Instrumentation for the intense laser field-condensed matter interaction studies

The instrumentation work carried out for performing the intense laser plasma experiments is presented. The laser system used and pulse characterization techniques employed are described in detail. X-ray and γ-ray detection schemes and calibration methods are discussed. Electronic circuits designed and fabricated for the experiments are presented.

5.1 Introduction

The work described in chapters six and seven is an experimental study of the absorption and emission processes in laser-driven condensed media plasmas. These describe the measurement of x-ray emissions from solid targets and liquid jets. In this chapter, the laser systems and the necessary experimental and diagnostic equipment organized for these studies are discussed in detail. At high laser intensities, air itself will act as a nonlinear medium, and hence a vacuum environment is essential for background free measurements. For x-ray emission studies, a minimum working pressure of $10^{-3}$ Torr is necessary to prevent air from absorbing the emissions and affecting the plasma expansion. Vacuum is essential for the plasma to attain high temperatures as well, since energy transfer to the ambient air has to be avoided. For the detection of ions generated from the plasma, a vacuum
of the order of $10^6$ Torr will be necessary. Therefore a high vacuum chamber, originally designed for laser-microdroplet interaction experiments, was modified to conduct the intense laser-solid target interaction studies. A high vacuum compatible solid target manipulator and its control electronics were used together with the vacuum chamber.

5.2 The Ti:sapphire laser system

The ultrafast laser system used for the experiments is essentially a combination of four different lasers. The main components of the laser system and a brief description of each are presented below.

5.2.1: Millennia Pro - the pump laser

The pump laser used for the ultrafast oscillator is a frequency doubled, all solid-state Nd:vanadate (Nd:YVO$_4$) continuous wave laser capable of producing 5.2 W output power at 532 nm (Millennia Pro-S, Spectra Physics). The Nd:vanadate crystal is pumped by a diode laser (809 nm, 40 W) coupled to the crystal via an optical fiber module. The fundamental emission from the vanadate crystal is frequency doubled to produce 532 nm, using a Lithium Triobate (LBO) crystal. The output beam has a TEM$_{00}$ spatial intensity distribution with a nominal beam width of 2.3 mm.

5.2.2: Tsunami - the ultrafast oscillator

The ultrafast oscillator (Tsunami, Spectra Physics) consists of a folded cavity with an acousto-optic modulator (AOM) and active feedback for generation of ultrashort pulses by regenerative mode-locking technique. Dispersion compensation of the laser cavity is achieved with a pair of prisms, and the wavelength can be tuned with an adjustable slit. The lasing material is a one centimeter long Ti:sapphire crystal rod. The crystal is pumped by a continuous wave diode pumped, frequency doubled Nd:YVO$_4$ laser (Millenia Pro, Spectra Physics) at 532 nm with an output power of up to 5.2 W. The ultrafast oscillator produces Gaussian pulses of approximately 100 fs duration at a repetition rate of 82 MHz. The output wavelength can be tuned from 700 nm to 1000 nm (Tsunami -
broadband version). A maximum average power output of 550 mW can be obtained at 809 nm, which is the peak of the tuning curve.

The titanium ion (Ti\(^{3+}\)) is responsible for the laser action of Ti:sapphire. The electronic ground state of the Ti\(^{3+}\) ion is split into a pair of vibronically broadened levels as shown in figure 5.1. Absorption transitions occur over a broad range of wavelengths from 400 nm to 600 nm. Fluorescence transitions occur from the lower vibrational levels of the excited state to the upper vibrational levels of the ground state. Although the fluorescence band starts from 600 nm, the lasing action is only possible at wavelengths longer than 670 nm. This is because of the fact that the long wavelength side of the absorption band overlaps the short wavelength end of the fluorescence spectrum. Additionally the tuning range is affected by mirror losses, tuning element losses, pump power and atmospheric absorption.

![Absorption and emission spectra of Ti:Sapphire.](image)

**Figure 5.1: Absorption and emission spectra of Ti:Sapphire.**

The pulse width tuning characteristics of Ti:sapphire are influenced by factors inherent in the Ti:sapphire material as well as the cavity parameters. The optical components in the laser cavity introduce positive group velocity dispersion (GVD) and cause pulse spreading in addition to that caused by self phase modulation in the Ti:sapphire rod. These effects are compensated with negative GVD, introduced in the cavity with the help of a pair of prisms \(1\).
Mode-locking in the Tsunami oscillator is achieved by the use of an AOM module, in a regenerative mode-locking configuration. Unlike conventional active mode-locking, the RF drive signal used to drive the AOM is derived directly from the cavity in the regenerative mode-locking configuration. This removes one of the greatest drawbacks of active mode-locking, i.e., the requirement that the cavity length match the external drive frequency. In regenerative mode-locking the drive signal to the modulator automatically changes depending on the cavity length.

When the laser is switched on, it operates in the continuous wave (CW) mode with oscillations from several longitudinal modes. These are partially phase-locked, and mode beating generates a laser output at a frequency of \( c/2L \). This mode beating is detected by a photodiode and then amplified. Since this signal is twice the required AOM modulation frequency \( \omega_{\text{mod}} \), it is divided by two and then the phase is adjusted such that the modulator is always at maximum transmission when the pulse is present. Finally, the signal is reamplified and fed to the AOM.

