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Superconducting analogue electronics for research and industry

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Abstract

This paper gives a brief review of superconducting electronics in research and industry. Examples will show how science benefits from the development and how superconducting devices have found their way into industry and to some commercial products. Impact in terms of enabling new research in other fields (e.g. radio astronomy, medicine), in industry (certification, safety, metrology, etc) and in terms of market will be addressed. From the examples, two fields will be emphasized: superconducting detectors for astronomy and the superconducting quantum interference devices (SQUIDs) employed for different applications.

1. Introduction

Superconducting electronics (SCE) has been competing for a sustainable place in society for many years, and is still searching for a widespread ‘killer application’. Several high-end applications, such as detectors, high-frequency mixers, fast sampling circuits, multiplexers and the superconducting quantum interference device (SQUID), used as, e.g. magnetometers, have excelled research in other fields, but none of these devices have reached a widespread market. While superconducting circuits employed in new instrumentation usually constitute the most important and vital part, they are often the smaller cost in the total system, however with a cryogenic overhead. This has resulted in fairly specialized high-end research instrumentations, tailor-made for a specific application. This means that it is difficult to produce large numbers of units on an industrial scale, and to reach a mass market. Larger and more complex circuits, where several functions are solved in an integrated SCE package may eventually give an overall system advantage in terms of price and performance.

In this review, we will briefly address the influence of SCE in other research areas, in industry and on the market. Since the economic value is not limited to the primary users or industries, also secondary impacts might be of high value.

We will give examples of how analogue SCE has found its way to the end users in two ways. The first example shows how SCE influences radio (and x-ray) astronomy, due to the requirement for ultimate resolution by the end user. Here, the technology pull has catalysed the development of sophisticated electronics for a specific field, resulting in a large variety of superconducting devices (mixers, bolometers, detectors, amplifiers, oscillators and multiplexers). These devices are mainly made from traditional low-T_c superconductors (LTS). In the second example, applications based on SQUID systems are finding end users from the specific solution that the system can offer. Here, a specific circuit, based on both LTS and high-T_c (HTS) materials, has succeeded in a technology push into certain applications. In both examples, the applications have some spin-offs in terms of new products, which are marketed by several companies. We will then briefly look at the actual and possible market value of SCE.

2. Why SCE? Why not?

We can see several areas where SCE has had an enormous value. Mostly this has been in serving other scientific fields. The value is typically not in terms of the number of devices or systems, but rather on the overall importance for a specific research fields.

Best sensitivity or energy resolution can in many cases only be achieved using superconducting devices, often with quantum-limited sensitivity. Examples include the superconductor–insulator–superconductor (SIS) mixers [1–3], hot-electron bolometer (HEB) mixers [4, 5], and transition edge bolometers [6] in radio and x-ray astronomy. Further to this list belong SQUIDs [7] for, e.g., biomagnetism (magnetoencephalography (MEG), magnetocardiography (MCG), and other applications, see below) and non-destructive evaluation (NDE) [8], measurements of small currents or voltages in characterizing transport phenomena in various materials (e.g. corrosion, or noise in materials or devices), and in the search for gravity waves [9]. The SQUID microscope has been used for fundamental studies of the order parameter symmetry in YBCO [10], to look at magnetically tagged biomolecules for *in vitro* diagnosis [11–16] and *in vivo* [17], and also sold commercially; see, for example, [18, 19][1].

There are many reasons for using SCE and some of the most important hallmarks of SCE are summarized as follows:

- extremely non-linear current–voltage (I–V) and resistance–temperature (R–T) characteristics;
- the Josephson effects $I = I_c \sin\varphi, \dot{\varphi} = 2eV/\hbar$, where $\varphi = \varphi_2 - \varphi_1$ is the superconducting phase difference across the Josephson junction;
- high frequency $f_J = (2\text{ eV h}^{-1}) \sim 483\text{ GHz mV}^{-1}$;
- high resolution and speed;
- quantum limited sensitivity;
- low dissipation, dispersion, noise and loss;
- low local oscillator power for mixers, i.e. less weight.

On the other hand, there are reasons and situations, which may decrease the motivation for using SCE:

- cooling and cryogenics add additional costs, power requirements, weight and possibly vibrations to the system;
- sensitivity could in some cases mean saturation from incoming signals or from electromagnetic interference (EMI);
- if price versus performance gives no advantage;
- if other technologies solve the problem.

See also [20, 21].

