MULTIPURPOSE ELECTRON BEAM FACILITY IN SLOVAKIA FOR RESEARCH AND INDUSTRIAL APPLICATIONS

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Abstract

The paper reports on basic parameters, operational experience and application potential of the electron-beam irradiation facility at the University Centre of Electron Accelerators of the Slovak Medical University. The centre is based on a 5 MeV 1 kW linear electron accelerator UELR-5-1S equipped with a beam-scanning system and a conveyor line. Although it could be used also for routine radiation processing in an industrial-like mode, its main purpose was focused to research. The research possibilities are presented in terms of deliverable types of radiation (electron beam or bremsstrahlung), available doses and dose-rates, ranges of electron beam in different materials and other relevant parameters. They are also demonstrated by examples of some research activities and most significant scientific achievements.

1. INTRODUCTION

Radiation processing belongs nowadays to modern and widely used tools for modification of material properties in a well-controlled way. It can be applied to variety of materials ranging from polymers (cross-linking) [1], elastomers (vulcanization), medical products (sterilization), food, chemical pollutants of environment (disintegration) and many others [2, 3]. These applications have reached an industrial-scale level and dedicated electron machines are commercially available as integral built-in parts of production lines.

Radiation processing had not been well-developed technology in Slovakia before 2011. It included one cyclotron for positron radioisotope production [4] and two electron beam (EB) accelerators as parts of production lines for sterilization and tyre crosslinking, those in private companies of foreign ownership. Accelerator utilization for research purposes was minimal. Situation changed during last decade. Since 2011 more ion accelerators have been installed, 3MV Pelletron tandem accelerator for material research and dating at Comenius University in Bratislava [5], 6 MV tandem accelerator and 500 kV ion implanter of Slovak University of Technology for material research in Trnava as well as 2 MV tandem accelerator of Slovak Academy of Sciences in Piestany.

Research possibilities were widened also by a new electron accelerator of Slovak Medical University placed in Trencin, designed for research and also industrial purposes. This multipurpose facility started its operation in 2012 with one main goal to introduce the radiation treatment technology into practise in Slovakia.

Physics research represents another application domain of electron accelerators. Here, radiation processing can be used for two main purposes: (1) as a technological tool for intentional and custom-tailored control of material properties of interest, and (2) as a tool for studying radiation damage, radiation hardness, aging, degradation and other radiation-induced effects in different materials, material structures, or even complex systems like integrated circuits, radiation detectors and electronic devices. The research possibilities are determined by deliverable types of radiation, achievable doses, dose-rates, ranges of electron beam in the material of interest etc. These parameters depend mainly on the beam characteristics and technical limits of the beam-delivery system. In the paper, we describe and discuss the above parameters for the UELR-5-1S linear electron accelerator at the University Centre of Electron Accelerators of the Slovak Medical University located in Trencin, Slovakia. Discussion is completed by demonstrative examples of some research activities and significant scientific results that have been achieved at this laboratory so far.

2. MULTIPURPOSE ELECTRON BEAM FACILITY IN TRENCIN

2.1. Irradiation facility

The facility is equipped with a 5 MeV electron LINAC (Fig. 1) and it has been focused on research purposes and on introduction of radiation processing in the country, when starting its operation in 2012. Research possibilities are influenced by accelerator parameters and in this case adjustable energy, scanning width, beam repetition rate as well as conveyor velocity and its distance from accelerator exit window lead to wide range of available dose-rates applied. The ranges of the most relevant accelerator parameters are listed in Table 1. The nominal electron energy of 5 MeV can be modified in the range from 3.6 up to 6.2 MeV. The beam repetition-rate together with the beam scanning width and the distance of irradiated object from the accelerator exit window tune the achievable dose-rate during irradiation. Practically, during irradiation with 5 MeV electrons on conveyor, the dose-rate can vary from 10 to 5600 kGy/h.

The accelerator can use a water cooled tungsten target of 3 mm thickness, so two types of radiation are available (electron beam and bremsstrahlung), which spreads its fields of application and research possibilities. Due to low efficiency of conversion, the dose rates for X-ray treatment are in different but also wide range from 26 up to 1400 Gy/h.

