T.1 CAT Table Top Terawatt Nd: glass laser system

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1. Introduction

Since the beginning of the last decade, there has been a great upsurge of interest in the area of high intensity, ultra-short laser pulse-matter interactions[1,2]. This has been possible due to the advent of Chirped Pulse Amplification (CPA) scheme[3], leading to development of very compact terawatt laser systems (also referred to as Table Top Terawatt or T^3 lasers). In contrast to huge-sized and extremely expensive terawatt lasers set up earlier for inertial confinement fusion research, delivering multi-kilojoules energy in a pulse of a nanosecond or few hundred picosecond duration, the CPA based multi-terawatt laser systems operate at much smaller pulse energy in a correspondingly much smaller pulse duration of a few tens of femtosecond to a picosecond. Hence these lasers can be set up at a much lower cost and operate at a higher repetition rate. These systems easily provide focused laser intensity of $\geq 10^{17}$ W/cm^2. In fact intensity as high as $\sim 10^{21}$ W/cm^2 has been achieved from pettawatt laser systems[4] comprising of large aperture Nd: phosphate glass amplifiers using the CPA scheme. It has thus become possible to subject matter to extremely high laser fields, leading to many new and exciting phenomena. In the near-solid density plasmas thus produced with ever increasing laser intensity, new effects continue to be discovered with many potential applications. The latter include concept of fast ignition[5] in laser driven fusion, production of laser driven 'table-top' versions of fusion neutron source[6], particle accelerators[7], and coherent x-ray radiation[1]. Very high enengy (MeV) protons, γ-rays and neutrons produced in these interactions can induce a variety of nuclear reactions[8,9] of interest for generation of radioisotopes, transmutation of long lived radioactive waste[10] etc. Many other spin-offs in various different fields e.g. ultrafast lattice dynamics[11] using femtosecond x-ray pulses are also being realized.

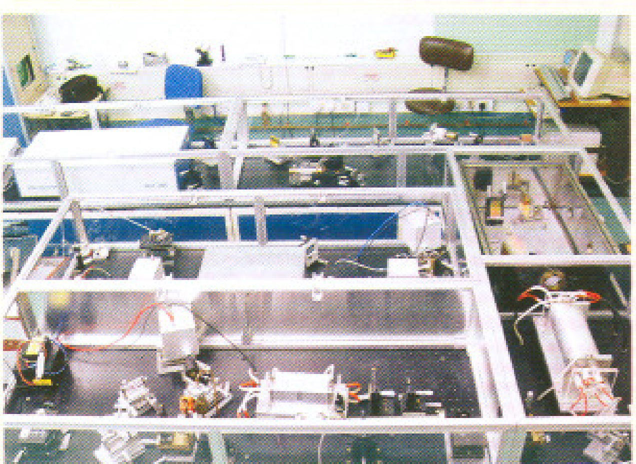

Fig.T.1.1 Photograph of the CAT Table Top Terawatt laser system

In view of the above-mentioned importance, we had undertaken an IX plan project to build a Table Top Terawatt Nd: glass laser system. This laser system has been designed, built and commissioned[12] (fig.T.1.1). It operates at 1054nm wavelength in a single shot mode, and delivers a pulse energy of ~1J in a duration of ~900fs to 1100fs. A brief description of the design scheme and details of various opto-mechanical and electronic sub-systems of this laser and their performance is given in this article.

2. Basic scheme of the T^3 laser system

A schematic of the Table Top Terawatt Nd:glass laser system is shown in fig.T.1.2. It consist of a master oscillator, a double pass grating based pulse stretcher, single pulse selector unit, an injector and ejector unit, an injection Q-switched regenerative amplifier, a pulse cleaner unit, a double pass amplifier, a single pass amplifier, a vacuum spatial filter cum image relay system, and finally a pulse compressor. Except the oscillator, all the sub-systems of the laser including power supplies, delay units, diagnostics systems, etc. are set up in-house. All the sub-systems are controlled by an indigenously developed PC based central control system. The details of the sub systems are given below.