Examples of devices that are built using SCE are:

- SIS tunnel junctions and Josephson weak links;
- SQUID magnetometers and gradiometers;
- SQUID current and voltage amplifiers;
- HEB devices;
- transition edge bolometers;
- digital electronics (e.g., rapid single flux quantum logic (RSFQ));
- π-junctions and Q-bits;

These are for, e.g., applications or uses towards

- microwave: radio and x-ray astronomy, terahertz (THz) Hilbert spectroscopy, oscillators (Josephson and flux-flow), filters;
- metrology, certification, standards, medicine, geology, NDE;
- high-resolution instrumentation;
- fundamental research.

The list can be made longer, but the bottom line is that devices based on SCE have usually reached an application due to one or several of the benefits listed earlier.

A specific example, to which this is applicable, is modern metrology and standards. This field is heavily dependent on research and has a large value for industrial development. The introduction of the Josephson voltage standard was one of the greatest achievements in modern metrology. The accuracy improved from parts in 10^6 with the Weston cell to parts in 10^9 or better with the Josephson voltage standard (see figure 1). Today, voltage standards can be bought from several sources, and have been developed to give up to 10 V standards.

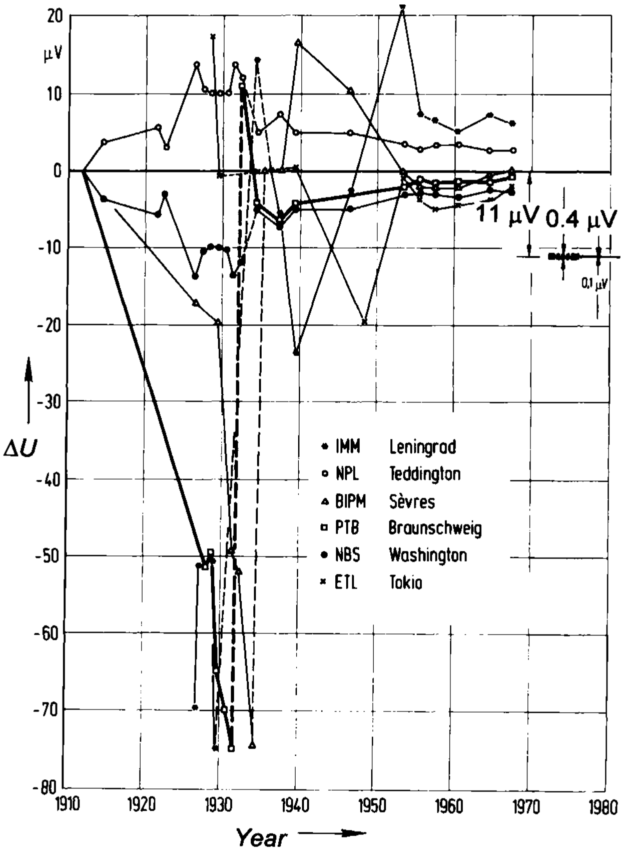

Figure 1. Data from international voltage comparisons between 1910 and 1980 from six metrology laboratories. The reference line ($\Delta U = 0$) is taken as the average voltage between the National Physical Laboratory (NPL) and the National Bureau of Standards (NBS)[2] [22].

The recent new development of alternating current (ac) voltage standards and arbitrary waveform generators based on Josephson circuits may have an impact both on metrology and high-speed devices for information technology [23]. Emerging single electron current standards may, together with the Josephson voltage standards and the quantum Hall effect, eventually determine the fundamental constants self-consistently.

There are also ongoing activities at several laboratories towards new Josephson noise thermometers as primary standards for certain temperature intervals.

3. Superconducting electronics in astronomy

Radio astronomy has benefited from the past two decades of development of superconducting devices. In figure 2, some of the receiver technologies for spectroscopy are listed. In figure 3, the noise temperatures of various state-of-the-art receivers are plotted versus frequency. In the region

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[1] Seiko Instruments Inc. 563 Takatsukashin-den Matsudo-shi, Chiba 270-2222, Japan.

[2] National Institude of Standards and Technology since 1988.

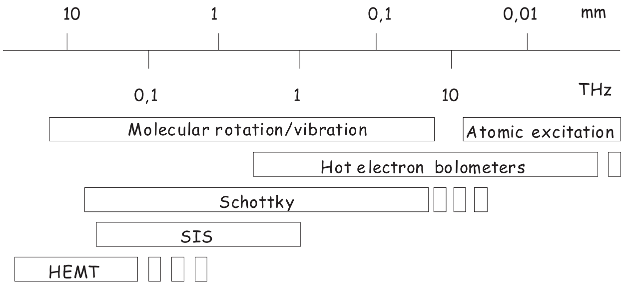

Figure 2. Frequency/wavelength regions for which different front-end technologies are used for low noise receivers.

