Chapter 9

Electron Beam Technology for Environment and Industry

– *Archana Sharma & K. C. Mittal*

In our daily life, any substance that has mass and takes up space by having volume is known as matter. All objects that can be touched can be called matter and matter is composed of atoms. Atom is the smallest unit of ordinary matter that forms a chemical element. Every solid, liquid, gas or plasma is composed of neutral or ionized atoms. An atom is further made up of protons, neutrons and electrons. Electron is the primary carrier of electricity in solids. Therefore, all matter consists of electrons. Soon after its discovery in the late 19th century, its potential for improving the quality of human life has been harnessed in various areas of science and technology. When a solid filament of tungsten or tantalum is heated in vacuum, electrons are emitted. A stream of electrons is known as electron beam. By applying electric and magnetic fields, free electron beam in vacuum can be accelerated to desired energy and deflected in any desired direction to produce a beam with desired parameters. Depending on beam energy, current and size, electron beams have applications in diverse fields of our daily life. Electron beams with energy from few keV to 10 MeV, current from 1 mA to 100 mA and power from 1 kW to 500 kW are currently available for material processing applications. Applications can be broadly divided in two categories: Thermal and Non-thermal. When beam collides with solid state matter, electrons are converted into heat or kinetic energy. This concentration of energy in a small volume can be precisely controlled electronically which brings many advantages leading to thermal applications of electron beams. Here total heat content of the beam is utilized for material applications. At higher energy, while passing through matter, electrons ionize the matter creating positive ions and secondary electrons. The positive ions make new bonds leading to modified properties of the medium. The processes wherein ionization aspects of electron beam are utilized are termed as Non-thermal applications of electron beams. There is another class of electron beam devices with beam energy of 0.1 MeV to 1 MeV and beam power in GW range for sub-microsecond durations. Such beams are converted into X-rays and are employed for industrial radiography and radiography of fast moving objects. This is known as Flash X-Ray radiography.

9.1 Thermal Applications of Electron Beams

Electron beam power density as a heat source is higher than the conventional gas flame and argon arc. The Table 9.1 gives a comparative power density data. Electron beam is generated

Table 9.1: Power Density of Heat Sources.

Sr No.	**Heat Source**	**Power Density (W/cm^2)**
1	Gas Flame $O_2 + C_2H_2$	10
2	Test Flame $O_2 + H_2$	30
3	Argon Arc (200 Ampere)	150
4	Electron Beam	10^3-10^7

in vacuum and the material to be processed is also kept in vacuum. The unique property to carry high energy in a minuscule volume, qualifies electron beam as a “high energy density” source. High energy density is achieved by focusing a high speed (80% speed of light in vacuum) directed stream of electrons to a very small spot. Any metal kept at this spot can reach high temperatures in virtually no time. This phenomenon plays a major role in welding thick metal sections at a much higher welding speeds than conventional methods. Due to high power density, intense electron beam in vacuum can melt materials with high melting points like refractory metals, weld dissimilar materials and can evaporate large volumes of metals for surface coatings. Due to rapid heating, only a surface layer of material is heated leading to applications like hardening, annealing, tempering, texturing and polishing of surfaces.

Electron beams [7, 30] can comfortably handle refractory and reactive metals with much ease than any other conventional technique. Needless to say more, electron beam technology is a game changer in the thermal processing of refractive and reactive metals.
Electron beam melting and welding have been playing an indispensable role in purification, alloying and joining of nuclear grade metals like uranium, zirconium, niobium, titanium to name a few. Owing to processing in high vacuum environment reactive metals like zirconium and titanium can be readily joined by electron beam. A good EB weld always ensures joint stronger than its parent metal. For electron beam evaporation and melting of refractory materials (like niobium, tantalum) in vacuum $< 10^{-4}$ torr for < 1 ppm contamination, 10 keV, 10 kW and 60 kV, 100 kW Evaporators are usually employed. In case of electron beam welding of zirconium, titanium, tantalum, a focused beam with 60-150 keV and power up to 100 kW with a power density of 10^7 W/cm^2 is typically employed. Because of localized heating, very narrow weld with penetration thickness from 0.5 mm to 200 mm can be produced.
Bhabha Atomic Research Centre (BARC), being a research hub of Department of Atomic Energy has established a deployable Electron beam technology for processing of metals and alloys and improving this technology consistently to meet new challenges. To meet the requirements, several electron beam machines have been developed and deployed for applications in nuclear, accelerator, automobile and others.

9.1.1 In Nuclear Industry

EB melting, welding and evaporation of refractory materials is an integral part of any nuclear plant. Figure 9.1 shows a compact electron beam welding machine developed at BARC. A sample of electron beam melted zirconium alloy is shown in Fig. 9.2.

Figure 9.1: An Electron Beam welding machine uses electrons as energy carrier (photograph Ref: www.barc.gov.in) [31].

Figure 9.2: Electron beam melted Zirconium alloy (Courtesy: NFC, Hyderabad).

9.1.2 In Accelerator Industry

Titanium is extensively used in accelerator industry. Being highly reactive metal, it is difficult to preserve the strength of component by conventional welding methods. Electron beam welding is the most sought after method of joining titanium for specialized application where the dimensional tolerances are of extreme importance. EB welding, owing to its low heat input in every mm length of weld, the thermal distortion of the component and strength of weld are never compromised. Figure 9.3 shows EB welded titanium ceramic bonded accelerator tube and Fig. 9.4 shows an EB welded niobium cavity which are deployed in high power superconducting RF accelerators.

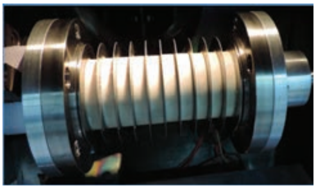

Figure 9.3: EB welded Titanium accelerator tube.

Figure 9.4: EB welded Niobium cavity.

Figure 9.5: EB welding of Automobile Gears.

