Superconductivity

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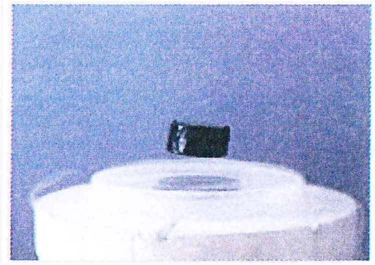


A magnet levitating above a high-temperature superconductor, cooled with liquid nitrogen. Persistent electric current flows on the surface of the superconductor, acting to exclude the magnetic field of the magnet (the Meissner effect). This current effectively forms an electromagnet that repels the magnet.

Superconductivity occurs in certain materials at very low temperatures. When superconductive, a material has an electrical resistance of exactly zero and no interior magnetic field (the Meissner effect). It was discovered by Heike Kamerlingh Onnes in 1911. Like ferromagnetism and atomic spectral lines, superconductivity is a quantum mechanical phenomenon. It cannot be understood simply as the idealization of "perfect conductivity" in classical physics.

The electrical resistivity of a metallic conductor decreases gradually as the temperature is lowered. However, in ordinary conductors such as copper and silver, this decrease is limited by impurities and other defects. Even near absolute zero, a real sample of copper shows some resistance. In a superconductor however, despite these imperfections, the resistance drops abruptly to zero when the material is cooled below its critical temperature. An electric current flowing in a loop of superconducting wire can persist indefinitely with no power source.[1]

Superconductivity occurs in many materials: simple elements like tin and aluminium, various metallic alloys and some heavily-doped semiconductors. Superconductivity does not occur in noble metals like gold and silver, nor in pure samples of ferromagnetic metals.

In 1986, it was discovered that some cuprate-perovskite ceramic materials have critical temperatures of more than 90 kelvin. These high-temperature superconductors renewed interest in the topic because the current theory could not explain them. From a practical perspective, 90 kelvin is easy to reach with the readily available liquid nitrogen (boiling point 77 kelvin). This means more experimentation and more commercial applications are feasible, especially if materials with even higher critical temperatures could be discovered.

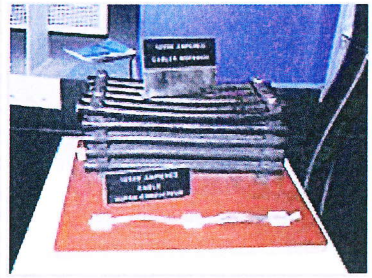
See also the history of superconductivity.

Elementary properties of superconductors

Most of the physical properties of superconductors vary from material to material, such as the heat capacity and the critical temperature, critical field, and critical current density at which superconductivity is destroyed.

On the other hand, there is a class of properties that are independent of the underlying material. For instance, all superconductors have *exactly* zero resistivity to low applied currents when there is no magnetic field present. The existence of these "universal" properties implies that superconductivity is a thermodynamic phase, and thus possesses certain distinguishing properties which are largely independent of microscopic details.

Zero electrical "dc" resistance


Electric cables for accelerators at CERN: top, regular cables for LEP; bottom, superconducting cables for the LHC.

The simplest method to measure the electrical resistance of a sample of some material is to place it in an electrical circuit in series with a current source I and measure the resulting voltage V across the sample. The resistance of the sample is given by Ohm's law as $R = V/I$. If the voltage is zero, this means that the resistance is zero and that the sample is in the superconducting state.

Superconductors are also able to maintain a current with no applied voltage whatsoever, a property exploited in superconducting electromagnets such as those found in MRI machines. Experiments have demonstrated that currents in superconducting coils can persist for years without any measurable degradation. Experimental evidence points to a current lifetime of at least 100,000 years. Theoretical estimates for the lifetime of a persistent current can exceed the estimated lifetime of the universe, depending on the wire geometry and the temperature. Thus, a superconductor does not have exactly zero resistance, however, the resistance is negligibly small.[1]

In a normal conductor, an electrical current may be visualized as a fluid of electrons moving across a heavy ionic lattice. The electrons are constantly colliding with the ions in the lattice, and during each collision some of the energy carried by the current is absorbed by the lattice and converted into heat, which is essentially the vibrational kinetic energy of the lattice ions. As a result, the energy carried by the current is constantly being dissipated. This is the phenomenon of electrical resistance.

