

## INSTRUCTIONS FOR AC MEASUREMENTS OF GATED QHE DEVICES

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## INTRODUCTION

The BIPM has developed a method using back-gates to optimize the ac behaviour of quantum Hall effect (QHE) devices. Using this method one can obtain a quantized Hall resistance featuring a low frequency coefficient, of the order of 1 to 2 parts in  $10^8$  per kHz, useful for capacitance and impedance metrology [1]. This report gives instructions for implementing the method. Although the method is general and can in principle be implemented with any QHE device, the report focuses on devices fabricated by the Laboratoires d'Électronique Philips (LEP) and placed on top of two gates. A couple of such devices have been mounted by the BIPM on printed circuit boards with gate electrodes. The boards feature 8 pins and fit the coaxial socket produced by the Swiss Federal Office of Metrology and Accreditation (METAS) in the framework of EUROMET project No. 540. This is intended to facilitate the possible use of these devices by other laboratories.

## DEVICE MOUNTING

Figure 1 shows the BIPM printed circuit board designed to accommodate an LEP 514 [2] heterostructure on top of two back-gates. The board has the same dimensions (overall diameter 16 mm) and pin lay-out as the original METAS board. Figure 2 represents an LEP device glued on top of the two gates and bonded to the relevant terminals. The eight pins include two pins connected to the gates ( $G^+$  and  $G^-$ ), two pins connected to the device current terminals ( $I^+$  and  $I^-$ ), two pins connected to the device central pair of voltage terminals ( $V^+$  and  $V^-$ ), and two “auxilliary” pins ( $A^+$  and  $A^-$ ) connected to two other device voltage terminals. The six pins connected to the device terminals are intended to be connected to the measuring bridge in such a way that they form what is called a triple series connection [3] where the Hall voltage is effectively sensed between the facing terminals  $V^+$  and  $V^-$ . The triple series connection works for a single direction of the magnetic flux density vector,  $\mathbf{B}$ . The direction to be used is that shown in Figures 1 and 2, where the  $\mathbf{B}$  vector points towards the reader. Once installed in the cryostat the sample faces the bottom of the cryostat, which means that the  $\mathbf{B}$  direction to be used corresponds to a vector pointing towards the cryostat bottom. With the LEP514 samples the nominal value of  $\mathbf{B}$  at the centre of the  $i = 2$  plateau is 10.5 T.

## COAXIAL AC BRIDGE

Figure 3 shows a coaxial ac bridge [4] with ratio 1/1 suitable for measurement of the impedance ratio between the quantized Hall resistance (QHR) and a conventional resistance of the same nominal value ( $12\,906\ \Omega$ ),  $R_0$ . To simplify the figure, the outer conductors of the coaxial cables are not shown. As usual, the current equalizers are represented by black rectangles parallel with the lines representing the coaxial cables.

The bridge is supplied by transformer  $T_1$ , a transformer with double screen (not shown in the figure) featuring taps with output voltages equal to  $+2U$ ,  $+U$ ,  $-U$  and  $-2U$ , where  $U$  is the nominal voltage applied to the quantum Hall device and to resistor  $R_0$ . Autotransformer  $T_2$  has a mid tap and is the metrological device which defines the 1/1 ratio. The mid tap of  $T_2$  is grounded in normal use. A Wagner branch (W) allows the load current  $i_0$  to be zeroed. The 1/1 ratio is calibrated by interchange of the positive and negative terminals of  $T_2$ . Fine balancing of the bridge is achieved by adjustment of autotransformer  $T_3$  which has a double output (phase and quadrature adjustments) and which supplies the injection transformer  $T_i$ . Two auxiliary autotransformers,  $T_5$  and  $T_4$ , are used to drive gates  $G^+$  and  $G^-$ .

The quantum Hall device is schematically represented by its equivalent circuit including sources and resistors [3]. The triple series connection is formed by connecting terminals  $\Gamma^+$ ,  $A^+$  and  $V^+$  to the  $+U$  terminals of  $T_2$ , and terminals  $\Gamma^-$ ,  $A^-$  and  $V^-$  to the low-potential terminals of  $R_0$ , as shown in Figure 3. The null indicator  $D$  is also connected to the “low” voltage terminal of  $R_0$ . A very useful feature of the triple series connection [3] is that it ensures an almost perfect realization of the defining conditions at ports  $V^+$  and  $V^-$  of the quantum Hall impedance, namely zero current at both ports, even in the presence of fairly large series resistances in the cables connecting the Hall device to the bridge.