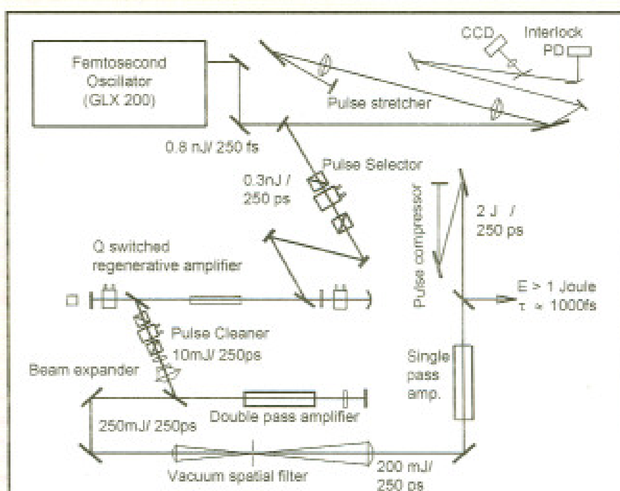

Fig. T.1.2 Schematic of the CPA based Table Top Terawatt Nd: glass laser system

3. Opto mechanical subsystems of the laser Oscillator

The master oscillator (GLX-200, procured from Time Bandwidth Products, Switzerland) is a diode pumped cw passively mode locked Nd: glass laser (λ =1053nm), which provides seed laser pulses of 0.8nJ, of pulse duration ~250fs, at 100MHz repetition rate. The spectral bandwidth of these pulses is ~5nm (FWHM) centered at 1054nm. This is the only commercial subsystem in the T^3 laser system.

Pulse stretcher: The laser pulses from the oscillator are stretched in a double pass pulse stretcher by a factor of 10^3 to about 250 picosecond. The stretcher consists of two holographic gratings (groove density 1740 lines/mm), two achromatic lenses of focal length 50cm, and a retro mirror pair. The separation between the lenses is 100cm and the effective stretching length in double pass is also 100cm. The overall efficiency of the stretcher is ~ 60%. The zero order reflection from the grating is used for laser diagnostics. This beam is dispersed with a grating (1180 lines per mm) and imaged on a CCD camera and displayed on a TV monitor. When the laser operates in cw mode locked condition, one obtains a long length spectrum on the TV monitor, corresponding to the spectral width of the short pulse. However, occasionally such oscillators malfunction and go to Q-switch mode. In such an event, the length of this line gets reduced by a large amount. An electronic safety interlock has been set up to detect this and to abort the charging and firing sequence.

Pulse selector: From the 100MHz train, a single stretched pulse is selected using a pulse selector consisting of DKDP (Deuterated Potassium Dihydrogen Phosphate) based double Pockel cell, and two crossed Glan polarizers. The input polarizer is parallel to the polarization of the oscillator pulse (horizontal polarization) and the output polarizer is perpendicular to it. A 5ns FWHM pulse of 3.5kV (generated using a high voltage MOSFET switch) rotates the polarization of only one laser pulse, which is then injected into the regenerative amplifier.

Regenerative amplifier: This is the most important subsystem of the laser chain. The regenerative (regen) amplifier consists of a flash lamp pumped Nd: phosphate glass rod, two thin film polarizers, a quarter wave plate, mode selection aperture, and two DKDP based single Pockel cells. The regen amplifier operates in Q-switch mode. It consists of three parts:1) resonator cavity with amplifying medium, 2) a pulse injector and 3) a pulse ejector (fig.T.1.3). The cavity consists of two 100% reflectivity dielectric coated multi layer mirrors, the one on injector side with radius of curvature of 8 meters and the one on ejector side being a flat mirror. The gain medium consists of a Nd: phosphate glass rod (10mm diameter, 150mm long) pumped by four flash lamps. The rod is cooled by circulating water at room temperature. The flash lamps are air cooled as the Nd: glass based amplifiers are operated at a low rep-rate (about two minute interval). The injector consists of a plate polarizer, a DKDP based pockel cell, and a quarter wave plate. In absence of any voltage on the Pockel cell, the quarter wave plate rotates the polarization of any light coming towards the injector by 90°. As a result, the light gets thrown out of the cavity by the plate polarizer. The injector thus acts as a Q-spoiler before it starts its main job as injector. When the regen amplifier is to be Q-switched, the pulse selector and the pulse injector are simultaneously fired.

