T.2: Laser power supplies and controllers for laser based nuclear field applications

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Abstract
Lasers have found a broad range of applications in material processing industry during the last few decades. Solid-state and fiber lasers are quite useful in nuclear field applications as remotely controlled in-situ material processing operations even at difficult to access constrained places as well as in presence of several nearby components is possible with these optical-fiber delivered lasers. Power supply systems for lamp pumped pulsed lasers delivering millisecond rectangular and complex shaped pulses and continuous wave (CW) lasers with modulation as well as diode pumped CW fiber lasers have been developed at RRCAT. The power supplies and laser tool controllers catering to various material processing applications in nuclear field including repairs and refurbishment of nuclear reactors have been developed and utilized to solve several problems in the nuclear field, which were either not possible or very difficult to solve by conventional means because of several practical complexities and complications. Utilization of these systems developed at RRCAT has resulted in significant reduction of manrem consumption, execution time and cost.

1. Introduction

Lasers have found a broad range of applications in material processing industry during the last few decades. Pulsed, quasi-continuous wave (quasi-CW) and CW operation of solid-state lasers is quite useful for many material-processing applications [1]. Nd:YAG lasers are quite versatile and commonly utilized solid-state lasers for various material processing applications such as laser cutting and welding. [2-7]. Solid-state and fiber lasers are quite useful in nuclear field applications as remotely controlled in-situ operations even at difficult to access constrained places as well as in presence of several nearby components is possible with these optical-fiber delivered lasers. In addition, laser operations produce less distortion and heat affected zones without affecting nearby components as precise amount of power or pulse energy can be delivered exactly at the required location and along the required trajectory through automated and precise control of position and speed of laser tool.

Considerable efforts are therefore directed towards the development of efficient, reliable and compact power supplies for pumping of different lasers finding use in these material processing applications and also towards development of laser tool controllers. Power supply systems for lamp pumped pulsed lasers having millisecond rectangular and complex current shape and continuous wave (CW) lasers with modulation as well as diode pumped CW fiber lasers are developed at RRCAT. The power supplies and laser tool controllers catering to various applications in nuclear field including repairs and refurbishment of nuclear reactors have been developed and utilized satisfactorily. The power supplies deliver electrical energy in the desired form to pump the laser and laser tool controllers positioning and driving the laser tool at the required parameters in the synchronized manner have been utilized to solve several problems in the nuclear field, which were either not possible or very difficult to solve, because of several practical complexities and complications, by conventional means. Their utilization has resulted in significant reduction of manrem consumption, execution time and cost.

Pulsed Nd:YAG lasers with millisecond duration are widely used for different material processing applications as they can provide high peak powers with sufficiently high pulse energy required for melting of different metals up to the depth of few mm [8]. A series of pulses each with different energy, duration and shape can produce a weld cycle for base metal pre-heating, initiate melting, welding, controlled solidification and weld cooling [1]. The penetration depth, melt area and porosity of spot welds are complex function of laser pulse energy, intensity, pulse duration and pulse shape [9]. Nd:YAG lasers with high pulse energy ($\geqslant$100 J) and pulse duration of the order of few milliseconds are highly useful in welding of metals and provide the advantage of localized heating with minimum heat affected zone as compared to CW lasers [7]. To meet different requirements of various material processing applications in the nuclear field, a pulse power source, which can deliver high current and high energy pulses of millisecond duration with adjustable pulse parameters over a wide range to flash lamp load was required to be developed [10].

Classically, pulsed flash lamps have been driven with a single-mesh RLC critically damped circuit [11]. A few circuits using multiple-mesh pulse forming network (PFN) have been explored for more strict control of the duration and to create output light pulses with flat tops [12]. In these schemes, the pulsed power source is realized by PFN charging source, PFN, control and discharging circuitry. Charging by using current limiting resistor/inductor, high leakage transformer, ferro-resonant transformer, voltage multiplier circuits, fly-back converter, DC resonant circuit are some of the schemes, which have been used [13,14]. These methods can be combined with the pulse transformer [15] and droop compensated PFN to deliver constant power to a wide range of loads with a proper load and transformer combination [16]. Partially activated PFN [15-17], modular PFN utilizing series/parallel operation of PFNs [18-21], sequentially switched inductor network using series and parallel switching schemes [22] have been explored to get flexibility in pulse parameter adjustment. With PFN based schemes, parameters can be tuned over a limited range only and the provision for tuning all the parameters is also not available in any single scheme. The third type of excitation circuits utilizes the active region of high-power transistors in class A or AB amplifier circuit to provide continuous adjustment of pulse parameters over a wide range [23], but efficiency of the system is low and also depends on pulse parameter values.

The output of different Nd:YAG laser beams have been combined to get rectangular modulated laser pulses and pulses superimposed on rectangular modulated laser pulses have been used to study the effect of various laser waveforms, which has led to better results in material processing applications [24].

A pulsed power supply based on switched mode buck converter operating in burst mode [25], has been developed at RRCAT, which can deliver rectangular current pulses through electrically non-linear flash lamp load with continuously adjustable pulse parameters viz., pulse current amplitude, duration and repetition rate over a wide range. Rise and fall times of the generated pulses are independent of the pulse duration. It can also deliver rectangular modulated complex shaped pulses having desired pulse shapes within a bandwidth of 200 Hz. In addition, a train of different shaped consecutive pulses can also be delivered as per the requirements.

In order to fulfill varied nature of requirements in nuclear field, different versions of power supplies, which can deliver average output power of 5 kW, 10 kW and 20 kW with peak output power up to 100 kW to each flash lamp load for single, dual or multiple flash lamp pumped lasers have been developed. These power supplies can feed electrical power to flash lamp pumped Nd:YAG lasers with average laser output power of 250 W, 500 W and 1 kW with corresponding peak power of 5 kW, 10 kW and 20 kW, respectively. A pulse power supply with low average output power of 500 W having peak output power up to 50 kW has also been developed for brachytherapy source assembly welding applications. Power supplies for arc lamp pumped modulated-CW Nd:YAG laser for deep penetration welding and diode pumped CW fiber laser have also been developed and are being utilized for the development of lasers for material processing applications. In addition, single mesh PFN based pulsed power supply for pulse duration of the order of 200 µs have been developed for laser shock peening and evaporation cutting applications. Power supplies of different power levels have been developed providing laser output power in the range of 25 W to 1 kW and have been commissioned as well as utilized satisfactorily for about twenty-five different material processing applications at various DAE units including NPCIL.

