

한국초전도저온학회
The Korean Society of Superconductivity and Cryogenics

2026 한국초전도저온학회 동계학술대회 초록집

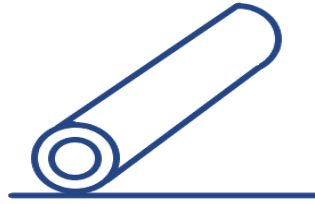
장소: 무주 덕유산 리조트

일시: 2026년 1월 26일 (월) ~ 1월 29일 (목)



CRYOGENIC LIQUID TANKS

- 초저온 저장탱크
- 액화헬륨 Dewar
- LGC 초저온용기
- 극저온 진공단열 압력용기
기술검토 맞춤 제작



VACUUM JACKETED PIPE

- 초저온 진공단열배관 시스템
- 초저온 진공자켓 밸브
- 초저온 진공단열 호스
- 초저온냉매 활용 산업체 제조설비
응용장치 제작/설계



Installation Test & inspection

- 고압가스시공 설치공사 & 기술검토 인허가
- 극저온소재, 부품 등 극저온시험
- 진공배기 및 진공시험
- 열손실 및 극저온장치 검증
- 극저온시험 외부용역 수행
- LNG 액화천연가스, 극저온유체 침지시험

두진의 35년, 대한민국 초저온기술 국산화

극저온 진공단열배관(VIP), 초저온 압력용기,
초저온저장탱크, 극저온 응용장치 제조 및 설치

1994년 설립 이래 두진은 CHART INC(구 MVE)의
LGC 초저온용기, 초저온 저장탱크 등을 국내에
공급하며 국내 극저온시장을 선도해 왔습니다.

국내최초의 진공단열배관(VIP) 제조, 진공용기,
초저온 응용장치, 국내 첫 LNG 충전소 등을
공급하며, 극저온 시장을 선도하였습니다.
연구소, 공학, 반도체, 식품생명, 의료분야 등의
응용 및 발전에 기여하고 있습니다.

두진은 초저온 Engineering을 포함하여
초저온기자재, 장비 등의 설계부터 시공, 인허가
까지 초저온 토탈 솔루션 기업으로서 유지보수,
기술지원 및 공급 체제를 갖추고 있습니다.



국내최초 하이창원(두산중공업)
LH2플랜트 진공단열배관 제작/설치공사



인천공항 T2 LH2 액화수소 충전소(SK)
LH2 TANK SKID 제작(범한메카텍)



국내최초 LH2 제조/충전시설준공(충남TP)



핵융합연구소/가속기연구소
극저온압력용기 제작



국내최초 LCNG 충전소
3개소 준공

(주)두진은 1994년 이래 CHART INC(차트/前 MVE)사의 국내 공식 AGENT 입니다.

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초대의 글

존경하는 한국초전도저온학회 회원 여러분께,

안녕하십니까? 2026년도 한국초전도저온학회 동계학술대회가 오는 1월 26일부터 29일까지, 전북 무주의 아름다운 자연 속에 자리한 무주리조트에서 개최됩니다. 한 해의 연구를 새롭게 시작하는 시점에 회원 여러분과 다시 한자리에 모여 소중한 학술 교류의 시간을 갖게 되어 매우 뜻깊게 생각합니다.

지난 몇 년간 우리 학회는 극한양자기능물질 연구센터(CeQMF), 그리고 응용 분야의 고온초전도자석 원천기술연구단(PRISM) 등 다양한 국가 연구개발 사업을 성공적으로 수행하며, 기초과학과 응용기술 양 측면에서 세계적인 수준의 연구 성과를 지속적으로 창출해 왔습니다. 이번 동계학술대회는 이러한 성과들이 한자리에 모여 공유되고, 향후 연구의 방향과 협력 가능성을 함께 모색하는 뜻깊은 장이 될 것입니다.

학회의 지속적인 발전을 위해서는 우수한 연구 성과가 학문적 성취에 머무르지 않고, 산업으로 확산되어 사회적 가치로 이어지는 선순환 구조가 무엇보다 중요합니다. 이번 학술대회가 학문과 산업을 잇는 연결 고리를 더욱 공고히 하고, 연구 성과의 실질적인 활용과 기술 확산을 촉진하는 계기가 되기를 기대합니다.

또한 최근 국가 연구개발 예산의 점진적인 회복과 함께, 회원 여러분의 연구 환경 역시 점차 개선될 것으로 기대되고 있습니다. 이러한 시점에서 개최되는 이번 동계학술대회가, 새로운 연구 도전을 준비하고 중장기적인 비전을 함께 그려보는 출발점이 되기를 바랍니다.

이번 학술대회에서는 실속 있고 다양한 프로그램을 통해 초전도 및 저온 과학 전반에 걸친 연구 성과와 아이디어가 활발히 교류될 예정입니다. 아울러, 이번 학술대회에서 발표된 소중한 연구 성과를 우리 학회의 SCOPUS 등재 학술지인 Progress in Superconductivity and Cryogenics (PSAC)에 적극 투고해 주시기를 부탁드립니다. 회원 여러분의 많은 관심과 참여를 기대합니다.

끝으로, 이번 동계학술대회를 위해 항상 아낌없는 후원을 보내주시는 여러 기업 및 기관 관계자 여러분께 진심으로 감사드리며, 학술위원회 위원님들과 사무국 관계자 여러분의 헌신적인 노력에도 깊이 감사의 말씀을 드립니다. 또한 보이지 않는 곳에서 학회를 염려하며 봉사해 주시는 모든 분들께도 이 자리를 빌려 감사의 뜻을 전합니다.

무주의 겨울 풍경 속에서 진행될 이번 동계학술대회가, 회원 여러분 모두에게 학문적 영감과 재충전의 시간이 되기를 바라며, 바쁘신 가운데서도 많은 관심과 적극적인 참여를 부탁드립니다.

무주에서 회원 여러분을 직접 뵙기를 고대하겠습니다. 감사합니다.

2026년 1월 26일

한국초전도저온학회 회장 김창영

인사말

존경하는 한국초전도저온학회 회원 여러분 안녕하십니까? 학술위원장 최세용입니다.

2026 한국초전도저온학회 동계학술대회에 참석하시는 회원 여러분과 모든 관계자 여러분께 깊은 환영과 감사의 인사를 드립니다. 우리 학회는 초전도 및 저온공학 분야의 이론, 물성, 소자, 재료, 응용에 이르기까지 폭넓은 연구 교류를 선도하며, 학문적 발전과 산업적 확산에 기여해 온 대표 학회입니다. 특히 회원 여러분의 탁월한 연구성과는 학문적 수월성을 기반으로 양자기술, 거대과학, 의생명·바이오, 전기추진, 국방 등 다양한 분야로 확장되며 국가 과학기술 경쟁력 제고에 이바지하고 있습니다. 이번 동계학술대회가 회원 여러분의 연구 성과를 공유하고 상호 협력을 강화하는 가운데, 초전도·저온공학 분야의 미래 방향을 함께 모색하는 뜻깊은 논의의 장이 되기를 기대합니다.

본 학술대회는 이론, 물성, 소자, 재료, 응용기기, 저온의 6개 부문으로 구성되어, 2026년 1월 26일부터 29일까지 무주 덕유산리조트에서 개최됩니다. 아울러 고온초전도자석 원천기술연구단(PRISM) 세션과 문제해결형 토론 세션 등 두 개의 특별세션을 마련하여, 보다 심도 있는 학술 발표와 토론이 이루어질 수 있도록 준비하였습니다. 이를 통해 국내 초전도·저온공학 연구의 성과가 한층 더 고도화 되고, 연구자 간 협력의 기반이 더욱 공고해지기를 바랍니다. 또한 학술대회에서 발표되는 연구성과는 SCOPUS 등재 학술지인 한국초전도·저온논문지 PSAC(Progress in Superconductivity and Cryogenics)에 투고하실 수 있으며, 동료평가를 거쳐 게재될 예정이오니 회원 여러분의 많은 관심과 적극적인 참여를 부탁드립니다.

끝으로, 본 학술대회의 성공적인 개최를 위하여 아낌없는 성원과 후원을 보내주신 참여 기업 여러분께 깊이 감사드립니다. 더불어 학술대회 준비와 운영을 위해 헌신해 주신 학술위원회 위원 여러분, 좌장님들, 사무국 관계자 여러분께도 진심으로 감사의 말씀을 드립니다.

회원 여러분의 건승과 평안을 기원하며, 무주에서 뵙기를 고대합니다. 감사합니다.

2026년 1월 26일

한국초전도저온학회 학술위원장 **최 세 용**

프로그램 약어 안내

PL : 기초 강연 (Plenary Talk)

IN : 초청 발표 (Invited Talk)

O : 구두 발표 (Oral Talk)

P : 포스터 발표 (Poster Session)

TP : 이론 / 물성 (Theory / Physical Properties)

ED : 전자·소자 (Electronics & Device Applications)

MM : 재료 (Materials)

LA : 응용기기 (Large Scale Applications)

CR : 저온 (Cryogenics)

PR : PRISM 특별세션

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PRISM I

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(Korea Electrotechnology Research Institute)

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기초강연 I

Two Decades of MgB₂ Superconducting Wire Research: Advances and Collaborative Insights from 2005 to 2025

Jung Ho Kim* (University of Wollongong)

Since the discovery of MgB₂ as a high-performance superconductor, extensive research has focused on enhancing its critical current density, mechanical robustness, and low-temperature performance. Over the past two decades, my research has systematically explored the development of MgB₂ superconducting wires, emphasizing multi-filament designs, carbon doping, microstructural optimization, and process predictability. By integrating advanced mechanical processing techniques with in-depth material characterization, I have addressed challenges such as anisotropy, filament breakage, and reproducibility. This presentation will highlight key milestones, including innovations in multi-filament architectures, the impact of carbon doping on superconducting properties, correlations between microstructure and performance, and strategies for scalable production. Recent collaborative studies with Sam Dong R&D, Kangwon National University, and Seoul National University have further advanced process reliability and predictive design strategies, providing a comprehensive roadmap for the continued development of MgB₂ wires in energy, medical, and industrial applications.

기초강연 Ⅱ

Current Situation of KIMM's Cryogenic Refrigerator Development

Hankil Yeom* (Korea Institute of Machinery and Materials)

The research team of cryogenic refrigerators at the Korea Institute of Machinery and Materials began research on cryogenic refrigerators for the first time in Korea in the mid-1980s. During the 1990s, the team accumulated research capabilities by developing compact pulse tube coolers, Stirling coolers, and cryopumps. In the 2000s, we focused on the development of small Stirling coolers for infrared (IR) sensor cooling and cryogenic cooling systems for high temperature superconducting (HTS) power devices (cable, flywheel, magnetic energy storage, and fault current limiter, etc.). Notable achievements include the domestic production and delivery of a compact cryogenic cooler for IR sensor cooling to the military in the early 2000s, achieving approximately KRW 19 Billion in import substitution. Furthermore, the team participated in a project to develop a 400 MHz NMR (nuclear magnetic resonance) system using only HTS wire, achieving 20 K conduction cooling and sub-micrometer vibration level. Recently, we successfully developed a Brayton refrigerator for LNG re-liquefaction with a cooling capacity of 10 kW at 80 K. We are currently developing a cryogenic system for LAES (liquid air energy storage) and a 4.2 K pulse tube cooler for quantum devices.

This presentation will introduce the development process for the 80 K Brayton refrigerator and the current progress of the 4.2 K pulse tube cooler.

Keywords : Stirling cooler, Brayton refrigerator, pulse tube cooler

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전자·소자 I

Fully van der Waals Superconducting Qubits with Microsecond Coherence

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Jesse Balgley (*Columbia University*),
Xuanjing Chu (*Columbia University*),
Ethan G. Arnault (*Syracuse University*),
Martin V. Gustaffson (*RTX BBN Technologies*),
Leonardo Ranzani (*RTX BBN Technologies*),
Madisen Holbrook (*Columbia University*),
Yangchen He (*University of Wisconsin-Madison*),
Kenji Watanabe (*National Institute for Material Science*),
Takashi Taniguchi (*National Institute for Material Science*),
Archana Kamal (*Northwestern University*),
James Hone (*Columbia University*),
Kin Chung Fong* (*Northeastern University*)

Superconducting qubits have traditionally relied on a narrow set of thin-film materials. Broadening this materials palette could enhance performance, expand operating regimes, and enable new device functionalities, yet conventional thin-film processes hinder systematic exploration of novel material combinations. Van der Waals (vdW) materials provide a modular, crystalline platform that overcomes these limitations, offering gate tunability, higher-temperature operation, and compact qubit architectures. However, it remains unknown whether a fully vdW superconducting qubit can maintain quantum coherence, or what mechanisms limit coherence across temperature regimes. Here, we demonstrate quantum-coherent merged-element transmons constructed entirely from vdW Josephson junctions. We observe robust Josephson coupling across 2-12 nm (3-18 atomic layers) of semiconducting WSe₂ and identify a clear crossover from proximity-dominated to tunneling-dominated behavior as the weak-link thickness increases. Leveraging these insights, we fabricate a prototype all-crystalline merged-element transmon whose frequency and anharmonicity closely match design targets. These first-generation, fully crystalline qubits achieve microsecond lifetimes in an ultra-compact footprint without external shunt capacitors. Energy-relaxation measurements, together with microwave characterization of vdW capacitors, indicate that dielectric loss dominates relaxation up to several hundred millikelvin. These results establish vdW materials as a viable and scalable platform for compact superconducting quantum devices.

Gatemon based on Cd_3As_2 Dirac semimetal nanowires

Bongkeon Kim (*Gwangju Institute of Science and Technology*),

Bob M Wang (*University of California at Davis*),

Dong Yu (*University of California at Davis*),

Yong-Joo Doh* (*Gwangju Institute of Science and Technology*)

Gatemons are superconducting qubits tuned via electrostatic voltage rather than magnetic flux, utilizing semiconductor-based Josephson junctions. Among candidate materials, Cd_3As_2 , a topological Dirac semimetal, provides a promising platform due to gate-tunable Josephson energy and potential for topological superconductivity. In this study, we demonstrate gatemons based on Cd_3As_2 nanowires (NWs). We contact Cd_3As_2 NWs with Ti/Al superconducting electrodes to form Josephson junctions and integrate them with NbTi-based superconducting resonators. The qubit frequencies are modulated from 1.5 to 4.3 GHz via electrostatic gating. Furthermore, time-domain measurements demonstrate damped Rabi oscillations, with the Rabi frequency scaling linearly with drive amplitude and exhibiting a chevron pattern with detuning. These results represent the first demonstration of topological material-based gatemons, paving the way toward topological quantum computing architectures.

This study was supported by the National Research Foundation of Korea through the Basic Science Research Program (RS-2018-NR030955, RS-2023-00207732, RS-2025-02317602), the ITRC program (IITP-2025-RS-2022-00164799) funded by the Ministry of Science and ICT.

Graphene Josephson Junction-based Adjustable Power and Frequency Microwave Generator

Jayeon Kim (*Pohang University of Science and Technology*),

Seong Jang (*Northeastern University*),

Gil-Ho Lee* (*Pohang University of Science and Technology*)

Graphene, a monolayer of carbon atoms known for its exceptional electron transport properties, has demonstrated considerable promise in applications involving Josephson junctions and the superconducting proximity effect. Its gate-tunable charge density enables precise control over the number of conduction channels, directly influencing the critical current of Josephson junctions. Josephson junctions, formed by weakly coupling two superconductors with a nanoscale insulator or mesoscopic conductor, emit microwaves when subjected to a DC voltage, owing to the AC Josephson effect, $2eV/\hbar = d\phi/dt$ corresponding to 0.483 GHz/ μV . In this study, we implemented a GHz-range microwave generator composed of graphene-based Josephson junctions and shunt resistors. The generated signals in our system exhibited power proportional to the square of the critical current and matched the theoretical power predictions within the same order of magnitude. This study focuses on manipulating graphene's gate-tunability to develop a cryogenic microwave generator capable of adjusting power and frequency. The proposed system is particularly suitable for integration into cryogenic high-frequency measurement setups, where local generation of microwaves reduces dependence on external signal sources and minimizes losses in long coaxial transmission lines. Furthermore, the cryogenically generated signals are inherently free from thermal noise and provide stable, high-quality microwave excitation, thereby offering a valuable tool for advanced low-temperature spectroscopy and high-frequency quantum transport experiments.

Quantum-Noise-Limited Broadband Readout for Axion Dark Matter Search

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Saebyeok Ahn (*Dark Matter Axion Group of Institute for Basic Science*),
Sergey V Uchaikin (*Dark Matter Axion Group of Institute for Basic Science*),
Pallavi Parashar (*Korea Advanced Institute of Science & Technology (KAIST)*),
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SungWoo Youn* (*Dark Matter Axion Group of Institute for Basic Science*)

The axion is a well-motivated candidate for the dark matter in the Universe. Searches for axion dark matter require ultra-sensitive detectors capable of identifying extremely weak signals arising from feeble interactions with ordinary matter. In this presentation, we investigate broadband readout approaches for axion scanning near the quantum noise limit. We demonstrate the performance of a Josephson parametric amplifier (JPA), analyze its intrinsic bandwidth limitations, and present strategies to extend the effective scanning range using parallel JPA configurations. We also introduce a complementary broadband scheme that combines state-of-the-art microwave bolometers with the heterodyne variance method, enabling wide frequency coverage with high sensitivity. In addition, we discuss prospects for graphene-based bolometers and single-photon detectors based on underdamped Josephson junctions. Finally, we present the concept and initial measurement results of a bolometer-based readout and discuss its potential advantages for future axion dark matter experiments.

PRISM I

Progress Report on Development of Common Base Technologies for High Temperature Superconductor Magnet

Seungyong Hahn (*Seoul National University*),

Jung Tae Lee (*Seoul National University*),

Haigun Lee (*Korea University*),

Sangkwon Jeong (*Korea Advanced Institute of Science & Technology*),

Jaemin Kim (*Standard Magnet*),

Jung Ho Kim (*University of Wollongong*),

Sangjin Lee* (*Seoul National University*)

From April 2022, a 5-year collaborative R&D program, titled “Project for Research and Innovation in Superconducting Magnet,” has been underway with support from the National Research Foundation of Korea (NRF) and the Ministry of Science and ICT. This paper presents the outcomes of the first sub-project, “Development of Common Base Technologies for High Temperature Superconductor Magnet (RS-2022-NR068574),” conducted for four years of the 5-year initiative. Through this project, achievements include the development of base technologies for high-temperature superconductor magnets and the facilitation of their application in other projects. The project has also contributed to the establishment of a platform for developing human resources in superconductivity research. Furthermore, accomplishments of active leadership in collaborative research initiatives with international institutions in major countries. Various committee activities are being carried out to ensure the successful operation of the PRISM program. The research results and development efforts carried out in the 4th year of the project will be discussed. Also, the plans for the last year of the entire project will be introduced.

This work was supported in part by National R&D Program through the National Research Foundation of Korea (NRF) funded by Ministry of Science and ICT (RS-2022-NR068574), and in part by the Applied Superconductivity Center, Electric Power Research Institute of Seoul National University.

Progress Report on Development of Design Technologies for High Temperature Superconductor Magnet

Wonju Jung (*Seoul National University*),
Jihyung Kim (*Jeju National University*),
Seungyong Hahn* (*Seoul National University*)

Since April 2022, a five-year joint R&D program entitled “Project for Research and Innovation in Superconducting Magnet” has been conducted with funding from the National Research Foundation of Korea (NRF) and the Ministry of Science and ICT. This large-scale effort brings together more than 220 researchers from 24 institutions, organized into seven specialized research areas. Among these, Project 2 (Development of Design Technologies for High-Temperature Superconductor Magnets, RS-2022-NR068569) aims to establish advanced design tools for various magnet configurations addressed in the sub-projects. This presentation summarizes the progress achieved over the first four years of the five-year program, including the development of core models for electromagnetic, mechanical stress, and thermal analyses, as well as studies on AC characteristics. As the program enters its final year, key outcomes from ongoing research and future research directions will be presented.

This work was supported in part by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT)(RS-2022-NR068569), and in part by the Applied Superconductivity Center, Electric Power Research Institute of Seoul National University.

