Oxford Gray Institute Linac Energy Determination

1. Introduction

In the original configuration of the SL75-5 Linear Accelerator the electron beam emerges at 90° to the waveguide axis by virtue of the bending magnet in the accelerator head. The X-ray target, which the electron beam hits as it reaches the end of the vacuum system, produces the X-ray beam which can be assessed at the point of interest. Should the electron beam energy change, its position on the target would change. A variety of compensation systems were used to correct for this and error signals from these could be used as approximate indicators of energy.

The Oxford 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 4 MeV beam will emerge just as a 6 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 stored in the waveguide and by the extent of waveguide loading by the beam charge. A method for energy determination had to be developed and the response of energy to machine settings explored.

2. Method

The gold-standard method to measure electron beam energy is with an ionization chamber and a water phantom. Using this approach a broad-beam depth-dose curve is obtained and established relationships between energy and the curve parameters are used. This method is certainly necessary for definitive measurements, but takes a long time to set up and is somewhat cumbersome. What is really needed is a method that could deliver a quick spot-check in addition to providing reliable results relatively fast and with minimum disturbance to any existing experimental set-up beyond the end of the beamline.

We currently obtain depth-dose profiles with the aid of HD-810 Gafchromic film (http://www.gafchromic.com) available from Vertec, Reading, UK; http://www.vertec.co.uk). This film does not require development and its use is widespread in applications which require mapping of radiation fields. To obtain a depth-dose record, a piece of film is sandwiched between two PMMA blocks, placed at right angles to the beam input direction, i.e. with an edge flush with the face seen by the beam, typically 1 metre away from the beamline output window. Such a block is shown in Figure 1. When a broad beam irradiation occurs the film will darken along the depth of dose deposited, i.e. the optical density will be proportional to the dose. The film is then scanned by a 2400 dpi resolution transmission flatbed scanner (Epson Expression 10000XL, http://www.epson.co.uk/Scanners/Epson-Expression-10000XL).

Figure 1: An irradiated Gafchromi film sandwiched between two PMMA blocks.

The image is imported into MATLAB and converted to an optical density map from which a depth-dose profile can be extracted. At this point we are looking at the depth dose in PMMA, and so to get the equivalent curve in water, a depth-scaling factor is applied. The AAPM protocol (American Association of Physicists in Medicine, Task Group 21, 1983) suggests the appropriate relationship between the mean incident energy of an electron beam and its R_{50} value (depth where dose drops to 50% of maximum) in water as $E_0 = 2.33 \times D_{50}$ (with energy in MeV and depth in cm).

3. Example measurement

Figure 2 shows the irradiated film, a MATLAB-generated isodose false colour map of the dose-distribution (the scanned area includes a border region around the actual film), and a depth dose profile of the middle section.

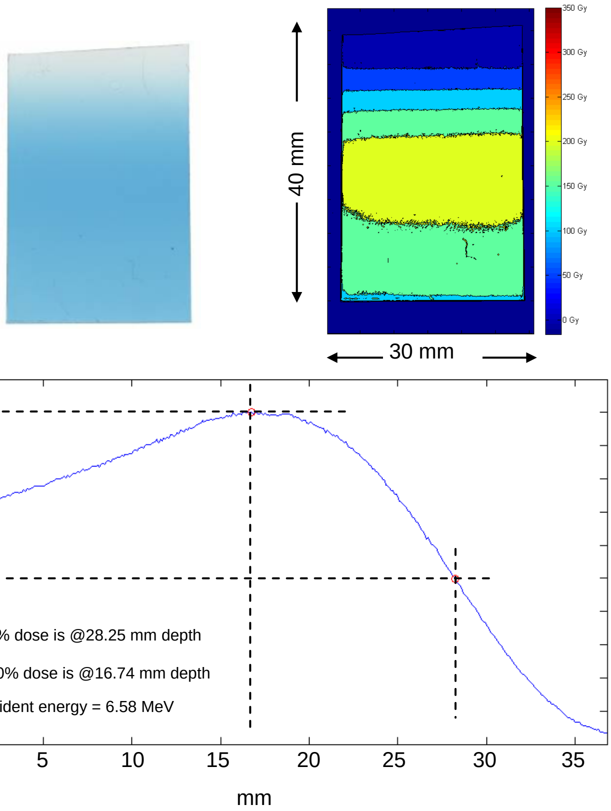

Figure 2: Representative results of beam depth-dose measurements. Top left: Gafchromic film; top right: isodose plot; bottom right: depth dose curve, with beam entering from the left.

Results

Three responses were investigated: that of the energy to magnetron frequency tuning at a set gun current, that of energy to gun current at a set magnetron condition, and that of energy to pulse width at a given gun and magnetron setting.

Magnetron tuning

Film was irradiated with 4 μs pulses at a conservative gun current as the magnetron frequency was changed in regular steps. The beam energy was measured using the method described above and the results plotted in Figure 3.

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.

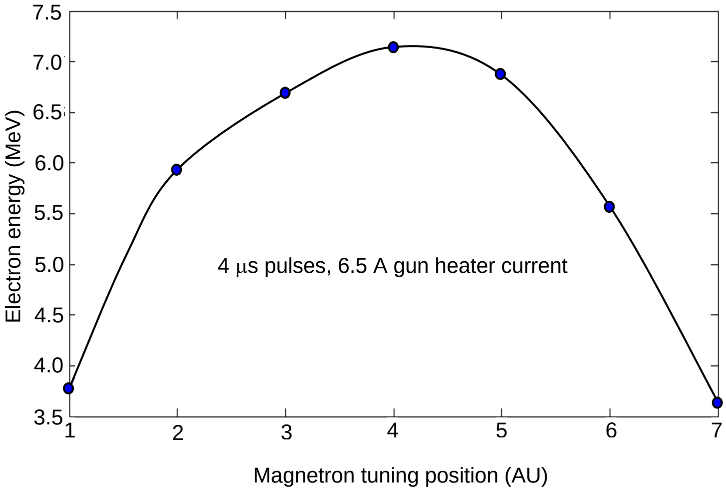

Figure 3: Variation of energy as a function of magnetron tuning.

