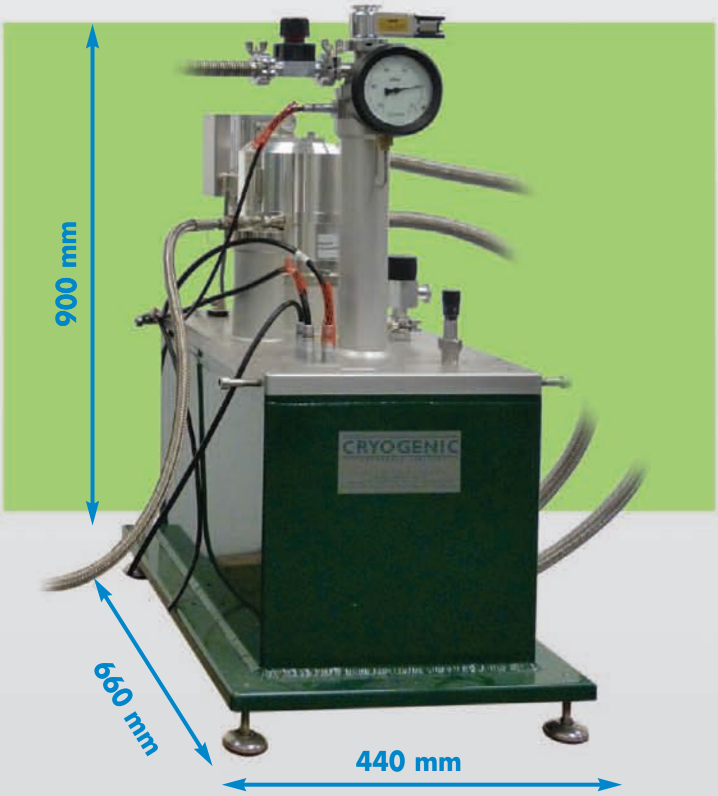
CRYOGENIC
CRYOGENIC LIMITED

MINI CRYOGEN-FREE MAGNET SYSTEMS 5-9 T (m-CFMS)



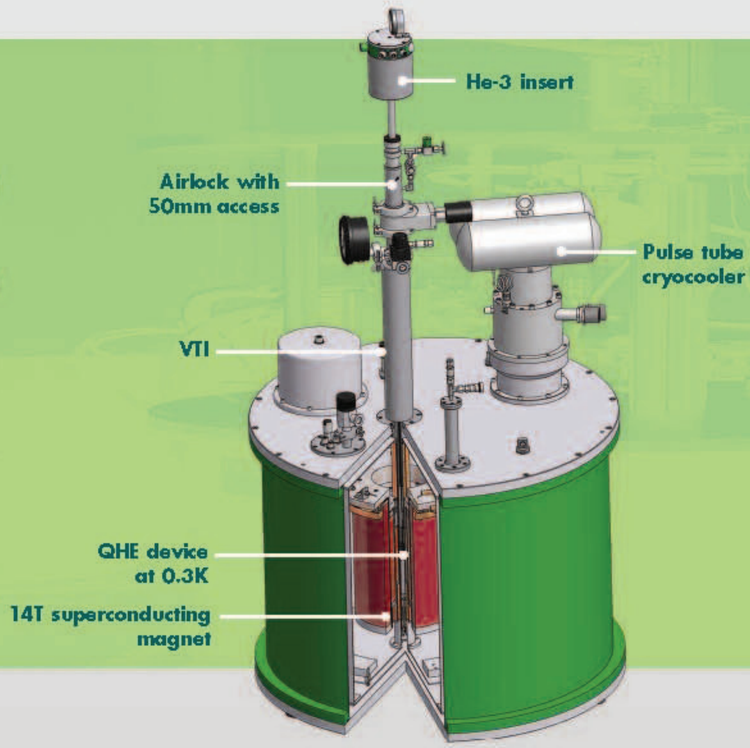
Suitable for next generation graphene samples

- Completely dry system requiring **no** liquid helium
- Magnetic field 5-9 tesla in a mini desk-top cryostat
- Sample space of 25 mm or 30 mm in the VTI
- Variable temperature range from 1.6 to 400 K
- Highly stable magnetic field
- He-3 Insert with temperatures down to 325 mK and 24 hours hold time (optional)
- High power Pulse Tube cryocooler with low vibration
- No maintenance for 3 ½ years continuous use
- Independent and easily transportable as it runs from standard electrical supply.

