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ORIGINAL ARTICLE

SUSTAINED PERFORMANCE OF 8 MEV MICROTRON

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ABSTRACT

The 8 MeV Microtron at Mangalore University, a pioneering electron accelerator in the country, has been instrumental in various collaborative research initiatives in radiation physics and allied sciences. Developed in collaboration with RRCAT Indore and BARC Mumbai, this accelerator has been operational since its inception, supporting researchers with its straightforward design, cost-effectiveness, and superior beam quality. The facility is notable for producing energetic electrons and intense bremsstrahlung radiation, which are used extensively in research programs involving premier institutions and regional universities. This paper provides an overview of the machine's reliability, the sustained efforts ensuring its continuous operation, and its significant applications in both physical and biological sciences.

KEYWORDS : radiation physics , continuous operation , straightforward design, cost-effectiveness.

INTRODUCTION

Established in 1995, the 8 MeV Microtron facilities at Mangalore University has become a crucial tool for researchers from national laboratories and regional universities. It supports systematic investigations in areas such as radiation dosimetry, radiation effects on semiconductor materials and devices, radiation damage studies in biological systems, radiation processing of food items, polymer cross-linking, angular distribution of photo-fission, and various other basic and interdisciplinary research studies. The findings from these studies have deepened the understanding of fundamental processes and have been valuable for application-oriented research.

The accelerator's inherent simplicity, excellent beam quality, and ease of operation and maintenance have made it a focal point for numerous research programs in collaboration with premier laboratories across the country. This versatile electron accelerator, the first of its kind in the nation, has been successfully delivering 8 MeV electrons, intense bremsstrahlung radiation with peak energy of 8 MeV, and high-flux neutrons for advanced research in radiation physics and allied sciences over the past decade and a half. The indigenously developed facility has consistently maintained a vacuum level around 7x10^-7 mbar, supported by two sputter ion pumps (270 l/s and 35 l/s) and a turbo-molecular pump (300 l/s). A variety of smaller experimental vacuum chambers have been utilized for different experiments at varying vacuum levels.

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COLLABORATIVE RESEARCH PROGRAM

A systematic collaborative research program is underway, facilitated by a triangular Memorandum of Understanding (MoU) between Mangalore University, RRCAT Indore, and BRNS, DAE, Government of India. This program involves multiple research groups from various institutions. Below is a brief overview of these activities along with sample results.

- **Dosimetry Studies**

Radiation dosimetry is crucial for any radiation installation. At the Microtron facility, dosimetry studies for high-energy photons and electrons have been conducted using a variety of chemical dosimeters and thermoluminescent dosimeters to measure radiation doses and dose distributions. The study employed Fricke dosimeters, FBX dosimeters, Glutamine, Alanine, and Thermoluminescent dosimeters for different dose ranges. Additionally, efforts are being made to explore various materials as dosimeters based on their behavior under radiation exposure.

These studies have revealed the electron beam distribution and its dependence on the beam line magnet fields. Dosimeters provided detailed dose information and beam distribution along the axis of propagation. Multiple trials at different distances from the titanium window indicated a uniform electron beam distribution of 40 mm on either side of the beam axis in both vertical and horizontal directions at a distance of 30 cm from the window. This uniform distribution was observed without using any beam flattener or scatterer. Thermoluminescent dosimeters were also utilized for radiation mapping of the Microtron room, providing insights into the radiation environment within the facility.

- **Photo-fission experiments**

The angular distribution of 237 Np fission fragments was measured across the energy range of 7.4 to 9.2 MeV in 0.4 MeV increments using bremsstrahlung radiation. The necessary vacuum chamber and target for these experiments were designed and fabricated in collaboration with the Nuclear Physics Division and Radiochemistry Division at BARC, Mumbai. Lexan polycarbonate films (SSNTD) were employed to detect the fission fragments, as this technique is simple and offers advantages over other methods.