고성능 고온초전도 자석용 선재의 기반기술 개발 과제의 2단계 1차년도 연구 결과

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최근 정부에서 초혁신경제 15대 프로젝트에 초전도 분야를 선정하는 등 상용화를 위한 다양한 연구개발 및 관심이 고조되고 있으며 관련하여 당 과제의 경우 고온초전도 자석의 상용화를 위해 필수적인 고온초전도 선재의 성능향상을 위한 연구를 총 4년째 수행하고 있으며 2026년 하반기에 최종 마무리될 것이다. 주요 연구 내용은 고온초전도 선재의 길이 방향 임계 전류 및 형상 균일성 향상 기술 개발, 고온초전도 선재의 고자기장 응용을 위한 자기장 특성 향상 기술 개발, 극박금속기관 가공 및 측정기술 개발, 고온초전도 선재의 전기-기계적 특성평가 기술 개발, 그리고 고강도 MgB_2 장선재 및 집합도체 개발이다. 아울러 고온초전도 선재의 절연 재료 개발 및 고자기장 특성 평가 기술 개발도 진행중이다. 본 발표에서는 이상의 연구개발 목표를 달성하기 위하여 최근 1년간 수행된 연구개발 내용 및 성과를 보고할 것이며, 특히 고온초전도 선재의 형상 균일화 기술 및 형상 측정 기술의 고도화, PLD 공정 최적화를 통한 자속고정점 도입 고자기장 특성 향상, 고온초전도 선재의 전기-기계적 특성 평가 결과, 고강도 MgB_2 선재 제조

및 집합도체 개발, 절연 소재 개발 등의 성과에 대해 발표하고자 한다. 본 사업을 통해 고온초전도 마그네틱의 고성능화 및 명품화를 위해 필수적인 고온초전도 선재의 상용화를 위한 핵심 기반기술을 확보할 것이다.

Keywords : 고온초전도 박막선재, 길이방향 균일성, 고자기장 특성, 전기기계적 특성평가, MgB_2 선재

이 성과는 정부(과학기술정보통신부)의 재원으로 한국연구재단의 지원을 받아 수행된 연구임 (RS-2022-NR068578).

이론 / 물성 I

Artificially designed magnetic Co atomic structures on a proximity-induced superconducting Cu(111) surface

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The interplay between superconductivity (SC) and Kondo lattices provides an interesting platform to explore the exciting physics of strongly correlated electron systems with induced superconducting pairing. Based on STM tip-induced atom-manipulation techniques, which offer a robust bottom-up approach for fabricating artificial low-dimensional structures on various substrates, we can now investigate and engineer Kondo systems at the atomic scale [1-2]. Here, we present scanning tunneling microscopy and spectroscopy investigations of artificially constructed cobalt (Co) lattices on a superconducting copper (Cu) surface. We introduce a superconducting pairing correlation to a normal conducting Cu(111) surface by growing Cu thin films on a conventional superconducting niobium (Nb)(110) substrate. For a single Co adatom on Cu(111), we observe a characteristic spectroscopic signature of a dip-shaped Fano resonance, accompanied by multiple peaks and low-energy sub-gap excitations within the proximity-induced superconducting gap. Through precise atom-by-atom assembly of Co adatoms, we fabricate artificial Co lattices with varying interatomic distances. This enables us to observe the spectroscopic evolution of both the Fano resonance and the sub-gap excitations, depending on the size of the artificial structures. Corroborated by a preliminary theoretical model, we discuss these spectral evolutions for artificial Co lattices in view of both Kondo and low-energy excitations within the superconducting gap. Our findings pave the way for designing novel artificial hybrid correlated electron systems incorporating a superconducting condensate [3].

- [1] L. Schneider et al. Proximity superconductivity in atom-by-atom crafted quantum dots. *Nature* 621, 60-65 (2023).
- [2] J. Figgins et al. Quantum engineered Kondo lattices. *Nat Commun* 10, 5588 (2019).
- [3] H. Kim et al. Artificially designed magnetic Co atomic structures on a proximity-induced superconducting Cu(111) surface, submitted (2025).

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Tracing the dynamics of superconducting order parameter via transient third harmonic generation

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Ultrafast optical control of quantum systems is an emerging field of physics. In particular, the possibility of light-driven superconductivity has attracted much of attention. To identify nonequilibrium superconductivity, it is necessary to measure fingerprints of superconductivity on ultrafast timescales. Recently, nonlinear THz third-harmonic generation (THG) was shown to directly probe the collective degrees of freedoms of the superconducting condensate, including the Higgs mode. Here, we extend this idea to light-driven nonequilibrium states in superconducting $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$, establishing an optical pump-THz-THG drive protocol to access the transient superconducting order-parameter quench and recovering on few-picosecond timescales. We show in particular the ability of two-dimensional TH spectroscopy to disentangle the effects of optically excited quasiparticles from the pure order-parameter dynamics, which are unavoidably mixed in the pump-driven linear THz response. Benchmarking the gap dynamics to existing experiments shows the ability of driven THG spectroscopy to overcome these limitations in ordinary pump-probe protocols.

재료 I

2세대 고온 초전도 선재의 단면 균일화 압연 기술 개발

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본 연구는 2세대 고온 초전도 선재의 형상 불균일성 문제를 해결하고, 코일 제작 시 요구되는 기계적 및 전기적 안정성을 확보하기 위한 압연 기반 형상 제어 기술을 제안한다. 일반적으로 고온 초전도 선재는 제작 과정에서 중심부에 비해 양 끝단이 두꺼운 독본(dog-bone) 형상을 나타내며, 이는 코일 권선 시 불균일한 응력 분포를 유발할 수 있으며 켄치(Quench) 발생 가능성을 높인다. 이를 개선하기 위해, 본 연구에서는 압연 공정을 적용하여 초전도 박막의 손상을 최소화하면서 양 끝단에 압력을 가해 중심부와 양단의 두께 차이를 줄이고자 하였다. 압연된 선재의 단면 형상을 관찰한 결과, 중심부와 양단의 두께 편차가 현저히 감소하며, 전체적으로 직사각형에 가까운 단면 형상이 구현되었음을 확인하였다. 두께 측정장치를 통해 압연율에 따른 두께 변화를 정량적으로 분석하였으며, Hall sensor를 이용한 간접적인 임계전류 특성을 평가하여 초전도 특성 저하 없이 형상 균일화가 가능함을 확인하였다. 이러한 압연 기술은 고온 초전도 선재의 자석 응용을 위한 효과적인 형상 균일화 공정으로, 향후 고성능 무절연 초전도 코일을 비롯한 다양한 초전도 응용 기술의 신뢰성을 높이는 데 크게 기여할 것으로 기대된다.

이 성과는 정부(과학기술정보통신부)의 재원으로 한국연구재단의 지원을 받아 수행된 연구임 (RS-2022-NR068578).

Challenges in standardization of the electromechanical property test method for REBCO tapes under cryogenic uniaxial tension

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As part of the standardization activities of Work Group 5 in IEC/TC90, round-robin tests have been proposed and successfully executed to establish the standard of the test method for measuring the mechanical properties and the superconducting properties in various composite superconducting wires. They have contributed significantly to the establishment of international standards (IS). With the development of high-performance HTS wires and their applications to coils/magnets, establishing standard test methods for evaluating their electromechanical properties (EMPs) at cryogenic temperatures has become important. However, no IS for the electromechanical properties of superconducting tapes has been established. In this context, an international round-robin test was conducted for the first time to establish a test method for the electromechanical properties of HTS composite wires at liquid nitrogen temperature. Tensile tests were performed to measure the critical current as a function of stress intervals at LN₂ temperatures for three REBCO tapes and one BSCCO tape. Samples were distributed to 6 participating laboratories in 5 countries for testing according to specified guidelines. Test results were evaluated using statistical tools to identify the main causes of scatter and assess their magnitude. The EMPs assessed were the reversible stress limit (R_{rev}) and the retention stress limit (R_{ret}) for the degradation of critical current (I_c) under tensile load, which were determined using a stress-based test method. The I_c measurements were conducted using broad and narrow stress intervals, and reversible and retention stress limits were defined based on specific 99 % I_{c0} recovery and 95 % I_{c0} retention criteria. From an industrial perspective, ensuring the validity and effectiveness of these criteria is important in establishing standards for the commercial trade of HTS wires. To this end, RRT was established to reflect industry needs and to establish an IEC standard for a testing method to measure the electromechanical properties of HTS REBCO tapes easily. RRT results are presented and discussed. Progress after RRT is also reported.

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Enhanced flux pinning property through BZO-based artificial pinning centers in (Bi, Pb)-2223 superconductors

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We investigated the effect of BaZrO₃ (BZO) particles with varying concentrations ($x = 0 - 1.0$ wt.%) added into the (Bi, Pb)-2223 superconducting phase, focusing on the critical current density (J_c) and pinning force density (F_p). Our results reveal that BZO additions influence the platelike grain structure of (Bi, Pb)-2223, with small spherical grains embedded in the superconducting matrix, confirmed as BZO particles by SEM and EDS analysis. Excess conductivity analysis indicates a dimensional crossover from 2D to 3D, reflecting an expanded 3D fluctuations region that enhances both J_c and F_p under low and high magnetic fields at 45 K and 65 K. Overall, these study demonstrates that dimensional modifications induced by BZO incorporation strengthen interlayer coupling and significantly improve pinning force density. Enhanced interlayer coupling, associated with an extended coherence length, promotes straight vortex lines that are more effectively pinned. These findings highlight the potential of BZO particles as a secondary phase for advancing (Bi, Pb)-2223 superconducting in power cable applications.

Keywords: (Bi, Pb)-2223, BZO, artificial pinning center, critical current density, pinning force density

PRISM II

The Fourth Year Annual Progress Report on Development of Core Technology for Ultra-High Field and High Field-Homogeneity High-Temperature-Superconductor Solenoid Magnet

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Ultra-high field solenoidal magnets are one of the most fundamental elements in both basic science and industrial technology. Since April 2022, we have been developing core technologies for high-temperature-superconductor solenoidal magnets wound using ReBCO tapes, which operate at ultra-high fields and have high field homogeneity. The core technologies cover seven fundamental ones: design, winding, joint, lead, structure, cooling, and operation. In Phase 1, we successfully developed these seven technologies, including a prototype magnet design targeting a field strength of 20 T, 300 ppm@10mmDSV uniformity, and a 50 mm room-temperature bore. We verified the reliability of the developed technology by achieving a field strength of 5.4 T with a sub-assembly consisting of 8 double pancake coils (DPC) in the middle section out of 18 DPCs of the entire magnet. In Phase 2, we have constructed additional 10 DPCs of the planned design to complete the entire magnet assembly, and will finally verify the developed technology by confirming the predicted magnetic field strength of 20 T and achieving the field uniformity of 300 ppm@10mmDSV through evaluation. This presentation reports the R&D progress during the first year of Phase 2. During this period, the stability of the 5.4 T sub-assembly and its operating system was confirmed through initial testing. Prior to full-scale fabrication, the design was re-examined based on a detailed evaluation of the conductor's critical current. To support this more, we are developing a system to measure the in-field performance of the conductors. Currently, for the final 20 T prototype assembly, the fabrication of the cryostat and all remaining DPCs has been completed, and the entire system is under assembly. Initial charging tests are planned to be conducted shortly, followed by a three-to-four-month system optimization and modifications.

Keywords : high-temperature superconductor, solenoid magnet, liquid-helium-free conduction cooling,
ultra-high field

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대전류 토로이드형 고온초전도 자석 제조를 위한 원천기술 개발

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최근 국제적인 저탄소 정책 및 RE100 활동 등과 더불어 핵융합과 그린 데이터 센터에 대한 필요성이 확대되고 있다. 핵융합로의 핵심기술인 고온초전도 자석은 플라즈마를 가둬두고 제어를 가능하게 하며, 데이터센터에는 전력 손실을 줄이고 효율을 높이기 위한 초전도 케이블 및 부스바로 활용할 수 있다. 과제5에서 진행하고 있는 “고온초전도 마그넷 기술개발사업” 중 “대전류 토로이드형 고온초전도 자석의 핵심기술 개발” 과제에서는 핵융합에 사용되는 대전류 토로이드형 고온초전도 자석 제조를 위한 원천기술과 데이터센터 및 DC 그리드 등의 전력손실 절감을 위한 대전력 케이블에 대해 사업화를 전제로 한 연구를 진행 중에 있다. 본 과제에서는 1) 총 64개의 HTS 선재가 적용되는 Twisted 적층도체형 케이블 제작 및 장치 개발 2) 국내만의 특수한 설계가 반영된 Non-Twisted 형태의 적층도체형 케이블 설계 및 제작, 장치 개발 3) 다양한 대전류 케이블을 평가하기 위한 평가장치 및 평가기법을 개발하고 있다. 또한, 4) 실제작 대전류 케이블을 적용한 D형 코일(10kA-turn급)일 개발은 PRISM 연구단에서 내세우고 있는 7대 기반 기술(설계, 권선, 구조, 접합, 리드, 냉각, 운전/평가)이 모두 적용될 수 있는 분야로써, 차년도에 설계 및 제작, 검증을 완료하기 위한 사전연구를 진행중에 있다. 본 발표에서는 현재까지의 연구 현황과 계획중인 연구계획을 상세히 소개하고 그 결과에 대해 논의하고자 한다.

Keyword: High-temperature superconductor, Twisted and No-Twisted Cable for high current, Stacked tape cable conductor, D-Shape coil

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고성능 고온초전도 레이스트랙 코일 핵심기술 개발과제 진행 현황

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미래형 모빌리티 개발의 필요성이 대두됨에 따라 기존 전기추진 시스템의 성능을 뛰어넘는 가볍고 강력한 고출력밀도의 전기추진 시스템이 요구되고 있다. 새로운 전기추진 시스템 구현을 위하여 ‘고온초전도 레이스트랙 코일’이 적용된 초전도 전기추진 시스템이 주목을 받고 있다. 이러한 기술적 요구에 대응하고 세계적 수준의 관련 기술 확보를 위해, 과학기술정보통신부의 ‘고온초전도 마그넷 기술개발 사업’의 일환으로 ‘고성능 고온초전도 레이스트랙 코일 핵심 기술 개발’을 최종 목표하는 연구 과제가 진행되고 있다. 본 과제는 초전도 전자석을 구성하는 7대 기반기술(설계, 권선, 구조, 접합, 리드, 냉각, 운전/평가)을 중심으로 고온초전도 레이스트랙 코일에 특화된 핵심기술 개발은 물론 산업화 연계를 위한 설계 및 제작 공정 표준화, 성능평가 기반 확보 등의 산업화 중계기술을 확보할 계획이다. 현재 2단계 1차년도까지 진행되었고, 1단계 1, 2, 3차년도에 개발된 요소기술들을 총합한 레이스트랙 코일을 회전형 모델기에 설치하여 전자기/열 평가를 수행하였고, 제작된 레이스트랙 코일의 전기적/열적 사이클을 반복하여 약 4개월 동안 100회 반복 장기 신뢰성 평가를 수행하였다. 2단계 2차년도에는 레이스트랙 코일을 회전상태에서 전자기/열/기계적 특성을 평가하여 핵심부품 고성능화를 달성하고 액체수소의 직접사용 및 간접사용을 대비하여 극저온 냉각기술 및 극저온 냉각 핵심부품의 설계/제작 기술을 검증할 계획이다. 전도성 에폭시를 적용한 특성저항 조절 기술, 모빌리티 및 대형선박용 회전기를 고려한 레이스트랙 코일 적용성 연구들을 수행할 계획이다. 본 발표에서는 현재까지 달성한 연구실적과 2단계 2차년도에 핵심적으로 진행 중인 연구내용에 대해 소개하고자 한다.

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고속충방전 새들, 다주기 위글러 고온초전도자석의 핵심기술개발 1단계 연구 결과 및 2단계 추진 계획

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“고온초전도 마그넷 기술개발사업”에서 수행 중인 “고속충방전 새들, 다주기 위글러 고온초전도 자석의 핵심기술 개발” 과제는 입자가속기에 적용될 수 있는 새들, 위글러 두 가지 형상의 고온초전도자석을 7대 HTS 전자석 제조기반기술을 중심으로 제작하고 보완, 검증하는 것을 목표로 하고 있다. 본 발표에서는 2025년 수행된 핵심 연구내용인 (1) 전용 로봇팔을 이용한 HTS 새들코일 권선 시험, (2) 극저온 환경에서 동작하는 적분자장 측정장치 개발, (3) 스프레이 방식의 고체절연법 개발, (4) 200 mH급 더미 로드를 이용한 고속충방전 제어 실험, (5) 설계 및 제작중인 위글러 시험용 자석의 설계를 소개한다.

Keyword: High Temperature Superconductor, Saddle Coil, Multipole Wiggler, Multi-axis Winding machine

This work was supported in part by National R&D Program through the National Research Foundation of Korea(NRF) funded by Ministry of Science and ICT(RS-2022-NR068573), and in part by the Applied Superconductivity Center, Electric Power Research Institute of Seoul National University.

전자·소자 Ⅱ

Electric field control of superconductivity and quantized anomalous Hall effects in rhombohedral tetralayer graphene

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Inducing superconducting correlations in chiral edge states is predicted to generate topologically protected modes with exotic quantum statistics. Past experimental efforts have focused on engineering interfaces between superconducting materials and quantum Hall systems. We present rhombohedral tetralayer graphene as an ideal platform for these hybrid interfaces leveraging the gate-tuned ground states between intrinsic superconductors and quantum anomalous Hall states. We find multiple superconducting states, including one phase with critical temperature $T_c = 55\text{mK}$ at superlattice filling $\nu \approx -3.5$ for layer polarization corresponding to a weak moire potential. Quantized anomalous Hall effect occurs at $\nu = -1$ for weak moire potential, with a measured Chern number $|C| = 4$. Remarkably, gate voltage can also trigger nonvolatile switching of chirality in the quantum anomalous Hall state, enabling reconfiguration of topological edge mode networks in devices with local gate. We also find fractional and integer Chern insulators at zero magnetic field via thermodynamic compressibility measurements at $\nu = +2/3$ and $+1$. These findings open new possibilities for hybrid interfaces between superconductors and topological edge states in the low-disorder limit.

Toward Quantitative Distinction Between Photon Assisted Tunnelling and Floquet-Andreev Replicas in Graphene Josephson Junctions

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Engineering quantum states via light-matter interaction has emerged as a powerful paradigm in condensed matter physics. A notable example is the Floquet-Bloch state, generated by time-periodic driving of Bloch wavefunctions in crystalline solids [1-3]. Previously, we investigated steady Floquet-Andreev states in graphene-based Josephson junctions by analyzing spectral replicas of Andreev states using superconducting tunnelling spectroscopy. However, similar spectral replicas can also arise from the photon-assisted tunnelling (PAT) effect, in which tunnelling electrons undergo inelastic scattering with incident photon, making it challenging to distinguish between the two phenomena. To resolve this ambiguity, we introduced a superconducting microwave resonator to quantitatively control both the amplitude and polarization of the microwave applied to the junctions. Our approach would provide a systematic framework to differentiate Floquet-engineered quantum states from PAT effect, and provide a versatile platform for coherent control of quantum matter via light-matter interaction.

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Josephson Diode Effect Associated with a Coherent Magnetic Moment in $\text{FeTe}_{0.55}\text{Se}_{0.45}$ van der Waals Junctions

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Iron-based van der Waals Josephson junctions offer a tunable platform to elucidate how interfacial magnetism reshapes superconducting transport. Here we fabricate vertical $\text{FeTe}_{0.55}\text{Se}_{0.45}$ (FTS) van der Waals Josephson junctions using a Peltier-stage-assisted micro-cleaving and stacking process to maintain high interfacial quality, and we probe their low-temperature transport to uncover the interfacial physics that governs device behavior. The junctions exhibit robust Josephson characteristics and show ferromagnetic-resonance signatures in the current-voltage response, indicating a magnetic degree of freedom coupled to junction dynamics. Magnetic-field interference and radio-frequency measurements reveal anomalous Fraunhofer patterns together with half-integer Shapiro steps, demonstrating that the Josephson current-phase relation is strongly non-sinusoidal and contains substantial higher-order contributions beyond $\sin \phi \sin \phi$, including pronounced $\sin(2\phi) \sin(2\phi)$ and $\cos(\phi) \cos(\phi)$ terms. In the same devices we observe a Josephson diode effect with nonreciprocal critical currents; its magnitude and polarity evolve systematically with in-plane magnetic field and temperature and remain finite at zero applied field. Taken together, these correlated signatures support a coherent magnetic moment confined to the FTS junction interface that couples to the Josephson phase, reshapes the phase-dependent supercurrent, and provides a microscopic picture for robust nonreciprocal Josephson transport in iron-based van der Waals junctions.

이론 / 물성 Ⅱ

Manipulating Correlated Electronic Structures and Magnetism in Ruthenates and Nickelates

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Control of emergent phenomena in quantum materials is a central goal of quantum technology. Strong electronic correlations play a key role in this control, enabling sensitive manipulation of otherwise robust quantum phases. Oxide heterostructures include thin films and superlattices are promising directions for the manipulation of the emergent phenomena of quantum materials, include correlated electronic structures and magnetism [1].

