T.2: High power solid state lasers for nuclear field applications

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Abstract

RRCAT has developed different versions of high power continuous wave (CW) and pulsed Nd:YAG lasers and fiber lasers of high efficiency and good beam quality for different material processing applications in nuclear field. The high peak power laser output is delivered through small diameter optical fibers for metal processing and also for remote operation. Special tools, fixtures and miniaturized nozzles have been developed and these along with the lasers have been used extensively for refurbishment of nuclear power reactors and medical applications. Over past several years, innovative laser material processing techniques including under water water-assisted cutting, thick plate cutting, miniature welding, etc. have been developed and successfully deployed in Indian nuclear power plants and nuclear field. Development and deployment of laser technology has solved several complex problems, which were not possible by conventional means and has also significantly reduced man-rem consumption, time and cost.

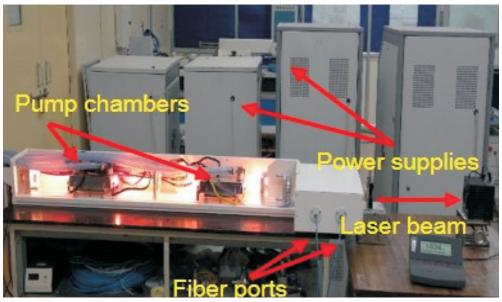
1. Introduction

High power Nd:YAG and fiber lasers with beam delivery through optical fibers have been well established as pointed thermal heating source for different material processing applications. CW Nd:YAG as well as fiber lasers are used for laser material processing as they provide high cutting and welding speed. Pulsed Nd:YAG lasers with millisecond (ms) duration provide high peak powers and pulse energies, which are sufficient for melting of metals up to larger depths of a few mm to tens of mm. The heat affected zone (HAZ) and thermal distortions are small as compared to their CW counterparts. Thus, pulsed Nd:YAG lasers are preferred over CW Nd:YAG lasers for good quality of cutting and welding. Further, ms pulsed lasers are easy to construct and can be built at a lower cost as compared to similar peak power CW lasers. In view of this, research and development on lamp pumped ms pulsed Nd:YAG lasers have been carried out and three different versions of 250 W, 500 W and 1 kW average power Nd:YAG lasers with corresponding peak powers of 5 kW, 10 kW and 20 kW have been developed.

For nuclear field applications [1,2], it is significantly important to deliver the beam through flexible optical fibers, so that in-situ remote processing becomes possible and laser beam can also reach to space restricted intricate locations in nuclear power plants. In order to generate high peak power density on the job, beam delivery through smaller diameter optical fibers is preferable, which in turn requires generation of good quality laser beams with best possible beam parameter product or M^2 value and stable operation of laser over a large range of input pump power. Initially, 250 W average power Nd:YAG laser was designed using gold coated elliptical reflectors and laser resonator was optimized to provide stable operation with beam quality good enough for delivery through 400 µm core diameter optical fibers [3]. In this laser, initially plane-plane symmetric resonator was designed, which showed poor misalignment sensitivity and pulse-to-pulse stability. Thus, a concave-plane hemispherical resonator was designed with rear mirror having 5 m radius of curvature to provide better misalignment sensitivity and pulse-to-pulse stability. The laser flash lamp is powered by indigenously developed power supply of 5 kW average electrical pump power. This laser provides maximum pulse energy of 100 J with variation in pulse duration in the range of 2-20 ms, maximum peak power of 5 kW and pulse frequency in the range of 1-100 Hz. Electrical to laser conversion efficiency was also maximized to a value of 5% by optimizing cooling water flow rate, using krypton filled flash-lamps in place of xenon filled flash-lamps and using samarium glass filter between rod and lamp, which converts unwanted ultraviolet (UV) radiation emitted from flashlamp to radiation in the pump spectral band of Nd:YAG rod. This efficiency is on higher side as compared to that from typical flash-lamp pumped systems available commercially.

