International Journal of Scientific Research and Engineering Development-– Volume 5 Issue 5, Sep- Oct 2022

Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Review on Applications of Superconducting Magnets in Medical Field

Gurunath*, Priyadarshinie**

* Department of Physics, Guru Nanak First Grade college, Bidar 585 403, Karnataka
Email:gurupanchal107@gmail.com.
** Department of Physics, Guru Nanak First Grade college, Bidar 585 403, Karnataka
Email:priyadarshinie.phy@gmail.com

--****************************----------------------------------

Abstract:

These superconducting magnets can be used in many fields for various applications in this Paper we have discussed about the medical applications of superconducting magnets, how they have been using in the different medical instruments and how that is going to work.

***Keywords*— Superconductivity, Superconducting Magnets, MRI, Cyclotron**

--****************************----------------------------------

I. INTRODUCTION:

After Kamerlingh Onnes's introducing exposition in 1908 that the last so-called "permanent gas" Helium could indeed be liquefied, his follow-up discovery of superconductivity in 1911 introduced the world to zero electrical current resistivity. It was speculated that one could go beyond the resistive limit of a copper wire to develop a superconductor that could convey any amount of current but without ohmic loss. Although strides were made with this theory, the small critical field Hc_1 and the limited current density Jc of early superconducting materials be in the way of practical applications in the early years. It wasn't until the 1960s—when practical superconducting materials that could support reasonably high magnetic fields and currents (such as NbTi and Nb3Sn) were discovered and wire lenghty enough for practical magnet winding were manufactured—that applied superconductivity was successfully implemented [1].This article will address the use of superconducting magnets in therapy and diagnostic applications.

II. SUPERCONDUCTING MAGNET FOR MRI

Magnetic Resonance Imaging (MRI) is entrenched on the concept of nuclear magnetic resonance, where an atomic nucleus placed in a magnetic field absorbs the energy of radio waves at a specific frequency. Building on the combination of radio frequency coils and main magnets, MRI provides images of the dissemination of hydrogen nuclei (protons) in the human body.

The imaging resolution is proportional to the field strength. The magnetic field strength of the MRI magnets currently and extensively used in clinical settings is 1.5 tesla. When this strength is significantly increased, observation of finer body structures and analysis of the body compositions of significantly smaller forms becomes possible . Since then, throughout the world MRI has become an essential medical tool to in vivo imaging, making it perhaps the greatest invention since the X-ray machine, which allowed the first diagnostic glimpse inside the human body. Unlike X-rays, which carry the risk of damaging human cells, MRI allows the physician to safely view the inside of the human body in 3D, with high-resolution, soft-tissue contrast and functional process and imaging.[2]

The conductor employed in nearly all modern superconducting MR scanners is niobium-titanium (NbTi) that set off superconductive below 9.4°K. Each wire is constitute of multiple NbTi microfilaments embedded in a copper core. The copper core has two functions:

1) To support and protect the fine microfilaments

2) To set out as a low resistance path for large currents in the event superconductivity is lost.

Scanners and spectrometers with field strengths greater than 10T frequently use a niobium-tin (Nb_3Sn) alloy. Magnesium diboride (MgB_2) is also come out as a new superconducting material for scanners and other magnetic instruments because of its much greater transition temperature (39°K).