In this talk, we discuss two classes of quantum materials, ruthenates and nickelates, and their manipulation in superlattices and thin films. The theoretical computations are performed using the density functional theory plus dynamical mean-field theory framework. For ruthenates, we investigate a $[\text{SrRuO}_3]_1\text{-}[\text{SrTiO}_3]_1$ superlattice under epitaxial strain. We show that epitaxial strain provides an effective control knob for the metal-insulator transition and the emergence of ferromagnetism in this system, in good agreement with experimental observations [2,3]. For nickelates, we study $[\text{LaNiO}_3]_n$ ($n=1,2,3$) thin films grown on $[\text{LaAlO}_3]$ substrates. We show that reduced dimensionality induces an orbital-selective Mott phase in the monolayer, whereas bilayer and trilayer films exhibit well-defined Fermi surfaces involving all active e_g orbitals, in good agreement with experimental observations [4]. These results suggest that future investigations focusing on the control of doping, interlayer coupling, and epitaxial strain could provide a promising pathway to realize new emergent quantum phases, including unconventional superconductivity.

Keywords : Quantum materials, Oxide heterostructures, Ruthenates, Nickelates, Density functional theory plus dynamical mean-field theory, Metal-insulator transition, Orbital-selective Mott phase, Magnetism

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Spin nematic state induced by quantum entanglement in a pyrochlore iridate

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Quantum entanglement is a fundamental resource underlying exotic phases and hidden orders in condensed matter systems, yet its direct quantification remains a major challenge. Here, we establish a spectroscopic framework for detecting and characterizing highly entangled electronic phases using resonant inelastic X-ray scattering (RIXS) and reveal the existence of a nematic phase. We show that entanglement across atomic sites produces distinctive interference patterns that cannot be explained by classical product states, and our model reproduces these features with high fidelity, enabling the extraction of hidden quantum states. Using this entanglement-resolved RIXS analysis, we identify a spin-nematic order emerging as a hidden order parameter. Furthermore, complementary Raman spectroscopy measurements corroborate this finding by revealing a possible two-magnon bound state below the lowest single-magnon excitation energy. This provides independent support for the presence of magnetic quadrupolar spin-nematic order coexisting with the all-in-all-out phase. Our results demonstrate that many-body entanglement can generate hidden emergent orders inaccessible to mean-field descriptions, opening a new avenue for probing and engineering unconventional phases in quantum materials.

저온 I

Microgravity Boiling Experiments: Visualization and Comparison of Liquid-Vapor Interface Dynamics

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A visualization experiment was conducted to investigate the behavior of the liquid–vapor interface of cryogenic fluids under microgravity conditions. Understanding interfacial dynamics in microgravity is essential for the design and operation of cryogenic propellant management systems in space applications, particularly under phase-change conditions such as boiling. In this study, experimental results obtained from two different microgravity platforms are compared: a 150 m-class free-fall facility, Asan Green Tower, and a microgravity experiment conducted at ZARM in Germany.

Due to the practical and safety limitations associated with the direct use of cryogenic fluids, a room-temperature surrogate fluid, Novec 7100, was employed to simulate key boiling and interfacial characteristics of cryogenic liquids. The experimental setup consisted of a transparent liquid container equipped with a controllable heat source installed at the bottom of the container. Boiling was initiated prior to the onset of microgravity, and the subsequent evolution of the liquid-vapor interface was recorded during the microgravity period using high-speed visualization techniques.

The experiments focused on examining the effects of liquid fill level and heater thermal capacity on the interfacial motion during and after boiling in reduced gravity. The results demonstrate that, in the absence of buoyancy-driven forces, the liquid-vapor interface exhibits markedly different dynamics compared to normal gravity conditions, including sustained interface deformation, bubble coalescence, and migration governed primarily by surface tension and inertial effects.

These findings provide valuable experimental insight into boiling-induced interfacial behavior under microgravity and contribute to the validation of ground-based microgravity simulation techniques. The comparative analysis presented in this study is expected to support future experimental design and modeling efforts related to cryogenic fluid management in space systems.

Keywords : microgravity, cryogenic, fluid, boiling, bubble, interface

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What Governs Convection in Cryogenic Systems

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Cryogenic fluids play a crucial role in various fields, including space transportation systems, cooling of electronic devices, and emerging energy technologies. Because of their extremely low boiling points, introducing cryogenic liquids into room-temperature systems triggers vigorous phase-change phenomena and demands more efficient utilization and storage strategies. In this work, an integrated theoretical, numerical, and experimental investigation is conducted to improve the understanding of convective phenomena in cryogenic systems. First, chilldown processes in cryogenic transfer lines and surfaces are examined, and the dominant factors governing the process are systematically analyzed. Second, transient natural convection within cryogenic storage tanks under various operating conditions is investigated, with particular emphasis on the physical mechanisms underlying thermal stratification. Finally, the findings are integrated to clarify convective behavior in cryogenic environments and its implications for system design and operation. The results offer insights that may help improve cryogenic fluid management and support future research on cryogenic engineering.

Keywords : Cryogenic transfer line, Cryogenic storage tank, Quenching, Thermal stratification

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Measurement of MLI effective thermal conductivity according to compression pressure variation

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In cryogenic liquefied hydrogen (LH₂) transfer systems for hydrogen transport vessels, the application of highly flexible hoses is essential to accommodate vibrations induced by ship motion as well as thermal contraction and expansion. In such flexible transfer piping, multilayer insulation (MLI), composed of alternating spacers and reflective foils, is employed as the primary thermal insulation method to minimize heat losses under cryogenic conditions. In general, increasing the number of MLI layers significantly enhances radiative heat-shielding performance. However, under actual operating conditions, flexible hoses are subjected to repeated mechanical deformations such as bending and twisting, which can lead to localized over-compression of the internal MLI layers. Such compressive deformation alters the interlayer spacing and structural configuration of the MLI, increasing contact heat transfer and potentially degrading the overall thermal insulation performance of the system. In this study, operating environments in which MLI experiences localized compression due to mechanical deformation of flexible piping were simulated, and the effects of compressive conditions on thermal insulation performance were quantitatively evaluated. Test specimens consisting of 50 layers of MLI were prepared under identical conditions, and the effective thermal conductivity of the MLI was measured under compressive stresses of 5 MPa and 10 MPa. To minimize direct contact between reflective foils induced by compression and to isolate changes in the intrinsic thermal insulation characteristics of the MLI, the spacers were fabricated with relatively larger dimensions compared to conventional designs. In addition, experiments were conducted at 20 K, 77 K, and 170 K, corresponding to temperature conditions encountered in practical cryogenic transfer pipelines. The experimental apparatus was configured with a centrally located heater and symmetric compressive loads applied from both sides, and the results obtained from both sides in a single experiment were

averaged to reduce measurement uncertainty. The experimental results show that the effective thermal conductivity measured at 10 MPa is approximately 2-3 times higher than that measured at 5 MPa. This increase is attributed not only to the shortening of heat-transfer paths under higher compressive stress but also to spacer deformation, which increases direct contact between reflective foils and thereby facilitates heat transfer. The findings of this study provide valuable baseline data for the design of MLI and the assessment of thermal insulation reliability in cryogenic LH₂ transfer systems and superconducting applications, where mechanical deformation of flexible piping must be taken into account.

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응용기기 I

고온초전도 자석 켄치 검출을 위한 병렬 경로 기반의 하이브리드 필터링 고정밀 절연 DAQ 시스템 개발

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고온초전도(HTS) 자석 및 전기차 배터리 진단 분야에서는 고전압 공통 모드 환경에서 발생하는 마이크로볼트(μV) 단위의 미세 과도 신호를 정밀하게 측정해야 한다. 그러나 기존 계측 시스템에서 노이즈 제거를 위해 강한 필터를 적용할 경우, 신호의 위상 지연(Group Delay)이 발생하여 켄치(Quench)와 같은 급격한 과도 현상을 정확한 타이밍에 포착하기 어렵다는 한계가 존재한다. 이에 본 연구에서는 신호 무결성을 확보하기 위해 병렬 경로(Parallel Path) 아키텍처를 적용한 고정밀 절연 DAQ(Data Acquisition) 시스템을 개발하였다. 제안하는 시스템은 입력 신호를 분기하여, 필터를 거치지 않은 원본 신호(Raw Path)와 아날로그 필터를 통과한 신호(Filtered Path)를 독립된 ADC 채널을 통해 동시에 획득한다. 이를 통해 노이즈가 제거된 데이터와 원본의 과도 응답 특성을 실시간으로 비교 분석할 수 있어, 필터링에 의한 신호 왜곡 없이 고신뢰성의 측정이 가능하다. 개발된 모듈은 채널 간 500 Vrms 이상의 절연 내압과 24-bit의 고분해능 성능을 갖추었으며, HTS 코일 충방전 실험을 통해 시스템의 유효성을 검증하였다. 본 기술은 향후 고정밀 계측이 요구되는 미래 모빌리티 및 거대 과학 설비의 핵심 진단 장비로 활용되는 것이 기대된다.

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Repetitive Short-Circuit Endurance Validation of an HTS Coil for SFCL via Turn-to-Turn Spacing Optimization Based on 3D Electromagnetic-Structural Coupled Analysis

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HTS coils for superconducting fault current limiters (SFCLs) are repeatedly exposed to large electromagnetic forces during short-circuit events, making mechanical integrity and performance drift—such as critical current reduction, resistance change, and variation in the first-peak current limiting behavior—key reliability concerns. This work defines turn-to-turn spacing as a primary design variable and employs a 3D electromagnetic-structural coupled finite element analysis to quantify Lorentz-force-induced stress hotspots under representative short-circuit conditions. Based on the simulation results, a spacing design window is established to mitigate stress concentration, and HTS coils are fabricated accordingly. Repetitive short-circuit endurance tests are then conducted using two commercially available REBCO coated conductors from different suppliers to assess the robustness of the proposed design approach. During the tests, the first-peak limiting characteristic, critical current retention, and resistance variation are tracked cycle by cycle. The coils demonstrate stable operation without meaningful degradation after the target number of repetitive fault events, indicating that the stress-informed spacing optimization effectively supports repetitive short-circuit endurance. The presented design–analysis–test workflow provides a practical guideline for enhancing SFCL HTS coil reliability and demonstrates applicability across different conductor types.

Interface Control Strategies to Suppress Critical Current Degradation of HTS Conductors in Epoxy-Impregnated No-Insulation Coils

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No-insulation (NI) winding enables current to bypass locally through adjacent turns via turn-to-turn electrical contact under local defects or overcurrent conditions, thereby enhancing thermal stability and self-protection capability. To secure the mechanical stability of NI coils, epoxy impregnation is often applied. However, it has been reported that thermal stress induced by the mismatch in coefficients of thermal expansion between epoxy and high-temperature superconducting (HTS) conductors during the cooling process can be transferred to the conductor, leading to delamination and degradation of the critical current. When the influence of epoxy impregnation on NI windings is evaluated solely based on the critical current, performance degradation at the conductor level may not be sufficiently revealed due to the current bypass characteristics inherent to the NI structure. In particular, even under identical transport current conditions, a reduction in the effective current contributing to magnetic field generation can alter the central magnetic field and the current-field transfer characteristics. As a result, changes in critical current and magnetic field performance may be observed inconsistently. In this study, a performance evaluation criterion is proposed to quantitatively assess conductor performance degradation in epoxy-impregnated NI structures by jointly employing critical-current-based and magnetic-field-based metrics. In addition, interface control structures aimed at mitigating stress transfer across material interfaces are introduced. Specifically, an evaluation framework is established in which the effects of bypass current on performance assessment are separated and analyzed by combining terminal-voltage-defined critical current, the magnetic field generation efficiency derived from the relationship between transport current and central magnetic field, and turn-to-turn contact resistance.

Furthermore, stainless-steel overbanding, PTFE spray coating, PTFE tape insertion, and polyimide tape insertion are proposed as interface control strategies. In future work, NI test specimens incorporating each interface control structure will be fabricated, and comparative experiments with directly impregnated structures will be conducted. Through these experiments, changes in critical current and magnetic field characteristics after cooling and repeated thermal cycling will be quantitatively analyzed. The objective of this study is to address the limitations of performance evaluation based solely on critical current and to establish a more appropriate conductor-centered performance assessment criterion that incorporates magnetic field characteristics.

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이론 / 물성 Ⅲ

Probing superconducting gap phases of Fe(Se,Te) by circular dichroism angle-resolved photoemission spectroscopy

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Iron-chalcogenide superconductors Fe(Se,Te) have attracted considerable interest as candidates for topological superconductor, as they host topological surface states in the normal state and exhibit unconventional superconductivity. More recently, multiple experiments have reported time-reversal symmetry breaking (TRSB) in the superconducting phase of Fe(Se,Te) indicating a complex superconducting order parameter and motivating discussions of possible chiral superconductivity in this system. Despite these advances, direct experimental constraints on the phase information of the superconducting gap remain largely unexplored.

In this presentation, we report a circular dichroism angle-resolved photoemission spectroscopy (CD-ARPES) study on Fe(Se,Te) across the superconducting transition. Using circularly polarized light, we observe a pronounced change in the dichroic signal between the normal and superconducting states. The temperature dependence of this signal shows that it emerges below $T_c \sim 14$ K, closely tracking the onset of superconductivity. By comparing the experimental results with theoretical calculations for different candidate gap symmetries, we demonstrate that the observed CD signatures place meaningful constraints on the allowed superconducting gap phase. Our results provide an experimental clue for further discussions of TRSB and unconventional superconductivity in this topological superconductor candidate and highlight CD-ARPES as a phase-sensitive probe of superconducting gap symmetry.

Long-Range Josephson Coupling through Atomically Abrupt Superconductor-Topological Material Interfaces

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Phase-coherent superconducting proximity in topological materials is critically limited by the transparency and cleanliness of the superconductor-topological material (SC-TM) interface, which is readily degraded by oxidation, polymer residues, and process-induced disorder during conventional top-contact fabrication. Here we implement a planarized, pre-patterned superconducting bottom-contact architecture in which recessed MoRe/Au electrodes are defined on the substrate prior to van der Waals crystal transfer, eliminating on-flake lithography and wet processing after transfer and thereby preserving a clean interface. Compared with conventionally fabricated Josephson junctions (JJs), pre-patterned devices exhibit an order-of-magnitude (or larger) enhancement in the Josephson figure of merit $I_c R_N$; notably, the advantage increases with junction length and Josephson coupling persists up to 3 μm . Contact resistance analysis indicates that this enhancement cannot be explained by a trivial reduction in normal-state contact resistance. Cross-sectional STEM/EDS (scanning transmission electron microscopy with energy-dispersive X-ray spectroscopy) directly reveals atomically abrupt, chemically well-separated SC-TM interfaces. Demonstrated in WTe_2 (quasi-ballistic) and $\text{Bi}_{1.5}\text{Sb}_{0.5}\text{Te}_{1.7}\text{Se}_{1.3}$ (BSTS; diffusive) junctions and verified by Fraunhofer interference and Shapiro steps, this approach provides a reliable route to clean, micrometer-scale Josephson platforms for van der Waals topological materials.

Topological insulator Josephson junction

Adaptive Parallel Tempering for Frustrated Classical Heisenberg Systems

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Ara Go* (전남대학교)

Geometrical frustration in classical Heisenberg systems gives rise to a complex free-energy landscape with numerous local minima, posing significant challenges for conventional Monte Carlo simulations. Parallel tempering, which employs multiple replicas at different temperatures and allows configuration exchanges between replicas, can substantially enhance sampling efficiency and accelerate convergence. In this study, we investigate how the exchange probability and the convergence of Monte Carlo estimators depend on the number of replicas within a fixed temperature range. Our goal is to determine an appropriate replica count that ensures efficient sampling while minimizing computational cost. To this end, we develop adaptive schemes for updating the temperature ladder, designed to maintain suitable swap acceptance rates between neighboring replicas. The performance of these adaptive strategies is evaluated through simulations of a classical Heisenberg model on a triangular lattice, demonstrating improved convergence and sampling efficiency compared to non-adaptive approaches.

재료 II

Development of a Real-Time Reel-to-Reel Thickness Measurement System for HTS CCs

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Yujin Seong (Korea Electrotechnology Research Institute),
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High-temperature superconducting coated conductors (HTS CCs) are indispensable for advanced applications, including high-field magnets, power transmission cables, and medical imaging devices. However, thickness inhomogeneity in the superconducting layer can severely degrade its performance and mechanical stability of HTS magnets. Currently, the lack of continuous, non-destructive monitoring systems during reel-to-reel (R2R) processing hinders effective quality control and production efficiency. To address this challenge, we developed a continuous R2R thickness measurement system utilizing a high-precision chromatic confocal displacement sensor. This system enables real-time monitoring with an accuracy of $\pm 1 \mu\text{m}$ and generates comprehensive 3D thickness profiles. While the current system operates stably at speeds up to 300 m/h, the system design incorporates vibration suppression mechanisms to support industrial-scale production rates of up to 600 m/h. By ensuring precise real-time quality assurance, this system is poised to enhance the manufacturing yield and reliability of HTS CCs required for critical high-field applications.

Keywords: HTS CCs, Thickness measurement system, Reel-to-reel, Confocal laser sensor

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Multi-functional properties of superconducting and near-ambient pressure hydrogen storage in TaNb₂HfZrTi high entropy alloy

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The coexistence of superconductivity and hydrogen storage within a single material platform offers a transformative pathway toward multifunctional energy and quantum technologies. Here, we report the dual superconducting and hydrogen storage functionalities in bulk TaNb₂HfZrTi high-entropy alloys (HEAs) synthesized by mechanical alloying followed by hot-press sintering. The optimized sample (HP-900) exhibits a sharp superconducting transition at $T_c = 7.8$ K, a high upper critical field $\mu_0 H_{c2}(0) = 10.85$ T, and a critical current density exceeding 2.9×10^5 A cm⁻² at 4 K, surpassing values reported for arc-melted and spark-plasma-sintered counterparts. The enhanced superconducting performance arises from refined grain boundaries, strong flux pinning, and high densification achieved through controlled hot pressing. Remarkably, the same bulk HEA demonstrates outstanding hydrogen storage capacity ($H/M = 2.23$, 3.8 wt% at 20 °C, 100 bar) without degradation of superconductivity, representing the highest room-temperature storage performance among bulk HEAs. These results establish TaNb₂HfZrTi as a multifunctional platform uniting superconductivity, mechanical integrity, and hydrogen storage capability-offering new design principles for energy-efficient cryogenic and solid-state hydrogen systems.

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Correlation between Heater Temperature Distribution, Phase and Longitudinal I_c Variation in R2R-PLD YBCO Tapes

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In reel-to-reel pulsed laser deposition (R2R-PLD), the superconducting performance of $Y_1Ba_2Cu_3O_{7-d}$ (YBCO) coated conductors often changes along the tape length, even when the deposition conditions are kept the same. Previous studies have separately reported temperature non-uniformity along the heater, position dependent changes in phase, and I_c variation in long length YBCO tape. However, the direct relationship between these factors has not yet been fully clarified. In this study, we aim to examine the connection between heater temperature distribution, phase, and I_c variation along the tape length in YBCO coated conductors grown by R2R-PLD. The temperature distribution and thermal history experienced by the tapes are measured using a thermocouple array attached to a dummy tape that follows the same reel-to-reel transport path. YBCO thin films are then deposited under identical conditions, and X-ray diffraction (XRD) mapping is carried out along the tape length and width to evaluate local phase. The variation of I_c along the tape length is measured using a hall-probe-based non-contact I_c measurement system, which allows direct comparison with the XRD result. By combining these measurements, this work aims to clarify how heater temperature distribution affects local film growth, phase, and superconducting performance in R2R-PLD processes. The results are expected to provide useful guidance for understanding and reducing performance variations in long-length YBCO coated conductors.

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응용기기 Ⅱ

Analysis and verification of a Non-Twisted HTS Stacked-in-Conduit Conductor (SICC)

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The development of next-generation fusion reactors is currently under active discussion, with preliminary design studies in progress. One proposed approach is the construction of a Compact Pilot Device (CPD) to demonstrate burning plasma operation. High-temperature superconducting (HTS) magnets are regarded as a key enabling technology for CPD, as they enable the generation of high magnetic fields required for advancing fusion energy systems. The development of reliable HTS conductors is a prerequisite for HTS magnet applications. In this context, a non-twisted high-temperature superconducting stacked-in-conduit conductor (HTS SICC) has been designed, and a prototype SICC sample is currently under fabrication. The conductor design and jacketing process are under evaluation to assess their mechanical feasibility and manufacturability. To ensure structural integrity and reliability during the winding process for coil fabrication, extensive structural analyses have been performed to identify critical technical challenges. This study presents the preliminary design of the non-twisted HTS SICC, the results of structural analyses applied to the prototype conductor, and initial experimental test results.

