FLUXONICS

NEWSLETTER - *A SPECIAL EDITION ABOUT SUPERCONDUCTOR QUANTUM ELECTRONICS FOUNDRY*

JANUARY 2024

SUPERCONDUCTING TECHNOLOGIES

ENERGY EFFICIENCY FOR ALL

SUPERCONDUCTING ELECTRONICS AND THE QUANTUM WORLD

As the world is struggling to limit the consequences of global warming, improving energy efficiency is the unique fundamental way to tackle this challenge. From a thermodynamical point of view, whatever we do, energy that is not used for the aimed purpose, be it transportation, electricity production and use, internet communication or video streaming, is transformed into heat. This is why the thermal engines of our cars, or the microprocessors of our computers are hot. Although a little part of this energy loss can be used for heating ourselves, the lost heat is rarely dissipated at the right place, at the right time.

The best way to solve this challenge, without compromising too much on our current way of life, is to avoid energy losses when we transform it. This can be done by:

- replacing thermal engines (whose energy efficiency is rarely above 30% of the theoretical efficiency) by electrical engines whose efficiency is above 90% for instance ;
- using better ways to process information in computers, to reach energy losses below 2% of the current dissipation ;
- developing much more sensitive detectors of signals for communications. Such detectors need just a few percent of the energy used by current sensors. Sensitive sensors require less powerful emitters at the same time, consequently saving energy and reducing the amount of electromagnetic energy around us. This limits potential harm for health as well.

These are just examples. There is a large variety of similar techniques that need to be considered. The field of electronics dealing in particular with digital technologies whose applications range from computers, mobile phones, Internet of Things (IoT), telecommunication technologies to cloud computing and Artificial Intelligence (AI) relies on microelectronics technologies. The internet traffic is growing exponentially and is expected to represent 21% of the World energy consumption by 2030 with a need of 9,000 terawatt-hours[1] which represents about 3 billion tons of carbon dioxide emissions per year. The World spending in the semiconductor field for 2020 was estimated to be between 4,000 and 4,200 billion euros, to be compared with the World car industry spending of 2,400 billion euros.

In this context, even a moderate gain of energy efficiency has a large influence at the global scale.

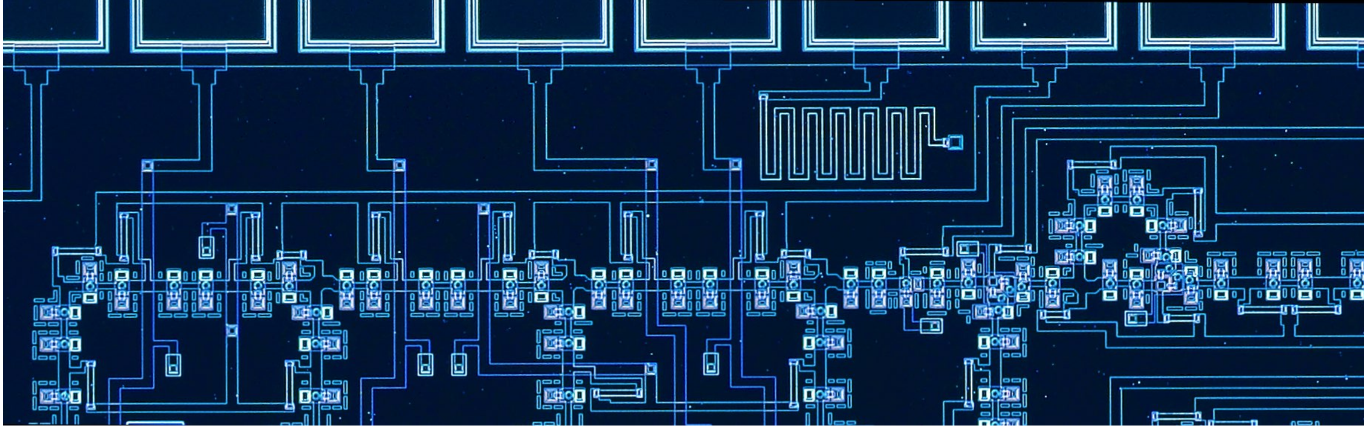
One technology which enables to overcome some of these hurdles relies on quantum physics-based superconductor devices.

Beside this, the Covid crisis has highlighted the lack of autonomy of European strategic industrial sectors in a context of international tensions in politics and economy. The missing sovereignty is nothing new for those involved in superconducting electronics or quantum computing development for energy saving in big data systems and high performance computing. While the European expertise is at par with major players in the game, in spite of being only a collection of understaffed teams, supported for more than ten years as the FLUXONICS network. Already in September 2015, the FLUXONICS Society pinpointed this difficult situation:

> *"The issue is not to pay lip service to a lobby by keeping understaffed teams alive but to launch a preindustrial deployment program presumably outside traditional academia."*

Nine years ago, FLUXONICS clearly defined its fundamental goal: a 24/7 microelectronics foundry dedicated to superconductor devices, allowing reliable mass fabrication of circuits and devices. Even before WWII, Superconductivity was recognized to be a quantum macroscopic state visualized in science popularization by the spectacular levitation effect. However everybody, sooner or later, will meet in daily life Magnetic Resonance Imaging (MRI) systems for medical exploration for which superconducting cables were a breakthrough. Less known, but used every day as well for everyone's telecommunications, the Volt standard of the International System of metrology is based on the superconductor-based

[1] N. Jones, "Data centres are chewing up vast amounts of energy," p. 5.



Josephson effect, allowing the quantum-accurate conversion of a frequency into a voltage.
Today, the convergence of *(i)* climate and energy conservation awareness with *(ii)* technological advances in the Quantum Information and Communication fields, and *(iii)* requirements for technological sovereignty in the European chip industry leads to the urgent need for a Generic Superconductor Foundry at a European level. *Generic Foundry* means on one hand that it should be able to deal with all techniques and families of superconducting devices and make use of their individual advances. This covers the realization of quantum devices, superconducting circuits and sensors, passive and active Radio-Frequency (RF) circuits, Photonics techniques and digital processing on the same chip. Fabricated systems must be able to embed analogue and digital sensors and front-ends in order to process and compute mixed signals, i.e. digital, analogue and quantum signals, in classical, quantum, or hybrid modules. On the other hand, this generic foundry should not be limited by private interests to support academics as well as companies in Europe.
Such steps have already been achieved years ago in leading nations like in the USA with the MIT-Lincoln Laboratory Superconductor Foundry[2] or more recently in Japan with the QuFab Foundry[3].

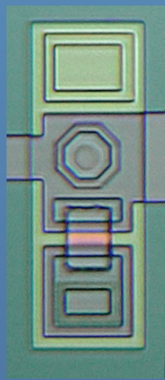
Why a Superconductor Quantum Electronics Foundry (SQEF) is a critical infrastructure necessary in Europe?

1. Superconducting electronics is to date the most mature and disruptive technology able to solve challenges that semiconducting devices face for fundamental reasons at the physical level: too high energy consumption and too low processing speed of data. It allows to develop a range of deep-tech capabilities based on a different paradigm, all favoring innovation, while in-line with climate change issues.
2. Europe is lagging behind in semiconductor technology fabrication with a world share continuously on the decrease since more than a decade. Technology, and associated Intellectual Property, is widely dominated by North American and Asian stakeholders. Although efforts are needed to limit and mitigate these drawbacks, chances to catch up with this situation, not even thinking about overtaking competitors, are slim, very costly and would require continuous and long-lasting efforts.
3. Superconducting technology is a solution with unique fundamental features naturally suited to go ahead with quantum computing systems, ultra-low energy superconducting super-computers, ultra-sensitive sensors with high signal bandwidths up to the THz range, consequently requiring much less power for telecommunication emitting stations.
4. Enabling technologies, like cryogenics for cooling, material developments for thermal insulation, or quantum optics for long-distance communications, are domains where Europe is in the forefront. This will push for technological advantage and relax sovereignty concerns.
5. Setting up a disruptive quantum-based technology using superconductors will be a huge boost for everyone in the society, as a range of new infrastructures will be needed ranging from cryogenics stations to superconducting cables and electronics fabrication plants, new technological high-bandwidth low-energy equipment. Dedicated education will be required and, as a consequence, a new range of new jobs will appear. Such changes are comparable to the progressive shift from candles to electricity with the installation of electrical cables in the 19th century, or more recently from gas stations to electric charging stations.

