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Superconductivity in medical diagnostic and treatment
An overview of selected applications

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Many modern electromagnetic technologies are used in medicine for the diagnosis, healing and rehabilitation of diseases. The development of new methods is related to the progress in the area of basic and applied sciences. It requires interdisciplinary research, ranging from medical, biological, chemical, physical, engineering and technical sciences to social and economic sciences. The presentation overviews selected applications of superconductivity phenomena that are already used in medicine and indicates those applications that have the potential for their implementation in medical practice in future.

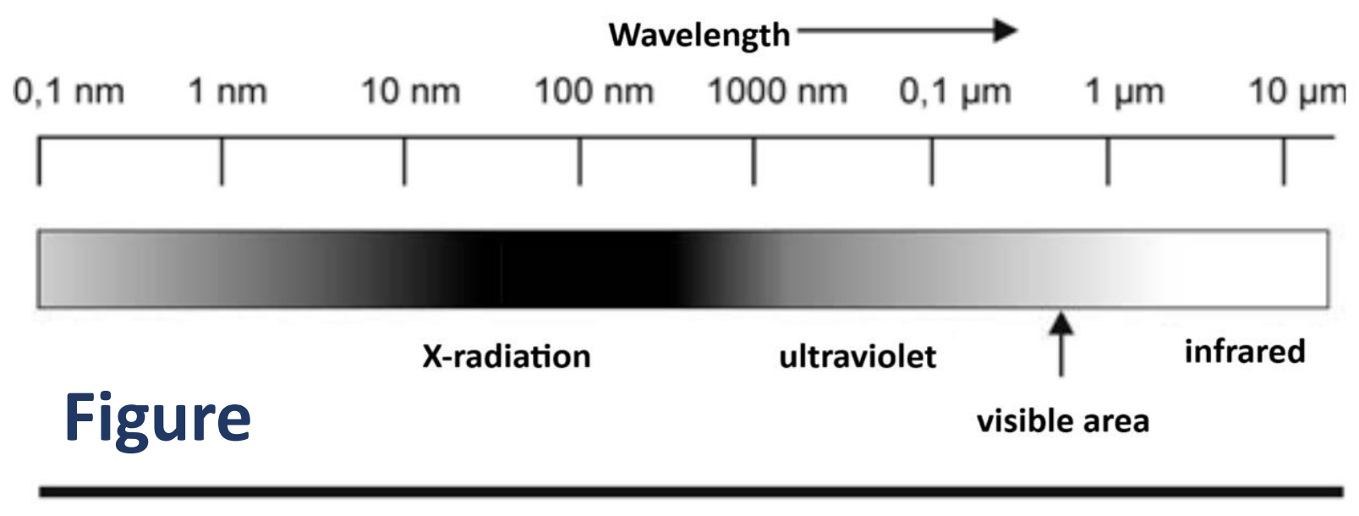
Physical phenomena in superconductivity

Phenomenon	Explorers	Definition
Current flow without resistance (1911)	H. Kamerlingh Onnes	Mercury cooled by liquid helium to 4.2K becomes a superconductor
BCS Theory (1957)	J. Bardeen, C. Cooper, J.R. Schiffer	The basis of the theory is the Cooper pair: 2 electrons with opposite spin and momentum, bound together in a system with resultant spin and momentum equal to zero
Josephson stationary phenomenon (1962)	Brian D. Josephson,	System consisting of two superconductors separated by a layer of insulator that plays the role of a barrier to the flowing current – macroscopic quantum phenomena
HTS superconductors (1986)	J. G. Bednarz i K.A. Muller z IBM Zurich	Superconducting properties at temperatures higher than helium - ceramic composites

Synchrotron radiation is produced today in circular accelerators called synchrotrons. Photon energies in synchrotron beams for medical applications range from 8-150 keV. In research aimed at the study of tissues, cells and subcellular structures, lower-energy photon beams are also used (Figure 1). For most diagnostic and radiotherapy applications in living organisms, beams of the highest possible intensity are needed, which are obtained from superconducting synchrotrons (so-called wigglers). Radiotherapy using high-powered synchrotron beams has proven to be particularly effective and low risk of complications in the treatment of tumours located in the central nervous system (gliomas) [4,5].

