THE GRAY LABORATORY'S 5 MeV LINEAR ACCELERATOR

This document was prepared by B Vojnovic and provides the following information:

- A brief historical overview of the accelerator.
- A description of the operation of the different sections of the accelerator.
- Waveforms present in various parts of the accelerator when operating under normal/typical conditions.
- Circuit diagrams of the accelerator.

Staff involved in the commissioning of the linac:

Mr KD Allen	Mr BL Hall	Mr C Tootel
Mr B Bloomfield	Dr BD Michael	Dr B Vojnovic
Mr M Grundon	Mr D Nash	Dr P Wardman
Mr J Draper	Mr RG Newman	Mr G West

Introduction and history of the accelerator.

The linac had been in use in the Radiotherapy Department of Mount Vernon Hospital from 1979 to 1993 and was used to generate repetitive photon pulses for therapy purposes. In late 1993, it was dismantled and most of the ancillary patient and accelerator movement and dosimetry equipment was discarded. At that time, it was decided to reconstruct the linac in such a way that it could be used to generate both repetitive and, more importantly, single-shot pulses of duration shorter than the 4 µs provided by the machine in its original form. More specifically, the intention was to 'repackage' the various power supplies and pulsing circuits so that they were to be contained in a single assembly rather than in several separate equipment racks and in a rotating gantry. This arrangement resulted in a system which may be conveniently screened to prevent the intense radio-frequency interference, resulting from the generation of short radiation pulses, from affecting relatively sensitive detection equipment used with the accelerator. The basic accelerator structure was not altered and the only addition to the vacuum system was the installation of an output beam line extension which incorporates an inductive pulse charge monitor used for dosimetry purposes.

The acquisition of the accelerator by the Gray Laboratory was initiated by BD Michael, in collaboration with P Wardman and B Vojnovic. The dismantling of the original accelerator was performed by the Physics Department of Mount Vernon Hospital in collaboration with the Mechanical Workshop of the Gray Laboratory and the operation was supervised by Mr Godfrey Mott who had been formerly in charge of accelerator maintenance at the hospital. G Mott also supervised the extensive mechanical modifications needed to reshape the linac and the majority of this work was performed by B Bloomfield, D Nash, J Draper, C Tootel and BL Hall. Some basic power distribution wiring was also completed at that time and operation of the microwave generating circuits was confirmed. Vacuum problems were dealt with by BL Hall and G Mott. In this initial phase of the commissioning, it was also established that the proposed methods of interference screening would indeed be adequate for our purposes. At that time, it was also decided that all control circuits would be housed within the accelerator so as to minimise the number of conductors which are placed outside the shielded enclosure.

There were a number of ways by which short pulses could be generated, these included the installation of a triode (Pierce) type of gun which can inject electrons into the waveguide by controlling the grid potential, the installation of beam deflection circuits which sweep the beam across a slit and the installation of a separately pulsed circuit which uses the existing (diode) gun to inject electrons for a short time during the nominally 4 µs RF envelope. All of these options were considered, but it was ultimately felt that the most expedient way was to use the last option. This was somewhat facilitated by the availability of a pulse transformer (just about adequate, salvaged from the Gray Laboratory's first 1.8 MeV linac) and by the fact

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that it required no modifications to the vacuum system. It was also decided that the triode gun approach would be ultimately installed and consequently the triggering/timing electronics were designed with this eventual purpose in mind. A prototype thyratron pulsing arrangement was constructed by KD Allen under the guidance of BD Michael. The limitations of the available pulse transformer became evident at that time and the circuit was modified by B Vojnovic to include a ‘double Blumlein line’ which reduced the stresses on the coaxial delay line cable. This arrangement was eventually installed in the accelerator and is in use at this time (October 1995).

The personnel safety interlock system used on the linac is essentially the same as that used on the laboratory’s Cobalt 60 source which is installed in the ‘DC room’ of the Van de Graaff accelerator. It was largely designed by BL Hall and constructed by M Grundon. It makes minimal use of electronic equipment but rather relies on electromechanical relays which have been shown in the past to be adequately rugged and reliable. It is tied to the Van de Graaff accelerator’s interlock system for indication purposes, since the linac is installed in one of the Van de Graaff’s radiation rooms, the ‘pulse’ room. The system requires the sequence ‘linac AC power on, room survey, close outer door, enable radiation on’ to be completed before closing a pair of contacts which energise the machine’s main HT, gun filament and focus power supplies. Opening the radiation room’s doors opens these contacts and de-energises these power supplies. In addition to this, activation of any of a series of ‘panic buttons’ around the ‘pulse’ room removes all AC power to the accelerator and to the associated pulse radiolysis detection equipment.

The final stages of commissioning of the accelerator were undertaken by G West, by RG Newman and by B Vojnovic. This involved the wiring up and testing of all control circuits and the installation of a control computer. First radiation beam output was obtained in mid October 1995 and the machine was almost completely aligned in late October 1995. The linac was put into service in late November 1995.

The end result of this work was that a very stable and, more importantly, electrically quiet accelerator was added to the extensive arsenal of the laboratory’s radiation sources. It should prove to be a major asset for pulse radiolysis work, essentially permitting a ‘turnkey’ operation of pulse radiolysis experiments to be achieved.

Description of accelerator.

It is assumed that the principles of operation of linear accelerators are understood by the reader. Useful descriptions of the operating principles can be found in the documents in the appendix. The present notes are specific to the accelerator installed in the Pulse Room of the Gray Laboratory and are intended to be updated as required when changes to the installation are implemented. This document was started in October 1995 at which time the accelerator was first commissioned to generate single-shot pulses required for pulse radiolysis work. When a reference is made to a ########.SCH diagram, this refers to an EASYPC schematic file. All diagrams are can be found in directory C:\PCB\GLLIN on the Electronics and Van de Graaff PC’s as well as on B Vojnovic’s PC.

If any work is carried out on the linac for servicing or other purposes, **it is absolutely essential that adequate safety procedures are observed.** Electrical and radiation safety procedures must be adhered to and no unqualified personnel are permitted to remove the copper enclosure shields. It is stressed that the accelerator is a potentially lethal piece of equipment, both from the radiation and electrical points of view. **Lethal voltages** are present in the accelerator enclosure even when it is switched off. These include a permanently energised ion pump (240 V AC and *ca* 2.5 kV DC)as well as potentially charged delay lines and pulse-forming networks. These items may have voltages in excess of 10 kV present. **It is thus essential that all high voltage circuits are discharged using earthing rods provided** prior to working in the vicinity of the gun, the magnetron and either of the two thyratrons. Remember that the radio-frequency sections of the accelerator are designed to provide power levels of up to 2 MW and that equipment associated with this must be treated with respect. **Do not work on this if you are tired and do not work on this if you are alone**. There can be no better advice than that which appears on every circuit diagram provided with the original installation: **IF IN DOUBT, ASK.** In addition, remember that it is possible to damage various items by operating them incorrectly and that there is a potential fire risk associated with incorrect connections to items operating at high power levels.

The electronics of the linear accelerator can be subdivided into a number of distinct sections which, although interconnected, can be operated independently. The control circuits are in fact designed to allow such separate operation to aid and to simplify fault-finding. Of course great care must still be exercised when powering up the separate sections; any test results must be correctly interpreted as the performance of any section may well be affected by its coupling to the other sections.

The main sections of the accelerator are as follows:

- The RF System consisting of the magnetron, input mode transformer, accelerating waveguide, output mode transformer and waveguide load.
- The magnetron pulsing system consisting of a fixed, regulated HT supply, thyratron (and associated driving circuit and power supplies), a pulse-forming network, pulse transformer and magnetron filament power supply.
- The gun filament, its variable, constant-current regulator and associated power and isolation transformers.
- The gun pulsing circuit consisting of a variable, regulated HT supply, a thyratron (and associated triggering circuits), pulse-forming coaxial delay lines and pulse transformer.
- Three magnetic beam focussing power supplies and associated solenoid coils.
- Four beam steering power supplies and associated magnetic deflection coils.
- A power distribution section with switching, soft-starting and overload trip circuits with inputs from the personnel safety interlock system and logic circuits controlled by the on-board computer.
- Low voltage (+/-15V regulated and +/- 24V unregulated) power supplies.
- Enabling/switching logic control/indicator panel used to interlock, enable and/or bypass commands from the computer.
- A programmable pulse generator/sequencing circuit used to control repetitive/single shot operating modes.
- A control computer (386 PC) with an analogue/digital I/O card, running LabWindows instrument control software.
- An inductive toroidal resonant charge per pulse monitoring circuit.
- A recirculating water chiller unit which is located in the Mechanical Workshop’s material stores and which is used to cool the power sections of the linac.

The fact that a control computer is placed within the screened enclosure results in only the following connections to the ‘outside world’ :

- Three phase power to accelerator
- Single phase power to the vacuum system
- Water cooling pipes
- Personnel safety interlock system connections
- SVGA monitor cable
- Computer mouse control cable
- Optional computer keyboard cable
- Dose monitor output

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All these cables carry relatively low frequency signals and could thus be filtered straightforwardly. Signals of higher bandwidth are coupled optically using low-cost polymer fibre-optic connections; these include the trigger input and output signals and possible control signals to the gun and pulsing circuits. Other connections are needed during servicing and thus the following cables were installed:

- eighteen co-axial lines used to carry analogue input and output signals
- one 25 way cable used to carry logic and enabling signals
- one 25 way cable used to carry analogue monitoring signals

The process of generation of electrons and their acceleration will now be described so that the peculiarities of the present installation are understood.

In its original form the machine was designed to produce repetitive pulses of 4 μs duration at rates up to 300 per second. These pulses were generated by triggering the magnetron and pulsing the filament simultaneously through a quadrifilar-wound pulse transformer. In the present modification a second pulse transformer and thyratron are used to separate the generation of the magnetron pulse from that of the filament gun injection pulse. In this way the injection pulse may be arranged to occur at any time during the 4 μs RF pulse resulting in the injection of electrons (provided they have the correct energy to be accepted by the accelerating waveguide) and thus acceleration of electrons for a time much shorter than the 4 μs provided by the original design. The duration of the electron pulse is determined primarily by the electrical lengths of a pair of delay lines and is nominally fixed to 250 ns. In practice, the edges of this injection pulse are degraded by the use of an inadequately fast pulse transformer, so that an essentially triangular pulse is fed to the gun. The actual electron pulse duration is thus a function of the peak injection pulse amplitude. If the gun filament is run at a low level, the electron pulse amplitude is also determined by the injection pulse amplitude. Too high an injector pulse amplitude results in a wide and distorted pulse, distorted because only a finite range of energies is acceptable to the waveguide input. This highly simplified description is shown in figure 1. If the gun filament is operated at a high level such that the electron density is high, higher injection voltages are needed so that the output electron pulse becomes more and more triangular.

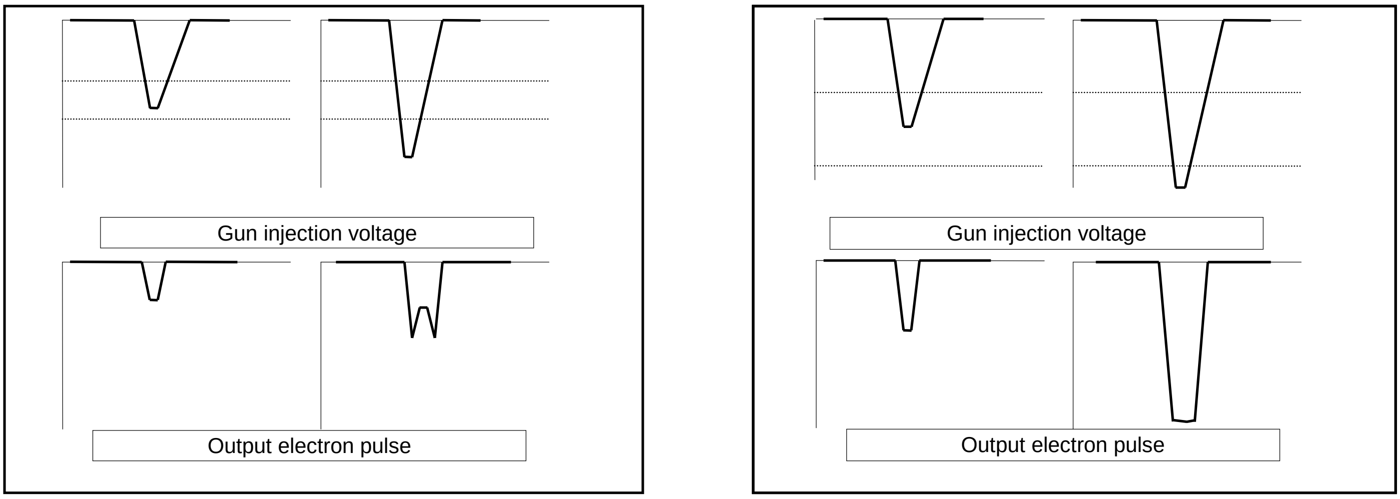

Figure 1. Electron pulse shape obtained as a function of injection pulse amplitude. On the left panel, the electron density is low and lower injection voltages are needed. On the right panel the injection voltage needs to be higher when high beam currents are required, resulting in longer pulses.The dotted lines represent the range of electron energies accepted by the input end of the accelerator.

