2022 Winter Conference of KSSC

Abstracts of
2022 Winter Conference of KSSC

On-line
Feb 21 ~ Feb 22, 2022

Edited by **Hankil Yeom**

Organized by
The Korean Society of Superconductivity and Cryogenics (KSSC)

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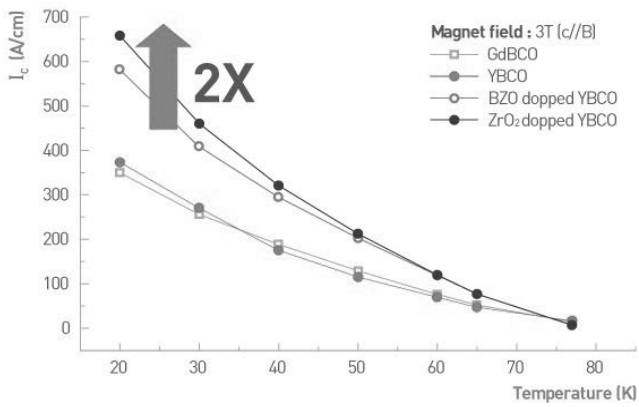

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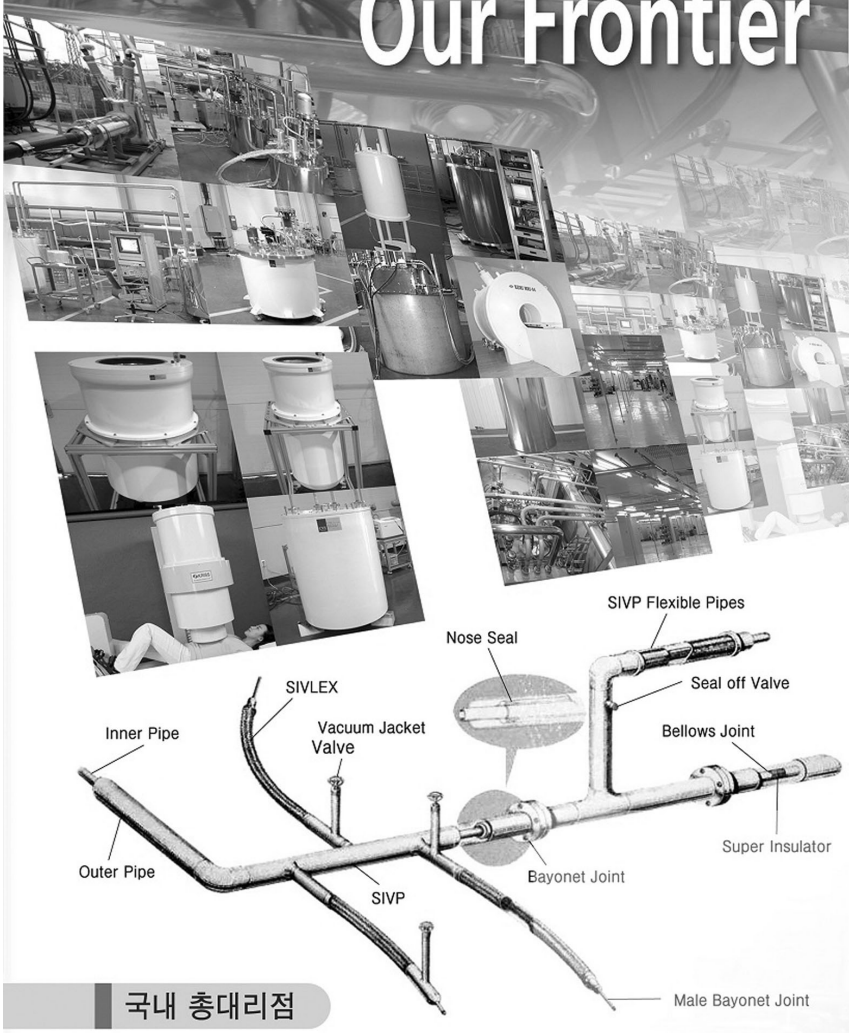

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특허법인 부경

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인 사 말

안녕하십니까?

2022 한국초전도저온학회 동계학술대회에 참여하시는 회원님들, 협력사들을 비롯한 모든 학회 관련자들께 감사말씀 드립니다. 지난 8월 하계학술대회 이후 오프라인에서 반가운 회원님들 뵙기를 희망하며 이번 동계학술대회를 준비하였습니다. 그러나 COVID-19의 변이 종에 하나인 오미크론이 우세종이 되면서 감염자가 폭발적으로 증가하는 상황에 직면, 이번 학술대회도 부득이 온라인으로 개최하게 되었습니다.

조직위원회는 지난 몇 번의 온라인 개최 경험을 최대한 살려 회원님들의 업적 공유 및 학술 논의에 부족함이 없도록 준비하였습니다. 회원님들의 변함없는 적극적 참여로 인해 우리학회가 좀 더 발전하는 모습으로 나아갈 수 있음을 확신합니다.

이번 학술대회도 6개 부문으로 나뉘어 논문발표가 진행됩니다. 특별히 이번에 “초전도 양자컴퓨터 시스템 개발”, “액체수소 수송선 연구개발 현황” 등 최근 관심의 중심에 있는 주제들에 대해 전문가를 모셔 초청 강연이 진행되니 많은 관심과 참여 부탁드립니다.

본 학술대회에 투고된 논문들은 심사를 거쳐 SCOPUS 등재지인 한국초전도저온학회 학회지 PSAC(Progress in Superconductivity and Cryogenics)에 게재됩니다.

온라인 학술대회임에도 불구하고 참여해 주신 기업들께도 다시 한 번 감사 드리고, 마지막으로 본 학술대회 준비에 힘써 주신 조직위원님들, 좌장님들, 그리고 보이지 않는 곳에서 염려해 주시고 도움 주시는 모든 관계자 여러분께 이 자리를 빌려 감사의 말씀 전해드립니다.

늘 건강과 행복이 회원님들과 함께하길 기원합니다.

감사합니다.

2022년 2월 21일

한국초전도저온학회 학술위원장 **염 한 길**

CONTENTS

PLENARY Ⅰ

PLENARY Ⅱ

SESSION Ⅰ : TE Ⅰ

Theory & Electronics & Device Applications - Ⅰ

SESSION Ⅱ : PP Ⅰ

Physical Properties - Ⅰ

SESSION Ⅲ : PP Ⅱ

Physical Properties - Ⅱ

SESSION Ⅳ : LA Ⅰ

Large Scale Applications - Ⅰ

SESSION Ⅴ : LA Ⅱ

Large Scale Applications - Ⅱ

SESSION Ⅵ : MM Ⅰ

Materials - Ⅰ

SESSION Ⅶ : CR Ⅰ

Cryogenics - Ⅰ

POSTER SESSION

Theory & Electronics & Device Applications

Physical Properties

Materials

Large Scale Applications

Cryogenics

PLENARY I

PLENARY

PL I

Development of a superconducting quantum computer : 5 qubits and more

Yonuk Chong* ***(SungKyunKwan University)***

Here we report our recent result of the 5-qubit superconducting quantum computerdevelopment.

We successfully demostrated a system-level operation of multiple qubit gate operations, from the device to the analysis, based on the 5-qubit Josephson quantum processor.

We will also present a future direction to more than 100 qubit level scaling up of the superconducting quantum computer system.

This work is done by the superconducting quantum computer deveopement team led by SKKU, in a close collaboration of SKKU, KRISS, UNIST, Kyungpook National Univ., Seoul National Univ., Korea Univ., Yonsei Univ.,

PLENARY II

R&D Status of Liquid Hydrogen(LH_2) Carrier

Giltae Roh* ***(Korean Register(KR), Busan, Korea)***,
Hyunyoung Lee *(Korean Register(KR), Busan, Korea)*

In response to the new and strong environmental regulations of the IMO due to climate crisis caused by global warming, the demand for the use of hydrogen fuel in ships and transportation of hydrogen by ships is increasing.

Also, most of country not only around the world announce many policies to realize the hydrogen economy, but also is consisting to make a network for public use of hydrogen.

Hydrogen can be stored in various ways, such as compressed, liquefied and in adsorbed to organic composite.

A safe and only way to transport large amount of hydrogen is using by ship, in order to safely transport hydrogen, many researches are being conducted to develop a liquid hydrogen carrier.

There are three Core technologies in liquid hydrogen carrier, which are Cargo Containment System(CCS), Cargo Handling System(CHS) and BOG Treatment System(BTS).

We would like to introduce at this presentation, R&D status of liquid hydrogen(LH_2) Carrier.

