NONDESTRUCTIVE HIGH-ACCURACY CHARGE MEASUREMENT OF THE PULSES OF A 27 MeV ELECTRON BEAM FROM A LINEAR ACCELERATOR

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Abstract

This work presents instruments and measurement procedures which enable the non-intercepting absolute measurement of the charge of single beam pulses (macro-pulses) from a 0.5 to 50 MeV electron linear accelerator (LINAC) with high accuracy, i.e. with a measurement uncertainty < 0.1 %.[1] We demonstrate the readout and calibration of a Bergoz integrating current transformer (ICT) for a 27 MeV beam. The signal from the ICT is calibrated against a custom-made Faraday cup (FC) with a high degree of collection efficiency (> 99 %) for electron beams in the energy range of 6 to 50 MeV.

INTRODUCTION

The National Metrology Institute of Germany, the Physikalisch-Technische Bundesanstalt (PTB), operates a custom-designed electron LINAC for fundamental research in dosimetry for radiation therapy (see Fig. 1). The LINAC works on the same principle as medical LINACs applied for cancer treatment. A pulsed electron beam is shot at a metal target for the generation of bremsstrahlung with therapeutically relevant dose rates. In contrast to medical LINACs, all beam parameters can be continuously adjusted and measured with a high degree of accuracy. In this way, it is possible to study radiation effects as a function of their fundamental physical quantities. One crucial quantity is the charge per beam pulse which is directly proportional to the dose of the generated photon radiation. Due to the discontinuous operating principle of a LINAC the charge of the pulses fluctuates somewhat (typical for PTB's research LINAC: 3 %). For the non-intercepting absolute measurement of the charge of the beam pulses, a beam intensity monitoring system based on an ICT, commercially available from Bergoz Instrumentation [1], is used. The signal from this monitoring system is calibrated against the charge measurement by means of a temporarily installed FC in combination with an electrometer, calibrated traceably to PTB's primary standards. The collection efficiency of the FC is determined by a cancellation measurement.

SETUP

The ICT (transformer winding: 50:1) is mounted directly as a vacuum component in the beamline ("G" in Fig. 1). A bare wire called a "Q-loop" is mounted within the ICT aperture by means of two additional flanges with an electrical feedthrough on both sides of the ICT as shown in Fig. 2. Via the Q-loop, the FC current can be conducted through the ICT for the determination of the collection efficiency of the FC.

The FC is temporarily installed behind the ICT (at "H" in Fig. 1). It shares the same vacuum as the beam. A photo of the FC glued into a vacuum adapter is shown in Fig. 3. The design of the FC is optimized with regard to high collection efficiency for electron beams with energies of 6 to 50 MeV. Its structure is shown in Fig. 4. The FC is composed of a sequence of 1.5 cm C, 2 cm Al, 2 cm Cu, and 4.2 cm WCu-alloy (80 % W).

The measurement of the charge collected by the FC is carried out by a precise electrometer (Keithley 616). In order to avoid saturation effects during a pulse, a 33 nF capacitor is installed at its input. The electrometer is thus suitable for pulse resolved charge measurements.

The ICT output voltage is recorded by means of a waveform digitizer (WD) also referred to as a transient recorder (Spectrum M3i.4142). Due to the high radiation exposure in the vicinity of the beamline, the WD is placed outside the radiation protection bunker. In order to improve the signal-to-noise ratio at the end of the required 40 m coaxial cable, a voltage amplifier (FEMTO HVA-200M-40-B) is used as a preamplifier at the output of the ICT. The preamplifier is enclosed by a pile of lead bricks. The wiring of the setup is shown in the block diagram in Fig. 5.

