Chapter 12

Superconductors for Medical Applications

S.S. Ali\(^1\)\(^*\) and M. Zulqarnain\(^2\)

\(^1\)School of Physical Sciences, University of the Punjab, Lahore 54590, Pakistan
\(^2\)Department of Physics, The University of Lahore, Lahore 54000, Pakistan

\[^*\] shahbaz.sps@pu.edu.pk

Abstract

Superconductivity plays a vital role in advanced medical diagnostic as well as in treatment of cancer. Smaller sized superconducting cyclotrons are developing as efficient techniques with carbon ions and protons for external beam therapy. This equipment further gives benefits of less cost and due to smaller size it is far easier to handle. Nowadays, superconductivity has been used commercially in numerous applications in medical sciences including low-temperature superconducting (LTS) materials and high field magnets in magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR), magnetic gene transfer, magnetic drug delivery system and cancer and internal hemorrhages detection. Almost all commercial medical systems based on superconductivity use LTS and the majority uses NbTi wires or superconducting quantum interference device (SQUID) made of LTS material.

Keywords

Magnetic Resonance Imaging (MRI), MRI based Food Inspection, Magnetic Gene Transfer, Magnetic Drug Delivery System (MDDS), Internal Hemorrhages Detection

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1. Introduction

In 1908, Kamerlingh Onnes’s successfully manifested the liquefaction of Helium, and this led to the demonstration of zero electrical current resistivity in 1911 and hence the discovery of superconductivity has been presented to the world. It was conceived that the resistive limits of copper can be surmounted, no matter what the amount of current is, to realize superconductors without having any ohmic losses. Although progresses have been carried out, however, small Hc1 and narrow Jc of primary superconductors inhibited the practical applications during that time. In 1960s the practical superconducting materials including NbTi and Nb3Sn have been made to support sufficiently high magnetic fields and currents. Furthermore, enough long wires have been manufactured that can be used in magnet winding which truly demonstrated the applied superconductivity [1].

Currently, out of total Gross Domestic Product (GDP) of United States, a considerable part represents the health care spending and this is further growing swiftly [2]. Although the mentioned cost regarding US is the biggest one around the globe, however even in other countries the health care spendings are going up which rigorously affects the economies of these nations.

The conventional attitude of disease treatment is reactive in which people wait until someone is sick before treating the disease with costly processes. As a result, large annual amounts have been spent on treatments and smaller amounts were used for identification and diagnosis. This attitude needed to be rectified to inhibit the big spendings on healthcare system. Therefore, it has been proposed by medical experts that full body medical check-ups should be carried out at least twice in a year to get prior information if some disease is developing in the body before it gets worsen [3].

Superconducting magnets are quite important regarding application point of view. They are being used extensively in MRI/NMR systems. Apart from these two major applications, these magnets are advantageous in magnetic separation to stimulate particles with weaker magnetic susceptibility in a medium of even smaller or non magnetic nature. In addition, superconductors are efficiently implemented in the systems for the medical processes including food inspection, magnetic drug delivery, magnetic gene transfer and cancer and internal haemorrhages detection [4].
2. Medical applications

2.1 Magnetic resonance imaging (MRI)

When a nucleus is positioned in an external magnetic field, it can absorb energy in the form of electromagnetic radiation of specific frequencies. This ability of nuclear magnetic resonance paves way towards the development of Magnetic Resonance Imaging (MRI) technology. The function of MRI is to provide the internal images of human body which further based on the distribution of hydrogen nuclei within a particular organ under observation.

In modern days MRI has become a dynamic diagnostic technique which provides accurate detection and information without putting any harmful effects due to presence of magnetic field on living cells in human body. With the advancement in technological aspects, a number of screening processes like cancer treatment, neurosurgical planning and angiography are being done comfortably through MRI which mainly includes for cancer treatment, angiography and neurosurgical planning [5,6].

Key parameter to get high resolution images is the stronger magnetic fields, that is why, a number of research teams around the globe struggling to get even stronger magnetic fields in MRI systems with ensured safety parameters. This field strength will eventually leads to the improved observation and diagnosis and hence will be helpful to better understand body compositions followed by even better treatment procedures [7].

2.1.1 Quench protection design of MRI superconducting magnet

MRI superconducting magnet of 9.4 T strength has been reported by S. Chen et al. having 800 mm diameter bigger bore. A five coaxial solenoid coils superconducting magnet has been developed with NbTi Wire-in-Channel (WIC) conductor keeping Cu to non Cu ratio from 5 to 10. Maintaining a larger level of stored energy (138 MJ), the magnet was designed to function at smaller current of about 224.5 A. To prevent the damage of magnet a protection method has been adopted. A set up of series combination of resistors and diodes through sectioned parts has been established. Quench has been enhanced through an active trigger heater. A detailed analysis based on this protection scheme has been performed with quench simulations of voltages, currents and temperatures [8].