9.1.3 In Automotive Industry

This industry revolves around use of materials and alloys like carbon steel, inconel and aluminum working in harsh environment like high torque and fatigue load. Benefits of Electron beam welding such as low heat affected zone, defect free high strength welds, ability to weld dissimilar metals, thin to thin and thin to thick sections meet the stringent requirements of this industry. Most importantly the precision weld control and automated weld process increases the productivity many fold with consistent performance of the welded components. Figure 9.5 shows an EB welded automobile gear.

Electron beam processing of metals and alloys has sustained about sixty years in the field of nuclear, accelerator and automobile industry. It has also expanded into space, defense and electrical industry due to its unique and competitive properties. It is now grooming itself in the field of rapid prototyping (aka 3D printing) to face the upcoming challenges in near future.

9.2 Pulse Power Applications for Flash X-Rays Radiography

Flash X-ray sources have higher radiation power than continuously emitting conventional X-ray tubes which makes them useful for the investigation of non-transparent high speed transient phenomena. Flash X-ray sources driven by pulsed power [32] find applications in industrial radiography, and a portable X-ray source is ideal where the radiography needs to be taken at the test site. A compact and portable flash X-ray (FXR) system [33] based on a Marx generator has been developed at BARC with the high voltage fed to the FXR tube via a cable feed-through arrangement. Figure 9.6 displays a photograph of the FXR system composed of the Compact Marx Generator, FXR Tube and the Control Panel.

Hard bremsstrahlung X-rays of few tens of nanosecond duration are generated by impinging intense electron beams on an anode target of high Z material. An industrial X-ray source is developed with source size as low as 1 mm. The system can be operated from 150 kV to 450 kV peak voltages. Figure 9.7 displays a radiograph of the different samples taken using this compact cable fed FXR system.

9.3 Non-Thermal Applications

Non-thermal applications are based on the beam produced ionization in the material. Electron beam is produced in electron gun in vacuum and then accelerated to high energies in vacuum using accelerating electric fields. Industrial electron accelerators which produce

Figure 9.6: A photograph of the FXR system composed of the Compact Marx Generator, FXR Tube and the Control Panel.

beams in the energy range of 100 keV to 10 MeV with average power from 1 kW to 500 kW are finding important radiation processing applications [34–36] in the fields of a) plastic modifications, b) medical products sterilizationsc) food preservation, and d) water and air pollution control. The main advantage of electron beam over gamma rays is the availability of very high power, energy and nuclear radiation free processing. Electron accelerators can handle large throughputs as compared to gamma ray sources. Table 9.2 lists various non-thermal applications of electron accelerator produced beams.

BARC had long back realized the enormous potential of these electron beams for non-thermal applications and chalked out an elaborate program to develop these accelerators. Depending on the product and the type of radiation processing, the requirements of energy and power vary vastly. A single accelerator or one type of accelerator cannot meet such diverse requirements. To cover most of the areas of applications [37], the following three accelerators have been under development at BARC namely: i) 500 keV Cock Croft Walton type multiplier DC accelerator [38], ii) 3 MeV parallel coupled self -capacitance type multiplier DC accelerator [39] and iii) 10 MeV RF Electron Linac [40–42]. These accelerators have been indigenously developed in India with an objective to demonstrate radiation processing applications in industry. Another 5 MeV RF accelerator procured from BINP Russia at BRIT Vashi has also been utilized for industrial radiation processing. Figures 9.8, 9.9 and 9.10 show views of

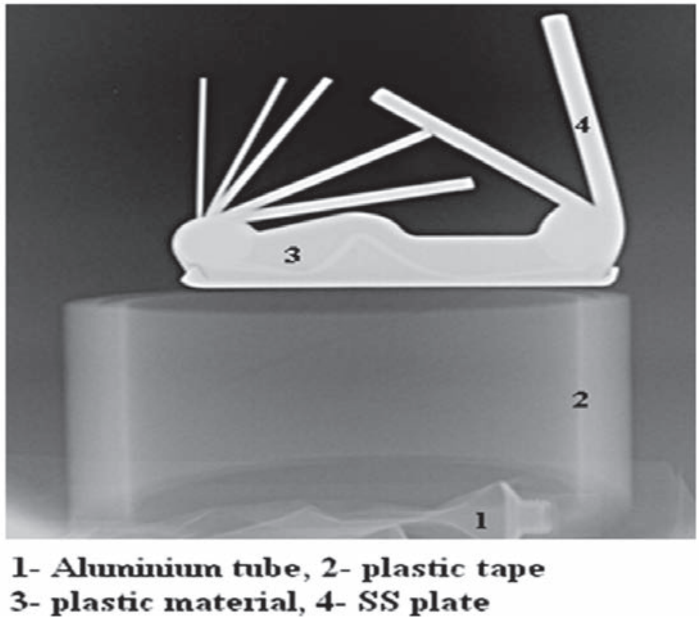

Figure 9.7: Radiograph of a sample. The object radiographed was kept at a distance of 40 cm from the X-ray source window and contains a plastic SS tool kit (part no: 3 and 4 in the image), an aluminium tube with adhesive (part no: 1), and a plastic tape roll (part no: 2).

500 keV, 3 MeV and 10 MeV electron accelerators respectively, developed at BARC. Various applications are discussed below:

9.3.1 Plastic Modifications

a) Polymerization: Low energy (75 keV to 300 keV) electron accelerators are used to cure (polymerize and cross link) coatings, adhesives and inks on paper, plastic and metal substrates. Such materials are monomers which polymerize on electron beam doses of less than 50 kGy. Fiber reinforced composite materials are cured at high energies up to 10 MeV.

b) Grafting: Graft copolymerization of monomers with preformed polymers can be used

Table 9.2: Applications of Electron Accelerators.

