Cryogenic Cooldown Performance of the GE HealthCare (HTIC) Compact 7 T MRI Magnet

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Abstract. A compact 7 Tesla ultra-high field and fully sealed low-cryogen magnetic resonance imaging (MRI) system has been developed for human brain imaging at the GE HealthCare Technology & Innovation Center (HTIC), Niskayuna, USA. The cold mass (magnet coils + coil support structure) has been cooled down to 4 K using only 12 Liters of liquid helium liquified with three SHI GM type RDE-412 two-stage cryocoolers. A gas tank has been charged to 15 MPa with pure helium at room temperature. Helium vapor is liquefied with several recondensing cups in contact with the cryocooler second stage. Recondensing liquid helium is collected in a liquid tank from where liquid helium flows into a closed-loop thermo-siphon system in thermal contact with the cold mass. The first stage of the cryocooler cools the thermal shield down to 40 K. Several pre-cooling lines are wrapped around the cold mass externally connected to an open-loop Bluefors/Cryomech MPC600 fast cold helium circulation system (CHCS). All three cryocoolers and the CHCS operate in tandem to cool the cold mass down to 50 K within 16 days. Upon reaching 50 K, the CHCS is turned off and cooldown continues with all three system cryocoolers, reaching a base temperature of 4 K within 5 days. This research explains the cryogenic cooling technique adapted for a compact 7 T MRI magnet. The cryogenic system performance during the magnet ramp to the designed magnetic field will be discussed as well.

Keywords – Low-cryogen, fully sealed, ultra-high field MRI magnet

1. Introduction

The GE HealthCare Technology & Innovation Center, Niskayuna, USA, has been developed a lightweight, low-cryogen, and compact 7.0 T (C7T) actively shielded low temperature superconducting (NbTi) MRI system under the NIH brain initiative award U01EB027696. The C7T is dedicated for human brain imaging with a warm bore of 62 cm and the total weight and footprint (mechanical & fringe field) like a clinical whole-body 3.0 T MRI system [1-4]. The C7T MRI platform provides better human brain imaging capability and accessibility than existing whole-body 7 T MR scanners [5-8]. The C7T magnet design parameters are mentioned in the Table 1 [8]. The cryogenic system of C7T magnet requires less than 1% of liquid helium where liquid/gaseous helium remains sealed inside the cooling system without any vent stack compared to a conventional bath-cooled superconducting MRI magnet. Three total units of SHI GM type RDE-412 two-stage cryocoolers have been used to cool-down the magnet cold mass [8, 9]. The cold mass remains in contact with a closed-loop thermo-siphon cooling system. In this system, helium vapor liquefies after recondensation with the second stage of cryocoolers. This process generates 12 Liters of liquid helium at 4.2 K, which is utilized to cool down the magnet coils to a temperature below 4 K. Meanwhile, the first stage of the cryocoolers is thermally linked to the thermal radiation shield, which is made of aluminium alloys and cools down to 40 K [10-14].

Table 1. C7T magnet design parameters [8].

Parameter	Value
Center field	7.0 T
Peak field	7.7 T
Operating current	448.1 A
Homogeneity	0.6 ppm @ 26 cm DSV
Stored magnetic energy	16.5 MJ
Axial force on large main coil	922 kN
Stray field (5 G line)	5 m (axial) x 3 m (radial)
Dimensions	2.25 m (L) x 2.25 m (W) x 2.39 m (H)
Weight	~ 8 tons

All three cryocoolers are mounted with an inclination angle of 20° on the magnet cryostat [15-17]. Figure 1 (a) shows the C7T system architecture installed at GE HTIC, Niskayuna and Figure 1 (b) shows the magnet has been parked in persistent current mode at 7.01 T magnetic field.

(a) (b)

Figure 1 (a). C7T system architecture installed at GE HTIC, Niskayuna, and **(b)** magnet has been parked at 7.01 T magnetic field.

