Advanced Study Institute (ASI) on
Science and Application of Spin Electronics
Hongkong, 15.8.2005

25 Years Quantum (not Spin) Hall Effect

K. v. Klitzing

Max-Planck-Institut für Festkörperforschung Stuttgart

FIRST PUBLICATION ABOUT THE QUANTUM HALL EFFECT

25 years + 4 days → 11 AUGUST 1980

VOLUME 45, NUMBER 6 PHYSICAL REVIEW LETTERS 11 AUGUST 1980

New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance

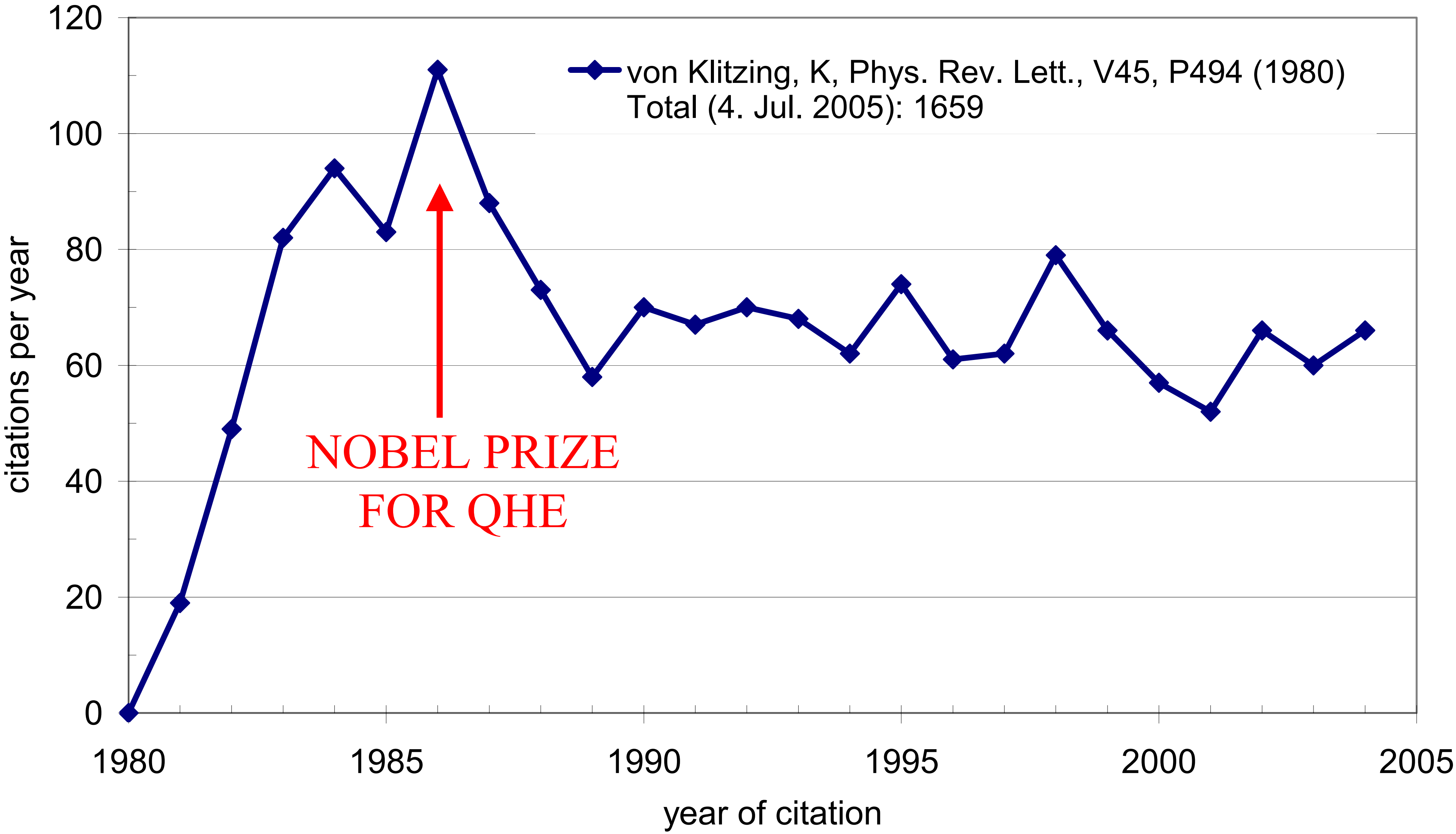
K. v. Klitzing
Physikalisches Institut der Universität Würzburg, D-8700 Würzburg, Federal Republic of Germany, and Hochfeld-Magnetlabor des Max-Planck-Instituts für Festkörperforschung, F-38042 Grenoble, France

and

G. Dorda
Forschungslaboratorien der Siemens AG, D-8000 München, Federal Republic of Germany

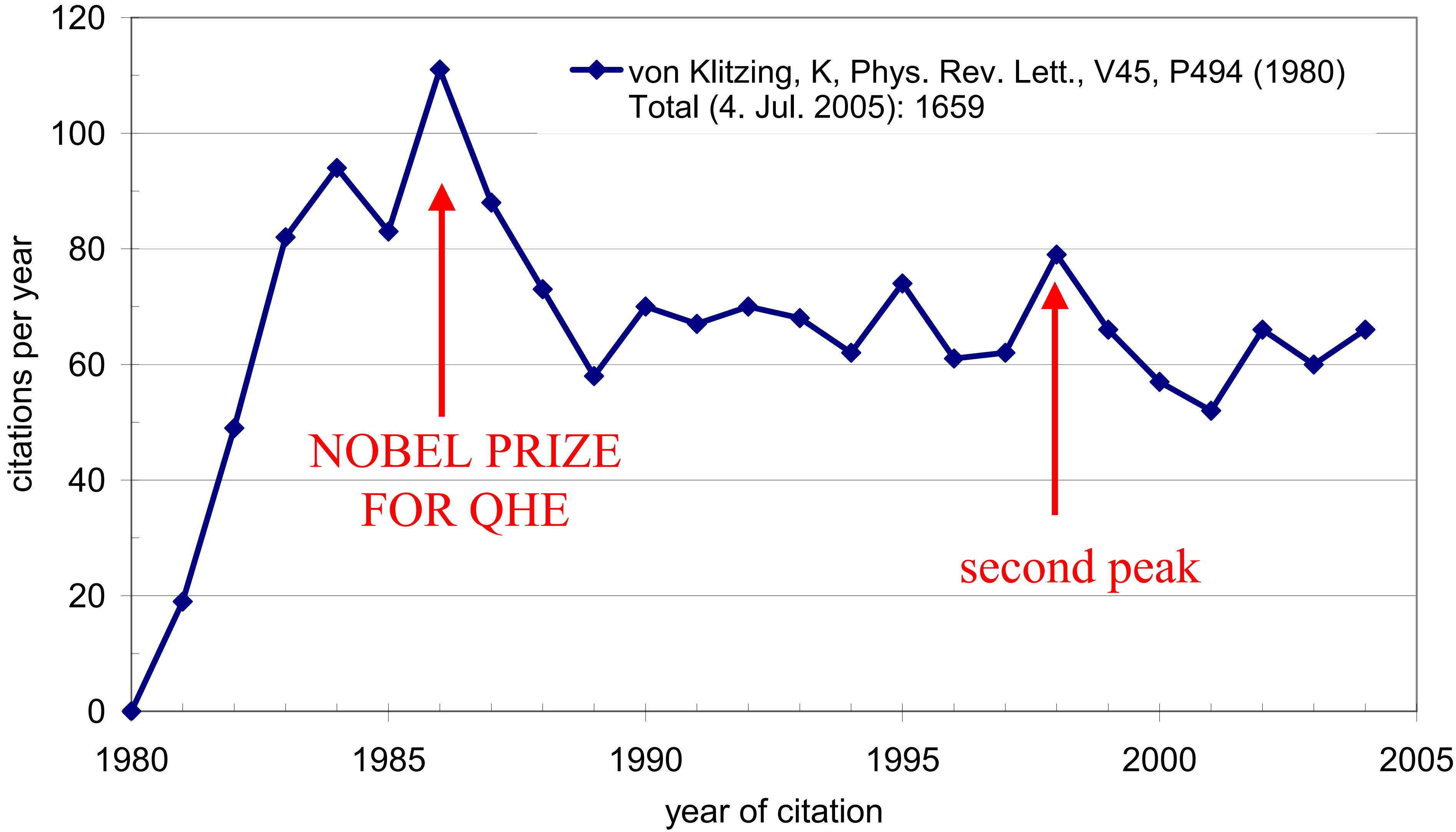
and

M. Pepper
Cavendish Laboratory, Cambridge CB3 0HE, United Kingdom
(Received 30 May 1980)



120
100
80
60
40
20
0
1980
1985
1990
1995
2000
2005
citations per year
year of citation
von Klitzing, K, Phys. Rev. Lett., V45, P494 (1980)
Total (4. Jul. 2005): 1659
NOBEL PRIZE
FOR QHE

Integer Quantum Hall Effect (Nobel Prize in Physics 1985)



von Klitzing, K, Phys. Rev. Lett., V45, P494 (1980)
Total (4. Jul. 2005): 1659
NOBEL PRIZE
FOR QHE
second peak
citations per year
year of citation
0
20
40
60
80
100
120
1980
1985
1990
1995
2000
2005

Fractional Quantum Hall Effect (Nobel Prize in Physics 1998)

The Integral and Fractional Quantum Hall Effects
Edited by
$R_K = h/ie^2$
$T = 278$ mK
$I = 0.255$ μA
GRADUATE TEXTS IN CONTEMPORARY PHYSICS
The Quantum Hall Effect
M. Janßen, O. Viehweger
U. Fastenrath and J. Hajdu
Introduction to the Theory of the Integer Quantum Hall Effect
Introduction to Quantum Hall Effect
SOLID-STATE SCIENCES
D. Yoshioka
The Quantum Hall Effect
Springer
Physikalisch Technische Bundesanstalt
Braunschweig und Berlin
3. Auflage, Nov. 1998
PIB
email: presse@ptb.de
WWW: http://www.ptb.de/
Composite Fermions
A Unified View of the Quantum Hall Regime
Editor
O. Heinonen
World Scientific
Proceedings of the International Symposium
"Quantum Hall Effect: Past, Present and Future"
Stuttgart, Germany
2–5 July 2003
Quantum Hall Effect: Past, Present, and Future
Editors
Rolf Haug
Dieter Weiss
T.Chakraborty
P. Pietiläinen
The Quantum Hall Effects
Fractional and Integral
Second Edition
Springer
Quantum Hall Effects
Field Theoretical Approach and Related Topics
Zyun F. Ezawa
Hall Effects
Novel Quantum Liquids in Low-Dimensional Semiconductor Structures
Edited by
Sankar Das Sarma
Aron Pinczuk
EFFECT
Editor
MICHAEL STONE
World Scientific

Si MOSFET

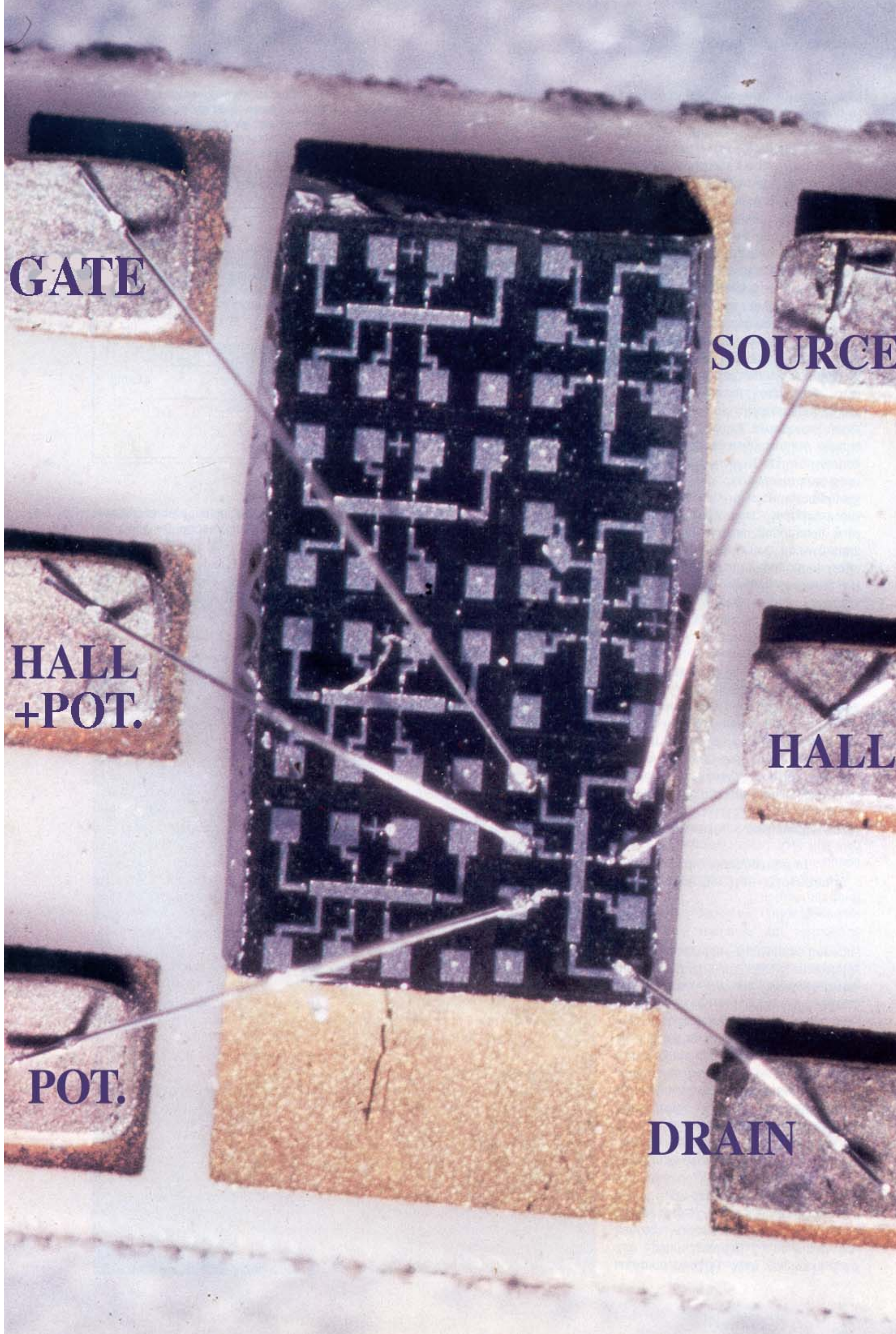
basic research on

such a device led

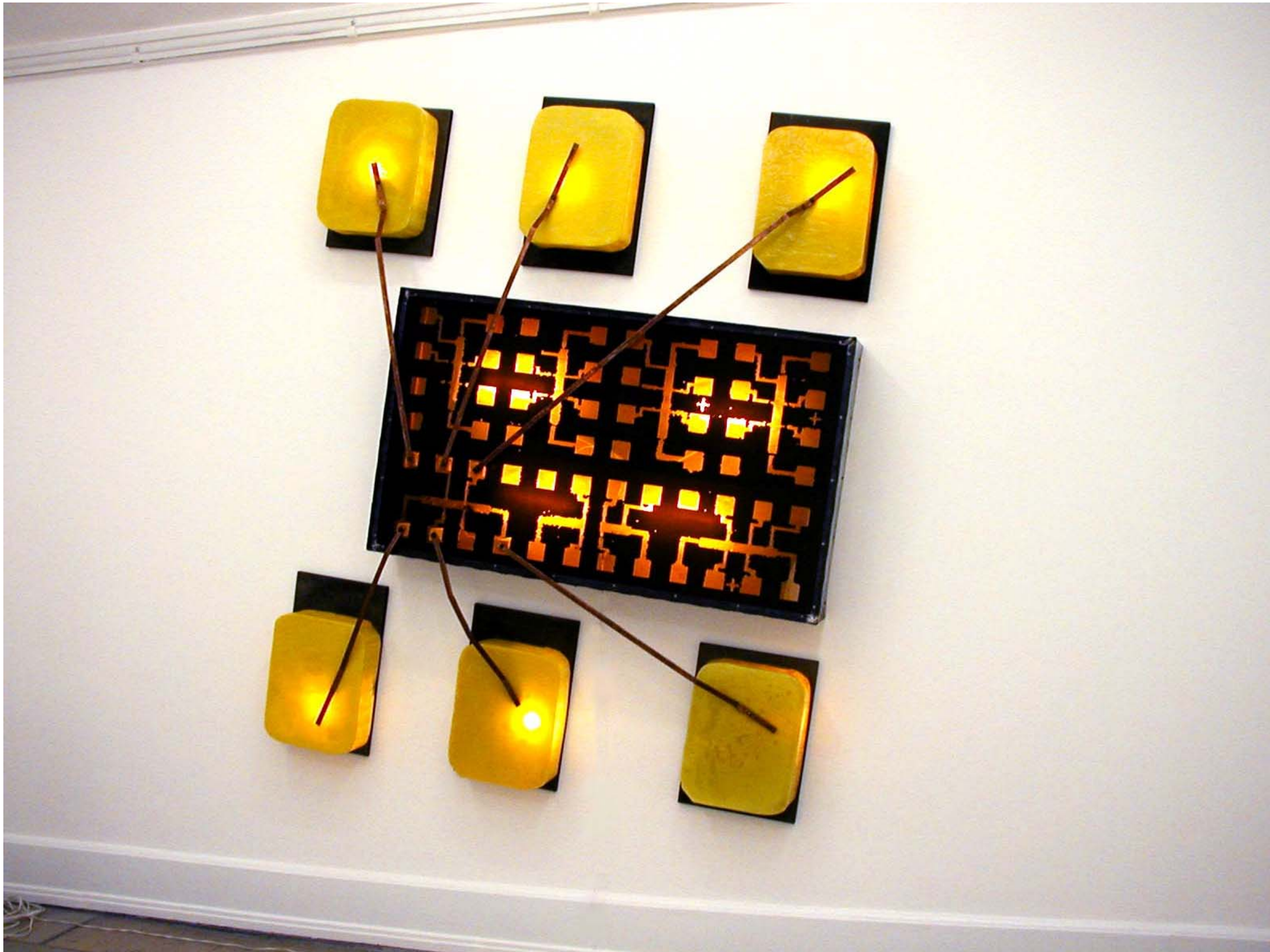
to the discovery

of the

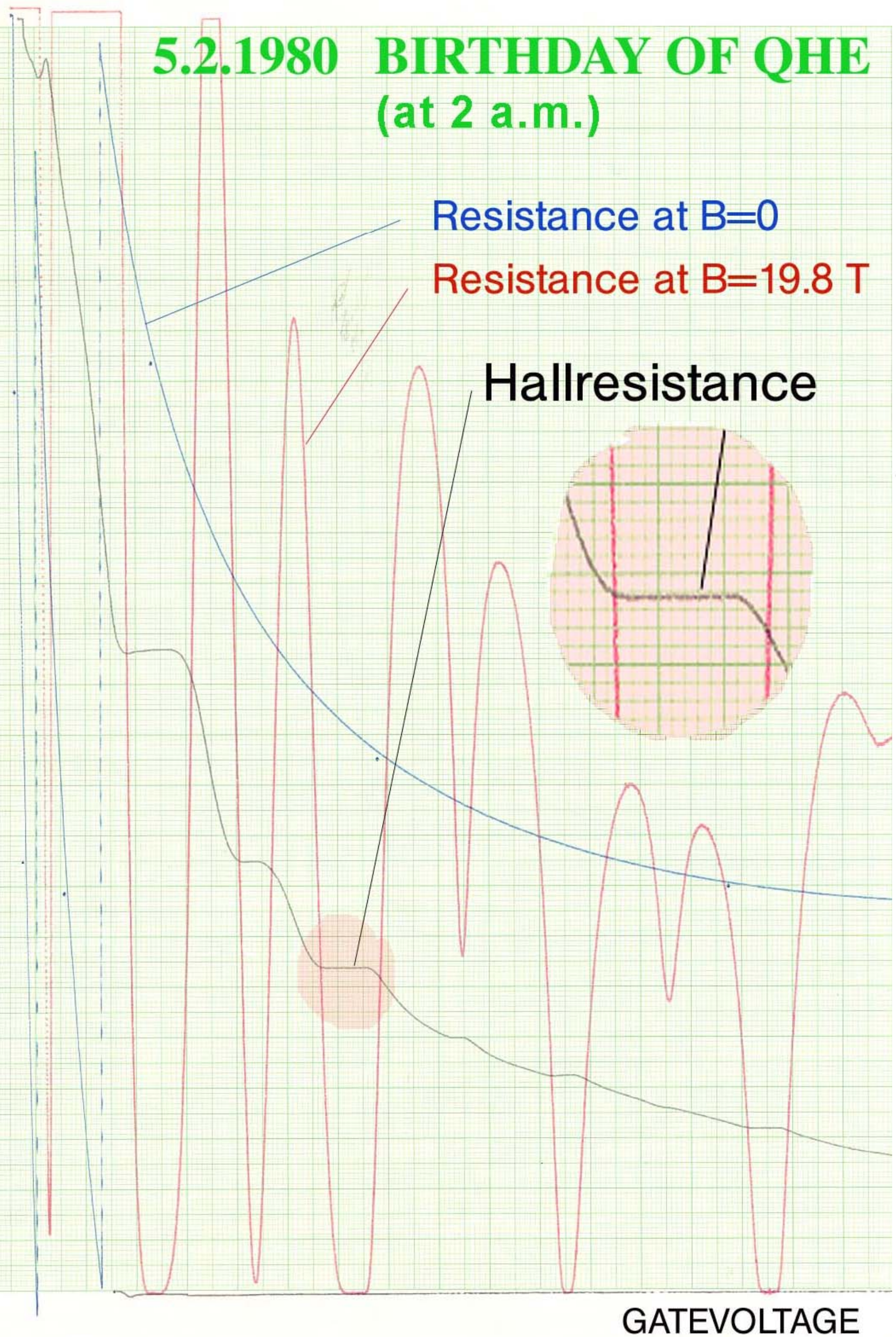
Quantum Hall Effect



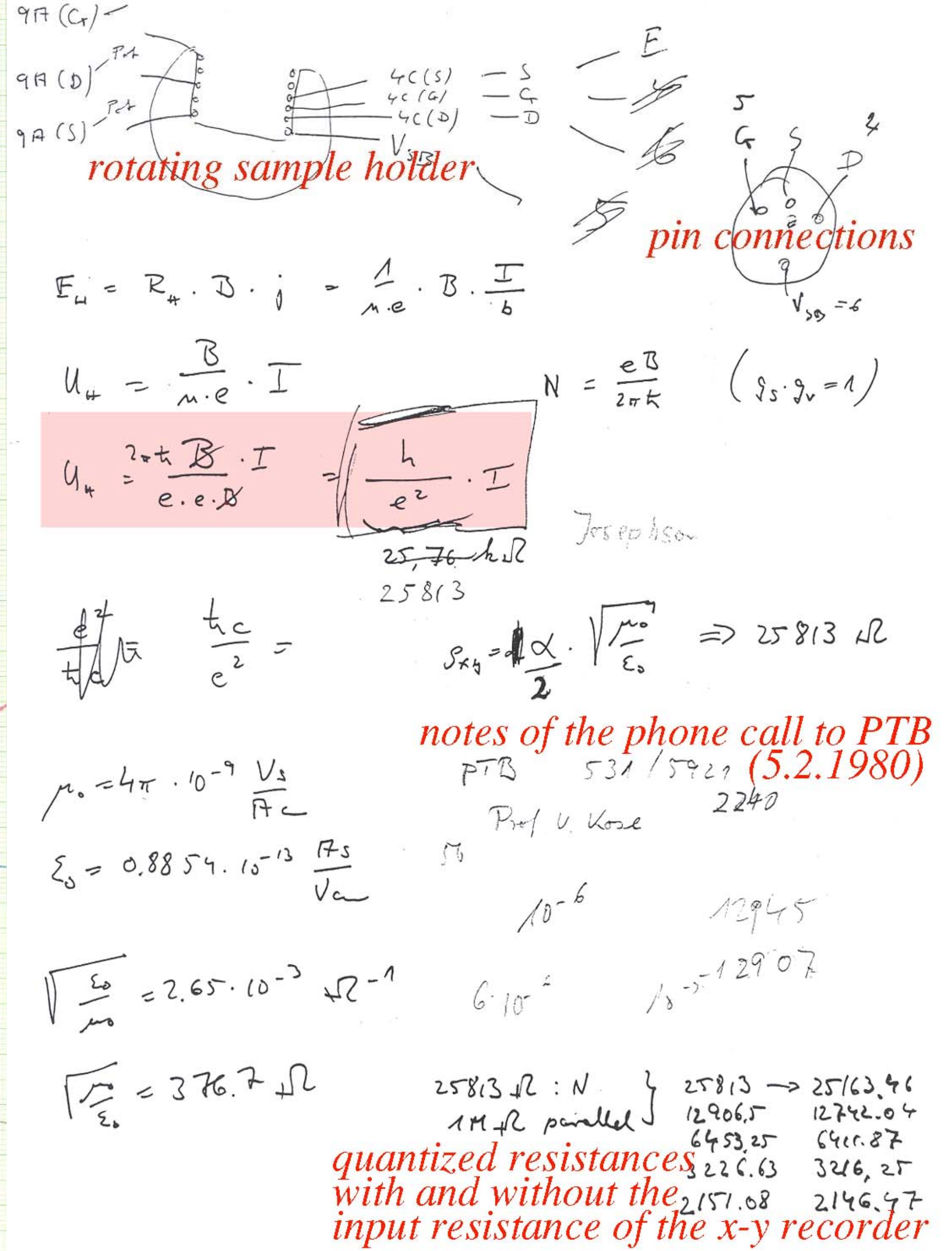
Quantum Hall Effect in the Museum



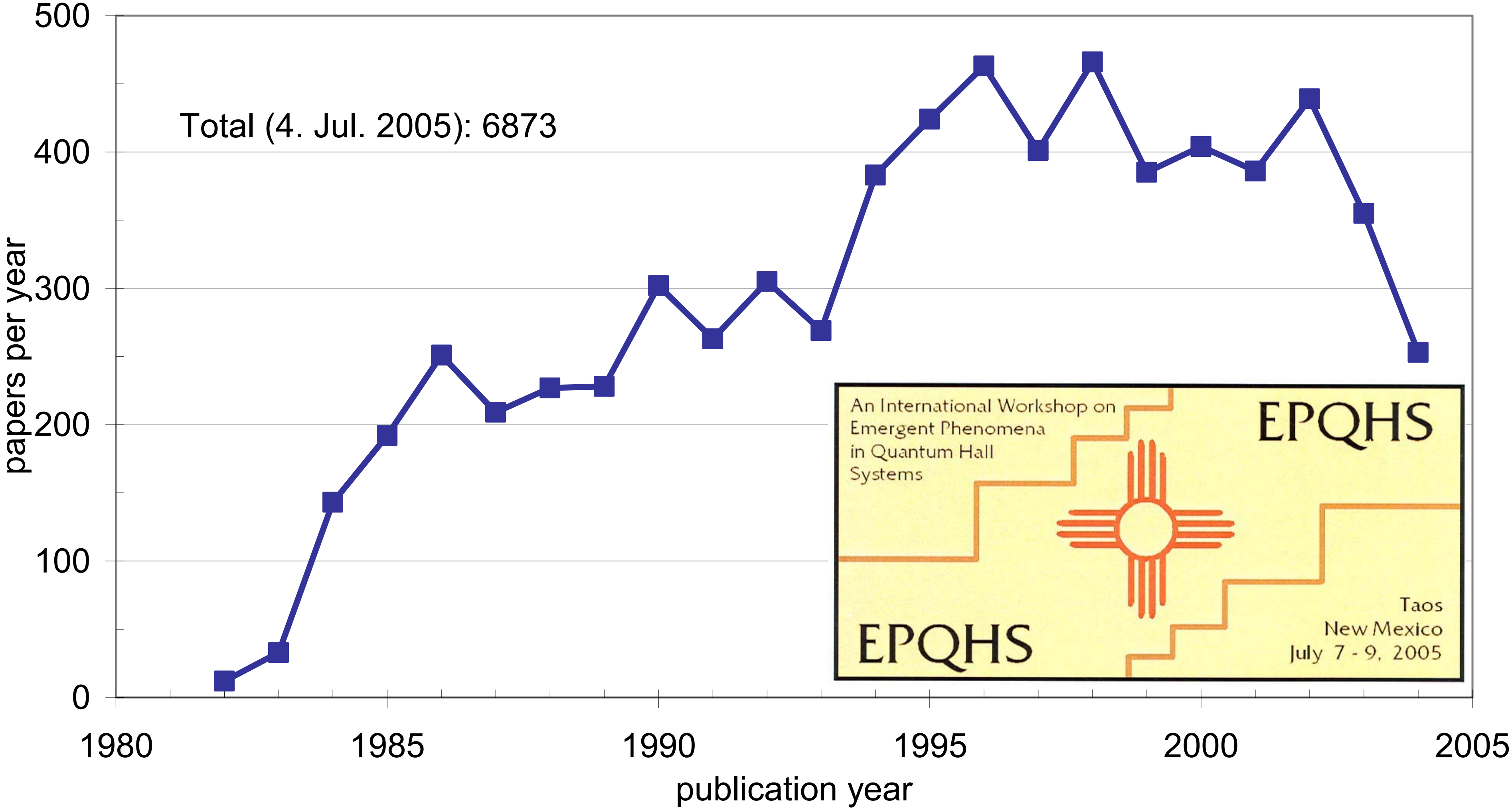
Exhibitions in Nürnberg and Basel



Notes 4./5.2.1980



Quantum Hall Effect papers in INSPEC



The quantum Hall effect- a phenomenon for (nearly) all area in physics

QUANTUM HALL EFFECT and BLACK HOLES

Edge States in Gravity and Black Hole Physics

A.P. Balachandran, L. Chandar, Arshad Momen

Department of Physics, Syracuse University,

Syracuse, NY 13244-1130, U.S.A.

Abstract

We show in the context of Einstein gravity that the removal of a spatial region leads to the appearance of an infinite set of observables and their associated edge states localized at its boundary. Such a boundary occurs in certain approaches to the physics of black holes like the one based on the membrane paradigm. The edge states can contribute to black hole entropy in these models. A "complementarity principle" is also shown to emerge whereby certain "edge" observables are accessible only to certain observers. The physical significance of edge observables and their states is discussed using their similarities to the corresponding quantities in the quantum Hall effect. The coupling of the edge states to the bulk gravitational field is demonstrated in the context of (2+1) dimensional gravity.

BTZ black hole and quantum Hall effect in the bulk/boundary dynamics

Y. S. Myung

Department of Physics, Inje University, Kimhae 621-749, Korea

Abstract

We point out an interesting analogy between the BTZ black hole and QHE (Quantum Hall effect) in the (2+1)-dimensional bulk/boundary theories. It is shown that the Chern-Simons/Liouville(Chern-Simons/chiral boson) is an effective description for the BTZ black hole (QHE). Also the IR(bulk)-UV(boundary) connection for a black hole information bound is realized as the UV(low-lying excitations on bulk)-IR(long-range excitations on boundary) connection in the QHE. An inflow of conformal anomaly($c = 1$ central charge) onto the timelike boundary of AdS_3 by the Noether current corresponds to an inflow of chiral anomaly onto the edge of disk by the Hall current.

QUANTUM HALL EFFECT and QUARKS

Quantum Hall quarks or Short distance physics of quantized Hall fluids

Martin Greiter
Department of Physics, Stanford University, Stanford, CA 94305, greiter@quantum.stanford.edu
(SU-ITP 96/30, cond-mat/9607014, July 2, 1996)

In order to obtain a local description of the short distance physics of fractionally quantized Hall states for realistic (e.g. Coulomb) interactions, I propose to view the zeros of the ground state wave function, as seen by an individual test electron from far away, as particles. I then present evidence in support of this interpretation, and argue that the electron effectively decomposes into quark-like constituent particles of fractional charge.