Formation of 9.4 T magnet for MRI system is shown in figure 1 illustrating MC1, MC2, MC3, MC4 and MC5 as the main coils and CC1 through CC4 as compensation coils. In table 1, other relevant specifications of MRI magnet having field strength of 9.4 T are tabulated. A field strength of 9.4 T is produced by the superconducting magnet maintaining a uniformity of $5 \times 10^{-8}$ with a diameter of 220 mm in the diameter spherical volume. Stored energy and operation current of the magnet are 138 MJ and 224.5 A respectively [9-11].

In simulation results, it has been assumed that initially the quench takes place in coil MC1_1. Figure 2 illustrates the variations in current, hot-spot temperature and voltage. After a time interval of 2.5 seconds the compensations coils and after 3 seconds all coils have been heated to quench. Considering the safety levels, highest voltage and current
values of 277 V and 365 A respectively in CC2 and MC4_2, and the peak temperature of 98 K are all well below the safety levels during the quench. Owing to close thermal contact between heater strip and coil, the temperature of each heater strip is less and near to the hot-spot of coil. All these observations manifested a reliable model of quench protection for 9.4 T field strength magnet to be used in MRI systems [8].

![Design of MRI magnet having 9.4 T strength](image)

*Figure 1. Design of MRI magnet having 9.4 T strength [8].*

<table>
<thead>
<tr>
<th>Coil</th>
<th>Inner diameter (cm)</th>
<th>Outer diameter (cm)</th>
<th>Length (cm)</th>
<th>Current density (A/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC1</td>
<td>91</td>
<td>101.0</td>
<td>300</td>
<td>2155.5</td>
</tr>
<tr>
<td>MC2</td>
<td>103.8</td>
<td>113.8</td>
<td>300</td>
<td>2405.85</td>
</tr>
<tr>
<td>MC3</td>
<td>116.6</td>
<td>126.1</td>
<td>300</td>
<td>2429.3</td>
</tr>
<tr>
<td>MC4</td>
<td>129.1</td>
<td>138.9</td>
<td>300</td>
<td>3163.25</td>
</tr>
<tr>
<td>MC5</td>
<td>142.1</td>
<td>150.9</td>
<td>300</td>
<td>6964.07</td>
</tr>
<tr>
<td>CC1</td>
<td>152</td>
<td>155.2</td>
<td>59.3</td>
<td>12,130</td>
</tr>
<tr>
<td>CC2</td>
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<td>CC3</td>
<td>155</td>
<td>157.9</td>
<td>8.1</td>
<td>-12,136</td>
</tr>
<tr>
<td>CC4</td>
<td>155</td>
<td>157.9</td>
<td>8.1</td>
<td>-12,136</td>
</tr>
</tbody>
</table>
Figure 2. Current, hot-spot temperature and voltage curves during quench [8].
2.1.2 Open MRI superconducting magnet

In magnetic resonance imaging (MRI) systems the crucial part is the magnet, which ensures the creation of high quality images through its exposure on body organs [12,13]. Uniformity of magnetic and stray fields should be controlled. In an open MRI system there is significant gap between the two poles of superconducting magnet [14–17]. This gap causes considerable difficulties in handling the uniformity of magnetic field, the balance of electromagnetic force and the performance of superconducting wire as well. Apart from all these hindrances, there are a number of benefits of open MRI systems as compared to conventional systems. For instance, it significantly reduces the claustrophobia feeling of patient due to bigger bore for patient and comparatively smaller length [18]. It also gives liberty to move the patient for better adjustment against exposure ensuring better images.

The initial approximation of a magnet design is proceeded through linear optimization principle which is shown in figure 3 as a meshed magnet space. The current estimation of existing techniques are shown in figure 3 (b) [20-25]. Without cross sectional area, for each element the thick solenoid is designed as current loop [26]. The unidentified currents of the rectangular are found through linear optimization. A concentrated current is taken in to account in this technique to show the distributed current and avoiding the dimensional content. Therefore, it is to be put on a thick mesh on certain difficult designs, for instance the magnet with extremely small size. Fig. 3(c) represents a design procedure, in which \((z_1, z_2, r_1, r_2)\) represents coordinate of the solenoid [19].

