Journal of Superconductivity and Novel Magnetism (2021) 34:1597–1600
https://doi.org/10.1007/s10948-020-05772-z

ORIGINAL PAPER

Consequences of Brian Josephson's Theoretical Discovery

A. I. Braginski[1]

Published online: 21 December 2020

Abstract
Theoretical discovery of Josephson effects has beneficial consequences for science and economy, and in the future promises more benefits for public health. The strongest impact thus far has the use of Josephson devices and circuits in many areas of science and in geophysical prospecting for minerals. I highlight a few examples of present and future benefits.

Keywords Josephson tunneling · SQUID · Astronomy · Metrology · Mineral mining · Biomagnetism · Noninvasive medical diagnostics

I missed the opportunity to ever meet Brian D. Josephson (BDJ) in person, since moved to superconductivity and superconducting technology rather late in my career, only in 1974, and to that of Josephson devices even later, around 1980. Already in 1962, BDJ, then a graduate student at Cambridge University, theoretically predicted the behavior of Cooper pairs tunneling between two superconductors weakly coupled via a thin tunneling barrier, and properties of thus resulting Josephson tunnel junctions (JJs), a discovery of what is today known as Josephson effects [1]. By 1974, he earned his Nobel Prize in physics (1973) and moved already to other, more esoteric pursuits. That discovery determined decisively the course of the last and longest segment of my professional itinerary that started long ago, back in wartime 1940s.

On the occasion of BDJ's 80th anniversary and to honor him, I like to briefly highlight some consequences the theoretical discovery of effects bearing his name had for various areas of activity beginning with science and ending with practical applications of Josephson-junction-based superconducting electronics (SCE) in many areas of technology. Some of these have or may still have a significant economic impact. In addition, I offer some remarks on social facets of activities associated with such applications.

Barely 2 years after the theoretical prediction [1] and only a year after the first experimental confirmation by Anderson and Rowell [2], a new milestone was set by the observation of quantum interference between two Josephson tunnel junctions by Jaklevic et al. at the Scientific Laboratory of the Ford Motor Company [3]. This observation set stage for the invention of the superconducting quantum interference device (known later as DC SQUID) consisting of two junctions connected in parallel on a superconducting loop. Thereafter, the same group introduced a device with only one junction shunted by a superconducting loop and not involving quantum interference [4], which in spite of it became known as RF SQUID. Both are counters of flux quanta Φ_0 threading the loop ($\Phi_0 = h/2e \approx 2.07 \times 10^{-15}$ Wb), but in conjunction with promptly developed in the same lab room-temperature flux-locked analog readout electronics they became relatively broadband magnetometers of flux and magnetic field change with resolution on the order of 10^{-6} to 10^{-7} Φ_0. Initially, due to fabrication simplicity, RF SQUIDs came into practical use. With maturing technological processing by micro and nanoelectronic methods, low-T_c DC SQUIDs are currently the most used and are considered to be the most sensitive.

SQUIDs provided science and technology with a new tool of then unsurpassed sensitivity not only for measurement of magnetic quantities, but also of virtually any other physical quantity that can be transduced into flux or magnetic field change. A whole series of essential contributions to DC SQUIDs and to their uses was then made by John Clarke himself or later with his students, postdocs, and collaborators at the University of California, Berkeley. This series begun with an independently demonstrated by him in mid-1960s, still when a graduate student at Cambridge, variant of SQUID named SLUG (Super conducting Low-inductance Undulating Galvanometer), which in turn lead John to the idea of using his SLUGs and eventually

In celebration of the 80th birthday of Brian D. Josephson.

✉ A. I. Braginski
a.braginski@fz-juelich.de

1 Research Center Juelich, D-52425 Juelich, Germany

SQUIDs as most sensitive low-noise amplifiers of small signals, today another essential use of these devices [5].

It is beyond the scope of this text to dwell on historical developments and to mention many other important early contributors to Josephson-effect-based devices and circuits making these sufficiently reliable for in-field uses, even in motion and in space. It suffices to observe that JJ-based SCE became a new area of applied superconductivity with its own dedicated community, although thus far having lesser direct economic and social impact than superconducting high-field magnets for MRI,[1] but also requiring much lesser investments than other, large-scale, superconductivity applications in science, such as particle accelerators, and prospective electric energy grid applications.

Examples of uses of JJs and SQUIDs in science range from sensitive femtovoltmeters through magnetometers to detectors in astronomy and cosmology, e.g., in the search for postulated exotic particles such as WIMPs[2] or axions. These uses are simply too many to mention all of these. Important is that some of these became irreplaceable and are enabling new discoveries. An arbitrary example are SQUID amplifiers in multiplexers for large astronomical cameras of superconducting detectors, currently with order of 10^4 pixels and with projections to at least 10^6 in the future. Installation of such cameras in several large telescopes located on several continents, including Antarctic (South Pole Telescope SPT-3G, with 16,000 sensor pixels and about 24,000 SQUIDs) resulted in discoveries of hundreds of distant galaxies and makes even possible to investigate potentially life-supporting exoplanets in some of these.