The photon intensity from the Microtron accelerator, measured at a distance of 15 cm from the bremsstrahlung converter (tantalum target), was estimated to be 10^{10} photons per second using the EGS-4 code. The photofission cross-section was determined by analyzing the angular distribution of fission fragments. These results were then compared with those obtained using the EMPIRE-II code, along with various barrier parameters from the RIPL-1 and RIPL-2 libraries, and a new analytical fission barrier formula based on the Hugenholtz–Van Hove theorem. The findings show good agreement with the predictions of the RIPL-1 barrier parameter and the analytical fission barrier formula.

- **Studies on Relative Biological Effectiveness**

A study in radiation biophysics has been initiated to evaluate the physical and biological parameters for bremsstrahlung and electron beams from the microtron. Systematic investigations are ongoing to understand various factors influencing biological responses to these radiation types. The extent of repairable and irreparable damage in living cells caused by ionizing radiation depends on the radiation quality. For sparsely ionizing radiation, dose rate and energy deposition patterns are crucial physical factors affecting cell damage.

Radio-sensitive and radio-resistant bacterial cells were exposed to an 8 MeV pulsed electron beam to assess cell-killing efficiency and determine the mean lethal dose. The dose was delivered in microsecond pulses at an instantaneous dose rate of 2.6 $\times 10^5$ Gy/s. The results were compared to those obtained from gamma ray exposure. The survival curve for the radio-resistant Deinococcus radiodurans

(DR) was sigmoidal, whereas the survival response for the radio-sensitive Escherichia coli (E. coli) was exponential without a shoulder. Comparing Do values indicated that irradiation with the pulsed electron beam resulted in greater cell-killing than gamma irradiation.

The differences in cell survival efficiency and dose rate effects in diploid yeast strains Saccharomyces cerevisiae X2180 and Saccharomyces cerevisiae D7 under euoxic and hypoxic conditions have been quantified. Irradiation was performed with a dose per pulse of 0.6 Gy and a pulse width of 2.3 μs, resulting in an instantaneous dose rate of 2.6 $x10^5$Gy/s. A significant difference in dose response was observed between euoxic and hypoxic conditions. The dose rate effect was studied by varying the pulse repetition rate of the electron beam. A notable dose rate effect was found for Saccharomyces cerevisiae X2180 under euoxic conditions, but this effect was absent under hypoxic conditions. For Saccharomyces cerevisiae D7, no dose rate effect was observed under either condition. The survival curves were sigmoidal in both conditions, with a wider shoulder observed under hypoxic conditions. Extensive research in this area is ongoing.

- **Irradiation Effects on Semiconductor Devices**

The study on the irradiation effects on semiconductor materials and devices aimed to investigate modifications in the basic characteristics of these materials and devices due to high-energy photon and electron irradiation. Semiconductor devices such as diodes, transistors, solar cells, and photodetectors, which are often used in space or radiation environments, need to be tested for radiation exposure to determine their tolerance and suitability for various applications. Understanding the effects of ionizing radiation on semiconductor materials and devices is crucial not only for a broader understanding of the damage processes leading to various modifications but also for assessing device performance in radiation environments.

A comparative study was conducted to examine the effects of 8 MeV electron irradiation on the electrical characteristics of CdTe and CIGS thin-film solar cells. This study followed an in-depth analysis of radiation's influence on various types of solar cells. The I–V characteristics of the cells under AM 1.5 illumination and capacitance-frequency measurements were taken before and after irradiation. Key solar cell parameters, including short circuit current (I_{sc}), open circuit voltage (V_{oc}), fill factor (FF), and efficiency (η), were calculated from the I–V characteristics. Results showed that the efficiency of both CIGS and CdTe solar cells decreased as the electron dose increased to 75 kGy, although FF and V_{oc} were not significantly affected by irradiation.

