Laser based Technologies and their Applications: DAE's Accomplishments

S. V. Nakhe and S. K. Dixit
Raja Ramanna Centre for Advanced Technology
Indore 452013, India

Email: nakhe@rrcat.gov.in

Preamble

Department of Atomic Energy (DAE) has been working in the areas of nuclear research and nuclear power program along with many other frontier areas of science and technology. Lasers is one such frontier area that has revolutionized concepts and technologies, and has been deployed across the whole gamut of present day applications in diverse fields such as industrial processing, manufacturing, meteorology, defence, communications, medical procedures, diagnosis, and scientific research. DAE is actively pursuing Research and Development in the area of laser and photonics as it finds direct applications for various core programs of DAE like material processing, nuclear reactor refurbishment, mineral exploration, safety systems, meteorology, societal health applications, specialized component manufacturing etc.

1. Historical Background

DAE initiatives in the development of laser technology and planning their applications go back, not lagging much behind the time when the first laser system was demonstrated in 1960 at Hughes Research Laboratories, USA. The DAE stalwarts including Dr. Raja Ramanna quickly grasped the importance of laser technology and the role it can play in shaping DAE future projects and this paved the way to start laser activities in BARC. In 1965, BARC demonstrated GaAs semiconductor laser to set up a line of sight open air optical communication link between BARC (Trombay) and TIFR (Colaba). The DAE laser program got a fillip when in 1967, Dr. Dilip Devidas Bhawalkar joined the program, at the behest of Dr. Ramanna, as Scientific Officer at BARC after resigning from his lectureship at Southampton University, UK. Dr. Bhawalkar has brought in the dual expertise, into the system, of laser physics and electronics, with the degrees of

M.Sc. (Physics) from Sagar University, MP, India and M.Sc. (Electronics) & Ph.D. (Laser Physics) from Southampton University, UK. Under stewardship of Dr. Bhawalkar, BARC developed mature laser technology of gas CO_2 lasers, solid state Nd: Glass, Nd: YAG, Ruby lasers and liquid Dye lasers. These laser technology developmental efforts were accorded due recognition in the department with creation of Laser Section in 1973, then Laser Division in 1984 in BARC. With steady progress on the front of laser technology, enough confidence was generated to plan and pursue large scale application of laser based technologies. These included, studies on high resolution laser spectroscopy, laser plasma interaction, laser isotope separation, encompassing several Divisions of BARC including Spectroscopy Division, Chemistry Division and Multi-Disciplinary Research Section (MDRS) with guidance and contributions from eminent personalities such as Dr. P. R. K. Rao, Dr. U. K. Chatterjee, Dr. J. P. Mittal, Dr. B. A. Dassancharya and Dr. S. K. Sikka.

With the laser program firmly in place in BARC and witnessing a steep growth, in 1980s there was a need felt at DAE that a new centre needs to be set up dedicated to R & D on laser systems due to space and manpower constraints at BARC which was inhibiting further expansion of program. This was with a view to fully exploit the potential of laser based technologies for the departmental projects as well as for the applications in engineering, instrumentation, medicine, defence and basic research. In 1981, the Atomic Energy Commission (AEC) took a decision to establish a new research centre, focussed on development of advanced light sources such as lasers and high energy electron accelerator based synchrotrons, and development of associated technologies. This decision was duly approved by Government of India and a site selection committee was constituted in 1982 under the Chairmanship of Dr. Ramanna. The committee finally chose Indore to host the new centre. In fact, Dr. Ramanna, much later, reflected on the choice of the site as,

"As I recall, the centre was started for the propagation of advanced Science and Technology in the state of Madhya Pradesh. The more information is available to the Universities and the public at large, the better it will be for the beautiful state of Madhya Pradesh to take up the leadership in these fields once again, as it did in the ancient past."

DAE decision to set up new R & D centre at Indore was very enthusiastically approved by Government of Madhya Pradesh and then by Government of India. About 650 hectares of land was made available, around the picturesque 'Sukhniwas Lake' to the new centre. DAE formally started the new institute, named as 'Centre for Advanced Technology (CAT)' by an official order dated 27th June, 1983. 'CAT' was inaugurated, for commencement of project work by Honourable President Shri Giani Zail Singh on 19th Feb, 1984 in the presence of Dr. Raja Ramanna (Chairman, AEC). The construction activity at CAT, started in May, 1984. In June, 1986, first batch of scientist and engineer shifted to CAT to initiate the scientific activities. On 13th March, 1987, Dr Bhawalkar assumed the charge as founding director of CAT at a relatively younger age of 47, a post he continued for 17 years till his superannuation in 2003.Dr. U. K. Chatterjee handled the laser activities at BARC for many years after Dr. Bhawalkar shifted to CAT. On 17th December, 2005, 'CAT' was renamed in the honour of late Dr. Ramanna, as 'RRCAT –Raja Ramanna Centre for Advanced Technology' by honourable Prime Minister Dr. Manmohan Singh.

