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ATOMIC ENERGY COMMISSION

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| 60 | *Abstract :* The pulse radiolysis facility is the experimental centerpiece of the radiation chemistry activities of the Radiation & Photochemistry Division (RPCD) of Bhabha Atomic Research Centre. This facility was created in 1986 which is based on a 7 MeV Linear Electron Accelerator (LINAC) procured from M/s Radiation Dynamics Ltd., UK. The electron energy is one of the principal parameters that influence the dose distribution within the sample irradiated with a beam of energetic electrons. An easy-to-use and robust device has been developed that can reliably detect day-today small variations in the beam energy. It consists of two identical aluminum plates except for their thickness, which are electrically insulated from each other. The thickness of each plate is carefully selected depending on the electron beam energy. The charge (or current) collected by each plate, under irradiation is measured. The ratio of the charge (or current) signal from the front plate to the sum of the signals from the front and rear plates is very sensitive to the beam energy. The high sensitivity and robustness make this device quite suitable for Electron energy measurement for Pulse radiolysis Facility at RPCD | |
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# सारांश


भाभा परमाणु अनुसंधान केंद्र के विकिरण एवं प्रकाश रासायनिकी प्रभाग की स्पंद विकिरण अपघटन सुविधा, विकिरण रासायनिकी गतिविधियों की प्रयोगात्मक स्तर पर एक महत्वपूर्ण सुविधा है । इस सुविधा का निर्माण वर्ष 1986 में हुआ था जो 7 MeV रैखिए इलेक्ट्रॉन त्वरक (LINAC) पर आधारित थी जिसका प्रापण मैसर्स रेडिएशन डाइनामिक्स लिमिटेड, यू.के. से किया गया था ।

इलेक्ट्रॉन ऊर्जा, प्रमुख प्राचलों में से एक है जो ऊर्जावान इलेक्ट्रॉन बीम सहित किरणित नमूनों के बीच मात्रा के वितरण को प्रभावित करती है । प्रयोग में आसान तथा मज़बूत एक युक्ति का (डिवाइस का) विकास कर लिया गया है जो बीम ऊर्जा में प्रतिदिन होने वाले लघु परिवर्तनों को विश्वसनीय रूप में संसूचित कर सकती है । इसमें मोटाई को छोडकर दो समान एल्युमीनियम की प्लेटें होती हैं जो एक दूसरे के साथ इलेक्ट्रिकल रूप से रोधित होती हैं । इलेक्ट्रॉन बीम ऊर्जा के आधार पर प्रत्येक प्लेट की मोटाई का चयन बड़ी सावधानीपूर्वक किया जाता है । किरणन के अंतर्गत प्रत्येक प्लेट द्वारा आवेश (अथवा धारा) का मापन किया जाता है । अग्रभाग प्लेट से अग्रभाग सिग्नलों के योग तक और विरल प्लेटों के आवेश (अथवा धार) अनुपात बीम ऊर्जा में बहुत संवेदनशील होता है । उच्च संवेदनशीलता और मज़बूती ने इस युक्ति (डिवाइस) को आरपीसीडी स्थित स्पंद विकिरण अपघटन सुविधा हेतु इलेक्ट्रॉन ऊर्जा के मापन के लिए बहुत उपयुक्त बना दिया है ।

**Electron Energy Device for LINAC based Pulse Radiolysis Facility of RPCD**

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## Abstract

The pulse radiolysis facility is the experimental centerpiece of the radiation chemistry activities of the Radiation & Photochemistry Division (RPCD) of Bhabha Atomic Research Centre. This facility was created in 1986 which is based on a 7 MeV Linear Electron Accelerator (LINAC) procured from M/s Radiation Dynamics Ltd., UK.

The electron energy is one of the principal parameters that influence the dose distribution within the sample irradiated with a beam of energetic electrons. An easy-to-use and robust device has been developed that can reliably detect day-today small variations in the beam energy. It consists of two identical aluminum plates except for their thickness, which are electrically insulated from each other. The thickness of each plate is carefully selected depending on the electron beam energy. The charge (or current) collected by each plate, under irradiation is measured. The ratio of the charge (or current) signal from the front plate to the sum of the signals from the front and rear plates is very sensitive to the beam energy. The high sensitivity and robustness make this device quite suitable for Electron energy measurement for Pulse radiolysis Facility at RPCD.

# Electron Energy Device for LINAC based Pulse Radiolysis Facility of RPCD

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## 1.Introduction

The LINAC is capable of delivering pulses of 7 MeV electrons ranging from 25-500 ns and 2 µs [1]. The schematic of Electron Accelerator and its sub systems are shown in Fig1. The source of the electrons is an electron gun, which consists of a tungsten filament heated by a filament transformer. This filament heats up indirectly a cathode (tungsten) pellet, and a 6 kV DC voltage is applied between the cathode and filament to back bombard electrons on the cathode. Electrons emitted from the tungsten cathode traverse through a hole in the anode disc. The electron beam is accelerated by an axial electric field associated with RF electromagnetic wave, traveling down a circular wave-guide. RF power is generated using a S-Band magnetron, which generates a peak power of 2 MW at 3 GHz frequency for a pulse duration of 2.6 µs. These electrons get accelerated from injection energy of 43 KeV to a final energy of 7 MeV as it travels along the wave guide. The electron beam emerges out through a 0.001 inch thick titanium window at the end of the wave-guide.

