Oxford Gray Institute Linac Irradiation Options

Introduction

The Elekta SL75-5 clinical linac is designed to produce a focused beam of electrons which hit a tungsten target at its central point and produce an X-ray field which is first flattened and then collimated. Three magnetic focusing and beam-steering systems are present within the accelerating structure:

- X-Y centering/deflection coils at the gun (input) end of the waveguide
- Three beam focussing solenoid coils along the length of the waveguide
- X-Y centering/deflection coils at the output end of the waveguide

Theses systems are preserved in the Gray Institute configuration. However, since the original machine was designed to produce hard X-rays only at right angles to the gantry-mounted machine body, the electron beam passed through a ~90° permanent bending magnet before impinging on the tungsten target. In our current configuration the accelerated electron beam simply exits the waveguide and continues along the same axis, arranged to be nominally horizontal, i.e. parallel to the floor. Four additional magnetic steering/focussing systems have been added along the beam path:

- A further solenoid focus coil to counteract any beam divergence
- A third set of X-Y steerers
- An achromatic bending magnet assembly capable of switching the beam path 90° to the left or to the right, in addition to providing a straight-through path
- Two quadrupole focus magnet assemblies for beam shaping in the straight through path

These 'external' beam control systems are shown in Figure 1. The 90 degree deflection system was originally used on an electron Van de Graaff accelerator, constructed by the High Voltage Engineering Corporation (Burlington, Massachusetts, USA), and arranged in the form of two 45° deflection magnets, separated by a quadrupole focusing magnet.