The situation is different in a superconductor. In a conventional superconductor, the electronic fluid cannot be resolved into individual electrons. Instead, it consists of bound *pairs* of electrons known as Cooper pairs. This pairing is caused by an attractive force between electrons from the exchange of phonons. Due to quantum mechanics, the energy spectrum of this Cooper pair fluid possesses an *energy gap*, meaning there is a minimum amount of energy ΔE that must be supplied in order to excite the fluid. Therefore, if ΔE is larger than the thermal energy of the lattice, given by kT, where k is Boltzmann's constant and T is the temperature, the fluid will not be scattered by the lattice. The Cooper pair fluid is thus a superfluid, meaning it can flow without energy dissipation.

In a class of superconductors known as **Type II superconductors**, including all known **high-temperature superconductors**, an extremely small amount of resistivity appears at temperatures not too far below the nominal superconducting transition when an electrical current is applied in conjunction with a strong magnetic field, which may be caused by the electrical current. This is due to the motion of vortices in the electronic superfluid, which dissipates some of the energy carried by the current. If the current is sufficiently small, the vortices are stationary, and the resistivity vanishes. The resistance due to this effect is tiny compared with that of non-superconducting materials, but must be taken into account in sensitive experiments. However, as the temperature decreases far enough below the nominal superconducting transition, these vortices can become frozen into a disordered but stationary phase known as a "vortex glass". Below this vortex glass transition temperature, the resistance of the material becomes truly zero.

History of superconductivity

Main article: History of superconductivity

Superconductivity was discovered in 1911 by Heike Kamerlingh Onnes, who was studying the resistance of solid mercury at cryogenic temperatures using the recently-discovered liquid helium as a refrigerant. At the temperature of 4.2 K, he observed that the resistance abruptly disappeared.[10] In subsequent decades, superconductivity was found in several other materials. In 1913, lead was found to superconduct at 7 K, and in 1941 niobium nitride was found to superconduct at 16 K.

The next important step in understanding superconductivity occurred in 1933, when Meissner and Ochsenfeld discovered that superconductors expelled applied magnetic fields, a phenomenon which has come to be known as the Meissner effect.[11] In 1935, F. and H. London showed that the Meissner effect was a consequence of the minimization of the electromagnetic free energy carried by superconducting current.[12]

In 1950, the phenomenological Ginzburg-Landau theory of superconductivity was devised by Landau and Ginzburg.[13] This theory, which combined Landau's theory of second-order phase transitions with a Schrödinger-like wave equation, had great success in explaining the macroscopic properties of superconductors. In particular, Abrikosov showed that Ginzburg-Landau theory predicts the division of superconductors into the two categories now referred to as Type I and Type II. Abrikosov and Ginzburg were awarded the 2003 Nobel Prize for their work (Landau had received the 1962 Nobel Prize for other work, and died in 1968).

Also in 1950, Maxwell and Reynolds *et al.* found that the critical temperature of a superconductor depends on the isotopic mass of the constituent element.[14][15] This important discovery pointed to the electron-phonon interaction as the microscopic mechanism responsible for superconductivity.

The complete microscopic theory of superconductivity was finally proposed in 1957 by Bardeen, Cooper, and Schrieffer.[9] Independently, the superconductivity phenomenon was explained by Nikolay Bogolyubov. This BCS theory explained the superconducting current as a superfluid of Cooper pairs, pairs of electrons interacting through the exchange of phonons. For this work, the authors were awarded the Nobel Prize in 1972.

The BCS theory was set on a firmer footing in 1958, when Bogoliubov showed that the BCS wavefunction, which had originally been derived from a variational argument, could be obtained using a canonical transformation of the electronic Hamiltonian.[16] In 1959, Lev Gor'kov showed that the BCS theory reduced to the Ginzburg-Landau theory close to the critical temperature.[17]

In 1962, the first commercial superconducting wire, a niobium-titanium alloy, was developed by researchers at Westinghouse, allowing the construction of the first practical superconducting magnets. In the same year, Josephson made the important theoretical prediction that a supercurrent can flow between two pieces of superconductor separated by a thin layer of insulator.[18] This phenomenon, now called the Josephson effect, is exploited by superconducting devices such as SQUIDs. It is used in the most accurate available measurements of the magnetic flux quantum $\Phi_0 = \frac{h}{2e}$, and thus (coupled with the quantum Hall resistivity) for Planck's constant h. Josephson was awarded the Nobel Prize for this work in 1973.