PACS numbers: 73.40.Hm,73.20.Dx,03.65.-w,03.80.+r

QUANTUM HALL EFFECT and QUANTUMCOMPUTER

ELSEVIER

2 March 1998

PHYSICS LETTERS A

Physics Letters A 239 (1998) 141–146

Quantum computation in quantum-Hall systems

V. Privman [a], I.D. Vagner [b], G. Kventsel [b,c]

[a] *Department of Physics, Clarkson University, Potsdam, NY 13699-5820, USA*

[b] *Grenoble High Magnetic Field Laboratory, Max-Planck-Institut für Festkörperforschung, and Centre National de la Recherche Scientifique, BP 166, F-38042, Grenoble Cedex 9, France*

[c] *Department of Chemistry, Technion – Israel Institute of Technology, Haifa 32000, Israel*

Received 17 July 1997; revised manuscript received 10 December 1997; accepted for publication 10 December 1997

Communicated by C.R. Doering

Abstract

We describe a quantum information processor (quantum computer) based on the hyperfine interactions between the conduction electrons and nuclear spins embedded in a two-dimensional electron system in the quantum-Hall regime. Nuclear spins can be controlled individually by electromagnetic pulses. Their interactions, which are of the spin-exchange type, can be possibly switched on and off pair-wise dynamically, for nearest neighbors, by controlling impurities. We also propose the way to feed in the initial data and explore ideas for reading off the final results.

CERN-TH.3913

THE EFFECTIVE ACTION FOR PHOTONS IN (2+1) DIMENSIONS

Richard J. Hughes

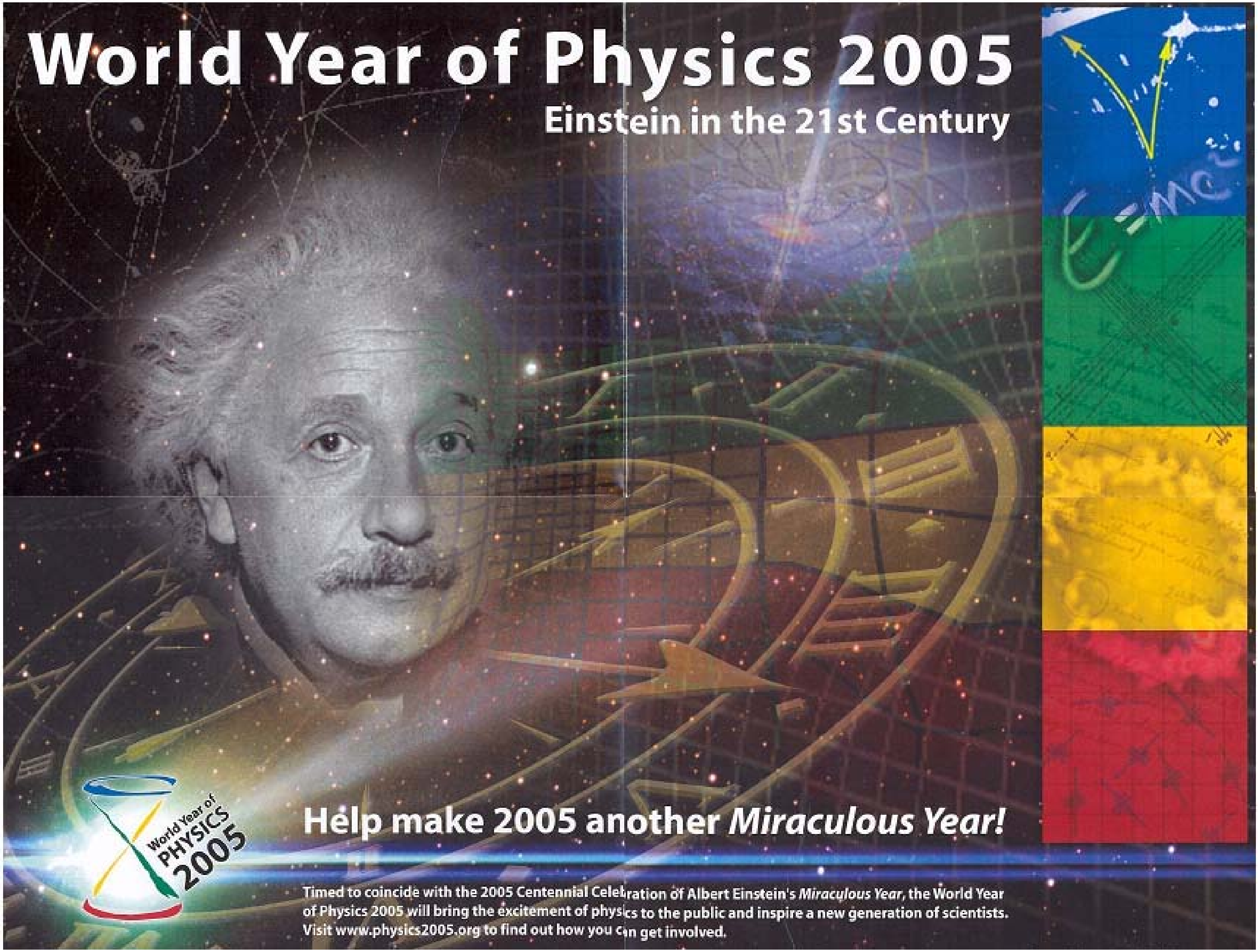
CERN - Geneva

QUANTUM HALL EFFECT and VACUUM

A B S T R A C T

The topological mass term in the Euler-Heisenberg effective action for (2+1) dimensional spinor QED is studied by functional and canonical methods. The mass term is associated with a quantum Hall effect in the vacuum, and with a vacuum charge in the special case of a pure magnetic field. This charge is shown to become depleted at non-zero temperature.

QHE and the Einstein Year
(25th, 50th, and 100th anniversary)



QUANTUM HALL EFFECT and GRAVITATION

A Four-Dimensional Generalization of the Quantum Hall Effect

Shou-Cheng Zhang and Jiangping Hu

We construct a generalization of the quantum Hall effect, where particles move in four dimensional space under a $SU(2)$ gauge field. This system has a macroscopic number of degenerate single particle states. At appropriate integer or fractional filling fractions the system forms an incompressible quantum liquid. Gapped elementary excitation in the bulk interior and gapless elementary excitations at the boundary are investigated.

PhysicsWeb: **The work by Shou-Cheng Zhang and Jianping Hu of Stanford University in California and Tsinghua University in China might even represent a small step towards one of the ultimate goals in theoretical physics - a quantum theory of gravity (S-C Zhang and J Hu 2001 *Science* 294 823).**

VOLUME 93, NUMBER 9 PHYSICAL REVIEW LETTERS week ending 27 AUGUST 2004

Is the Quantum Hall Effect Influenced by the Gravitational Field?

Friedrich W. Hehl,[1,2,*] Yuri N. Obukhov,[1,3,†] and Bernd Rosenow[1,‡]

[1]*Institut für Theoretische Physik, Universität zu Köln, 50923 Köln, Germany*

[2]*Department of Physics and Astronomy, University of Missouri–Columbia, Columbia, Missouri 65211, USA*

[3]*Department of Theoretical Physics, Moscow State University, 117234 Moscow, Russia*

(Received 13 October 2003; published 26 August 2004)

Most of the experiments on the quantum Hall effect (QHE) were made at approximately the same height above sea level. A future international comparison will determine whether the gravitational field $\mathbf{g}(x)$ influences the QHE. In the realm of $(1 + 2)$-dimensional phenomenological macroscopic electrodynamics, the Ohm-Hall law is metric independent ("topological"). This suggests that it does not couple to $\mathbf{g}(x)$. We corroborate this result by a microscopic calculation of the Hall conductance in the presence of a post-Newtonian gravitational field.

DOI: 10.1103/PhysRevLett.93.096804 PACS numbers: 73.43.Cd, 03.50.De, 04.20.–q, 73.43.Fj

Published by Institute of Physics Publishing for SISSA/ISAS
Received: *April 8, 2002*
Accepted: *May 21, 2002*

QUANTUM HALL EFFECT and STRING THEORY

Higher-dimensional quantum Hall effect in string theory

Contents

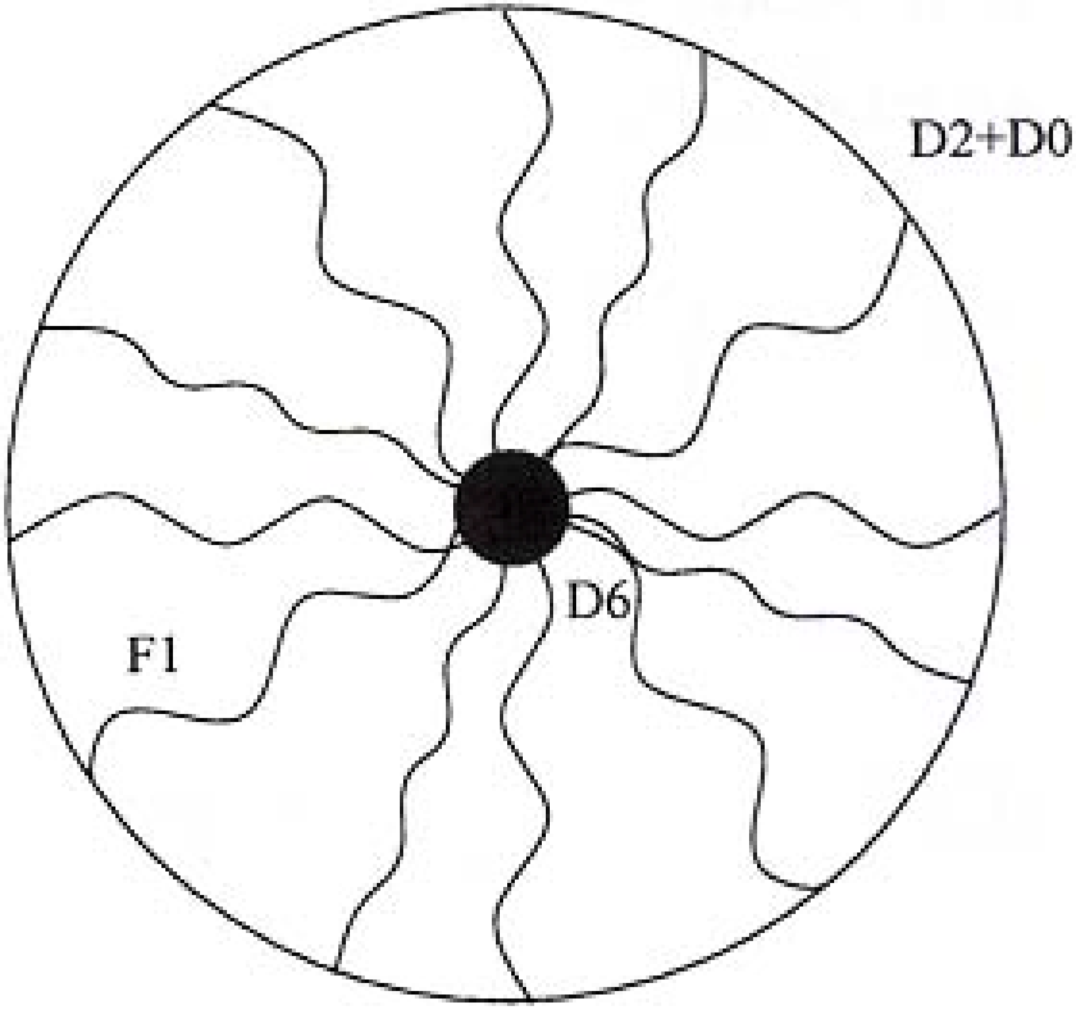


Fig1: This picture shows a string theory realization of the 2+1d **quantum Hall effect** on a two-sphere.

*(from M. Fabinger in Journal High Energy Physics,**5** (2002) 037)*

THE PHYSICAL REVIEW
AND
PHYSICAL REVIEW LETTERS
(PUBLISHED FOR THE AMERICAN PHYSICAL SOCIETY)
BROOKHAVEN NATIONAL LABORATORY, UPTON, LONG ISLAND, NEW YORK 11973
TELEPHONE (516) 345-2540
(516) 924-5533

OUR NEW ADDRESS:
1 RESEARCH ROAD
BOX 1000
RIDGE, NEW YORK 11961

June 25, 1980

Dr. K.v. Klitzing
Physikalisches Institut der
Universität Würzburg
D-8700 Würzburg
Federal Republic of Germany

Dear Dr. Klitzing:

The manuscript by

K.v. Klitzing, G. Dorda, and M. Pepper

entitled:

IN REPLY REFER TO
LS1509

Realization of a resistance standard based on fundamental constants

has been reviewed by our referee(s). On the basis of the resulting report(s), we judge that the paper is not suitable for publication in Physical Review Letters in its present form, but might be made so by appropriate revision. Pertinent criticism extracted from the report(s) is enclosed. While we cannot made a definite commitment, the probable course of action if you choose to resubmit is indicated below.

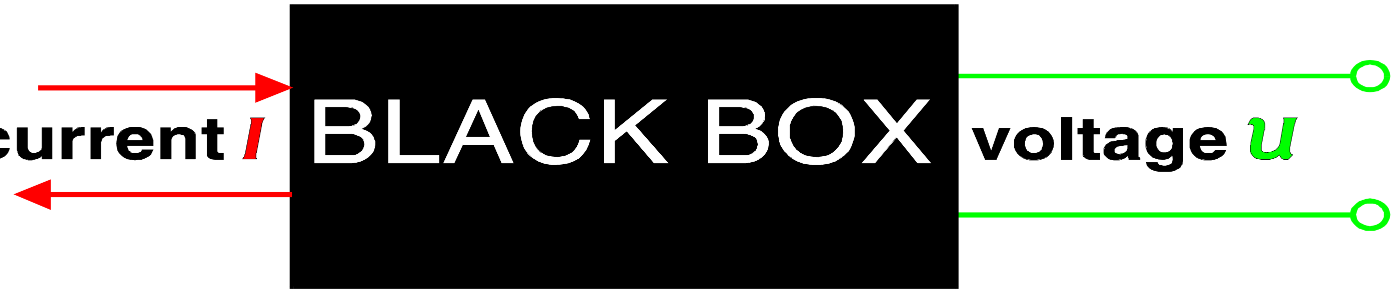
( ) Acceptance, if the editors can judge that all or most of the criticism has been met.

( ) ~~Return~~ to the original referee(s) for judgement.

(✓) Submittal to new referee(s) for judgement.

FINAL RESULT OF

QUANTUM HALL EFFECT (QHE)



(Hall-) Resistance $R_H = U/I$

The “BLACK BOX”
(MOSFET at low temperatures in high magnetic fields)
has always the resistance value R_H = 25812,807 Ohm

INSTITUTE OF PHYSICS PUBLISHING METROLOGIA
Metrologia **40** (2003) 217-223 PII: S0026-1394(03)65585-4

Revised technical guidelines for reliable dc measurements of the quantized Hall resistance

F Delahaye[1] and B Jeckelmann[2]

[1] Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres Cedex, France
[2] Swiss Federal Office of Metrology and Accreditation, Lindenweg 50, CH-3003 Bern-Wabern, Switzerland

Received 30 May 2003
Published OCTOBER 2003
Online at stacks.iop.org/Met/40

Abstract
This paper describes the main tests and precautions necessary for both reproducible and accurate results in the use of the quantum Hall effect as a means to establish a reference standard of dc resistance having a relative uncertainty of a few parts in 10^9.

QUANTIZED HALL RESISTANCE IN SI OHM (up to 1990)

CSIRO, Australia	25 812.809 (2) Ω
NPL, UK	25 812.809 (1) Ω
BNM-LCIE, France	25 812.802 (6) Ω
ETL, Japan	25 812.806 (6) Ω
NIST, USA	25 812.807 (1) Ω
VNIIM, Russia	25 812.806 (8) Ω
VSL, Netherland	25 812.802 (5) Ω
NRC, Canada	25 812.814 (6) Ω
EAM, Switzerland	25 812.809 (4) Ω
PTB, Germany	25 812.802 (3) Ω
NIM, China	25 812.805 (16) Ω
CSIRO/BIPM	25 812.809 (2) Ω
CSIRO/Japan	25 812.813 (2) Ω

BEST VALUE (1990): R_K=25 812.807 (5) Ω

R_{K-90}=25 812.807 000 Ω

Recommendations Comité International des Poids et Mesures

(October 4-6, 1988)

recommends

- that 25 812,807 Ω exactly be adopted as a conventional value, denoted by R_{K-90}, for the von Klitzing constant, R_K,
- that this value be used from 1st January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,
- that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with R_{K-90},
- that in the use of the quantum Hall effect to establish a laboratory reference standard of resistance, laboratories follow the most recent edition of the technical guidelines for reliable measurements of the quantized Hall resistance drawn up by the Comité Consultatif d'Electricité and published by the Bureau International des Poids et Mesures,

and is of the opinion

- that no change in this recommended value of the von Klitzing constant will be necessary in the foreseeable future.

http://physics.nist.gov/

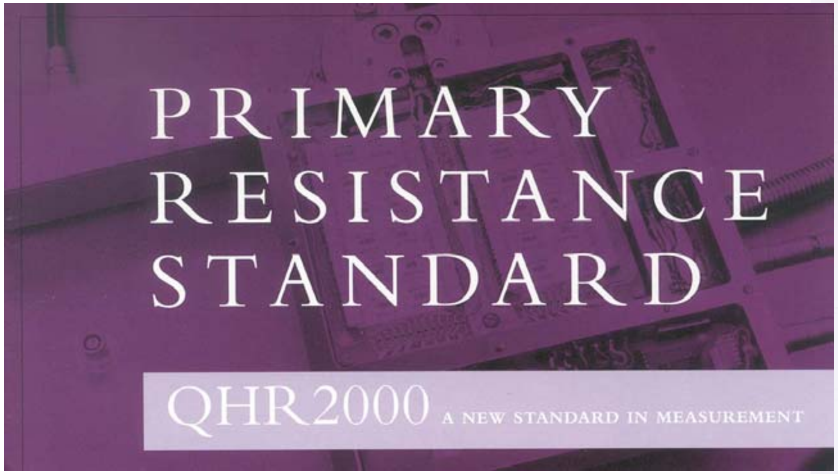
The NIST Reference on Constants, Units, and Uncertainty

Source: ~~1998~~ 2002 CODATA recommended values

the conventional value is by definition constant!

von Klitzing constant R_K in SI units		conventional value of von Klitzing constant R_{K-90}	
Value	25 812.807 ~~572~~ 449 Ω	Value	25 812.807 Ω
Standard uncertainty	0.000 ~~095~~ 86 Ω	Standard uncertainty	(exact)
Relative standard uncertainty	3.~~7~~ 3 x 10^{-9}	Relative standard uncertainty	(exact)
Concise form	~~25 812.807 572(95) Ω~~ 25 812.807 449 (86) Ω	Concise form	25 812.807 Ω

This label on calibrated resistors indicate, that the calibration is based on the *conventional value* for the **von Klitzing constant R_{K-90}** fixed (without uncertainty) in 1990

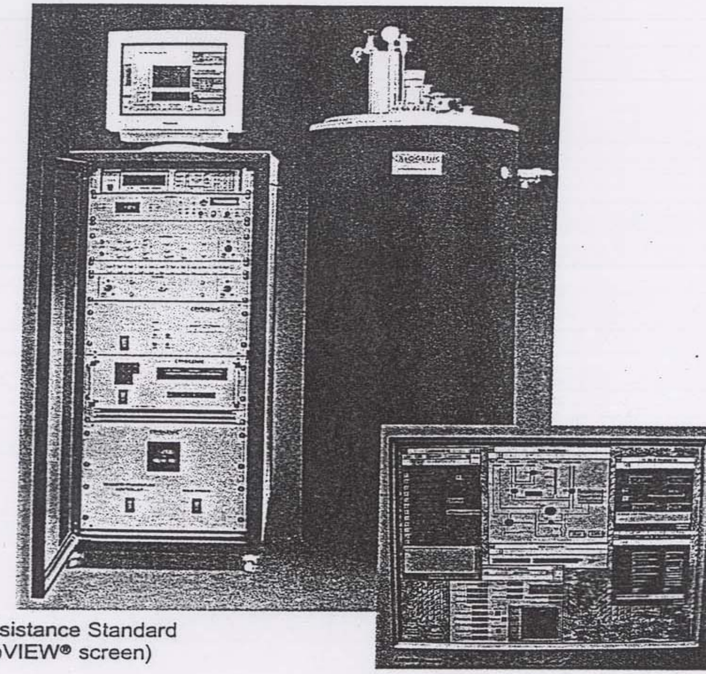


EVERYONE IN THE WORLD

(if he spends about 300 T€ for this equipment)

IS ABLE TO CALIBRATE RESISTANCES WITH AN UNCERTAINTY OF LESS THAN 10^{-8}

"The better choice for your Primary Resistance Standard - QHR2000"



Quantum Hall Resistance Standard
(Inset; typical LabVIEW® screen)

The QHR2000 is a primary resistance standard system developed by Cryogenic Ltd. based upon the Quantum Hall Effect. It allows calibration of a nominally 100Ω standard resistor against the von Klitzing constant with a precision of 10^{-8}.

The Cryogenic Current Comparator (CCC) used enables precision measurement and control to 10^{-9}. It may be used independently to carry out very accurate bridge circuit measurements.

CRYOGENIC
CRYOGENIC LIMITED

For further information please contact us at:
Unit 30, Acton Park Industrial Estate. The Vale,
London W3 7QE. UK
Tel: +44 181 743 6049 Fax: +44 181 749 5315
E-mail: cryogenic@cix.compulink.co.uk

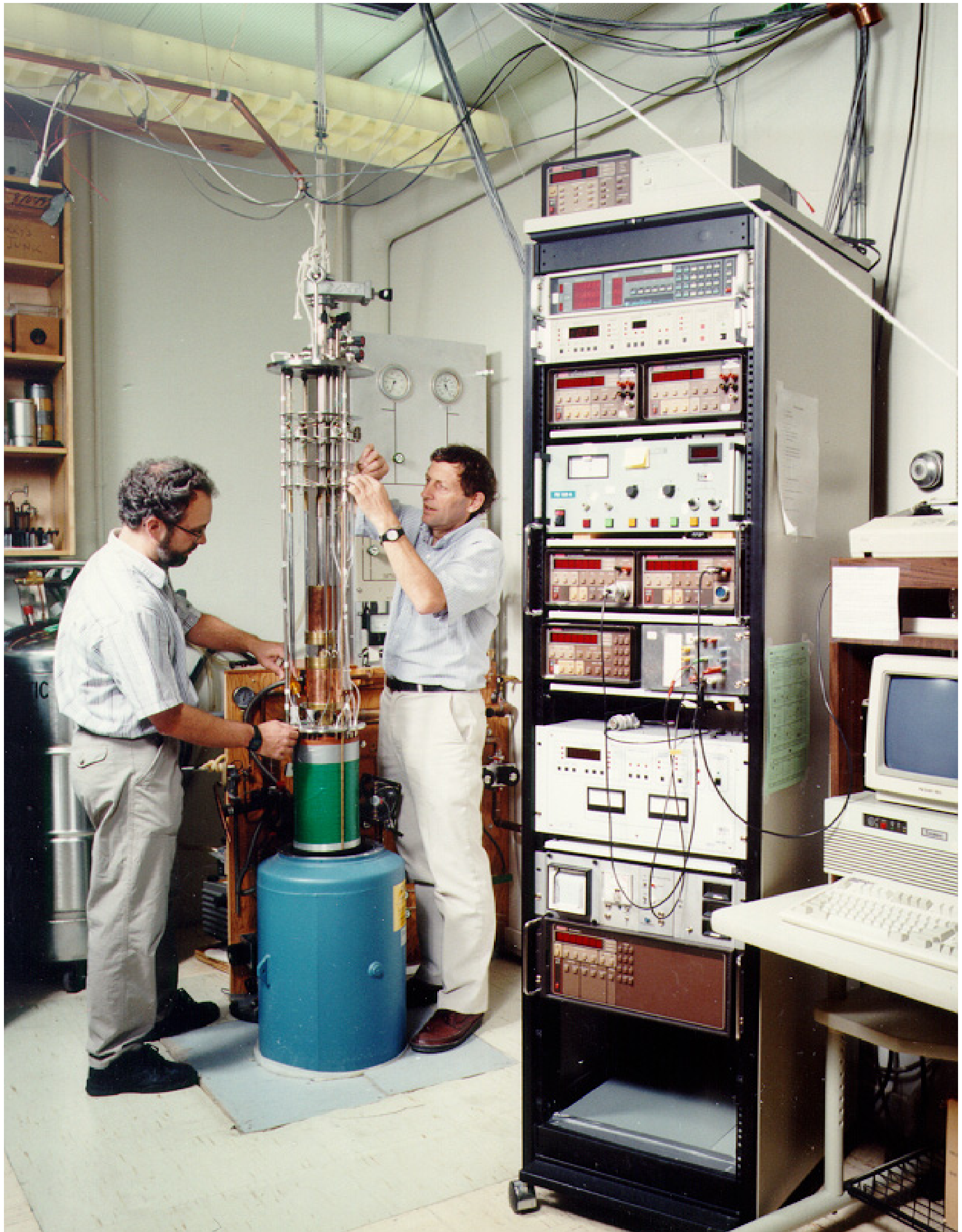
® National Instruments

The QHR2000's principle features are:-

- Comparison of the 100Ω standard with R_K to 1 part in 10^8.
- Precision comparison of 100Ω standard to resistances from 1Ω to 10kΩ.
- Portable CCC insert for independent use with low LHe consumption.
- LabVIEW® software for automated operation, measurement and analysis.
- 14 Tesla magnet at 4.2K allowing easy use of plateaux up to n=2.
- Fully shielded, a screened room is not required.

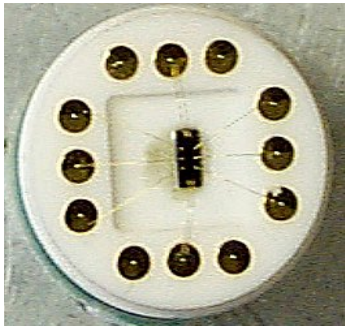
INSERT 10 ON REPLY CARD

DC Quantum Hall - Resistance

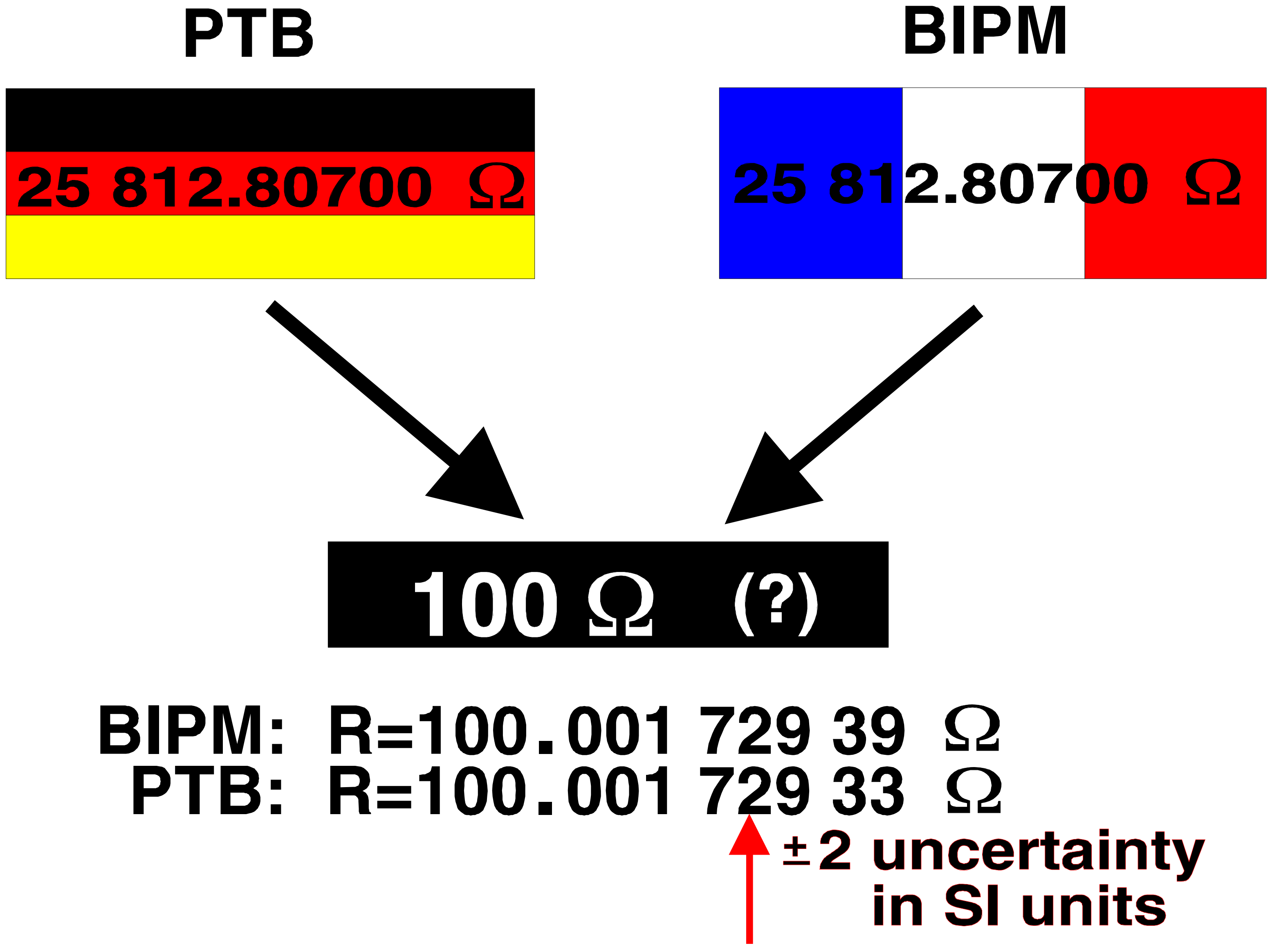


Primary Standard

14T Magnet
^{3}He Cryostat
CCC Bridge
DC samples from

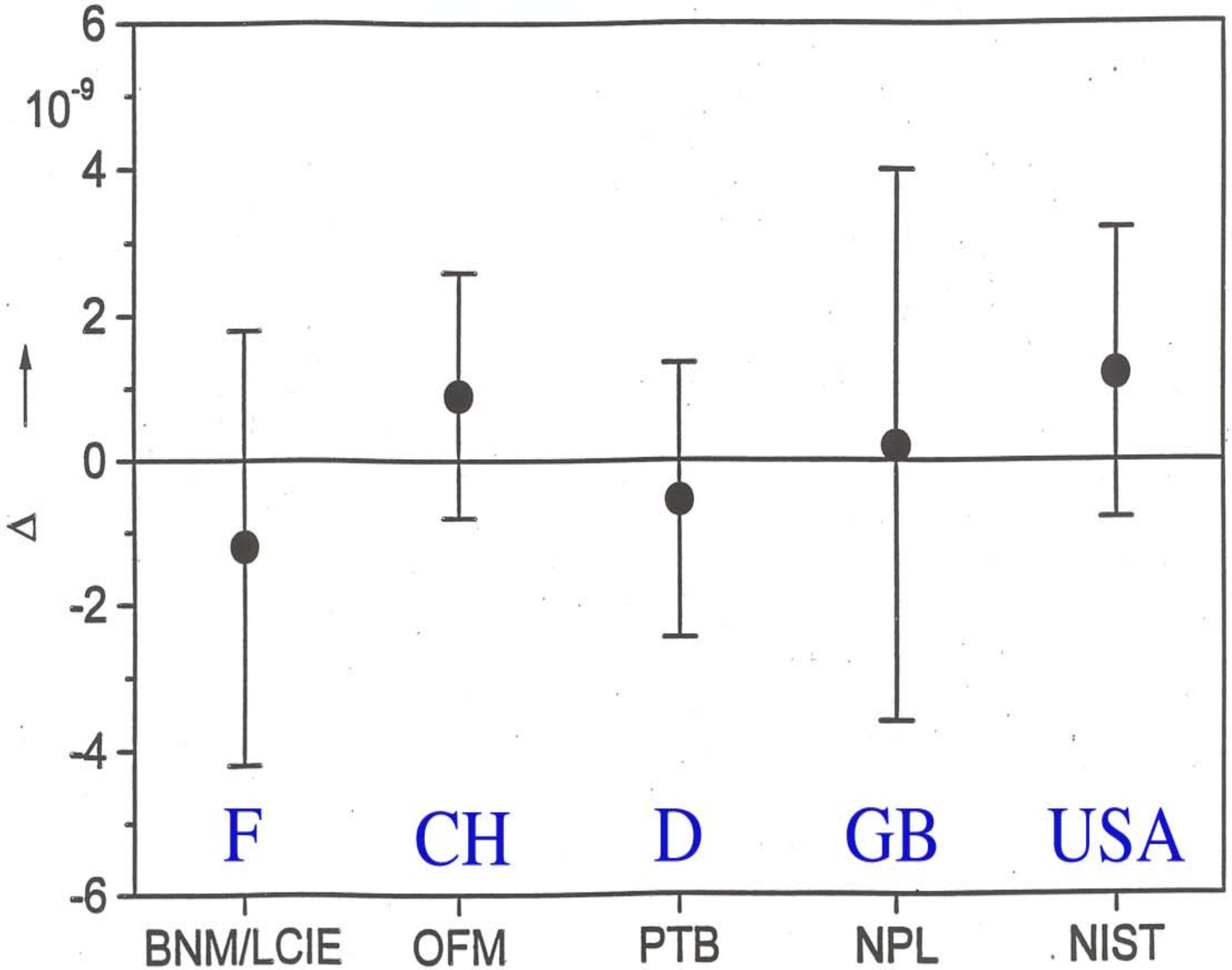


LEP, DFM
PTB, OFMET
NRC, ...