RRCAT now stands to be the largest scientific institute in the country engaged in research, technology development, establishing facilities and utilization of Lasers. Particle accelerators is the other major work area of RRCAT. Synchrotron based light sources Indus-1 and Indus-2 are developed at RRCAT and now operating as National facility in round the clock mode. RRCAT has distinction to be the only place in the country having synchrotron based light sources. Overall, RRCAT is spearheading the efforts in country on generating awareness on the application of laser/light sources in the spirit of 'Photons in The Service of Mankind through Science and Technology'. The subsequent sections of this article present the noteworthy DAE accomplishments in the field of development of laser systems, laser/photonics based technologies and their applications. Considering limitation of the space some of the major accomplishments are covered having substantial contemporary relevance.

2. Laser Technology Development

It has always been the motto of DAE to indigenously develop advanced technologies so that the technology deployment and utilization continue unhindered largely independent of imports. DAE primarily took the projects on the development of laser technology based on potential applications within the department. The laser systems crucial for DAE programs such as Copper vapour laser (CVL), Dye laser, Nd:YAG, Nd:Glass laser, Fiber laser, CO_2 laser, optical parametric oscillators, etc. have been developed at RRCAT/BARC. Brief description of these developed laser systems is mentioned below. The drafting of developed laser systems into the laser based technologies is elucidated in the next section.

2.1 CVL and CVL Pumped Dye Laser Oscillator-Amplifier Chain

Atomic vapour laser isotope separation was considered to be an efficient solution because of high separation factor. In this process, the isotopic atom can be selectively excited by matching laser wavelength (without affecting other isotopes) which is finally photo-ionized and separated out. DAE embarked on the development of laser based technology for this objective. The kHz repetition rate, 10s of ns pulse duration, high average power CVLs and their configuration to operation in oscillator-amplifier (MOPA) chain as the pump source of wavelength tunable high power dye laser chain, provided the best solution. The development facility of high repetition rate (5 -10 kHz) copper vapour laser (wavelengths, 510 nm & 578 nm), as a pump source to wavelength tunable dye laser is established at RRCAT. Simultaneously, development of dye laser oscillator-amplifier MOPA was taken up in BARC. In collaboration, RRCAT developed CVLs are used (as pump source) in BARC dye laser facility, aimed at isotope selective excitation/ionization based on multi-colour resonance ionization. The establishment of CVL and Dye Lasers chain systems made a very good success story of laser technology development and deployment in DAE.

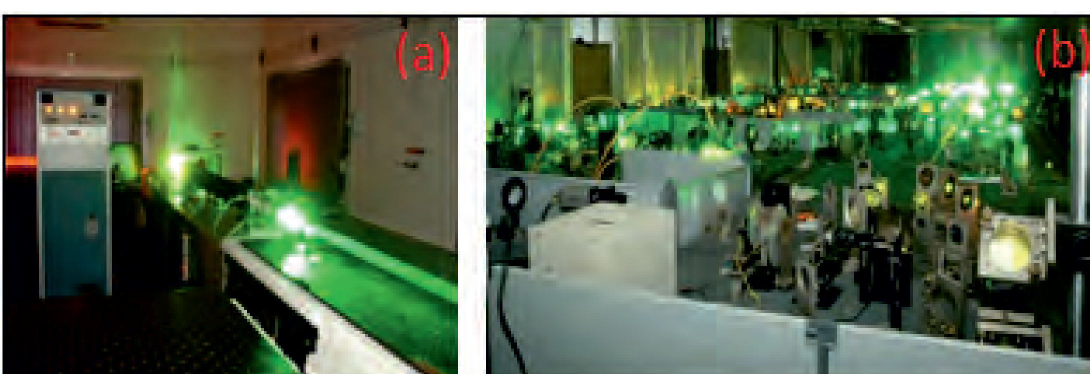

Fig. 1: (a) CVL developed at RRCAT, (b) CVL pumped dye laser system developed at BARC

2.2 Nd: YAG and Nd: Glass Lasers

DAE has established expertise in the development of Nd: YAG, Nd: Glass and other solid state lasers. RRCAT developed pulsed and continuous wave (cw) Nd:YAG lasers are the work-horses in laser based systems used within DAE for material processing applications such as metal cutting, drilling, welding, shock peening and additive manufacturing. Single frequency cw solid state lasers find application in precision laser interferometry. High pulse energy Nd:Glass laser MOPA systems are established at RRCAT/BARC for basic research in laser plasma interaction and shock wave physics. The laser systems developed at RRCAT are,

(a) Flashlamp pumped, high average power (250 -1000 W), high peak power (5 -20 kW), 2-40 mspulse duration, 1-100 Hz repetition rate,IR (~ 1064 nm) Nd:YAG laser systems

