Final Report on the activities of the CCEM Working Group on AC Measurements of QHR from 1997-06-25 to 2009-03-10

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The meetings are numbered consecutively for both meetings held at the BIPM (7) and the informal ones (4), held as satellite meetings during CPEM conferences.

There has been a report written by E. Braun concerning the activities of the CCEM Working Group on AC Measurements of QHR covering the period 1997-06-25 to 2002-09-09 1st to 5th meeting (CCEM2002-14) this is included and repeated below:

At its 21st meeting on 1997-06-25, the CCE (now CCEM) agreed on the creation of a working group on AC measurements of QHR (ACQHR) to foster the co-operation among researchers and with the objective, eventually, of developing a set of guidelines for accurate measurement of AC QHR. BIPM, BNM-LCIE (now BNM-LNE), CSIRO, IEN, NIST, NPL, NRC, OFMET, PTB, VNIIM and VTT became members of the working group. Dr. Braun (PTB) was chosen chairman.

1997-06-25 to 2002-09-09 (CCEM2002-14, E. Braun)

The Working Group had the following meetings:

1st meeting on 1997-06-25 at the BIPM:

In a short meeting immediately after its formation the following items were resolved:

- it was premature to recommend guidelines for accurate measurement of AC QHR,
- an interchangeable sample holder system was agreed allowing an exchange programme of QHR samples for AC measurements,
- an Internet website was created to improve communication between the members. (In the meantime the website is closed. The BIPM restricted website for the Working Group will replace it in the future.)

Between this first meeting and the next one in 2000 an intensive exchange of experience and co-operation started since most of the members of the Working Group co-operated additionally within EUROMET projects on AC QHR and within an EU-sponsored project on a "Modular System for the Calibration of Capacitance Standards Based on the Quantum Hall Effect".

2nd meeting on 2000-05-18 in Sydney:

This meeting was held during CPEM 2000. The meeting started with a report of the experimental results obtained so far from some of the participants. Three institutes are already using the quantum Hall effect for the maintenance of the farad. However, they use DC measurements of a quantized Hall resistance in connection with a special designed DC/AC transfer resistance, the frequency dependence of which has been calculated.

All groups which have obtained experimental results from measurements of quantized Hall resistances with alternating current in the frequency range below 10 kHz do not observe flat plateaus as they are observed in DC measurements. There are maxima at the edges and wiggles in between. All groups can reproduce the Hall resistance value in the middle of the plateau with a relative uncertainty below 10^{-6}. All groups observe a linear dependence on frequency, which is in the order of 10^{-7}/kHz. It is not clear whether this frequency dependence also depends on the step number. If the frequency dependent data are extrapolated to $f = 0$, one institute obtains the DC data, another one observes deviations in the 10^{-6}-range. Two groups have found that one could adjust electrical potentials in the neighbourhood of the sample (gates) which allow to suppress the frequency dependence and to flatten the plateaus in addition. One group uses a split gate on the back side of the sample, the other one has surrounded and enclosed the sample with additional Hall geometries. One institute observes a dependence on electric current, an other one observes independence. One institute observes the plateaus at different magnetic field values for AC and DC measurements, other institutes observe the plateaus at the same values.

The chairman informed that at the PTB a project has been installed in the department for fundamentals of physics in metrology where theoreticians are working on the frequency dependent quantum Hall effect. Up to now neither this group nor other groups have established models which give some guidance to the experiments.

In summary, it turned out that some of the results of different institutes were not in agreement and sometimes they were even in contradiction. Remembering the positive experience in the past when the knowledge of the DC-properties of QHE samples was advanced by exchanging samples between different institutes, it was proposed to exchange samples between different institutes for AC measurements as well.

3rd meeting on 2000-09-11 at BIPM:

PTB reported experiments obtained with a specially designed sample with an internal and external gate. Adjusting appropriate gate voltages resulted in a vanishing of the frequency dependence of the Hall resistance, which is usually observed in AC measurements. In addition the plateau of the Hall voltage became flat within a few parts in 10^8.