2. Power supply for flash lamp pumped pulsed 250 W average power Nd:YAG laser for laser cutting applications in refurbishment of nuclear reactors

Krypton filled flash lamps are widely used for optical pumping of high power long pulse (of the order of few ms) and continuous-wave (CW) Nd:YAG lasers for different material processing applications [13]. The load to the power supply is a water cooled krypton filled flash lamp, which is used as light source for pumping of the Nd:YAG laser medium. In cold conditions, the flash lamp offers very high impedance and behaves like capacitance of the order of 100-500 pF. A high-voltage trigger pulse is applied across the lamp for initiating the gas breakdown resulting into spark streamer between the electrodes.

The generated spark first establishes between one of the electrodes and the inside wall in proximity and then propagates all along the envelope up to the formation of an ionized channel linking the electrodes. The impedance of the lamp is lower with fill gas in ionized state [26].

To maintain a low impedance path for the main discharge, the simmer current is required to be established continuously between the two electrodes of the lamp. So, as soon as the flash lamp is triggered by high voltage pulses from HV-trigger supply, a simmer DC current discharge is established between the electrodes by simmer current source. The voltage across the lamp is about 110 to 130 V with simmer current of 500 mA. To achieve stable operation of lamp, the simmer current and voltage, are maintained to be in the negative region near the start of positive region of the voltage-current characteristic of the lamp. The benefit of simmer operation is improved pulse-to-pulse stability of laser output and the requirement of the high-voltage trigger pulse is avoided for every powering current pulse.

Once the simmer current is established in the flash lamp, impedance of the lamp is reduced from mega ohms range to hundreds of ohms range and it is ready to take up the main current pulse to pump the laser. To produce desirable laser pulses to meet the requirements of the material processing applications, need arises to have flexibility of pulsed discharge current generation through the flash lamp with programmable pulse parameters over wide range.

The HV-trigger and simmer current sources are based on full bridge series resonant converter operating at 100 kHz. The HV-trigger source generates 20 kV, 10 µs pulse to initiate ionization through the lamp. The simmer current source delivers simmer current upto 500 mA at output voltage of ~ 110 V. The open circuit voltage of the simmer current source is about 1500 V. A 12-pulse rectifier-based input stage fed from 3-phase 50 Hz AC supply charges input bulk capacitor bank of the close-loop controlled Buck converter-based DC to DC converter operating at 20 kHz with IGBT as a switch. The block diagram of the power supply is shown in Figure T.2.1.

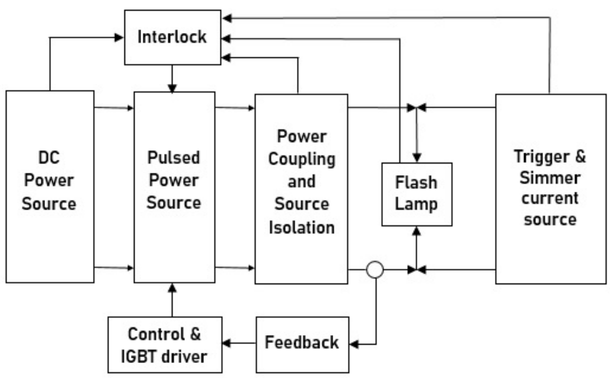


Fig. T.2.1: Block diagram of the power supply depicting major subsystems.

The system incorporates various interlocks and protections to protect against over-voltage, under-voltage, over-current, short-circuit, reverse phase sequence, single-phasing, over-temperature of coolant and obstructed or low coolant water flow rate. Brief specifications of the power supply are listed in Table T.2.1.

Table T.2.1: Specifications of the power supply for flash lamp pumped 250 W average power pulsed Nd:YAG laser.

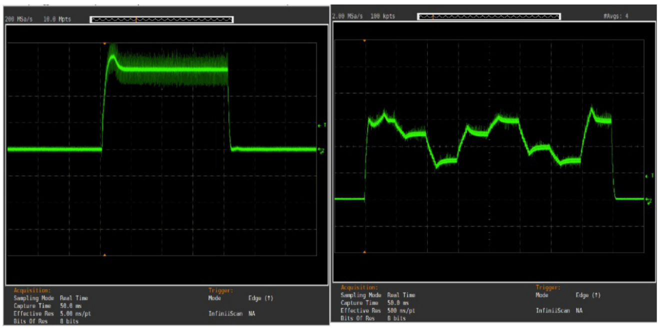
Parameter	Value
Input AC supply	400 V ±10%, 3-phase,
Average output power	5 kW
Peak output power	100 kW
Output pulse amplitude	110 to 300 A
Output pulse duration	2 to 40 ms
Output pulse repetition rate	0.5 to 100 Hz
Simmer current source	100 W, 0.5 A with no load voltage of ~ 1500 V
Trigger source	~ 20 kV, 10 µs

The photographs of internal and outer front views of the 5 kW power supply for flash lamp pumped 250 W average power pulsed Nd:YAG laser are shown in Figure T.2.2 (a) and T.2.2(b), respectively.

(a) (b)

Fig. T.2.2: Photographs of 5 kW power supply for flash lamp pumped 250 W average power pulsed Nd:YAG laser (a) internal front view, and (b) outer front view.

Figure T.2.3(a) and T.2.3(b) depicts rectangular and 8-segmented complex shaped temporal current profile through the flash lamp.



(a) (b)

Fig. T.2.3: (a) Rectangular flash lamp current pulse, and (b) 8-segmented temporal flash lamp current profile.