In 2008 it was discovered by Valerii Vinokur and Tatyana Baturina that the same mechanism that produces superconductivity could produce a superinsulator state in some materials, with almost infinite electrical resistance.[19]

High temperature superconductivity

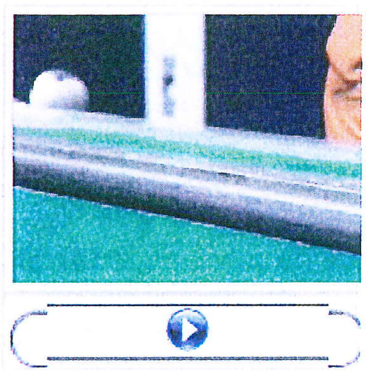
Until 1986, physicists had believed that BCS theory forbade superconductivity at temperatures above about 30 K. In that year, Bednorz and Müller discovered superconductivity in a lanthanum-based cuprate perovskite material, which had a transition temperature of 35 K (Nobel Prize in Physics, 1987).[20] It was shortly found that replacing the lanthanum with yttrium, i.e. making YBCO, raised the critical temperature to 92 K, which was important because liquid nitrogen could then be used as a refrigerant (at atmospheric pressure, the boiling point of nitrogen is 77 K)[21]. This is important commercially because liquid nitrogen can be produced cheaply on-site from air, and is not prone to some of the problems (for instance solid air plugs) of helium in piping. Many other cuprate superconductors have since been discovered, and the theory of superconductivity in these materials is one of the major outstanding challenges of theoretical condensed matter physics.

From about 1993, the highest temperature superconductor was a ceramic material consisting of thallium, mercury, copper, barium, calcium, and oxygen ($HgBa_2Ca_2Cu_3O_{8+\delta}$) with T_c=138 K.[22]

In February 2008, an iron-based family of high temperature superconductors was discovered.[23][24] Hideo Hosono, of the Tokyo Institute of Technology, and colleagues found lanthanum oxygen fluorine iron arsenide ($LaO_{1-x}F_xFeAs$), an oxypnictide that superconducts below 26 K. Replacing the lanthanum in $LaO_{1-x}F_xFeAs$ with samarium leads to superconductors that work at 55 K.[25]

Superconducting magnets are some of the most powerful electromagnets known. They are used in MRI and NMR machines, mass spectrometers, and the beam-steering magnets used in particle accelerators. They can also be used for magnetic separation, where weakly magnetic particles are extracted from a background of less or non-magnetic particles, as in the pigment industries.

Superconductors have also been used to make digital circuits (e.g. based on the rapid single flux quantum technology) and RF and microwave filters for mobile phone base stations.



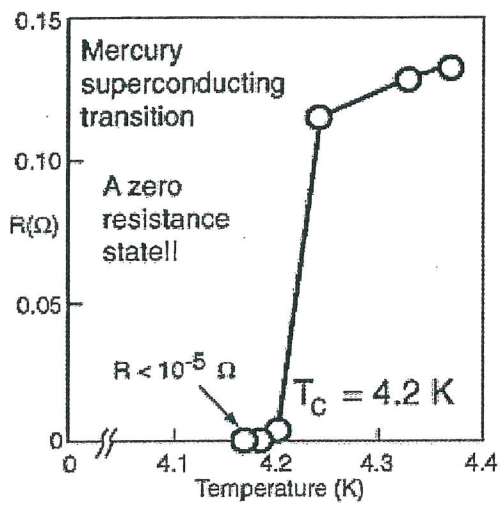
Video of superconducting levitation of YBCO

Superconductors are used to build Josephson junctions which are the building blocks of SQUIDs (superconducting quantum interference devices), the most sensitive magnetometers known. SQUIDs are used in scanning SQUID microscopes. Series of Josephson devices are used to define the SI volt. Depending on the particular mode of operation, a Josephson junction can be used as a photon detector or as a mixer. The large resistance change at the transition from the normal- to the superconducting state is used to build thermometers in cryogenic micro-calorimeter photon detectors.

Other early markets are arising where the relative efficiency, size and weight advantages of devices based on high-temperature superconductivity outweigh the additional costs involved.

Promising future applications include high-performance smart grid electric power transmission, transformers, power storage devices, electric motors (e.g. for vehicle propulsion, as in vactrains or maglev trains), magnetic levitation devices, fault current limiters, nanoscopic materials such as buckyballs, nanotubes, composite materials, and superconducting magnetic refrigeration. However, superconductivity is sensitive to moving magnetic fields so applications that use alternating current (e.g. transformers) will be more difficult to develop than those that rely upon direct current.