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RF and magnetron pulsing system.

The heart of this system is a magnetron (EEV type M 5125) which is operated at a pulsed (4 μs) HT voltage of *ca* 40 kV and at a current of *ca* 100 A. The magnetron nominal operating frequency is 3 GHz (S band), the actual frequency may be set by tuning the magnetron's cavity; this is performed using a motor drive/gearbox/limit switch located above the magnetron. The magnetron is operated with its anode at ground potential, i.e. its filament (heater/cathode) is pulsed to -40 kV. The HT pulse is derived from a bifilar wound pulse transformer (see circuit MAGTHYR.SCH) with heater DC power applied across the windings. The pulse transformer is actually a quadrifilar wound device but two of the windings are not used in the present arrangement; they were used in the original machine to power the accelerator filament, which was pulsed synchronously with the RF generating pulse. The magnetron's filament power could be set to zero, 6.5 V or 13.5 V in the original design; this was so because at high RF repetition rates the cathode is heated by the circulating electrons, and hence the filament power needs to be reduced to prevent overheating. In the present arrangement, the maximum repetition rate allowed is 50 Hz and hence the filament is operated at 13.5 V. The HT to the magnetron must not be applied when its filament is cold, the magnetron will then not oscillate and the voltage will rise to >45 kV, at which point a spark gap across the magnetron will break down. This condition should be avoided as current of >1 kA will flow during spark gap breakdown and this may cause damage to nearby electronics, especially in the focus power supplies.

It is quite normal for the magnetron to misfire once in every several hundred to several thousand pulses. This misfiring is sometimes heard as a 'pinging' sound emanating from the magnetron and low or zero RF output is obtained under these conditions. The HT will also rise at that time but should be 'caught' by a reverse diode assembly (see reverse diode trip circuit in MAGTHYR.SCH). This misfiring is quite dependant on correct tuning of the magnetron, i.e. it is more likely to take place if the magnetron is mistuned. Magnetrons are very rugged devices and can take a fair amount of mistreatment, though this should clearly be avoided. Eventually, when the misfiring rate becomes unacceptable, the tube must be replaced. Take care to use non-magnetic tools for this purpose and don't keep credit cards in your pocket, and remove your watches!

The microwave (RF) output from the magnetron is coupled through a waveguide and its associated vacuum window and through a mode transformer to the accelerating waveguide assembly. This unit is the essential element of the accelerator; electrons, injected through the mode transformer are accelerated through it and the RF electric field imparts energy to the resulting electron bunch. During acceleration, RF power is reduced along the accelerating waveguide and any remaining power is coupled through the output mode transformer to a matched, cooled load.

The magnetron pulsing system consists of a fixed voltage, regulated HT supply, thyratron (together with its driving circuit and power supplies), a pulse-forming network, pulse transformer and magnetron filament power supply. Details of this are also found in MAGTHYR.SCH. The HT supply is considerably over-rated for the present operation, as it was originally designed to power both the magnetron and the electron injection system at repetition rates of up to 300 Hz. The system works as follows: a three-phase (star-delta) transformer supplies a rectifier to charge a pulse-forming network to *ca* 10 kV. These items are located below the accelerator body, under a perspex cover which should be removed only with extreme caution. The pulse forming network is a lumped element LC delay line. It is discharged by a thyratron (EEV type CX 1140) into the primary of the pulse transformer, believed to be of 1:5 ratio. The output pulse is 4 μs long. There are a number of monitoring points in this arrangement and typical traces are found in figure 2. The thyratron is located in the lower part of the screened cabinet at the rear end of the accelerator. It is triggered by an SCR trigger amplifier which produces a +300 V pulse by discharging a lumped LC line through an isolating pulse transformer. The SCR is triggered by a +10 V pulse provided by an optical receiver, shown in circuit THYRTRIG.SCH. This receives a trigger pulse from a polymer fibre fed from the accelerator's timing logic (LINDEL1.SCH). This optical receiver may be bypassed for test purposes; this is achieved by

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injecting a +10 V, 10 μs pulse into the thyratron trigger BNC socket on the BNC test panel at the rear of the accelerator and by patching this through in a cable available next to the SCR trigger board, at the top left of the screened thyratron rack. Refer to circuit diagram INTCON1.SCH to see this in detail.

Although not normally monitored, useful diagnostic outputs may be obtained from two detectors which monitor the RF levels in two cavities, one tuned above, the other below the correct magnetron operating frequency. These outputs are available at the BNC panel at the rear of the accelerator. These detectors are straightforward silicon diodes and can be operated into 50 Ω to show the RF envelope profile; the interference levels are quite significant when operated in this mode and it is generally preferable to load the detectors with the 1 MΩ input impedance of an oscilloscope. In this instance the integrated output is obtained and typical outputs are shown in figure 3.

Gun filament and regulator.

The filament power supply used in the original machine provided DC excitation of the gun filament, supplied directly from the second pair of bifilar windings of the magnetron pulse transformer. The gun filament in the current arrangement had to be powered through the new gun pulsing transformer; the current rating of its windings were unknown (but probably round 1 A) and it was thus considered safer to take gun filament excitation power at a higher voltage through the transformer and then to transform it down to the 5-10 V required by the filament. This dictated the development of a constant current AC power supply. The availability of a 10:1 auto-transformer (at the high voltage end of the pulse transformer) determined the operating voltage of around 100 V. A pulse-width modulation scheme is employed, using a power MOSFET as the switching element placed across a current-steering bridge rectifier, as shown in GUNMOD.SCH. A current sensing resistor, 2 Ω, is used to sample the current flowing in the pulse transformer 'low' terminals; the resulting voltage is a filtered, chopped sine wave which is synchronously rectified to provide a DC signal proportional to the average AC current flowing through the filament. This DC signal is fed to an error amplifier, along with a heavily filtered input set-point DC signal. The feedback loop is completed by using the resulting error signal to modulate a simple triangular wave pulse-width modulator, the output of which is used to drive the gate of the control MOSFET. The high frequency performance of the output auto-transformer is probably poor enough to remove most of the switching frequency (nominally 10 kHz) and its harmonics, but nevertheless a small choke is added to the output circuit to ensure that a relatively clean sine wave is fed to the gun filament.

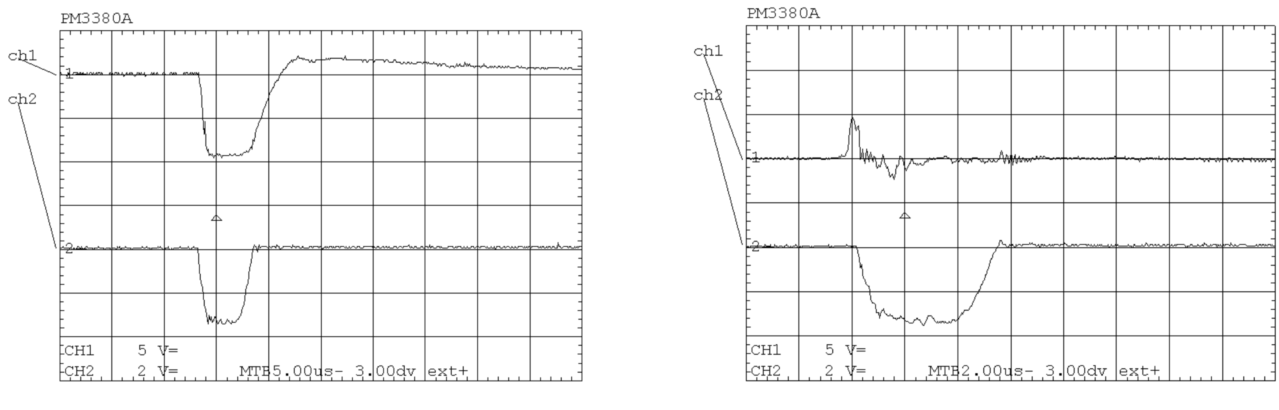

Figure 2. Waveforms related to operation of magnetron. *Left panel*: Upper trace (5 V/div, 5 μs/div): pulse voltage applied to magnetron, monitored into 50 Ω through accelerator-installed resistor (sensitivity not known). Lower trace (2 V/div, 5 μs/div): Current pulse through thyratron, monitored into 50 Ω from accelerator-installed current probe (50 A/V). *Right panel*: Upper trace (5 V/div, 2 μs/div): thyratron trigger pulse monitor output, into 50 Ω termination. Lower trace (2 V/div, 2 μs/div): thyratron output current pulse, as above.

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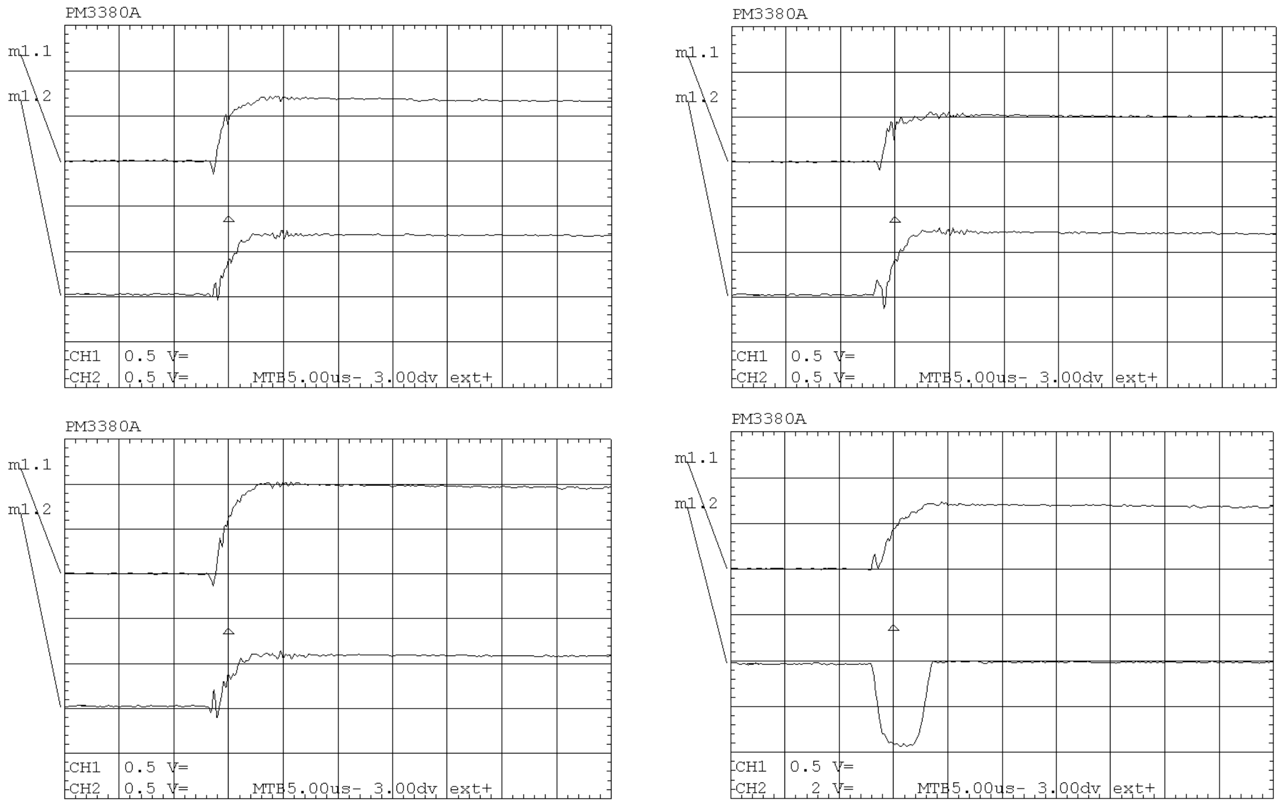

Figure 3. Waveforms obtained from the frequency tuning cavities. *Left panels*: Cavity detector outputs into 1 Mohm input impedance (500 mV/div, 5 us/div); upper panel: magnetron optimally tuned; lower panel: magnetron tuned to a frequency too high. *Right panels*: upper, as above, but magnetron frequency tuning too low. Lower panel shows thyratron current pulse (conditions as in figure 2) and tuning cavity output. In all cases a 5 point software filter is applied to reduce noise on cavity outputs.

