氏　　　名	Garfias Dávalos Diego Armando
学位(専攻分野)	博士(工学)
学 位 記 番 号	総研大甲第 2480 号
学位授与の日付	2024 年 3 月 22 日
学位授与の要件	物理科学研究科　核融合科学専攻 学位規則第6条第1項該当
学 位 論 文 題 目	Applicability of High-Temperature Superconducting Stacked-Tape Large-Current Conductors to Fusion Magnets
論 文 審 査 委 員	主　査　平野　直樹 核融合科学コース　教授 柳　長門 核融合科学コース　教授 力石　浩孝 核融合科学コース　准教授 野口　聡 北海道大学　情報科学研究院　教授 伊藤　悟 東北大学　大学院工学研究科　准教授

(Form 3)

Summary of Doctoral Thesis

Name in full - Garfias Dávalos Diego Armando

Title - Applicability of High-Temperature Superconducting Stacked-Tape Large-Current Conductors to Fusion Magnets

Magnets based on High-Temperature Superconductors (HTS) are a promising option for the next-generation fusion devices. HTS can achieve higher current density than Low-Temperature Superconductors (LTS), which results in a more compact magnet geometry, increasing the magnetic field and improving the magnetic confinement performance of fusion plasmas.

Non-uniform current distribution (NUCD) and fast ramp rates are both causes of unstable operation in LTS magnets. It is required to use twisting and transposition of superconducting strands to ensure a more uniform current distribution among them. Slow ramp rates allow the current to redistribute, so each superconducting strand carries a similar amount of current during the charging process of a magnet, defining the threshold for a Ramp Rate Limitation (RRL), above which the current handling capability of an LTS magnet deteriorates.

For superconducting strands, the formation of NUCD is equivalent to the generation of circulation currents flowing across the strands, since there is no resistance along the strands, except in the terminals usually connected through normal-conducting parts. The phenomenon associated with NUCD / circulation currents was widely observed and investigated in LTS Cable-in-Conduit (CIC) Conductors in the 1990s and 2000s. A number of big magnet experiments, such as Demo Poloidal Coil (1994), LHD poloidal coils (1998, 2003), and JT60-SA CS coils (2018), have explored NUCD / circulation current effects on the cryogenic stability and AC losses of CIC conductors.

A circulation current might develop among superconducting strands to cause a large imbalance of current among them, and if the critical current of any strand is surpassed, a normal-transition may occur. Understanding the phenomenon in HTS, accounting for their higher cryogenic stability compared to LTS, will help understand to which threshold it might be a concern for stable operation of large-current HTS magnets based on simple-stacking under DC operation. We here note that the higher cryogenic stability of HTS due to the increased heat capacity operating at a temperature of 20 K or higher suggests that twisting and transposition might not be required for HTS magnets operating especially in a DC current mode. The HTS, especially its second-generation REBCO, generally has the form of a planar tape and may lose part of its current handling

capacity if deformed. Reducing the deformation steps in the manufacturing of a large-current HTS cable also reduces the chances of degrading the total current handling capacity.

When bending a simple-stacking cable into a coil shape, there is a concern about unstable operation caused by the formation of NUCD because of the non-uniform distribution of self-inductances among the combined tapes, and current may not timely redistribute in all the HTS tapes before the superconducting state is lost. Due to the length and confined area differences between inner and outer HTS tapes, the inductance varies among them, and a NUCD gets formed.

At National Institute for Fusion Science (NIFS), high-current HTS cables have been explored, based on the simple-stacking concept from the beginning, to operate especially in DC current mode to be applied to the helical fusion reactor. These are the STARS and WISE conductors. The goal of this thesis research is to determine if there are threshold values of high-inductance and/or fast ramp rate, after which the operation becomes unstable, and a twisted or transposed HTS cable would be required.

In recent years, three experiments have been performed at NIFS, to further clarify the viability of simple-stacking for high-current HTS magnet, in addition to the non-observation of RRL for short conductor samples in the early development phase. One experiment was done for a straight cable, and two experiments for a coil shape. They confirm that simple-stacking HTS conductors have high stability for NUCD (despite the inductance difference of simple-stacking in a coil shape), and no RRL was found below a fast ramp-up rate of 2000 [A/s].

In parallel, numerical calculations have been developed, to clarify the current distribution in both straight conductors (R circuit with terminals) and coil conductors (RL circuit), which consider the superconducting characteristics of HTS conductors.