Beam deflection plates are used to 'time slice' the 2µs pulse to generate short period pulses (25ns – 500 ns). In the short pulse mode of operation, the electrons emerging from the cathode of the gun are normally kept away from entering the accelerating wave guide structure by a positive potential (10 kV) applied to one of the deflector plates. This enables the electrons to enter the accelerating structure for the short period determined by the duration of the beam modulator pulse. Table 1 gives the important parameters of the electron accelerator:

**Table 1: Specifications of the Linear Electron Accelerator**

| | | |
|---|---|---|
| 1. | Output | Electron Beam |
| 2. | Electron Energy | 7 MeV |
| 3. | Energy Spread | ± 0.4 MeV |
| 4. | Pulse Width | 25, 50, 500, 2000 nsec |
| 5. | Peak current | 900, 400, 90, 70 mA |
| 6. | Pulse Rep. Rate | 12.5 to 500 pps in steps of 12.5 pps |
| 7. | Beam Diameter | 3mm at exit window |
| 8. | Beam divergence | 1.5 mrad (1/2 angle in vacuum) |
| 9. | Focus coil current | Buncher focus: 228 A, Main focus : 208 A |
| 10. | Magnetron | RF Freq : 3 GHz, RF power : 2MW (Peak) |
| 11. | Vacuum | $10^{-7}$ - $10^{-8}$ Torr |

The RPCD LINAC is primarily intended for producing electrons which emerge on the same axis as the waveguide. Any changes in beam energy for whatever reason result in only minor differences in beam deviation away from the central axis: a 5 MeV beam will emerge just at a 7 MeV beam and without an actual energy measurement or specific detection system we can no longer simply assume that the machine itself will regulate the energy. The energy is determined by the tuning of the magnetron (at resonance the accelerating fields are maximal), by the total charge stores in the waveguide loading by the beam charge. In this report we discuss a method for energy determination and the response of energy to various machine settings are explored. We have also undertaken energy determination using radiochromic EBT films separately to corroborate our data which is presented as Appendix at the end.

## 2. Methodology

There are various methods to accomplish this.

(i) Electron activation method:

This method exploits a nuclear reaction that has threshold energy near the energy of interest : for example, $^{65}Cu + e \rightarrow {}^{64}Cu + n$. The threshold energy for this reaction is 9.91 MeV. Thus, electrons with energy above this value can be detected through this reaction. The product nucleus $^{64}Cu$ is radioactive with half-life of 12.7 h. The procedure is quite elaborate, thus is used sparingly.

(ii) Depth–dose distribution:

This method exploits the relationship of depth–dose variation with electron-beam energy [2]. The dose variation with depth is generally determined by using either a stack-geometry or a wedge-pair made of a conducting material. This method is generally used during operational qualification of facility.

(iii) Charge-deposition distribution:

This technique exploits the dependence of charge deposition with depth on the electron-beam energy. This method is the subject of the present work.

There are only a few studies reported in the literature [3 - 8] for beam energy measurement by using this technique. There are various theoretical computations to calculate the charge deposition distribution with depth for various materials [9] but not much experimental work has been done in this field so far. In this report we have used this method of depth-charge distribution to monitor changes in the beam energy. The primary advantage is that the measurements can be done almost ‘on-line’.

### 2.1 Energy device and Beam energy determination

Aluminum was chosen as the material for the energy device because of its ruggedness, ease of manufacture, low backscattering coefficient [4] and high threshold energy for (γ; n) reaction ($E_{th}$ = 13.1 MeV) [5].

To optimize the design of the energy device, it is necessary to determine the charge-deposition distribution with depth. This can be done by using several aluminum disks of 0.5 mm thick and 100 mm diameter; the thickness of the collecting plate can be increased by adding one such disc at a time after each charge measurement. Care may be taken while adding each additional disk to ensure that the central axis of the resulting plate (the stack of disks) always coincided with the beam axis. Fig 2 shows the differential charge-deposition distributions in aluminum with electron beam facility at ISOF-CNR Institute, Italy (experimental), and for 5 and 10 MeV mono-energetic beams (calculated) [9] taken from works of Mehta et al [7]. The y-axis in this figure represents electrons collected by a unit thickness of aluminum plate per unit incident electron.

Based on the results of the charge-deposition distribution, the energy device was constructed. The detail of the device is given in Fig. 3A and 3B. It consists of four aluminum plates having various thickness assembled with three 10 mm thick perspex glass insulating spacers. The front and the rear plates are for holding the two measuring plates placed in the middle with four M6 screws running along the length. The thickness of the front measuring plate, 12 mm in our case, was determined by the position of the peak in the differential charge-distribution curve in the material of construction (see Fig. 2). The rear plate has a thickness of 25 mm which is sufficient to stop all the electrons at the maximum operating beam energy. The two plates are connected by two long coaxial cables to digital storage oscilloscope (Tektronix Model: TDS 2024), placed outside the cave room. The rear plate is grounded for measurements.

When the beam strikes the energy device, the currents were measured from the two plates simultaneously. Energy ratio was then calculated as follows:

Energy ratio = (Current from the front plate) / (Sum of the currents from the two plates).

To use the energy device as a monitoring tool for the electron beam energy, it is necessary to establish a relation between the output of the energy device (energy ratio) and the electron beam energy. The data in Fig. 4 show that there is a good linear correlation between these two parameters, suggesting that this relationship can be exploited for quickly assessing any variation in the beam energy. All measurements were carried out at the Institute of Isotopes (II), Hungary using the 4 - 6 MeV TESLA LPR-4 type linear electron accelerator (II accelerator) while higher electron energy of 7 - 10 MeV was obtained from the Vickers-type accelerator at ISOF-CNR Institute, Italy (ISOF accelerator) . The correlation in the range of 4 – 10 Mev shows 95% prediction limits, which represents about ± 0.5 MeV.