The gun pulsing circuit.

This circuit is also shown in large part on GUNMOD.SCH. Once again a thyratron is used to discharge a pulse-forming device through the input of a 1:5 pulse transformer. This time, however, the pulse width is determined by two equal lengths of coaxial cable; each length is made up from two 50 ohm RG 58 cables in parallel, to make up two lengths of 25 Ω cable. These are arranged in a Blumlein type of double line circuit which has the desirable property that an output voltage equal to the DC charging voltage is obtained into a matched load. This means that the DC voltage stress on the delay line cables is reduced, particularly important in the present case because we need to generate pulse injection voltages of up to around 45 kV; this could in principle be achieved with 18 kV DC and a conventional circuit using a 1:5 pulse transformer. However, the high frequency performance of the available pulse transformer was quite poor and the device behaved more like a 1:3 transformer for short pulses, probably due to excessive leakage inductance losses. Using the present voltage doubling arrangement, we can generate in excess of 45 kV with just under 15 kV DC line charging voltage. The pulse transformer output load resistor is made up from 80 series-connected non-inductive resistors, each 15 Ω, resulting in a load resistance of 1.2 kΩ.

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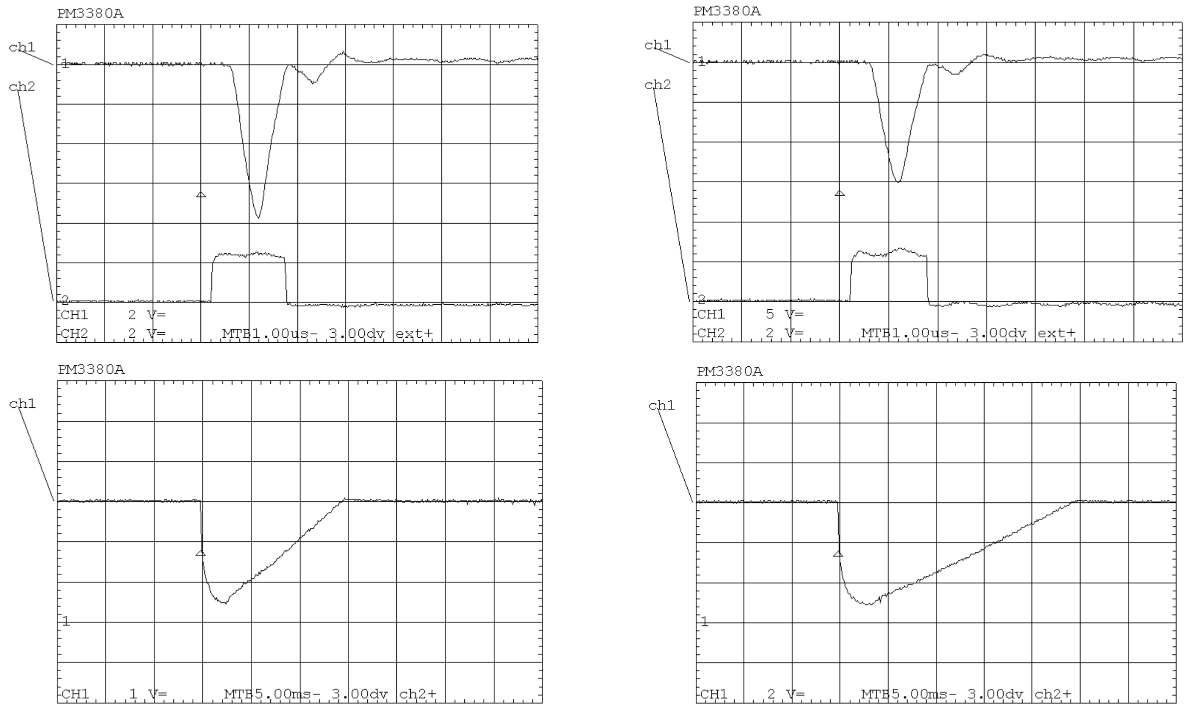

Figure 4. Waveforms relating to the operation of the thyratron gun pulsing circuit. *Upper panels*: Gun injection output pulse (upper traces, acquired with installed capacitive probe + attenuator on pulse transformer, into 1 MΩ of scope (left, 4 kV/div, 1 μs/div; right, 10 kV/div, 1 μs/div) using charging voltages of 5 and 10 kV respectively. Lower traces in the upper panels are the thyratron trigger pulse monitor output, through 50 Ω x 10 attenuator.
Lower panels: Pulse HT supply output voltage recovery after trigger, when charging at 5 kV (left) and 10 kV (right). In both cases the timebase is 5 ms/div.

The delay line is charged through a nominally 100 KΩ (actual value 97 kΩ) resistor fed from a voltage-programmable, current limited power supply capable of providing 16 kV maximum output voltage. This was a customised unit, manufactured by Applied Kilovolts Ltd and the reader is referred to correspondence related to that power supply in the appendix. Typical traces of the injector waveforms are shown in figure 4.

The thyratron, of the same type used in the magnetron pulsing circuit, EEV type CX 1140, is triggered by a +300 V positive pulse provided by what may seem an excessively ‘good’ pulse amplifier, shown in detail in POSPAMP.SCH. This design, however, was intended to drive the grid/cathode of a triode type of gun, discussed earlier. This assembly makes use of a fast MOSFET and a coaxial inverting transformer to generate fast pulses (50 ns and longer) with sharp (<5 ns) edges. It is in turn triggered optically through a polymer fibre coupled to a photodetector/comparator. Two DC-DC converter modules provide voltages of up to +350 V for the FET (output pulse amplitude) and -150 V (thyratron grid bias (or gun control grid bias in the case of a future triode gun).

Beam focus power supplies.

There are three essentially similar focus power supplies which feed three solenoidal focus coils along the length of the accelerator. Although similar in design, they operate at different voltage/current levels; the circuit is shown in FOCUS.SCH. Each supply is fed from a different phase of the three-phase supply and each consists of a transformer feeding a diode/SCR rectifier bridge. The SCR’s are phase controlled through a discrete 50 Hz triggered pulse-width modulator. The input to the modulator is the output signal from an error amplifier (741 (IC1)) which compares the attenuated input control signal and the voltage developed across a current-sensing resistor (R2, *ca* 0.004 ohms) in the output circuit of the supply. The full-wave-

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rectified DC output is smoothed by an output inductor and indeed by the inductance of the focus coil itself. Nevertheless a significant degree of 100 Hz ripple is present in the output current as shown in figure 4. Current setting control inputs are in the range of 0 to +5V, while the output current levels result in voltages of the order of tens of millivolts across the current sensing resistors. Two other op-amps (IC2, 3, also 741's) are connected as comparators with positive feedback and are used to sense output overcurrent and undercurrent conditions. This is achieved by comparing the output current, or rather voltage across the output current sensing resistor, with preset voltages adjusted by means of VR1 and VR2. The output of the comparators are joined together such that a negative trip output voltage (*ca* -12 V) is an indication of correct operation while a 0V output is an indication of a fault condition, i.e. that an overcurrent or undercurrent condition exists.

Two of the focus power supplies (Focus 2 and 3) are mounted behind the computer's Faraday cage and can only be accessed by removing the computer and screened cage. Focus 1 supply is mounted underneath the output beam line. Focus 1 supply feeds the focus coil nearest to the gun, Focus 2 supply feeds the coil in the centre of the accelerator and Focus 3 powers the coil nearest to the output. When working on the focus power supplies take care around the rectifier/bridge heatsink: this is not grounded and you will blow the 40 A power supply fuse if the heatsink is accidentally shorted to earth.

Beam steering power supplies.

There are four similar bipolar controlled constant-current supplies which excite four sets of deflection coils, two of which (Steerers 1,2) are located at the gun end, the other two (Steerers 3,4) being near the output end of the machine. Each set of coils deflects the beam in an up-down or a left-right direction. The power supplies are housed in a chassis at the rear of the accelerator and each accepts a bipolar input, nominally +/-5V. The circuit is shown in DEFLECT.SCH. The output current from each supply is sensed using a1 Ω resistor (R15) in series with the deflection coil. The error amplifier is once again a 741 which feeds a x4 voltage amplifying stage, supplied from +/-24V (TR1-4). There are no trip/fault outputs. The alignment of the waveguide and gun is such that relatively little deflection is required to thread the beam through the magnetic axis of the focus coils.

Power distribution.

The circuit diagram of the three-phase power distribution within the accelerator is shown in PWRDIS.SCH. Three phase power is supplied from a contactor in the 'cleaner's cupboard room' near the lift shaft just off the Van de Graaff console area. This contactor is tripped when any 'panic' button is activated in the 'pulse room'. This in fact also cuts off single phase AC power to the linac's vacuum system and to the pulse radiolysis instrumentation system. Power may be restored only by activating a reset switch which is inside the interlock system cabinet (normally locked, key inside Van de Graaff key cabinet). Under normal operating conditions, the three phase contactor is energised by operating the front panel keyswitch on the interlock panel, as described below in the safety interlock system description; once again the key to energise the linac is kept in the Van de Graaff key cabinet. The operation of this key energises the water chiller unit, located in the Mechanical Workshop's metal stores.

In addition to the 'cleaner's cupboard', the three phase linac power may be cut off by deactivating an isolator switch in the pulse room, this is located on the rear (left) wall of the pulse room. Under normal conditions, three-phase power is thus present in the linac enclosure, and indication of this is by means of three neons located on the front of the power distribution panel, located at the rear front of the accelerator. These and other indicators are not visible when the copper shielding is installed. The linac power input latch may now be energised by operating either the red push button on the front of the accelerator, near the vacuum gauge or a similar push button on the power distribution front panel at the rear of the machine. This latch will only set if the safety interlock system is in the safe, unsurveyed state (see later description). Once set, three other

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neon indicators are lit and power to most low voltage systems is applied and the control computer is activated. Provided various machine safety interlocks are made (water, vacuum etc.) and the magnetron filament is energised, a 10 minute time delay is started as well as a 5 minute time delay (see GUNMOD.SCH). During this time the two thyratron and the magnetron heaters are warming up. When the time delays expire, main and pulse injector HT's will be energised provided the appropriate enabling inputs are present (under manual or PC control) and the personnel safety interlock output is in the 'irradiate' state. The main HT supply incorporates a 'soft start', current limited system on its input. A similar 'soft start' circuit is present on the focus power supplies feed. Focus power supplies are de-energised when the main HT is off.

The personnel safety interlock system turns off the gun filament, the main HT and the focus supplies when in the unsurveyed mode. Other aspects of power distribution are self-explanatory in PWRDIS.SCH. Overload trip switches are installed on the separate subsystems; if tripped they can only be reset manually. It is advised that appropriate trip switches are de-energised during servicing of the accelerator and that power is fed only to the circuits which are absolutely needed. There is generally no reason why the main HT supply switch should ever be switched on at any time that the copper covers are removed.