BIPM and NPL, in a co-operation, had obtained similar results and had developed a model describing the ac losses in a quantum Hall sample with dissipative charging of the device along its edges. By properly adjusting voltages to gates which had been placed under the sample edges the residual QHR frequency coefficients did not exceed ± 2 parts in 10^8 per kHz.

The results of these two groups are very promising with respect to the application of the quantum Hall effect to AC resistance measurements, however it has to be proofed whether these results can be reproduced at other institutes.

IEN reported AC measurements of the longitudinal resistance also using a gated sample and especially mentioned that a very low frequency dependence was observed on a sample with larger dimensions than the others. R. Haug (guest from University Hannover) explained the measurements which had been made at his institute with much higher frequencies than those used in the NMIs.

The previous meeting in Sydney had shown that some of the experimental observations by the various groups were contradictory - e.g. current dependence of the AC Hall resistance. It was not clear what is really a sample property and what is caused by the individual experimental set-up. Therefore a project on exchanging samples was started. About seven samples were exchanged between BIPM and PTB, between PTB and NPL, and between NRC and OFMET. AC measurements should be undertaken at these laboratories. It was decided to start with these experiments immediately and to discuss the results soon. The experimental results on the various samples were not available during 2001 due to other workload in the institutes. The working group therefore used the possibility during CPEM 2002 for a short informal meeting.

4th Meeting on 2002-06-15 in Ottawa:

From the reports at this meeting and from the discussions during the CPEM new experimental results were reported. Measurements on samples which had no gates at all showed no frequency dependence at these samples within their measurement uncertainty. Up to this date all samples had shown a frequency dependence. As before, it was found that this dependence could be removed by strategically placed and properly adjusted gates.

It seems at the moment still not absolutely clear, how the sample has to be prepared and how has the measurement instrumentation has to be set up. Therefore it is of great advantage, that NRC offered the possibility that for some weeks a co-operation of NRC, METAS and PTB can take place at NRC. It might be necessary to continue this co-operation at METAS and at PTB as well.

5th. meeting on 2000-09-09 at BIPM:

This meeting was attended by representatives of 11 institutes (a list with the names and email addresses is attached), which demonstrates the great interest in this subject. A status report was given by each institute. These reports did not change the general view, that a sample dependent frequency dependence of the Hall resistance exists and that this dependence can be suppressed by gates. An interesting proposal was made by IEN to make a three-layer hetero-structure with the two outer 2DEG layers becoming gates. PTB will inform the Working Group whether such a sample could be manufactured at their clean room facilities. An exchange of samples between BIPM and METAS has demonstrated reproducibility between measurements in both institutes. Since the begin of September two colleagues from METAS and PTB have started a collaboration at NRC with the colleagues of this institute.

Since the present chairman (E. Braun) of the Working Group has retired from PTB, he also resigned from the chairmanship of this Working Group. After a short discussion the members of the Working Group decided to recommend to the CCEM, to nominate Jürgen Melcher (PTB) as the new chairman.

During this meeting the question was roused whether – after eventually having successfully recommended guidelines for reliable AC QHR measurements – this would replace the

realization of the Farad via the Calculable Capacitor. The Working Group clearly wants to state, that this is not the case. Guidelines for AC QHR measurements will lead to worldwide uniformity of AC calibrations and independence of them from time and location. However – as in DC calibrations on the basis of the DC QHE – they will not lead to a SI value. Therefore the Calculable Capacitor is still required as a link from the reference values provided by the quantum effects to the SI. Not every institute will need to have a Calculable Capacitor, but several of the institutes must have one.

Conclusions:

1.) A strong co-operation among the partners of the Working Group on AC measurements of the QHR has been created.

2.) Doing experiments on the AC QHR one observes "plateaus" which are not flat over a large range of magnetic field, as observed with DC. one also observes a more or less pronounced dependence of the Hall resistance on frequency.