Mercury Superconducting Transition



Mercury was historically the first to show superconductivity, and it is an example of a Type I superconductor. Its practical usefulness is limited by the fact that its critical magnetic field is only 0.019 T, so the amount of electric current it can carry is also limited.

- [x] Mercury, $T_c = 4.2$ K
- [ ] Nb_3Sn, $T_c = 18$ K
- [ ] LaBaCuO, $T_c = 30$ K
- [ ] YBaCuO, $T_c = 92$ K

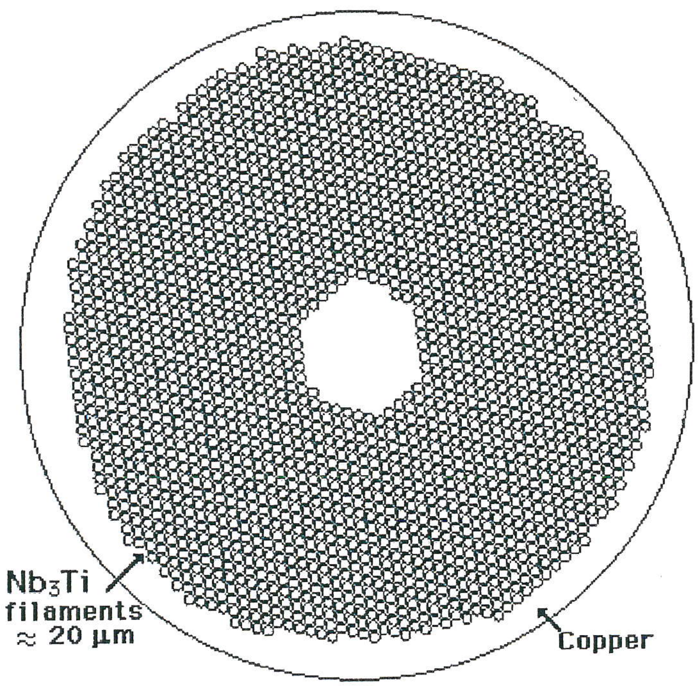
Superconducting Magnets

Type II superconductors such as niobium-tin and niobium-titanium are used to make the coil windings for superconducting magnets. These two materials can be fabricated into wires and can withstand high magnetic fields. Typical construction of the coils is to embed a large number of fine filaments (20 micrometers diameter) in a copper matrix. The solid copper gives mechanical stability and provides a path for the large currents in case the superconducting state is lost. These superconducting magnets must be cooled with liquid helium. Superconducting magnets can use solenoid geometries as do ordinary electromagnets.

Most high energy accelerators now use superconducting magnets. The proton accelerator at Fermilab uses 774 superconducting magnets in a ring of circumference 6.2 kilometers. They have also found wide application in the construction of magnetic resonance imaging (MRI) apparatus for medical imaging.

Niobium-Titanium Superconductor

Niobium-titanium is a Type-II superconductor with a critical temperature of 10 K and a critical magnetic field of 15 Tesla. While both of these values are lower than those for niobium-tin, this material has become the material of choice for superconducting magnets because of its mechanical properties.



Superconducting Magnet Wire of Niobium-Titanium

Ohanian's Physics has a photograph of a cross- section of copper wire of diameter 0.7 mm with 2100 filaments of niobium-titanium embedded in it. This is an approximate sketch of the geometry. Although copper is one of the best room-temperature conductors, it acts almost as an insulator between the strands.

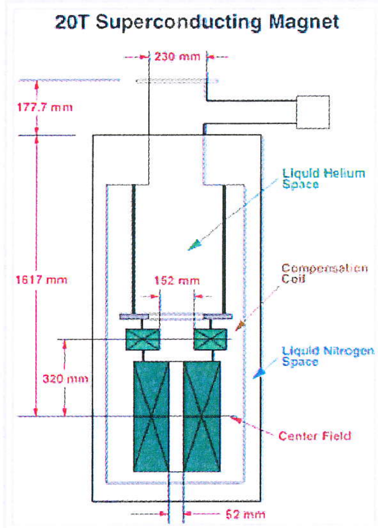
Superconducting magnet

From Wikipedia, the free encyclopedia

A **superconducting magnet** is an electromagnet that is built using coils of superconducting wire. They must be cooled to cryogenic temperatures during operation. Their advantages are that they can produce stronger magnetic fields than ordinary iron-core electromagnets, and can be cheaper to operate, since no power is lost to ohmic resistance in the windings.