Low voltage power supplies.

These supplies are shown in LOVPWR.SCH. There are two power supplies: a +/-15 V regulated supply and a nominally +/-24 V unregulated but smoothed supply. They are located at the back end of the accelerator in two 19" chassis. The +/-15 V chassis also contains a +5 V and a +300 V supply, although these are not used in the current arrangement.

The regulated supply is of conventional if somewhat dated design relying on a LM305 regulator chip for the +15 V side and a LM304 chip for the -15 V supply. This power supply is used to power the control circuits of the three focus and four steering supplies, the vacuum interlock/trip circuit and the toroidal charge monitor.

Enabling/switching logic.

This system is located at the back of the accelerator, above the low voltage power supplies and the BNC panel. Its purpose is to provide convenient routing/enabling/disabling of PC and manual over-ride logic signals. The front panel controls are shown in TESTPAN.SCH and the circuit can be found in PCINT.SCH. The circuit is based on a number of inverting, open collector power drivers (Darlingtons), type ULN 2803, which ultimately drive relay coils in the power distribution sections of the accelerator as well as local indicator LED's. Three way switches in each of the circuits allow any particular system to be permanently disabled (centre position), permanently enabled (lower position) or to be under the control of the PC interface. All the input and output connections to the PC are thus standardised to 5 V logic levels. Local control of magnetron operating frequency tuning may also be performed on this panel. The circuit is self explanatory and this panel need be accessed only during servicing or at times when the linac is controlled manually. Remember to return the toggle switches to PC control (upper position) following servicing.

Toroidal charge monitoring circuit.

This is shown in QMON.SCH and the arrangement functions as a non-intercepting beam charge per pulse monitor. It is located at the output end of the accelerator beam line, in a diecast box attached to the beam line. A toroidally wound coil envelops the beam line and behaves as the secondary of a transformer where the moving bunch of electrons in the beam pulse forms a single turn primary. A current is thus induced in this 'secondary'. The winding is arranged to be part of a tuned circuit which oscillates at its resonant frequency when excited by the beam pulse. It can be shown that the peak tuned circuit output voltage is

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proportional to the total charge in the beam if the period of oscillation is much longer than the duration of the electron pulse. For calibration purposes, a single turn winding has been threaded through the toroidal core and a current pulse can be injected through this into a 50 Ω load. The connections to this test turn are available on two coaxial connectors to the side of the toroid housing.

The amplitude of the triggered oscillation eventually decays to zero in a time determined by the Q-factor of the tuned circuit. A differential, low-noise amplifier (SSM 2015) both amplifies the damped sinewave and provides an adjustable degree of positive feedback to act as a Q multiplier and to ensure that the oscillation decay relatively slowly. The output of this amplifier is coupled to a latched peak detector circuit and to a comparator which detects the onset of oscillation, i.e. at the start of the next beam pulse. Its output is fed to a monostable which re-enables the comparator after its time delay (nominally 20 ms) and to a reset arrangement which ensures that the peak detector is reset at every electron pulse. The peak detector actually measures the amplitude of the second half-cycle; this is essentially the same as the peak tuned circuit amplitude as long as the Q is reasonably high. In this way a continuously updated peak detector output is obtained without the need for any external trigger/reset signals. The output of the circuit is available for monitoring/feeding to the PC and is separately brought out on a balanced connector so that it may be injected into the dose monitoring arrangement of the pulse radiolysis instrumentation.

Pulse generator/sequencing circuit.

A block diagram of the timing electronics is shown in LINTRIG.SCH and detailed circuits are shown in LINDEL1.SCH and LINDEL2.SCH. The sequencing system is constructed on two boards located in a chassis frame within the PC Faraday cage. Two modes of operation are possible: continuous or repetitive pulsing and single shot operation. Most parameters are programmable although the unit will work in a preset fashion by unplugging the various data latches and replacing them with DIL switches. A layout of these is provided in figure 5. The repetitive operation mode is self-evident while single-shot operation refers to a repetitive RF pulsing mode with the production of a single electron pulse following the generation of a predetermined number of RF pulses. As described earlier, the circuit details are more complex than needed but the arrangement caters for the future addition of a triode type of gun which will be capable of producing shorter pulse widths and which requires optical isolation of certain signals through the use of optical fibres.

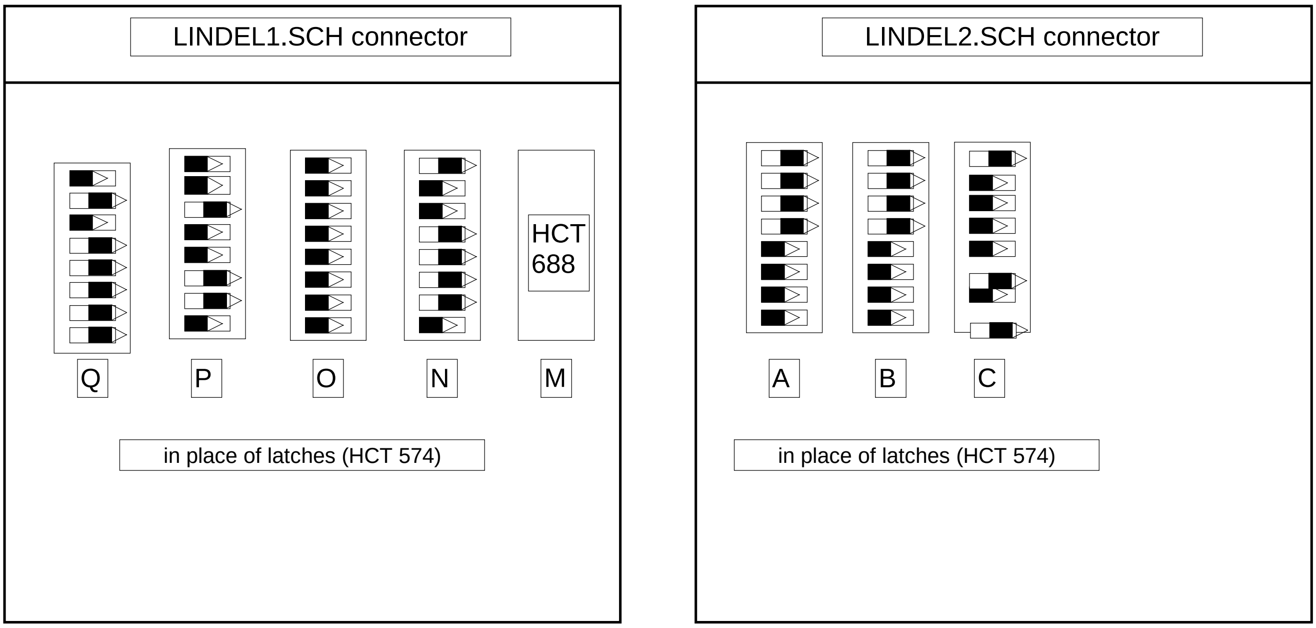

Figure 5. Layout of manual DIL switches that could be used in place of data output latches whenever PC or programmed operation is not required.

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The generation of all trigger pulses is synchronised with 50 Hz AC mains; this is needed because of the poor ripple performance of some of the power supplies associated with the linac. The actual trigger point on the AC cycle is determined by a 'phase' delay (chip J) preset on LINDEL2 board: this preset should be adjusted with caution as the eventual peak pulse current performance of the linac will be affected. The maximum repetition rate available is 50 Hz, though lower rates (:2 (25 Hz), :3 (16.66 Hz, :4 (12.5 Hz) etc. down to 3.125 Hz) are possible and are achieved by passing the input trigger pulses through a programmable divider (CD 4526B chip I on LINDEL2). The continuous or repetitive mode will now be described and the reader should bear in mind that electron or gun trigger pulses must be produced such that electrons are injected during the machine's 4 μs RF pulse. The component references are with reference to diagram LINDEL1.SCH:

The mains-locked input triggers are routed through gate H to a clock synchronising dual flip-flop (chip J); they also reset two 11 bit programmable digitally clocked delays which can provide independently settable delays over the range 0-40.96 μs in 20 ns steps i.e. using a 50 MHz clock. The synchronising circuit generates a single 'load' pulse to the programmable delays to start a new delay; the load pulse is synchronous with the 'next' cycle of the 50 MHz clock. The programmable delays are each based on three 74AC163 counters (chips A, B, C in the case of electron trigger delay, D, E, F in the case of the RF delay). The differential delay is actually the important parameter, though for flexibility each delay is made programmable. The delay generators actually provide pulses of width equal to the programmed delay and the falling edges of these pulse widths trigger a dual monostable (74HCT123, chip R) The lower half is used to generate *ca* 10 us wide pulses which are fed to a fast LED driver (74F5302, chip U). The optical output from the LED ultimately triggers the RF thyratron and hence the magnetron. The other half of the monostable is used to generate a number of electron pulse widths, though only the 1 us width is used in the present injector implementation to trigger the pulse thyratron. A 3 bit code determines one of eight possible widths, where 2 us, 1 us, 0.5 us and 0.2 us pulse widths are selected using switch S (74HCT4051) to switch in one of four possible presets into the timing RC circuit of the monostable. The shorter pulse widths are generated by delaying the 200 ns monostable output using delay line Y and 'anding' a selected delayed output with the undelayed output in the driver U (74F5302). The selection of the delay line output is performed with switch V (74HCT4051) which is used, along with the delay line, to generate 100 ns, 50 ns, 20 ns and 10 ns LED output pulses. The LED's generate infra-red pulses which are guided along polymer fibre-optic cables to the two thyratron driving circuits. Two further LED's and drivers (chip T, 74F5302) are used to provide output pulses, for pulse radiolysis instrumentation synchronising purposes, one of which is coincident with the electron pulse, the other being the 40 ns trigger pulse which initiates the start of the digital delays (pre-trigger output). The degree of pre-trigger obtained depends on the value loaded into the digital delays.

In the case of single shot operation, the same sequence of events as described above takes place except that the electron pulses are inhibited by gate G (74AC00, pins 11,12,13) until a programmed number of RF pulses has been generated, as shown in the timing diagram in LINTRIG.SCH. The number of RF pre-pulses can be 2 to 64 as determined by the input to comparator M (74HCT688, LINDEL1.SCH). The single shot sequence is initiated by an optical trigger pulse (10 us duration) which sets the bistable made from gates K (74HCT132, pins 1-6). This allows the mains phase locked pulses to be counted by counter L (74HCT393), the output state of which is connected to comparator M. When the required number of pulses is counted, the bistable K is reset. The time delay between the arrival of the single shot trigger pulse and the production of the electron pulse is thus not fixed but can vary from m.n/50 to m.(n+1)/50 seconds, where n is the number of RF prepulses and m is the 50 Hz repetition rate divisor, the exact delay time depending on when the input trigger pulse occurs relative to the repetition rate phase.

An independent circuit is also constructed on one of the timing boards (LINDEL2.SCH). This consists of two 8 bit pulse width modulators, more correctly mark-space modulators, running at a frequency of approximately 200 kHz. The pulse trains are used to modulate optically the outputs of two LEDs/polymer fibres with the eventual intention of using these to determine DC voltages in a triode gun. DC voltages can

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be obtained by integrating the pulse train. Once again this feature is not used but the pulse train outputs are integrated using the TLO72 operational amplifiers and the 4053 analogue switch. These provide a variable output of up to +10 V to provide control (set-point) inputs to the gun filament supply and the pulse HT supply. In effect an 8 bit digital-to-analogue converter is thus implemented. In the triode gun version we have also two D/A’s which are capable of voltage isolation of tens of kilovolts, determined by the optical fibre. The digital pulse width modulators are implemented using two 4 bit programmable counters (4526Bs, chips D,E and F,G) in each channel. Every 256 clock pulses the counters are reset by counter J (4520B). As well as providing this form of mark-space ratio control, a further facility is provided by selector switch L (4502B) and board preset switch to allow an external pulse width modulated signal to control one of the selected outputs. This external signal is injected through an input optical fibre and allows the option of manual remote control of beam charge delivered the accelerator to be readily performed.

