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APPLICATIONS OF HIGH ENERGY ELECTRON ACCELERATORS FOR DIVERSE SOCIETAL FIELDS: PRESENT, FUTURE & CHALLENGES

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Abstract

Electron beam has established an imperative role in the field of radiation treatment to modify physico-chemical characteristics of materials which requires to cater the different societal needs. Applicability of electron accelerators has created huge interest among researchers of various areas in last few decades. The driving force in this regard is reliability in interaction of electron beam with materials. The inimitable part of electron beam treatment is its full controllability and the treatment implementation on the final stage of product, even post packaging at normal atmospheric conditions. These make it very attractive over the conventional alternative approaches including chemical treatments, autoclave etc. In the present document we emphasize the utilization of electron accelerators, at EBC, BARC, in diverse fields like agriculture, semiconductor industries, polymers, food preservation, waste management, material science, radiography & security and other basic researches. The scopes of futuristic development, in this field, along with associated challenges are also elaborated.

Key words: Chitosan, diodes, dose, conducting polymer, dosimeter, radiography, cargo scanning.

बहुमुखी सामाजिक क्षेत्रों मे इ बी सी स्थित उच्च ऊर्जावान इलेक्ट्रान त्वरको की उपयोगिता: वर्तमान, भविष्य और चुनौतियाँ

निशान्त चौधरी, आर बी चव्हाण, डी भट्टाचार्जी, मुकेश कुमार, पी सी सरोज, अर्चना शर्मा
इलेक्ट्रान बीम केंद्र, त्वरक एवं स्पंदक शक्ति प्रभाग
भाभा परमाणु अनुसंधान केंद्र, मुंबई

विकिरण प्रसंस्करण द्वारा पदार्थों के भौतिक-रसायानिक गुणों के संवर्धन क्षेत्र में त्वरित इलेक्ट्रान तरंगों का महत्वपूर्ण स्थान है जिससे विभिन्न सामाजिक जरूरतों को सम्पोषित किया जाता है। विगत कुछ दशकों में इलेक्ट्रान त्वरकों की अति उपयोगिता ने वैज्ञानिक समुदाय में काफी दिलचस्पी पैदा की है। इस क्षेत्र में उत्प्रेरक बल का कार्य इलेक्ट्रान बीम और पदार्थों के बीच विश्वसनीय संस्क्रिया करता है। इलेक्ट्रान बीम प्रसंस्करण विधि की मुख्य विशेषता इसका पूर्णतः नियंत्रित और अनंतिम डिब्बबंद अवस्था में सामान्य वातावरण अंतर्गत निष्पादित होना है। इन विशेषताओं के कारण ही यह काफी लोकप्रिय बन चुका है खासकर सामान्य दूसरी प्रक्रियाओं जैसे रसायनिक, ताप-दाब सन्चलन और यहाँ तक की गामा किरण प्रक्रिया। प्रस्तुत आलेख में हमलोग इ बी सी, बी ए आर सी, स्थित इलेक्ट्रान त्वरको की विभिन्न क्षेत्रों जैसे कृषि, पॉलीमर, अर्धचालक उपकरणों, खाद्य प्रसंस्करण, परित्यक्त पदार्थ व्यवस्थापन, पदार्थ विज़्यान, पदार्थ अन्तः संरचन, सुरक्षा एवं अन्य सामान्य अन्वेषणों में उपयोगिता का जिक्र कर रहे हैं। तदनन्तर इस क्षेत्र में भविष्य संवर्धन अवसरों के साथ सम्मिलित चुनौतियों को भी व्याख्यापित किया गया है।