Estimating REBCO Coil Contact Resistance by Measuring Tape-Wise Pressure-Dependent Surface Contact Resistivity

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Inter-turn contact resistance in REBCO coils strongly affects electromagnetic response, stability, and quench behavior, particularly in no-insulation (NI) coils. However, the quantitative relationship between tape-level contact properties and coil-level contact resistance has not yet been fully clarified and is still under active investigation. In this study, the contact resistance of an NI REBCO coil is estimated by experimentally measuring pressure-dependent surface contact resistivity at the tape level and comparing it with direct measurements obtained from a coil wound using the same conductor. Tape-to-tape surface contact resistivity is measured using a custom experimental setup in which controlled normal pressure is applied to REBCO tape samples. The contact resistivity is evaluated as a function of applied pressure and exhibits a systematic decrease with increasing pressure. Based on these measurements, the pressure-dependent contact characteristics of the REBCO tape are obtained. Using the same tape, a no-insulation (NI) coil is wound with controlled winding tension to achieve a target inter-turn contact resistance estimated from the tape-level measurements. The effective inter-turn contact resistance of the NI coil is evaluated through electrical measurements during current excitation. The measured coil-level contact resistance is then compared with values estimated from the tape-wise surface contact resistivity, taking into account the winding geometry and inter-turn pressure. The results demonstrate the applicability of tape-level pressure-dependent contact resistivity measurements for estimating coil-level contact resistance in NI REBCO coils. This approach may provide a practical framework for evaluating and designing NI coils based on experimentally obtained tape-wise contact properties.

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Surface-Modified Nano- Al_2O_3 /Paraffin Impregnants for Thermally Reliable HTS Coils

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Younghoon Kim (*Korea University*),
Min Kyu Sun (*Korea University*),
Kihong Kim (*Korea University*),
Haigun Lee* (*Korea University*)

초전도 코일에서 함침재료는 턴 간 기계적 고정과 진동 감소, 절연 신뢰성, 그리고 열전달 경로 확보에 핵심적이다. 그러나 현재 함침재료 중 파라핀계 함침은 저온에서의 균열 발생과 낮은 열전도도를 이유로 활용도가 떨어지는 재료이다. 기존 설계·평가에서는 함침재를 균질 고체로 가정하거나 에폭시 기준 지표를 인용하는 경우가 많아, 파라핀 왁스 계열에서의 표면화학-열거동-코일의 상관관계가 충분히 다뤄지지 않았다. 본 연구는 이러한 부분을 보완하고자, 올레산(OA)으로 표면 개질한 나노 Al_2O_3 (OA- Al_2O_3)를 각각 5/10 wt%로 도입한 파라핀 복합 함침재를 제조하여, 표면 결합(FT-IR), 결정상(XRD), 열거동(DSC)을 분석하고, 고온초전도 코일 적용 시 열적 전기적 특성에 미치는 영향을 정리하였다. 이를 위해 순수 파라핀과 Al_2O_3 5/10 wt%, OA- Al_2O_3 5/10 wt% 조성의 복합재를 비교분석하였다. 이 결과를 바탕으로, 파라핀 복합 함침은 Al_2O_3 필러에 따른 유효 열전도도 향상과 OA 기반 계면 안정화로 인한 열전도도의 개선에 대해 논의하고자한다.

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이론 / 물성 IV

Disorder vs entanglement:
the microscopic mechanism of strange metal

Sang-Jin Sin* (Hanyang University)

Recently, it is known that all to all interaction with spatially Random coupling in 2+1 dimension leads to the linear resistivity. We present a reason why all to all interaction can be canonically realized in a class of quantum material.

Field Theoretic Description of Superconductors of s-wave with and without inhomogeneity

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SeungJun Jeon* (*Sungkyunkwan University*),
Hanwool Song (*KIAS*)

We discuss the effective field theory including the Cooper pair, photon, and phonon with or without inhomogeneity for description of conventional and superconductors. The obtained field theoretical results are compared with those of the well-known Ginzburg-Landau theory and other field theory models of a complex scalar field. The following issues are clarified in this talk in the framework of the constructed field theory:

- Similarity and difference among our field theory, the Ginzburg-Landau theory, and the Abelian Higgs model.
- Comparison of the Abrikosov limit and the Bogomolny-Prasad-Sommerfield limit.
- Additional types in addition to type I and II superconductors and the role of phonon.
- Neutral and charged topological vortices.
- Energetics for flux pinning and the vortex trapping by lattice.

Keywords: Abrikosov limit as BPS, neutral and charged vortices, flux pinning, type of superconductivity

AIMD study on the CDW and double-dome superconductivity of CsV_3Sb_5 from a thermal decoupling perspective

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Dongkyu Lee (*Seoul National University*),
Gun-Do Lee* (*Seoul National University*)

The AV_3Sb_5 ($A = \text{K}, \text{Rb}, \text{Cs}$) family of kagome materials hosts a variety of intriguing phenomena, including charge density wave (CDW) order, superconductivity, nematicity, and time-reversal symmetry breaking. Notably, these materials exhibit a double-dome superconducting phase in temperature-pressure and doping phase diagrams, the origin of which remains poorly understood. In this study, we employed ab initio molecular dynamics (AIMD) simulations to explore the CDW transition in a kagome material CsV_3Sb_5 . In our AIMD simulation, we identified the structural change to the CDW and confirmed that the CDW structure is a staggered TrH structure that matches the lowest energy structure from DFT calculations. In our simulations, the CDW temperature is much lower than the CDW temperature in the experiment. In our study of CsV_3Sb_5 , we found the thermal decoupling [1] which was reported in cuprates superconductors, and the thermal decoupling was found to be the cause of the temperature difference. We also found that the CDW transition temperature gradually decreases under pressure and superconducting double dome of CsV_3Sb_5 under high pressure can be explained by thermal decoupling point of view.

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포스터세션

TP : 이론 / 물성

ED : 전자·소자

MM : 재료

LA : 응용기기

CR : 저온

Data-Driven Bath Initialization for Efficient DMFT Bath Fitting: A Study of Layered Perovskites

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 Jungmoo Lee (*Chonnam National University*),
 Ara Go* (*Chonnam National University*)

Bath fitting is a major computational bottleneck in exact-diagonalization (ED)-based dynamical mean-field theory (DMFT), where a continuous hybridization function must be approximated using a finite set of discrete bath parameters. This discretization leads to a rugged optimization landscape with many local minima, rapidly increasing computational cost with bath size, and strong sensitivity to the initial guess, which can result in slow convergence or convergence to unphysical solutions. Here we present a data-driven bath initialization scheme that learns physically informed initial guesses for bath parameters, thereby accelerating DMFT bath fitting for layered perovskites. As a testbed, we consider the layered ruthenate. We construct lattice Hamiltonians including both and hopping processes and map them to an impurity problem. To enable controlled dataset generation, we set so that the self-energy vanishes and the target hybridization function is fully determined by the noninteracting lattice problem. Starting from Slater-Koster parameters that reproduce the known band structure, we systematically vary oxygen positions to generate symmetry-preserving structural distortions, extract tight-binding parameters for each structure, and obtain converged bath parameters by conjugate-gradient minimization of the Weiss-field mismatch. We use the lattice hybridization function as input features and the converged bath parameters as labels. Time-reversal symmetry is exploited to reduce the dimensionality of both features and labels. We train a kernel ridge regression model with an RBF kernel to map to physically valid bath initializations that respect symmetry and relevant sum rules. Compared to a heuristic baseline, the machine-learned initialization reproduces the target hybridization more accurately and yields a significantly lower initial . Under identical fitting criteria, it consistently reduces the number of iterations required for bath fitting. Overall, this approach improves both accessibility and efficiency of ED-DMFT by automating physically informed bath construction and mitigating sensitivity to initialization.

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Active Learning-Adaptive Truncation Configuration Interaction for DMFT: Bath-Size Dependence in Sr_2RuO_4

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Ara Go* (*Chonnam National University*)

Dynamical mean-field theory (DMFT) has become an essential tool for investigating strongly correlated materials. The impurity solver is a central component of DMFT, and among the available solvers, exact diagonalization (ED) provides complementary strengths to methods such as quantum Monte Carlo and the numerical renormalization group. However, ED is critically limited by the accessible Hilbert-space size, which restricts the number of bath orbitals that can be included. As a result, ED often struggles to represent the hybridization function with sufficient fidelity. In this work, we investigate the dependence of DMFT results on the number of bath orbitals using a newly developed impurity solver, active learning–adaptive truncation configuration interaction (AL-ATCI). We quantify how limitations in bath discretization affect impurity observables and lead to discrepancies between impurity and lattice quantities. Applying our method to the multiorbital correlated material Sr_2RuO_4 , we demonstrate that AL-ATCI can handle realistic systems with Slater-Kanamori interactions while maintaining computational efficiency. Our results clarify the bath-size requirements for reliable ED-like DMFT calculations and demonstrate how AL-ATCI mitigates finite-bath effects.

Superconducting and structural properties of Co-Zr alloys synthesized via self-propagating high-temperature synthesis

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Co-Zr alloys exhibit diverse magnetic properties, but CoZr_2 and CoZr_3 are conventional superconductors with critical temperatures (T_c) of approximately 5.2 K and 3.4 K, respectively [1]. These compounds have typically been synthesized by the arc-melting method. In this study, we employ self-propagating high-temperature synthesis (SHS), which utilizes exothermic reaction energy and has rarely been applied to intermetallic superconductors [2]. In a previous study, although the SHS synthesis targeting nominal CoZr_2 produced a multiphase containing CoZr_3 , and unidentified phases, the T_c was found to be enhanced (~ 7 K). To clarify the origin of enhanced T_c , we systematically varied the starting powder ratio from $\text{Co:Zr} = 1:2$ to $1:1$ by reducing the Zr concentration. X-ray diffraction and resistivity measurements were performed on selected samples from each composition. The observed T_c enhancement in SHS-synthesized nominal CoZr_2 is likely associated with off-stoichiometry relative to the ideal $1:2$ composition, based on comparisons with previous studies [1, 3]. We will discuss the relationship between structural variation and superconductivity in the Co-Zr alloys.

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Alteration of MgB₂ thin films by 1MeV metalloid Ge-ion irradiation

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In this study, we studied the physical properties of MgB₂ thin films irradiated by Ge-ion. The films were synthesized via hybrid physical-chemical vapor deposition and then exposed to 1-MeV Ge ions at irradiation doses of 1×10^{13} , 5×10^{13} , and 7×10^{13} ions/cm². Resistivity against temperatures measurement showed a systematic suppression of the superconducting transition temperature, with T_c decreasing from 37.36 K to 22.32 K as the irradiation dose increased. Notably, the sample irradiated at 5×10^{13} ions/cm² exhibited the highest upper critical field ($\mu_0 H_{c2}$), indicating an optimal dose for balance between defects introduction and superconducting property enhancement. The irradiation process introduces lattice defects such as vacancies and structural disorder, which act as vortex pinning centers, thereby limiting vortex motion and enhancing $\mu_0 H_{c2}$. X-ray diffraction analysis revealed irradiation induced lattice distortions, which impede current and contribute to the degradation of T_c . Raman spectroscopy further demonstrated a monotonic reduction in the electron-phonon coupling strength with increasing irradiation dose. In the low-frequency regime, reflectance spectra showed a progressive decrease with higher irradiation levels, while optical conductivity analysis indicated pronounced charge localization effects. The ion irradiation induced modifications influence the superconducting behavior of MgB₂ and provide important insights for optimizing ion-irradiated MgB₂ materials for practical applications.

Breakdown of the Mott State in La_2CuO_4 Films on LSCO

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The Mott insulator La_2CuO_4 (LCO) exhibits insulating behavior despite its half-filled electronic configuration. To investigate its electronic structure while avoiding charging effects, we synthesized LCO thin films on a metallic $\text{La}_{1.75}\text{Sr}_{0.25}\text{CuO}_4$ (LSCO) layer, which acts as a charge reservoir. Angle-resolved photoemission spectroscopy (ARPES) measurements revealed that a 10-unit-cell-thick LCO film grown on LSCO displayed a sharp Fermi surface with near-zero hole doping, indicating a breakdown of the Mott insulating state. To determine the effective range of this metallic influence, we performed thickness-dependent ARPES studies. For LCO films thinner than 10 unit cells, finite hole doping was observed, likely due to cation intermixing and charge carrier redistribution. As the LCO thickness increased, the spectral weight at the Fermi level gradually decreased; however, a distinct Fermi edge remained visible even in 50-unit-cell-thick samples. Remarkably, the Fermi edge persisted even when an insulating LaSrAlO_4 (LSAO) layer was inserted between LCO and LSCO, suggesting that the Mott state suppression extends beyond direct charge transfer.

Growth and Characterization of LiV_2O_4 Films by Pulsed Laser Deposition

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Dongjin Oh (*Massachusetts Institute of Technology*),

Changyoung Kim* (*서울대학교*)

LiV_2O_4 (LVO) has recently attracted significant attention as a 3d transition-metal oxide exhibiting a sharp flat band near the Fermi level at low temperatures, characteristic of a heavy-fermion system. In this study, LVO thin films with a thickness of approximately 60 nm were grown on SrTiO_3 (001) and SrTiO_3 (111) substrates using pulsed laser deposition (PLD). To address the lithium volatility that likely occurs during the laser ablation process, Li_2CO_3 and V_2O_5 powders were used to fabricate a Li-excess PLD target with a nominal composition of LiV_2O_4 . The crystalline quality of the films was evaluated by high-resolution X-ray diffraction (HR-XRD) to determine the lattice constant and the full width at half maximum (FWHM) of the film peaks. Temperature-dependent resistivity (R-T) measurements were performed using a Physical Property Measurement System (PPMS) to confirm whether the films exhibit heavy-fermion behavior at low temperatures. Furthermore, in-situ ARPES measurements were carried out on the LVO films using an ultrahigh-vacuum transfer system connecting the PLD and ARPES chambers.

Strain-tuned orbital-dependent electronic correlations in FeTe thin films

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Changyoung Kim* (*Seoul National University*)

Iron chalcogenides exhibit rich phenomena which are governed by orbital-dependent electronic interactions and strong electronic correlation. In particular, many studies have explored orbital selectivity in FeTe through Se doping. Here, applying tensile strain to thin films allows us to precisely control the system without other impurities that may arise from chemical doping to investigate the emergent behaviors in FeTe. Using angle-resolved photoemission spectroscopy, we observe a spectral weight transfer between d_{xy} and d_{z^2} orbitals, evidence of an orbital-selective Mott phase (OSMP). Beyond OSMP, we reveal hitherto unobserved strain-induced effects, distinct from chemical doping. The evolution of d_{xz} orbital demonstrates how electron hopping mechanism plays an important role in defining the electronic properties of the system. Our findings highlight a direct correlation between epitaxial strain and the evolution of electronic structures in FeTe.

Optical study on charge density waves in Cr-doped CsV₃Sb₅ Kagome metals

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Many studies on CsV₃Sb₅ doped with various dopants have been conducted to explore the relationship between charge density waves (CDWs) and superconductivity. Among them, only Cr-doped CsV₃Sb₅ (Cs(V_{1-x}Cr_x)₃Sb₅) exhibits a simultaneous weakening of the CDW and superconductivity as the doping concentration increases. In this study, we investigated two Cr-doped CsV₃Sb₅ samples with doping levels of $x = 0.024$ and 0.057 using optical spectroscopy with a focus on the CDW phase. From a two-Drude-Lorentz model analysis, CDW-related selective spectral weight transfer was confirmed to exist in the Cr-doped samples and systematically changed with Cr doping. We observed that the spectral weight of the narrow Drude component decreased as the Cr doping increased, leading to a reduction in superconductivity. We extracted the CDW gaps of the two Cr-doped samples and found that the CDW order was suppressed more rapidly with Cr doping than expected based solely on the transition temperature. Furthermore, by combining the experimental results with first-principles calculations, we found that the low-energy interband transitions were significantly enhanced by Cr doping. We expect that our results will provide insights into understanding the simultaneous weakening of both the CDW and superconductivity in Cr-doped CsV₃Sb₅.

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Development of Critical Current Measurement System for High-Temperature Superconductors under a 15 T Background Magnetic Field

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Second-generation (2G) high-temperature superconducting (HTS) wires have emerged as key materials for high-field magnet applications due to their high critical current density characteristics. However, due to the strong anisotropy arising from the crystal structure of REBCO tapes, magnetic field angle-dependent critical current (I_c) data is essential for designing practical superconducting devices. Currently, domestic infrastructure for measuring the magnetic field angle-dependent I_c of HTS tapes under high magnetic fields is limited. In response to this need, we developed and constructed a customized measurement system. In this study, we evaluated the performance of an I_c Measurement System (ICM) capable of characterizing the angular dependence of HTS tapes within 15 T center field magnet. Ultimately this study is expected to contribute to the optimized design and accurate performance prediction of practical high-field magnets by providing an extensive database of magnetic field angle-dependent I_c characteristics.

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Optical study on the Kondo-lattice compound YbCuAs₂ via a comparative study with YCuAs₂

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Electrical resistivity measurements on YbCuAs₂ exhibit canonical Kondo-lattice behavior, featuring a broad local maximum near 125 K and a secondary hump around 20 K, indicative of strong hybridization between 4f and conduction electrons. Here, we investigate single crystals of YbCuAs₂ and YCuAs₂ using optical spectroscopy at various temperatures across a wide energy range. Both compounds crystallize in the tetragonal HfCuSi₂-type structure (P4/nmm). In the infrared regime, the optical conductivity of YCuAs₂ shows a temperature-dependent trend similar to that observed iron-based superconductors, commonly attributed to Hund's coupling. Interestingly, the optical conductivity of YbCuAs₂ exhibits an additional feature associated with the hybridization between 4f and conduction electrons and an enhanced conductivity across the measured energy range relative to YCuAs₂. These results indicate a substantial f-electron contribution near the Fermi level, consistent with the calculated density of states. By subtracting the optical conductivity of YCuAs₂ from that of YbCuAs₂, we isolate a remnant optical conductivity attributable to f electrons, revealing a well-defined hybridization gap along with a pronounced peak centered at approximately 0.4 eV. Given that YbCuAs₂ and YCuAs₂ share the same transition metal, it is reasonable to consider that Hund's coupling may also be operative in YbCuAs₂. Consequently, YbCuAs₂ emerges as an interesting correlated-electron system wherein Kondo physics and Hund's coupling may coexist.

Engineering Magnetic Ground State of RuO₂ Thin Film via Controlling Dimensionality

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The collinear magnetism with antiparallel magnetic order and broken time-reversal symmetry, as known as altermagnetism, has recently garnered tremendous interest from both theoretical and experimental condensed matter physics. The rutile RuO₂ has been considered as one of the altermagnetic candidate material expected to exhibit large spin-splitting in electronic band structure. However, many recent researches suggest that the magnetic ground state of the stoichiometric rutile RuO₂ is non-magnet and its magnetic ground state is very sensitive to extrinsic factors like stoichiometry, strain, etc.. Here, we suggest that the dimensionality might be the key of engineering the strongly correlated phenomena and the magnetic ground state of RuO₂. To manipulate the dimensionality of rutile RuO₂, we utilized pulsed-laser deposition (PLD) and angle-resolved photoemission spectroscopy (APRES). We succeeded to measure indications of the strongly correlated behavior of atomically thin RuO₂ film using ARPES. It imply that the Mott insulator-driven antiferromagnetism might be stabilized in atomically thin RuO₂ film.

Presence or absence of CDW phase in Kagome magnets

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The kagome metal FeGe has emerged as a model system for studying the interplay between magnetism, charge order, and lattice instabilities. It exhibits a rare coexistence of A-type AFM order and a short-range $2\times 2\times 2$ CDW phase [1]. The strong correlation between the CDW and a debated incommensurate spin order highlights the coupling among spin, charge, and lattice degrees of freedom [2-4]. Despite extensive studies, including attempts to tune the CDW via Ge vacancies [5], its microscopic mechanism remains unresolved. In this study, we take an alternative approach by examining its derivative compound, ScFe_6Ge_6 , to extend the framework established for FeGe. We investigate the interplay between multiple degrees of freedom in single-crystal ScFe_6Ge_6 through comprehensive spectroscopic measurements. Magnetic susceptibility data confirm multiple magnetic phase transitions, including a magnetic transition at $T^*\sim 200$ K. Temperature-dependent ARPES identifies orbital-selective renormalization of a kagome Dirac band (DB) near T^* , while Raman spectroscopy suggests moderate magnetoelastic coupling involving an A_{1g} phonon mode and subtle Fe spin-canting. These results demonstrate that ScFe_6Ge_6 and the FeGe family more broadly exhibit entangled spin, lattice, and electronic correlations, with out-of-plane physical modulations playing a decisive role in their emergent properties. Overall, our study advances the understanding of the mechanisms that promote or suppress CDW order in kagome magnets.

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QUBO Formulation of a Binary-Constrained Minimum Norm Estimation Problem

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Minimum norm estimation (MNE) is a widely used technique for source localization in magnetoencephalography (MEG) and electroencephalography (EEG), providing a minimum-energy solution to an ill-posed inverse problem. In this study, we propose a reformulation of the MNE problem into a quadratic unconstrained binary optimization (QUBO) framework by representing the estimation variables and constraints using binary encoding. The proposed formulation translates the conventional continuous MNE problem into a combinatorial energy minimization model, enabling the incorporation of discrete structural constraints within a unified QUBO representation. We describe the construction of the QUBO model and outline a simulation-based evaluation framework for analyzing the characteristics of the resulting energy landscape and solution space. This formulation establishes a foundation for future numerical studies and potential implementation on annealing-based optimization platforms, including quantum annealers.