[2] https://www.ll.mit.edu/research-and-development/advanced-technology/microsystems-prototyping-foundry/superconducting
[3] https://sj.jst.go.jp/stories/2023/s0111-01p.html

WHAT IS SUPERCONDUCTING ELECTRONICS?

Superconducting electronics is a quantum technology based on superconducting materials which have the property of presenting no energy loss below a certain temperature, called the critical temperature.

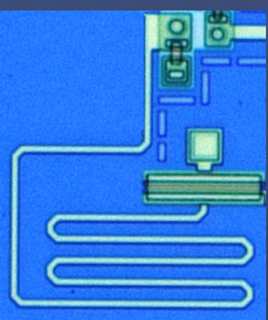


Superconductors are pure macroscopic quantum objects. Many well-known metals are superconductors like aluminum, niobium or lead, below their critical temperature. One of the key element for superconducting electronics is the so-called Josephson junction, which is the equivalent of transistors used in current electronics systems. The quantum behavior of Josephson junctions, associated with the unique features of superconductivity, has been used for a range of applications since Brian Josephson explained in 1962 the tunneling properties of charges across a thin insulating barrier separating two superconducting electrodes. Josephson junctions are used when ultimate sensitivity or quantum features, not attainable by other technologies, are required.

Two different kinds of charged particles can cross a Josephson junction barrier, namely Cooper pairs which flow without resistance, and quasiparticles which have similarities with electrons. Both types of charges are always present and can tunnel through the barrier of a Josephson junction between absolute zero temperature and the critical temperature *Tc* of the superconducting electrodes.

Due to the fundamental difference between bosons and fermions associated to the symmetry of the quantum wave function, different properties and manifestations of their nature can emerge when Josephson junctions are used. The superposition of several bosons in a single microscopic or even macroscopic state is often analyzed with the wave formalism of the wave-particle duality in quantum mechanics. Like for photons, the striking feature of interferences and diffraction happens for Cooper pairs as well. To understand this phenomenon in Optics, the wave description of the electric field of light is used. It considers not only the amplitude but also the phase of the field, since interferences cannot be explained only with light intensity or energy considerations. That is the same for Cooper pairs where the amplitude and phase of the superconductor macroscopic quantum wave function allow to explain experimental observations when a magnetic field is applied to a superconductor. This has led to the invention of one of the most important devices based on Josephson junctions: the Superconducting Quantum Interference Device (SQUID) which is still today the most sensitive, quantum-accurate, wideband magnetometer.

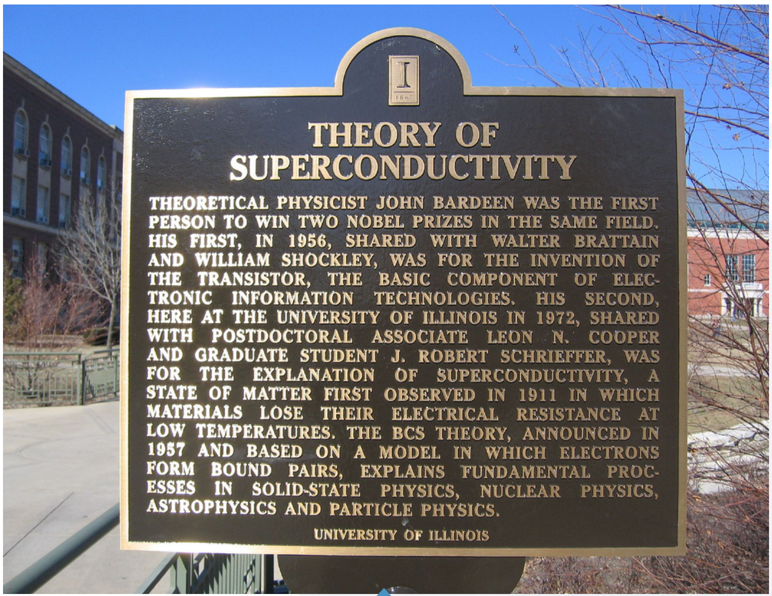
In addition to Cooper pairs, quasiparticles are always present below *Tc* and can tunnel through the Josephson junction barrier as well. They either result from thermal effects that break a Cooper pair into two quasiparticles, or from externally assisted phenomena. One of them is the photo-assisted effect (Einstein Nobel Prize in 1921) where, for instance, a monochromatic light of frequency ν incoming on the system can increase, in some conditions fixed by quantum mechanics, the energy of a particle by $E = h\nu$ where h is the Planck constant. This effect is used for astronomy detectors in the THz range and is also investigated for future systems based on 6G quantum-based coherent communications.



In pure quantum regimes where the quantum system must evolve with as little interaction as possible with its noisier environment, which is required for instance for quantum computing, quasiparticles are not desired since they are associated with classical lossy mechanisms linked to heat dissipation leading to the destruction of quantum coherence. To reduce the quasiparticles density, temperature must be lowered typically close to 10 mK, very close to the absolute zero temperature. In this case, the Josephson junction can be used as part of an artificial atom and can exhibit a pure quantum behavior where the discretization of its energy levels can be engineered.

A crucial property of superconducting electronics technology is that the same manufacturing process can be used to design a wide range of different circuits and devices, be them purely quantum or simply only energy-efficient and ultrafast. This limits the needs for hybridation and eventually reduces the cost of fabrication.

SUPERCONDUCTING ELECTRONICS: PAST, PRESENT, FUTURE



A commemorative plaque placed in the Bardeen Engineering Quad at the University of Illinois at Urbana-Champaign. It commemorates the Theory of Superconductivity developed here by John Bardeen and his students, for which they won a Nobel Prize for Physics in 1972. [Credit: Wikipedia]

Historically, the discovery of superconductors happened in 1911 in Leiden by Heike Kammerlingh Onnes and his student Gilles Holst In 1933 the Meissner-Ochsenfeld effect discovered by two German physicists has led to one of the most impressive manifestation of the quantum nature of superconductors: the levitation of bulk superconducting objects in presence of magnets. A number of scientists, theoreticians, and experimentalists investigated the causes of superconductivity, which led to phenomenological models by the London brothers, then by Ginzburg and Landau, up to the microscopic theory of superconductivity in 1956 proposed by Bardeen, Cooper and Schrieffer, known as the BCS theory.

In retrospect, Brian Josephson opened the era of superconducting electronics in 1962 with the postulate of the Josephson effect. It was followed in 1963 by the first Josephson junction (JJ) made by John Rowell and Philip Anderson at Bell Labs and in 1964 by the invention of SQUIDs by Robert Jaklevic, John Lambe, Arnold Silver and James Mercereau at Ford Research Laboratories.

Today, superconductors are used in magnetic levitation high-speed trains, for instance in Japan between Tokyo and Osaka or in Shanghai.

Less known is the role of superconductors to carry electricity with low losses cables, like in the grid of the city of Essen in the industrial Ruhr area of Germany, in Munich[4], or in Chicago[5].

Even less visible are all the applications related to superconducting electronics since they are mostly embedded in small systems relying on electronics chips, like in the semiconductor industry. To give only a few examples of realizations, superconducting electronics is currently present to define the unit of voltage, the volt, in the international system of units. This allows quantum-accurate calibration of electrical equipment, giving for instance their ultimate accuracy to GPS systems. Also, a range of quantum−accurate detectors have been developed and used so far: THz and sub-mm wave receivers for astronomical applications from radio-waves to X−rays, magnetic field detectors for geophysical and biomedical applications, single-photon detectors for long-distance quantum optics communications, calorimeters for accurate temperature measurements, high-Q RF filters for telecommunications are common examples. More details are presented in the next sections.