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1. INTRODUCTION

In last few decades, the techniques to tailor the characteristics of materials for societal benefits, using electron accelerators, have become very popular and economical. It has more public acceptability and outweighs over gamma irradiation or other techniques (like chemical, thermal etc.) because it is simple and capable to deliver kGy dose levels in few seconds [1]. The unique aspect of electron beam treatment is that it is carried out on the final stage of production, even post packaging at normal atmospheric conditions, which makes it very attractive over the conventional alternative approaches including chemical treatments, autoclave etc. Therefore the utilization of electron accelerators has also become very hot topic among researchers of various areas to modify the physico-chemical characteristics like electrical, mechanical and thermal properties of organic as well as inorganic materials. Highly reliable interaction is the key driver for the EB accelerator technology and also the fully controllable nature of the system leads to safe atmosphere. Electron accelerators have the ability to produce dose rates ranging from a few Gy/s to 10^6 Gy/s and also to provide a large energy range from 300 keV to 10 MeV. In all application fields, other than research, the electron beam energy is limited up to 10 MeV to avoid the possibility of induced radioactivity [1 & 2]. When the energetic electrons are impinged onto the materials, the amount of radiation energy absorbed per unit mass is known as radiation dose (D) and is measured in joules per kg or gray (Gy). The quantification of induced chemical changes in a material is referred as "G" values, called radiation chemical yield. G value is expressed in terms of the number of molecular events arising per 100 eV of energy absorbed in the medium. D and G are related by: D (kGy) = 9.65×10^6 / (G × mol. wt.). For many reactions, G-values are typically ranging 0.1 - 10. It is evident from the relation between D and G that why most of industrial applications of electron-beam are focused on organic materials with high molecular weights instead of inorganic materials [1]. In case of organic materials the dose required is small as compared to inorganic counterparts in which it requires very high to carry out same modifications. The organic materials absorb radiant energy and active species (such as radicals) have been created, which in turn, initiate various chemical reactions. In the present report we describe few important applications of electron beam accelerators done at EBC for last few years in diverse fields including agriculture, semiconductor industries, food preservation, waste management, radiography, security, material science and other basic researches. Afterward we discuss future prospects of some electron beam application technology along with the possibility to transform it from experimental to industrial level. Finally, we present the planning and associated challenges to develop in house characterization facilities.

2. APPLICATION OF ELECTRON BEAM ACCELERATORS: PRESENT

2.1. Agriculture Field for Sugarcane Production (Chitosan Irradiation)

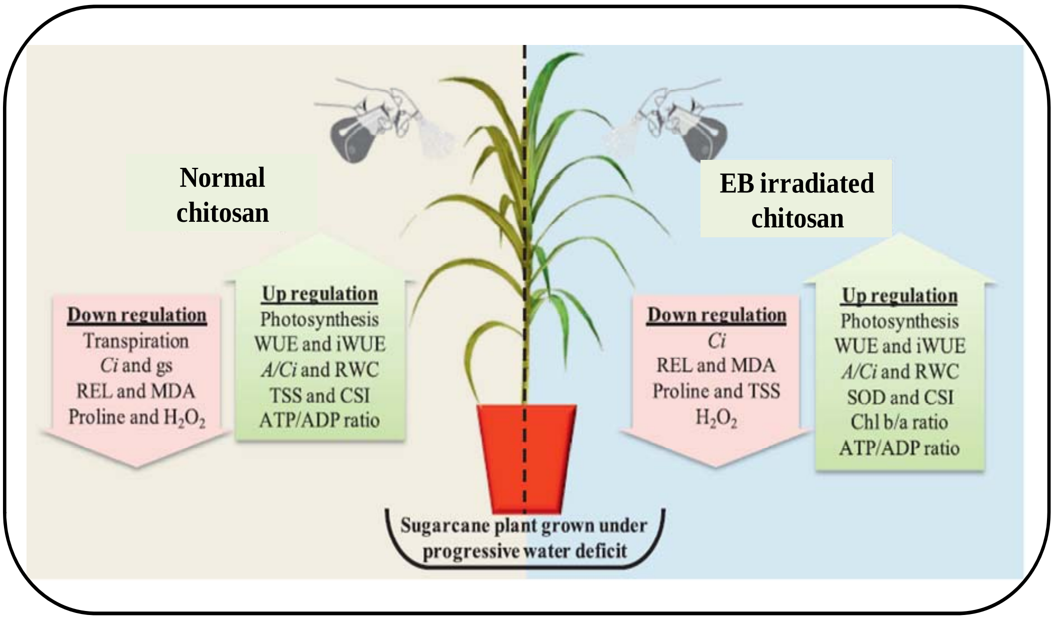

Fig.1. Electron beam treated chitosan provides better germination, proper tillering of plant and regulate photosynthesis.