The power supplies, which can deliver average output power of 10 kW and 20 kW have been developed with peak output power up to 100 kW to each flash lamp load for dual and quad flash lamp pumped 500 W and 1 kW average power lasers, respectively. The input stage is designed to handle the required power, while modules for pulse power source of 5 kW, HV-trigger source and simmer current source have been developed and used for each flash lamp.

Power supply controllers have been developed for flash lamp pumped Nd:YAG laser power supplies. Each control channel monitors flash lamp load current and provides PWM signals for driving IGBT device of switching convertor in order to regulate the output current. These controllers can be used to control and operate one to four flash lamps pumped Nd:YAG laser with adjustable pulse parameters and with maximum average output laser powers from 250 W to 1 kW [27].

The power supply controller has been designed using microcontroller C8051F120 operating at 44.2368 MHz system clock. For all the channels, the analog reference voltage waveform is generated by using a 12-bit, serial digital to analog converter (DAC) TLV5618 and dedicated PWM controllers SG3525 have been used for error amplification, proportional-integral (PI) control loop implementation and PWM signal generation for switching devices of buck convertor based pulsed power supplies. The GUI provides user friendly interface using a WVGA color TFT display having resolution of 800 x 480 pixels, with resistive touch screen panel, interfaced on universal asynchronous receiver transmitter (UART) port of microcontroller using RS232 interface. It also allows the user to program the laser operation in rectangular pulse mode with adjustable pulse amplitude from 110 to 300 A, pulse duration from 2 to 40 ms and pulse repetition rate from 0.5 to 100 Hz. The GUI provides various notifications as well as fault indications visually with audible alert. The power supply controller units have been used with all the laser power supplies for various material processing applications at different DAE units including NPCIL.

3. Power supply for arc lamp pumped modulated-CW Nd:YAG laser system for laser welding applications

Modulated-CW Nd:YAG laser offers better welding performance due to increased weld speed, depth of focus and penetration with reduced thermal diffusion effects and weld porosity [28]. In order to fulfil the requirement of modulation of laser output power, a power supply capable of driving arc lamp with adjustable and regulated sine as well as square modulated output current in addition to DC current is designed and developed. The block diagram of the power supply is shown in Figure T.2.4.

The power supply is based on modular system architecture and consists of three major subsystems. Three units of 410 V, 4 kW single-phase power factor corrected (PFC) active rectifiers based on dual-interleaved boost converter operating at switching frequency of 70 kHz [29] forms low-harmonic, high-power-factor input AC to DC stage of the power supply.

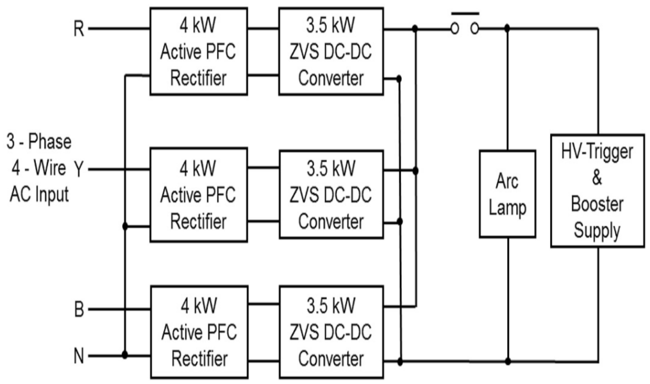


Fig. T.2.4: Block diagram of the power supply depicting major subsystems.

Output DC to DC stage of the power supply is realized by three units of 250 V, 3.5 kW phase-shifted pulse-width modulated (PWM) controlled zero voltage switching (ZVS) full-bridge DC-DC converters operating at switching frequency of 100 kHz having topological improvements leading to extension of ZVS operation upto no-load condition [30]. Power supply also consists of HV-trigger and booster supply as a start-up subsystem. HV-trigger supply provides multiple high-voltage (HV) pulses to cause initial ignition of the arc lamp and incorporates burst mode parallel triggering scheme [31]. Once the lamp is triggered, ionization of the filled gas is enhanced further by discharging pre-charged capacitor of booster supply through lamp. After sufficient reduction of lamp impedance, DC-DC converters can deliver DC current through it and take over the discharge to stable positive impedance region of the lamp electrical characteristics for establishing controlled operating condition. Outputs of the DC-DC converters are connected in parallel and collectively drives the arc lamp with adjustable DC output current upto 50 A as well as sine and square modulated output current upto peak value of 84 A to modulate the laser output power required for better laser welding performance. Key specifications of the power supply are listed in Table T.2.2. Figure T.2.5 gives view of complete 10 kW power supply.

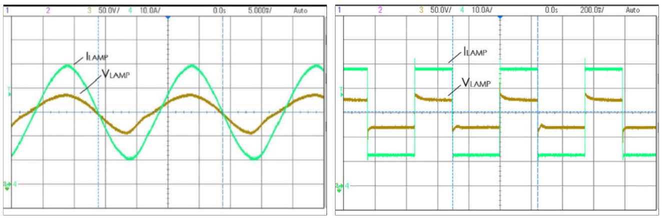
Table T.2.2: Specifications of the 10 kW arc lamp power supply for modulated-CW Nd:YAG laser.

Parameter	Value
Input AC supply	400 V ±10%, 3-phase
Input current THD	< 6%
Average output power	10 kW
Peak output power	20 kW
Output current modes	DC, sine modulated and square modulated
DC output voltage	200 V
DC output current	50 A
Peak output voltage	250 V
Peak output current	84 A
Modulation frequency	1 to 100 Hz

Fig. T.2.5: External view of the modulated-CW 10 kW laser power supply.

The power supply draws low-harmonic sinusoidal currents from input AC supply in compliance to IEC 61000-3-12 standard. Figure T.2.6 (a) shows waveform of input AC line currents along with phase voltage when power supply is delivering rated DC output power of 10 kW. Figure T.2.6 (b) and T.2.6(c) depicts arc lamp voltage and current with sine modulation at 50 Hz and square modulation at 2 Hz, respectively.