PTB
25 812.80700 Ω
BIPM
25 812.80700 Ω
100 Ω (?)
BIPM: R=100.001 729 39 Ω
PTB: R=100.001 729 33 Ω
±2 uncertainty
in SI units

Electrical resistances calibrated on the basis of the QHE agree within an uncertainty of about $2 \cdot 10^{-9}$

(but the resistance value in SI Ohm is only known within $2 \cdot 10^{-7}$)



CODATA *Recommended Values of the Fundamental Physical Constants*

J.Phys.Ref.Data, Vol.28,No.6, 1999

The theory of the QHE predicts, and the experimentally observed universality of R_K is consistent with the prediction, that

$$R_K = \frac{h}{e^2} = \frac{\mu_0 c}{2\alpha} \approx 25\,813\ \Omega,$$

Is this exact without any correction??

NEW RESISTOR WITH

$R_K = h/e^2$

DETERMINATION

OF $R_K = h/e^2$

IF A RESISTOR CALIBRATED IN

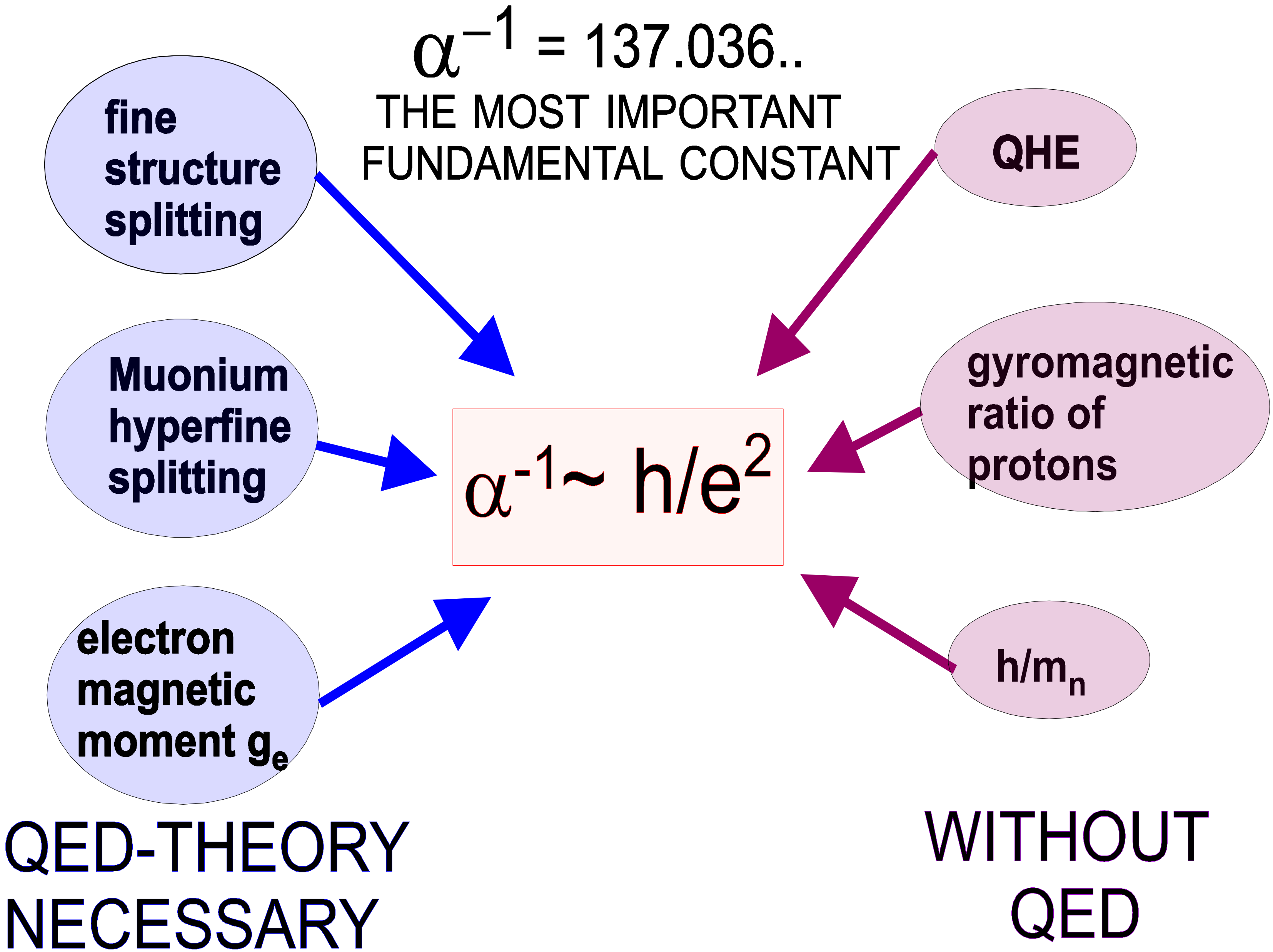
SI UNITS IS AVAILABLE

RESISTANCE STANDARD

(WITH FIXED R_{K-90})

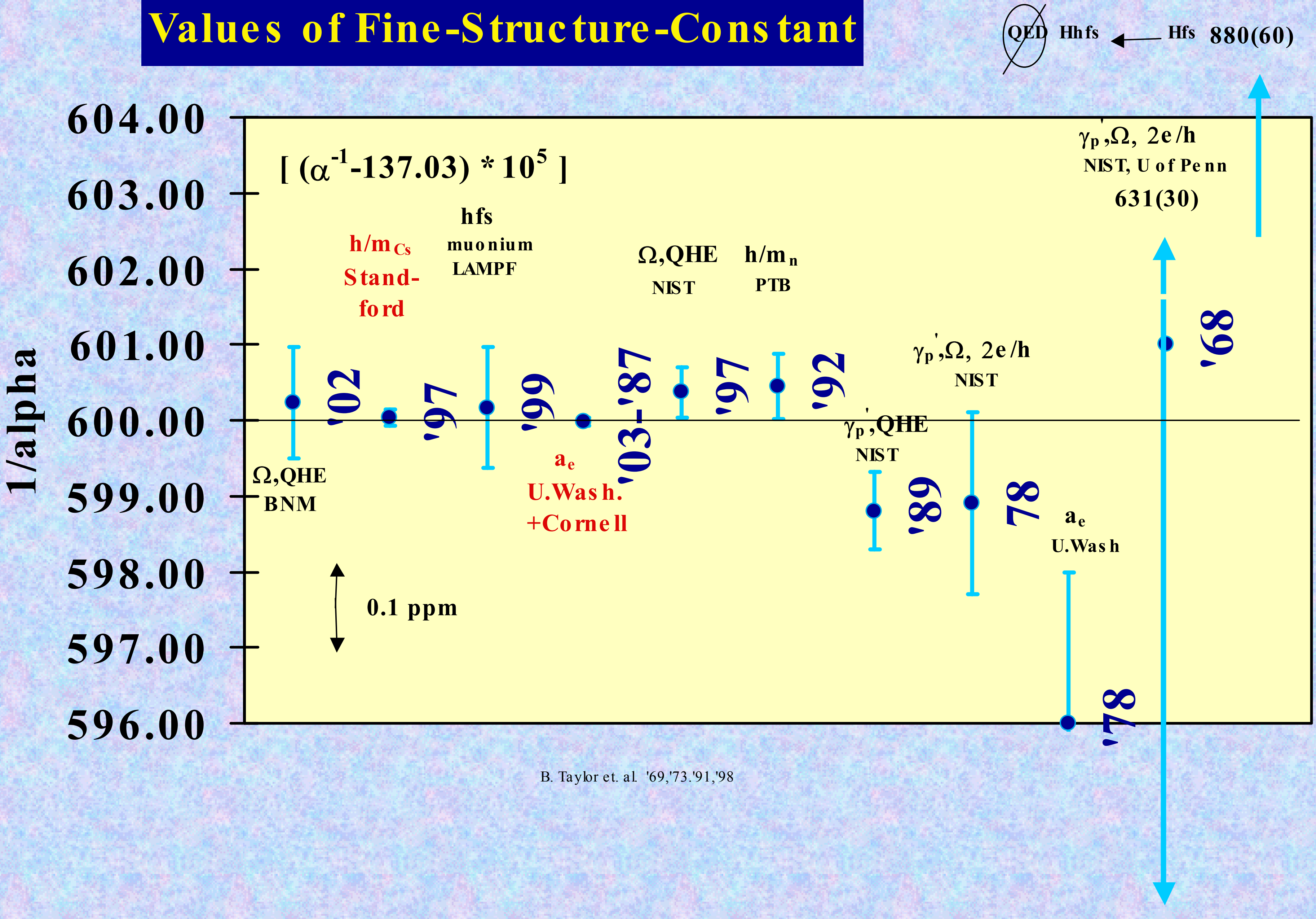
SIMILAR TO THE APPLICATION

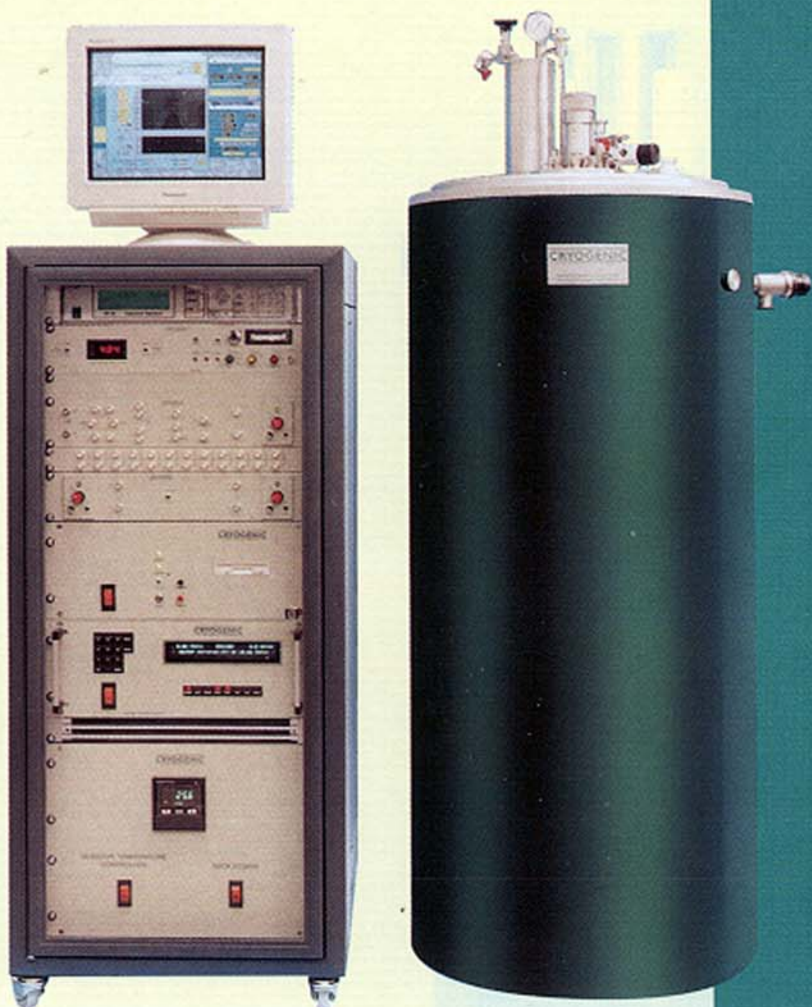
OF THE JOSEPHSON EFFECT



$\alpha^{-1} = 137.036..$
THE MOST IMPORTANT
FUNDAMENTAL CONSTANT
fine structure splitting
Muonium hyperfine splitting
electron magnetic moment g_e
$\alpha^{-1} \sim h/e^2$
QHE
gyromagnetic ratio of protons
h/m_n
QED-THEORY NECESSARY
WITHOUT QED

Values of Fine-Structure-Constant



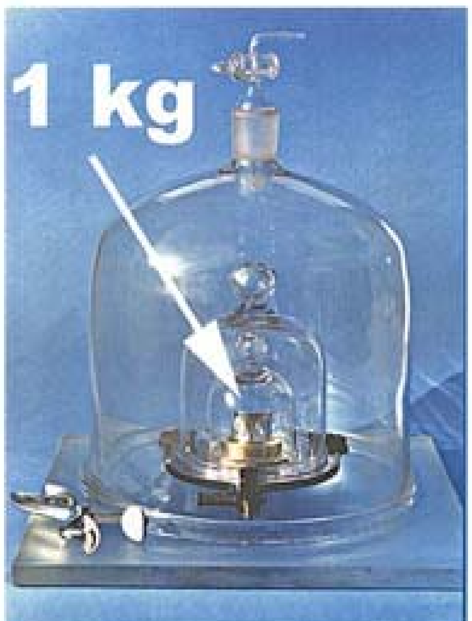


NEW QHR MAGNET FOR THE NPL

Cryogenic has been selected once again by the National Physical Laboratory (NPL) to design and manufacture a high field magnet complete with a low loss cryostat for Quantum Hall Metrology. The magnet has been delivered for use as a Quantum Hall Resistance transfer standard. It will form part of a basic physics and fundamental constant experiment, which seeks to determine the kilogram in terms of electrical standards. This follows a successful delivery of a similar project carried out for the Physikalisch-Technische Bundesanstalt (PTB) in Germany last year. The system is installed in a stainless steel cryostat and provides a 14 Tesla magnetic field.

Cryogenic have also supplied the NPL with a glass fibre helium cryostat with HTS leads to be used for their 100 Amp Cryogenic Current Comparator for precision metrology.

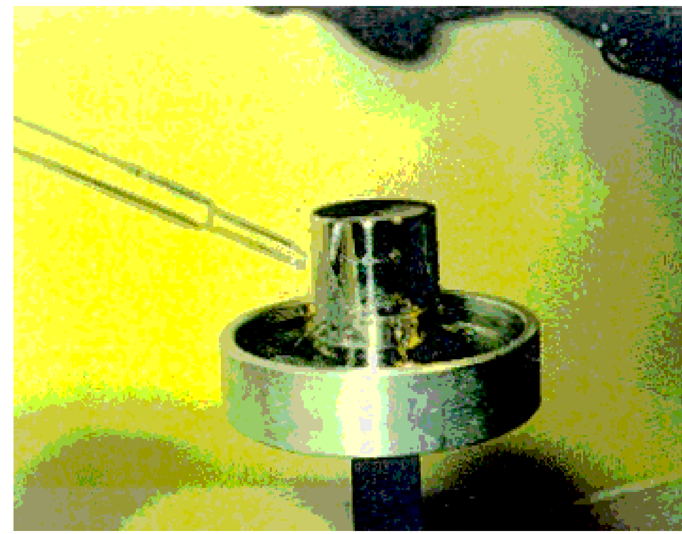
SI unit of mass



Safe in Paris

"The Kilogram is equal to the mass of the International Prototype of the Kilogram **after cleaning and washing using the BIPM method."**

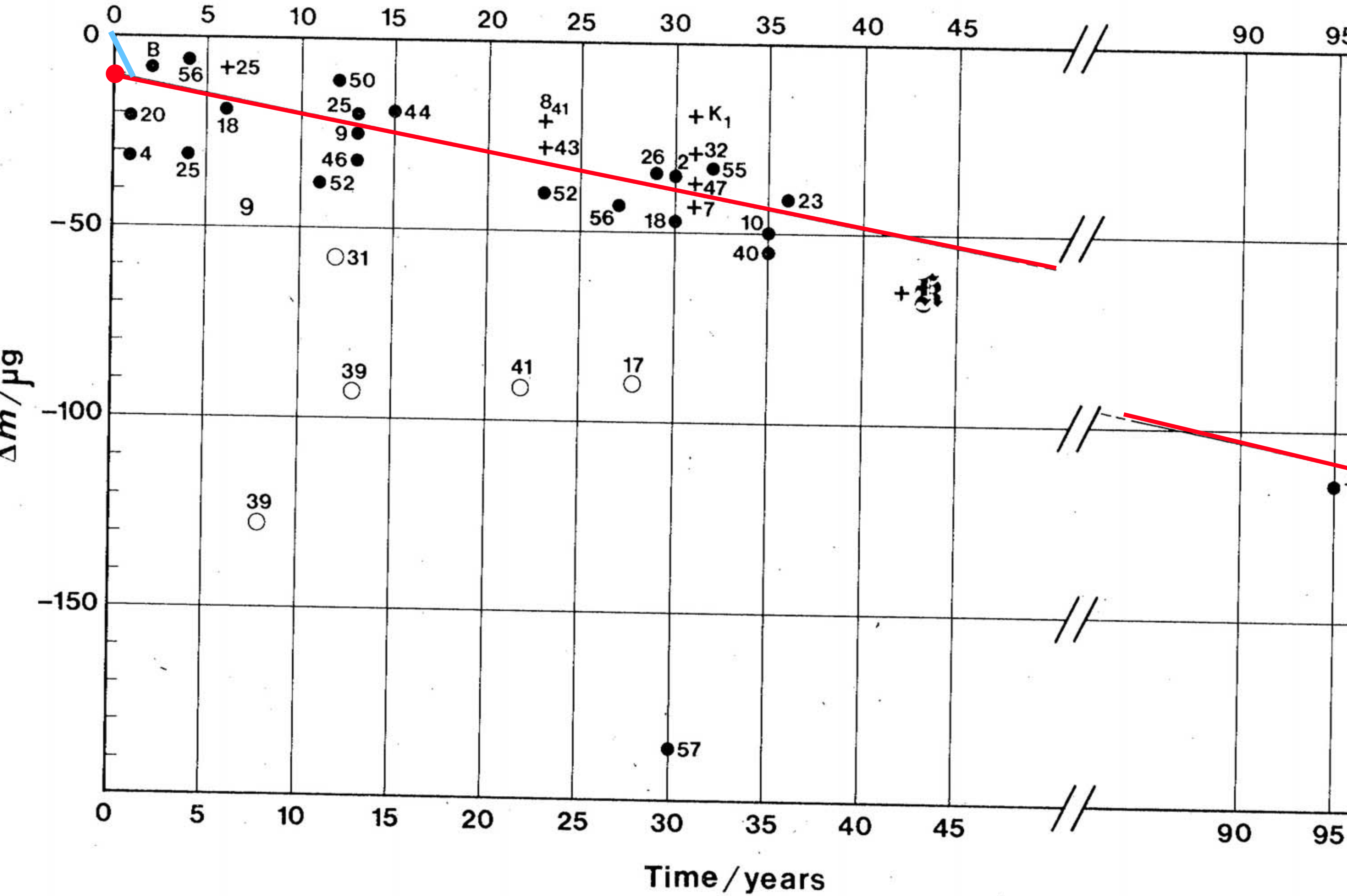
(CIPM, 1989)



BIPM Cleaning Method

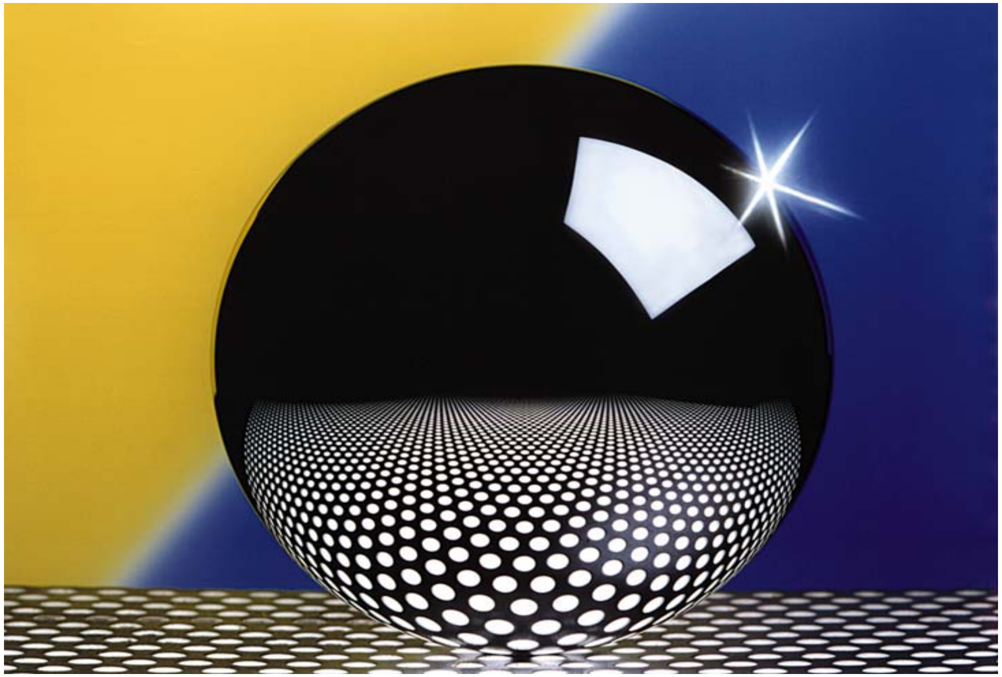
- Rub artifact with chamois cloth soaked in ether / alcohol mixture.
- Wash in a jet of steam.

mass change after cleaning



Alternative realization of the unit of mass:

The kilogram is a certain number of silicon atoms



Why not

$$E = mc^2 \quad \text{(EINSTEIN)}$$

together with

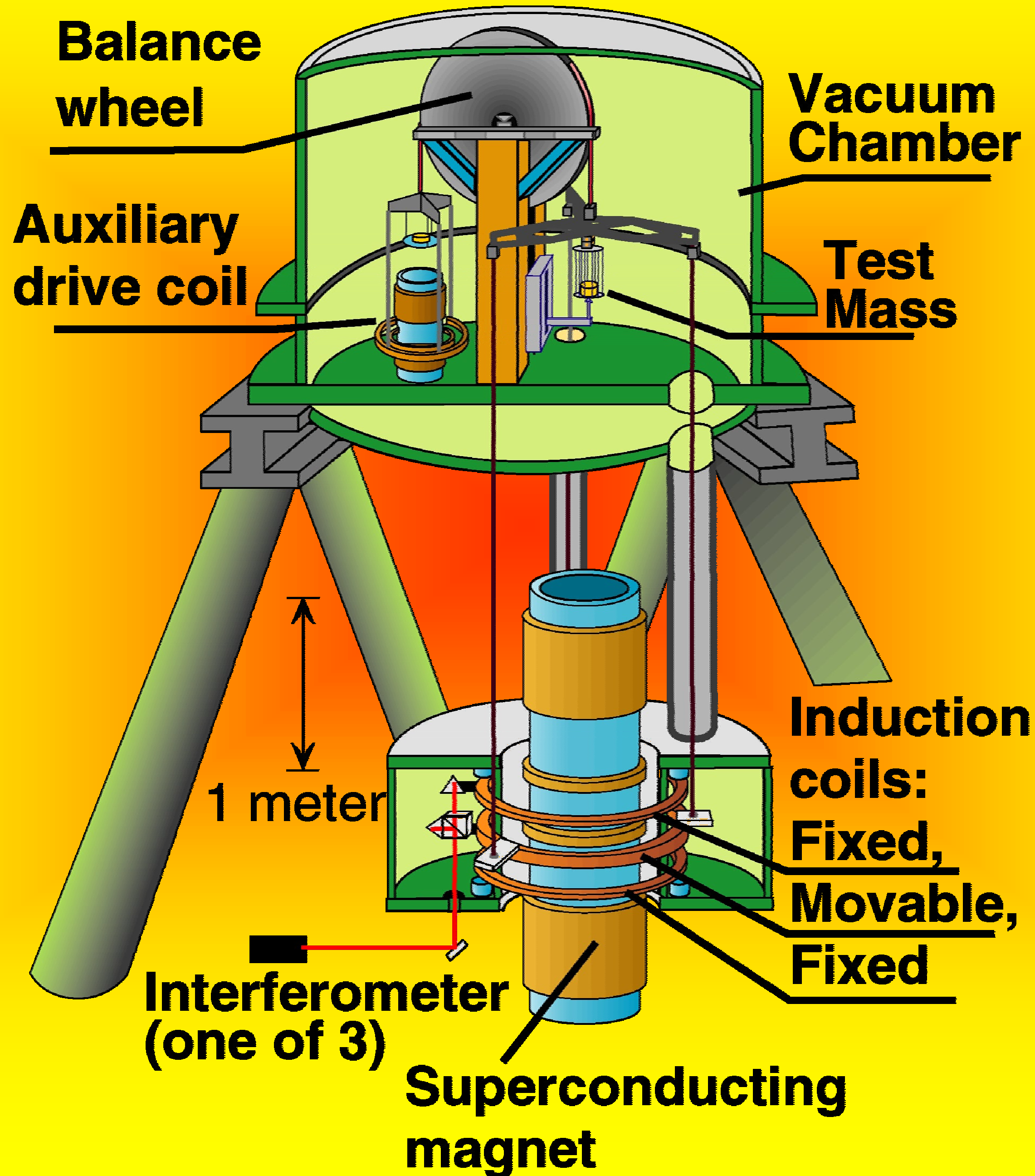
$$E = h\nu \quad \text{(PLANCK)}$$

$$m = h\nu/c^2$$

A new building for the Watt balance (using QHE)

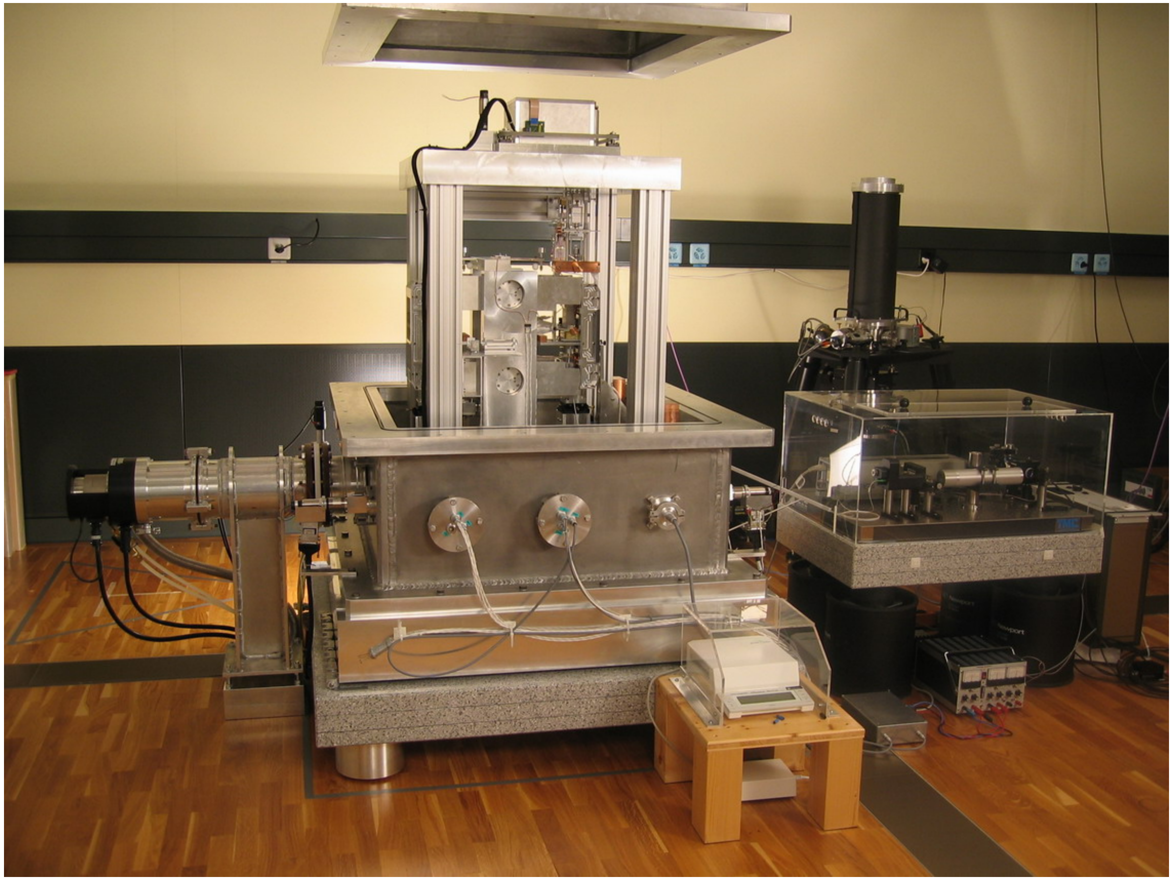
National Institute of Standards and Technology