An early practical application of SCE that has been generally accepted are Josephson voltage standards for metrology, first introduced in 1980s–1990s. They decisively contributed to orders of magnitude improved measurement accuracy and eventually to making possible the newly (2019) introduced system of SI base units entirely based on fundamental physical constants.

The first industrial company that has been truly profitable with JJs-containing products is Quantum Design (QD). It developed and marketed SQUID magnetometers in the QD Magnetic Properties Measurement System [6]. It experienced a real boom after the discovery of high-T_c cuprate superconductors in 1986, when researchers around the world suddenly needed high numbers of such sensitive and versatile instruments.

However, the highest albeit indirect economic impact thus far has the use of SQUID-magnetometry-based equipment methods for geophysical exploration of minerals [7, 8]. In the 1st decade of this century, portable ground-based and airborne geophysical instrumentation attained performance clearly superior to conventional equivalents and became generally accepted in mineral exploration and mining. While the exploration results are as a rule proprietary, the value of discovered ore deposits in the past two decades is generally estimated to be in rather high multi-billion US dollar range. Such SQUID equipment was successfully pioneered by CSIRO[3] using high-T_c SQUIDs, and IPHT-Jena[4] using both low-T_c and high-T_c devices.

Low numbers of portable instruments (thus requiring only modest capital investment and acceptable maintenance cost) are being sold or rented to exploration companies and have been operating in Australia, Canada, South Africa, and northern Europe on behalf of worldwide largest Western mining companies, among them BHP,[5] Glencore and Anglo American.[6] In China, Chinese SQUID-based equipment, low- and high-T_c, has been also developed and successfully tested by developers in Inner Mongolia.[7] However, nothing is known about industrial in-field use by largest mining companies, such as China Shenhua Energy and others. To give just one example of exploration successes: thanks to the use of low-T_c SQUID instrumentation for large depths, Anglo American discovered in 2009 the main Sakatti Ore Body in Finland—the largest ever found resource in Europe with significant grade of ore at large depth (principal base metals copper, nickel and cobalt, lesser amounts of platinum, palladium, gold, and silver).[8]

In most practical applications, the main obstacle to a broad use of SCE is operation at low and moderate cryogenic temperatures, and the related capital and maintenance cost. While many such applications were investigated and their significant technical or other benefits demonstrated, the tradeoffs have not been sufficiently attractive to warrant a broad implementation.

Of numerous practical applications that thus far did not make it big, in spite of high potential benefits to users or patients, I mention here only the noninvasive and contactless biomagnetic diagnostic instrumentation. Probably no other application area absorbed so much dedicated effort and imagination by academia and industry as this one. For example, very weak local magnetic fields generated by physiological

[1] Magnetic resonance imaging for medical diagnostic purposes.

[2] Weakly interacting massive particles.

[3] Acronym of Australian Commonwealth Scientific and Industrial Research Organization in Lindfield, New South Wales, AU.

[4] Leibniz Institute of Photonic Technology, Jena, Germany (formerly Institute of Physical High Technology).

[5] BHP stands for Broken Hill Propriety Company Ltd., the name the company was incorporated under in 1885.

[6] A bit later, analogous equipment has been developed in Japan by ISTEC, and later SUSTERA.

[7] Low-Tc equipment developed and tested by SIMIT (*Shanghai* Institute of Microsystem and Information Technology). Private information by Dr. Xiaoming Xie, SIMIT.

[8] Information provided by R. Stolz, IPHT-Jena, based on information by exploration and mining companies.

currents of many human organs, especially of the heart and brain, can be recorded by SQUIDs and these currents are mapped or imaged by approximate solutions to the inverse problem in loose analogy to mapping of mineral ore deposits deep underground.[9] In 1980s–1990s, development of such equipment and methods was pursued by some very large companies (Siemens, GE, Philips, and Hitachi) and many small. Indeed, resulting multichannel magnetocardiograph (MCG) and magnetoencephalograph (MEG) systems for clinical use appeared on the market in early1990s, but have not been accepted by the medical profession, with very few exceptions. All large companies, but one (Hitachi), withdrew rather quickly; the small continued and almost all eventually went bankrupt or suspended operation. Magnetoencephalography found small niches in medical, psychological and linguistic research, and in a few clinical environments.[10] Magnetocardiography and fetal magnetocardiography have been used to advantage in only very few clinical institutions worldwide. Overall, low hundreds of such multichannel systems have been sold in the last 3 decades; hence, the direct economic impact has been small.[11] Examples of other biomagnetic applications include liver susceptometry, immunoassays, and low-field MRI, all using SQUID sensors. Of these applications, only the liver susceptometry has been accepted and used clinically. Its success has been due to significant patient benefits for a rather small but international community of patients from Mediterranean countries suffering of thalassemia (Mediterranean anemia).

Continuing lack of broader clinical acceptance for clinical diagnostic imaging has three main reasons: (1) high capital investment and expensive cooling, mostly to liquid He temperatures, (2) instrumentation inflexibility in clinical environments (e.g., need of large and expensive magnetic shielded rooms) and, last but not least, (3) the clinical practitioners' preference for anatomical rather than purely functional imaging and fear of reducing income from lucrative, although invasive diagnostic procedures (such as cathetering, for example). Of these three obstacles, only the first has been recently reduced in large MEG installations incorporating He recovery, purification, and re-liquefaction in a closed system, of course, at an additional cost.