FIG. 1. Photograph of the accelerator (left) and view into irradiating room (right).

TABLE 1. PARAMETERS OF THE LINEAR ELECTRON ACCELERATOR UELR-5-1S

Parameter	Ranges
Maximal beam power	1 kW
Beam energy	3.6 – 6.2 MeV
Beam scanning width	40, 45, 50 cm
Beam scanning frequency	0.25 – 5 Hz
Beam repetition-rate	5 – 240 Hz
Beam initial diameter	11 mm
Maximal distance from exit window	170 cm

2.2. Dosimetry

A routine dosimetric system used at the facility is based on B3 radiochromic films (1 cm in diameter and 18 µm thick films of pararosaniline dye dissolved in polyvinyl butyral). Ionizing radiation activates the B3 dye centres which in turn cause the B3 film to undergo a predictable colour change from clear to deepening shades of pink magenta. The radio chemical yield of the dye results in a colour change that is evaluated by a Spectrophotometer Genesys20. The routine dosimetric system can be used in the range of doses of 1 – 100 kGy. The B3 dosimetric system is calibrated by RISO polystyrene calorimeters, traceable to national standards. For dosimetry of lower doses, in the range of Gy, the FARMER ionization chamber is used at the facility.

2.3. Software simulation tools

The dose absorbed in an object irradiated by high-energy electrons depends on parameters of irradiating particle (its energy, fluence) and on the parameters of irradiated object (its density, elemental composition, dimensions and arrangement in the electron beam). Moreover, the absorbed dose varies with the depth of irradiated material. The facility is equipped with the software for the simulation of electron-beam, X-ray and gamma-ray radiation processing, the RT-Office, designed especially for calculation of absorbed dose in objects irradiated with scanned electron beam. The code has several modes, which are dedicated to particular type of irradiated objects: thin multilayer flat packages (ModePEB), products on industrial radiation-technological lines (ModeRTL) and multilayer circular objects like wires, cables and pipes (ModeCEB) by pulsed electron beam of energy from 0.1 up to 25 MeV. The code contains also the programme for objects irradiated by X-ray beams (ModeXR) in an industrial radiation facility based on electron accelerator with X-ray converter in the energy range from 1 to 50 MeV.

This way, the dose depth profile for chosen object is simulated, which is then verified by experimental irradiation of prepared phantom, finally followed by irradiation of the object. The examples of dose depth profiles of chosen materials irradiated by 5 MeV electrons with 10 Hz beam repetition rate are depicted in Fig. 2. It can be seen, that the dose firstly increases with the depth of material and after reaching the maximum value, the decrease to zero (practical range) can be observed. The practical range of electrons in particular material depends strongly on the material density (Table 2.) and its elemental composition.

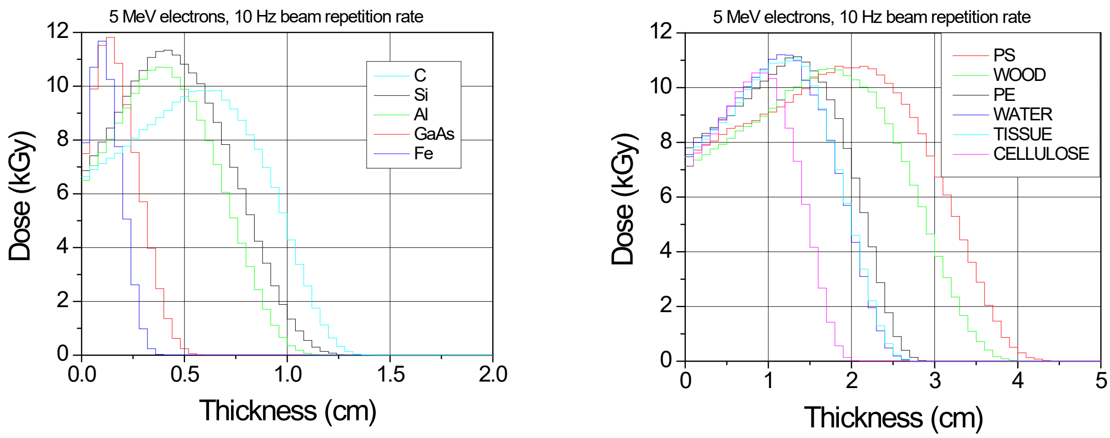

FIG. 2. Dose depth profiles of 5 MeV electrons in materials from elements (left) and from suitable compounds for radiation treatment (right).