Further, average output power was enhanced to 500 W by using two Nd:YAG laser rods and optical heads in a single resonator with special design of plane-plane rod imaging configuration [4]. However, due to longer length of resonator, misalignment sensitivity of the laser was found to be poor. In view of this, a ceramic reflector based dual lamp pump chamber and resonator was designed to generate 500 W of average power. This laser provides a maximum peak power of 10 kW at 20 ms pulse duration and maximum pulse energy of 300 J at 40 ms pulse duration with variation in pulse duration in the range of 2-40 ms and pulse frequency in the range of 1-100 Hz. The electrical to laser conversion efficiency was maximized to 5% and beam quality was maintained, to deliver it through 400 µm core diameter optical fibers [5]. The gold coated reflectors have to be refurbished periodically since the gold coating peels off with time. It is significantly important that ceramic reflectors provide a much longer life of more than five years as compared to gold coated elliptical reflectors, which make the system more reliable in long term operations. The laser pump chamber of 500 W average power laser was designed to incorporate two flash lamps in single Nd:YAG housing. This led to compact laser size, however, the beam quality was slightly poor as compared to 250 W average power Nd:YAG laser due to enhanced thermal lensing. The laser beam was good enough for coupling through optical fiber of 400 µm diameter. The average output power was further enhanced to 1 kW level by using two dual lamp pump chambers in a single resonator in rod imaging configuration. Peak power was enhanced to a maximum of 20 kW at 20 ms pulse duration and pulse energy to a maximum of 600 J at 40 ms duration, while maintaining beam quality, so that it is again possible to deliver the beam through 400 µm core diameter optical fibers [6,7]. The Nd:YAG lasers of 250 W, 500 W and 1 kW average power Nd:YAG lasers are capable of cutting of 18 mm, 25 mm and 35 mm thick steel sheets and welding up to depths of 2 mm, 4 mm and 6 mm, respectively. Figure T.2.1(a) shows a view of indigenously developed ceramic reflector based 1 kW average power and 20 kW peak power pulsed Nd:YAG laser [6]. Figure T.2.1(b) shows laser cutting of 35 mm thick SS plate using 1kW average power Nd:YAG laser and Figure T.2.1(c) shows laser cut sample of 35 mm thickness. About 25 number of different versions of Nd:YAG lasers have been deployed at different DAE units for different applications. The Nd:YAG laser consists of discrete resonator components involving pump chambers and two resonator mirrors, which are placed apart by ~ 1 m separation and aligned highly parallel to each other to achieve maximum laser output and efficiency. Even a small misalignment of the resonator mirrors results in huge reduction in output power. The tuning of the laser resonators is required over a period of time. Further, these lasers need to be tuned in case of transportation from one place to another.

In view of misalignment issues, now a days, fiber lasers with all fiber monolithic integration and single mode output are gaining more popularity due to in-built fiber Bragg grating mirrors, which makes them free from any misalignment and are highly rugged. The schematic of typical fiber laser is shown in Figure T.2.2(a). The laser medium is Yb-doped glass fiber and can be pumped by laser diodes operating at wavelength of 915 / 975 nm. The pump diodes are coupled to the gain fiber by pump to signal beam combiner as shown in the figure. HR indicates the high reflecting mirror at the lasing wavelength and is transparent to pump wavelength. The individual components are available commercially and are spliced together using a state of art splicing machine. The splice joint should be free of scattering center and highly transparent to avoid burning or damage during high power laser operation. There are no moving parts in this laser and it is completely sealed off, thus it is highly rugged and preferred for commercial operations. Due to the full absorption of pump beam in the gain medium, the fiber lasers are highly efficient. We have initiated R&D on development of state of art high power CW and pulsed fiber lasers. Significant progress has been made in this regard and recently, an engineered version of 250 W output power Yb-doped CW fiber laser has been developed and installed at R&D NPCIL, Tarapur for cutting of thin sheets of up to 5 mm and welding of up 1 mm thick SS [8]. Further, development of up to 700 W of single mode CW output from Yb-doped fiber laser with ~76% of optical-to-optical slope efficiency has been carried out and its engineered version is underway [9]. Figure T.2.2(a) shows schematic of 250 W Yb-doped CW fiber laser and Figure T.2.2(b) shows a view of compact packaged version of 250 W fiber laser installed at R&D NPCIL, Tarapur.



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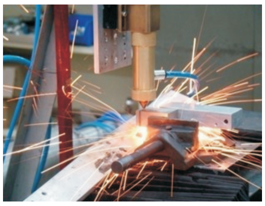
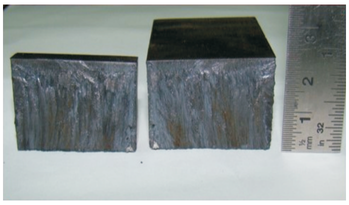
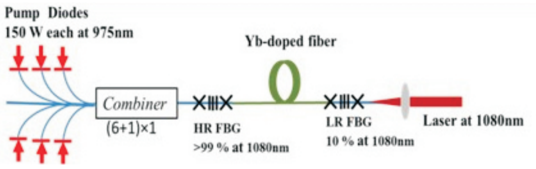




(b) (c)

Fig. T.2.1: (a) A view of indigenously developed ceramic reflector based 1kW average power Nd:YAG laser, (b) laser cutting of 35 mm thick SS plate using 1 kW average power Nd:YAG laser, and (c) laser cut sample of 35 mm thickness.



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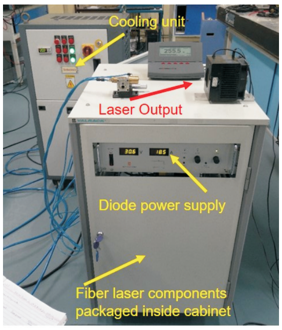


(b)

Fig. T.2.2: (a) Schematic of the indigenously developed 250 W Yb-doped CW fiber laser, and (b) a view of compact packaged version of indigenously developed 250 W Yb-doped CW fiber laser.