High purity helium gas is charged in the gas tank at 15 MPa pressure and room temperature whereas liquid helium is collected in a liquid tank after liquefaction and flows through the closed-loop circuit attached to the cold mass. The C7T low-cryogen magnet does not require refilling or charging with helium once it cools the magnet. A set of open-loop pre-cooling lines have also been installed on the magnet cold mass which are externally connected/disconnected to an open-loop Bluefors/Cryomech MPC600 fast cold helium circulation system (CHCS). The MPC600 circulates the cold helium gas at a controlled flow rate and gas temperature which regulates the rate of cool-down of the magnet. Magnet cool-down starts by simultaneously turning on all three GM cryocoolers and the MPC600. The cold mass temperature reaches 50 K in 16 days. The MPC600 is then turned off and disconnected to continue with the magnet cool-down using only GM cryocoolers which takes a further 5 days to cool down to less than 4 K temperature. The MRI magnet operates through the integration of various sub-systems, such as gradient coils and RF coils. A functioning MRI system undergoes different types of operations that can create an additional heat load on the cryogenic system. This paper explains the overall working methodology and operational thermal performance of the C7T cryogenic system in detail.

2. Cryogenic system of the C7T

The fully sealed cryogenic system of the C7T magnet has been designed to cool down the cold mass of the magnet to 4 K with the help of 12 Liters of liquid helium. The cryogenic system comprises two stainless steel tanks where one tank is utilized to store helium gas, and another for collecting liquid helium after liquefaction. Both tanks are connected to each other and position of gas tank remains gravitationally above the liquid tank to collect the low-density helium vapor compared to high density liquid helium. Initially, high purity (99.99999%) helium gas is charged at 15 MPa pressure (tanks and cooling lines have been tested up to 21.5 MPa pressure as per ASME Pressure Vessel Code Section VIII, 2019 requirements) to the tank and cooling circuit. Three units of SHI GM type RDE-412 two-stage cryocoolers (1.2 W @ 4.2 K) are connected to the cooling circuit where each cryocooler has its own recondenser cup in contact with the 2nd stage whereas the 1st stage is thermally coupled to thermal radiation shield. A gas manifold attached to the recondenser cups is connected to the gas tank whereas the liquid manifold from the recondenser cups is connected to the liquid tank. Multi-layer insulation (MLI) has been fitted on the thermal radiation shield (40 K) to protect the magnet from thermal radiation heat load from room temperature (300 K) vacuum vessel. 4 K emissivity control has also been applied on the magnet cold mass. The coil support structure (CSS) is made of an aluminium alloy where low temperature superconducting (NbTi) magnet coils are mounted on the CSS. Several series/parallel combinations of cooling circuits are thermally connected to the cold mass (magnet coils and CSS). A simplified line diagram is illustrated in Figure 2 (a). The magnet cold mass cross section is displayed in Figure 2 (b). After the helium gas is liquefied at its saturated pressure and temperature inside the recondenser, liquid helium flows through the cooling tubes due to gravity, conductively cooling the cold mass. Liquid helium boils off when it thermally connects and removes enthalpy from the cold mass, changing its phase to helium vapor. The helium vapor flows upward to collect in the gas tank and eventually reaches the recondenser to be liquefied again. This closed-loop liquefaction cycle continues until the cold mass reaches a base temperature of 4 K.

In addition to the main cooling circuit, there is another cooling circuit which is thermally connected to the cold mass that is known as pre-cooling circuit which helps to cool down the cold mass to 50 K when simultaneously operating with three cryocoolers. The pre-cooling circuit consists of an open-loop tube connections with adapters available on the cryostat to connect the pre-cooler externally to the cryostat. An open-loop Bluefors/Cryomech MPC600 CHCS is used as a pre-cooler which circulates the cold helium gas with the help of its own cryofan. Cold helium gas reduces the cold mass temperature while circulating from the pre-cooling tubes by extracting the enthalpy of the cold mass. The flow rate and temperature of the circulating cold helium gas can be controlled by adjusting the speed of the cryofan and cold-head heater power of the MPC600. The cold mass is surrounded by the thermal radiation shield made of aluminium alloys. The thermal radiation shield is connected to the 1st stage of cryocoolers only and cools down to 40 K temperature. After the cold mass temperature reaches 50 K, the MPC600 is disconnected, and further cool-down continues with only three cryocoolers.