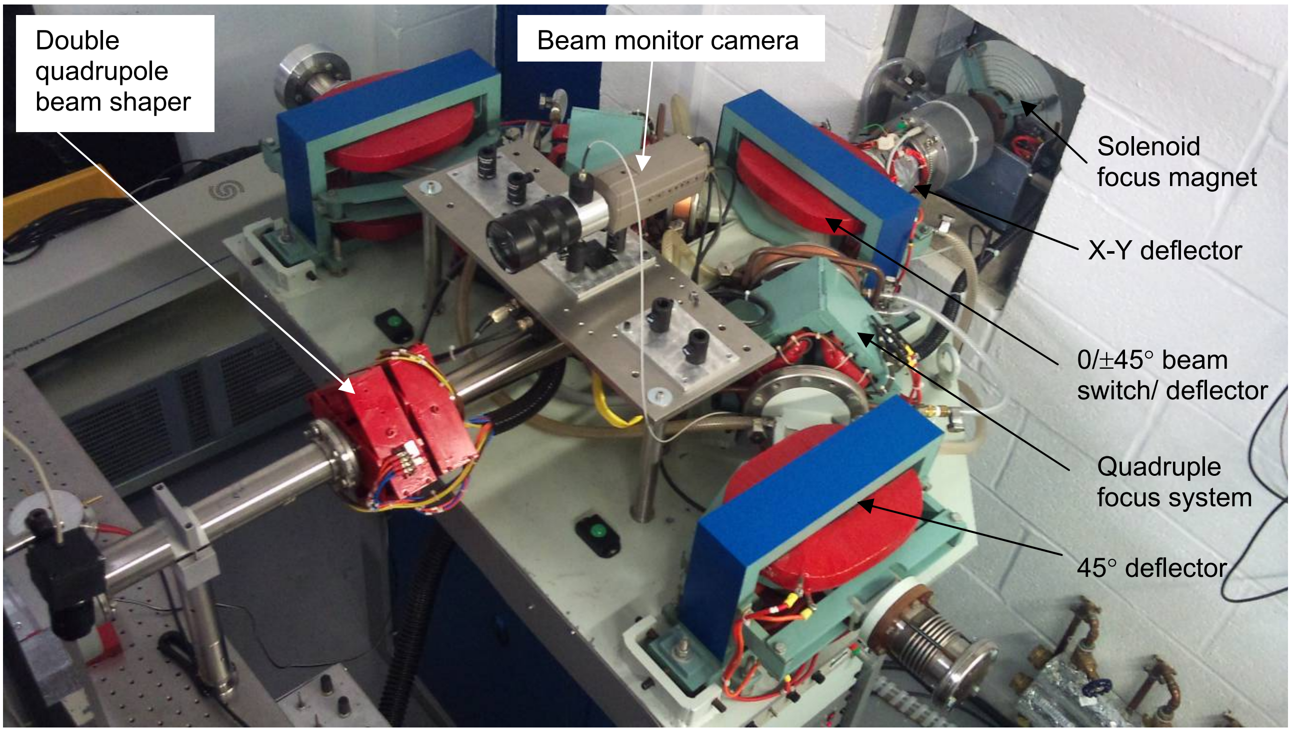


Figure 1: The linac's external beam control optics, used to shape the straight-through beam and to provide two additional orthogonal beam lines.

When properly set up, this arrangement provides energy-independent deflection: beams of higher energy are deflected less than 45° and deflected by the quadrupole so as to enter the second 45° deflector at a shallower angle. The opposite is true at lower beam energies. To date we have not used the orthogonal lines 'in anger' so we describe in this note the performance of the 'straight-through beam path.

In this path, the beam control options are:

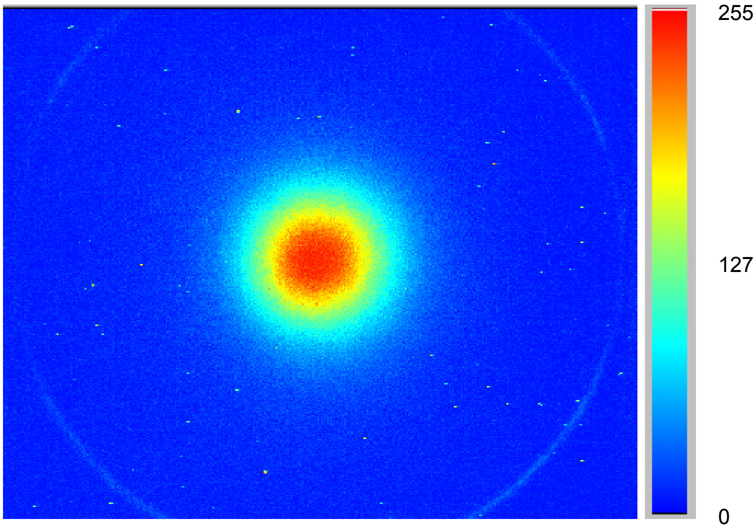
- Whether to produce a spot (focused) beam or a diffuse beam,
- In the case of a spot beam, where to position it with respect to the central axis
- Starting with a diffuse beam to shape it into an elliptical beam , either in the X or Y direction.

The final quadrupole focusing system is powered by multiple power supplies and wired so as to allow a further X or Y lateral shift by introducing differences in the currents of opposing coils.

Spot / pencil beam

This is the default SL75-5 beam profile, essentially providing a 'image' of the electron gun thermionic cathode. The beam shape is shown in Figure 2. The linac output beam is relayed to the output of the straight-through beam line window. This mainly brings into play the extra solenoid focus coil and the deflectors, which centre the beam with respect to the exit window. The outline of the window (30 mm diameter) can be seen in Figure 2.

Beam shape imaging and alignment is performed using the optical method briefly described in our note "Development of the Gray Institute single pulse electron linear accelerator Pt 2". This is method uses a thin (~2 mm) Suprasil silica disc at the output of the beam, placed about 60 mm away from the beam line output window. Čerenkov light generated by the electron pulse travelling through this disc is reflected by a periscope. Several LEDs are placed close the second periscope mirror and are appropriately angled so as to illuminate the output window and silica disc.



