Radiat. Phys. Chem. Vol. 24, No. 5/6, pp. 517–522, 1985
Printed in the U.S.A.

0146–5724/85 $3.00 + .00

A SENSITIVE SINGLE-PULSE BEAM CHARGE MONITOR FOR USE WITH CHARGED PARTICLE ACCELERATORS

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Abstract—An inductive, non-intercepting beam charge monitor which measures the charge in single bunches of accelerated electrons over the range 5 *pC*–2 μ*C* is described. The range of electron pulse widths covered by the monitor is 1.5 ns–5 μs. The charge response is essentially linear and independent of pulse width. The device is used for beam alignment and for recording pulse-to-pulse variations of dose in a target cell during pulse radiolysis experiments.

THE MEASUREMENT of beam charge from pulsed radiation sources is a common requirement in accelerator installations. In particular, for pulse radiolysis work with accelerated electrons, it is necessary, for dosimetry purposes, to determine the charge in a single pulse.(1) The device described here has been designed for use with a Van de Graaff accelerator delivering 1.5 ns–5 μs wide pulses of electrons at peak currents of up to 5A, but could be used for beam-monitoring purposes with other types of accelerator and charged particle apparatus.

The magnetic field associated with a moving electron bunch can be made to induce a voltage in a coupled inductive circuit. In this way, the monitor does not interfere with the beam, in contrast to collection methods. If the electron beam is assumed to be a current filament moving through the axis of a toroidally wound coil of n turns, it can be considered as a single-turn primary, generating a voltage $E = \mathrm{n}d\phi/dt$ across the coil, where $d\phi/dt$ is the rate of change in magnetic flux due to the moving charge, and the voltage signal approximates to the first time differential of the beam current. However, if the coil is operated into a low loading resistance, the shape of the electron pulse can be followed and subsequently integrated.(2) A bandwidth of a few hundred megahertz would have been required to accurately follow the shortest electron pulses in our installation. Alternatively, the coil can be made part of a tuned circuit,(3) excited by the electron pulse and producing a series of oscillations. If the oscillation period is long compared with the electron pulse width, the peak amplitude is proportional to the beam charge. When the coil, of inductance L, is shunted by a capacitor C, the peak capacitor voltage e_p due to the moving electron charge Q is given by:

$$e_p = Q/Cn$$

assuming negligible coil leakage inductance or other circuit losses, and assuming that the pulse width is much smaller than $2\pi(LC)^{1/2}$. When the device is used with wide pulses, charge proportionality does not hold; the treatment of errors in such cases can be found in Ref. 3.

The monitor described here is operated in this way, as only relatively low-frequency electronic circuits are required, and hence circuit and pick-up noise problems can be minimised. In practice, the tuned circuit oscillations are damped by circuit losses and by any loading resistance. However, the integrating properties are not affected by the damping unless the peak electron currents become so large as to cause saturation in the coil core material. The maximum tuned circuit voltage is sampled using a peak detector circuit, thus avoiding the requirement of a sampling pulse synchronised with the electron beam. Previously described monitors of this type(3–5) have used ferrite-loaded coils, necessitating the use of a relatively large number of turns so as to obtain an inductance high enough to integrate microsecond electron pulses. The present monitor, however, makes use of a Mumetal tape core with a small number of turns (n = 30; core 110 mm O.D., 70 mm I.D., 46 mm wide, made of 0.1 mm thick Mumetal; inductance 100 mH at 500 Hz so that the sensitivity for a given capacitor value is considerably improved. The voltage sensitivity of the monitor, e_p/Q, is proportional to the permeability of the core material and its cross-sectional area, but is inversely proportional to the mean core diameter. The dynamic range of the monitor can be extended by switching various loading capacitors. These are arranged to provide roughly decade ranges, as shown in Table 1. It should be pointed out that the more sensitive ranges cannot be used with wide pulses. However, it is generally difficult to generate stable, low-amplitude, wide electron pulses from Van de Graaff accelerators, so that this feature is usually of no practical consequence. It should also be pointed out that the charge proportionality should hold for pulses shorter than 1.5 ns, down to zero pulse width.