Two such units of 10 kW power supplies are developed and installed at ILAL, LTD, RRCAT, where single arc lamp pumped 500 W [32] and dual arc lamp pumped 1 kW modulated-CW Nd:YAG laser systems have been developed and work on their applications in high performance keyhole laser welding of thick stainless-steel components and other materials are in progress.



(a) (b)

Fig. T.2.6: Waveforms of voltage and current (a) with sine modulation at 50 Hz, and (b) square modulation at 2 Hz.

4. Power supply for flash lamp pumped pulsed Nd:YAG laser for laser shock peening and evaporation cutting applications

In pulse power applications, a capacitor charged to certain voltage represents a useful source of energy as an intense burst of energy in short time can be obtained by rapidly discharging it through the load. The pulse power supply system for the flash lamp pumped pulsed Nd:YAG laser and other solid-state lasers generally consists of a capacitor charging power supply (CCPS), capacitive energy storage, a pulse shaping device and a flash lamp trigger unit [13]. A pulse forming network (PFN) is a single or multi-mesh LC network, which performs both the functions of pulse shaping and energy storage. Block diagram of the 1830 V, 200 J, 5 Hz flash lamp pulse power supply incorporating input AC-DC stage, CCPS and single-mesh PFN along with HV-trigger and simmer power supply is shown in Figure T.2.7.

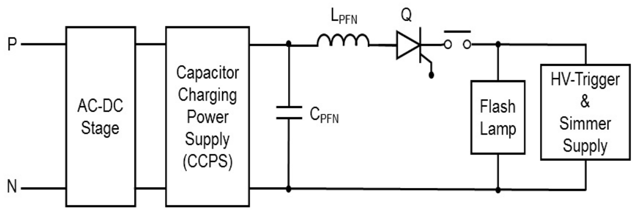


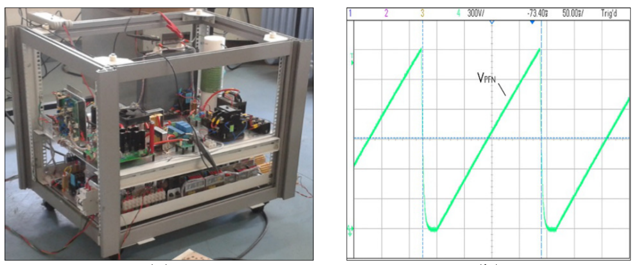
Fig. T.2.7: Block diagram of the 1 kW power supply for flash lamp pumped pulsed Nd:YAG laser.

CCPS is based on zero voltage switching (ZVS) full-bridge LCL-T resonant converter operating at constant switching frequency of 100 kHz and employs constant current capacitor charging. LCL-T resonant converter has got unique property of behaving as a current source, when operated at resonant frequency [33]. Under this condition, output current is constant irrespective of changes in the load if input voltage is constant. It also provides high efficiency due to soft switching, small size due to high frequency operation, low electromagnetic interference (EMI) due to sinusoidal waveforms and beneficial utilization of transformer leakage inductance by absorbing it into resonant network. Furthermore, inherent load independent constant current charging of the PFN capacitor eliminates the need of sensing and control of charging current and represents the most efficient method of energy transfer from power supply to the capacitor. HV-trigger and simmer supply is required to create as well as maintain the ionization of the flash lamp, so that the main discharge can occur. HV-trigger supply provides high voltage (HV) pulse of about 20 kV, 10 µs to ignite a gas breakdown and cause initial ionization of the flash lamp.

After triggering, simmer supply with no-load striking voltage of 1500 V maintains ionization of the flash lamp by continuously flowing DC current of about 400 mA through it. Simmering of the flash lamp not only helps in minimizing the EMI by avoiding HV triggering of flash lamp at every power pulse, but also provides higher conversion efficiency, improved pulse-to-pulse stability as well as longer flash lamp life [34]. Simmer supply is based on resistive ballast-less scheme and implemented by ZVS full-bridge series resonant converter operating in above resonance mode [35]. Key specifications of the power supply are given in Table T.2.3.

Table T.2.3: Specifications of the 1 kW flash lamp power supply.

Parameter	Value
Input AC supply	230 V ±10%, 1-phase,
PFN charging voltage	500 V to 1830 V
PFN type	Single-mesh
PFN capacitance, C_{PFN}	120 µF
PFN inductance, L_{PFN}	38 µH
Peak discharge current	1200 A
Discharge current pulse width	220 µs
Repetition rate	1 Hz to 5 Hz
Max. energy per pulse	200 J
HV- trigger pulse	~ 20 kV, 10 µs
Simmer current	300 mA to 500 mA



(a) (b)

Fig. T.2.8: (a) Inside view of the integrated pulse power supply, and (b) waveform of PFN energy storage capacitor voltage.

Once the PFN energy storage capacitor, C_{PFN} is charged to required voltage corresponding to desired energy by the CCPS, firing of the SCR, Q is initiated and stored energy of the capacitor is delivered to the flash lamp through the PFN inductor, L_{PFN} in the form of current pulse. Figure T.2.8(a) shows inside view of assembled power supply, whereas Figure T.2.8(b) depicts the PFN capacitor voltage waveform, when it is charged to 1830 V with repetition rate of 4.6 Hz. Linear charging profile of the capacitor voltage signifies constant current charging. The developed power supply is installed and has been operational at ILAL, LTD, RRCAT for the development of free running as well as Q-switched version of the flash lamp pumped pulsed Nd:YAG laser system having potential applications in laser shock peening based surface treatment as well as evaporation cutting of different materials.