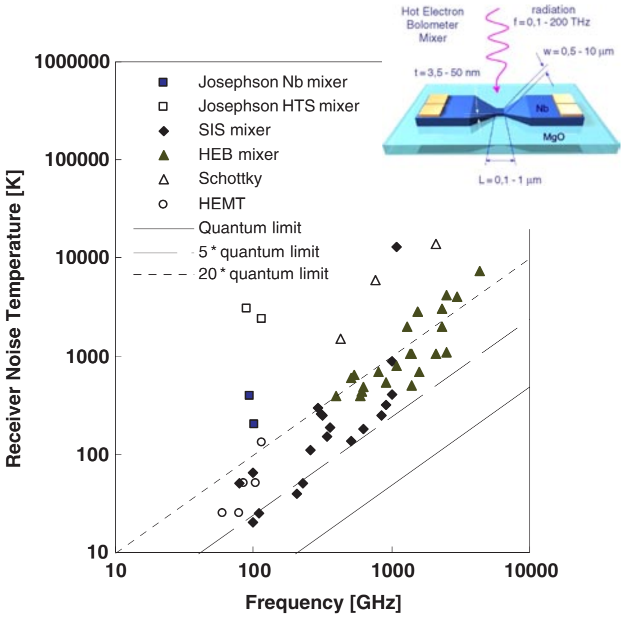

Figure 3. Receiver noise temperatures for different front-end technologies.

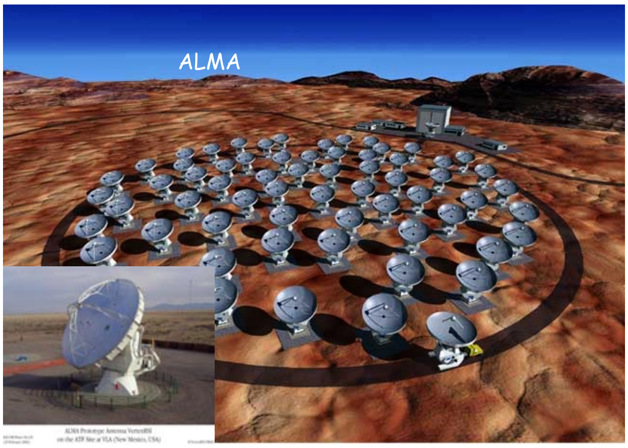

Figure 4. Conceptual picture of the ALMA facility. The inset shows one of the antennaes to be evaluated for the array (Courtesy of the European Southern Observatory) [27].

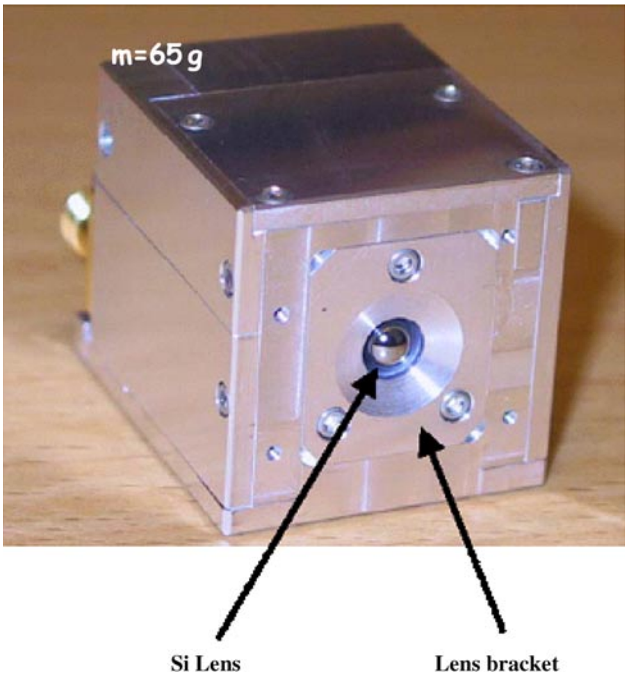

Figure 5. HEB mixer mount with a silicon lens for the Herschel satellite. Two frequency bands are developed at Chalmers: 1.41–1.75 and 1.62–1.92 THz [30].

0.1–10 THz, there are no competing technologies to SIS and HEB mixers. The SIS mixer can be designed to give quantum limited performance and even conversion gain [24–26]. It requires very low local oscillator power, and can be integrated with superconducting tuning circuits and antennae. The SIS mixer is the dominant technology at major radio astronomy facilities for the millimetre and submillimetre ranges. Recently, one of the largest projects started in radio astronomy is the Atacama Large Millimeter Array Facility (ALMA), a joint effort between the US, Europe, and possibly Japan [27]. A synthetic aperture antenna with a diameter of 12 km is going to be built up by 64 dishes, each 12 m in diameter (see figure 4).