Superconducting future applications mainly deal with the development of complex digital, quantum, and mixed-signal circuits for a range of more challenging applications. Building upon current knowledge and achievements it is now possible to design complex circuits that can mix quantum sensors with on-chip digital pre-processing for a range of applications such as quantum computing[6], as well as (medical) imaging systems[7] or energy-efficient processors[8]. Complex circuits designs have been enabled by recent developments of powerful simulation tools[9].

[4] https://tinyurl.com/Nexans-Germany-1 ; https://tinyurl.com/Nexans-Germany-2 – http://tinyurl.com/55d26du5

[5] https://tinyurl.com/Nexans-Chicago

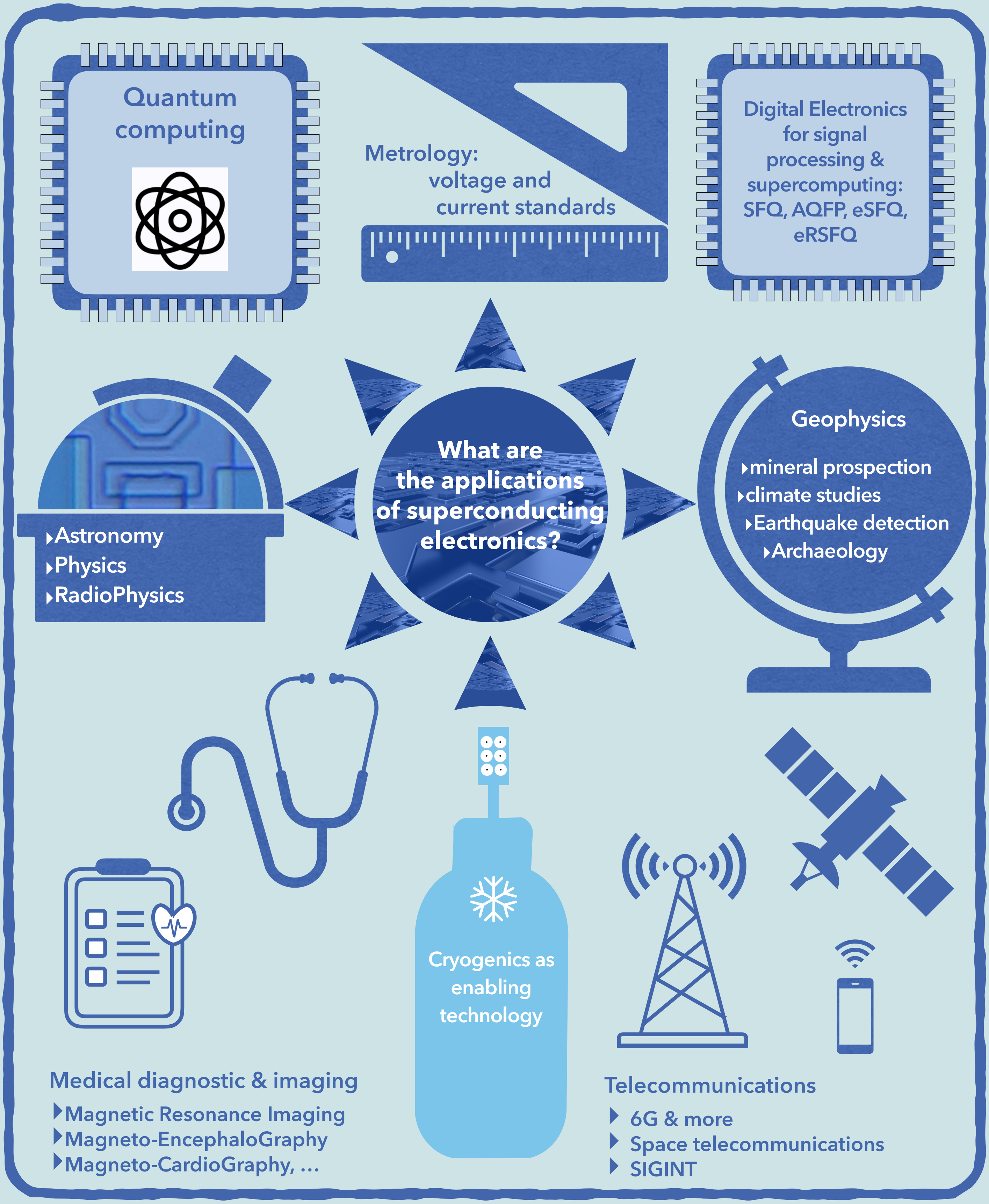
[6] https://seeqc.com/technology

[7] https://www.isasi.cnr.it/en/units/urt-meg-bioapp-en/

[8] https://doi.org/10.1063/5.0148273

[9] https://doi.org/10.1109/TASC.2023.3306381

A GENERIC TECHNOLOGY WITH A RANGE OF CHALLENGES AND APPLICATIONS, FOR AN ENERGY-EFFICIENT SUSTAINABLE TOMORROW



AN OPEN INNOVATIVE ECOSYSTEM TO BUILD AROUND AN ADVANCED FOUNDRY

There exists a number of European research organisations and companies that are capable to fabricate low temperature superconducting solid-state circuits and detectors/sensors but mainly for their specific applications. In the large majority of cases, only circuits of limited complexity or functionality can be manufactured, since a chip comprising a large number of devices implies very high reproducibility, reliability, and low dispersion of parameters. This can only be reached by advanced process with adequate funding and sustainability. Besides those smaller scale facilities, some European foundry services are nevertheless provided for academic and industrial customers e.g. by Leibniz IPHT in Germany, VTT in Finland, and SeeQC Europe. In this latter case, the foundry is located in the USA but accessible to European partners. The table below gives an overview of their current technological status.

At the international level, advanced foundries have been established at MIT Lincoln Lab (USA, restricted access), QUFAB (Japan, limited access), and SIMIT (China, unknown access), to enable the fabrication of the most ambitious circuits for quantum and exa-scale applications.

Current overview of superconducting electronics foundries in Europe

EU FOUNDRIES	Leibniz IPHT	VTT / MICRONOVA	SeeQC Europe
Location of foundry	Germany	Finland	USA (accessible for EU partners)
Technologies	Nb, NbN_X	Nb	Nb, NbN_X
Current density [kA/cm^2]	1/1.7	0.01 - 4	0.1 / 1 / 4.5 / 10
Minimum JJ size [µm]	3.5/0.6	2	0.6
Superconducting layers	3	3	8
Maximum wafer size	4 inch	150 & 200 mm	150 mm
Resistor material	PdAu, Mo	TiW	PdAu, MoN_X
Interlayer dielectric	PECVD SiO_2, SiO_X	PECVD SiO_2 PEALD Al_2O_3	PECVD SiO_2, low-loss SiN_X
Complexity	small and medium	small and medium	high