## 3. Results and Discussion

Three sets of parametric investigations were carried out with (i) magnetron tuning at a set gun current (ii) gun current at a set magnetron condition and (iii) pulse width at a given gun and magnetron setting.

### 3.1 Magnetron tuning

LINAC was operated in single shot mode for 2 μs pulses at 50 pps with a conservative gun current as the magnetron frequency was changed in regular steps. The beam energy was measured using the method described above and results are plotted in Figure 5.

The plot illustrates how, as the magnetron frequency is increased from a low value, the energy transferred to the electrons from the RF energy in the waveguide increases until it reaches an optimum and then reduces again. At this particular gun current the electrons can reach in excess of 7 MeV.

### 3.2 Gun current

Having established the effect magnetron frequency has on electron beam energy, the effect of gun current was investigated. Due to beam loading it is expected that an increase in gun filament current would result in a reduction of the electron beam energy. For these experiments 2 μs pulses were chosen, and complete measurements were taken at the magnetron close to its maximum energy position.

Since our LINAC works on indirectly heated cathode, the various current parameters like filament, bombardment and peak currents are related to each other. Before proceeding to measure the energy variation with gun current, we took the task of getting the interdependence of these current parameters. While the filament current has linear relationship, the peak current rises sharply with bombardment current ( Fig 6,7). Changing the bombardment HT voltage from 4.5 to 5.5 kV, a family of curves are obtained. The chemical dosimeter based on KSCN solution yield the obtainable doses in Gray (Gy) with various filament, bombardment and peak currents shown in Fig 8 & 9.

After characterizing various currents, the energy measurement exercise now carried out with various gun filament currents which are shown in Fig 10. As can be seen from the plot in Figure 10, the effect of increasing the beam current by increasing gun filament current increases the average energy. At filament current as 14.25 A, the energy reaches to its peak value. Further increase in filament current does not show any increase in energy instead the electron energy starts decreasing. To get the maximum electron dose, we have to increase filament current as well as energy, and this can be achieved by reducing the pulse width.

**3.3 Pulse width**

Finally the relationship between pulse width, which can be controlled on our LINAC, and electron beam energy was explored. This is shown in Figure 11. Very short pulse widths are associated with higher average energies. This indicates beam loading effect but with the timescale of a single pulse, suggesting that the accelerator waveguide is operating in the stored charge mode. In other words it seems that within the first 100 ns of a pulse there is good energy transfer from the waveguide RF to the electrons but at later times this effect becomes less significant.

**4. Conclusion**

Sometimes the actual energy of an electron beam is unimportant compared to the more relevant measure of interest: the dose delivered. However, if large energy variations occur then the range of the electrons is affected and thus the shape of the depth dose curve. This will have some impact on irradiations, when regions of the sample receive significantly different doses compared to other regions, or different to that expected because of the modified dose distribution.

It is therefore necessary to know the electron beam energy for a given linac state and the requirement is for each combination to be measured. It is probably best to keep the magnetron tuning fixed and to explore the gun current/pulse width/dose/energy space. Given these data the procedure would be to specify a dose and an energy tolerance and look up the gun current/pulse width combinations which are available

The data collected for the present work clearly shows that such an energy device can also be used for lower energy electrons. The advantages of this device include: (i) rugged construction (ii) easy on-line use, and (iii) precision suitable for radiation processing applications.

***Acknowledgements***

*This work was done for the first time in this facility after commissioning to gain insight about the LINAC performance as a part of our O/M programme. We acknowledge the constant encouragement and support of Dr. D. K. Palit, Head, RPCD and technical support of APPD, EBC and RP&AD, BARC.*