(b) 1 kW average power CW diode pumped, IR (~ 1064 nm) Nd:YAG lasers

(c) 7 J/10 ns, flashlamp pumped, IR (~ 1064 nm) Nd:YAG system

(d) Frequency doubled, green 532 nm, kHz repetition rate, 10s of ns pulse duration diode PumpedNd:YAG lasers

(e) Single frequency diode pumped CW Nd:YAG and Nd:YVO_4 lasers

(g) 100 J/1ns flashlamp pumped, IR (~1054 nm)Nd:Glass MOPA system

So far about 50 solid state laser systems have already been developed and are being utilized at different DAE institutes, majority of them in reactor maintenance as described in next section.

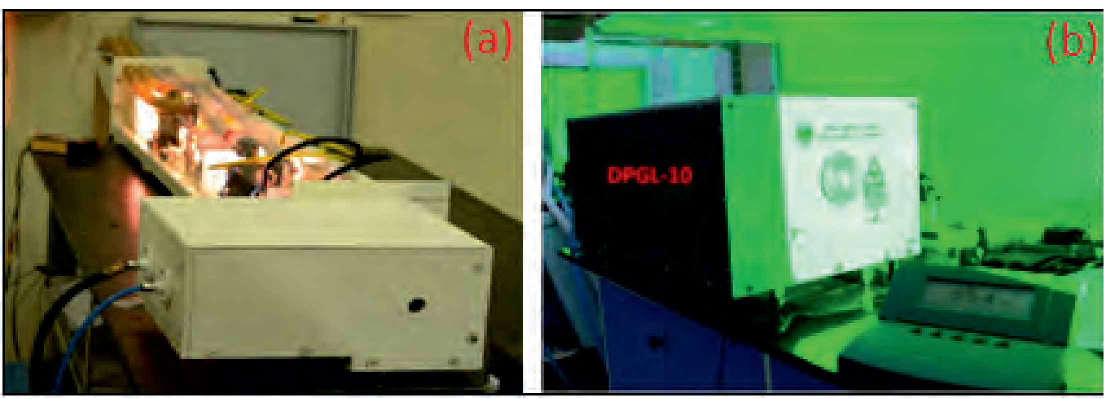

Fig. 2: RRCAT developed (a) Flashlamppumped IRNd:YAG laser and (b) Diode pumped greenNd:YAG laser

2.3 Fiber Lasers

Fiber laser systems are projected to be the future of industrial processing, additive manufacturing and medicine (surgery) industry. This is due to fiber lasers being highly robust, efficient, compact and high beam quality even at kW level average laser powers. No external optics is needed as fiber Bragg gratings (FBGs), fused with gain fiber at both the ends, act as resonator mirrors. Hence fiber lasers are free from alignment issues which are quite prevalent in other lasers. RRCAT took projects in the development of kW class CW fiber laser systems for field deployment as well as the development of femto-second pulse duration mode locked fiber laser for basic research. The major accomplishments are,

(a) Development of 1000 W, laser diode pumped Yb doped CW fiber laser system (~1080 nm) for material processing applications

(b) Development of 100 W, laser diode pumped Thulium doped CW fiber laser system (~1940 nm) in eye safe regime for surgical applications

(c) Development of 50 W, laser diode pumped Erbium doped CW fiber laser system (~1600nm) for sensing applications

(d) Development of 4 W, mode locked (~ 160 fs) Yb doped fiber laser MOPA system

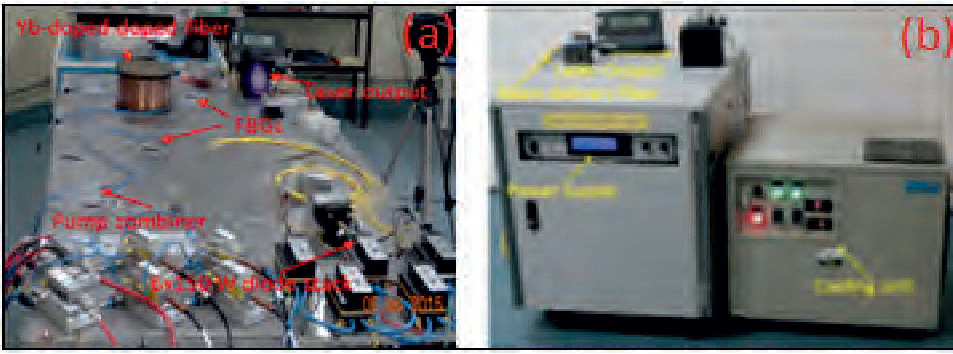

Fig. 3: RRCAT developed CW Fiber Laser (a) Inside component view, (b) Assembled Laser system

