氏　　　名	青木 学
学位（専攻分野）	博士（工学）
学 位 記 番 号	総研大甲第 2265 号
学位授与の日付	2021年9月 28日
学位授与の要件	高エネルギー加速器科学研究科　加速器科学専攻 学位規則第6条第1項該当
学 位 論 文 題 目	Study on thermal and mechanical stability of the superconducting coil with liquid helium permeable structure
論 文 審 査 委 員	主　査　荻津　透 加速器科学専攻　教授 槙田　康博 素粒子原子核専攻　教授 飯尾　雅実 加速器科学専攻　准教授 王　旭東 加速器科学専攻　助教 佐々木　憲一 加速器科学専攻　教授 谷貝　剛 上智大学　理工学部　教授

(Form 3)

Summary of Doctoral Thesis

Name in full AOKI Manabu

Title Study on thermal and mechanical stability of the superconducting coil with liquid helium permeable structure

Some superconducting magnets for particle accelerators have the liquid helium cooling channels within the coil windings to improve the thermal stability. On the other hand, a closely wound coil using the monolithic superconducting wires can not have similar cooling channels due to structural constraints, but the coil using the self-bonding wires can have voids into which liquid helium can permeate (hereafter referred to as "helium-permeable structure"). However, the larger helium-permeable structures could make the coil windings fragile and lose the mechanical stability of superconducting coils. Therefore, we developed a three-point bending test stand working at a cryogenic temperature of 4.2 K within a magnet field, which can evaluate a strain for the magnet quench (hereafter referred to as "quench strain") as the mechanical stability including statistical variation. Besides, we evaluated a minimum heater energy for the quench as the thermal stability to verify the cooling effect of this structure.

The test coils were racetrack-shaped (200 mm×50 mm), and two straight sections were bent with the three-point bending test stand. Superconducting wires were NbTi multifilament monolithic wire coated with polyvinyl formal and a self-bonding resin. The helium-permeable structures existed in the area surrounded by three wires and occupied about 2 % of the cross-section. For comparison, the test coils without the helium-permeable structure were made by putting additional self-bonding resin during the winding process. The test coils were energized from 150 A to 250 A in the magnetic field of 5.8 T, and the critical current margin defined as the ratio of operation current to the conductor critical current was from 32.0 % to 53.3 %.

The minimum heater energy for the quench of the test coils with the helium-permeable structure were 5.6 mJ to 22 mJ, which were about 2.3 to 3.1 times higher than the test coils without the helium-permeable structure. These results indicated that the helium permeable structure improved the thermal stability of the superconducting coil. However, the differences of the minimum heater energy for the quench between both types of the test coils tended to decrease when the current of the test coil became larger.

The quench strains of the test coils with helium-permeable structure were about 1.6 times larger compared to the test coils without the helium-permeable structure when the current of the test coil was 150 A (the critical current margin 32.0 %). On the other hand, there were almost no differences of the quench strains between both types of the test

coils when the current of the test coil was 185 A or more (the critical current margin 39.4 % or more). Although the quench strains depended on the current of the test coil, the helium permeable structure had the effect to improve the mechanical stability of the superconducting coil.

The frequency of the voltage spikes, which indicate that mechanical disturbance occurred in the coil winding, were almost the same regardless of the presence or absence of the helium-permeable structure. The presence of the helium-permeable structure did not increase the number of mechanical disturbances. We consider that this is because the phenoxy resin applied as the self-bonding resin has three times larger fracture toughness than that of the epoxy resin. The higher fracture toughness restrained crack growth in the resin; therefore, the test coils with the helium-permeable structure seemed not to lose the quench stability.

The cooling mechanism of helium-permeable structure was investigated by a transient thermal analysis of the coil windings. It was found that the helium-permeable structure functions as a type of temperature fixed point and enhances thermal stability. However, it was also found that there is almost no difference in the initial temperature rise from 4.2 K to 5.7 K regardless of the presence or absence of the helium-permeable structure. This result shows that the cooling effect of the helium-permeable structure can not be expected under the condition of the high critical current margin where the current sharing temperature is low.