5. Power supply for flash lamp pumped pulsed 25 W average power Nd:YAG laser for laser welding of brachytherapy source assembly and cutting of steam generator tubes

Brachytherapy is an internal radiation therapy in which the radiation source is placed inside the body of the patient to kill cancer cells and shrink tumors. It is a very effective method for treating tumors in eye (retinoblastoma) and prostate cancer [36,37]. The radiation source is encapsulated in a tiny capsule of titanium with dimensions of 4.75 mm (*l*) x 0.8 mm (ϕ) [37] and wall thickness of ~ 50 µm. It is extremely difficult to carry out welding of the source assembly by conventional welding methods. Thus, pulsed laser welding method with pointed Nd:YAG laser beam has been adopted to have minimum heat affected zone (HAZ) and also to avoid physical damage to radioactive sources [38].

The block diagram of the power supply is shown in Figure T.2.9. The single-phase AC mains of 230 V, 50 Hz feeds the boost converter based power factor correction (PFC) module through an EMI filter to improve the input power factor and comply with IEC 61000-3-2 standard. The output of 370 V DC from PFC module feeds the half bridge converter based capacitor charging source with converter switching at 100 kHz. It charges the capacitor bank of 23 mF to a voltage level adjustable from 300 V to 500 V. The pulsed power source is realized by buck converter operating in burst mode using IGBT switching at 20 kHz. The HV-trigger and simmer current sources trigger to initiate the flash lamp and maintain a simmer current of about 400 mA through it. Key specifications of the power supply are listed in Table T.2.4.

Table T.2.4: Specifications of the 500 W pulsed power supply.

Parameter	Value
Input AC supply	230 V ±10%, 1-phase
Input current THD	≤ 10%
Average output power	500 W
Peak output power	50 kW
Pulsed output current	80 to 150 A
Pulse width	4 to 12 ms
Repetition rate	1 Hz to 4 Hz
Max. energy per pulse	500 J
HV- trigger pulse	~ 20 kV, 10 µs
Simmer current	~ 400 mA

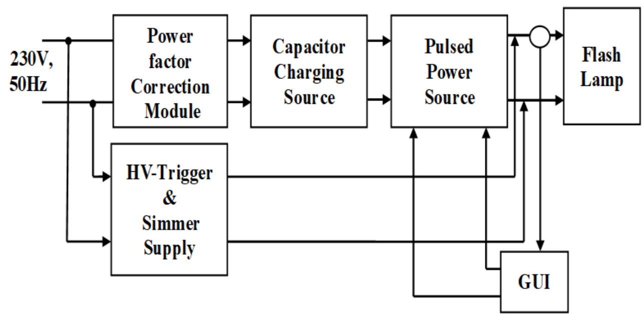


Fig. T.2.9: Block diagram of 500 W pulse power supply.

Fig. T.2.10: External view of the laser system installed at RPhD, BARC with current pulse waveform.

Figure T.2.10 shows the laser system installed at RPhD, BARC and also depicts the pulsed lamp current. Iodine-125 low dose rate (LDR) brachytherapy sources welded at RPhD, BARC have been used for brachytherapy of more than fifteen eye cancer patients at different hospitals [36]. Patients have also been treated for prostate cancer using a permanent implantation of 50 to 100 Nos. of Iodine-125 LDR sources [37].

Two more power supplies with similar specifications have been developed with current pulse profile tuned and optimized for laser welding and cutting applications. One is for welding of iridium (Ir-192) high dose rate (HDR) brachytherapy sources for treatment of lung, liver and throat cancer. This system has been installed at BRIT, Mumbai. Other power supply is for cutting of 1 mm thick SS steam generator (SG) tubes. The system has been installed at ILAL, LTD and utilized for development of the laser system and optimization of parameters for cutting of steam generator (SG) tubes.

6. Laser diode power supply for 1 kW diode pumped fiber laser system

Laser diode pumped fiber lasers fall in the category of most efficient laser systems, do not involve high voltages, have zero moving parts, are free from misalignment and are most rugged systems [36-39]. The power converter based current source drives a regulated current with low ripple through multiple high-power laser diodes (LDs) connected in series, each typically emitting 160 W of laser power at 915 nm. The Yb-doped glass fiber, which is the lasing medium, is pumped by these LDs simultaneously through a combiner.

With the electrical input to output efficiency of power supply about 93%, electrical to optical efficiency of laser diodes being 48% [39] and optical to optical slope efficiency of fiber laser being 76% [40] leads to a wall plug efficiency of ~33 %. Thus, a power supply for diode pumped 1 kW Yb-doped 1080 nm fiber laser has been designed and developed to deliver 3 kW output power at 270 V and 11 A of output voltage and current, respectively. The block diagram of the power supply is shown in Figure T.2.11.

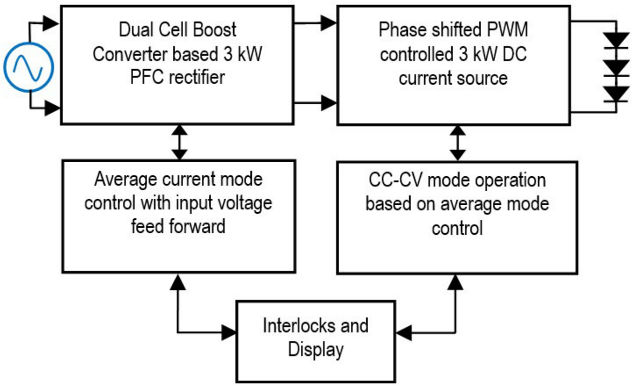


Fig. T.2.11: Block diagram of the power supply depicting major subsystems.

The power supply consists of two stages viz., (a) a 3.3 kW PFC rectifier based on dual cell interleaved boost converter in continuous conduction mode (Figure T.2.12) and (b) a modified phase-shifted PWM DC-DC converter rated for 3 kW. The PFC converter [29] with switching frequency of 70 kHz employs dust cores for twin boost inductors, low gate charge COOLMOS MOSFET as power switches undergoing soft-switching at turn-off and SiC Schottky diode as boost diodes. It generates a regulated 410 V ± 10 V DC link voltage to feed the 3170 W downstream DC-DC converter that is configured as a current source. The average-mode controlled DC-DC converter ensures ZVS operation of power MOSFETs at turn-on as well as turn-off from no load to full load condition [30]. The power supply is housed in 10U, 19" standard rack. Key specifications of the power supply are listed in Table T.2.5.