Technology Administration, U.S. Department of Commerce

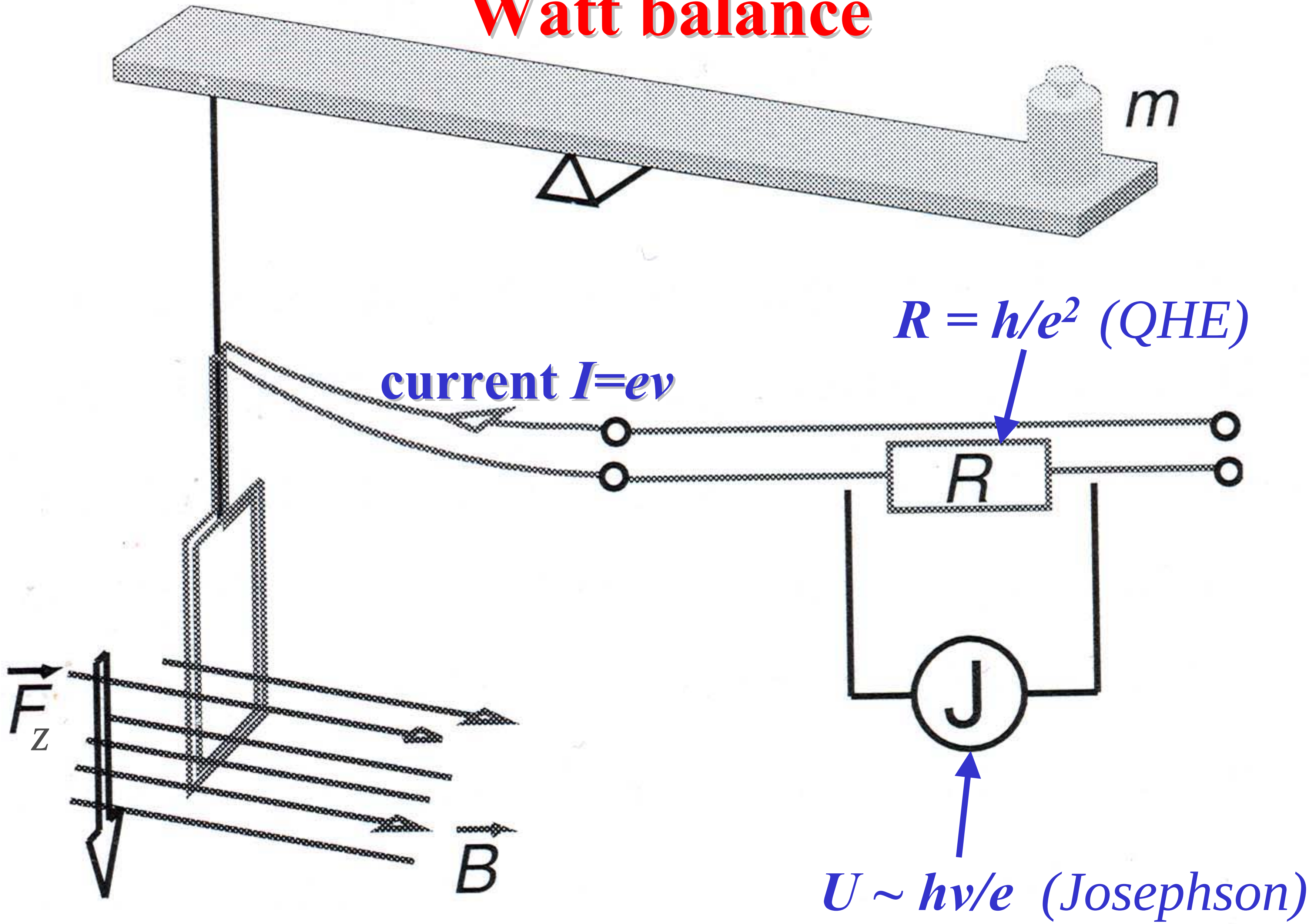

Balance wheel
Vacuum Chamber
Auxiliary drive coil
Test Mass
1 meter
Induction coils:
Fixed,
Movable,
Fixed
Interferometer (one of 3)
Superconducting magnet

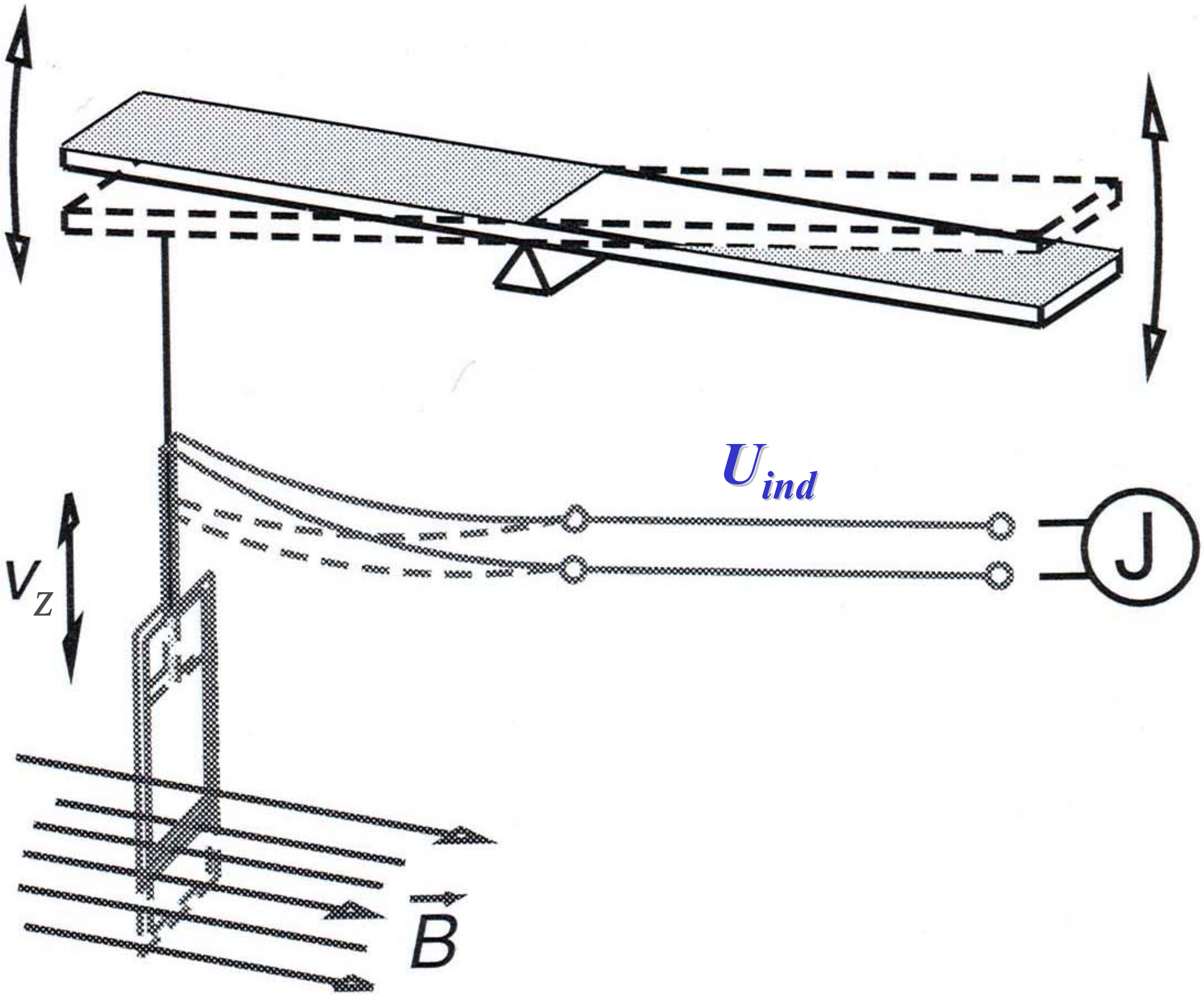
The **metas** watt balance

(Switzerland)



Watt balance





U_{ind}
J
v_z
$\vec{B}$

$$F = -\partial \Phi / \partial z \cdot I$$

$$U_{ind} = -\partial \Phi / \partial z \; v$$

$$U_{ind} \cdot I = F \cdot v$$

$\sim h/e$ $\sim e$ $m \cdot g$

The most inaccurate quantities in this equation are the Planck constant h and the mass m

$h \sim m$

$g = 9.780..m/s^2$ at equator

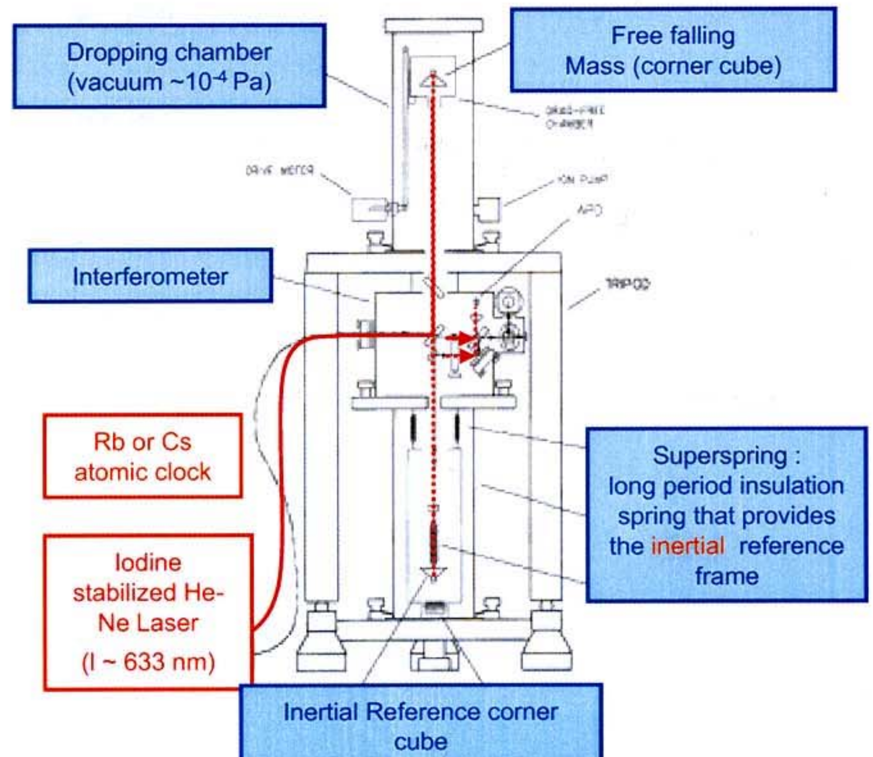
$g = 9.832..m/s^2$ at north pole

Absolute Gravimeter

(FG5 from Micro-g Solutions Inc.)

Free fall trajectory of an optical object in vacuum

Accuracy: 2×10^{-8} m/s^2 (2 parts in 10^9)



Accurate Measurement of the Planck Constant

Edwin R. Williams,* Richard L. Steiner,* David B. Newell,* and Paul T. Olsen†
National Institute of Standards and Technology,‡ Gaithersburg, Maryland 20899
(Received 1 July 1998)

Using a moving coil watt balance, electric power measured in terms of the Josephson and quantum Hall effects is compared with mechanical power measured in terms of the meter, kilogram, and second. We find the Planck constant $h = 6.626\,068\,91(58) \times 10^{-34}$ J s. The quoted standard uncertainty (1 standard deviation estimate) corresponds to $(8.7 \times 10^{-8})h$. Comparing this measurement to an earlier measurement places an upper limit of 2×10^{-8}/yr on the drift rate of the SI unit of mass, the kilogram. [S0031-9007(98)07164-6]

PACS numbers: 06.20.Jr, 06.20.Fn, 06.30.Dr

TABLE I. Fundamental constants improved by this measurement and values used to calculate them. The International Committee for Weights and Measures, CIPM, adopted the indicated values in 1990 [2]. u_r means relative standard uncertainty.

Constant	Symbol	Value	Unc. u_r (10^{-8})
Planck constant	h	$6.626\,068\,91(58) \times 10^{-34}$ J s	8.7 this work
Josephson constant (SI)	$K_J = 2e/h$	483 597.892(21) GHz/V	4.4 this work
Electron mass	m_e	$9.109\,382\,11(80) \times 10^{-31}$ kg	8.8 this work
Proton mass	m_p	$1.672\,621\,62(15) \times 10^{-27}$ kg	8.9 this work
Avogadro constant	N_A	$6.022\,141\,84(52) \times 10^{23}$ mole^{-1}	8.7 this work
Elementary charge	e	$1.602\,176\,48(7) \times 10^{-19}$ C	4.4 this work
Josephson constant	$K_{J\text{-}90}$	483 597.9 GHz/V	exact (CIPM)
von Klitzing constant	$R_{K\text{-}90}$	25 812.807 Ω	exact (CIPM)
1/(fine-structure constant)	$1/\alpha$	137.035 999 93(52)	0.38[a]
Rydberg constant	R_∞	10 973 731.568 639(91) m^{-1}	0.000 83[b]
Electron's atomic mass	m_e/m_u	0.000 548 579 911 1(12)	0.021[c]

[a]Reference [3]. [b]Reference [4]. [c]Reference [5].

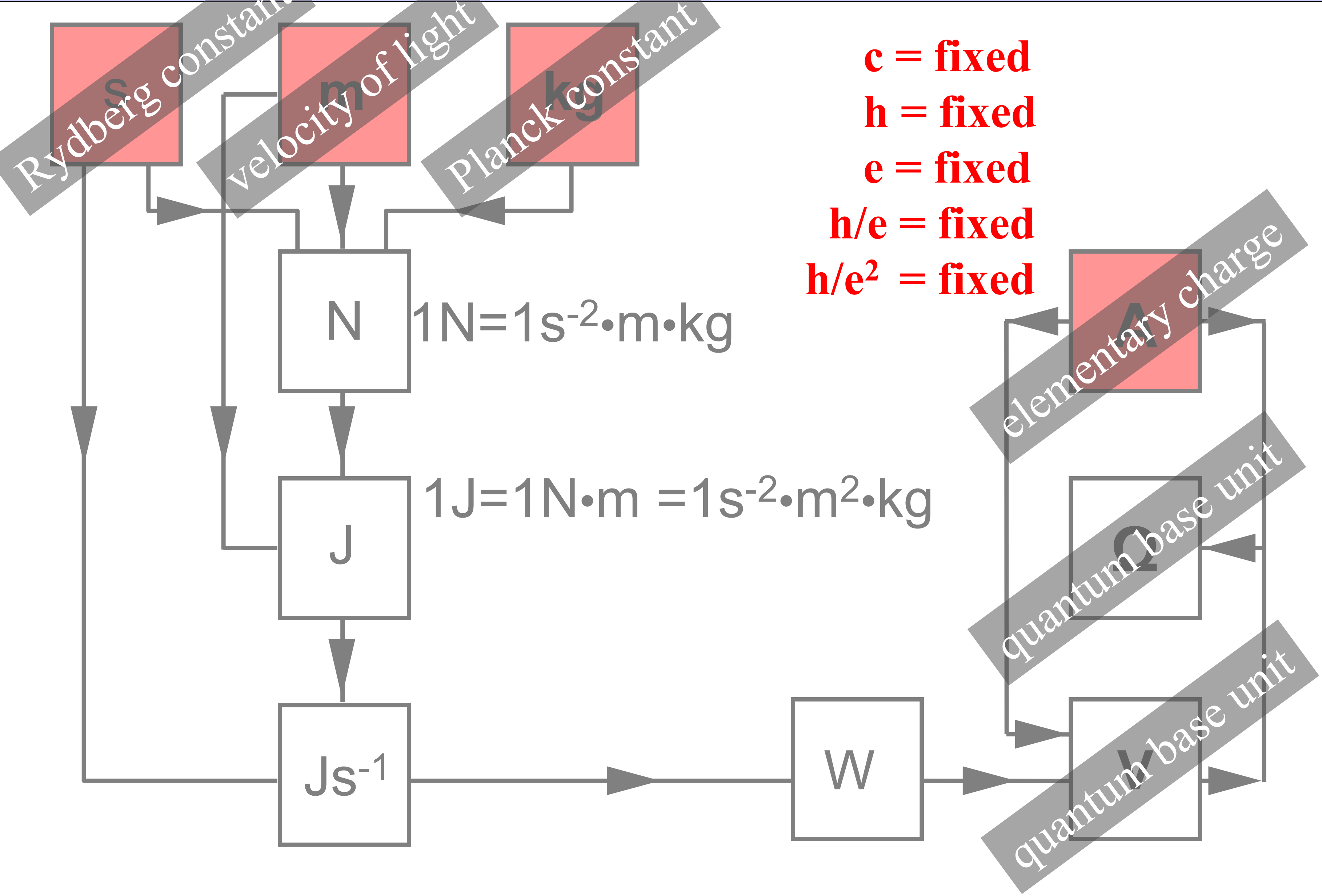
A possibility for a new definition of the kilogram:

The kilogram is the mass, which by comparison of mechanical and electrical power results in a value of the Planck constant of

h=6.626 068 91 x 10^{-34} Js (exact).

(electrical power: $U^2/R \sim h$)

International System (basic SI units)



Physics of the QHE

a) two-dimensional electron gas (2DEG)

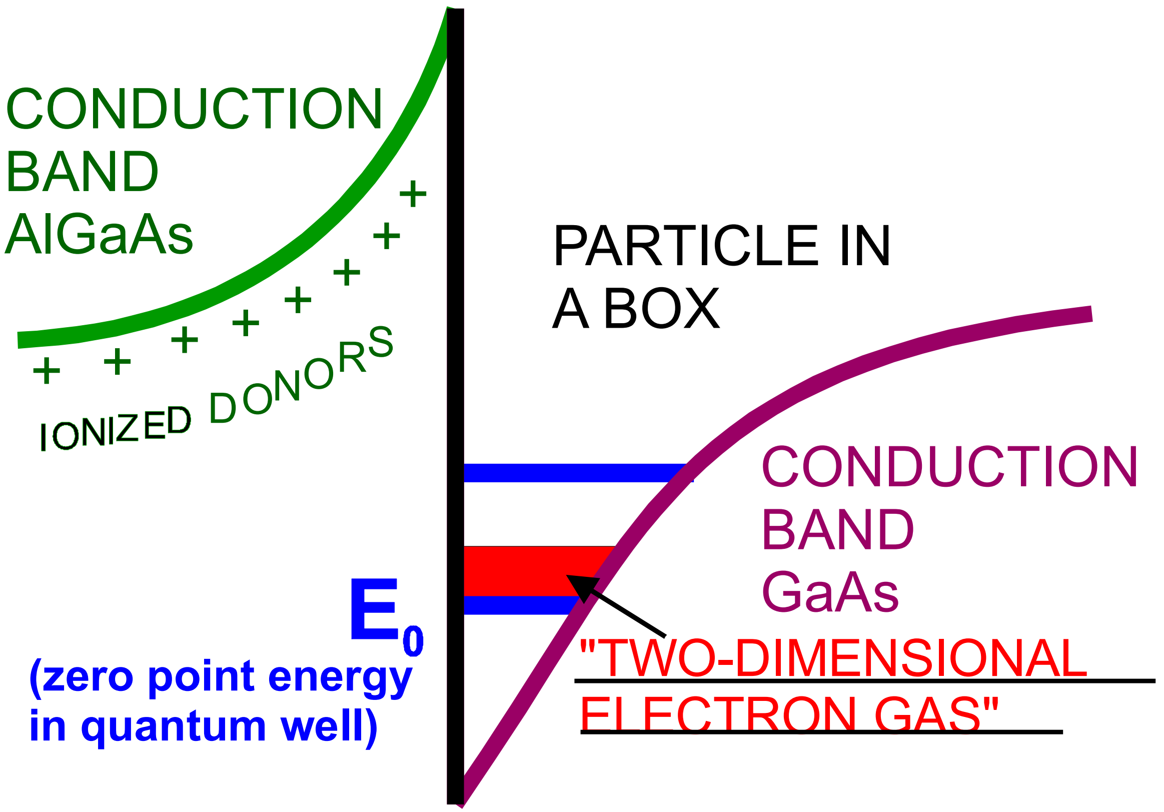
b) electrons in strong magnetic field

c) disorder

d) edge phenomena

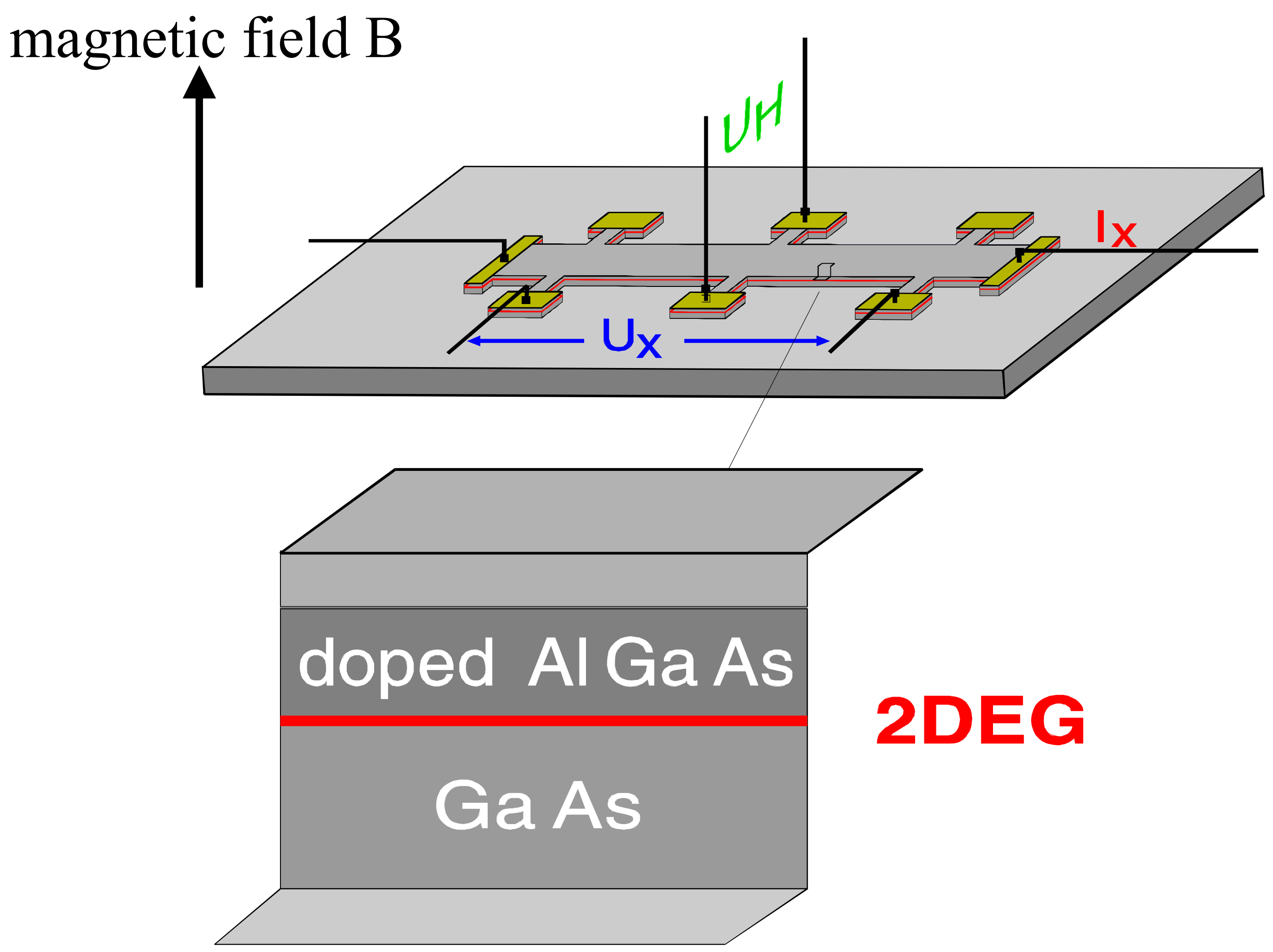
e) FQHE

2DEG = 2-Dimensional Electronen Gas = HEMT, TEGFET

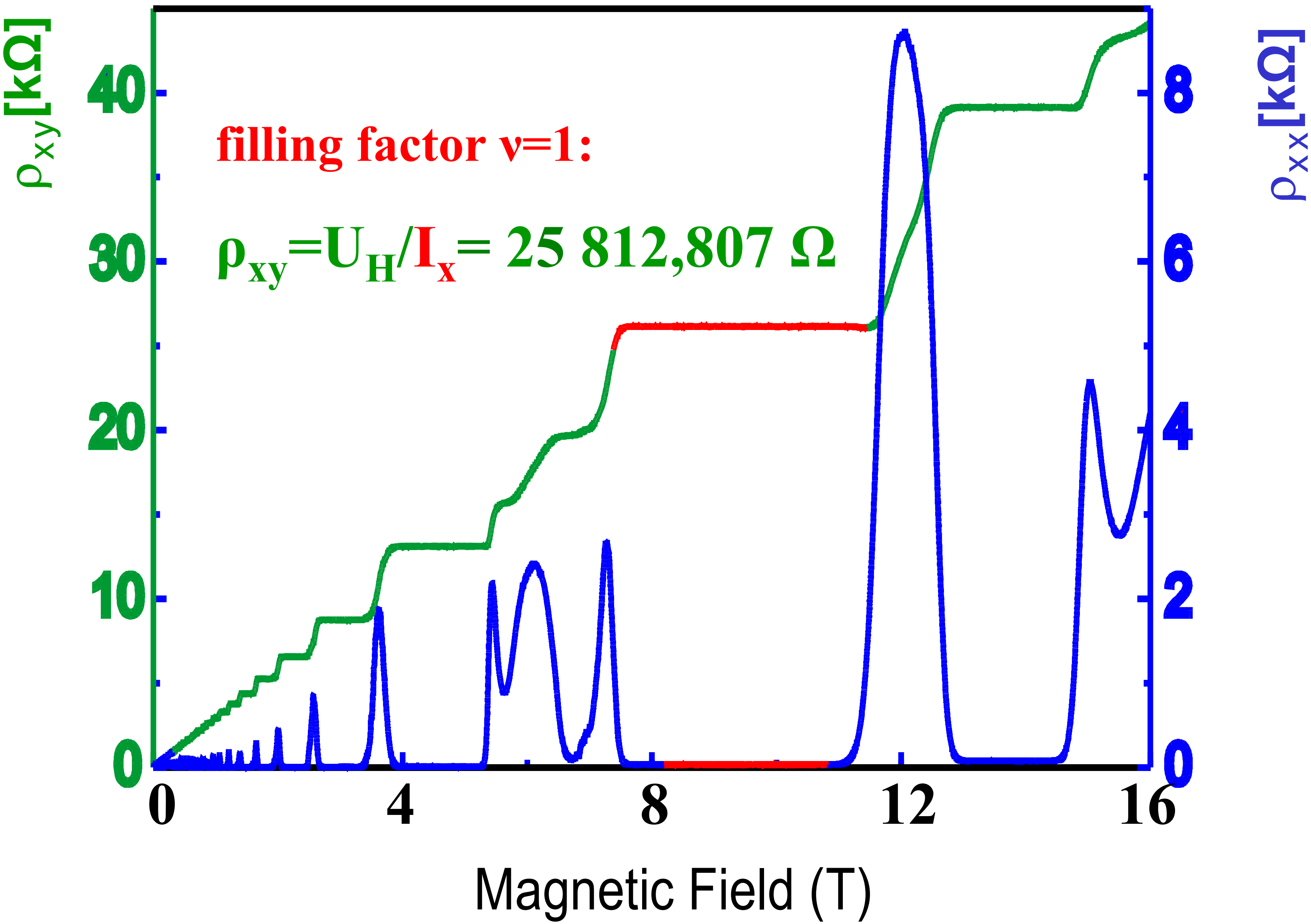


ENERGY OF "FREE" ELECTRONS IN A QUANTUM WELL

$E = E_0$ + kinetic energy of motion in the interface plane

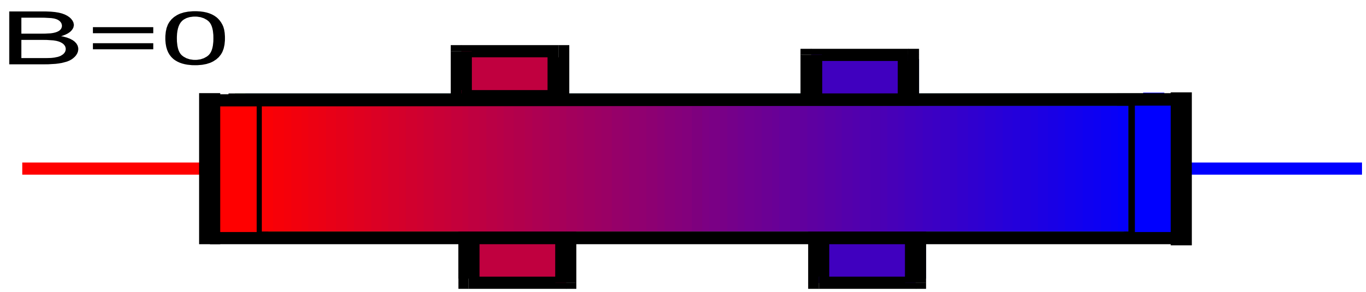


Typical device used for QHE experiments

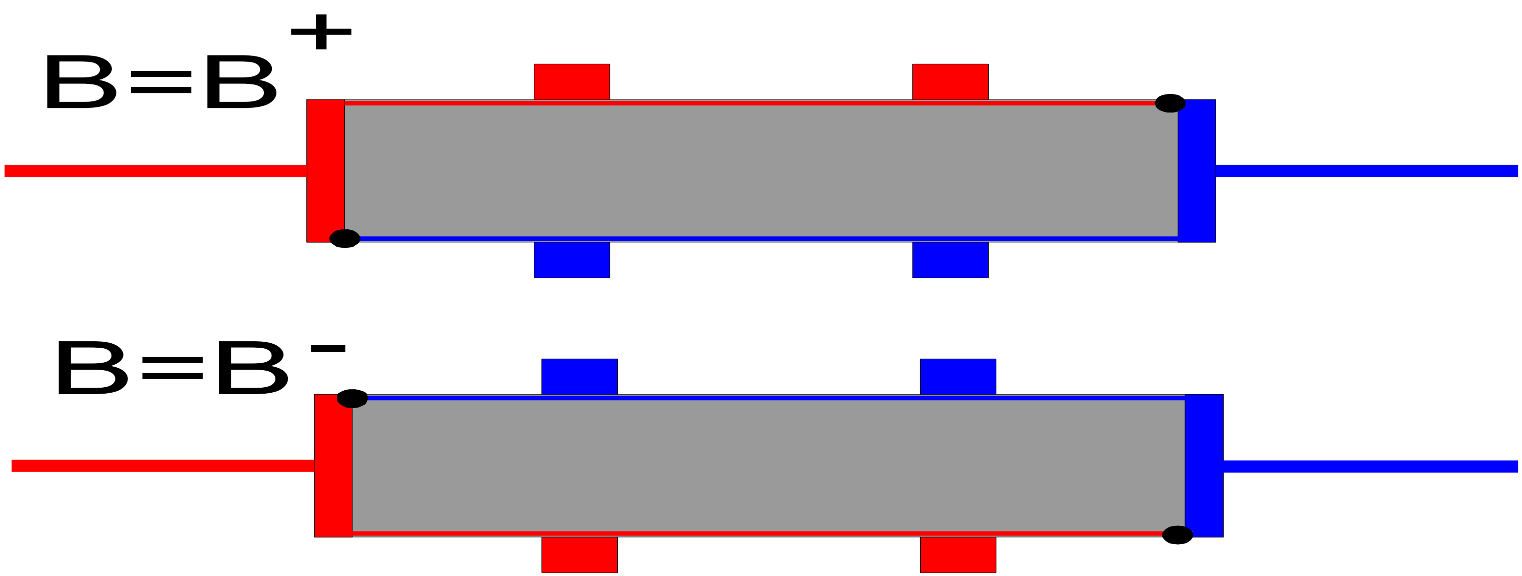


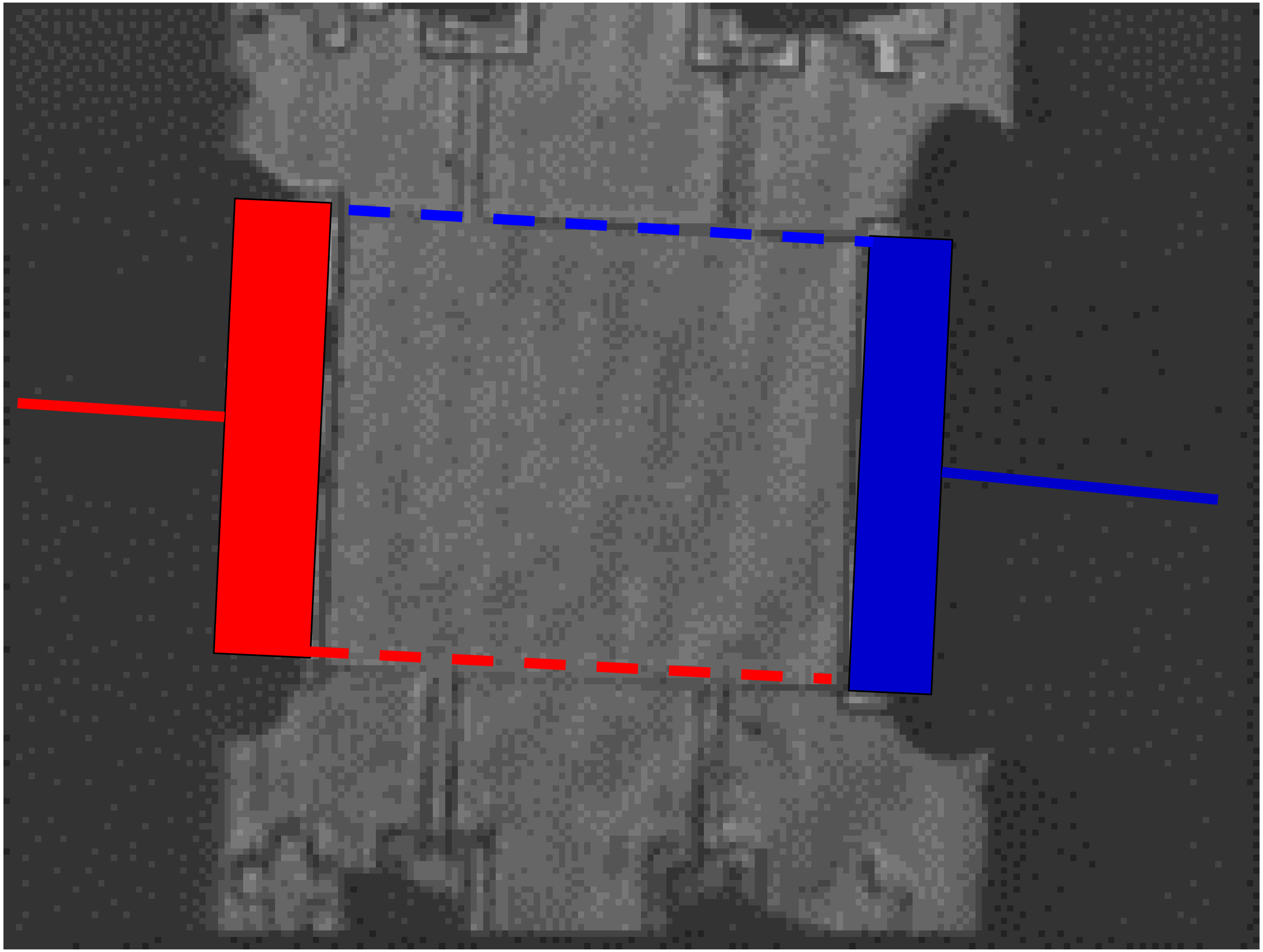
ρxy[kΩ]
ρxx[kΩ]
filling factor ν=1:
ρxy=UH/Ix= 25 812,807 Ω
0
10
20
30
40
0
2
4
6
8
0
4
8
12
16
Magnetic Field (T)