Keywords : LH_2, Liquid Hydrogen carrier, Cargo containment system, BOG, Cryogenic

SESSION I : TE I

Theory & Electronics & Device Applications - I

ORAL

O TE I-1

A Comparative Study on the Scalability of Superconducting Quantum Information Processor with or without Direct Coupler between Qubits

Seong Hyeon Park ***(Seoul National University)***,
Geonyoung Kim *(Seoul National University)*,
Insung Park *(Seoul National University)*,
Seungyong Hahn* *(Seoul National University)*

After the past 20 years of remarkable breakthroughs in superconducting quantum information processors, planar superconducting quantum information processor with more than 100 qubits have recently been unveiled. To scale up the number of superconducting qubits further, there are challenges to be addressed such as coupling between qubits, connectivity between qubits, decoherence due to the interactions with adjacent qubits, and dense wiring required for control and readout. In general, coupling between qubits can be implemented with coplanar waveguide structured coupler to prevent unintended interactions. However, the dense wiring problem can be worse by placing additional couplers between qubits. Meanwhile, it is possible to implement coupled qubits system by placing a qubit right next to the each other. In this paper, we compare the advantages and disadvantages of directly coupled qubits system with coupler imbedded system. Transmon qubits of double pad structure are assumed to provide universality while couplers are assumed to be non-tunable. By using black-box quantization method, we propose a quantitative coupling strength and scalability of superconducting quantum information processor with or without coupler between qubits.

This research was supported by Samsung Electronics Co., Ltd.

ORAL

O TE I-2

Absence of supercurrent in edge-free Corbino graphene Josephson junction in the quantum Hall regime

Seong Jang *(Pohang University of Science and Technology)*,
Sein Park *(Pohang University of Science and Technology)*,
Jinho Park *(Pohang University of Science and Technology)*,
Kenji Watanabe *(National Institute for Materials Science)*,
Takashi Taniguchi *(National Institute for Materials Science)*,
Gil-Ho Lee* *(Pohang University of Science and Technology)*

The first observation of the supercurrent in graphene Josephson junction in the quantum Hall regime has attracted considerable attention, which demonstrated the hybridization of two seemingly incompatible phases: quantum Hall state and superconducting state. However, the mechanism of the quantum Hall supercurrent is still controversial due to not exactly quantized resistance at quantum all plateau. This suggests that the supercurrent may flow through not perfectly insulating bulk state instead of quantum Hall edge states. In order to specify this issue, we fabricated and measured graphene Josephson junction both in conventional rectangular geometry with edges and Corbino geometry without any edge. Highly transparent molybdenum/rhenium superconducting contacts are realized to achieve Josephson coupling as high as $I_C R_N \sim 350$ μV at zero magnetic field in both rectangular and Corbino geometry. In the quantum Hall regime, supercurrent was observed in rectangular graphene Josephson junction with edges, however, supercurrent was absent in edge-free Corbino graphene Josephson junction. Our results strongly support that the supercurrent observed in quantum Hall regime flows along the edges of graphene.

S.J., S.P., J.P. and G.-H.L. acknowledge the support of the Samsung Science and Technology Foundation (project no. SSTF-BA1702-05) for device fabrications and low temperature measurements. The authors also acknowledge the support of the Asia Pacific Center for Theoretical Physics.

ORAL

O TE I-3

Steady Floquet-Andreev states in graphene Josephson junctions

Sein Park *(Postech)*,
Wonjun Lee *(Postech)*,
Seong Jang *(Postech)*,
Yong-Bin Choi *(Postech)*,
Jinho Park *(Postech)*,
Woochan Jung *(Postech)*,
Kenji Watanabe *(NIIMS)*,
Takashi Taniguchi *(NIMS)*,
Gil Young Cho *(Postech)*,
Gil-Ho Lee* *(Postech)*

Engineering quantum states through light-matter interaction has created a new paradigm in condensed matter physics. A representative example is the Floquet-Bloch state, which is generated by time-periodically driving the Bloch wavefunctions in crystals. Previous attempts to realise such states in condensed matter systems have been limited by the transient nature of the Floquet states produced by optical pulses1-3, which masks the universal properties of non-equilibrium physics. Here, we report the generation of steady Floquet-Andreev (F-A) states in graphene Josephson junctions by continuous microwave application and direct measurement of their spectra by superconducting tunnelling spectroscopy. We present quantitative analysis of the spectral characteristics of the F-A states while varying the phase difference of superconductors, temperature, microwave frequency and power. The oscillations of the F-A state spectrum with phase difference agreed with our theoretical calculations. Moreover, we confirmed the steady nature of the F-A states by establishing a sum rule of tunnelling conductance4, and analysed the spectral density of Floquet states depending on Floquet interaction strength. This study provides a basis for understanding and engineering non-equilibrium quantum states in nano-devices.

We thank H.-J. Lee, K.W. Kim, J.C.W. Song, D. Cho, K. C. Fong, and C. Lee for critical reading of the manuscript. We also thank C. B. Winkelmann for a fruitful discussion about Tien-Gordon model. S.P., S.J., Y.-B.C. and G.-H.L. acknowledge the support of the Samsung Science and Technology Foundation (project no. SSTF-BA1702-05) for device fabrications and low-temperature measurements. W.J. and G.-H.L. acknowledge the support of National Research Foundation of Korea (NRF) funded by the Korean Government for data analysis. W.L. and G.Y.C. acknowledge the support of the National Research Foundation of Korea (NRF) funded by the Korean Government (Grant No. 2020R1C1C1006048 and 2020R1A4A3079707), as well as Grant No. IBS-R014-D1. W.L and G.Y.C. are also supported by the Air Force Office of Scientific Research under Award No. FA2386-20-1-4029.

ORAL

O TE I-4

Exotic Thermal Transitions with Spontaneous Symmetry Breaking

Hanbit Oh ***(Korea Advanced Institute of Science and Technology)***,
Eun-Gook Moon* *(Korea Advanced Institute of Science and Technology)*

We show that exotic spontaneous symmetry breaking appears in thermal topological phases by perturbing the exact solutions of quantum rotor models coupled to the three-dimensional toric code. The exotic Ising and XY transitions are shown to be in the same universality class in drastic contrast to the conventional Wilson-Fisher classes without topological orders. Our results indicate that topological orders must be included to pin down universality classes of thermal transitions in addition to order parameter symmetry and spatial dimension. We evaluate all the critical exponents and find that the exotic universality class is more stable under the couplings to acoustic phonons and disorder. Applying our results to experiments, we provide a plausible scenario in puzzlings of strongly correlated systems, including the absence of specific heat anomaly in doped $RbFe_2As_2$.

ORAL

O TE I-5

Machine-Learning-Guided Prediction Models of Critical Temperature of Cuprates

Sooran Kim* ***(Kyungpook National University)***

Cuprates have been at the center of long debate regarding their superconducting mechanism; therefore, predicting the critical temperatures of cuprates remains elusive. Herein, using machine learning and first-principles calculations, we predict the maximum superconducting transition temperature ($T_{c,max}$) of hole-doped cuprates and suggest the functional form for $T_{c,max}$ with the root-mean-square-error of 3.705 K and R2 of 0.969. We have found that the Bader charge of apical oxygen, the bond strength between apical atoms, and the number of superconducting layers are essential to estimate $T_{c,max}$. Furthermore, we predict the $T_{c,max}$ of hypothetical cuprates generated by replacing apical cations with other elements. Among the hypothetical structures, the cuprates with Ga show the highest predicted $T_{c,max}$ values, which are 71, 117, and 131 K for one, two, and three CuO_2 layers, respectively. These findings suggest that machine learning could guide the design of new high-T_c superconductors in the future.

Reference: J. Phys. Chem. Lett. 2021, 12, 6211-6217

SESSION II : PP I

Physical Properties - I

ORAL

O PP I-1

Kondo interaction and its potential role in the magnetic phase of FeTe

Younsik Kim *(Seoul National University)*,
Minsoo Kim *(Seoul National University)*,
Cheng-Maw Cheng *(National Synchrotron Radiation Research Center)*,
Joonyoung Choi *(Kyungpook National University)*,
Saegyeol Jung *(Seoul National University)*,
Donghui Lu *(Stanford Synchrotron Radiation Light source)*,
Jong Hyuk Kim *(Yonsei University)*,
Soohyun Cho *(Chinese Academy of Sciences)*,
Dongjoon Song *(Seoul National University)*,
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Young Jai Choi *(Yonsei University)*,
Hyeong-Do Kim *(Pohang Accelerator Laboratory)*,
Younjung Jo *(Kyungpook National University)*,
Jung Hoon Han *(Sungkyunkwan University)*,
Soonsang Huh *(Seoul National University)*,
Changyoung Kim* *(Seoul National University)*

Finding d-electron heavy fermion (HF) states has been an important topic as the diversity in d-electron materials can lead to many exotic Kondo effect-related phenomena or new states of matter such as topological Kondo insulator. Yet, obtaining direct spectroscopic evidence for a d-electron HF system has been elusive to date. Here, we report the observation of Kondo lattice behavior in an antiferromagnetic metal, FeTe, via angle-resolved photoemission spectroscopy (ARPES) and transport properties measurements. The Kondo lattice behavior is represented by the emergence of a sharp quasiparticle at low temperatures. The transport property measurements confirm the low-temperature Fermi liquid behavior and reveal successive coherent-incoherent crossover upon increasing temperature. We interpret the Kondo lattice behavior as a result of hybridization between localized Fe 3dxy and itinerant Te 5pz orbitals. Our observations suggest unusual cooperation of Kondo lattice behavior and long-range antiferromagnetism.