International superconducting electronics foundries

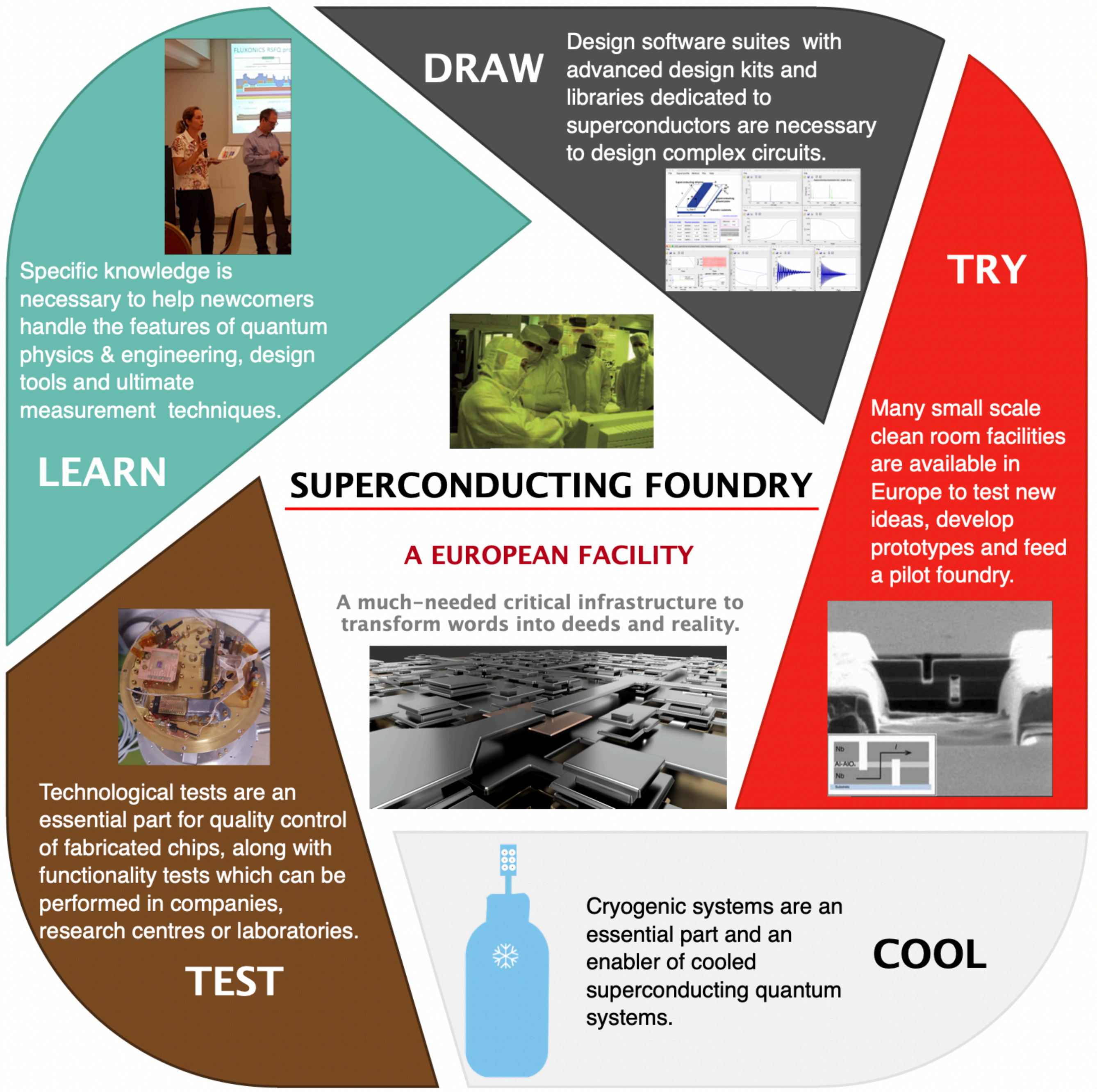
INT'L FOUNDRIES	MIT-Lincoln Lab (USA)	QUFAB (Japan)	SIMIT (China)
Technologies	Nb, NbN_X	Nb	Nb, NbN_X
Current density [kA/cm^2]	10 - 50	10/20	6
Minimum JJ size [µm]	0.2	1	1.4
Superconducting layers	8	9	3
Maximum wafer size	200mm	3 inch	150 mm
Complexity	High	High	Small and medium

Superconductor logic offers an extremely attractive high-speed and low-power computing solution, either standalone for boolean superconductor exa-scale computing systems or as control and readout processors for pure quantum computers or annealers. While the fabrication of circuits with small complexity was mainly done on a research level so far, the use of superconductor circuits for real computing currently requires fabrication of large-area, high-density, superconductive circuits with reasonable yield.

During the assessment of the US Hybrid Technology MultiThreaded (HTMT) petaflops project[10], it was estimated that 4,096 superconducting microprocessors operating at a clock frequency of 50 GHz at least, comprised of roughly 37,000 chips containing a total of 100 billion Josephson junctions would be required.

Manufacturing superconductive circuits of the required complexity and in the projected volume requests for fabrication processes comparable to semiconductor industry in a clean room of class 3 or 4 (ISO 14644). The technological requirements (feature size, linewidth, complexity, processes etc.) correspond to the semiconductor technology of the mid-1990s. Some details are: 300 mm silicon wafers, deep-UV stepper, sub-micrometer diameter junctions (robust 0.5 µm - 0.8 µm technology at the beginning; 90 nm technology in the long term), planarization by chemical-mechanical polishing (CMP).

The same technology is eventually needed for quantum chips based on near-million qubits.



[10] https://apps.dtic.mil/sti/pdfs/ADA464659.pdf

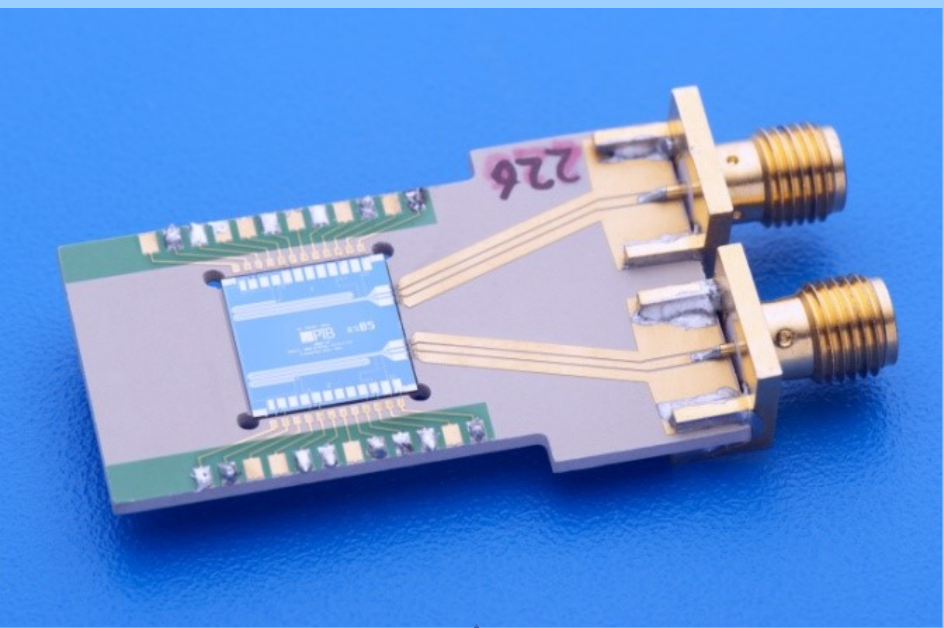
SUPERCONDUCTIVE ELECTRONICS IN METROLOGY

Exciting applications of superconductive electronics have successfully been established in metrology, the science of ultra-precise measurements. So far, the outstanding metrological application is the Josephson voltage standard. Its most remarkable feature is its characteristic of being a quantum standard, which enables the reference of the volt (the unit of electrical voltage) only to well-known physical constants and a frequency at the highest level of accuracy. Superconductivity, as a macroscopic quantum effect, plays an essential role here.

While Josephson voltage standards have been in use for dc applications in more than 50 laboratories worldwide for a long time, their use has been extended from dc to ac in the past 15 years. Highly integrated series arrays containing some 10,000 or even some 100,000 Josephson junctions fabricated in thin-film technology under cleanroom conditions are required for voltage standards delivering 1 V or 10 V, respectively. An advanced fabrication technology is therefore a major prerequisite for modern Josephson voltage standards. Some versions of them are already commercially available.

Prototype measurement set-up of the AC Quantum Voltmeter. It is based on a series array of nearly 70,000 Josephson junctions delivering output voltages of up to +/-10 V and is used for calibration of commercially available calibrators [2017].

The most advanced real ac Josephson voltage standard is based on a pulse drive of very short current pulses; as it allows the generation of arbitrary ac waveforms, it is often called Josephson Arbitrary Waveform Synthesizer (JAWS). Its output voltage is presently limited to about 4 V because of the complex microwave design and the huge number of more than 500,000 Josephson junctions, which would be required for output voltages of 10 V. While the fabrication of circuits containing up to about 100,000 Josephson junctions is possible in existing institutes, a specialized foundry is required for circuits containing a significantly larger number of junctions.



