

ANALYSIS OF THE POWER SYSTEM FROM AN ELECTRON BEAM ACCELERATOR AND THE CORRELATION WITH THE THEORETICAL DOSIMETRY FOR RADIATION PROCESSING

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ABSTRACT

Dynamitron DC1500/25/04 type electron beam accelerator (EBA), model JOB 188, was manufactured by IBA Industrial (Radiation Dynamics, Inc.) and installed at IPEN/CNEN-SP in 1978. The technical specifications of the EBA are: energy 0.5 to 1.5 MeV; beam current: 0.3 to 25.0 mA; beam scanning: 60 to 120 cm; beam width: 25.4 mm and frequency: 100 Hz. Nowadays, this accelerator has been used for innumerable applications, such as: for sterilization of medical, pharmaceutical and biological products; treatment of industrial and domestic effluents and sludge; preservation and disinfestations of foods and agricultural products; lignocellulosic material irradiation as a pre-treatment to produce ethanol bio-fuel; decontamination of pesticide packing; solid residues remediation; organic compounds removal from wastewater; treatment of effluent from petroleum production units; crosslinking of foams, wires and electric cables; composite and nanocomposite materials and carbon fibers irradiation; irradiated grafting ion-exchange membranes for fuel cells application; natural polymers and multilayer packages irradiation, and biodegradable blends production. The energy of the electron beam is calculated as a function of the current in the accelerator high-voltage divisor, taking into account the thickness and density of the material to be irradiated. This energy is calculated considering the electron through the entire material and the distance from the titanium foil window, so that the absorbed doses at the point of entrance and exit are equivalent on the material. The dose is directly proportional to the beam current and the exposure time of the material under the electron beam and inversely proportional to the scan width. The aim of this paper is to analyze the power system parameters of the EBA Dynamitron DC1500/25/04 accelerator, such as, voltage and root-mean-square (RMS) current in the oscillator system, high voltage generator and waveform, using software developed in the Radiation Technology Center at IPEN/CNEN-SP to simulate the energy efficiency of this industrial accelerator. Finally, it is also targeted to compare theoretical dosimetry using parameters of energy and beam current with data from the accelerator power system. This knowledge and technology will be very useful and essential for the control system upgrade of EBA, mainly Dynamitron DC1500/25/04, in view that radiation processing technology for industrial and environmental applications has been developed and used worldwide.

1. INTRODUCTION

Electron beam processing is an important technology that the International Atomic Energy Agency (IAEA) supports and promotes, having several programs to facilitate its use in developing Member States. This technology is used in diverse industries to enhance the physical and chemical properties of materials and to reduce undesirable contaminants, such as pathogens or toxic by-products [1].

The industrial uses of electron beam accelerator (EBA) started in the late 1950's, with the crosslinking of polyethylene wire insulation. Nowadays, the number of EBA in use for various radiation processing applications exceeds 1,500 radioactive facilities. These accelerators are used mainly in plastics, automotive field, wire and electric cables,

semiconductors, health care, aerospace and environmental industries, as well as, numerous research and development facilities around the world [2,3].

Crosslinking provides significant commercial benefits to wire and cable insulation. Ionizing energy, as provided by an accelerated electron beam (EB), is an efficient means of crosslinking the polymers that are used for wire and cable jacketing. In this process, chemical bonds are formed between polymer molecules to produce a three-dimensional insoluble network. EB processing is faster, more controllable and more economical than thermal and/or chemical crosslinking, when used in the production of insulated wires and cables [4].

The most important specification for any irradiation process is the absorbed dose. The quantitative effects of the process are related to this factor. Absorbed dose is proportional to the ionizing energy delivered per unit mass of material. The international unit of dose is the Gray (Gy), which is defined as the absorption of one joule per kilogram (J/kg). A more convenient unit for most radiation processing applications is the kilogray (kJ/kg or J/g) [5].

The objective is to analyze the power system parameters of the EBA Dynamitron DC1500/25/04 accelerator, such as, voltage and root-mean-square (RMS) current in the oscillator system, high voltage generator and waveform, using software developed to simulate the energy efficiency of this industrial accelerator. It is also targeted to compare theoretical dosimetry using parameters of energy and beam current with data from the accelerator power system.

The basic operation of the accelerator electron DC1500/25/4- JOB188 oscillator panel turns 440 Volts AC - 60Hz, for up to 10,000 Volts, with a frequency of 100 kHz, connected to the pressure vessel. In the pressure vessel, there is a resonant electronic circuit, which takes up a voltage 10.000 Volts/100 kHz generated by the oscillator panel and processed in an order of 1,500 kV DC. The voltage inside the pressure vessel is very high: to avoid sparks or short circuit inside the pressure vessel, an insulating gas (SF₆ sulfur hexafluoreto) is used; to measure the high voltage in the pressure vessel, a shunt (resistors) is used, indicating an electrical current, called HVD. The tension generated in the pressure vessel of up to 1,500,000 Volts DC polarizes the Beam tube assembly, where the penetration energy of the beam electrons was determined, through the shunt (resistors); the bias current measurement of the tube is called BTD; the LVR is the sum of electric currents, which involve the tube beam current (BTD), the current of high voltage (HVD) and other currents. Polarizing the tungsten filament, and by heating, a beam current of the electron accelerator is generated. The scan system and optics contain some coils that are polarized with a certain voltage/frequency, determined by the frequency scanning [6-9].