Although the SIS mixer is the best front-end device in terms of noise and conversion efficiency, it is limited by twice the superconducting energy gap frequency ($2f_{\mathrm{g}} = 2 * 2\Delta/h$, slightly beyond 1 THz for, e.g., Nb). Fortunately, as receiver technology and instrument requirements were going beyond 1 THz, superconducting HEB mixers were entering the stage; a low noise device with possibilities to bridge the gap between radio waves and the optical range [4, 5]. Advantages with this device are that it has very small parasitic reactances and, like the SIS mixer, it requires very little local oscillator power. At present, there are three HEB receivers in operation above 1 THz [28]. The Herschel Space Telescope [29], a European Space Agency (ESA) project, to be launched 2007, will have HEB mixers (see figure 5) covering a couple of bands above 1 THz [30]. For a recent review, see [28].

During the last decade, the development has gone towards integrating several functions in one and the same package or circuit (see figure 6). Examples of this are the integration of flux-flow oscillators (FFOs) with the SIS mixer [31, 32], and the recent development of intermediate frequency SQUID amplifiers.

Similarly, SQUID multiplexers (see figure 7) are handling the information from large arrays of transition edge bolometers [33]. In the x-ray area, microcalorimeter arrays composed of transition edge sensors (TES) are integrated with SQUID

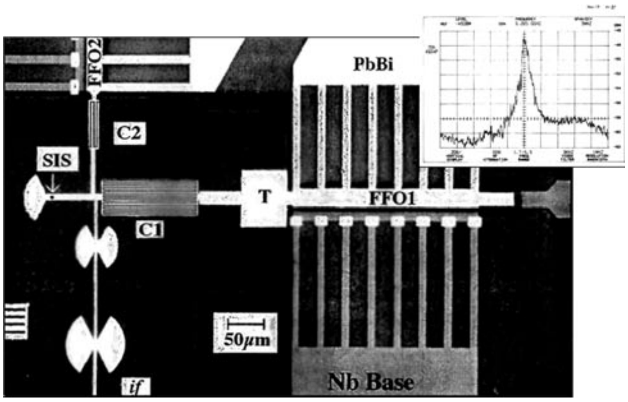

Figure 6. SIS mixer integrated with two FFOs. The inset shows the intermediate frequency spectrum from the mixing of the two FFOs in the SIS mixer [31].

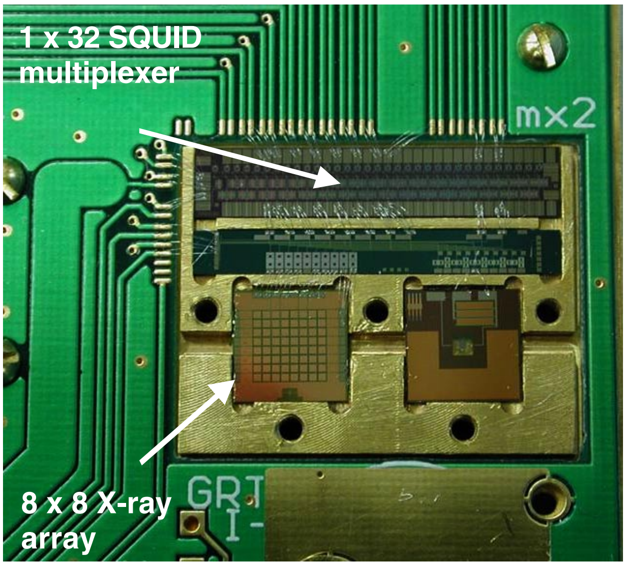

Figure 7. Eight pixels of an 8 × 8 x-ray array being read out in a 1 × 8 multiplexed column (courtesy of K D Irwin).

time-domain multiplexers for the SCUBA-2 project [34], for NASA's Constellation-X mission [35] and using frequency-domain SQUID multiplexers for ESA's XEUS mission [36]. TES bolometer arrays are also developed together with SQUID multiplexers for a >10 000 pixels submillimetre camera, which will be installed on the James Clerk Maxwell telescope [37] in Hawaii [38]. In parallel, there has been the development of frequency-domain SQUID multiplexers [39]. The integration of imaging arrays of superconducting sensors together with post-signal data handling is particularly attractive when low system heat losses are required, and efficient recovery of a large amount of data is demanded. Possibly here is also an area where superconducting digital electronics could find some applications, before making a market breakthrough.

4. SQUIDs in different systems

There are several industrial values in SQUID systems, and in this respect we will somewhat superficially divide the SQUID treatment into this section and section 5.