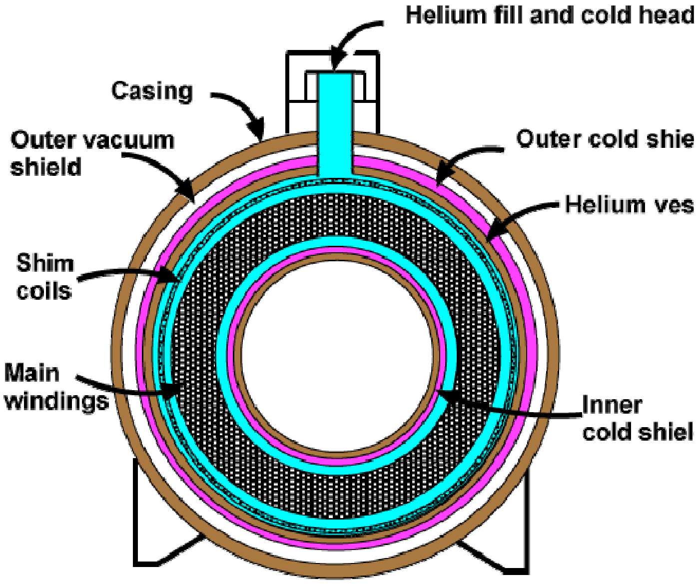

Fig 1: Representative cross-section of a typical superconducting magnet (designs vary). LIquid helium chambers are colored aqua. Active shielding coils (not pictured) are near the shim coils at the two scanner ends.

The wires are wound in contact with either a glass-reinforced polymer or aluminum former (cylinder) in layers set apart by epoxy and dividers. Rather than using a single continuous main field winding, homogeneity is ameliorated by breaking up the main coil into 6-10 separate windings with gaps.

The main magnet windings are dipped in liquid helium (4°K) in a structure called a cryostat. The cryostat is a multi-compartmental structure that functions like a Thermos bottle. It contains not only the main magnet windings and channels for liquid helium, but also numerous insulating and vacuum layers to thermally shield the coils from the warm external environment. The cryostat also commonly contains superconducting shim coils (to improve homogeneity) and active shielding coils (to minimize stray/fringe fields).

The external casing of the cryostat as well as the helium vessel inner and outer shells are commonly made of non-magnetic stainless steel. The walls of the vacuum chambers are build of either nonmagnetic stainless steel or glass-reinforced polymer. The cold shields are commonly 3-10 mm thick and made from a low emissivity/high thermal conductivity material such as aluminum. Because of global helium deficiency and increased expense, hawkers have developed new scanner designs that use only a small amount (~ 10 L) of liquid helium that is sealed into the scanner all along manufacturing and never needs to be refilled. The magnet coils sit in a vacuum alternately within a liquid helium bath. They are in contact with cooling tubes that circulate liquid helium from their small storage compartments. During ubrupt loss of superconductivity, no gaseous helium can escape. Thus these systems do not need a quench tube making them easier to site[3].

III. RING-SHAPED SUPERCONDUCTING PERMANENT MAGNET

At present, magnetic resonance imaging (MRI) is practically used in the diagnosis of oral and maxillofacial tumors [4] and temporomandibular joint diseases [5] in the department of stomatology. Moreover , it is found that MRI can also acquire clear images of tooth structures such as enamel, dentin, pulp and periodontal tissue; it can categorize carious lesions and micro-crack structures; it can also be used to assess decay, vitality and angiogenesis; detect early-stage periapical lesions; and categorize periapical periodontitis from cystic lesions [6]. Therefore, MRI can become a safe and sucessful auxiliary examination method in the research and clinical treatment of endodontics in the future. However, due to the high cost and the risk of carriage, it is currently difficult for MRI to be used in the stomatology department. In recent years, with the great development of high-temperature superconducting (HTS) technology, the ring-shaped superconducting magnet, with its advantages of possible size and high trapped field, has become a potential candidate for MRI systems. Portable MRI systems based on this technology can place the foundation for the improvement of the overall medical level of stomatology. The ring-shaped trapped field magnet, first proposed by G. A. Levin et al. in 2008 [7], was fabricated through spitting the HTS coated conductors, moulding them into a ring, and stacking them up. Its joint-free structure allows persistent current in the coils without decay and it can accounts a huge range of trapped field by flexibly adjusting the number of turns, with a recent record of 4.60 T trapped field by a double-stacked HTS ring-shaped magnet [8]. Thus, the ring-shaped magnet has been adopted in many industrial applications, including MRI [9–13], superconducting transformers [14], superconducting fault current limiters [15–17] and so on. Magnetization mechanisms and the structural optimization of ring-shaped magnets have been systematically investigated through numerical models and experiments. C. Rong et al. and D. Qiu et al. studied the characteristics of the trapped magnetic field, including relaxation of persistent current and magnetic field stability [18,19], while Vagner Santos da Cruz et al. discussed the voltage behavior of the ring-shaped magnet, classifying different magnetization stages by the magnitude of the induced current [20]. Jie Sheng et al. preliminarily introduced the cumulative effect of the trapped field under multi-pulse magnetization as well as the trapped field under demagnetization [21], and then proposed a hybrid magnet, which combines HTS stack tapes and a ring-shaped magnet to elevate the trapped field [22]. Seyeon Lee et al. proposed a new winding method, named as “Wind-and-Flip”, which cuts the superconducting tape into two parts, winding them as two coils and then flipping one of the coils so as to generate a magnetic field in the same direction [23]. Changxin Chi et al. compared the low-frequency magnetic field shielding effect of coils with different numbers of pancakes [24]. With 80 dB of shielding effectiveness it was shown that ring-shaped magnets could be further applied in precision instruments. Nevertheless, the unique electromagnetic characteristics of the ring-shaped magnet due to its asymmetric structure remain to be discussed.