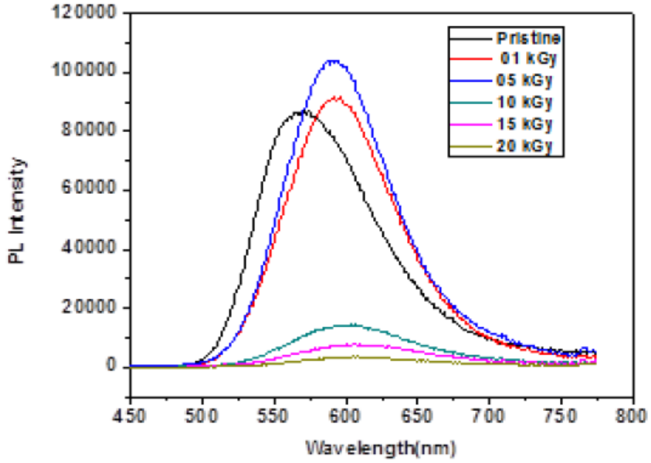
Additionally, p-CdTe/n-CdS thin-film solar cells were exposed to electrons and characterized under both dark and illuminated conditions to assess device stability in a radiation environment. Parameters such as short circuit current, open circuit voltage, fill factor, conversion efficiency, saturation current, and ideality factor were evaluated. The study revealed that these thin-film solar cells demonstrate good stability against electron doses up to 100 kGy.

Irradiation studies conducted on p-Si and SS/CdTe/Au Schottky diodes reveal that the impact of irradiation becomes more pronounced at higher voltages compared to lower voltages. The primary effect observed is a reduction in forward current with increasing dose, indicating degradation in diode properties possibly due to the introduction of radiation-induced interfacial defects through displacement damage.

Furthermore, the effect of 8 MeV electrons on Silicon Photodetectors, fabricated by phosphorous diffusion into p-type mono-crystalline silicon wafers with <100> orientation, was investigated. A p+ back surface field layer was formed on the rear surface of the silicon wafer through aluminum deposition. Metallic coatings comprising titanium, palladium, and silver, deposited using ion beam sputtering, served as front and back ohmic contacts. These silicon photodetectors were characterized, and solar cell parameters were determined under both dark and AM0 conditions. The study revealed that both forward and reverse currents systematically increased with electron dose.

Moreover, a systematic investigation into solar cells' behavior in a radiation environment is underway, employing various types of solar cells with different conversion efficiencies. Extensive electrical characterizations under various conditions are being conducted in collaboration with UNAM Mexico and NREL, USA.

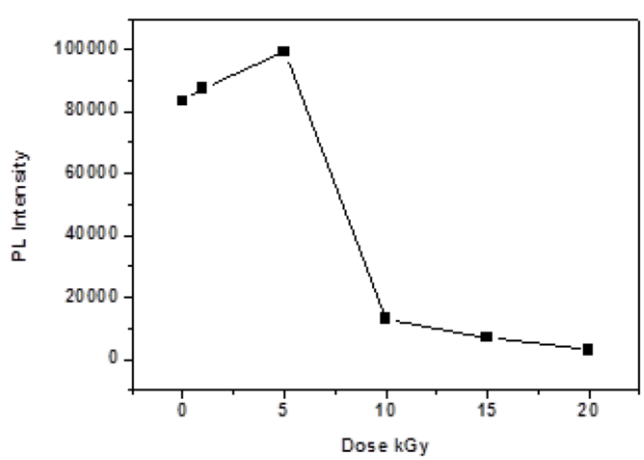
Figure 1.1 Photoluminescent Spectra of CdTe quantum dots at various electron doses



- **Radiation effects on Quantum dots**

A new one-pot synthesis method for CdTe Quantum dots (QD) has been developed using the hydrothermal technique, with Na_2TeO_3 as the source of Te and $CdCl_2$ as the source of cadmium. CdTe QDs were subjected to electron doses ranging from 1 kGy to 20 kGy. Characterization of the samples revealed intriguing changes in photoluminescence properties, as illustrated in above figure. An increase in emission intensity was observed for doses up to 5 kGy, followed by a decrease in intensity for doses exceeding 5 kGy. Additionally, a red shift in the emission spectra was noted.

Figure 1.2 Photoluminescent yield (peak) at different electron doses



The findings were confirmed through time-resolved emission spectroscopy and X-ray photoelectron spectroscopy of the QDs. These CdTe QDs hold potential for bio-tagging applications, as the formation of a CdS layer on the CdTe core upon irradiation is biocompatible. Moreover, the CdS formation can amplify photoemission, leading to bright emissions for the straightforward detection of tagged DNA or any other biomaterial. Extensive research in this domain is currently ongoing.

