The Potential Superconducting Materials in MRI Scanner— Comparison between NbTi and MgB_2

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Abstract. Although the technology used in commercial MRI scanners is in a very mature state, there are still many reasons for researchers to keep exploring how it can be optimized, such as the pursuit of higher image quality and greater patient comfort while keeping costs low. Changing the material of the superconducting magnets in MRI scanners is one of these ways. Currently, NbTi is the most commonly used superconducting magnet in MRI scanners, while in situ MgB_2 is one of the hottest candidates for MRI superconductors. This paper presents the advantages of NbTi being able to be realistically installed in MRI scanners for many years and also analyzes the match of in situ MgB_2 to various requirements of superconducting magnets in MRI scanners. The comparison shows that it is still NbTi that is more advantageous in recent years to come. MgB_2, on the other hand, does almost match the requirements of commercial MRI scanners, if cost is not considered. However, this does not mean that MgB_2 can be installed in commercial MRI scanners, and a lot of technical modifications and developments are still needed to adapt MgB_2 to commercial MRI scanners before that.

Keywords: Superconductor, MRI scanner, NbTi, MgB_2.

1. Introduction

1.1. The History and Classification of Superconductors

The concept of superconductors (SC) was introduced by the discovery of a material with no resistance in an experiment in which researchers found that liquid mercury had zero resistance below 4.2 K [1]. After the discovery of the superconductivity of mercury, researchers began to study superconducting materials. Table 1 shows some types of SC and their transition temperature.

Table 1. Various types of SC and transition temperature Tc [1]

Type of SC	Substance	T_c (K)
Simple metal SC	Al	1.17
	Sn	3.72
	Pb	7.20
	Nb	9.25
A15 SC	Nb_3Sn	18.0
	Nb_3Ge	23.2
Fullerene SC	$C_{60}Rb_3$	31
Cuprate SC	$La_{2-x}Sr_xCuO_4$	38
	$Tl_2Ba_2Ca_2Cu_3O_{10}$	125
	$HgBa_2Ca_2Cu_3O_8$	135
Magnesium diboride SC	MgB_2	39
Iron-based SC	FeSe	8
	$Sr_{0.5}Sm_{0.5}FeAsF$	56

One of the most well-known ideas is the BCS Theory, and the superconductors that the BCS Theory could explain are known as conventional superconductors while the others are known as non-conventional superconductors. However, the BCS Theory can only explain the existence of the I type of superconductors, whose superconducting state would be broke if the applied magnetic field breaks through the critical magnetic field Hc. The existence of the II type of superconductors had been foretold by the GL Theory. Comparing with the I type of superconductors, the II type of superconductors have two Hc, and the superconductors allow part of the magnetic field penetrate it. Among the superconductors that has been discovered, most of the elemental superconductors are the I type (except vanadium, niobium and technetium), and majority of alloy superconductors and compound superconductors are belong to the II type.

In addition to the above three classifications, the classification according to the value of Tc is also widely used. Superconductors with a Tc above the boiling point of liquid nitrogen (77 K) are called high temperature superconductors (HTS) and those below 77 K are defined as low temperature superconductors (LTS). in 1986, cuprate high temperature superconductors were discovered, which is known as the second revolution in the field of superconductivity. Ever since superconductivity was discovered, there have been high hopes for its potential, such as maglev trains, superconducting magnets and generators. Table 2 provides a summary of the uses of cuprate high-temperature superconductors. The variety of applications for superconductors expanded with the discovery of HTS.

Table 2. High-Temperature Superconductors [1]

Electronics	Basic Research	Medical Technique	Microwave Technique	Power Engineering	Traffic Engineering
Sensors	High-Field Magnets	SQUID Diagnostics	Filters	Generators	Magnetic Transport Systems
Supercomputers	SQUID Sensors	Magnetic Resonance Imaging (MRI)	Antenna	Motors	Ship's Engines
Cryoelectronic Components	Bolometers		Resonators	Transformers	Maglev Trains
	Particle Detectors		Delay Lines	Current Limiters	
			Active Components	Switchers	
				Cables Energy Storages	

It still takes a while to find the right superconducting materials for various devices and applications, despite the fact that many materials with superconducting properties have been discovered. These conditions include high critical temperature Tc, high critical current density jc, high critical magnetic field Hc, stable mechanical properties and low cost of production, so it still takes quite a long time to find suitable superconducting materials for different applications and devices.