Applications	**Energy (MeV)**	**Power (kW)**	**Dose (kGy)**
Cross linking of PE	0.3-10	10	50-300
Lubrication property of teflon	2	10	100-500
Food preservation	05-10	10-100	0.1-10
Sterilization of medical products	01-10	10-50	25-50
Polymerization and curing of surface coatings, adhesives and paints	0.15-0.5	10	20-500
Purification of exhaust gases	0.3-1.5	100	10-15
Vulcanization of rubber	0.5-1.5	30-100	20-500
Exotic colors in diamonds	04-07	10	> 1000

Figure 9.8: 500 keV DCAccelerator with shielding and product conveyor.

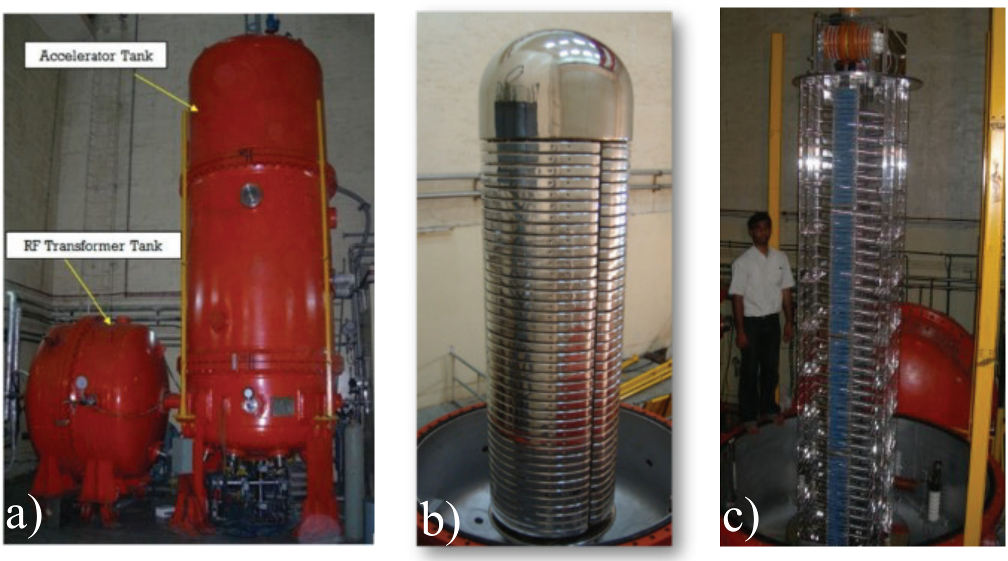

Figure 9.9: a) 3 MeV Accelerator tank, b) 3 MV HV column and c) 3 MV Voltage Multiplier.

to modify the properties of their surfaces. Plastic films, membranes, fibers and textiles are suitable products. Hydrophilic properties can be added to hydrophobic polymers to make permselective membranes. Grafting can improve biocompatibility of polymers for medical applications.

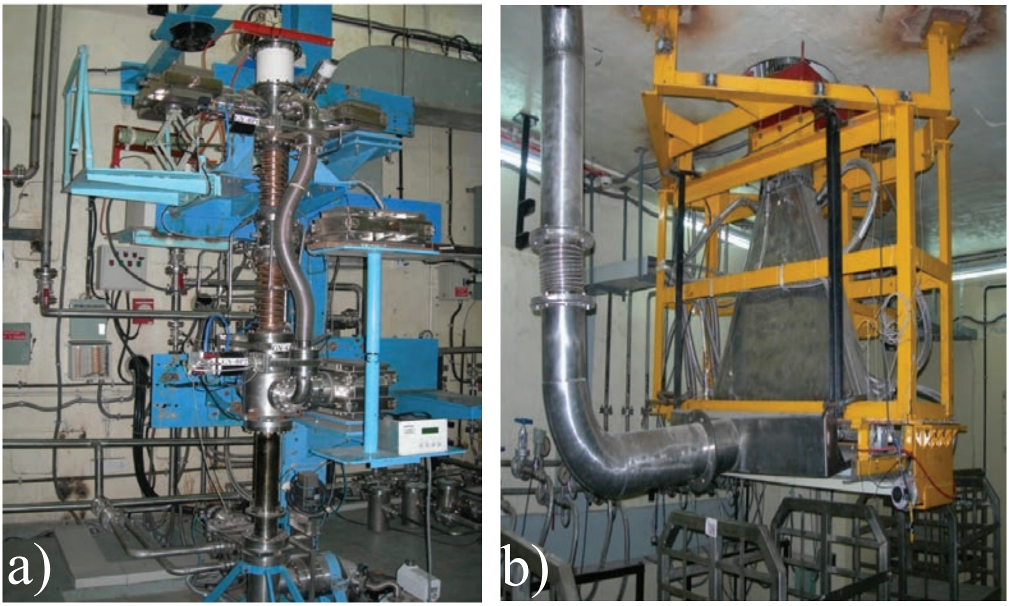

Figure 9.10: a) First Floor View of RF Linac, b) Ground Floor view of RF Linac.

c) Crosslinking and degrading: Electron radiation can ionize the polymers breaking carbon and hydrogen bonds in polymers. Then carbon carbon bond formation results in three dimensional network in the polymeric material that can withstand high temperature and improve material strength. This is known as crosslinking. However, with excess dose, more bonds can be broken which leads to degrading. Insulated wires and cables are crosslinked to improve fire resistance and higher temperature withstanding capability. Heat shrinkable plastic tubing and films, automobile tyres, plastic pipes, plastic foam and hydrogels are other products wherein electron radiation is used. Also PTFE, Cellulose and polypropylene can be degraded with electron dose.

9.3.2 Medical Products Sterilization

The use of electron beams for sterilization of medical products was initiated in 1950s. Since the 10 MeV electron accelerators have been used for sterilizing packaged medical devices. Mid energy accelerators with 3 to 5 MeV have also been used for low bulk density packages. The packages can be irradiated from both sides which increases the penetration thickness to 2.4 times. X-rays produced by electron accelerators have also been employed for sterilization. However, regulation restrict beams up to 7 MeV only. Dose requirements are in the range of 10 kGy to 30 kGy.