CHSH based performance metric for benchmarking Quantum Circuit Execution

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현재 양자컴퓨터는 다양한 플랫폼을 통해 경쟁적으로 구현되고 있어 명확한 표준이 없다. 양자컴퓨터는 하드웨어의 구성과 그에 따른 상태 준비, 양자 게이트 구현, 상태 측정, 오류 등이 갖는 특성들이 복합적으로 작용하여 성능을 지배하므로, 하드웨어적 관점에서 현재의 양자 컴퓨터 시스템을 평가하려는 시도는 독립적으로는 매우 효과적이지만 복합적인 효과를 직관적으로 드러내는 데에는 한계가 있다. 한편, 하드웨어적 차이가 있더라도, 게이트 기반 양자컴퓨터의 경우 궁극적으로 양자 회로를 효과적으로 실행하는 것에 그 목적이 있으므로, 양자컴퓨터가 얼마나 양자 회로를 잘 실행하는가를 기준으로 평가하는 것은 매우 유용하다. 이에 따라 Fidelity, Quantum Volume, #AQ, Q-Score 등의 성능 평가 척도들이 제시되었지만, 보편적이면서도 실용적인 의미가 있는 양자회로를 대표하기에는 한계가 있다. 여기에서는 트랜스몬 큐비트 기반 양자 컴퓨터를 활용하여 얽힘과 비고전적인 특성을 복합적으로 나타내는 지표인 CHSH 실험의 S 파라미터의 최댓값을 구하는 회로를 구성하고, S 파라미터를 활용하는 다양한 양자 회로 성능 평가 척도들을 제안한다. 더하여, 각 큐비트 쌍들이 보이는 S 파라미터 기반 척도들의 분포를 구성하여, 양자 회로 실행을 위한 최적의 큐비트 조합을 찾는다.

Keywords: CHSH, CHSH based performance metric, CHSH parameter S

A QUBO-Based Formulation of Support Vector Machines for Quantum Annealing

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Many researchers utilize machine learning across a wide range of fields. In supervised learning, which is one of the main categories of machine learning, the quality of learning can be improved by using high-quality data or large volumes of data. However, the latter approach leads to an increase in computational cost as the amount of data grows. As computational complexity increases, various issues arise, including increased computational burden, memory limitations, and numerical instability. To address these problems, a support vector machine (SVM), which is one of the machine learning techniques, is trained using the D-Wave system, a quantum computer optimized for quantum annealing, instead of a classical computer. The D-Wave system is a superconducting quantum annealing computer based on RF-SQUIDS, and compared to other superconducting quantum computers, it can generate multiple low-energy solutions, employs a relatively simple control scheme, and does not require long coherence times, thereby reducing the accumulation of errors. In the process of converting a classical SVM into a quantum SVM, the dual formulation of the classical SVM is transformed into a quadratic unconstrained binary optimization (QUBO) form in order to alleviate computational complexity. Furthermore, the QUBO formulation experimentally exhibits several advantages, such as providing a distribution of approximate solutions rather than a single global optimum and improving learning performance in low-data regimes. In this study, these advantages are verified using real-world data.

Bimodal switching current distributions in NbTi-Bi₂Se₃-NbTi Josephson junctions

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Majorana zero modes (MZMs) in topological superconductors are promising for realizing fault-tolerant quantum computing, yet their conclusive detection remains elusive. Conventional experimental signatures such as zero-bias conductance peak and Shapiro-step doubling can arise from nontopological effects, leading to ongoing controversy over MZM confirmation. Although a bimodal switching current distribution (SCD) has been theoretically predicted in topological Josephson junction (JJ) [N. Abboud et al., *Phys. Rev. B* 105, 214521 (2022)], experimental evidence has been lacking. Here, we report the observation of bimodal SCDs in JJs based on Sb-doped Bi₂Se₃ topological insulator nanoribbons. The bimodal SCDs emerge at low temperatures below 0.5 K and are attributed to parity-dependent Josephson potential in presence of MZMs. Furthermore, microwave-irradiated measurements reveal the absence of the first ($n = 1$) Shapiro step, confirming the presence of a 4π -periodic supercurrent. The simultaneous observation of bimodal SCDs and missing Shapiro steps provides a more reliable route toward verifying MZMs in topological JJs.

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Unimodal switching current distributions of Al-InAs 2DEG-Al Josephson junctions

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Majorana zero modes (MZMs) are essential for realizing fault-tolerant quantum computing, yet their experimental verification remains challenging. Topological Josephson junctions (JJs) exhibiting a 4π -periodic current-phase relation are expected to show missing Shapiro steps, often regarded as a potential signature of MZMs. However, such behavior can also originate from non-topological Landau-Zener transitions (LZTs). Theoretically, a bimodal switching current distribution (SCD) has been proposed as an alternative indicator in topological JJs [N. Abboud et al., Phys. Rev. B 105, 214521 (2022)]. We fabricated highly transparent Al/InAs two-dimensional electron gas (2DEG) JJs operating in the ballistic regime and investigated their Shapiro steps, SCDs, and multiple Andreev reflections. While the first Shapiro step missing was observed at low temperatures, the SCD remained unimodal, implying a single-well Josephson potential. Subgap conductance analysis revealed a superconducting gap $D = 156$ meV and junction transparency $t = 0.8$. These results indicate that the missing Shapiro step in Al/InAs 2DEG JJ originates from LZTs rather than topological Josephson effect. Complementary measurements of Shapiro steps and SCDs provide a more reliable MZM verification in topological JJs.

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Field-resilient resonators with various superconducting films on Si/SiO₂

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Superconducting coplanar waveguide (SCPW) resonators are crucial tools for circuit quantum electrodynamics (cQED) and enable the quantum state readout of coupled qubits. In cQED systems, gate-tunable qubits require gate-dielectrics for electrostatic control and operate under magnetic fields. External magnetic fields and gate-dielectrics, however, degrade resonator performance. Herein, we investigate SCPW resonators on thermally grown SiO₂ with varying superconducting film thickness ($t = 23 - 154$ nm) using high upper critical field materials (Nb, NbTi, NbTiN, or MoRe). We characterize their field-resilience under increasing magnetic fields at 1.8 K, and NbTi shows the optimal performance. The internal quality factor (Q_i) for NbTi (45 nm) remains above 104 in parallel fields up to 0.5 T. To investigate loss mechanisms, we measure thicker NbTi (154 nm) resonators at millikelvin temperatures. Two-level systems (TLS) in SiO₂ and at the substrate-superconductor interface limit Q_i to ~ 105 . Our results demonstrate field-resilient SCPW resonators and identify TLS as the dominant loss mechanism in this regime. They provide a pathway for integrating gate-tunable qubits into cQED architectures.

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Design and Analysis of Superconducting Quantum Circuits using KQCircuits

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Research on quantum computing hardware and algorithms has recently gained significant momentum, driving the need for comprehensive education in the field. Currently, Chungbuk National University (CBNU) operates the IQM Spark, a superconducting 5-qubit quantum computer, to conduct research focused on educational algorithms. However, to acquire a comprehensive knowledge of the principles of quantum computing, it is essential to understand the physical implementation of the Quantum Processing Unit (QPU) beyond the algorithmic level. This study presents a methodology to deepen the understanding of essential QPU components, such as Coplanar Waveguides (CPW) and transmon qubits, through practical design exercises. We utilized KQCircuits, an open-source automated design library for superconducting quantum circuits developed by IQM and Aalto University. Using this Python-based framework, we generated layout designs for core quantum elements and conducted signal simulations based on the designed circuits. This approach demonstrates that integrating design automation tools into research can significantly broaden the perspective from educational software to the physical complexities of quantum hardware.

Keywords: Quantum computer

Pulsed Wire Method Magnetic Field Measurement for Superconductor Magnet

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The pulsed wire method (PWM) is an attractive magnetic field measurement technique for narrow-gap undulators or superconducting undulators operating in cryogenic environments, where measurement access is restricted. However, in practical measurements, the accuracy of PWM is limited by signal distortions arising from the dispersive properties of the wire, finite current pulse width, and sensor response characteristics. These effects lead to amplitude reduction and temporal delay in the measured wire displacement signals, complicating the accurate reconstruction of magnetic field distributions. In this study, we implement and experimentally validate a correction algorithm that simultaneously accounts for dispersion and finite pulse-width effects. The dispersion relation of the wire is extracted from frequency-domain phase analysis of displacement signals measured at different sensor positions, enabling the construction of a dispersive wire model incorporating both tension and bending stiffness. Based on this model, appropriate scaling functions are applied for short- and long-pulse conditions to compensate for pulse-width-induced amplitude attenuation and temporal delay.

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HTS 냉각을 위한 질소 삼중 용기의 풀 비등 수치해석

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최근 대형 데이터 센터의 급격한 확장에 따라 대용량 전력 전송을 위한 고온 초전도 케이블과 이를 안정적으로 운용하기 위한 고효율 극저온 냉각 기술의 중요성이 증대되고 있다. 특히 고온 초전도 시스템에서는 냉각 매체의 온도 균일성이 전기적 안정성과 직결되므로, 효과적인 열 관리 기술이 필수적이다. 본 연구에서는 과냉 액체 질소와 포화 액체 질소를 동시에 활용하는 삼중 용기 냉각 시스템을 대상으로, 실물 크기 조건에서의 풀 비등 거동과 온도 균일성을 수치적으로 분석하였다. 외부 챔버에서 발생하는 포화 액체 질소의 비등을 통해 내부 챔버에 위치한 초전도체를 냉각하는 구조로, 기존 전도 냉각 방식 대비 콜드 헤드 온도를 상대적으로 높게 유지함으로써 냉동기 용량 활용도를 극대화할 수 있는 장점을 가진다. 수치 해석은 Ansys Fluent를 이용하여 수행하였으며, 액-기 상분포와 비등 현상 재현을 위해 VOF(Volume of Fluid) 모델을 적용하였다. 해석 결과, 외부 챔버 벽면의 온도는 응축수가 유입되는 국소 영역을 제외한 대부분의 영역에서 원주 및 높이 방향으로 매우 균일한 분포를 나타냈다. 응축수 유입에 따른 국소적인 온도 저하는 최대 0.05 K 이내로 제한적이었으며, 원주 방향에서는 기포 생성 및 이탈에 따른 미소한 온도 변동만이 관찰되었다. 벽면 열전달계수는 약 200 W/m² 수준에서 안정적으로 유지되었다. 또한 정수압 효과로 인해 포화 온도는 깊이에 따라 최대 약 2 K의 차이를 보였으나, 깊이 방향의 온도 균일성에는 유의미한 영향을 미치지 않았다. 상변화는 과열도가 양(+)으로 전환되는 챔버 중간 높이 영역부터 활발하게 발생하였다. 본 연구를 통해 삼중 용기 냉각 시스템이 실물 크기 조건에서도 높은 온도 균일성을 안정적으로 유지함을 확인하였으며, 이는 대용량 초전도 전력 공급 시스템의 열적 안정성 확보에 효과적인 냉각 방식임을 검증한다.

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Tunneling Spectroscopy of Superconducting proximity induced Gap in Bilayer Graphene

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Superconductivity can be induced in non-superconducting materials through the proximity effect, which is characterized by its superconducting gap. In this study, we conduct tunneling spectroscopy to measure the proximity-induced superconducting gap in bilayer graphene, which exhibits a gate-tunable Fermi velocity with parabolic band dispersion. Tunnel probe has advantage in fabrication of large numbers once the process conditions are optimized. We fabricated the device at defined distances from the superconducting contact by controlled etching and subsequent aluminum deposition. As a result, the differential conductance of tunnel probe coincides with the quasiparticle density of states described by the Dynes model and the induced gap was scaled with the Fermi velocity in bilayer graphene. Also, the proximity effect remained detectable at tunnel probes up to 1 μm from the superconducting contact, implying the ballistic transport over the superconducting coherence length.

Real-Time Non-Contact Laser Measurement of Winding Diameter for Precision Control

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초전도 자석은 의료 영상 진단, 입자가속기, 핵융합 장치 등 다양한 분야에서 핵심 부품으로 활용되며, 응용 분야에 따라 자기장세기, 자속 밀도, 균일도 등이 엄밀하게 요구된다. 이상적인 성능 구현을 위해서는 권선 횟수, 외경 등 물리적 사양의 정밀한 제어와 제작된 자석들 간 일관된 품질 유지가 필수적이다. 기존에는 권선 중 주기적으로 작업을 멈추고 버니어 캘리퍼스 같은 정밀 측정 기구로 치수를 측정해야 하므로, 제작 시간이 증가하고, 측정하는 사람에게 의존되는 측정이 주를 이루었다. 본 연구에서는 Keyence 레이저 측정 장비를 권선기에 통합하고 LabVIEW 기반 통합 제어 프로그램을 개발하여, 권선 공정 중외경, 정렬, 장력을 실시간으로 모니터링하는 비접촉 측정 시스템을 구축하였다. 또한 자석 제작에 적용한 결과, 설계값과 실제선재 두께 간 편차를 조기에 감지하고 보정함으로써 최종 자석의 사양 일치도를 향상시켰다. 본 연구는 권선 공정의 정밀도와 재현성을 개선하고, 전체 제작 데이터를 자동 기록하여 분석 가능한 형태로 가공하는 시스템을 제시한다.

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Decoupling the effects of ion size variance and incidental RE₂O₃ nanoparticle formation on in-field critical current densities of hybrid PLD films

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High temperature superconducting REBa₂Cu₃O_{7-x} coated conductors offer irreplaceable advantages for the design of nuclear fusion magnets, due to their high irreversibility fields and critical temperatures. However, the factors affecting high field, low temperature (20 T, 20 K) current carrying performances of coated conductors has not been fully understood. In this study, we investigate the intricate interplay of some of these factors and understand their individual effects using epitaxial thin films grown by hybrid-pulsed laser deposition (PLD) technique. Hybrid PLD exploits non-stoichiometric PLD targets with the aim of taking advantage of excess liquid and incidental RE₂O₃ vortex-pinning nanoparticles. Different combinations of Y_xRe'_yRe''_{1-x-y}Ba_{1.7}Cu_{2.7}O₇ targets were made with varying ion size variance and rare earth content. The effects of liquid phase, and their effects on the crystallinity of the film, were studied in correlation to the in-field critical current density. We find that the incidental inclusion of (Y,RE',RE'')₂O₃ 0D pinning centres from increased ion size variance is not beneficial in solid state deposition condition. However, an inclusion of liquid phase ensured high crystalline perfection even in the presence of secondary nanoparticles, and the (Y,RE',RE'')₂O₃ particles could act as additional pinning centres resulting in an enhancement in J_c. We also show that large ion size variance is detrimental to J_c, even in the presence of liquid phase, since cation disorder is produced which impairs the crystalline perfection further. Overall, we are able to determine the optimum base target composition, to which further artificial pinning centres should be added.

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Reactive Sputtering of AlN Thin Films for Enhanced Electrical Insulation and Thermal Conductivity

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High-temperature superconducting (HTS) tapes consist of multiple layers, including a REBa₂Cu₃O_{7- δ} (REBCO, RE = Y, rare earth elements) superconducting layer on a metal substrate. These layers establish biaxial texture and provide chemical and mechanical stability. In coil-shaped superconducting magnets, each tape turn requires electrical insulation to direct current flow efficiently during fast charging and discharging. The insulating layer must exhibit both high electrical resistivity and thermal conductivity to mitigate quench-induced heat dissipation. Aluminum nitride (AlN) is a promising insulator due to its excellent electrical insulation and high thermal conductivity. This study investigates AlN thin films deposited via DC magnetron sputtering on Si wafers and metal substrates. Crystallographic and morphological properties were analyzed using X-ray diffraction (XRD) and scanning electron microscopy (SEM). Electrical resistivity and thermal conductivity were evaluated using the 2-point probe method and the Laser Flash Analysis (LFA) technique, respectively. LFA measurements showed that the AlN-coated sample exhibited higher thru-plane thermal conductivity than the bare substrate, indicating that the sputtered AlN layer enhances heat transport within the HTS tape structure. The findings highlight AlN's potential as an effective insulating layer in HTS applications.

Keywords: HTS wire, Superconducting magnet, AlN Thin film, Sputtering

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Magnetic levitation force of multi-seeded melt growth processed $Y_{1.6}Ba_{2.3}Cu_{2.3}O_x$ bulk superconductors: a comparison of 30 mm and 40 mm diameters

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YBCO bulk superconductors are promising candidates for non-contact magnetic bearings in energy storage systems due to their high magnetic levitation forces [1]. In this study, single-grain and multi-grain YBCO superconductors with diameters of 30 mm and 40 mm were fabricated using the Multi-Seeded Melt Growth (MSMG) technique with 1, 4, and 5 seeds. To facilitate oxygen diffusion and reduce the porosity that develops during the process [2], nine holes were introduced into each sample. The maximum levitation force (F_{max}) measured in the zero-field-cooled (ZFC) condition for the 40 mm single-seed sample was 64.7 N. This value decreased to 60.9 N and 57.6 N as the number of seeds (n) increased to 4 and 5, respectively. A similar trend was observed in the 30 mm samples; the F_{max} for the single-seed sample was 38.3 N, which decreased to 26.6 N and 23.4 N as n increased to 4 and 5. In contrast, F_{max} measured under the field-cooled (FC) condition was lower than those measured under ZFC. Specifically, F_{max} for the 40 mm single-seed sample was 19 N, which increased to 25.8 N and 23.9 N as n increased to 4 and 5. For the 30 mm samples, the F_{max} of the single-seed sample was 14 N and decreased to 10.4 N and 9 N as n increased to 4 and 5. The low magnetic levitation forces in the 30 mm sample appear to be due to the smaller superconducting surface area.

Effects of the purity of BaCO_3 on the magnetic levitation force of YBCO bulk superconductors

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YBCO superconductors are made using powders as raw materials through a series of complex processes, including forming, sintering, and melt processing. To enhance the economic viability of YBCO superconductors, it is crucial to control the properties of these raw powders. The manufacturing costs can be reduced by utilizing raw powders with lower purity levels. In this study, YBCO powders were synthesized using 99.9 % CuO , 99.9 % Y_2O_3 powders, and BaCO_3 powders with two different purities: 99.9 % (high-purity) and 98 % (low-purity). Using these precursor powders, Single-grain YBCO bulk superconductors with a diameter of 40 mm were produced through a seeded growth process. The magnetic levitation forces of YBCO superconductors at 77 K were measured under two conditions: zero-field-cooled (ZFC) and field-cooled (FC). The maximum magnetic levitation force (F_{max}) of the high-purity YBCO sample, cooled in the absence of an external magnetic field (ZFC), was 67 N, while that of the low-purity YBCO sample was 36 N. Additionally, the F_{max} and maximum attractive force (F_{attr}) of the high-purity YBCO sample, when cooled in a magnetic field of an Nd-B-Fe magnet with a 2 mm gap, were 18 N and -28 N, respectively. In comparison, the low-purity YBCO sample exhibited F_{max} and F_{attr} values of 23 N and -8 N, respectively. These findings indicate that the purity of BaCO_3 significantly influences the magnetic levitation and flux pinning capabilities of YBCO superconductors.

Al₂O₃ Coating Using a Low-Temperature Brushing Technique for Magnet Insulation

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No-insulation (NI) superconducting wires enable stable coil fabrication without an insulation layer; however, they suffer from slow magnetic field ramp-up due to turn-to-turn current redistribution. To address this issue, a low-temperature insulation coating process was developed by applying an Al₂O₃ slurry using a brushing method and drying it at temperatures below 100 °C. Scanning electron microscopy (SEM), Energy-dispersive spectroscopy (EDS), and X-ray diffraction (XRD) analyses confirmed the formation of a uniform insulating layer under these conditions, while the thermal properties were evaluated using the Laser flash method (LFA). This approach provides a simple and practical solution to improve current distribution, enhance magnetic field ramp-up speed, and increase operational stability in NI superconducting magnets.

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Microstructural and Diffusion Behavior Analysis of High Jc Nb₃Sn Wires with SnCuTi Alloy Addition

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High Jc Nb₃Sn wires are gaining attention in high magnetic field applications such as fusion reactors and accelerators due to their high critical current density and excellent performance in high magnetic environments. Since 2004, Kiswire Advanced Technology Ltd. (KAT) has been developing Nb₃Sn for fusion reactors, and is now focusing on the development of high-performance wires for next-generation fusion reactors and accelerators using the Distributed Barrier Strand (DBS) method. For improving the performance of High Jc Nb₃Sn wires, the formation of a uniform and stable Nb₃Sn phase during heat treatment is essential. In this study, a ternary SnCuTi alloy powder, with 5 wt% Cu added, was fabricated and applied to Nb filament-based wires. Micro-sized SnCuTi alloy particles were embedded into the wires through powder metallurgy, followed by a series of heat treatments. The resulting phase transformations and diffusion behavior were analyzed. Additionally, changes in microstructure, Nb₃Sn formation, and critical current properties were evaluated. This study aims to understand the impact of SnCuTi alloy application on the performance enhancement of High Jc Nb₃Sn wires and expand the high magnetic field application domain through the development of high-performance High Jc Nb₃Sn wires.