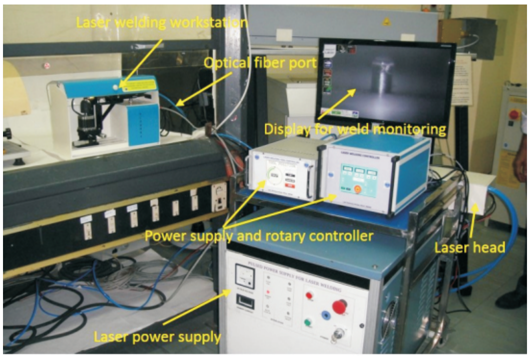
The indigenously developed Nd:YAG lasers have been extensively deployed for refurbishment of nuclear power reactor and applications in nuclear filed. A brief description of some of the applications of Nd:YAG lasers in nuclear field is mentioned in the following section and sub-section of this article.

2. Nuclear field applications

2.1. Nd:YAG laser system for welding of iodine-125 brachytherapy sources

For treatment of tumors such as ocular melanoma and retinoblastoma, radioisotope sources of low energy such as ^{103}Pd, ^{125}I, and ^{106}Ru are being used worldwide. For their complete remission, these tumors are treated with low energy radiation sources. While designing the encapsulation for these radioactive sources, factors such as mechanical strength and environmental conditions under which the source is likely to be used is carefully evaluated. Pure titanium metal encapsulation is normally used for sealing of these sources, since titanium is a light weight metal and is also body adoptive. Radiopharmaceutical Division (RPhD), BARC has already developed indigenous technology for production of ^{125}I brachytherapy sources for the treatment of ocular cancer patients in India. For treatment of ocular cancer, tiny sealed sources of dimension 4.75 mm (*l*) x 0.8 mm (φ) are made by adsorption of radioiodine (^{125}I) on palladium-coated silver rods to incorporate 3-4 mCi of radioactivity. Since wall thickness of titanium encapsulation is only 50 μm, its welding is not possible by conventional welding methods due to broader heat source and larger heat affected region. Thus, pulsed laser welding method is adopted, which provides less heat affected zone, good weld quality and does not damage radioactive source. Encapsulation of these ^{125}I sources was earlier being done at RPhD, BARC using pulsed Nd:YAG laser welding since past several years using an imported system. Weld qualification for medical application is being carried out as per Atomic Energy Regulatory Board norms. The costly imported laser system has aged and has become prone to failures. Thus, in order to have redundancy and non-stop production of such sources for society, we have indigenously developed and installed a trolley mounted compact fiber coupled pulse Nd:YAG laser system with a maximum of 12.5 J pulse energy, 2-12 ms pulse duration and 1-4 Hz repetition rate along with a laser welding workstation for production of these brachytherapy sources in close collaboration with RPhD, BARC [10].

The laser welding workstation consists of a self-centered rotary chuck, which holds a circular disc having a cylindrical bore at its center for precise positioning and holding of brachytherapy encapsulation at the center of the disc. Rotary chuck is mounted on a stepper motor for circular rotation of encapsulation. Stepper motor is mounted on an XY-stage for centering of laser beam on the job. Laser welding nozzle is held on a linear Z-stage for laser beam centering at weld location. A motion controller has also been developed to precisely control stepper motor with a step size of 3.6°. A CCD camera based viewing set up with a magnification of 80 X has been provided on the welding workstation to view the miniature size encapsulation on the monitor for precision in alignment of laser beam for welding. A cover with an LED light has also been provided for visualization of weld region on monitor during welding process. Figure T.2.3(a) shows laser welding system installed at RPhD for miniature brachytherapy encapsulation and Figure T.2.3(b) shows laser welded miniature size I-125 brachytherapy source.



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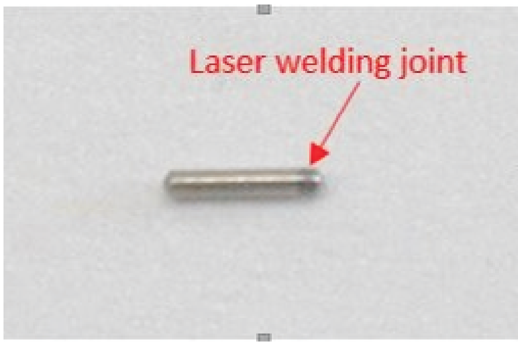


(b)

Fig. T.2.3: (a) A view of Nd:YAG laser system indigenously developed and installed at RPhD, BARC for welding of brachytherapy encapsulation, and (b) laser welded I-125 brachytherapy source encapsulation of size ϕ0.8 mm x 4.75 mm.

Laser welding parameters such as pulse energy, pulse duration, pulse frequency, speed of rotation and gas flow rate were systematically optimized to achieve good quality leak tight welding. Optimum value of pulse energy for welding was found to be 0.5 J at 10 ms pulse duration. In order to minimize heating of encapsulation, welding has been optimized at 1 Hz repetition rate. Interlock for gas purging has been provided by tool controller, which sends sync command to laser power supply controller to initiate laser pulses for welding. Laser pulses will not start without inert gas purging, which avoids damage of encapsulation. Welding for each brachytherapy encapsulation takes 60 seconds time. Weld quality characterization has been carried out by RPhD, BARC and found to be at par as compared to that from imported system. A better bead appearance has been achieved with indigenously developed system due to coaxial inert gas purging along with the laser beam, whereas in the case of imported system, inert gas purging is not coaxial, rather it is from the side of the welding nozzle. This laser welding system is now being used regularly at RPhD, BARC for welding of brachytherapy sources.