Cryogenic Limited,
Unit 30, Acton Park Industrial Estate,
The Vale, Acton, London, W3 7QE. United Kingdom.
Tel: +44 (0) 20 8743 6049
Fax: +44 (0) 20 8749 5315
E-mail: sales@cryogenic.co.uk

www.cryogenic.co.uk

CRYOGEN-FREE PRIMARY RESISTANCE STANDARD



- Re-condensing CCC cryostat with 50mm access suitable for up to 14 Tesla Cryogen Free Magnet
- Integrated Variable Temperature Insert from 1.6 to 300K
- Automated measurement and data acquisition.
- Helium^{-3} system down to 300mK
- Absolute value of Resistance constant to the Von Klitzing constant of 25812.807 ohms.
- Comparison of the 100 Ohm standard with RK to 1 part in 10^{8}.
- Wide range of ratios for resistance comparison over the 1 to 13K Ohm range.
- Completely turn-key system.
- Automated operation, measurement and analysis.

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PRIMARY RESISTANCE STANDARD QHR2000

QHR2000 - A new standard in measurement

- Comparison of the 100 Ohm standard with R_K to 1 part in 10^8.
- Portable Cryogenic Current Comparator (CCC) for independent use with low LHe consumption.
- Wide range of ratios for comparing other resistances over the range 1 Ohm to 10k Ohm.
- CCC fully shielded with turns ratio accuracy of 10^{-10}.
- LabVIEW® software for automated operation, measurement and analysis.
- Integrated system, only one cryostat required for QHR comparisons with low He consumption.
- Full environmental shielding, a screened room is not necessary.
- 14 Tesla at 4.2K allowing use of plateaux up to n=2.

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"The Better Choice"

Introduction

The QHR2000 with its Cryogenic Current Comparator bridge is a breakthrough in the science of electrical measurement. It provides the ability to resolve and measure currents and resistance values to an accuracy of 10^{-9} *.*

The QHR2000 was developed to meet the needs of standards laboratories around the world for a new level of accuracy in the calibration and maintenance of primary resistance standards.

The technology used in the QHR also opens up new possibilities for studying small signal effects in the presence of large backgrounds. Typical examples would include measurements using a differential bolometer or strain gauges. Indeed any experiment which involves a very precise comparison of two resistive elements.

The QHR2000 consists of two parts. The first is a Quantum Hall Resistance system which provides an absolute value of resistance related to the von Klitzing constant of 25812.807 Ohms. To provide this reference, a Quantum Hall semiconducting device is maintained at 0.3K with a He-3 refrigerator in a magnetic field of up to 14 Tesla, generated by a superconducting magnet. Under these conditions the Quantum Hall plateaux of resistance are easily obtained.

The second part is the CCC Bridge, which allows two independent and isolated currents of different values to be compared and controlled with an accuracy of 10^{-9}*. The CCC forms part of a bridge circuit driving current into the two resistors which are to be compared. The differential voltage is measured with a sensitive nanovoltmeter. Provided that sufficient care is taken with connections and cabling in the bridge circuit, the comparison can be made to very high levels of accuracy.*

The QHR2000 is supplied as a full turn-key system for metrology purposes. For other applications, the CCC bridge can be supplied as an independent instrument.

The Cryogenic Current Comparator (CCC)

The CCC is a remarkable device which uses the shielding properties of a superconductor to make it possible to balance and control DC currents to very high precision.

The currents are fed to two coaxial coils enclosed in a toroidal superconducting shield. The shield is not a closed loop but is designed in such a way that the magnetic field escaping from the shield depends only on the ampere turns of the coil inside the shield and not on the coil's position or size.

