

About Magnets and Superconductors of Mr Scanners

Željko Đ. Vujović (✉ etracon@t-com.me)

Boulevard Save Kovačevića

Research

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Abstract

The topic of this paper are parts of modern MR devices, in which the magnet windings are located. MR scanner magnets are made of four types of electromagnetic windings: 1) The main magnet, made of superconducting material, creates a variable magnetic field; 2) X coil, made of a resistive material, creates a variable magnetic field, horizontally, from left to right, across scanning tube; 3) Y coil creates varying magnetic field, vertically, from bottom to top; 4) Z coil creates varying magnetic field, longitudinally, from head to toe, within scanning tube. Superconductors, which create the main magnetic field, should be cooled by liquid helium and liquid nitrogen. Main magnets made of superconductors should use cryostat, with cooling vessels with liquid helium and liquid nitrogen, thermal insulation and other protective elements of magnet system. The types of magnets that exist in the basic configurations of MR scanners are analyzed. Scanners in the form of a closed cylindrical cavity create their own, magnetic, fields by passing current through the solenoid, which is held at the temperature of the superconductor. The superconductors used exclusively are: niobium-titanium (NbTi), niobium-tin (Nb_3Sn), vanadium-gallium (V_3Ga) and magnesium-diboride (MgB_2). Only magnesium diboride is a high temperature superconductor, with a critical temperature $T_c = 39^0K$. The three remaining superconductors are low temperature. New high-temperature superconductors have been discovered, as well as room-temperature superconductors. Newly discovered superconducting materials are not used in MR scanners. The magnet structure of the MR scanner is complex. The resonant frequency changes at each point of the field in a controlled manner. The windings of the main magnet made of superconducting material in the form of microspiral fibers are built into the copper core. The nonlinear gradient field is created by windings of conductive material. It is added to the main magnetic field. Thus, the resulting magnetic field is obtained.

1. Background

Paul Lauterbur and Peter Mansfield received the Nobel Prize in Medicine in 2003, "for discoveries related to the visual representation of magnetic resonance imaging", thirty years after the publication of the results of Paul Lauterbur's experiment. Graphical representation of these results, published on March 16, 1973, is shown on the next Figures. What is the structure and working principle of magnets used in modern MR scanners? It is an interesting and significant question, which deserves a comprehensive account.

MR scanner magnets are made of main magnet windings, gradient windings and RF windings. The windings for the main magnets are made of superconducting materials and the windings for gradients and RF windings are made of resistant materials. The field created by the main magnet is necessary to bring the system of nuclear spins, on which it acts, to a state in which magnetic resonance is possible. The induction strength of the main magnetic field is the most important quantity for obtaining and for the strength of the magnetic resonance signal. Almost all modern MR scanners use a superconductor made of niobium-titanium ($NbTi$), which becomes superconducting below $9,4^0K$. niobium-tin (Nb_3Sn), vanadium-gallium (V_3Ga) and magnesium-diboride (MgB_2) are also used. Only MgB_2 is a high temperature

superconductor with critical temperature $T_c=39^0\text{K}$. Nb_3S_n is low temperature with $T_c=18,3^0\text{C}$ and V_3Ga low temperature with $T_c=14,2^0\text{C}$.

Gradient system produce calibrated distorsion of main magnetic field in x-, y- or z- direction. RF coils are responsible for perturbing the nuclear spin system, while Patient coils are responsible for MR signal detection. New high temperature superconducting materials have been discovered as well as room temperature superconductors, $(\text{Ti}_5\text{P}_{b2}) \text{Ba}_2\text{M}_{g2}\text{Cu}_9\text{O}_{18+}$, $T_c=28^0\text{C}(310^0\text{K}/55^0\text{K})$ and $(\text{Ti}_5\text{P}_{b2}) \text{B}_{u2}\text{M}_{g2,5}\text{C}_{u8,5}\text{O}_{17+}$, $T_c=30^0\text{C}(303^0\text{K}/58^0\text{F})$ are given as an example. The hypotesis that main magnets could be made of high temperature superconductors and room temperature superconductors has not been proven. On the contrary, it has been shown that this is, for now, imposible because there are many difficulties in the application of newly discovered superconductors (instability in the magnetic field, low current density, the need to make high quality and extremely expensive materials...). All practical solutions must be cooled at this time.

