The super century

One hundred years after its discovery, superconductivity is still one of the most fascinating and challenging topics in condensed-matter physics.

On 8 April 1911, Heike Kamerlingh Onnes and his assistants were measuring the low-temperature electrical properties of mercury. As soon as liquid-helium temperature was reached the resistance became "practically zero"[1]. Those words noted by the Dutch physicist in his lab book signed the beginning of the superconductivity era.

This month we celebrate the one-hundreth anniversary of Kamerlingh Onnes's discovery with a number of editorial articles about some successful applications of superconductors and the obstacles that limit their wider use.

The ability of carrying high electrical currents without resistance immediately suggested the possibility of generating high magnetic fields with superconducting coils. This could work as long as the field itself was lower than a critical value that would destroy superconductivity. For this purpose, type II superconductors became particularly promising. In these materials an external magnetic field penetrates the superconducting phase through regions in which the magnetic flux is quantized, known as vortices or fluxons, and the critical magnetic field can reach several teslas. The first prototypes of superconducting magnets emerged in the mid 1950s, and nowadays they are used in several disciplines. Most notably, they are essential in magnetic resonance imaging (MRI).

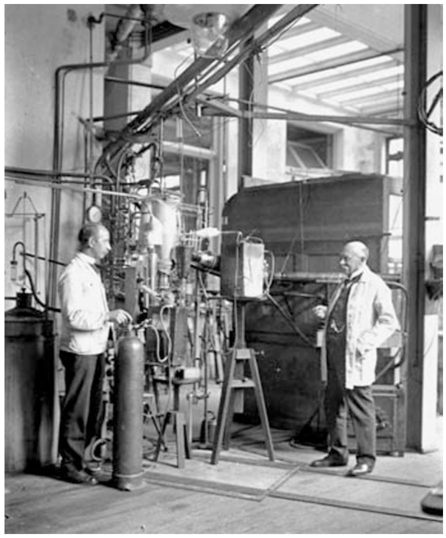
The other successful application based on superconducting metals is the superconducting quantum interference device, or SQUID, which is based on the effect discovered by Brian Josephson in 1962. In his interview[2], John Clarke provides an overview of the diverse fields in which SQUIDs are used. Although most applications so far are in academia, recent developments hold promise for a wider use, for example in the imaging of tumour tissues in low-frequency MRI.

Despite these successes, the use of metal and metal alloy superconductors is limited by the low transition temperature (T_c), which is mostly below 30 K and requires costly cooling systems, usually based on liquid helium. The discovery of superconductivity in the cuprates[3], which can have a T_c higher than that of liquid nitrogen (77 K), brought prospects for more affordable applications, with dreams of integration in the power grid. But, despite some prototypes, mainly in power cables and engines[4], the widespread use of these materials has not occurred. Three years ago, superconductivity was discovered in a class of iron-based materials[5] — in some cases these materials can have a T_c higher than 50 K. However, whether the conditions for their applicability are more favourable is still under debate.

In his commentary, Alex Gurevich examines the challenges faced by these two classes of material[6]. To allow the flow of high superconducting currents the vortices need to be pinned. This is quite feasible at low temperature, but the thermal fluctuations make it difficult at high temperature, a situation worsened by the anisotropy of these layered compounds. Furthermore, highly misaligned grains in polycrystalline films decrease the maximum current that can be carried without dissipation. To solve this problem, superconducting films have to be embedded in large layered structures, increasing complexity of fabrication and costs. Fe-based superconductors have a lower anisotropy, but manufacturing of these materials is still at too early a stage.

From a fundamental perspective, superconductors are exceptional models of correlated electron systems, involving the interplay of electronic, phononic and magnetic interactions. It is generally agreed that superconductivity in metals and metallic alloys can be explained by the BCS theory (from Bardeen, Cooper and Schrieffer)[7]. But such theory does not work for cuprates or Fe-based superconductors, and a consensus on a comprehensive description has not been reached yet. However, sophisticated experimental tools, based for example on neutron scattering, angle-resolved photoemission spectroscopy (ARPES) and scanning transmission microscopy have provided enormous insight into the electronic structure and phase diagram of these materials.

What now for the new century? More superconductors will be discovered. Recently, superconductivity with T_c around 30 K in the new family of Fe-based materials $A_xFe_2Se_2$ (A= K or Cs)[8] was reported. The observation is generating excitement, especially as new results point towards different electronic and magnetic properties from all other Fe-based superconductors. For example, a paper published in this issue discusses ARPES results that imply a so far unique electronic structure[9].



Heike Kamerlingh Onnes (right) and his chief technician Gerrit Flim, circa 1911.

New insight into the origin of high-T_c superconductivity will emerge. Advances in materials science and engineering may improve the conditions for use in applications. Above all, more superconducting classes will appear, potentially with a T_c higher than those known at present. According to Paul Canfield[10], current knowledge of the cuprates and the Fe-based superconductors may suggest where to look for materials that are readily less problematic for applications. The probability that high-temperature superconductivity is relegated uniquely to these two specific classes of materials is very low. So prepare to watch the resistance drop to zero again, many times. ❐

References

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