The discovery of superconductivity by Kamerling Onnes initiated research into the application of superconductivity and related phenomena, such as strong field magnets, cryogenics, nuclear medicine, cyclotrons as particle beam sources, protons, synchrotron radiation, high sensitivity magnetometry [1,2,3]. Superconductivity applications in medical imaging, diagnosis and treatment include:

- radiotherapy - cyclotrons, accelerators
- synchrotron radiation
- isotope production
- proton and ion beam delivery
- magnetic resonance imaging MRI
- nuclear magnetic resonance spectroscopy NMR
- ultrasensitive electro-magnetic signal transducers SQUIDs



Figure

synchrotron radiation use area

Definitions of critical parameters for type I and II superconductors [1,7]

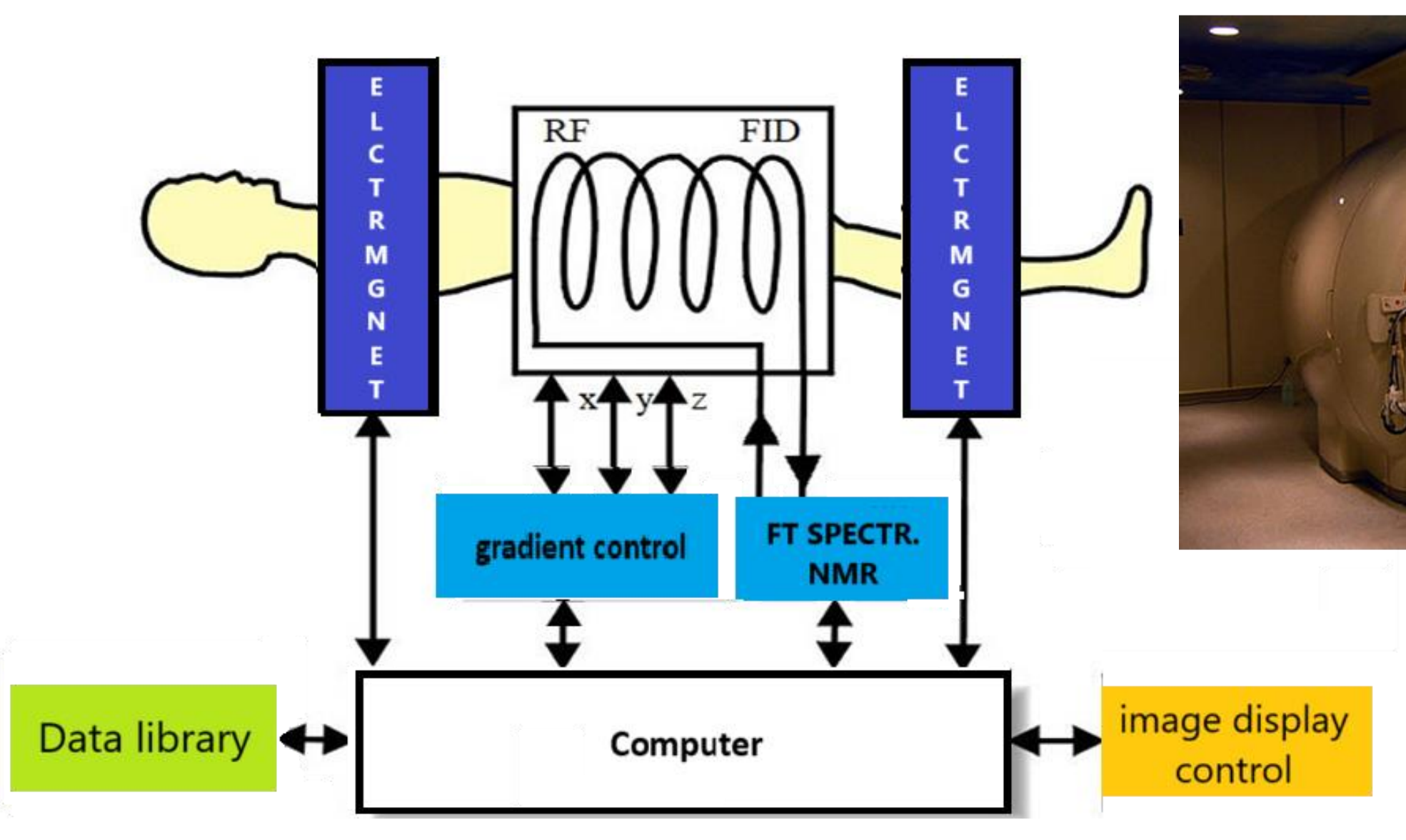
Name and symbol		Definition
critical temperature	T_C	temperature below which a superconductor exhibits superconductivity at zero critical field strength and zero critical current
lower critical magnetic field strength	H_{C1}	magnetic field strength at which the first fluxon enters the volume of a type II superconductor, causing a departure from ideal diamagnetism
upper critical magnetic strength	H_{C2}	the maximum magnetic field strength below which a type II superconductor is in the mixed state
critical current	I_c	the maximum direct current that can be considered to flow in a superconductor without resistance
critical current density	J_c	electric current density at the critical current, determined for the whole superconducting cross-section or the un-stabilised part thereof, when a stabiliser is present.