For a planar magnet fig. 4(a) shows the magnet-space mesh of the cross-section, the structure supports are indicated by slashes. Due to regular design, just a quarter has been taken into account in design procedure [Fig. 4(b)]. The diameter and height of magnet coil in meters are 2.4 and 2.0 respectively. These dimensions are suitable for 2.0 T magnet.
scheme [27] and open MRI set up of 1.0 T. The magnet scheme is between two open systems for 1.5 T with exterior diameter bigger than 1.2 T and lesser than 2.0 T system [16,27]. As compared to 0.7 T open MRI design, the open bore has larger spacing of 0.72 m and diameter of 1.5 m [21].

![Magnet design space and Gradient assembly](image)

**Figure 4.** The mesh structure of the magnet-space: (a) the rectangular mesh for a full magnet model (b) a quarter of the full mesh model [19].

### 2.1.3 MRI food inspection system

Nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) with ultra low field (ULF) have attracted considerable attention due to its proposed compact size, easiness in handling and being inexpensive as compared to existing NMR/MRI systems [28-31]. SQUID can be employed as a detector of NMR signals at such a low frequency range due to efficient sensitivity without being influenced from frequency. Low temperature superconductor (LTS) SQUID has smaller magnetic noise as compared to that of HTS, however, still HTS SQUID has been used in a number of applications because of its merits including lower cost, compact size, better portability and user friendliness as well [32-35].

For the detection of contaminent in food and drink, utilizing an HTS-SQUID, Y. Hatsukade *et al.* developed an ULF nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) system. In detection procedure the protons in water samples have been polarized through a 1.1 T magnet. NMR signals have been measured for pure water and the one having impurities of aluminum, stainless steel and glass. Contaminant detection has been performed based on the fact that in the presence of SUS304 ball, the signal intensity was much smaller as compared to the intensity in the absence of contaminant owing to the remnant field. Non magnetic contaminants have been detected through one-dimensional (1D) MRIs. A change in position of contaminant causes corresponding change in 1D MRI spectra. Theses observations show the efficiency of the system for identification of contaminations in food items [36].
The ULF-NMR/MRI setup developed by Y. Hatsukade et al. is presented in Fig. 5. The major components of the system are cryostat, Helmholtz-type measurement coil, HTS-rf-SQUID, SQUID electronics, sample transfer apparatus, function generator and spectrum analyzer.

For measurements, a magnetic field of 45 μT and 56 nT/cm gradient field has been applied too. Fig. 6 (a-d) illustrates the MRI spectra of pure and contaminated water samples, where contaminants are (a) ceramic, (b) aluminum, (c) glass and (d) nylon. The MRI spectra of contaminated samples is altered around the frequency of about 1914 Hz unlike the analysis for pure water. The particular mentioned frequency corresponds to the location of the contaminants. The presence of contaminants influences the distribution of protons of water [36].

2.2 Magnetic gene transfer

Introduction of tumor suppression genes in carcinomatous lesion makes gene therapy an efficient tool for cancer treatment. In this technique gene carriers are inoculated in the body part affected by cancer, however the uptake ability is declined through DNA carriers diffusion. This depreciated uptake efficiency of cell after wide distribution and diffusion of DNA carriers is a problem to be addressed. One direct solution to this problem is to increase the contact probability of DNA with the tumor cell. This could be possible by putting some physical force on DNA carriers to get them concentrated in a localized region of interest and this in turn improve the effectiveness of gene transfer into the affected tissues.
Such investigation has been carried out by K. Nakagawa et al. considering the transmission of ferromagnetic DNA carriers. This diffusion has been realized in the presence of magnetic field with higher intensity produced by HTS magnet [37, 38].

Figure 6. Observations of 1D-MRI for (a) Just water, and water + ceramic (b) Water + aluminum ball (c) Water + glass ball (d) Water + nylon ball. Ball diameter = 5 mm [36].

Magnetic gene transfer has been analyzed using the ferromagnetic DNA carriers (Magnetite complexes). Suppressed particle diffusion has been analyzed up to 10 mm through simulated results at the cost of magnetic field. The outcomes of investigations revealed enhanced gene expression through magnetic field.

Aligning the target region with the central axis of magnet, the insertion of the particles was made at the bottom of the said region and based on this scheme the diffusion was calculated (Fig. 7). After 30 minutes of inoculation, the calculated results of horizontal distribution of particles are shown in Fig. 8. The particle distribution rate in the range of 1 cm was found 27% in the absence of magnet, however, 44%, 59% and 73% at 50 mm, 30
mm and 20 mm respectively above the magnet. As compared to the situation of without having a magnet, the concentration of carriers has been found 2.7 times larger in the case when the magnet was placed at 20 mm from the target [37].