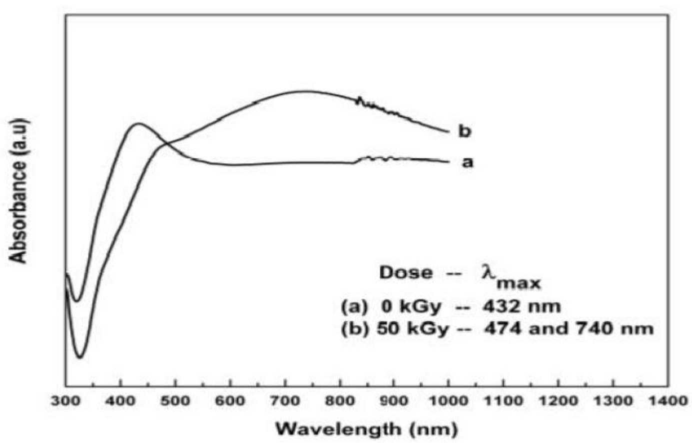
- **Nanoparticle Synthesis**

Stable and non-toxic Ag nanoparticles were synthesized by subjecting an aqueous solution of $AgNO_3$ and polyvinyl alcohol (PVA) with two different degrees of hydrolysis, acting as the stabilizer, to 8 MeV electrons. The rate of nanoparticle formation was controlled by adjusting either the electron dose or the relative concentration of the precursors. The size, shape, and rate of formation of the nanoparticles were found to depend on the final dosage and the weight ratio of $AgNO_3$ to PVA. Confirmation of Ag nanoparticle formation was achieved through UV–Vis spectroscopy, and nanoparticle size was determined via TEM analysis. Increasing the irradiation dosage appeared to favor the formation of polygonal nanostructures. Additionally, DSC measurements indicated a strong interaction between the PVA matrix and the Ag nanoparticles. This clean synthesis method holds promise for various medical applications.

- **Radiation effects on thin films**

The investigation focused on the electrical behavior of silver particulate films deposited on electron beam-irradiated polystyrene (PS) coated substrates held at a temperature of 455K in a vacuum of 8×10^{-6} torr, maintaining a constant deposition rate of 0.4 nm/s. It was observed that electron irradiation can induce polymer-metal interaction in inert polymers like PS. Additionally, the morphology of the deposited films was found to be dependent on this polymer-metal interaction. Films deposited on PS irradiated to doses of 20 kGy and 25 kGy exhibited smaller clusters with reduced inter-cluster separation, making them more suitable for sensor applications. The induced polymer-metal interaction is attributed to the creation of free radicals due to electron beam irradiation.

Figure 1.3 Optical absorption spectra of Ag films deposited on unirradiated and 50 kGy irradiated PS



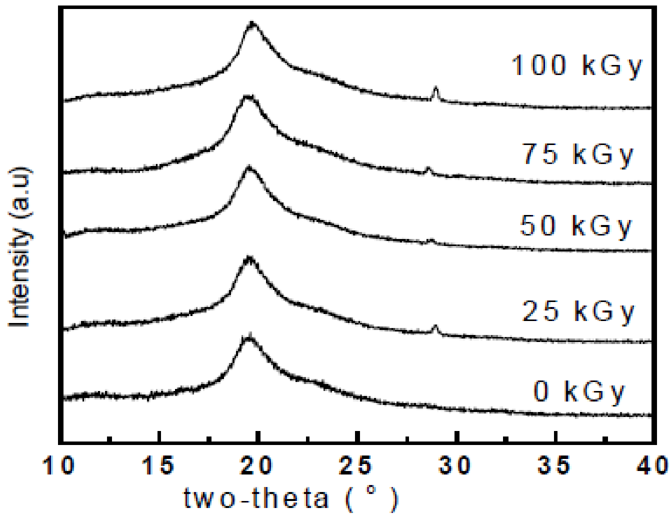
Radiation Processing

A range of polymers and materials have been examined through exposure to energetic electrons at various doses. Below are some of the materials studied:

