T.1: Electron accelerator based radiation processing facility at Indore

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Abstract

Electron accelerators are extremely useful devices for bulk radiation processing of health-care, industrial and agricultural products. The capability to apply this technology requires availability of three main elements viz. high energy, high power electron accelerators, electron beam processing equipment and know-how of the process techniques. Design, development and testing in all three areas have been pursued at RRCAT and a first of its kind electron accelerator based radiation processing facility is developed at Indore. This article describes various aspects of the electron beam radiation processing and work done towards the facility development.

1. Introduction

A first of its kind electron accelerator based radiation processing facility named Agricultural Radiation Processing Facility (ARPF) is being set-up by the Department of Atomic Energy at Devi Ahilyabai Holkar Fruit and Vegetable Mandi, Indore (Figure T.1.1). The facility is based on 10 MeV, 5 kW linear accelerators (linacs) developed in RRCAT. The facility will be used for technology demonstration of indigenous linacs, process equipment and the know-how for carrying out electron beam processing of health-care, industrial and agricultural products.

Fig. T.1.1: Electron beam radiation processing facility, ARPF, developed by DAE at Indore.

Particle accelerators are used to accelerate the charged particles like electrons. Accelerators are high technology machines which were initially developed for R&D applications. However, accelerators have found varied applications in multiple areas including the fields of health-care, industry and agriculture. Accelerators for societal applications must meet the regulatory, functional and viability requirements. Accelerators for bulk irradiation are required to generate high energy (5 to 10 MeV) and high power (several kW) electron beam. Furthermore, these accelerators should have high degree of precise control of the beam parameters with high repeatability and reliability. One very important requirement in Indian context is the availability of local know-how for servicing of the accelerators economically. Linacs are a class of accelerators where particle beam is accelerated in a straight line using radio frequency technology. Different applications need different beam delivery requirements, hence the accelerators, process equipment and the process controls need fine-tuning to cater to different applications.

ARPF is operational and has already provided electron beam irradiation services to a large number of R&D institutions. Now, the work on various quality management and regulatory processes to obtain licenses for carrying out processing of user products is in progress.

2. Applications of the electron beam radiation processing

The electron beam processing can be utilized for various applications like sterilization of medical devices, irradiation of electronic components, phytosanitary treatment of agricultural produce (required for international trade), microbial decontamination of spices and Ayurvedic products, and electron beam irradiation of seeds for mutation breeding for improved crop varieties etc.

The accelerator based radiation processing has the following benefits over conventional facilities (using chemical fumigation, isotopes or heat).

- Accelerators are electrically operated radiation sources which can be switched off after use, thereby, there is no potential threat of accidental radiation exposure when not in use.
- No radioactive materials are used in the process.
- The process time for each product box is small and suitable for irradiation of frozen products.
- Chances of recontamination are avoided as processing is done without opening the primary packaging.
- The process leaves no chemical residues on the products.
- Being a room temperature process, the aroma (for example in spices) is preserved.

However, the technology to provide stable, repeatable and reliable operation of the high power accelerators and developing process performance as per the applicable standards are quite challenging tasks.

3. Electron beam interactions with materials

Energetic electrons can modify the chemical bonds of materials and this property is used in the radiation processing. Large and complex molecules like DNA have much higher chances of interaction as compared to smaller molecules which are mostly left unaffected. This happens, for example, in the sterilization of medical devices and processing of agricultural products. Some industrial applications require modification of base materials. In these latter cases, a large number of bonds are to be modified and, therefore, higher doses are required, for example, in cross linking of plastics and colour change of gems. High energy electron beams can penetrate into the bulk materials and this property is used for irradiation of products in large package formats.

4. Regulatory aspects

Various national and international regulatory bodies have approved the use of electron beam for sterilization of medical devices and food irradiation with specified quality controls. The quality control requirements to be met include the electron energy, dose, stability of process parameters, process integrity, product classes etc. The quality management system of the facility needs to comply with the stipulated requirements for sterilization of medical devices (for example ISO:13485) [1]. Organizations like International Atomic Energy Agency (IAEA), World Health Organization (WHO), International Organization for Standardization (ISO), American Society for Testing and Materials (ASTM) and Atomic Energy Regulatory Board (AERB) have developed guidelines, practices and standards for regulating various aspects ensuring the safety and quality of the electron beam processing.

