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THE UTRECHT 850 kV CASCADE GENERATOR

II. THE BEAM INTEGRATOR AND GALVANOMETER

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A current integrator is described for the integration of currents from 0.01 to 500 μA with an accuracy of 0.1%. The principle used is essentially the same as that of the excellent circuit described earlier by Helmer and Hemmendinger. The modifications effected result in a considerable reduction in expense, as well as a lower input impedance. Due to increased high frequency gain much smaller condensers are necessary in order to maintain the input voltage within some hundredths of a volt of ground, at all times. The integrated current is measured as the number of output pulses, each pulse representing a fixed amount of charge. Except for the condensers, no special components are used. A low-impedance electronic galvanometer for operation in series with this integrator is also described. This circuit combines the advantages of imperceptible zero drift, fixed calibration, and essentially absolute protection against burn-out.

1. The Current Integrator

In section 1 follows a description of the new current integrator as well as a short discussion (section 1.1) of the motives underlying its development.

1.1. INTRODUCTION

In recent years great progress has been made in constructing current integrators, combining the qualities of accuracy (accurately quantized charge removal), low input impedance and high switching rate[1,2]. To date, the instrument which best satisfies these requirements is that of Helmer and Hemmendinger. These authors utilize a vibrating reed electrometer to detect input error. The removal of charge is accomplished in their circuit by a reversing condenser connected between the input and a precision voltage, the reversing rate being controlled by a variable frequency multivibrator. In addition the feedback connection of the vibrating reed electrometer is connected to the input through a condenser, thus lowering the input impedance. In the description of the circuit the suggestion is made that it should be possible to build a similar integrator without the use of such an expensive device as the vibrating reed electrometer. The present integrator is the direct result of this suggestion. It is felt that it is worthwhile to report upon the results obtained since an extremely accurate, wide-range instrument has been built at very low cost. Furthermore an improvement has been effected over the original circuit by feeding back with a low enough impedance and a high enough high-frequency gain, so that the input is maintained virtually at ground even during the switching pulses. Since the feedback condenser is effectively increased by the gain of the amplifier it is possible to use switching condensers one-fourth or one-fifth of the feedback condenser (in comparison with 1/600 in the circuit of Helmer and Hemmendinger). This has permitted an increase of the current range to fifteen times that of the original circuit, although using smaller condensers.

1.2. PRINCIPLE

The principle of operation may be seen from fig. 1. The beam current enters at the input of a two-stage direct-coupled balanced amplifier with

[1]) R. J. Helmer and A. Hemmendinger, Rev. Sci. Instr. 28 (1957) 649.

[2]) I. A. D. Lewis and B. Collinge, Rev. Sci. Instr. 24 (1953) 1113.

negative feedback condenser C_2. This feedback holds the input close to ground potential while the output voltage is $e_2 \approx -1/C_2 \int i\,dt$. When this voltage reaches the trigger level a pulse goes to the scale of two and the relay is closed or opened, which results in a reversal of the condenser C_1. By this action a charge $2BC_1$, where B is a precision reference voltage, is removed from the input. Thus the output raises by about $2BC_1/C_2$, and the trigger flips back to its original position. Meanwhile, the beam current goes on charging C_2 and the process described is repeated when the trigger level is reached again. The trigger pulses are also fed to a scaler. If the number of pulses is n, the integral of the current is $2nBC_1$.

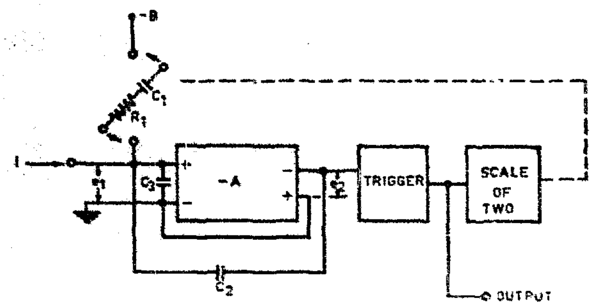

Fig. 1. Block diagram of the integrator.

The resistor R_1 in series with C_1 limits the current flow during the switching to a value low enough that the amplifier may cope with it. The condenser C_3 is necessary only in order to handle the surge of current before the amplifier has had time to act. Its value is not critical, and the charge flowing into it is very small compared to that flowing into C_2. The precision with which the output is given by the integral of the input, depends upon the gain, output impedance and frequency response of the amplifier. Under favorable conditions rather high precision is obtainable and a useful integrator can be made by determining the limits over which the output varies by a trigger tube[3]). The precision is normally limited by drifts of the trigger tube. Furthermore, to extend the range to more than one cycle (which is usually essential for general use) further errors are inevitably introduced by the time needed for the recycling procedure.

