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ENGINEERING DESIGN AND FABRICATION TECHNOLOGY FOR SUPERCONDUCTING MAGNETS IN CYCLOTRON

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Abstract

Magnets play an import role in cyclotrons. Application of superconducting magnets can make the cyclotron more compact, magnet field higher, and operation cost lower. In recent years superconducting cyclotrons is increasing number in heavy iron therapy application, and they are an easy and cheap way to get ion beams. As a superconducting magnet besides the electromagnetic design to meet the beam transport requirement, there are many special engineering design points, including mechanical, cooling, stability, safety, measurement and so on. To fabricate the superconducting magnets, especially those with specially winding shape and configuration, need to study the process including winding, resin vacuum pressure impregnation, superconductor welding, assembling and so on. This report describes the trends of superconducting magnet in cyclotron. Some projects and products developed in Bama Superconductive Tech Co. Ltd are also presented in this report,

INTRODUCTION

The applications of cyclotron accelerators have covered a number of research areas, such as for medical or industrial applications. One typical application of cyclotron as particle therapy system is shown in Fig 1. The basic modular of a particle therapy system include beam production system, beam transport system and beam delivery system. Magnets play import roles in each modular. In beam production system magnets are used in the cyclotron to accelerate the beam to designed energy level. In beam transport system magnet are used to guide the beam. In delivery system magnets are used to deliver the beam to the exact location of focal lesions.

Application of superconducting magnets can make the cyclotron more compact, magnet field higher, and operation cost lower. From 1982 the first external beam was extracted from the K500 cyclotron at MSU, cyclotrons based on superconducting magnets became a popular research field in science, research, medicine and so on. Especially in recent years superconducting cyclotrons is increasing number in heavy iron therapy application, and they are an easy and cheap way to get ion beams.

With the development of superconductive materials and superconducting magnet technology, many new design and fabricating technology are proposed. As a superconducting magnet besides the electromagnetic design to meet the beam transport requirement, there are many special engineering design points, including mechanical, cooling, stability, safety, measurement and so on. To fabricate the superconducting magnet, especially those with specially winding shape and configuration, need to study the process including winding, resin vacuum pressure impregnation, super-conductor welding, assembling and so on. This report describes the trends of superconducting magnet in cyclotron. Some projects and products developed in Bama Superconductive Tech Co. Ltd are also presented in this report.

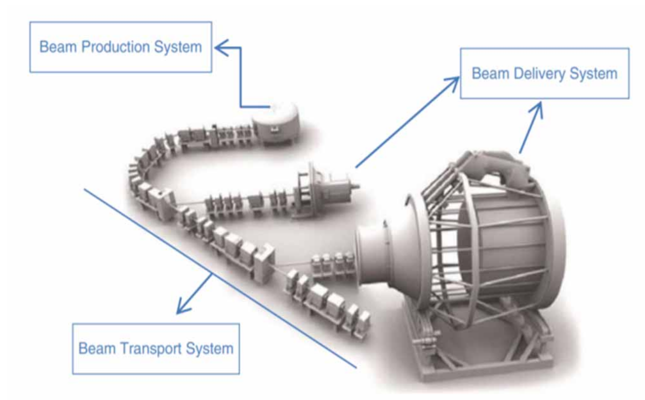

Figure 1: Basic modular design of particle therapy systems [1].

TRENDS OF SUPERCONDUCITNG MAGNETS IN CYCLOTRON

With the development of superconducting magnets technology and the requirement of particle therapy systems. Some new trends appeared in recent years.

Cryogen-free Superconducting Magnet

A superconducting azimuthally varying field (AVF) cyclotron, SC230, was developed for proton therapy by Sumitomo Heavy Industries, Ltd. in 2021. This isochronous cyclotron is compact owing to the high magnetic field generated by NbTi superconducting coils. The average magnetic field is 3.9 T at the outer region, and the extraction radius is 0.6 m. Because iron magnetization brings a limitation to iron-yoke isochronous cyclotrons, this SC230 SHI designed is probably at the lower limit in terms of weight and size. The coils are cryogen-free and cooled by conduction cooling using four 4 K-GM cryocoolers. The system is highly safe and easy to maintain, which reduces the effects of unstable helium supply. The heat inputs to the coils during beam operation are larger owing to the leakage radio frequency (RF) and beam loss are considered in detailed. The magnet is designed to have a sufficient temperature margin for stable operation. The coil temperature during the RF excitation is about 4.5 K. It was confirmed that the coil cools sufficiently at the critical temperature [2-3]. The schematic of the AVF cyclotron SC230 are shown in Fig. 2.