1.1. Absorbed Dose versus Electron Beam Current and Area Throughput Rate [5]

Dose is calculated by equation (1):

$$D = E / M \quad (1)$$

In which,

D = Dose (kGy);

E = Absorbed energy (kJ);

M = Mass (kg).

Additionally,

Absorbed energy (kJ) = Beam power, P (kW) * Treatment time, T (s);
Beam power, P (kW) = Electron energy, E (MeV) * Beam current, I (mA);
Electron energy, E (MeV) = D(e) (MeV cm²/g) * Z (g/cm²);
D(e) = Energy deposition per unit area density per incident electron;
Z = Thickness (cm) * Volume density (g/cm³);
Z = Mass, M (g) / Area, A (cm²) or Area density (g/cm²);
Mass, M (g) = Z (g/cm²) * Area A (cm²).

Then,

D (kGy) = P (kW) * T (s) / M (kg);
D (kGy) = E (MeV) * I (mA) * T (s) / M (kg);
D (kGy) = D(e) (MeV cm²/g) * Z (g/cm²) * I (mA) * T (s) / M (kg);
D (kGy) = D(e) * Z * I * T / [Z * A (cm²) * 10⁻³];
D (kGy) = D(e) * I * T / [A (m²) * 10].

Furthermore, dose at depth z in the irradiated material is calculated by equation 2,

D(z) = Dose at depth z in the irradiated material;
D(e, z) = Electron energy deposition at depth z in the material;
F(i) = Fraction of emitted beam current intercepted by the material.

Then,

D(z) = D(e, z) * F(i) * I * T / (10 * A) or

$$\mathbf{D(z) = D(e, z) * F(i) * I / (10 * A / T)} \quad (2)$$

2. METHODS, MATERIALS AND TESTING PROCEDURES

The curve of dose distribution with raised cellulose triacetate (CTA) dosimeter (density, $\rho = 1.32 \text{ g/cm}^3$) for EB energy of 1.5 MeV, from which the remaining curves were constructed in this study is shown in Fig. 1. In this curve, it was considered the desired dose on the surface of the material and the dose distribution, in percentage, at this bulk area density function ($\sigma =$ density against thickness) in g/cm^2 . The curve was prepared at the IPEN/CNEN-SP's Dosimetry Laboratory.

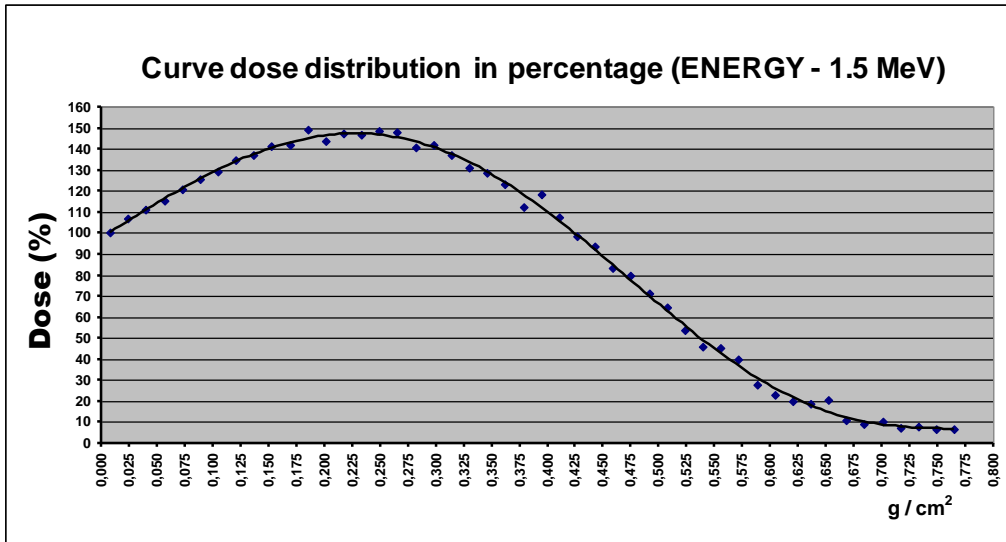


Figure 1: Dose distribution with raised CTA dosimeter for EB energy of 1.5 MeV.

In Fig. 2 the power system schematic diagram of the EBA is shown, with its properties of voltage, current and other electrical parameters and measurement points, using scope meter, multimeters and probes to specific current measures and voltage.

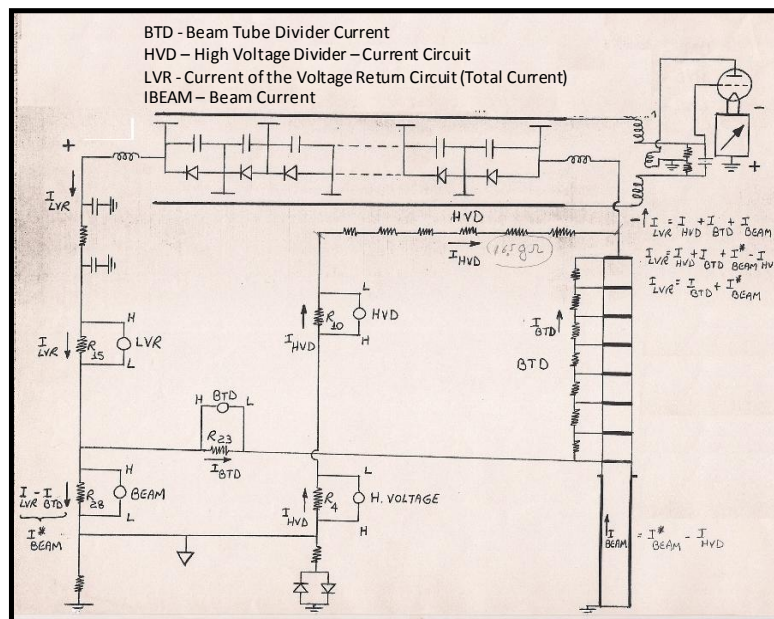


Figure 2: Power system schematic diagram of the EBA.