SIGNAL ACQUISITION

Faraday Cup

Every charge pulse from the FC fed into the electrometer input causes a voltage step at its analog output. The output voltage U_{out} is measured by a high-accuracy digital multimeter (Agilent 3458A). It is controlled by a LabVIEW program (see Fig. 5). At every LINAC trigger event, the device records 200 data points with an interval of 200 μs (6 ms pre-trigger, 34 ms post-trigger). The voltage difference ΔU_{out} between before and after the charge pulse is determined. If U_{out} exceeds -100 V, then the electrometer is discharged by closing the remote "zero" contact. The electrometer is calibrated by a reference charge Q_{ref} generated by means of custom-made air capacitors with traceably calibrated capacitance C_{air} and a reference voltage U_{ref}. The charge Q_{ref} collected by the electrometer at a change in the reference voltage by ΔU_{ref} amounts to

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[1] All uncertainties quoted in this article are expanded uncertainties based on a coverage factor $k = 2$ (two standard deviations), providing a coverage probability of about 95 %.

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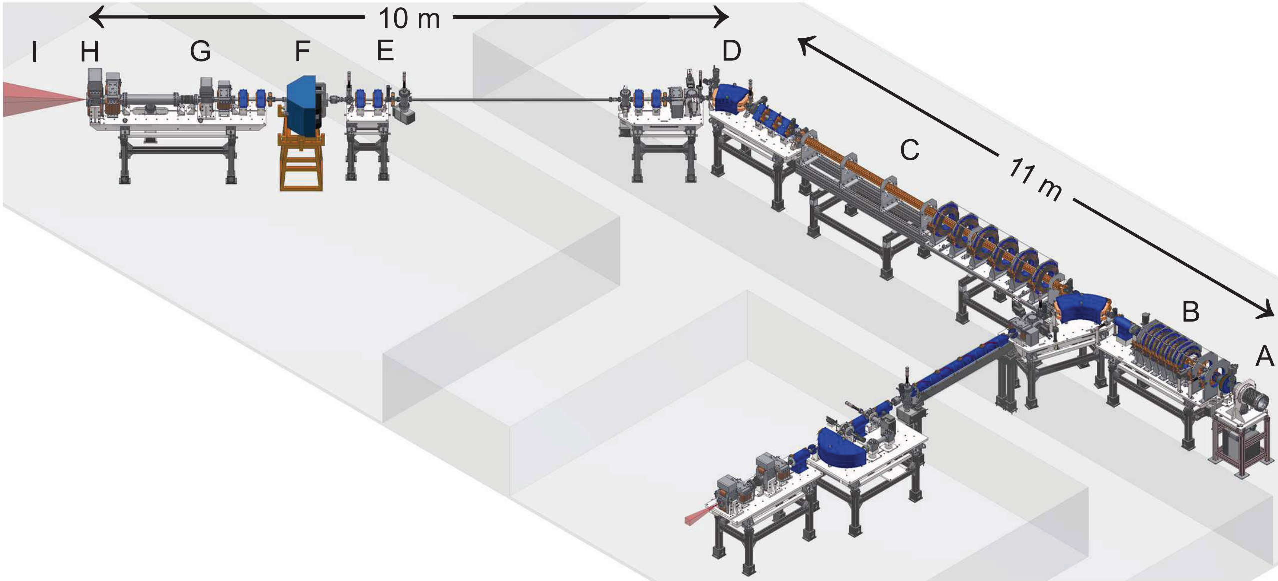

Figure 1: Drawing of PTB's electron LINAC for fundamental research in dosimetry for radiation therapy. A: electron gun. B: low-energy section (0.5 to 10 MeV). C: high-energy section (6 to 50 MeV). D: dipole magnet for energy separation and beam dump. E: collimator. F: magnetic spectrometer. G: ICT. H: Faraday cup or metal target. I: photon radiation. Gray areas: walls of the radiation protection bunker.