2.2 Nd:YAG laser system for welding of fuel pins at IF3, BARC

Laser welding of fuel pins made of dissimilar materials, such as nickel alloy and SS321 material was required by Integrated Fuel Fabrication Facility (IFFF), BARC as welding trials failed when conventional TIG welding process has been used. Using conventional TIG welding process, heat affected zone is found to be large, deformation and defects resulted in high rejection rate of welded fuel pins. In view of this, R&D was successfully carried out using laser welding of these fuel pins using 250 W fiber coupled pulsed Nd:YAG laser with required weld depth of ~ 0.6 mm and weld bead size of ~ 1.2 mm. The laser welding parameters were optimized to obtain good quality of weld, without root pockets, cracks/porosities and also qualified helium leak test. The laser based welding was found to be superior compared to TIG welding process and rejection rate has reduced drastically. A 250 W pulsed Nd:YAG laser system with three port time shared fiber optic beam delivery has been installed at IF3, BARC for laser welding of fuel pins. This laser system provides maximum pulse energy of 100 J at 20 ms pulse duration with variable pulse duration in the range of 2-20 ms and pulse frequency in the range of 1-100 Hz. A compact laser welding chamber with evacuation facility, argon gas purging facility, easy loading of part of fuel pin and precise positioning of weld location was developed. A motion controller for fuel pin welding along with CCD camera based online weld monitoring set up for alignment and inspection of welded fuel pins was also provided. Interlocks of motion control of fuel pins and gas purging with ON/OFF for laser welding have been incorporated on a single user friendly trolley. Figure T.2.4(a) shows laser welding system and welding chamber developed for IF3, BARC and Figure T.2.4(b) shows laser welded fuel pin samples.

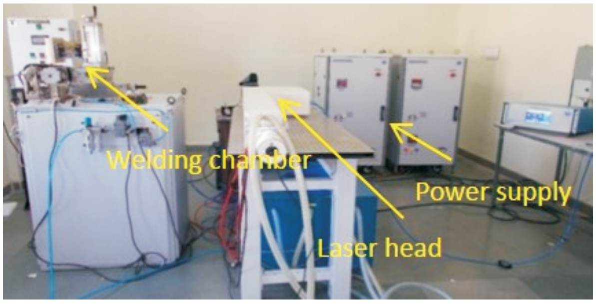
(a)

(b)

Fig. T.2.4: (a) A view of 250 W average power Nd:YAG laser system and welding chamber installed at IF3, BARC for welding of fuel pins, and (b) laser welded fuel pin samples for IF3, BARC.

2.3 Deployment of 500 W average power pulsed Nd:YAG laser for welding of fuel pins at Fuel Fabrication (FF), BARC, Tarapur

A ceramic reflector based double lamp pump chamber and laser system providing an average output power of 540 W and 10 kW peak power with maximum pulse energy of 280 J has been developed for laser welding of D9 fuel tube with SS316 LN end plug for proto-type fast breeder reactor (PFBR) and zircaloy-2 fuel tube with zircaloy-2 end plug for boiling water reactor (BWR). This laser provides an electrical to laser conversion efficiency of 5.4%, which is better than reported in the literature for similar systems. It can be operated with variation in pulse duration in the range of 2-40 ms and repetition rate in the range of 1-100 Hz. It also includes development of two power supplies of 5 kW average power each, to simultaneously and synchronously drive two flash lamps along with a controller to vary pulse current, pulse duration and pulse repetition rate. Laser output has been delivered through optical fibers of 600 µm and 400 µm core diameter with 90% transmission efficiency. This laser has been equipped with three time shared ports. At the exit fiber end, material processing objectives with 1:1, 1:1.5, 1:2 and 1:3 imaging ratio were provided to achieve beam diameters in the range of 600 µm to 1.2 mm. Two fiber ports are being used for laser welding and one port is being used for cutting of up to 25 mm thick SS tubes/sheets. It was required to achieve crack free welding of D9 fuel tube with SS316LN end plug and convex shape of weld bead at weld location. Since, weld bead is prone to develop solidification cracks due to the fast cooling rate in case of pulsed welding, so, it was challenging to achieve crack free weld joint with convex shape of weld bead.



(a)

(b)

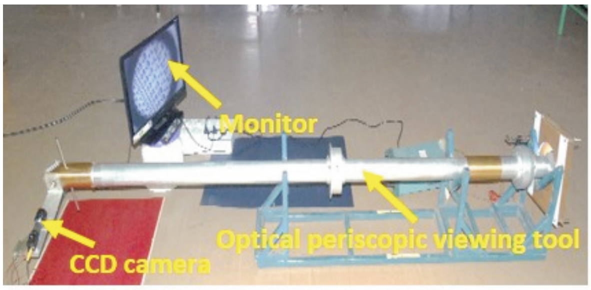
Fig. T.2.5: (a) 500 W average power Nd:YAG laser system installed at FF, BARC, Tarapur, and (b) a view of laser welded PFBR fuel pins.