3.) Several institutes have shown that strategically placed and properly adjusted gates, allow to suppress the frequency dependence below the measurement uncertainty and additionally flatten the plateaus over a wide range of magnetic field.

4.) Several institutes have measured Hall resistance values with sufficient low uncertainty for a metrological application.

5.) However, up to now the experimental results were not reproducible from one to the other institutes. This is the most important problem to be solved. A collaboration covering this item is on the way.

6.) It is still premature to develop a set of guidelines for accurate AC measurements of the QHR.

7.) Nevertheless, the Working Group is convinced that the metrological application of the QHR for AC measurements with frequencies up to about 10 kHz will be possible.

2003-11-03 to 2009-03-10 (J. Melcher, F. Ahlers)

6th Meeting on 2003-11-03 at BIPM:

no minutes available

7th meeting on 2005-03-16 at BIPM:

21 people from 16 NMIs met on March 16, 2005 at the BIPM. The agenda was slightly modified to allow the participants to read the working document from PTB, NRC and METAS which was distributed before the meeting.

1. Shakil Awan from NPL gave a presentation on "High frequency calculable resistance standards". He explained how this work which is aiming at frequencies of up to 100 MHz can be related to the ACQHR measurements in the kHz range.

2. Review of accurate ACQHR measurements

Brian Ricketts from NMIA reported the present status of the ACQHR measurements in Australia. At present only relative measurement results are available revealing differences of order parts in 10^6.

NMIA now has an adapter which would allow to work with samples on EUROMET/METAS headers and therefore to exchange samples with other groups.

Jürgen Melcher from PTB reported about the present status of the trilateral co-operation between NRC, METAS and PTB. The discrepancies between the results in the different institutes have been lowered to a level of order parts in 10^8. However, some of the remaining discrepancies seem to be significant.

It is now possible to measure potential differences on both sides of the Hall bar which was possible in the past only for the low potential side. The results are up to now difficult to be interpreted. In general the basis of experimental data is quite small, sometimes results only for just one sample are available.

3. Discussion of the progress of research

The results and reports were discussed. It was pointed out that the apparent AC-DC difference at about 1 kHz of 3 parts in 10^8 has to be seen against the uncertainty of the calculable resistors of about 1 part in 10^8 and the fact that an uncertainty of this order is difficult to achieve for the classical way starting from the Thompson-Lampard capacitor or even for this capacitor alone.

4. Time frame for the preparation of guidelines for accurate measurements of the QHR with AC

Due to the mentioned remaining significant differences in the results, the not yet understood shape of the plateaux and the small experimental basis the group decided to shift this decision to the next meeting.

5. Proposals for activities of the WG ACQHR

Due to the fact that the ACQHR work is closely related to capacitance metrology the whole group expressed the wish to extend the working field and to modify the name to "working group on Measurements of the Quantized Hall Resistance with Alternating Current and related measurements". The appropriate decision is recommended to the CCEM.

6. Proposals for the next meeting

It is proposed to meet 2006 either directly before or directly after CPEM in Torino. The chairman will make the necessary arrangements. The group expressed that formal convocations are not necessary.

7. Miscellaneous

It was decided to ask BIPM to install a restricted website for discussion and exchange of information regarding the work of this group. The list of email addresses will be updated by the chairman if he receives an inquiry via email. All participants agreed to receive email messages in the case that the information on the website has changed.

8th meeting on 2006-07-11 Torino, Italy (Franz Ahlers)

An informal meeting of the WG-ACQHR was held as a satellite meeting of the CPEM2006 at 18:00 on July 11, 2006. In addition to the Working Group members other interested persons from several NMIs attended the meeting.

In order to stimulate the discussion about the possible preparation of guidelines for accurate ACQHR measurements the current status of the research work performed by the consortium of METAS, NRC and PTB was presented in the first part of the meeting.