ORAL

O PP I-2

Spectroscopic Study on Pseudogap and Kondo Hybridization in Heavy-fermion under Pressure

Harim Jang *(Sungkyunkwan University)*,
Hong Thi Anh Vuong *(Sungkyunkwan University)*,
Jihyun Kim *(Sungkyunkwan University)*,
Tuson Park* *(Sungkyunkwan University)*

We report the emergent pseudogap in the prototypical heavy-fermion superconductor $CeCoIn_5$ via the quasi-particle scattering spectroscopy under hydrostatic pressure. Energy-resolved differential conductance (dI/dV) spectrum revealed a pseudogap with energy Dg in the normal state above the superconducting transition temperature of 2.3 K and below the characteristic temperature of TPG. With increasing pressure, both Δg and TPG gradually increase: TPG (Dg) is 5 K (1.6 meV) at ambient pressure and increases to 15 K (4.0 meV) at 2.3 GPa. The dependence on the external pressure of Dg and TPG are similar to that of the transport Kondo coherence temperature Tcoh, suggesting that the pseudogap in $CeCoIn_5$ is correlated to Kondo hybridization effects. The characteristic of the pseudogap along with the Fano asymmetric behavior in Kondo lattice $CeCoIn_5$ will be discussed in this talk.

This work was supported by the National Research Foundation (NRF) of Korea through a grant funded by the Korean Ministry of Science and ICT (No. 2021R1A2C2010925).

ORAL

O PP I-3

Strong antiferromagnetic proximity coupling in a heterostructured superconductor $Sr_2VO_{3-\delta}FeAs$

Chang Il Kwon ***(Center for Artificial Low Dimensional Electronic Systems, Institute for Basic Science (IBS), Pohang 37673, Korea; Department of Physics, Pohang University of Science and Technology, Pohang 37673, Korea)***,
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We report observation of strong magnetic proximity coupling in a heterostructured superconductor $Sr_2VO_{3-\delta}FeAs$, determined by the upper critical fields $Hc_2(T)$ measurements up to 65 T. Using the resistivity and the radio-frequency measurements for both H∥ab and H∥c, we found a strong upward curvature of $Hc_2(T)$ for H∥c, together with a steep increase of $Hc_2(T)$ for H∥ab near T_c, yielding the anisotropic factor γH, is Hc_2 ratio of H∥ab to H∥c, up to~20, much higher than those of other iron-based superconductors. These are attributed to the Jaccarino-Peter effect, rather than to the multiband effect, due to strong exchange interaction between itinerant Fe spins of the FeAs layers and localized V spins of Mott-insulating $SrVO_{3-\delta}$layers. These findings provide evidence for strong antiferromagnetic proximity coupling, comparable with the intralayer superexchange interaction of $SrVO_{3-\delta}$layer and sufficient to induce magnetic frustration in $Sr_2VO_{3-\delta}FeAs$

The authors thank Y. G. Bang for fruitful discussion. We also thank H. G. Kim in Pohang Accelerator Laboratory(PAL) for the technical support. This work was supported by the Institute for Basic Science(IBS) through the Center for Artificial Low Dimensional Electronic Systems(no. IBS-R014-D1) and by the National Research Foundation of Korea(NRF) through SRC(Grant No. 2018R1A5A6075964) and the Max Planck-POSTECH Center for Complex Phase Materials(Grant No. 2016K1A4A4A01922028). W.K. acknowledges the support by NRF (No. 2018R1D1A1B07050087, 2018R1A6A1A03025340), and Y.J.J. was supported by NRF(No. NRF-2019R1A2C1089017). J.M.O. acknowledges support from Korea Basic Science Institute(National research Facilities and Equipment Center)grant funded by the Ministry of Education(Grant No. 2021R1A6C101A429) and NRF grant funded by the Korea government(MSIT) (No.2021R1F1A1056934). A portion of this work was performed at the National Science Foundation CooperativeAgreement No.DMR-1644779.

ORAL

O PP I-4

Topological Josephson effect in hinge state of WTe_2

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Jinho Park *(POSTECH)*,
Woochan Jung *(POSTECH)*,
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Higher order topology is a fascinating system for realizing topological superconductivity with topologically protected one-dimensional hinge states. The hinge states are analogous to the topological boundary states of two-dimensional topological insulator, however, there have been only a few experimental studies reported. Recently, non-centrosymmetric Td-WTe_2 is suggested to have hinge states, but the evidence of topological nature is inconclusive. Here, we investigated the Shapiro steps under the microwave irradiation in Al-WTe_2-Al proximity Josephson junctions and suggest conclusive results of topological nature of the hinge states. We analyzed the voltage step doubling features at various microwave frequency and power, which are explained by 4π-periodic current-phase relationship of topological Josephson junctions. Our observation supports the topological nature of the hinge states in Td-WTe_2. Also our work would stimulate the experimental investigation of topological superconductivity with topological hinge states in superconducting hybrid devices based on higher order topological insulators, leading toward realizing Majorana zero-modes and topological quantum computer applications.

SESSION III : PP II

Physical Properties - II

ORAL

O PP II-1

B1g-Phonon Anomaly Driven by Fermi Surface Instability at Intermediate Temperature in $YBa_2Cu_3O_{7-\delta}$

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Younsik Kim *(Seoul National University)*,
Shigeki Miyasaka *(Osaka University)*,
Setsuko Tajima *(Osaka University)*,
Jin Mo Bok *(Pohang University of Science and Technology)*,
Yunkyu Bang *(Pohang University of Science and Technology)*,
Seung Ryong Park *(Incheon National University)*,
Changyoung Kim* *(Seoul National University)*

We performed temperature- and doping-dependent high-resolution Raman spectroscopy experiments on $YBa_2Cu_3O_{7-\delta}$ to study B1g phonons. The temperature dependence of the real part of the phonon self-energy shows a distinct kink at $T = T_{B1g}$ above T_c due to softening, in addition to the one due to the onset of the superconductivity. T_{B1g} is clearly different from the pseudogap temperature with a maximum in the underdoped region and resembles charge density wave onset temperature, T_{CDW}. We attribute the B1g-phonon softening to an energy gap on the Fermi surface induced by a charge density wave order, which is consistent with the results of a recent electronic Raman scattering study. Our work demonstrates a way to investigate Fermi surface instabilities above T_c via phonon Raman studies.

ORAL

O PP II-2

Magnetooptical properties of superconducting Nb thin films in the terahertz region

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Kyung Ik Sim *(Yonsei University)*,
Younjung Jo *(Kyungpook National University)*,
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We studied the pair breaking effect of an external magnetic field up to 7 T on the type-II superconductor niobium (Nb) using terahertz time-domain spectroscopy at 1.5 K. Our measurement technique can directly obtain transmission spectra of Nb thin films and extract the optical conductivity. The superconductivity is systematically suppressed by the external magnetic field as the quasiparticle excitation gap closes. We confirmed this by fitting the pair-breaking parameter and the superconducting order parameter data to the theory of Skalski et. al. [1].

[1] Skalski, S., Betbeder-Matibet, O. & Weiss, P. R. Properties of superconducting alloys containing paramagnetic impurities. Phys. Rev. 136, A1500-A1518 (1964).

This study was supported by grants from the Samsung Science and Technology Foundation (SSTF-BA2102-04).