Almost all medical applications of superconductivity are based on LTS superconductors, which require liquid helium or complex cryogenic systems for cooling. The main reasons for not using HTS at 77 K are: (1) the complex interdisciplinary nature of the superconductivity phenomenon involving areas as diverse as thermodynamics, quantum physics, cryogenics, materials engineering, electrical and electronic engineering; (2) the lack of a proven microscopic theory of superconductivity in HTS materials, not allowing the prediction of new superconducting materials with higher T_C values. Properties of HTS materials include high resistance in the normal state, proximity of superconductivity to the competing antiferromagnetic state and high anisotropy; (3) geometrical shapes of HTS wire limited to strips, the production of which requires specialised technology. The most important factor hindering the use of HTS-based medical systems is the overall high cost of the devices [6,7,8].

Selected medical applications of superconductivity

Magnetic resonance imaging

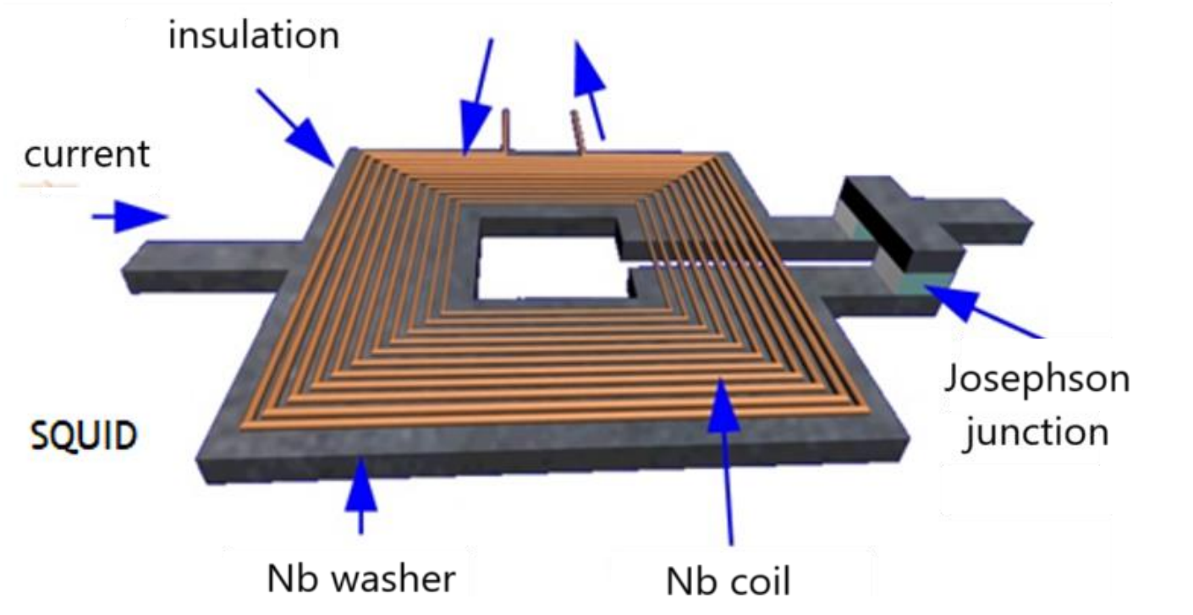
The traditional MRI system currently uses 1.5T or 3.0T electromagnetic fields. Several MR scanners with a superconducting magnet of 4T induction are currently in operation in the US [8].