In Fig. 3 energy curves between LVR of the current return circuit voltage and power in the oscillator triode EBA system are shown. Curves of power determined in the oscillator panel show that the effectiveness of the EBA is 45.53%. This means that beam energy of 15 kW, should have a power triode of 32.94kW, in the oscillator panel.

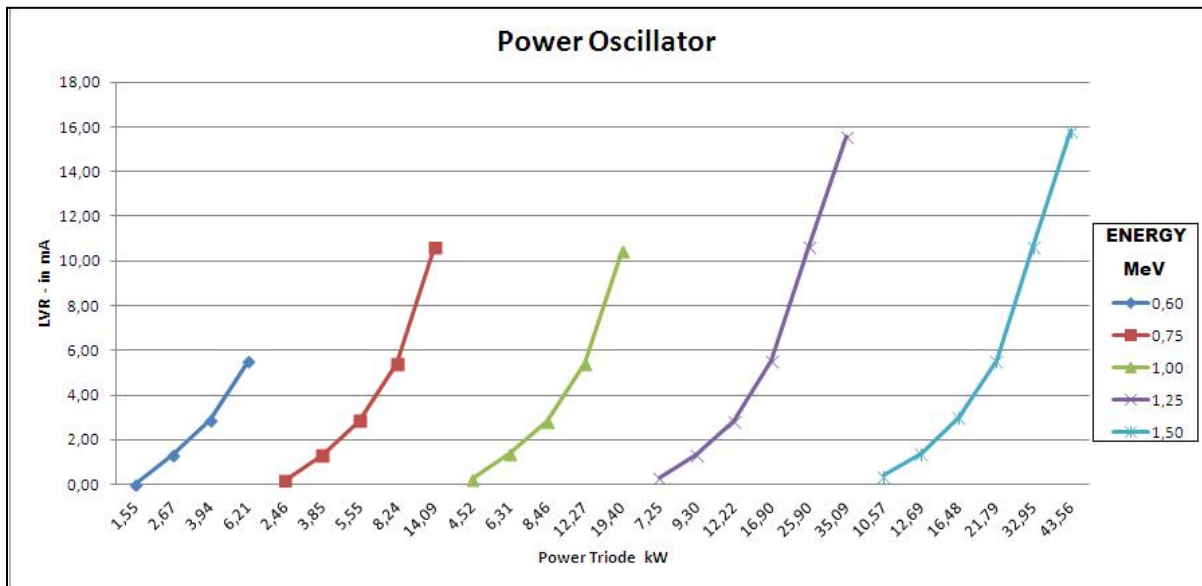


Figure 3: Energy curves (MeV) of LVR current (mA) versus power triode (kW).

In Fig. 4 curves of electron energies and high voltage in the pressure vessel of accelerator are shown. Curves ratio between high voltage and energy, and ratio between energy (MeV) with high voltage divider (HVD) are also shown.

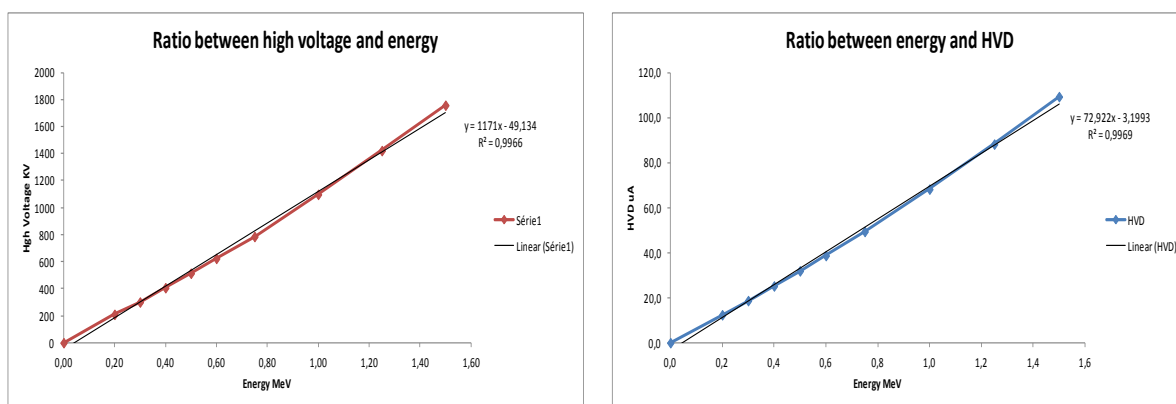


Figure 4: Curves of high voltage (kV) versus energy (MeV) and HVD (μA) versus energy (MeV).

2.1. Types and Forms of Irradiation Processes - Plan Materials

The irradiation system for this type of material consists of conveyor roller driven currents, which are placed on trays where the materials are distributed to be irradiated. This conveyor is composed of two modules: one-way, which takes the tray with the material inside the irradiation chamber (Fig. 5) to the irradiator (electron accelerator) and another (that brings back) the tray out of the irradiation chamber. After the tray with the material passes through

the electron beam, it is transported by currents to the module return (back), again passing through the beam.