FIRST ZMR NMR IMAGE

2. Material

2.1. Magnetom Terra 7T scanner from Siemens Healthcare, the first ultra-high field MR scanner to be approved for clinical use. Noise level: base load $\leq 56.7\text{dB (A) 8}$, full load $\leq 102.2\text{dB (A) 8}$. Siemens promoted it as a revolutionary innovation.

2.2. Superconducting magnet: an electromagnet made from superconducting windings. The windings must be cooled, during operation, below their critical temperature, at which they pass from the basic state to the superconductor state. A cryostat is a system for maintaining a very low temperature. It is thermally insulated from the environment. A typical cryostat, used in MR scanners, consists of three vessels, located one inside the other. The outhervessel is filled with a vacuum. It acts as a thermal insulator. Beneth this vessel is a vessel filled with liquid nitrogen. It serves as a protection, insulation, middle shield, which prevents the action of heath from the outhervessel, on the inner vessel. The inner vessel contains cryogen (cooler-liquid helium).

2.3. Low-temperature, high-temperature and room temperature superconductors.

2.4. Gradient windings of resistive conductors.

3. Results

3.1.

3.2.

Main field (B_0) Coils (Principal magnet windings plus superconducting shim and shield coils) – produce B_0 . Shim coils (to improve homogeneity). Gradient Coils (for imaging, including their active shields).

Radiofrequency (RF) Body Coil (transmits B_1 field). Patient Coils (primarily to detect MR signal, some are transmit/receive). Complete gradient system is consisted of coils mounted along the inner bore of the system. Produces calibrated distorsion of main magnetic field in x-, y- or z-direction. Radio frequency (RF) Coils.

Figure 5 - Representative cross-section of a superconducting scanner, showing the nested arrangement of “coils”. Both superconducting and resistive coils are shown. Two different types of patient coils are also illustrated: a spinal chain receiver only, and a knee carrier / receiver

3.3.

3.4.

4. Discussion

5.1. The image with the Terra 7T Siemens Healthcare Magnet encouraged the work of this article.

5.2. MR scanner magnets are a set of three components: main magnet, gradient magnets (x, y, z) and RF magnets. Together, they create the preconditions for magnetic resonance imaging to occur. In this set of magnets, the main magnet stands out in size and weight, which is made of superconductors, although the main magnet can also be made of permanent magnets and resistive conductors. The other two components of the MR magnet system are made of resistive conductors.

5.3. In order to achieve the superconductivity of the material, which creates the main magnetic field, a crystal is used, with cooling vessels for liquid helium and liquid nitrogen, thermal insulation and other elements to protect the main magnet system. These elements determine the dimensions and size of the device. Initially, nitrogen should be replenished weekly and helium monthly. This was, gradually, perfected, so that liquid helium had to be replenished every 2–3 years. There are data that, lately, zero temperature cooling systems (ZBO) have become the standard.

In the case of a superconducting magnet, the power supply is connected on both sides of the coil segment. The current through the coil increases gradually, over several hours, until the desired field is reached. The current continues to flow in a closed loop, without a significant drop. The resulting property is that the magnetic field is always present. The construction of superconducting magnets is considered to be extremely expensive, and cryogenic helium is expensive and difficult to maintain. Nevertheless, today they are the most common type of magnet found in MRI scanners. It is estimated that investing in the production of new usable superconductors would be a process that does not pay off.