Construction

Cooling



Schematic of a 20 tesla superconducting magnet with vertical bore

During operation, the magnet windings must be cooled below their critical temperature; the temperature at which the winding material changes from the normal resistive state and becomes a superconductor. Liquid helium is used as a coolant for most superconductive windings, even those with critical temperatures far above its boiling point of 4.2 K. This is because the lower the temperature, the better superconductive windings work - the higher the currents and magnetic fields they can stand without returning to their nonsuperconductive state. The magnet and coolant are contained in a thermally insulated container (dewar) called a cryostat. To keep the helium from boiling away, the cryostat is usually constructed with an outer jacket containing (significantly cheaper) liquid nitrogen at 77 K. One of the goals of the search for high temperature superconductors is to build magnets that can be cooled by liquid nitrogen alone. At temperatures above about 20 K cooling can be achieved without boiling off cryogenic liquids.

Materials

The maximum magnetic field achievable in a superconducting magnet is limited by the field at which the winding material ceases to be superconducting, its 'critical field', H_c, which for type-II superconductors is its upper critical field. Another limiting factor is the 'critical current', I_c at which the winding material also ceases to be superconducting. Advances in magnets have focused on creating better winding materials.

The superconducting portions of most current magnets are composed of niobium-titanium.[1] This material has critical temperature of 10 kelvin and remains in this state until about 15 teslas. More expensive magnets can be made of niobium-tin (Nb_3Sn). These have a T_c of 18 K. When operating at 4.2 K they are able to withstand a much higher magnetic field intensity, up to 25 to 30 teslas. Unfortunately, it is far more difficult to make the required filaments from this material. This is why sometimes a combination of Nb_3Sn for the high field sections and Nb_3Ti for the lower field sections is used.

High temperature superconductors (eg. BSCCO or YBCO) may be used for high-field inserts when magnetic fields are required which are higher than Nb_3Sn can manage. BSCCO, YBCO or magnesium diboride may also be used for current leads, conducting high currents from room temperature into the cold magnet without an accompanying large heat leak from resistive leads.

Coil windings

The coil windings of a superconducting magnet are made of wires or tapes of Type II superconductors (e.g.niobium-titanium or niobium-tin). The wire or tape itself may be made of tiny filaments (about 20 micrometers thick) of superconductor in a copper matrix. The copper is needed to add mechanical stability, and to provide a low resistance path for the large currents in case the temperature rises above T_c or the current rises above I_c and superconductivity is lost. These filaments need to be this small because in this type of superconductor the current only flows skin-deep. The coil must be carefully designed to withstand (or counteract) magnetic pressure and Lorentz forces that could otherwise cause wire fracture or crushing of insulation between adjacent turns.

Operation

Power supply

The current to the coil windings is provided by a high current, very low voltage DC power supply, since in steady state the only voltage across the magnet is due to the resistance of the feeder wires. Any change to the current through the magnet must be done very slowly, first because electrically the magnet is a large inductor and an abrupt current change will result in a large voltage spike across the windings, and more importantly because fast changes in current can cause eddy currents and mechanical stresses in the windings that can precipitate a quench (see below). So the power supply is usually microprocessor-controlled, programmed to accomplish current changes in gentle ramps. It usually takes several minutes to energize or deenergize a laboratory sized magnet.

7 T horizontal bore superconducting magnet, part of a mass spectrometer. The magnet itself is inside the cylindrical cryostat.

Persistent mode

An alternate operating mode, once the magnet has been energized, is to short-circuit the windings with a piece of superconductor. The windings become a closed superconducting loop, the power supply can be turned off, and persistent currents will flow for months, preserving the magnetic field. The advantage of this *persistent mode* is that stability of the magnetic field is better than is achievable with the best power supplies, and no energy is needed to power the windings. The short circuit is made by a 'persistent switch', a piece of superconductor inside the magnet connected across the winding ends, attached to a small heater. In normal mode, the switch wire is heated above its transition temperature, so it is resistive. Since the winding itself has no resistance, no current flows through the switch wire. To go to persistent mode, the current is adjusted until the desired magnetic field is obtained, then the heater is turned off. The persistent switch cools to its superconducting temperature, short circuiting the windings. The current and the magnetic field will not actually persist forever, but will decay slowly according to a normal L/R time constant:

$$H = H_0 e^{-(R/L)t}$$

where R is a small residual resistance in the superconducting windings due to joints or a phenomenon called flux motion resistance. Nearly all commercial superconducting magnets are equipped with persistent switches.