Chitosan is the 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 plants and regulates photosynthesis through minimizing the transpiration from leaves and stabilizing chlorophyll levels, shown in (Fig.1). The chitosan (mixed with 1% acetic acid) was irradiated with 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 two times in sugarcane fields, one is before sawing the seeds and another is when the tillering of plants were over. This is successfully carried out for actual field application in collaboration with Vasantdada Sugar Institute (VSI), Pune and NABTD, BARC. Presently 10 MeV Linac facility has been used to irradiated chitosan on large scale for actual field applications in collaboration with VSI, Pune. The irradiation of chitosan at EBC and view of accelerator operation are given in (Fig.2).

Fig.2. (a) & (b) Placement of chitosan sample on to & fro conveyor system, (c) 10 MeV Linac control room

2.2. 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 (t_{rr}) was reduced from 15 μs to 6 μs after delivering 4 kGy optimized dose, as depicted in (Fig.3). In addition leakage current is around 16 mA and reverse voltage is 2.0 kV whereas the same have been achieved through gold doping to 160 mA and 2.3 kV respectively (Fig.4). 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 (~ 25 s) to complete one batch processing containing around 200 diode chips. The whole exercise is exemplary joint partnership between industry and research institution.

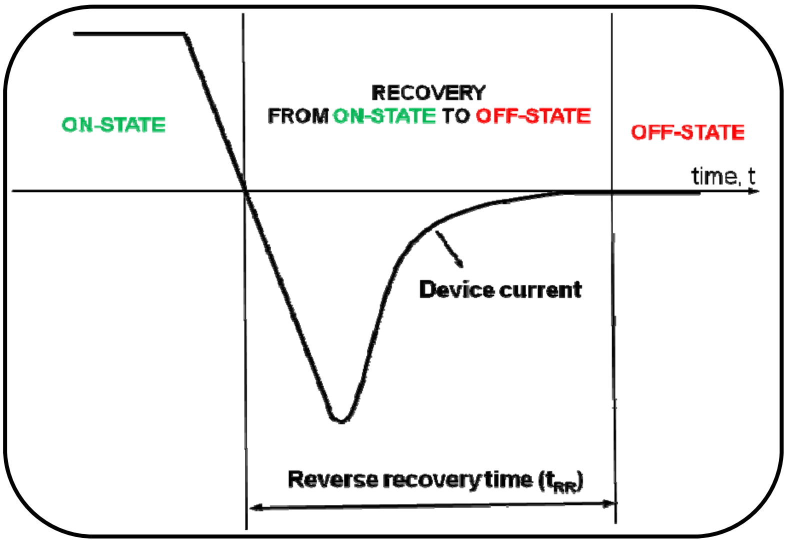

Fig.3. Reverse recovery process in a semiconductor device.