Thus, a large number of trials were carried out to optimize process parameters and achieve crack free welding by means of a proper combination of pulse energy, pulse frequency, and speed of welding. It is normally observed to have concave shape of weld bead due to flow of molten material on edges of the weld bead. To achieve convex shape of the weld bead, beam diameter, pulse frequency and speed of welding were critically optimized. Similarly, in the case of welding of zircaloy-2 fuel tube and zircaloy-2 end plug, welding parameters were optimized to achieve crack free and convex shape of the weld bead. This laser system has been commissioned at FF, Tarapur in production line for fuel fabrication and cutting of irradiated components. Figure T.2.5(a) shows a view of 500 W average power Nd:YAG laser welding system installed at FF, Integrated Nuclear Recycling Plant (INRP), BARC, Tarapur and Figure T.2.5(b) shows laser welded fuel pin samples for PFBR.

2.4 Optical viewing system for end-shield leak detection at MAPS-1 reactor

Madras Atomic Power Station Unit-1 started its commercial operation in 1984 and has served the nation for about 34 years. A few years back, minor leak of water from the end-shield was observed in MAPS-1 reactor, however its exact location was difficult to establish due to only access through lattice tube. During biennial shutdown, in-situ inspection of pressure tube was carried out, which revealed indications in pressure tubes of two coolant channels, thus it was required to remove pressure tubes and end fittings of two coolant channels O-9 and Q-9 for post irradiation examination. Further, it was identified that the probable location of the end-shield leak is also around these coolant channels due to clear visible water marks at the outer periphery of these channels. It was suspected that either a) any of the lattice tubes of these coolant channels might have developed leak, or b) welding joint of lattice tube with tube sheet may have developed leak, or c) the ligament of lattice tube side tube sheet may have developed leak. As the gap between the lattice tube sheet and calandria side tube sheet was only 38 mm, it was difficult to conceptualize any optical viewing system for its in-situ inspection. Further, radiation field was also very high, of the order of 100 Rad./hr., even after the use of shielding plug in the calandria tube. So, it was not possible to use any ordinary CCD camera based device for lattice tube and end shield ligament inspection. Thus, a metallic mirror based periscopic optical imaging system was conceptualized, designed and developed with online CCD camera based viewing system having view at 90° with respect to radiation field emission direction to protect damage of the CCD camera [11].

Optical viewing system consists of a long tubular section of about 2.5 m length and 2.5 inch diameter having two discs, one for locking the tool at the face of lattice tube and another to guide the tool at the end of lattice tube to avoid sagging of tool while inspection. At the ends of the tubular section, mirror mounts having provision for tilting in two planes have been provided. Metallic mirrors of 2 inch diameter have been mounted on these mirror mounts. Image collected by front mirror is transferred to the other end of the tube using an optical imaging system of two lenses having focal lengths of 500 mm and 200 mm, respectively. A CCD camera has been mounted at 90° with respect to tubular tool axis to avoid radiation exposure of CCD camera. Image of lattice tube ligament is transferred to CCD camera using these metallic mirrors and optical imaging lenses. Prior positioning of mirror field of view during mock up is essential to image different sections of ligament. This tool has been equipped with a handle to rotate the tool and see any desired location of ligament in circumferential direction. Miniature LED based lighting system mounted on back face of the mirror holder has also been provided with the tool for lighting of dark location of end shield. This tool has a total length of 2.5 m and provides a magnification of ~8.5. Thus, a 50 μm crack width becomes visible with size of 0.425 mm on monitor screen. It is possible to clearly view a circular region of 38 mm diameter at a time for a fixed location of tool. Using this optical viewing system, end shield tube sheet ligament, lattice tube and weld joint of lattice tube with tube sheet can be inspected. Tool mounting can be done by using a single locking nut on E-face of coolant channel, which takes about two minutes time. Image monitoring was performed remotely from a distance of ~30 m from E-face to minimize radiation dose consumption. Figure T.2.6(a) shows in-house developed optical viewing system for end shield leak detection and Figure T.2.6(b) shows in-situ end shield leak detection with optical viewing system in MAPS-1 reactor.



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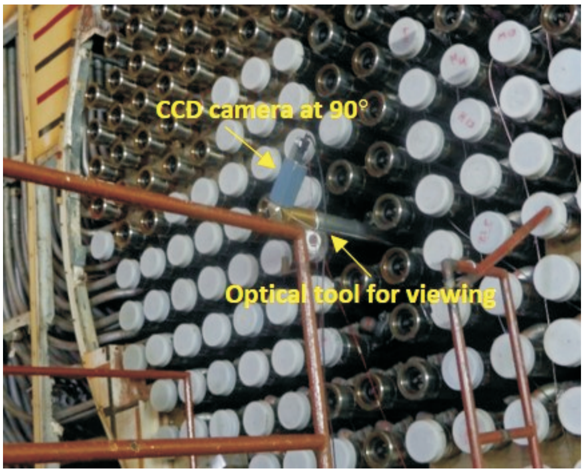


(b)

Fig. T.2.6: (a) Optical viewing system for end shield leak detection, and (b) in-situ end-shield leak detection with optical viewing system.