The first experiment by T. Meulenbroeks et al. confirmed, for a short-straight cable of 1.3 m and 5 HTS tapes, stable operation under the worst-case scenario of NUCD, by feeding the current only through the topmost tape. A second experiment by M. Morbey et al. showed that the contact resistance among HTS tapes was about two orders of magnitude higher than the expected value.

A numerical calculation was then developed based on the resistance of superconducting and copper current paths (R circuit), to understand the current distribution among stacked tapes, accounting for the experimental contact resistance. The results indicate along with the experimental data, that a stepwise transfer of current between tapes occurs after reaching the critical current in each tape, and the process continues as the total current increases.

The second experiment is the 20-kA-class STARS conductor, for a 6 m total length, solenoid coil shape with 3 turns and 600 mm in diameter, operating between 20 K and 40 K. The nominal current of 18 kA achieved with 1 kA/s ramp up and down tests, confirmed stable operation and no discernible degradation for more than 100 cycles. There was a clear observation of the residual magnetic field after the transport current reached zero for ramping down, and it was considered as circulation currents among the 15 REBCO tapes. The time constant of the decay of the residual magnetic field was evaluated to be ~10 s with a condition of 20 K temperature and 8 T of background magnetic field.

Then, the second experiment was done for the 20-kA-class STARS conductor, where I contributed placing additional magnetic (Hall) sensors to track closer the circulation currents. An additional 100 cycles were performed at 18 kA and 1 kA/s, and a maximum ramp rate of 2 kA/s were also achieved. Via the Hall sensors, it was observed that the circulation currents have the same decay rate at different points of the conductor, and their magnitude was higher close to the current lead section of the coil.

For the third experiment, the L-RAISER experiment was designed and developed, a HTS solenoid coil of a 10m total length with 30 turns and 100 mm diameter, using 5 REBCO tapes of 4-mm width on a simple-stacking configuration, operating at liquid nitrogen temperature (77 K). By decreasing the diameter of the solenoid and increasing the number of turns, a higher self-inductance per HTS tape stack was obtained, compared to the 20-kA-class STARS conductor. L-RAISER was tested in two operating scenarios, both under the worst-case scenario of current feeding (by feeding the current through the innermost HTS tape in the stack) and on a better case scenario of uniform current feeding. We tried to observe if good stability was also possible in the worst-case scenario for a coil shape.

For the worst-case scenario of current feeding, a current above the critical current of one REBCO tape at self-magnetic field (200 A) was achieved at a ramp-up rate of 700 A/s. There were no indications of RRL being reached, and a faster ramp rate was deemed possible, yet due to issues with the input current controller, no higher ramp rate was tested. A voltage rose only in the innermost REBCO tape, indicated that it was conducting most of the total current, so to avoid any damage to the tape stack, no higher input current was tested.

Then, the REBCO tapes were cut in the terminals into a staircase-like shape to go to the second test scenario, forming a better case-scenario of uniform current distribution, where a maximum current of 500 (A) and a ramp rate up to 2 (kA/s) were achieved. In this case, the circulation currents were observed with a time constant of ~1 (s).

For a third test scenario, the 5 REBCO tapes were cut before the current lead region, and 5 BSCCO tapes were soldered in each, increasing the contact resistance area by also adding soldered extension on the opposite side of the current lead. The silver matrix in the BSCCO tapes allow for a uniform current feeding, same as the second scenario, A maximum current of 550 A and 2 kA/s were achieved, and the decay time constant of ~3 s, with no indication of a RRL threshold being reached.

An analytical derivation of the circulation currents, for a simplified model of 2 HTS tapes, allows to make comparisons with the experimental data obtained both for the second (20-kA-class STARS) and third experiments (L-RAISER). Observing the evolution of circulating currents over time, help to determine how close where the circulation currents to add up reaching the critical current in a superconducting strand.

Additionally, I developed a constant-temperature numerical calculation, with a circuit considering both the resistance and inductance of the HTS tapes due to their geometry (RL circuit), allowing to get some additional insights regarding the effect of inductance, mutual inductance and contact resistance; into the current transfer between HTS tapes. Then, obtaining the current distribution per HTS tape becomes available for analysis.

Inductance difference among strands, and ramp rate, define the circulation current magnitude that may flow inside the HTS cable. No RRL value has been observed in high-current HTS cables based on simple-stacking so far, from the experiments described. However, when increasing the size towards a bigger coil, the increase in inductance may result in a lower RRL.

The RL numerical calculation was done for both the 20-kA-class STARS and L-RAISER conductors, adapted for a 5 HTS tapes model in both cases, where a similar decay time was obtained to the value observed experimentally. An additional numerical calculation was done, extrapolating for a bigger HTS magnet for DC operation was done, choosing as analysis case a double-pancake (DP) inside ITER Toroidal Field Coil (TFC). The inductance and conductor longitude parameters were estimated, based on the current design of ITER TFC DP with LTS materials, and switching the conditions to a simple-stacking case with HTS materials.