The SQUID can be designed to reach quantum limited resolution. Since it is a magnetic flux-to-voltage transducer, anything that can be converted to a magnetic flux, such as current, voltage, motion, etc, can be read out by the SQUID with extremely high resolution. The SQUID has found several uses, the most well known is sensitive magnetometers and gradiometers for biomagnetism and geophysics.

The impact of SQUIDs in biomagnetism is similar to SCE devices in astronomy, but in addition there is a commercial market which has followed, and several companies are producing arrays of SQUID sensors for medical use (e.g., 4D Neuroimaging [40], Neuromag [41], Tristan [18], CTI [42], Cardiomag [43]; see also the review by Itozaki [44]).

Large systems comprising several hundred sensors are being built for MEG, and smaller systems both HTS and LTS for MCG.

There is a development of methods using SQUIDs as magnetic readout for immunoassays [11–16]. Essentially, there are two different methods being suggested, using (i) Neél relaxation and (ii) Brownian motion relaxation. In the first method, the internal relaxation of nanoparticles (or the decaying remanence of magnetic particles) is studied at binding sites on a substrate using a SQUID microscope, while in Brownian motion relaxation, the dynamics of thermally blocked magnetic nanoparticles are studied in the liquid itself. Among the advantages of these methods are that the dynamics of the reacted particles are quite different from those which have not bonded chemically to the target molecules, resulting in differences in the magnetic response in the time (or frequency) domain. This means that the influence of the background magnetic particles does not pose a problem, as may be the case for fluorescent background signals using optical methods. Important issues to address are dynamic range, sensitivity, specificity, speed, multiplexing, avoiding cross-contamination, preferably using disposable chips—while customers pay for each analysis (not for the instrument).

Somewhat related to the medical application of biomagnetism are the applications of superconductivity in nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI). The development here has traditionally been towards higher magnetic fields using large superconducting magnets and higher frequencies. System improvements have been made by using superconducting pick-up coils. New possibilities open up with low-field and low-frequency NMR and MRI using superconducting pick-up loops and SQUIDs in the read-out electronics. Both human tissue [45] and peppers have been imaged [46].

In addition to magnetic imaging using SQUID microscopes, imaging is also used for NDE and the SQUID has some very important benefits compared to other technologies (see the next section). In geophysics applications and mineral prospecting SQUID systems have been used to find rich mineral deposits [47].

5. Industry and products

Many superconducting devices developed for other research areas have also found their way into products, such as the transition edge bolometers for energy dispersive x-ray

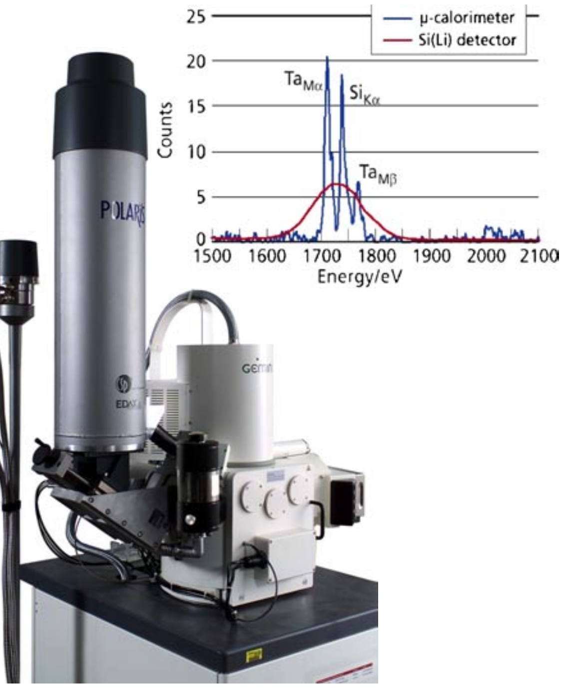

Figure 8. The Polaris^{TM} EDS unit. The inset shows a comparison between a Si(Li) detector and a TES with SQUID read-out with spectral data of $TaSi_2$ measured at 5 kV, 203 pA and 60 s acquisition time [48, 49] (courtesy of EDAX and Vericold).

spectrometers (EDS; see figure 8) [48, 49], HEB single photon detectors, etc. One of the most successful commercial products is the superconducting filter base station, which seems to be reaching a self-supporting business based on a market pull. Superconductor Technologies Inc. (STI) has merged its activities with Conductus and has a substantial number of systems sold (more than 3000) [50].

However, for most cases, the true impact of SCE in industry has been to support existing technologies in terms of testing and certification. One example is monitoring partial discharge in high voltage insulation [51] using SQUIDs (see figure 9). Another is noise characterization of E-field sensors [52] for detecting foreign submarines (see figure 10).