Several stages of radiological and industrial safety approvals for ARPF have been obtained from AERB and various local government bodies. AERB has granted approval for operation of the facility in January 2019 (under the category "Industrial Accelerator Radiation Processing Facility"). To carry out product processing for users, a quality management system and Food and Drug Administration (FDA) license as manufacturer are required, and work towards completing these steps is in progress.

5. Description of the facility

ARPF is a large facility having a building area of about 55 m X 36 m. Layout of the facility is shown in Figure T.1.2 and Figure T.1.3. Two 10 MeV, 5 kW linacs are installed in the shielded vault adjacent to each other in horizontal orientation (one operational and one standby). The configuration may be modified for optimization of utilization. The process operations are monitored and controlled through a computerized control system from control room. A roller

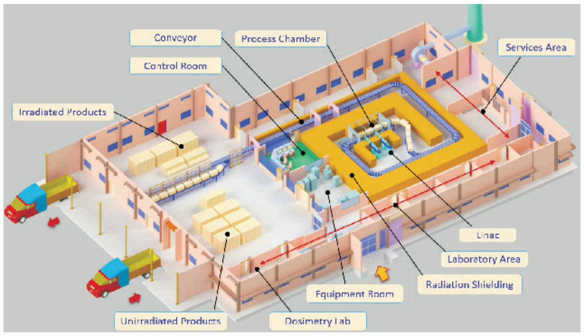
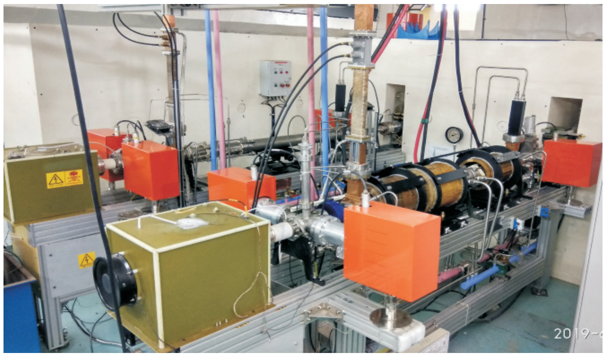


Fig. T.1.2: Electron beam radiation processing facility layout. The radiological vault having thick walls is on the right. Two 10 MeV, 5 kW linacs are seen inside the vault. Various areas like process chamber, control room, equipment room, dosimetry lab and the product hall can be seen in the layout.



(a)

(b)

Fig. T.1.3: Configuration of the electron beam processing arrangement at the facility. (a) Two linacs in the vault. (b) Two beam scanners and product conveyor.

conveyor transports the products from the product hall to the process chamber. The conveyor cycle is controlled through a programmable logic controller (PLC) system with a control on translation speed, number of passes and the sides of the products to be irradiated. A well-engineered ventilation system provides required air flow in various areas of the facility.

The radiological shielding of the vault is designed as per National Council on Radiation Protection & Measurements (NCRP) Report No. 51 [2]. Design of the shielding and various safety systems is approved by AERB.

6. Linear accelerators

The linacs installed at ARPF have been developed at RRCAT. These linacs have undergone detailed functional and endurance tests (Figure T.1.4). The 10 MeV linacs are based on the travelling wave design operating in 2π/3 mode. The electron linac mainly consists of a 50 keV triode electron gun, and 2856 MHz bunching and accelerating structure, which are developed using in-house physics and engineering design.

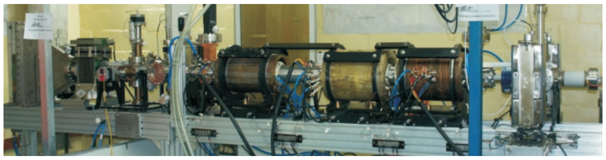


Fig. T.1.4: Linac-2 during developmental beam testing at RRCAT.