1.2. MRI

One of the most important diagnostic techniques in medicine is magnetic resonance imaging (MRI), which is also the only one capable of chemically sensitive in vivo imaging and high resolution soft tissue contrast. This means it can provide relevant images of soft tissues and organs to help doctors identify lesions.

More than 70% of MRI scanners installed worldwide use superconducting magnets and approximately 75% of MRI scanners installed each year use superconducting systems [2]. The maximum patient throughput, the quickest scan times, and high signal-to-noise ratios are only a few benefits of superconducting MRI systems. Researchers have been working hard for this, for example for high resolution, high efficiency and high signal-to-noise ratio. The mainstream approach is to use high-intensity gradient coils to improve image quality and reduce scan time, but this means that it requires additional space for efficient and expensive cooling equipment. More and more high magnetic field systems are being used, which means that the central field (B0) is being increased in these systems. While 1.5T scanners were the clinical standard in the past, 3T scanners are currently gaining ground and may eventually hold 25% of the market [3]. However, as all aspects are upgraded, MRI scanners as mass-produced commodities also need to control costs. This is why the search for more suitable superconducting materials for superconducting MRI scanners is an ongoing effort by researchers. In the following, two commonly used superconducting materials for scanners will be described.

2. NbTi

NbTi is currently the dominant material for superconducting magnets in MRI scanners. Approximately, 2500 t of NbTi superconducting wires (wire-in-channel, WIC wire) are consumed by MRI each year [4].

The coils of the superconducting magnets are wound from a fine wire of NbTi alloy. In order to produce a wire with high critical current density, the filamentary microstructure of NbTi must be a two-phase nanostructure after finishing processing. NbTi superconducting wires must also be composed of multi-filaments and fine filaments in order to minimize losses brought on by hysteresis and eddy currents in the conductor [4]. In order to investigate what formulation would allow this fine wire to be produced at low cost and on a large scale, the researchers conducted several comparative tests. The first variable was the ratio of copper to NbTi alloy, then different extrusion techniques were used, such as warm hydrostatic extrusion and short time intermediate heat treatments, to find a way to slow down the intermetallic formation without the need for diffusion barriers. Finally, there is the use of different assembly methods to achieve the goal of assembling large numbers of filaments together. The first is the stacking of more than four thousand copper-clad monofilament NbTi rods. This single method allows for a uniform environment for the filaments and secondly, the yield is increased due to less loss during extension. The second is the 5914 series and Hydrostatic series billets, which are manufactured using the double stacking method [4]. With this method there are fewer components to handle during assembly and many filaments can be produced to very fine sizes (1 μm or less).

2.1. Stability, Cooling and Quench Protection

One of the key factors in LTS conductor design is conductor stability, which means limiting the range of potential frictional movement of the conductor and coil to a few microns. For example, structural support for stress is provided primarily by copper, so changing the ratio of NbTi to high purity copper can improve the stability of the coil.

LTS conductors have extremely low Ic and cooling them with liquid helium is a widely used method. In applications where LTS conductors are cooled by liquid nitrogen, the conductors are often subjected to extremely high currents, even at the limit of their current carrying capacity. In such circumstances, a very small quantity of heat can induce the wire to transition from a superconducting state to a normal state. Sometimes the heat can be removed by conduction of the wire and by absorption of liquid helium, allowing the wire to return to a superconducting state. However, there are also times when the region in the normal state expands along the conductor. In this case, the magnet needs to be de-energized quickly to avoid permanent damage to the magnet [5].

There are various techniques to simulate quenching, such as heating methods using fiber diode lasers [6, 7] and coupled electromagnetic-thermal models that concentrate on the heat exchange with liquid helium and its resulting effects [7, 8].

For example, in [8] an experiment was designed to analyze the quench development of NbTi in boiling liquid helium in order to evaluate the minimum energy (quench energy, QE) at which NbTi cannot recover the superconducting state when there is energy deposition, and to study the propagation speed of the normal zone (NZPV) for the purpose of designing magnets that operate safely at the highest current density. Fig. 1 shows the measured and computed QEs for NbTi wire.