Magnetic nanoparticles and sensors

SQUIDs for breast cancer cells

Mammography fails to detect 10-25% of tumours. The emerging application of magnetic relaxometry, particularly using SQUIDs, is rapid and potentially more specific than mammography. Magnetic relaxometry is theoretically more specific than MRI detection, as only nanoparticles associated with the target are detected [9, 10,11].



Biofunctionalised magnetic markers

To use magnetic methods in clinical practice, their superiority over conventional methods needs to be confirmed. Further refinement of the complex properties of magnetic markers is needed to optimise detection methods, which are based on measurements of (1) ac susceptibility, (2) magnetic relaxation time and (3) remanence and require nanoparticles with different magnetic properties (Figure 2) [12,13]

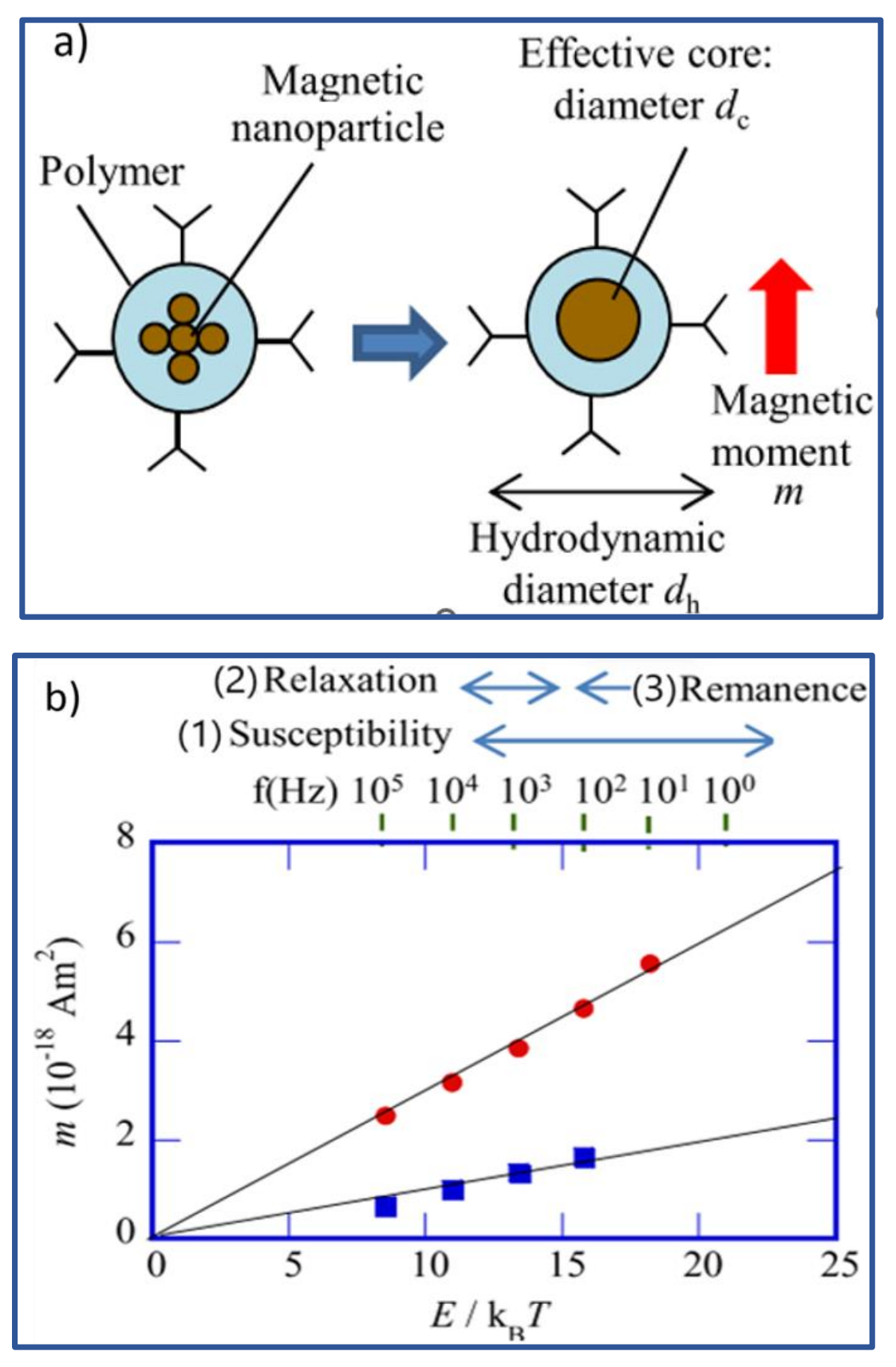


Figure 2 a) schematic of the magnetic marker; b) relationship between magnetic moment *m* and anisotropy energy *E* for two different markers