Using this tool, leak locations in the end shield tube sheet ligament of MAPS-1 reactor were successfully spotted. Further, the leak path and crack site were also clearly seen from the online images of end shield tube sheet. This has now opened path to seal the leak location and further operate this reactor for power generation. This optical viewing system has now been established as a unique tool for such inspection requirements in calandria in future also.

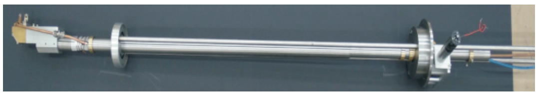
2.5 Removal of single selected coolant channels of 220 MWe and 540 MWe Indian nuclear power plants

The Indian pressurized heavy water reactors of 220/540 MWe power consist of 306/392 coolant channels. These coolant channels contain nuclear fuel and are placed horizontally in the calandria. The primary coolant passing through the coolant channel removes the heat generated during fission reaction. The coolant channel assembly of pressurized heavy water reactor (PHWR) is complex structure consisting of end fitting, liner tube and pressure tube (PT). The pressure tube is made of Zr-2.5% Nb alloy or Zr-2 and holds the nuclear fuel, whereas it is attached with end fittings made of SS410 by rolling. The temperature of coolant at the inlet and outlet of coolant channel are 25 °C and 300 °C, respectively. Among the different parts of the coolant channel, the pressure tube works under harsh environment of high temperature, high pressure and neutron flux, thus the operating life of the coolant channel is limited. It is relevant to monitor the health of coolant channels of the nuclear reactor by removing a single selected coolant channel from 220 MWe and 540 MWe reactor core, often required as a regulatory measure for post-irradiation examination (PIE) of pressure tube or to study the reasons of failure of pressure tube. It is difficult to remove single selected coolant channel by conventional mechanical techniques because of obstruction from several feeder pipes and yoke assemblies of adjacent coolant channels from top and bottom. In view of high radiation field and restricted approach with almost no space available for insertion of laser cutting tool to directly cut the bellow lips for the removal of end fittings and pressure tube, remotely operable laser cutting technique has been developed. This technique involves development of three different types of laser cutting tools and compact straight and bending nozzles. Laser cutting for removal of 220 MWe single coolant channel is performed in the following sequence: (i) cutting of pressure tube at a distance of ~2250 mm from E-face performed by NPCIL using mechanical chip-less cutter, (ii) laser cutting of 4 mm thick liner tube using 90 degree bending nozzle at a distance of ~ 926 mm from E-face from inside of the tube, followed by pulling it approximately by 20 mm to generate a space for placing laser cutting nozzle to cut end fitting both from north and south vaults, (iii) laser cutting at a distance of ~905 mm from E-face of 11 mm thick end fitting using 90 degree bending nozzle from inside of the tube. The outboard end fitting can now be removed and would create empty space, (iv) using this empty space of outboard end fitting, laser cutting of bellow lip weld joint can be easily performed using a new tool and miniature nozzle of 20 mm diameter, ~ 60 mm length, (v) the bellow lip joints are separated from both end mechanically using special tool, and slight jacking of feeder pipes is required to remove inboard end fittings, (vi) the outboard and inboard end fittings are re-welded to axially cut pressure tube stubs at rolled joint position. The pressure tube stubs are retrieved in underwater condition at active workshop. Over past few years, laser cutting technology for in-situ removal of single selected coolant channel of 220 MWe from a matrix of 306 coolant channels under severe space restrictions has been deployed successfully at KAPS-1, KAPS-2, RAPS-4, and KGS-1 reactors with minimum possible radiation exposure [12-15].

Recently, it was necessary to remove one of the coolant channels of 540 MWe nuclear power plant at TAPS-4 reactor for PIE studies. 540 MWe nuclear power plants have 392 coolant channels and design of the coolant channel is altogether different as compared to 220 MWe reactors. Further, the bellow weld joint is also of different type as it is welded with the lattice tube. The nearby space of the channel was obstructed by six feeder pipes from top and bottom along with yoke assembly of nearby channels, so it was not possible to approach directly for cutting of bellow weld joint to remove this channel as in the case of 220 MWe reactors. In view of obstructions and narrow space, remotely operable laser cutting technology for liner tube, end fitting, bellow weld joint with lattice tube and bellow ring detachment from bellow was developed along with a new set of tools and fixtures for in-situ removal of L-8 coolant channel of TAPS-4 reactor [16].

Home-built fiber coupled pulsed Nd:YAG laser of 250 W average power and 5 kW peak power was utilized for in-situ laser cutting operation. Four different types of tools were designed and developed for laser cutting of liner tube and end fitting, bellow lip cutting, bellow ring detachment and PT stub cutting. Laser cutting of liner tube (4.2 mm thick SS304) was carried out at 1560 mm from E-face and end fitting (13 mm thick SS410) was carried out at 1520 mm from E-face. After removal of outboard end fitting, bellow weld joint with lattice tube was cut using laser and separated from lattice tube. Further, ring attached with bellow was also detached by laser cutting using a 45° bending compact laser cutting nozzle. After this cutting, inboard end fitting and pressure tube were removed. Figure T.2.7(a) shows laser cutting tool for liner tube and end fitting, Figure T.2.7(b) shows laser cutting tool for bellow lip weld joint, Figure T.2.7(c) shows in-situ laser cutting of end fitting and Figure T.2.7(d) shows in-situ laser cutting of bellow lip of L-8 coolant channel of TAPS-4 reactor.