2.4 CO_2 Laser, Excimer Laser and N_2 Laser

The development of high average power and pulse energy IR (~ 10.6 µm) CO_2 laser started very early in BARC and subsequently taken up in RRCAT. This is in view of their large applications due to their high absorption in organics, glass, plastic, tissues and water. Variety of CO_2 lasers of CW operation with kW average power, pulsed operation with several Joules pulse energy and line-tunable lasers have been developed in RRCAT. There is a recent trend to replace CO_2 laser with solid state lasers with advantage of fiber optic beam delivery. However, for niche applications, CO_2 laser are still being heavily used. DAE has also successfully developed pulsed UV (250-350 nm) Excimer and N_2 lasers. Utilization of Co_2 and N_2 lasers in industrial/ medical applications is successfully demonstrated by RRCAT by taking onboard the end users.

2.5 IR Free Electron Laser (IR-FEL)

RRCAT has designed, developed and commissioned an IR-FEL. This laser system is a very complex technology based on the suitable combination of a high energy electron linear accelerator (LINAC), an undulator and the laser resonator. Electron linac of energy, 18 – 25 MeV is used to obtain tunable 12.5 – 40 µm, wavelength laser operation with high peak pulse power and low average power. This IR tunable FEL is a complementary coherent laser source to the laser systems already discussed and have huge application potential in material science and other fields.

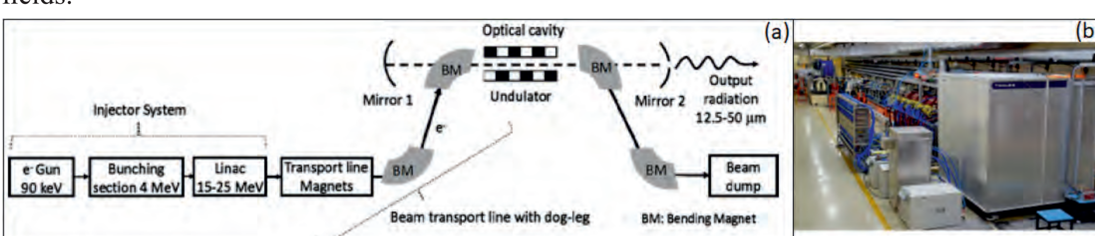

Fig. 4: RRCAT developed IR FEL, (a) System schematic, (b) IR-FEL system depicting e Gun bunching, bunching section and linac part.

3. Laser and Photonics Based Technologies and their Applications

In DAE, the lased based technologies, mostly based on laser systems developed at RRCAT and also a few of them based on readily available laser sources, have been developed and deployed with excellent outcomes. The deployment has been in the field our nuclear power programs, industry, production, healthcare application etc. Some of these technology applications pursued are presented here.

3.1 Nuclear Power Programme

Laser based cutting/welding technologies to address specific challenging demands related to maintenance of nuclear power reactors are very much required. Some novel, unique solutions are developed for this purpose by RRCAT. The laser systems have performed extremely well. Deployment of the laser systems at various Nuclear power plant sites is indicated in Table 1.

Table 1: RRCAT developed laser systems as deployed for nuclear reactor refurbishment

Laser system deployed for	Nuclear Site	Year
Bellow lip cutting during en-masse coolant channel replacement (EMCCR) campaigns	*NAPS-1, NAPS-2, KAPS-1, KAPS-2, KAPS-1*	*2006, 2008, 2009, 2017, 2018*
Removal of single selected coolant channels for PIE studies	*KAPS-2, KAPS-1, RAPS-4, TAPS-4, KGS-1*	*2005, 2012, 2016, 2017, 2018-19*
Retrieval of PT stubs for PIE studies	*KAPS-2, KAPS-1, RAPS-4, TAPS-4, KGS-1*	*2013, 2016, 2017, 2018-19*
Cutting of triangular yoke blocks	*RAPS-3*	*2014, 2016, 2018*
Cutting of SG tube and axial slitting at rolled joint region	*NAPS-2, RAPS-5&6, KGS-3&4*	*2009, 2014, 2018*
Removal of SG tubes for condition monitoring	*KKNPP-2*	*2016*

In these systems fiber coupled flash pumped Nd:YAG lasers are used. This technology brings in the high advantage of remote and faster material processing in difficult to reach locations such as between the congested 306/392 coolant channels of 220/540 MWe PHWRs as well as in Boiling Water Reactors (BWRs) and Pressurised Water Reactors (PWRs). Special optical beam delivery methods with/without assist gas, nozzles, mechanical fixtures, etc. are developed as a part of the system. Enormous reduction in process time, MANREM consumption, and cost are the attributes of laser based technology as applied to nuclear reactor refurbishment as compared to conventional mechanical techniques. This is essential for safe use of nuclear reactors with longer operating lifetimes. Laser welding process for Prototype Fast Breeder Reactor (PFBR) fuel pins is also established using RRCAT developed pulsed Nd:YAG laser. RRCAT also developed and patented laser welding of superconducting RF niobium cavities. Fabrication of these RF cavities is a crucial technology area for development of advanced accelerators.