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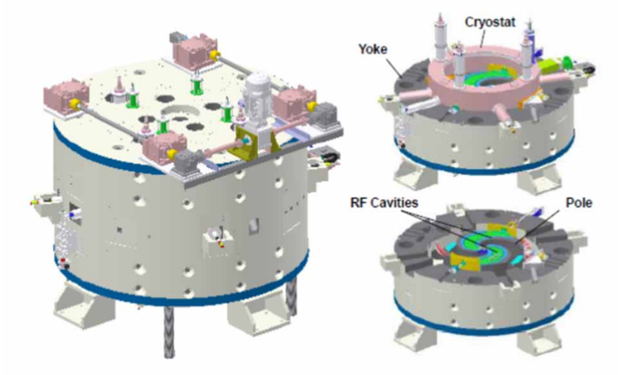

Figure 2: Schematic of the AVF cyclotron SC230 [3].

Ironless Cyclotron Superconducting Magnet

A concept of ironless superconducting magnet was proposed for further weight reduction of the cyclotron by Massachusetts Institute of Technology [4-5]. Their work demonstrates how multiple sets of superconducting coils can be used to replace the iron return yoke and pole pieces of a conventional cyclotron. Coil number, location, and current are used as optimization parameters for the required field profile and active shielding requirements of the machine. In comparison to the commercial Mevion Monarch 250 synchrocyclotron for proton therapy, the weight of the cyclotron magnet system is reduced by a factor of 6 by using the superconducting ironless design. Iron-free designs may also offer increased tuning ease during mass production, in the fashion of magnetic resonance magnets, and increased access to the midplane. Figure 3 shows the schematic of the ironless cyclotron superconducting magnet [4-5].

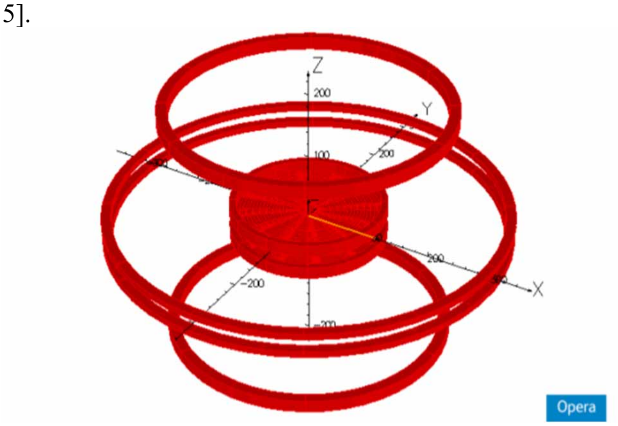

Figure 3: Schematic of the Ironless Cyclotron Superconducting Magnet [4].

High Temperature Superconducting Magnet

A study of high-temperature superconducting (HTS) magnets in cyclotron for particle therapy was carried out by the Research Centre for Nuclear Physics in Osaka, Japan [6]. This concept applies the quality improvements seen in HTS tapes over recent years to coils for the use in medical accelerators. The aim is also a yoke-free, ultra-compact, efficient, and high-energy AVF cyclotron with much reduced power consumption. Bean-shaped coils above and below the beam chamber are implemented in order to create a suitable AVF magnetic field structure needed for beam stability. The concept is still in early stages of development, and the technical difficulties of realizing any iron-free cyclotron requiring rapid energy variations for clinical treatment are not trivial. Figure 4 shows schematic of the HTS magnets in cyclotron [6].

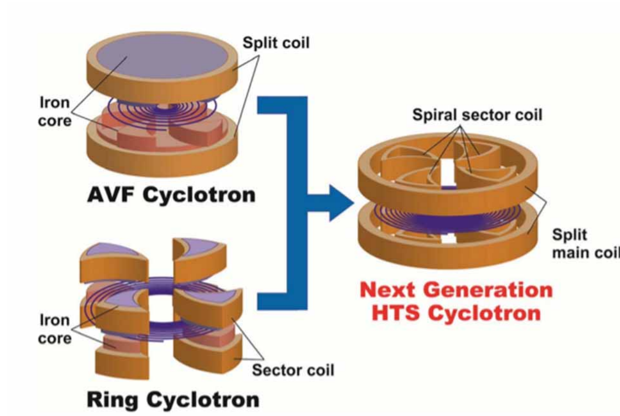

Figure 4: Schematic of the HTS magnets in cyclotron [6].