POTENTIAL DISTRIBUTION

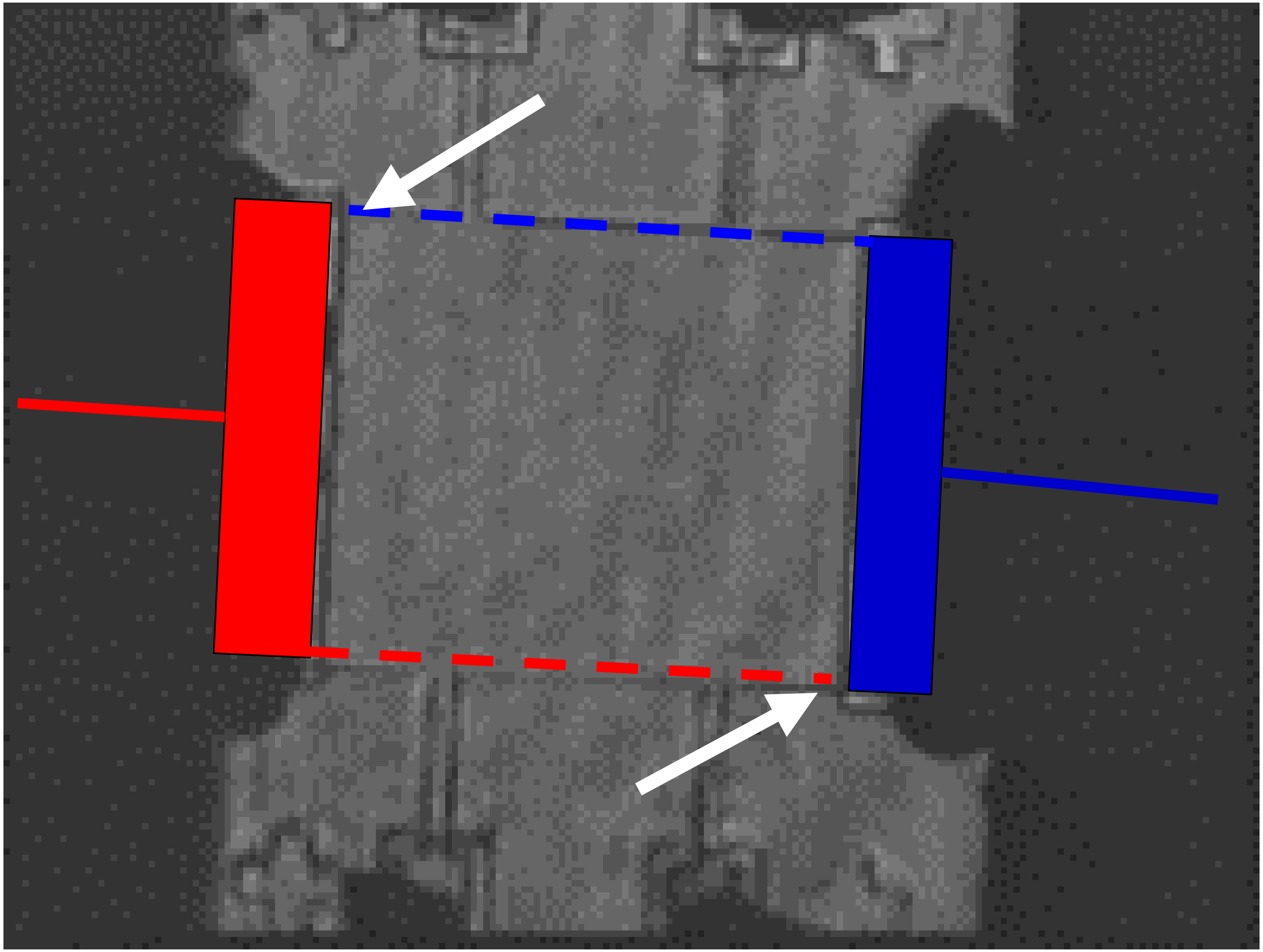


Quantum Hall Effect





W. Dietsche and coworkers, MPI-FKF

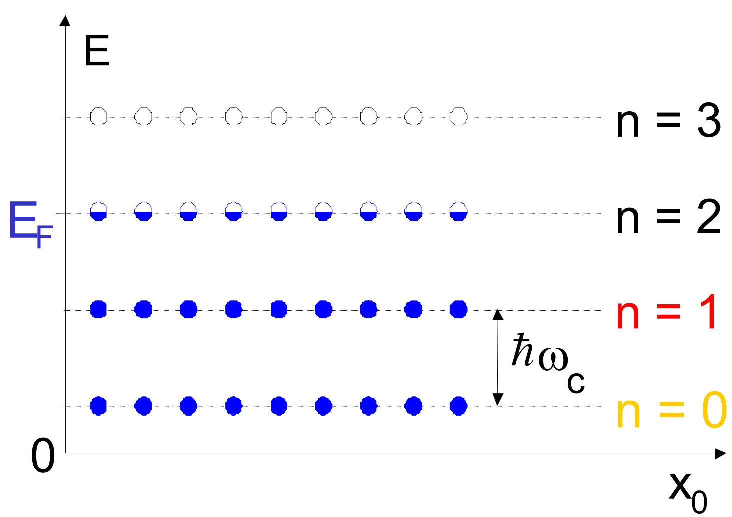


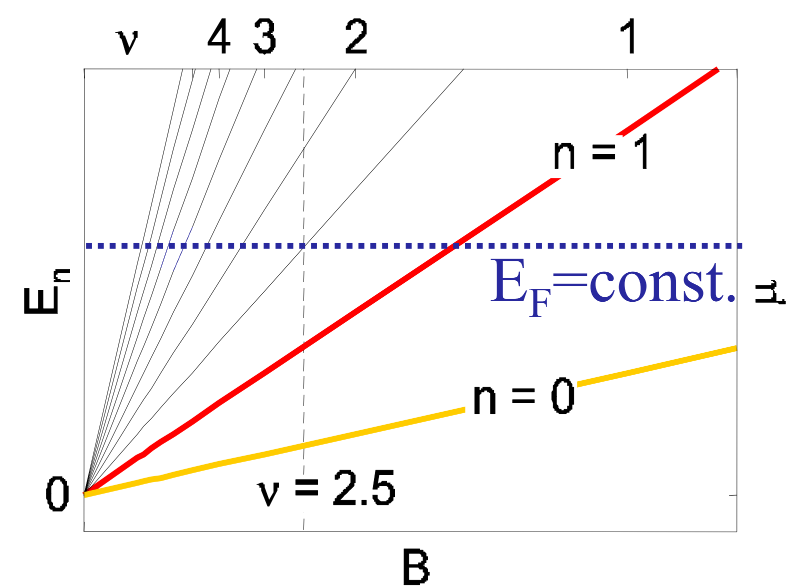
W. Dietsche and coworkers, MPI-FKF

PHYSICS OF QHE

Energy Gaps (e.g. cyclotron energy $\hbar\omega_c$)

Homogeneous 2DES
(no spin, no edges, no disorder,no el.-el. interaction)

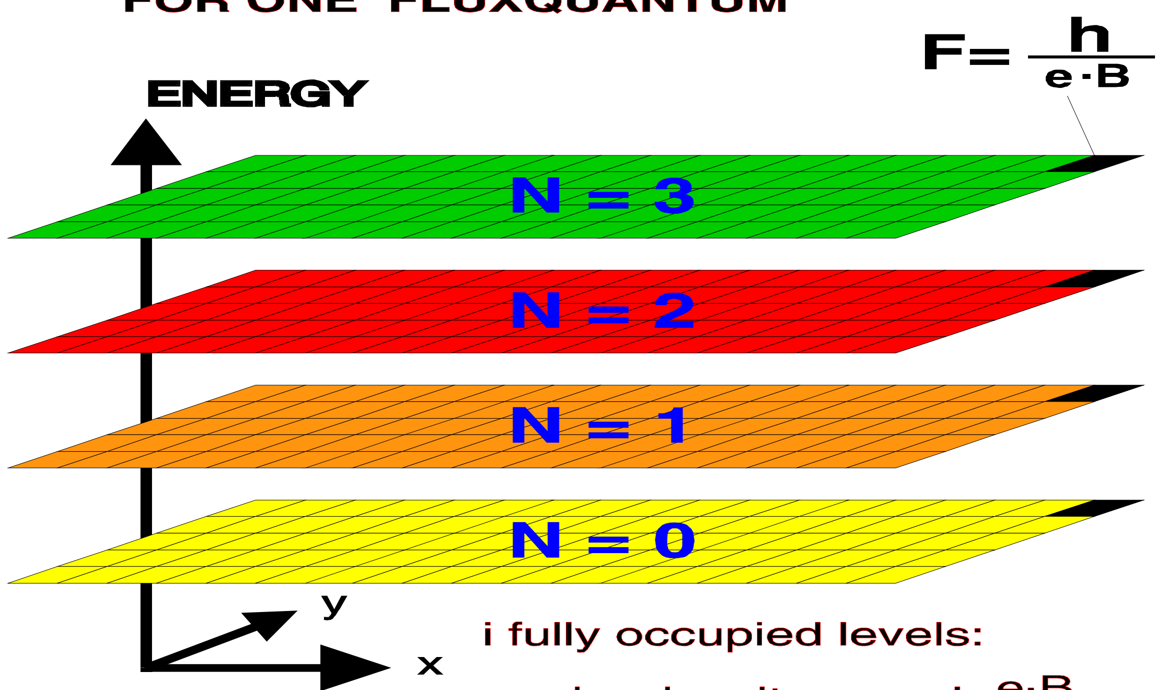




Each electronic state $E(N,s)$ occupies in real space the area $F = \frac{h}{e \cdot B}$

(flux $F \cdot B = h/e$)

FILLING FACTOR =
NUMBER OF ELECTRONS
FOR ONE FLUXQUANTUM



i fully occupied levels:

carrier density $n_S = i \cdot \frac{e \cdot B}{h}$

HALLEFFECT: $U_H = \frac{B}{n_S \cdot e} \cdot I = \frac{h}{i \cdot e^2} \cdot I$

Explanation of QHE

(Deutsches Museum Bonn)

Discrete energy levels for two-dimensional electron system (size quantization) in strong magnetic fields (Landau quantization)

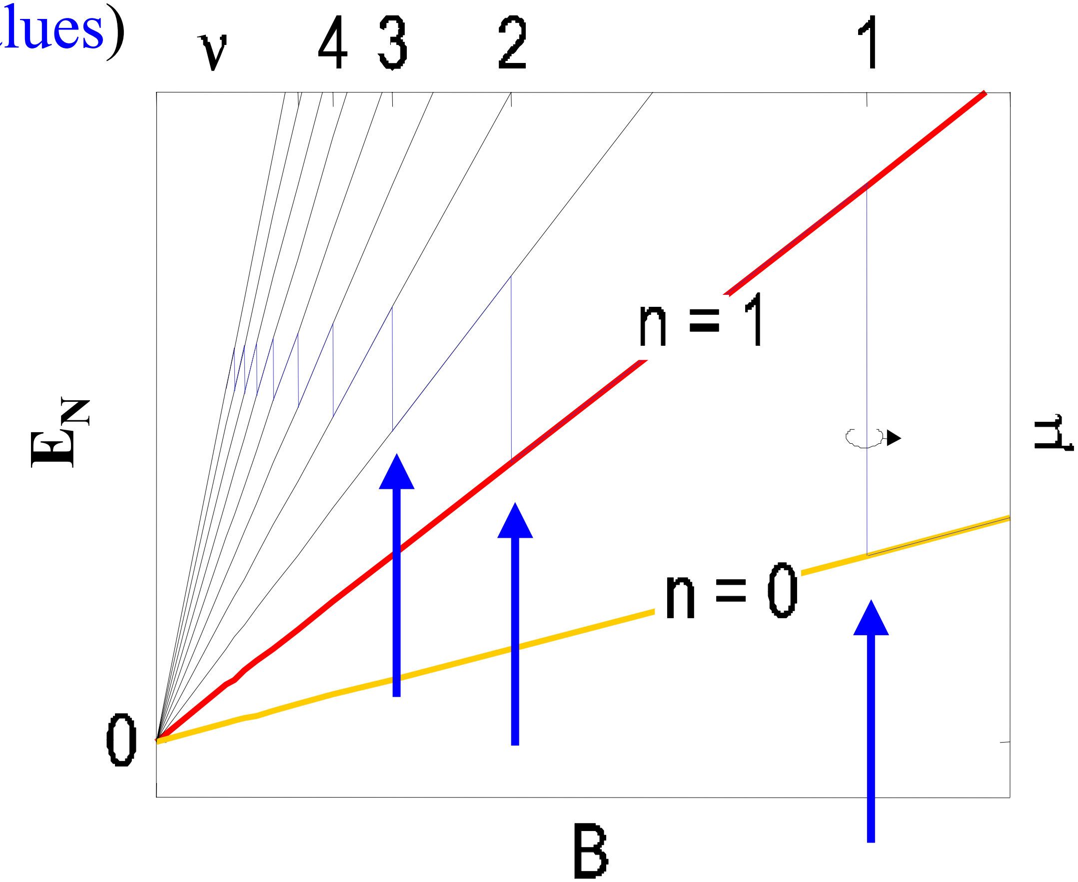
Classical Hall effect if an integer number i of energy levels is **fully** occupied with electrons:

$$U_H = \frac{h}{i \cdot e^2} \cdot I$$

(useful for Ph.D. examination with correct result but INCORRECT DEVIATION!)

PROBLEMS:

#1: NO quantum Hall **plateaus** since Fermi energy jumps (the condition of fully occupied Landaulevel is fulfilled only for very special magnetic field values)

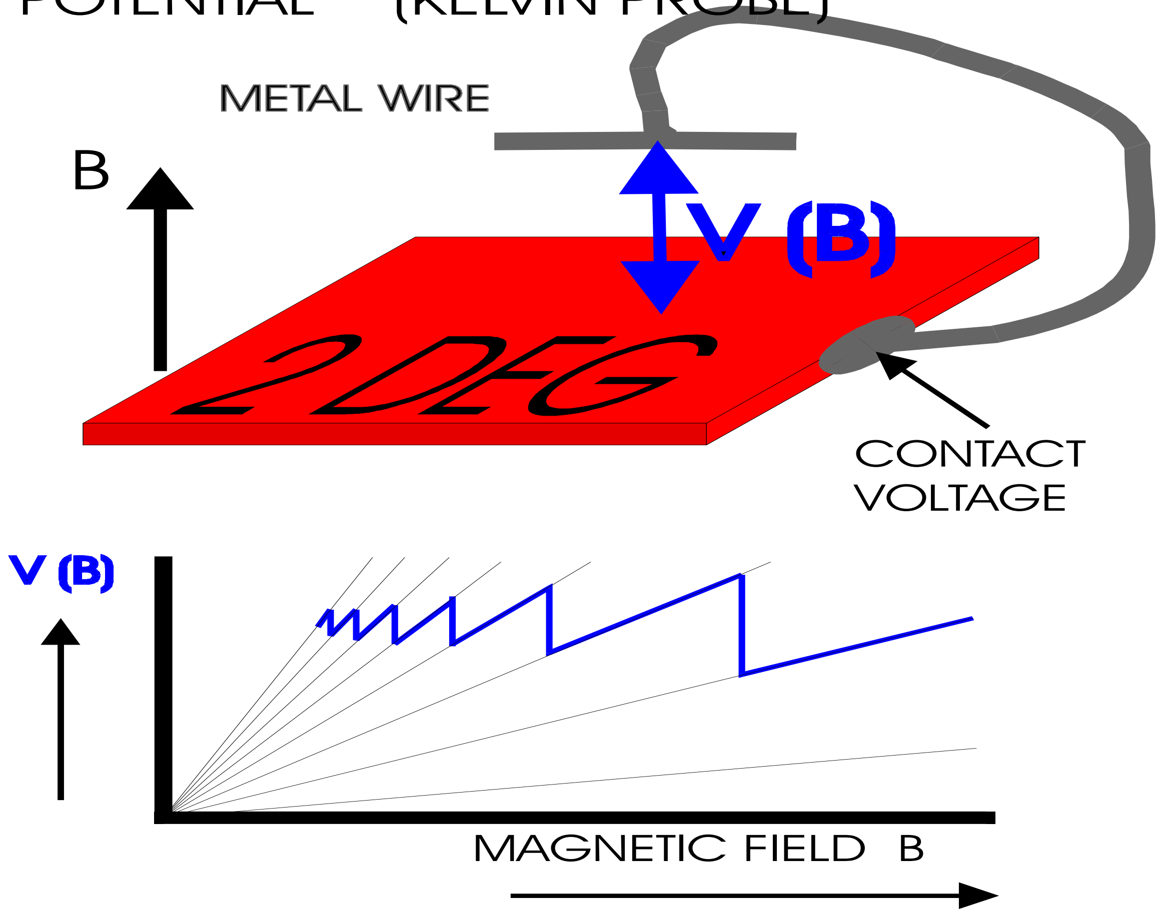


#2: Real samples with finite size have **NO GAPS** in the energy spectrum!

THERMODYNAMIC EQUILIBRIUM:

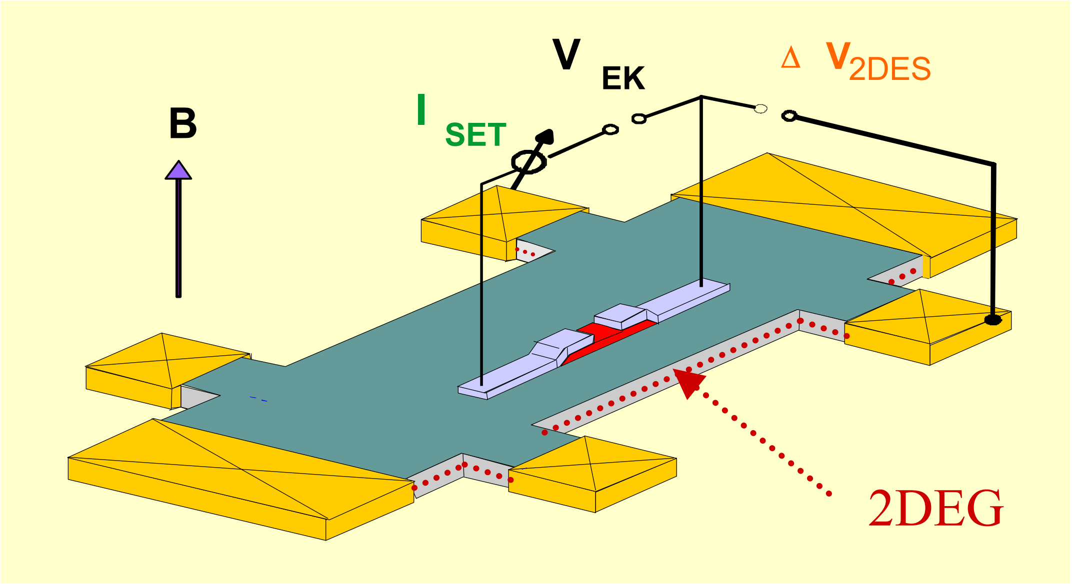
CONSTANT ELECTROCHEMICAL

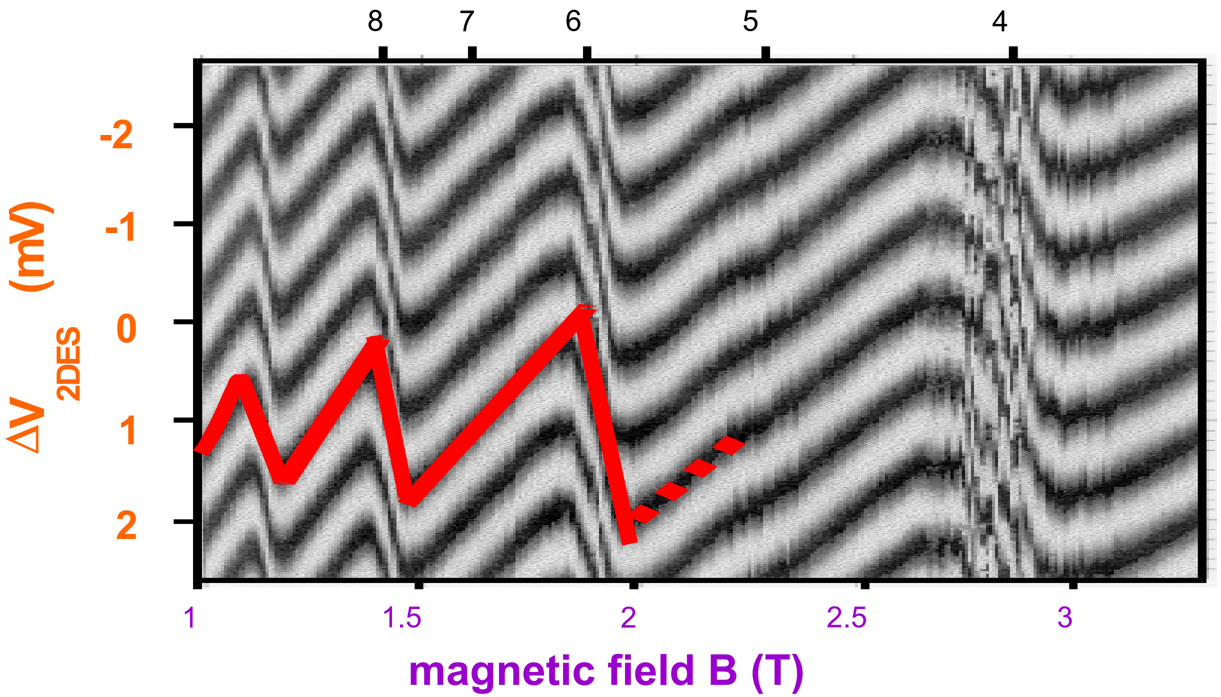
POTENTIAL (KELVIN PROBE)



Single Electron Transistor (SET)

as an extremely sensitive electrometer for measurements on a 2DEG

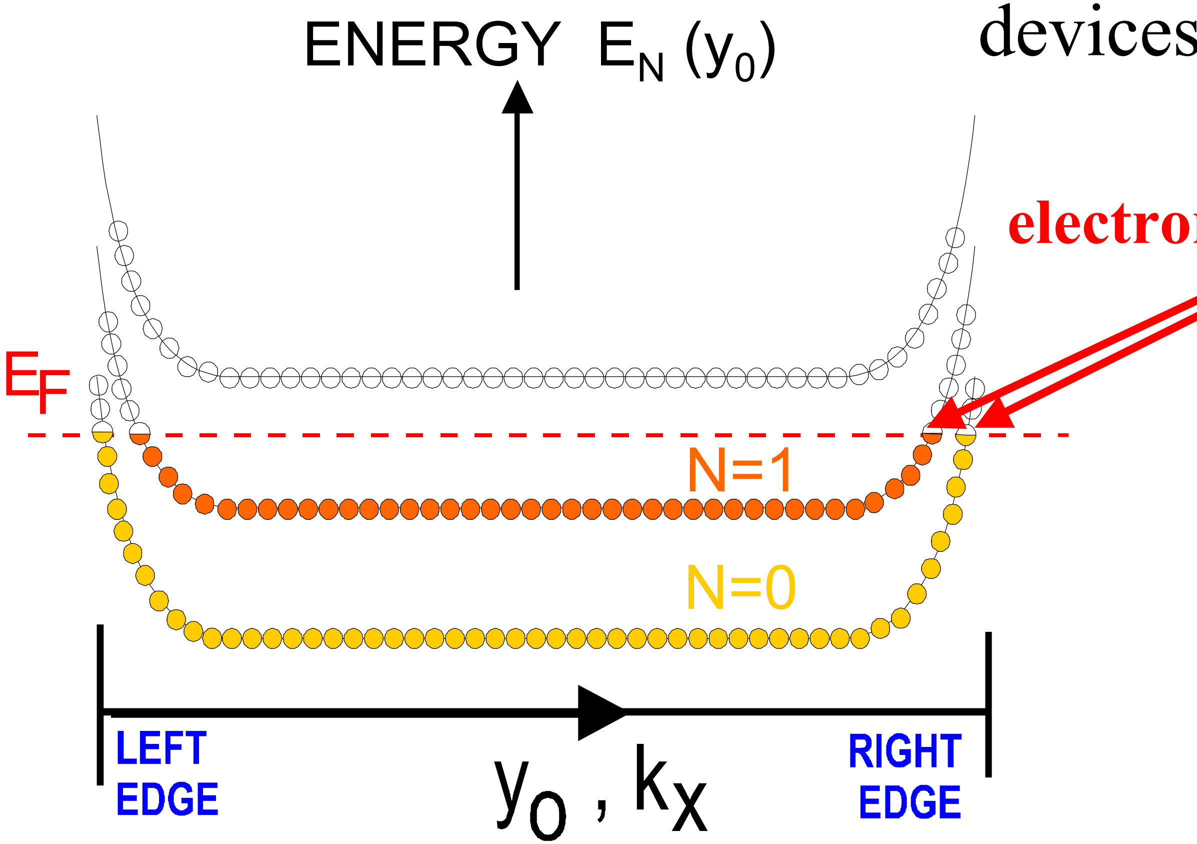




Y. Y. Wei et al.

Problem #2

NO energy gaps for real devices with finite width

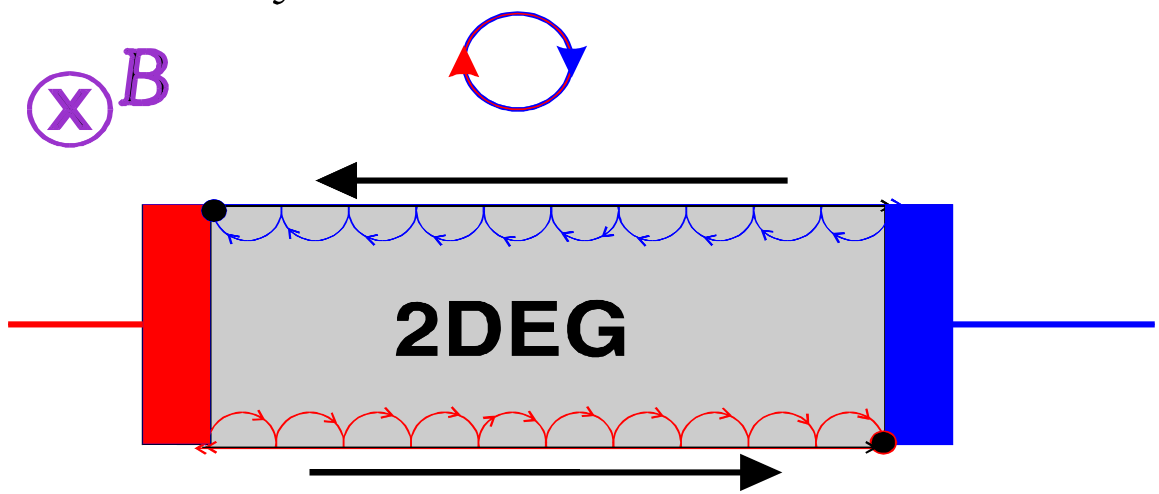


$$y_0 = \frac{\hbar k_x}{eB}$$

$$\Psi_{N,y_0} \propto e^{ik_x x} \cdot \Phi_N\left(y - y_0\right)$$

2DEG IN THE QHE-REGIME CORRESPONDS TO AN IDEAL ONE - DIMENSIONAL SYSTEM WITHOUT SCATTERING (EDGE CHANNELS)

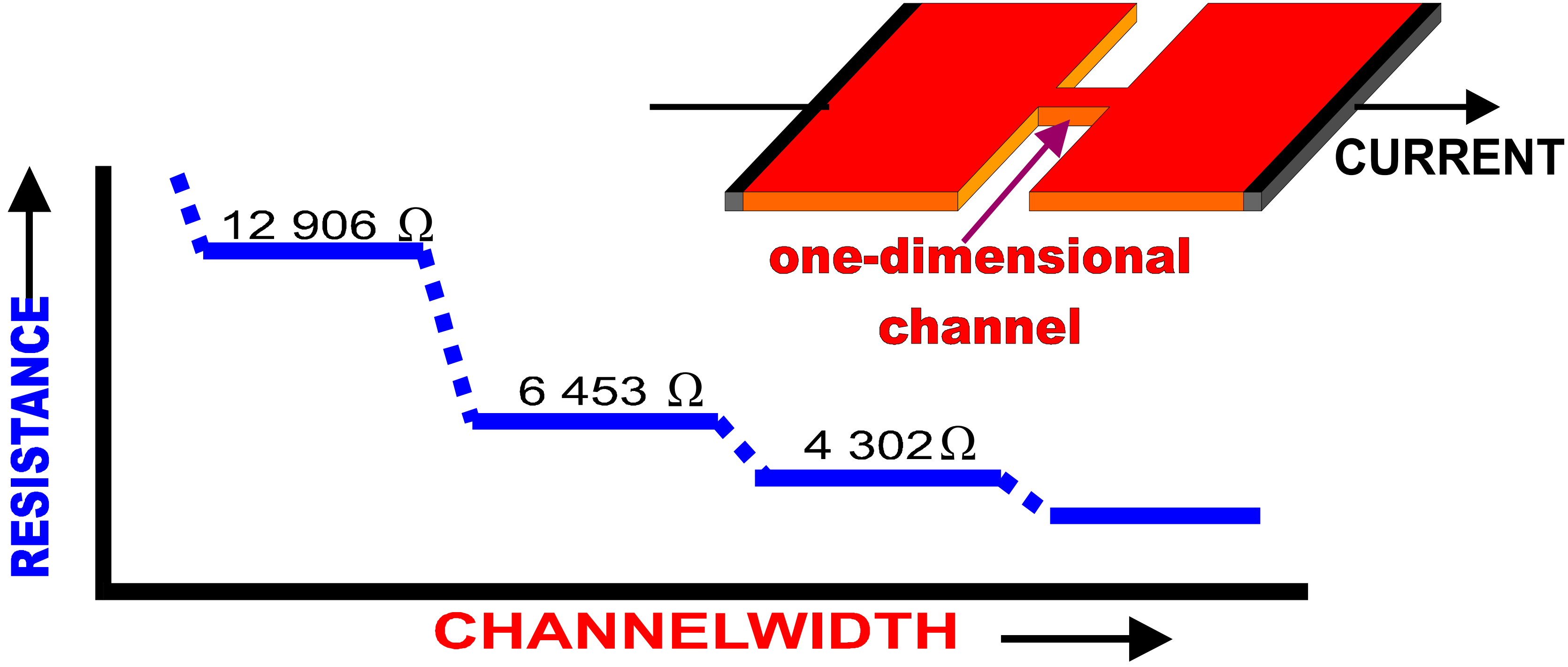
Classical cyclotron motion:



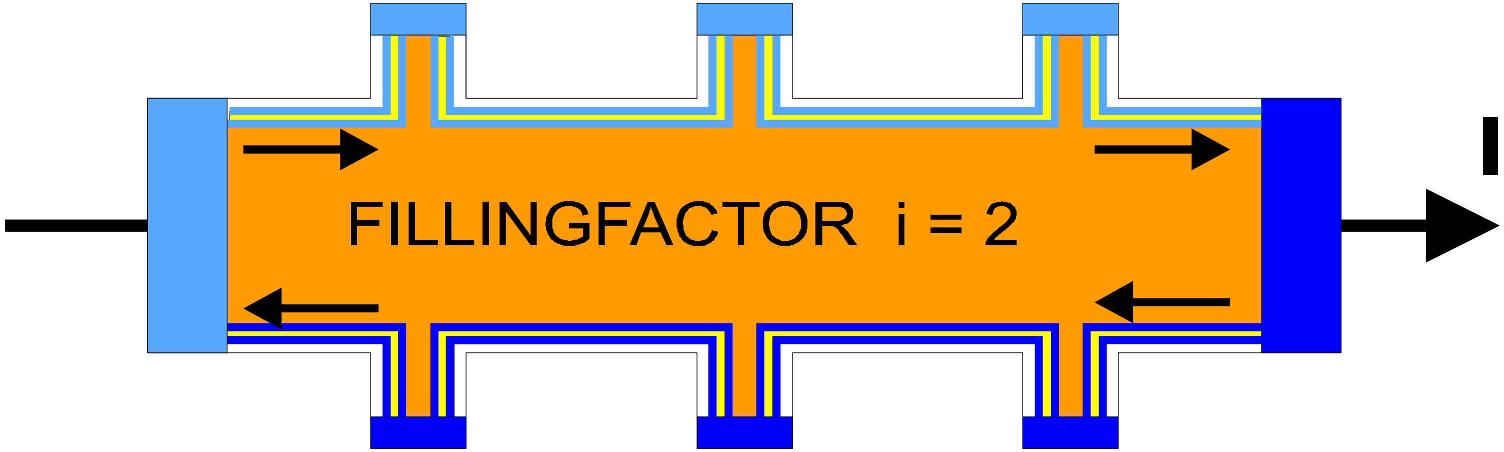
DIAMAGNETIC CURRENT (SKIPPING ORBITS)

THE ELECTRICAL RESISTANCE OF A CONSTRICTION IS DETERMINED BY THE NUMBER OF ONE-DIMENSIONAL CHANNELS

(each channel contributes to the conductance with $2e^2/h$)

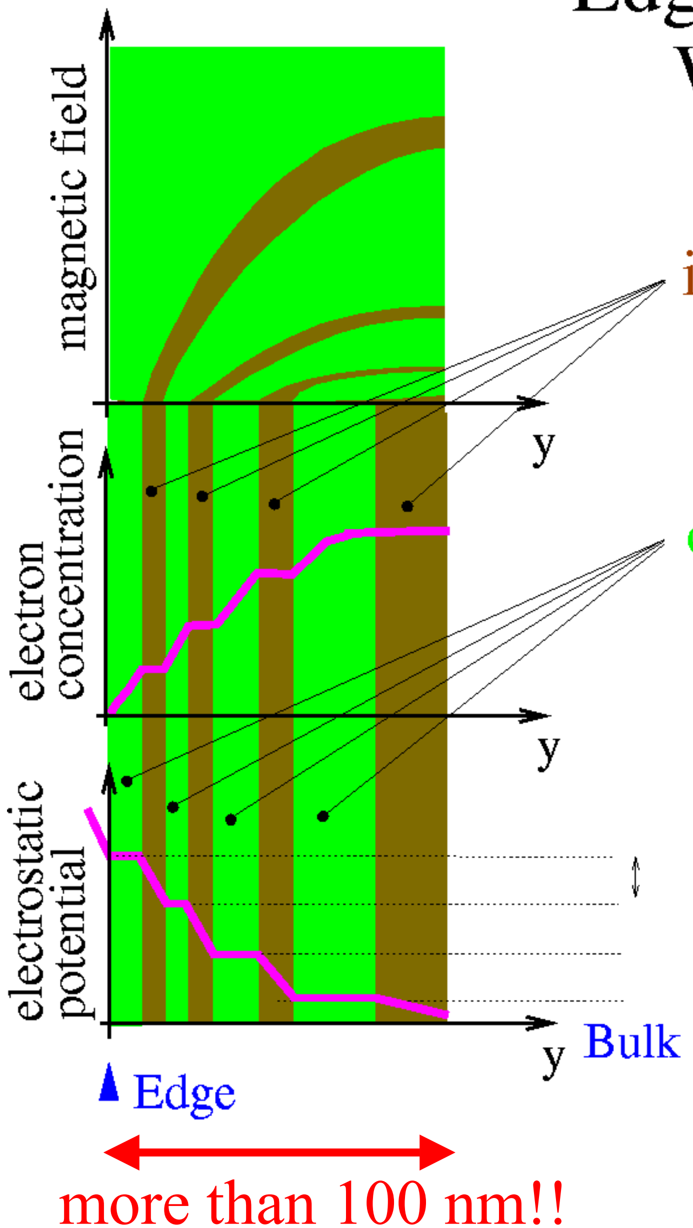


LANDAUER BÜTTIKER FORMALISM
UNDER QUANTUM HALL CONDITIONS



NO BACKSCATTERING!

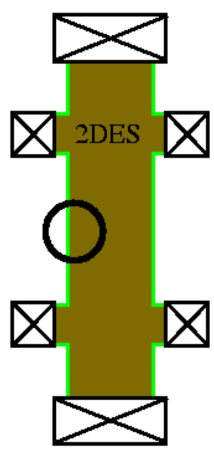
Edge Strips Evolving With Magnetic Field



incompressible strips

– not conducting
– electrical isolating
– not screening

compressible strips

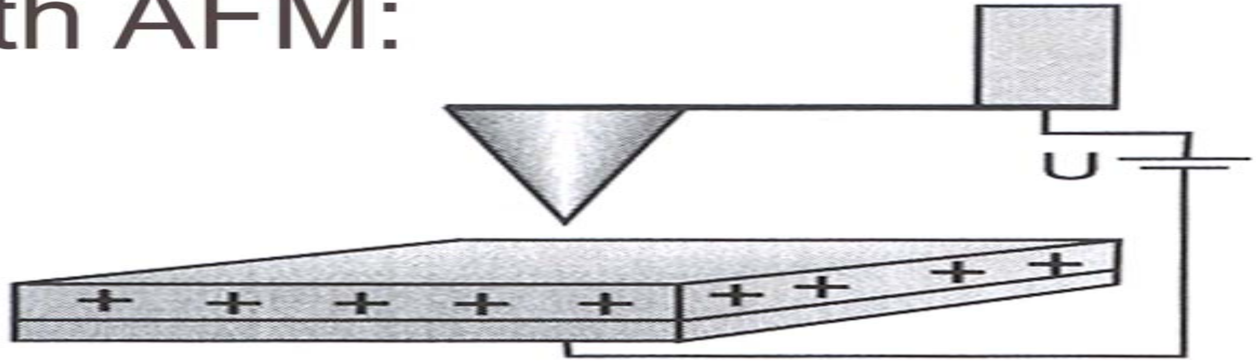


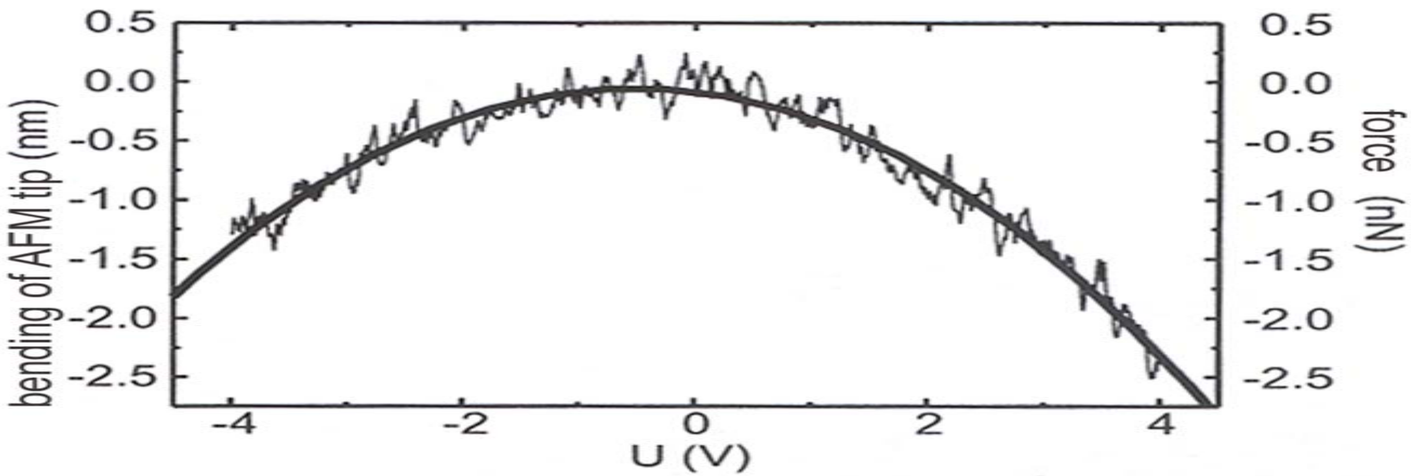
K. Lier and R.R. Gerhardts,
Phys. Rev. B 50, 7757 (1994).

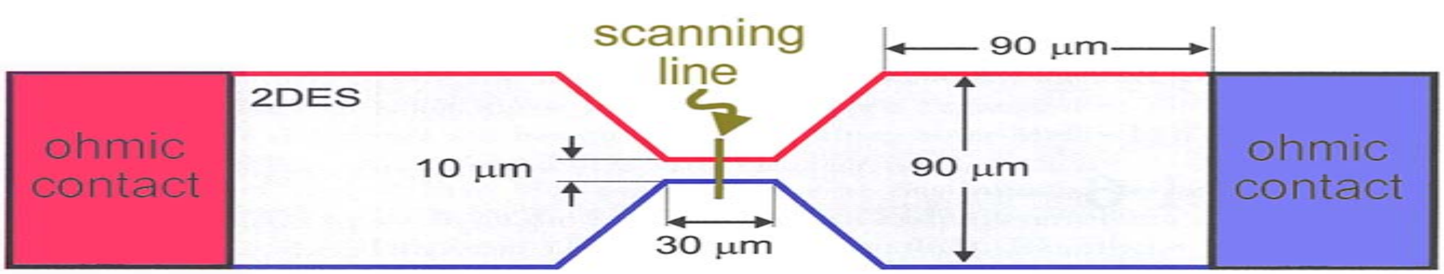
Chklovskii, Shklovskii, Glazman,
Phys. Rev. B 46, 4026 (1992).

Chklovskii, Matveev, and Shklovskii
Phys. Rev. B 47, 12605 (1993).

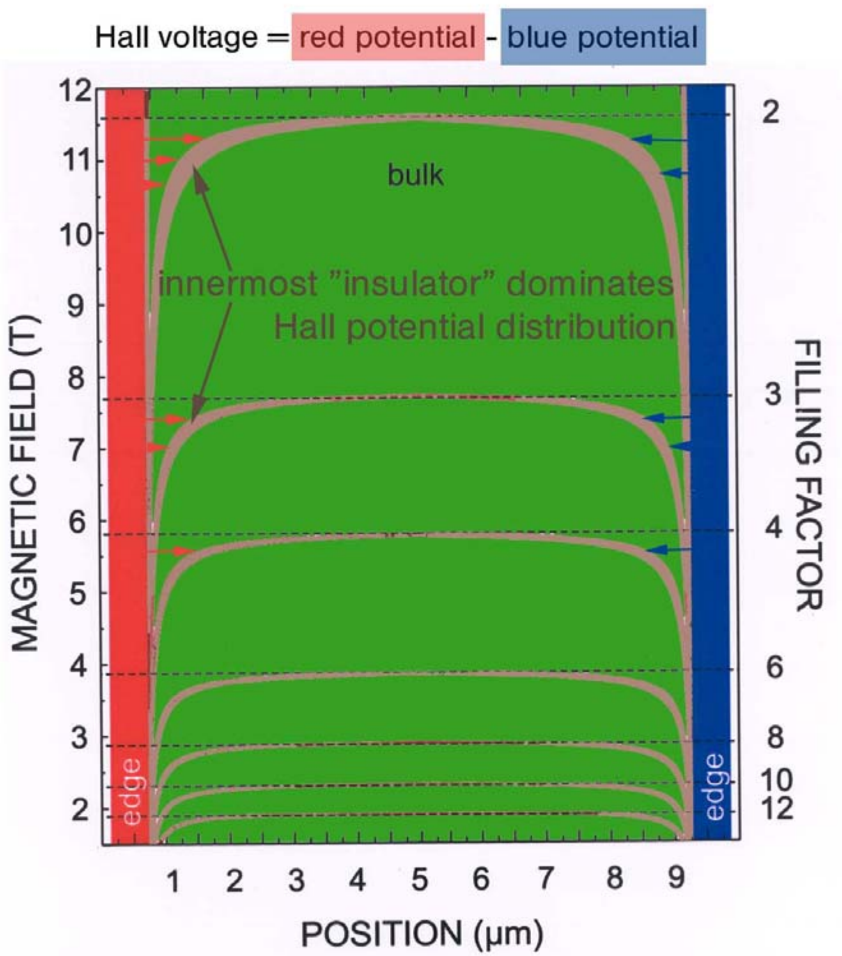
Locally resolved potential with AFM:





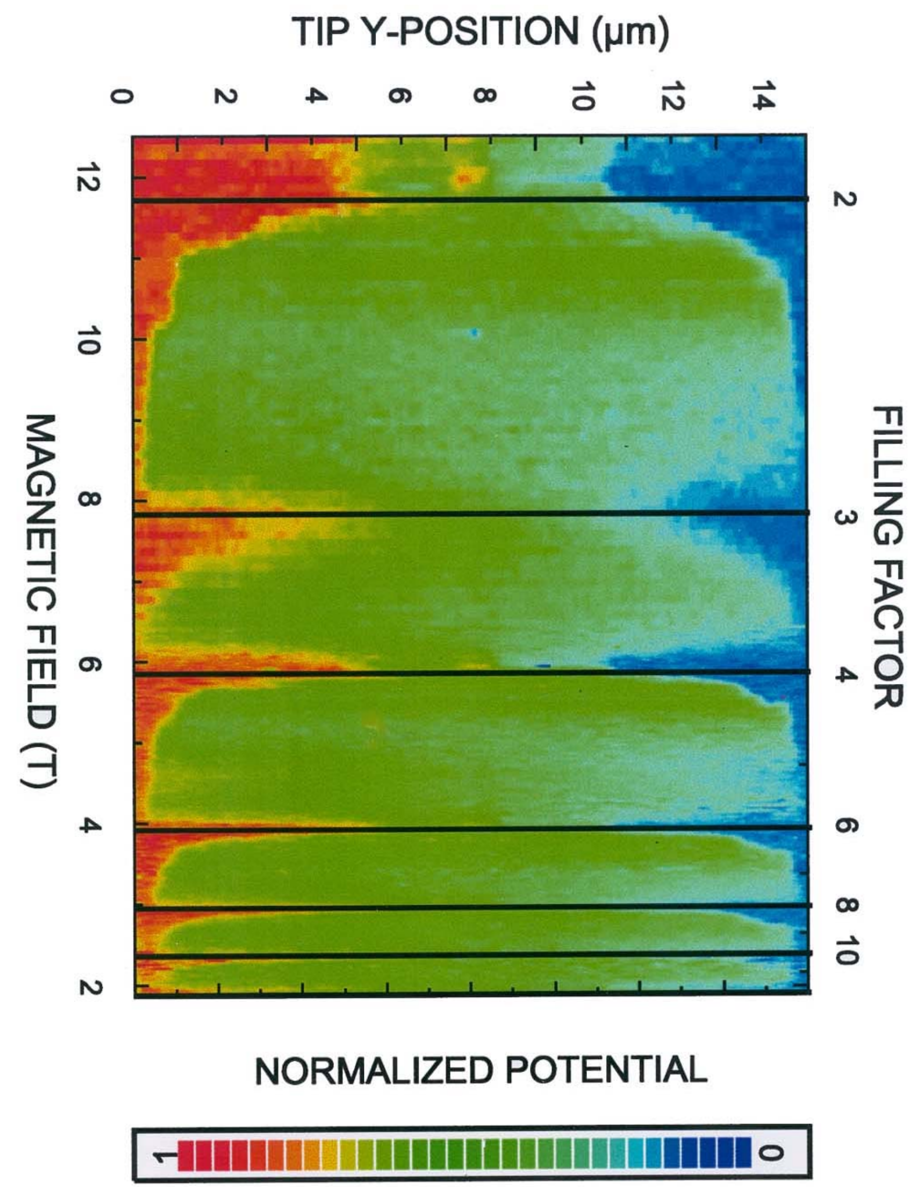


POSITION OF INCOMPRESSIBLE (= INSULATING) REGIONS AS A FUNCTION OF MAGNETIC FIELD

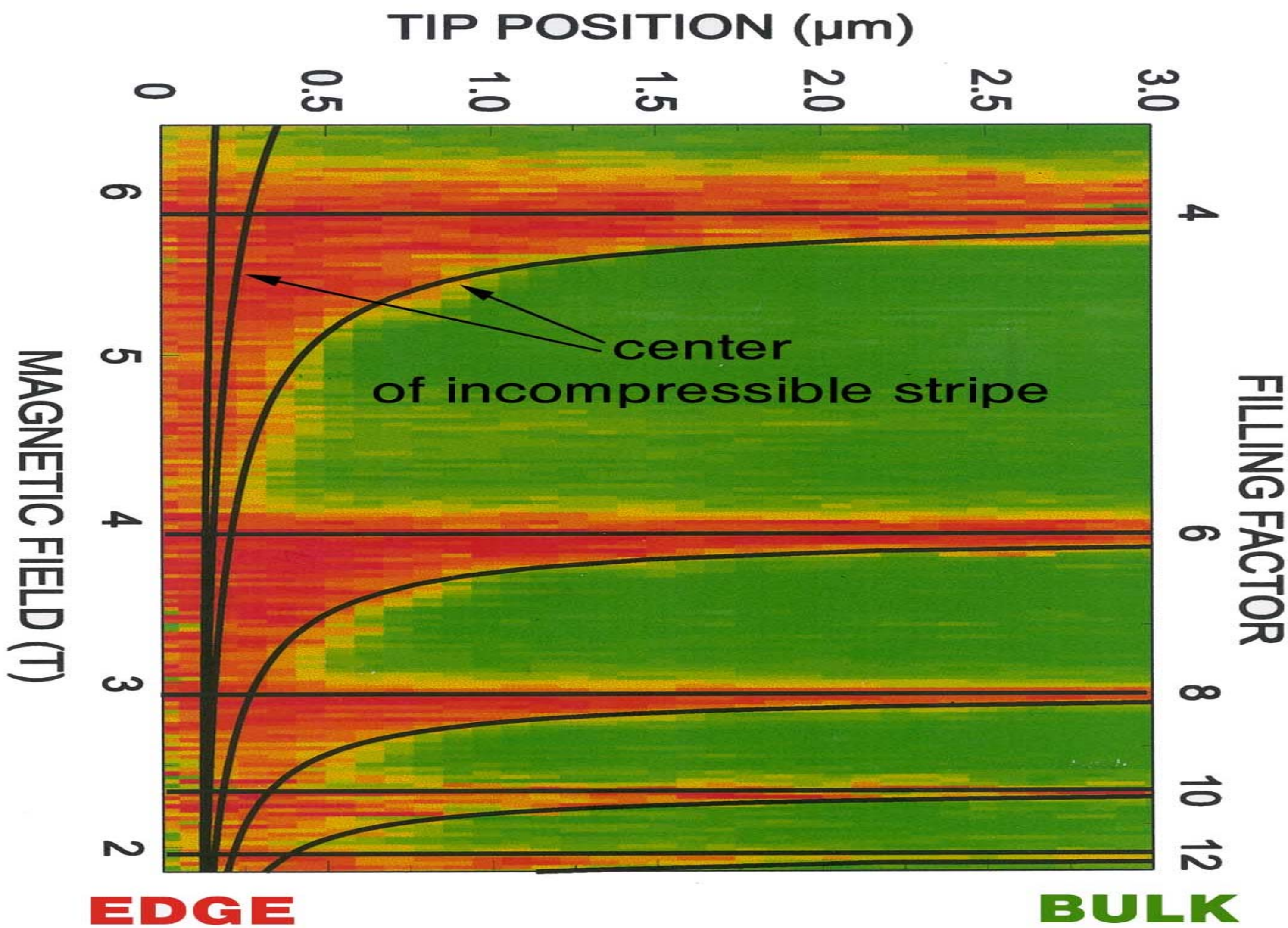


AFM-Measurement of the Hall Potential

(E. Ahlswede, J Weis, P. Weitz)



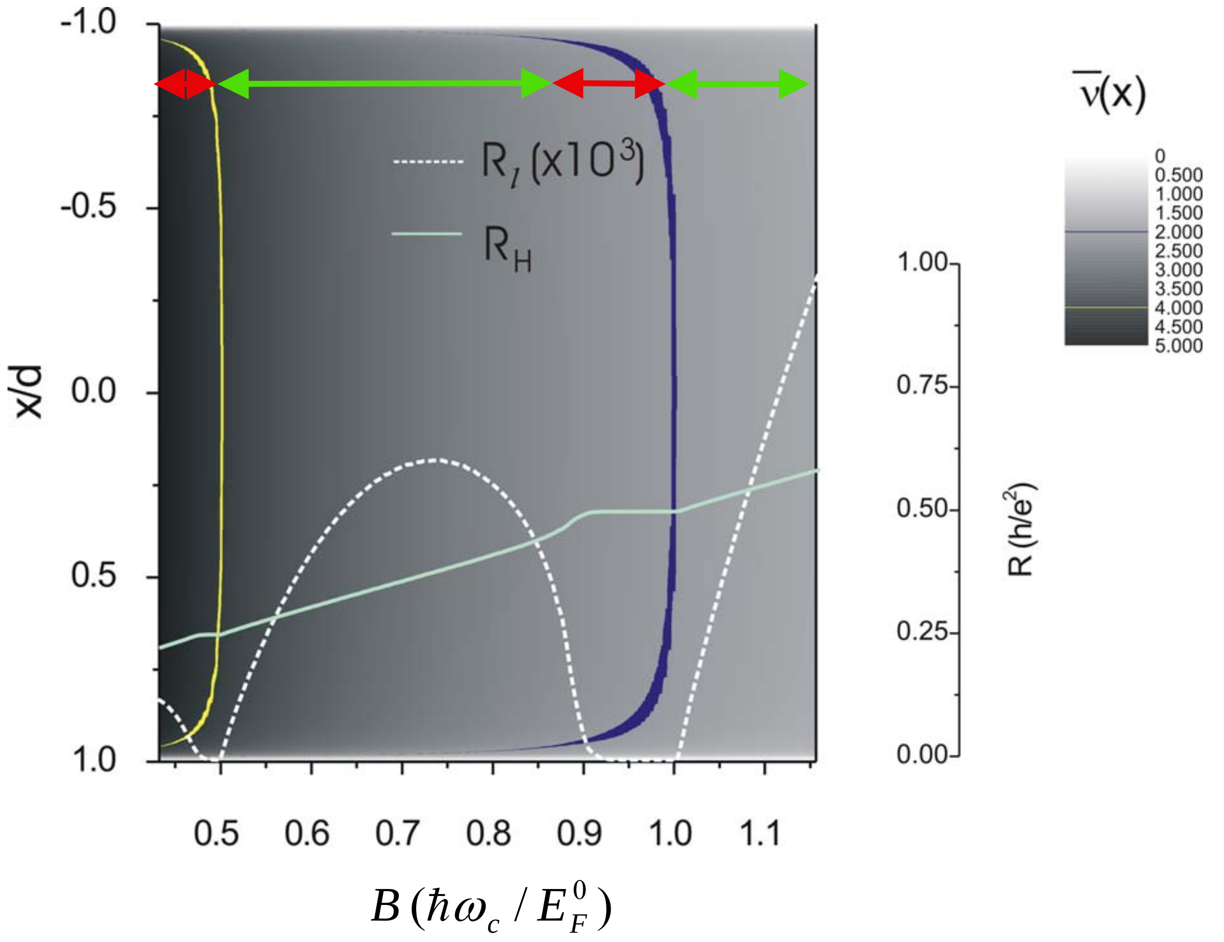
HALL POTENTIAL DISTRIBUTION CLOSE TO THE EDGE



Calculation for an ideal system with finite size
(R.Gerhardts, A.Siddiki)

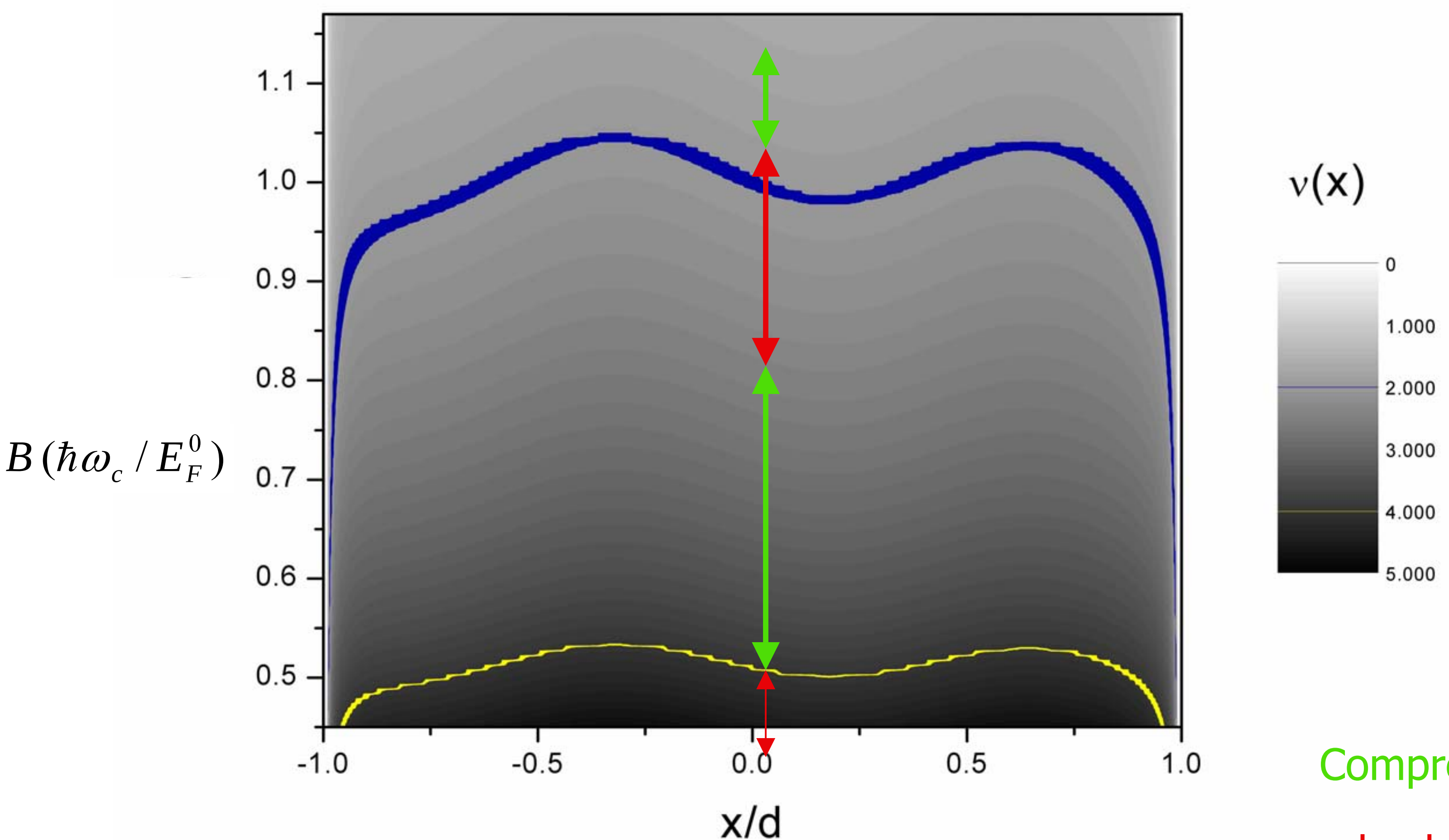
Compressible

no backscattering



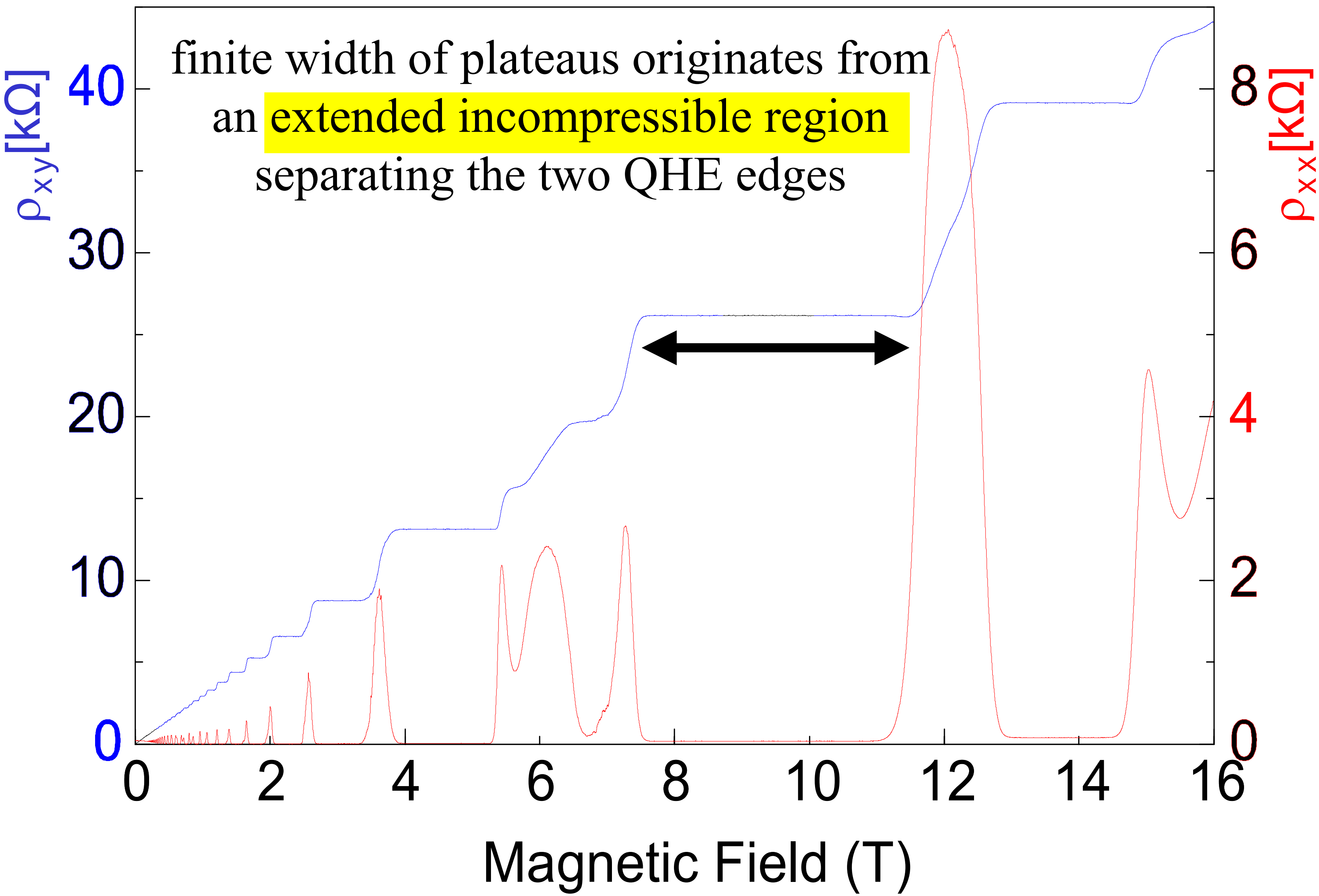
Theory with one-dimensional disorder
(R.Gerhardts, A.Siddiki)