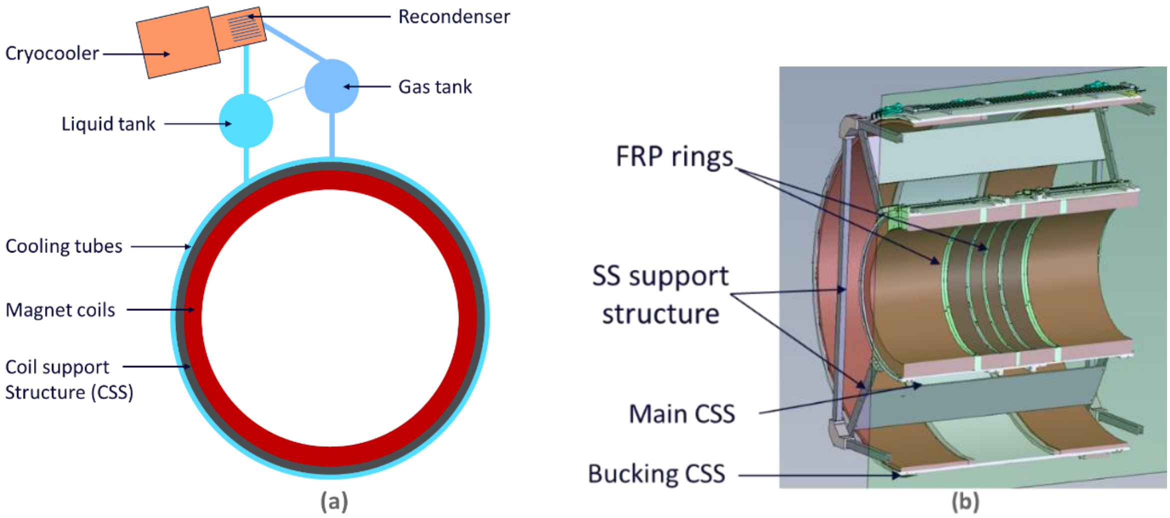

Figure 2 (a). Cryogenic closed-loop fully sealed cooling system of C7T [8], and **(b)** cross section view of C7T cold mass (CSS + magnet coils) with support structure [8].

Magnet ramping to the operating field and shimming to achieve the designed homogeneity using active/passive shimming are challenging tasks and require additional thermal margin. Static and dynamic heat loads on the magnet consumes lots of liquid helium and refrigeration power. The magnet can be ramped to full 7 T magnetic field with 448.1 A current in a single step or multiple steps depending on the base temperature of the cold mass, ramping voltage, and liquid helium volume. C7T operates in persistent current mode. A persistent current switch is connected parallel to the magnet that remains at normal conducting state during the magnet ramp which incorporates additional heat load to the cryogenic system. The cryogenic system should also be able to perform well during the gradient coil operation. AC interaction with superconducting coils and electrically conductive parts of the cryostat (magnet-gradient interaction) can raise the base temperature of the cold mass. The magnet should also be able to maintain the base temperature during any power failure that can be caused by cryocooler shutdown or failure. The cryogenic system should have enough refrigeration capacity available to maintain the base temperature for a certain period for power recovery or magnet ramp down to a suitable magnetic field to replace the failed cryocooler. For this case, the duration is designated as “ride-through” time. The cryogenic system design of the C7T is optimised for weight and space to maintain the 4 K base temperature during ramping, shimming, ride-through time and magnet-gradient interaction (MGI) through intentional design of the available refrigeration capacity at the 2nd stage of three cryocoolers, the amount of liquid helium, and helium gas charge pressure.

3. Cool-down performance of the C7T

Cryogenic cool-down performance of the magnet is dependent on the different operational conditions of the magnet such as magnet cool-down, ride-through, ramping, MGI losses, and shimming. In this section, cryogenic performance of the C7T magnet has been discussed in different operational conditions.