![Figure 5.2: The Tsunami oscillator along with the Millennia pump laser.](image)

5.2.3: The Ti:sapphire chirped pulse amplifier (CPA)

The pulse energy levels (generally in nanojoules) from the Tsunami ultrafast oscillator are sufficient for many applications like multi-photon fluorescence microscopy, femtosecond writing, fluorescence lifetime measurements etc \{2,3\}. However, it is necessary to have much higher pulse energies (and hence high peak powers) for performing intense laser field experiments. So a regenerative "chirped pulse amplifier" is added to the system for obtaining high energy ultrafast pulses. It
is not possible to amplify the ultrashort pulses directly to high energy levels, as this leads to intensities which are above the damage threshold of the amplifying medium. A technique called chirped pulse amplification (CPA) helps us to overcome this difficulty. In the CPA technique, the pulse to be amplified is first stretched in time by a large factor (typically 10,000) in order to reduce the peak power. This pulse can be then safely amplified, and after amplification, can be compressed back nearly to the original input pulse width \{4,5\}.

In our titanium sapphire amplifier (TSA 10, Spectra Physics), the 100 fs pulses from the femtosecond oscillator are sent to a pulse stretcher, which broadens the pulse to about 300 ps width. An individual pulse is then picked from the 82 MHz pulse train using an electro-optic modulator. The selected pulse is seeded into a regenerative cavity, which contains an optically pumped Ti:sapphire crystal. The principle of regenerative amplification is to confine, by polarization, a single pulse (selected from a mode-locked pulse train), amplify it to an appropriate energy level, and then "cavity dump" the output. The pulse oscillates in the cavity, gaining energy in each trip as it passes through the crystal. After several round trips, the pulse gains sufficient energy and is reflected out of the cavity using an electro-optic switch. Typically an input pulse of energy of a few nanojoules can be amplified to over 5 mJ in a single Ti:sapphire laser rod in the regenerative cavity. The cavity-dumped pulse is then fed to a double-pass linear amplifier for further amplification. The amplified pulse is then sent to a grating compressor, which compresses the pulse back to the original 100 fs width. The TSA-10 generates 100 fs pulses of 10 mJ energy at a repetition rate of 10 Hz.

Pulse stretching and compression in this system is achieved by the use of diffraction gratings. In a pulse stretcher, the input beam is incident on a diffraction grating, causing the different frequencies in the ultrafast laser pulse to disperse. The stretcher gratings are configured in such a way that the bluer frequency components have to travel further through the stretcher than the redder components so that the pulse gets stretched temporally.

Pulse compression is essentially the reverse of pulse stretching. In this case, the gratings are arranged such that the bluer frequencies travel the shortest path,
catching up with the redder frequencies and thus compressing the pulse (details of the CPA technique can be found in chapter 1).

![Image of CPA system](image)

**Figure 5.3:** The CPA system used for the experiments (view from above).

### 5.2.4: Quanta Ray – pump laser for CPA

The CPA is pumped by a frequency doubled, Q-switched Nd:YAG laser (Quanta Ray, Spectra Physics) operating at 10 Hz with a nominal pulse width of 7 ns. This flash lamp pumped laser is capable of producing pulses of 275 mJ energy at 532 nm using a KDP crystal for frequency doubling.

### 5.2.5: Fast electronics: synchronization and delay generator (SDG)

The timings associated with the switching of the Pockels cells in the CPA is very critical. In order to ensure that a single pulse is admitted to the resonator, the input Pockels cell must be switched at the same time, with respect to the mode-locked pulse train. To achieve this, the Pockels cell switching is synchronized to the RF signal generated by the mode-locker of the ultrafast oscillator, using a synchronization and delay generator (SDG) unit. The phase of the switching (the time at which the Pockels cell switches with respect to the pulse train) can also be adjusted: following synchronization, there is a 0-1275 ns delay that allows phase
adjustment. The SDG then produces the separate triggers, with adjustable delays, to drive the Pockels cells. The output Pockels cell switches the laser pulse out of the resonator. The pulse must be ejected only after sufficient number of round trips, and hence a delay of approximately 200 ns is employed between the switching of the two Pockels cells.

Figure 5.4: Photograph of the high energy ultrafast laser system used for the experiments.

5.3: Ultrafast laser pulse characterization

5.3.1: Measurement of the pulse width

The measurement of femtosecond pulse durations is always a challenging task, as one cannot use the normal electronic diagnostics for this purpose. The fastest electronic diagnostic tools available today are limited to a few pico seconds (e.g. the streak camera). Once the pulse durations are in the sub-picosecond regime, one employs the light pulse itself to measure its temporal duration in an autocorrelation setup \cite{4}. We make use of the mathematical entity, the correlation function of two functions for this diagnostic technique.
The correlation function of a function $F(t)$ is defined as,

$$C(\tau) = \int_{-\infty}^{\infty} F'(t)F(t-\tau)dt$$  \hspace{1cm} -(5.1)$$

where $C(\tau)$ is a measurable first order correlation function and $F(t)$ is the function to be known. $F'(t)$ is a known test function. In the present case, since it is extremely difficult to produce a test pulse of the same duration as the light pulse, we use the light pulse itself as the test pulse. Such a correlation technique is known as autocorrelation. In this case the laser pulse is split into two and recombined with known, adjustable time delays $\tau$, and their correlation is studied as a function of $\tau$.

![Figure 5.5: Schematic of the second order autocorrelation measurement.](attachment:image)

Figure 5.5: Schematic of the second order autocorrelation measurement.