The defining condition ( $i = 0$ ) at the “high” voltage terminal of  $R_0$  is obtained by adjustment of an auxiliary resistor  $R$ , of the same nominal value as  $R_0$ , and of a parallel capacitance. These two components are supplied by the  $-2U$  tap of transformer  $T_1$ . A detection transformer (not shown in Figure 3) is used to sense and null current  $i$ .

As usual in coaxial ac bridges, a small cable correction must be applied to the measurements. This applies to the cables at the  $V^+$  and  $\Gamma^-$  ports of the QHE device as well as to the cable at the “high” voltage terminal of  $R_0$ . The correction depends only on the cable characteristics (series inductance and parallel capacitance) and is proportional to the square of the frequency.

The relatively high series resistance of the coaxial cables in the cryostat limits the efficiency of passive current equalizers normally used in coaxial ac bridges. It is usually necessary to use active current equalizers in the critical coaxial cables in order to keep the uncertainty arising from imperfect current equalization below 1 part in  $10^8$ . The critical cables are those connected to terminals  $A^+$ ,  $\Gamma^+$ ,  $V^-$  and to the “high” voltage and current terminals of  $R_0$ . Figure 4 is a schematic representation of an active current equalizer used at the BIPM. The coaxial cable is wound around

two cores. A detection winding senses the magnetic flux in one of the cores and a feed-back current is applied to the regulation winding on the other core. This maintains the flux in the first core almost equal to zero and ensures almost perfect equality between the currents in the inner and outer conductors of the coaxial cable. A control winding allows the residual flux in the first core to be estimated and to any electrical oscillation in the electronic circuit to be detected.

In Figure 3 the coaxial cables linking transformers  $T_4$  and  $T_5$  to the gate terminals  $G^+$  and  $G^-$  are shown without current equalizer. This is appropriate only if the outer conductors of these coaxial cables are *not* connected to the shield interconnection point located on a small printed circuit board in the EUROMET socket. If the outer conductors *are* connected to this point, current equalizers must be used.

## ADJUSTMENT PROCEDURE

The basic idea is to adjust the gate potentials so that the QHR current (or voltage) coefficient is equal to zero. Under these conditions one generally obtains a very low QHR frequency coefficient [1].

Let us denote by  $U^- = xU$  the potential of the gate located under the device low-potential edge (gate  $G^-$ ), and by  $U^+ = yU$  that of the gate located under the device high-potential edge (gate  $G^+$ ). The values of  $x$  and  $y$  are adjusted using transformers  $T_4$  and  $T_5$ . If  $T_4$  and  $T_5$  are connected to the  $+U$  and  $+2U$  taps of supplying transformer  $T_1$ , as shown in Figure 3, then the values of  $x$  and  $y$  are positive. To obtain negative values,  $T_4$  and  $T_5$  should be connected to the  $-U$  and  $-2U$  taps.

Initially, arbitrary values of  $x$  and  $y$  are chosen, for instance  $x = 0$  and  $y = 1$ , and the shape of the  $R_H(2)$  resistance plateau is recorded as a function of the magnetic flux density  $B$ . This allows  $B$  to be set at a value corresponding to the “centre” of the plateau. The nominal value is 10.5 T for the LEP 514 devices.

The QHR current coefficient should then be measured. This demands particular care as the resistance ratio measurements must be made with a resolution of 1 part in  $10^8$  or better. It is essential to use a comparison resistor ( $R_0$ ) with negligible current coefficient and with the best possible short- and mid-term stability. An adequate stability requires the use of a hermetically sealed and temperature-controlled enclosure for  $R_0$ . The QHR current coefficient is proportional to frequency, and therefore it is useful to work at relatively high frequency. Also use of a fairly high measuring current helps to improve the resolution. The measurements can be carried out at 3 kHz, for instance, and the rms current through the LEP514 device increased from 20  $\mu$ A to 40  $\mu$ A in order to evaluate the current coefficient. The maximum current to be used must be determined initially by evaluating the current range for which the QHR is a linear function of the measuring current.