Figure 7. *A representation of simulation model.*

Figure 8. *The estimated horizontal distribution of particle after 30 min of insertion.*

### 2.3 Magnetic drug delivery system

A scheme which is being used to control the distribution and circulation of the drug dose in the body as well as at the target (affected part or organ) is known as drug delivery system (DDS). The system can minimize the unsafe effects and enhances the medicinal effects. In order to ensure more efficiency than the DDS, a method called magnetic drug delivery
system (MDDS) has been employed in which magnetic forces are used to regulate the ferromagnetic drug to the target within a human body.

M. Chuzawa et al. reported the MDDS method to ensure the ferromagnetic drug so that its dose may concentrate at localized regions with the application of strong magnetic field provided by HTS magnets [39-46]. They attempted to alter the magnetic field, so that a uniform and intense field can be maintained in body to gather ferromagnetic drugs.

Figure 9 shows Magnet-rotating MDDS analyzing the confined concentration in a liver diseased part having around 10 mm of diameter. The spreading of magnetic field is presented in Fig. 10. The simulation has been performed while keeping a magnet circling around the capillary vessel. The coordinates have been selected such that its location within the vessel’s inlet remains exactly at the center. The three axes have been adjusted as: x along the blood flow, y is vertically downward and z is at 90° to both x and y axes [Fig. 10].

![Figure 9. Magnet-rotating MDDS illustration for a rat [47].](image)

The kinetics of ferromagnetic drugs inside the body have been analyzed through simulation in order to realize applied MDDS. It has been manifested that, it is possible to concentrate the ferromagnetic particles at the target region. Such analyses can be carried out in future investigations to further mature the procedure for the accumulation of drug particles at certain body parts. Furthermore, for the accuracy of the simulation outcomes, the model experiment can be performed by using a model organ [47].
2.4 Cancer and internal hemorrhage detection

Lorentz Force Electrical Impedance Tomography (LFEIT) is an advanced, portable, and easy to operate device which can be used for the detection of both cancer and internal hemorrhage [48-50]. As the value of the electrical impedance alters significantly in case of soft tissues as well as in pathological state so that is why LFEIT possesses excellent capability to provide pathological and physiological situation of body parts whereas ultrasonic imaging technology is unable to detect such affected tissues [51]. Apart from carcinomas, body tissues in the situation of hemorrhage or ischemia displays different permittivity and conductivity of body fluid and blood as compared to other soft tissues i.e. both exhibit different electrical properties [52]. An LFEIT arrangement is shown schematically in figure 11. LFEIT works on the principle of measurement of electrical signals emerging on the propagation of an ultrasound wave through condutive region, and the region is subjected perpendicularly to a magnetic field. This electrical signal has a direct relation with magnetic field intensity and ultrasound wave pressure [48].

A model of superconducting Halbach Array (HA) magnet consisting of 8 coils (90° phase change for each coil) and 12 coils (60° phase change for each coil) was presented by B. Shen et al. as shown in Fig. 12. Partial Differential Equation (PDE) model with 2D H-formulation, COMSOL Multiphysics has been utilized for the modelling of superconducting magnet. Multiple tapes having sheets of layered conductor have been illustrated by continuous area bulk approximation. These have been employed to enhance the speed of model simulation [53].

Fig. 13 (a,b) shows the loop for superconducting Halbach Array designs consisting of 8 and 12 HTS coils respectively. Coils’ stacks are denoted via bulk approximation. As manifested in Fig. 13, air is in the centre of the ring. Each coil contains a supply of 120 A direct current. Multiple coils can be used by Halbach Array configuration keeping the total
amount of superconductors same. This can be achieved through reduction of size of each coil and enhancing amount of coils from 8 to 12 [53].

Figure 11. Schematic representation of superconducting Lorentz Force Electrical Impedance Tomography (LFEIT).

Figure 12. Superconducting Halbach Array electromagnet with, (a) 8 and (b) 12, HTS coils.
Conclusions

Over the decades after their discovery, superconductors have been emerged as powerful and efficient materials for a number of commercial applications specifically including magnetic resonance imaging (MRI), nuclear magnetic resonance spectroscopy (NMR), magnetic drug delivery systems, magnetic gene transfer mechanism and their use in cancer treatments. With the passage of time superconductors find even more and more applications in field of medical devices. A number of research groups have investigated and still working to achieve critical temperatures as high as possible to get it closer and closer to room temperature. This of course will let the industry to get rid of helium and nitrogen based cryogenics for low and high temperature superconductors respectively. The overall high cost of HTS based applications is still the dominant factor to limit the widespread of technology. Supposedly, even if all the technical problems yet existing with HTS are resolved, still HTS based systems are quite expensive which inhibits their applicability in a number of poor of even developing countries. It is believed that prevalent use of HTS in medical sector would be possible if some new families of superconductors will be developed. Such room temperature superconductors will not depend on cryogenics making them less in cost, squeezed in size and more feasible regarding maintenance.

References

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