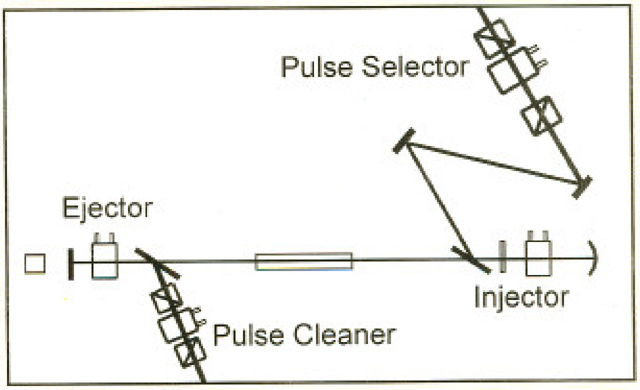

Fig.T.1. 3 Layout of the regenerative amplifier

There is a small delay introduced in the firing of the step pulse on the injector so that the injected pulse crosses the injector before it fires. The step quarter wave voltage on the Pockel cell nullifies the effect of the quarter wave plate thereby trapping the injected pulse inside the regen cavity. This pulse of nanojoule level energy acts as a seed to the regen where the pulse builds up as a seeded Q-switched envelope. When the pulse has built up to its maximum, the ejector is fired. The pulse build-up is sensed from the small amount of light leaking from the cavity mirror by a fast photodiode kept behind the cavity mirror. The ejector consists of a DKDP based Pockel cell and a plate polarizer. A fast rising step pulse of 3.5kV is applied to the Pockel cell, which acts as a quarter wave plate and the amplified pulse inside the cavity is switched out from the ejector polarizer. The firing time of the ejector is preset by looking at the envelope of the leaked pulse envelope. Pulse energy up to 10mJ has been measured at output of regen amplifier at electrical pump energy of 600J. The regenerative amplifier has been characterized for pulse build up time at different electrical pump energies and at different seed pulse energies. The amplifier is also characterized for gain narrowing at different number of round trips as well as at different seed pulse energies for fixed number of round trips.

Pulse cleaner: Even before the ejector is fired, the amplified spontaneous emission (ASE) from the regen laser rod as well as a small part of the circulating pulse can leak out of the output polarizer. This can build up substantially in the amplifier stages, which follow the regen amplifier. This long pre-pulse due to ASE or short pre-pulses due to leaked pulse from regen can create serious problem in laser plasma experiments. For this purpose, it is necessary to clean up the pulse going into the amplifiers. This is done using a pulse cleaner. This is a subsystem basically same as the pulse selector. It has two polarizers and a DKDP cell to which a pulsed (5ns duration) voltage is applied to rotate the polarization by 90°. Only during this window, the light can go through the pulse cleaner. At all other times, the light incident on it is rejected. This unit is fired simultaneously with the pulse ejector so that only the ejected pulse is allowed to go to the amplifiers. The leaked pulses and the ASE (except that in the time window of 5ns) are cut off by the pulse cleaner. The transmitted pulse is passed through a half wave plate to make it polarization vertical to enable it enter the double pass amplifier.

Beam expander: The next stage amplifier (i.e. the double pass amplifier) has a rod of diameter 15mm, the beam is expanded to fill up the gain medium. This is done by the beam expander which magnifies the beam ~ 3 times using a Galilean telescope consisting of two lenses (plano concave and plano convex) of focal lengths f_1= - 50mm and f_2 = + 150mm. The separation between the lenses is kept little less than 100mm in order to have a slightly diverging beam to fill up the double pass amplifier rod. This increased divergence is later on compensated by the vacuum spatial filter.

Double pass amplifier: The expanded beam is amplified in a double pass amplifier. This consists of a coupling polarizer, Nd:phosphate glass amplifier head, a quarter wave plate and a 100% reflectivity plane dielectric mirror. The laser rod has 15mm diameter, and a length of 200mm. It is pumped by four flash lamps and is cooled by water circulation. This amplifier gives an output energy up to 250mJ at electrical pump energy of 1.8 kJ.