Control computer (386 PC) with an analogue/digital I/O card.
An IBM compatible 386 PC is located in a separate Faraday cage within the accelerator screened assembly, at the front of the machine. This secondary Faraday cage also houses the timing chassis boards described above. A data acquisition system is located on a separate circuit board (ANIN.SCH and LININT.SCH) within this chassis and is intimately tied to a PC bus data acquisition card (Amplicon PC30A) within the computer, the two systems being interconnected with a 50 way ribbon cable. All connections in and out of the Faraday cage are extensively filtered using decoupled sockets; AC power to the cage is separately filtered and comes in through an IEC connector at the back of the cage. The computer’s input/output controls are similarly filtered (see FILT.SCH) and are brought out to a small SVGA display and ‘mouse’ at the pulse radiolysis console area. In normal operation these are the only accessible controls and settings are adjusted using a Graphical User Interface, developed using National Instruments LabWindows software. The software is described separately.

The PC30A card provides 16 analogue input channels (12 bit resolution), four analogue output channels and three 8-bit digital parallel I/O ports. Of these, the 16 analogue inputs are used and two of the digital ports. The analogue inputs digitise conditioned signals from various points in the accelerator; these are listed below. Signal conditioning is performed using sixteen instrumentation amplifiers (INA 114, described in ANAL.SCH). The input senstivity of the card is fixed at +/- 10 V fsd, single-ended, and the inputs to the differential INA 114 amplifiers are heavily low-pass filtered to prevent RF interference from affecting the readings. The following signals are acquired:

Focus 1 output current	Steerer 3 output current	Spare channel for future quadrupole
Focus 2 output current	Steerer 4 output current	Main HT supply current
Focus 3 output current	Pulse HT supply current	Water temperature
Steerer 1 output current	Pulse HT supply voltage	Charge per pulse monitor
Steerer 2 output current	Vacuum pressure	

The digital I/O is somewhat more complex because of the number of digital output lines required and is arranged so that 8-bit data words can be latched into sixteen registers. Eight of those registers are part of the digital to analogue converters (AD 7524 on LININT.SCH) which are used to provide DC output voltages for the three focus supplies, the four steerer supplies and a future quadrupole focussing lens. The focus outputs are unipolar and can be set over the range 0 - +5 V . The steerer outputs are bipolar and can provide up to +/- 5 V. The other eight digital words are arranged in the following way: individual bits of one of the words are used to enable/disable power supply systems:

- main HT supply	- gun filament supply
- pulse HT supply	- magnetron tune up
- magnetron system	- magnetron tune down
- focus supplies	- spare

Two other words are used to set the mark-space ratio of the pulse width modulators described in the previous section and are in effect used as two further digital to analogue converters which set the gun filament current level and the pulse HT injector voltage. A fourth word is used to set the number of RF pre-pulses during single-shot operation (6 bits), to initiate the single shot trigger (1 bit) and to set the mode of external dose control (1 bit) . The fifth word sets the repetition rate (4 bits), the electron pulse width (3 bits) and initiates the repetitive mode of operation (1 bit). The remaining three words are used to set the delays (0 - 40 μs) between trigger to RF pulse and trigger to electron pulse events respectively and to enable/disable those events.

The final use of the digital I/O is to address a 16 bit multiplexer which monitors the status of power supplies and fault conditions. The sixteen states are multiplexed on a single digital input line and the following states are monitored:

- main HT supply on	- gun supply on	- tune limit reached	- vacuum 10^{-5} trip
- focus supplies on	- interlock system	- focus 1 fault	- vacuum 10^{-4} trip
- magnetron system on	- tune down on	- focus 2 fault	- water fault
- pulse HT supply on	- tune up on	- focus 3 fault	- water OK

Manual operation of the accelerator.

During servicing/fault finding it is desirable to be able to operate the accelerator without the computer's intervention and facilities have been provided to allow this. All the control voltages/set point inputs are brought out on the BNC panel at the rear of the accelerator and are normally patched through with short BNC links to the computer system's D/A outputs. When these cables are unplugged a set of BNC leads from the console area (see CABLES.SCH) can be plugged in and connected to a box of control potentiometers, as shown in MANTEST.SCH. Excitation of the potentiometers can be from a +/- 12 V bench power supply or the unit can be interconnected using a short DIN cable to a metering / logic controller, also shown in MANTEST.SCH. A 'D-type' plug terminated 25 way flat cable is now connected to the rear left-hand socket on the controller and to the cable normally plugged into 'D-type' socket X on the PC's Faraday cage. All the logic and status functions which the PC would have provided are now available on the controller, which is powered through the flat ribbon cable. The controller also incorporates a 4.5 digit panel meter which can be used in conjunction with a rotary selector switch to monitor various voltages around the accelerator. This, however, is only achieved when a second 25 way 'D-type' cable is plugged into the controller (right hand socket) at one end and to the cable normally connected to socket Y on the PC's Faraday cage at the other. This cable is a round screened cable and is connected to the cable which normally carries analogue inputs to the PC.

In this mode of operation care must be taken with the timing circuits since they are under PC control. There are two ways of dealing with this: either the data latches in the timing chassis boards can be replaced with DIL switches as shown in figure 5 or the timing circuits are bypassed altogether by injecting optical trigger signals directly into the two thyratron input amplifiers. The optical triggers can be derived from a dual output pulse generator feeding two LEDs and polymer fibres.

Vacuum system.

The vacuum pumping system on the linac is extremely simple and consists of a cartridge type of ion pump and associated power supply. The pump is a non-servicable item, and, as far as we can tell at the time of writing, replacements can only be obtained from Philips. A cooling fan has been fitted behind the pump to help with pumping efficiency. During the commissioning phases of the accelerator, the pump proved incapable of pumping down the system when the filament or the RF were energised. Ion pumps should in

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any case not be operated at pressures above 10^{-4} Torr and the only way to coax the pump into action was to couple a turbomolecular and rotary backing pump to the system through a flexible connection on the isolating valve port next to the gun end of the accelerator. It is presumed that a similar situation will arise when the filament will need replacing and the system is brought up to atmospheric pressure. With the ion pump power supply turned off, the ion pump was heated with a hot air gun in an attempt to 'bake' it. The whole process took several days; this is not too surprising as there seem to be severe restrictions in the pumping layout, especially around the mode transformer at the gun end of the accelerator.

Ion pumps of course also behave as vacuum gauges and the vacuum pressure can be determined from the power supply output current and the calibration chart in the appendix. An integral part of the current monitoring circuit on the original machine was the vacuum indication meter. Its internal resistance was specific to an additional non-linear network at the input to the vacuum trip monitoring system. Unfortunately this meter was damaged in transit to the Gray Lab and no internal resistance or fsd markings could be found on the meter. The meter also had a 270° scale with calibrated markings, similar to meters normally used on vacuum indicators. No replacement meter could be obtained and thus the circuit was modified to insert a 'floating' 3 mA meter in series with the pump's power supply output and the trip comparators. This arrangement is shown in PCINT.SCH. The meter thus encompasses the low pressure end of the scale. The comparators are located on a circuit board behind the pump power supply.

It is normal for the vacuum to rise and then to recover when repetitive RF pulses are energised. The microwave power breaks up any high molecular weight impurities within the waveguide into lower molecular weight material more readily pumped by the ion pump. Similarly, energisation of the filament will produce the same effect as impurities adsorbed on the now heated filament are being expelled. The pumping speeds are quite low so it is advisable not to energise the filament at full power at the start of the working day, but rather to allow time for the pump to recover at lowish gun filament settings.

Safety interlock system.

This system is located in the Van de Graaff control area to the left of the pulse radiolysis instrumentation rack. The circuit diagrams are LNINTLK.SCH and INTLKL.SCH. The radiation stop in the pulse room, operated from the Van de Graaff's safety interlock system, may only be moved to the 'irradiate' position if the pulse room and magnet room are surveyed as far as the Van de Graaff system is concerned. There is no possibility of irradiating personnel in the magnet room through the Van de Graaff beam line as this would require the use of the Van de Graaff 'bypass' key, to enter the magnet room. Activation of the 'bypass' key drops the pulse room survey, thus rotating the radiation stop to the safe position in the pulse room.

The linac can only be set ready for irradiation (i.e. the main HT, gun filament and focus supplies energised) if the sequence *'Survey pulse room, Close outer pulse room maze door within allowed time delay, Activate red 'irradiate' button on the interlock system front panel*' is performed.

This is achieved provided the interlock system operated correctly the previous time it was used; if not the procedure is disabled (see contacts RLE/2, RLB/1). The sequence is as follows: When the survey button in the pulse room is pressed momentarily, RLA is energised for a time determined by the 100 kΩ/220 μF time constant, sounding the siren through RLA/1. Should RLA remain energised for some reason, the accelerator cannot be switched on the next time due to contacts RLA/2 (at the bottom of the diagram). DC power (+27 V nominal) through three series-connected diodes (1N 4001) and through the upper 'closed' door switch is applied to RLB when the door is closed; the 220 μF capacitor across RLB coil takes care of door switch/relay contact bounce in the next phase of the sequence. At that point RLB/1 changes over, latching RLB on through the upper door 'closed' switch. Contacts RLB/2 now energise the 'room ready' indicator on the interlock system panel and the 'danger' indicator in the pulse room. Closing the door also energises RLD and thereafter RLE. One of the contacts of RLE, (RLE/1) allows latch RLC and RLC/1 to be turned on when

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the 'radiation on' push button is activated on the interlock system front panel. Relays RLX and RLXX are energised through RLC/2, provided RLD/1 had changed over. RLX/1 contacts are the 'output' of the interlock and allow the HT/Gun/Focus to be energised. Contacts RLX/2 are used to illuminate the large 'Radiation Hazard' wall-mounted indicator outside the pulse room while RLXX/1 and RLXX/2 are used to illuminate appropriately the small red/green indicators next to the pulse room door.

The linac keyswitch must be activated initially for the above sequence to take place. There are two contacts on the keyswitch. The lower one is simply in series with the interlock output. The upper contact causes RLT to be energised momentarily through a 4700 μF capacitor (and normally made i.e. inactivated 'panic' switches). Contacts RLT/1 then latch RLT on while contacts RLT/2 activate the three phase contactor in the 'cleaner's cupboard' room. Relay RLS is normally always energised and maintains single phase power to the accelerator and the pulse room instrumentation. Should any of the panic buttons be activated both RLS and RLT drop out and all power is removed. The system may then be restarted only by opening the interlock system front panel and pressing the 'panic reset' switch; this turns on RLT and RLS by discharging the 4700 μF capacitor through 15 ohms but the keyswitch must be on if the three phase power is to be restored.

In normal operation the keyswitch is turned only at the start and at the end of the working day. Should the linac be turned off inadvertently at the key switch, it will not be possible to restart it before the 4700 μF capacitor has fully discharged; this process may be speeded up by pressing the 'panic reset' button as described above.

Water chiller unit.
The water chiller/circulator is located in the Mechanical Workshop's metal stores, next to the corridor of the 'tunnel entrance' to the laboratory. It is supplied from its own local three phase supply and is activated when the linac keyswitch on the interlock panel is turned on. It supplies water to the accelerator at a rate of up to 22 litres/minute, dependant on the load, at a temperature which is adjustable and which is at present set to 12 deg C. Adjustment to the output temperature can be made on the thermostat which is revealed by removing the top front panel.

The unit is a standard closed loop system consisting of a chilling compressor and a circulating pump. This unit can be serviced by any competent refrigeration engineer. The system does not make up for lost water in the event of a leak and this must be done manually by removing the lower front cover and by operating the appropriate valves in a logical sequence, one that becomes obvious once the cover is removed. There were no circuit diagrams supplied with the unit and only partial circuit details are available on LNINTLK.SCH.

Performance of the accelerator.
It is normal for the output energy of electron pulses from linacs to be reduced when the charge per pulse is increased. This accelerator is no different in this respect and this loading effect is shown in figure 6.

As was described near the beginning of this report, a range of pulse widths and shapes may be obtained and some typical examples are shown in figures 7, 8, 9, 10.