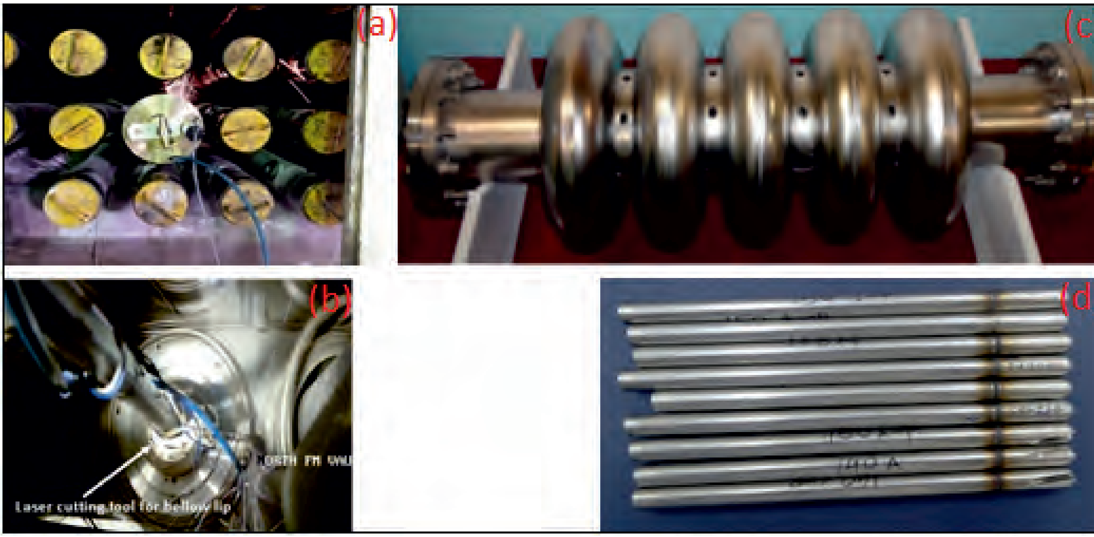

Fig. 5: RRCAT developed Laser based technologies for departmental applications, (a) In situ laser cutting during EMCCR, (b) Bellow lip cutting of TAPS-4, (c) Laser welded 5 cell SCRF niobium cavity (d) Laser welded PFBR fuel pins

3.2 Fiber Sensors

RRCAT has established a laser based technology for production of Fiber Bragg Grating (FBG) sensors. These fiber sensors are basically used for temperature and strain monitoring. These sensors are immune to electro-magnetic interference (EMI) and can withstand nuclear radiation, thus have vast applications in high EMI/radiation, nuclear and accelerator installations of DAE. FBG fabrication facility is a truly indigenous technology as the laser (CVL), its second harmonic (λ = 255 nm), and FBG writing set up, are all developed at RRCAT. The FBG temperature sensor is based on monitoring/recording the Bragg Wavelength shift (BWS) vs change in object temperature to which FBGs are attached in proximity. Single point/distributed FBG based temperature sensors have been installed at Advanced Fuel Fabrication Facility (AFFF), Tarapur and at Indus-2, Indore. RRCAT developed FBGs are being shared with national research institutes and industries for sensor development for different applications. Under the RRCAT incubation centre, custom made FBGs are being shared with a startup based at IISc Bengaluru. The sensors are found to be satisfactory in field trials by the startup company for various safety monitoring systems for Indian Railways. Deployment of many innovative systems for the railways will be possible due to availability of the FBG sensor fabrication technology from RRCAT.

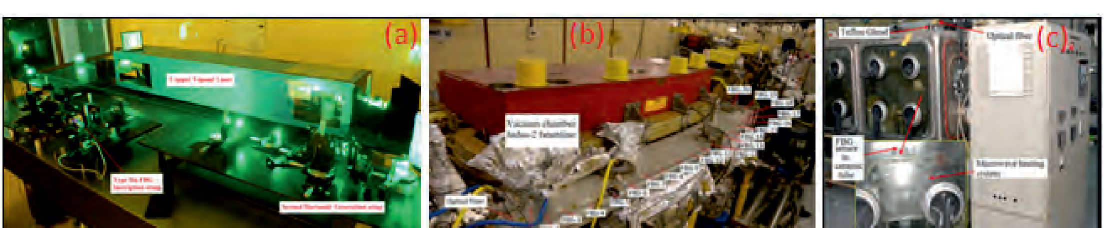

Fig. 6: RRCAT developed FBG Sensor technologies (a) FBG fabrication set up; Distributed FBG temperature sensors installed at (b) Indus-2 vacuum chamber& (c) AFFF, Tarapur

RRCAT also developed another type of distributed fiber temperature sensor based on optical Raman scattering of laser pulses, propagating in a multimode optical fiber. This sensor system is named 'Agni Rakshak (AR)' in view its potential to detect the onset of fire as well as marking the fire location. Raman backscattered 'anti-Stokes' signal determine the temperature of hot spot/fire and Optical time domain reflectometry (OTDR) principle determines the location of fire. The 'Agni Rakshak (AR)' is installed, as fire safety system, in 172 m circumference ring of Indus-2, all along high current cable that powers Indus-2 subsystems. The AR technology is being transferred to industry and is also made available under incubation.