The present circuit uses the relationship between input and output only incidentally as a means of determining the rate at which charge should be removed from the input. Since at the moment of each trigger pulse the value of e_2 and so the charge on C_2 is the same, the charge which has flowed into the integrator must be equal to the charge removed per count and so the precision ultimately depends on the constancy of this charge "quantum". This is given by:

$$Q = 2BC_1\left(1 + \frac{V}{B}\right), \tag{1}$$

if V is the input voltage at the moment C_1 is reversed. The delay time τ of the relay and the output impedance R_0 cause this voltage to depend somwehat on current:

$$V = V_0 + \frac{i\tau}{AC_2} + \frac{iR_0}{A}, \tag{2}$$

if V_0 is the voltage that would obtain at the input when the output reaches the trigger level, under conditions of [illegible]. Differentiation of (1) assuming [illegible] gives for the relative error in Q

$$\frac{\Delta Q}{Q} = \frac{\Delta B}{B} + \frac{\Delta V_0}{B} + \text{[illegible]}$$

The first term on the right hand represents instability of the constant voltage source, the second term drift at the amplifier input and the last term is the current dependent error. The last two terms can be made negligible compared to $\Delta B/B$ by choosing suitable values of B, C_2 and R_0, so that the precision [illegible] wholly on the stability of B. An interesting [illegible] is, that for a given current the error is [illegible] dent of the switching [illegible] the highest [illegible] operate safely. [illegible] $A = 120$, $R_0 \approx 2$ kΩ, τ [illegible] and [illegible] for opening and closing the [illegible] the factors [illegible] and [illegible] than 3×10^{-4} for all currents to be [illegible]

[3]) W. A. Higinbotham and S. Rankowitz, Rev. Sci. Instr. 22 (1951) 688.