- ***Poly Vinyl Alcohol***

PVA, a commonly used synthetic polymer, possesses several advantageous properties including being non-toxic, water-soluble, biocompatible, and biodegradable. It exhibits excellent mechanical characteristics such as flexibility and the ability to form high-quality films with outstanding gas barrier properties. The effects of irradiation on microstructural parameters in PVA films have been investigated using Wide Angle X-ray Scattering (WAXS) data. Crystal imperfection parameters, such as crystal size <N>, lattice strain (g in %), and enthalpy (*), have been determined through Line Profile Analysis (LPA) utilizing the Fourier method developed by Warren.

Figure 1.4 XRD scans

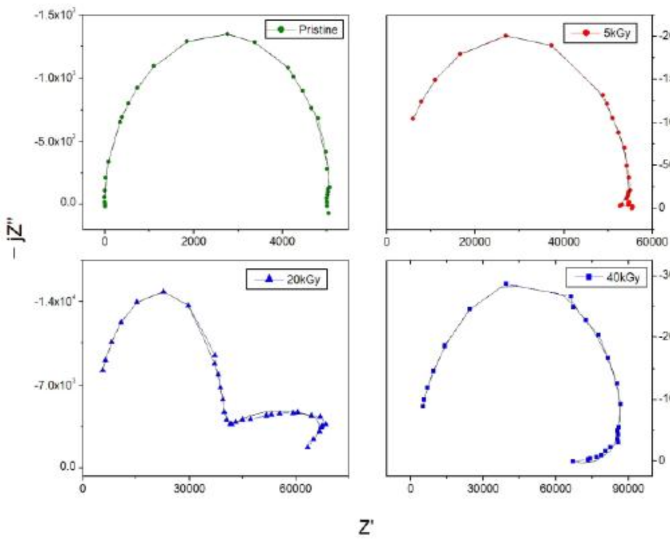


The WAXS study revealed notable alterations in the values of microstructural parameters following irradiation, despite minimal changes in the position of the X-ray reflection. Additionally, the crystallinity of the polymer was observed to decrease with an increase in radiation dose.

- **Polyaniline (PAni)**

Electron beam irradiation of PAni has induced crystallization in interfacially polymerized polyaniline, as confirmed by UV-Visible spectra, XRD, and impedance analysis. PAni crystallizes in the orthorhombic system at an optimal electron dose of 20 kGy, representing the most notable observation. While low-dose electron irradiation improves crystallinity in PAni, it concurrently reduces conductivity due to electron-induced chain scission. Conversely, a dose of 40 kGy results in crosslinking of the polymer chain, leading to amorphization. Impedance analysis of PAni subjected to various irradiation doses produces Nyquist plots.

Figure 1.5 Nyquist plots for pristine and electron induced polyaniline nanomaterial



The Nyquist plots depicted above illustrate the electrical properties of pristine and electron-irradiated PAni nanomaterial at doses of 5, 20, and 40 kGy. Pristine PAni exhibits a single semi-circle, indicating a singular relaxation process. At 5 kGy, the Nyquist plot displays a single semi-circle with a pseudocapacitance loop at the low-frequency region.

Upon interfacial polymerization and subsequent irradiation with 8 MeV electron beams, PAni undergoes electron-induced chain scission at low doses and crosslinking. This structural transformation is reflected in the electrical properties of PAni. At 20 kGy, the formation of subgrains manifests in two semi-circles: one at the grain boundary and the other at the grain interior. It is concluded that crystalline polyaniline can be achieved through 8 MeV electron beam irradiation, with 20 kGy identified as the optimal dose.