The dose depth profile and particularly the practical electron range in material is strongly dependant on the electron kinetic energy, as it can be seen in Fig. 3. Here, the dose depth profiles of high-energy electrons in silicon are depicted for three different energies of electrons: the minimal energy (3.6 MeV), the nominal energy (5 MeV) and for the maximum energy (6.2 MeV) obtainable by the accelerator. The maximum dose absorbed by the object can be very well controlled by the period of irradiation or conveyor velocity. Preserving the period of irradiation, the maximum dose will be managed by the electron beam repetition rate, which influences the dose rate. In Fig. 4, the dose depth profiles of 5 MeV electrons in polyethylene (PE) are shown. As the repetition rate of the beam increases, the maximum dose grows as well.

TABLE 2. DENSITY OF MATERIALS PREPARED FOR IRRADIATION

Material	Density (g/cm^3)	Material	Density (g/cm^3)
Fe	7.87	Water	1
GaAs	5.32	Soft tissue	1
Al	2.70	PE	0.93
Si	2.33	Birch wood	0.71
C	2.26	PS	0.64
Cellulose	1.40	Old wood	0.50

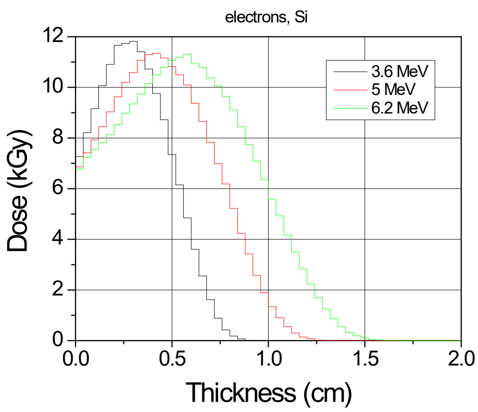

FIG. 3. Dose depth profiles of electrons of various energies in silicon

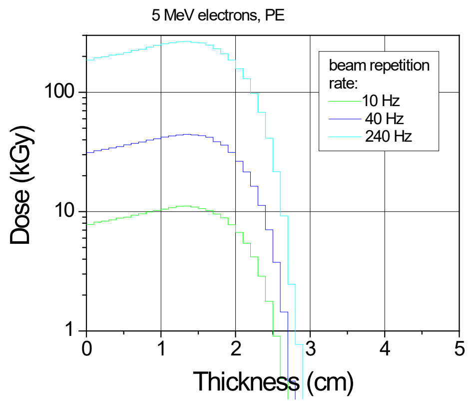

FIG. 4. Dose depth profiles of 5 MeV electrons of various beam repetition rate in polyethylene

It is obvious, that the dose depth distribution of electrons varies from material to material and for practical reasons the prompt calculation of treatable material thickness would be very useful, especially in the research field, where objects are specific and diverse. Based on the experience from preparations of irradiations, the simple function for ideal material thickness treatable by 5 MeV electrons connected to its density was prepared. In relevant density range of materials the simulations of dose depth profiles were calculated using ModeRTL. The ideal material thickness was set as a thickness of material, where the dose of electrons reaches the same value like on its surface for one-side irradiation. In the case of double-side irradiation, the ideal material thickness was determined as the thickness, when the dose in the middle of the material is equal to dose on both surfaces, see Fig. 5. The obtained values of ideal thickness were depicted with respect to material densities. Simple semi-empirical functions were obtained fitting the obtained points (Fig. 6) for one-side irradiation: t_o *[cm]= 1.87/d* and for double side irradiation: t_d *[cm]= 4.31/d*, where *d* is the density of the material in [g/cm^3].