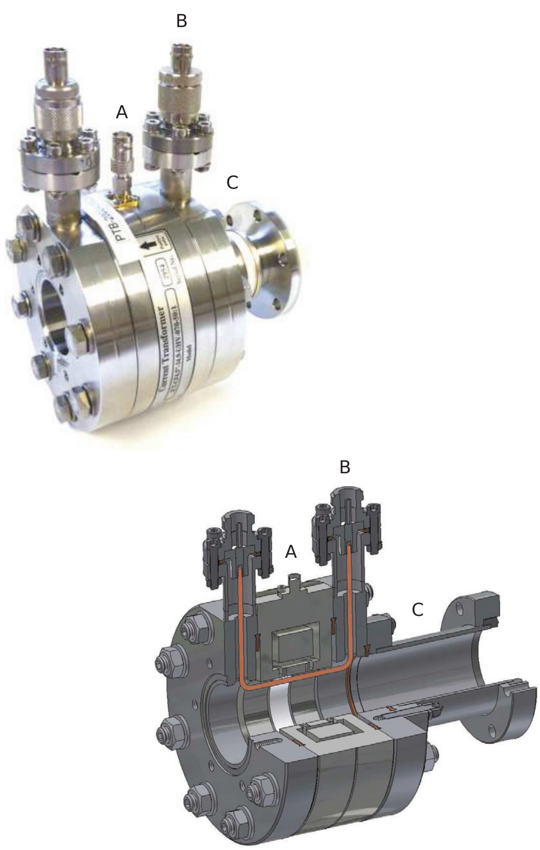

Figure 2: Photo (top) and sectional drawing (bottom) of the ICT (A) with an in situ wire (Q-loop) through the ICT screwed on electrical feedthroughs at additional flanges (B) and a vacuum ceramic break (C).

Figure 3: Photo of the Faraday cup glued into a vacuum adapter with a water cooling coil welded on the outside wall.

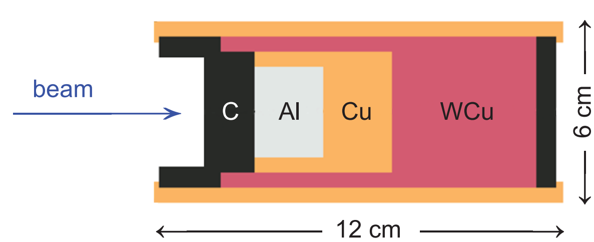

Figure 4: Drawing of the structure of the Faraday cup.

$Q_{\mathrm{ref}} = C_{\mathrm{air}} \cdot \Delta U_{\mathrm{ref}}$. From the corresponding electrometer response ΔU_{out}, the calibration coefficient is determined to be $N_{\mathrm{E}} = Q_{\mathrm{ref}}/\Delta U_{\mathrm{out}}$. The relative uncertainty of the calibration coefficient is $u(N_{\mathrm{E}})/N_{\mathrm{E}} = 0.007$ %. The charge from the FC is $S_{\mathrm{FC}} = N_{\mathrm{E}} \cdot \Delta U_{\mathrm{out}}$. The statistical uncertainty contribution due to random noise at the readout of the electrometer amounts to $u_{\mathrm{stat}}(S_{\mathrm{FC}}) = 0.008$ nC (0.013 % of the pulse charge to be measured). The relative uncertainty of the mea-

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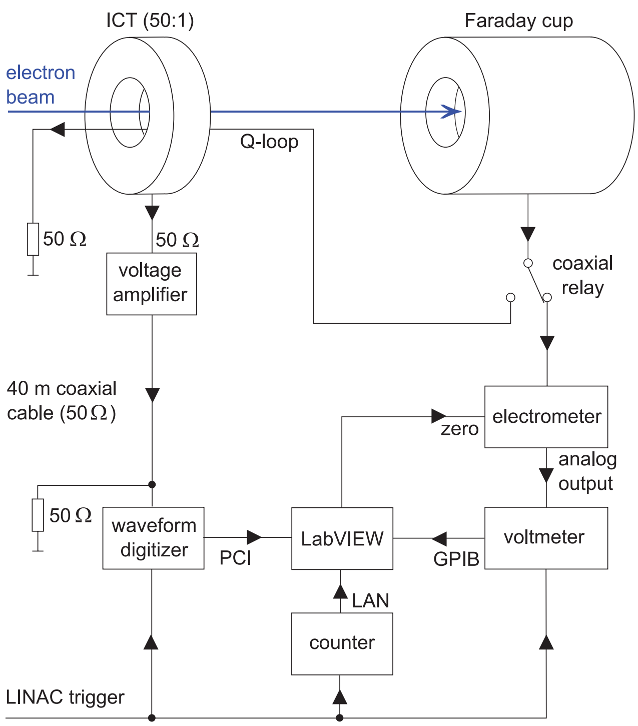