This status can be summarized as follows:

- There do not exist any more significant discrepancies between results on ac-QHR measurements obtained in the participating institutes.
- Reliable ac-QHR measurements can be carried out with an uncertainty in the range of (1 to 3) x 10^{-8} for kHz frequencies if one compensates or corrects for capacitive effects and the associated ac losses (which cause frequency- and current-dependent deviations of the resistance measured at ac with respect to the dc QHR value).
- Empirical methods have been developed which allow such compensation or correction. The methods differ for gated and ungated devices, but they have in common that they either extrapolate to the condition or establish the condition that the longitudinal resistance $R_{xx} = 0$. A detailed microscopic understanding of why the empirical methods work has not yet been achieved.
- Not only the $R_{xx} = 0$ condition, but practically all other experimental requirements (e.g. contact resistance, operating temperature) were found to be the same in the ac measurements as compared to the dc measurements.
- An improved understanding of the issues related to the coaxial ac-bridges, as well as to the behaviour of the calculable resistors has been reached.
- A still existing limitation is the relatively small number of investigated samples. A larger experimental survey could increase the confidence in the results.

The impressive results and the considerable progress achieved in the consortium during the last years were explicitly acknowledged by the Working Group.

The Group discussed whether in light of these results the writing of 'Guidelines for accurate ACQHR measurements' should be the next step to undertake. In spite of the progress listed

above some objections were raised. The major ones were that a better understanding of the microscopic details of the applied empirical methods is desired, and that the experimental evidence is still limited to a relatively small number of samples. In this sense the phrase 'Guidelines' was considered as possibly too restrictive in that it could leave an impression of the AC-QHR as an already settled and readily applicable effect with no further research needs. Another objection was that the community of interested readers might be too small to justify the considerable effort of writing such a document.

Nevertheless it was considered desirable in general to make the extensive know-how and experience collected within the trilateral cooperation available in a compact and concise form. Although all results have been published in several papers a summarizing review of the work could help groups at other NMIs to get started quickly if they wanted to apply the ac-QHR as an impedance standard. This applies especially to the peculiarities of setting up the coaxial ac-bridges for low uncertainty impedance comparisons with the QHR. The Working Group issued the recommendation to the consortium to prepare such a document. Details were left to the consortium, and the timeframe for a draft document was set to be the next meeting of the WG-ACQHR.

It was announced that the next meeting of the Working Group will be held before the CCEM meeting which is scheduled for 15 and 16 March, 2007.

The informal meeting of the WG-ACQHR ended at 19:40.

Franz Ahlers

Participants: 26, from WG ACQHR institutes: 11

9^{th} meeting on 2007-03-13 at BIPM:

no minutes available

10^{th} meeting on 2008-06-12, Broomfield, Colorado

Jürgen Melcher suggests an agenda with the main topics

1. Compendium on the ac-QHR
2. Questionnaire about ac-QHR
3. ac-QHR related website
4. Terms of Reference for the WG-ACQHR
5. Miscellaneous

Jürgen Melcher also announces that the next meeting will most likely take place during the time from 9. - 13. March 2009 in Paris.

Contributions from the participants make it evident that topics 1 to 4 cannot be discussed independently. Beat Jeckelmann questions the scope of the WG and remarks that this should be redefined before any discussions of the ToR or other topics commence. This opinion is supported by several participants.

Dave Inglis redirects the discussion to topic 1, which can and should be discussed before the future of the WG as such is discussed. In response Franz Ahlers reports that he will try to have a presentable version of the compendium ready before October 2008. As suggested by B.W. and B.Jeann., the text would follow the line of arguments put forward in Franz Ahlers's talk on the ac-QHR given in CPEM's special session on the QHE previously that day.

Jürgen Melcher then asks participants, in anticipation of a central query of the planned questionnaire, whether NMIs plan to (re)start utilizing ac-QHR measurements. Nobuhisa Kaneko from NMIJ states they would definitely start this work. Gregory Kyriazis from INMETRO says that INMETRO seriously considers it.

An intense discussion is then started on the future of the WGACQHR and whether it scope should be extended or whether it should continue its work at all.