Single chip of the Josephson Arbitrary Waveform Synthesizer (JAWS) mounted in the sample holder. The JAWS is based on pulse-driven Josephson junctions. The 10 mm x 10 mm chip contains two series arrays of 12,000 Josephson junctions each [2018].

SUPERCONDUCTING SENSORS AT THE QUANTUM LIMIT

Superconductivity also provides solid-state technologies as a base for sensors and detectors with extreme sensitivity and resolution which may get very close to the quantum limit. These technologies have a long standing history but are still extremely attractive for future and emerging developments, especially in evolving research focus on quantum sensing.

A SQUID magnetometer system in use on the field. The inset of the bottom right shows the superconducting SQUID chip where the loop that captures the magnetic flux is visible. Copyright: Leibniz IPHT and Supracon AG 2019.

Those superconducting sensors and detectors are based on superconducting effects and properties of the material such as the Josephson effects, Meissner effect, flux quantization, ultra-small energy gaps, very steep normal- to superconductor transition, strong electron-phonon coupling and many more. The variety of sensing principles[11] will grow when new materials, effects, and especially the nature of unconventional superconductors will be unravelled.

Superconducting sensors and detectors will have a significant and far-reaching impact in an extremely wide range of applications in physics, chemistry, material science, accelerator science, astronomy, geosciences and archaeology, biotechnologies and medicine up to satellite communications. There is a significant advantage of the superconducting solid-state sensing technology since it can be integrated on-chip with almost noise-free signal amplification, (de-) multiplexing technologies, analogue-to-digital conversion and signal processing which will allow for intelligent and large-scale sensor/detector arrays for example for future astronomical instruments. Modern and innovative micro- and nano-fabrication techniques will, besides advanced cooling technologies down to the milli-Kelvin range, enable the development of a new generation of ultra-sensitive, ultra-fast, and ultra-low-power superconducting electronics. Their future use will translate into benefits to our societies and economies and will help to solve unmet needs of our societies.

[11] The superconducting sensors and detectors today range from radiation sensors/detectors for a wide spectral range such as Transition Edge Sensor (TES), Superconducting strip detector (SSD) like Superconducting nanowire single-photon detector (SNSPD), Hot Electron Bolometer (HEB), Kinetic Inductance Detector (KID), Single Tunnel Junction detectors (STJ), Superconductor-Insulator-Superconductor (SIS) mixers over gravity or gravity gradient sensors, current and voltage sensors up to magnetic field sensors such as SQUIDs, Andreev Interferometers, or Kinetic inductance magnetometers, etc.

SUPERCONDUCTING QUANTUM SENSORS FOR MEDICAL DIAGNOSTICS

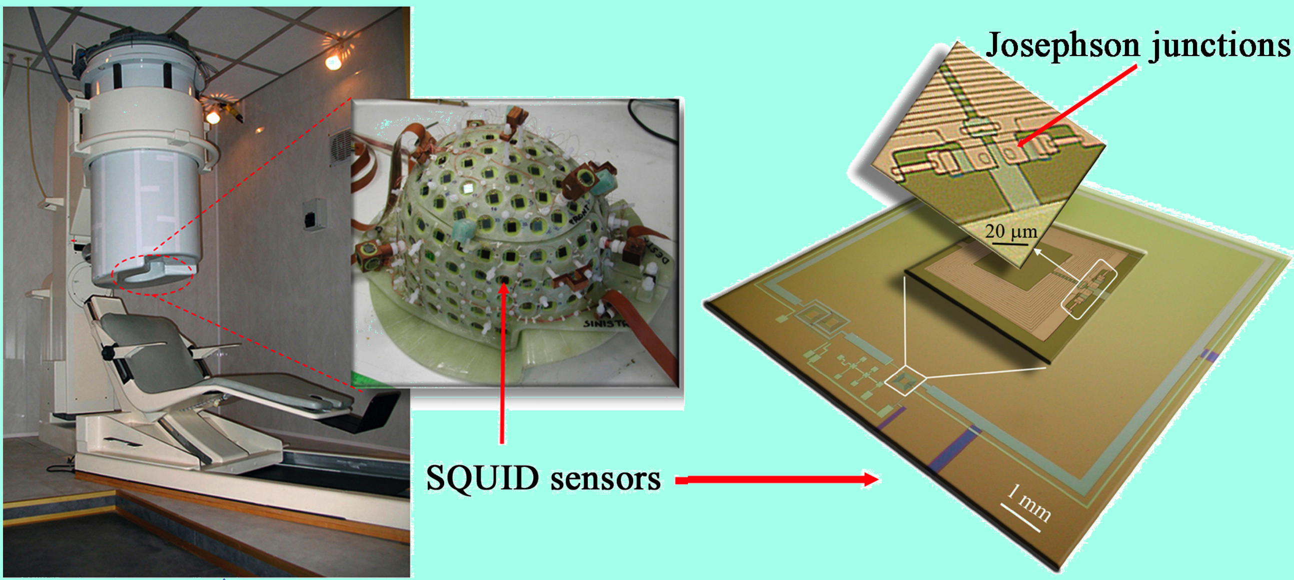
Superconducting quantum interference devices (SQUIDs), are well suited quantum magnetometers for the measurement of a magnetic field amplitude of less than 1 fT (or 10^{-15} Tesla), i.e. 50 billion times smaller than the Earth's magnetic field. Thanks to this very high sensitivity and ultra-low noise, SQUIDs are employed in many fields.

Biomagnetism, namely the study of magnetic field often associated to the electric activity in the human body, is one of the most important applications of SQUIDs. Many diagnostic not-invasive techniques have been developed for the various organs and tissues of the human body such as magnetoencephalography (MEG), magnetocardiography (MCG), magnetomyography (MMG), magnetoneurography (MNG), magnetogastrography (MGG), magnetoenterography (MENG). Among them, the most consolidated and important technique is MEG. The objective of MEG is to accurately measure the magnetic fields generated by the neuronal currents and precisely localize the sources through suitable data processing and analysis.

MEG[12] has a very high temporal resolution (about 1 ms), allowing the study of brain activity on a time scale not accessible to other functional brain imaging methods. In other words, MEG is able to follow very fast events over time, unlike other techniques that provide a time-averaged image. This peculiarity of MEG is particularly important for studying communication between neurons.

Compared to electroencephalo-graphy (EEG), which measures electrical potentials, MEG allows the reconstruction of the sources that generated the magnetic field in a more precise and clear manner as the tissues above the cerebral cortex (skull, scalp) are practically transparent to the magnetic field. Contrary, they distort the field and electrical potentials measured by the EEG.

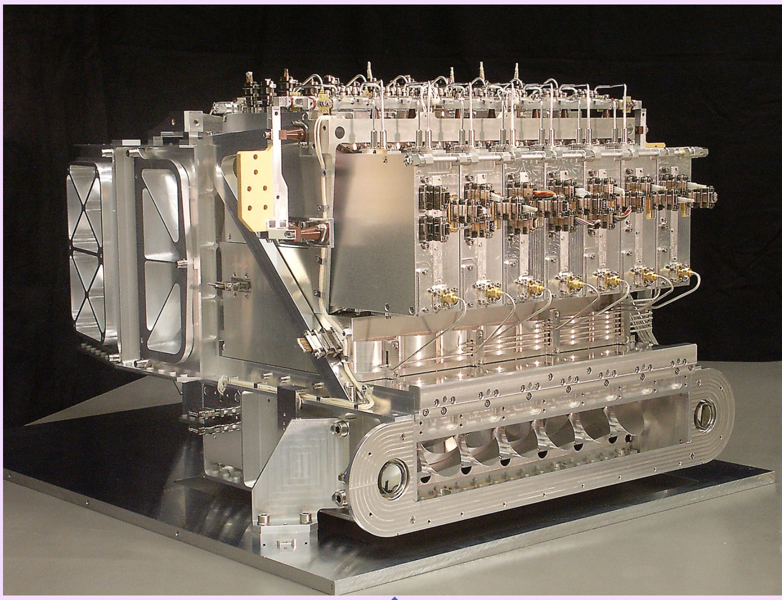
MEG provides extremely useful functional images both for basic neuroscience studies and for clinical applications such as the identification of epileptic foci and the mapping of brain areas before surgical interventions in order to make the operation less invasive. It is also of considerable interest in the clinical field for the study of neuro-degenerative diseases (Alzheimer's syndrome, Parkinson's disease, amyotrophic lateral sclerosis, frontotemporal dementia). In these cases, the goal is to use magnetoencephalography to select biomarkers to monitor disease progression and improve our understanding of the pathophysiology of neurodegeneration.