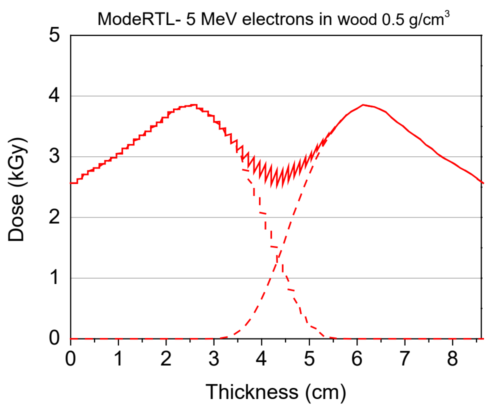

FIG. 5. Dose depth distribution of 5 MeV electrons in wood during double-side irradiation.

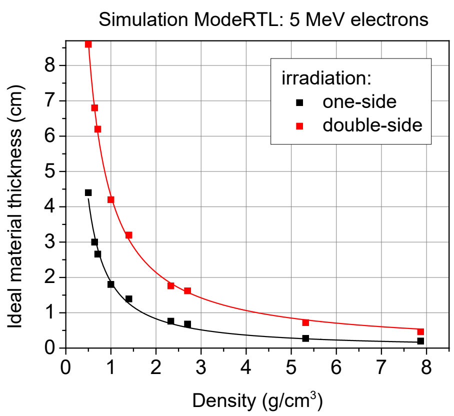

FIG 6. Graphical demonstration of ideal material thickness for treatment by 5 MeV electrons with respect to its density.

3. PRACTICAL ACHIEVEMENTS

During a decade since the multipurpose electron beam facility in Trencin has started its operation, wide range of research experiments was realized with many promising socioeconomic impacts. The research activities have been in the field of radiation aging, medicine, environment and cultural heritage.

3.1. Radiation aging

Estimating the lifetime of devices in radiation harsh environment like accelerator facilities, nuclear power plants or space can be performed by radiation hardness tests at accelerators. A long term study of semiconductor detectors of ionizing radiation based on GaAs (Fig. 7) was realized at the facility. For 5 years the detectors were irradiated by 5 MeV electrons systematically increasing the cumulative dose from 1 to 2000 kGy and testing their spectrometric properties [6]. Another example of radiation hardness tests conducted at the facility was irradiation of semiconductor devices (Fig. 8) for the power supply source for the first Slovak satellite, the skCUBE [7], which launched in June 2017. The devices were tested by doses of X-rays up to 1.3 kGy representing the dose accumulated in devices during approximately 3 years at planned orbit of the satellite in 400 km distance from the Earth surface.

FIG. 7. Photograph of GaAs detectors of ionizing radiation prepared for irradiation.

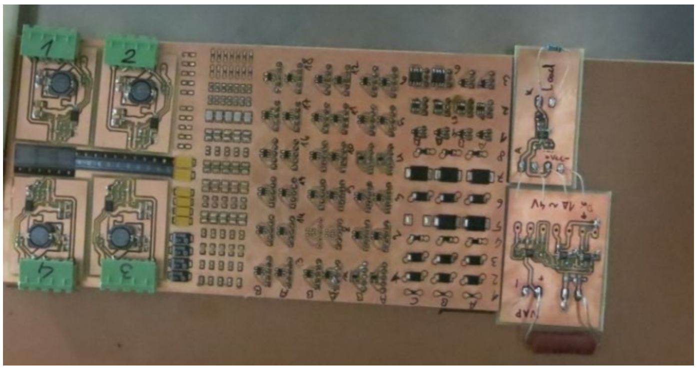

FIG. 8. Photograph of semiconductor devices prepared for irradiation.

3.2. Human health

The facility utilized the high dose rate during irradiation to decontaminate the transplants placed on dry ice like corneas (Fig. 9) dedicated for transplantation or animal skin (Fig. 10) utilized for protection of burned tissue until the new skin is grown. Interesting results were achieved during research, where the facility simulated radiotherapy for molecular hydrogen research in biomedicine [8]. Here the doses of X-rays in the range from 10 to 20 Gy were delivered.

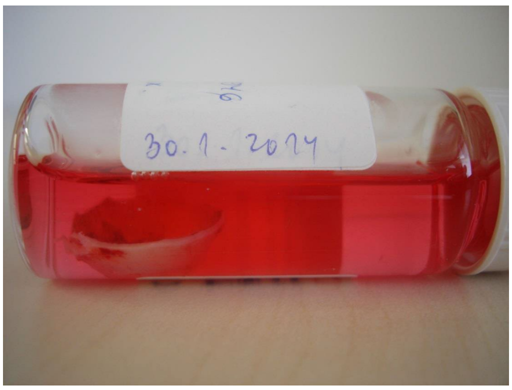

FIG. 9. Photograph of cornea in ethylene-oxide solution prepared for irradiation.

