintains its macroscopic charge neutrality. The angular frequency of these collective electron oscillations, called the (electron) plasma frequency, is given by

\[ \omega_{pe} = \left( \frac{n_e e^2}{m_i e_0} \right)^{1/2} \]  

(6.3)

Collisions between electrons and neutral particles tend to damp these collective oscillations and gradually diminish their amplitude. If the oscillations are
to be only slightly damped, it is necessary that the electron-neutral collision frequency \( v_{en} \) be smaller than the electron plasma frequency,

\[
\nu_{pe} > \nu_{en}
\]

where \( \nu_{pe} = \omega_{pe} / 2\pi \). Otherwise, the electrons will not be able to behave in an independent way, but will be forced by collisions to be in complete equilibrium with the neutrals, and the medium can be treated as a neutral gas. Equation 6.4 constitutes, therefore, the fourth criterion for the existence of plasma. This criterion can be alternatively written as \( \omega \tau > 1 \) where \( \tau = 1 / \nu_{en} \) represents the average time an electron travels between collisions with neutrals, and \( \omega \) stands for the angular frequency of plasma oscillations. It implies that the average time between electron-neutral collisions must be large compared to the characteristic time during which the plasma physical parameters are changing.

### 6.4 Absorption mechanisms in a plasma

Plasma is a strongly absorbing medium. As an electromagnetic wave propagates through a plasma, energy will be transferred from the EM wave to the plasma through different routes. Some of the important energy transfer mechanisms are discussed in the following subsections.

#### 6.4.1 Collisional absorption (Inverse Bremsstrahlung)

Collisional absorption is the main energy transfer mechanism between the laser pulse and the plasma at relatively low intensities. The electrons, while oscillating under the influence of the laser field, collide with the ions, transferring a part of electromagnetic energy to the plasma, thus heating up essentially the plasma electrons to higher temperature \( T_e \). Since these collisions are inelastic, their net result is an equilibration with surroundings – this defines the average or 'cold' temperature of the plasma. Here, it has to be noted that the electron-electron and ion-ion collision frequencies are larger compared to the electron-ion collision rates. These provide local thermalization, and essentially a two-fluid description with two distinct temperatures – electrons and ions are in respective local thermal
equilibria. The collisions between similar particles, however, do not cause an effective energy transfer as there is no significant momentum transfer. Collisional behaviour becomes important when the number of electrons in the Debye sphere is less. The electrons performing quiver oscillations in the laser field undergo collisions with the ions thereby converting a part of the coherent oscillation energy into thermal energy of the electrons and thus heating up the plasma.

When an electron of mass $m_e$ moving with a velocity $v$ collides with an ion of charge $Ze$ the change in momentum experienced by the electron is given by the product of Coulomb force and time of interaction $(2b/v)$, with $b$ being the impact parameter (the distance of closest approach). The time required to undergo a substantial momentum change such that $\Delta v_{ms} \sim v$ defines the electron-ion collision frequency $\gamma_{ei}$, which is a function of the range of values of $v$, $b$ and ion density. For a Maxwellian velocity distribution, this collision frequency is given as \cite{10-12}:

$$\gamma_{ei} = \frac{Zne^4 \ln \Lambda}{3(2\pi)^{3/2} \epsilon_0 c_0^2 m_e^{1/2} (k_B T_e)^{3/2}}$$

$\Lambda$ being the ratio of the maximum (Debye length) to minimum (largest of the classical distance of closet approach or the De Broglie wavelength of electron) impact parameter. $\ln \Lambda$ is referred to as the Coulomb logarithm \cite{13,14}.

One can obtain the damping caused to an electromagnetic wave passing through a collisional plasma given the electron-ion collision frequency. From this the amount of collisional absorption suffered by the laser can be found out. Considering the motion of the electron in the laser electric field and incorporating the damping due to the electron-ion collision, the dielectric function of the collisional plasma, for the light frequency $\omega$, can be obtained as:

$$\varepsilon = 1 - \frac{\omega_{pe}^2}{\omega^2 \left( 1 + i \frac{\gamma_{ei}}{\omega} \right)}$$

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The dispersion relation for light wave in collisional plasma is given by:

\[ \omega^2 = k^2 c^2 + \frac{\omega_{pe}^2}{1 + i \frac{\gamma_{ei}}{\omega}} \]  

(6.7)

The imaginary term in the dispersion relation of uniform plasma indicates the energy damping rate, viz.

\[ \omega_i = -\frac{n_e}{2n_{cr}} \gamma_{ei} \]  

(6.8)

The efficiency of collisional absorption decreases with decrease in the laser pulse width. Equation 6.5 shows that the electron-ion collision rates reduce as the velocity of electrons \((T_e)\) is increased. As the laser pulse intensity becomes greater than \(10^{15} \text{ W/cm}^2\), the electron temperature increases significantly \(\{15\}\), as the rate at which the electrons gain energy is much larger than the rate at which the electrons thermalize with other electrons \(\{16\}\). At very high laser intensities, the electron quiver energy will be so large that the quiver velocity dominates the thermal velocity of the electrons. Under this condition collisional absorption is no longer a dominant laser absorption mechanism in plasma \(\{17\}\). For high density plasma, it is indicated that collisional absorption, with nonlinear terms, is an efficient absorption mechanism \(\{18\}\).