We used the second order autocorrelation (also known as the intensity autocorrelation) technique to measure the temporal width of our ultrafast laser pulse. We choose the intensity autocorrelation technique due to the simplicity in its analysis and the zero background. The easiest way to implement a second order autocorrelation is to study second harmonic generation in a nonlinear crystal as a function of time delay between the two pulses. The experimental setup used for this purpose is shown in figure 5.5.
The incoming laser beam is split into two using a suitable beam splitter. The path length of one of the arms is fixed and other is delayed with respect to the first using an optical delay line. Two mirrors mounted on a translation stage in a retro reflector configuration acts as the optical delay generator. In our setup this translation stage can be moved in steps of 1.25 micrometers, which corresponds to an optical temporal delay of 4 fs. Both beams are then allowed to fall on a SHG nonlinear crystal in a non-collinear geometry, as shown in the schematic. The second harmonic generated in the crystal will be non-collinear with both the beams and hence can be separated using a simple slit, which is then fed to a photodetector. The averaged autocorrelation now will have the form,

$$C(\tau) = K \int_{-\infty}^{+\infty} I(t)I(t-\tau)dt$$  \hspace{1cm} (5.2)

where $K$ is a constant related to the nonlinear susceptibility of the crystal ($K = |\chi^{(2)}|^2$) and $\tau$ is the relative delay between the two pulses. In this case the crystal does the multiplication of the intensities ($I(t)I(t-\tau)$) during the process of second harmonic generation. Since the detector used is too slow to resolve the variation of intensity in time (we used a slow photodiode which had a pulse rise time of about 40 ns), it will measure only the integrated intensity. In other words, the output from the photo detector readily corresponds to the intensity autocorrelation of the two pulses. From the obtained autocorrelation trace, the input pulse width can be calculated, provided the pulse shape of the input pulse is known. For a Gaussian pulse, the autocorrelation width is $\sqrt{2}$ times the input pulse width, whereas for a sech$^2$ pulse, the autocorrelation width is 1.543 times the input pulse width \cite{6}. In our case the ultrafast pulse shape is nearly Gaussian, and the pulse width measured using intensity autocorrelation is 93 fs. For the sake of simplicity, the pulse width is taken as 100 fs throughout the discussions in this thesis.
Figure 5.6: Measured intensity autocorrelation of the ultrafast laser.

5.3.2: Spectral characteristics

Since the ultrafast pulse is generated by mode-locking a large number of laser cavity modes, it is broad in the spectral domain. For a Gaussian pulse, the relationship between the spectral and temporal width is given by $\Delta \nu \Delta t \geq 0.441$ \cite{7}, which corresponds to a bandwidth ($\Delta \lambda$) of about 9 nm for a chirp-free pulsewidth ($\Delta t$) of 100 fs, at 800 nm wavelength.

Figure 5.7: Wavelength spectrum of the ultrafast laser pulse.
The spectrum of the ultrafast pulse (output from TSA-10) is measured using a CCD based single shot fiber optic spectrometer (Avaspec 2014, Avantes BV) and the $\Delta \lambda$ obtained is approximately 12 nm (FWHM) at a central wavelength of 804 nm (figure 5.7).

5.3.3: Spatial intensity profile

The cross-sectional intensity profile of a beam is another important parameter, which is crucial in determining the focused spot size as well as the irradiance of the beam. We used a CCD beam profiler (ML3754, Metrolux GMBH) to record the spatial intensity profile of the beam. The beam diameter also can be measured using the beam profiler, by calibrating the pixel size. A Gaussian spatial beam profile is obtained, which is given by,

$$I = I_0 e^{-r^2/\omega^2}$$

where $r$ is the position along the radial direction of the beam. $I_0$ is the intensity at $r=0$, and $2\omega$ is the beam diameter (FWHM). The beam diameter measured using the beam profiler is 7 mm.

Figure 5.8: Spatial intensity profile of the ultrashort laser pulse.
5.3.4: Beam diameter and spot size measurements

In addition to imaging by the beam profiler, we also used the conventional knife-edge method to determine the beam diameter. In the knife-edge method, a knife-edge is scanned across the transverse profile of the beam and the beam power after the knife-edge is recorded using a photodetector. The detector output corresponds to the integrated intensity, which when differentiated gives the input laser spatial profile.

![Power Transmitted past knife-edge](image1)

**Figure 5.9:** Beam diameter measurement using the knife-edge technique.

Assuming the laser spatial profile to be a Gaussian, the beam diameter can be calculated by fitting a Gaussian to the derivative of the photo detector output. The beam diameter calculated using this method is 7.4 mm, which matches well with the value obtained from the beam profiler measurements.

For measuring the spot size (radius of the beam at the focus) of the beam at the focal point of a focusing lens, the beam diameters at different z positions after the lens along the beam propagation direction are measured. For a paraxial beam of wavelength $\lambda$, the beam radius $\omega$ at any given point $z$ is given by the equation,

$$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2}$$  \hfill (5.4)
where $\omega_0$ is the spotsize and $z_0$ is the diffraction length (Rayleigh range) given by the equation $z_0 = \frac{\pi \omega_0^2}{\lambda}$.

A theoretical fit done using the above equation to the experimental result helps us to extrapolate the curve to the focal point. From the best fit obtained for the experimental data, the value of the spotsize can be obtained. The results from these measurements are presented in figure 5.10.

![Figure 5.10: Spotsize measurement for the ultrafast laser beam focused by a plano-convex lens of 11 cm focal length at 800 nm.](image)

The measurements were done using a 11 cm focal length (800 nm) lens and the value obtained for the spotsize is 8 micrometers. This value is used for the calculations in the laser – planar liquid jet experiments discussed in chapter 6.