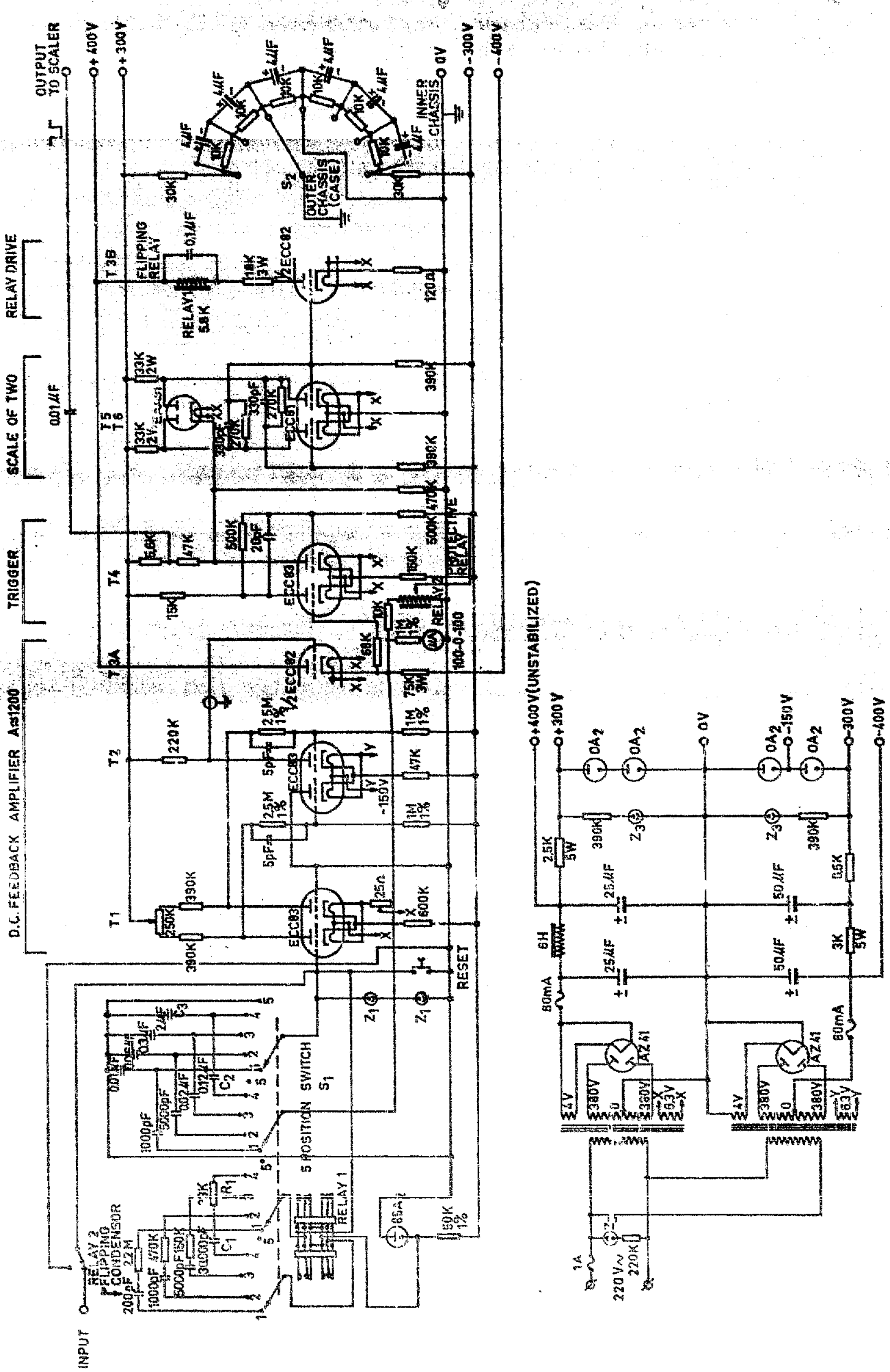

Fig. 2. Circuit diagram of the integrator.

The drift of the amplifier input is smaller than 0.01 V in several hours, resulting in a value of $\Delta V_0/B$ of the order of 10^{-4}. The ultimate stability thus depends on the 85 A2 voltage reference tube, which, according to the manufacturer, should give 0.1% stability under suitable conditions.

The peak to peak value of the input voltage is in our apparatus about 0.04 V. The mean input level however does not exceed a value of 0.02 V from ground for all currents to be measured. This value determines the leakage which may be permitted between target and ground. If, for instance, one wants to measure a current of 10 μA with 0.1% precision the leakage resistance must be higher than 2 MΩ, which is low enough to make use of watercooled targets.

1.3. CONSTRUCTION

A complete circuit, including plate voltage supplies, is given in fig. 2. Tubes T_1 and T_2 form the dc-amplifier. The heater voltage on the first tube is 4 V. By varying the cathode resistor a working point has been found where the grid current is $\approx 1.5 \times 10^{-11}$ A in the whole range used. This limits the practical use of the apparatus to currents higher than 10^{-9} A, which is low enough for practically all applications in nuclear physics. Tube T_3A is a cathode follower used to reduce the output impedance. This stage may be omitted when only the first three ranges of the apparatus are used. This fact is mentioned since currents above 85 μA (maximum permissible on scale 3) are not needed frequently and the elimination of the cathode follower results in a circuit which is absolutely stable. The phase-advance condensers in the grids of T_2 have been found, however, to produce complete stability when the cathode follower is included in the feedback loop. Admittedly a solution to the stability problem possessing a higher degree of safety could be found (the values of these condensers are quite critical), but further work was not deemed worthwhile since no trouble has been experienced with incident or recurring oscillations. Through the four pole five position switch, S_1, one can choose four different sets of R_1, C_1, C_2 and C_3 while in the fifth position the input is short circuited. The time constant R_1C_1 is kept smaller than one eighth of the smallest time between two switchings, so that C_1 is always discharged to less than 0.03% of its original charge.

Tube T_4 is wired as a Schmitt trigger. The trigger level is about — 15 V and the hysteresis is 10 V. Tubes T_5 and T_6 form the scale of two, while T_3B is the relay driving tube. The reference voltage, B, is delivered by an 85 A 2 tube T_7 fed through precision resistors. The circuit is never turned off so as to guarantee the highest possible constancy of ambient conditions, and thus voltage, for this tube. The apparatus is protected in two ways: if the absolute value of the output of the amplifier becomes higher than 60 volts the relay 2 falls in and disconnects the input. If this relay does not work, for instance because the voltage supplies are out of order, two neon tubes connected between the input and ground protect the condensers against overvoltage.