5.4. The microsil fibers of one of the superconductors, NiTi, Nb_3Sn , Va_3Ga or MgB_2 , are inserted into the copper conductors. Copper acts as an insulator at low temperatures, relative to the zero resistance of the

microsial fiber alloy. Supports and protects alloy windings from damage, provides mechanical strength, prevents deformations and vibrations. It takes over the conduction of electricity, if, due to a fault, the superconducting mode is lost. (Quench)

5.5. A linear gradient is added to the main magnetic field, a balanced disturbance of the fundamental field along the axis of the magnet (x-side-side, y-front-back, z-head-heel). The cross section of all three axes is the isocenter of the magnet. In it, the basic magnetic induction has, always, the same value.

The construction of the z-gradient is usually based on circular coils, while the transverse(x-and y-) gradients typically have a saddle winding configuration. More precisely, the basic design of the z-direction gradient is Helmholtz's pair of coils: two loops with currents flowing in opposite directions.

Helmholtz coils produce a gradually changing field, which is zero in the magnetic isocenter, but increases linearly outward, in both directions + z and -z. When this is added to the constant field B_0 , the result is a gradual increase in the gradient along the z-axis.

With the help of gradient windings, the value of the strength of the magnetic induction at each point of the three-dimensional space of the magnet is changed in a controlled manner. The resonant (Larmor) frequency is proportional to the strength of the magnetic induction. So, it has been achieved that the resonant frequency changes, controlled in every point of three-dimensional space. This also means that the magnetic resonance signal is different at each point. The signal strength is proportional to the spin concentration at the observed point. By measuring the magnetic resonance signal, the concentration of spins in various parts of the sample can be determined.

5.6. The time-varying radio frequency field (RF), used in MR, is denoted by B_1 . It must be normal to the main magnetic field B_0 . It is produced by special RF windings. RF windings can be transmitters, receivers, or both. If the oscillation B_1 has a value close to the precession of the nuclear spins (Larmor frequency), the energy is deposited in the spin system, causing a change in its net magnetization. B_1 is only switched on for short periods of time (several milliseconds), called "RF pulses". By adjusting the magnitude or duration of these B_1 pulses, the nuclear spin system can rotate at variable angles of rotation, such as 90° and 180° .

5.7. A superconductor, unlike a conductor, conducts electricity indefinitely, without energy losses. This is an important characteristic of these materials and a challenge for their use. They do not lose electricity! For the main magnets of MR scanners are used: niobium-titanium (NbTi), $T_c = 10\text{K}$, $B_0 \sim 15\text{T}$ (Since 1960), niobium-tin (Nb_3Sn), $T_c = 18,3^\circ\text{K}$ $254.8^\circ\text{C} / -426.7\text{F}$, $B_0 \sim 25\text{T}$ to 30T (Since 1960), vanadium-gallium (V_3Ga), $T_c = 14.2^\circ\text{K}$, $B_0 \sim 19\text{T}$, magnesium-diboride (MgB_2), $T_c = 39^\circ\text{K}$ ($-234^\circ\text{C} / -389^\circ\text{F}$) (Since 2001). It can be noticed that out of four superconductors, three are low-temperature and one is high-temperature.

Professor Allen D. Elster states that there is, in the experimental phase, re-production of MR scanners using "high temperature" superconductors. An example is magnesium-diboride (MgB_2), with a critical temperature $T_c = 39^0K$ and others. He envisions the use of these superconductors, in the future, to build MR scanners. This was an incentive for digression from the main topic of this paper and a review of the current state and chronology of superconductors (Fig. 12). It can be seen that a significant number of high temperature superconductors and room temperature superconductors were discovered. Their application in practice is far away. The question is whether and when, these superconductors will be usable because of the properties they have. From the chronology of the discovery of superconductors, the following events can be singled out as markers: 1941. niobium-nitride, $T_c = 160^0K$, 1945. described perovskite, 1962. made the first commercial superconductor NbTi. At that time the use of niobium-tin, Nb₃Sn, began. In 1972, the BSC theory of superconductivity (Burden-Cooper-Schiffer) was published. 2001. Described by MgB_2 .