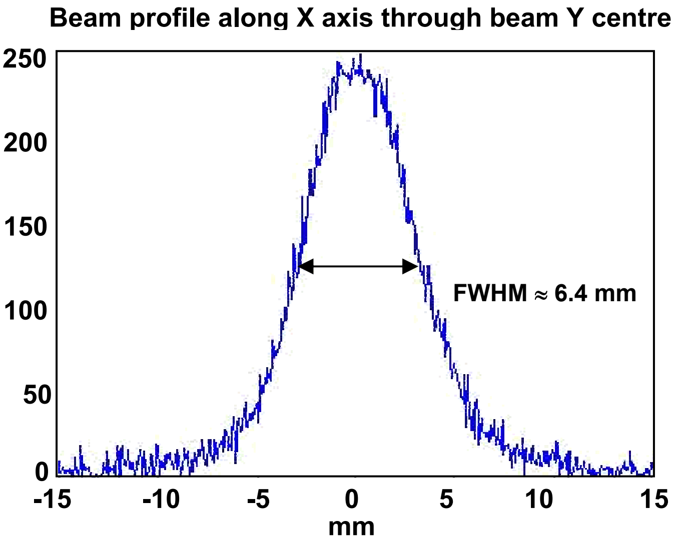


Figure 2: Beam profile of the focused spot/pencil beam

The Čerenkov light is sampled by a lens/camera system placed above the deflection magnet assembly as shown in Figure 1. Most of the captured Čerenkov light goes through to the CCD, but around 20% is reflected onto a short focal length lens which guides it onto a 1 mm diameter polymer fibre. This fibre is coupled to a miniature photomultiplier tube and allows monitoring of the temporal pulse profile.

The use of a thin disc minimises particle scatter which would otherwise increase the apparent beam size, but it also inevitably reduces the available light signal. Determining the spatial dimensions of the camera field is performed with the use of an optical target of known dimensions. This beam monitoring arrangement is shown in Figure 3.