The construction of the monitor can be seen in Figs. 1 and 4. Two cores (Telcon Metals Ltd., type 11c) are stacked to provide the required thickness, placed around the beam line, but outside the vac-

Table 1. Showing the toroid circuit performance when loaded by various capacitors. The coil inductance of 100 mH (at 500 Hz) is reduced at higher frequencies because of the fall-off of core permeability at higher frequencies. The sensitivity values obtained, as shown in the final column, refer to the output of the monitor amplifier circuit and are obtained with a front-end gain setting of ×50; they can be improved by a factor of 10 when the front-end gain is increased to ×500

Loading capacitor nF (nom.)	Resonant frequency kHz	Maximum pulse width μs	Charge sensitivity at monitor output nC V^{-1}
2200	0.3	30	220
220	1	10	20
22	4	4	2.2
2.3	16	1	0.24

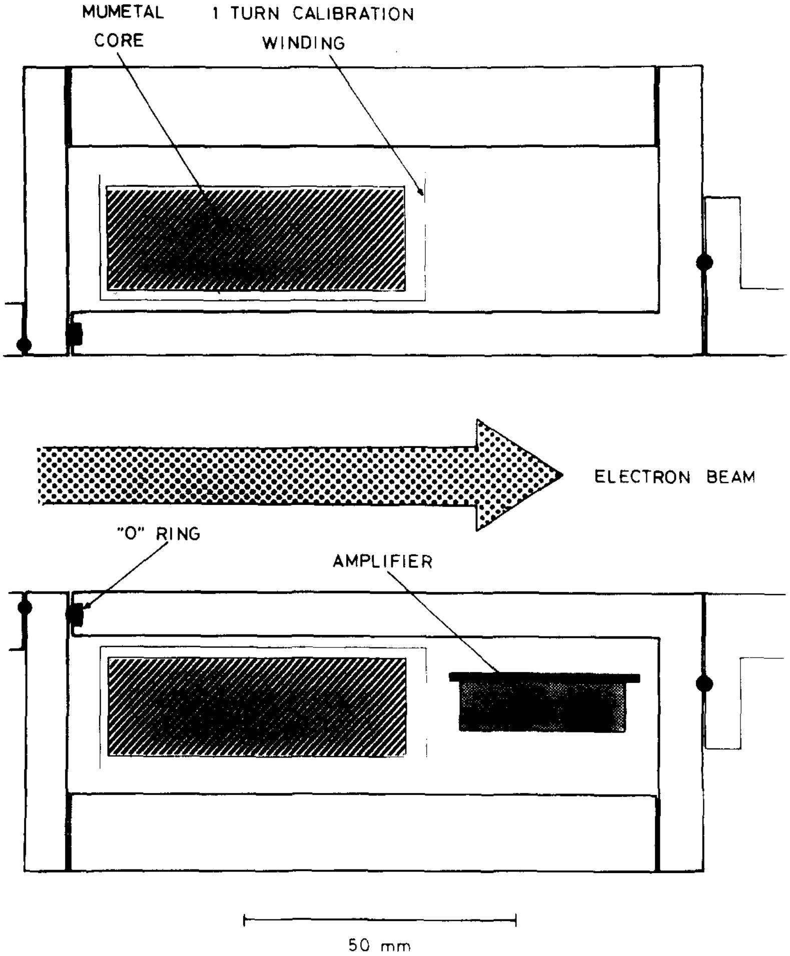

Fig. 1. Construction of toroidal dose monitor.