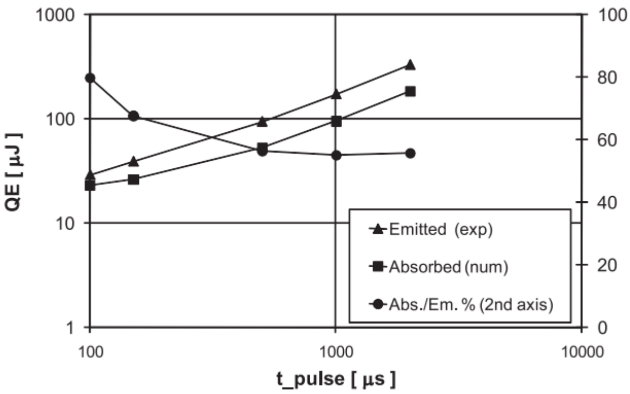

Figure 1. Measured and computed QEs for NbTi wire at 6 T, Iop = 85% IC, and different values of tpulse [8].

A commercial MRI scanner will equip the magnet with a monitoring system and an emergency system. The monitoring system is used to check important parameters, such as helium levels, and to record and report abnormalities. If necessary, the emergency system is equipped so that the heater can start a quench and swiftly discharge the magnet.

2.2. Insulation

Insulation materials are also an important part of magnet design. Insulation materials need to be low cost, high quality and compatible with other technologies used in magnets, such as cryogenics. Two types of insulation are generally used for commercial NbTi conductors. One is varnish, usually formvar, which is applied approximately 40 microns thick. Varnish is a low cost, high strength insulating material which has a breakdown voltage (BDV) greater than 3kV [9]. In the process of varnishing NbTi conductors, the conductors are briefly heated to over 400℃. During this process, the superconductivity of the wire must be ensured that it is not damaged or depleted. However, because Formvar is a low thermal class material with a grade of 105, any exposure above 130℃ may result in damage to the insulation [9]. During application and curing, epoxy resin can be used at temperatures below 120℃, whereas vacuum impregnated coils (VPI) are usually cured at temperatures around 200℃. Epoxy impregnated coils can therefore employ Formvar insulated conductors. However, varnish is not suitable for conductors with irregular and uneven cross sections, such as WIC conductors and HTS tapes with sharp corners, as the upper layer of deposited varnish can pose a challenge for the conductor.

The other is the polyester braided insulation commonly used for WIC conductors. Conductors with braided insulation can be used for dry-wound, wet-wound and VPI coils. However, unless epoxy resins with high thermal conductivity deeply permeate the braid, its high thermal resistance is harmful to non-low temperature magnets.

2.3. Cost and Magnet Maintenance

The diameter of the NbTi wire must be small enough to reduce losses in NBTi superconducting wires, which also necessitates a high degree of composition uniformity. Vacuum smelting technology was successful in producing high homogeneity NbTi alloys in the late 1970s [10], allowing for higher critical current densities and lower losses. Additionally, all raw materials for NbTi superconductors have good deformability, allowing for the production of long NbTi superconducting wires. The cost of making NbTi superconducting wire is minimal since the raw ingredients are easily accessible. Additionally, this NbTi superconductor exhibits high Cu/NbTi ratio, high residual resistance ratio (RRR), and high critical current [4]. This makes it highly reliable in MRI, with much slower performance degradation during magnet fabrication and operation, which also helps to reduce the cost of MRI. However, NbTi is a low temperature superconductor, which means that its cooling cost is higher than that of high temperature superconductors. Due to the usage of NbTi conductors, MRI is the largest consumer of helium in the world, using 20% of it [2].

Magnets in MRI scanners are a volume commercial product, so it is aimed at minimising costs in different ways. the multi-generational development and increasing capacity of Gifford-McMahon cryocoolers has led to liquid nitrogen no longer being used as a heat shielding coolant. The zero boiling point design (0BO) uses a helium recondenser, which is a significant increase in the helium recharge interval. The implementation of this design has significantly increased the helium recharge interval. The pulse tube cooler has less vibration and fewer moving parts.