5.4: The vacuum chamber

The vacuum chamber used is of 1 meter diameter and 40 centimeter height, and has a volume of approximately 300 litres. Such a high volume is not necessary for the experiments reported in this thesis; however we decided to use this chamber because it was available in the lab. It was originally built for liquid droplet - laser interaction studies, and a detailed description of the chamber design can be found.
in the reference {8}. To make the chamber suitable for solid target studies, we fabricated a high vacuum compatible target manipulator, which was fixed on top of the chamber (details of the solid target manipulator are given in section 5.5).

![Figure 5.11: The vacuum chamber used for the experiments.](image)

There are 16 ports along the periphery of the chamber as shown in figure 5.11. All ports are centered to the interaction region in the center of the chamber. X-ray, γ-ray and visible emissions can be measured by placing appropriate detectors in front of these ports. This design helps us to take simultaneous measurements of the angular distribution of plasma emission in real time.

To obtain an oil-free vacuum, the chamber is pumped using a turbo molecular pump backed by a dry pump. Oil-free vacuum is preferred for our experiments as continuous pumping using a rotary pump could leave a layer of oil on the target surfaces, which would affect the surface conditions, especially on polished and coated targets. We used a Pfeiffer 2000 l/s turbo molecular pump (TPU 2101 PC) backed by a Pfeiffer 180 l/min (Unidry DBP 050-4) dry pump. The turbo molecular pump is connected to the chamber through an electro-pneumatically actuated gate valve, for isolating the pump from the chamber. Another electro-pneumatically actuated gate valve is used in between the turbo molecular pump and the backing dry pump. Option is provided to connect the backing dry pump to the
chamber directly (bypassing the turbo molecular pump) using another manually operated gate valve. This option allows us to use the same backing pump for pumping down the chamber to pre-vacuum levels required for some experiments (like reflectivity studies), completely isolating the turbo molecular pump from the chamber.

![Chamber pumping equipment](image)

**Figure 5.12: Chamber pumping equipment.**

The dry pump can evacuate the chamber to a pressure of $5 \times 10^{-2}$ Torr in about five minutes. A Pirani gauge is used to measure the rough vacuum. The Pirani gauge essentially uses the thermal conduction of the gas to measure the pressure. The gauge head is placed around a heated wire that is exposed to the gas. The resistance of the wire is temperature dependent. When the gas molecules collide with the wire its temperature and hence its resistance decreases. When the pressure in the chamber decreases, the number of colliding molecules decreases and hence the temperature of the wire increases. A calibration of this temperature dependent resistance makes it useful for pressure measurement. The Pirani gauge can be used for measuring a vacuum range of 750 Torr to $3.75 \times 10^{-4}$ Torr. Lower pressures are measured by using a cold cathode gauge, which has a measuring range of $7.5 \times 10^{-3}$ Torr to $1.5 \times 10^{-9}$ Torr. The cold cathode gauge (Penning gauge) is an ionization gauge in which a high voltage discharge produces an electron beam that ionizes the gas in the chamber. These ions will create a current in the anode and the anode current will be proportional to the pressure of the chamber. A magnetic field is applied to
increase the path of the charged particles and ionization current. In our experimental setup, the turbo molecular pump in conjunction with the dry pump can pump the chamber pressure down to $5 \times 10^6$ Torr in about twenty minutes. An ultimate pressure of $5 \times 10^7$ Torr can be achieved in about an hour.

![Image of vacuum chamber](image)

**Figure 5.13:** View of the vacuum chamber from the bottom side.

### 5.5: The solid target manipulator

Since the sample kept at the focus gets modified at each laser shot, it is important to move the sample during irradiation, so that the laser sees a fresh sample surface at each shot. In the case of solid targets, a vacuum compatible translation stage is necessary to achieve this. There are two approaches to this problem. One is by placing vacuum compatible XY translation stages, available commercially, inside the vacuum chamber and wiring the connections via a vacuum compatible electrical feed-through. The alternative is to have an ordinary XY translation stage outside the vacuum chamber and couple its translation via a Wilson seal to the vacuum compatible target holder placed inside the chamber. We preferred the second approach as it offers more flexibility and is comparatively cheaper. Also, while the vacuum compatible translation stages have a vacuum limit of $10^6$ Torr, the second approach gives vacuum levels at least two orders of magnitude higher.
We designed the solid target manipulator in such a way that the target could be moved in the horizontal and vertical directions, in a range of 50 mm in both directions with a positional accuracy of 12.5 micrometers. The 100 CF port on the top of the chamber was used for attaching the solid target manipulator. The schematic of the target manipulator is presented in figure 5.14.

Figure 5.14: UHV compatible solid target manipulator schematic.

Figure 5.15 is the schematic of a Wilson feed-through designed to attach the solid targets to the above mentioned target manipulator. The target can be fixed at the M4 tapped end of a 1 cm stainless steel thick rod, which is attached to a 63 CF blank port using an O-ring Wilson sealed movable joint. This indigenous design allows us to control the target tilt and it gives us more freedom on the Y-axis positioning. Bi-polar stepper motors X and Y control the motion of the target inside the vacuum chamber. The stepper motors used have a full step movement of 1.8 degree per pulse. There is also a provision for the manual control of the
manipulator. The leak rate observed under helium leak test for the target manipulator is below $2 \times 10^{-10}$ cc/sec.

Figure 5.15: Schematic of the Wilson feed-through used to attach the solid targets to the target manipulator.

Figure 5.16: A photograph of the vacuum chamber with the solid target manipulator attached on the top CF 100 flange.
5.6: The target motion controller

The stepper motors of the target manipulator need to be controlled and synchronized with the laser for ensuring proper measurements. The motors should be controlled in such a fashion that the manipulator first moves in the X direction, from one end to the other, halting at regular intervals as specified by the user. The laser should be allowed to fall on the target at each stop and the corresponding emission data needs to be taken. When the target reaches one end of the translation stage, the Y motor should be enabled so that the target is shifted vertically to the next line. It should then be moved in the opposite X direction, and so on. We designed and implemented the electronics and software needed to perform these tasks.