Excess Conductivity in RFeO₃ (R = Gd, La)-Added GdBa₂Cu₃O_{7-x} Bulk Superconductors

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In this work, the effect of adding gadolinium orthoferrite (GdFeO₃, GFO) and lanthanum orthoferrite (LaFeO₃, LFO) in the range of 0 - 1.0 wt. % into GdBa₂Cu₃O_{7-x} (GdBCO) bulk superconductors was investigated. The influence of RFeO₃ (R = Gd, La) additions on superconducting properties was examined through excess conductivity analysis above the superconducting transition temperature. Resistance-temperature characteristics were measured using a conventional four-point probe method. The crossover temperature TLD, corresponding to the dimensional transition from three-dimensional to two-dimensional superconducting fluctuations, was found to decrease with increasing RFeO₃ content. Interlayer coupling strength J, effective interplanar spacing d and c-axis coherence length were calculated using the Aslamazov-Larkin (AL) and Lawrence-Doniach (LD) models. The analysis of excess conductivity provides insight into superconducting fluctuation phenomena and the interaction between magnetic secondary phases and the superconducting matrix.

Keywords: GdBCO, GFO, LFO, excess conductivity

Effect of Filament Size on Engineering Current Density (J_e) in Bi-2212 Round Wires

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Bi-2212 round wire is a representative high-temperature superconducting conductor for high-field magnet applications, and its engineering current density (J_e) is known to be strongly governed by microstructural parameters developed during wire processing and reaction heat treatment. Previous studies have shown that J_e in Bi-2212 wires is limited by microstructural defects such as gas bubbles, porosity, filament bridging, and non-uniform connectivity, which interrupt percolative current paths and reduce the effective superconducting cross-section. In addition, crystallographic texture formed during melt processing has been reported to play an important role in filament connectivity and current transport behavior. The formation of these microstructural defects and texture is closely related to geometric confinement during reaction heat treatment, and filament size, which defines the degree of such confinement, can be considered a key microstructural control parameter influencing gas diffusion and bubble behavior, filament densification and connectivity, as well as texture development. In this study, filament size in Bi-2212 round wires was selected as a microstructural control parameter, and the effect of filament size variation on the engineering current density (J_e) was systematically investigated.

Python-based High-throughput XRD Analysis for Evaluating Phase Uniformity in Reel-to-Reel System

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2세대 고온초전도 선재는 초전도 케이블, 전자석 등과 같은 응용 분야에 따라 수십에서 수백 미터 이상의 장선재 제조가 요구된다. 이에 따라, 선재를 안정적으로 이송하기 위해 제조 공정 전반에 Reel-to-Reel(R2R) 기반 이송 시스템 적용이 필수적이다. 그러나 선재의 이송에 따른 박막의 상(Phase) 및 결정 배향(texture)의 불균일성은 장선재화된 코팅 도체의 초전도 성능 편차를 유발할 수 있다. 이러한 위치 의존적 박막 성장 편차를 정량적으로 이해하기 위해서는 다수의 X선 회절(XRD) 데이터를 효율적으로 처리하고 비교·분석할 수 있는 도구가 필요하다. 본 연구에서는 R2R 기반 펄스레이저 증착(PLD) 공정으로 제작된 고온초전도 선재에 대하여 길이 방향 및 폭 방향, 즉 증착 구간 내 위치에 따른 박막 성장과 상 형성의 불균일성을 확인하였다. 이에 관찰된 θ - 2θ scan에서 피크(Peak) 강도(Intensity) 및 반가폭(FWHM)과 상 변화 지표를 Python을 기반으로 정량화할 수 있는 분석 툴을 설계하였으며, 이를 통해 어떤 변인이 위치에 따른 박막 상과 배향의 불균일성에 지배적인 영향을 끼치는지 분석하였다. 본 연구에서 제안하는 Python 기반의 XRD 고속 분석 방법은 R2R기반 고온초전도 박막 연속 증착 공정에서 박막 상 균일성 진단 및 공정 조건 최적화를 위한 기초 데이터 및 지표를 제공할 것으로 기대된다.

Time-Varying Performance Characteristics of HTS Tapes with Different Solder Fluxes

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Hyun Sung Hyun Sung (*Korea University*),

Min Kyu Sun (*Korea University*),

Kihong Kim (*Korea University*),

Haigun Lee* (*Korea University*)

고온초전도 선재를 활용한 초전도 코일 제작 과정에서는 선재 간 접합 및 전류 리드와의 접합을 위해 솔더링 공정을 필수적으로 수행해야 한다. 이 과정에서 일반적으로 플럭스가 사용되며, 플럭스는 구리 안정화층의 산화막을 제거하여 납땜 품질을 향상시키는 데 중요한 역할을 한다. 그러나 솔더링 후 잔류 플럭스가 표면에 남거나 코일의 턴사이에 침투할 경우, 시간이 지남에 따라 부식과 오염이 점차 심화되어 선재 및 전류 리드의 특성을 크게 저하시킬 수 있다. 이러한 문제는 응용 기기의 장기적 신뢰성을 저해하는 주요 원인으로 작용한다. 본 연구에서는 서로 다른 조성을 가진 두 종류의 플럭스를 사용하여 초전도 코일을 제작한 뒤, 장기간 보관하여 주기적으로 코일의 표면 상태 및 전기적 특성을 관찰하고 비교하였다. 이를 통해 플럭스의 종류와 시간 경과에 따른 잔류 플럭스의 영향을 분석하고, 초전도 코일의 성능과 안정성을 유지하기 위한 효과적인 방안을 제시하고자 한다.

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Effect of Operations to the Stability of the Solder Layer in Current Leads

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 Hyun Sung Noh (Korea University),
 Younghoon Kim (Korea University),
 Kihong Kim (Korea University),
 Haigun Lee* (Korea University)

솔더링은 전기 시스템 내에서 연결부를 구축하는 가장 효율적인 방법 중 하나로, 현재 사용되는 대부분의 초전도 시스템 역시 내부에 필연적으로 이러한 솔더링을 통한 접합부를 포함하고 있다. 하지만 솔더링에 사용되는 소재들은 가공성을 위해 기계적 강도를 포기하여 기계적으로 가장 취약한 부분이자 동시에 화학적 변성에도 노출되기 쉬운 취약점이기도 하다. 그렇기에 이러한 취약점으로써의 솔더가 장기 운전 과정에서 받는 영향 및 이를 예측하는 기법에 대한 관심은 꾸준히 존재해왔다. 하지만 이러한 시도들 중 1년 이상의 장기 보관 및 운전을 동반한 실험의 빈도는 여전히 부족한 상태이다. 본 연구에서는 운전의 횟수 및 운전 환경에서 노출되는 물질에 의해 받는 영향을 평가하고자 약 2년간 약 1천 회의 꾸준한 충방전에 노출된 전류리드의 터미널 저항 변화 데이터와 해당 샘플과 같은 방식으로 제작되어 1년간 장기 보관되었으나 그 과정에서 운전만을 거친 샘플의 성능을 비교하였다. 또한 과거 장기 보관 및 운전 실험에서 시도하였던 다양한 모델들에 기반한 데이터 변화 추이 예측이 완전히 다른 실험 횟수를 갖는 샘플에도 여전히 적용 가능한지 평가하여 전류리드 샘플의 장기보관 과정에서 성능에 영향을 주는 요인에 대해 논의하고자 한다.

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Investigation of ice impregnation enhanced with ethanol and Zylon fillers for improved HTS coil performance

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초전도 코일을 사용하는 회전 장치에서는 회전진동과 강한 자기장에 의해 발생하는 로렌츠 힘으로부터 코일을 보호하기 위해 함침 기술이 필수적으로 적용된다. 일반적으로 고온 초전도체(HTS)코일에는 가격이 저렴하고 접착력이 높으며 기계적 강도가 우수한 에폭시가 함침재로 사용된다. 그러나 에폭시는 낮은 열전도성으로 인해 열 구배(thermal gradient)를 형성하고, 에폭시와 HTS 선재와의 큰 열팽창 계수 차이로 초전도 특성을 저하시킬 수 있는 문제가 존재한다. 이를 해결하기 위한 대안으로, 물에서 얼음으로 상전이 되는 과정에서 부피 팽창하는 특성을 이용한 얼음 함침법을 제안되었지만, 얼음 자체의 낮은 기계적 강도 때문에 적용에 한계가 있었다. 본 연구에서는 이러한 문제점을 보완하기 위해 얼음과 에탄올을 filler로 활용한 얼음 함침 기술을 제안하였다. 이 방법은 에탄올 filler를 첨가하여 물의 결빙 과정에서 발생하는 공극(void)과 균열(crack)을 최소화하고, 고강도이면서 음의 열팽창을 가지는 Zylon filler를 사용하여 얼음 함침의 기계적 특성을 향상시키는 방식이다. Zylon과 에탄올을 필러로 사용한 얼음 함침이 HTS 코일의 열적 및 전기적 특성에 미치는 영향을 평가하기 위해 cool down test, repetitive cooling test, compressive test를 수행하였으며, 냉각 시 filler에 따른 얼음의 팽창 특성을 비교하기 위해 expansion test를 추가적으로 수행했다.

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A study on screening current induced voltage in no-insulation REBCO pancake coils

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고온초전도체의 일종인 rare-earth barium copper oxide (REBCO)는 핵융합, MRI 등 대전류 및 고자기장이 요구되는 분야에 널리 활용되고 있다. REBCO 테이프 로 권선한 무절연 팬케이크 코일의 임계전류 측정 과정에서, 전류-전압 그래프 상에 예상치 못한 저항성 기울기가 발생함을 확인하였다. 이러한 저항성 기울기는 코일의 충전 구간에서만 관찰되었으며, 충전방전을 반복할수록 감소하는 경향을 보였다. 우리는 위 현상의 원인이 REBCO 도체 내부에 발생하는 차폐전류 및 그에 따른 유도전압에 기인한다고 추정하였다. 테이프 형상인 REBCO 선재의 특성 상, 테이프의 넓은 면에 수직인 방향으로 자기장의 영향을 크게 받아 차폐전류가 생성되고, 이로 인해 유도 전압이 발생하여 전류-전압 그래프 상의 저항성 기울기가 관측된 것으로 판단된다. 이러한 차폐전류 및 유도 전압은 임계전류 측정 오차를 유발한다. 임계전류는 초전도 자석의 설계 및 운전에서 있어 가장 중요한 요소 중 하나이다. 본 연구에서는 유한요소해석을 기반으로 무절연 고온초전도 코일에서 발생하는 차폐전류 및 유도 전압을 해석적으로 구현한다. T-A formulation을 적용한 2차원 축대칭 모델을 사용하여, 전류-전압 그래프에서의 저항성 기울기를 재현하고, 그 결과를 실험값과 비교하여 해석 모델의 타당성을 검증한다.

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Analysis of magnetization loss in HTS coils using TSTC-CORC hybrid conductors

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초전도체를 교류 전력기에 응용할 경우 필연적으로 발생하는 교류손실은 냉각 효율과 기기 운전 안전성에 영향을 미친다. 따라서 고온초전도 전력기기의 상용화를 위해서는 기기에서 발생하는 교류 손실을 정확하게 예측하고, 감소시킬 수 있는 방법이 필요하다. 대부분의 전력 기기는 코일의 형태를 가지기 때문에 본 연구에서는 CORC(Conductors on Round Core)의 원통형 포머 내에 TSTC를 삽입한 TSTC-CORC 하이브리드형 도체로 권선된 코일에서 발생하는 교류손실 특성을 분석한다. TSTC-CORC 하이브리드 코일의 교류손실 분석은 권선에 사용되는 TSTC-CORC 샘플 도체의 손실 측정결과를 적용하여 진행한다. 또한, 고온초전도 코일의 도체 구성을 CORC만을 이용한 경우와 TSTC-CORC 하이브리드형 도체를 이용한 경우로 나누어 손실 해석을 진행하고, 이를 통해 고온초전도 코일 손실의 차이를 비교 분석한다.

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Critical Current Estimation Based on Magnetization Loss in Multi-Stacked HTS Tapes

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대용량 초전도 기기 개발을 위해서는 초전도 선재의 다적층화가 필수적이나, 적층된 선재의 임계전류를 정확히 평가하는 데에는 기술적 한계가 존재한다. 기존의 통전 측정 방식은 직접적인 접촉에 의해 통전이 필요하므로 샘플에 손상을 줄 우려가 있고 적층도체를 구성하는 각각의 선재에 통전전류가 원활하게 흐를 수 있도록 구성되어야 하므로 전류도입부의 제작이 쉽지 않아 정확한 측정 방법을 확립하기 어렵다. 본 연구에서는 샘플에 수직방향으로 인가되는 외부 자기장에 의해 샘플에서 발생하는 자화손실 측정값을 이용한 임계전류 추정 방법을 제안하고 그 가능성을 검토한다. 단일 선재, 2, 3, 4 적층 선재 샘플에 대해 LPC (Linked Pick up coil) 시스템을 이용해 외부 자장에 의한 수직 자화손실을 측정하고 또한, 동일한 샘플들에 대해 통전 실험을 통해 임계전류를 직접 측정한다. 자화손실 모델을 통해 추정된 임계전류 값과 실측된 임계전류 값의 비교 검토를 통해 다적층 도체에서의 간접적 임계전류 평가 방법의 적용 가능성을 확인한다.

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Terminal Joint of Multilayer CORC High-Temperature Superconducting Cables

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본 연구에서는 고온초전도 선재 기반 CORC(Conductor on Round Core) 케이블을 16층 적층 구조로 구성한 10 kA급 Twisted 적층 케이블을 대전류 환경에서의 안정적 운용을 위한 터미널 접합 기술을 연구하였다. 이를 위해 각 층의 초전도 테이프 간 전기적 연속성을 확보하고 선재 끝단을 견고히 고정하여 장력을 유지할 수 있도록 케이블을 층별로 테이퍼(Taper) 형태로 가공하였다. 이후 구리 와이어로 각 층을 고정하고 인듐-주석(InSn) 기반 솔더링 기법을 적용함으로써 전체 구조의 기계적 안정성을 확보하였다. 또한 금속 터미널과 Twisted 적층 케이블의 접속을 위해서 인듐-주석 솔더를 접속부 내부에 주입한 뒤 터미널 덮개를 씌우고 볼트를 체결하는 방식으로 최종 터미널-케이블 접합을 완성하였다. 제작된 터미널 시편은 액화질소 온도(77 K)에서의 임계전류 측정 및 전기적 접합 저항 평가를 통해 신뢰성을 검증하였다. 본 연구는 대전류용 초전도 응용 시스템에서 CORC 케이블과 터미널 사이의 접속 신뢰성을 확보하기 위한 기반 기술로 기초 자료를 제공할 것으로 기대된다.

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Design Study of an AC Loss-Reduced HTS TF Magnet

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This study presents an AC loss analysis of a high-temperature superconducting (HTS) toroidal field (TF) magnet considering the electromagnetic effect of the central solenoid (CS), and examines how these CS-induced losses vary with different coil geometries and layout configurations. Conventional low-temperature superconducting (LTS) coils face inherent challenges under high magnetic fields and demanding cooling requirements, whereas REBCO-based HTS coils offer higher critical fields and efficient operation at 20-40 K, making them promising candidates for advanced fusion applications. A two-dimensional (2D) axisymmetric model was developed based on the design specifications of the SPARC tokamak-jointly developed by the MIT Plasma Science and Fusion Center (PSFC) and Commonwealth Fusion Systems (CFS)-and includes both the CS and the HTS TF coils. The TF coil was represented as a copper-stabilized cable, in which stacked REBCO tapes were approximated as a single equivalent bulk laminate. A 2D H-formulation was employed to calculate AC losses induced by the time-varying magnetic fields generated by the CS. Electromagnetic coupling effects were treated by superposing the CS-induced magnetic field onto the TF coil cross-section. The analysis workflow included computation of J·E losses, temperature rise, and the corresponding cooling power requirements. Results indicate that AC losses are predominantly induced by the radial component of the CS-induced field. Design modifications, such as relocating the TF coil and optimizing the copper stabilizer thickness, effectively reduced losses and cooling requirements, and the TF coil geometry and layout that minimize the AC losses were identified. The proposed 2D H-formulation-based method provides a reliable framework for evaluating AC losses of the HTS TF coils under realistic tokamak operating conditions. Future work will extend the analysis to 3D models and multi-physics simulations to support robust and efficient HTS TF coil design.

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Electromagnetic Design of a 2D Cross-Section for an HTS Combined Function Saddle Magnet

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Recent particle accelerators increasingly demand high magnetic field strength and high field precision to achieve enhanced performance and system miniaturization. In this context, high-temperature superconductors (HTS) have emerged as a promising alternative due to their superior current-carrying capability under high magnetic fields. In accelerator dipole magnets, it is essential not only to generate the target high magnetic field within the bore, but also to maintain extremely high field uniformity across the entire cross-section. Achieving such field quality using HTS tapes is particularly challenging, as the ideal analytical solution requires a continuous trigonometric current distribution, whereas practical HTS conductors are inherently discretized and constrained by bobbin geometry and manufacturability. Therefore, when designing saddle-type HTS dipole magnets, a systematic design methodology is required to determine the angular placement and orientation of tape segments with respect to the bore. Such a methodology is not only critical for dipole magnets, but can also provide valuable insights for the future design of other accelerator magnets, such as quadrupoles. In this study, we focus on the electromagnetic characteristics of REBCO HTS tapes to design the two-dimensional cross-section layout of an accelerator dipole magnet. The design explicitly accounts for tape geometry, bobbin-induced minimum spacing constraints, and physical feasibility. Furthermore, the reduction of critical current under high magnetic fields is incorporated to evaluate the current margin and electromagnetic stability of the proposed 2D design.

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Singular Value Decomposition based Identification of Magnetic Field Inhomogeneity

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We propose a rapid error identification technique based on Singular Value Decomposition (SVD) analysis of a single Free Induction Decay (FID) signal. In this study, we modeled FID signals distorted by specific harmonic error terms (Z_1 , Z_2 , X , and ZX) using MATLAB simulations. The time-domain signals were structured into a matrix form, and SVD was applied to extract the principal component vectors representing the unique decay patterns of each error field. By calculating the similarity scores via the dot product between the extracted vectors and a pre-constructed reference basis, the dominant error components were identified. Simulation results demonstrated that the proposed algorithm successfully classified the error types with high similarity scores, proving its capability to distinguish between orthogonal and higher-order field gradients. This signal-processing-based approach offers a feasible and rapid alternative to conventional field mapping for diagnosing magnet inhomogeneity.

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A Study on the Fabrication of Shimming Coils for Temporal Stability and Spatial Homogeneity in High-Temperature Superconducting Magnets

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High-temperature superconducting (HTS) magnets offer significant advantages for generating high magnetic fields; however, screening currents induced within the HTS tapes inherently degrade both temporal stability and spatial homogeneity. Previous studies indicate that these screening currents particularly amplify low-order error harmonics, such as $Z1$ and $Z2$, making a precise shimming system essential for error compensation. In this study, we designed an integrated shim coil system encompassing both Zonal and Tesseral components using the Target Field Method. Initially, wire-wound Zonal coils ($Z0$, $Z1$, $Z2$) were fabricated and tested. However, discrepancies arose between the measured data and theoretical values due to fabrication tolerances. To address this, we validated the reliability of the analytical model by applying two correction techniques: an effective diameter correction based on the actual winding turns, and a current density recalibration accounting for the actual conductor area. Furthermore, for Tesseral coils (X , Y) which possess complex geometries, Flexible PCB (FPCB) technology was adopted to ensure fabrication precision and facilitate stacking. Consequently, by integrating the verified wire-wound Zonal coils with the FPCB-based Tesseral coils, this study presents a practical fabrication methodology to maximize the performance of HTS magnet systems.

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FEM-based Thermal Stress Analysis of Cryogenic Sensor Packaging for Stable Sensor Attachment

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Cryogenic sensors are widely used in superconducting and low-temperature systems, where thermal contraction during cooldown can induce mechanical stress at material interfaces. Among various cryogenic sensors, Hall sensors are commonly employed for magnetic field measurement and require reliable mechanical attachment under cryogenic conditions. Mismatch in coefficients of thermal expansion (CTE) among sensor, adhesive, and substrate materials may lead to stress concentration and potential delamination, affecting the reliability of sensor attachment. In this study, a finite element method (FEM) is employed to analyze the thermal behavior of a layered structure consisting of a sensor, an adhesive, and a substrate, subjected to cooling from 300 K to 77 K. Different sensor-adhesive-substrate combinations are modeled with appropriate boundary conditions and analyzed to identify dominant stress mechanisms within interfacial regions. Stress concentration along material interfaces is observed under cryogenic cooling, indicating potential interfacial detachment. The FEM results provide a basis for subsequent cryogenic thermal cycling tests and adhesion-related experiments to examine the predicted thermal contraction trends and interfacial stability. This work aims to identify mechanically stable material combinations for cryogenic sensor attachment and to progressively address persistent problems in cryogenic sensor packaging.