After laser based removal of coolant channel, it was also required to retrieve PT stubs near the rolled joint from both the



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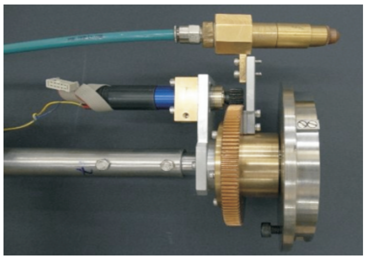

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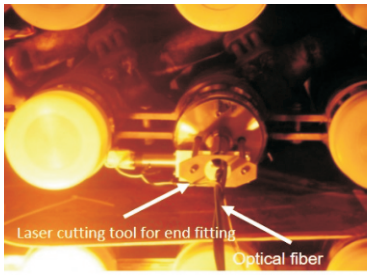

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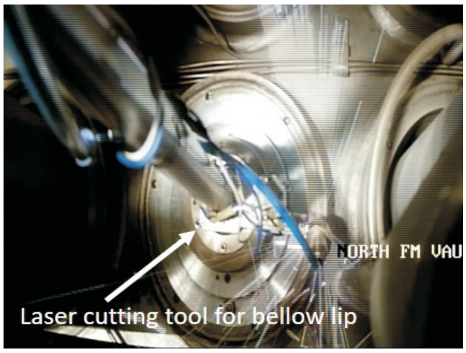


(d)

Fig. T.2.7: (a) Laser cutting tool for liner tube and end fitting of 540 MWe TAPS-4 reactor, (b) laser cutting tool for bellow lip weld joint of 540 MWe TAPS-4 reactor, (c) in-situ laser cutting of end fitting of L-8 coolant channel of TAPS-4 reactor, and (d) in-situ laser cutting of bellow lip of L-8 coolant channel of TAPS-4 reactor.

ends of end fittings for PIE studies. It was a challenging task due to (a) high radiation field from end fitting of ~1000 Rad/hr. and (b) risk of airborne activity during underwater laser cutting and PT stub retrieval process. As compared to 220 MWe reactor PT (ID 82 mm, thickness 3.6 mm), 540 MWe PT has a larger inner diameter and larger thickness (ID 103.4 mm, thickness 4.3 mm). Further, in the case of 220 MWe reactor, outboard and inboard end fittings are welded and HEPA filter is connected with feeder coupling hub of outboard end fitting [14]. However, in case of 540 MWe reactor, due to much longer length of end fitting, PT stub retrieval was performed without welding of outboard end fitting with inboard end fitting. Thus, a new laser cutting tool of ~1.5 m length along with controller and cutting process was developed and tool locking was done from ID of inboard end fitting. In this case, a vent was provided through laser cutting tool for connection with HEPA filter to filter air released from water during underwater laser cutting process. Each PT stub was ~125 mm long and four axial cuts were carried out. Total laser cutting time for each PT stub was ~3 hrs. Figure T.2.8 shows laser cutting set up for PT stubs and laser cut PT stubs. There is no alternate technique for retrieval of PT stubs except underwater laser cutting. Further, non-contact nature of laser cutting helps in retaining stress properties of PT after long irradiation and underwater laser cutting also minimizes heat affected zone, which are vital for analyzing irradiated PT stubs for life extension studies. This laser technology was successfully deployed at TAPS-4 for removal of L-8 coolant channel for PIE studies on pressure tube and PT stubs without any radiation hazard. After safe removal of L-8 coolant channel, reactor was started again for power generation.

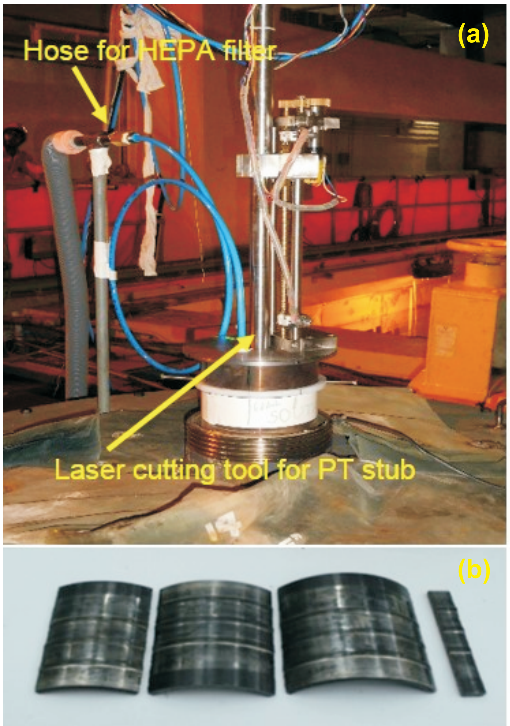
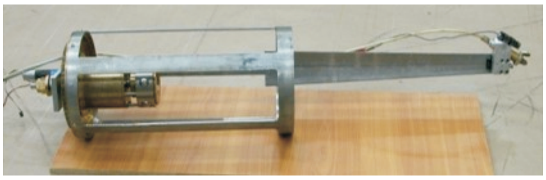


Fig. T.2.8: (a) Underwater laser cutting of pressure tube stubs of L-8 coolant channel of 540 MWe TAPS-4 reactor, and, (b) laser cut PT stubs.