ORAL

O PP II-3

Improvement of flux pinning effect at grain boundaries of MgB_2 thin films via ion irradiation

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Jung Min Lee *(Sungkyunkwan University)*,
Yoonseok Han *(Sungkyunkwan University)*,
Jaegu Song *(Sungkyunkwan University)*,
Chorong Kim *(Korea Atomic Energy Research Institute)*,
Jaekwon Suk *(Korea Atomic Energy Research Institute)*,
Byung-Hyuk Jun *(Korea Atomic Energy Research Institute)*,
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Grain boundaries (GBs) in metallic materials can serve as effective sinks of irradiation-induced defects because the defect diffusion barrier near GBs is lower than the diffusion barrier within grains. In small-grained samples, therefore, the distribution of irradiation-induced defects differs significantly from coarse-grained samples. In this talk, we report the effect of ion irradiation on MgB_2 thin films with small grain sizes of approximately 122 and 140 nm via 120-keV Mn-ion irradiation. High-field Jc of both MgB_2 films increases with an increase in the number of irradiated ions, accompanied by a change in the dominant flux pinning source of those films from weak pinning to strong pinning after ion irradiation. Magnetic field dependence of the flux pinning force density of irradiated MgB_2 thin films with the small grain sizes is consistent with strong pinning model, which is in contrast to the single-crystalline MgB_2 films where normal point pinning was dominant after ion irradiation. These results suggest that irradiation-induced defects are accumulated near the grain boundaries in MgB_2 thin films, providing new insights to improve the high-field J_c of MgB_2 superconductors.

We wish to acknowledge the support of the accelerator group and operators of KOMAC (KAERI). This study was supported by the National Research Foundation (NRF) of Korea through a grant funded by the Korean Ministry of Science and ICT (No. 2021R1A2C2010925) and by the Basic Science Research Program through the NRF of Korea funded by the Ministry of Education (NRF-2019R1F1A1055284 and NRF-2021R1I1A1A01043885). This work was also supported by the National Research Foundation Grant (NRF-2020M2D8A2047959) funded from Ministry of Science and ICT (MSIT) of Republic of Korea. L.L would like to acknowledge the Chinese Scholarship Council (CSC) for fellowship support.

ORAL

O PP II-4

Growth of high-quality high-entropy-alloy superconducting thin films and its outstanding irradiation resistance

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Jin Hee Kim *(Kyung Hee University)*,
Rahmatul Hidayati *(Kyung Hee University)*,
Jong-Soo Rhyee *(Kyung Hee University)*,
Jung Min Lee *(Sungkyunkwan University)*,
Won Nam Kang *(Sungkyunkwan University)*,
Woo Seok Choi *(Sungkyunkwan University)*,
Hye-ran Jeon *(Korea Atomic Energy Research Institute)*,
Jaekwon Suk *(Korea Atomic Energy Research Institute)*,
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High-entropy alloys (HEAs), typically composed of multiple metallic elements, are new class of functional materials due to their superior physical and mechanical properties to conventional alloys. Since the discovery of the superconductivity of Ta-Nb-Hf-Zr-Ti HEAs in 2014, however, the critical current density (J_c), the maximum current that can maintain a superconducting (SC) state without any resistance, has not yet been properly characterized in HEA superconductors. In this talk, we present the HEA SC thin films with a high J_c, and remarkable irradiation resistance. The high-quality HEA SC thin films were fabricated using a pulsed laser deposition technique with KrF (248 nm) excimer laser. The film deposited at 520 °C shows a high SC transition temperature (T_c = 7.28 K) and a large J_c (> 1 MA/cm^2 at 4.2 K), indicating promise for various technological applications, such as SC devices as well as high-field SC magnets. In addition, we found the extremely robust superconductivity of the HEA superconductor against irradiation damage, which was verified via 200-keV Kr-ion irradiation. The superconductivity of HEA SC thin films is over 1000-fold resistant to irradiation-induced disorder compared to other representative superconductors for technological applications, such as MgB_2, Nb_3Sn, Fe-based superconductors, and high-T_c cuprates. Our results indicate that the HEA superconductor is a novel SC material with considerable potential for practical applications in various extreme areas, such as aerospace, nuclear reactors, and high-field SC magnets.

We wish to acknowledge the outstanding support of the accelerator group and operators of KOMAC, KAERI. This study was supported by the National Research Foundation (NRF) of Korea through a grant funded by the Korean Ministry of Science and ICT (No. 2021R1A2C2010925 and 2021R1A2C2011340) and by the Basic Science Research Program through the NRF of Korea funded by the Ministry of Education (NRF-2019R1F1A1055284, NRF-2020R1I1A1A01067677, and NRF-2021R1I1A1A01043885).

SESSION IV : LA I

Large Scale Applications - I

ORAL

O LA I-1

An Option to Explore a Higher Field: An HTS Magnet with Module Coils Connected in Parallel

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Jonghoon Yoon *(Department of Electrical and Computer Engineering, Seoul National University)*,
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Wonseok Jang *(Department of Electrical and Computer Engineering, Seoul National University)*,
Seungyong Hahn* *(Department of Electrical and Computer Engineering, Seoul National University)*

High-temperature superconductor (HTS) magnet demonstrated its outstanding ability to reach a higher magnetic field realm compared with its low-temperature superconductor or resistive counterpart. This remarkable achievement may be a granted result due to the superiority in the current-carrying capacity of HTS under a high field environment. However, from the record high field 45.5 T high-temperature superconducting magnet, we learned that the improvement of conventional methodologies in developing HTS magnets might be needed. Therefore, conventional methods in the design, construction, and operation of HTS magnets were revisited. As a result, we confirmed the common feature that all the HTS magnets consist of multiple module coils connected in series. In this paper, we thus propose to connect individual module coils of an HTS magnet in parallel as an alternative to the series connection. We performed the design, construction, and operation of a laboratory HTS magnet, a stack of four double pancake coils connected in parallel. The test magnet was cooled down to 77 K with liquid nitrogen, was activated by the operating current up to 360 A, and generated the central magnetic field up to 0.6 T. We can conclude from experimental results that an HTS magnet based on our proposed concept of the parallel connection may be advantageous in generating a higher field than its series connection counterpart. We believe our approach of the parallel connection would be an option to explore a higher field realm by using an HTS magnet.

This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 1711138068, KMDF_PR_20200901_0063).

ORAL

O LA I-2

Thermal Design of 6 T High Temperature Superconducting Magnet for MRI

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Jeongmin Mun *(Changwon National University)*,
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MRI currently commercialized was manufactured using low-temperature superconductors. It is difficult to fabricate an MRI having a high magnetic field of 7 T or more with a LTS wire, and a lot of cost. Furthermore, MRI uses liquid helium for cooling. However, as the cost of liquid helium continues to rise, the maintenance cost of operating an MRI is increasing. When manufacturing MRI using a high-temperature superconducting wire, it is advantageous to generate an ultra-high magnetic field of 7 T or more. In addition, it operates at about 20 K, so it can be cooled only by conduction cooling using a cryogenic refrigerator without the need for a liquid refrigerant. This makes it possible to drive MRI without the use of liquid helium. 6 T Magnet for MRI is using STS tape and HTS wire with no-insulation method for cooling performance and electrical stability. However, there is no special contact condition, HTS magnets have risks that the magnet may be damaged if the temperature is severely raised locally due to quenching or poor cooling. Therefore, it is very important to design a coil using a high-temperature superconducting wire in consideration of the temperature gradient and the cooling path. This paper describes the thermal design of a HTS magnet for 6 T MRI. The cooling path was configured to keep the maximum temperature in the coil below 20 K while minimizing the temperature gradient of the coil. Metal materials were considered for the temperature gradient in the axial and circumferential directions, and the thermal conductivity between coil turns was analyzed using the radial equivalent thermal conductivity of an uninsulated coil. The thermal contact conditions were applied between the conduction plate and the coil surface. The cooling capacity of the pulse tube refrigerator, which can minimize vibration, was used as a boundary condition. The results of this paper will be used as basic data for manufacturing high-temperature superconducting MRI magnets in the future.

This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 1711138068, KMDF_PR_20200901_0063) and the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2019R1A5A8083201).

ORAL

O LA I-3

Numerical evaluation of strain in HTS single pancake coil using a conceptually designed load-application jig

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Chaemin Im *(Seoul National University)*,
Jonghoon Yoon *(Seoul National University)*,
Geonyoung Kim *(Seoul National University)*,
Jeonghwan Park *(Seoul National University)*,
Jung Tae Lee *(Seoul National University)*,
Jeseok Bang *(Seoul National University)*,
Seungyong Hahn* *(Seoul National University)*

In this paper, the conceptual design of a load-application jig which applies a mechanical force to the high-temperature superconducting (HTS) coil is introduced to investigate the mechanical effects of the high-field magnet by replicating the operation of the magnet in a high magnetic field. Using the conceptually designed jig, we numerically calculate the strain and displacement of a HTS single pancake coil on using COMSOL multiphysics software. The simulation results of the stress and strain of the pancake coil under the wide range of mechanical forces caused by the load-application jig are presented. Also, the results are compared with the numerical results for the same pancake coil that electromagnetic forces applied.

This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 1711138068, KMDF_PR_20200901_0063).