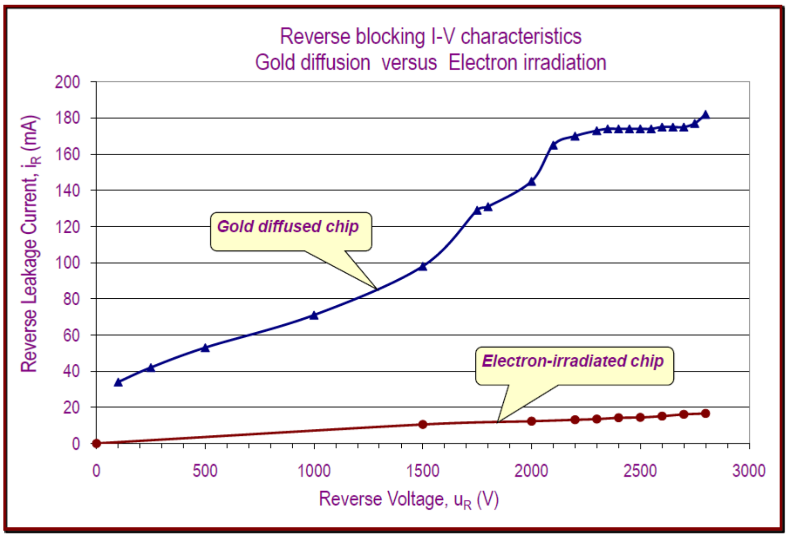

Fig.4. Gold diffusion resulting in higher leakage current compared to 10 MeV EB irradiation process.

2.3. Radiation Hardening Studies of Solar Cells

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 to 60000 km from the earth) the electron (having energy 0.1 -12 MeV) fluences is in the order of 10^{13} e^{0}_{-1} /cm^2. The communication satellites are located at height of 36000 km, called geosynchronous orbit. For a period of 15 years (normal life of satellite) it receives in order of 10^{15} electrons /cm^2. This much fluence has been delivered with 10 MeV and 1 MeV accelerators and the study has concluded that the efficiency falls from 28 % to 18 %. This scientific investigation helps ISRO to plan the solar panel matrix accordingly, on a satellite. Fig.5 depicts multi-junction solar cells irradiation at EBC.

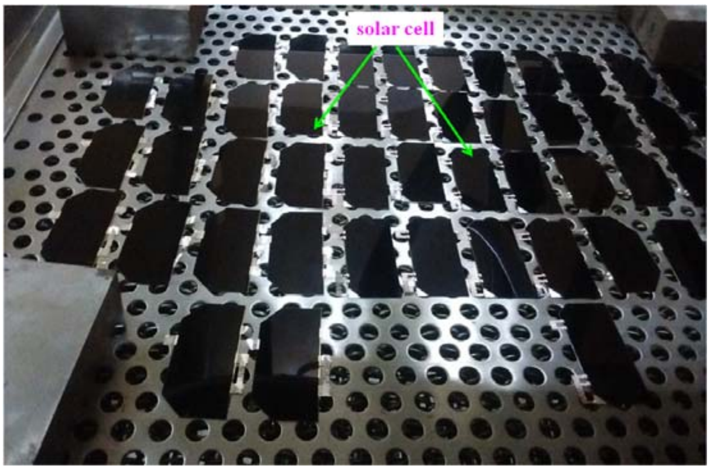

Fig.5. Solar cells irradiation in electron accelerator at EBC.

2.4. Nodular Corrosion Analysis for Zirconium Alloy

Zirconium (97.5%) and niobium (2.5%) alloy is used as pressure tube in pressurized heavy water nuclear reactors to hold fuel bundles and carry the heavy water in CO_2 environment. The oxidation of this metal alloy, in presence of high radiation field and in simulated reactor conditions, has been analyzed using 10 MeV EB. The accumulated dose delivered to the sample is around 400 MGy at rate of 1.0 MGy/h. The signature of oxidation in alloy was observed after imparting dose of 150 MGy and it is growing as dose increases. The experiment is still continuing jointly with RED, BARC and ChD, BARC and the exclusive conclusions are awaited.

2.5. Food Preservation

The irradiation of food products like potato, mango, semolina, dry fruits, spices and coriander powder, to achieve preservation goal, have successfully been done using 10 MeV electron beam at EBC, Kharghar. The doses delivered to these products are limited in the window of 0.4 – 14 kGy. The experimentally achieved dose uniformity ratio allows the facility to be used for food irradiation on large scale.