Vacuum spatial filter cum image relay system: The output beam from the double pass amplifier is relayed to a single pass amplifier by a vacuum spatial cum image relay system. This system consists of an evacuated pinhole chamber. The input lens is a plano-convex lens of focal length f_1 = 450mm. The pinhole is kept in the focal plane of this lens. The output lens is also a plano-convex lens of focal length f_2 = 750mm and is placed to have the pinhole in its front focal plane. The distances from the two amplifiers are adjusted so as to relay the mid-plane of the double pass amplifier onto the mid-plane of the single pass amplifier with a beam magnification of 5/3.

Single pass amplifier: This amplifier consists of a Nd:phosphate glass rod of 25mm diameter and 300mm length. It is water cooled and pumped by six flash lamps. Unlike the regen and single pass amplifier, which have cloverleaf type electro-polished aluminum reflectors, this amplifier has a circular reflector. This amplifier amplifies the laser pulse to energy in excess of 2J.

Vacuum pulse compressor: After the single pass amplifier, the beam enters the vacuum compressor for pulse compression. As the intensity of the compressed pulse is high, the compressed beam is transported to the plasma chamber through a vacuum line at rotary level vacuum (~10^{-2} torr). The compressor consists of two large size gratings (80mm x 110mm, 1740 lines per mm) and a dielectric multi-layer mirror retro reflector pair (two mirrors, each of size 70mm x 50mm). A dielectric pick-up mirror sends the compressed beam (~ 1J energy in ~ 900-1100fs) to the plasma chamber for experiments.

Beam diagnostics setups: To characterize the ultra short laser in terms its pulse duration and pulse front tilt of the beam, several diagnostics have been set up. A single shot second order auto-correlator based on second harmonic generation in a KDP crystal has been made[13]. This can measure the pulse duration of femtosecond laser pulses in a single shot and picosecond pulses in scanning mode in multiple shots. To measure any pulse front tilt in the laser beam, a special setup based on second order auto-correlator has been made[14].

4. Electronic subsystems of the laser

The electronic sub-systems consist of: 1) Pulse selector unit, 2) Pulse injector and ejector unit, 3) Oscillator diagnostic unit, and 4) PC based control and power conditioning units. The electronic control system for the laser chain is designed to carry out the following functions:

i. Select a single laser pulse from the 100MHz output pulse train from the laser oscillator.
ii. Inject the selected laser pulse into regenerative amplifier stage with a controlled delay of ~ 1-2ns, trap it in the cavity, and eject it out after preset time (~500ns)
iii. Charge the power supplies of the amplifier chain and fire them through the flash lamps (flash lamp current pulse width ~ 350μs). The laser pulse has to be synchronized to pass through the amplifiers at the time of their peak gain.
iv. Monitor proper operation of the laser oscillator using diagnostic and interlock circuitry.
v. Provide monitoring circuit for proper mode locking in the laser oscillator and safe limit of energy level in the regenerative amplifier stage, thereby providing corresponding interlocks in the laser system.

Overall block diagram showing various electronic subsystems is shown in fig. T.1.4, and they are briefly described in the following.

Pulse selector unit: Function of the pulse selector unit is to generate low jitter trigger signals with proper time delays for various high voltage solid state switches, thereby biasing the double Pockel cells to select a single femto second laser pulse from the mode locked oscillator. It also generates a reference signal for other diagnostics and set-ups used in the laser plasma interaction experiments. The unit consists of a high-speed comparator, a low propagation delay flip-flop, avalanche transistor based driver stage and high-speed high voltage solid-state switches. The femto-second oscillator provides a synchronized train of 100MHz voltage pulses from an in-built photodiode. On receipt of an external trigger signal from the laser control unit, the pulse selector circuit generates a synchronized trigger signal for high voltage switch, which in turn biases the double pockel cell with a 5ns FWHM pulse of 3.5kV in the pulse selector stage. An interlock is provided in the pulse selector stage to check the mode locking in the laser oscillator. It is realized by monitoring the photodiode signal in the pulse stretcher stage.