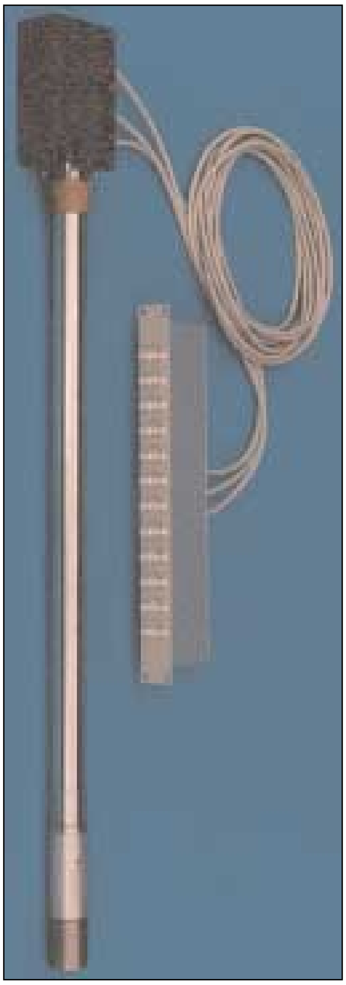
Thus, two coils with equal and opposite ampere turns generate no external field. A Superconducting Quantum Interference Device (SQUID) is used to detect the presence of external field and in this way it is easy to control the currents to ensure their accurate balance.

With 12 or more coils enclosed in a single shield, it is possible to produce many different current ratios and to hold all of them to high precision. In the CCC, current ratios of up to 200:1 can easily be produced. The ratios must of course be made up from a series of integer turn coils.

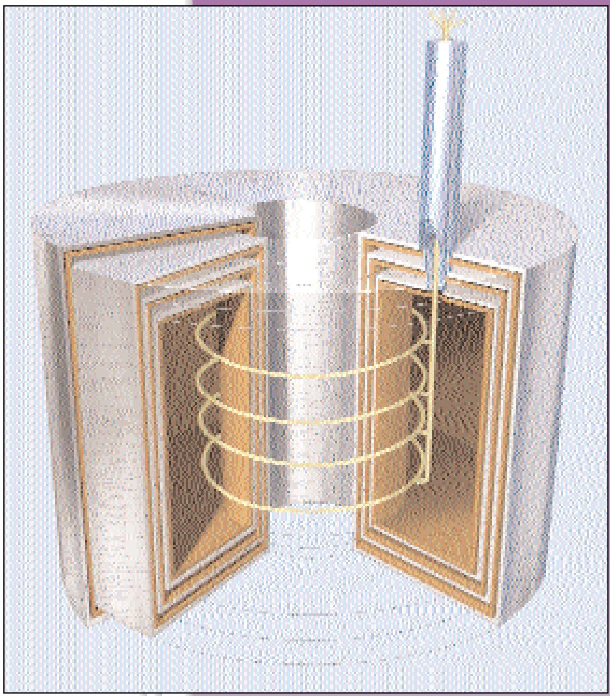
The standard instrument controls and compares currents within the range of 50 millamps to 10 microamps, all with similar accuracy. Other current ranges are possible. Tests on the CCC have shown that the turns ratio errors are maintained to better than 10^{-10} absolute accuracy. This level of absolute accuracy is unprecedented in any analogue device with DC currents.

As with any SQUID system it is essential to avoid magnetic noise and RF interference. Great care is taken in the design of the CCC and its associated circuits to make it proof against externally or internally generated interference. As a result the QHR2000 can operate independently of a screened room.

The CCC is supplied complete with its own current sources and the SQUID electronics. To ensure isolation of the current sources and the proper balance of the bridge the current sources are battery powered. The probe itself is well shielded from magnetic and RF interference. The isolation of all the windings and their connections are maintained to a very high level.



Cryogenic Current Comparator (CCC).



The Cryogenic Current Comparator showing the single toroidal screen which encloses the coils by wrapping round itself 3 times without any electrical contact between the layers.

Communication to and from the control computer is via fibre optic cables which are used to set the current in the bridge without introducing noise or reducing isolation from ground.