ORAL

O LA I-4

Numerical study on harmonic analysis for MRI magnet considering pancake winding

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Seong Hyeon Park *(Seoul National University)*,
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Since 2021, the national R&D project to develop a 6 T 320 mm all-REBCO (RE-Ba_2-Cu_3-O_{7-x}, RE: rare Earth) magnetic resonance imaging (MRI) magnet has been progressed. Since field homogeneity is crucial to the construction of an MRI magnet, it is important to calculate and predict the harmonic coefficient of the spatial magnetic field. In general, the harmonic analysis has been performed with an assumption in which a high temperature superconducting (HTS) pancake coil is considered an ideal circular winding. However, the field homogeneity of the MRI magnet can be sensitive so the effect on the field homogeneity due to actual pancake winding should be analyzed. In order to predict the discrepancy of harmonic coefficient between the design and the fabrication, we compared harmonic coefficients of an MRI magnet with a consideration of actual pancake winding's trajectory to an ideal circular winding assumption. Using the formulae induced from Biot-Savart's law, the harmonic coefficients were calculated. The results would be applied to the 6 T all-REBCO MRI magnet project during the construction of the main magnet.

This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 1711138068, KMDF_PR_20200901_0063).

SESSION V : LA II

Large Scale Applications - II

INVITED

IN LA II-1

Electromagnetic Analysis of No-insulation HTS Magnet Array

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Seungyong Hahn* *(Seoul National University)*

The key idea of 'multi-bore NMR', which was first patented in 2018, is sharing some common parts, especially cryogenic system and current lead, thus the overall multi-bore NMR system could be substantially more compact than the same number of single-bore NMR systems. However, due to the close positioning of multiple HTS magnets in multi-bore NMR, potential electromagnetic issues are anticipated including: (1) distortion of the field quality; (2) critical current degradation; and (3) change of the 5-gauss line. In this paper, we investigate the aforementioned electromagnetic issues with respect to the configuration of the magnet array including: (1) the arrangement of the magnetic pole; (2) a number of magnet array; and (3) the distance of each magnet component. Based on the investigation, we select an appropriate configuration of the magnet array assuming that the array consists of multiple 400 MHz no-insulation HTS NMR magnets; a single magnet component has been developed by Korea Basic Science Institute. Finally, a set of ferromagnetic shims is designed to correct the distorted field quality of each magnet component.

This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 1711138068, KMDF_PR_20200901_0063).

ORAL

O LA II-1

Comparison of EU-DEMO React & Wind Nb_3Sn TF CICC Current Sharing Temperature against Wind & React Nb_3Sn CICCs

Soun Pil Kwon* ***(Korea Institute of Fusion Energy)***

European efforts to design superconducting conductors for a future tokamak have involved Nb_3Sn cable-in-conduit conductor (CICC). Nb_3Sn coils which undergo heat treatment to activate the Nb_3Sn material are mostly produced through the wind-then-react route. However, some Nb_3Sn coils have been proposed with CICCs of the react-then-wind route. The latter CICCs are physically constrained due to handling limitations which if not adhered to will result in irrecoverable damage to the Nb_3Sn cable inside, nullifying any performance advantage. A group at the Swiss Plasma Center has proposed such CICC designs, constructing samples and testing them for performance. The characteristics and performance of these react & wind (R&W) CICCs are compared with the more common wind & react (W&R) CICCs, and it is found that the R&W designs show more extreme characteristics than typical W&R Nb_3Sn CICCs for some parameters that are known to influence CICC performance. Where the R&W CICCs extend the range of those parameters, they also continue trends formed by the W&R CICCs with the parameters. The main observation, however, is that although the current sharing temperature performances of the R&W samples are above the average of the W&R samples they were compared to, they are not the highest. A similar observation applies to a cost comparison of the superconducting material where the R&W CICCs are found to be relatively cheap but not the cheapest. Given these results, clear practical advantages to the R&W CICC design is not evident.

Support for this work was provided by the Korea Institute of Fusion Energy under a R&D program (project code 1711124794) funded by the government of the Republic of Korea.

ORAL

O LA II-2

Mechanical Stress and Critical Current Investigation on the D-shaped NI HTS Coil for the KSTAR-scale TF Magnet Design

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Jeseok Bang *(Department of Electrical and Computer Engineering, Seoul National University)*,
Hyun Wook Kim *(Korea Institute of Fusion Energy)*,
Sangjun Oh *(Korea Institute of Fusion Energy)*,
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High temperature superconductors (HTS) have been recognized as an enabling technology for the high magnetic field, a compact fusion that is expected to accelerate the development of fusion energy. Meanwhile, the no-insulation (NI) winding technique and its variations (e.g. metal-as-insulation) have been applied to several high-field HTS solenoid magnets showing successful operations in their individual missions. Thus with such a promising technology incorporated, a toroidal field coil is designed considering the size of the Korea Superconducting Tokamak Advanced Research (KSTAR) in an effort to upgrade its magnetic performance for the next generation fusion reactor. The aim of this research is to investigate the upper limit of the toroidal magnetic field as an initial design step considering the criterion of the mechanical stress and the critical current, which are two of the most important aspects of fusion magnet design. Assuming 20 K operation temperature condition, the design is carried out by changing the number of cable-turns which changes the midplane cross section's winding arrangement followed by the critical current calculation and finite element analysis to acquire the stress distribution. The results show that ~ 8.6 T can be achieved with 80 cable-turns of commercial HTS tapes where the design satisfies the mechanical stress criterion of the support structure and the coil considering about 20 % margin in the operating current.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2018R1A2B3009249), and also partly by R&D program of "code No. CN2101" through the Korea institute of Fusion Energy (KFE) funded by the Government funds.

ORAL

O LA II-3

Equivalent Circuit Analysis on Operation of Synchronous Rotating Machine with NI HTS Field Windings

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Hongsoo Ha *(Korea Electrotechnology Research Institute)*,
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Recently, active research is being conducted to adopt cryogenic and superconducting technology into the propulsion motors mainly for electric aircraft. The high current density of superconducting coil can lead to high power density, so that is considered as one of the enabler technology for electric aircraft. Several superconducting motor designs with a power density of >20 kW/kg have been suggested, however, maintaining superconducting coil stable in a rotating environment still remains a problem. No-insulation (NI) high-temperature superconductor (HTS) winding technique, which has been adopted to numerous high-field magnets, could be one of solution for the problem, but a study to apply NI HTS winding technique to the superconducting motors is quite limited. NI technique could be applied to field windings of synchronous machines, and the effect induced from leak currents needs to be understood prior to applying actual applications. In this study, we present the equivalent circuit of the superconducting synchronous motor with NI field windings and analyze the operating characteristics of the motor in steady-state and transient operation. Torque, electromotive force, coils' voltage, and current are obtained through equivalent circuit simulation as well as experiment and compared with insulated counterpart.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2018R1A2B3009249).

ORAL

O LA II-4

Post-Quench Analysis on 6 T Metal Insulated HTS MRI Magnet

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In this paper, we discuss multi-physical phenomena that occur after a quench of a 6 T metal-insulated (MI) high temperature superconductor (HTS) magnetic resonance imaging (MRI) magnet. Quench accident of a superconducting magnet can occur for a number of reasons, and the effect on the magnet by the accident should be carefully considered. In particular, in the case of MRI magnets, serious accidents that may occur due to a quench should be prevented in advance when used in clinical practice. Therefore, it is necessary to secure a protocol that can safely discharge the energy charged in the magnet even in case of a quench accident by analyzing electromagnetic, mechanical, and thermal stability. In this paper, a situation that the critical current of the half coil abruptly decreases to 40 % of their initial value in the 6 T MRI is assumed as quench. Electromagnetic, mechanical, and thermal phenomena occurring after the quench are analyzed using FEM and equivalent circuit models of MI HTS MRI magnet. Simulation results show that the magnet is in a safe range during the post-quench operation.

This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 1711138068, KMDF_PR_20200901_0063).