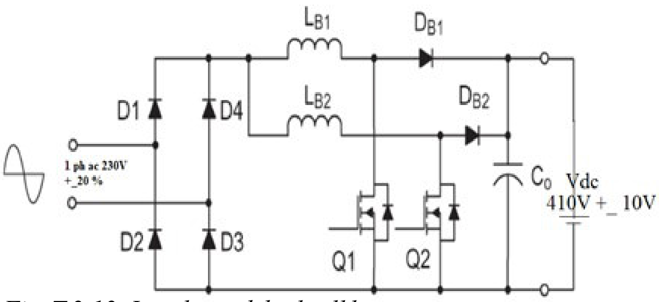
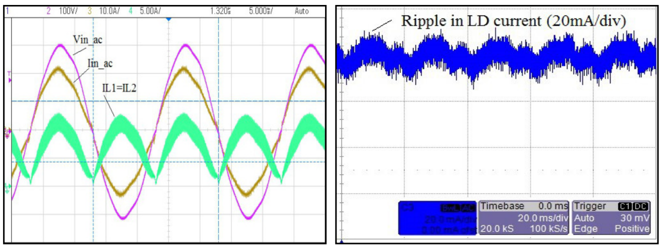


Fig. T.2.12: Interleaved dual cell boost converter.

Table T.2.5: Specifications of the 3 kW power supply for laser diode pumped fiber laser.

Parameter	Value
Input AC supply	230 V ±20%, 1-phase
Input current THD	<6%
Average output power	3 kW
DC output current	1 A to 11 A
Current ripple	20 mA pk-pk @ 11 A load
8-hour stability; CC mode	15×10^{-5}
Line regulation: -20% to +20% input voltage	<4 mA
DC Output compliance voltage; CV mode	270 V maximum
Efficiency at 230 Vac input & full load	93%

The power supply draws near sine current from single phase AC utility mains and complies with IEC-61000-3-2 standards. Figure T.2.13(a) depicts the input AC voltage, input current and inductor current of either cell. Fig. T.2.13(b) shows ripple level measured in LD current. The LD power supply has been installed at ILAL, LTD, RRCAT and integrated with LD pumped 1 kW fiber laser lasing at 1080 nm. It has been in continuous use and working satisfactorily.



(a) (b)

Fig. T.2.13: Waveforms depicting (a) input AC voltage, input current and inductor current of either cell, and (b) ripple level in LD current.

7. Tool controllers for laser based material processing applications at different units of DAE and nuclear reactor sites

7.1. Introduction

Requirement of laser-based material processing applications in nuclear reactors and different units of DAE has increased significantly during last one decade. For laser-based material processing applications, position and movement of the tool or the job is required to be controlled as per the process requirements and in synchronizm with power supply and laser system along with implementation of suitable operational as well as safety interlocks. The tool controller basically comprises of a microcontroller-based control circuitry, motor driver and user interface with touch screen display. Various tool controllers have been designed and developed to meet requirements of material processing applications at different units of DAE and nuclear reactor sites, which are briefly described as below:

7.1.1 Tool controller for laser cutting of bellow-lip weld joints for EMCCR

In PHWRs en-masse coolant channel replacement (EMCCR) campaign is carried out in about 15 years to replace all the pressure tubes. Indian 220 MWe PHWRs have 306 coolant channels placed very close to each other. These coolant channels can be replaced without damaging the bellows, if the welded bellow rings are detached at the weld joint.

A tool controller for cutting of bellow-lip weld-joint has been designed and developed around dsPIC33FJ256MC710, a 16-bit microcontroller. The user interface is designed on a 7" touch display. The system operates in two different modes viz., tool testing mode and laser flash mode. Tool testing mode is an independent mode, where tool movement can be checked for any obstruction in the cutting path. In laser flash mode, tool controller is synchronized with the power supply controller for operation related to tool movement, power supply and laser pulses. The block diagram of the tool controller depicting major subsystems is shown in Figure T.2.14. Key specifications of the tool controller are listed in Table T.2.6.

Four units have been successfully deployed for laser-based cutting of bellow-lip weld joints of all the coolant channels at KAPS-2, and KAPS-1, Kakrapar during EMCCR campaigns.

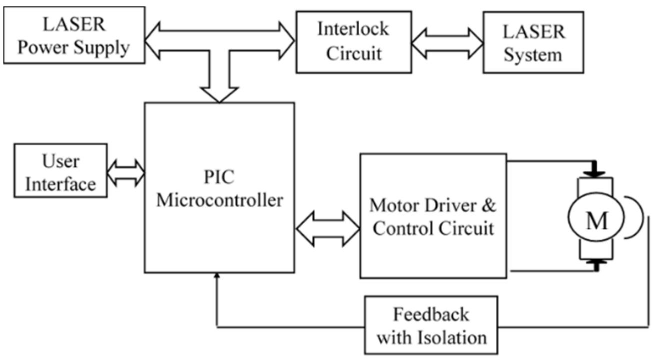


Fig. T.2.14: Block diagram of the tool controller depicting major subsystems.

Table T.2.6: Specifications of the tool controller.

Parameter	Value
Input AC supply	230 V ±10%
Tool speed (rpm)	0.05 rpm to 0.4 rpm; Resolution: 0.1 rpm
Round trip count	1 to 5; Resolution: 1
Overlap degree	Up to 30 degree; Resolution: 1 degree
Direction	CW and CCW
Cutting delay time	250 ms to 3.5 s; Resolution: 0.25 s
Modes	Tool testing mode Laser flash mode
Interlocks	Gas valve position, Tool obstruction detect, PS synchronization
Display	7" Touch screen

7.1.2 Tool controller for in-situ laser cutting of triangular blocks of yoke assembly at RAPS-3

The shock absorber assemblies of PHWR coolant channels have a provision for axial creep adjustment. The two halves of yoke assembly, which holds coolant channel, is tightened using 18 mm thick triangular blocks at RAPS-3. It was required to remove the apex part of triangular blocks to increase creep margin by 18 mm resulting in extension of the coolant channel by about 9 years. A multi-pass laser grooving method was adopted to remove the block with cutting in an arc shape to remove molten material. The material at the ends was able to remove easily, but at the center, a larger number of cutting operation rounds was required. Thus, a triangular block cutting tool controller was designed and developed with sector based cutting facility. The system can operate two different nozzle mounted tools for laser cutting in different directions viz., left-side or right-side cutting direction depending on the location of the obstructions for the motion of the tool. The user can select among different modes viz., Auto mode, Manual mode and Sector-scan mode.