6.4.2 Collisionless absorption – resonance absorption and vacuum heating

Resonant absorption depends on the collective motion of the particles in the plasma. The collective motion in the plasma is through longitudinal oscillations, with a characteristic frequency. Resonance Absorption is less effective if the plasma spatial density gradient is extremely sharp. This is because plasma waves can be set up only if there is a finite length of the plasma in existence. If the quiver amplitude of the electron in the laser field is greater than the plasma length, no plasma wave can be set up as the electron is taken farther away to the vacuum, breaking the plasma wave in each half cycle of the laser oscillation. Under this condition, another mechanism named ‘vacuum heating’ has to be considered. The principal idea here is
that the electrons are dragged into the vacuum on one half of the light period and
returned to the target as the light reverses, with a velocity close to the electron
quiver velocity. A large number of electrons get accelerated into the target and
their kinetic energy is deposited at the over-dense plasma where the laser field
cannot penetrate {19}. The ratio of the absorbed power to the incident laser power
per cycle in the vacuum heating is given as:

\[ f_{\text{VH}} = \left( \frac{\eta}{2\pi} \right) \frac{e}{m_0 c \cos \theta} \left( \frac{E_0}{E_L^2} \right) \]  

where \( \eta = 1.75(1 + 2v_{th}/v_{osc}) \). \( E_L \) is the incident laser field and \( E_0 \) is the total incident
and reflected field {19,20}. In vacuum heating the energy from the laser is directly
coupled to the electrons.

6.5 X-ray production in plasma

During the interaction of a high intensity laser with plasma, x-rays are
produced {21,22}. For x-ray generation in a laser produced plasma, three emission
mechanisms are important, namely bremsstrahlung (free-free transition), radiative
recombination (free-bound transition), and radiative de-excitation (bound-bound
transition).

Free-free (ff) transitions: When a free electron is decelerated by an ion (Coulomb
collision), the system emits continuum radiation since both the initial and final
states are free electron states. This bremsstrahlung process can be described by,

\[ e^- + i \rightarrow e^- + i + \gamma \]  

where \( e^- \) denotes a free electron, \( i \) denotes an ion and \( \gamma \) is the emitted photon.

Free-bound (fb) transitions: When a free electron is trapped in an orbit of an ion,
the excess energy is released in the form of radiation. This process is called
radiative recombination. It can be described by,

\[ e^- + i \rightarrow i_2 + \gamma \]  

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Here $i_1$ and $i_2$ represent different charge states of the ion.

**Bound-bound (bb) transitions:** Electron transition from an upper orbit to a lower orbit yields line emission. However in the case of high $Z$-atoms several emission lines are possible and due to line broadening (e.g. Doppler) the discrete line emission often changes to a band emission \(^{(23)}\). Bound-bound transitions can be represented by,

$$i_a \rightarrow i_b + \gamma \quad (6.12)$$

where $i_a$ and $i_b$ describe the quantum numbers of the ion states.

![Diagram of different x-ray production mechanisms in a plasma.](Image)

**Figure 6.2:** Different x-ray production mechanisms in a plasma.

### 6.6 Experimental setup

For performing the experiments, a thin planar liquid jet of 250 μm thickness was obtained using a flat metal nozzle and a liquid pump. Pure de-ionized water, a colloidal solution of silver nanoparticles, and an aqueous solution of silver nitrate were used as the liquid samples. The jet was irradiated with ultrafast laser pulses from a mode-locked chirped pulse amplifier Ti: Sapphire laser (Spectra physics TSA-10), delivering linearly polarized 100 fs pulses at 800 nm at a repetition rate of 10 Hz. The beam is focused to the jet using a plano-convex lens of 11 cm focal length. An
input pulse energy of 6 mJ was used for the experiments, which results in an intensity of $\sim 10^{16}$ W/cm$^2$ at the focus. A schematic of the experimental setup can be seen in figure 6.3. Since self-focusing gets limited at these high intensities, there is no intensity enhancement inside the liquid. The laser interaction with the liquid in the present studies is in the intensity regime of over-the-barrier and tunnel ionization. The Rayleigh range in the present setup is slightly more than 250 $\mu$m. Hence when the jet is aligned exactly at the focus, the liquid sees a uniform intensity along the laser propagation direction. However, there will be plasma creation at the first surface of the liquid jet and the interaction of the later part of the pulse with the created plasma determines the depth of penetration of the laser light into the jet.