The relationship between voltage (V) and current (I) on a superconductor can be described by (1).

$$\frac{V}{V_c} = \left(\frac{I}{I_c}\right)^n \tag{1}$$

where Vc is the voltage criterion, Ic is the critical current, and n is an important parameter of superconductivity, generally referred to as exponent n or n-value. N-value represents the uniformity of characterized superconductor [11]. The n-value of NbTi is usually over 40.

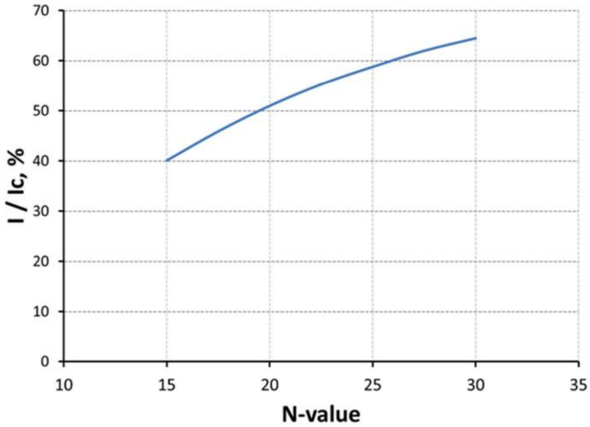

Figure 2. Operating current versus N-value [2]

2.4. Space and patient's experience

In modern whole-body (WB) MRI systems, the main magnet of the background field, the gradient system and the RF extracorporeal coil need to be crammed into the same annular space, which limits patient comfort and accommodation [3]. The patient bore is around 60cm in commercial MRI scanners.

3. MgB_2

MgB_2 is a kind of HTS. The application of HTS in MRI magnets has been a widespread concern in the MRI community.

The critical temperature of MgB_2 is 39 K, which is higher than that of NbTi. The MgB_2 sample selected for this comparison was from Hyper Tech Research Inc. Based on MgB_2, Hyper Tech has designed a new product named "1811 Nb/Cu/Monel" superconductor wire. They use a process called continuous tube filling and forming (CTFF) to make MgB_2 superconductors. Hyper Tech uses an in situ process to make MgB_2 superconductor wires, in which magnesium and boron powders are added directly to a metal tube, which is then stretched and heated. During the heating process, the magnesium and boron react to form MgB_2.

3.1. Stability, Cooling and Quench Protection

Because of the rapidly increased enthalpy and temperature margins, HTS has a high minimum quench energy, meaning that it can be site warm during transport and there is no concern for premature quenching.

Forced magnet quenching is a common method of rapid cooling, allowing the vast majority of the stored energy to be released into the cryostat. MgB_2, despite being extremely stable, has several properties that can make quench protection difficult, particularly in commercial systems where the average current density exceeds 100Amm-2 and the stored energy surpasses 0.5MJ [2]. very stable has aspects that can pose challenges for quench protection, especially for commercial configurations where the stored energy exceeds 0.5MJ and the average current density exceeds [2]. The normal region (the region where the temperature is above the critical temperature) extends very slowly, which makes the detection time of the quench device longer and may cause local quench overheating before the quench protection system can respond. The adiabatic MIIT criterion can be used to calculate the maximum value of the protection time, that is, the time before which the current must be reduced to 0.

$$\int_{T_0}^{T_{max}} CdT/\rho = \int_0^{t_0} J^2 dt \quad (2)$$

In (2), T_{max} and T_0 are the maximum and initial conductor temperatures that are permissible at the hot-spot location. C is the specific heat and ρ is the resistivity of the conductor. If the other components on the coil are not considered and the focus is only on the enthalpy of the conductor itself, then a theoretical value lower than the true value is obtained. The integral for the left side of the various materials is available in [12]. The integral is around 1015 Amp2_s m−4 for NbTi [2]. In contrast, the maximum quench time of MgB_2, if it is assumed that half of the cross-sectional area is occupied by low-resistance shunting materials, is 2.2s when J is equal to 150 Amp mm−2and it is 10 s when J is equal to 100 Amp mm−2 [2, 13].