With  $x = 0$  and  $y = 1$  the QHR current coefficient is usually found to be positive, of order a few

parts in  $10^9$  per  $\mu\text{A}$  at 3 kHz. This is due to an excess of losses associated with positive charging of the device high-potential edge compared with losses associated with negative charging of the low-potential edge [1]. The strategy is then, for instance, to keep  $x = 0$  and to increase  $y$  (which decreases the positive charging of the high-potential edge) until a QHR current coefficient equal to zero to within the measurement resolution is obtained. In practice, at 3 kHz it is desirable to obtain a change of the QHR lower than 1 part in  $10^8$  when the current is increased from 20  $\mu\text{A}$  to 40  $\mu\text{A}$ . Each time  $y$  (or  $x$ ) is changed, the Wagner branch of the bridge must be readjusted.

Once the QHR current coefficient has been adjusted to zero, the ratio between the QHR and resistance  $R_0$  can be measured at various frequencies as well as at dc. If the frequency dependence of  $R_0$  is known, we can estimate the residual frequency dependence of the QHR at zero current coefficient. At the BIPM we have found that the residual frequency dependence of LEP 514 samples is linear with frequency in the range from dc to 3 kHz, and the residual frequency coefficient is usually within  $\pm 2$  parts in  $10^8$  per kHz. If the frequency coefficient of  $R_0$  is not known, its value can be estimated from the measurements if it is assumed that the QHR residual frequency coefficient is 0 part in  $10^8$  per kHz with a standard uncertainty of order 2 parts in  $10^8$  per kHz.

For each value of  $x$  there exists a single value of  $y$  which makes the QHR current coefficient equal to zero (and vice versa). It is interesting to repeat the above measurements with different values of  $x$ . It is usually found that the QHR residual frequency coefficient is almost independent of the value of  $x$  (or  $y$ ). Also it is possible to repeat the measurements after having interchanged the connections to the “positive” and “negative” terminals of the device: terminals  $\Gamma^+$  and  $\Gamma^-$  are interchanged, as well as terminals  $V^+$  and  $V^-$ ,  $A^+$  and  $A^-$ ,  $G^+$  and  $G^-$ . In the following section we denote this interchanged configuration by “ $\Gamma^-$ ” and the original configuration by “ $\Gamma^+$ ”.

## RESULTS OBTAINED WITH TWO LEP 514 DEVICES

We denote LEP B and LEP C the two LEP 514 devices which have been mounted on printed circuit boards compatible with the EUROMET socket. Figure 5 shows, as a function of  $B$ , the shape of the  $R_H(2)$  plateau (real part  $R$  and imaginary part  $X$ ) obtained for both devices for a particular setting of  $x$  and  $y$  which makes the QHR current coefficient equal to zero. The bath temperature is 1.3 K, the frequency 3 kHz and the current 20  $\mu\text{A}$ .

Figure 6 represents, in the  $x$ - $y$  plane the results obtained at 1.3 K with both devices operated at the centre of the  $R_H(2)$  plateau, and this for both configurations  $\Gamma^+$  and  $\Gamma^-$ . The plotted points correspond to  $(x, y)$  settings for which the measured QHR current coefficient is zero to within the resolution of the measurements. The number associated with each point is the measured value, expressed in parts in  $10^8$  per kHz, of the QHR residual frequency coefficient for the corresponding  $(x, y)$  setting. The total standard uncertainty associated with these measurements is estimated to be 0.7 parts in  $10^8$  per kHz. This includes the uncertainty associated with the frequency dependence of the comparison resistance  $R_0$  as well as that associated with the coaxial

ac bridge. It can be seen that for both devices the residual frequency coefficients are small. The average of the plotted values is  $+1.7$  parts in  $10^8$  per kHz for device LEPB and  $+1.3$  parts in  $10^8$  per kHz for device LEP C.

## CONCLUSION

The method presented here allows residual QHR frequency coefficients of the order of 1 to 2 parts in  $10^8$  per kHz to be obtained when LEP 514 devices are used. Two such devices have been mounted on headers compatible with the EUROMET socket.