15 μm sample with some random disorder

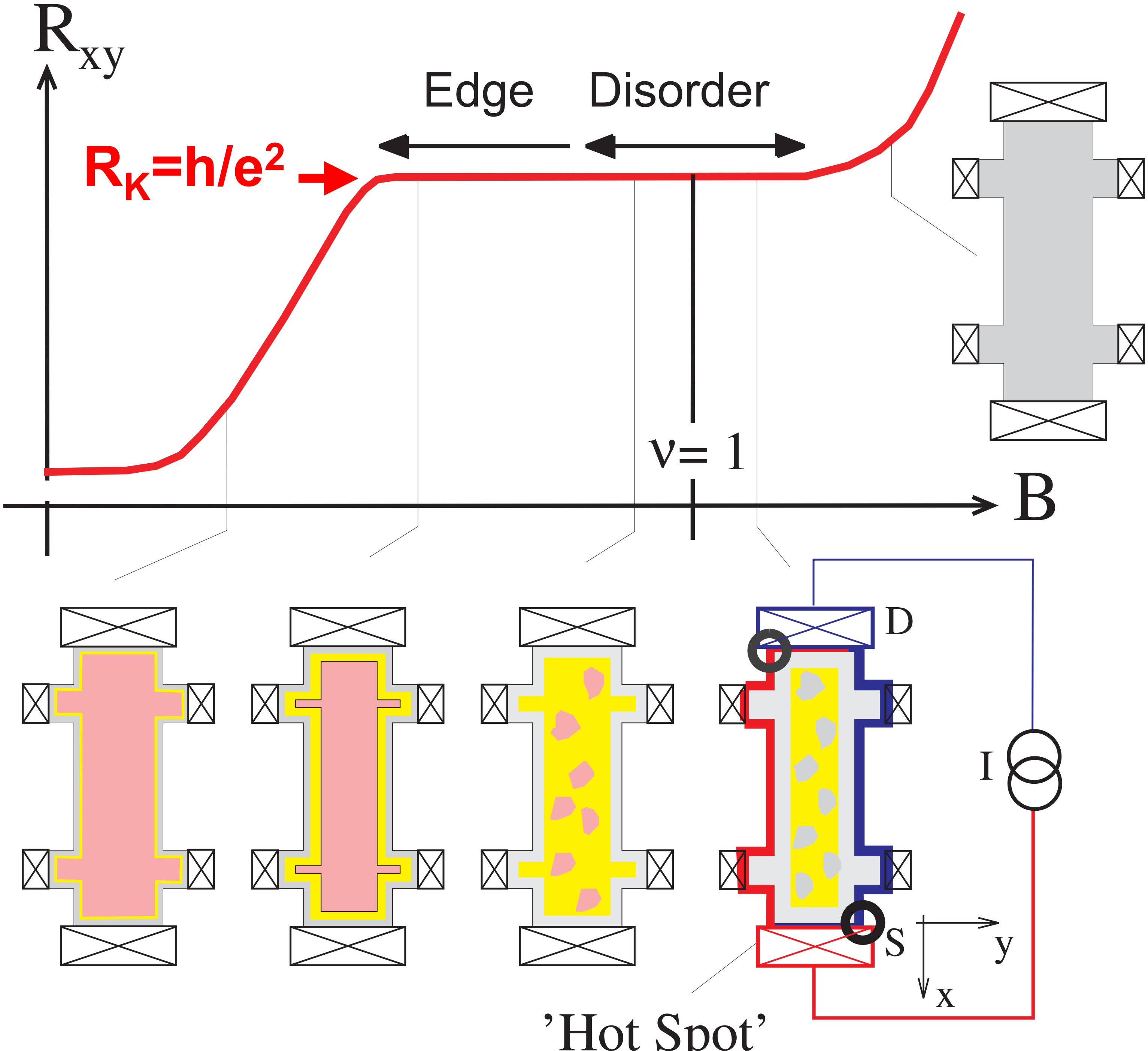


Compressible

no backscattering



finite width of plateaus originates from
an extended incompressible region
separating the two QHE edges
ρxy[kΩ]
ρxx[kΩ]
0
10
20
30
40
0
2
4
6
8
0
2
4
6
8
10
12
14
16
Magnetic Field (T)

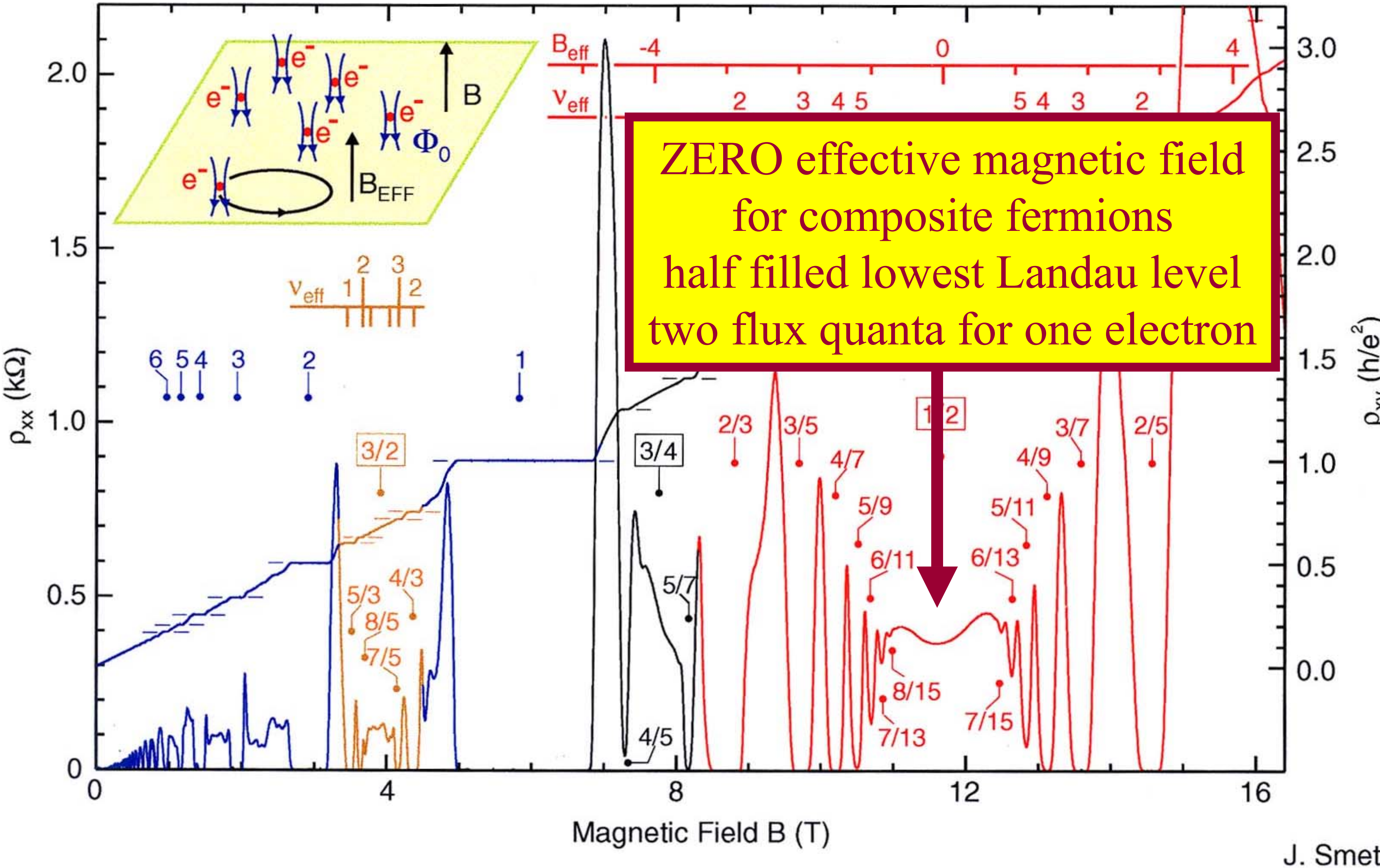


R_{xy}
Edge
Disorder
$R_K=h/e^2$
ν= 1
B
D
I
S
y
x
'Hot Spot'

NEW ENERGY GAPS DUE TO ELECTRON-ELECTRON INTERACTION

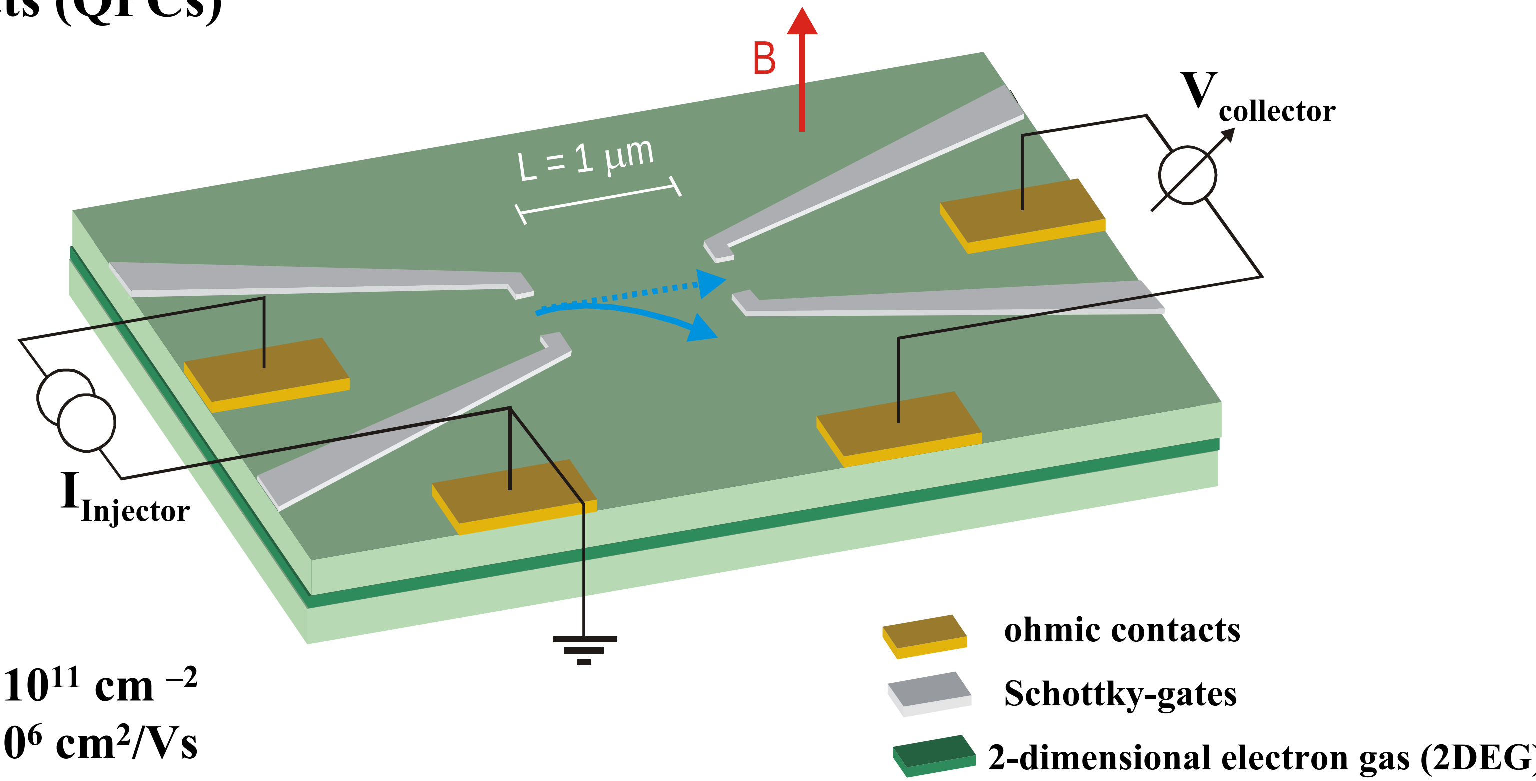
(fractional quantum Hall effect)

Similarity between IQHE and FQHE



Ballistic transport – electrons and Composite Fermions

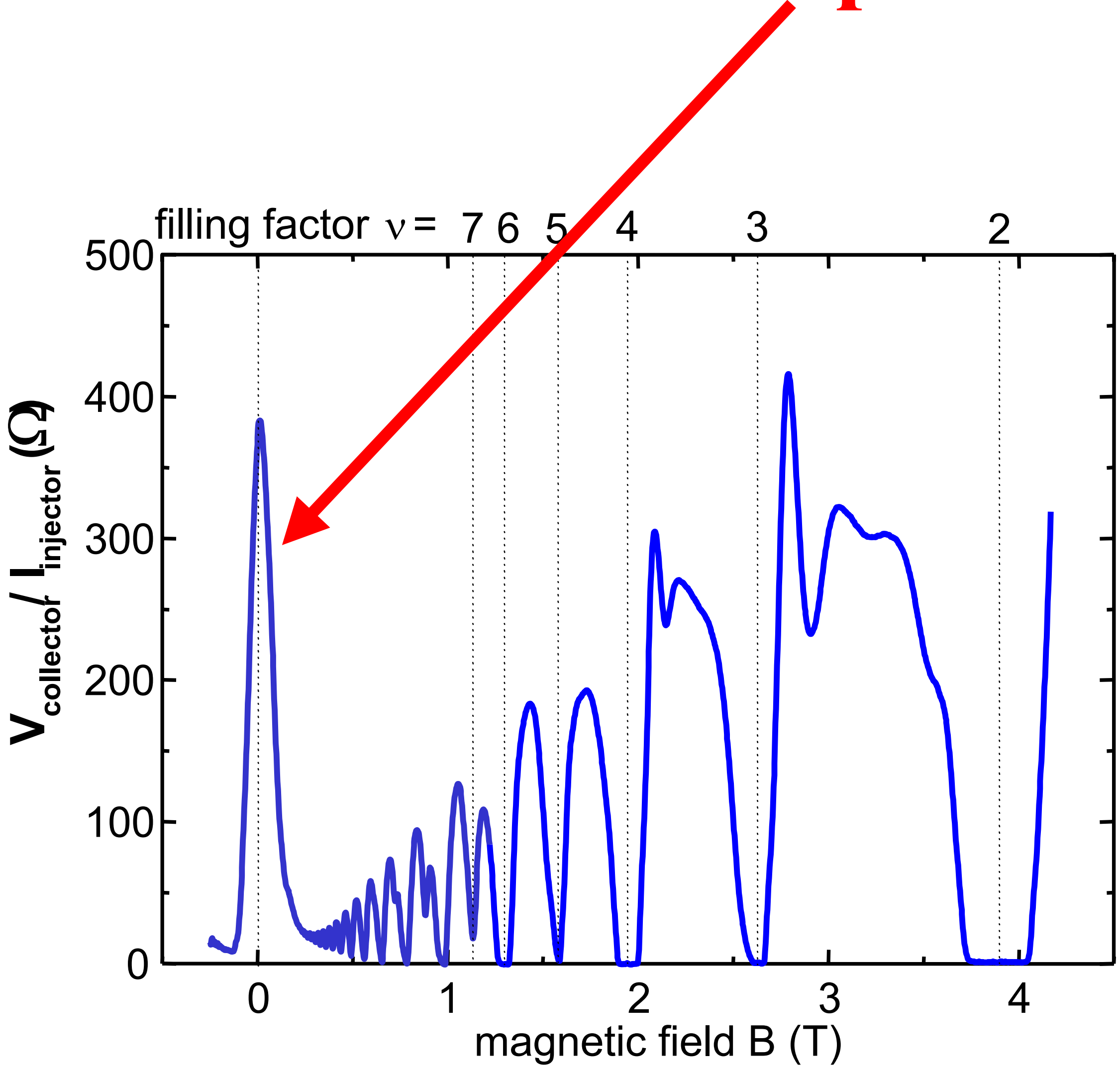
- high mobility 2-dimensional electron gas with long mean free path forms at the interface of an GaAs/AlGaAs heterostructure
- lateral surface Schottky-gates define two opposing Quantum-Point-Contacts (QPCs)



$n = 1.92 \cdot 10^{11}\ cm^{-2}$
$\mu = 5.8 \cdot 10^{6}\ cm^2/Vs$

Jörn Göres

Ballistic transport of electrons

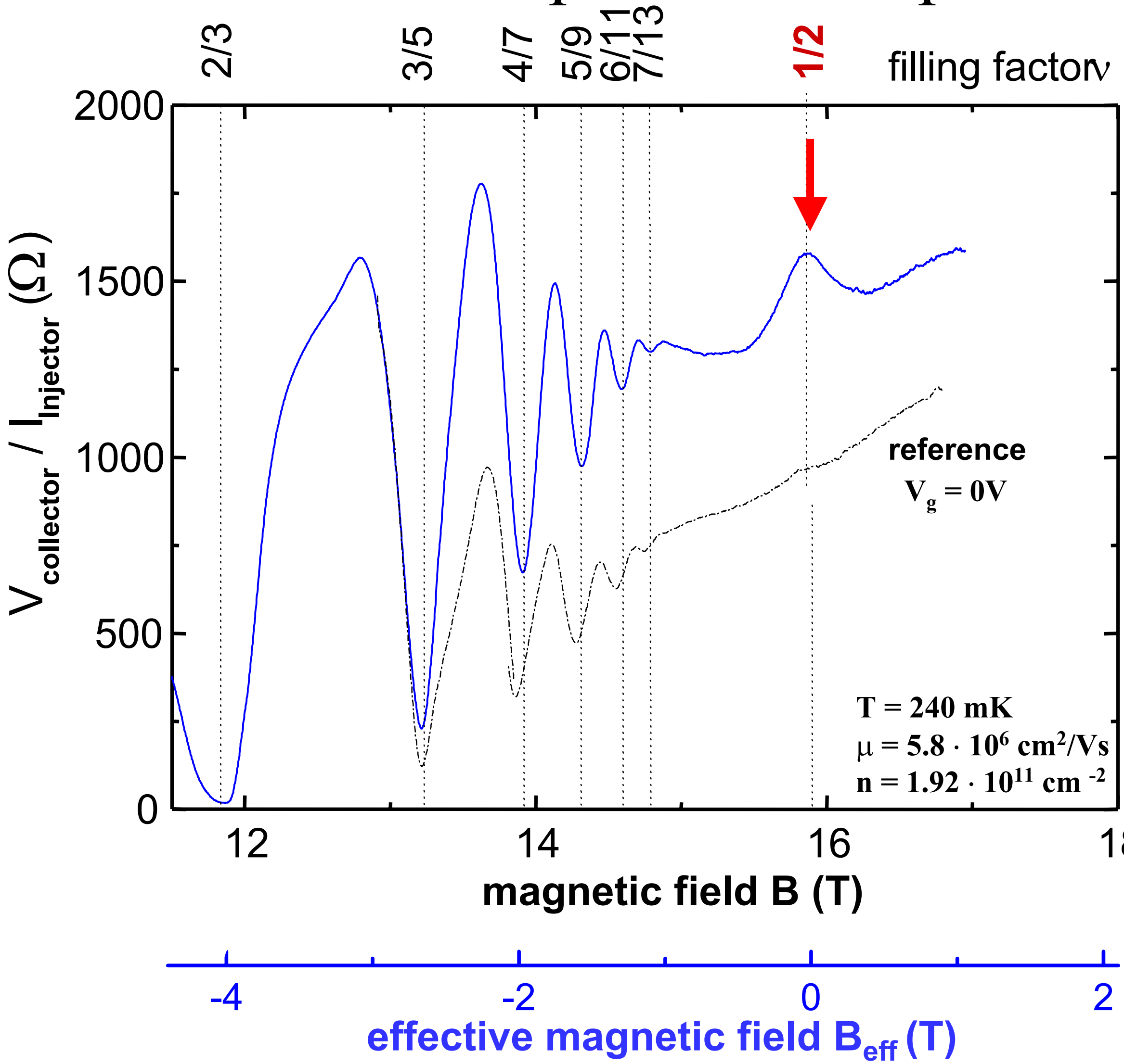


- at B = 0 straight, ballistic transport of electrons occurs from the injector to the collector Quantum-Point-Contact
- away from B = 0 Shubnikov-deHaas oscillations and the Quantum Hall Effect develop

T = 240 mK
$\mu = 5.8 \cdot 10^6$ cm^2/Vs
n = $1.92 \cdot 10^{11}$ cm $^{-2}$

SIMILAR OBSERVATIONS IN STRONG MAGNETIC FIELDS (16 Tesla) ?

Ballistic transport of Composite Fermions (CFs)

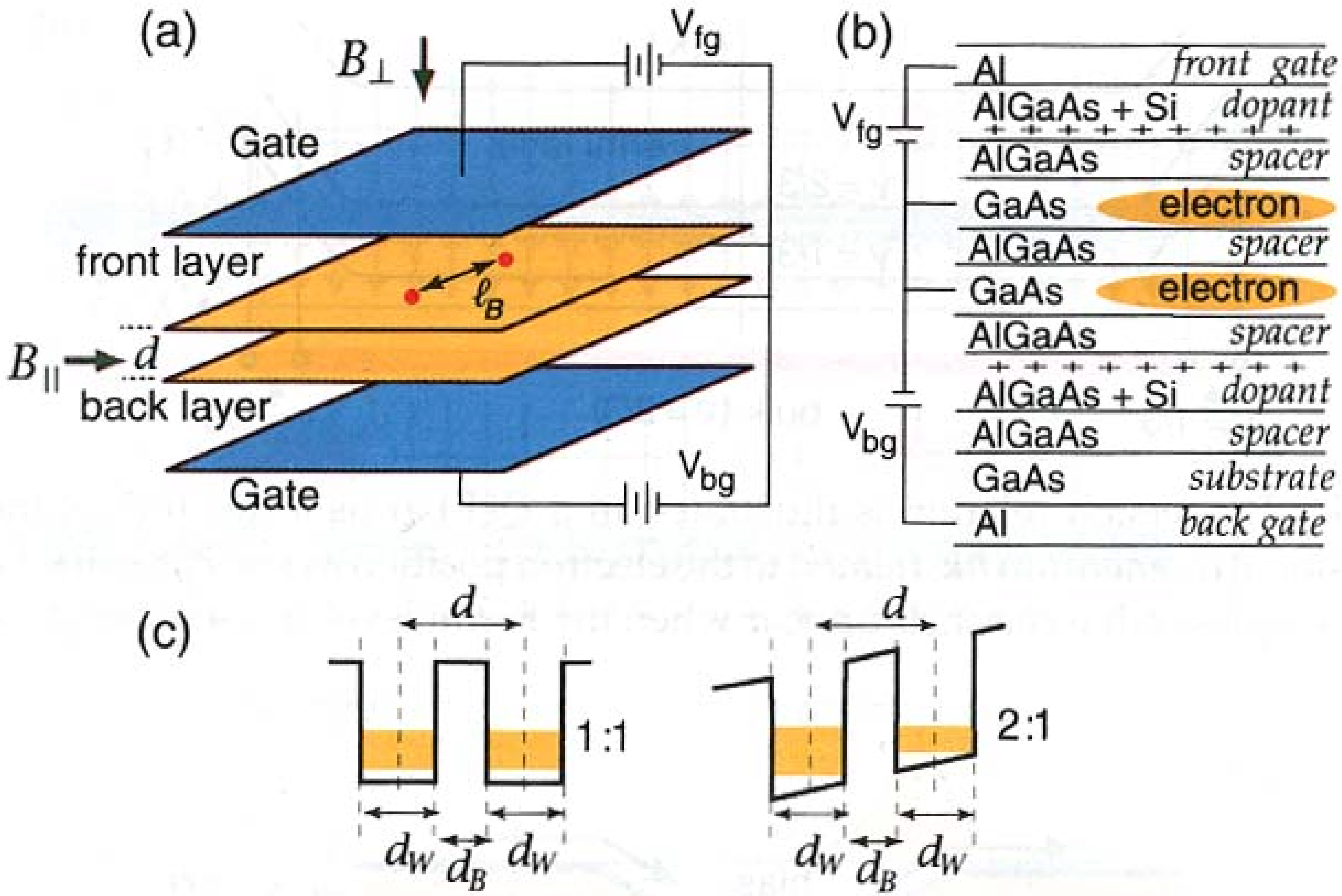


(Jörn Göres, J. Smet)

- CFs experience effective magnetic field B_{eff}, dramatically different from external field B
- existence of a Fermi sea of CFs at $B_{eff} = 0$ and Landau levels containing CFs at $B_{eff} \neq 0$
- Fractional Quantum Hall Effect of electrons can be viewed as Integer Quantum Hall Effect of CFs

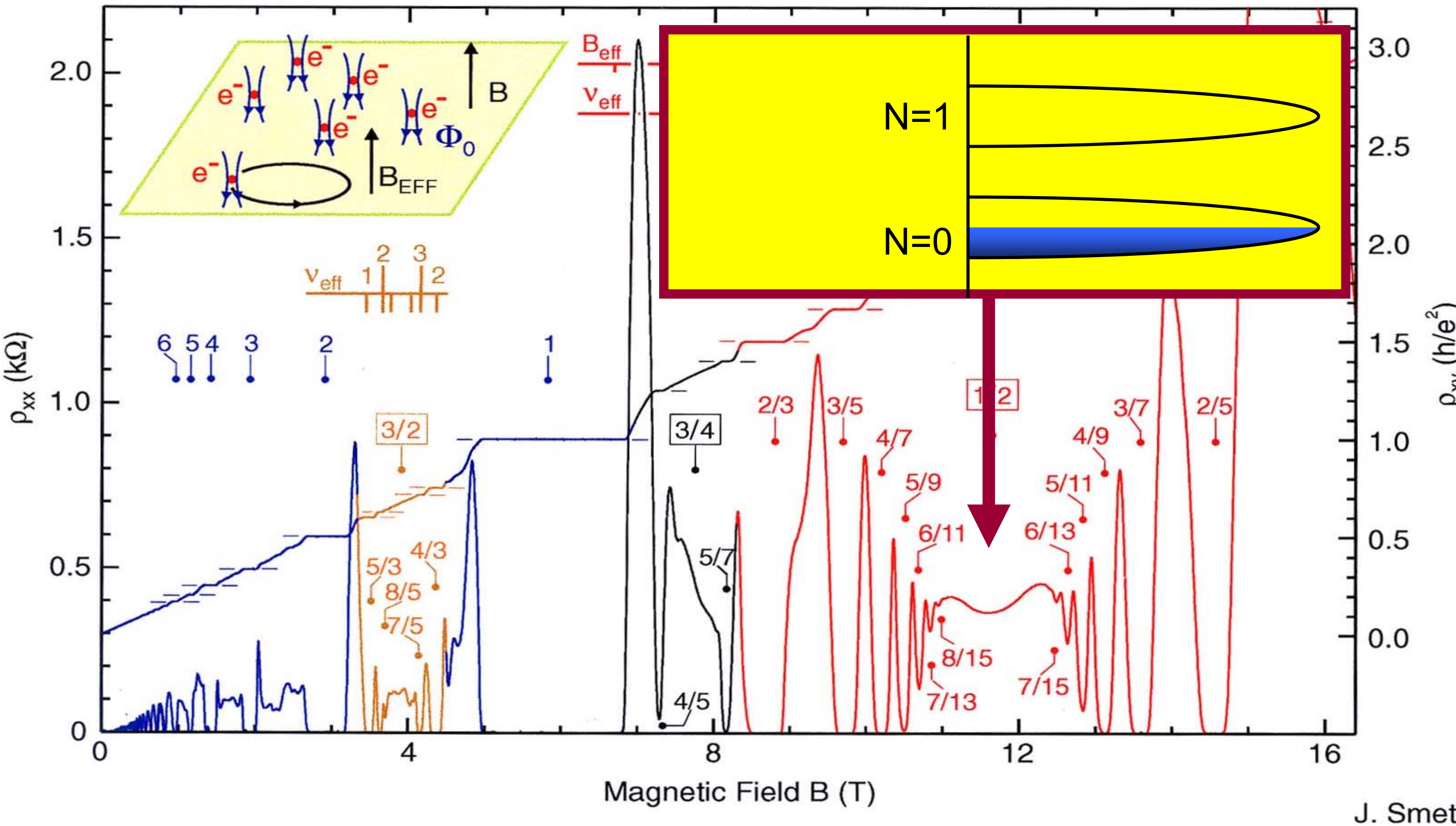
$$B_{eff} = B - 2\,\Phi_0\,n$$

New QHE-phenomena for double-layer system

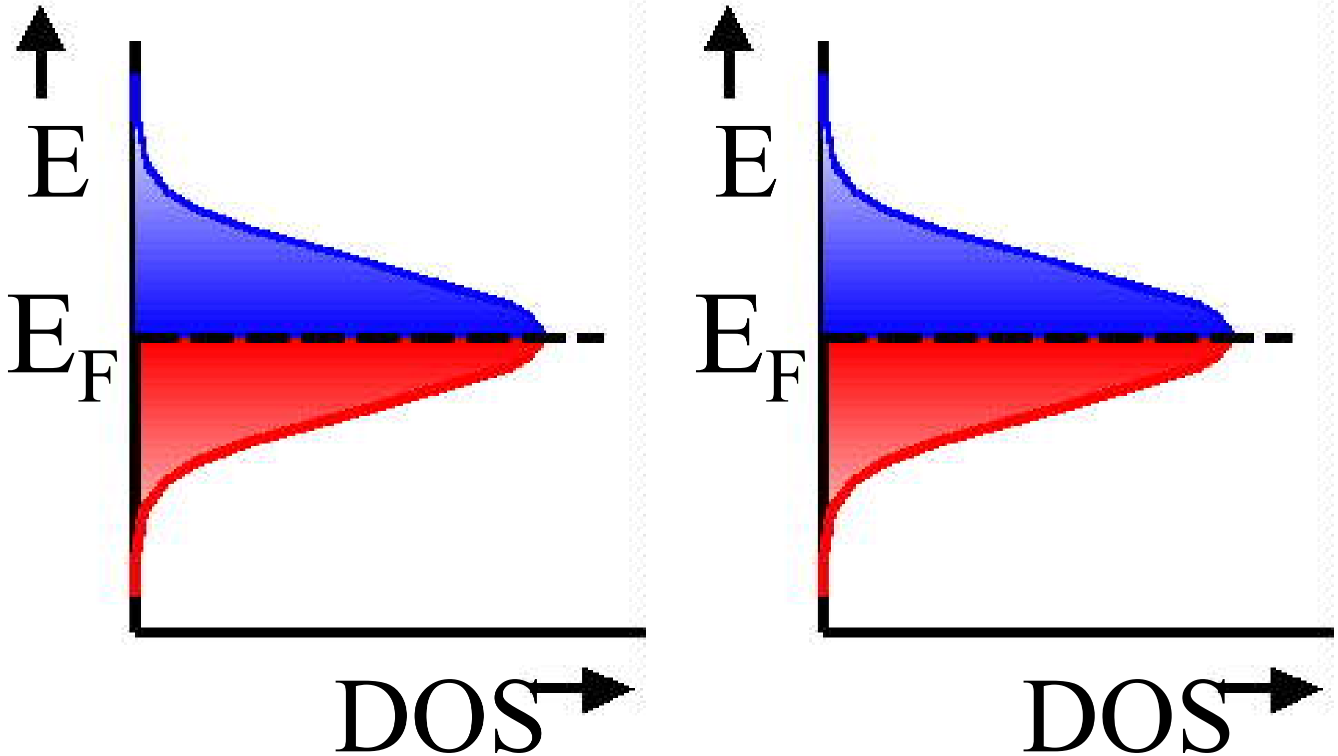


Zyun F. Ezawa: *Quantum Hall Effects*

Integer (fractional) QHE

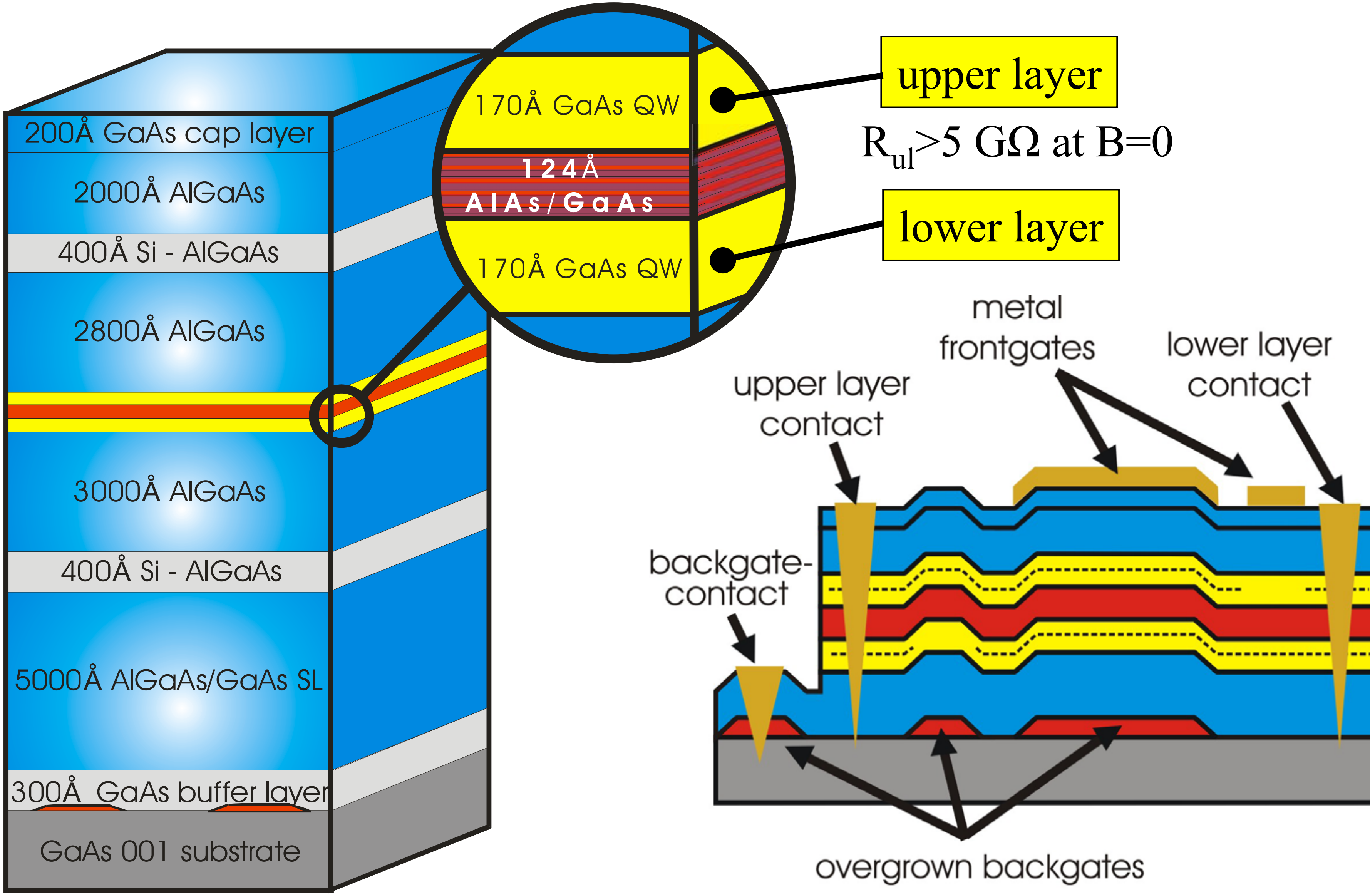


Coulomb interaction between two layers with half-filled bands!?

