A New Era for the Ampere

A precision quantum current source has been designed to calibrate currents in terms of the soon-to-be-redefined International System of Units.

by Mark W. Keller* and José Aumentado†

Metrologists are conservative by nature, knowing that the premature adoption of a new measurement standard could lead to confusion in both science and commerce. So it is a big deal that the International System of Units (SI) is poised to undergo its first major overhaul since its birth in 1960. Two years from now at the General Conference on Weights and Measures in Paris, officials will adopt a new SI in which every unit can be obtained from fixed values of several fundamental constants [1]. All eyes are on the kilogram, which will no longer be defined by the mass of a cylinder of platinum-iridium alloy that has been kept in a Parisian vault since it was fabricated in 1889. Somewhat overlooked, however, are advances in standards for electrical resistance and voltage, without which the new SI would not be possible. A new report [2] from Wilfrid Poirier and colleagues at France’s metrology and testing laboratory, LNE, puts these electrical standards in the spotlight by combining them to create a current source based on the electron charge $e$ (as opposed to Ampère’s law). The source, which has an unprecedentedly low uncertainty, will enable current calibrations that are consistent with the redefined SI and boost efforts to close the so-called quantum metrology triangle [3].

The new current source is essentially a quantum realization of Ohm’s law, $I = V/R$, where $I$ is current, $V$ is voltage, and $R$ is resistance. The electron charge $e$ enters because $V$ and $R$ are each provided by a quantum electrical device whose outputs involve $e$ [4]. The voltage source is an array of $n_j$ superconducting Josephson junctions, which, when driven by microwaves at frequency $f_j$, produces a voltage $V_j = n_j f_j (h/2e)$, where $h$ is the Planck constant. The resistance comes from a two-dimensional electron gas that is placed in its $i$th quantum Hall state by a large magnetic field, in which it has a Hall resistance $R_H = (h/e^2)/i$. Ohm’s law for the quantum current then becomes $I_Q = (n_j f_j i/2)e$. Since $n_j$ and $i$ are known exactly and the uncertainty of $f_j$ is negligibly small, the uncertainty of $I_Q$ is limited by such seemingly little things as the “lead resistance” contributed by connecting wires and various sources of random noise.

These technical details are, however, the crux of why it’s challenging to make a high-precision quantum current source. To understand the problem, consider a simplified approach. (APS/Alan Stonebraker)

![Figure 1: A simplified circuit diagram showing a quantum current source.](image)

*(Quantum Electromagnetics Division, National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA)
†Applied Physics Division, National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA

 physics.aps.org © 2016 American Physical Society 12 December 2016 Physics 9, 144
The quantum Hall resistor ($R_H$), and the amplifier based on a superconducting cryogenic current comparator (CCC)—is in a separate cryostat (blue circle). The quantum Hall resistor must also be placed in a large magnetic field $B$. Each dotted line on the quantum Hall resistor indicates a uniform electrostatic potential for electrons. The existence of such equipotential lines minimizes the contribution of lead resistance, enabling a more accurate output current than in Fig. 1. (APS/Alan Stonebraker)

Our description does not do justice to the size and complexity of the actual apparatus. Each of the three main elements—the resistor, the voltage source, and the current amplifier—must be cooled to within a few degrees of absolute zero. For practical reasons, the French team did so using a separate cryostat for each element. With the ancillary electronics for controlling each device and the data-acquisition system, the complete setup occupies a laboratory space equal to a typical American two-car garage. They plan to reduce the footprint considerably by placing all three elements in one cryostat. A key step toward this will be to use a quantum Hall device based on graphene that can operate in a smaller magnetic field (potentially as low as 3.5 T instead of 10 T) and at a higher temperature (4 K instead of 1 K) [6].

As a calibration standard, the quantum current source designed by Poirier and colleagues has 100 times lower uncertainty than what is routinely offered by metrology institutes around the world. Not only will it enable calibrations of today’s best commercial ammeters directly in terms of the new SI ampere (based on $e$), but it will also ensure that metrologists can support future instruments.

The new source will also impact cutting-edge metrology. Groups at several national measurement institutes are pursuing single-electron tunneling (SET) devices that clock the flow of individual electrons at a frequency $f$, thus producing a current $I_{SET} = ef$ in the pA to nA range. Precise comparisons between $I_{SET}$ and a quantum current derived from $V_f$ and $R_H$ would realize a longstanding goal known as the quantum metrology triangle [3]. Showing that the two currents are identical would provide strong evidence for the ideal relations linking $V_f$, $R_H$, and $I_{SET}$ to $e$ and $h$; finding a discrepancy would spark a fervent search for the physics that modifies one or more of these relations. The best triangle experiment to date has found no deviation within an uncertainty of $9 \times 10^{-7}$ [7].

This research is published in Physical Review X.

REFERENCES


[5] This is the same topological effect for which David Thouless was awarded the 2016 Nobel prize in Physics. The Nobel Prize in Physics 2016.


10.1103/Physics.9.144