9.3.3 Food Preservation

A variety of effects can be obtained by irradiating fresh foods. Low doses in the range of 0.1 kGy to 1.0 kGy can inhibit sprouting of potatoes, onions, garlic, roots and nuts: insects can be disinfested in cereals and legumes, fresh and dried fruits, dried fish and meat; parasites can be disinfested in fresh pork, freshwater fish and fresh fruits; and delayed ripening of some fruits. Medium doses of 1 kGy to 7 kGy can extend shelf life of raw fish and sea foods as well as fruits and vegetables; pathogenic and spoilage bacteria can be eliminated from raw and frozen seafoods, meat and poultry, spices and dried vegetables. High doses of 10 kGy to 30 kGy can sterilize meat, poultry, seafood, sausages, prepared meals etc; natural gums and gels can be decontaminated.

9.3.4 Water and Air Pollution Control

Today most of the tasks are performed by machine. Therefore power consumption per capita has been increased. Most of the power is generated from fossil fuels. The fossil fuels release flue gas (SO_x, NO_x, CO_2) in the atmosphere, the increasing usage of these fuels to meet increasing demand of power will lead to doubling the concentration of pollutants in atmosphere in the coming 50-75 years that may lead to severe climate changes. Expansion of various industries like chemical, textile, refinery, foundry in urban area has lead to pollution of water bodies as most of the waste effluents are discharged directly which are non-biodegradable. This is harmful to human population as well as marine life which disturbs ecology.
High power electron accelerators with energy of 0.5 MeV to 10 MeV and power from 1 kW to 100 kW are being employed for pollution control in the exhaust of thermal power stations (SO_x/ NO_x) as well as for treatment of sludge for safe disposal. It has been found that a dose of 0.2 kGy to 1 kGy is sufficient for treatment of ballast water. Therefore, it is suggested that electron accelerators can be installed at ports for treating ballast water from the ships.

9.3.5 Non-Thermal Applications of EBs at EBC Kharghar

A. Surface Modifications and Radiation Damage Studies at Low Energy (< 500 keV)

500 keV facility was utilised for industrial applications. Several products viz. PE granules from Reliance industry, Graft-polymerization for rubber tiles from SBC, paint curing on wood laminates etc. have been treated. Product conveyor can handle roll of thin sheets as well as batch-processing of items up to 1 m x 1 m size. Recently, samples of Solar penal structural materials were irradiated for long time of electron-fluence damage study. Treatment of cloth fabric samples from Bombay Textile Research Association (BTRA) Mumbai for improvement of properties of clothe fabric has also been demonstrated.

B. Flue Gas Treatment at 1 MeV Electron Beam

Flue gas is emitted in thermal power generation by burning fossil fuels like coal, diesel, natural gas etc. Besides CO_2, the other atmospheric pollutants are the oxides of sulphur and nitrogen usually known as SO_x and NO_x. Experiments on flue gas treatment by EB have been conducted in 1 MeV. Flue gas was simulated by producing CO_2 from the combustion of LPG and then diluting it with air. External cylinders of SO_2, NO_2, NH_3 were used to introduce these gases into the main flow in a controlled manner by using mass flow controllers along with water (to maintain humidity). Highly reactive OH free radicals, as a result of EB interaction with humid water droplets, have been produced. It reacts with the pollutants to produce sulphuric acid and nitric acids which ultimately leads to ammonium sulfate and ammonium nitrate (useful fertilizers) as neutralized by ammonia in the moist environment. The optimized dose is 15 kGy to achieve highly efficient removal of SO_2 and NO_2. The demonstration experiment was done in collaboration with BHEL Ranipet. Figure 9.11 shows the concept of electron beam flue gas treatment facility. Figure 9.12 shows the facility and results of SO_2 and NO_2 reduction as a function of beam current. Significant reduction was observed. These results show that Flue Gas treatment facilities can be set up using electron accelerators.

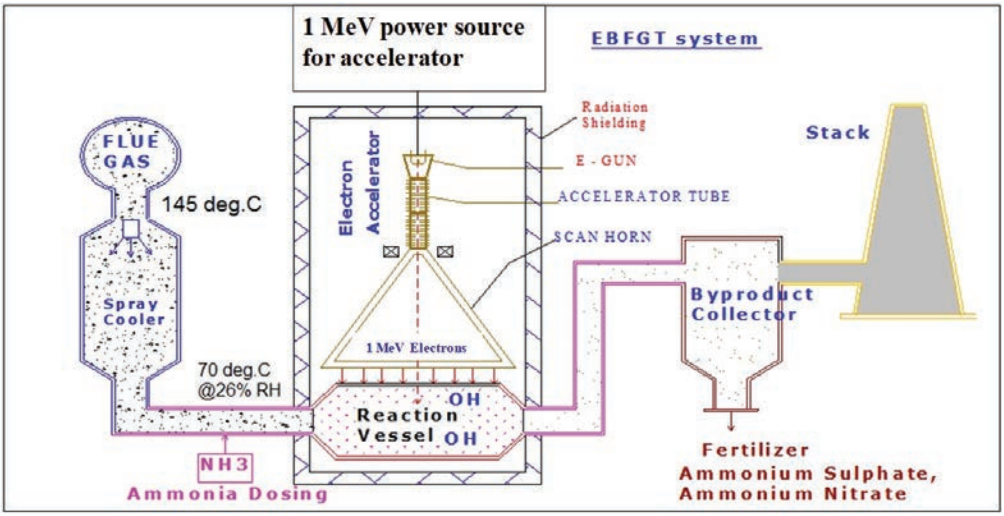

Figure 9.11: Concept of Electron Beam Flue Gas Treatment Facility.