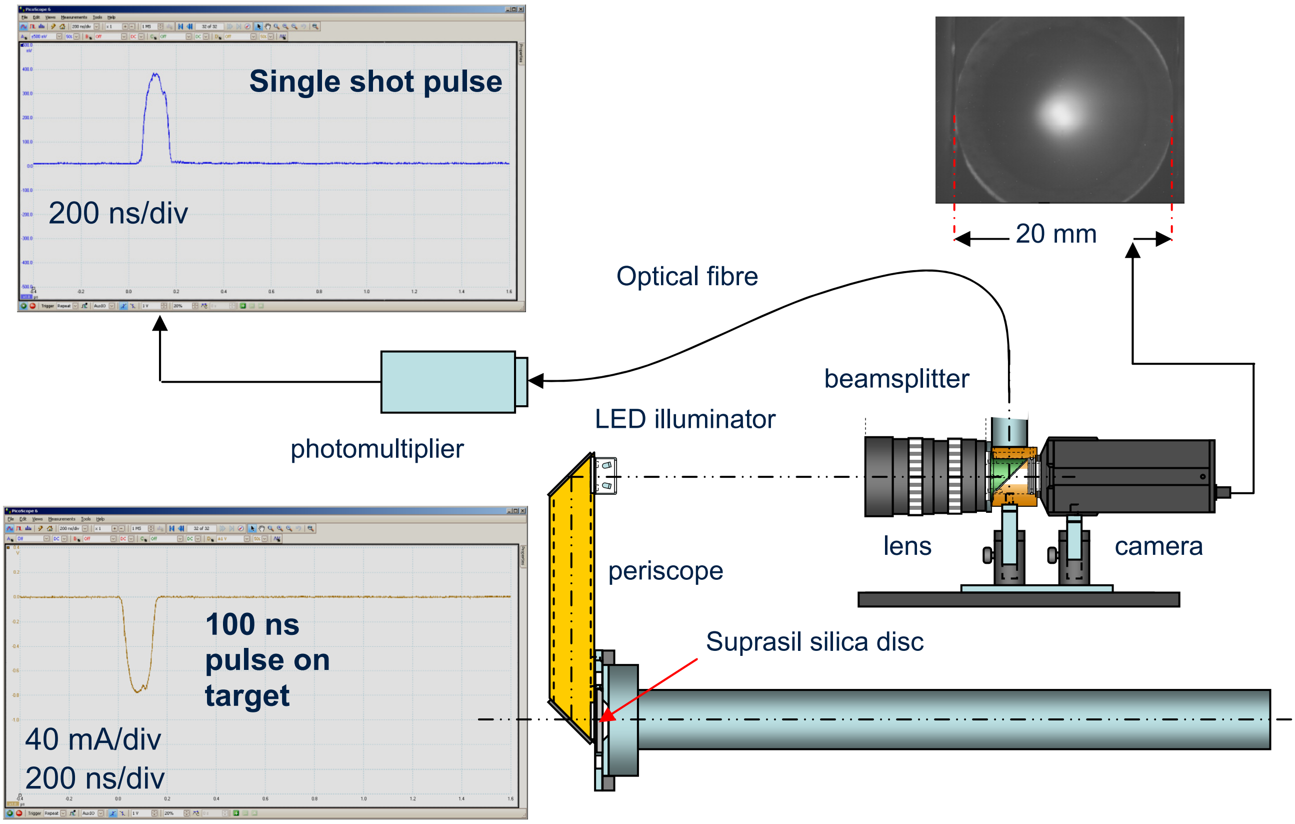


Figure 3: Details of the spatial and temporal beam monitoring arrangement based on imaging/ quantification of Čerenkov light generated by a electrons passing through a thin Suprasil disc.

The lens/camera/beamsplitter can be rotated through +/- 90 degrees and the 'outputs' of any of the three beam lines can thus be monitored. The camera/lens assembly is mounted on posts and the whole assembly can be relocated on other post pairs, which can be seen to the left and right of Figure 1.

We use the venerable Cohu 4900 series camera which can operate in a triggered integration mode. The exposure of the camera can thus be synchronized to the beam pulse and the resulting image can be captured using a frame grabber. We are grateful to Brian Reece Scientific (BRSL Ltd, http://www.brsl.co.uk/) for supplying us with a stand-alone frame grabber. Suprasil discs can be obtained from http://optics.heraeus-quarzglas.com/; we note that the more commonly available Spectrasil material is not as resistant to ionising radiation, and although much superior to common quartz (silica), it does have a tendency to darken due to the formation of colour centres in the material.

Figure 2 shows a false-colour map of the beam image and a profile of the pixel intensity centrally in the Y axis of the original greyscale camera image. Using the same beam parameters we can compare this to an alternative, more definitive, method to measure the spatial profile of the beam.

Here, Gafchromic film (HD-810, http://www.gafchromic.com/) was placed at the same position as the Suprasil disc.

After irradiation, the film can be scanned and the resulting data are converted into an image in which intensity is proportional to dose. A normalised image following such a procedure is shown in Figure 4.

The top panel is a scanned image of the Gafchromic film irradiated by a single 1 μs electron pulse. The middle panel shows a contour map of the absorbed dose which the film darkening represents (a dose calibration is applied to the film in MATLAB (www.mathworks.co.uk) and the colour map generated). A profile taken in the X direction in the middle of the Y direction across this contour map is presented in the bottom panel.

This shows a similarly 'clean' symmetrical profile which is somewhat tighter (5.6 *vs.* 6.4 mm) than that obtained from the light emission image. The finite thickness of the silica disc, inevitable beam scattering and an imperfect imaging modulation transfer function as well as some non-linearity in the triggered camera Čerenkov image all contribute to the apparent broadening. Nevertheless, the optical method reveals quickly any issues with beam alignment and uniformity. It can then be followed by the slower Gafchromic film examination process if required.