![Figure 6.3: Schematic of the experimental setup.](image)

A calibrated Si:PIN detector kept at a distance of 15 cm from the jet was used for measuring the x-ray emission spectra from the plasma. X-rays in the range of 1.5 keV to 30 keV were measured during the experiment. The x-ray counts were recorded for each laser shot and were integrated for 3000 laser shots. The laser incidence was normal to the jet. X-ray emissions at various angles with respect to the laser propagation direction were recorded, by placing the Si:PIN detector appropriately.

The Si:PIN detector was used in conjunction with the XR 100 CR amplifier. The gain of the amplifier was set to 0.5 and RTD (Real Time Discrimination) was switched on. An MCA connected to the amplifier collected the data. The MCA used
was set to an ADC resolution of 2048 channels. The laser pulse energy was low enough such that there was only a feeble plasma formation in air, and no detectable x-rays were produced, when the liquid jet was switched off. This background x-ray spectrum obtained from air is shown in figure 6.4. The laser pulse energy, focusing and the detector integration time are the same as those used for measurements with the liquid jet switched on.

![Background x-ray emission spectrum from the interaction of ultrafast laser pulses with air, when the liquid jet is switched off.](image)

**Figure 6.4:** Background x-ray emission spectrum from the interaction of ultrafast laser pulses with air, when the liquid jet is switched off.

The Si:PIN detectors have an intrinsic detection efficiency (figure 6.5) and the spectrum shown above is not compensated for the detector efficiency. A polynomial fit is done to the detector intrinsic efficiency curve and the polynomial equation obtained is used for normalizing the obtained spectra. The detector efficiency in the range of 4 to 10 keV is close to 100%. Since RTD was switched on during the measurements, the detector intrinsic efficiency curve was not valid below 2 keV. Hence for simplicity of calculation, only energies above 10 keV are considered for the polynomial fit. The detector efficiency curve along with the best polynomial fit is shown in figure 6.5.
Fig. 6.5: Detector intrinsic efficiency curve (hollow circles) with the best polynomial fit (solid line).

Figure 6.6 shows the as obtained and normalized spectra for the radiation of Am$^{241}$. It can be seen that the normalized spectrum is identical to the standard radiation spectrum of Am$^{241}$ (given in the inset of figure 6.6) thereby validating the normalization curve. The extra peaks seen at 55 keV and 62 keV are from stray counts, which got amplified excessively during the normalization due to the low detector sensitivity in the high energy region.

Fig. 6.6: x-ray emission spectrum of Am$^{241}$ normalized for the detector efficiency.
Inset shows a standard Am$^{241}$ emission spectrum.
All the emission spectra obtained using the Amptek XR100 CR detector were normalized for the detector efficiency by this method. The experiments were done using de-ionized water, silver nanoparticle colloidal solution and an aqueous solution of silver nitrate. The results obtained are discussed in the following sections.

6.7 X-ray emission from a water jet

De-ionized water was used as sample for the measurements. The forward laser propagation direction was taken as 0°. X-rays were measured in 10° steps around the water jet. The normalized x-ray spectra at various angles around the jet are shown in figure 6.7 and figure 6.8 respectively. Since RTD was switched on during the measurements, x-ray photons below 1.5 keV were cut off from the spectra.
Figure 6.7: X-ray emission spectra obtained from the planar water jet for detection angles (A) 10°, (B) 20°, (C) 30°, (D) 40°, (E) 60°, and (F) 70°.
Figure 6.8: X-ray emission spectra obtained from the planar water jet for detection angles (A) $110^\circ$, (B) $120^\circ$, (C) $130^\circ$, (D) $140^\circ$, (E) $150^\circ$, and (F) $160^\circ$. 
A polar diagram was plotted for the x-ray count obtained at different angles around the water jet with respect to the laser propagation direction (figure 6.9). The plot shown here is drawn by taking measurements for the 180 degrees on the right side of the beam and assuming the left side to be identical. We have confirmed this assumption by taking x-ray counts at a few corresponding points on the left side of the jet. Since the jet assembly and the liquid pump were obstructing the viewing angle on the left side, all corresponding points can not be measured but, only a few points could be taken.