Figure 5: Block diagram of the setup.

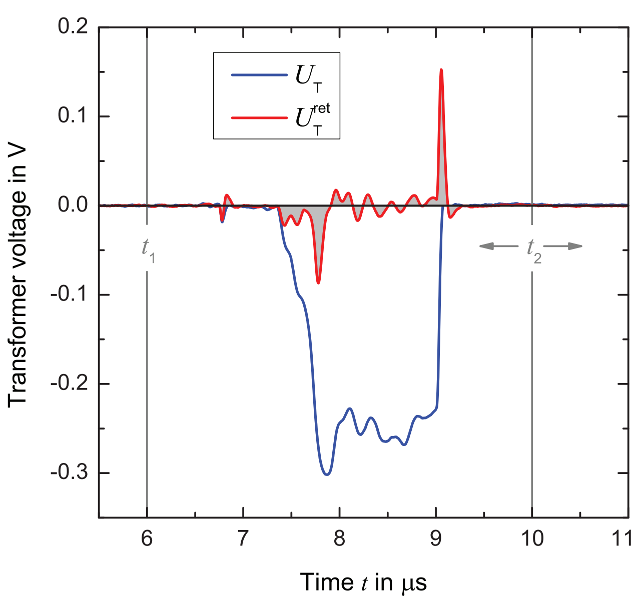

Figure 6: Blue curve: time resolved transformer voltage $U_T(t)$ for a typical LINAC beam pulse (27 MeV, −60 nC). Red curve: transformer voltage at return of the FC current through the ICT via the Q-loop $U_T^{ret}(t)$. Pulse integration limits: $t_1 = 6\ \mu$s and $t_2 \geq 9.3\ \mu$s.

surement of a single charge pulse from the FC amounts to $u(S_{FC})/S_{FC} = 0.033$ %.

Current Transformer

The blue curve in Fig. 6 shows the transformer voltage $U_T(t)$ from the preamplifier connected to the ICT for a typical LINAC beam pulse (27 MeV, −60 nC) as a function of time with respect to the LINAC trigger, as recorded by the WD. The offset is already subtracted in $U_T(t)$. The voltage-time integral of the ICT output pulse is proportional to the charge of the beam pulse. The transformer signal in terms of a charge is given by

$$S_T = \frac{n_T}{n_G R_T} \int_{t_1}^{t_2} U_T(t)\mathrm{d}t \qquad (1)$$

where $n_T = 50$ is the number of turns of the transformer winding, $R_T = 25\ \Omega$ is the nominal load impedance of the transformer[2], and $n_G = 10$ is the nominal gain of the preamplifier (20 dB). The integration limits $t_1 = 6\ \mu$s and $t_2 \geq 9.3\ \mu$s contain the pulse edges. S_T depends on t_2 due to the signal droop of the transformer, i.e. a transformer voltage $U_T(t) > 0$ after the negative peak of the pulse. The peak ends at $t \approx 9.1\ \mu$s, therefore $t_2 = 9.3\ \mu$s is a reasonable choice.