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Report ISSN 0917-8015, Research Institute of Advanced Science and Technology,
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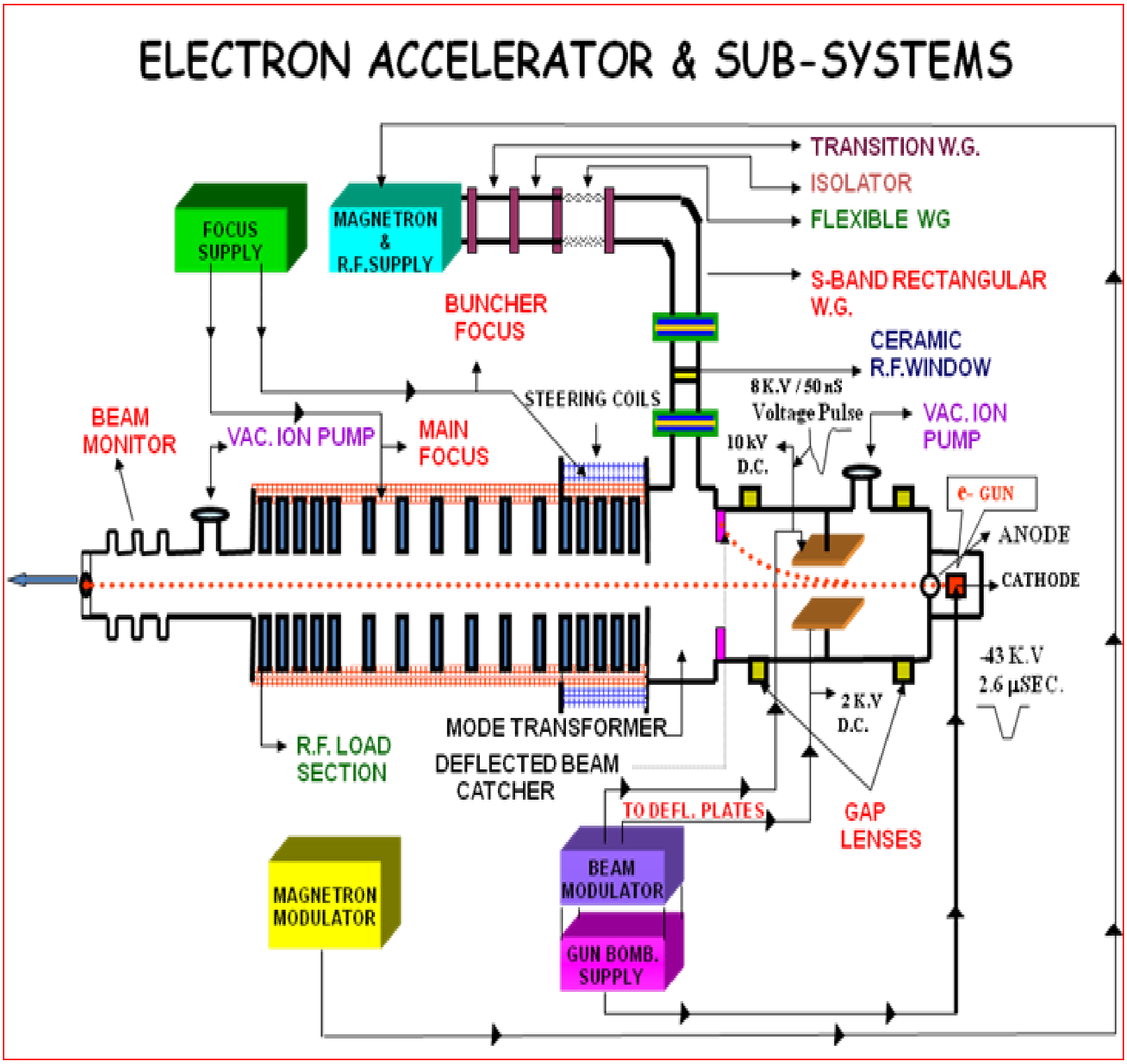



**Fig 1 : Electron accelerator and sub systems in pulse radiolysis facility**

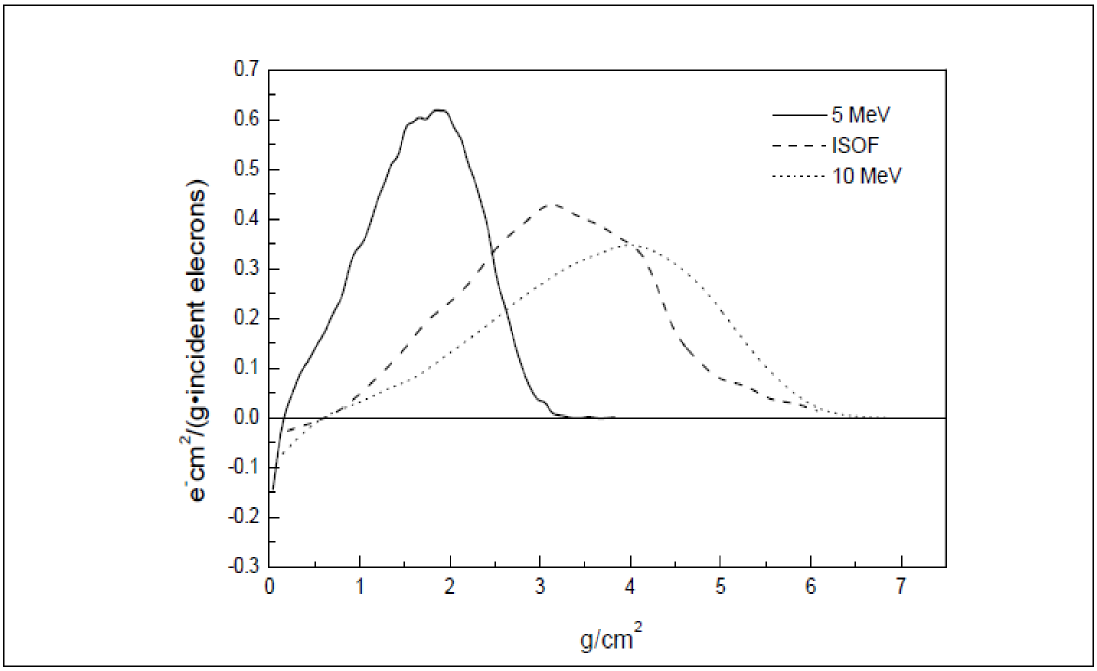
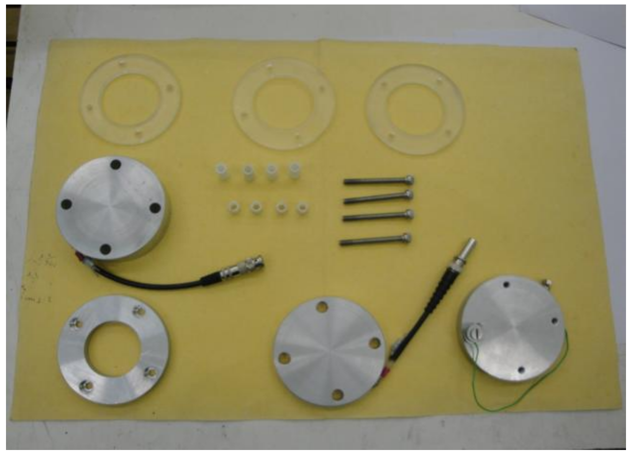
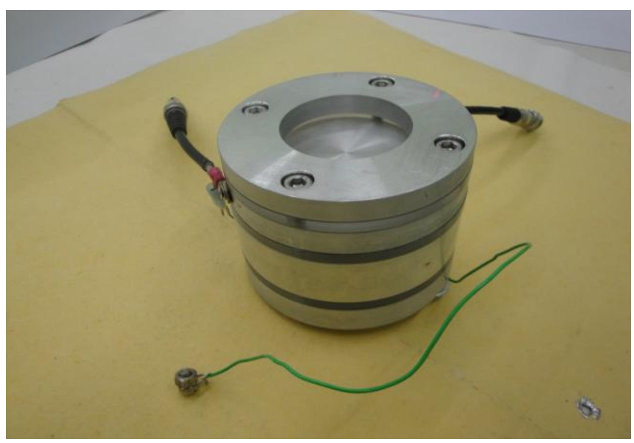