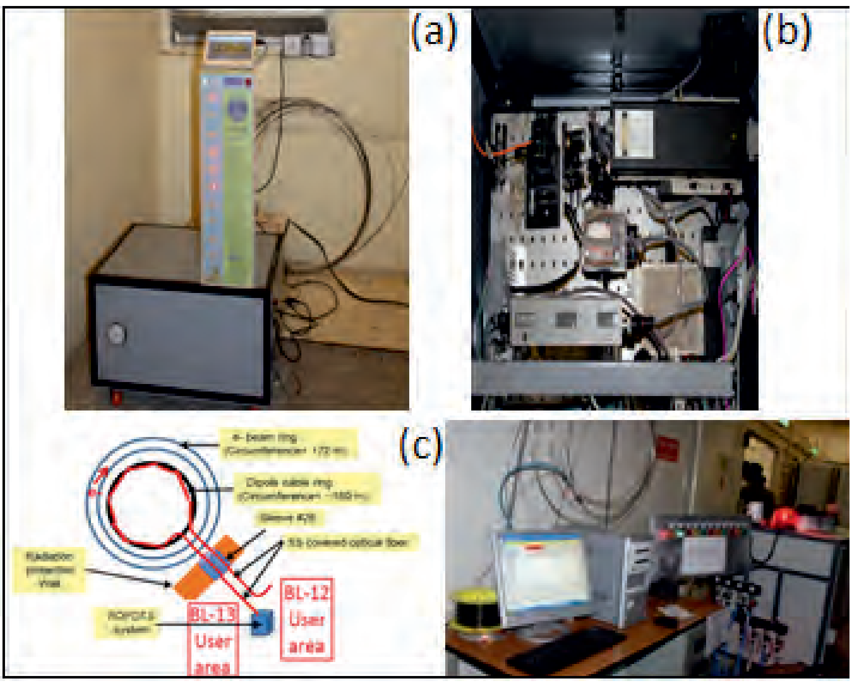

Fig. 7: RRCAT developed Laser based technologies for departmental applications, (a) In situ laser cutting during EMCCR, (b) Bellow lip cutting of TAPS-4, (c) Laser welded 5 cell SCRF niobium cavity (d) Laser welded PFBR fuel pins

3.3 Meteorology and inspection

RRCAT has developed photonics machine-vision based technologies for precision metrology i.e. dimension measurement of nuclear components such as fuel pellets, fuel pins, end caps, end plate, bearing & spacer pad, spring support, etc. Conventionally these tasks, handled by skilled operators, are time consuming and prone to errors. Repetitive high speed performance along with the desired accuracy (~ a few microns) of the measurement system as desired for quality assurance purpose for the expanding nuclear power program is achieved by the machine vision systems. The collimated light (LED) based system captures the 2D shadowgraph of the illuminated object on a CCD camera. The image is processed using advanced machine vision algorithms to extract dimensional data of the object. Many such systems have been developed in RRCAT and are incorporated in the production line of NFC, Hyderabad, for the meteorology and inspection of components fabricated for PHWR, BWR and FBTR.