Magnet quench

A quench is an abnormal termination of magnet operation that occurs when part of the superconducting coil enters the normal (resistive) state. This can be because the field inside the magnet is too great, the rate of change of field is too great (causing eddy currents and resultant heating in the copper support matrix), or a combination of the two. More rarely a defect in the magnet can cause a quench. When this happens, that particular spot is subject to rapid Joule heating, which raises the temperature of the surrounding regions. This pushes these into the normal state as well, which leads to more heating in a chain reaction. The entire magnet rapidly becomes normal (this can take several seconds, depending on the size of the superconducting coil). This is accompanied by a loud bang as the energy in the magnetic field is converted to heat, and rapid boil-off of the cryogenic fluid. The abrupt decrease of current can result in kilovolt inductive voltage spikes and arcing. Permanent damage to the magnet is rare, but components can be damaged by localised heating or large mechanical forces. Practical magnets usually have safety devices to remove the current or limit it when the beginning of a quench is detected. If a large magnet undergoes a quench, the inert vapor formed by the evaporating cryogenic fluid can present a significant asphyxiation hazard to operators by displacing breathable air. A large section of the superconducting magnets in CERN's Large Hadron Collider unexpectedly quenched during start-up operations in 2008, necessitating a replacement of a number of magnets.[2]

History

Although the idea of making electromagnets with superconducting wire was proposed by Heike Kamerlingh Onnes shortly after he discovered superconductivity in 1911, a practical superconducting electromagnet had to await the discovery of type-II superconductors that could stand high magnetic fields. The first successful superconducting magnet was built by George Yntema in 1954 using niobium wire and achieved a field of 0.71 T at 4.2 K.[3] Widespread interest was sparked by Kunzler's 1961 discovery of the advantages of niobium-tin as a high H_c, high current winding material.[4]

In 1986, the discovery of high temperature superconductors by Georg Bednorz and Karl Muller energized the field, raising the possibility of magnets that could by cooled by liquid nitrogen instead of the more difficult to work with helium.

In 2007 a magnet with windings of YBCO achieved a world record field of 26.8 teslas.[5] The US National Research Council has a goal of creating a 30 tesla superconducting magnet.

Uses

Superconducting magnets have a number of advantages over resistive electromagnets. They can achieve an order of magnitude stronger field than ordinary ferromagnetic-core electromagnets, which are limited to fields of around 2 T. The field is generally more stable, resulting in less noisy measurements. They can be smaller, and the area at the center of the magnet where the field is created is empty rather than being occupied by an iron core. Most importantly, for large magnets they can consume much less power. In the persistent state (above), the only power the magnet consumes is that needed for any refrigeration equipment to preserve the cryogenic temperature. Higher fields, however can be achieved with special cooled resistive electromagnets, as superconducting coils will enter the normal (non-superconducting) state (see quench, above) at high fields.

Superconducting magnets are widely used in MRI machines, NMR equipment, mass spectrometers, magnetic separation processes, and particle accelerators.

One of the most challenging use of SC magnets is in the LHC particle accelerator [6]. The niobium-titanium (Nb-Ti) magnets will operate at 1.9 K to allow them to run safely at 8.3 T. Each magnet will store 7 MJ. In total the magnets will store 10.4 GJ. Once or twice a day, as the protons are accelerated from 450 GeV to 7 TeV, the field of the superconducting bending magnets will be increased from 0.54 T to 8.3 T.

The central solenoid and toroidal field superconducting magnets designed for the ITER fusion reactor use niobium-tin (Nb_3Sn) as a superconductor. The Central Solenoid coil will carry 46 kA and produce a field of 13.5 teslas. The 18 Toroidal Field coils at max field of 11.8 T will store 41 GJ (total?). They have been tested at a record 80 kA. Other lower field ITER magnets (PF and CC) will use niobium-titanium. Most of the ITER magnets will have their field varied many times per hour.

See also

- Fault current limiter
- Flux pumping

References

1. ^ "Characteristics of Superconducting Magnets (http://www.americanmagnetics.com/tutorial/charactr.html) ". *Superconductivity Basics*. American Magnetics Inc. website (http://americanmagnetics.com/magapps.php) . 2008. http://www.americanmagnetics.com/tutorial/charactr.html. Retrieved 2008-10-11.
2. ^ "Interim Summary Report on the Analysis of the 19 September 2008 Incident at the LHC (https://edms.cern.ch/file/973073/1/Report_on_080919_incident_at_LHC__2_.pdf) " (PDF). CERN.