We used the LPT port (parallel port) of a PC to send the control signals to the target manipulator and the laser trigger input. An electronic buffer circuit is necessary between the computer and the motor as the stepper motor requires high currents to run, which cannot be sourced by the computer. This circuit should also provide good isolation between the PC and the stepper motors to prevent damage of the PC from high back emfs generated in the motor. In addition the circuit should be capable of selecting the appropriate stepper motor for X or Y movement as per instructions from the PC. The electronics used should be able to provide the current required by the stepper motor (typically around 2 A in our case) and should also have a provision for triggering a relay-energized mechanical shutter, which is used for selecting a single laser pulse from a 10 Hz pulse train. An electronic circuit is designed taking all these factors into account. The circuit diagram can be seen in figure 5.17. A printed circuit board (PCB) is designed for the same using a computer aided design (CAD) software. The PCB design schematic and the populated PCB are shown in figure 5.18.
The circuit developed is capable of driving both unipolar and bipolar type stepper motors up to a current of 4 A. Provisions for mechanical shutter control and optional trigger outputs are also included in the design. The TTL pulses from the parallel port of the computer are fed to the ULN2003, which contains an array of seven darlington pairs. This acts as a buffer between the parallel port and the next stage of the electronic circuit, thereby limiting the current drawn from the parallel port. The output of this current amplifier is fed to KP1040, which is a four-channel optocoupler. This provides the necessary electrical isolation between the PC and the stepper motor. The first four outputs of the optocoupler are the control signals for the stepper motor. These signals are then fed to the IC L298, which is a dual bridged driver, which is capable of driving high current loads up to 4 A. This IC drives the X
translation stage stepper motor. The same signals are fed to another L298, which
drives the Y stage. Selection between the two is made by the fifth signal from the
parallel port, which is fed to the enable pins of L298. The enable signal to the X
translation L298 IC is inverted using an npn transistor. If the fifth signal is low, the
enable pin of stage X L298 becomes high thereby enabling the output to the X
stepper motor. The stage Y L298 stays disabled at this time as its enable input value
stays at low. Subsequently stage Y can be selected by making the fifth signal go
high. The sixth signal from the parallel port is used to energize a relay that controls
the mechanical shutter. The seventh signal is made available at the connector
marked *optional* in the PCB, which can be used to trigger any other optional
accessories that need to be controlled using the program.

![Variable, regulated power supply for the target motion controller](image)

**Figure 5.19:** Variable, regulated power supply for the target motion controller

A regulated power supply with a variable output from 0 to 18 V with a
current capacity of 5 A for the motion controller electronics was also designed and
implemented. This includes a separate 5 V regulated output as well for the digital
gates included in the stepper controller design. A PCB was designed and fabricated
for this circuit. The designed PCB can be seen in figure 5.19. The circuit diagram and
a brief description of the same can be found in the appendix.

During the experiment the target has to be moved from position \((x_1, y_1)\) to
\((x_2, y_2)\). In this period the laser pulses should be blocked by the mechanical shutter.
After moving the target through this definite distance, the laser must be allowed to
fall on it by opening the shutter. If the user stops the measurements in between for
some reason, the program must store the (x, y) value of the location where the
target manipulator was stopped. If the experiment resumes at a later time, it must
start from this position. A program was written in LabVIEW™ keeping all these
factors in mind. The front panel of the target motion controller program is given in
figure 5.20.

![Target Motion Controller](image)

Figure 5.20: Front panel of the target motion control program.

The program will start when the OK button is pressed after entering all the
necessary input parameters in the appropriate columns. The live position on the
target where the laser is incident is displayed as a red spot in the graph. The two
vertical progress bars indicate the progress of the experiment. STOP button can be
used to stop the experiment at any point, if required. The VI is developed for targets
of 5 cm x 5 cm dimension. For any values of x or y greater than these values, an
error message will be displayed, indicating that the target manipulator has reached
the limits.
5.7 Solid-state radiation detectors

Solid-state detectors are preferred over gas-filled detectors for measuring high energy radiations as they have material densities three orders of magnitude higher than gases. As the material density increases the number of interaction sites increases, leading to enhanced interaction probabilities so that the detector dimensions are considerably reduced. We chose Si-PIN and NaI(Tl) solid-state detectors for measuring the x-ray and γ-ray emissions from the laser produced plasma. Details of these detectors as well as their calibration methods are discussed below.

5.7.1 Si-PIN: x-ray detector

The depletion region of semiconductor diodes possess properties appropriate for a radiation detection medium. When the radiation deposits energy in a semiconductor detector, an equal number of conduction electrons and holes are created within a few picoseconds along the radiation track. An electric field applied across the detector active volume will ensure that the electron-hole pair created will experience an electrostatic force. Due to this electrostatic force, the electron-hole pair created in the active region will drift to the corresponding electrodes and be collected as the corresponding electrical signal. The number of electron-hole pairs produced corresponds to the incident radiation energy provided the radiation is completely absorbed. The ionization energy for silicon is about 3 eV whereas for gases it is about 30 eV. Hence ten times more number of electron-hole pairs are produced in these solid-state detectors for the same incident radiation as compared to the gas detectors. This is very advantageous in the case of soft x-ray detection, as they do not create many electron-hole pairs.