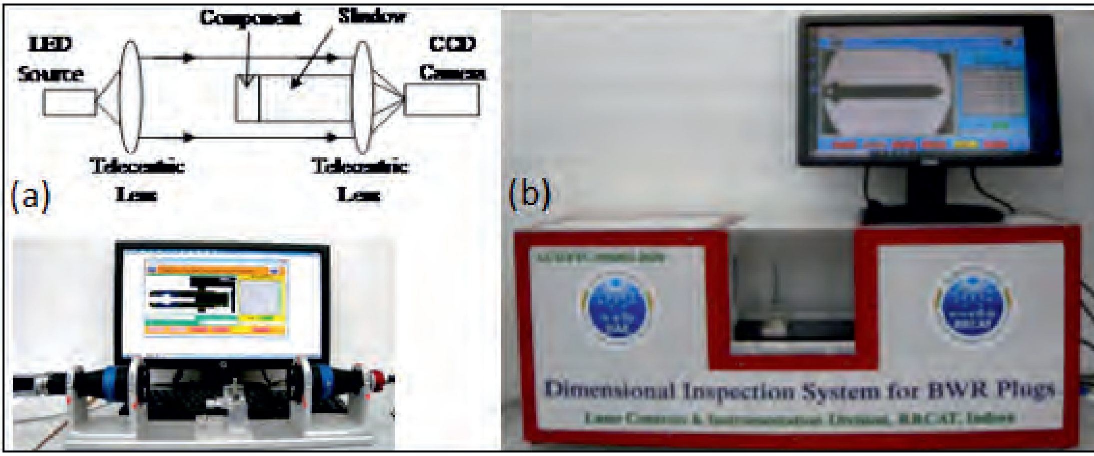

Fig. 8: RRCAT developed nuclear metrology set up, (a) Operating principle, (b) Full System

3.4 Additive Manufacturing

Laser Additive Manufacturing (LAM), opened up novel ways to manufacture components of very complex shapes and of varied material combination, hitherto considered very difficult or impossible. In view of high potential of LAM technology, RRCAT initiated a comprehensive LAM R&D activity involving system design and development, material processing, material testing, qualification and validation, and multi-physics process modelling. RRCAT developed and established both types of LAM system technologies, based on Laser Directed Energy Deposition (DED) and Powder Bed Fusion (PBF).

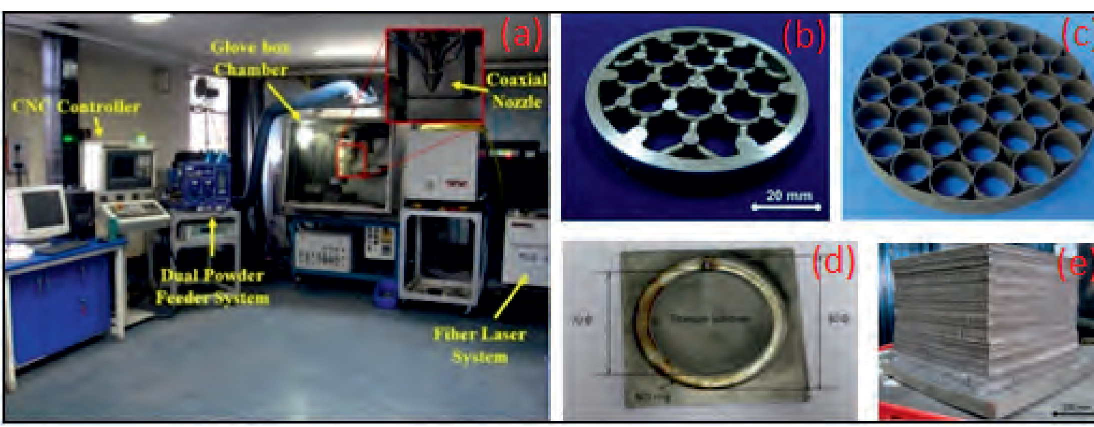

Fig. 9: 8RRCAT developed nuclear metrology set up, (a) Operating principle, (b) Full System

The DED system is equipped with 2 kW CW fiber laser, twin powder feeder, glove box chamber, gas analyser and five-axis manipulator. The PBF system, uses a CW fiber laser of 500 W power. Both systems have maximum building volume of 250 x 250 x 250 mm^3. Few examples of components, recently developed using LAM facility at RRCAT,

(i) *Honeycomb geometry orifice plate* as pressure drop device in Fast Breeder Reactor (FBR) for enhancing the desired temperature and flow distribution of liquid sodium coolant.

(ii) *Mesh type spacers as* needed in 540 MWe PHWR fuel bundle for fuel cluster simulator.

(iii) *Nickel-Titanium (Ni-Ti) Shape Memory Alloy (SMA) structure as* actuator in micro-pump and valves in Micro-Electro-Mechanical-Systems (MEMS).

(iv) *Other Components:*200µm thick SiC layers on Zircaloy tube and Molybdenum deposition on CuCrZrfor high temperature applications such as ITER.

RRCAT LAM expertise is being shared with other DAE units and the spare capacity will be shared with industry under Incubation policy of RRCAT.

3.5Biomedical applications

A very active and focussed program on Biomedical Applications of Laser/Light sources is being pursued at RRCAT. The aim is to develop novel optical technologies for advanced diagnosis and also for treatment of disease and dysfunction. Active research areas include the development of point-of-care medical devices for improved healthcare.

Table 2 lists the details of some of the recent RRCAT developed healthcare technologies. It is interesting to note that the earlier models of OncoDiagnoScope were based on N_2 laser. However in the latest models, a LED is used as the source of UV radiation.