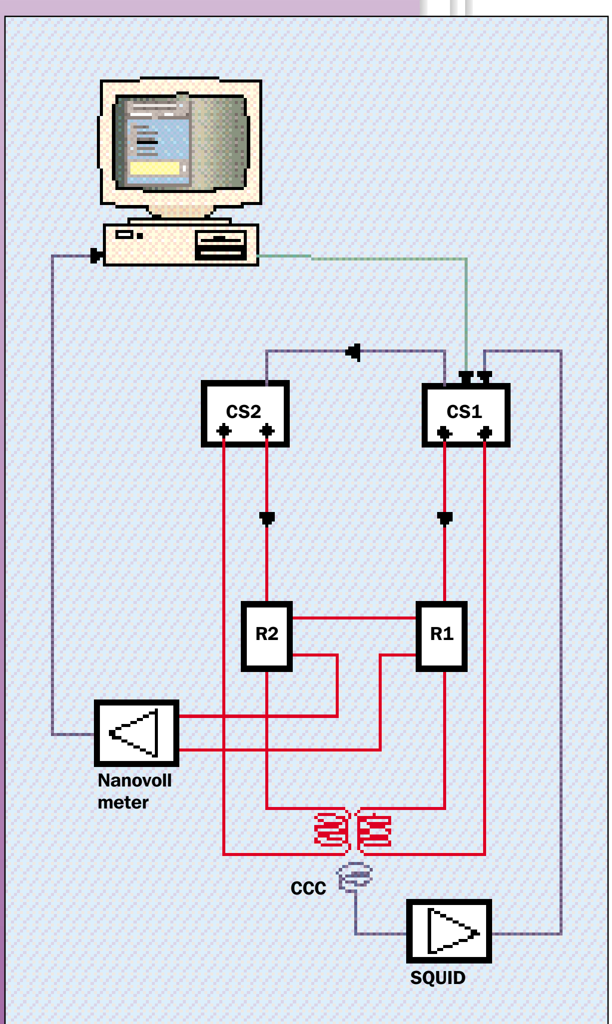
The CCC and its control electronics are available as an independent unit. They can be used to establish a bridge circuit for any analogue measurement which requires exceptional accuracy and control.

The whole Cryogenic Current Comparator is engineered to be flexible in use, easy to understand and simple to operate, while at the same time maintaining the highest level of measurement precision. The device including the SQUID null detector is mounted into a single probe that can be installed in any suitable cryostat or helium storage dewar.

The Bridge Circuit

The DC bridge circuit is shown in the illustration. It consists of two fully isolated power supplies, CS1 and CS2 providing currents to the two resistors under test.

The currents in CS1 and CS2 are set to first order from the computer in the appropriate ratio for the resistive elements of the bridge. Precise control within the limits of the CCC to 10^{-9} or better is provided by feedback from the SQUID output. The resistors can be just two resistors of the same or different values, a resistor and a QHE device or even two QHE devices for comparison of their performance.



CCC Bridge circuit

Measurements are carried out under computer control with the currents ramped to a pre-set value, both positive and negative, where they are held constant with sufficiently low noise and drift to allow very precise measurements to be made.

The currents are normally chosen to provide a voltage drop of 0.5 volts across the test resistors. The nanovolt amplifier is capable of very low level measurements when measuring suitable source resistances so as to provide the resolution required.

The voltage measured across the bridge by the nanovolt meter represents the difference in the value of the two resistors after allowing for the current ratios of the CCC.

Providing that the offset voltage is 10ppm or less, measurement of the offset voltage to a precision of 10^{-3}, a relatively simple task, is sufficient to give an overall accuracy of 10^{-8} for the bridge comparison.

To obtain more accurate results for metrological purposes an alternative arrangement is preferred. The current ratio is altered in a precisely known fashion by the software to provide a null voltage across the bridge. The ratio of currents is then the ratio of resistance values.

Repeating the measurement by reversing the current to positive and negative values for 10 cycles allows the elimination of thermo-electric offsets and gives a statistical estimate of the random error (type B).

The nanovoltmeter and both current sources are all seperately battery driven. The rechargeable cells allow up to 16 hours continuous powered operation. A separate charger allows for overnight re-charging. The use of batteries is essential to ensure the total isolation of the bridge, a necessity for ultra precise and linear measurements and the avoidance of systematic error (Type A).