SESSION VI : MM I

Materials - I

ORAL

O MM I-1

The role of instability of CuO_2 plane on the flux pinning mechanism in $GdBa_2Cu_3O_{7-x}/La_{0.7}Sr_{0.3}MnO_3$ heterostructure

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Here we propose an approach for an enhancement of flux pinning in the high-T_c cuprate/manganite system by controlling a lattice instability of CuO_2 plane. The flux pinning mechanism in this system is discussed from a new perspective of unstable behavior of local lattice observed in the CuO_2 plane, which is strongly linked to structural coupling between cuprate and manganite layers. Lattice instability in the planar Cu-O bond of high-T_c cuprate is probed by the Cu K-edge extended X-ray absorption fine structure (EXAFS) analyses on the epitaxial bilayer systems consisting of $GdBa_2Cu_3O_{7-x}$ (GdBCO) with varying thickness on top of $La_{0.7}Sr_{0.3}$←MnO_3 (LSMO) buffered (001) $SrTiO_3$ (STO) substrate. The Debye-Waller factor (DWF) of the in-plane Cu-O bonds has been used as an order parameter to examine the local atomic disorder, and the general form of the instability criterion is derived by utilizing disorder state of Cu-O bond. Detailed analysis of the Cu-O bond dependence of DWF in respect to the flux pinning reveals an emergence of additional pinning contribution, which is originated from local lattice instability of Cu-O bonds. It further shows that controlling the thickness of GdBCO modifies the structural relationships and consequently, the degree of additional pinning contribution aroused by the disorder on the CuO_2 plane can be adjusted. These results, therefore, suggest a possibility of controlling complex flux pinning through an optimization of local instability of Cu-O bonds by adjusting the thickness of GdBCO.

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2021R1I1A3044518).

ORAL

O MM I-2

Low-rotation mechanical milling as an approach to powder processing for structural control of MgB_2 materials

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Powder-in-tube (or powder filling) processes are widely employed to produce commercial MgB_2 superconducting wires with lengths of kilometers. The structural control of wire cores can be achieved, for example by powder processing through mechanical milling or alloying. Accordingly, studies utilizing high-energy shaker or planetary mills have been carried out so far in most cases. Although the two mills were demonstrated to be useful for structural modification, there are still many kinds of ball mills, for example, attritor mills, uniball mills, and tumbler mills/mixers. Especially the latter types are known as low-energy and economical mills. This is because the development of the powder processing towards large-scale production can be relatively easier compared with the other mills. Since high production costs of superconducting materials are always major drawbacks to their practical applications, the development of such a processing technology for mass production with structural control is important in terms of cost-effectiveness. In fact, the tumbler mills have been utilized for mechanical milling or alloying of various materials in industrial settings as well as in laboratory-scale facilities. To date, however, systematic studies on such a processing approach for MgB_2 materials have not been conducted. Here, we have focused on a tumbler mill and undertaken the study. The operation speed was fixed at 40 rpm. The rotation rate is much lower than typical conditions used for planetary mills. Instead of such low speed, the other processing parameters were controlled to increase the energy transfer from the balls to powders. The applied milling conditions resulted in severe plastic deformation of the raw powders for MgB_2 wires. In addition, we elucidated the mechanism of the structural changes and their effects on the transport critical current property. The current approach by the tumbler mill offers potential as effective powder processing for structural control of MgB_2 materials.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-2020R1A2C1013662). The authors would like to express their deepest gratitude to Chuncheon city and Gangwon province for the support of this study.

ORAL

O MM I-3

Development of ex-situ processed MgB_2 superconducting wires at Sam Dong

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Magnesium diboride (MgB_2) superconductor having a high critical temperature has the advantage of using a refrigerator at 10-20 K without using expensive liquid helium. The manufacturing method of MgB_2 superconducting wire is classified into two processes: in-situ and ex-situ. The ex-situ process has a significant advantage in price competitiveness because it does not require niobium barriers, but the critical current properties are inferior to in-situ due to weaker grain connectivity. Therefore, it is considered to be suitable for use as a low-cost and low-field application device that does not require high properties. Sam Dong Co., Ltd. manufactured high-quality ex-situ MgB_2 powder and manufactured Fe-sheathed mono wire using it to diversify the product line and meet customers' needs. The critical current of the manufactured wire was estimated to be 239 A at 4.2 K and self-field. In this study, by applying the ball milling process of ex-situ MgB_2 powder, the critical current based on 4.2 K and self-field reached 355 A, which was improved by about 48% compared to the non-milled powder.

This work was supported by the National Research Foundation Grant (NRF-2020M2D8A2047959) funded from Ministry of Science and ICT (MSIT) of Republic of Korea.

ORAL

O MM I-4

초전도 박막 선재의 폭 방향 두께 균일화를 위한 안정화재 차등 증착 기술 연구

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최근 고온초전도 코일의 큰 문제점 중 하나였던 퀜치현상을 막을 수 있는 무절연 고온초전도 코일 제작기술이 개발됨으로 인해 전 세계적으로 다양한 고온초전도 코일 응용기술 개발이 폭발적으로 이루어지고 있다. 이에 따라 우수한 성능의 2세대 고온초전도 선재가 요구되고 있으며 특히, 우수한 고자기장하 선재 전류밀도, 균일한 두께 및 폭, 임계전류 균일성, 그리고 우수한 기계적 강도를 갖는 2세대 고온초전도 선재 개발 필요성이 높아지고 있다. 전 세계 대부분의 2세대 고온초전도 선재 연구자들은 주로 초전도층의 성능 향상을 통한 고자기장중 임계전류 밀도 향상 연구에 집중해 왔으며 일부 극박 금속기판을 이용한 고온초전도 선재 개발연구가 진행되면서 기계적 특성 향상에 관한 연구가 이루어져 왔다. 하지만 2세대 고온초전도 선재를 이용하여 우수한 응용기기를 개발하기 위해서는 고온초전도 선재 자체의 성능도 중요하지만, 선재 길이 방향으로 임계전류 및 형상의 균일성이 크게 요구된다. 특히, 2세대 고온초전도 선재 제조 공정상 발생하는 두께 불균일로 인해 코일 권선시 많은 문제가 발생하고 있다. 일반적으로 2세대 고온초전도 선재 제조시 안정화재인 은(Ag)을 증착한 후 최종적으로 구리(Cu)를 증착하여 선재를 완성하게 된다. 이때 구리는 습식도금 공정을 이용하게 되는데 양 끝부분이 상대적으로 두꺼워지는 독본(dog-bone) 형태가 되기 쉽다. 본 논문에서는 습식공정 대신 스퍼터법을 이용하여 구리층을 증착하였으며 폭 방향의 두께 불균일을 해결하기 위하여 증착 영역을 선택적으로 가리는 치구를 이용하여 증착하였다. 증착 후 단면 형상을 기존 선재와 비교하여 그 결과를 보고하고자 한다.

SESSION VII : CR I

Cryogenics - I

ORAL

O CR I-1

Simulation of LN2 pre-cooling, initial filling, and storage on a Zero Boil Off liquid hydrogen tank

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For the upcoming hydrogen economy, liquid hydrogen-based infrastructure is essential for large-capacity storage, transportation, and utilization of hydrogen. When gas hydrogen is liquefied at atmospheric pressure and 20 K, the transport efficiency is 780 times than gas, and the facility size can also be reduced. When hydrogen is stored in a liquid, heat loss is unavoidable due to the temperature difference between liquid hydrogen and the outside atmosphere. So an insulated storage tank is required to minimize heat loss and evaporation. The existing insulated storage tank maintains an appropriate pressure through a gas vent when the tank pressure increases. However, there is a perception that combustible hydrogen gas is dangerous when vented into the atmosphere, and it is not economical. The zero boil off (ZBO) tank is relatively safe and economical because there is no vented hydrogen gas by liquefying the evaporated hydrogen gas using a cryocooler in the tank to maintain the proper pressure. Prior to the manufacture and operation of the ZBO storage tank, it is necessary to analyze the liquid nitrogen pre-cooling scenario, liquid hydrogen initial filling scenario and to predict the liquid level of the ZBO tank according to cryocooler operation. In this paper, the thermal design was conducted in consideration of heat loss on ZBO tank using Comsol that commercial finite element simulator. Using Thermal desktop, a 1-D Thermal & fluid network analysis program, pre-cooling scenario using liquid nitrogen, initial cooling scenario of liquid hydrogen in ZBO tank and liquid level prediction according to cryocooler operation during storage were analyzed.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2019R1A5A8083201) and the Basic Research Fund of the Korea Institute of Machinery and Materials(KIMM).