Dried apricots and quinces were irradiated with dose up to 4 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 self life. In addition the study suggests that sugar content is increased up to 20 % along with β-carotene after irradiation [3]. Thus the EB treatment also enhances the nutritionally rich and biologically active constituent in these dry fruits.

The irradiation of dry spices like coriander powder with 14 kGy optimized dose was also done, shown in (Fig.6). Post irradiation microbial count analysis was done using dilution method at regular interval in a span of 1 year. The analysis concluded that the microbial count remains nil even after 1 year post irradiation storage under normal room conditions (Fig.7). It settles that the storage life (in room conditions) of spices enhanced up to 1 year by irradiating with 14 kGy, which is important since the food production cycle in India is of 1 year.

Fig.6. Coriander powder irradiation in 10 MeV at EBC.

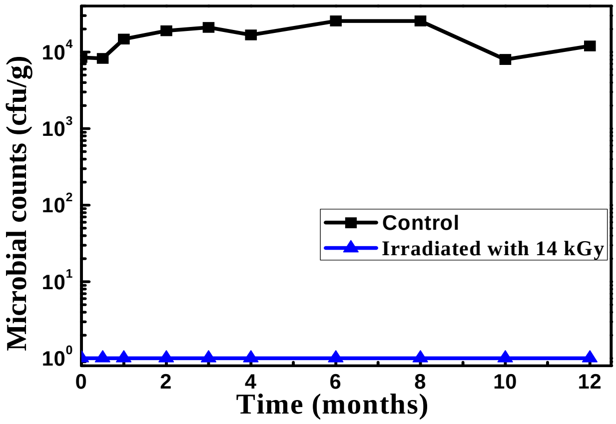

Fig.7. Microbial counts for un-irradiated and 14 kGy EB irradiated coriander powder in 1 year span.

2.6. Waste Water Treatment

EB treatment has been used to reduce Chemical Oxygen Demand (COD) from textile as well as municipal waste water. This is an Advance Oxidation Process (AOP) to mineralize or degrade the heavy organic molecules present in dye. EB dose of 75 kGy has been delivered, to achieve 90% mineralization in simulated textile dye water in presence of potassium persulfate solution (4×10^{-2} mol/dm^3). COD achieved in the dye water is less than 100 ppm (well below the allowed limit of 250 ppm) with respect to original COD around 2500 ppm in un-irradiated water [4]. It has also been proven that EB treatment is more economical than other AOPs including ozonolysis, UV treatment, gamma radiolysis and photo-catalysis.

2.7. Electronic Waste Disposal

Printed Circuit Board (PCB) disposed from scraped electronic devices like computers, TVs, mobiles etc, have become major threat as electronic waste. It has been demonstrated that the adhesion between base and top layer (metallic) of PCBs is broken and pure copper has been recovered through EB irradiation. The irradiation was done with dose of 300 kGy. Post EB irradiation, copper pulled off from PCB which is 99.9% pure and fully reusable and the remaining components of PCB become easily degradable (Fig.8). The process is carried out in actual atmospheric condition without use of any chemical catalysts.

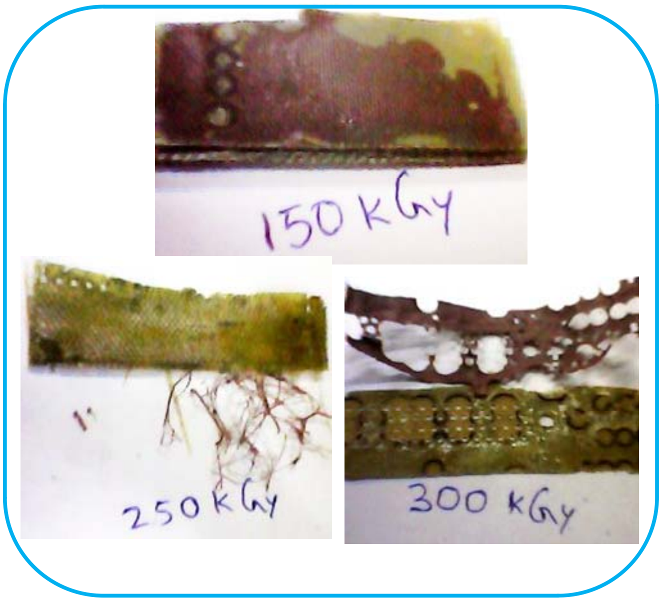

Fig.8. 150, 250 and 300 kGy EB irradiated samples of PCB.