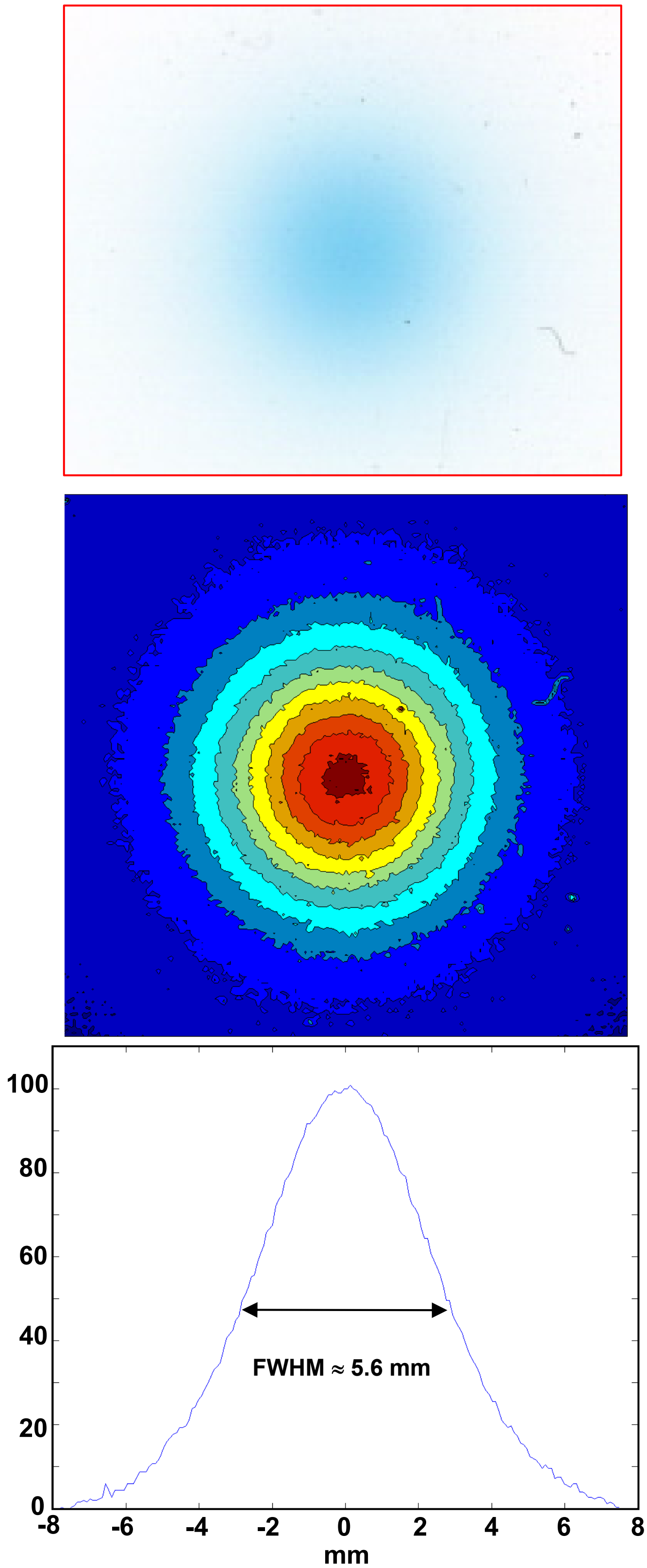


Figure 4: Focused beam profile determined by irradiation of Gafchromic film. Upper panel: image of film; Middle panel: isointensity contour plot; Bottom panel: beam profile plot.

Broad / diffuse beam

Broad beam irradiation of a sample can be achieved in one of two ways. The first method exploits the action of focusing magnets (strictly speaking defocusing action). The second method exploits scattering of electrons after exiting the machine. Of course the electron beam is scattered to some extent by the output window itself and this scattering contributes to the apparently poor focus of the 'spot' beam.

Should high doses per pulse over an extended area be required, the defocus method is the method of choice. On the other hand a scattered beam is likely to produce a superior uniformity of dose, though is inevitably associated with beam loss.

Figure 5 shows an isointensity contour map of the beam intensity in the central region (one square centimetre) of a broad, defocused and scattered beam (25 μm gold foil), acquired with scanned

Gafchromic film, placed about 60 mm away from the electron beam exit window. This is fairly close for such an irradiation and therefore presents a stern test of the possibilities of such a set-up.