Fibre optic cables are used between the computer and the current sources to ensure that the bridge is both isolated and free from RFI and other noise sources. The nanovolt detection circuit is similarly isolated by a linear isolation amplifier with a guaranteed isolation exceeding 10^{16} Ohms.

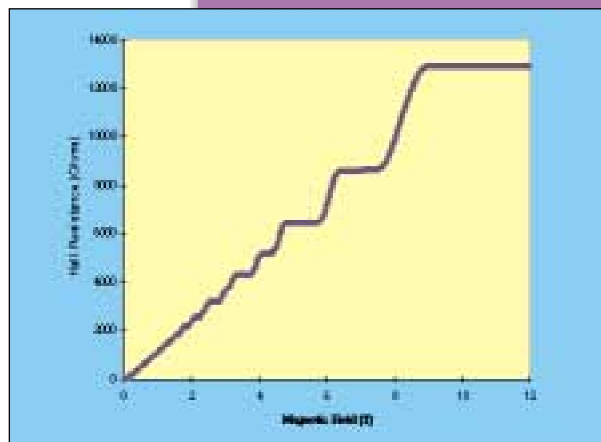
It is particularly important that, where the bridge is used for metrology applications, it should be possible for the user to carry out independent checks on all aspects of the system, to guard against unexpected systematic errors. For this reason, we prefer to use discrete circuits with reliable hand made connections between the major items for metrological determination of the 100 Ohm standard. For routine measurements, calibrating a batch of resistors, it is appropriate to use a form of scanner circuit. Scanners allow collection of data from several resistors automatically under computer control. They do also introduce additional noise and drift. They are available as an option for use with the CCC.

The QHR2000 uses the Quantum Hall Effect (QHE) to provide an absolute value of resistance which is dependent only on the value of Planck's constant and that of the electron charge. This value is known as the von Klitzing constant and is taken as 25812.807 Ohms.

Measurements are made to characterise the QHE devices using the standard software of the QHR 2000. A typical set of plateaux is shown.

The linearity of the 2 and 4 plateaux can readily be seen. For resistance characterisation the n=2 and n=4 plateaux are used giving resistance values of 12906.4035 Ohms and 6453.2017 Ohms. They are at 11 and 5.5 Tesla, respectively.

A low resistance in the direction of the current along the device is also important, as it means that the geometry of the Hall probe leads will not affect the Quantum Hall Resistance. The QHR2000 allows measurement of the forward voltage along the device. At the centre of the plateaux it should be zero.



The quantised Hall resistance as a function of magnetic field, with an excitation current of 10 μA.

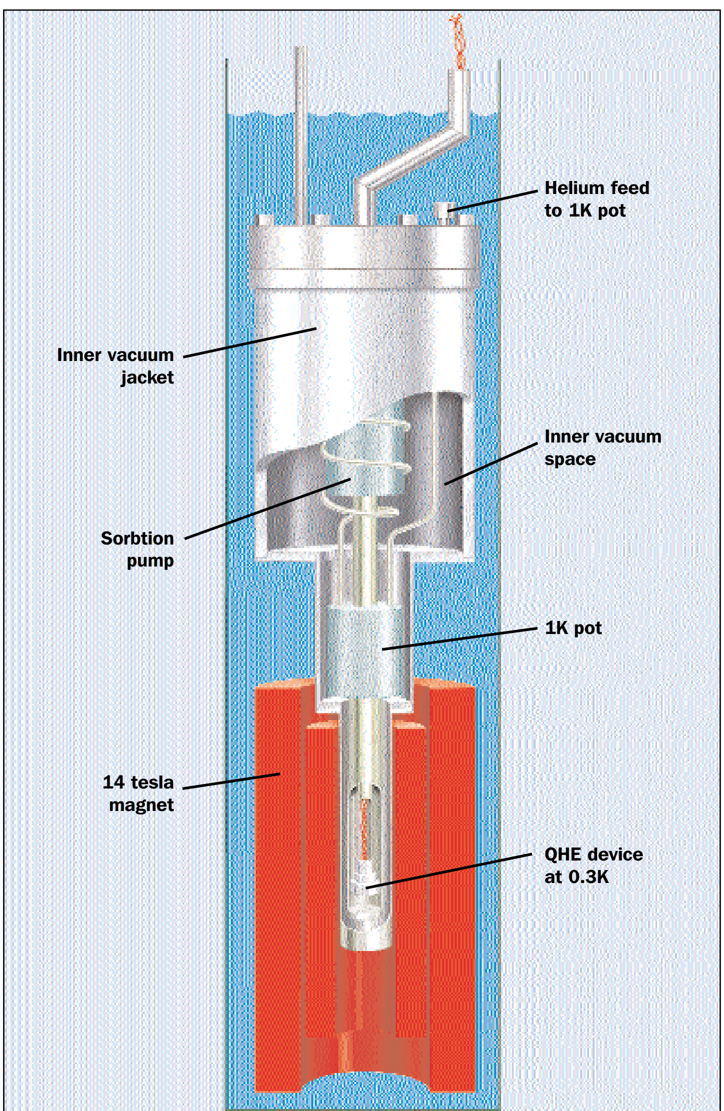
The use of the two plateaux gives added security to the reliability of the measurement as it provides a further independent check for systematic errors.