2.8. Radiography

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 (Fig.9). 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) penetrameters [5 & 6]. The achieved sensitivity was 2% and the focal spot size was ~ 1 mm [7]. It was concluded that the 6 MeV Linac (developed by APPD, BARC in house) is suitable for radiography of materials having thickness up to 200 mm steel equivalent.

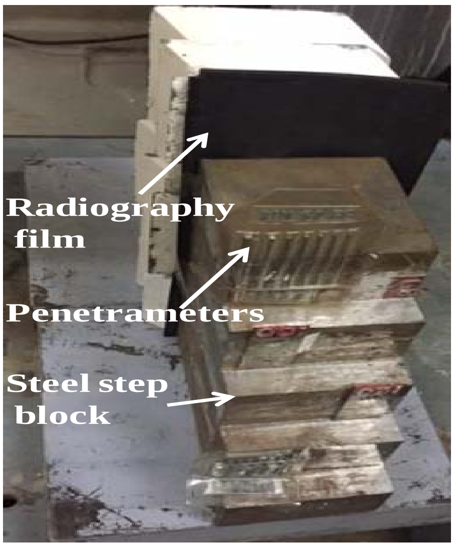

Fig.9. Exposure arrangements of steel step wedge block for radiography at EBC.

2.9. 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. 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. It is a major application of electron Linac on security front.

2.10. Organic Film Based Device Modifications & Developments as Research Applications

10 MeV accelerator is utilized to tailor the electrical and mechanical characteristics of organic films, 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 [8]. The linear rise in electrical conductance of 20 nm ZnPc flexible thin films up to 18 kGy dose makes it potential radiation dosimeter [9]. PANI-Ag nano-composite films exposed to 10 MeV EB with dose of 30 kGy, that enhances its electrical conductivity by two orders of magnitude [10]. In addition its sensitivity towards ppm level of H_2S gas has been improved after EB irradiation. The conductivity and thermoelectric power generation capacity of flexible films of conducting polymer PEDOT:PSS have also been improved with 10 MeV EB treatment up to 25 kGy dose which enables it as potential radaition dosimeter [11].

3. APPLICATION OF ELECTRON BEAM ACCELERATORS: FUTURE PROSPECTS

3.1. Cargo Scanning

The internal image of cargo has successfully been produced with x-ray generated by 6 MeV Linac. This energy range of x-ray photons (i.e. MeV) give only shape related signature of the material and not any identification. The material discrimination can be possible by using x-ray having two different end point energies as the attenuation of same material is different for separate energies. Based upon the attenuation ratio, it is possible to identify material because it is function of atomic number. Thus a Linac is required which is able to generate electron beam of distinguishable energies with pulse to pulse variation.

In order to identify the two energy limits, several iterations and literature surveys have been done and it was concluded that energies should be 6 MeV (called high energy) and 3-4 MeV (called low energy). Considering this a dual energy Linac has been designed and developed by APPD and its dosimetry characterizations were carried out at EBC which includes the x-ray dose profile generation, energy point identification for both low and high mode, beam spot size measurements, leakage radiation quantification and operational parameter standardizations. ASME tests and other associated imagining experiments have also been done with this accelerator. The system is shifted to site (at Gamma Field, BARC) for actual application, post successful qualification tests at EBC. Presently the dual energy based cargo scanner with facility of material discrimination is of great demand on security front.