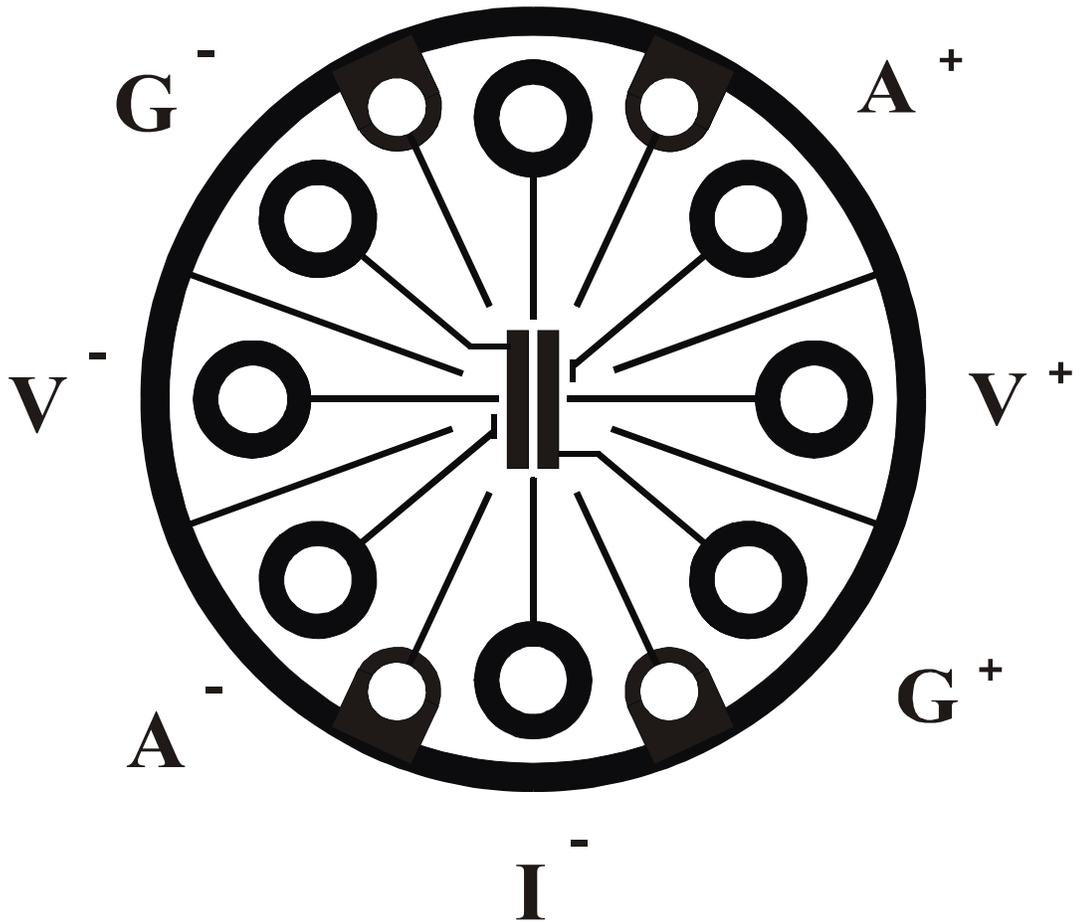
## REFERENCES

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- [2] Piquemal F., Genevès G., Delahaye F., André J. P., Patillon J. N., Frijlink P., Report on a joint BIPM-EUROMET project for the fabrication of QHE samples by the LEP, *IEEE Trans. Instrum. Meas.*, 1993, **42**, 264-268.
- [3] Delahaye F., Series and parallel connection of multiterminal quantum Hall-effect devices, *J. Appl. Phys*, 1993, **73**, 7914-7920.
- [4] Kibble B. P., Rayner G. H., *Coaxial ac Bridges*, Hilger, Bristol, 1984.