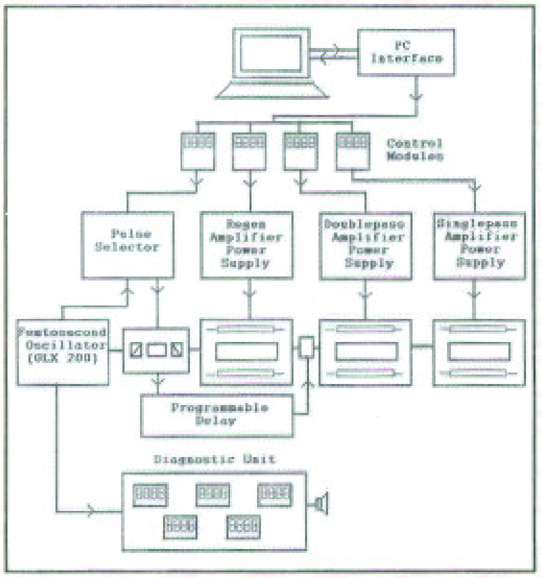

Fig T.1.4 Overall block diagram showing various electronic subsystems of the T^3 laser

Pulse injector and ejector unit: Role of this stage is to generate trigger signals for high voltage switches to pulse the pockel cells with appropriate time delays such that the selected laser pulse is injected into the regenerative amplifier stage and eject out after the set number of round trips in the laser cavity i.e. after sufficient gain has been achieved. Time delays between the trigger for respective Pockel cells are achieved by a combination of propagation delays in the RG-58 co-axial cable and by using a delay generator IC AD 9501. The regenerative stage trigger signal is generated around 250μsec prior to the trigger pulse, which selects the femtosecond laser pulse. Advance firing of the regenerative amplifier is done such that gain in the regenerative stage is at its peak when the single laser pulse is selected. However, firing of the regenerative stage also generates noise, which has the potential of triggering the active circuitry in this unit. Therefore, all the trigger signals are transmitted through shielded co-axial cables. Grounds of the high voltage source and the pulse selector circuits are isolated. The high voltage switch along with corresponding pockel cells are mounted in properly designed shielded aluminum enclosures, to avoid false or premature triggering of the high voltage switches.

Oscillator diagnostics unit: There are several parameters of the femtosecond laser oscillator, which require monitoring and alarm indication in case certain threshold limits get crossed. This is required to avoid permanent damage to the laser rod or other optics inside the laser oscillator. The parameters to be monitored are diode temperature and the crystal temperature. The circuit monitoring each parameter consists of an amplifier stage followed by a window comparator to monitor the upper and lower threshold limits. In case any of the above mentioned parameter crosses the threshold limit, an audio alarm is generated by a piezo beeper along with visual indication by an LED.

PC based control and power conditioning units: Power conditioning units for the regenerative, double pass and single pass amplifiers operate under a PC based control unit[15,16]. Each unit consists of a capacitor bank charging unit and a SCR based flash lamp trigger circuit. The capacitor charging to a set voltage is carried out through a constant current stage and a full wave rectifier. The capacitor voltage is continuously monitored by a potential divider feed back network. After the capacitor voltage reaches the set value, a charging over signal is generated by the control unit. On receipt of a trigger signal from the control unit the capacitor voltage is discharged to the flash lamp through a pulse-forming network consisting of the secondary of the trigger transformer, the energy storage capacitors and the flash lamp pair. The digital and analog signals between the control unit and the power supplies are isolated by opto-coupler and isolation amplifier stages respectively. A provision is made to set the upper safety limit for voltage on the capacitor banks.

The main features of the laser control system software are:

1. The program enables the user to enter various parameters such as voltages on the power supplies, their trigger delays etc. through the keyboard with a menu driven program. This data can be saved into and retrieved from files.
2. The laser can be operated in repetitive mode in charge and trigger, and charge and dump modes. In addition, it is possible to program parameters related to the laser in different sets and operate the laser sequentially, executing one set at a time.
3. The results after each shot are automatically saved in a file, for later examination.

5. Conclusion

In conclusion, a CPA based Table Top Terawatt Nd:phosphate glass laser system has been designed and built in-house. Various subsystems have been set up and characterized for their performance. The full system is operational providing output laser pulse of ~1 J energy in a pulse duration of 900fs to 1100fs i.e ~1TW power. The system can be scaled up to higher power by addition of large aperture Nd: glass amplifier stages and larger size grating compressor.

6. References

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