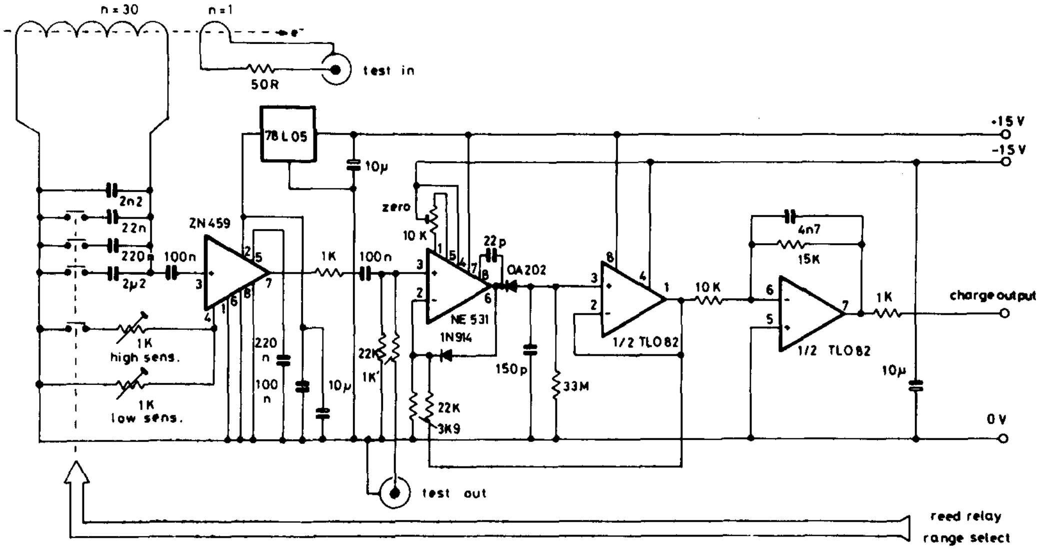

Fig. 2. Circuit diagram of buffer amplifier and peak detector curcuit used with the toroidal dose monitor.

uum system. An '*O*' ring serves the dual purpose of vacuum seal and insulator to prevent the formation of a shorted turn around the core, and to maintain this, there is a clearance of about 0.25 mm between the metal faces around the '*O*' ring. The monitor housing is machined from aluminium; the electronic circuit following the tuned circuit is placed close to the toroid and shielded by the housing. Van de Graaff accelerators are relatively noise-free machines, so a single screen was found to be adequate in this instance, even for the most sensitive range.

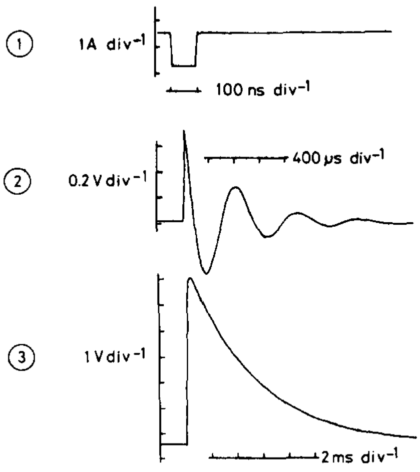

Fig. 3. Oscillograms showing toroidal dose monitor circuit performance: (1) input test pulse; (2) induced oscillations, amplified by ZN459 amplifier, as seen on 'test' output; (3) final dose monitor output after peak detection and filtering.

The circuit diagram of the electronics used with the toroid is shown in Fig. 2. The capacitor used for the various ranges can be switched remotely using reed relays. A very low noise bipolar front-end amplifier is used, and its noise performance (<1 nVHz$^{-1/2}$ from an optimum source impedance) determines the ultimate toroid sensitivity. In this instance, the noise performance is slightly degraded because the source impedance is not resistive and because of the inclusion of a gain-setting resistor.(6) Two amplifier gain values are provided ($\times 50$, $\times 500$); this further increases the dynamic range. The amplified toroid output is then coupled to a precision peak detector circuit with a voltage gain of $\times 6.5$, followed by a low pass filter with a gain of $\times 1.5$. In this way, the limited (<2 V peak) maximum signal swing of the first stage is stepped up to a maximum output of 10 V peak. The decay time constant of the peak detector is made 5 ms so that the charges of individual pulses at a repetition rate of 50 Hz can be followed. This feature is particularly useful during the setting up of the electron beam, commonly performed at a 50 Hz rate. It should be pointed out that a relatively simple precision rectifier circuit has been used, where the rectifier diode forward voltage drop v_d is compensated by the open-loop gain, A, of the NE531 amplifier and reduced to v_d/A. The limited high-frequency open-loop gain of the amplifier used results in im-

Fig. 4. The completed dose monitor can be seen in the bottom part of the picture. The final section of beam line to the exit window, and an additional single-turn, ferrite-loaded beam monitor used for pulse shape measurements can be seen in the middle of the picture. The electron beam enters the monitor from the bottom left.

perfect compensation at low outputs and below 100 mV the circuit becomes progressively less linear; nevertheless a 100:1 span of output is obtained within one range. This was felt to be of little practice consequence as five decades can be covered by the switching capacitor and the front-end gain.