If the grounding of the ICT is connected to the grounding of the beamline, then synchronous noise from the running LINAC picked up on the transmission cable results in a significant zero signal and thus an offset b_1 in S_T with large fluctuations (about 1 % of the charge to be measured). In order to realize a floating connection with respect to the beamline grounding, the ICT is mounted in a galvanically isolated manner between two vacuum ceramic breaks ("C" in Fig. 2). For the isolated ICT (at $t_2 = 9.3\ \mu$s), the offset due to the synchronous noise is $b_1 < 0.005$ nC (< 0.01 % of the charge to be measured) and is thus negligible.

The uncertainty contribution due to random noise from the WD and the preamplifier increases linearly with t_2. For $t_2 = 9.3\ \mu$s, it amounts to about 0.03 nC. Thus, the statistical contribution to the relative uncertainty of the measurement of the charge of a single beam pulse of about −60 nC is $u_{stat}(S_T)/S_T = 0.05$ %.

FARADAY CUP COLLECTION EFFICIENCY

The collection efficiency of the FC is determined by a cancellation measurement as proposed by Pruitt [2]. It is based on a comparison of the beam current, measured by means of the ICT, with the FC current, measured by the same ICT. For this purpose, the FC current is returned through the ICT via the Q-loop. The effects of the electron beam current and the counteracting FC current on the ICT are canceled out if both are equal. Otherwise, the FC collection efficiency can be determined from the residual transformer voltage. The red curve in Fig. 6 shows the residual transformer voltage U_T^{ret} at the return of the FC current through the ICT. Since the FC current transits the ICT with a certain delay with respect to the electron beam pulse, negative or positive spikes appear where the beam pulse shape

[2] 50 Ω embedded in the ICT and 50 Ω termination at the input of the preamplifier are connected in parallel.

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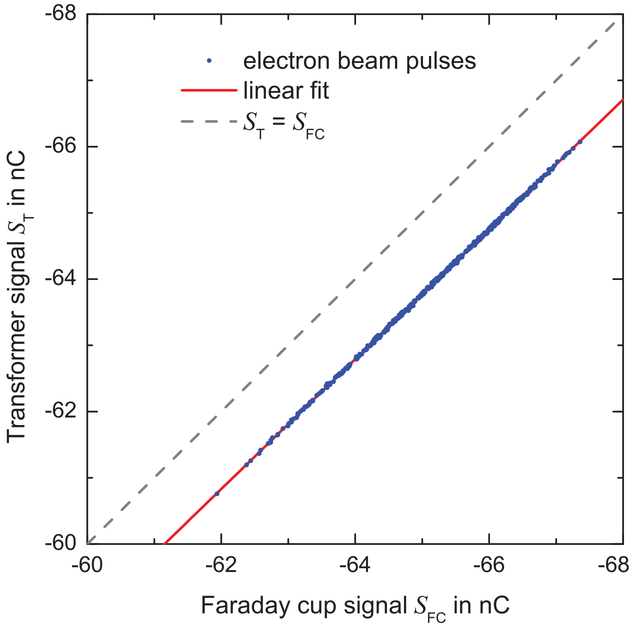

Figure 7: Transformer signal S_T of 500 sequent single beam pulses as a function of the simultaneously collected corresponding charge S_{FC} from the FC.

features falling or rising edges, respectively. From the residual transformer signal S_T^{ret} (replacing U_T by U_T^{ret} in Eq. (1)), the loss L of the FC is determined as $L = \langle S_T^{ret} \rangle / \langle S_T \rangle$. S_T^{ret} and S_T are alternately measured by means of a coaxial relay, which switches randomly between feeding the FC current in the electrometer or in the Q-loop (see Fig. 5).

A signal droop after the pulse is not resolved in $U_T^{ret}(t)$. Thus, S_T^{ret} is independent of t_2 (for $t_2 > 15$ μs).[3] S_T depends on t_2 but since S_T^{ret} is small, the collection efficiency $\eta = 1 - L$ changes only marginally with t_2. Effects due to the signal droop on η are thus negligible (<0.01 %).