Fig. T.1.5: Microwave system for linacs

Various other sub-systems viz. microwave power system delivering a peak power of 6 MW in 12 microsecond pulses with a repetition rate from 1 to 250 Hz (Figure T.1.5), solenoids for beam focusing, VME bus based control system for remote operation, beam diagnostic devices, linac vacuum envelope evacuated to a vacuum of the order of 10^{-7} mbar, beam scanning system with scan profile shape control, power supplies, cooling system and electron beam window have been designed and fabricated at RRCAT. Except for the klystron, all major sub-systems have been developed indigenously.

Extensive efforts towards the development of special manufacturing facilities, assembly infrastructure and multiple radiation shielded test areas were made. Design, problem solving and the preparations of next stage test set-ups were repeatedly done. Considerable emphasis was placed on the detailed testing of various sub-systems and the linacs. These linacs are tested for dose delivery through volumetric dosimetry tests. Table T.1.1 gives the main parameters of the linacs [3].

Table T.1.1: Design parameters of the RRCAT developed linacs.

Nominal frequency	2856 MHz
Mode	TW, 2π/3
Injection energy	50 keV
Output energy	10 MeV
Pulse current	200-300 mA
Beam pulse duration	10 µs
Pulse repetition rate	1-250 Hz
Average beam power	5 kW

7. Description of the processing technique

Electron beam processing configuration at ARPF is shown in Figure T.1.3 (b). The linacs generate 10 MeV electron beam having a typical beam diameter of 20 mm. The beam is scanned in a vertical direction with the help of a time-varying magnetic field to achieve wide radiation field. The scanned beam makes a transition from vacuum to atmosphere through a thin titanium foil mounted at the end of the scanner. The product box to be processed is transported to the processing area on a roller conveyor and the box is made to pass through the scanned beam. Computerized control systems are used to monitor and regulate the process from control room (Figure T.1.6). By selecting suitable combination of process parameters (e.g. scanning frequency, conveyor speed, product box thickness and double sided irradiation) a wide range of dose can be delivered to the products.

Fig. T.1.6: Main control system at ARPF for monitoring and regulating linac and process operations.

8. Dosimetry systems

When ionizing radiation passes through a medium it deposits its energy in the medium. The amount of energy absorbed per unit mass in a medium (food/medical products etc.) is known as absorbed dose. Delivery of predetermined dose of ionizing energy is the final objective of radiation processing.

The dose delivered in the product volume is measured by dosimetry. Dosimetry is applied for the process qualification and also in the routine process control. “Routine dosimetry” is carried out during processing for independent verification of the process controls.

The SI unit of dose is gray (Gy). One gray represents deposition of 1 J energy in 1 kg of material.

A secondary standard dosimetry lab has been set-up at RRCAT which is equipped with Radiochromic Film Dosimetry system (Figure T.1.7) and Alanine Electron Paramagnetic Resonance (EPR) system (Figure T.1.8). Calibration of the dosimetry systems has been carried out in dose ranges of 0.5-50 kGy (B3 film) and 0.05-1 kGy (GafChromic film) at Bhabha Atomic Research Centre, Mumbai using the standard Co-60 source. Dosimetric measurements are being carried out in accordance with ISO/ASTM 51607 and 51275 [4, 5].

9. Microbiology laboratory

In order to establish the procedures for quality control of incoming and outgoing materials, a quality control set-up is developed at RRCAT. The measurement and test systems include microbial count (bacterial, fungal) measurements, physicochemical analysis in fruits, vegetables, dehydrated food and medicinal herbs. Bioburden assessment in disposable medical devices and verification of sterilization using biological indicators (Bacillus pumilus) can be done at this laboratory. These facilities are required for the quality checks of the products processed byelectron beam.

Fig. T.1.7: Radiochromic film dosimetry system.

Fig. T.1.8: Alanine EPR dosimetry system.

10. Qualification tests carried out at the facility

The facility is to be qualified as per ASTM:51649 and ISO:11137 at three stages of installation, operation and performance, the tests for which are to be carried out and repeated periodically. Furthermore, re-qualification is to be done when a new product is processed or any change is made in the facility equipment. A brief description of the tests carried out at ARPF is as follows.

Characterization of the electron beam parameters namely electron energy, average beam current, beam size, scan width and scan uniformity was carried out. The most probable energy of the electron beam is measured using depth dose distribution in aluminum wedge as per ISO/ASTM 51649 (Figure T.1.9) [6].