A study of HTS magnet for the 2 GeV FFAG accelerator lattice scheme was carried out by China Institute of Atomic Energy (CIAE) from 2019. In order to demonstrate the feasibility of manufacturing a spiral-shaped HTS magnet with concave edges based on ReBCO tapes, a 1:4 scaled HTS model magnet has been developed in CIAE. The whole assembled HTS magnet was cooled down to 23 K using helium gas pipeline contact cooling and operated on 300 A for over 24 hours. The central magnetic field reached 719.5 mT, without iron [7-8]. Figure 5 shows the Schematic of the HTS magnet for the 2 GeV FFAG accelerator in CIAE.

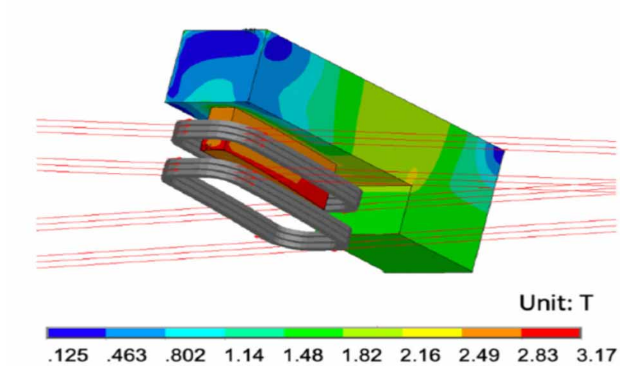

Figure 5: Schematic of the HTS magnet for the 2 GeV FFAG accelerator in CIAE [8].

Alternating-Gradient Canted Cosine Theta Superconducting Magnet

The concept of alternating-gradient canted cosine theta (AG-CCT) superconducting magnets for application in a gantry for proton therapy are proposed by Weishi Wan et al. [9]. The AG-CCT magnet allows a large momentum acceptance. A very big advantage is that all this can be done

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while keeping the AG-CCT fields fixed. This reduces the need for fast field ramping of the superconducting magnets between the successive beam energies used for the scanning in depth and it is important for medical application since this reduces the technical risk (e.g., a quench) associated with fast field changes in superconducting magnets. For proton gantries the corresponding superconducting magnet system holds promise of dramatic reduction in weight. For heavier ion gantries there may furthermore be a significant reduction in size. A systematic design procedure for an AG-CCT superconducting gantry is study in Huazhong University of Science and Technology in China, and Figure 6 shows the Schematic of the AG-CCT superconducting gantry [10].

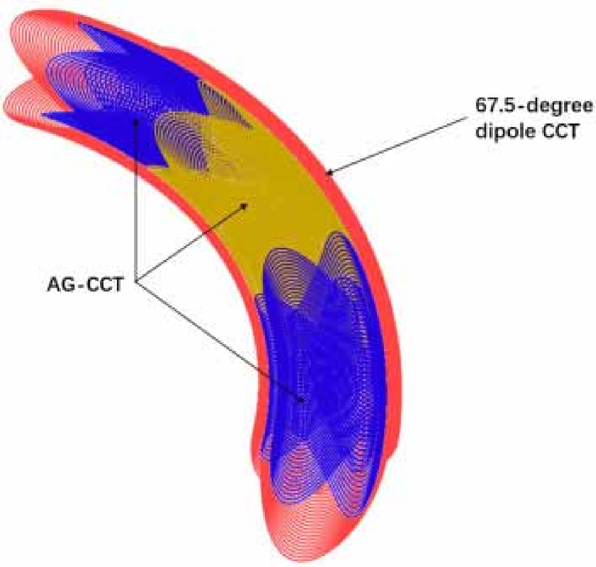

Figure 6: Schematic of the AG-CCT superconducting gantry in Huazhong University of Science and Technology [10].

TYPICAL SUPERCONDUCTING MAGNETS TECHNOLOG CASES IN BAMA SUPERCONDUCTIVE TECH CO.

Bama Superconductive Tech Co. Ltd was found in 2018 in China. It focuses on technology and equipment for ultimate environment creation including high magnetic, cryogenics and vacuum, especially on superconducting magnets.

Superconducting Magnet Technology

Bama has designed various superconducting magnets for big science projects, research instruments, industry and medical fields. The design technology including electromagnetism optimal design, cooling system design, mechanical design, power and quench protection system design for superconducting magnets.

Key components fabrication technology in superconducting magnets has been studied in Bama, including superconductor wire welding, vacuum pressure impregnation for superconducting magnets, high temperature current leads, high thermal conductive strips et al.

Customized and standard series NbTi magnets have been designed and fabricated by Bama. Figure 7 shows a equipment for HTS tape properties measurement using warm bore of a 5T superconducting magnet by Bama. Figure 8 shows the ReBCO defocusing magnet of 2 GeV FFAG accelerator in CIAE by Bama.