In all cases the spatial beam shape was optimised by appropriate focussing and the '50 Hz phase' was adjusted optimally to yield the most intense pulse for a given set of injection conditions. This phase delay was then not altered during the acquisition of this series of electron pulse recordings. In practice, there is also little variation of electron pulse amplitude as the electron pulse is 'moved' within the RF pulse, except near the rise/fall times of the magnetron's output pulse. These recordings were obtained with the RF pulse-to-electron pulse delay fixed and with the electron pulse occurring near the middle of the RF pulse. The electron pulse was collected on a Faraday cup target which was mechanically and electrically attached to the beam line. The output from the target was connected to a 50 Ω termination through RG 58 50 Ω cable.

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Figure 6. Drop of electron beam energy as a function of total charge per pulse.

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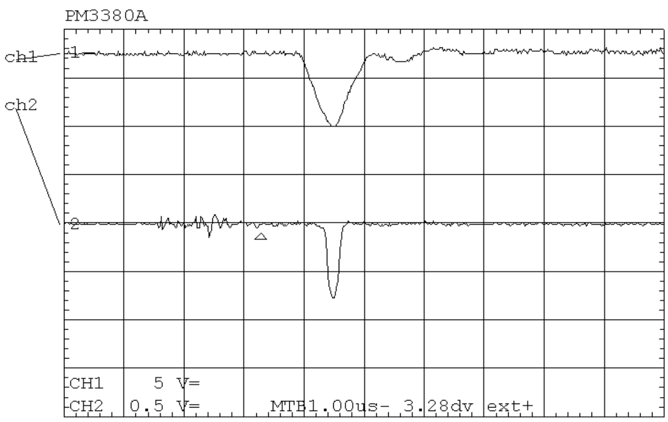
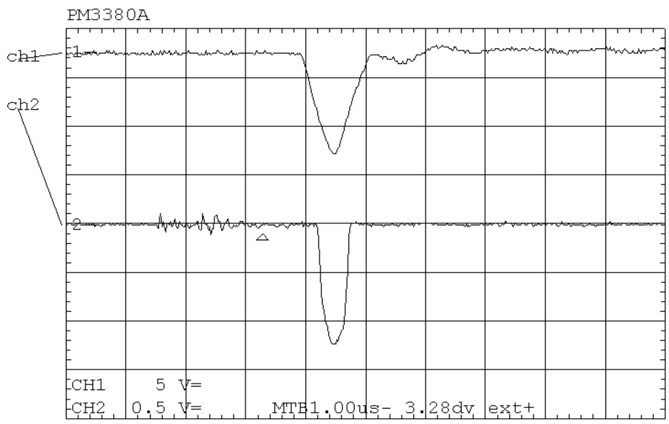
Gun filament set-point 5.4 V



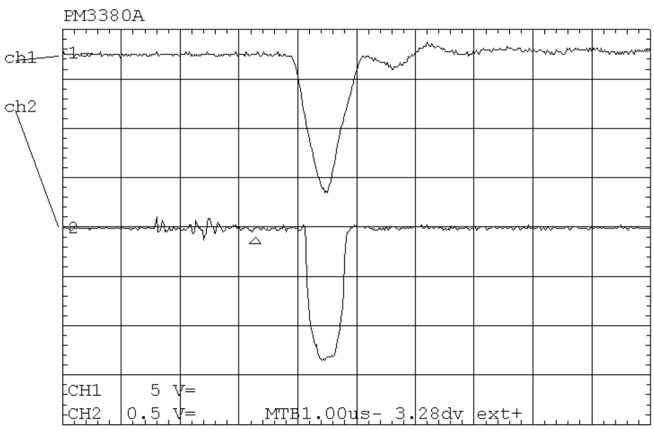
(a) 5.0 kV charging 10 kV/div (top), 10 mA/div (bottom)

Gun filament set-point 5.4 V



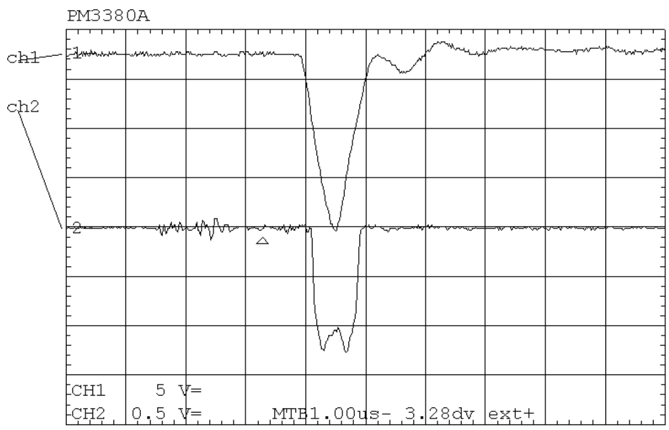
(b) 6.7 kV charging 10 kV/div (top), 10 mA/div (bottom)

Gun filament set-point 5.4 V



(c) 9.2 kV charging 10 kV/div (top), 10 mA/div (bottom)

Gun filament set-point 5.4 V



(d) 11.7 kV charging 10 kV/div (top), 10 mA/div (bottom)

Figure 7: Injection voltage (upper traces in each panel) acquired with capacitive probe (mounted on gun pulse transformer) and attenuator & output beam pulse (lower traces in each panel), collected on a 50 Ω terminated target. Panels a-d are acquired with increasing line charging voltages. All traces acquired at 1 μs/div and in single-shot operation mode with 6 RF pre-pulses at 10 Hz.

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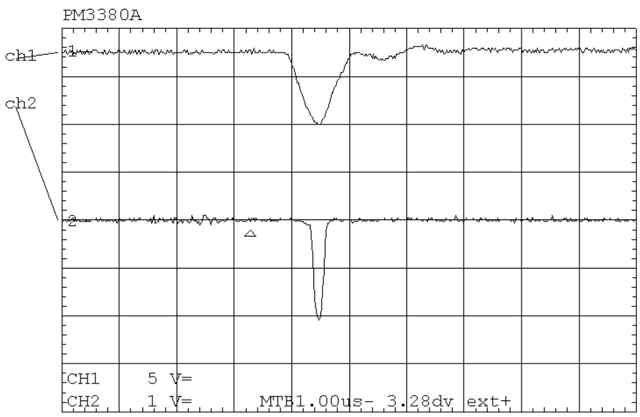
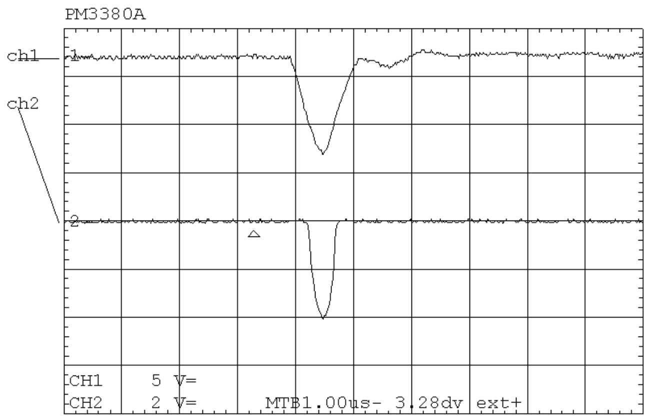
Gun filament set-point 6.0 V



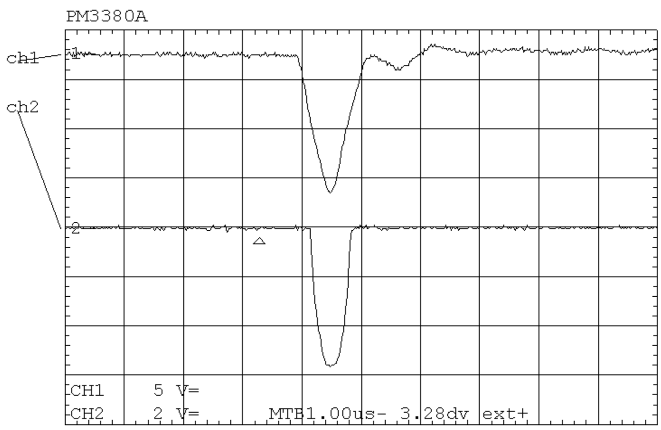
(a) 5.0 kV charging 10 kV/div (top), 20 mA/div (bottom)

Gun filament set-point 6.0 V



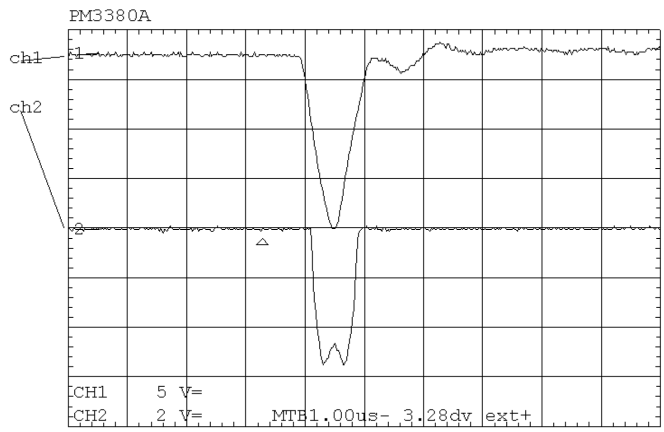
(b) 6.7 kV charging 10 kV/div (top), 20 mA/div (bottom)

Gun filament set-point 6.0 V



(c) 9.2 kV charging 10 kV/div (top), 40 mA/div (bottom)

Gun filament set-point 6.0 V



(d) 11.7 kV charging 10 kV/div (top), 40 mA/div (bottom)

Figure 8: Injection voltage (upper traces in each panel) acquired with capacitive probe (mounted on gun pulse transformer) and attenuator & output beam pulse (lower traces in each panel), collected on a 50 Ω terminated target. Panels a-d are acquired with increasing line charging voltages. All traces are acquired at 1 μs/div and in single-shot operation with 6 RF pre-pulses at 10 Hz.

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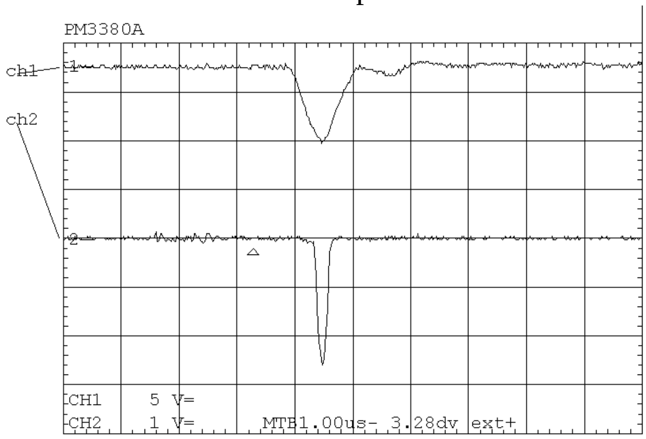
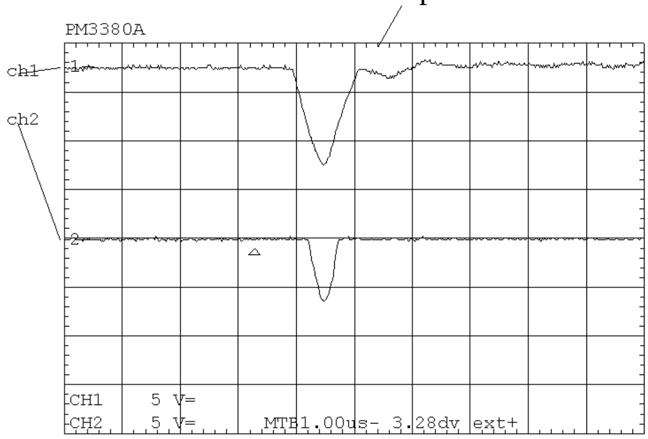
Gun filament set-point 6.5 V