3.1 Cool-down of the C7T

Before starting the cool-down the cryostat has been evacuated down to 10^{-05} mbar vacuum level. A high vacuum has been achieved using a combination of roots & turbo-molecular pumps (TMP), and an attached cryopump. A MPC600 pre-cooler is connected with the pre-cooling lines and turned on. Also, all three compressors of the cryocoolers are turned on. The thermal radiation shield is suspended from the magnet cold mass. Main coil support structure and bucking coil support structure is connected with each other using a dedicated stainless steel support structure. An analytical stress analysis has been conducted to analyse the maximum allowable cool-down stress level of different suspension systems of coil support structures. A cool-down rate within an allowable temperature difference between thermal radiation shield and bucking coil support structure has been calculated to avoid over cooling of thermal shield compared to bucking coil which ultimately limits the stress concentrations. High temperature difference could lead to excessive strain in the suspension system between the thermal radiation shield and cold mass. Since the thermal shield is only coupled with the first stages of cryocoolers, different cryocoolers were turned on and off as necessary during cool-down to maintain the temperature difference within allowable stress limits of the suspension system and avoid any buckling. Figure 3 shows the allowable temperature difference between thermal shield and bucking coil versus bucking coil temperature with respect to the initial tention of the thermal shield suspension system.

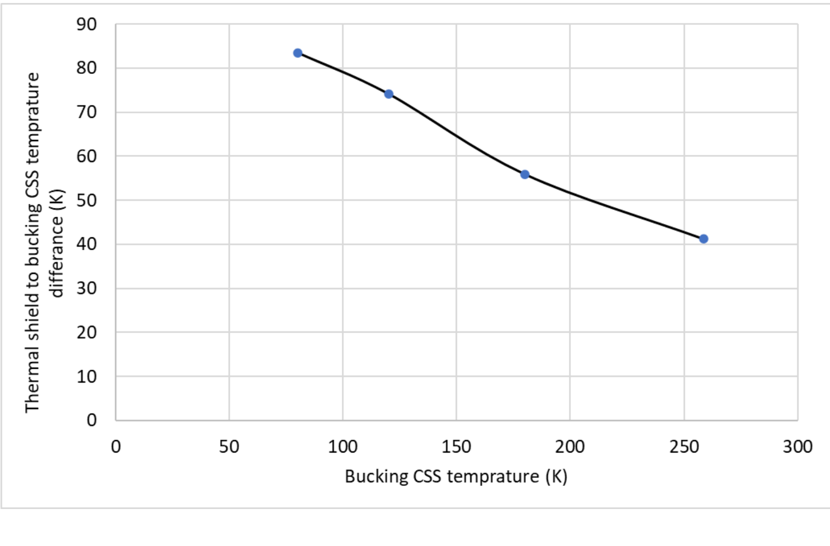

Figure 3. Maximum temperature difference in between thermal shield and bucking coil support structure to avoid stress concentrations.

IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012136 doi:10.1088/1757-899X/1344/1/012136

Figure 4 shows the cool-down plot of the C7T. It takes 16 days to cool-down to 50 K temperature when all three cryocoolers and MPC600 pre-cooler work simultaneously. On the 17^{th} day, the MPC600 is turned off and cool-down continues with three cryocoolers only. It takes another 5 days to reach the 4 K base temperature. The horizontal double-sided arrow on the plot shows the temperature decrease per day. The maximum temperature decrease, 26.7 K had occurred when the MPC600 was disconnected. Refrigeration capacity of MPC600 reduces below 60 K temperature which slows the cool down. When the MPC600 is disconnected, cooling rate increased significantly with three cryocoolers. The total cool-down time is 21 days. The thermal shield cools down to 39-44 K whereas the cold mass cools down to 3.4-3.8 K.