At present, the main carrier of hopes for a major clinical use and impact in the future is a combination into one multichannel SQUID system of MEG and ultra-low-field MRI system (MEGMRI), an idea originated in John Clarke's laboratory and then pursued mainly at LANL and, with European Union funding, at Aalto University near Helsinki, Finland.[12] It could eliminate the need for and imprecision of inverse solutions, and provide the physician with both functional and anatomical diagnostic information. Moreover, patients with electronic implants such as defibrillators, who cannot be examined by high-field MRI at all, could benefit from MRI diagnoses. The high number of SQUID channels in the MEG system would enhance the signal-to-noise ratio of ULFMRI (by roughly square root of the number of SQUIDs) resulting in spatial resolution comparable to that of a clinical high-field MRI system.

In my opinion, based on hands-on experience, benefits of early detection of cardiovascular diseases (CVD) by contactless and fast mass screening of population at large[13] using relatively few multichannel MCG instruments could obviate the economical and inflexibility arguments, but changing the negative attitude of a distinct majority of clinicians may be more difficult.

The imagination and enthusiasm of a large fraction of the SCE community are currently fired up by prospects of quantum computing (QC) and energy-efficient computing. It is too early to predict that superconducting qubits will win the competition with several other possible physical embodiments for QC. However, at this juncture, the tradeoffs look favorable and worldwide largest high-technology companies such as Google, Microsoft, and IBM, support massive R&D efforts in QC processors and related software such as error correction algorithms. In the US, superconducting energy-efficient computing has been enjoying continuing support over several past years, cost shared between the government and industry. Such novel computing technologies and applications might become directly significant economically, although being still only niches in the generally semiconductor-dominated field of computing. Nevertheless, this is by no means certain. One should never underestimate the present enormous industrial manpower and capital investment base of semiconducting technologies coupled with high inventiveness of involved engineers and scientists.

Before concluding, I like to note that the still rather small international SCE community is dedicated and mutually supportive, in spite of understandable personal and institutional competition. Many of its members have been devoting their whole career to this fascinating field. This can be seen as a direct social consequence of Brian Josephson's discovery. In the future, a very large social potential in terms of benefits to patients might have a broad adoption of contactless noninvasive medical diagnostics using SQUIDs.

[9] Approximate solutions to the inverse problem are used in both fields, but the characteristics of signals measured are different.

[10] Mostly for preoperative localization of epileptic foci to minimize brain damage during surgery.

[11] A current price of a modern multichannel MEG system is about US$ 2 million.

[12] In the laboratory of Prof. Risto Ilmoniemi, in cooperation with several other European laboratories.

[13] 20–30 s per human subject test.

In conclusion, beneficial consequences of BDJ's discovery are and still may be many, especially where low numbers of SCE instruments result in significant benefits in terms of new scientific discoveries, trade advantages through improved metrology, industrial economic gains, and also availability of natural resources, e.g., of minerals. In coming decades, more economic benefits, indirect and direct, can be expected. Public health may also benefit at much larger scale than today, although this is by no means certain.

Acknowledgments John Clarke has my deep gratitude for his critical remarks, pointing out errors and providing an update on progress in biomagnetism, especially on MEGMRI.

I also like to thank Cathy Foley, Ronny Stolz, and Xiaoming Xie for their most helpful updates on the current status of geophysical exploration of minerals. Robert (Bob) Fagaly provided a helpful update on liver susceptometry.

Funding Open Access funding enabled and organized by Projekt DEAL.

References

1. Josephson, B.D.: Phys. Lett. **1**, 251 (1962)
2. Anderson, P.W., Rowell, J.M.: Phys. Rev. Lett. **10**, 230 (1963)
3. Jaklevic, R.C., Lambe, J., Silver, A.H., Mercereau, J.E.: Phys. Rev. Lett. **12**, 159 (1964)
4. Silver, A.H., Zimmerman, J.E.: Phys. Rev. **157**(317), (1967)
5. Clarke, J. in: J. Clarke and A.I. Braginski (eds.), *The SQUID Handbook*, vol. II, Chapter 8, Wiley-VCH (2006). ISBN: 3-527-40408-2
6. Sager, R. in: Rogalla, H., Kes, P. (eds.) *100 Years of Superconductivity*, Taylor & Francis Ltd (2011). ISBN-13: 978–1–4398-4946-0
7. Clem, T. R., Foley, C. P. and Keene, M. N. in: J. Clarke and A.I. Braginski (eds.), *The SQUID Handbook*, vol. II, Chapter 14, Wiley-VCH (2006). ISBN: 3-527-40408-2
8. Stolz, R., Schmelz, M., Zakosarenko, V, Foley, C, Tanabe, K., Xie, X. and Fagaly, R. L., submitted to *Supercond. Techn. Sci.* (2020), unpublished