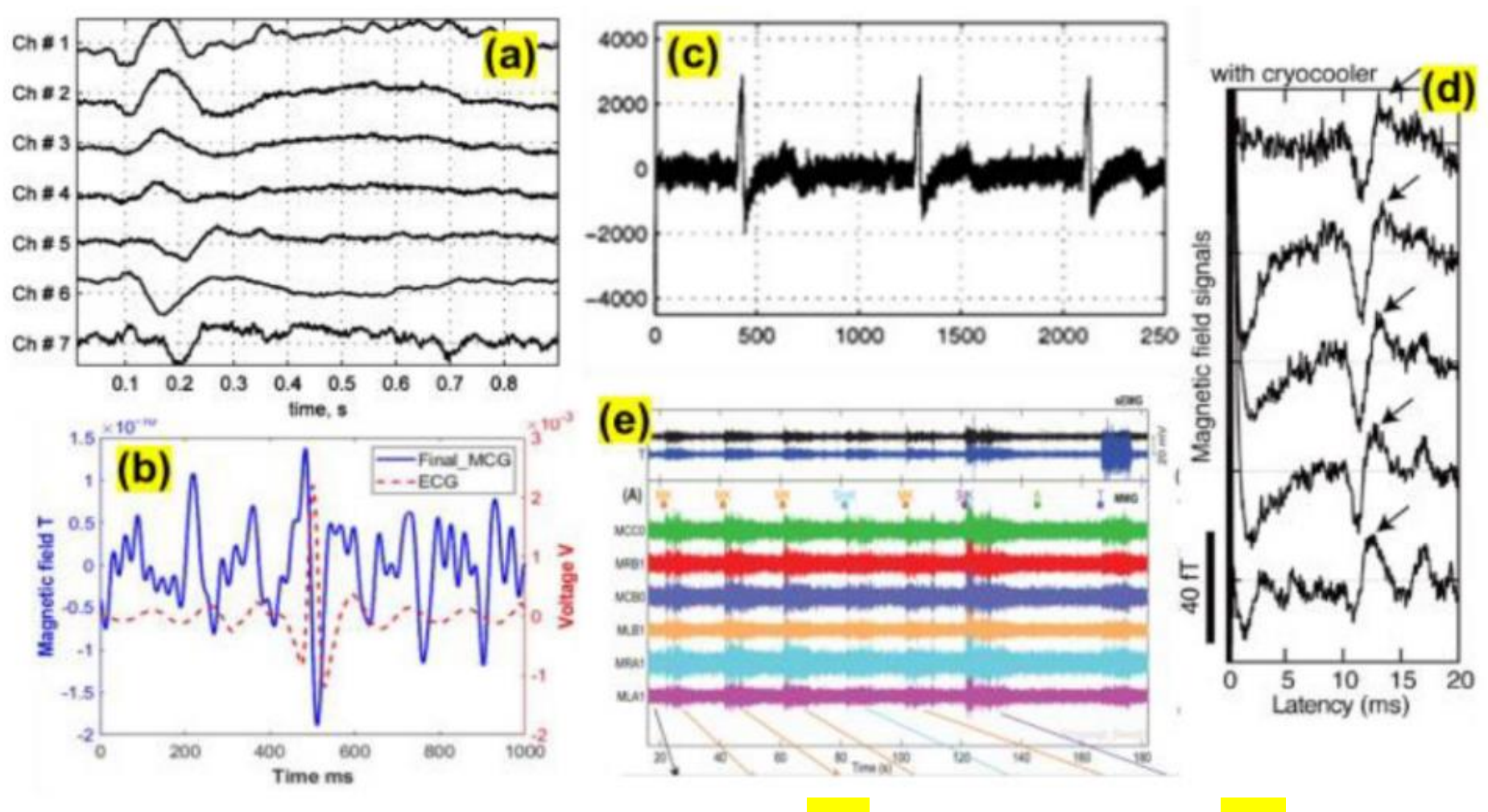