The QHR2000 can use any suitable QHE device mounted on a standard connector. Cryogenic Ltd will normally provide a GaAs high mobility device from a well established source.

To provide the best and most versatile performance, the QHR2000 is equipped with a closed cycle He-3 refrigerator to produce an operating temperature of 0.3K for the QHE device. Although the steps are present at 1K, at a temperature of 0.3K the quality of the step is greatly improved.

Fields of up to 14 Tesla at 4.2K are available with the QHR2000 to allow for future flexibility. Typically, the field for the n=2 plateaux on the QHE device supplied is approximately 11 Tesla.

The Ultra Compact magnet design used in the QHR2000 gives only a small stray field. There is no requirement for special safety precautions due to the stray field.



QHR2000 He-3 refrigerator and superconducting magnet assembly

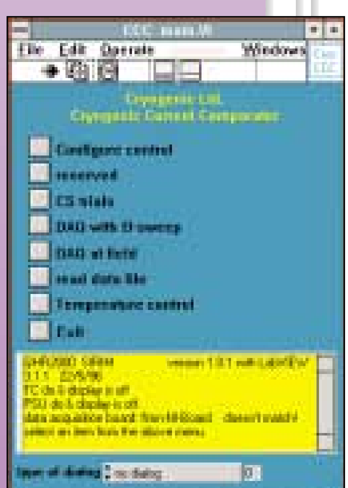
The Cryogenic System

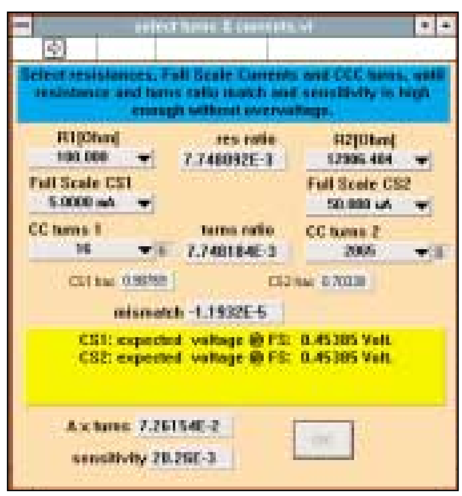
The complete instrument is built into a single purpose built vibration isolated helium cryostat. Both a liquid nitrogen cooled shield and a gas cooled shield are fitted to minimise liquid helium consumption. A large 90 litre helium reservoir gives a long hold time to avoid frequent refills.