5.8. This study confirmed, as important, that room temperature superconductors, although discovered, are not in the field of research of the world's leading laboratories, as possible materials for making magnets for MR scanners. Their indisputable discoveries are imposed, for research and application. The current situation is such that there is no known scientific method by which they could be turned into useful, application, which should be eliminated. It is estimated that research to achieve this is extremely expensive. Scientific optimism gives hope that it is a matter of time before they become applicable, and that the practical benefits of their discovery will be obtained.

5. Conclusion

This paper is important, primarily, because it explains the complex structure of the MR scanner magnet and the way in which the resonant frequency changes in a controlled manner at each point of the magnetic field. The principle realization of the scanner, the cross section of the windings of a superconducting magnet with microsil fibers, the principle of creating a nonlinear gradient and its role in creating the resultant magnetic field, the chronology of the discoveries in the field of high temperature superconductors and room temperature superconductors are presented.

The paper emphasized the importance of the discovery of high-temperature superconductors and room temperature superconductors, which were awarded Nobel Prizes, but also the lag in the application of these discoveries for practical purposes. Objective reasons for this are given.

The initial assumption that the main magnets of MR scanners are made of high-temperature superconductors and room temperature superconductors has not been proven. On the contrary, it has been shown that these superconductors cannot be used to make the main magnets of MR scanners. This remains as a possible idea for some future work, if and when, the newly discovered superconductors are brought to a level that is practically applicable. There are no new proposals for the main magnets of the MR scanner.

6. Research Method

Analysis, synthesis, abstraction, generalization, concretization, description, systematization and others.

Declarations

- **ETHICS APPROVAL AND CONSENT TO PARTICIPATE**

Not applicable

- **CONSENT FOR PUBLICATION**

Not applicable

- **COMPETING INTERESTS**

The author declare that he have no, financial competing interests. The author declare that he have no known non-financial competetive interests .

- **FUNDING**

Not applicabele

- **AUTHOR'S CONTRIBUTION**

The conception, design, acquisition, analysis and interpretation of data are, on the whole, the contribution of the author. This is, on the whole, individual research work.

The author agrees that issues related to the accuracy or integrity of any part, even those in which the author is not personally involved, should be investigated, resolved and the resolution documented in the literature.

- **ACKNOWLEDGEMENTS**

Not applicable.

- **AVAILABILITY OF DATA AND MATERIAL**

All data generated or analysed during this study are included in this published article [and its supplementary files]

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Figures

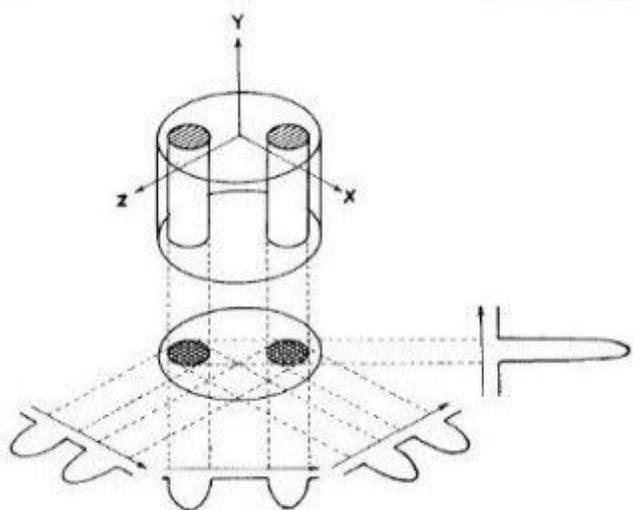


Figure 1

Relationship between a three-dimensional object, its two-dimensional projections along the Y-axis, and four one-dimensional projections at 45 intervals in the XZ-plane. The arrows show the directions



Figure 2

Proton nuclear magnetic resonance zeugmatogram of the object described in the text, using the four relative orientations of the object and gradients as in Figure 1 (zeugmatogram = “what is used to connect”)