Therefore, for each tray back on the conveyer (input and output tray of the irradiation chamber), the material passes twice by the electron beam.

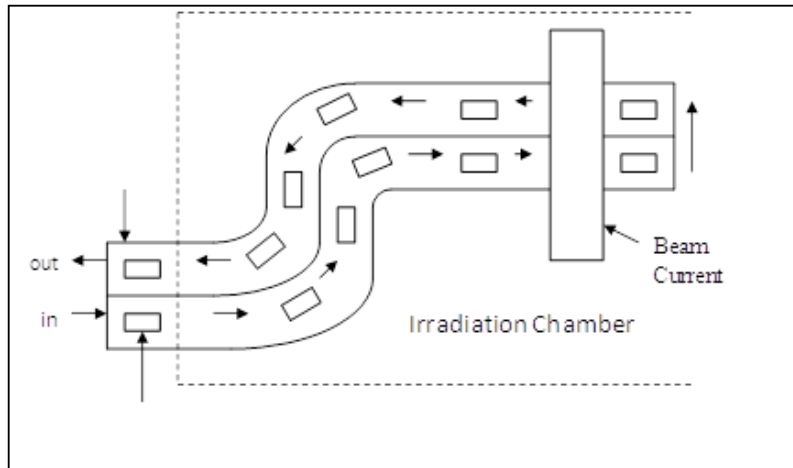


Figure 5: Conveyor installed in the irradiation chamber at IPEN/CNEN-SP.

2.1.1. Irradiation form I – plan material

In this irradiation form I, the electron beam runs through the material so that the doses at the point of input and output are equals (Fig. 6).

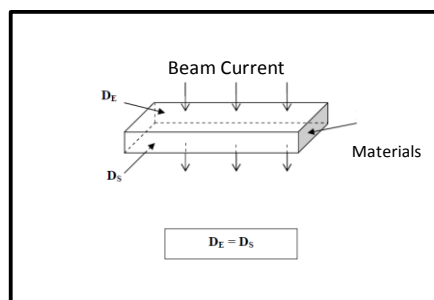


Figure 6: Irradiation form I - plan material irradiation diagram.

The curve of dose distribution (irradiation form I) is shown in Fig. 7, take into account the following irradiation parameters,

- Energy (E): 1.5MeV;
- Beam current (I): 10mA;
- Scanning beam: 100cm;
- Material transport speed (v): 10m/min;
- Number of electron beam passes (P): 2 (1 turn on the treadmill);
- Dose for pass (D/P): 6kGy;
- Total dose (TD): 12kGy;

- Dose rate: 40kGy/s;
- Density (ρ): 1g/cm³;
- Thickness: 4.45mm.

Take into account the power beam of 15kW and beam thickness of 25.4mm (1”), dose in the irradiated material is calculated by equation 3,

$$D \text{ (kGy)} = 15 \text{ kW} \cdot \text{time(s)} / M(\text{kg}) \quad *$$

* Application of equation 3 is not so evident, since a number of factors should be considered, such as the size and the shape of the object to calculate the area, volume and mass. The fraction of energy deposited on the material, by back scattering dispersion of the beam, can be calculated by means of Monte Carlo simulation [5].

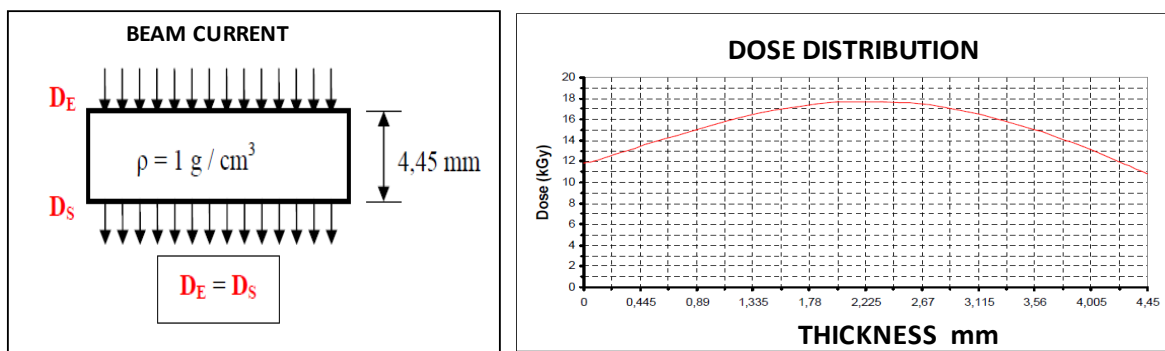


Figure 7: Irradiation form I – plan material irradiation diagram and dose distribution curve as a function of the sample thickness (kGy per mm).

2.1.2. Irradiation form II - plan material

In this irradiation form II, the electron beam cannot pass through the entire material. It is necessary to irradiate it on both sides, so that after being irradiated from both sides, the dose on the surfaces of the material and the medium are equals (Fig. 8).

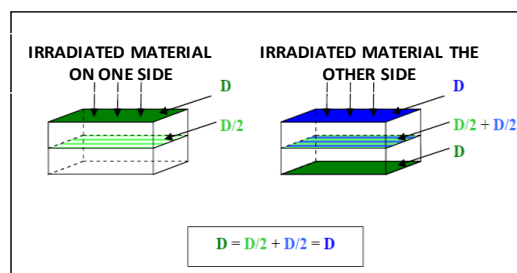


Figure 8: Irradiation form II – plan material irradiation diagram.