In the silicon p-i-n diode configuration, a high resistivity i-region is introduced between the p and n non-injecting contacts on either surface. This particular configuration helps to reduce the leakage current. Semiconductors generally show a finite conductivity even in the absence of ionizing radiations. Hence there is an inherent leakage current, which may fluctuate enough to suppress signals originating from a true ionizing radiation, if the signal is weak. So
to get a better signal to noise ratio, the leakage current should be kept at a minimum and hence a p-i-n configuration is preferred. Another source of leakage current is the thermally induced electron-hole pairs at the depletion layer. This can be controlled by operating the detector at low temperatures. The detectors are usually cooled thermo-electrically or using liquid nitrogen to temperatures of the order of 200 K. Si-PIN detectors are generally used for detecting x-rays in the 1 keV to 100 keV regime. The relatively small number of electron-hole pairs created by a low energy x-ray photon demands maximum reduction in the detector noise level for a faithful detection.

We used two XR-100CR Si-PIN detectors from Amptek for x-ray detection in our measurements. The XR-100CR is a new high performance x-ray detector, preamplifier, and cooler system using a thermoelectrically cooled Si-PIN photodiode as an x-ray detector. Also mounted on the 2-stage cooler are the input field-effect transistors (FET) and a novel feedback circuit. These components are kept at approximately -55 °C, and are monitored by an internal temperature sensor. Cooling the FET reduces its leakage current and increases the transconductance, both of which reduce the electronic noise of the system. The hermetic TO-8 package of the detector has a light tight, vacuum tight thin Beryllium window to enable soft x-ray detection. The Beryllium (Be) window filters low energy photons, thereby reducing low energy background. As the thickness of the Be window increases, the filtering effect increases. So by carefully choosing the Be window thickness, one can strike a balance between the background noise and the detection efficiency. The detector is used in conjunction with an analog linear amplifier, PX2CR (Amptek USA). The standard shaping time constant of the linear amplifier PX2CR is 12 µs, and a higher energy resolution is obtained if 20 µs shaping time is chosen. The detector XR100CR with 7 mm² area and 300 µm thickness having a Be window of 0.5 mil (1 mil = 1/1000th of an inch = 25.4 µm) thickness is capable of detecting in the < 1 keV to 30 keV range (pulse shaping time of 20 µs). The other XR100CR detector with 5 mm² area and 500 µm thickness has a Be window of 1 mil thickness, and it is capable of detection in the 2 keV to 90 keV range (pulse shaping time of 12 µs). These detectors have an approximate energy resolution of 190 eV. The intrinsic full energy detection efficiencies of these detectors {9} are shown in figure 5.21.
Figure 5.21: Intrinsic full energy detection efficiency of a Si-PIN detector.

Electron-hole pairs created by the radiation, which interacts with the Si near the back contact of the detector, result in fluctuations in charge collection times. These fluctuations will be observed as rise time variations of the voltage step at the output of the charge sensitive preamplifier. As a result the acquired spectra will suffer from increased background counts and a degraded energy resolution. To reduce these effects, a real time discriminator (RTD) option is incorporated in the linear amplifier PX2CR. When RTD is active, the shaped pulses are internally gated and only pulses corresponding to full charge collection are allowed to be sent to the MCA for analysis. The internal threshold of this RTD gating is set around 2 keV. RTD should be inactivated if radiations below 2 keV are to be measured.

5.7.2. NaI(Tl): γ-ray detector

The three important mechanisms of γ-ray interaction with matter that leads to their detection are the photoelectric effect, Compton scattering and pair production. As a result of these mechanisms the γ-ray will either completely disappear, or scatter to very large angles. The predominant mode of interaction of x-rays and low energy γ-rays with matter is the photoelectric process. In the photoelectric process the photon will be absorbed by the absorber atom, creating a photoelectron with a kinetic energy equivalent to the difference in energy between the incident photon and the binding energy of the electron. This process is enhanced for materials with
higher atomic number and hence most of the $\gamma$-ray detectors are made with constituents of high atomic mass. The Compton scattering probability depends on the number of electrons available. Hence the Compton scattering probability per atom increases with the atomic number. Pair production occurs if the $\gamma$-ray energy exceeds twice the rest mass energy of an electron (1.02 MeV). The probability of pair production approximately scales as the square of the atomic number of the absorber. The probability of these three interactions as a function of energy is plotted \cite{10} in figure 5.22.

![Graph showing interaction probabilities vs. incident photon energy](image)

**Figure 5.22:** Computed interaction probabilities \cite{10} in the 30 mm X 30 mm Amptek make NaI(Tl) detector chosen for the present studies.

Scintillation detectors use crystals that emit light when gamma rays interact with the atoms in the crystals. The intensity of the light produced is proportional to the energy deposited in the crystal by the gamma ray. These detectors are often coupled to a photomultiplier, which converts the light generated to the corresponding electrical signal. The first solid medium used for $\gamma$-ray detection is thallium-doped sodium iodide (NaI(Tl)), often known as the sodium iodide detector. Since NaI(Tl) can be produced in large crystals, yielding good efficiency, and it produces intense bursts of light compared to other spectroscopic scintillators, NaI(Tl) still continues to be one of the most widely used scintillation material. The conversion mechanism in a scintillator involves the conversion of the incident $\gamma$-ray to the corresponding optical emissions and then the creation of the photoelectrons.
Thus a $\gamma$-ray detector should act as a conversion medium for the incident $\gamma$-rays to yield one or more fast electrons, and it must act as a conventional radiation detector for the fast electrons. The relatively high atomic number 53 of its iodine constituent ensures that photoelectric effect will be the dominant process in the NaI(Tl) detector. Generally the energy resolution of a radiation detector is determined by the charge collection statistics, electronic noise, variation in the detector response over its active volume, and drift in the operation parameters over time. For the scintillation detectors, the fluctuations in the gain of the photo multiplier tube also is a determining factor of the resolution. Hence the energy resolution of a scintillation detector is basically limited by the photoelectron statistical fluctuations.