*B*



$I^+$



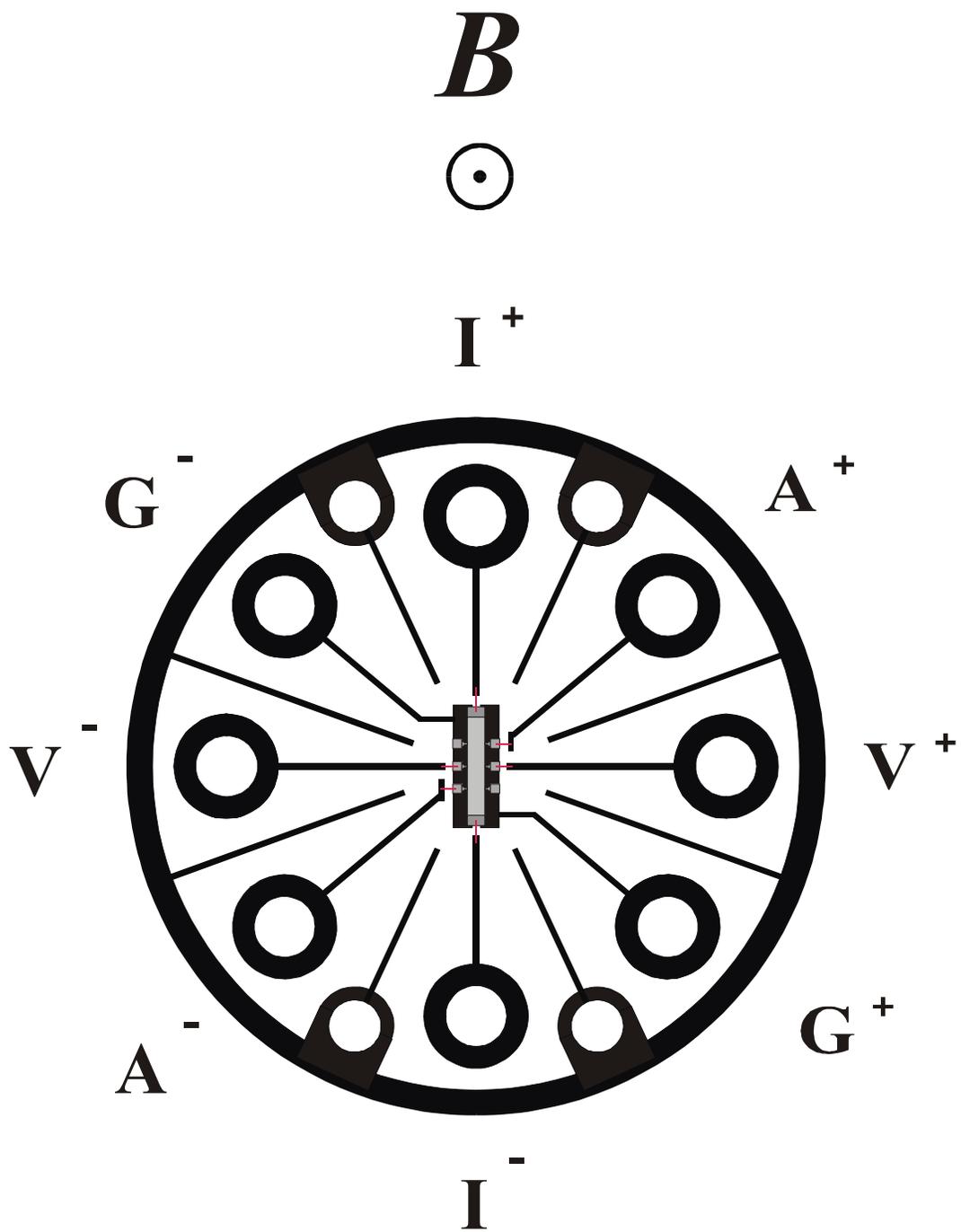


Figure 1: Printed circuit board with gates

Figure 2: LEP 514 device mounted on the printed circuit board.