Also interesting is the possibility of using instruments based on SCE to test the quality and processing of semiconducting materials from wafers and devices all the way to a packaged chip. SQUID microscopes (see figures 11 and 12) have been developed to determine the doping level in wafers from reading out the magnetic field from relaxing photo-induced currents on the surface with a SQUID microscope [53]. The resolution is determined in this case by the laser spot.

Having quality controlled the wafer, flaws in the fabrication process for bare or already flip-chip bonded circuits [19] can be imaged by a SQUID microscope (see figure 12). Finally, instrumentation based on THz HEB single photon detectors are being developed for troubleshooting latching n-CMOS circuits [54].

NDE is another area where we can use the high sensitivity of the SQUID down to low frequencies, e.g., to find cracks in aeroplane wheels or to monitor corrosion in steel reinforced concrete highway bridges [55, 56] (see figure 13).

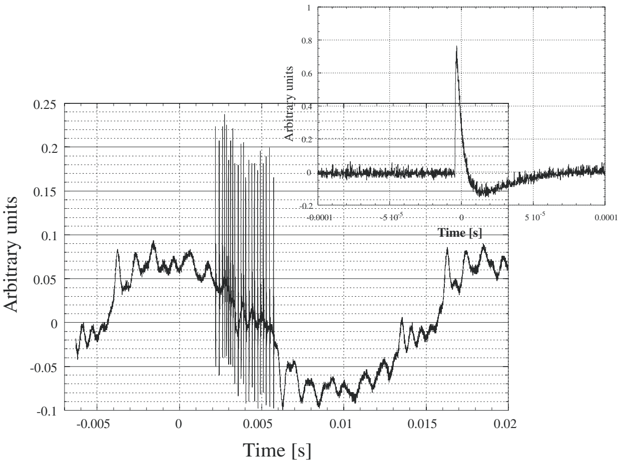

Figure 9. Partial discharges across a 50 Hz period recorded using a HTS SQUID-based current amplifier. The inset shows a single event [51].

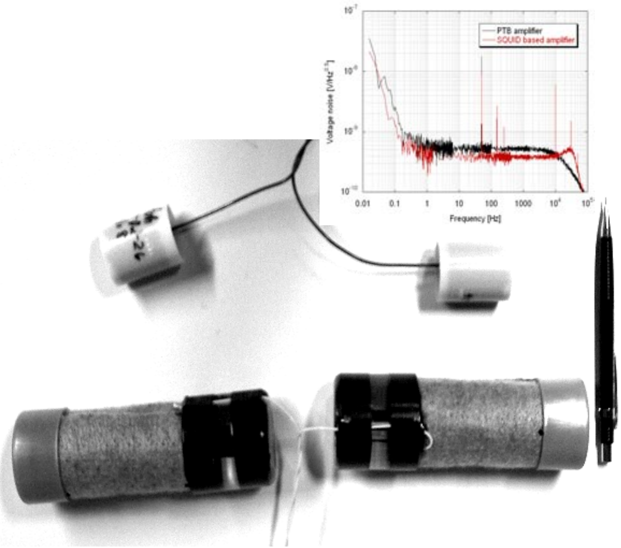

Figure 10. Salt water electrodes for submarine detection [52]. The inset shows the noise measured for the carbon fibre electrodes with room temperature electronics (upper curve) and a SQUID picovoltmeter (lower curve) where the noise floor is determined by the Johnson noise from the carbon fibre electrodes alone [52].

Another interesting application is using SQUID NDE for quality control of Nb sheets [57] used for producing cavities for the new Tesla superconducting accelerometer at Desy outside Hamburg. Ta inclusions in Nb are devastating for the *Q*-value of the finished cavity. Since there is much labour involved in producing the cavities from Nb sheet metals, it is important to eliminate the Ta inclusions before work is done (see figure 14).

For the Tesla accelerometer, 400 000 plates, each 30 × 30 cm^2 will be needed. SQUID NDE may be the only way of detecting the Ta inclusions on such a scale.

In terms of safety and public health, sensor systems are making their way into the food industry, and SQUIDs could possibly find a market niche in monitoring metallized packaging of food for detection of foreign metal parts.