Table2: RRCAT developed biophotonics healthcare technologies

Devicefor Healthcare application	Functioning	Current status
TuBerculoScope	*Fluorescence imaging device for rapid detection of tuberculosis*	*Technology transferred, 2018, 2 units shared for clinical trials at hospitals in Varanasi*
OncoDiagnoScope	*Optical spectroscopybased point-of-care device for instant non invasive diagnosis of oral cavity cancer*	*Technology transferred, 2019, Validation at cancer screening camps and clinical trials at hospitals*
OncoVision	*Fluorescence imaging tool for identification of malignant and potentially malignant lesions of oral cavity*	*Technology transferred, 2022*
Raman Probe	*In situ measurement of good quality Raman spectra from low Raman active materials like biological tissues*	*Technology transferred, 2018*
NeelBhasmi (नीलभस्मी)	*UV based area sanitization device to inactivate various micro-organisms including corona viruses*	*Technology transferred, 2020. Deployed in many installations.*

RRCAT also developed medical technologies such as '*Green Laser Photocoagulator*' for diabetic retinopathy which was demonstrated and successfully used in hospital. Technology of precision Laser welding of titanium heart pacemaker was developed and transferred to Industry. RRCAT is also pursuing research on non-invasive, in-vivo Raman scattering based differentiation between normal and malignant tissues. Research into Photodynamic therapy and low level laser therapy is also being carried out.

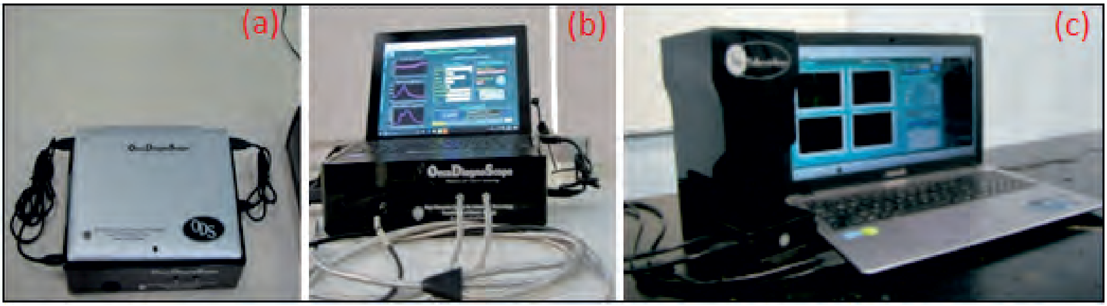

Fig. 10: RRCAT developed healthcaretechnologies, (a) OncoDiagnoScope, (b) GUI for OncoDiagnoScope, (c)TuBerculoScope

3.6 Research and Development Activities in the Advanced Areas Using Lasers

Laboratory facilities are established at RRCAT and BARC based either on in-house developed laser systems or imported laser systems for research and development in advanced areas. This includes setting up of high energy, high power Nd: Glass laser chain for studies at high pressure & temperature. Ti-Sapphire laser system with peak power of 1PW and 25 fs pulse duration is recently commissioned at RRCAT. The high peak power laser systems are used for studies at ultra-high intensity, electron acceleration, wakefield acceleration etc. Ultra-low temperature studies using laser cooled atoms, demonstration of atom chip and Bose-Einstein condensate are also carried out at RRCAT. Laser Interferometer Gravitational Wave Observatory (LIGO) is a much talked Mega-Science project and RRCAT is the nodal agency for establishing the Laser Interferometer Gravitational Wave Observatory in India with other institutes like, IPR (Gandhinagar), IUCAA (Pune) and DCSEM (Mumbai) in collaboration with partners in USA. A site in Hingoli district in Maharashtra state is being developed to set up the LIGO observatory which will complement two similar observatories in the USA. This challenging and prestigious project got in principle approval in 2016. The LIGO facility in India will open up new vistas in the field of science.

4. Concluding Remarks

This article covers the initiation and development of laser program activities in Department of Atomic Energy (DAE). Historical perspective on formation of Raja Ramanna Centre for Advanced Technology, Indore, the premier institute in India in the area of laser is presented. Laser systems developed in RRCAT are briefly covered along with their prominent applications. Overview of Photonics based systems developed at RRCAT, as a part of laser program activity, is given. The machine vision based systems are developed to specifically address the DAE specific requirements whereas the biophotonics systems for societal health applications are outcome of research in the area of lasers in biology and medicine. Research and development activities taken up in the advanced areas using specialized laser systems are briefly indicated. RRCAT/BARC built laser technologies not only supported the departmental projects but has also been applied to the industry and healthcare fields and have been instrumental in creating awareness of the importance of laser field throughout the country.

Acknowledgements

The authors acknowledge the dedicated efforts of all the colleagues in BARC and RRCAT, instrumental for the development and utilization of the laser based technologies as presented in this article. Efforts of trainees, researchers and partners outside the DAE, in developing the laser systems and applications of the laser systems, are duly acknowledged.