3.2. Radiography

As discussed above in section 2.8, 6 MeV Linac is qualified for radiography applications with reference to ASTM standards [5-7]. The same Linac needs to be installed at BARC as a central facility to carry out radiography of thick materials (having thickness up to 200 mm steel equivalent). In addition the technology should be transferred to ECIL for mass production as it is highly applicable for heavy material manufacturer and associated industries.

3.3. Cancer Therapy

In the medical field for cancer treatment presently accelerators based upon S-bend microwave source (frequency ranging 2 - 4 GHz) are highly popular and 6 MeV as well as 15 MeV Linac operable in x-ray mode have massive demand. We have successfully developed and demonstrated many Linacs (4 to 10 MeV) working with S-bend microwave source for different applications. Now we should target to develop 6 MeV (and/or 15 MeV) Linac for medical application like cancer treatment as presently our country faces big lack on this front. In addition to use the high energy electron beam as brachytherapy source the Linac based upon C-bend microwave source (frequency ranging 4 - 8 GHz) is required. It is completely new technology for our country and therefore we have to make a concretized objective for the same to deliver it successfully within a practical limited time frame.

3.4. Waste Water Treatment on Industrial Scale

The experiments for waste water treatments have already been carried out at EBC on laboratory scale and proven that EB treatment is more economical than other AOPs including ozonolysis, UV treatment, gamma radiolysis and photo-catalysis [4]. It is desirous to exploit the technology on industrial scale with EB. In this regard a project of DC electron accelerator having parameters 1 MeV, 100 kW is taken and very soon it will be realized. It also leads the transfer of laboratory level experiments to industrial application.

3.5. Electronic Waste Disposal on Bulk Level

Similar to waste water treatment, the electronic waste disposal technique has been established by EB irradiation with support of ICT, Mumbai and RTDD, BARC. Now it is demand of time that we should target the applicability of this technology on mass scale with the help of suitable industrial partner. Interestingly for the time being it can be done with our existing 10 MeV system and no need to built new facility to scale up the experiment in bulk level. Appropriate initiatives in this regard have been taken with help of RTDD, BARC.

3.6. In House Development of Radiation Dosimeters

The organic film based dosimeters are the most popular dosimeter for routine dosimetry applications in electron beam facilities as they have excellent material-material and material-air interface characteristics. The thickness of film dosimeters is in the order of micron and therefore it doesn’t create any air void inside material which can hamper thedose uniformity. In addition it doesn’t attenuate the beam energy significantly and in this way not interfere in irradiation of a product to get a requisite dose. One of the major drawbacks with conventional film dosimeters is its dependence on visible light. If these films are exposed pre or post irradiation with visible light, their optical density changes and thus the dose values can't be measured accurately. To overcome the above problem organic semiconductor film based radiation dosimeter can act as a technical alternative because it is almost stable in visible light as well as normal environmental conditions. It has been demonstrated that the electrical conductivity of molecular semiconductor, zinc phthalocyanine (ZnPc) and conducting polymer, polyaniline-silver (PANI-Ag) nanocomposite films vary linearly with electron beam dose up to 18 kGy and 30 kGy respectively. Therefore these are suitable candidate for the potential dosimeters. In addition the electrical conductivity of PEDOT: PSS, conducting polymer, films has also been varying with dose in the range up to 25 kGy. This film is also fit for latent radiation dosimeter for the said dose range. The reproducibility of associated results of these films with dose has to be checked to use these as routine dosimeter.

3.7. Enhancement in Characteristics of Organic Materials with Electron Beam

As discussed earlier that the modifications in characteristics of organic materials with electron beam requires very less dose as compared to its inorganic counterpart to achieve the same results. Therefore performance of organic semiconductor based devices like organic field effect transistors, thermoelectric power generators, gas sensors, solar cells etc can be improved by irradiating with electron beam. In addition the electron beam induced modifications in a new class of hybrid materials (organic-inorganic composites), in which the characteristics of organic and inorganic can be utilized optimaly, should be tried. This may help to develop new material as well as new device with improved characteristics having various utilizations and it will be a very good research & development application of accelerator in the field of material science. Also the enhancement in thermal, mechanical and electrical characteristics of different organic materials with electron beam can be tried.