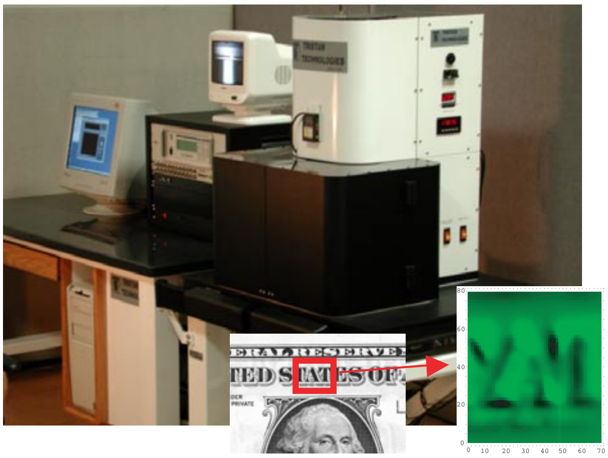

Figure 11. SQUID microscopes: Tristan Model SMM-770. The insets show magnetic imaging of the printed surface of a bill [18].

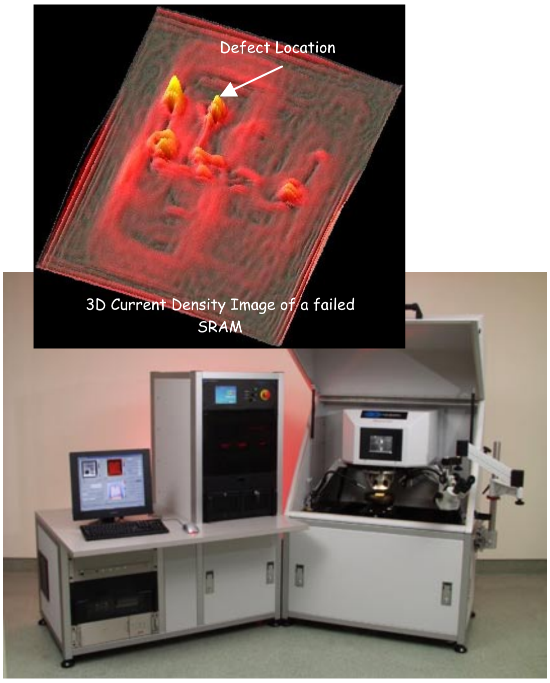

Figure 12. SQUID microscopes: Neocera's MAGMA C20. The inset shows an image on a defect static random access memory (SRAM) (courtesy of IBM) [19].

The advantage of the SQUID system is that the eddy current probing could be carried out at such a low frequency that the skin depth is much larger than the thickness of the metallization [58].

6. Market

There has always been a question concerning the market potential for SCE. Will we see any new devices or new applications? Is there any 'killer application'? In December 2001, Conectus [59] estimated the worldwide market for superconductivity and their analysis is reproduced in table 1.

The larger part in terms of market shares is magnets for MRI systems, followed by the research and technology development (RTD).

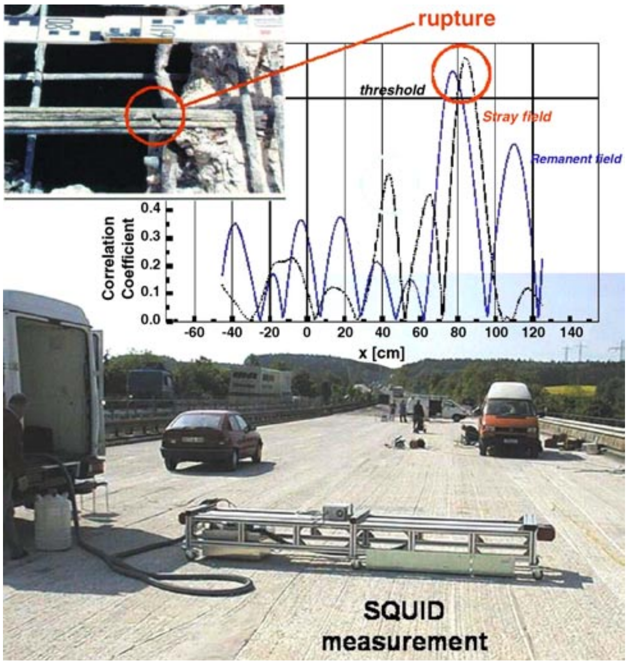

Figure 13. Localizing a rupture in a steel rebar in German highway bridge with a SQUID. The bar is magnetized and the stray field around cracks determined [56].