The effect of pulse waveforms on the trapped field will be discussed, and the cumulative effect of the magnetic field under multi-pulse magnetization will be demonstrated by the circuit model. The current distribution of the multi-turn HTS ring-shaped magnet during the decay process has been studied and the working characteristics under different working situations have also been explored to provide a guideline for future magnet design.

Contrary to superconducting bulks, the induced current in superconducting ring-shaped magnets can only flow in the region where the superconducting layer is located. The traditional three-dimensional finite element modeling is quite complicated and the amount of calculation required is huge. However, because of the restricted induced current path, the magnetization process of the ring-shaped coil can be simulated by the field-circuit coupling method.

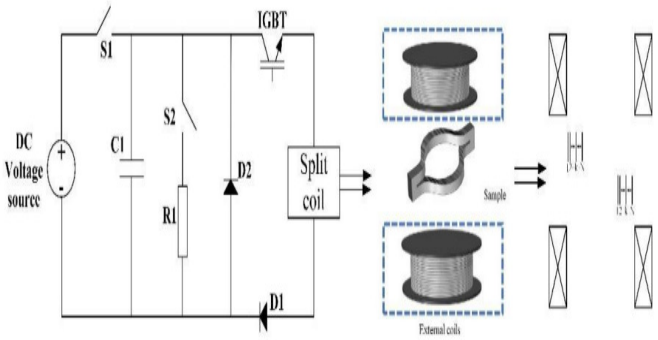

Figure 2. Geometry and magnetization system circuit for ring–shaped magnet.