Also shown is a profile in the X direction across the centre of the field. With this set-up the field intensity peaks in the middle as expected and falls to ~90% of this value 5 mm away in any direction. Naturally, the corners of the field receive the least dose, but no less than 75% of the maximum. A large part (95%) of the area presented receives a dose within ±10% of the median dose.

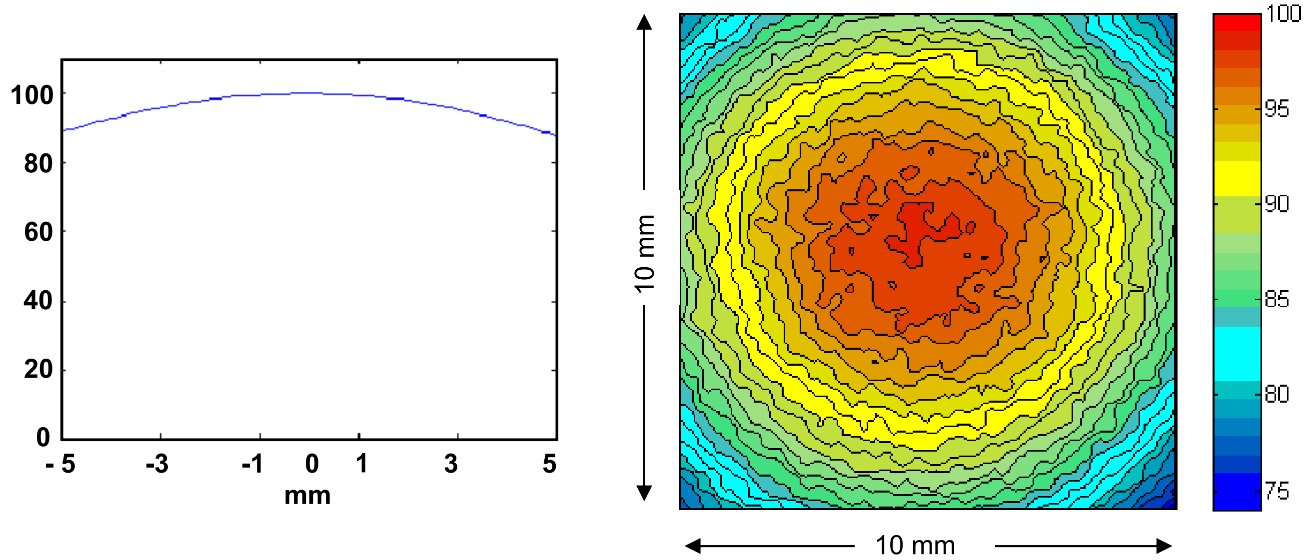


Figure 5: Beam profile of linac broad beam (left) and iso-intensity contour map of the same beam.

Dose delivery

One of the features of the Gray Institute linac is its ability to deliver single pulses with a variable width and peak current during the radiofrequency acceleration envelope, although the standard mode of dose delivery (injection of electrons synchronous with the radiofrequency pulse) using repetitive pulsing remains.

Single shot mode

The single shot mode of is made possible by using two modulators: one to produce radiofrequency pulses, the other to drive the accelerator gun. This second modulator is arranged to produce a high voltage pulse during the radiofrequency pulse, for a time shorter than the duration of the radiofrequency pulse. Since this pulse determines the time during which electrons from the gun can be injected (and subsequently accelerated), it determines the duration of the accelerator output pulse.

Such a mode of operation is particularly useful when investigating radiation effects at the sub-microsecond timescale. Though the pulse width is continuously variable, we restrict this to discrete pulse widths of 10, 20, 50, 100, 200, 500 and 1000 ns as well as a user-defined pulse width, should the user not be satisfied with this extensive range!