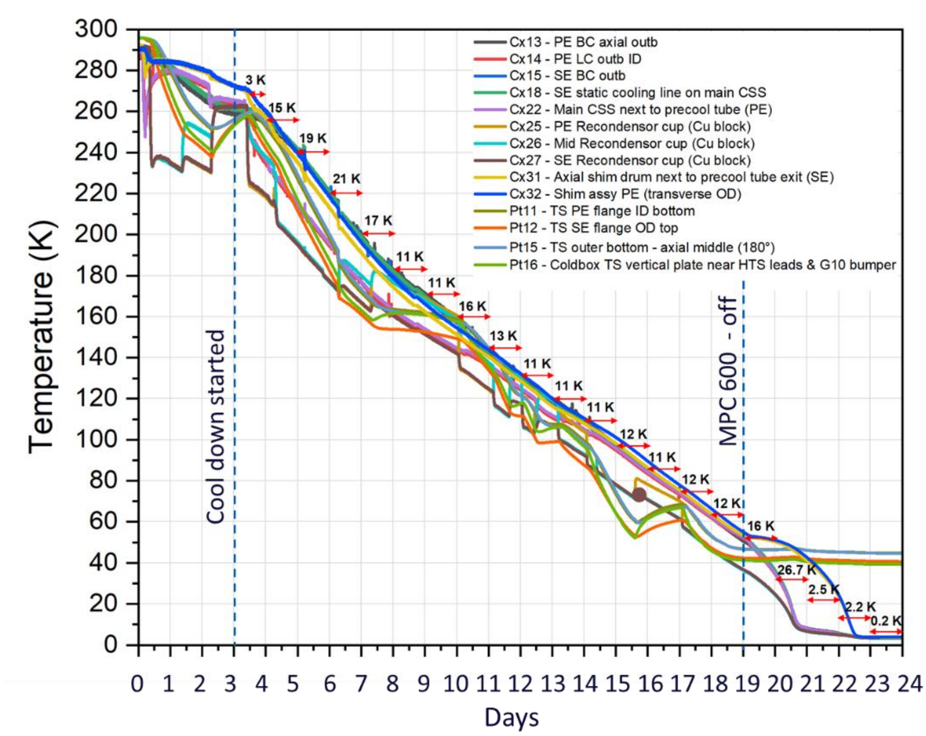

Figure 4. Cool-down plot of the C7T.

3.2 Ride-through time

The cryogenic system was designed to liquefy 12 Liters of liquid helium at 4.2 K but the lowest temperature is 3.4 K which allows to collect 18 Liters of liquid helium. The liquid tank dryout temperature is 4.54 K and quench threshold temperature of the magnet is 5.2 K. A ride-through experiment has been conducted by turning off all three cryocoolers one by one to observe the amount of time allowable by the cryogenic system before liquid helium dry out reaching the threshold temperature limit for the magnet quench. Figure 5 shows the experimental plot of the ride-through test. When all three cryocoolers are turned off, the 5.2 K quench threshold temperature is reached in 5 hours. This means that in the event of a power failure, when all three compressors are turned off, the magnet remains safe without quenching for approximately 5 hours. When two cryocoolers are turned off, the 5.2 K quench threshold temperature is reached in 11 hours. It is very unlikely that two cryocoolers would fail due to compressor issues. When only one cryocooler is turned off, the cold mass temperature remains at 4.7 K with 6.8 Liters of liquid helium, allowing the magnet to ramp down to 5 T (almost a 50% reduction in total stored magnetic energy) before quenching. The most likely event is the failure of only one of the compressors.