The curve of dose distribution (irradiation form II) is shown in Fig. 9, take into account the following irradiation parameters,

- Energy (E) 1.5MeV;
- Beam current (I): 10mA;

- Scanning beam: 100cm;
- Material transport speed (v): 10m/min;
- Number of electron beam passes (P): 2 (1 turn on the treadmill, on one side of the material) plus 2 (1 turn on the treadmill, on the other side of the material);
- Dose for pass (D/P): 6kGy;
- Total dose (TD): 12kGy;
- Dose rate (D): 40kGy/s;
- Density (ρ): 1g/cm³;
- Thickness: 11.3mm.

Take into account the power beam of 15kW and beam thickness of 25.4mm (1”), dose in the irradiated material is calculated by equation 3.

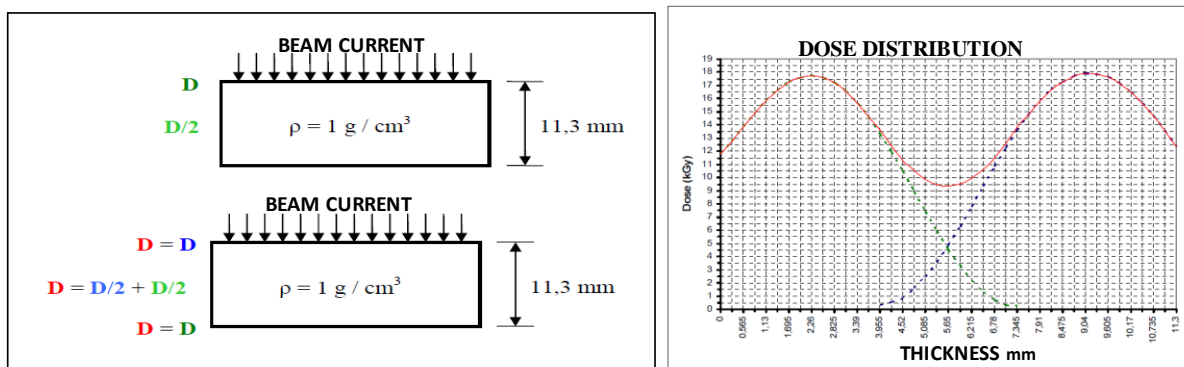


Figure 9: Irradiation form II – plan material irradiation diagram and dose distribution curves as a function of the sample thickness (kGy per mm).

2.2. Irradiation of Wires and Electric Cables

The irradiation system for wires and electric cables consists of two sets of pulleys, with 24 pulleys each, placed in parallel so that the electron beam is between them. The electric cable passing from a sheave of a pulley set for the other set is irradiated and, to make the contrary path, in the position diametrically opposite to the previous one, is again irradiated. This going and return of electric cable is called link.

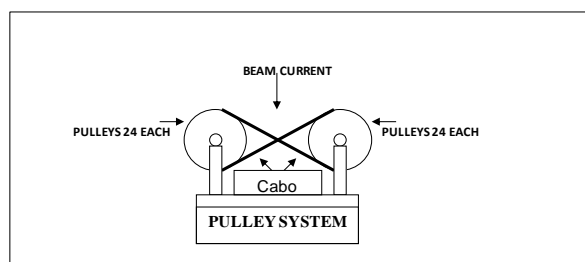


Figure 10: Pulley system for wires and electric cables irradiation by electron beam.

2.2.1. Irradiation form I – wires and electric cables

In this irradiation form I, the electric cable is fully irradiated in two positions (roundtrip), passing through the electron beam. Taking into account the internal diameter (wire diameter)

and the outside diameter (overall cable diameter), the electron traverses across the tangent line to the conductor (greater extension insulator), so that the dose at the points of input and output are equals (Fig. 11).

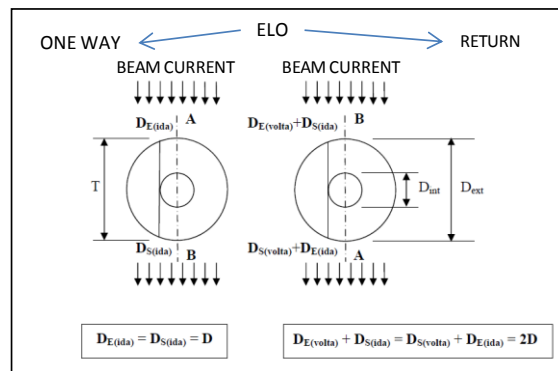


Figure 11: Irradiation form I – wires and electric cables.

Examples of irradiation conditions of wires and electric cables in pulley system are shown in Fig. 12. The curve of dose distribution (irradiation form I) is shown in Fig. 13, take into account the following irradiation parameters,

- Energy (E): 1.5MeV;
- Beam current (I): 10mA;
- Scanning beam: 100cm;
- Speed (v): 100m/min;
- Number of electron beam passes (P): 48 (24 links);
- Total dose (TD): 28.8kGy;
- Dose rate (D): 40kGy/s;
- Density of the insulating (ρ): 1g/cm³;
- Core (internal diameter): 1mm (wire diameter);
- Outside diameter: 4.56mm (overall diameter of the electric cable);
- Power beam: 15kW;
- Beam thickness: 25.4mm (1”).

Take into account the power beam of 15kW and beam thickness of 25.4mm (1”), dose in the irradiated material is calculated by equation 3.