A single turn, terminated in 50 Ω, has also been included around the toroid, for calibration purposes. This is formed by a cylinder of brass shim around the inside diameter of the core so as to ensure even coupling to the monitor coil. The performance of the circuit when tested with a calibration pulse is shown in Fig. 3; similar waveforms are obtained when the device is used with electron pulses.

For pulse radiolysis work, single-shot operation is generally required and the height of the monitor output pulse must be measured for eventual display on a DPM. This function is performed by a second precision rectifier circuit of conventional design,

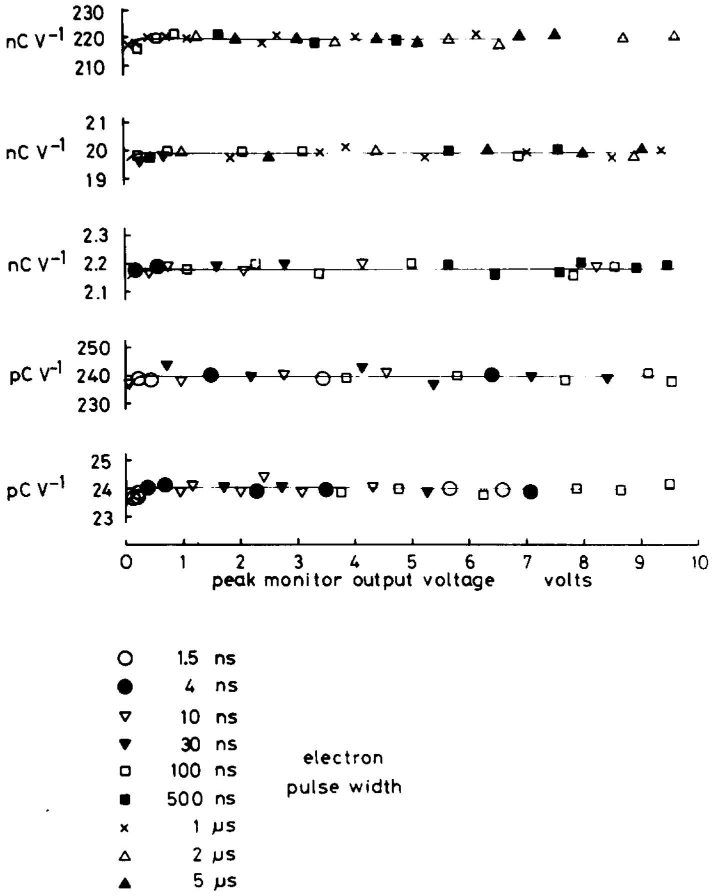

FIG. 5. Performance of monitor when excited by electron pulses over the range 3 pC–2 μC and 1.5 ns–5 μs. The top four graphs correspond to the four ranges in Table 1 (loading capacitors 2200–2.2 nF). The bottom graph refers to a loading capacitor of 2.2 nF but with the front-end gain increased by a factor of 10 to ×500.

but arranged to have a long decay time constant. The peak detector storage capacitor is discharged about 100 ms before the next electron pulse. No critical timing signals are involved in this approach although a sample-and-hold circuit or even a fast-converting DPM could be used just as well.

Tests with a pulse generator delivering a maximum current of 100 mA and with electron beam pulses of up to a few amps peak current indicate that pulse charges ranging from 5 pC to 2 μC can be measured to within ± 1.5%. During the electron pulse measurements, the pulse charge was measured by collecting the beam in a Faraday cup and integrating on a Keithley 616 electrometer. Figure 5 shows that the monitor behaves as a good integrator over a wide range of beam pulse widths and charges.

A characteristic feature of this type of monitor is that it only responds to rapid changes in current and hence 'dark' current, as from a faulty cathode, cannot be detected. However, for pulse radiolysis work, the pulse current must be measured independently of the dark current.

In conclusion, the monitor described here is capable of resolving much smaller beam charges than was possible with previously described devices, and has therefore proved useful for certain types of work involving a small dose per pulse. The minimum dose which can be resolved is strongly dependent on beam alignment, focussing, and collimation in front of the target cell. In the Gray Laboratory installation, doses of less than 10^{-3} Gy per pulse can be determined using the system described.

Acknowledgements—The support of the Cancer Research Campaign is gratefully acknowledged. The author also wishes to thank Mr M. Cox and Mr B. L. Hall for

their help during the construction and installation of the device.

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