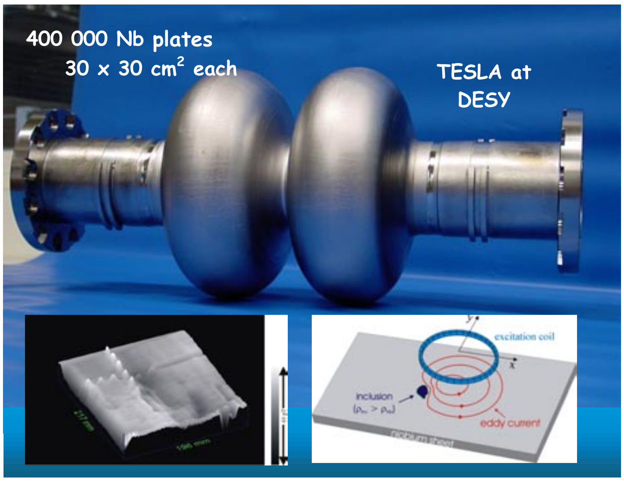

Figure 14. Photograph of Nb cavity built for the Tesla accelerometer [57]. The insets show a test image and the principle (courtesy of DESY and ez SQUID).

The SCE market share is one to two orders of magnitude smaller than the previous two, but is forecast to reach about a quarter of the MRI market by 2010.

A possible route towards this projection is partly given by STI [50], who has sold about 3000 HTS filter receiver front ends in the field (see figure 15), and believe they will sell 2000 units in 2003 and 4000 units in 2004. The demand might possibly become larger when the telecom industry has to renew their existing network and with the third generation network, which is now entering the market.

Looking at SQUID applications outside MCG and MEG, the number of SQUIDs sold is rather small, and it may seem impossible to make business just looking at the earnings

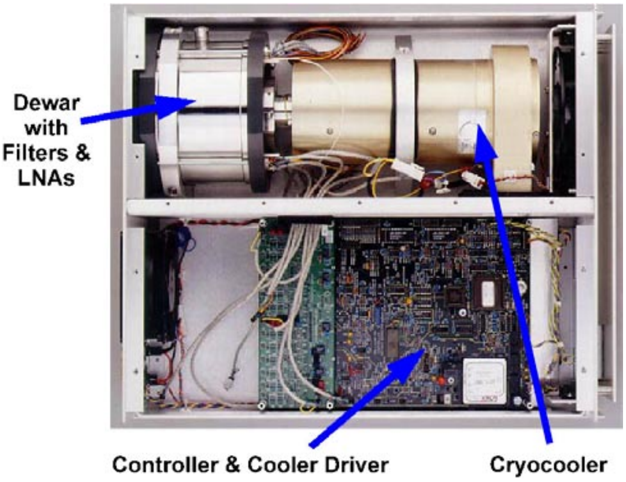

Figure 15. Superconducting filter base station from STI and Conductus (courtesy of STI).

Table 1. Worldwide market for superconductivity and market shares for LTS and HTS in M€ (Conectus, December 2001) [59].

Business field	1997	2000	2003	2010
RTD	355	415	550	840
MRI	1400	1900	2100	2750
Total	1755	2315	2650	3590
New large-scale applications	35	25	55	980
New electronics applications	20	30	75	680
Total	55	55	130	1660
Total worldwide market	1810	2370	2780	5250
Market shares for LTS	1805	2355	2730	3650
Market shares for HTS	5	15	50	1600

from the devices themselves. Looking from the end user's perspective, the primary interest is not to use SCE, but to have a system that does something exceptional. Although each SCE device may not make a business, a system would. An example of this might be the superconducting rock magnetometer, where 2G Enterprises [60] has installed around a hundred units since the mid-1980s across the world. In the larger scientific projects, such as ALMA and Herschel, the budget might be much larger than 500 M€ each. Although being a very small part of the costs, SCE certainly plays one of the most important roles in the total system performance.

7. Future and speculations

What would make SCE enter the market place? One of the largest impediments for SCE is, of course, the cooling and cryogenics. As listed earlier, the power requirements for the SCE are very small and hence large installations should not be necessary, although the efficiency decreases with increasing lift in temperature. Ideally, only the SCE chip should be packaged for a small cooling stage. The wish list on cryocoolers would have words such as cheap, small, invisible, efficient, stable, reliable, vibration-free, non-magnetic, or non-metallic parts moving. Many companies are now presenting closed cycle stages for temperatures down to below 60 K, which are not much larger than two cans of soda. However, this is neither invisible nor inexpensive. A viable route to solve this might be to go to micromachined structures made in materials that can be mass fabricated at low cost [61].

The SIS and HEB receiver development for radio astronomy could also find new applications in molecular spectroscopy for pollution and environment monitoring, advanced process control, and in THz frequency airport security [62]. Digital electronics may follow after the implementation of the SQUID multiplexers for the signal treatment.

The development of high-T_c devices may give useful circuits for several applications, could voltage standards be made from the intrinsic Josephson effect [63]. Finally, new opportunities for SCE might be just around the corner where we least expect it.

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