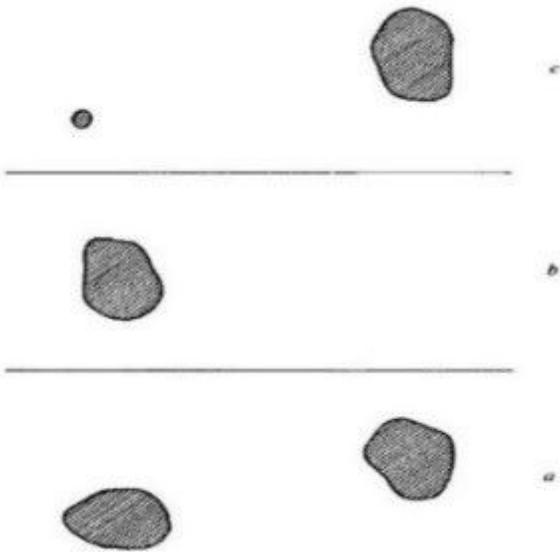


Figure 3

Representative cross section of a typical superconducting magnet (designs vary). Liquid helium chambers are green-blue.

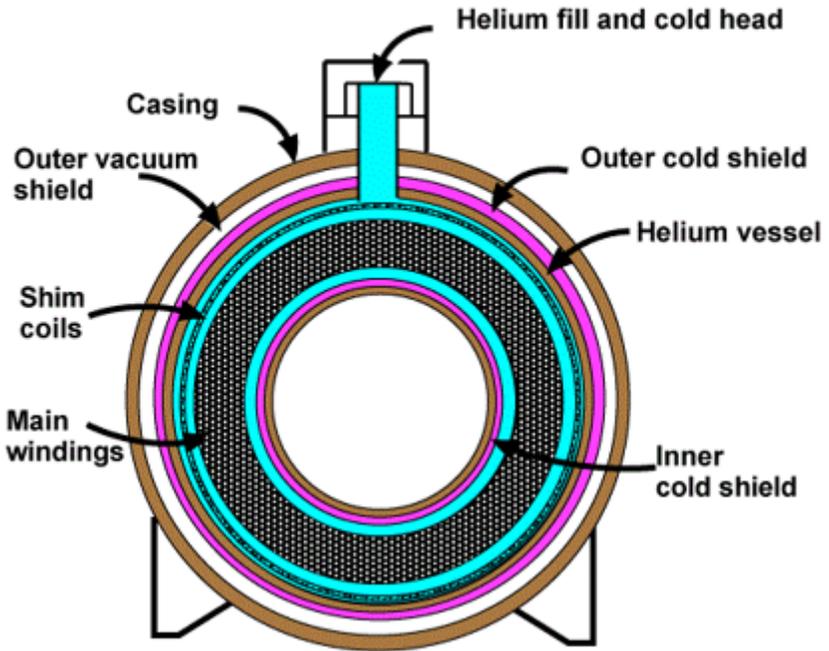


Figure 4

Representative cross section of a typical superconducting magnet (designs vary). Liquid helium chambers are green-blue.