All condensers connected to the input are Leclanché polystyrene condensers except the 2 μF condenser. Since the voltage [illegible] so small (maximum 0.04 V) [illegible] not be important. Switch S1 is [illegible] switch with silicone deck. The relays are [illegible] Trls 151/71e. The two halves [illegible] connected in parallel. Its insulation proved to be good enough, the leakage current being less than 10^{-11} A. The noise of this relay was reduced to an agreeable level by mounting it in [illegible] rubber house.

The integrator is mounted on a chassis which is insulated with perspex. The chassis [illegible] with respect to ground may be varied [illegible] to — 150 V by means of the seven [illegible] switch S2. This may be used as a check [illegible] working of the suppressor [illegible] ary electrons [illegible] ure the resistance between target [illegible] The meter connected to the output [illegible] amplifier is used to control the [illegible] ance and may also be used to measure [illegible] current.

1.4. DISCUSSION

The performance of this integrator has been such as to warrant the construction of a duplicate for the Utrecht 3 MeV electrostatic accelerator. Both have been in daily use for many months and have shown themselves to be extremely flexible and reliable. Calibration checks have disclosed that the linearity is better than 0.1%.

2. The Galvanometer

In the following an electronic galvanometer suitable for use in combination with the integrator is described.

2.1. INTRODUCTION

The integrator just described makes it possible to perform high precision charge measurements even if the insulation of the target is not especially good. In order to take advantage of this property a low-impedance galvanometer must also be used since the galvanometer is usually in series with the integrator. Conventional moving-coil galvanometers of adequate sensitivity are generally of very low resistance, but possess several practical disadvantages. They are seldom robust, usually cumbersome, and of course, quite expensive, while subject to easy burnout. In addition the limited frequency response of such instruments sometimes deprives the accelerator operator of essential information on fast beam fluctuations.

For these reasons an electronic galvanometer has been constructed, combining in a simple circuit the following advantages:

(a) An input impedance given by 20 kΩ divided by the number of microamperes for full-scale deflection;

(b) A non-adjustable deflection sensitivity which is at least as precise and constant as a high-quality commercial galvanometer;

(c) No zero-set adjustment; the zero does not drift nor change perceptibly for scale changes from 0.1 μA to 1 mA full-scale deflection; and

(d) Essentially complete safety from burnout even if quite high positive or negative voltages are accidentally connected to the input.

2.2. DESCRIPTION

The circuit makes use of unity voltage feedback around a two-stage balanced amplifier. The operation may be understood by reference to fig. 3. The amplifier is adequately represented by a real voltage gain, A, an infinite input impedance, and an output impedance, R_0. The input impedance is given by R_f/A (within an error of $1:A$, i.e., 1:1000 in our circuit). The meter current is iR_f/R_m†, where i is the input current. Thus the deflection sensitivity depends only upon precision resistors and a robust meter whose calibration can be expected to be extremely constant since it can never be subjected to serious overload (see below for further discussion of this point).

The lack of zero-drift is perhaps the most important innovation involved in this circuit. Because of the unity feedback the drift at the

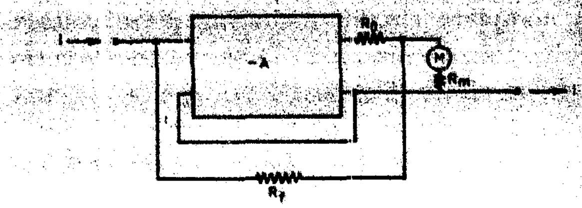

Fig. 3. Block diagram of the electronic galvanometer.

output is just equal to the drift at the input. Since the input is a balanced stage operating under essentially ideal conditions, we can expect this drift never to exceed 50 mV. Full-scale deflection of the meter corresponds to an output voltage of 20 volts, hence the zero drift should never exceed 1/400 of full scale, an undetectable deflection. It should be noted that in designing such a circuit there is considerable latitude in the parameters, but that vanishingly small zero-shift must be purchased for the price of increasing the input impedance. This could be circumvented by increasing the circuit gain, however in order to hold the circuit to two

† The correct expression is actually

$$i\frac{R_f}{R_m}\,\frac{\left(1+\dfrac{R_0}{AR_f}\right)}{\left(1-\dfrac{1}{A}-\dfrac{R_0}{AR_m}\right)}.$$

The correction terms can at most amount to 0.2%, or less than a detectable deflection.

double triodes this expedient was not resorted to in this case.