The manual mode is provided for alignment of the laser tool and the job. In auto mode, user can set the angular position, number of rounds and return waiting time. Tool starts from its default position, completes set number of cutting cycles within the extreme limits and returns to its home position or default position.

In sector-scan mode, user can set parameters like cutting sector, size and number of scans. The user interface is designed on a 5.7" touch display. The speed and position control of the motor has been achieved by using the optical encoder output from the motor as feedback to the microcontroller.

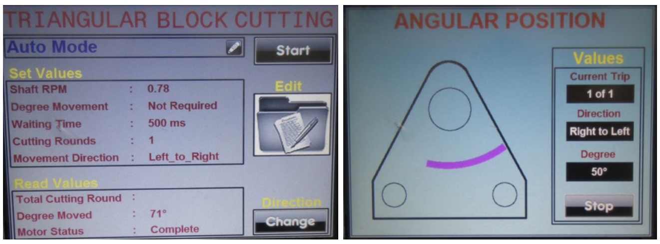


Fig. T.2.15: Screen shots of different screens of tool controller.

The tool controller unit has been successfully utilized for laser-based cutting of 56 triangular blocks of coolant channels in four different cutting campaigns during biannual shutdown periods at RAPS-3.

7.1.3 Tool controller for water-jet assisted underwater cutting of flared fuel tubes at Dhruva, BARC

Spent fuel tubes of Dhruva reactor lying at the bottom of spent fuel storage bay (SFSB), were required to be cut underwater at a depth of 7 m using laser, to extract spent fuel pellets and other radioactive materials before storing the remaining nuclear waste appropriately. A tool controller for this operation has been designed and developed using dsPIC33FJ256MC710 and 5.7" touch screen display.

The shaft rpm can be adjusted from 0.04 rpm to 0.5 rpm with resolution of up to 0.01 rpm accordingly with different settings of fuel bundle diameter and motor gear selection. The motor parameters like angular position can be set from 1° to 360° in steps of 1°, round-trip count from 1 to 5, fuel tube diameter from 50 mm to 70 mm. The position and speed control of the motor has been achieved by using the optical encoder output from the motor as feedback to the system.

A total of twelve spent fuel tubes, made of 2.5 mm thick aluminium, lying underwater at the bottom of SFSB have been cut successfully.

7.1.4 Tool controller for in-situ laser cutting of single selected coolant channel

In reactor operation, it is sometimes required to remove single selected coolant channel for post irradiation examination or other purposes, while keeping all other channels intact. The cutting operation is to be carried out in presence of all other nearby components. For execution of this operation, first of all liner tube, which is present inside the coolant channel, is required to be removed followed by cutting of the end-fitting and bellow-lip weld-joint. Thus, the system operates in three modes to operate different tools required for cutting of liner tube, end fitting and bellow-lip weld joint in the required order. All the modes have different settings and ranges of parameters viz., tool rpm, cutting rounds, direction and overlap degree for optimized operation. The motor is brought to halt when the required position, round trip and overlap angle is achieved. The tool controller operates in synchronization with power supply and laser system for laser cutting.

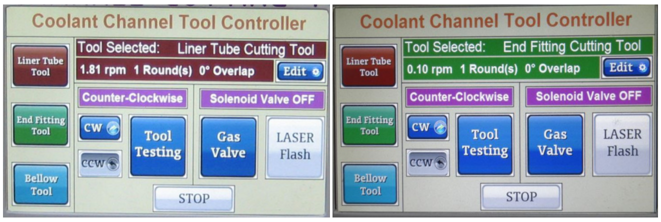


Fig. T.2.16: Screen shots of different screens of single selected coolant channel tool controller.

The controller has been developed, installed and integrated with laser cutting system at ILAL, LTD, RRCAT.

7.1.5 Tool controller for welding of fuel pins at IFFF, BARC

The system is designed around PIC18F8722, 8-bit microcontroller with stepper motor driver and control along with a user-friendly interface on a 5.7" display. The system operates in different modes viz., remote-mode, tool-testing-mode and laser-flash-mode and incorporates operational safety interlocks related with laser power supply controller and gas valve operation. User can set different parameters like shaft rpm, tool rounds, overlap degree and change the direction of motion of the laser welding tool. The shaft rpm can be varied from 0.125 to 5 rpm in steps of 0.125 rpm. The welding rounds can be varied from 1 round to 3 rounds and overlap from 10° to 130° in steps of 10°.

The tool-testing-mode is for identifying and correcting any irregularities during motion of the tool. To operate the welding system in the remote-mode, a control panel is designed with different instruments mounted for fixed sequence of operation. The user interface simulates the movement of the laser cutting tool during the welding operation to give visual indication of the progress of the operation. In both remote-mode and laser-flash-mode, the laser pulses are stopped on completion of the set process or on detection of any obstruction to the tool movement with suitable indication of completion or obstruction on the screen.

7.1.6 Tool controller for welding of brachytherapy capsule assembly at RPhD, BARC

Treatment of ocular cancer requires tiny sources of dimension 4.5 mm (l) x 0.8 mm (φ), which are made by adsorption of radioiodine (^{125}I) on palladium-coated silver rods to provide 3 to 4 mCi of dose [38]. The wall thickness of the titanium encapsulation is only 50 µm and thus its welding is difficult to be carried with conventional welding methods [38]. As the wall thickness of the capsule is only 50 µm, the cap of the capsule is to be spot welded at different locations around the periphery before the actual laser welding operation is carried out. To meet the requirements of low tool speed in the range of 1.8° per second to 36° per second, stepper motor is used for precise control. Three modes of operation for tool testing, spot marking and laser flash welding have been designed and implemented for meeting different requirements of laser welding.