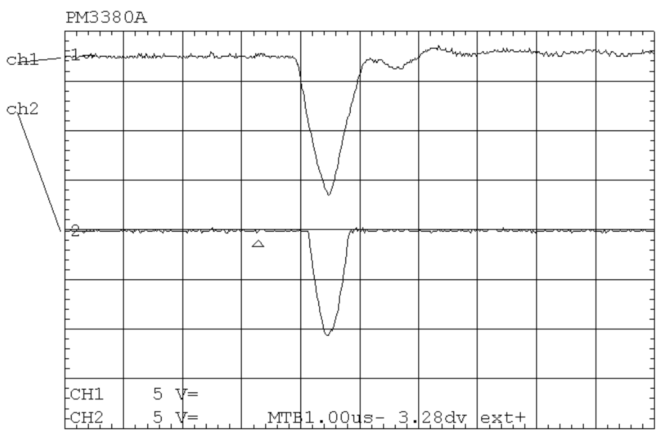
(a) 5.0 kV charging 10 kV/div (top), 20 mA/div (bottom)

Gun filament set-point 6.5 V



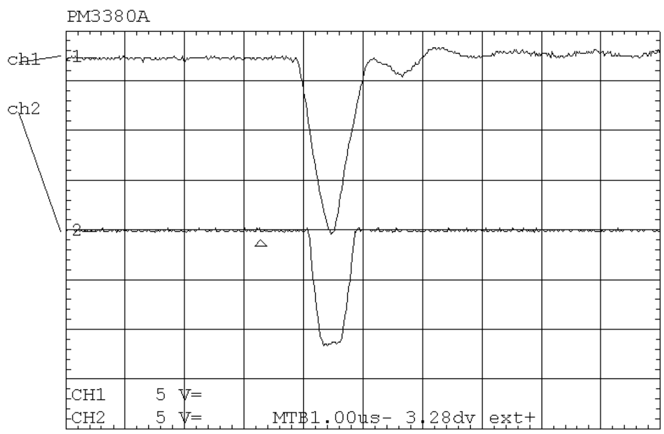
(b) 6.7 kV charging 10 kV/div (top), 100 mA/div (bottom)

Gun filament set-point 6.5 V



(c) 9.2 kV charging 10 kV/div (top), 100 mA/div (bottom)

Gun filament set-point 6.5 V



(d) 11.7 kV charging 10 kV/div (top), 100 mA/div (bottom)

Figure 9: Injection voltage (upper traces in each panel) acquired with capacitive probe (mounted on gun pulse transformer) and attenuator & output beam pulse (lower traces in each panel), collected on a 50 Ω terminated target. Panels a-d are acquired with increasing line charging voltages. All traces are acquired at 1 μs/div and in single-shot operation with 6 RF pre-pulses at 10 Hz.

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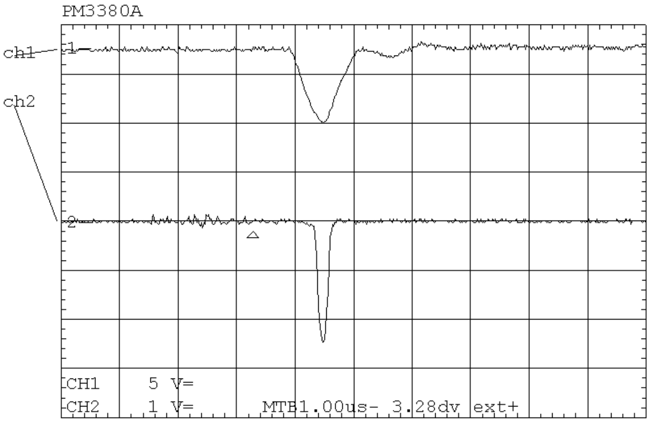
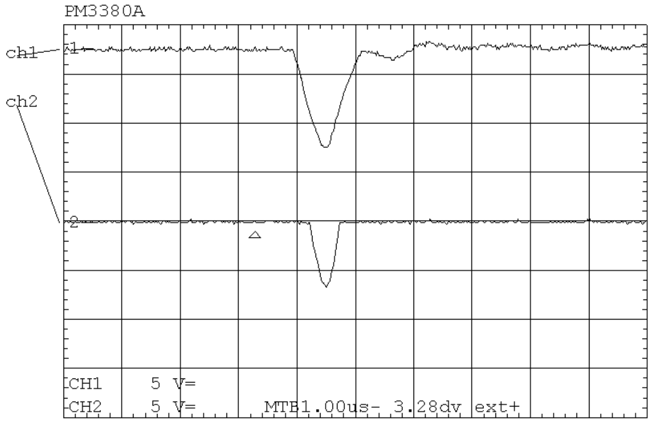
Gun filament set-point 7.0 V



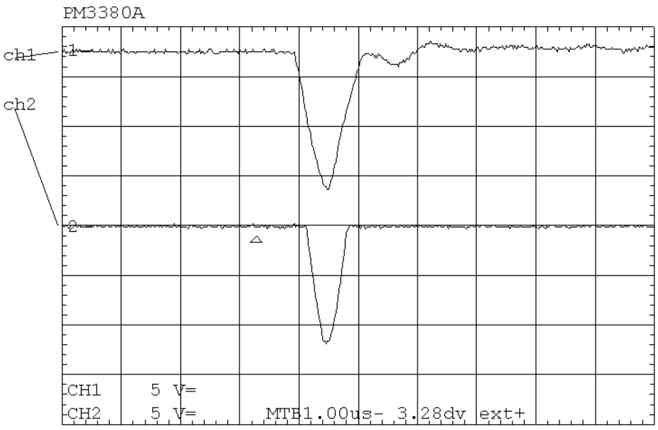
(a) 5.0 kV charging 10 kV/div (top), 20 mA/div (bottom)

Gun filament set-point 7.0 V



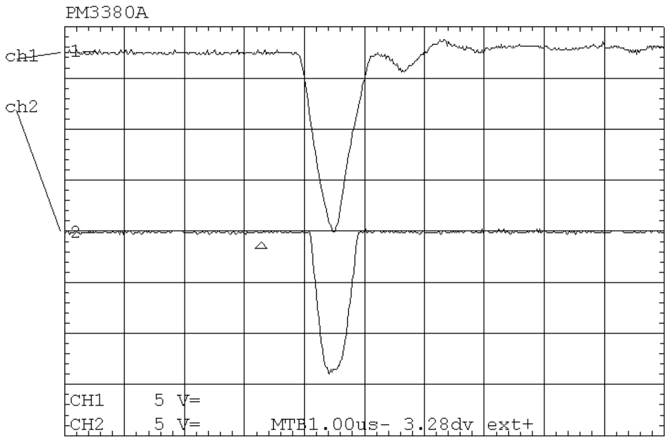
(b) 6.7 kV charging 10 kV/div (top), 100 mA/div (bottom)

Gun filament set-point 7.0 V



(c) 9.2 kV charging 10 kV/div (top), 100 mA/div (bottom)

Gun filament set-point 7.0 V



(d) 11.7 kV charging 10 kV/div (top), 100 mA/div (bottom)

Figure 10: Injection voltage (upper traces in each panel) acquired with capacitive probe (mounted on gun pulse transformer) and attenuator & output beam pulse (lower traces in each panel), collected on a 50 Ω terminated target. Panels a-d are acquired with increasing line charging voltages. All traces are acquired at 1 μs/div and in single-shot operation with 6 RF pre-pulses at 10 Hz.

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Useful items required during servicing of the accelerator.

Only the most important tools and instruments are listed here; the instruments described were used to obtain most of the information listed in this report.

High voltage meter:	Brandenburg type 88 M
Oscilloscope	Fluke type PM 3380A
High voltage probe	Tektronix type 6015
General purpose DVM	Fluke type 87
Manual single shot trigger	In house constructed, drawing OPTRIG.SCH
Fibre optic receiver	In house constructed, drawing OPTRIG.SCH
Manual signal source/interface	In house constructed, drawing MANTEST.SCH
Linac high voltage attenuator probe	In house constructed, atten 2000:1 with installed cables, capacitive
50 ohm coaxial components	Two 10:1 attenuators, coaxial T pieces, six through terminations
Electron beam target	Faraday cup, in house developed, attached to end of beam line

Description of software and listing of interface registers.
The interface registers and channels are organised as follows:
Data is 8 bits available on port A of PC30A interface card, data flow from PC30A to interface electronics.
Address locations (16 off), address available on LSB's of port B of PC30A interface card:

Address hex 0	Function	Trigger to electron pulse least significant bits
Address hex 1	Function	Trigger to RF pulse least significant bits
Address hex 2	Function	1, 2, 4: trigger to RF pulse most significant bits; 8: enable RF pulse; 16, 32, 64: trigger to electron pulse most significant bits; 128: enable electron pulse
Address hex 3	Function	1, 2, 4, 8, 16, 32: number of RF prepulses; 64: external dose control mode (0 = filament, 1 = pulse amplitude)
Address hex 4	Function	Pulse amplitude (mark-space control) value
Address hex 5	Function	Gun filament current (mark-space control)
Address hex 6	Function	1, 2, 4: Electron pulse width; 8: repetitive pulsing on/off (1 = on, 0 = off); 16, 32, 64, 128: 50 Hz repetition rate divisor;
Address hex 7	Function	Accelerator systems enabling: 1: enable gun filament power supply 2: enable main HT power supply 4: enable magnetron power supplies 8: enable focus supplies 16: tune up magnetron 32: tune down magnetron 64: injector HT supply on / reset 128: not used.
Address hex 8	Function	Focus 1 power supply set-point value (D/A converter #1)
Address hex 9	Function	Focus 2 power supply set-point value (D/A converter #2)
Address hex A	Function	Focus 3 power supply set-point value (D/A converter #3)
Address hex B	Function	Reserved for quadrupole supply set-point (D/A converter #4)
Address hex C	Function	Steerer 1 power supply set-point value (D/A converter #5)
Address hex D	Function	Steerer 2 power supply set-point value (D/A converter #6)
Address hex E	Function	Steerer 3 power supply set-point value (D/A converter #7)
Address hex F	Function	Steerer 4 power supply set-point value (D/A converter #8)

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No analogue output data from PC30A card to interface electronics is used.

Data from interface electronics to PC30A card;
Digital data (1 bit) selected by address available on LSB's of port B of PC30A interface card:

Address hex 0	Function	Confirmation focus supply is enabled
Address hex 1	Function	Confirmation magnetron system is enabled
Address hex 2	Function	Confirmation main HT supply is enabled
Address hex 3	Function	Confirmation gun filament supply is enabled
Address hex 4	Function	10^{-4} Torr vacuum trip
Address hex 5	Function	10^{-5} Torr vacuum trip
Address hex 6	Function	Water flow present
Address hex 7	Function	Water flow absent
Address hex 8	Function	Confirmation magnetron tuning down
Address hex 9	Function	Confirmation magnetron tuning up
Address hex A	Function	Magnetron tuning limit reached
Address hex B	Function	Confirmation injector HT supply enabled
Address hex C	Function	Confirmation safety interlock system enabled
Address hex D	Function	Focus 3 power supply fault
Address hex E	Function	Focus 2 power supply fault
Address hex F	Function	Focus 1 power supply fault

Analogue data from interface electronics to PC30A interface card

Channel 0	Function	Spare / not used
Channel 1	Function	Focus 1 power supply output current
Channel 2	Function	Focus 2 power supply output current
Channel 3	Function	Focus 3 power supply output current
Channel 4	Function	Reserved for quadrupole power supply
Channel 5	Function	Steerer 1 power supply output current
Channel 6	Function	Steerer 2 power supply output current
Channel 7	Function	Steerer 3 power supply output current
Channel 8	Function	Steerer 4 power supply output current
Channel 9	Function	Injector HT power supply output voltage
Channel 10	Function	Main HT power supply output current
Channel 11	Function	Injector HT power supply output current
Channel 12	Function	Vacuum pressure reading
Channel 13	Function	Charge per pulse monitor output voltage
Channel 14	Function	Gun filament power supply output current
Channel 15	Function	Water temperature reading

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Listing of accelerator circuit diagrams.

Total number of original accelerator drawings, only paper copies available = 50; these are available for background information only; do not refer to them for servicing/fault finding purposes.