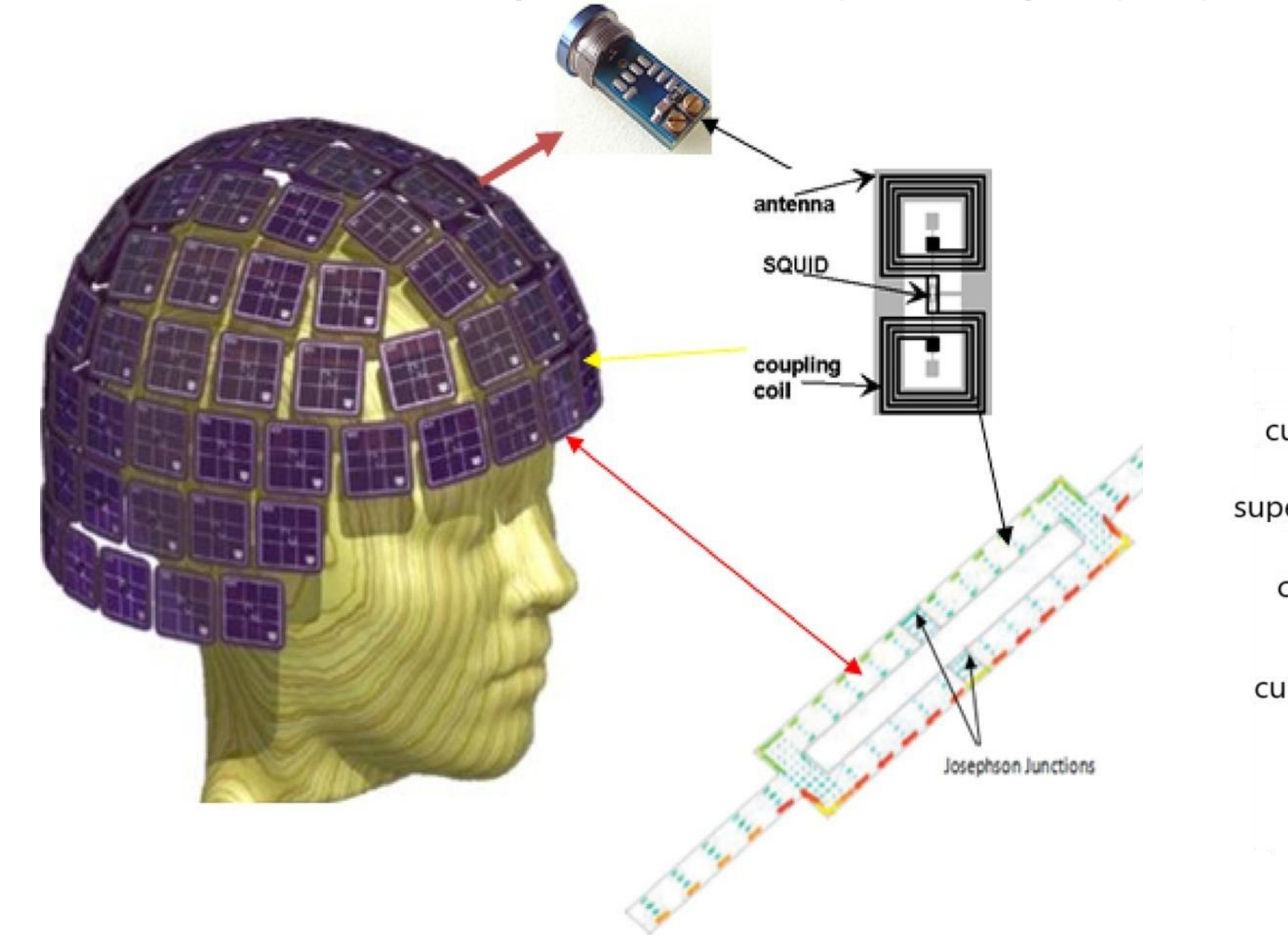
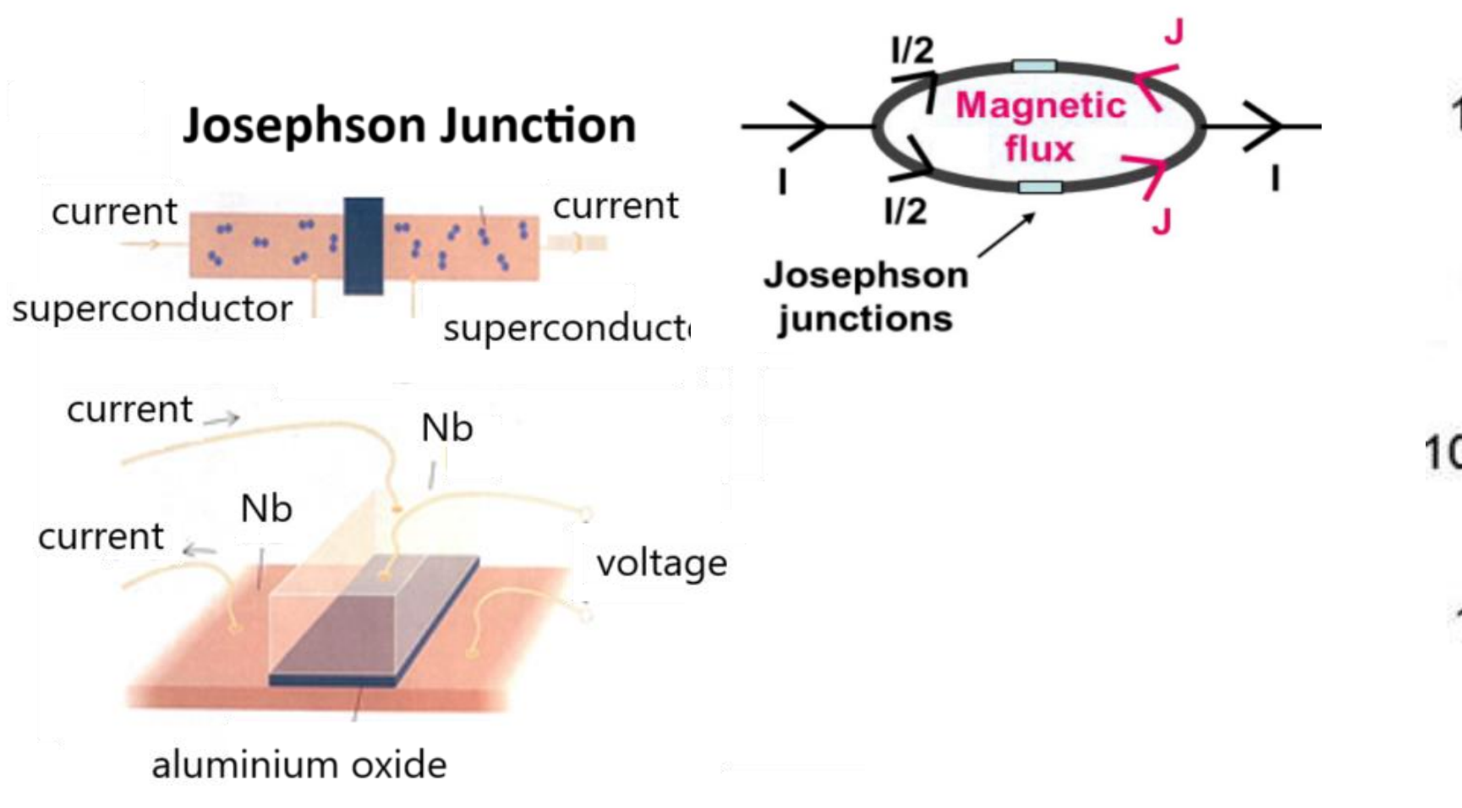