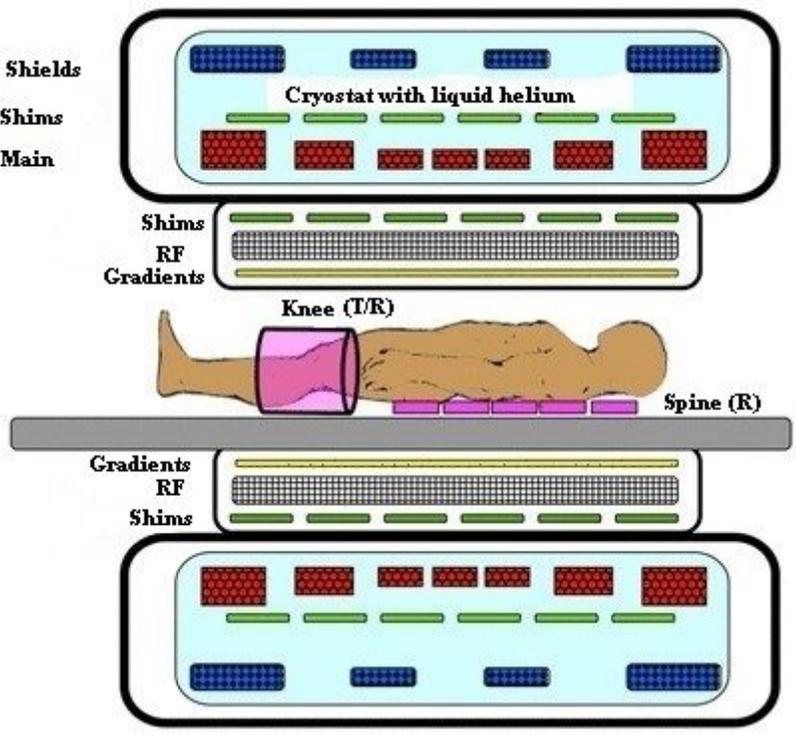


Figure 5

Representative cross-section of a superconducting scanner, showing the nested arrangement of “coils”. Both superconducting and resistive coils are shown. Two different types of patient coils are also illustrated: a spinal chain receiver only, and a knee carrier / receiver

CREATING REFINED ANATOMICAL IMAGES

Within the metallic cocoon of an MRI scanner, the patient is surrounded by four electromagnetic coils and the components of a transceiver

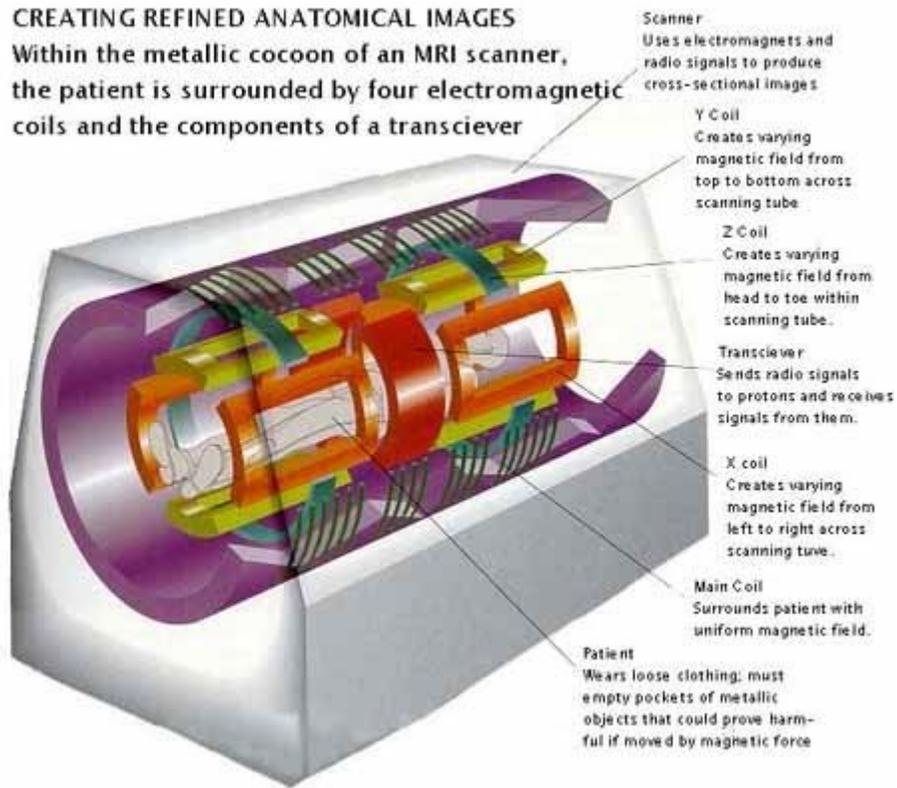


Figure 6

Representation of the principle realization of the MR scanner magnet

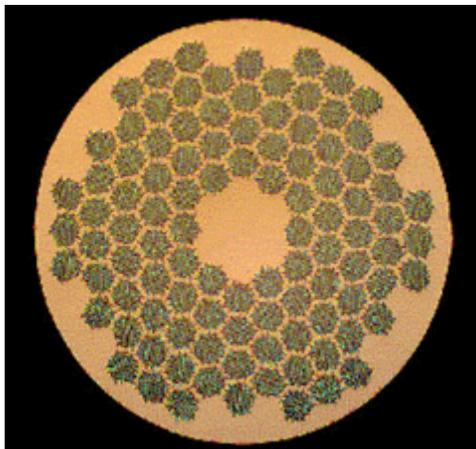


Figure 7

Cross section of the windings of a superconducting NbTi magnet with microsil fibers embeded in the Cu core.