4. CHALLENGES AND SCOPE

In view of the mentioned future prospects of EB accelerator application in various fields, some set up are required in house. It includes both the electron beam characterization and the analysis of post irradiated samples as part of process control, quality assurance, research and development.

4.1. Beam Spot Size

The measurement of output beam spot size falls under dosimetry and is extremely required for all applications especially cargo scanning and radiography. It is also desirous and applicable in development of subsystems like electron gun, buncher cavity etc. The beam spot size measurement requires three parts (i) a pin hole camera (made of proper thickness of alternate low and high density materials like mylar and copper), (ii) radiochromic (or radiosensitive) films to work in "Gy" dose order with sufficient size and (iii) densitometer to measure the optical density pattern of irradiated films. This set up will also be helpful in proposed C-bend microwave source based Linac characterization. The films and densitometer may also be useful to carry out basic ASME standardization experiments which is very important for radiography and cargo scanning systems.

In addition to above a water (or perspex) phantom is required to determine the dose deposition profile especially needful for futuristic S-bend as well as C-bend accelerators to be used in cancer therapy. The radiochromic films and film based dosimeters are very useful for these applications.

4.2. Electrical Conductivity

In order to characterize the organic (organic-inorganic hybrid) films, pre and post irradiated, its electrical conductivity has to be quantified. Normally it is carried out with two (or four) probe techniques and since the current is in order of micro to tens of pico ampere, it requires picoammeter/voltage source (Keithley 6487 or equivalent) [9-11]. This set up having computer based data acquisition system, to record the *I-V* plot, is required in house. It is also useful in developing ion chamber based radiation detector for electron beam facility. It may also applicable to measure the dose rate in order of "kGy/min" online which is desirous for many experiments.

4.3. Crosslinking Analysis of Polymers

The radiation induced modifications in polymers take place mostly because of crosslinking or chain scissioning which can tailor its electrical, mechanical and thermal properties of preformed parts and also in bulk. Both polymer crosslinking and degradation by chain scission occur during radiation treatment, but one or the other of these effects may dominate at a specified time [12 & 13]. This distinction goes along with the chemical nature of polymers and the radiation dose. Materials with G(S)/G(X) ratio below 4.0 (where G(S) and G(X) respectively defines the yield of scissioning and cross-linking) are favored for crosslinking applications. G(S) and G(X) both change with increasing dose [14 & 15]. So, it is possible that upon reaching a certain dose level, crosslinking dominated polymers, e.g. polyethylene or natural rubber latex can change to degradation dominated or vice versa. G(X) and G(S) also depend on irradiation conditions, such as temperature and atmosphere. To conclude the dominance of crosslinking or scissioning, the most important method is sol-gel analysis which is done by Soxhlet extraction method. For this purpose the Soxhlet extraction set up is required in house to identify the crosslinking or chain scissioning dominance in post irradiated polymers. It consists of three important components: (i) the percolator which circulates the solvent and it contains heater and reflux, (ii) the thimble which is normally made of thick filter paper and it retains the solid to be laved, (iii) the siphon mechanism which periodically empties the thimble. Alternatively Differential Scanning Calorimeter (DSC) or Thermo-Gravimetric Analysis (TGA) system can also be used to decide crosslinking or scissioning dominance in polymers post irradiation [16].

5. CONCLUSION

A range of applications of electron accelerators are successfully demonstrated at EBC, BARC: quite a few for societal benefits and research have been elaborated. These act as building block to transform the electron accelerator technology from laboratory scale to industrial levels. Additionally, it has also been verified through these experiments that EB technology is a powerful tool to replace conventional approaches even radiation process through Co-60. The future prospects and associated challenges to carry out in house development were also discussed. These are needful to accelerate our developmental program and utilize the facility for scientific up brings.

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