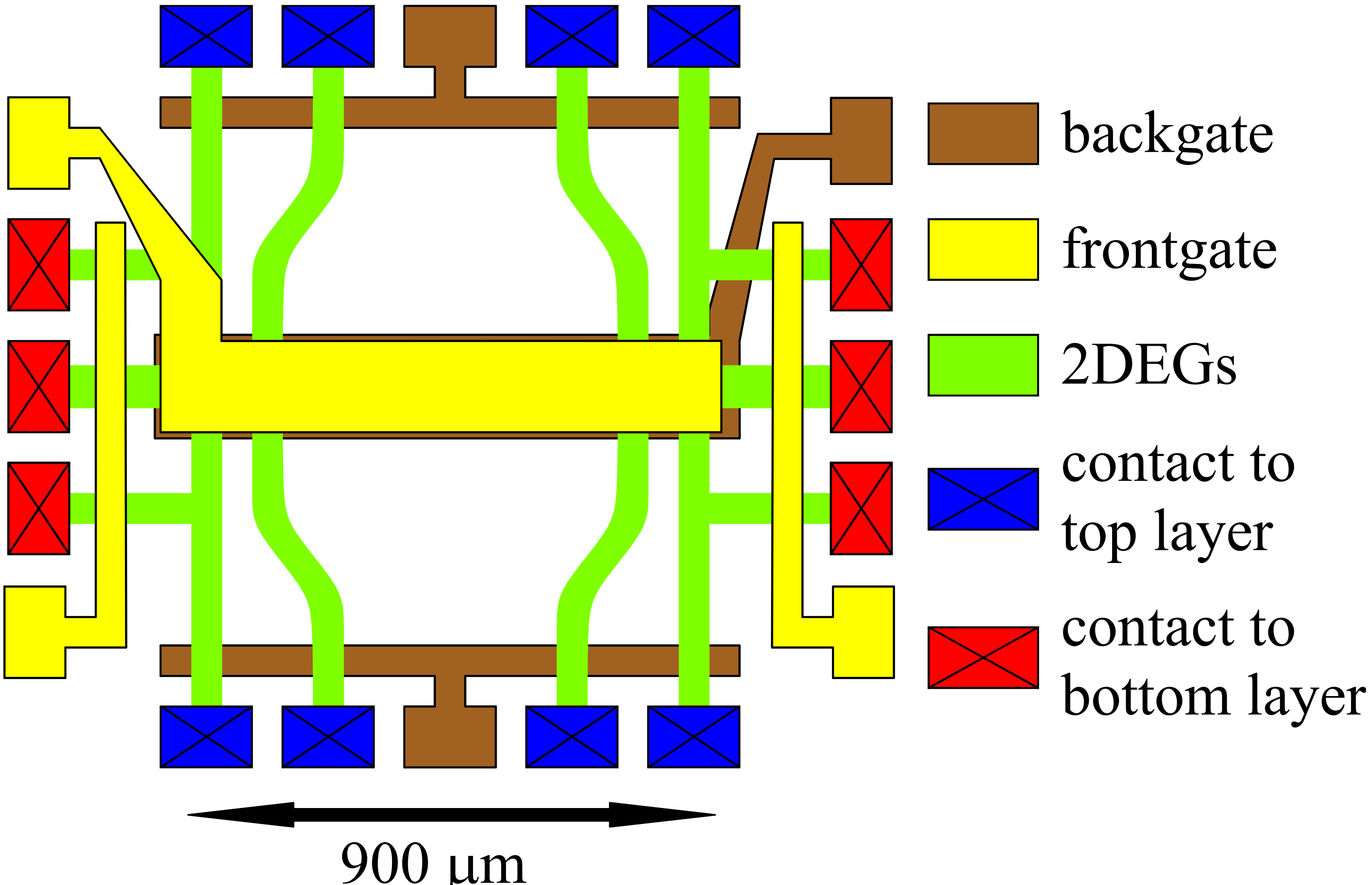


Important parameter: distance d between the two layers relative to the distance l_B between electrons within a layer

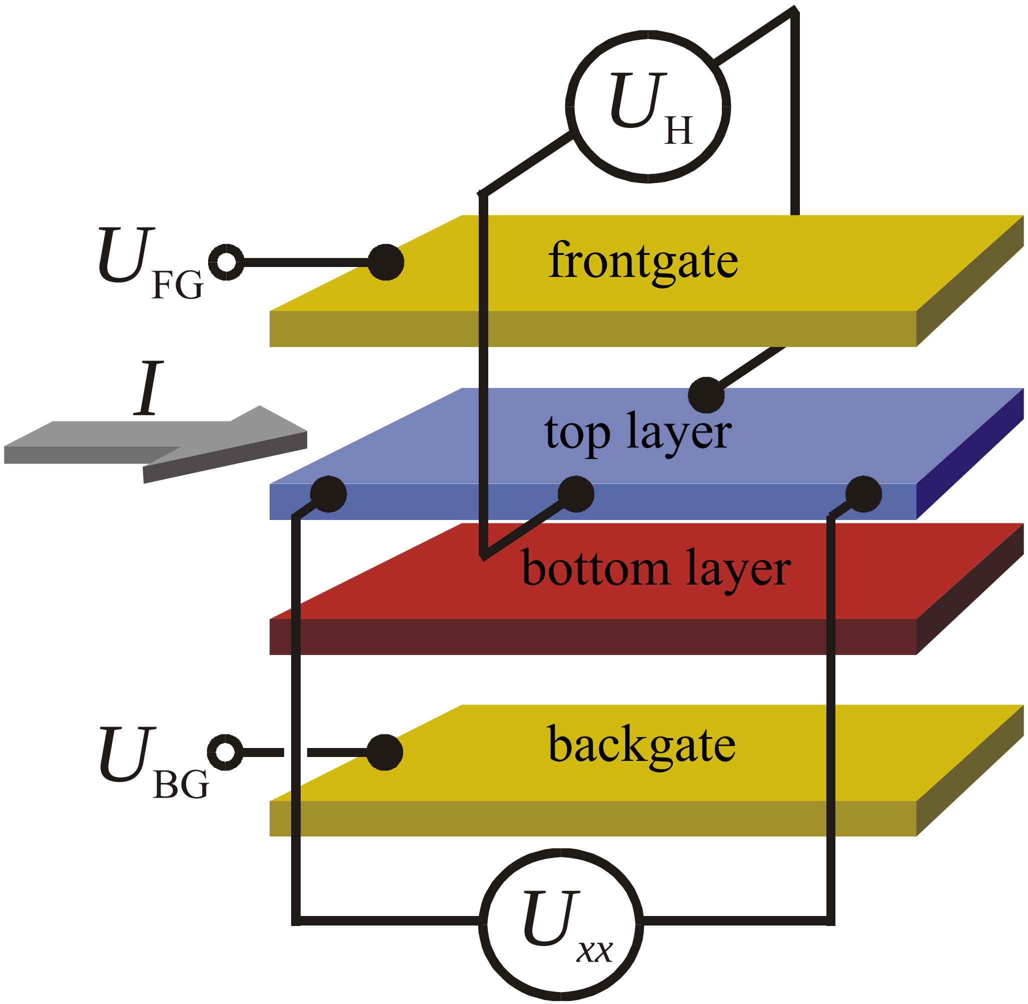
double layer system with separate electrical contacts *(group Dietsche)*



Double Layer Hall Device with separate contacts



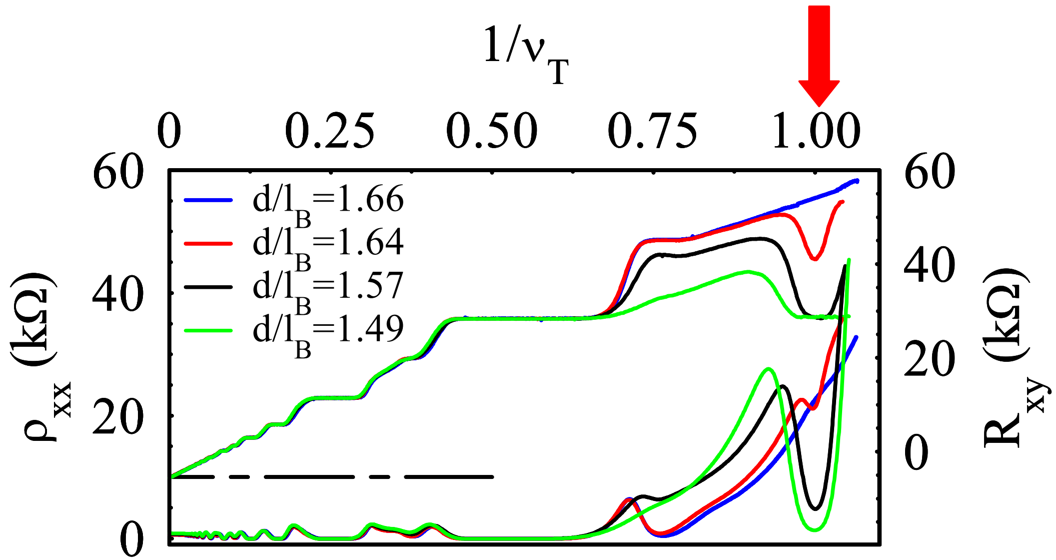
Bilayer el-el Systems



Au frontgate
20 nm GaAs
40 nm AlGaAs:Si
60 nm AlGaAs
15 nm GaAs
22 nm AlGaAs
15 nm GaAs
80 nm AlGaAs
40 nm AlGaAs:Si
300 nm superlattice
***n*+ backgate**

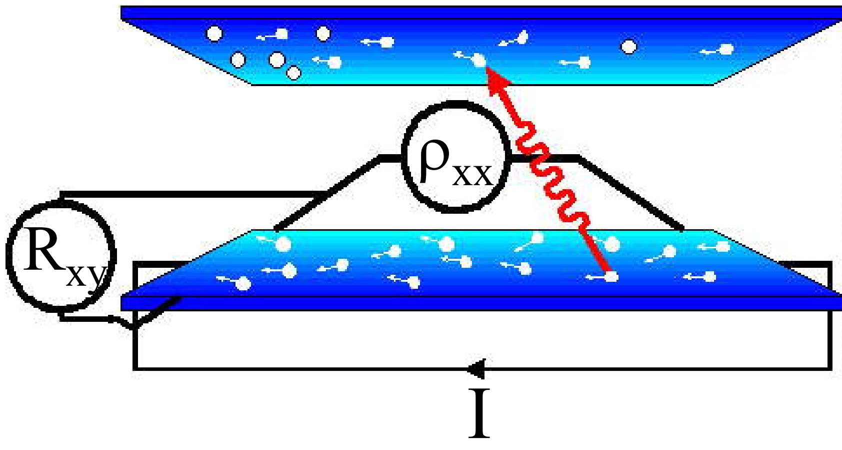
Variation of d/l_B

(R.Wiersma, S.Lok, S.Kraus, W.Dietsche)



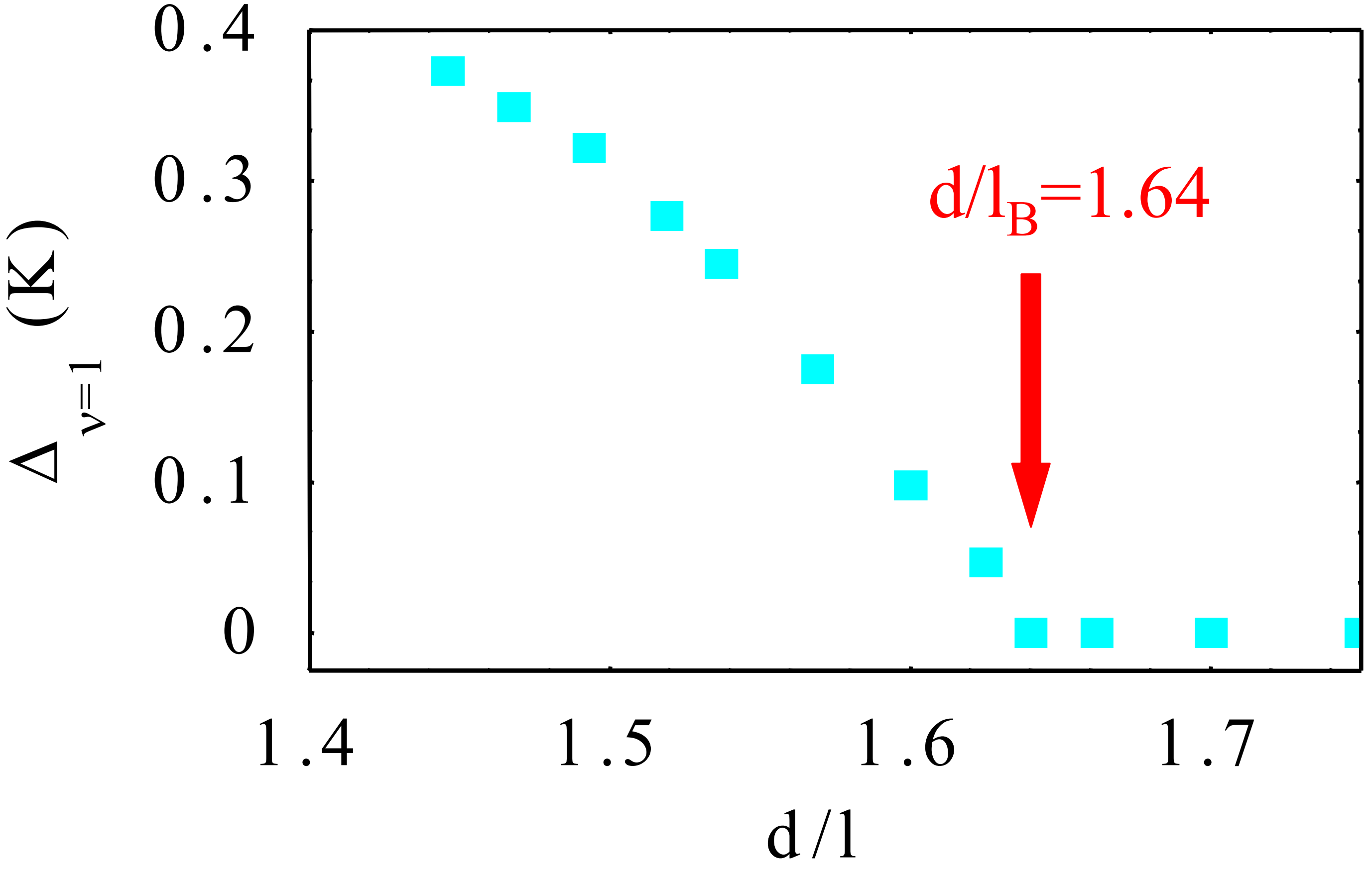
REDUCTION OF d/l_B

= smaller carrier density

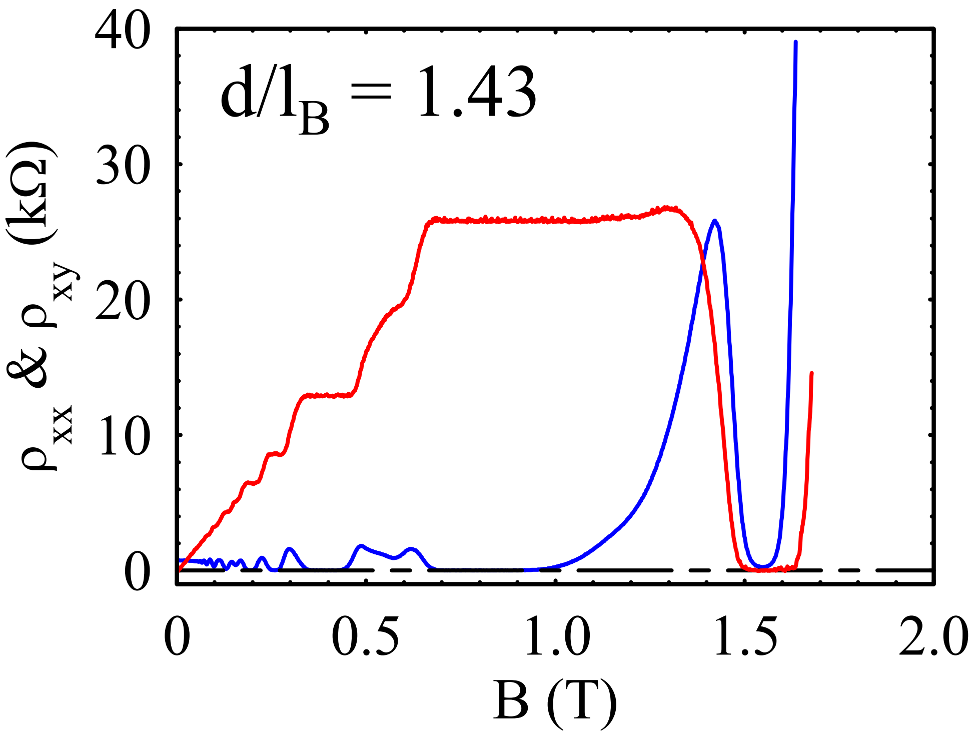


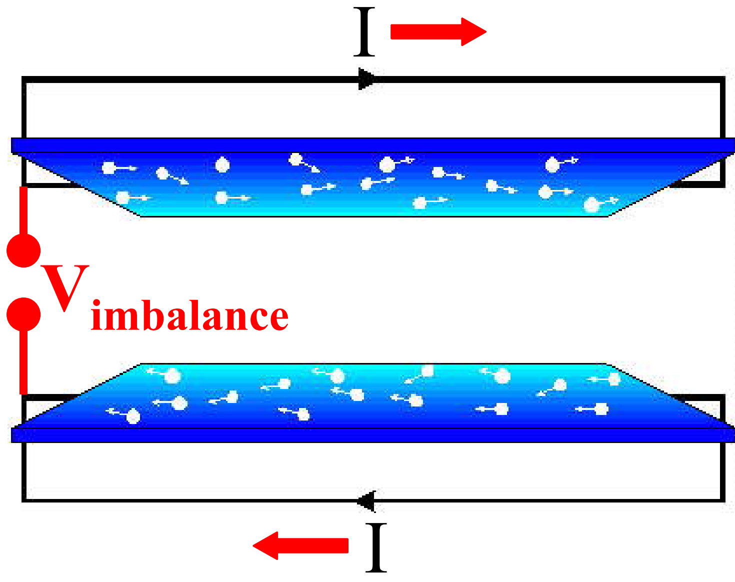
(Eisenstein 2003; Tutuc 2004; Wiersma 2004)

NEW GAP FOR TOTAL FILLING FACTOR $\nu = 1$ AT $d/l_B < 1.64$



counter-current superfluidity

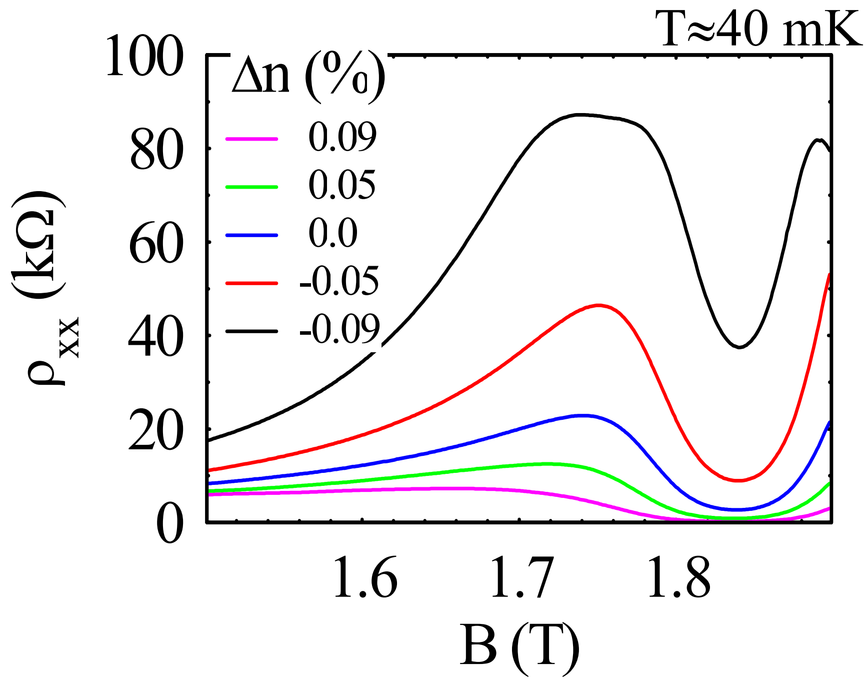


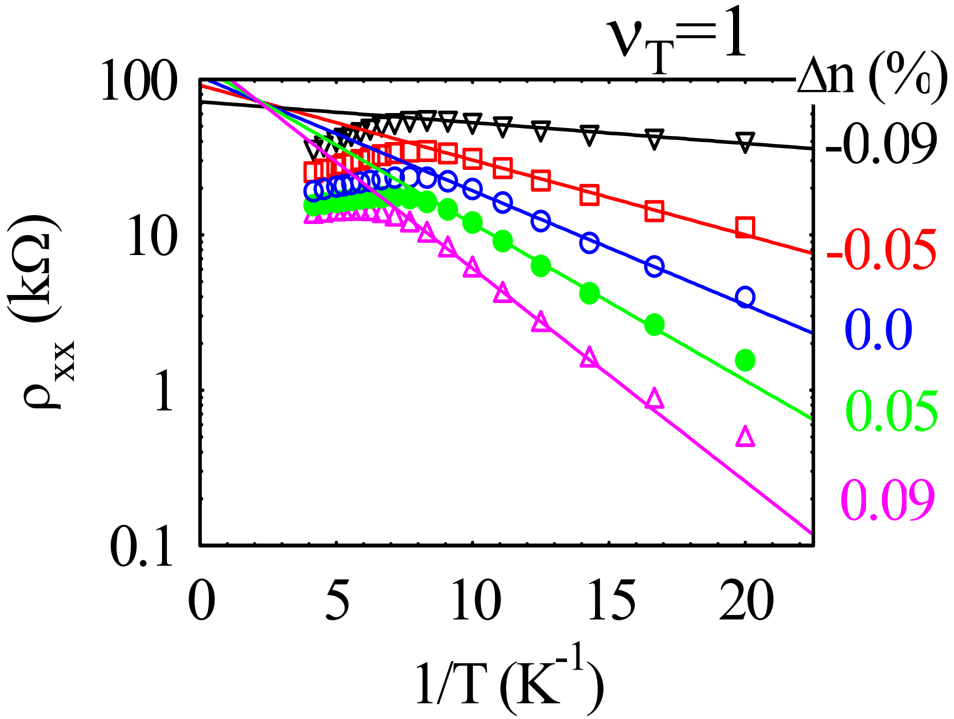


- with equal counter-flowing *I*, both ρ_{xx} and ρ_{xy} tend to zero

(Eisenstein 2004; Tutuc 2004; Wiersma 2004)

IMBALANCE AT TOTAL FILLING FACTOR 1
(e.g. ν_l=0.49 and ν_u=0.51)

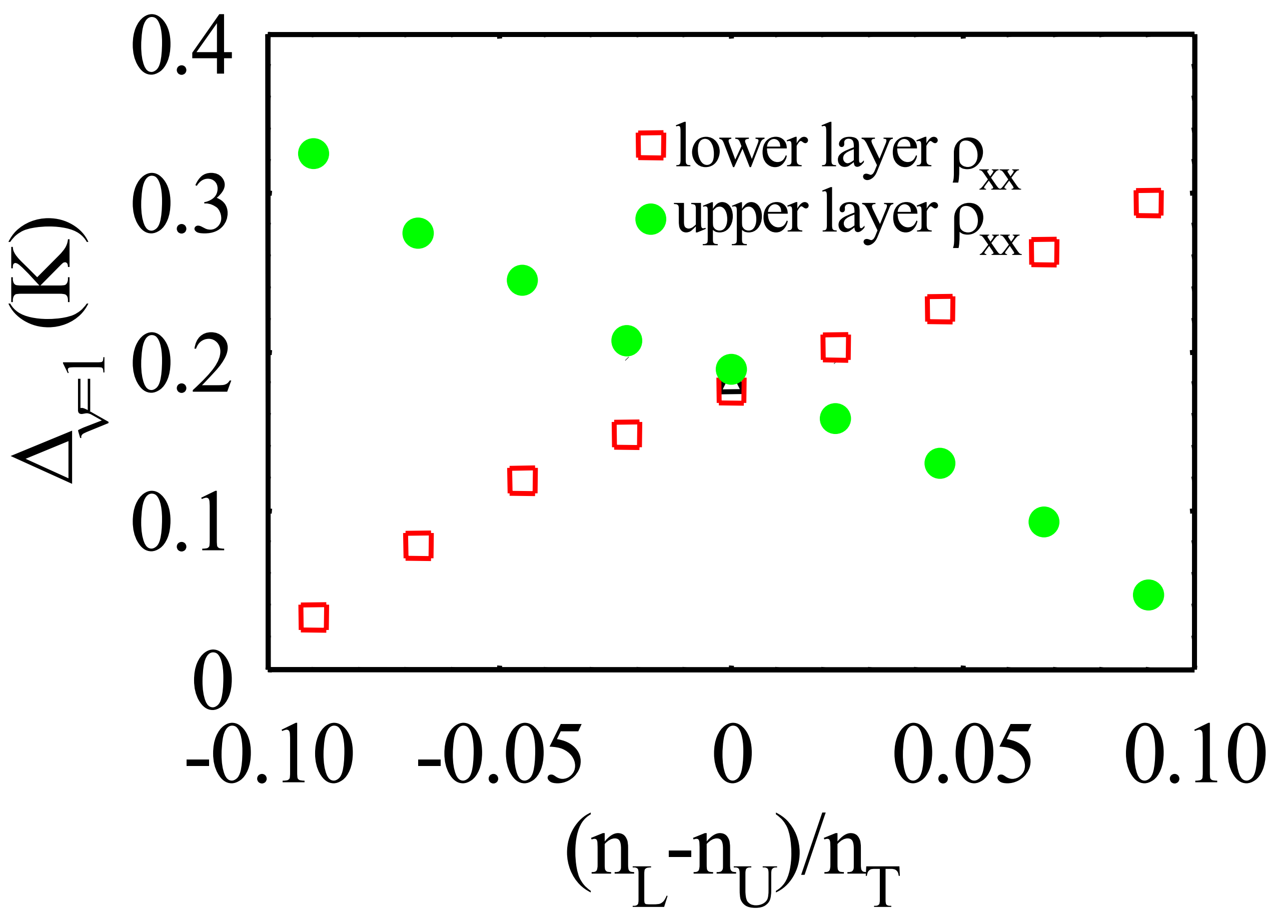




the total filling factor remains 1, but charge is transferred from layer1 to layer2

- **The two layers behave very differently upon a symmetric density imbalance......**
- **Larger energy gap for layer with larger carrier density**

Activation energy at $\nu_{tot}=1$ for each layer as function of imbalance



- Asymmetric activation energy upon symmetric density imbalance

SUMMARY

THE USE OF THE QHE IN METROLOGY IS THE MOST IMPORTANT APPLICATION OF THIS EFFECT BUT MORE GENERAL:

TWO-DIMENSIONAL SYSTEMS IN STRONG MAGNETIC FIELDS ARE MODEL SYSTEMS FOR MANY FUNDAMENTAL PHENOMENA IN SOLID STATE PHYSICS!