We used an Amptek GAMMA-8000 series scintillation detector for $\gamma$-ray detection which has a standard 30 mm x 30 mm NaI(Tl) scintillator crystal. It also includes a standard 3 mm PMT and a Cockroft Walton high voltage generator. The scintillation crystal is housed in an anodized aluminium case of thickness 0.5 mm, which reduces the background signals to the detector. The typical energy resolution of this detector is $< 7.5\%$ FWHM at 662 keV and $< 14\%$ FWHM at 59.5 keV.

5.7.3 Multichannel analyzer (MCA)

The operation of a multichannel analyzer is based on the conversion of the pulse amplitude from a radiation detector to a corresponding digital number. The radiation detector generates electrical signals corresponding to the input radiation and a pulse height analyzer in a radiation detection system records the amplitude distribution of pulses produced by the detector. This is then fed to a linear amplifier, which shapes and increases the amplitude of these pulses to match it with the input of the multichannel analyzer. The key component of an MCA is an analog to digital converter (ADC). These ADCs are designed in such a way that they produce a single output value for each analog pulse presented to their input, which is proportional to the peak amplitude of that pulse and hence named as peak sensing ADCs. The output of the ADC appears in a register that is used to address a digital memory that has addressable locations referred to as the channels into which the spectrum is subdivided. Each channel corresponds to a specific input energy value,
which can be calibrated using known spectra from standard radiation sources. The slope and the y-intercept of the straight line of calibration can be determined, if one knows two of the energy lines, preferably those at the initial and final positions of the energy range of interest. A third energy value at the mid point will ensure linear calibration. An ideal MCA will execute a perfectly linear conversion of the pulse height to the channel number. Hence a plot of the pulse height versus the channel number will be a straight line. A lower threshold of the pulse amplitude can be set for the MCA, which helps to suppress the high-count rates from small noise pulses. This threshold is adjustable from the software control of the MCA data acquisition. As described earlier, the signal from the detector is first sent to a linear amplifier so that the signal amplitude is increased to match the set voltage levels of the ADC in the MCA. By increasing the gain of the linear amplifier, the amplitude of each signal can be increased. Hence the corresponding pulse height in the MCA will be increased, thereby changing the slope of the calibration curve. A photograph of the detectors along with respective preamplifiers and MCA can be seen in figure 5.23.

![Figure 5.23: A photograph of the x-ray and γ-ray detectors.](image)

The Amptek pocket MCA8000A used in our detector system has software selectable number of channels/memory locations of 16k, 8k, 4k, 2k, 1k, 0.5k, and 0.25k. The number of channels used for recording the spectra will determine its resolution. This MCA which is specially designed for the GAMMA 8000 series detectors, powers the detector electronics as well. The data can be transferred to
the PC using a serial port (RS-232) and the acquisition parameters can be selected from the PCMCA software through the same interface.

5.8 Calibration of the solid-state detectors

The MCA only sorts the radiation peaks detected to different channels. In order to assign the energy values of the peaks that are stored in different channels of the MCA, the system needs to be calibrated with a known spectrum of a standard radiation source. Also since the gain control of the preamplifier changes the calibration curve, a re-calibration becomes necessary whenever the gain of the preamplifier is adjusted. This is true in the case of the channel number setting of the MCA as well. Hence a calibration of the detection system becomes necessary at the start of each fresh experiment for a faithful detection of the radiation energy spectrum.

5.8.1 Calibration of the x-ray detector

We used an Americium 241 source for the calibration of the x-ray detector. The standard radiation spectrum \{9,11\} of Am$^{241}$ is given in figure 5.24. The obtained spectral peaks are compared to this standard and the corresponding energy values are assigned to the channel numbers.

![Figure 5.24: Radiation spectrum of Am$^{241}$](image)

Figure 5.24: Radiation spectrum of Am$^{241}$.
Americium-241 is a silver-grey colored metal. It decays primarily by alpha particle emission to neptunium-237, which has a half-life of 2,144,000 years. Low energy gamma radiation accompanies these decays, with the 59.5 keV gamma emission being the most prominent. The decay scheme of Am$^{241}$ is shown in figure 5.25.

![Decay scheme of Am$^{241}$](image)

Figure 5.25: Decay scheme of Am$^{241}$.

The spectra obtained from the Am$^{241}$ source using the 5 mm$^2$ Si-PiN detector with 1 mil Be window and 500 µm detector thickness are given below. Figure 5.26, 5.27 and 5.28 are the spectra obtained with the linear amplifier gain set to 0.5, 0.7 and 0.9 respectively. The ADC resolution is kept constant at 4096 channels, in all these measurements.

It can be seen that the spectrum shifts to the right giving more resolution to the obtained peaks. The increased gain increases the amplitude of the pulse given to the ADC. Thus a pulse that would have been detected at a lower channel now will be detected at a higher channel, giving the option to discriminate the lower channels to suppress the low amplitude intrinsic noise. It is to be noted that for a chosen ADC resolution, the measurable range decreases with the increase in linear gain.
Figure 5.26: X-ray spectra obtained from Am$^{241}$ with the amplifier gain set to 0.5.