The circuit is outstanding as to capacity to withstand overload. This can be of importance in accelerator use where short circuits (or gas discharges) between target and secondary-

2.3. CIRCUIT DIAGRAM

The complete circuit diagram is shown in fig. 4. The power is provided by a transformer insulated with perspex, so that the insulation to ground is quite as good as that required for the input of the integrator. The entire circuit, in-

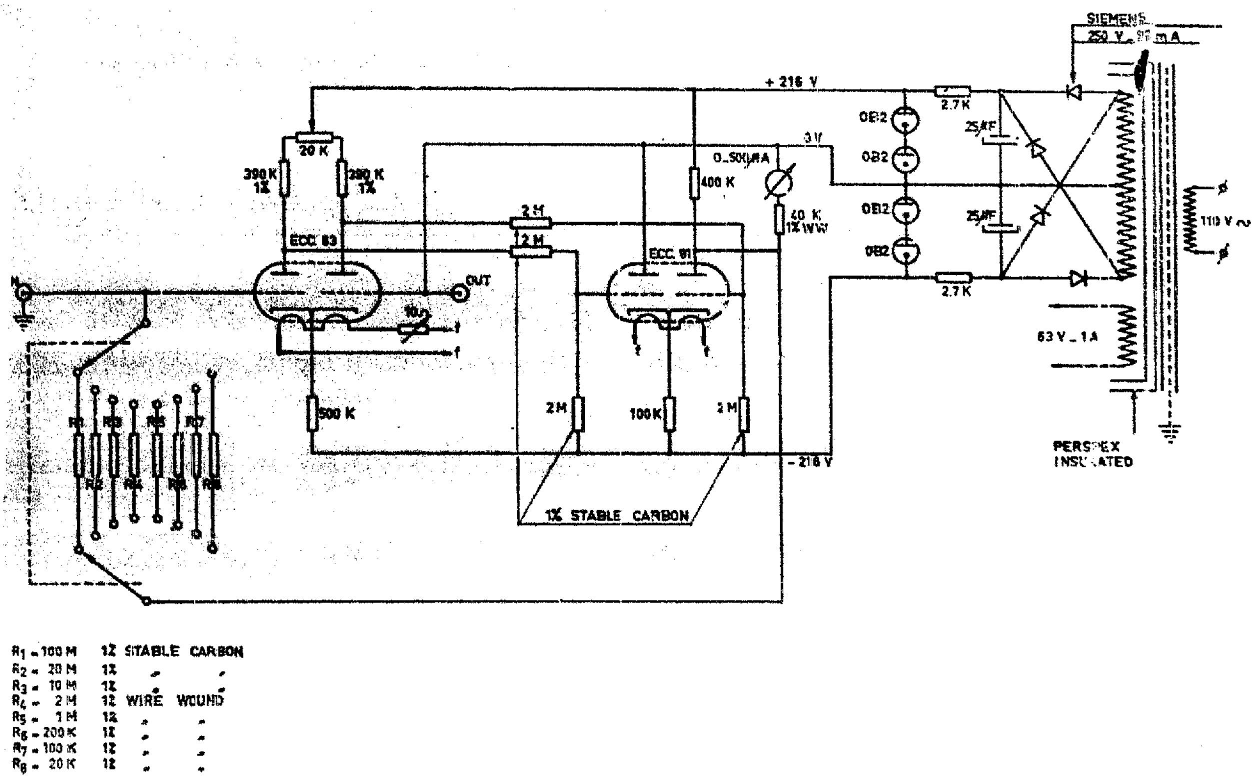

Fig. 4. Circuit diagram of the electronic galvanometer.

electron suppressor are a possibility. Under overload conditions (that is, with the voltage measured at the input more than a few tenths of a volt) the amplifier itself can deliver no more than 1 mA to the meter, this amounting to only a factor of two overload. Increasing the applied input voltage up to 40 volts on the 1 mA scale and up to more than 200 volts on all other scales decreases the overload since the input current flows through the meter in the opposite direction to that of the amplifier output current. The input tube itself, since the cathode resistor is very high, can easily follow positive input voltages of as much as 200 volts without destructive grid current, and in most cases can tolerate a negative grid voltage of 200 volts for a short time without breaking down.

cluding power supply, is built onto the back of the meter itself, thus making for an extremely compact unit.

2.4. CONCLUSION

As in the case of the integrator, identical circuits have been built for both the Van de Graaff accelerator and the cascade generator. The operation of both has been completely trouble free for several months.

Acknowledgements

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