**Fig 2 : Differential charge-deposition distributions in aluminum for ISOF beam (experimental), and for 5 and 10MeV mono-energetic beams (calculated). [ ref text at section 2 ]**

**Fig 3A: Camera pictures of the energy device in parts and as a whole assembly**





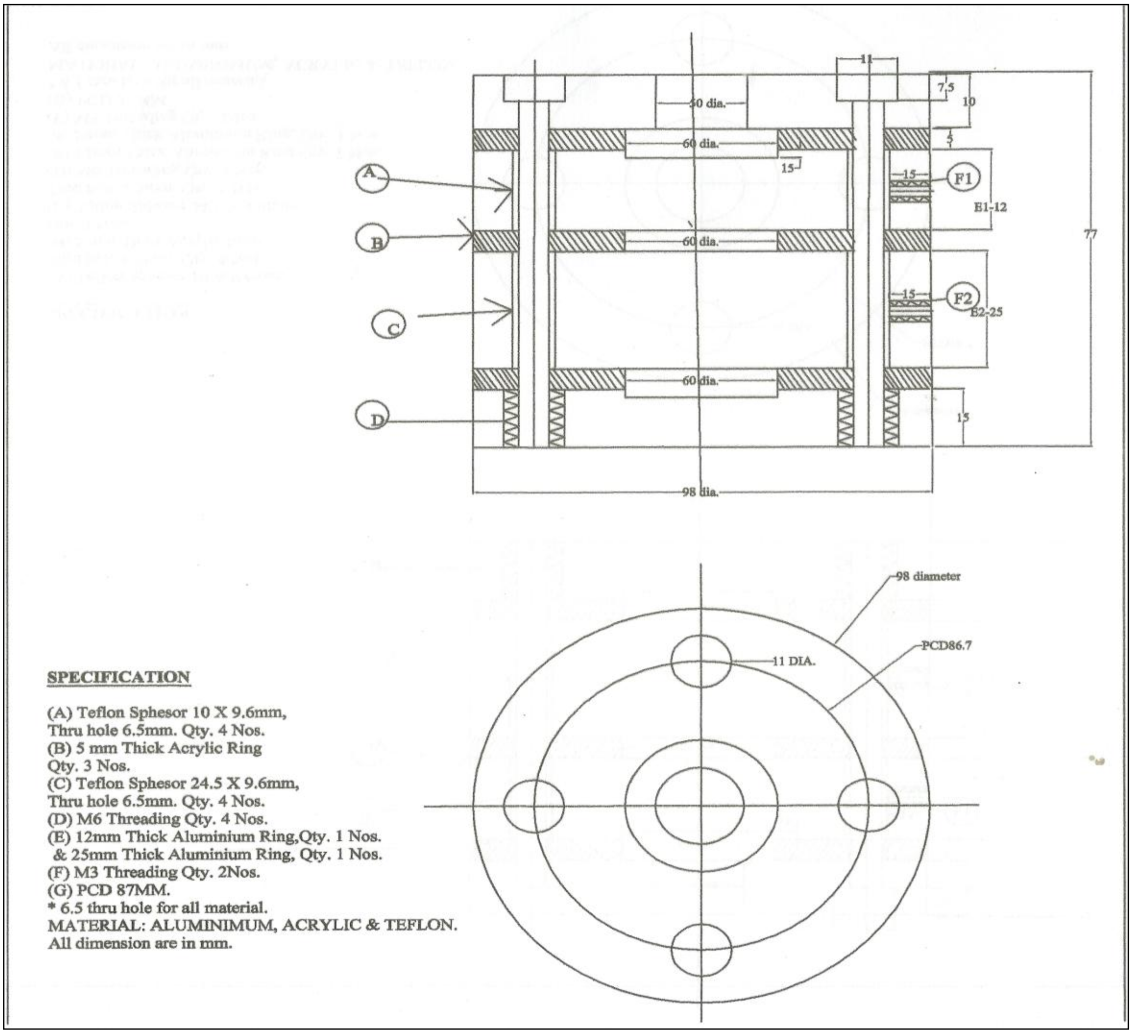



**Fig 3B: Cross Sectional view of the energy measurement device**

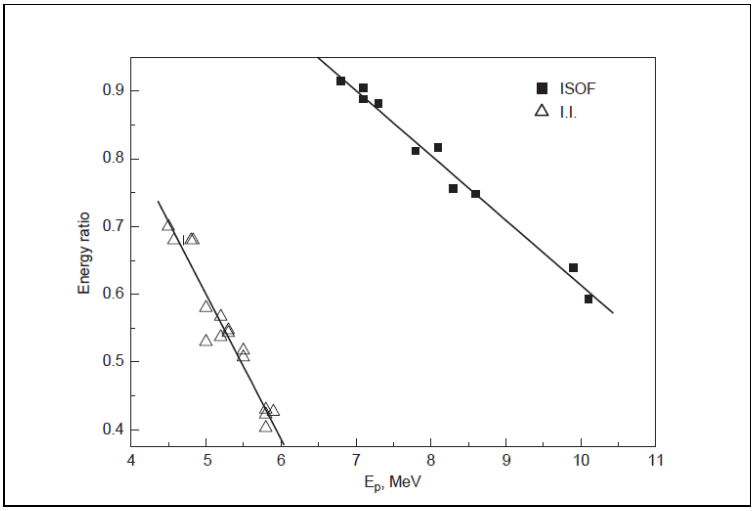



**Fig 4: Correlation between the measured values of the energy ratio and the