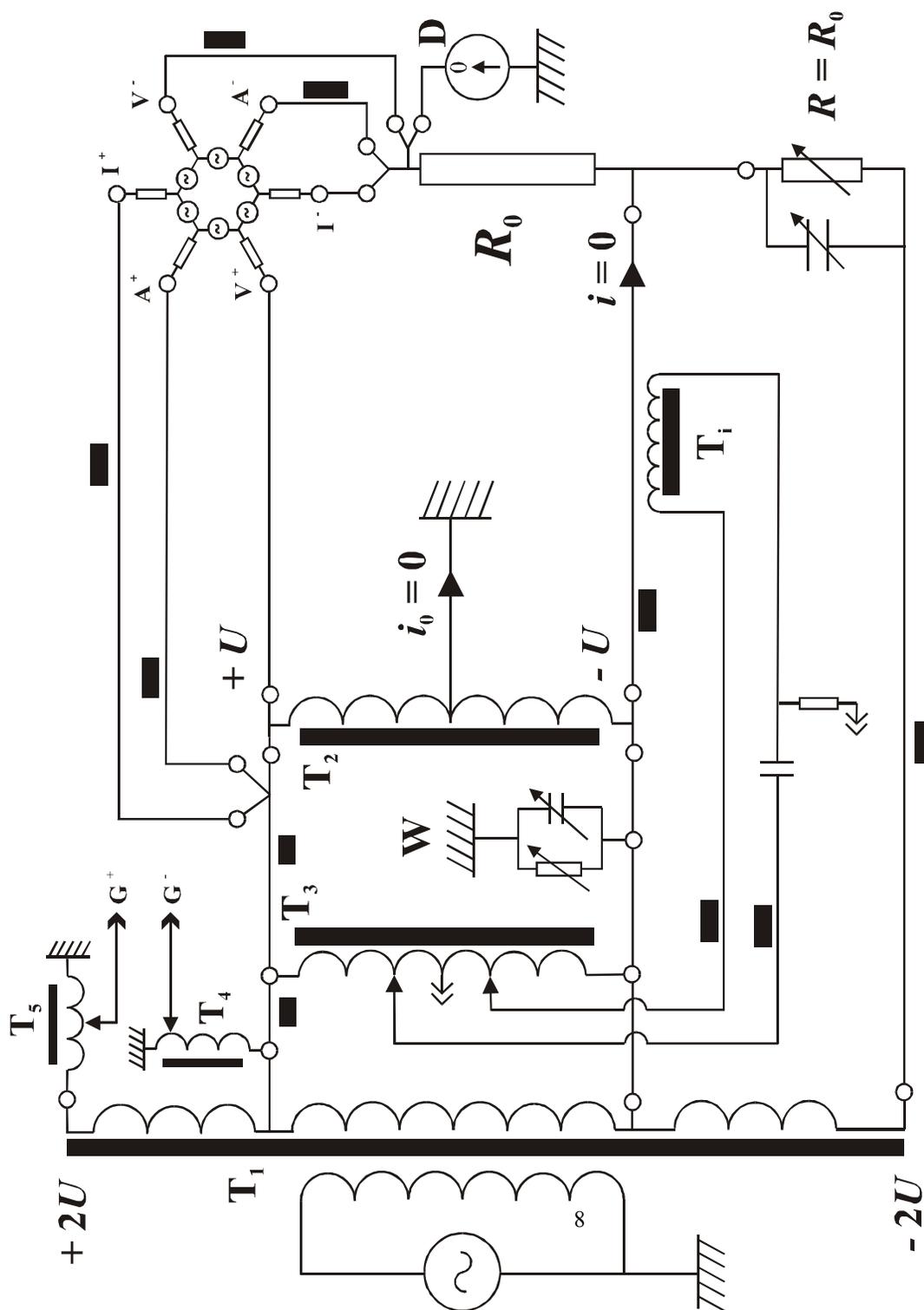


Figure 3: Coaxial ac bridge for QHR measurements

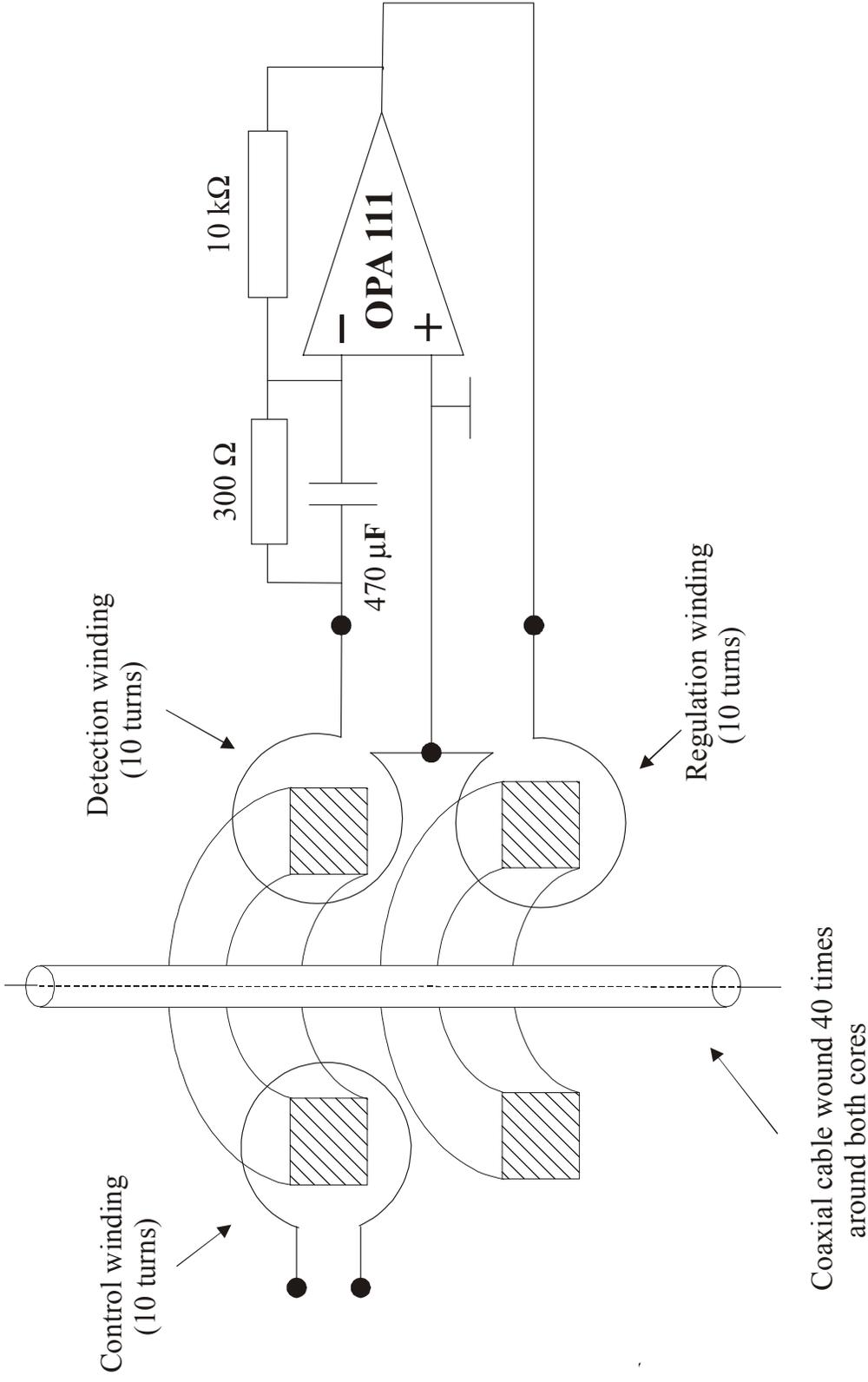


Figure 4: Active current equalizer



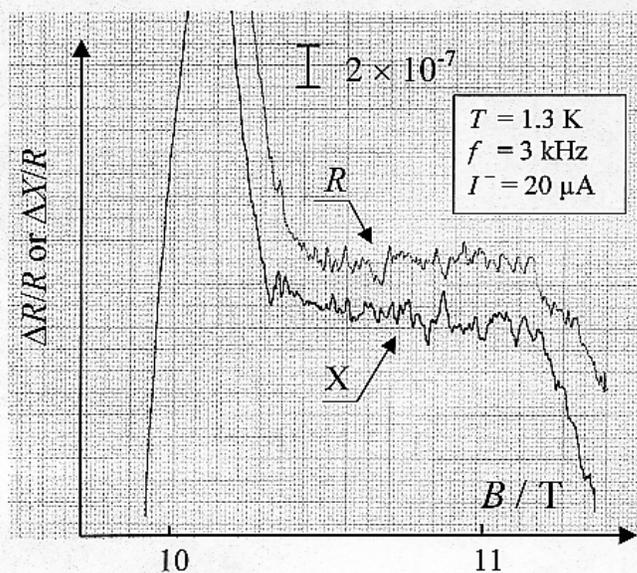


Figure 5a : Real and imaginary parts of the Hall impedance  $R + jX$  