IV. CYCLOTRONS FOR THERAPY

Isochronous cyclotrons work correctly when the magnetic field design is valid for a given ion and final energy. Since their introduction in the late 1950s, however, resistive-magnet-based cyclotrons designs have been challenged by the nonlinearity of the pole and return yoke steel. In a typical project, a succession of model magnets would be construct to validate and optimize the magnetic field configuration before the design of the actual machine could be concluded. It was realized in the early 1970s that, by substitution of the standard hollow copper conductor-based resistive coils in isochronous cyclotrons with superconducting coils having higher current density and substantially more ampere turns for a given size, the iron in the poles would saturate and become computationally linear [25]. This meant that for the first time one could design computationally an isochronous cyclotron, and build it with the supposition that it would work as designed. Quickly, it was shown that one had to make a choice between high bending strength and high flutter — the former yielding heavy ion machines and the latter leading to energetic proton machines [26]. The engineering superconductor of choice at that time being NbTi led immediately to cyclotrons in the 3–5 T range. The first of these was the variable energy K500 heavy ion cyclotron at MSU [27]. At 5 T, the K500 is roughly one-tenth the overall size and mass of an equivalent resistive-magnet-based cyclotron, and consumes roughly one-third the wall plug power, including the cryogenic systems. In addition to making the machines more compact, there were operational advantages to going superconducting: reduced thermal cycling, less magnet charging hysteresis, smaller/lower power RF systems, and wider tuning ranges in the variable energy machines. However, this came with new engineering challenges: complex cryostat designs, higher magnetic forces, handling cryogens and quench protection systems. But, once commissioned, these cyclotrons have lifetimes measured in decades; all have met their performance goals, and cryogen plants have been replaced by mechanical cryocoolers in the latest systems. The K500 produced its first extracted beam in 1982, and is still in routine operation at the present time at MSU. The emphasis here on the MSU K500 is not an accident. All of the superconducting cyclotron designs now being developed for cancer therapy share most of its overall features. An elegant configuration at the present time has the cyclotron closely coupled to the gantry, equipping beam to a single or just a pair of treatment rooms. This significantly reduces the cost of a therapy facility and is seen as a key to wider emplacement of proton therapy systems. The Mevion Monarch (superconducting synchrocyclotron), the Varian Medical Systems PROSCAN (superconducting isochronous), both in operation, and the upcoming IBA S2C2 (superconducting synchrocyclotron) are all based on this configuration. The Varian ProScan, first built by ACCEL, now a division of Varian Medical Systems in Germany, has also been installed in the until-now-standard multiroom configuration. But, before narrating these systems, the first superconducting machine to deliver therapeutic beams will be set out.

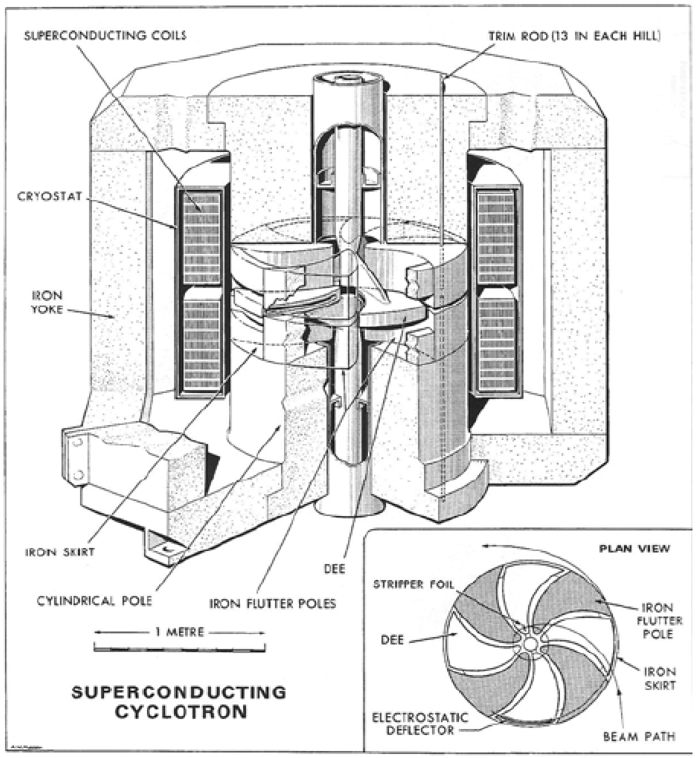

Fig 3: Superconducting Cyclotron design

V. CONCLUSION:

Superconductivity is certainly playing a crucial role in modern diagnostic imaging. In fact, MRI magnets are now the largest commercial application for superconducting material, and appear for a level of technological maturity that is truly remarkable. That so much stored energy, at cryogenic temperatures, can be safely installed and accepted in clinical environments is a concept which pioneers in the field would have believed optimistic, if not unthinkable. Building on this remarkable achievement, further developments are proceeding. Higher-field magnets will galvanize to continued improvements in image quality and, through novel techniques and high-precision imaging, will become powerful tools for unraveling the complexities of human diseases and abnormalities. Development of new materials that remain superconducting at higher temperatures and higher fields will further expand capabilities, and decrease the hardware and operations costs of units, bringing MRI within substantially greater universal reach for universal healthcare.