The repetition rate of the single-shot pulses is currently restricted to around 1 Hz, determined by the time taken to recharge the modulator delay lines (~ 100 ms) and by the generation of several radiofrequency pulses prior to the single-shot event. Firing a magnetron for approximately 20 pulses (at a 50 Hz rate), stabilises the stability (and hence tuning) of the magnetron. This 1 Hz restriction is a self-imposed one, as all of our current experiments require long periods between single-shot events; it is however possible, in principle, to generate pulses at rates of 10 Hz (or more if a higher current modulator power supply is fitted) in a continuous burst, i.e. ~20 magnetron pulses fired at the start of the burst mode, when no electrons are produced, followed by gun modulator pulses.

Repetitive pulsing mode

This mode is used for delivering extremely high electron doses and photon doses. Each pulse is nominally 4 μs long and pulsing can occur at 50 Hz. Higher pulse repetition rates are available but are subject to approval by the University Safety Office because of the high background dose-rates which can be produced. The hardware can deliver pulse rates at up to 300 Hz. This mode of operation is the 'native' linac mode: the injection potential of the gun is synchronous with the magnetron drive pulse. In this mode the following must be considered:

- Heating of the sample is likely to occur because of the amount of energy deposited. Heat sinking techniques must therefore be employed. At a 50 Hz repetition rate, the pulse period is 20 ms is and each pulse lasts for ~ 4 μs. At a peak pulse current of 100 mA, the average current is ~20 μA and hence the beam power is >100 watts at a beam energy of 6 MeV. At 300 Hz, this would increase to >700 watts! The accelerator is capable of generating peak currents of up to 400 mA, i.e. close to 3 kW could be deposited in the sample.
- The SL75-5 focus coil cooling system was originally designed with a patient treatment schedule in mind i.e. a low duty cycle. Running currents in the coils are typically between 10 and 30 A and the coils operate at voltages of >30 V; they thus dissipate several kilowatts and coil cooling is essential. In its intended operating schedule, the coils would have sufficient time to cool down between irradiations. Longer experimental irradiations (>20 minutes) demand careful monitoring of the coil temperatures, and whilst an extra air-cooling system has been implemented to allow more extended operation, we have, to date, not operated the machine for periods longer than 1 hour.

Pulse characteristics

The output pulse shape in the single shot mode depends on a variety of machine settings, including single-shot modulator charging voltage, gun heater setting, etc. and on the method used to pick up the output pulse. A range of single shot pulse widths is shown in Figure 6, along with one of the longer repetitive pulses. These data have been obtained with an aluminium target in air, placed approximately 40 mm after the machine output window. No particular effort was made to match the target impedance to that of the subsequent 50 Ω cable and the pulse shapes should be taken only as an indication of the range of possible pulses obtainable, and the actual pulse shapes, overshoot, undershoot etc. are probably different to those shown here.

An alternative pulse shape monitoring process, as shown in the upper panel of Figure 6, using a silica disc (see Figures 2 and 3) shows a distinctly cleaner output pulse. The target however allows to determine approximately the output pulse charge. The actual pulse charge is somewhat different from that measured here and is not affected by the inevitable secondary electron production (and ion production) by the target.

Dose characteristics

The linear accelerator is capable of producing a very wide range of doses, dose rates and sequences of dose delivery. For example, as shown in Figure 7, the peak output pulse current can be varied over at least a 100:1 range, at a given pulse width, by varying the gun heater current. By varying the pulse width over the range of 50 ns to 1000 ns, this range can be extended to a 2000:1 range. The dose per pulse obviously depends very much on the irradiation geometry, but doses/pulse ranging from 0.05 Gy to 100 Gy are readily achievable when a diffuse beam is used. When tightly focused, non-scattered beams are used, in excess of 100 Gy in a 100 ns pulse is achievable.