Left: Multi-channel MEG system with 165 sensors operating in a neurological clinic (Hermitage in Naples, Italy)[12], the SQUID sensors are arranged in a helmet configuration to adapt to the anatomy of the skull. Right: SQUID magnetometer showing a field sensitivity of 1 fT/Hz$^{1/2}$. The outer square loop transduces the field into magnetic flux in the SQUID with its depicted Josephson junctions.

[12] https://www.isasi.cnr.it/en/units/hermitage_en-2/

THz IMAGING AND TELECOMMUNICATIONS



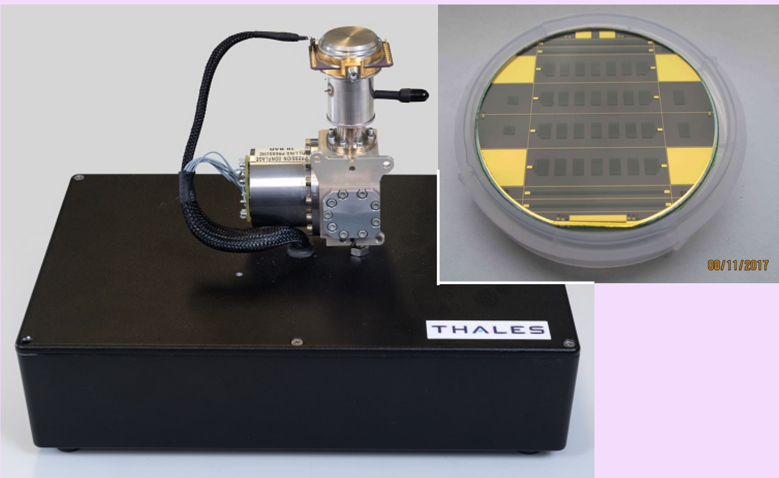
The HIFI Focal Plane Unit. This unit is located in the cryostat of the Herschel Space Observatory. Inside this unit are 14 superconducting heterodyne detectors that operated at 1.8 K in space.

Active heterodyne receivers have been used so far mostly in radioastronomy from 100 GHz to several THz as superconductor-based mixers exhibit sensitivity unmatched by other technologies. Nevertheless, the frequencies in communication technologies increase progressively with new generations like 5G, and 6G in the future. Sub-THz communication techniques progressively become relevant to increase the bandwidth (and the number of channels) of future telecommunication systems, namely base stations that can be placed in several districts of cities for medium-distance, high-throughput, real-time data transfers, or in autonomous vehicles and drones, since some superconductor-based systems below 2 kW of power can provide energy-efficiency performance with low levels of signal powers that cannot be matched with other technologies.

Regarding passive superconducting components, signal processing benefits from significant performance improvements, thanks to the much reduced loss from DC up to RF frequency. Very high quality factors have been achieved with resonators based on superconducting thin films, bringing several advantages, among which:

- low phase noise of oscillators;
- low insertion loss of filters, which is crucial in the front-end of any sensitive receiver ;
- high selectivity, or steepness of the roll-off domain, of a filter ;
- small size and weight of the component, as the components are 2D, and the conductive parts can be shrunk much below the millimeter scale without significant loss increase ;
- and very high reproducibility in the fabrication, as microfabrication techniques allow a submicron accuracy, which eliminates the need for any tuning screw.

In addition, new functionalities, such as multiplexers / demultiplexers which are not possible with conventional materials, have been achieved. These advantages well compensate the cost for cryogenic cooling, at least for high-Tc superconductors. This technology allows an optimal exploitation of the frequency spectrum, with very good separation of channels and may be the best for the development of 6G communications.



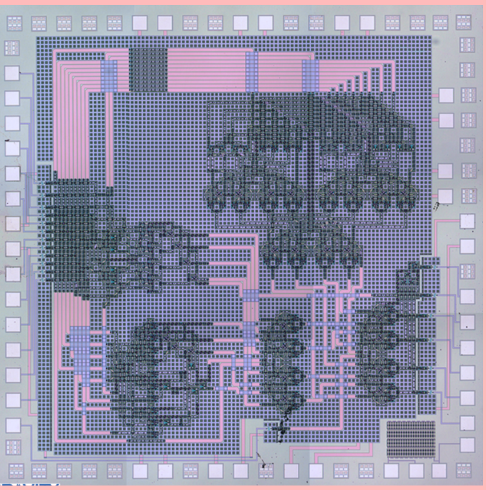
UHF filter system consisting of a 1cm² HTS chip placed in a sealed vacuum cryostat, cooled by a Stirling rotary machine. The 20cm x 14cm x 5cm black box contains the driving electronics. Right: Four microwave filters on a 2" wafer. Copyright THALES 2009.

SUPERCONDUCTING DIGITAL ELECTRONICS

Superconducting digital electronics (SDE) brings to superconducting electronics what digital techniques based on CMOS technology have brought to the ancient analogue world based on vacuum tubes, telephones, radio-emitters and receivers: more functionalities based on more complex circuits, more flexibility, and more capabilities, in particular regarding the development of smart sensors that combine quantum-accurate detectors with on-chip pre-processing units.

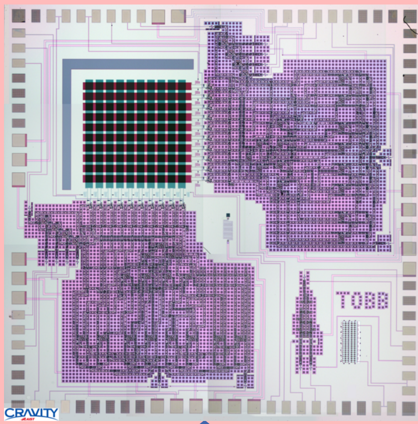
Compared with its semiconductor counterparts SDE complements them by bringing three main interesting properties that can be used alone or together, depending on applications:

- very high speeds with complex circuits demonstrated with 40-120 GHz clock frequencies, and simple logic gates operating till 770 GHz[13];
- ultra high energy efficiencies that push the CMOS energy wall further away for specific tasks;
- intrinsic quantum-limited sensitivity, that allows to manipulate very weak signals, useful for instance for analogue-to-digital conversion of RF signals.



4-bit, pipelined Arithmetic-Logic Unit (ALU) - 2016. Copyright: TOBB ETU

Like in the semiconductor world, a range of different families has emerged, starting with the Rapid Single Flux Quantum (RSFQ) logic proposed at the end of nineteen eighties, that triggered even more sensitive families like RQL, eSFQ and ERSFQ, or the Adiabatic Quantum Flux Parametron (AQFP) logic more recently. For instance, AQFP logic is widely seen as a well suited enabling technology candidate for readout of systems of quantum bits and quantum computing.

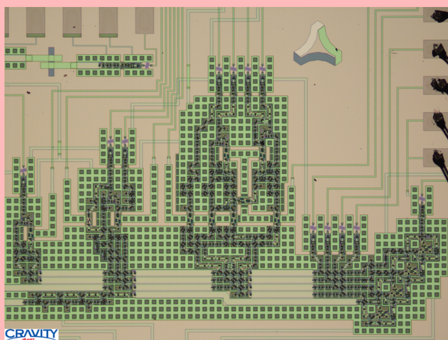


10x10 detector read-out and address encoder circuit-2017. Copyright: TOBB ETU

Since SDE is a pulsed logic it operates in a dynamic way, like the brain does. Indeed, neuromorphic-based systems rely on a different way to process information with the following properties:

- the information is not processed in a Boolean and sequential way; memory and processing are co-located; processing is distributed over neurons and not centralized;
- the information is transported with voltage pulses to mimic the brain operation and minimize energy consumption; this results in the low-energy ability;
- the brain architecture takes advantage of three-dimensional connectivity with very high fan-out of several thousands;
- neuromorphic systems can be reconfigured dynamically to take into account the experience (the past).