REFERENCES

[1] P. F. Dahl, Superconductivity: Its Historical Roots and Development from Mercury to the Ceramic Oxides, American Institute of Physics, New York, 1992, pp. 261-264.

[2] Magnetic Resonance Imaging Equipment: A Global Strategic Business Report. Global Industry Analysts, Inc.

[3] Superconducting Magnets design. https://mriquestions.com/superconductive-design.html

[4] Lam, P.; Auyeung, K.; Cheng, P.; Wei, W.I.; Yuen, A.P.-W.; Trendell-Smith, N.; Li, J.H.C.; Li, R. Correlating MRI and Histologic Tumor Thickness in the Assessment of Oral Tongue Cancer. Am. J. Roentgenol. 2004, 182, 803–808.

[5] Varol, A.; Sencimen, M.; Gulses, A.; Altug, H.A.; Dumlu, A.; Kurt, B. Diagnostic importance of MRI and CT scans for synovial osteochondromatosis of the temporomandibular joint. Cranio-J. Craniomandib. Pract. 2011, 29, 313–317.

[6] Olt, S.; Jakob, P.M. Contrast-enhanced dental MRI for visualization of the teeth and jaw. Magn. Reson. Med. Off. J. Soc. Magn. Reson. Med. 2004, 52, 174.

[7] Levin, G.A.; Barnes, P.N.; Murphy, J.; Brunke, L.; Long, J.D.; Horwath, J.; Turgut, Z. Persistent current in coils made out of second-generation high temperature superconductor wire. Appl. Phys. Lett. 2008, 93, 631.

[8] Ali, M.Z.; Zheng, J.; Huber, F.; Zhang, Z.; Yuan, W.; Zhang, M. 4.6 T generated by a high-temperature superconducting ring magnet. Supercond. Sci. Technol. 2020, 33, 04LT01.

[9] Kim, W.-S.; Lee, S.; Kim, Y.; Lee, J.Y.; Park, S.-H.; Lee, J.-K.; Hong, G.-W.; Han, J.; Choi, K. Persistent Current Mode of a 1-T-Class HTS Pancake Coil for NMR/MRI Applications. IEEE Trans. Appl. Supercond. 2015, 25, 1–4.

[10] Qu, T.; Michael, P.C.; Bascuñán, J.; Lécrevisse, T.; Guan, M.; Hahn, S.; Iwasa, Y. Test of an 8.66-T REBCO Insert Coil with Overbending Radial Build for a 1.3-GHz LTS/HTS NMR Magnet. IEEE Trans. Appl. Supercond. 2017, 27, 1–5.

[11] Qu, T.; Michael, P.C.; Voccio, J.; Bascunan, J.; Hahn, S.; Iwasa, Y. Persistent-current switch for pancake coils of rare earth-barium-copper-oxidehigh-temperature superconductor: Design and test results of a double-pancake coil operated in liquid nitrogen (77–65 K) and in solid nitrogen (60–57 K). Appl. Phys. Lett. 2016, 109, 4301205.

[12] Kosa, J.; Vajda, I.; Gyore, A. Application possibilities with continuous YBCO loops made of HTS wire. J. Phys. Conf. 2010, 234, 032030.

[13] Lee, H.-G.; Kim, J.-G.; Lee, S.-W.; Kim, W.-S.; Lee, S.-W.; Choi, K.-D.; Hong, G.-W.; Ko, T.-K. Design and fabrication of permanent mode magnet by using coated conductor. Physic C Supercond. 2006, 445, 1099–1102.