The tool controller for laser welding of small capsule joints has been designed using an 8-bit microcontroller, PIC18F8722. The interlocks for synchronization with the laser power supply controller and the welding tool have been incorporated in addition to the 5.7" touch-panel based user interface. Different tool parameters that can be adjusted are number of spot counts, spot position angle, tool speed, number of welding rounds, tool overlap degree and tool movement direction. Key specifications of the tool controller are listed in Table T.2.7.

Table T.2.7: Specifications of the tool controller.

Parameter	Value
Input AC supply	230 V ±10%
Tool speed	1.8° to 36°/s
Round trip count	1 to 3
Overlap degree	Up to 130°
Modes	Spot marking, Tool testing & Laser flash
Spot anble/count	0°, 90°, 120°, 180° (1 to 4)
Display	5.7" touch based

Tool testing mode is for checking the operation and alignment of the laser welding tool with respect to brachytherapy capsule without inert gas flow and laser pulses. In spot marking mode, user can select either the number of spot counts or spot position angle.

The number of spot count can be selected from 1 to 4 and spot position angle from 4 options of 0°, 90°, 120° and 180°. These spot marking are carried out before the actual laser welding operation to securely hold the tiny cap on the capsule at the required position during the welding operation. In this mode, the gas flow through the nozzle is required. Once the gas flow is established, the laser pulses can also be initiated by activating the laser flash mode. The tool controller is synchronized with the power supply controller.

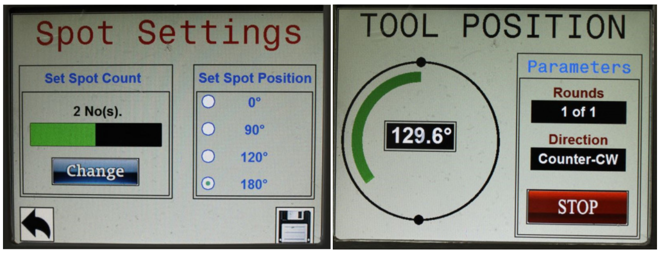


Fig. T.2.17: Screen shots of different screens of welding tool controller for I-125 brachytherapy capsules.

The system has been installed at RPhD, BARC and welding of brachytherapy Iodine capsules is being carried out satisfactorily.

8. Deployment of laser power supplies and tool controllers at various DAE units and NPCIL sites

Developed laser power supplies and tool controllers have been installed at different units of DAE and nuclear reactor sites and utilized successfully for following major applications [41]:

1. Laser cutting of bellow-lip weld joints of all the coolant channels as a part of EMCCR at KAPS-1, KAPS-2, NAPS-1 and NAPS-2 reactors.
2. Cutting and removal of single selected coolant channel at TAPS-4, KAPS -1&2, KGS-1 and RAPS-4 reactors.
3. Under-water pressure tube stub cutting at TAPS-4, KAPS-1&2, KGS-1 and RAPS-4 reactors.
4. Cutting of triangular blocks for extension of life of 28 coolant channels of RAPS-3 reactor during four different campaigns.
5. Cutting of rear nuts of shock absorber assembly at RAPS-3
6. Cutting of high-pressure feeder coupling studs at NAPS-1 raector.
7. Cutting of secondary shutdown system pipeline at KKNPP-1 reactor.
8. Laser cutting and removal of steam generator (SG) pulling bolt at RAPS-6.
9. Cutting of FBTR fuel subassembly at IGCAR for post irradiation examination (PIE).
10. Laser cutting of thoria bundle end-plates at PRTRF, BARC.
11. Laser cutting of PHWR Zr-pressure tubes (pyrophoric) at MAPS-1 for easy storage.
12. Laser cutting of SG tubes at KKNPP-2.
13. Underwater water-jet assisted laser cutting of flared aluminum fuel tubes lying at bottom of SFSB of Dhruva reactor.
14. Power supply for 800 W Nd:YAG laser for laser rapid manufacturing applications at MSD, BARC.
15. Development of laser welding system for brachytherapy source assemblies for BRIT, Mumbai.
16. Illumination system for imaging to detect and locate leak in the end-shield of MAPS-1.
17. Motion control system for non-contact in-situ sag measurement of calandria tubes at KAPS-1.
18. Laser welding of SCRF cavities at Cryomodule Development & Cryoengineering Application Section, RRCAT.
19. Laser welding of fuel-pins at IFFF, NFG, BARC.
20. Laser welding of PFBR fuel-pins at FF, BARC, Tarapur.
21. Development of CW Nd:YAG laser with sine and square wave super modulation at ILAL, LTD, RRCAT for laser based deep penetration welding.
22. Brachytherapy source assembly welding at RPhD, BARC for treatment of cancer.
23. Development of laser diode pumped 1 kW fiber laser operating at 1080 nm wavelength at ILAL, LTD, RRCAT.
24. Development of laser-based evaporation cutting system at ILAL, LTD, RRCAT.

9. Conclusion

Power supply systems for lamp pumped pulsed lasers delivering millisecond rectangular and complex shaped pulses and continuous wave (CW) lasers with modulation as well as for diode pumped CW fiber lasers have been developed at RRCAT. Utilization of these power supplies and the laser tool controllers in various material processing applications at different units of DAE and NPCIL sites including maintenance and refurbishment of nuclear reactors has resulted in significant reduction of manrem consumption, execution time and cost. Further efforts are being put in to develop power supply systems for further higher power solid-state and fiber lasers with input stage incorporating power factor correction to reduce the pollution of electrical line input and also to develop laser systems for higher cutting thickness and welding depths to meet ever increasing and challenging requirements from different units of DAE including NPCIL.

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