Since the Q-loop wire is placed at the inner edge of the ICT aperture (see Fig. 2), effects due to a spatial inhomogeneity, i.e. due to the different positions of the beam and the Q-loop, are investigated. The Q-loop is gradually shifted to the center of the ICT aperture and along the inner edge, while a charge pulse from a pulse generator is sent through the ICT aperture via the Q-loop. Effects due to a spatial inhomogeneity are negligible (<0.01 %).

The collection efficiency of the FC for 27 MeV electrons determined by the cancellation measurement is $\eta = 0.9921$. The relative uncertainty is $u(\eta)/\eta = 0.052$ %. The pulse charge is $Q_P = S_{FC}/\eta$.

CALIBRATION

The transformer signal S_T may deviate from the beam pulse charge, among other things, due to the voltage loss at the 40 m coaxial cable between the ICT and the WD, due to the signal droop of the ICT, or due to the gain error of the preamplifier or the WD. Therefore, S_T is calibrated against the corresponding absolute measured charge from the FC. The transformer signal S_T and the FC signal S_{FC} of each beam pulse are acquired and evaluated simultaneously. In order to ensure a clear assignment of $S_T(i)$ to $S_{FC}(i)$, the current pulse number i is verified in real-time by means of a stand-alone counter (see Fig. 5).

The blue dots in Fig. 7 represent the transformer signals S_T of about 500 sequent single LINAC beam pulses as a function of the simultaneously collected FC charges S_{FC}. The red line results from a linear fit $S_T = m_1 \cdot S_{FC} + b_1$. From the standard deviation of the residua from the linear fit, the statistical contribution to the relative uncertainty is determined to be $u_{stat}(S_T)/S_T = 0.05$ %.[4] The calibration factor $N_T = 1/m_1$ is obtained from the slope m_1. The dashed line in Fig. 7 indicates the equality $S_T = S_{FC}$ and visualizes the deviation to be corrected. The deviation is mainly caused by the voltage loss at the 40 m coaxial cable.

In order to determine the pulse charge Q_P, the transformer signal calibrated to the FC signal has to be corrected by the FC collection efficiency η. The charge of a single beam pulse measured nondestructively by means of the beam intensity monitoring system is given by

$$Q_P = N_T \cdot (S_T - b_1)/\eta. \tag{2}$$

The relative uncertainty of the nondestructive measurement of a single LINAC beam pulse of about −60 nC amounts to $u(Q_P)/Q_P = 0.082$ %.

CONCLUSION

The charge of each single electron beam pulse from PTB's research LINAC can be measured nondestructively (non-intercepting) with a relative measurement uncertainty < 0.1 % by means of a beam intensity monitoring system based on an ICT. The system is traceably calibrated to PTB's primary standards. The calibration factor N_T is valid for the actual setup (in particular including the 40 m coaxial cable) and the chosen integration interval (t_2 in eq. (1)). The offset due to synchronous noise b_1 is small if the ICT is isolated from the beamline grounding and it can be neglected in most cases.

A full description of the beam intensity monitoring system and its characterization is the subject of a longer article submitted for publication [3].

REFERENCES

[1] Bergoz Instrumentation, `http://www.bergoz.com`

[2] J. Pruitt, "Electron beam current monitoring system", *Nucl. Instr. Meth.*, vol. 92, pp. 285–297, 1971.

[3] A. Schüller *et al.*, "High-accuracy nondestructive charge measurement of the pulses of a 27 MeV electron beam from a linear accelerator", submitted for publication.

[3] $U_T^{ret} = 0$ not until $t > 15$ μs since a small part of the signal is delayed due to pulse-shape deformations caused by cable reflections.

[4] The noise at the readout of the FC is about four times less than the noise at the readout of the ICT and thus contributes only marginally to the combined statistical uncertainty.

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