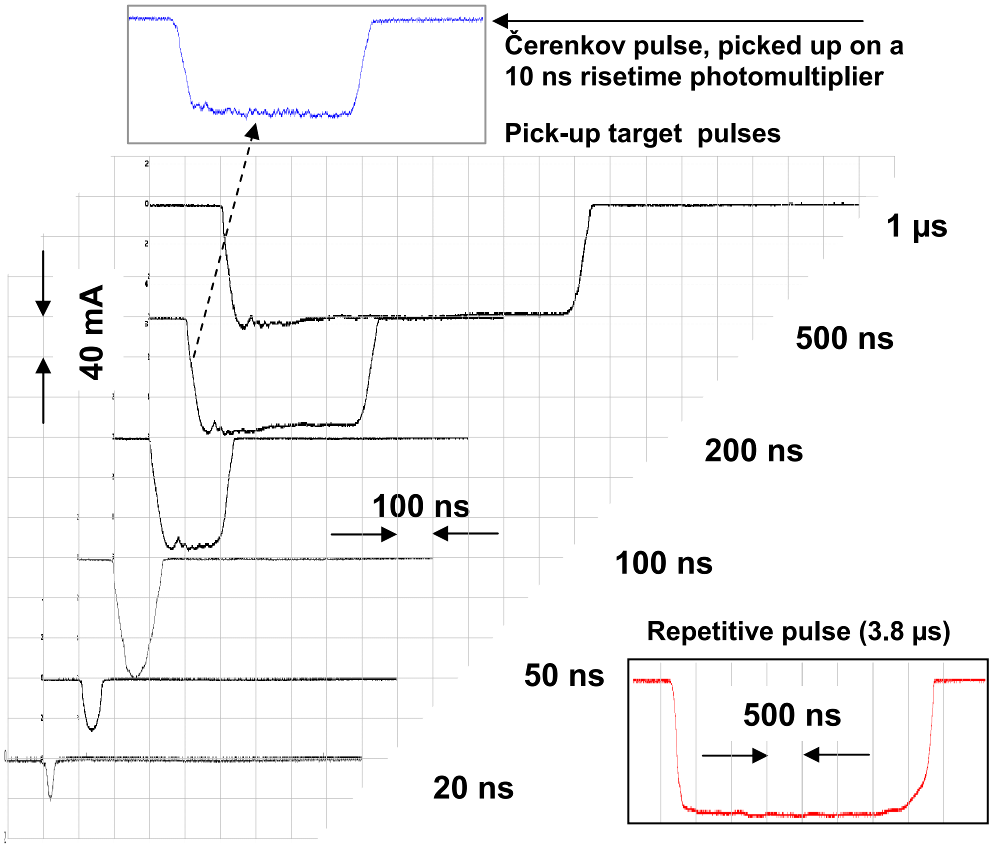


Figure 6: Single-shot electron pulse shapes with varying widths obtained by collecting the output pulses on a metal target. Electrical characteristics of the target are not well controlled, leading to overshoots/undershoots etc. The inset panel at the top shows the corresponding Čerenkov optical signal collected by a photomultiplier, indicating that a 'clean' output pulse shape is in fact produced. The bottom inset panel shows on the repetitive electron output pulses, of nominal 4 µs width.

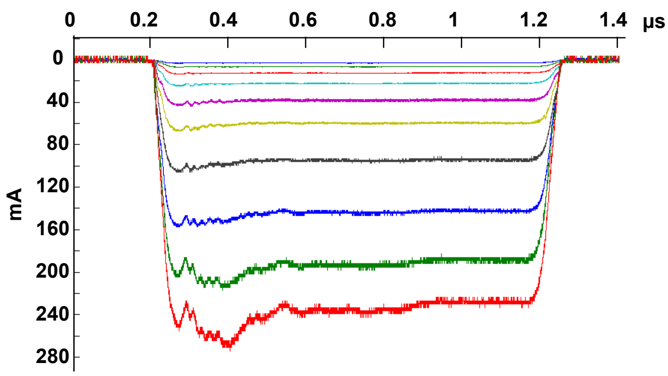


Figure 7: Single shot 1 µs pulses of increasing peak current resulting from operation over a range of gun heater currents (5.75 – 8 A). This gun heater current range is adequate for the vast majority of possible beam outputs.

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