SDE combines the advantage of ultrafast speed with latencies in the picosecond range with very low energy, lower than $\Phi_0 . I_C \approx 1$ attojoule where Φ_0 is the quantum of magnetic flux $h/2e = 2.10^{-15}$ V.s and I_C is the critical current of Josephson junctions, of the order of 50 to 100 µA. It is then a good candidate for future advanced architectures as well, that are of interest for artificial intelligence (AI).



Arithmetic and logic units based on artificial neurons (XOR, Full adder, Multiplier) - 2019. Copyright: TOBB ETU

[13] W. Chen, A. V. Rylyakov, V. Patel, J. E. Lukens, and K. K. Likharev,"Rapid single flux quantum T-flip flop operating up to 770 GHz," IEEE Trans. Appl. Supercond., vol. 9, pp. 3212-3215, June 1999

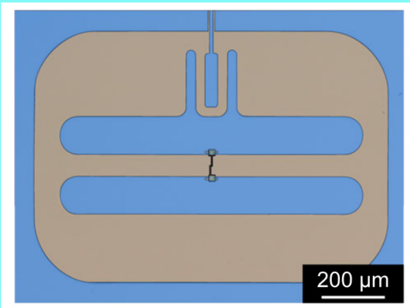
SUPERCONDUCTORS FOR QUANTUM COMPUTING

Superconductors exhibit quantum behavior on a macroscopic scale, making them a natural candidate for driving the progress of quantum technologies and computing. Their large-scale properties provide a sturdy foundation for developing quantum processors. Superconductors inherently possess quantization features that enable the creation of qubits, the fundamental units of quantum information. These superconducting qubits can be maintained coherently, a crucial prerequisite for error-free quantum computations over extended periods, leveraging the materials and technology. Furthermore, this technology can be applied to various qubit types[14] based on charge (e.g., transmon[15]), flux (e.g., fluxonium[16]), or phase of resonance (e.g., cat state qubits[17]).

Furthermore, leveraging the existing tools for superconductor fabrication allows us to engineer diverse superconducting qubit architectures integrated with on-chip resonator circuits. This advancement enables the creation of multi-qubit systems capable of executing complex quantum algorithms, a significant step toward achieving quantum supremacy, as exemplified by Google Quantum-AI[18]. Scaling quantum computers promises transformative applications in cryptography, optimization, medicine, and materials science. However, a primary challenge in scaling lies in the limited decay and decoherence times, which hinder algorithms with substantial circuit depth. As ongoing research uncovers new superconducting materials, qubit designs, and fabrication techniques, the prospect of scalable, error-tolerant quantum computing becomes increasingly likely.

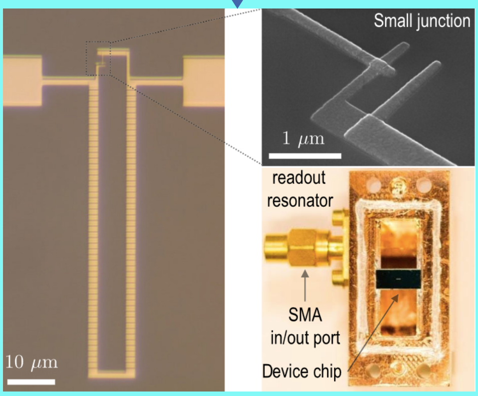
Another hurdle to scaling quantum systems is the precise readout and control of qubits, necessitating the generation of microwave signals and amplification that traverse multiple layers of wiring and connections, spanning high thermal gradients from room temperature to millikelvin temperatures. Such control methods are impractical for large-scale quantum computers capable of executing complex quantum algorithms. A promising solution is paving the way for the superconductor circuits for control and readout and to get the advantage of high frequency, low noise and power dissipation, and low-temperature stage of these circuits.

Therefore, superconductors represent a foundational technology for quantum computing, not only as the basis for qubits but also as a medium for control and readout, driving us closer to realizing the full potential of quantum systems for solving problems beyond the reach of classical computers.

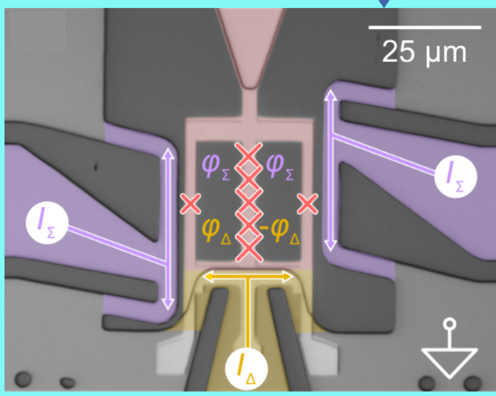


Transmon qubit [15]

Fluxonium qubit [16]



Cat-state qubit [17]



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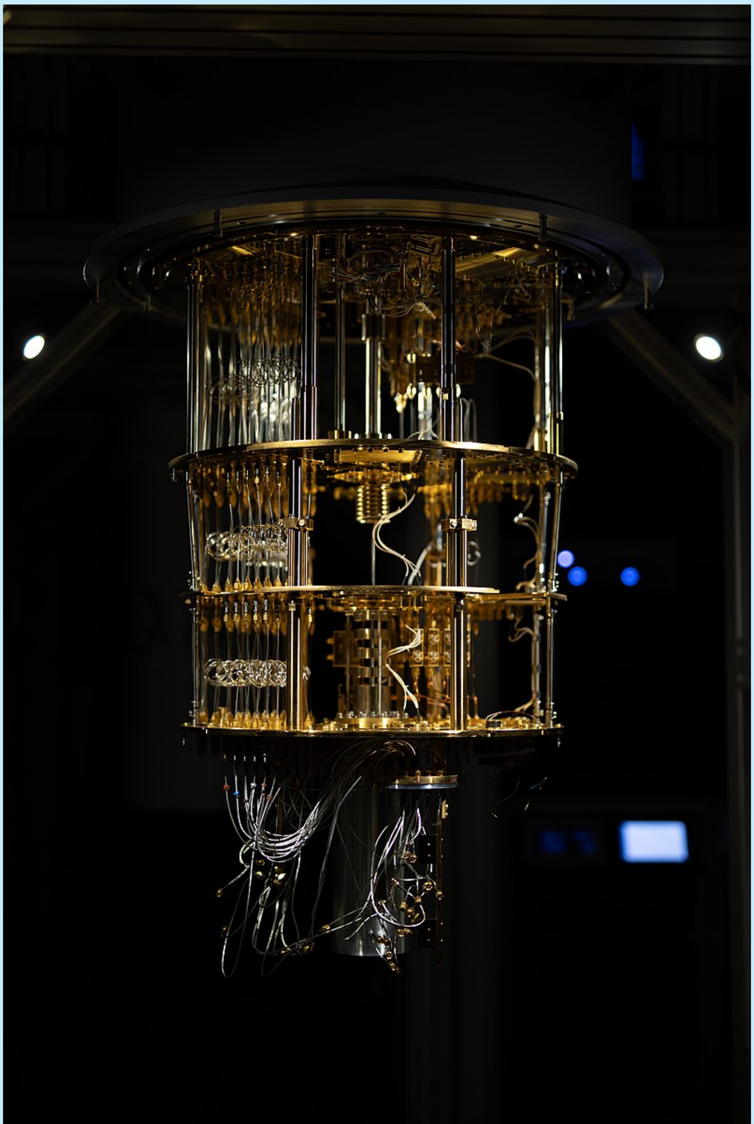
CRYOGENICS

Cryogenics is an important enabling technology to support superconducting electronics and/or quantum computing systems operation. It refers not only to cryorefrigerators but also to their integration in the systems, efficiency and reliability of both being of major importance for correct and efficient system operation.