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 experiment 500 ns pulses were chosen, and for completeness measurements were taken both with the magnetron close to its ‘maximum energy’ position and also off-tune.

As can be seen by the plots in Figure 4, the effect of increasing the beam current by increasing gun filament current lowers the average energy. What this gives us however is a handle on the magnitude of the effect, and this helps in deciding how to irradiate in the high dose-per-pulse region. For example, if we calculate that a 100 ns pulse at a gun current of 8 Amps should give us our required dose but see that the electron energy would be below 5 MeV we might want to preserve a higher electron energy of 6.5 MeV and therefore preferentially choose a longer pulse but at a lower gun current, say a 500 ns pulse at 7 Amps.

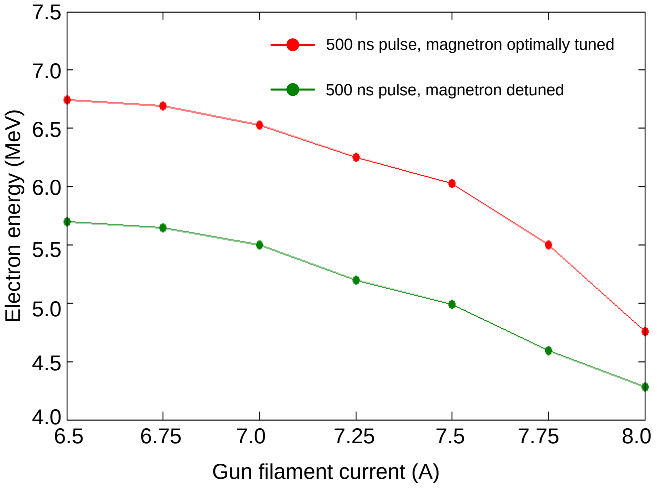

Figure 4: Variation of energy as a function of gun filament current.

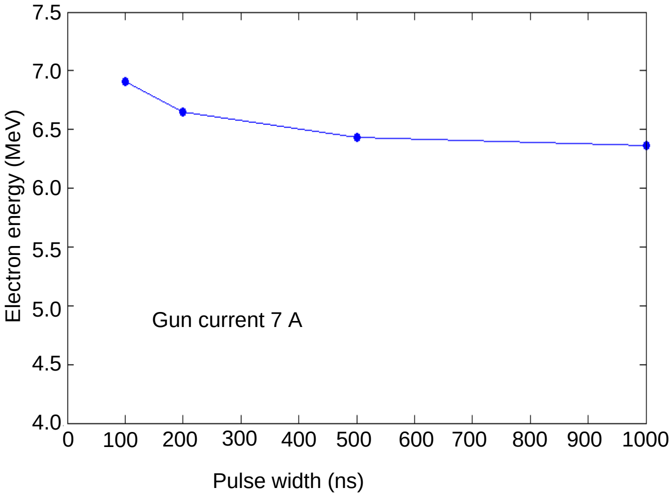

Figure 5: Variation of energy as a function of electron pulse width.

Pulse width

Finally any connection between pulse width, which can be controlled on this linac, and electron beam energy was explored. This is shown in Figure 5. Very short pulse widths are associated with higher average energies. This hints at a beam loading effect but within 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. The energy ‘measured’ by the film is the sum of this distribution and is seen to decrease as the pulse lengthens. However, the effect seems to flatten off fairly quickly.

Validation

To test this method of electron beam energy determination, measurements were taken on a multi-energy Varian linac at the Churchill Hospital, Oxford, UK. The results were compared against those taken by the Physics Department using the optimum water tank and ionization chamber method. Many thanks go to Rosemary Belton and her staff for helping with the experiments and giving their time outside normal working hours.

Nominal energy (MeV)	6	9	12
E_0 (Churchill) (MeV)	5.7 ± 0.1	8.3 ± 0.1	11.5 ± 0.1
E_0 (Gray) (MeV)	5.56 ± 0.2	8.36 ± 0.2	11.44 ± 0.2

The agreement is excellent, and validates the Gafchromic film method as a respectable way of making relatively quick and easy energy determinations whilst being backed up by a longer term schedule of water tank measurements.

Conclusions and use

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.

Another potentially even faster method to determine beam energy involves the imaging of luminescence from a plastic scintillator block, as shown in Figure 6. Here, the electron beam impinges on one of the surfaces of the block. When viewed side-on the fluorescence essentially indicates the dose distribution (integrated along the line of sight). Indeed, this method is described in ‘A new tool for measuring therapeutic electron beam energies with scintillation light’ by M. Ishigami *et al.* in 2007 (Nuclear Science Symposium Conference Record, 2007. NSS '07. IEEE). Their measurements on a linac at the Kitisato University Hospital in Japan showed that it was possible to measure beam energy with an error of <2%. The full method employs a video camera to capture the scintillation image and profiling of the image intensity along the beam direction axis to reveal the depth-dose curve. Such a scintillator block was purchased (EJ-200 material from Southern Scientific Ltd, Lancing, UK, http://www.southernscientific.co.uk) and while it is certainly could be a very useful tool for viewing the beam profile and seeing in real-time how the electron range varies with magnetron tuning, this system has not been fully developed at time of writing. In the future, the potential of such a system will be explored.

Figure 5: Imaging Bicron 400 scintillator luminescence, with the imager placed at right angles to the beam, entering the scintillator block from the right side.

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