The practical range (R_p in cm) has been derived from the depth dose profile as shown in Figure T.1.10. The practical range is used to determine the most probable energy of the beam (9.3 MeV) using empirical relations. Beam current is measured with a fast current transformer (ACCT) installed at the exit of accelerating structure.

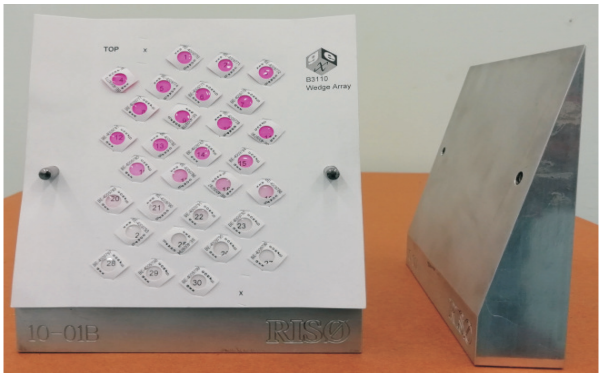


Fig. T.1.9: Colour change seen in the radiochromic film based energy card after receiving electron beam exposure in the aluminium wedge.

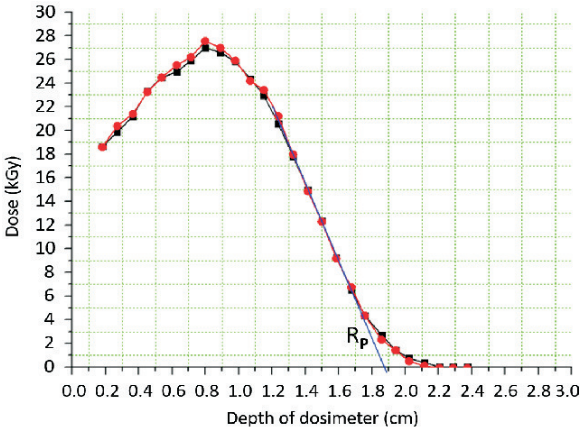


Fig. T.1.10: Depth dose profile measured in aluminium wedge to determine the most probable beam energy.

Cellulose triacetate (CTA) dosimetry film was used to measure the beam spot size of the un-scanned beam at the exit of scanner and at 45 cm from the window foil (at the location of plane of the product) as shown in Figure T.1.11. The measured FWHM of the beam size at the exit of scanner and on the product surface is found to be ~ 7 mm and 48 mm, respectively.

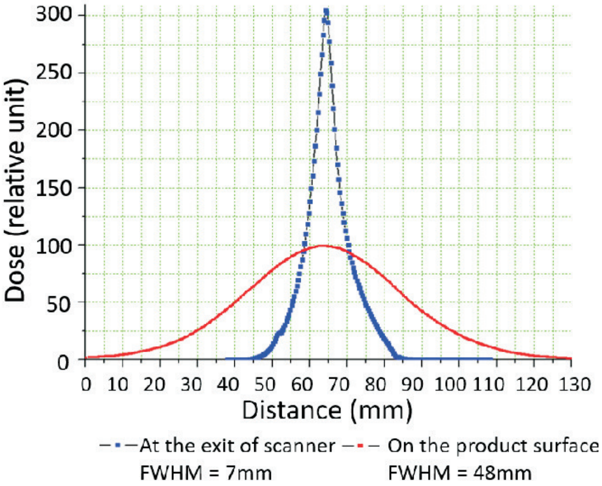


Fig. T.1.11: Un-scanned beam dose profile.

The accelerated electron beam is scanned on the product surface with a time varying magnetic field using a selected current profile. The scan width and scan uniformity measured by placing the CTA film dosimeter strip on the surface of the product box is shown in Figure T.1.12.

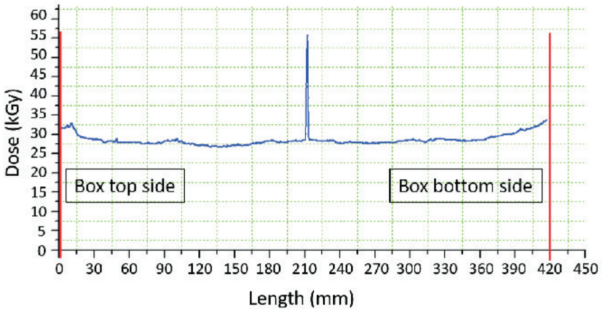


Fig. T.1.12: Dose uniformity along scanning direction (vertical plane).