The numerical calculation was also done for a 5 HTS tape simplified scenario. The result indicates that for these ITER TFC DP coil parameters, a ramp-rate of a few kA/s (<8 kA/s) would be available, while reaching at that threshold "only" 95% of the critical current threshold in the innermost HTS tape. Then this 8 kA/s threshold value is deemed a first estimate of what a RRL may be for a large HTS DC magnet based on simple-stacking. In reality, a magnet of such dimensions would be charged at a slow ramp-rate (e.g. 10 A/s or less) and as such, operation would be expected more stable.

As detailed thermal analysis for simple-stacking conductors remains as future work, a zero-dimensional thermal estimation was done for the 20-kA-class conductor. It was determined that under the current distribution from the numerical calculation at 1 kA/s, a marginal temperature rise may occur (<0.1 K for the stabilizer available volume), even with no cooling during the process.

By scanning different combinations of variables in a calculation, it may be possible to keep estimating quantitatively the operation response of bigger coils. Related to experiments, a coil with small inductance and fast ramp rate, as the two coiled experiments described before, may provide a similar circulation current fraction than a big inductance coil with a slow ramp rate, and give a comparable performance for stable operation.

Experimental results so far suggest that there is further room for constructing longer length high-current HTS conductors, with similar stable operation. Numerical calculations suggest that even if inductance variation if present among the HTS tapes, stable operation is available, and the high cryogenic stability of HTS operating (available by operating at e.g. 20 K) causes marginal temperature rise, that can be exhausted by the cooling system. Detailed thermal analysis remains as future work, to further explore how much the critical current and RRL may be reduced, depending on cooling and heat exhaust conditions for a large fusion-size HTS magnet based on simple-stacking.

（別紙１ Separate Sheet 1）

Results of the doctoral thesis defense

博士論文審査結果

氏名 (Name in Full)　Garfias Dávalos Diego Armando

論文題目 (Title)　Applicability of High-Temperature Superconducting Stacked-Tape Large-Current Conductors to Fusion Magnets

Garfias Dávalos Diego Armando 氏から提出のあった総合研究大学院大学課程博士に係る論文の公開発表会ならびに審査会を令和 6 年 1 月 24 日 13 時 30 分から 3 時間かけて実施した。Garfias 氏による研究内容説明と質疑応答を行った後に、これらの結果と提出書類にもとづいて審査を行った。Garfias 氏は、高温超伝導線材を単純に積層した構造の大電流導体について、線材間の非一様な電流分布を伴っても高い安定性を有し、主に直流通電用途では大型コイルにも適用できる可能性があることを、実験ならびに数値解析によって明らかにした。

従来の金属系超伝導線材を集合して構成した大電流導体を用いたコイルでは、導体内部の線材間でインダクタンスの差があると特に電流変化の速い場合に非一様な電流分布が形成され、導体の通電特性を不安定にすることが知られている。このため、集合導体を構成するには超伝導線材を撚り合わせたり転位したりする構造を取ることが不可欠であるとされてきた。一方、高温超伝導線材を集合して大電流導体を構成する場合、特に REBCO 系線材はテープ形状をしているため、撚りや転位の導入には複雑な構造が採用されることが一般的であるが､線材に機械的な無理が生じ､局所的な特性劣化を引き起こす懸念がある。これに対して、核融合科学研究所で開発が進んできた高温超伝導導体の場合には線材間に撚りや転位を全く入れない単純積層構造を世界に先駆ける形で当初より提唱し、機械的に強固で線材劣化の心配の少ない導体が設計・試作されてきた。これは、高温超伝導線材の有する極低温における高い温度マージンにより、撚りや転位のない単純積層構造で非一様な電流分布が形成されたとしても不安定性が発展せず、高い通電特性が得られるためであると考えられ、実際、短尺導体による導体試験においてその安定な通電特性が示されてきた。Garfias 氏の研究では、これをさらなる実験および数値計算で定量的に示し、単純積層導体の大型コイルへの適用可能性について定量的に調べた。