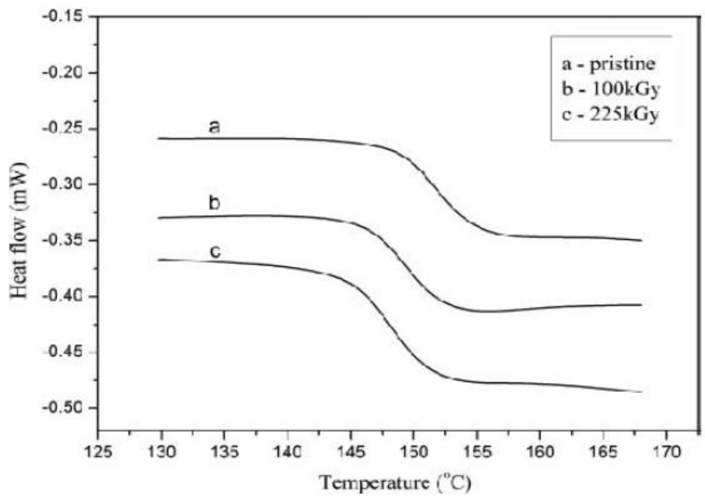
- ***PMMA***

The fluorescence properties of electron-irradiated chalcone-doped PMMA films, related to free volume, were investigated using positron annihilation and fluorescence spectroscopic techniques. In this polymer composite, fluorescence was observed to increase at lower doses of irradiation and decrease at higher doses. Positron annihilation studies indicated that at lower doses, irradiation induced crosslinking, which impacted the free volume properties and hindered molecular rotation of chalcone. Conversely, at higher doses, chain scission processes affected matrix relaxation. Under these constrained conditions, chromophore molecules are likely to emit enhanced fluorescence, with their mobility directly linked to the surrounding free volume.

- ***Lexan Polycarbonate films***

The properties of Lexan polycarbonate (Lexan) films exposed to 8 MeV electrons were investigated, revealing several modifications. UV-Visible spectroscopy analysis indicated a decrease in optical energy gap and optical activation energy, along with an increase in the number of carbon atoms per cluster as the electron dose increased. Chemical changes resulting from electron irradiation-induced chain-scission and reconstruction were observed through FTIR spectroscopy. Correlation between positron lifetime studies and optical measurements facilitated an understanding of microstructural modifications induced by electron irradiation within the polymer. XRD patterns indicated a decrease in crystallite size and percentage of crystallinity, resulting in a transition from a semi-crystalline to an amorphous structure due to bond breakage. SEM analysis revealed the formation of blisters of various sizes upon electron irradiation, indicating surface morphology changes, along with gradual degradation in the network structure. DSC studies showed a decrease in glass transition temperature and heat of fusion after irradiation, suggesting a shift towards a more disordered state due to chain-scission. Additionally, thermal decomposition temperature of Lexan polycarbonate increased upon irradiation.

Figure 1.6 DSC thermogram for the pristine and electron-irradiated Lexan films



The glass transition temperature (Tg) of the pristine Lexan sample was approximately 150ºC. At a dose of 100 kGy, the DSC curve revealed a shift of Tg to 146ºC, and at 225 kGy, Tg was observed at 143ºC. This shift towards lower temperatures post-irradiation indicates that electron irradiation induces chain scission, subsequently reducing molecular weight and leading the polymeric system towards a more disordered state.

Furthermore, the a.c conductivity and dielectric constant of the Lexan film were found to increase with the electron dose, attributed to the breakage of chemical bonds, which in turn increases the number of free radicals. The formation of defects, chromophores, as well as the presence of impurities, additives, and unsaturation, were investigated using photoluminescence techniques.

Additionally, various collaborative research activities are underway in the fields of materials science, fisheries, radiobiology, radio-protectiveness of various plant extracts, and radiation processing of ayurvedic medicines for shelf-life enhancement, among other related aspects.

1. Program for users

Workshops, seminars, and user meetings across diverse research domains are being coordinated to stimulate the enhancement of laboratory infrastructure and facilitate the utilization of facilities for conducting cutting-edge research in the respective fields.

2. Future plans

With the support of BRNS, plans are underway to upgrade the current accelerator facility, increasing its beam power to better serve the requirements of Microtron Users. This enhancement will enable more detailed neutron-based studies on various aspects, further strengthening ongoing activities. Additionally, there are plans to extend access to the Microtron facility to postgraduate students for their laboratory experiments and project work.

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