The result of this discussion is summarised as follows:

After completing and publishing the compendium it will be presented to CCEM in its upcoming meeting in March 2009. The bottom line of the compendium will be that the ac-QHR can successfully be used at an uncertainty level of $3\ 10^{-8}$. This is relevant for impedance calibrations, while clear potential for lower uncertainty exists. CCEM should then decide whether the work of the WGACQHR has come to a successful end. CCEM may in addition give the mandate to extend the compendium to a formal 'guidelines' document which would define the procedures and precautions for metrological application of ac-QHR more sharply.

It is expected that in any case the lifetime of the WGACQHR will cease after its successful work.

Independent of this a website will be set up and administered by Jürgen Melcher during a test phase, which makes the know-how collected during the many years of cooperative work commonly available and allows a controlled group of participants to add to and to share this knowledge. The use of this website by the community will decide on whether it will be continued.

The aforementioned questionnaire will, in addition to inquiring potential interest of NMIs in applying ac-QHE, also announce the availability of this website.

Since the meeting was informal and open to non-WG-members, no formal decision was taken, but the above opinion was generally shared.

Franz Ahlers, Jürgen Melcher

<u>11th and last meeting on 2009-03-13 at BIPM:</u>

1. Minutes of the meeting of the WG-ACQHR at CPEM 2008, 2008-06-12, Broomfield, Colorado, Working Doc. WGACHR/09-02 [1].

   These minutes have been accepted without dissenting vote

2. Discussion of the Compendium for precise ac measurements of the quantum Hall resistance, Working Doc. WGACHR/09-03

   There was little discussion on this document.

   Jürgen Melcher explained the discussion about the wording of the title of this document. As there is no theoretical explanation neither for the DC- nor the ACQHR a strict proof is not possible. Only experimental evidence can give up to now a foundation that ACQHR measurements are giving reliable results for impedance measurements. The experimental basis, however, at the moment is quite small. Therefore the word compendium instead of guidelines seems to be more appropriate.

3. ac-QHR related website

test, 6 month

(Due to the small number of accesses it has been closed after the test phase.)

4. Scope of a Report to the CCEM

   The report shall cover the whole work of this working group and shall be agreed upon by correspondence.

5. Miscellaneous

   Further discussion seems to be useful, but not necessarily in the frame of a CCEM WG

Summary of the work of the CCEM Working Group on AC Measurements of QHR

There were two initial goals of this working group:

1) to foster the co-operation among researchers and
2) to develop a set of guidelines for accurate measurement of AC QHR.

Over the more of 10 years the first was quite successful, cooperation among institutes with exchanges of scientists took place, a lot of joint papers have been published and considerable progress was achieved in carrying out reliable measurement of the quantum Hall resistance with AC currents in the audio frequency range. The uncertainty of these measurements came down from about 3 parts in 10^6 in 1992 to less than 1 part in 10^8 now. The discussions during the meetings showed that there is a great worldwide interest in the results of these collaborations but that the total number of institutes really working in this special field was limited to 5.

The second point, the formulation of a draft of a set of guidelines for accurate measurement of AC QHR could not be reached; however, a Compendium for precise ac measurements of the quantum Hall resistance has been worked out by three groups and has been published. This Compendium summarizes the status reached until CPEM 2008 but does not cover the development afterwards. In this development a refined shielding strategy has been used to fully eliminate the frequency dependence within the experimental uncertainty (Type A) which is below 1 part in 10^8 at 1 kHz [2]. At present it seems that AC measurements of the quantum Hall resistance at frequencies around 1 kHz are as precise as their well-established DC counterparts. Currently there is cooperation in this field between PTB and NMIJ.

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[1] F.J. Ahlers, B. Jeanneret, F. Overney, J. Schurr, and B.M. Wood, “Compendium for precise ac measurements of the quantum Hall resistance,” *Metrologia*, vol. 46, 2009, p. R1-R11.

[2] J. Schurr, J. Kučera, K. Pierz, and B.P. Kibble, “The quantum Hall impedance standard,” *Metrologia*, vol. 48, Feb. 2011, pp. 47-57.