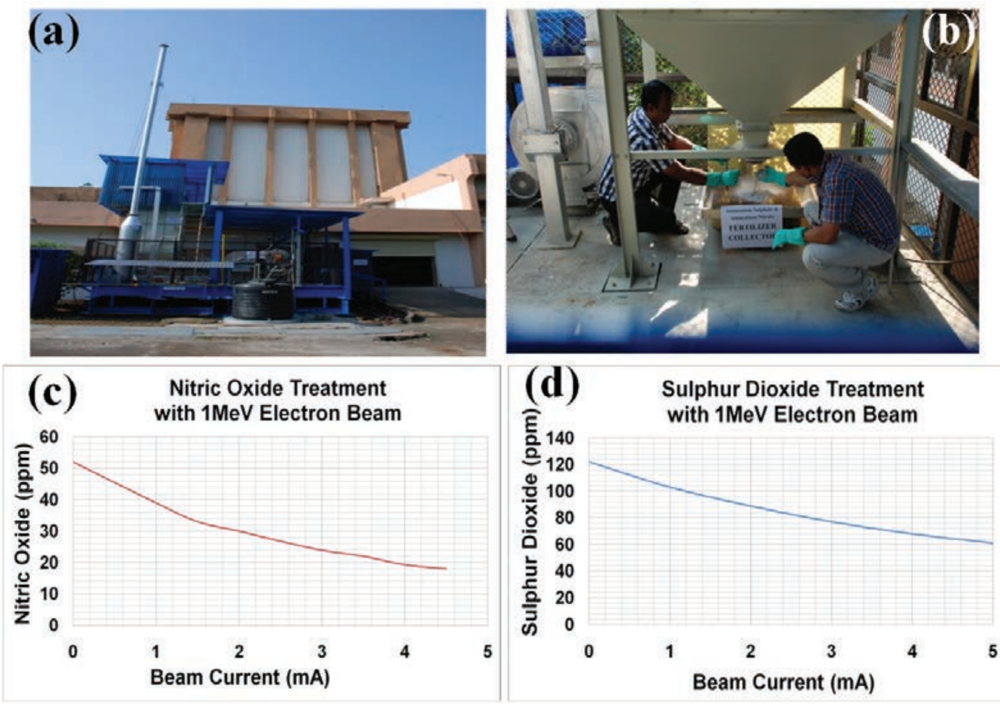

Figure 9.12: (a) Experimental set up, (b) experiments, (c) & (d) results of EBFGT done at EBC.

C. Waste Water Treatment

Waste water discharged by dyeing and textile industries pollutes natural water and deteriorates its quality. In textile industry, water is used for cleaning raw materials and for many flushing steps. Textile waste water includes a large variety of dyes and chemical additives those make environment polluted. The pollution from textile industry mainly comes from dyeing and finishing processes. These dyes are generally organic compounds having complex structures. Azo-dyes are among the most widely used synthetic dyes and usually become major pollutants in these wastewaters. As these dyes are having complex chemical structure they cannot be degraded easily by ordinary chemical treatments. Most textile dyes are photochemically stable and refractory towards chemical oxidation and these characteristics render them resistant towards decolourisation by conventional biochemical and physico-chemical methods. In this regard, various approaches have been forwarded to decontaminate these effluents. Ionising radiation is a promising tool for the treatment of textile dye effluents and attracted considerable attention in the recent years. The radiolysis of water is very well documented and it has been known that it produces primary free radicals like, hydroxyl radicals (OH^*), hydrated electrons (e^-_{aq}), hydrogen atom (H), and molecular products like, H_2, H_2O_2, HO_2, H_3O^+ in varying amounts depending upon the linear energy transfer (LET) value of a particular radiation. Radiation induced degradation of textile dyes such as, procion MX-8G

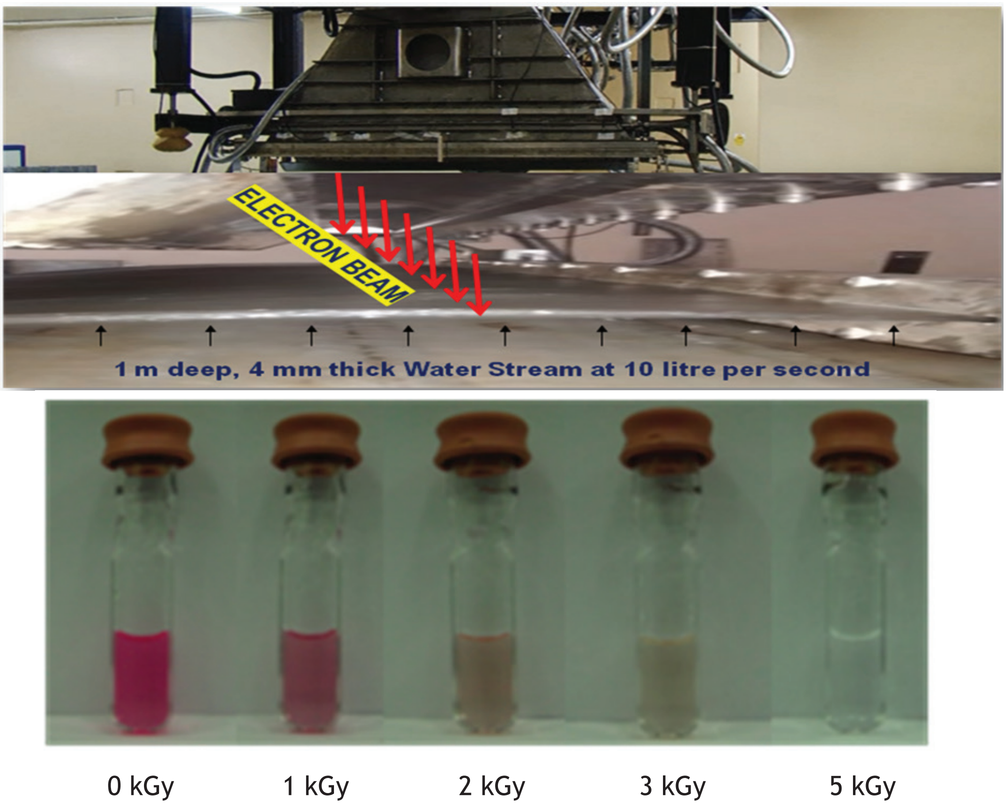

Figure 9.13: (Top) Experimental Set Up, (Bottom) Decolouration of dye with dose.