Figure 7: Schematic of an equipment for HTS tape properties measurement using warm bore of a 5T superconducting magnet by Bama .

Figure 8: Schematic of the ReBCO defocusing magnet of 2 GeV FFAG accelerator in CIAE by Bama.

GM Cryocoolers Technology

GM Cryocooler is the key components for cooking superconducting magnets. Bama has development series GM cryocoolers and helium compressors, including 4 K series for lower temperature superconducting magnets, 10 K series for cryo-vacuum pumps and 70 K single stage cryocoolers for thermal shields, high temperature superconducting magnets et al. These GM cryocoolers have been applied in many superconducting products of Bama, and are suppled in the market. Figure 9 shows the model of GM Cryocoolers by Bama.

CONCLUSION

Magnets play an import role in cyclotrons. Application of superconducting magnets can make the cyclotron more compact, magnet field higher, and operation cost lower. Many new trends of superconducting magnets in cyclotrons appeared in recent years including conduction cooling magnets, ironless magnets, HTS magnet and alternating-gradient canted cosine theta superconducting magnet.

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Figure 9: Model of GM Cryocoolers by Bama.

Bama Superconductive Tech Co. Ltd focuses on technology and equipment for ultimate environment creation including high magnetic, cryogenics and vacuum, especially on superconducting magnets. Bama has developed various Customized and standard series NbTi magnets and HTS magnet. GM Cryocooler as a key component for cooling superconducting magnets has also been developed and supplied in the market by Bama.

REFERENCES

[1] E. Pearson *et al.*, "Development of Cyclotrons for Proton and Particle Therapy", in *Particle Radiotherapy*, A. Rath, N. Sahoo, Eds. Springer, New Delhi, India, 2016, pp. 21-35. doi:10.1007/978-81-322-2622-2

[2] H. Tsutsui, A. Hashimoto, Y. Mikami, *et al.*, "Design study f a superconducting AVF cyclotron for proton therapy", in *Proc. Cyclotrons'13*, Vancouver, BC, Canada, Sep. 2013, paper MO3PB02, pp. 102-104.

[3] Y. Ebara *et al.*, "Performance of Cryogen-free Superconducting Magnet in Isochronous Cyclotron for Proton Therapy", in *IEEE Trans. Appl. Supercond.*, pp. 1-5, Feb. 2023. doi:10.1109/TASC.2023.3245563

[4] A. Radovinsky, J. V. Minervini, C. E. Miller, L. Bromberg, P. C. Michael, and M. Maggiore, "Superconducting Magnets for Ultra Light and Magnetically Shielded, Compact Cyclotrons for Medical, Scientific, and Security Applications", in *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 1-5, p 4402505, June 2014. doi:10.1109/TASC.2013.2287853

[5] A.L. Radovinsky, J.V. Minervini, P.C. Michael, L. Bromberg, and C.E. Miller, "Variable Energy Acceleration in a Single Iron-Free Synchrocyclotron", Sep. 2013, PSFC/RR-13. http://www1.psfc.mit.edu/library1/catalog/reports/2010/13rr/13rr009/13rr009_full.pdf

[6] H. Ueda *et al.*, "Conceptual Design of Next Generation HTS Cyclotron", in *IEEE Trans. Appl. Supercond*, vol. 23, no. 3, p. 4100205, June 2013. doi:10.1109/TASC.2012.2232955

[7] C. Wang *et al.*, "Preliminary Study of the High Temperature Superconducting Solution for 2 GeV CW FFAG Magnet", in *IEEE Trans. Appl. Supercond*, vol. 30, p. 4101804, Jun. 2020. doi:10.1109/TASC.2020.2981298

[8] W. Fu *et al.*, "Fabrication and Test of a 1:4 Scaled HTS Coil for the Defocusing Magnet of 2 GeV FFAG Accelerator", in *IEEE Trans. Appl. Supercond*, vol. 32, p. 4005404, Sep. 2022. doi:10.1109/TASC.2022.3159297

[9] W. Wan, L. Brouwer, S. Caspi, *et al.,* "Alternating-gradient canted cosine theta superconducting magnets for future compact proton gantries", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 103501, 2015. doi:10.1103/PhysRevSTAB.18.103501

[10] R. Zhao, B. Qin, Y. Liao, X. Liu, *et al.*, "Achieving a realistic design for a superconducting gantry with large momentum acceptance for proton therapy", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1015, p. 165773, 2021. doi:10.1016/j.nima.2021.165773