From the above results, we had three design guidelines of the superconducting coil with the helium-permeable structure: 1) Expansion of the helium-permeable structure is expected to improve the quench stability, since the mechanical stability was not impaired even if the helium-permeable structure that occupies 2 % of the coil cross-sectional area was applied. Furthermore, past studies of magnets for LHC (Large Hadron Collider) revealed that the expansion of the cooling perimeter of the superconducting strand increases MQE (Minimum Quench Energy). When the helium-permeable structure is expanded to a cross-sectional area ratio of 6 %, the cooling perimeter is expanded from 22 % to 47 %, and further improvement of the quench stability is expected. 2) The number of training quenches can be reduced under the condition of the low critical current margin without expanding the helium permeation structure. In the results of the three-point bending test, it was found that the quench stability was improved under the critical current margin of 32.0 % or less. 3) The Young's modulus of the self-bonded coil tended to be lower than that of the prepreg coil. Therefore, when a self-bonded coil is applied, it is necessary to reinforce a support structure according to the magnitude of the electromagnetic force in order to suppress the deformation of the coil winding.

Form8・Separate Sheet
（様式８・別紙１）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　　名　青木　学

Title
論文題目　Study on thermal and mechanical stability of the superconducting coil with liquid helium permeable structure

本研究では、MRI 用超伝導電磁石の熱的・機械的安定性を向上させるための新しいコイル構造の開発を行うと共に、試験用コイルに直接機械的擾乱を加えることで直接的にコイルの安定性を検証する装置を開発し新しいコイル構造の安定性検証を行っている。ここでは、MRI 超伝導電磁石の安定性を向上させるために、従来のエポキシ含浸コイルに変わって、加速器用超伝導電磁石の技術から導入したヘリウム浸透構造を取り入れた。ヘリウム浸透構造コイルの成形に低温での破壊靭性の高い自己融着樹脂を用いることでコイル内のヘリウム流路の制御を行うとともに、樹脂割れなどによる機械的擾乱の発生を抑えた。この技術を使った試験用レーストラックコイルに外部磁場と三点曲げ応力をかけられる試験装置を開発し、製作したヘリウム浸透構造コイルの熱的・機械的安定性向上を実験的に検証した。また同時にヒーター加熱による熱的安定性の検証も行った。三点曲げ試験によって、浸透構造コイルにおける樹脂割れによる擾乱が、含浸コイルより有意に減少していることを確認した。また熱的安定性について、少なくとも運転マージンの大きな領域では大幅な改善があることを三点曲げ試験及びヒーター試験両方で確認し、双方の実験結果に一貫性があることも確認した。本研究成果は、MRI 磁石のクエンチに対する安定性を著しく向上させるもので、クエンチによる医療スケジュールへの障害や液体ヘリウムの損失を大幅に減少させる。現在 MRI 磁石は、より高精度な診断を目指して磁石の高磁場化が進められているが、これは一方で超伝導電磁石のクエンチ安定性を低下させるリスクを持つ。これらの高磁場磁石において本技術が採用されればクエンチ安定性を大幅に向上させ高磁場 MRI の可用性を大幅に向上させる可能性を持つ重要な価値のある研究と考える。

本審査会では、青木氏は研究内容を明瞭かつ簡潔に発表し、質疑に対しても予備審査での指摘事項も含めて的確に回答した。本研究に関連した研究成果についても国際学会で２回発表するとともに査読つきプロシーディングとして英文論文を１本出している。また本博士論文も英語で書かれている。これらのことから国際シーンで研究活動するに十分な英語能力を有すると判断される。

以上のことから、論文の趣旨及び内容は博士論文として十分であるとの判断から審査委員全員一致で審査を合格とした。