氏　　名　DHAKARWAL MUKESH

学位(専攻分野)　博士(学術)

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学 位 論 文 題 目　STUDY OF MgB2 BASED TRANSMISSION LINE MAGNET FOR ACCELERATOR SYSTEMS

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(Form 3)

Summary of Doctoral Thesis

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Title STUDY OF MgB_2 BASED TRANSMISSION LINE MAGNET FOR ACCELERATOR SYSTEMS

The aim of this doctoral thesis entitled "Study of MgB_2 based Transmission line magnet for Accelerator systems" is to present a combined function magnet design with warm iron yoke and MgB_2 as a possible conductor for transmission line to energize magnet, for the upgrade of J-PARC Main Ring (MR).

Since, J-PARC is one of the leading accelerator facility for several ground-breaking experiments such as T2K, KOTO and upcoming facility (COMET) and Proton on Target (POT) as principle requirement. Shortage of POT puts limitation on operation time of experimental facilities. In order to fulfill this increasing future demand of POT, apart from the ongoing increase in the beam power, one of the possible option is to upgrade the current facility with a new ring (stretcher ring) in the present tunnel. Limited tunnel space, a compact and simple SR design is required to install in the present MR. For this reason, study of superconducting combined function magnet with warm iron yoke and superconducting transmission line as primary candidate for field below 2T is undertaken.

This thesis first presents, the optimization of iron yoke by singular value decomposition (SVD) and mechanically stable transmission line cable structure to handle forces acting on the conductor without degrading the field quality in the volume of interest (VOI).

Secondly, electromechanical investigation of several MgB_2 samples produced by Hitachi, Columbus and Hypertech are undertaken. Characterization of critical current dependence on external magnetic field and applied strain was performed at 4.2K using customized test probe in order to determine the operating limitation of the MgB_2 as transmission line conductor. Stress and strain tests are performed at 4.2 K ,77 K and RT in order to determine the maximum stress and strain limit for fabrication and operation of the transmission line conductor.

The result shown that the optimization of iron yoke using SVD gave the pole shape for the target field with significantly reduction of all the higher order field components, but the shape generated by the singular value decomposition is a quite complex is not feasible form the manufacturing point of view. In order to get the optimized pole shape feasible for the manufacturing process, we had modified the optimization process and instead of considering amplitude of each shimming point, total number of shimming points are divided into pairs 5 shimming and an average is of each pair shimming point amplitude is taken in consideration for successive iterations.

Considering the modified approach, a much smoother optimized pole shape is generated which is feasible for large scale manufacturing process as well as good field quality in the volume of interest (VOI) or beam area.

The set of 4 transmission line conductor which carry a maximum of 80 kA, with each cable carrying a maximum of 20 kA current, due to large current the conductor is subjected to large amount of forces, support structure plays a vital role in order to handle this force. In order to minimize the cost of the overall system and for free flow of GHe, the total number of support structures in the transmission line need to be placed at a optimized distance which fulfill the target of cost reduction and structural stability. The structural analysis using ANSYS FEA static structural module offered an optimized distance for transmission line cable support. The analysis was performed taking into consideration a sufficient safety factor and properties of OFHC copper are taken for the analysis.

The electro-mechanical characterization comprises of mechanical characterization to test the stress and strain limit for the conductor wire for cable manufacturing at RT and operation at GHe environment (around 10 K – 20 K), and electrical characterization to check the critical current degradation due to the forces acting on the conductor during operations which can cause strain on the cable. Experimental results show that, MgB_2 conductor produced by Hitachi have the highest stress and strain limit both at RT and 4.2 K as compare to Columbus and HyperTech samples, with a high critical current density, that are investigated in this study. The results show satisfactory performance and can be considered as a strong candidate for the transmission line magnet with the desired operating condition of current and magnetic field with the mechanically stable cable structure.

The future recommendation is even though the single wire shows good results in order to make a final decision on the conductor selection, further testing of MgB_2 cable to be undertaken in order to determine the actual performance of the transmission as several factors during cabling process can affect the overall performance of the superconductor.

Form8・Separate Sheet
(様式8・別紙)

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　名　DHAKARWAL MUKESH

Title
論文題目　STUDY OF MgB_2 BASED TRANSMISSION LINE MAGNET FOR ACCELERATOR SYSTEMS

J-PARC の MR ではニュートリノ実験施設とハドロン実験施設の同時運転ができないためにビームを有効活用できない状況が続いている。この問題を解決するために MR トンネルの中に STRETCHER RING を設置し２つの施設の同時運転を可能にする提案がなされている。本論文では、この STRETCHER RING の主要な磁石となる超伝導結合機能型磁石の設計および基本設計から見込まれた課題に関して計算および実験にて解析を行っている。

ここで超伝導結合型磁石は、鉄ポールを用いた磁石に MgB_2 超伝導線を用いた超伝導送電線を組み合わせた TRANSMISSION LINE（送電線）型の磁石で建設および運転の最適化を目指している。この磁石の設計において２極磁場、４極磁場、６極磁場を同時発生する鉄ポールの形の最適化が必要になる。このために SINGULAR VALUE DECOMPOSITION(SVD)と FEM(OPERA)を組み合わせた手法を開発し、解析的な近似解からまず２極磁場単体での最適化ができることを示し引き続き、４極６極磁場も含んだ結合機能型磁石のポール形状においても最適解が得られることを示した。また初期の解法ではポール形状が非常に複雑で工学的に製造が難しかったため、最適化の手法を改造し工学的に製造しやすいポール形状が実現できる最適化法を確立した。

また超伝導送電線の設計の中で送電線にかかる電磁力が送電線を変形させそれが送電線の劣化や磁場性能の劣化を生み出す可能性があった。そこで変位量と磁場性能の劣化の関係を計算し磁場性能の観点からの許容変位量を求めた。また変位量を力学的に推定するための基礎データーとして室温、液体窒素温度、および液体ヘリウム温度で候補となりうる MgB_2 超伝導線３種類についての応力ひずみ特性を測定した。また送電線の劣化に対する耐性を調べるため MgB_2 超伝導線の引っ張り応力ひずみ下での臨界電流特性をヘリウム温度中で測定しひずみがどの線においても 0.3-0.4%を超えなければ劣化がないことを確認した。3種類の MgB_2 超伝導線のうちの１つは日本国内で新規開発されたものでこのような測定はこれまでされたことがなかったが、他の外国製の線に比べて臨界電流特性が磁場に対しても歪に対しても非常に高い性能を保持していることが確認された、また超伝導送電線の構造モデルを ANSYS で構築しこれらの基礎データーを元に支持構造の計算を行い最低限度必要な支持構造の条件を導き出し今後の詳細工学設計のための指針を得た。また送電線のクエンチ時の温度上昇による損傷を防ぐため送電線に付加する保護銅の量を遮断時間１秒の仮定から推定し必要な銅の量を得た。これによりクエンチ保護に向けての詳細システム設計のための指針が得られた。

これらの業績から、STRETCHER RING の超伝導結合機能型磁石の概念設計が概ね確立され、今後の詳細設計に向けての必要な指針がほぼ確立されたこの業績は非常に大きいと考えら

れる。よって本論文は博士課程の論文として十分なものと考えられる。