for the LEP B device, for gate settings corresponding to  $x = 0.17$  and  $y = 1.17$ .

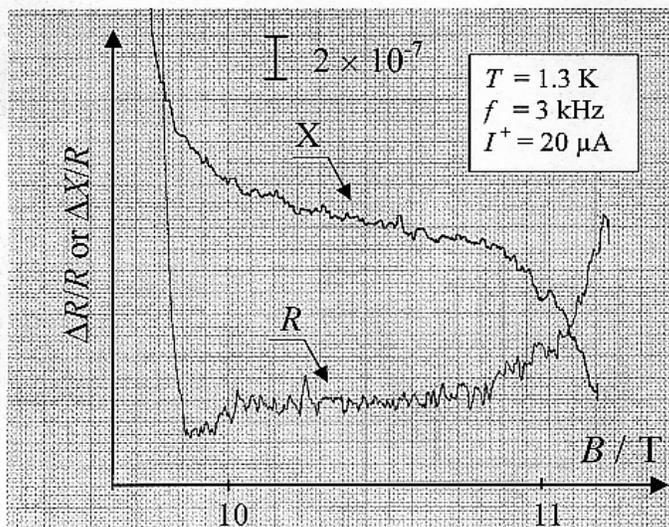


Figure 5b : Real and imaginary parts of the Hall impedance  $R + jX$  for the LEP C device, for gate settings corresponding to  $x = 0.1$  and  $y = 1.1$ .