One dimensional depth dose profile measurement is done by placing the dosimeters, spaced apart at equal distances in the electron beam penetration direction, along the centre line of a box filled with homogeneous phantom material (cardboard sheets, density 0.13 g/cc). Figure T.1.13 shows the dose profile obtained as a function of depth. This depth-dose profile is used for verification of the depth-dose characteristics.

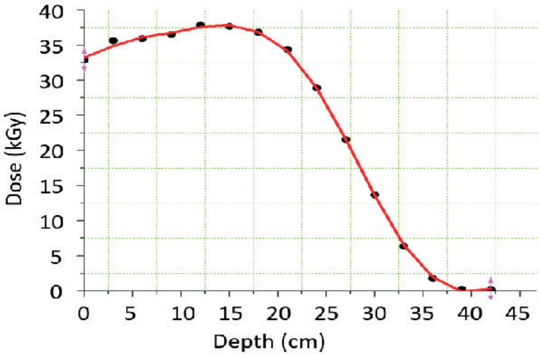


Fig. T.1.13: Depth dose profile in phantom material.

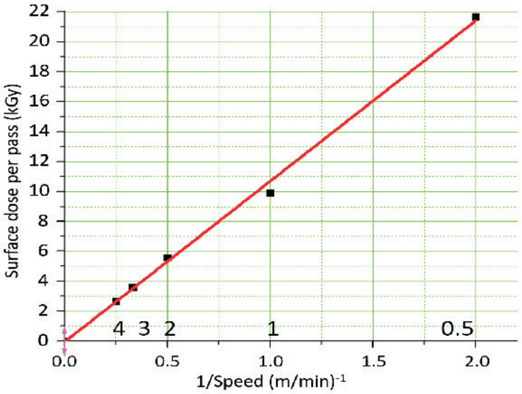


Fig. T.1.14: Dose as a function of conveyor speed.

Effect of conveyor speed and number of passes on the dose delivered is determined. A linear relationship between the dose delivered and conveyor speed is verified (Figure T.1.14).

Volumetric dosimetry in actual products is done to test and verify the process capability to deliver the required doses in the product volume. This includes identification of minimum dose (D_{min}) and maximum dose (D_{max}) positions, determination of routine monitoring position, dimensions and density of the product box, orientation of the products within the package, irradiation format (single sided/double sided), repeatability of dose at D_{max} and D_{min} positions and ratio of D_{max} to D_{min}. A batch of 32 boxes filled with petri dishes (apparent density 0.13 g/cc, each box containing 9.1 kg, total process load of 290 kg) was processed for this test. Three boxes were prepared for 3-D volumetric dose mapping. Each dosimetry box is divided into five planes A, B, C, D and E (A and E are extreme lateral planes, C is the central plane and B and D are sub-lateral planes). Individually numbered dosimeters (in duplicate) are placed at nine locations in each of the five vertical planes as shown in Figure T.1.15 (total 90 dosimeters). These boxes are placed on conveyor in sequence of P-P-P-P-D_s-P-P-P-P-D_s-P-P-P-P… as shown in Figure T.1.16. In this sequence of boxes, letter P denotes the relative positions of boxes filled with phantom material and D_s represents the relative positions of the dosimetry boxes.

Fig. T.1.15: Volumetric dosimetry planes for dosimetry using electron beam from Linac-1.

The batch was processed at a conveyor speed of 1.9 m/min with double sided irradiation (5 passes each side). The process cycle time for delivering 25 kGy dose was 90 minutes. The Dose uniformity ratio (DUR) of 1.6 was achieved.

Fig. T.1.16: Test processing of medical products.

11. Conclusion

Development of linacs, infrastructure and process equipment for the electron accelerator based radiation processing facility has been carried out with intensive team efforts in last ten years. Several measurements and tests have been carried out in accordance with National/International standards to test the electron beam properties and the process performance. AERB license for operation of the facility has been received. Work is in progress to get FDA license for taking up processing of user products.

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