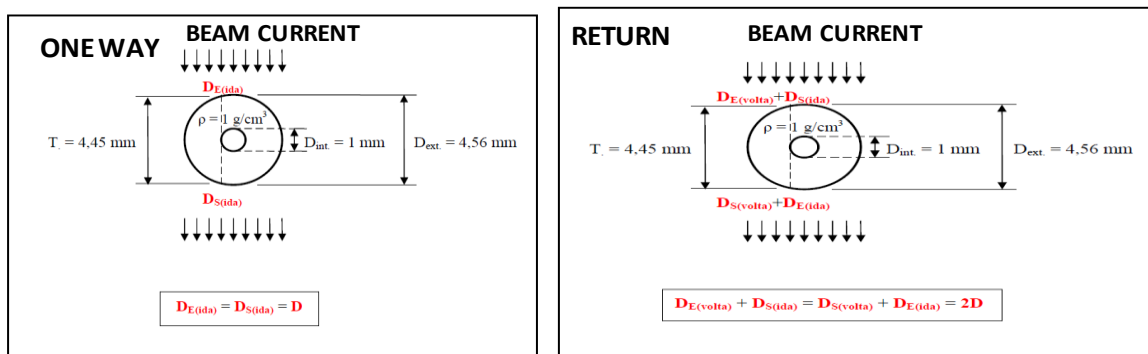


Figure 12: Irradiation form I – wires and electric cables in pulley system.

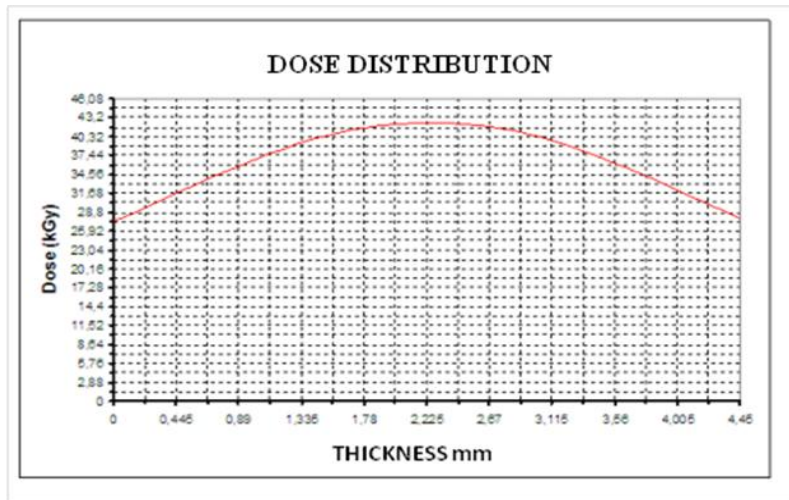


Figure 13: Curve of distributed dose I - wires and electric cables (kGy per mm).

2.2.2. Irradiation form II – wires and electric cables

In this irradiation form II, the electric cable will only be completely irradiated after completing the link. When passing through the electrons beam, it cannot fully penetrate the cable; the irradiation is completed, when the cable passing through the electron beam in position diametrically opposite to the previous one. Taking into account the internal diameter (wire diameter) and the outside diameter (overall cable diameter), after the cable is irradiated at diametrically opposed positions, the dose and the end points and middle of the line tangent to the conductor (greater extension insulator) are equals (Fig. 14).

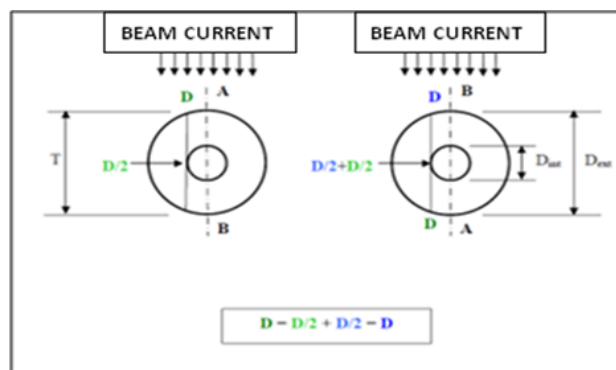


Figure 14: Irradiation form II – wires and electric cables.

Examples of irradiation conditions of wires and electric cables in pulley system are shown in Fig. 15. The curve of dose distribution (irradiation form II) is shown in Fig. 16, take into account the following irradiation parameters,

- Energy (E) 1.5MeV;
- Beam current (I): 10mA;
- Scanning beam: 100cm;
- Speed (v): 100m/min;
- Number of electron beam passes (P): 48 (24 links);

- Total dose (TD): 14.4kGy;
- Dose rate (D): 40kGy/s;
- Density of the insulating (ρ): 1g/cm³;
- Core (internal diameter): 1mm (wire diameter);
- Outside diameter: 11.34mm (overall diameter of the electric cable);
- Power beam: 15kW;
- Beam thickness: 25.4mm (1”).

Take into account the power beam of 15kW and beam thickness of 25.4mm (1”), dose in the irradiated material is calculated by equation 3.