(yellow), procion-MX-8B (Fuchsia) and procion-MX-G (Torquoise) and the mechanism of their degradation have been investigated for various parameters [43]. Photograph shows the experimental results performed on 'procion-MX-8B'. With increase in electron beam dose, decoloration of the dye is observed. This occurs due to Azo (N=N) bond breakage. As an effect of radiation, complex organic dye is converted to biodegradable fragments. Therefore, electron beam technology can be employed for waste water treatment. At EBC Kharghar, a 1 MeV, 100 kW Electron Beam Waste Water Treatment (EBWWT) an industrial demonstration system is being developed for reducing COD/BOD levels of effluents and dye water on industrial scale to treat 1-2 MLD of water.

D. Chitosan Irradiation for Enhanced Sugarcane Production

Chitosan is most promising biological macromolecule, derived from chitin, having biodegradable and non toxic properties. It is used as bio-stimulator (natural plant growth promoter) for sugarcane. It provides better germination, proper tillering of plant and regulates photosynthesis through minimizing the transpiration from leaves & stabilizing chlorophyll levels. The chitosan (mixed with 1% acetic acid) was irradiated with optimized 10 MeV electron beam (EB) at optimized dose point of 50 kGy and it was observed that the sugarcane production enhanced by 1.3 times as compared to un-irradiated chitosan. The irradiated chitosan is used twice in sugarcane field, one is before sowing the seeds and another is when the tillering of plants was over. This is successfully carried out for actual field application in collaboration with Vasantdada Sugar Institute (VSI), Pune and NABTD, BARC. Figure 9.14 shows the impact of radiation on plant growth.

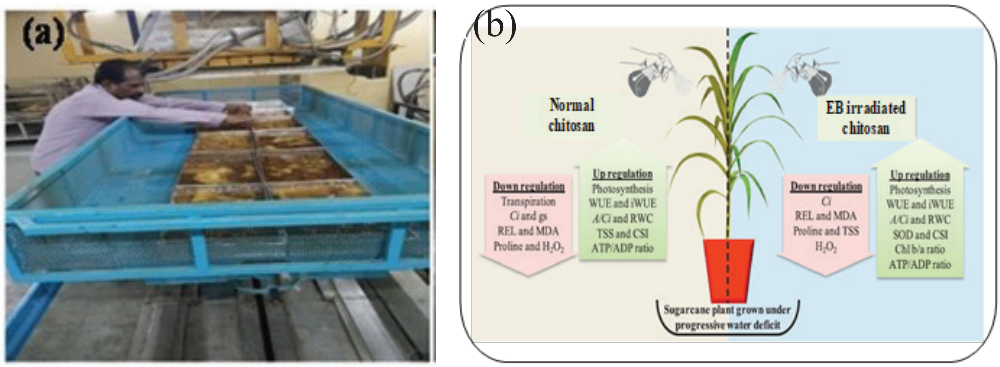

Figure 9.14: a) Chitosan sample under the beam, and b) Normal and EB irradiated chitosan impact on sugarcane plant.

E. Food Preservation

10 MeV EB has been used to carry out the irradiation (in collaboration with FTD, BARC and ApSD, BARC) of dried apricot and quince with dose up to 4 kGy in steps of 1 kGy to enhance the physico-chemical and antioxidant characteristics. The rehydration ratio, i.e. water holding capacity, decreases from 0.84 to 0.76 leading to enhancement in shelf life. In addition the study suggests that sugar content increase up to 20% along with β-carotene after irradiation. Thus the EB treatment also enhances the nutritionally rich and biologically active constituent in these dry fruits. An example of radiation effect on coriander powder is shown in Fig. 9.15.

F. Semiconductor Irradiation for Industry (Power Diode Irradiation)

The irradiation of power diode rated 2.6 kV, 700 A, used as switching device in turbo generators of Bharat Heavy Electricals Limited (BHEL), has been done in 10 MeV. The reverse recovery time (trr) was reduced from 15 μs to 6 μs after delivering 4 kGy optimized dose. In

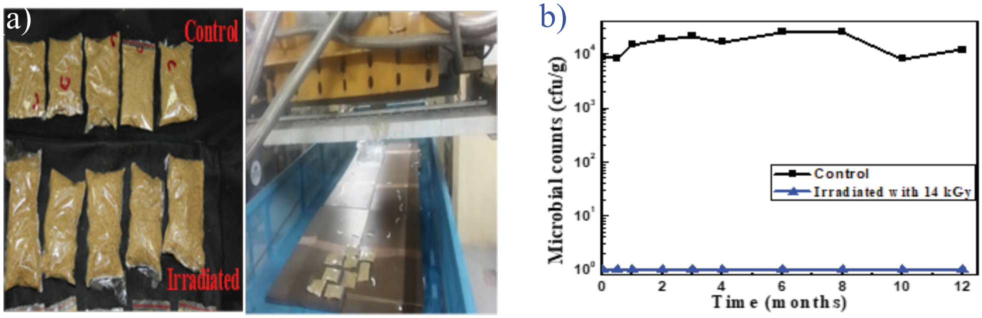

Figure 9.15: a) Coriander Powder Irradiation in 10 MeV Linac at EBC, and b) Microbial counts for un-irradiated and irradiated coriander powder 12 months.

addition leakage current is around 20 mA and forward voltage drop is 2.0 V in comparison to 150 mA and 2.3 V achieved through gold doping. Figure 9.16 shows the results of beam irradiation on diode performance. This is the first time an EB accelerator is used for control of semiconductor device parameters in India. With this facility, the required exposure time is found to be much shorter ($\sim$ 25 s) to complete one batch processing containing around 200 diode chips. The whole exercise is exemplary of joint partnership between industry and research institution.