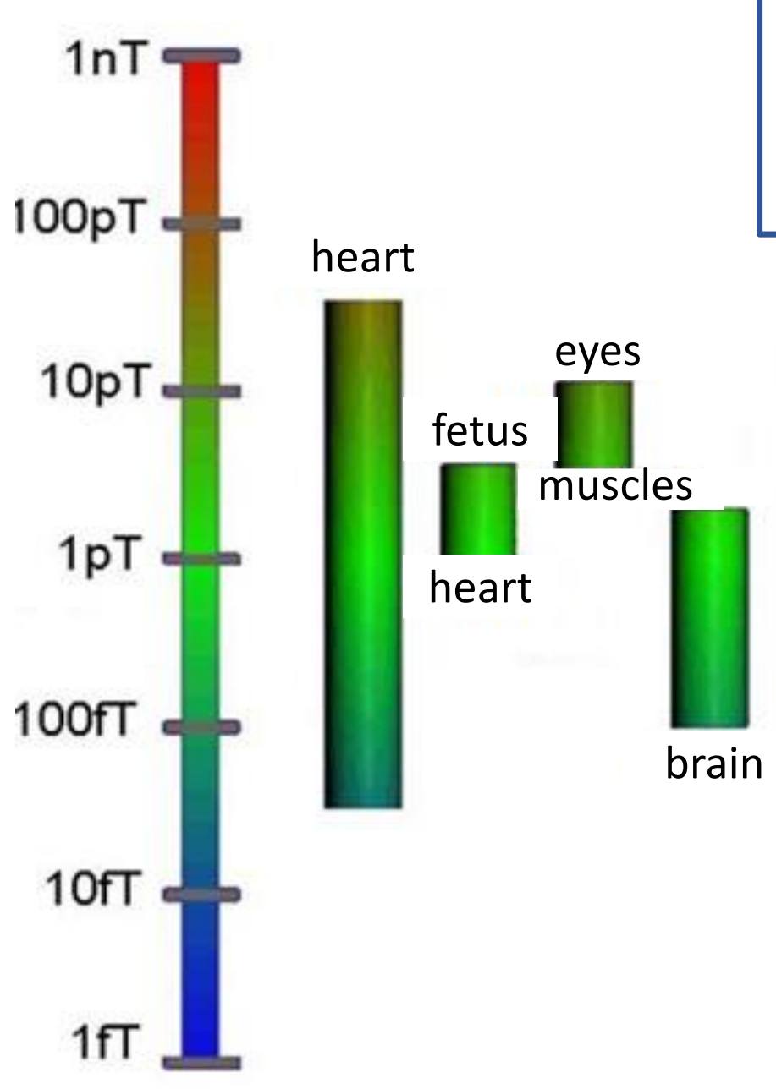