most probable beam energy [ ref text at section 2 ]**

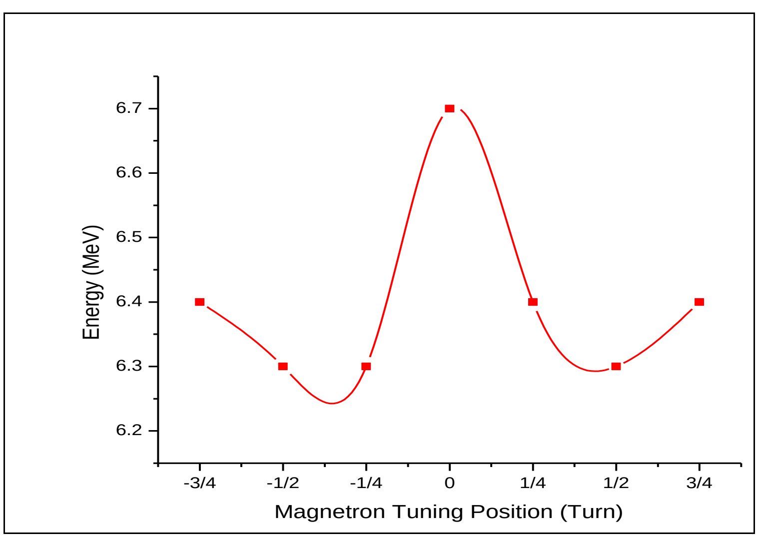



**Fig 5: Electron Energy Vs Magnetron tuning position**

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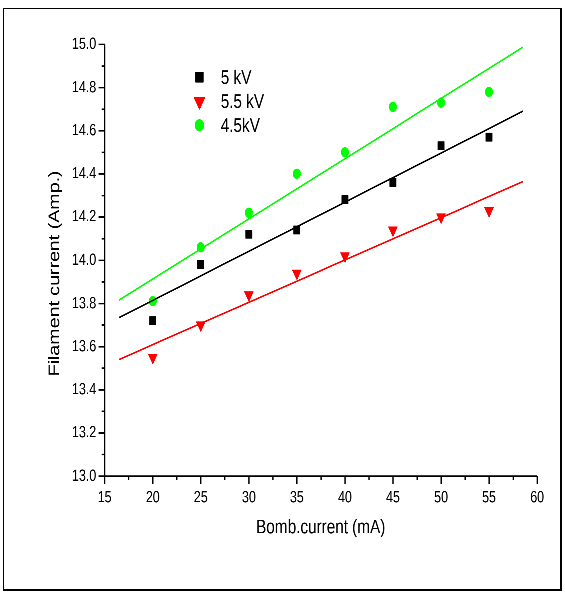
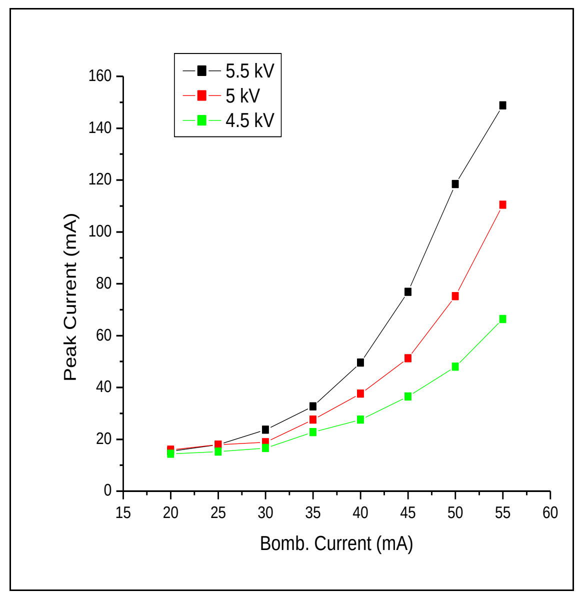
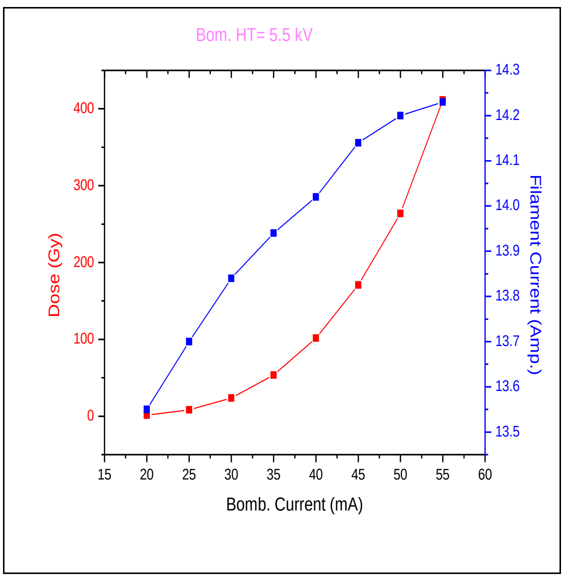
| <br> | <br> |
| **Fig 6: Bombardment Current versus Filament Current @ various HT setting** | **Fig7: Bombardment Current versus Peak Current @ various HT setting** |