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Analysis of Winding Stress Distribution in HTS coils with Various Racetrack Geometries

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This study aims to compare and analyze the winding stress distribution in racetrack-type high-temperature superconducting (HTS) coils according to variations in coil geometry using the finite element method (FEM). Racetrack coils have varying curvature at the junctions between the straight and curved sections. Such geometric characteristics directly influence the winding stress distribution generated during the winding process. In this work, a baseline racetrack geometry is defined, and modified racetrack shapes with different curvature distributions, including elliptical and bulged geometries, are considered. Under identical winding tension conditions, the winding stress distributions corresponding to each geometry are analyzed using FEM. The numerical model incorporates the mechanical properties of the superconducting tape and the bobbin, with particular emphasis on regions of large curvature variation and geometric transition zones, where winding stress behavior is expected to be sensitive to shape changes. This study presents a FEM model for evaluating geometry-dependent winding stress distributions in racetrack-type coils and provides a fundamental basis for analyzing turn-to-turn contact pressure and electrical characteristics.

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Numerical and experimental investigation of Screening Currents Induced Stress in NI High-Field REBCO Magnets for the Muon Collider Cooling Stage

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High-field high-temperature superconducting (HTS) magnets based on REBCO conductors are a key enabling technology for next-generation particle accelerators, including the Muon Collider. However, their design and operation are strongly affected by screening currents and the resulting screening-current-induced stress (SCS). Despite extensive modeling efforts, significant uncertainties remain regarding the actual current distribution in REBCO tapes, as simplified approaches based on fixed power-law models fail to capture the complex flux penetration and creep regimes, which depend on magnetic field, temperature, and material properties. This work presents a combined numerical and experimental study of screening current distributions and SCS in high-field NI REBCO magnets, with the goal of assessing which modeling assumptions commonly adopted during the design phase are physically justified for high field magnets. A modular modeling framework based on the T-A formulation is developed, allowing radial currents arising during magnet charging to emerge naturally without coupling to external circuit models. Additional effects, including slit-edge effects, tape tilting, strain-dependent critical current, and frictional interactions between pancakes and spacers, are incorporated. Numerical results are compared with experimental measurements, providing insights into SCS mitigation strategies and supporting more reliable design choices for future high-field HTS magnets.

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Amortized Heteroscedastic Prediction of Critical Current in Commercial REBCO Tapes

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Predicting the critical current (I_c) of commercial REBCO tapes is difficult because I_c depends on operating conditions (magnetic-field magnitude, field angle, and temperature) while also varying systematically from tape to tape due to manufacturing heterogeneity. We present a modular, tape-conditioned predictor that explicitly accounts for both effects. For each tape, a Transformer-based set encoder reads its tape-specific measurement set (pairs of operating conditions and measured I_c) and infers a latent tape representation together with its uncertainty. This uncertainty naturally shrinks when more measurements from the same tape are available. A Kolmogorov-Arnold Network (KAN)-based decoder then takes the operating conditions and a sampled latent tape representation to output a predictive mean and an input-dependent variance, enabling heteroscedastic uncertainty estimation. The final prediction aggregates multiple samples of the latent tape representation, producing a tape-adapted predictive distribution rather than a single deterministic value. Using commercial tape data, we confirm that the proposed architecture yields stable I_c predictions and that its uncertainty estimates qualitatively reflect regimes where measurements are harder to explain. These results demonstrate the feasibility of probabilistic tape conditioning as a basis for stricter generalization tests and uncertainty-aware benchmarking.

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Experimental Investigation of Heat-treated Insulation Material for REBCO Coated Conductors

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This study experimentally investigates heat-treated insulation material applied to REBCO coated conductors. A mixed insulation layer composed of SH-2 and SPI-707 was coated onto the surface of REBCO tapes, followed by heat treatment at different temperatures. The effects of heat treatment on the critical current characteristics and insulation performance of the coated conductors were evaluated. Critical current measurements were conducted to assess potential superconducting degradation due to thermal exposure, while insulation properties were examined to determine the thermal stability and effectiveness of the insulation layer. The dependence of superconducting and insulation performance on heat treatment temperature was systematically analyzed. In addition, the influence of the mixing ratio of the insulation materials was briefly considered as a preliminary assessment. The results provide practical insight into appropriate heat treatment conditions for insulated REBCO coated conductors

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Fast Ramping Behavior of Partially Insulated REBCO Saddle Coils

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High-field magnets are essential for future particle accelerators, and REBCO high-temperature superconductors (HTS) are among the most promising candidates for enabling such systems. In dipole magnets, the magnetic field must track the beam momentum; therefore, rapid acceleration and deceleration of the beam require fast charging and discharging of the dipole coil. Achieving high ramp rates in REBCO dipole magnets necessitates the use of partially insulated winding techniques to overcome the charging-delay limitations of no-insulation (NI) coils. In this study, a partially insulated REBCO saddle module coil is fabricated to investigate its fast ramping behavior. Experiments are conducted in liquid nitrogen at 77 K, and various current profiles are applied to evaluate the transient electrical response and derive an equivalent circuit model of the coil. Based on the measured dynamic characteristics, we further determine the current profiles required to generate a quasi-linear magnetic field ramp.

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Cryogenic Motor Performance Analysis using Single Coil Testing and Electro-Thermal Modeling

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This paper presents a comprehensive performance analysis of a cryogenic motor, employing a hybrid approach of single-coil experimental testing and electro-thermal modeling. While cryogenic motors offer significant advantages in power density and efficiency, full-scale prototyping entails high costs and technical complexities. To address this, we constructed a single-coil test rig to characterize the critical current, AC losses, and heat transfer characteristics under operating temperatures. Subsequently, a coupled electro-thermal model was developed and validated against the experimental data obtained from the single-coil tests. The validated model was then extrapolated to predict the electromagnetic torque, efficiency, and thermal stability of the full-scale motor. The results demonstrate that the proposed method effectively estimates the operational margins and cooling requirements, providing a reliable design framework for high-performance cryogenic motors.

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Joint Resistivity Change of a Solderless REBCO Coil after Paraffin Impregnation

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Solderless technology enables REBCO magnets to operate without delamination caused by displacement during winding, thermal contraction, and electromagnetic loading. Recently, as part of the PRISM project, a national R&D program in Korea, paraffin vacuum-pressure impregnation (VPI) has been considered for application to solderless coils to prevent the penetration of moisture and air into the magnet, which can cause issues such as oxidation. However, concerns have been raised that paraffin infiltration during VPI may degrade the joint resistivity of mechanically contacted joints. In this study, a REBCO coil with mechanically contacted joints was fabricated, where an indium sheet was inserted between the contact surfaces. The coil consisted of two single pancake coils connected by one solderless inner joint. The coil was first tested in liquid nitrogen (LN₂) to measure the inner joint resistance. Subsequently, paraffin VPI was performed with the coil enclosed in an aluminum can. After impregnation, the coil was tested twice again in LN₂. The first post-VPI test showed that the joint resistance increased by 55 % compared to the virgin coil before VPI. In the second post-VPI test, the joint resistance further increased by 6.0 % relative to the first post-VPI measurement.

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Characterization of Humidity and Water Induced Degradations of REBCO Conductors and Solder Joints

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Rare-Earth Barium Copper Oxide (REBCO) based High-Temperature Superconductor (HTS) tapes are used for large scale applications that usually rely on solder to join individual tapes. Therefore, the characterization of conductors and solder joints at cryogenics temperature under various conditions has been conducted by several laboratories. However, as concerns regarding long term reliability grows, operation of some magnets over a year resulted in some unexpected failures. While the causes of these failures remain unclear, the need to characterize long term failures is becoming increasingly important. In this study, the effects of humidity and water exposure on REBCO conductors and their solder joints are investigated. Magnets and cables for power applications are sometimes expected to operate in liquid nitrogen, implying that special care is required to prevent water contamination during warm-up processes. One of the objectives of this study is to assess whether humidity must be strictly minimized and, if not, to quantify the extent of the damage caused by humidity and water exposure. All samples were first characterized at liquid nitrogen temperature. They were then placed in small room temperature storages with different saturated salt solution to control the humidity levels. After a defined exposure duration, the samples were tested again at liquid nitrogen temperature. During each test, the critical current, n-value and resistivity for joints were controlled.

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비상변화 내조와 상변화 외조를 적용한 압력 제어형 3중 용기 초전도체 냉각 시스템의 설계 및 성능 평가

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본 연구에서는 침지냉각의 온도 균일화를 위한 구리 블록 사용으로 인한 비용과 구조적 복잡화의 한계를 극복하기 위해 상변화 제어 개념을 적용한 3중 용기 기반 초전도체 냉각 구조를 제안한다. 제안된 시스템은 초전도체가 액체 질소에 침지되어 비상변화 조건으로 냉각되는 내조, 외부 액체 질소의 상변화를 이용하여 열 (1 ~ 1.8 kW) 을 제거하는 외조(증발·응축 영역), 그리고 외부 열유입을 차단하기 위한 진공조로 구성된다. 내조는 초전도체의 안정적인 운전을 위해 3 bar, 74 K 조건을 유지함으로써 액체 질소의 비등을 억제하도록 설계되었으며, 외조는 약 0.4 bar의 감압 조건에서 액체 질소의 상변화 냉각을 유도하여 내조로부터 전달된 열을 효과적으로 제거한다. 외조에서 발생하는 증발량과 극저온 냉동기에 의한 응축량의 열적 균형을 유지하기 위해 GM 냉동기를 적용하였으며, 안정적인 장기 운전을 위해 열전달 면적, 포화온도 분포, 응축기 구조 및 배치에 대한 수치해석 결과를 바탕으로 최적화 설계를 수행하였다. 이를 바탕으로 정상 운전 조건에서 내조 온도가 목표 온도 이하로 안정적으로 유지되는지를 평가하고, 증발-응축 균형 조건에서의 시스템 열적 안정성을 분석하였다. 본 연구 결과는 상변화를 능동적으로 제어한 다중 용기 구조가 기존 구리 기반 열균일화 구조를 대체할 수 있는 실질적인 초전도체 냉각 방식임을 보여주며, 향후 대형 초전도 시스템 및 에너지 효율형 극저온 냉각 시스템에 적용 가능한 설계 기준을 제시한다.

이 논문은 2022년도 과학기술정보통신부의 재원으로 한국연구재단의 지원 (NO. RS-2022-NR068576)과 LS Electric 의 연구비 지원을 받아 수행된 연구임.

Experimental Study on Reinforcement Structure of Solenoid Coil under Cyclic Loading using Mechanical

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High-field solenoid coils have strong potential for use in a wide range of applications, including superconducting magnets and high-energy electromagnetic systems. However, stable operation of such coils requires mechanically robust reinforcement structures to withstand large Lorentz forces generated during high-field operation. Accordingly, various reinforcement structures have been explored and optimized through analytical and numerical approaches. In this study, an experimental comparison of different reinforcement structures for high-field solenoid coils is conducted using a dedicated mechanical loading apparatus. Several solenoid coil specimens with different reinforcement configurations are fabricated and subjected to controlled mechanical loading that simulates the radial Lorentz forces acting on the coils. The mechanical responses, including hoop strain and structural stability, are systematically measured and compared to evaluate the reinforcement effectiveness of each structure. The results provide experimental insight into the mechanical performance of reinforced solenoid coils and support the selection and optimization of reinforcement structures for high-field applications.

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Fabrication and Evaluation of HTS Racetrack Coils for Rotating Machine Applications Using Electrically-Conductive Epoxy Composites with Controlled Contact Resistance and Self-Protection Characteristics

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High-temperature superconductor (HTS) racetrack coils have attracted considerable attention in rotating machine applications due to their high torque density and efficiency. However, coil protection under quench remains an important design issue. The no-insulation (NI) technique provides inherent self-protection by allowing current to bypass through adjacent turns. Nevertheless, the absence of turn-to-turn insulation leads to radial current paths, resulting in charge/discharge delays in the magnetic field. To address this phenomenon, an electrically-conductive epoxy impregnation method is proposed in this study. Graphite and silver powders were added to the epoxy resin to improve electrical conductivity, and the contact resistance was controlled by varying the mixing ratios of the powders. Based on the proposed compositions, eight impregnated HTS racetrack coils were fabricated. For comparison, one NI coil was also prepared, resulting in a total of nine coils for experimental evaluation. Sudden-discharge tests were conducted to estimate the contact resistance, and over-current tests were performed to assess the critical current and self-protection characteristics. The experimental results demonstrated that all tested coils exhibited effective self-protection characteristics. In particular, a specific composite showed a time constant approximately ten times faster than that of the NI coil. This composite was subsequently applied to the fabrication of larger HTS racetrack coils. The contact resistance and critical current of the fabricated large-scale coils were evaluated to examine their applicability to rotating machine systems.

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Comparative Study on Guidance Force Characteristics of Independent Double-Circuit Asymmetric Null-Flux Coil for Guidance Force Enhancement

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Electrodynamic Suspension (EDS) systems are gaining significant attention as next-generation high-speed transportation technology due to their inherent self-stabilizing characteristics and superior lift-to-drag ratios. Conventional figure-eight null-flux coils used in EDS systems provide the advantage of simultaneously realizing levitation and guidance within a single structure. However, due to their structural mechanism, the levitation and guidance forces are strongly coupled, which limits the independent enhancement of guidance performance. To address the limitations of conventional cross-connected null-flux coils, this study proposes an independent inner–outer double-circuit asymmetric null-flux coil structure. The guidance characteristics of the proposed structure were quantitatively evaluated and compared with those of the conventional symmetric model using three-dimensional Finite Element Method (3D FEM) analysis. The simulation results demonstrate that the proposed asymmetric coil achieves approximately 6.47 % improvement in guidance force at a 50-mm lateral displacement compared to the conventional model (20.08 kN), indicating its strong potential to enhance the driving stability of EDS systems.

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Design and Experimental Evaluation of a Tank Circuit for an NMR Magnetometer for High-Field Superconducting Magnets

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NMR systems require high magnetic field homogeneity and temporal field stability of superconducting magnets to achieve high-resolution measurements. Typically, the magnetic field is measured using Hall-effect-based magnetometers and subsequently improved through shimming processes. However, Hall-effect magnetometers suffer from limited resolution; therefore, NMR magnetometers are employed for high-resolution magnetic field measurements. Commercial NMR magnetometers generally use probes and variable capacitors installed inside the magnet bore, resulting in a relatively limited dynamic range. This limitation makes it difficult to measure the magnetic field over the entire effective volume of high-temperature superconducting (HTS) magnets. To address this issue, unlike conventional bore-installed NMR probes, a PCB-based tank circuit employing non-magnetic variable capacitors was designed for a 900 MHz hydrogen NMR signal (or a 140 MHz deuterium NMR signal) corresponding to a 20 T magnetic field, achieving a return loss below -30 dB, and incorporated into an NMR magnetometer. The proposed NMR magnetometer was experimentally evaluated through magnetic field measurements of a commercial 900 MHz NMR magnet.

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Experimental Study on Stationary Conduction Cooling and Rotating LN2 Dunk Cooling Operation of Iron-cored Multi-pole NI HTS Field Winding

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No-insulation (NI) high-temperature superconducting (HTS) field coils emerge as a promising solution to enhance the operational reliability of superconducting motors. From a topological perspective, an iron-cored HTS field winding is a viable option due to its advantage in reducing HTS consumption. In this paper, we design and fabricate a four-pole NI HTS field winding with salient iron-core, and implement current charging experiments in a 20 K stationary conduction-cooled environment and motor operation test under rotating liquid nitrogen dunk cooling system. Under stationary conduction-cooling conditions, the current charging characteristics were investigated up to the magnetic saturation region of the iron core, considering non-uniform contact resistivity among individual poles. In addition, under rotating dunk-cooling conditions, the transient response of the NI HTS field winding was examined under variations in load output power. We used a lumped circuit model with finite element method (FEM) for analysis of coil voltage profile considering non-linear properties of iron-core and radial leak current of NI HTS field winding. In addition, to analyze the motor operation characteristics of NI HTS coils, a coupled modeling approach combining MATLAB/Simulink and FEM analysis was employed.

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Comparison of the critical current calculation methods for REBCO cables

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Accurate estimation of the critical current of superconducting cables is essential for determining conductor requirements and for preliminary cost assessment in large-scale superconducting applications. Conventionally, the critical current of REBCO pancake coils is estimated by combining interpolated critical current data as a function of magnetic field and temperature with the expected magnetic field distribution. However, the self-field depends on the transport current distribution, while the current distribution itself is influenced by the local critical current distribution, leading to a coupled and nonlinear problem. This complexity becomes more pronounced in superconducting cables, where multiple tapes are electrically connected in parallel, and different assumptions on current sharing result in different predicted J_c distributions. Furthermore, the calculated cable critical current varies depending on how the relationship between local J_c and the total transport current I_c is defined. In this study, the differences in calculated critical current are systematically evaluated by comparing various assumptions on operating current density distribution and J_c - I_c relations for different cable configurations under a range of background magnetic field and temperature conditions.

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Design of a MW-Class Superconducting Motor for Marine Propulsion Considering Multiple Operating Points and Operating Temperature

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This study presents an optimized design of a MW-class superconducting motor for marine propulsion applications, aimed at maximizing efficiency and minimizing volume across multiple representative operating points. In practical marine applications, motor design must account not only for rated output conditions but also for a range of operating points arising from varying load and speed requirements. By exploiting the controllability of the superconducting field magnet, the motor can be operated over multiple operating points without the need to maintain maximum cooling power at all times, offering potential advantages in system efficiency. Based on this concept, the motor was designed through a comprehensive evaluation of key electromagnetic and thermal parameters, with REBCO conductors adopted for the field magnet. The optimization process incorporates electromagnetic performance, thermal behavior, and system-level integration to ensure applicability to real marine propulsion systems. Detailed calculations include the structural design of the cryostat and stator housing, as well as thermal management considerations reflecting the efficiency of the cryogenic cooling system. The results confirm that the proposed design achieves a compact and high-performance configuration suitable for marine propulsion applications.

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Investigation of Transverse Compressive Behavior in Stacked HTS Tapes under Cyclic Loading

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During operation, High-Temperature Superconducting (HTS) magnets undergo a breathing motion, subjecting the coil windings to repeated stress. Due to the inherent surface irregularities of HTS tapes, they exhibit complex compressive characteristics that significantly differs from the mechanical properties of composite materials. This issue leads to discrepancies between stress simulations and actual magnet behavior. While some research on HTS compressibility exists, quantitative studies on compressive behavior under cyclic loading remain insufficient. This study experimentally analyzes the compressive characteristics of HTS tapes to address the non-linear stress-strain relationship under the load cycles. To imitate a coil winding, HTS tapes were stacked, and their displacement was measured under various load cycles. A hydraulic press machine and a laser displacement sensor were employed to measure the compression of the stacked HTS tapes under constant pressure. Then, we analyzed the evolution of stress-strain curves over repeated cycles to quantitatively assess the HTS tape's compressibility and stiffness changes. These findings provide realistic experimental data to improve the accuracy of stress analysis and ensuring the mechanical reliability of HTS magnets in repetitive operations.

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Winding Tension Control for Large Inner-Outer Radius Ratio Pancake Coil

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This study presents a PLC-based dynamic tension control system for superconducting pancake coil winding. In conventional high-temperature superconducting pancake coil winding, a constant tension is commonly applied; however, for coils with a large inner-to-outer radius ratio ($\alpha > 4$), this approach often leads to instability or collapse of the winding surface. To address this issue, a radius-dependent tension control scheme is employed, in which the target tension is reduced inversely with the winding radius. The winding turn count is measured using an encoder, and the target tension is estimated based on the accumulated turns. The calculated tension command is regulated through a PID control algorithm implemented in a PLC and transmitted to analog tension controllers as a real-time 0-10 V command signal. To support co-winding of a superconducting conductor and a stainless-steel (SUS) tape, the system is extended to independently control four tension channels, each following its own predefined tension profile. The proposed system demonstrates stable and repeatable multi-channel tension control during winding. Future work will focus on simplifying the ladder program and integrating an HMI-based interface for intuitive parameter input.