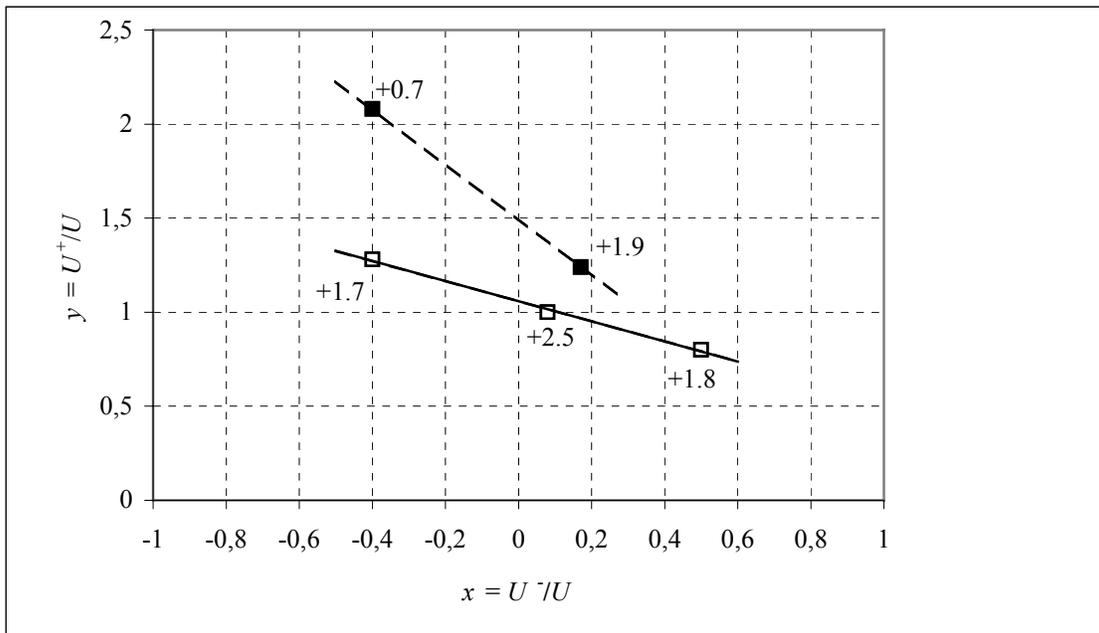


Figure 6a : Residual QHR frequency coefficients of the LEP B device, in parts in  $10^8$  per kHz, for different values of  $(x, y)$  corresponding to a QHR current coefficient equal to zero.

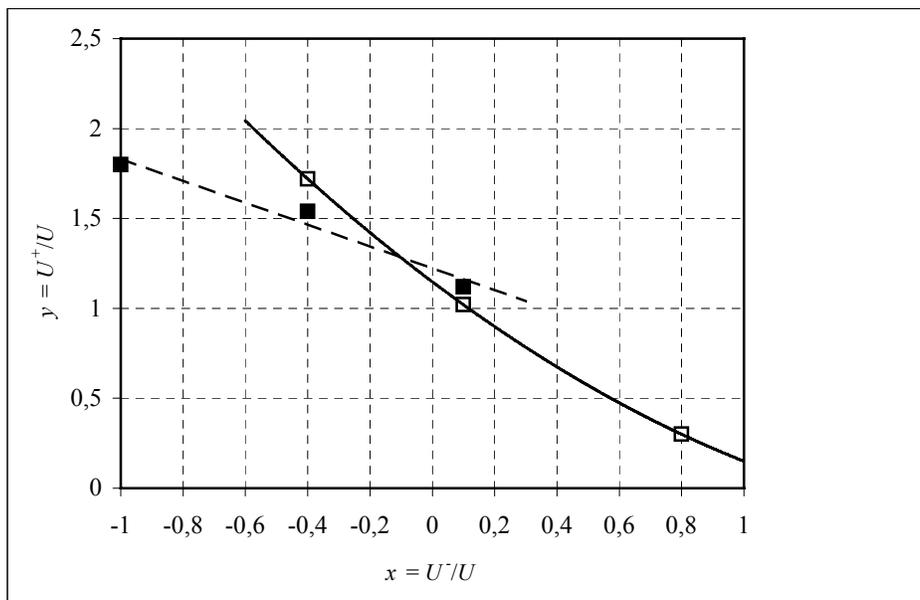


Figure 6b : Residual QHR frequency coefficients of the LEP C device, in parts in  $10^8$  per kHz, for different values of  $(x, y)$  corresponding to a QHR current coefficient equal to zero