FIG. 10. Photograph of animal skin on dry ice prepared for irradiation.

3.3. Environment

Polychlorinated biphenyls (PCBs) are chemically and thermally stable hydrophobic compounds which were widely used in industry until their toxicity was revealed. Unfortunately they were released also into the environment, like in Eastern Slovakia. Their concentration in the sediments of the canal Strážsky kanál exceeds allowed limits more than ten times for years. The facility has studied the possibility of their radiation degradation. Various co-solvents and doses were combined to achieve the most effective radiolythic dechlorination of PCBs in canal sediments [9, 10]. The facility participated also at comparison of electron beam vs. gamma ray irradiation of sludge from drinking-water-treatment plant with the aim to decontaminate the sludge from microorganisms. The doses of 5 MeV electrons used were in the range from 1 to 25 kGy [11].

3.4. Cultural heritage

The facility participated at the preservation of late gothic wooden altar (1516) from St. George Church in Spišská Sobota in Poprad, Slovakia. Altar parts were heavily attacted by woodworms. Radiation treatment of altar wings (Fig. 11) (4.5 cm thick) by electron dose 1.8-1.4 kGy, wooden sculptures by X-ray dose 3-0.4 kGy was realized in September 2018 [12]. The altar was then restorated at the Monuments Board of the SR at Levoča ateliers. Successful installation of renovated altar followed in August 2019.

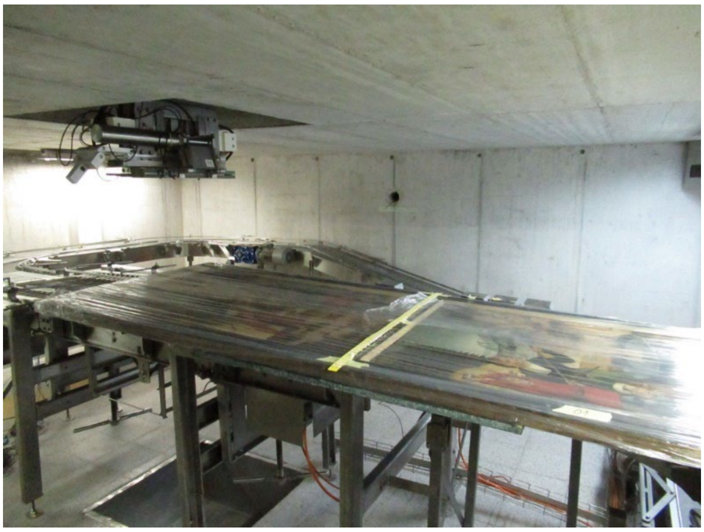

FIG. 11. Photograph of altar wing prepared for irradiation.

4. CONCLUSIONS

The operational experience and wide application potential of the electron-beam irradiation facility at the University Centre of Electron Accelerators of the Slovak Medical University is reviewed. This facility is used for scientific research and the knowledge gained from this research is used in the field of applied science, e.g. radiation hardness of detectors of ionizing radiation, electronics for space applications and accelerator and nuclear power plant components. The research is also focused on the use of electron beam irradiation equipment in medicine, environment, cultural heritage and education. In medicine we collaborated on research of radiation treatment of skin, corneas and in the research aimed on radiotherapy. Our research is aimed also to the serious environmental problematics in Slovakia, the contamination of soil and ground water by PCB (PolyChlorinated Biphenyls), were we use the accelerator to decontaminate environment. We collaborated with Serbian colleagues in research on radiation treatment of waste sludge from drinking-water-treatment plant. Big impact might also have our successful story of preservation of a late-gothic wooden altar with help of radiation, which will open the gates for utilization the radiation technologies in the field of cultural heritage in Slovakia. On the theoretical side, the simulations of dose depth profiles calculated using ModeRTL can be used to select the appropriate sample thickness for efficient treatment.

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