The cooling requirements may range from a few watts or kilowatts at 5 K-1.8 K for superconducting applications to a few tens of microwatts or milliwatts down to less than 20 mK for quantum computing.

In Europe, there is a strong experience - gained in large projects like Tore Supra and ITER tokamaks or CERN LHC hadron collider - for kilowatt range efficient and reliable Brayton type cryorefrigerators allowing cooling down to 5 K-1.8 K. But integration in an exa-scale superconducting supercomputer will require important innovative integration designs. In the few watts range cooling down to 3 K, the leadership is clearly in the US, but several small size companies in Europe have already demonstrated their capability to integrate directly such Pulse Tube type cryorefrigerators in superconducting system or in refrigeration by forced circulation of liquid helium in closed loops. These companies are still developing new concepts which may be of great interest for superconducting electronics applications.

For the Josephson junctions qubits cooling, the situation is almost clear up to, let's say, 40 microwatt of power at 20 mK systems corresponding to about a few tens of qubits operation. Commercial dilution fridges are available in Europe and currently operated with high reliability and relative efficiency in many laboratories worldwide. Regarding future systems including hundreds of thousands up to millions of qubits, the story is different. No cryorefrigerator with cooling power of thousands or more microwatts below 20 mK is available nowadays with a reasonable efficiency. New concepts should be developed and demonstrated. The integration is also an open and complicated subject with two major concerns. The precooling and cooling of the coaxial lines and wires required to manipulate and read the JJ's qubits is an issue requiring subKelvin multiplexers to be developed to drastically reduce the lines and numbers of wires (today the state of the art is about 3- 4 wires per qubit and about 10 qubits required for error correction of a single "active" qubit). The second point is to design an integration architecture allowing for a system modularity avoiding a warmup of the whole system in case of failure of a few percentages of qubits or associated superconducting circuits. A strong effort on innovative integration solutions development and demonstration will be required. European companies are surely capable to become world leaders in such developments.



IQM Quantum Computer refrigerator in Espoo, Finland. Credit: Wikipedia

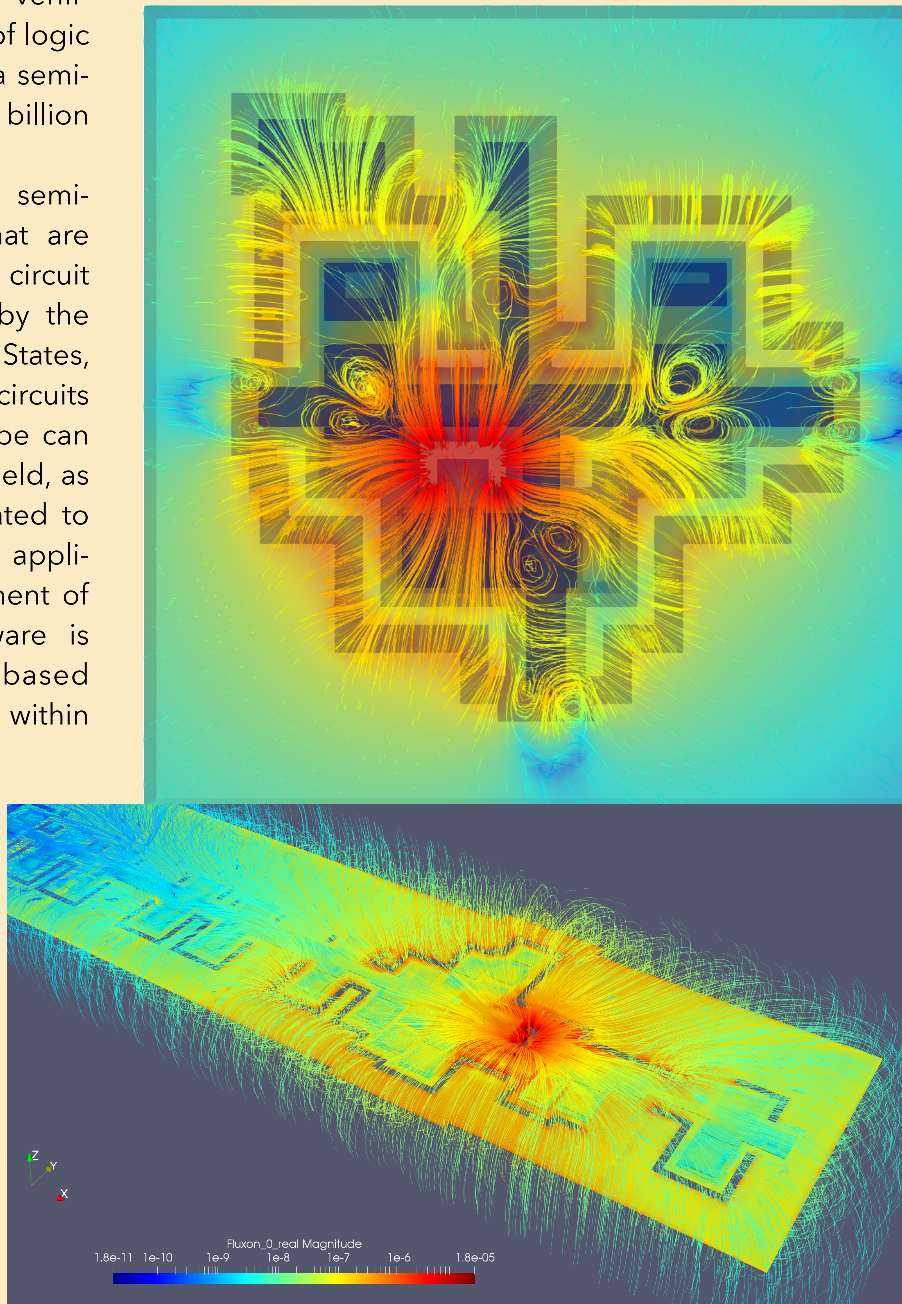
SOFTWARE TOOLS

Software tools for the design of complex integrated circuits are mostly focused on semiconductor devices and circuits. Synopsys, Cadence, and Mentor Graphics are the largest companies that provide such software tools. These tools cover every aspect of integrated circuit design, from technology computer-aided design (TCAD) at the device level to synthesis, placement, routing, timing analysis and verification of large digital circuits with billions of logic gates. These companies are powered by a semiconductor electronics market of US$500 billion per year.

Despite the power of design tools for semiconductors, there are very few tools that are applicable to superconducting electronic circuit design. Synopsys has an effort funded by the IARPA SuperTools program in the United States, largely focused on the synthesis of digital circuits for microprocessors. In this respect, Europe can still make significant contributions to the field, as research and development efforts dedicated to superconducting electronics find more applications in particular due to the development of quantum computers. A range of software is necessary to design superconductor-based circuits. So far, they have been developed within research groups but the lack of generic design tools appears more and more as a bottleneck towards the development of complex superconductor circuits, be them for detectors, digital, analogue or quantum electronics. Digital simulator tools like JSIM, WRSPICE[19], PSCAN[20] or JoSIM[21] are now separately available.

One of the necessary tools for superconductor circuit design is the development of parameter extraction and layout verification software tools that allow more optimal design and evaluation of superconductor devices and circuits, and has found application from analogue systems such as gradiometers and micro-calorimeters to quantum electronics interfaces by customers all over the world.

More efforts are on-going regarding the development of software for quantum design such as QKIT[22], QISKIT[23], LEAP[24] or Quantum Composer[25], as a few examples.



Extraction of magnetic flux lines of superconducting digital circuits. Copyright: Stellenbosch University and SunMagnetics, South Africa – 2023.

[19] http://www.wrcad.com/wrspice.html
[20] http://pscan2sim.org
[21] https://joeydelp.github.io/JoSIM
[22] https://github.com/qkitgroup/qkit
[23] https://qiskit.org/metal
[24] https://cloud.dwavesys.com/leap
[25] https://www.quatomic.com

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