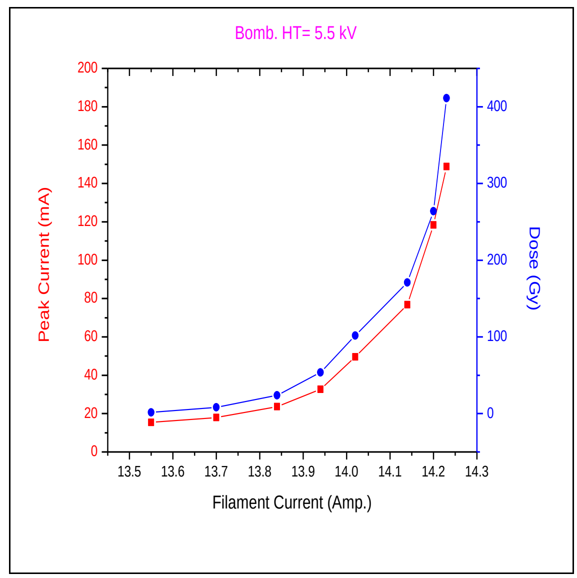




**Fig 8: Dose versus Bombardment Current & Filament Current @ Bomb HT 5.5kVdc**

**Fig 9: Dose versus Filament Current & Peak Current @ Bomb HT 5.5kVdc**

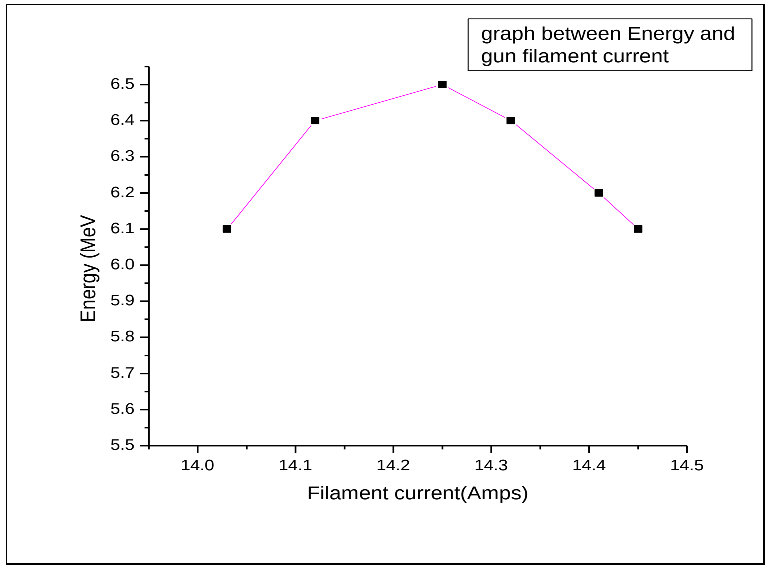



**Fig 10: Electron Energy versus Filament Current @ bomb HT 5.5 kVdc**

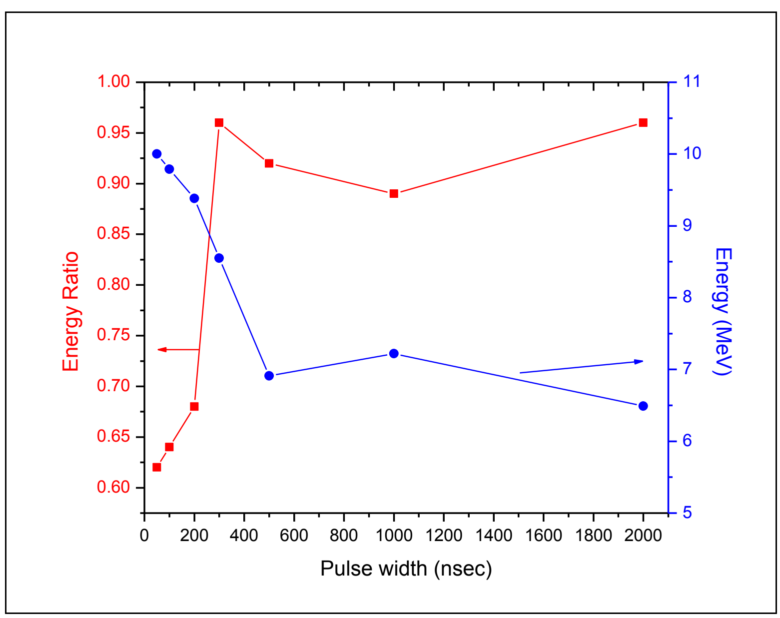



**Fig 11: Electron Energy and Energy ratio versus Pulse width**

**Appendix : Electron Energy determination using Radiochromic EBT films**

The objective of this study was to determine the electron energy using radio-chromic EBT films. The measurements were carried out in static mode of sample irradiation in the horizontal geometry. The experimental arrangement is illustrated in Fig.A1. The operational parameters of the accelerator are: pulse width in the range of 25 to 2000 nsec at pulse repetition rate from 12.5 to 500 pps and peak current from 70 to 900 mA. The average beam power of the accelerator is 2 kW. The various sample for radiolysis purposes are placed at sample holder near the exit window of the LINAC in horizontal geometry.