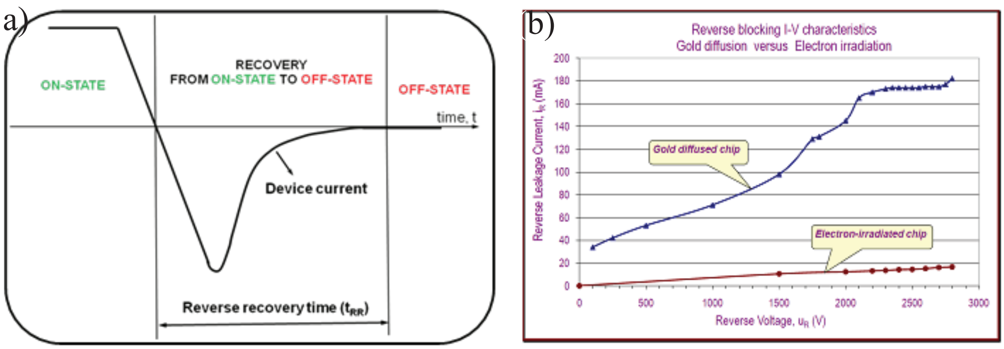

Figure 9.16: a) Reverse recovery process in a diode, and b) Comparison of Gold diffusion and irradiated Diode.

G. Radiation Hardening Studies of Solar Cell

The radiation hardening studies of multi-junction solar cells, InGaP/GaAs/Ge, have been done for ISRO. In outer van-allen belt of space (at 13000 km to 60000 km from the earth) the electron (having energy 0.1-12 MeV) fluences is in the order of 10^{13} electrons/cm^2. The communications satellites are located at height of 36000 km, called geosynchronous orbit. For a period of 15 years (normal life of satellite) it receives 10^{15} electrons/cm^2. This much fluence has been delivered with 10 MeV and 1 MeV accelerators and the study concluded that the efficiency falls from 28% to 18%. This scientific investigation helps ISRO to plan the solar panel matrix on a satellite.

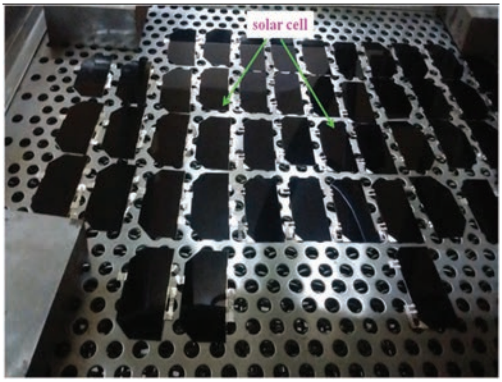

Figure 9.17: Solar cell irradiation at 10 MeV.

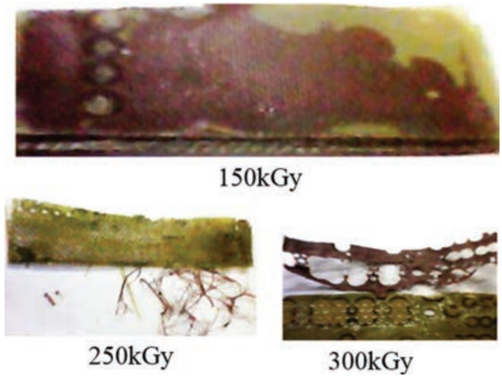

Figure 9.18: EB irradiated sample of PCB.

H. Electronic Waste Disposal

Printed circuit board (PCB) disposed from scarped electronic devices like computers, TVs, mobiles etc, have become a major threat as electronic waste. It has been demonstrated that the adhesion between base and top layer (metallic) of PCBs was broken and pure copper will be recovered through EB irradiation. The irradiation was done with 10 MeV up to dose of 350 kGy, the copper can be pulled off from PCB which is 99.9% pure and fully reusable. Post copper removal the PCB becomes easily degradable. The process can be carried out in actual atmospheric condition without use of any chemical catalysts. This experiment was demonstrated on Lab. Scale with active support of Institute of Chemical Technology, Mumbai and Radiation Technology Development Division of BARC. It can be seen from Fig. 9.18 that copper foil and the copper circuit can be removed from the composite board without any trouble. Also since no harsh environment or process is used, quality and quantity remains good.

I. Diamond Colouration

Electron beam irradiation induces exotic colours in diamonds and gemstones at very high dose. Figure 9.19 shows results of some experiments carried out at ILU6 facility at BRIT, Vashi and at EBC, Kharghar.

J. Industrial Radiography of Thick Steel

Radiography experiments were carried out using 6 MeV Linac with a steel step block having thickness 100 mm to 200 mm with 25 mm step thickness. The radiography parameters such as thickness range, sensitivity and focal spot size have been evaluated by means of both wire type (ASTM E 747) and hole type (ASTM E 1025) penetrometers. The achieved sensitivity is 2% and the focal spot size is $\sim$1 mm. It was concluded that the 6 MeV Linac (developed at EBC) is suitable for radiography of materials having thickness up to 200 mm steel equivalent.