2.6 Bellow lip weld joints cutting during en-masse coolant channel replacement (EMCCR) operations

As mentioned in the previous section that pressure tubes has limited life of ~ 10 – 15 years and it is obligatory to replace coolant channel. This replacement is carried out during en-masse coolant channel replacement (EMCCR) operation. The analysis of PIE data of pressure tube removed from coolant channels is critical in the determination of EMCCR campaign. The EMCCR is a challenging task due to space restrictions and high radiation exposure. As the yoke assembly and feeder pipes have been removed by conventional mechanical techniques during EMCCR operation, thus, there is no space restriction to approach bellow lip weld joint. The coolant channels are attached to the end shield of the reactor by means of bellows. One end of the bellow is welded to a ring made of carbon steel which is shrink fit on the end fitting of the coolant channel at a distance of ~ 945 mm from the E-face and the other end is attached with the outer face of the end shield. Thus, for removal of coolant channels, cutting of bellow lip weld joint from both sides is required. The depth of bellow lip weld joint is ~ 3 mm and cutting is performed by using specially developed remotely operated tools. The cutting can be performed by mechanical cutting tools, but the mechanical cutters are bulky, require regular change of cutting blades. The major disadvantage for mechanical cutting process is that it is time consuming and cannot be accomplished remotely. This leads to high man-rem. The laser cutting technology developed earlier for bellow lip weld joint was successfully utilized for EMCCR operations at NAPS-1, NAPS-2 and KAPS-1 reactors [1,2]. Based on previous experience, bellow lip weld joint cutting technology was updated with improved tool design providing higher rigidity along with electronic safety interlocks for tool rotation, to prevent motor damage and controller for more reliable operations during repeated cutting process. A motorized circumferential rotary arrangement has been used for laser cutting of bellow lip. This tool can be tightened using a single bolt for fixing it on bore of E-face of end fitting. A small laser cutting nozzle is attached on the tool to take care of the position tolerance of both bellow lip and diameter of coolant channel by roller attached on the tool. Care should be taken while separating the bellow ring so that there is no damage to outer ring and it can be reused during re-commissioning. Laser grooving up to depth of ~ 4 mm is needed at the weld location. Laser grooving is a difficult process compared to cutting of material through and through. During grooving, laser beam is kept at an angle with the job to allow the debris to eject out at an angle. The laser parameters were optimized for grooving process for carbon steel and the technique was established. Cutting time of each bellow lip weld joint is about 6 minutes. During recent EMCCR campaigns performed at two nuclear power plants i.e., KAPS-1 & KAPS-2 reactor, laser cutting of all the 612 bellow lip weld joints in both the reactors was carried out and task of separation of bellow rings was also completed in seven days by working in round-the-clock operation [17]. Two home built 250 W average power and 5 kW peak power Nd:YAG laser systems with time shared multi-port beam delivery through optical fibers were deployed to cut remotely from both north and south vaults simultaneously. Radiation dose consumption was also lower as compared to EMCCR operations in the past due to higher rigidity of tool and for carrying out automatic control of several process parameters and imparting training to unskilled workers. This home built technology of laser based cutting for bellow lip weld joints has enormously reduced man-rem, time and cost in comparison to conventional mechanical techniques. Figure T.2.9(a) shows bellow lip cutting tool and Figure T.2.9(b) shows in-situ laser cutting of bellow lip weld joints at KAPS-2 reactor and Figure T.2.9(c) shows laser cut and separated bellow lip weld joint.



(a)

(b)

(c)

Fig. T.2.9: (a) Laser cutting tool for bellow lip weld joints,(b) in-situ laser cutting of bellow lip weld joints during EMCCR campaign at KAPS-2 reactor, and (c) laser cut and separated bellow lip weld joint.

3. Summary

In summary, RRCAT has indigenously developed different versions of highly efficient fiber coupled flash lamp pumped pulsed Nd:YAG lasers for remote cutting and welding applications in nuclear field. These lasers have been successfully deployed in several nuclear field applications and have enormously reduced radiation dose consumption, time and cost. Specialized remotely operated tools and fixtures have been developed and deployed in highly radioactive environment. The state of art highly rugged fiber lasers up to cw power of 700 W have been developed and 250 W engineered prototype system has been installed at R&D NPCIL, Tarapur. Further efforts are going on to increase the laser output power to provide the capability to enhance cutting thickness and welding depths to cater to the challenging requirements in future in nuclear field applications.

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