In order not to degrade the conductor performance during quenching, the design should ensure that the conductor can operate under adiabatic conditions and at full current, and that the temperature does not exceed 100℃ operating twice to [14] presents a preliminary estimation method for to. In this respect MgB_2 does not yet meet the requirements to be put into manufacture, and passive quenching protection is not suitable for MgB_2 superconductors that are intended to be used in whole-body MRI scanners. Therefore, an external energy dump is performed using embedded leads and an external high voltage dump [3].

3.2. Insulation

MgB_2 is usually insulated with kapton tape. Although this tape can be used to insulate smaller magnets, it has a relatively low BDV, which means that the gaps that are inevitably created during the winding process can lead to electrical shorts or even damage to the magnet.

Uninsulated is also a viable option for quench protection of HTS with stored energy below 1 MJ [15]. However, it also has disadvantages. Such magnets require long ramp times and setting times, and are likely to shield the current and affect uniformity.

3.3. Cost and Magnet Maintenance

The n-value in HTS is typically less than 30 or even 20. from (1) it can be seen that if the n-value is reduced to half of its original value, it needs to operate at a current reduction of about 30%. Due to the wide variance in the magnetic field on the coil, it is impossible to predict the precise impact of n-value on the voltage rise and fall of the magnet and should be determined for each unique magnet and conductor arrangement. In the case of MgB_2 magnets, the influence of other factors, such as possible temperature variations, has to be added. Fig. 2 shows the relationship between operating current and critical current ratio and n-value. For example, if the n-value of a conductor is 15, the operating current should not exceed 40% of the critical current.

3.4. Space and patient's experience

In contrast, HTS materials are an advantageous technique for using unshielded gradient coils in MRI magnets. The elimination of gradient coil shielding allows MRI magnet coil fabricators to create a larger warm bore, reducing the potential for patient claustrophobia. There is also the option to change the warm bore size of the superconducting magnet to reduce cost while retaining the size of the patient's warm bore.

4. Conclusion

This overview assesses the advantages and disadvantages of NbTi and MgB_2 in terms of stability, hardening protection, insulation, cost, magnet maintenance and patient experience in becoming commercially available MRI scanners, and thus infers which of them has a better chance of dominating the MRI scanner market in the coming years.

NbTi is an established material for magnets in MRI scanners and has been used for many years, and this time he did not lose out to MgB_2, a popular candidate for MRI magnet material, even though MgB_2 as HTS does result in cost savings in terms of cooling compared to NbTi.

In terms of quench protection, the slower normal zone extension makes it a big challenge to overcome with quench protection technology.

MgB_2 also needs a suitable, high quality and low-cost insulating material and a Formvar type varnish would be a good choice.

NbTi is used in MRI magnets at a rate of 2,500t per year, and MgB_2 needs to be produced at a guaranteed rate of 100t per year if it is to be used in commercial MRI scanners so that the market can consider it as an alternative to NbTi. And a uniform production standard would have to be proposed so that different suppliers could produce MgB_2 superconductor wires of the same formulation and size.

MgB_2 is still a long way from true commercialisation and needs new ways of improving stability and reducing losses. This method needs to be simple, efficient and inexpensive. Nevertheless, superconductor suppliers also prefer superconductors that do not require processing.

Another important issue is that, even if MgB_2 meets all the requirements for commercialization, a new set of techniques will need to be invented to assemble MgB_2 with other materials and devices into magnets that can be assembled into MRI scanners. It may even be necessary to invent some new equipment; devices that can operate in NbTi superconductors that may not be suitable for working in MgB_2 superconductors, so the full set of equipment for NbTi cannot be directly transposed.

Finally, there is also the question of whether the market will accept MgB_2 as an MRI scanner for superconductors. How long a new system designed for MgB_2 will last, the cost of parts in the new system, service costs and installation costs are all issues that will be considered. So for the time being MgB_2 will not become a superconducting magnet in mainstream MRI scanners.

Future research may focus on solving the problems I mentioned above and making MgB_2 a conductor in more MRI scanners. It is also possible to discover or invent new superconducting magnets that are compatible with commercial MRI scanners.

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