K. Cargo Scanning

6 MeV Linac, developed by APPD, has successfully been qualified for cargo scanning applications through which imaging of the cargos is carried out to prevent the transport of contraband objects [44, 45]. The internal images of actual cargos were generated, at BARC site, with 6 MeV Linac producing X-ray dose rate 1 Gy/min at 1 m. 6/4 MeV dual energy

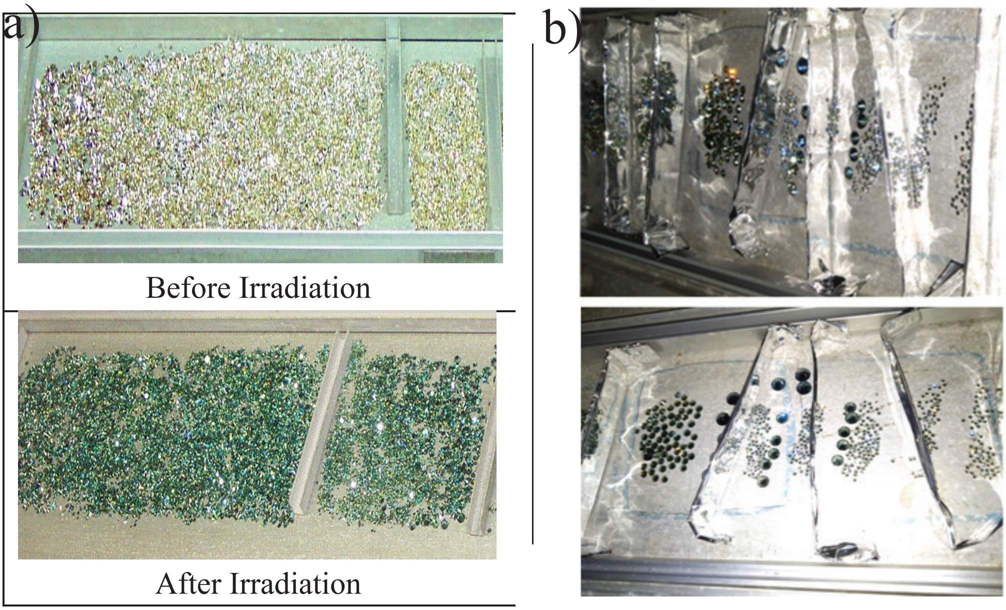

Figure 9.19: a) Diamonds irradiated at ILU6, and b) Gemstones irradiated at EBC Kharghar.

Linac can distinguish between low and high density materials in the image. Figure 9.20 shows a dual energy Linac developed at EBC. It is major application of electron Linac on security front.

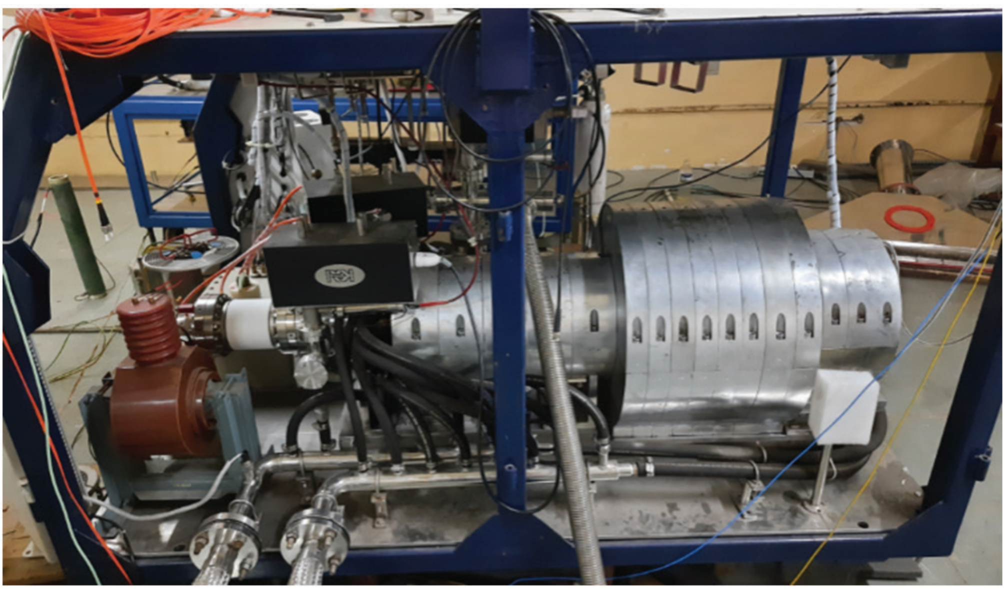

Figure 9.20: 6/4 MeV dual energy linac.

L. Organic Film Based Irradiation Studies

10 MeV accelerator was utilized to tailor the electrical and mechanical characteristics of organic films [46, 47] as insulating (BOPET) and semiconducting like molecular semiconductor (zinc phthalocyanine, ZnPc) & conducting polymers (PANI, PEDOT), with emphasis to deploy the modified films for device applications such as gas sensors and radiation dosimeters. The enhancement in mechanical properties of BOPET with 8 kGy dose has been achieved that makes it better packaging materials for food & medical product radiation sterilization

9.4 Conclusions

Electron beams have many applications in all fields of our daily life. Depending on beam energy and power, beams play different roles for material processing. At low energy and high power, beams are a very efficient sources of heat that can be manipulated to required shape for processing. When focussed, they are utilised for welding, when spread over large area, they are efficient source for melting and evaporation. Gigawatt pulsed (sub μsecond) beams are employed for radiography of thick objects and also for fast moving objects. High energy high power beams produced in electron accelerators employ ionisation aspects of electrons for material processing. For energies less than 500 keV, they are employed for modification of material surfaces. For energies $>$ 500 keV and less than 3 MeV, the beams have several industrial applications like crosslinking of polymers for electrical cable insulation etc. Beams with 5 MeV to 10 MeV compete with the Co-60 and Cs-137 Gamma sources for radiation preservation of food products and medical sterilisation. Unlike gamma sources which always remain ON, electron accelerators can be put ON and OFF at will. Electron accelerators are inherently safe compared to risk of theft. As a result, use of electron accelerators is increasing in the world at a faster rate as compared to Co-60 sources.

Acknowledgements

This article is basically a compilation of inputs collected from a large number of scientists from Beam Technology Development Group of BARC and many other Divisions of BARC who participated in collaborative experiments. The authors thank all those who contributed for preparation of this article.