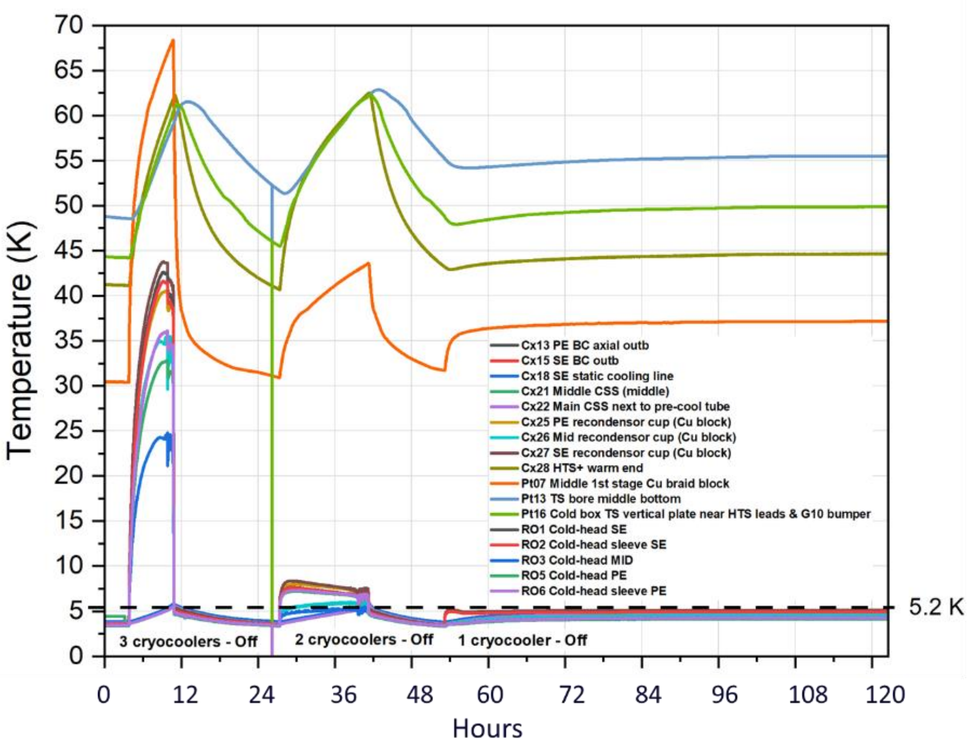

Figure 5. Experimental test of ride-through time of the C7T magnet.

3.3 Magnet ramping

The C7T magnet was ramped to 7 T and successfully parked in persistent current mode. Figure 6 shows the final step of the magnet ramp profile and corresponding cold mass temperature. During the last ramp step to full field, the superconducting switch temperature was maintained at 9.1 K.

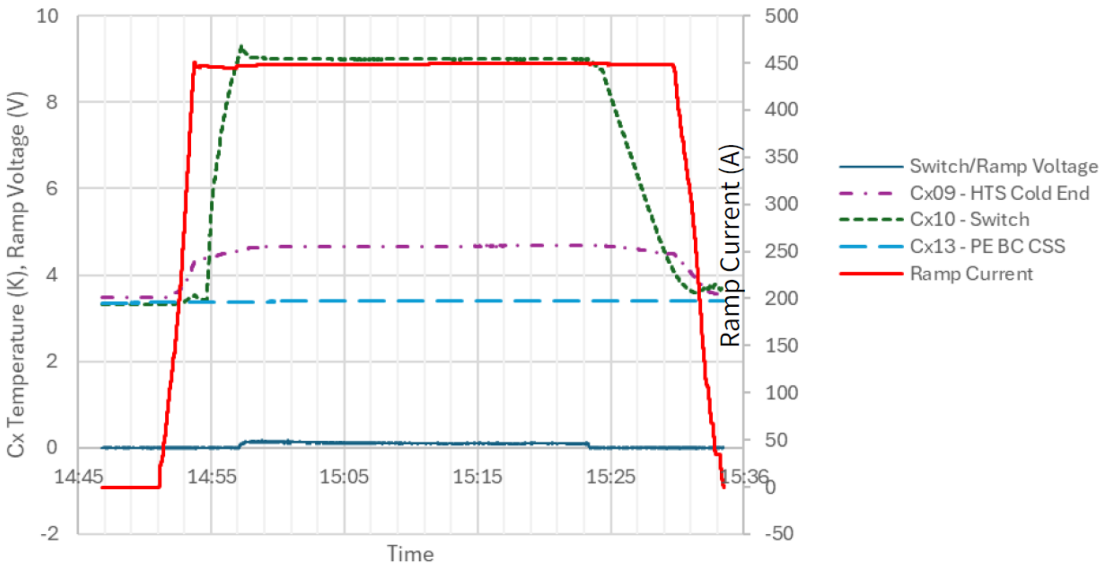

Figure 6. Thermal profile of the C7T magnet during ramp to full field.