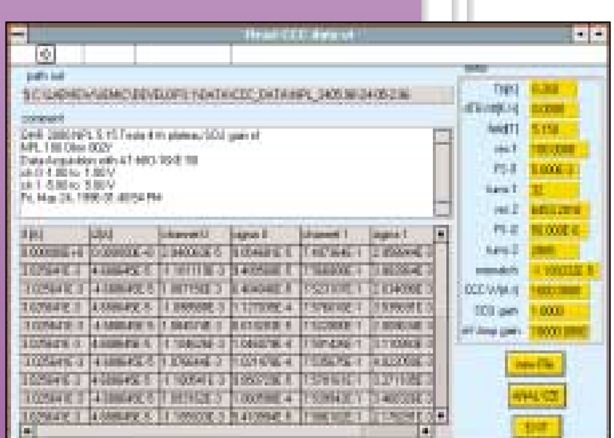
Since the CCC bridge can be used independently of the QHE device for resistance calibration between the 100 Ohm standard and other values, it is not necessary to cool the complete QHR2000 system to make these measurements. The CCC may be used independently and mounted in any suitable small liquid helium vessel. It can also fit into a helium transport vessel.

Every effort is made in the design and engineering of the system to reduce the operating costs, which are mainly liquid helium, to the minimum. All the pumps, hoses, cables, valves, etc, needed to operate the system are included in the package. Particular attention has been paid to making the design easily operated by personnel who do not have extensive experience with low temperature equipment. The He-3 system itself is very easy to understand and operate. The software also guides the user and makes for easily understood measurement procedures.

Automation and Software







The control system for the QHR2000 and the CCC uses the well established and flexible LabVIEW® software running in a fast Pentium based computer. National Instrument IEEE and data acquisition cards are fitted to ensure a high level of reliability.

The LabVIEW® software allows an open measurement structure to be developed. The software is graphical and is composed using icons for functions. Virtual Instruments are called up on the screen which graphically display the logical structure of the program.

Program development is by drawing new logical structures on the screen rather than by writing line by line code. This process is far faster and more secure, as well as more user friendly than older programming systems. It makes the QHR2000 that much easier to use.

The open software structure allows the metrologist to oversee the program and to control the instrument's operation, reducing the possibility of undetected systematic errors.

All functions of the system, including operation of the He-3 refrigerator can be controlled from the computer. Individual VI windows allow the magnetic field to be set to a fixed value or swept to display the plateaux in the Quantum Hall voltage. Other VI's such as those shown allow set-up of the system and analysis of the data collected.

Technical Specification

System Specifications	
Primary resistance standard:	100 Ohm
Accuracy of determination to the von Klitzing constant:	10^{-8}
Systematic error determination by reference to NPL standard:	+/- $3x10^{-8}$
or by special option:	+/- $1x10^{-8}$
System isolation better than (dry conditions 20°C ambient temperature):	1000 Gigaohm
Helium consumption:	3 litres per day
Helium hold time:	30 days
Typical measurement sequence time:	25 mins
Cryogenic Current Comparator Bridge	
Coil sets included:	1,1,2,4,8,16,32,40,400,400, 400, 1200 and 2065
Ratio self calibration accuracy:	10^{10}
Gain factor:	$3x10^{3}$ Volts/Ampere-turns
Noise level:	1.5 x 10^{-9} Ampere-turns
Normal operating ampere turns:	80 milliamp turns
Maximum operating ampere turns (coil set):	10,000 milliamp turns
Maximum available current:	50 milliamp turns
Sweep ramp rate (typical coil set):	20 milliamp turns / second

For confirmation of the latest specification, please contact the Sales Department at Cryogenic Ltd.

Performance and Test Procedures

Rigorous test procedures are applied during all stages of manufacture with particular care given to the key electronic and cryogenic components. An error budget is produced and evaluated for each system. As the units are produced in series, Cryogenic applies a policy of continuing product improvement and development, in common with all its research systems.

Formal tests are carried out in our works followed by a full evaluation at the National Physical Laboratory in London. The systematic and random errors are assessed. Comparisons are also made to the NPL calibrated values. Clients are welcome to attend these tests to have the best understanding of the system and to receive initial training in its operation.

All systems are installed at the customers facility by our own engineers who provide training for local personnel and ensure that the system is fully operational on-site to the standards required for metrological applications.

For further information or a comprehensive quotation, please contact our Sales Department as follows:-

Cryogenic Ltd,
Unit 30,
Acton Park Industrial Estate,
The Vale,
London W3 7QE, UK

International Telephone:
(+44) 181 743 6049
International Facsimile:
(+44) 181 749 5315

E-mail: cryogenic@cix.compulink.co.uk

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