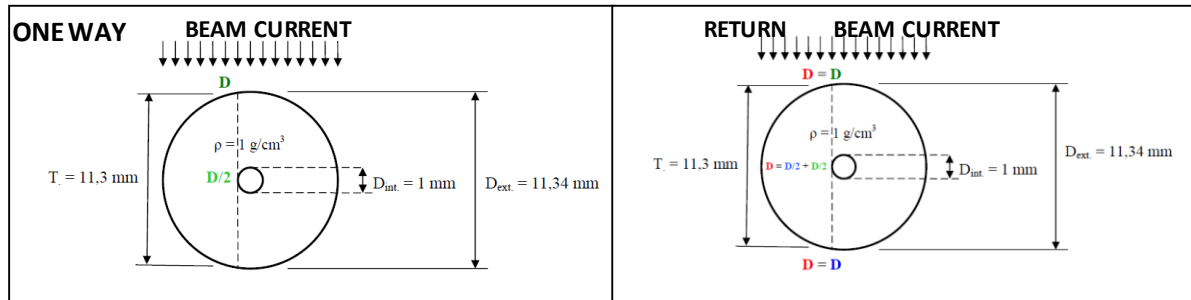


Figure 15: Irradiation form II - wires and electric cables in pulley system.

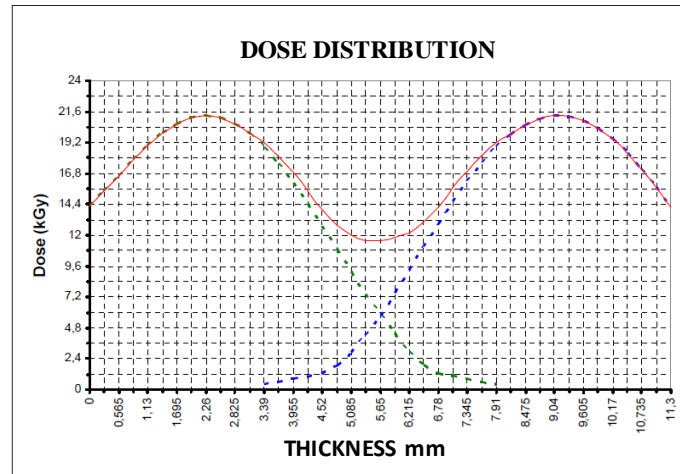


Figure 16: Curve of distributed dose II – wires and electric cables (kGy per mm).

3. THICKNESS OF THE MATERIAL TO BE IRRADIATED AND ITS DENSITY FOR THE ENERGY OF 1.5MEV

The graph below (Fig. 17) was obtained using the calculations for determining the conditions of irradiation, for the Electron Accelerator Dynamitron DC1500/25/4 - JOB 188.

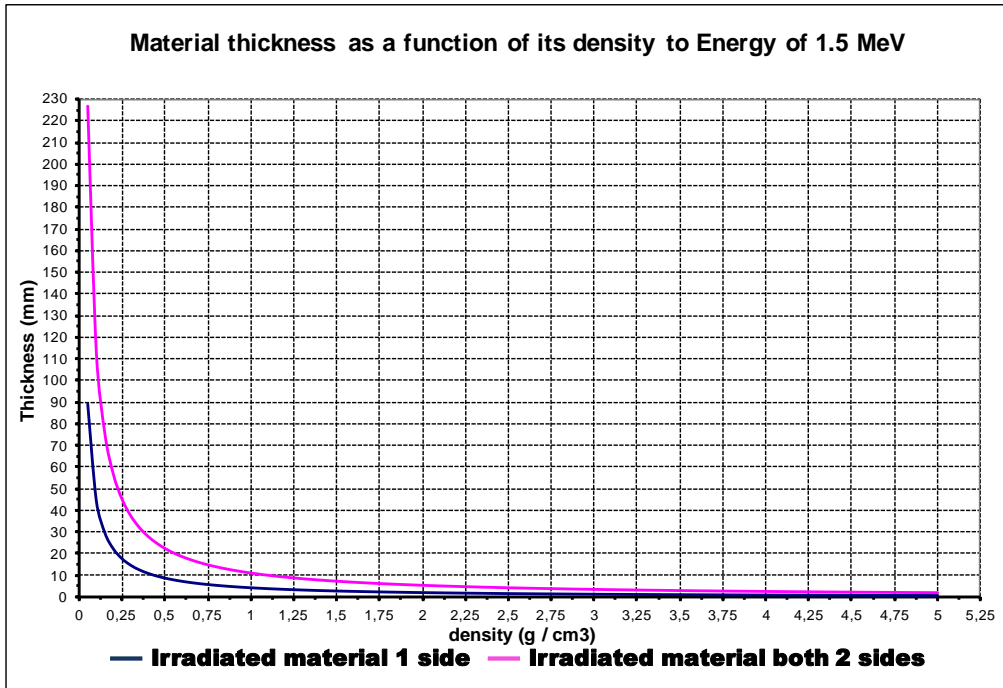


Figure 17: Graph thickness (mm) versus density (g/cm^3) for irradiated materials by Electron Accelerator Dynamitron DC1500/25/4 - JOB 188.

In Fig. 18 is shown the dissociation of the graph thickness (mm) versus density (g/cm^3) for irradiated materials in two intervals, with different density values, for better accuracy.