4. Summary

A fully sealed, thermo-siphon, closed-loop cryogenic system has been successfully developed for the C7T magnet. The cold mass has been cooled down to a temperature range of 3.4-3.8 K using three cryocoolers. In addition, more than 18 Liters of liquid helium have been collected in the liquid tank, with a helium gas charge pressure of 15 MPa at room temperature. The C7T magnet has been ramped to 7 Tesla magnetic field and parked in persistent current mode without any thermal issues. The magnet ride-through test provided a better understanding of magnet operation in the event of a cryocooler failure or a power outage. MGI testing and magnet shimming will be performed within the next few months, and the results will be published in future.

Acknowledgments
The authors would like to thank all the team members of MR & SC magnet group, GE HTIC, Niskayuna and GE HealthCare, Florence. This project has been funded by NIH contract award NIH U01EB027696.

References

[1] T. Foo, Y. Shu, and D.Xu, "Lightweight, compact, low-cryogen, head-only 7T MRI for high-spatial resolution brain imaging," in Proc. NIH BRAIN Initiative: Dissemination Non-Invasive Imag. Technol. Workshop, 2021.
[2] T. Foo et al., "Compact 7T: Progress in construction and assembly of a low-cryogen, high-performance, head-only high-field MRI system," in Proc. 31st Sci. Meeting ISMRM, 2023.
[3] T. Foo et al., "Design and construction of a low-cryogen, lightweight, high-performance, head-only compact 7T MRI," in Proc. 29th Sci. Meeting ISMRM, 2021.
[4] T. Foo et al., "Lightweight, compact, and high-performance 3TMRsystem for imaging the brain and extremities," *Magn. Reson. Med.*, vol. 80, no. 5, pp. 2232–2245, Nov. 2018.
[5] H. Liebel "High field superconducting magnets". In: High Field MRI imaging, Springer, 2011
[6] Rory Warner 2016 Supercond. Sci. Technol. **29** 094006.
[7] MAGNETOM Terra – 7T MRI Scanner - Siemens Healthineers USA. Available at: https://www.siemens-healthineers.com.
[8] A. Wu et al., "Design and Construction of a Low-Cryogen, Lightweight, Head-Only 7T MRI Magnet," in IEEE Transactions on Applied Superconductivity, vol. 34, no. 5, pp. 1-5, Aug. 2024, Art no. 4402205, doi: 10.1109/TASC.2024.3352551.
[9] Y. Lvovsky, E. W. Stautner, and T. Zhang, "Novel technologies and configurations of superconducting magnets for MRI," Supercond. Sci. Technol., vol. 26, 2013, Art. no. 093001.
[10] E. T. Laskaris et al., "Cooling system and method for cooling superconducting magnet devices," U.S. Patent 8 374 663, Feb. 12, 2013.
[11] X. Hang et al., "Cryogenic system and method for superconducting magnets and MRI with a fully closed-loop cooling path," U.S. Patent 8 643 367, Feb. 4, 2014.
[12] W. Stautner et al., "The cryogenics of a thermosiphon-cooled HTS MRI magnet - assembly and component testing," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 2096–2099, Jun. 2011.
[13] M. Parizh and W. Stautner, "MRI magnets," in *Handbook of Superconductivity*, vol. 3, 2nd ed., D. Cardwell, D. Larbalestier, and A. Braginski, Eds. New York, NY, USA: Taylor & Francis, 2022, ch. H1.3,pp. 437–492.
[14] Stautner W Torrey D Xu M Wu A Parizh M Soni V Cryogenic aspects of a 20 MW class low-temperature superconducting generator for the renewables industry 2024 IOP Conf. Ser.: Mater. Sci. Eng. 1301 012048
[15] Stautner W Cryocoolers for Superconducting Generators" Chapter 6 in Atrey M (ed.), Cryocoolers – Theory and Applications, International Cryogenics Monograph Series Springer Publishing 2020
[16] Stautner W Cryocoolers for Healthcare" Chapter 9 in Atrey M (ed.) Cryocoolers – Theory and Applications International Cryogenics Monograph Series Springer Publishing 2020.
[17] Stautner W, Soni V et al., C1Or2B-04, Parasitic Heat Load Reduction of Cryocoolers, CEC/ICMC, Reno NV 2025.