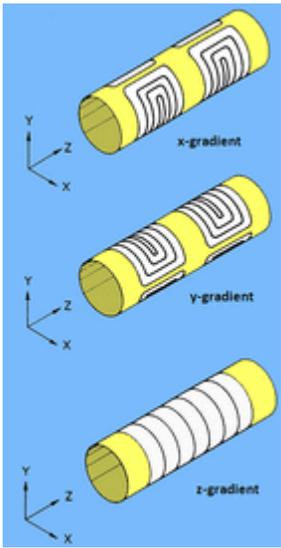


Figure 8

Gradient windings for the three basic directions Gradients x and y act only to create a “tilt” of the z-component B_0

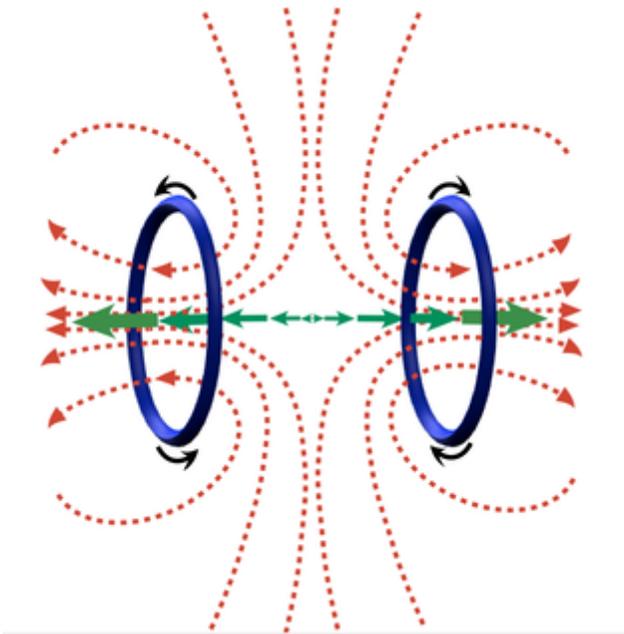


Figure 9

Magnetic field produced by z-windings. Currents flow through two loops in opposite directions (Helmholtz pair). The gradient field (large red arrows) is zero in the middle, but grows stronger in the $z+$ and $z-$ directions.

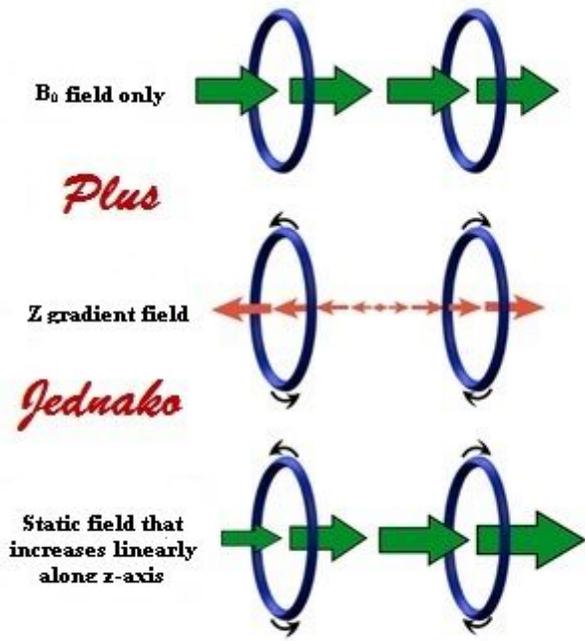


Figure 10

Diagram showing how the z-gradient field is added to the base field B_0 , to obtain a field that increases linearly from $-z$ to $+z$