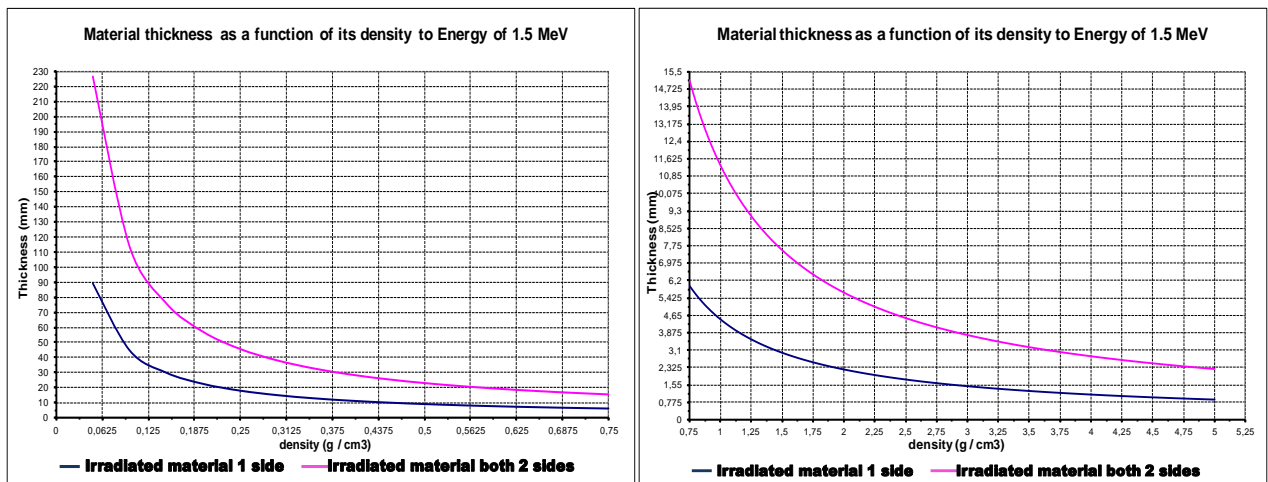


Figure 18: Graphs with two intervals of density (g/cm^3) and material thickness (mm) values.

4. TITANIUM WINDOW AND ENERGY LOSS

As the high voltage is directly associated with the energy of the electron beam, should we also to be considerate that, in the acceleration process, there are to a loss of energy through

the window titanium which isolates the areas in vacuum (the scan horn and beam tube) of the environment with normal atmosphere and by where passes the electron beam. In Fig. 20 is shown the curve of energy loss in window (titanium foil).

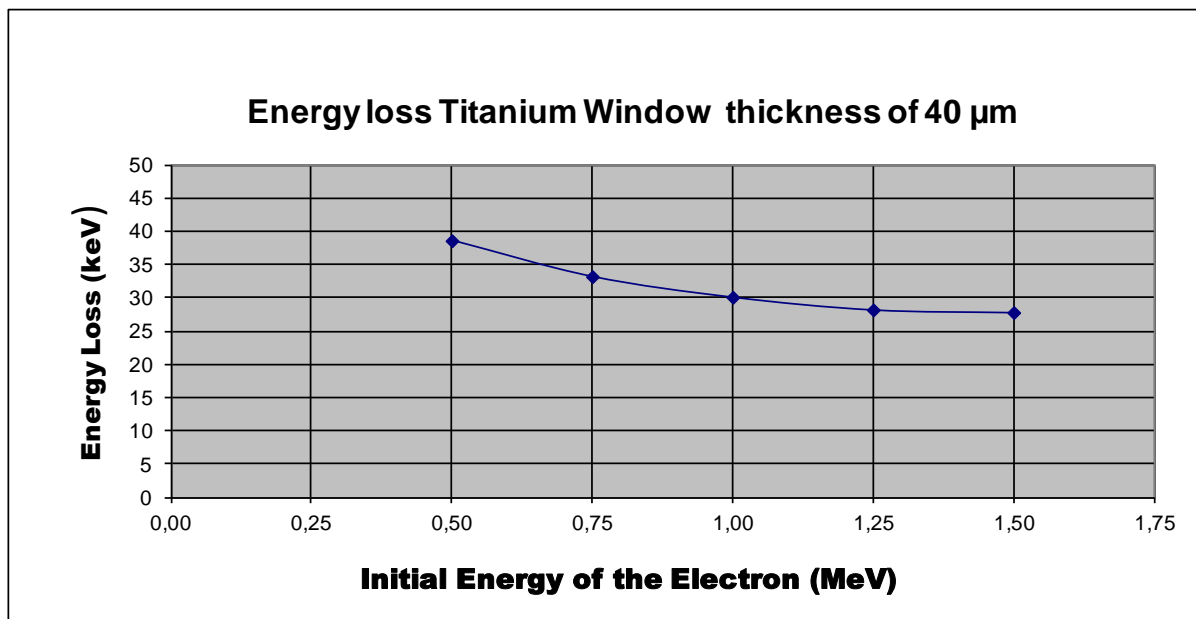


Figure 20: Curve of energy loss in window (titanium foil).

5. CONCLUSIONS

Through this study, the reliability of the equations used in the calculations of the irradiation conditions for flat materials and cables could be verified, both for form I and form II of irradiation. These calculations were developed for use in irradiation with the Electron Accelerator Dynamitron DC/1500/25/4 JOB188 at IPEN/CNEN-SP.

Thus, it was concluded:

- In the form I of irradiation, using the calculated thickness of 4.45 mm, a small difference between the doses on the upper and on the lower surfaces of the material was found. In the graph, the correct thickness was 4.3 mm, 0.15 mm different from the calculated (approximately 3.37% less), so that these doses were equal;
- In the form of irradiation II, using the calculated thickness of 11.3 mm, a difference between the doses was found, between the dose on the surface of the material and in its middle. The graph shows the correct thickness of 10.7 mm, 0.6 mm different from the calculated (about 5.3% lower), so that these doses were equal;
- This study allows the equivalence between the electrical parameters (beam power), used by industries, and the dose absorbed by the material (kGy) in the electron beam processing. It, also, explains to researchers the use of the electron irradiation process, the limits of penetration, distribution and dose rates.

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