[14] Kosa, J.; Vajda, I. Novel 3-Phase Self-Limiting Transformer with Magnetic Flux Applied by Perfect Closed YBCO Wire Loops. IEEE Trans. Appl. Supercond. 2011, 21, 1388–1392. Crystals 2022, 12, 1438 12 of 12

[15] Kosa, J.; Vajda, I.; Gyore, A.; Kohari, Z. Fault current limiter with novel arrangement of perfect YBCO loops made of HTS wire. In Proceedings of the 14th International Power Electronics and Motion Control

Conference EPE-PEMC 2010, Ohrid, Macedonia, 6–8 September 2010

[16] Chen, X.; Zhang, M.; Chen, Y.; Jiang, S.; Gou, H.; Lei, Y.; Shen, B. Superconducting fault current limiter (SFCL) for fail-safe DC-DC conversion: From power electronic device to micro grid protection. Superconductivity 2022, 1, 100003.

[17] Sotelo, G.G.; dos Santos, G.; Sass, F.; Franca, B.W.; Dias, D.H.; Fortes, M.Z.; Polasek, A.; de Andrade, R. A Review of Superconducting Fault Current Limiters Compared with Other Proven Technologies. Superconductivity 2022, 3, 100018.

[18] Rong, C.C.; Barnes, P.N.; Levin, G.A.; Miller, J.D.; Santosusso, D.J.; Fitzpatrick, B.K. Investigation of the Relaxation of Persistent Current in Superconducting Closed Loops Made Out of YBCO Coated Conductors. IEEE Trans. Appl. Supercond. 2015, 25, 1–5.

[19] Qiu, D.; Wu, W.; Pan, Y.; Xu, S.; Zhang, Z.M.; Li, Z.L.; Li, Z.Y.; Wang, Y.; Wang, L.; Zhao, Y.; et al. Experiment and Numerical Analysis on Magnetic Field Stability of Persistent Current Mode Coil Made of HTS-Coated Conductors. IEEE Trans. Appl. Supercond. 2017, 27, 1–5.

[20] da Cruz, V.S.; Telles, G.; Santos, B.M.O.; Ferreira, A.; de Andrade, R. Study of the Voltage Behavior of Jointless Superconducting 2G Loops During Pulse Magnetization. IEEE Trans. Appl. Supercond. 2020,30, 8200306

[21] Sheng, J.; Zhang, M.; Wang, Y.; Li, X.; Patel, J.; Yuan, W. A new ring-shape high-temperature superconducting trapped-field magnet. Supercond. Sci. Technol. 2017, 30, 094002.

[22] Sheng, J.; Pan, Y.; Jiang, J.; Li, W.; Shen, B.; Zhang, Z.-W.; Wu, W. A New Concept of a Hybrid Trapped Field Magnet. IEEE Trans. Appl. Supercond. 2019, 29, 0603805.

[23] Lee, S.; Kim, W.-S.; Kim, Y.; Park, S.H.; Lee, J.-K.; Hahn, J.-H.; Hong, G.-W.; Park, I.H.; Park, C.; Choi, K. Characteristics of an HTS Pancake Coil in Persistent Current Mode Using Wind-and-Flip Winding Method. IEEE Trans. Appl. Supercond. 2017, 23, 4601305.

[24] Chi, C.; Cai, C.; Zhou, D.; Guo, Y.; Yan, W.; Bai, C.; Liu, Z.; Lu, Y.; Fan, F.; Li, M.; et al. Low-frequency magnetic field shielding effect of artificial joint-free REBCO coils. Supercond. Sci. Technol. 2020, 33, 095001.

[25] J. S. Fraser and P. R. Tunnicliffe, A study of a superconducting heavy ion cyclotron as a post accelerator for the CRNL MP Tandem, Chalk River National Laboratory report CNRL-1045 (1974).

[26] H. Blosser and D. Johnson, Focusing properties of superconducting cyclotron magnets, Nucl. Instrum. Methods 121, 301–306 (1976).

[27] H. Blosser and F. Resmini, Progress report on the 500 MeV superconducting cyclotron, in Proc. Part. Accel. Conf., IEEE NS-26 (1979), pp. 3653–3658.