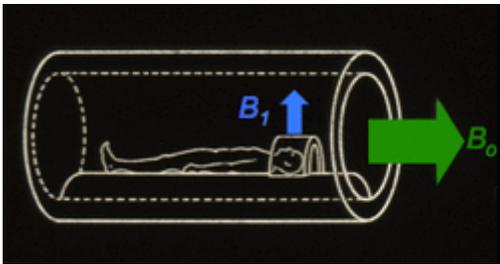


Figure 11

RF field B_1 is normal to B_0

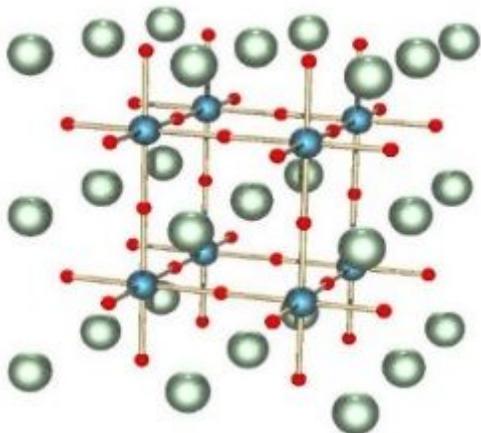


Figure 12

Perovskite structure with general chemical formula ABX_3 . The red spheres are X atoms (usually oxygen), the blue spheres are B atoms (smaller metal cations, such as Ti^{4+}), and the undistorted cubic structure; the symmetry is lowered to orthorhombic, tetragonal, or triangular in many perovskites

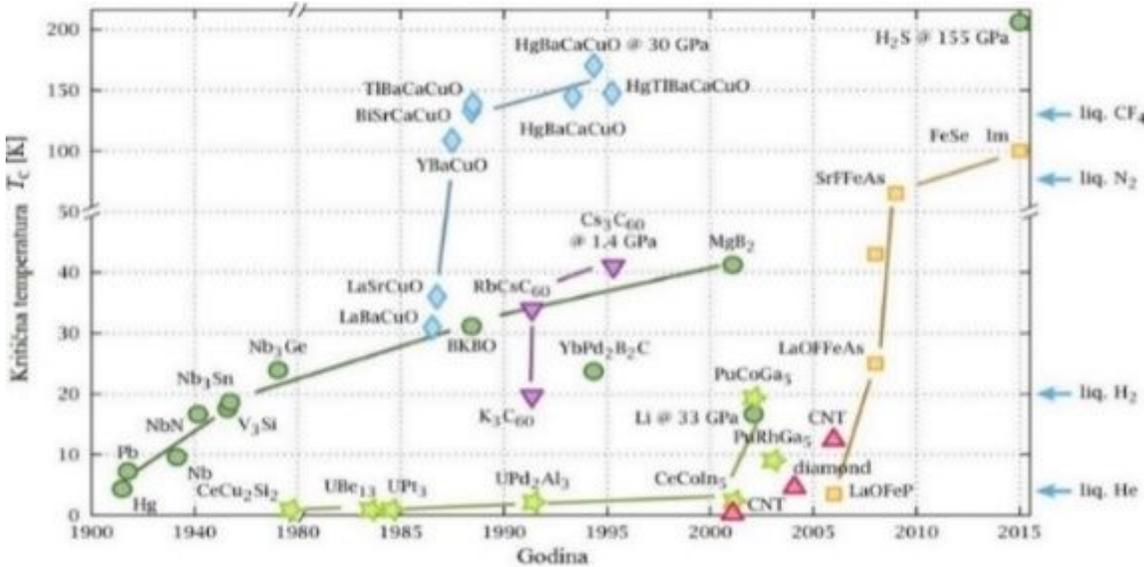


Figure 13

Superconductor timeline. BSC (Burden-Cooper-Schiffer) superconductors are shown as green circles, cuprates as blue diamonds, and iron-based superconductors as yellow squares