Figure 6.9: Angular distribution of x-ray emission from the laser-irradiated planar water jet. The arrow indicates the laser propagation direction. Solid line is an aid to the eye.

It can be seen that the x-rays from the water jet are preferentially emitted in the backward direction. This can be attributed to the reflection of the laser from the critical layer and the subsequent absorption of the same by the plasma already formed at the back surface of the jet by the leading part of the laser pulse.

6.8 X-ray emission from a silver nanoparticle colloidal jet

Enhancement in the x-ray emission from ultrafast laser-irradiated solids using surface modifications and by coating the surface with nanoparticles has been
reported recently in literature \cite{25,26}. To investigate this effect in the liquid phase we did x-ray emission measurements with a silver nanoparticle colloidal solution jet. Silver nanoparticles were prepared by the reduction of AgNO$_3$ by tri-sodium citrate (Details of the preparation method are given in chapter 2.). X-ray emission spectra obtained from these measurements at various angles around the liquid jet are given in figure 6.10 and figure 6.11.
Figure 6.10: X-ray emission spectra obtained from a planar silver nanoparticle colloidal jet for detection angles (A) 10°, (B) 30°, (C) 40°, (D) 50°, (E) 70°, and (F) 90°.
Figure 6.11: X-ray emission spectra obtained from a planar silver nanoparticle colloidal jet for detection angles (A) 100°, (B) 120°, (C) 130°, (D) 140°, (E) 150°, and (F) 160°.
Compared to the graphs obtained for water jets, it can be seen that now there is another peak around 5 keV in addition to the Bremsstrahlung emission centered around 1.8 keV seen in water. The emission counts also are quite large in this case, compared to the emission from the water jet. The polar diagram plotted for the x-ray count at different angles around the water jet with respect to the laser propagation direction is shown in figure 6.12.

![Figure 6.12: Spatial distribution of x-ray emission in the plasma produced from a planar jet of silver nanoparticle colloidal solution. The arrow indicates the laser propagation direction. Solid lines are drawn as an aid to the eye.](image)

It can also be seen that the emission yield of x-rays from the silver nanoparticle colloid jet on average is about three times better than that from the water jet. The enhancement is as high as ten in the case of the front side emission. To investigate whether this enhancement comes from the silver and other ions present in the sample, we prepared a salt solution using all the ingredients used for the nanoparticle solution in the same amounts. The experiments were repeated on this silver nitrate + tri-sodium citrate salt solution and corresponding x-ray emissions were recorded.
6.9 X-ray emission from an AgNO₃ solution jet

The x-ray emission spectra obtained from the aqueous silver nitrate + tri-sodium citrate salt solution are given in figure 6.13. As can be seen from the x-ray spectra, there is only a slight enhancement in the x-ray emission yield, which is not sufficient to explain the significant enhancement seen in the silver nanoparticle colloidal solution.
Figure 6.13: X-ray emission spectra obtained from a planar silver salt solution jet for detection angles (A) 10°, (B) 30°, (C) 100°, (D) 120°, (E) 140°, and (F) 160°.
6.10 Discussion

The fact that there is an enhancement of x-ray yield in the silver nanoparticle solution while there is almost none in the plain salt solution suggests that the metal nanoparticles are causing the enhancement. We consider a simple model to explain this as follows.

\[ V(r, \theta) = -E_0 (r - \frac{R^3}{r^2}) \cos \theta \]  

Figure 6.14: Field lines near a metallic sphere placed in an electric field.

Consider a metallic sphere placed in an electric field \( E_0 \). The potential \( V \) at a distance \( r \) from the centre of the sphere is given by (a simple derivation can be found in appendix II)

\[ V(r, \theta) = -E_0 (r - \frac{R^3}{r^2}) \cos \theta \]

where \( R \) is the radius of the sphere and \( \theta \) is the angle between \( r \) and \( z \)-axis (i.e. external field vector). The electric field at the surface of the sphere can be calculated as

\[ E_R = -\nabla V \big|_{r = R} \]

Hence from equation 6.13, we can write
From equation 6.15 it can be seen that the local field on the metallic surfaces can have larger values than the incident field. This increase in local field intensity near the metallic nanostructure causes an increased emission from the silver nanoparticle solution sample. A similar effect with surface modified solid samples has been reported earlier in literature [24].

### 6.11 Conclusions

Experiments conducted in thin planar liquid jets in ambient condition show that even in the absence of a vacuum, a substantial amount of soft x-rays can be obtained from an ultrafast laser induced plasma. It is shown that the x-ray emission range and emission yield can be enhanced by adding metal nanoparticles into a clear liquid. This enhancement is explained in terms of the increase of local electric field in the vicinity of metal spheres embedded in a dielectric medium.
References