ORAL

O CR I-2

Three Options in Thermodynamic Cycle for 5 T/d Hydrogen Liquefaction with LNG Pre-cooling

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Three different thermodynamic cycles are selected and compared as a candidate for 5 T/d hydrogen liquefaction system with LNG pre-cooling. The governmental project is underway to design, construct, and demonstrate a pilot plant with capacity of 0.5 T/d and the next step is to present a detailed process design of 5 T/d liquefaction. Based upon our ongoing thermodynamic efforts for efficient liquefaction, three feasible cycles are identified for 5 T/d liquefaction. The first is two-stage helium Brayton refrigeration cycle, which is substantially identical to 0.5 T/d pilot system. The main advantage is the low pressure (~ 1 MPa) operation and the simple scale-up (by 10 times) of the fully proven technology through the pilot operation. On the other hand, this cycle suffers from an excessive flow rate of helium and the need of high-power cryogenic turbo-expanders. The second is the standard Claude cycle, as used in most commercial liquefiers with liquid-nitrogen pre-cooling. In this cycle, hydrogen itself is the working fluid and no other refrigerant is necessary. In general, the Claude cycle could be efficient, but requires a higher pressure (5~10 MPa) of hydrogen and the precise flow control in the diverted flow. The third is a cascade Joule-Thomson cycle without any use of cryogenic turbo-expander. According to the authors' recent publication, two-stage Linde-Hampson cycle with two-stage nitrogen and LNG pre-cooling is recommended. This cycle is slightly lower in efficiency and requires an even higher pressure (12~16 MPa) of nitrogen, but has an intrinsic merit of simple and stable operation, because there is no moving parts at cryogenic temperature. Thermodynamic optimization is performed to achieve the maximum efficiency in each cycle. The results are compared in terms of specific energy consumption (SEC), pressure levels, and estimated equipment costs. The pros and cons are quantitatively discussed towards the most suitable thermodynamic cycle for domestic development of 5 T/d plant. Keywords : hydrogen liquefaction, LNG pre-cooling, Brayton cycle, Claude cycle, cascade cycle, thermodynamics

This work is supported by a grant (KAIA22IHTP-C151603-04) of the Korea Agency for Infrastructure Technology Advancement (KAIA) funded by the Ministry of Land, Infrastructure and Transport (MOLIT).

ORAL

O CR I-3

Experimental study on supply of cryogenic fluid to mock-up HTS magnet using Pressure Build-up method

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Recently, the need for effective storage and supply of cryogenic fluids has emerged, especially in the hydrogen industry and aerospace fields. In particular, in order to overcome the density limitation, cryogenic liquid hydrogen is stored in transportation using hydrogen fuel cells so that it can be larger than high pressure storage. A motor to which a high-temperature superconductor (HTS) is applied has the same size as a conventional motor and has a high power density, but it must be cooled to a cryogenic temperature below a critical temperature. These conditions enable the storage tank to design a system in which cryogenic liquid hydrogen is supplied without a separate cooling system to cool the HTS motor and supply it to the fuel cell. The PBU (Pressure Build-up) method supplies liquid by increasing pressure to the cryogenic liquid storage device and the basic external heat load of internal heating without any separate mechanical parts. In this research, make a test device capable of supplying fluid by PBU method was manufactured by applying a cryogenic fluid storage tank, a coolant, and a reservoir serving as a buffer to a vacuum chamber using liquid nitrogen fluid. Using the test device, the flow rate and pressure raised according to the no-load conditions and heat load conditions of the tank were measured to check the internal behavior when delivering the fluid.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2019R1A5A8083201).

ORAL

O CR I-4

Prediction model of 4.5 K sorption cooler for integrating with adiabatic demagnetization refrigerator (ADR)

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Sorption cooler, which utilizes helium-4 as a working fluid, was previously developed and tested. The cooler consists of a sorption pump, and a thermosyphon. The developed sorption cooler aims to pre-cool a certain amount of the magnetic refrigerant of an adiabatic demagnetization refrigerator (ADR) from 4.5 K to 2.5 K. In the previous research, the empirical correlation of adsorbate concentration which predicts the adsorption capacity of the developed sorption pump was proposed. The experimental result showed that, however, the pumping speed of the sorption pump calculated by the proposed correlation did not match with the actual pumping speed during the transient sorption cool-down process. Since the correlation was developed under the equilibrium condition, the correlation couldn't predict the transient case accurately. Thus, based on the experimentally obtained pumping speed, a prediction model for the sorption cooler is developed in this study. The model predicts the amount of liquid helium for evaporative cooling and the required time for the sorption cooling process. It is confirmed that the performance of the sorption cooler is enhanced by reducing the volume of the thermosiphon. Detailed results and discussions are presented.

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF-2017R1A2B3003152) funded by the Ministry of Science, ICT & Future Planning (MSIP).

ORAL

O CR I-5

Conceptual Design of Liquid Hydrogen-powered Air Vehicle

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Dohoon Kwon *(Korea Advanced Institute of Science and Technology)*,
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Urban air mobility (UAM) is an air vehicle that can conveniently transport people or goods in the city. UAM has recently attracted lots of attention as a solution to urban centralization. Two fundamental necessities of UAM are the implementation of the ability to take off vertically without a runway and the lightness of an air vehicle for efficient energy usage without negative environmental impact. To achieve this requirement using clean advanced technology, we propose a consolidated concept design of an electric tiltrotor air vehicle with the fuel cells powered by liquid hydrogen (LH2). In the design of the air vehicle, the power distribution between the battery and the fuel cell system is adapted appropriately to improve the performance of the air vehicle for applicable flight scenarios. An LH2 storage tank in the air vehicle allows hydrogen to be stored in higher density than that of the compressed gaseous hydrogen and it lightens the overall fuselage of the air vehicle. Hybridizing the LH2-powered fuel cell and the battery for a particular flight scenario is an important strategy to optimize the whole power system for an energy-efficient vehicle. This paper presents a detailed concept of a cryogenic storage tank for LH2 and shows how much it can reduce the weight of the fuel cell system compared to an electric powertrain system that uses only batteries. Our conceptual design provides the pragmatic idea of applying LH2 technology to the burgeoning infrastructure of various-scaled air vehicles as the primary clean power source.

POSTER SESSION

TE : Theory
& Electronics & Device Applications

PP : Physical Properties

MM : Materials

LA : Large Scale Applications

CR : Cryogenics

Superconducting microwave LC resonator for optical-microwave photon conversion

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Duk Y. Kim *(Agency for Defense Development)*,
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Superconducting qubits for quantum computation operate with gigahertz microwaves. On the other hand, modern techniques for quantum communications utilize visible and infrared lasers. In order to interconnect quantum computers with a quantum information network, measures to convert quantum states between microwave and optical frequencies are required. Optomechanical systems is one of the candidates for such an intermediate converter. A mechanical oscillator with a high quality factor can couple to microwave and optical fields simultaneously and mediate coherent conversions between them. We fabricate a superconducting LC microwave resonator using a silicon-nitride membrane as a mediator for the optical-microwave photon conversion. The microwave resonator consists of superconducting electrodes on the membrane and other circuit elements on silicon chip, forming a capacitor between them through the superconducting electrodes. Multistep fabrications and a precise alignment are required to construct the combined circuit. Then, we measure the resonance by detecting microwave signal reflected from the superconducting LC resonator. The optomechanical device provides an excellent opportunity to develop a hybrid quantum system for the quantum network.

This work was supported by the Defense Acquisition Program Administration and the Agency for Defense Development.

Cryogenic voltage sampling for arbitrary RF signals transmitted through a 2DEG channel

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Recently developed quantum technologies for solid-state qubits generally demand a high-speed operation in a range of 10^6 - 10^9 Hz. To enhance device performance, it is needed to confirm whether such high-speed signal is fully transmitted through quantum devices operated at low temperatures ≤ 4 K, while maintaining the initial waveform. We demonstrate a cryogenic voltage sampling based on a surface Schottky gate for a GaAs/AlGaAs two-dimensional-electron-gas (2DEG) channel to investigate a deformation of waveform in a range of a few 10^6 Hz, which is transmitted through the channel. After feeding a square waveform into the channel, the voltage sampling was performed by applying a voltage pulse to the gate, which allows a partial transmission of the waveform only in the gate pulse region in a time domain. Then, we obtain a current as a function of delay time, $I(t_d)$, between the waveform and gate-voltage pulse. As a result, $I(t_d)$ corresponds to the waveform at the gate location, where the waveform travels from the incident point and gate location. By that way, we could confirm a 10^6 Hz range keeps the initial waveform along a few micro meter channel.

Coupling a membrane resonator with a superconducting microwave cavity

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Recently, optomechanical systems have been employed in developing a quantum conversion system. A mechanical resonator can be coupled with two different optical resonators simultaneously and mediate coherent interactions between electromagnetic waves in two different frequencies. An efficient conversion system can preserve entanglement in quantum signals and enable versatile applications. We have fabricated a nano-mechanical membrane resonator and coupled it with a superconducting 3-dimensional microwave resonator. We have demonstrated that the high-order resonance in the microwave cavity can be used to drive the mechanical resonator. The coupled optomechanical system constitutes a promising platform for quantum network and standoff sensing research.

This work was supported by the Defense Acquisition Program Administration and the Agency for Defense Development.