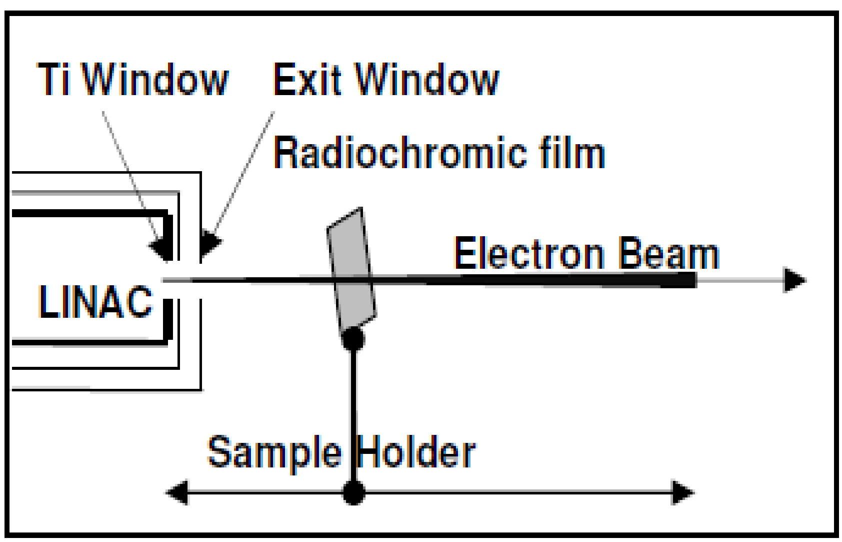



**Fig A1: Schematic of Experimental Set up**

During the experiment, a piece of EBT-3 films (3x3 $cm^2$) were sandwiched between 2 mm absorber plates placed in a plane perpendicular to the beam direction. The film was exposed for 3 second at different distances (0 mm to 100 mm) from accelerator exit window. The exposure was repeated for Al, PMMA and Polystyrene separately. Each exposed film was scanned by document scanner and analyzed by Image J PC-based software. The images of exposed films were obtained and pixel values were recorded. The plots between absorber thicknesses and normalized pixel values were generated for each absorber material. The practical range (Rp) of monoenergetic electrons was determined in each absorber and used for determination of electron beam energy.

Measured attenuation curves w.r.t. depths 7 MeV electron beam in Aluminum, PMMA and Polystyrene are shown in Fig.A2. The practical electron range ($R_p$) recorded from these curves were used for determining most probable energy ($E_p$) of the 7 MeV electron beam at the entrance surface of these materials. The Ep values so determined are 6.66 to 7.2 MeV in materials Al, PMMA and Polystyrene.

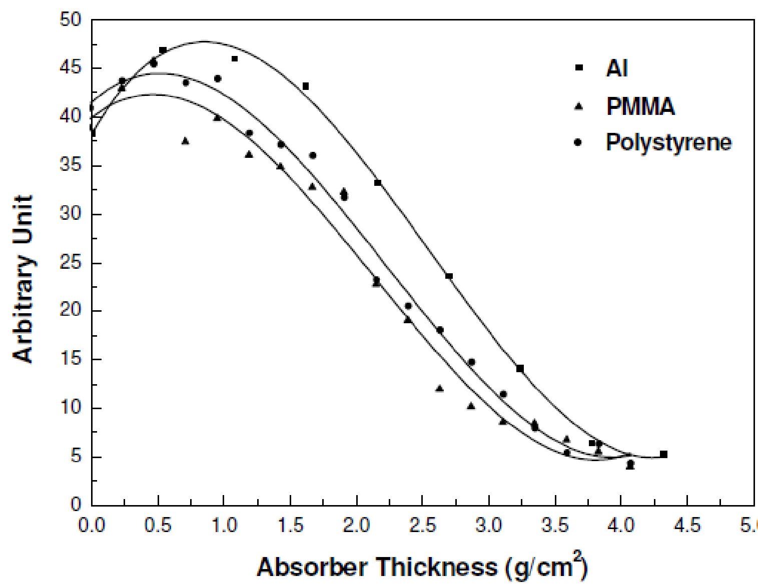



**Fig A2: 7MeV electron beam depth profile in Al, PMMA and Polystyrene absorbers respectively.**

Energy - Range Relations (ISO/ASTM, 2004: ref [2] ):

Polystyrene:

$R_p = 0.533\ E - 0.159 = 3.572\ g/cm^2$ , 2 MeV < E < 12 MeV

Observed $R_p = 3.392\ g/cm^2$

E = 6.66 MeV

PMMA:

As per the literature, the CSDA (continuous-slowing-down-approximation) range of the 7 MeV mono-energetic electron beam in Polystyrene and PMMA is almost same (theoretically) thus following equation hold good for both with good confidence. On the other hand, energy-range relation for water do not hold good in case of PMMA (after incorporating appropriate corrections in the relation) in this current measurements.

$R_p = 0.533\ E – 0.159 = 3.656\ g/cm^2$, for 2 MeV < E < 12 MeV

Observed $R_p = 3.57\ g/cm^2$ (revised)

E = 6.995 MeV

ALUMINUM:

E (MeV) = 0.2 + 5.09 x $R_p$ (cm), for 5 MeV < E < 25 MeV

Observed $R_p$ = 1.5 cm

E = 7.8 MeV ; Little higher value could be due to air gaps between the Al sheets.