本研究では、高温超伝導線材の単純積層による大電流導体を用いた大型コイルの実現可能性を明らかにするため、3 種類の実験に対する解析が行われている。1 つ目は 4 mm 幅の REBCO 系テープ線材 5 本を単純積層した 1.3 m 長さの直線形状の導体における実験であり、高温超伝導線材の超伝導特性を考慮した電流分布計算コードを独自に開発し、実験結果の解析が行われた。人為的に非一様な電流分布を最初から与えた場合には電流値の高い線材で臨界電流に達した後、線材間で電流の段階的な移動が発生し、合計電流が増加するプロセスが線材全体の臨界電流の総和になるまで継続することを示すことに成功し、実験結果を良く説明できた。

2 番目の実験は、電流容量 20 kA クラスの単純積層導体を用いた全長 6 m、3 ターン、直

径 600 mm のソレノイドコイル形状サンプルの通電実験であり、導体には 12 mm 幅のREBCO 系テープ線材 15 本が使用された。絶対温度 20 K のヘリウムガス冷却、外部印加磁場 8 T において、18 kA の定格電流が 1 kA/s の速い掃引速度において達成され、100 サイクルを超えても安定した通電ができることが確認された。本実験において Garfias 氏が設置したホール素子を用いた磁場計測により、電流減少時に電源からの供給電流がゼロに達した後まで減衰を続ける残留磁場が明確に観察された。これは、電流減少時に積層線材間で生じた非一様な電流分布が緩和する際に線材間を渡る循環電流となるものと解釈でき、その減衰時定数が最大で 100 秒程度となることを観測した。

3 番目の実験では、循環電流の挙動をより明確に把握するため、4 mm 幅の REBCO 系テープ線材を 5 本使用し、全長 10 m、30 ターン、直径 100 mm のソレノイドコイルを設計、製作した。2 番目の実験と比較して小規模および液体窒素冷却による簡便なものであるものの、コイル形状の工夫によって、より高い自己インダクタンスおよび線材各層のインダクタンスの差を得ることができ、速い通電電流の変化により循環電流が有意に生成されることに成功した。この実験では電極端子部における接続抵抗が大きいことが原因で循環電流の時定数は 2 番目の実験より短く 3 秒程度であったが、線材間を渡る際に各線材に発生する電圧とその減衰について計測に成功した。これは、20 kA クラスの単純積層導体では導体内部に電気絶縁を入れた構造のため観察することが難しかったものである。

2 番目と 3 番目の実験結果を説明するため、超伝導線材の特性と形状に起因するインダクタンスの両方を考慮した線材間の電流転流の解析を行い、線材ごとの自己インダクタンス、線材間の相互インダクタンス、端部における接続抵抗の電流転流に与える影響を考慮し、線材間のインダクタンスの差と電流変化率によって、超伝導線材内を流れる循環電流の大きさが決まることを示した。これをもとに、各実験結果のシミュレーションを行い、現状は簡略化したモデルとしているものの実験結果を説明する一定の結果を得たことで、この理解が正しいことを示した。これらの成果は、より大型の超伝導コイルの動作応答を定量的に推定できる手法に発展できるものであり、今後、高温超伝導線材を積層した導体の大型コイルへの適用について、導体長さや通電速度などの適用限界を定量的に評価する際に大きく貢献するものである。

そこで、大型コイルの例として ITER のトロイダル磁場コイルを解析対象として、高温超伝導単純積層導体を用いたダブルパンケーキコイルを仮定した解析検討を行った。この解析からは、数 kA/s のランプレートにおいてもこの導体が適用可能であり、一番内側の高温超伝導テープ線材の電流負荷率が臨界電流値の 95% に達する例が示された。これは、単純積層に基づく大型高温超伝導導体を用いた直流磁石の電流変化速度限界を議論するうえで有益である。実際には、大型超伝導コイルは極めて遅い電流変化速度(たとえば 10 A/s 以下) で励磁されるため、安定な励磁が実現できると予想される。また、数値計算によると、高温超伝導テープ線材間にインダクタンスのばらつきが存在し、線材の一部が臨界に達した場合でも､たとえば 20 K で動作する場合は温度上昇は 0.3 K 程度と極めて小さく、安定に通電できる可能性が示された。

Garfias 氏の研究成果は、核融合炉も含めた大型超伝導コイルの社会実装を実現していく上で重要な成果であり、学術的な価値も高いと評価でき、今後の発展も大いに期待できるものである。Garfias 氏は第一著者である査読付き英文論文 1 編と、共同研究による共著論

文2編を発表している他、第一著者英文論文1編を学術雑誌に投稿予定としている。また、国際会議や国内学会で3件の口頭発表と1件のポスター発表の実績があり、十分な英語表現能力も有していると判断できる。

以上のとおり、Garfias氏の研究内容や発表実績を確認し、審査委員全員一致で本論文が学位の授与に値するものであると判断した。