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고온초전도자석의 고속충방전 운전을 위한 설계기준 도출

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새들형 HTS 마그넷은 가속기 응용분야에서 제한된 공간과 시스템 효율을 고려한 소형경량화 자석 구현에 유리하며, 입자 빔 가속을 위해 요구되는 고속 충방전 운전이 필수적이다. 그러나 고속 충방전 조건에서 무절연 및 변형 무절연 방식의 경우 권선 간 결합에 따른 누설전류와 접촉 특성에 의해 유효한 시정수가 결정되며, 이는 목표 램핑속도에서 충전 지연 현상을 유발할 수 있다. 본 연구는 새들형 HTS 마그넷을 대상으로 집중정수회로법을 통한 시정수-접촉저항 관계를 이용하여 고속충방전 운전을 위한 설계 기준을 도출하였다. 마그넷 스케일에 따른 인덕턴스와 특성저항의 관계에 관하여 시정수를 평가하였으며, 시정수 변화에 따른 고속충방전 응답 특성을 비교하여 고속충방전 구현 가능한 시정수 범위를 확인하였다. 이를 2T 마그넷의 1T/s 운전 조건에 적용하여 목표 시정수를 만족하는 접촉저항 요구 조건을 평가하였다. 본 결과를 통해 새들형 마그넷의 고속충방전 운전 설계 개선 및 절연 방식 결정에 적용 될 예정이며, 향후 마그넷 제작에 따라 고속충방전 시험 평가에 활용 될 것이다.

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The international collaborative development for the process verification of 1.3 GHz 9-cell SRF cavity fabrication by using copper prototypes

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As a part of the ILC (International Linear Collider) development program, the fabrication of 1.3 GHz 9-cell SRF (Superconducting Radio Frequency) cavities using high-purity niobium requires rigorous validation of fabrication process prior to full superconducting production. In this study, copper cavities were manufactured as process-verification prototypes to assess forming, machining, and electron-beam welding techniques. The project was carried out under the ITN (ILC Technology Network) as an international collaborative effort among KEK (Japan), Korea University, and KAT (Kiswire Advanced Technology Co., Ltd.) as the industrial manufacturer. A total of three 1.3 GHz 9-cell cavities were successfully fabricated following the same geometric specifications and key manufacturing steps intended for niobium SRF cavities. All cavities underwent comprehensive quality evaluations successfully, including helium leak testing and radio-frequency resonance measurements. The leak rate of each cavity was less than $1.0\text{E-}10$ mbar-L/sec, the measured resonant frequencies were in good agreement with design values within 0.05 % tolerance, demonstrating excellent geometric accuracy and fabrication reproducibility. The successful fabrication and validation of these copper cavities verify the robustness of the established manufacturing process and provide a reliable technical basis for subsequent production of superconducting niobium cavities for ILC program.

Keywords : ILC, SRF, Superconducting, Cavity

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Measurement of Liquefied Nitrogen Boil-Off Rate and Identification of Radial Temperature Non-Uniformity for Condenser Design

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In this study, a storage Dewar for liquefied nitrogen was designed and fabrication. To accurately estimate the liquefied nitrogen inventory, the nitrogen boil-off rate (BOR) was experimentally measured using a level meter and multiple sensors. The designed Dewar demonstrated satisfactory performance, achieving a BOR of approximately 2 %/day. In addition, to establish a basis for condenser design prior to nitrogen liquefaction using GM cryocooler, the cold-head temperature distribution was measured with high precision. The measured data were then incorporated as an experimentally informed base-temperature condition for a fin-type condenser, providing a design foundation aimed at maximizing the nitrogen liquefaction rate

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Determination of Thermodynamic Cycle Operating Parameters for COP Maximization of a 4 K 10 W He-JT Cryocooler

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With the increasing integration density of qubits in quantum computers, the heat load in the cryogenic environment, particularly at the 4 K stage, is rising exponentially. Conventional 4 K Pulse Tube cryocoolers exhibit a low Coefficient of Performance (COP) due to the reduced specific heat of regenerator materials in this temperature range, leading to significant power consumption in large-scale systems. To overcome these limitations, this study aims to maximize power efficiency by optimizing the thermodynamic cycle operating parameters of a Helium Joule-Thomson (He-JT) cryocooler targeting a cooling capacity of 10 W at 4 K. A He-JT cycle utilizing commercial Pulse Tube cryocoolers (e.g., PT450, PT820) as precoolers was modeled. To address the nonlinearity of helium properties near the critical point and the numerical instability associated with existing analysis methods, a revised numerical calculation algorithm was established by combining the actual cooling capacity map of the precooler with the required heat load of the JT cycle. Through this, the variations in system COP and mass flow rate were analyzed across various high-pressure conditions (2-42 bar) and precooling temperatures. The results identified an optimal operating point where the COP is maximized for a specific combination of high pressure and precooling temperature. This research is expected to serve as foundational data for the design of high-efficiency He-JT cryocooler capable of significantly reducing the power consumption of large-scale quantum computer cooling systems

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Conductance Analysis and Ultimate Pressure Characteristics of a Dilution Refrigerator Vacuum Pumping System

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To ensure the optimal performance of a dilution refrigerator, maintaining the purity of the helium mixture through initial evacuation is essential. However, since the tubing connected to the Mixing Chamber (MXC) employs a narrow diameter to minimize thermal conduction, conventional unidirectional pumping faces limitations in achieving the target vacuum due to high flow resistance. In this study, to overcome these structural constraints and maximize pumping efficiency, we implemented and validated a bidirectional pumping method capable of bypassing the bottleneck caused by the capillary. The vacuum system was modeled using an equivalent circuit to analyze gas flow characteristics, which were then compared with experimental data. The results demonstrated that bidirectional pumping significantly reduced convergence time and improved the ultimate pressure compared to the unidirectional approach. However, a significant pressure differential of approximately 55 mTorr persisted between the Still (~9.0 mTorr) and the MXC (~63.8 mTorr) even with bidirectional pumping. Theoretical analysis confirmed that this differential was not due to a system leak, but rather a natural pressure equilibrium resulting from the flow resistance defined by the conductance of the interconnecting tubing between the Still and the MXC. In conclusion, this study experimentally validates the efficiency of bidirectional pumping and demonstrates that the observed residual pressure phenomena can be physically explained through vacuum engineering modeling. These findings serve as a fundamental reference for evaluating the integrity of dilution refrigerator vacuum systems and designing optimized pumping configurations.

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Effect of Radiation Shield on Two-Stage Gifford-McMahon (GM) Cryocooler Performance

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A radiation shield is a thermal barrier designed to reduce radiative heat transfer from the ambient environment to cryogenic components by providing an intermediate temperature surface. Multi-layer insulation (MLI) is often added to the shield to further reduce radiative heat loads. This study investigates how this thermal protection strategies affect the performance of two-stage Gifford-McMahon (GM) cryocoolers, considering the thermodynamic coupling between stages. A numerical model was developed using the electrical circuit analogy for enclosure radiation and the modified Lockheed equation for MLI heat transfer. The cryocooler response was modeled via 2D spline interpolation of the Sumitomo RDK-415D cooling capacity map. Equilibrium temperatures were determined through an iterative algorithm. Three configurations were analyzed: no shield, shield without MLI, and shield with 10-layer MLI. Surprisingly, adding MLI increases the second stage equilibrium temperature from 2.54 K to 2.75 K. This occurs because MLI reduces the first stage heat load, shifting the cryocooler operating point to a less favorable region of the cooling capacity map where both stages share interdependent cooling capacities. Experiment was conducted to confirm numerical analysis: second stage temperatures was measured 3.98 K without shield and 2.50 K with MLI-wrapped shield, compared to calculated values of 4.11 K and 2.75 K respectively. Attempt to optimize layer count and density showed that MLI layer presence affect the heat load while specific number does not. These results suggest that for applications requiring minimum second stage temperature, a bare radiation shield without MLI may be optimal.

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1D Thermal-Fluid Modeling of a GHe Circulating Cooling System Using a Cryogenic Blower for Hydrogen-Fueled Mobility

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To ensure the thermal reliability of High-Temperature Superconducting (HTS) motors for hydrogen-fueled mobility, this study proposes a closed-loop Gas Helium (GHe) cooling cycle driven by a cryogenic blower, utilizing Liquid Hydrogen (LH₂) as a heat sink via an indirect cooling method. A one-dimensional (1D) thermal-fluid model was developed to analyze the system, incorporating key components such as the cryogenic blower, heat exchanger, piping network, and the HTS motor. The model accounts for the temperature- and pressure-dependent properties of helium and reflects the performance curves of the cryocooler used to simulate the LH₂ environment. By applying transient heat loads according to various mission profiles, the study identifies critical design parameters, including the required mass flow rate, total pressure drop, heat exchanger performance (UA), and the optimal operating point of the cryogenic blower. The validity of the proposed model was rigorously established through cross-validation with recognized property databases and experimental data obtained from a laboratory-scale test rig. The proposed framework demonstrates that this GHe circulation approach reduces system complexity compared to liquid refrigerant methods while maintaining compatibility with LH₂ infrastructure, thereby significantly enhancing both the energy efficiency and safety of HTS propulsion systems.

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Thermal Performance Evaluation of a Heat Pipe-Based Cooling Channel for High-Temperature Superconducting Rotating Systems

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High-temperature superconducting (HTS) rotating systems require a uniform thermal environment under cryogenic conditions to ensure stable operation and high system reliability. Conventional solid conduction-based cooling structures are prone to generating localized temperature gradients due to geometric constraints, which can adversely affect the thermal stability of superconducting magnets. In this study, the applicability of a heat pipe-based cooling channel is investigated as an alternative thermal management approach for superconducting magnet structures. Under cryogenic operating conditions using nitrogen as the working fluid, the thermal characteristics of a SUS block-based cooling structure and a SUS heat pipe-based cooling channel are compared. To evaluate the influence of cooling channel configuration on heat transfer behavior under identical material conditions, the temperature difference between designated high-temperature and low-temperature regions is adopted as the primary performance metric. Based on this comparative evaluation, the thermal behavior of the SUS heat pipe-based cooling channel is examined under cryogenic nitrogen operation, and its applicability to practical HTS rotating systems is discussed from a thermal management perspective. Furthermore, key thermal considerations associated with structural integration of the proposed cooling channel are identified and summarized. This study compares the thermal characteristics of cryogenic SUS-based structures with different cooling channel configurations and explores the feasibility of heat pipe-based cooling channels as a cooling solution for HTS rotating machinery. The design and evaluation framework presented in this work is expected to be extendable to cooling systems employing other cryogenic working fluids, such as liquid hydrogen or neon, for operation at lower temperature ranges. The findings provide fundamental insights into the design of cryogenic thermal management structures for superconducting systems.

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Multiphysics-Based Rotordynamic Analysis of a Cryogenic Rotor System Under Thermal-Structural Effects

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Superconducting motors can significantly enhance power density by reducing electrical losses and enabling high-magnetic-field generation, thereby decreasing the overall volume for a given power output. However, since superconductivity is maintained only under cryogenic conditions, appropriate cooling and thermal insulation technologies are essential. The dynamic behavior of rotor systems, including those in superconducting motors, is heavily influenced by unbalance, dynamic characteristics, and gyroscopic effects during operation. Resonance occurring at specific rotational speeds can amplify vibrations, leading to structural damage. Particularly in cryogenic environments, material properties change due to temperature gradients, and preloads are induced by thermal contraction, making the dynamic evaluation of the rotor system in its post-cooling state crucial. The Campbell chart is a vital tool for representing the modal frequencies of a rotor as a function of rotational speed, displaying both the natural frequency curves and excitation lines. The intersection of these lines indicates where the natural frequency matches the excitation frequency, identifying the "critical speed." Consequently, Campbell charts serve as a key metric for assessing resonance risk zones and separation margins within the operating range. In this study, a multi-physics thermal-structural analysis was performed on a cryogenic rotor model, with the results integrated into the rotordynamic analysis. The hydrogen reservoir and torque disc, core components of the superconducting motor, were 3D modeled to incorporate specific temperature and initial loading conditions. Rotordynamic analyses were conducted for both ambient and post-cooling states to compare the results and identify shifts in the Campbell chart caused by initial cooling and loading conditions. This research quantifies the impact of changing boundary conditions-driven by cooling and preloads-on rotor response, ultimately proposing an analytical procedure to minimize critical speed prediction errors inherent in ambient-temperature-based designs.

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고온 초전도 케이블 냉각을 위한 밀폐형 냉각 시스템 열역학 설계 및 최적화

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고온 초전도체(HTS) 케이블 시스템은 높은 전류 밀도와 안정적인 장거리 운전을 위해 신뢰성 높은 극저온 냉각 기술이 필수적이다. 본 연구에서는 운전 온도 78 K에서 약 10 kW의 열적 부하를 갖는 HTS 케이블 냉각을 목표로, 외부 액체질소의 추가 공급이나 증발 손실을 배제한 밀폐형 냉각 시스템을 열역학적으로 설계하였다. 액체질소 기반 냉각이 갖는 2상 유동 및 장거리 운전 한계를 고려하여, 본 시스템에서는 헬륨(He)을 작동 유체로 사용하는 기체 냉각 방식을 채택하였으며, 이를 구현하기 위한 역브레이튼(Reverse Brayton) 냉각 사이클을 기본 구조로 설정하였다. 사이클의 순환 구조가 완전하게 구속되는 조건을 바탕으로, 압축기 개수, 압축비, 최고·최저 압력 등 설계 변수를 체계적으로 구분하였다. 공정 과정 시뮬레이터인 Aspen HYSYS와 실제 작동 유체 물성치를 반영하기 위해 NIST REFPROP을 연동하여 단일 역브레이튼 사이클의 열역학적 성능을 해석하고 최적화를 수행하였다. 해석 결과, 최저 압력이 낮아질수록 냉각 성능 지표(Figure of Merit, FOM)가 증가하는 경향은 확인되었으나, FOM에 대한 영향은 제한적인 것으로 나타났다. 반면, 압축기의 개수와 압축비는 독립적인 인자가 아니라, 작동 유체의 최고 압력과 최저 압력의 비율에 의해 지배되며, 해당 압력비 조합에 따라 FOM이 최대화되는 최적 운전점이 존재함을 확인하였다. 추가적으로, 액체질소 기반 줄-톰슨(Joule-Thomson, JT) 냉각 사이클을 역브레이튼 사이클과 결합하여, 역브레이튼 사이클의 최저 온도를 상승시키는 예냉 구조를 제안하였다. 이를 통해 역브레이튼 예냉 구간의 FOM을 향상시키고, JT 냉각 시스템에 추가적인 동력을 투입함으로써 전체 냉각 시스템의 종합 FOM을 증가시킬 수 있는 가능성을 분석하였다. 본 연구는 HTS 케이블 냉각 시스템에 적용 가능한 헬륨 기반 역브레이튼 및 JT-역브레이튼 하이브리드 냉각 구조의 열역학적 설계 기준과 최적화 방향을 제시하고자 한다.

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Analysis of Demagnetization Conditions and Thermal Performance of a Thermosyphon for 1 K Operation in a cADR System

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Stable operation of quantum devices in quantum computing systems requires the realization of an ultra-cryogenic environment. To date, such environments have primarily been achieved using dilution refrigerators; however, their application is limited by the high cost and restricted availability of helium-3, as well as the complexity of gas handling systems, which complicate system integration and long-term operation. As an alternative approach, adiabatic demagnetization refrigerators (ADRs) that do not rely on helium-3 have attracted increasing attention as next-generation cryogenic cooling technologies. ADRs utilize the magnetocaloric effect of magnetic refrigerants to achieve high cooling efficiency, and multi-stage continuous ADR (cADR) systems are required for sustained low-temperature operation. In this study, a cADR configuration is considered in which gadolinium gallium garnet (GGG) is employed in the first cooling stage to maintain temperatures around 1 K while accommodating thermal loads transferred from subsequent stages (second and third stages). Particular attention is given to the applicability of a passive thermosyphon as a thermal switch to ensure the thermal stability of the first stage. When the target operating temperature approaches approximately 1 K, helium-4 used as the working fluid undergoes a transition to the superfluid state, leading to a sharp increase in thermal conductivity and potential degradation of the thermal isolation performance of the heat switch. Therefore, this study focuses on the thermal behavior of the passive thermosyphon during the superfluid helium transition and the temperature holding period following attainment of the target temperature. Time-dependent thermal simulations based on MATLAB are performed to investigate the effects of demagnetization control—specifically, variations in demagnetization amount or duration after temperature stabilization—on the thermal response of the first-stage ADR under repetitive cooling cycles. The results of this study provide operational strategies and design considerations for achieving long-term stable operation near 1 K in cADR systems employing passive thermosyphon-based thermal switches.

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Design of a Single-Stage ADR System Using a GGG Salt Pill

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Adiabatic demagnetization refrigerators (ADRs) are essential cooling technologies for achieving sub-Kelvin temperature environments required in a wide range of cryogenic applications, including superconducting devices, ultra-sensitive sensors, and quantum research. In particular, when combined with a cryocooler-based precooling stage, single-stage ADR systems offer a compact and reliable solution for reaching temperatures below 1 K. However, the achievable base temperature and cooling performance strongly depend on the integrated design of key components, such as the salt pill, thermal bus, heat switch, and mechanical support structures. In this study, a single-stage ADR system employing a gadolinium gallium garnet (GGG) salt pill is designed with the objective of achieving a base temperature of 0.5 K. To analyze the thermal behavior of the ADR system, a two-dimensional (2D) numerical model is developed, enabling systematic evaluation of heat flow paths and temperature distributions during the magnetization and demagnetization processes. Based on the developed 2D model, the major components of the ADR system including the GGG salt pill, thermal bus, thermal interfaces, and structural elements are designed at an engineering level. The analysis results are used to verify the feasibility of the proposed design and to identify the dominant thermal resistances and heat leakage paths affecting the cooling performance. Following the design validation, key components required for constructing a single-stage ADR prototype are fabricated according to the derived design parameters. The developed system serves as a test platform for sub-Kelvin cooling and provides a foundation for future extension toward multi-stage or continuous ADR systems. This work presents a practical design methodology that bridges numerical modeling and hardware realization for single-stage ADR development.

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Thermal Resistance Characteristics of a Gas Blow Coupling for Cryogenic HTS Rotor Cooling under Stationary Conditions

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High-temperature superconducting (HTS) rotating machines offer superior power density and efficiency owing to their ability to operate at extremely high current densities. However, the practical implementation of such systems critically depends on maintaining the HTS rotor at cryogenic temperatures, which necessitates a reliable thermal linkage between stationary and rotating components. Conventional rotor cooling approaches often suffer from inherent limitations, including increased system mass due to onboard cryocoolers, reduced cooling effectiveness, and structural complexity associated with integrating heat exchange passages within the rotor. Moreover, the presence of cryogenic fluid channels in a rotating environment raises concerns related to leakage and mechanical reliability, thereby restricting their applicability in high-speed rotating machinery. To address these challenges, this study proposes a novel thermal coupling concept referred to as the Gas-Blow Thermal Coupling (GBC). The proposed configuration employs a sealed gaseous refrigerant within an internal rotor channel, where fluid motion is induced by an impeller-type flow driver embedded in the rotating structure. During rotation, the generated forced convection enhances heat transfer between the rotor and the stationary thermal interface without direct mechanical contact. In addition to steady-state operation, HTS rotating machines require an initial cooldown process to reach temperatures below the superconducting transition prior to startup. Accordingly, the GBC structure is designed to provide sufficient thermal conduction even under stationary conditions, enabling effective precooling of the HTS rotor. Once rotation commences, convective heat transfer is significantly intensified by the impeller-driven gas flow, allowing the system to reach and maintain the rated operating temperature. The feasibility of the proposed GBC concept was investigated through finite element method (FEM)-based thermal and structural analyses, followed by the fabrication of a scaled experimental prototype. Experimental evaluations were conducted to quantify the thermal resistance of the system under stationary conditions with applied external heat loads, assessing its

capability to achieve the required initial cooldown temperature. Furthermore, helium leak testing was performed to verify the integrity and applicability of the sealed cooling configuration for HTS rotor systems.

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Design of a Hybrid SFCL Cryostat Compatible with Both Brayton and GM Refrigerators

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Superconducting fault current limiters (SFCLs) require reliable cryogenic cooling to ensure stable operation under both steady-state and transient grid conditions. While Gifford-McMahon (GM) refrigerators have been widely adopted for SFCL cryostats due to their relatively low cost and practical availability, Brayton refrigerators are favored in superconducting power applications for their higher thermodynamic efficiency and scalable cooling capacity. This paper presents the design of a hybrid SFCL cryostat compatible with both Brayton and GM refrigerators, enabling flexible cooling architectures across a wide range of deployment scenarios. The proposed cryostat incorporates modular top-plate interfaces to accommodate (i) a Brayton-based primary cooler, (ii) a multi-GM configuration that provides distributed cooling through multiple cold heads to achieve performance comparable to a Brayton refrigerator, and (iii) a combined configuration in which one or more GM refrigerators supplement a Brayton refrigerator to compensate for insufficient cooling capacity and improve operational margin. A key feature of the design is interchangeable top-plate modules that enable rapid reconfiguration without major cryostat modifications. Engineering analyses are conducted to evaluate thermal performance, temperature uniformity, and steady-state thermal behavior under representative heat-load conditions. The proposed design provides a practical pathway for integrating legacy GM-based infrastructure with Brayton-based cooling systems used for superconducting cables for next-generation SFCL installations.