Figure 3 Biomagnetic signals for (a) Brain (MEG); (b) Heart (MCG): MCG and ECG signal; (c) Nerve (MNG): raw measurement of evoked MNG in the peripheral nervous system; (d) Spine (MSG); (e) Muscle (MMG)

SQUIDs in in magnetoencephalography MEG







The magnetic field detection method with SQUID is based on the interference that occurs during the transmission of supply currents and induced currents in the sensor. A single sensor consists of two Josephson junctions connected in parallel. For accurate temporal and spatial neuroimaging, MEG magnetoencephalography and MRI have been proposed.

TABLE 1. Bio-magnetic signal features for different sources.

Source	Range	Frequency	Bandwidth
Brain (MEG)	100 fT – 1 pT	0.5 - 500 Hz (clinically relevant <70Hz)	~500 Hz / 70 Hz
Heart (MCG)	50 -100 pT	<75 Hz	75 Hz
Nerve (MNG)	5 fT – 8 pT	6-500 Hz	494 Hz
Spine (MSG)	1 – 100 fT	100-5000 Hz	4900 Hz
Hand/Leg/ Head Muscle (MMG)	1 fT – 1 pT	1-300 Hz	300 Hz

SUMMARY

The high manufacturing and operating costs of HTS mean that they are not being deployed in medical applications on the scale that is in demand. Progress is seen in the use of materials for magnet windings operating at higher temperatures - ferroelectric superconductors and MgB_2. The future of HTS medical applications is still an ongoing question that will only be answered once the scientific and technological challenges hindering their large-scale use are understood.

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