Figure 5.27: X-ray spectra obtained from Am$^{241}$ with the amplifier gain set to 0.7.
Figure 5.28: X-ray spectra obtained from Am$^{241}$ with the amplifier gain set to 0.9.

Figure 5.29: Calibrated x-ray spectra obtained from Am$^{241}$ with the linear amplifier gain set to 0.5 and the ADC resolution set to 2048.

Figure 5.29 shows the spectrum obtained after calibration for the linear amplifier setting of 0.5 and an ADC resolution of 2048. The calibrated spectrum obtained from the 7 mm$^2$ detector with 0.5 mil Be window and 300 μm detector.
thickness is given in figure 5.30. Since the detector thickness is smaller in this case, the detection efficiency too is lower and hence the spectrum is noisier.

Figure 5.30: Calibrated x-ray spectra obtained from Am$^{241}$ with the linear amplifier gain set to 0.5 and the ADC resolution set to 1024. The detector used in this case had a smaller active interaction depth.

5.8.2 Calibration of the $\gamma$-ray detector

For the $\gamma$-ray scintillation detector calibration, we used Co$^{60}$ and Cs$^{137}$ as the calibration standards. The decay schemes of these two radiation sources \cite{13} are shown in figure 5.31.

Figure 5.31: Decay scheme for the $\gamma$-ray reference sources Co$^{60}$ and Cs$^{137}$. 
The standard radiation spectra of Co\(^{60}\) and Cs\(^{137}\) are shown in figure 5.32 \({10}\). The NaI(Tl) detector is first calibrated using the Co\(^{60}\) source and the calibration is validated using the Cs\(^{137}\) source.

![Figure 5.32: Standard emission spectra for the sources Co\(^{60}\) and Cs\(^{137}\).](image)

The γ-rays emitted are nearly monoenergetic as nuclear states have well defined energies. Hence any line width obtained for the spectrum is indicative of the detector’s resolution rather than any variation in the incident γ-ray energy. The Cs\(^{137}\) source which we used to calibrate the γ-ray detector has a strength of 3.3 mCi and the Co\(^{60}\) source has a strength of 2.4 mCi.

![Figure 5.33: Calibration of the NaI(Tl) detector system using Cs\(^{137}\).](image)
5.9 Time gating of the detectors and laser synchronization

The x-ray and γ-ray detectors are susceptible to background radiation noise, which is more so in the case of the NaI(Tl) detector. A carefully chosen time gate can improve the signal to noise ratio. The amptek MCA has two such gating options available. Of the two gates, one is active HIGH TTL compatible and the other is active LOW TTL compatible. When the first gate input is high, the analog input pulses are gated off and the live clock is stopped. In the other gate this happens if the gate input is low. The gating must occur at or prior to the peak of the analog pulse and should extend for at least 1 μs after the peak for optimum performance. MCA gating can be applied also to attain a data accumulation time shorter than one second or for non-integer accumulation times.

The femtosecond laser system works at a repetition rate of 10 Hz, and it would have been ideal if the sample could be moved to a new position for each laser pulse. This means that the target needs to be moved to the next position within 100 ms. But the movement of the target manipulator is rather slow, and can lead to positioning errors if driven fast. This might turn out to be even trickier if the loads on the manipulator are high. Therefore to ensure error free positioning, it is better to allow at least about 500 ms time interval between the successive irradiation of the target. So an external synchronization system becomes necessary for synchronizing the laser triggering, target positioning, MCA gating and data acquisition. Triggering the laser externally at user specified times is a typical solution to this, but not the preferred one in the present case. The pulse to pulse energy stability of the CPA laser system will be ensured only if the crystals are irradiated near a 10 Hz repetition rate, and hence triggering the laser at user specified repetition rates will sacrifice the energy stability of the system. This is due to the fact that the system is optimized to compensate for thermal lensing and associated effects at the repetition rate of 10 Hz. Changing the repetition frequency hence will adversely affect the energy stability of the system. Therefore we chose an alternate method, where we operated the laser at 10 Hz, but used a mechanical shutter to select single pulses from the 10 Hz pulse train at user specified intervals. This shutter is a “pulse picker”, and needs to be synchronized with the 10 Hz laser repetition and the user defined trigger pulses. An electronic circuit was designed
and fabricated for this purpose. The circuit diagram and the PCB fabricated can be seen in figure 5.34.

![Circuit Diagram](image)

**Figure 5.34:** The electronic circuit designed for synchronized laser pulse picker.

The heart of the circuit is a 7476 flip-flop. The input from the laser Q-switch and the user trigger are given to an AND gate which energizes the flip-flop and thereby a relay, only when both the pulses are present. The output of the flip-flop is fed back to the input in such a way that the second pulse in the laser train will switch the relay off. A small piece of Aluminium attached to the relay moves across the beam path when the relay is energized, thus acting as the shutter. This indigenous design ensures that a single pulse can be selected from the 10 Hz pulse train at will. A photodiode placed after the shutter acts as the input trigger signal to a function generator wired in the burst trigger mode. We used a 25 MHz function generator (AFG 3022B, Tektronix) for this purpose. The function generator parameters were set such that when triggered, it produces a single pulse of 50 μs duration [14]. This pulse is used as the gating signal for the MCA. The schematic of the experimental setup is shown in figure 5.35.
Figure 5.35: Experimental setup for gated, synchronized x-ray measurements from the laser-solid interaction.

5.10: Conclusions

We have developed in-house the entire infrastructure needed for x-ray and γ-ray measurements from intense laser-condensed matter interactions. All the electronics required were developed and fabricated, and the software was coded.
References