Total number of drawings in C:\PCB\GLLIN directory = 30

Diagram # 1	PWRDIS.SCH	AC Power distribution, circuit breakers etc.
Diagram # 2	GUNMOD.SCH	Gun injector, pulse amplifier and gun filament regulator
Diagram # 3	POSPAMP.SCH	Pulse thyratron driver amplifier
Diagram # 4	THYRTRIG.SCH	Fibre optic magnetron thyratron trigger amplifier
Diagram # 5	MAGTHYR.SCH	Magnetron thyratron and RF modulator details
Diagram # 6	PCINT.SCH	Manual over-ride computer interface / power supplies enabling
Diagram # 7	TESTPAN.SCH	Layout of manual over-ride controls
Diagram # 8	INTCON1.SCH	Internal signal & logic wiring / unit interconnections part 1
Diagram # 9	INTCON2.SCH	Internal signal & logic wiring / unit interconnections part 2
Diagram # 10	LOVPWR.SCH	+/- 15 V and +/- 24 V low voltage power supplies
Diagram # 11	DEFLECT.SCH	Beam deflection / steering power supply (one of four)
Diagram # 12	FOCUS.SCH	Beam focussing power supply (one of three)
Diagram # 13	FILT.SCH	RFI filtering to outside of main Faraday cage
Diagram # 14	MANCONT.SCH	Manual control units for external/non PC use of accelerator
Diagram # 15	CABLES.SCH	Test cables installed in trunking to pulse room
Diagram # 16	QMON.SCH	Toroidal charge / dose monitor
Diagram # 17	QUAD.SCH	Details of beam flattening quadrupole
Diagram # 18	LINTRIG.SCH	Timing electronics block diagram
Diagram # 19	LININT.SCH	Interface to PC / Digital-to-analogue conversion
Diagram # 20	LINDEL1.SCH	Timing electronics/repetition and pulse generation circuits
Diagram # 21	LINDEL2.SCH	Timing electronics/mains sync/pulse width modulators
Diagram # 22	LINBRD.SCH	Layout of timing/interface boards
Diagram # 23	LINPS.SCH	Timing and interface electronics power supply
Diagram # 24	ANIN.SCH	Interface to PC / Analogue signal conditioning
Diagram # 25	LINSOFT.SCH	Details of interface electronics registers
Diagram # 26	OPTRIG.SCH	Optical trigger and receiver test modules
Diagram # 27		Spare
Diagram # 28	LNINTLK.SCH	Personnel safety interlock panel
Diagram # 29	INTLKL.SCH	Interlock system indicators /VdG and water chiller connections
Diagram # 30	INDEX.SCH	Index of drawings

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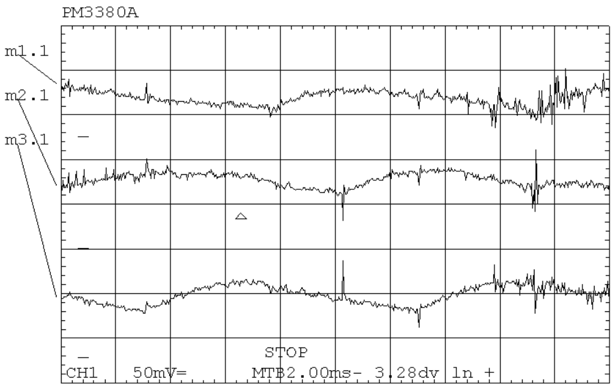
Typical circuit waveforms

In figures 11 to 14 are depicted typical waveforms in parts of the linac circuitry. Figure 11 shows the ripple associated with the DC output of the focus supplies. Figure 12 shows AC current waveforms as monitored across the sensing resistor at the output of the gun filament regulator with different set-point inputs applied to the regulator, while figure 13 shows the settling time of the regulator at and following switch-on. Figure 14 shows a typical relationship in time between the RF thyratron current pulse and the electron pulse, with the scope being triggered by the optical receiver unit.



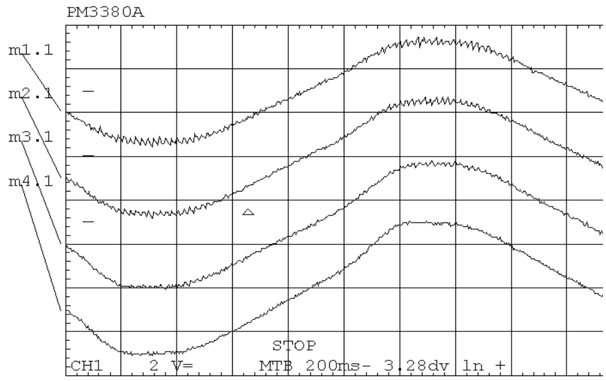


Figure 11: (above) Output ourrent waveforms from the three focus power supplies: focus 1: upper trace, focus 2: middle trace, focus 3: lower trace. DC zero for each trace is indicated by a notch to the left of the panel, below each trace.

Figure 12: (above right) Output ourrent waveforms from the gun filament regulator, measured across 2 Ω sensing resistor (traces top to bottom filament set-points 5.4 V, 6.0 V, 6.5 V, 7.0 V.

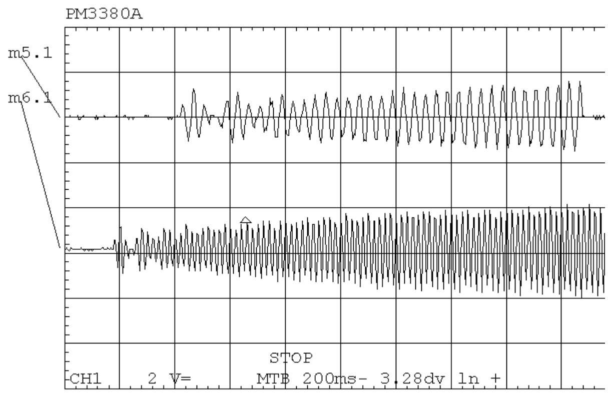


Figure 13: (right) Output ourrent waveforms from the filament regulator at switch-on (top trace, 100 ms/div) and following switch-on (bottom trace, 200 ms/div)

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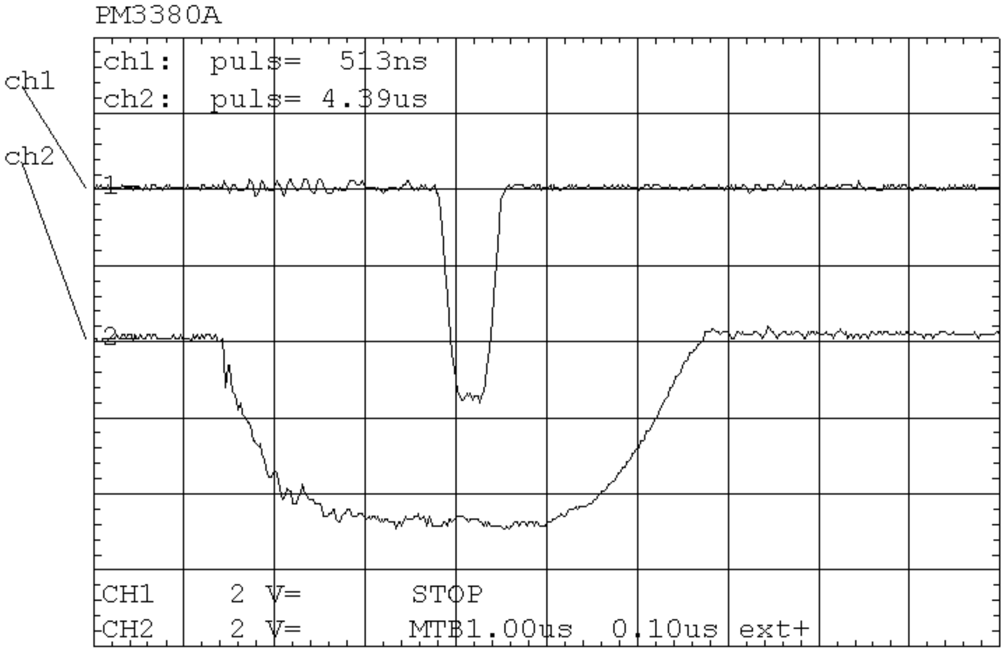

Figure 13: (right) Output pulse ourrent from the linear accelerator (top trace), and the 4 µs RF thyratron current pulse (bottom trace) showing how the gun is pulsed during the RF burst envelope.

Conclusion

This manual describes the development of the Gray Laboratory's 5 MeV linear accelerator up to November 1995. It is not intended to be complete and it is hoped that additions will be described in subsequent pages. In particular, relatively little operational experience with the accelerator has been had and a detailed log of all faults should be maintained.

Additions and modifications to the Gray Laboratory Linac during December 1995.

Interlock system.

The operation of the HT and interlock systems was modified in December 1995 to enable the installation of an HT discharge relay used to bring the HT supply down to zero volts following its de-energisation. This relay is now shown in the top RH corner of circuit PWRDIS.SCH. This relay is mounted above the HT transformer and is accessible from the front of the accelerator following removal of the perspex protective covers. The HT reservoir capacitor is discharged through a 15 K resistor, thereby limiting the current to around 600 mA, discharge being complete in less than 100 ms. This is in contrast to several tens of seconds prior to the installation of this relay.

In addition to the HT discharge contacts, two microswitches have been fitted to the assembly. One of these operates when the relay is fully closed i.e. de-energised, the other when the contacts are open, i.e. the relay coil energised. In order to prevent the possibility of applying HT to the closed contacts/resistor, the HT start relays RLC and RLC' are powered through the coil energised microswitch. To bring the HT on therefore, the discharge relay coil is energised, the discharge short is removed, the microswitch operates and this in turn energises relays RLC,RLC'.

The second microswitch is used to monitor the and confirm the fact that the discharge relay contacts are closed, i.e. that the HT is at zero, when the accelerator is in a 'safe' condition. Should this additional microswitch be 'on' in the safe condition, a warning siren is activated through the normally closed contacts of the interlock output relay RLS. This arrangement also tests the integrity of the contact assembly of RLS in the following manner: at switch-on, +24V DC is applied momentarily to the siren through the normally closed RLS contacts and the 470 mF capacitor / 39 Ω current limit resistor across the HT discharge relay microswitch. Should RLS contacts be open for some reason no such siren activation will take place. Furthermore, when RLS contact is open, i.e. when the personnel safety interlock is in the 'irradiate' condition, this capacitor is discharged through the parallel 100 K resistor, ready for the next 'safe' condition of the personnel safety interlock system. In other words, every time the accelerator is in the 'safe' mode, the siren is momentarily activated.

The coil of the HT discharge relay is not driven directly but rather through an electronic 'boost' circuit arrangement which provides a high pull-in force while maintaining a low holding coil current once the relay has energised. No details of this circuit arrangement are provided since they are proprietary to the supplier of the relay. An unforeseen consequence of this is that the 'coil' current at turn-on is around 10 A which loaded the 24 AC control power to an unacceptable degree: the result was that the timer clutch would on occasions trip out, causing the start of a new 5 minute timing cycle. This clearly unacceptable situation was remedied by installing a separate 24 V AC power transformer to power the timer and magnetron filament control power. No detrimental effects were noticed on any of the other 24 V AC energised coils due to the high loading of the HT discharge relay.

Charge monitor.

The original charge monitor circuit was found to be unreliable at low charge per pulse operation. The problem was due to excessive RF interference affecting the operation of the circuit's peak detector. Surprisingly, the RF interference did not affect the operation of the resonant system pre-amplifier and this was retained in its original form to provide a damped oscillatory signal, of amplitude proportional to charge per pulse, to the pulse radiolysis dose monitoring circuits. The internal peak dose monitor circuit was taken out of service pending reconstruction of the arrangement with improved RF screening.

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Magnetron tuning.

It was found, under certain conditions of malfunction of the control software, that it was possible for the magnetron tuning motor to be energised continuously, causing the motor to drive to its end limit(s). This condition was rectified in the software and in addition the PC tuning outputs were fitted with timing capacitors/diodes (see PCINT.SCH) so that, should this condition occur in the future, at least the tuning motor will be moved from its correct position only slightly.

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