Observation of superconductivity and charge-density wave in transition metal dichalcogenide via nonlinear optical probe

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Relationship between superconductivity and charge-density wave has been a long standing issue in many material classes. Here, we report the observation of superconductivity (SC) and charge-density wave (CDW) in prototypical superconducting transition metal chalcogenide $NbSe_2$ via rotational anisotropy of second harmonic generation (RA-SHG). We observed the enhancement of the SHG intensity at the onset of the CDW transition, demonstrating the SHG intensity can be used as a direct probe of the CDW order parameter. Competitive relationship between both phases is represented by the suppression of the SHG intensity slightly above the SC transition temperature. Our observations suggest new insight into the competition behavior and the possible existence of superconducting fluctuation.

$La_{1.85}Sr_{0.15}CuO_4$ thin film growth and in-situ ARPES

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Cuprate thin films are showing novel physical properties that are different from bulk, such as strain effects from substrate or proximity effects of heterostructure. And their electronic structures can be directly probed by Angle-resolved photoemission spectroscopy(ARPES). Since ARPES is highly surface sensitive, it requires a flat and clean surface of sample and UHV transfer process to carry out thin film ARPES. We have grown $La_{1.85}Sr_{0.15}CuO_4$ (LSCO) thin film On $LaSrAlO_4$(LSAO) Substrate with 5 Unit cell(UC) thickness by pulsed laser deposition(PLD). The thickness of the film was monitored with in-situ reflection high energy electron diffraction(RHEED). With our UHV transfer system connected with PLD and ARPES chamber, we performed in-situ ARPES of 5 UC LSCO thin film. We obtained Fermi surface map data and measured superconducting gap at the antinodal region of the band.

Mirror symmetry breaking beyond critical doping in (Pb,Bi)2212

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The phase diagram of cuprate High-temperature superconductors features an enigmatic strange metal region in which in-plane resistivity varies linearly with temperature. In this V-shaped region, there is general agreement that T* or pseudogap temeperature can be defined by deviation from linear resistivity below critical doping. However, there is no consensus on Tup or upturn temeperature which is also defined by deviation from linear resistivity beyond critical doping. Here, we present Second harmonic optical anisotropy measurement on (Pb,Bi)2212 beyond critical doping. Taking our symmetry analysis from SHG, as well as resistivity and heat capacity measurement, we found this mirror symmetry breaking occurs at Tup. This result may suggest Tup region beyond critical doping coincides with mirror symmetry breaking order.

High irradiation tolerance of Ta-Nb-Hf-Zr-Ti high-entropy alloy superconducting thin films

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We investigate the effect of ion irradiation on Ta-Nb-Hf-Zr-Ti high-entropy alloy (HEA) superconducting (SC) thin films with a thickness of 115 nm via 200-keV Kr-ion irradiation. The pristine film shows SC critical temperature (T_c) of 7.0 K, and the T_c of HEA SC thin films gradually decreases with increasing displacements per atom (dpa), which are proportional to the dose of irradiated ions. The superconductivity of HEA SC thin films, however, exhibits an excellent robustness to irradiation damage compared to that of other representative superconductors, such as MgB_2, Fe-based superconductors, and high-T_c cuprates. The T_c of the HEA SC thin film remains 3.8 K at dpa = 12.82, and surprisingly, the T_c shows a slight increase rather than a decrease with further increases in the dap level; T_c = 4.3 K at the extreme damage level of dpa = 76.92. In this presentation, we will discuss the origin of high irradiation tolerance of HEA superconductors, especially the connection with their high configuration entropy and crystallography.

Keywords: Ta-Nb-Hf-Zr-Ti, high-entropy alloy superconductor, thin films, displacement per atom

We wish to acknowledge the outstanding support of the accelerator group and operators of KOMAC, KAERI. This study was supported by the National Research Foundation (NRF) of Korea through a grant funded by the Korean Ministry of Science and ICT (No. 2021R1A2C2010925 and 2021R1A2C2011340) and by the Basic Science Research Program through the NRF of Korea funded by the Ministry of Education (NRF-2019R1F1A1055284, NRF-2020R1I1A1A01067677, and NRF-2021R1I1A1A01043885).

Electric Field Effects on Heavy Fermion $CeIrIn_5$ Thin Films

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Here we report the deposition results of $CeIrIn_5$ thin film via the Pulsed Laser Deposition (PLD) technique and its anomalous physical properties due to electric field. The deposited films characterized by the X-ray Diffraction analysis showed polycrystalline structure. The surface and electrical properties were also analyzed by SEM and RT measurements. The characteristic features of the heavy fermion superconductor (i.e. Kondo scattering, coherence peak and superconductivity) were clearly observed similar to the bulk single crystal case. In addition, the effect of electric field by utilizing a simple device structure was investigated to study the relationship between carrier density and superconductivity. We expect that these results can provide a guideline in heavy fermion thin film deposition as well as trigger novel research interest of electric field effects on the Ce based HF superconductors.

Searching for Majorana bound state by Shapiro step measurement in $FeSe_{0.45}Te_{0.55}$ Josephson junction

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Topological superconductors have a Majorana bound state (MBS) at their boundaries or vortices on the surface. Such MBS follow non-Abelian exchange statistics, so they can be used as a fault-tolerant topological quantum computer. $FeSe_{0.45}Te_{0.55}$ (FST), an iron-based superconductor, is one of the candidates for topological superconductors. FST is expected to have a topological surface state and zero-energy vortex bound state (ZVBS) under the external magnetic field. To prove the topological superconductivity of FST, we fabricated full-van der Waals vertical Josephson junction through low-temperature micro-cleaving technique. We will discuss our investigation about the Shapiro steps upon irradiating microwave as a function of the strength of the external magnetic field.

Isotropic Superconducting Gap in High-Entropy-Alloy probed via Quasi-Particle Scattering Spectroscopy

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Even though the intriguing features of superconducting (SC) nature in high-entropy-alloy superconductor (HEAS) have attracted great interests, its SC pairing symmetry has not been identified. Here, we report the SC energy gap (Δ) of the HEAS $Ta_{1/6}Nb_{2/6}Hf_{1/6}Zr_{1/6}Ti_{1/6}$ probed by using quasi-particle scattering spectroscopy. The signature of Andreev reflection is observed in the differential conductance (dI/dV) spectra below the SC transition temperature (T_c) of 7.85 K, which was reasonably explained by the modified Blonder-Tinkham-Klapwijk (BTK) model. The evolution of the Δ as a function of temperature and magnetic field follows the BCS theory with $\Delta(T = 0) = 1.36$ meV. The gap-to-T_c ratio, $2\Delta(0)/kBT_c$, is 4, which is larger than the BCS prediction of 3.54, indicating that the HEAS $Ta_{1/6}Nb_{2/6}Hf_{1/6}Zr_{1/6}Ti_{1/6}$ belongs to the class of the moderate-coupled conventional superconductors.

This study was supported by the National Research Foundation (NRF) of Korea through a grant funded by the Korean Ministry of Science and ICT (No. 2021R1A2C2010925) and by the Basic Science Research Program through the NRF of Korea funded by the Ministry of Education (NRF-2020R1I1A1A01067677 and NRF-2021R1I1A1A01043885).

Evaluation of cryogenic tensile properties of composite materials fabricated by a FDM 3D printer

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Recently, research on applying composite materials to various industrial fields is being actively conducted. In particular, composite materials fabricated by FDM-based 3D printers have more advantages than existing materials as they have less restrictions on manufacturing shape, reduce time required, and reduce weight. With these advantages, it is possible to consider utilizing composite materials in cryogenic environments such as the application of liquid oxygen and liquid hydrogen, which are mainly used in aerospace and mobilities. However, FDM composite materials are not verified in cryogenic environments less than 150 K. This study evaluates the characteristics of composite materials such as tensile strength and strain using a UTM (Universal Testing Machine). The specimen is immersed in liquid nitrogen (77 K) to cool down during the test. The specimen is fabricated using Markforged Marktwo 3D print, and can be manufactured by stacking reinforced fibers such as Carbon fiber, Fiber glass, and Armid fiber (Kevlar). For the experimental method and specimen shape, international standards ASTM D638 and ASTM D3039 for tensile testing of composite materials were referenced.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2019R1A5A8083201)

Effect of Sr doping on the structural properties of $LaMnO_3$ thin films as a buffer layer for $GdBa_2Cu_3O_{7-x}$

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Interaction between superconductivity and ferromagnetism in the superconductor/ferromagnet bilayer system has been an interesting topic. $La_{1-x}Sr_xMnO_3$ (LSMO), one of representative ferromagnet materials, is found to reveal various physical properties by varying the Sr dopant amount x. In this research, we investigate the effect of Sr doping on the structural and transport properties of LSMO buffer layers. Series of LSMO thin films with varying x = 0.2, 0.3, and 0.5, and with varying thickness of 25 nm and 100 nm, were deposited on (001) $SrTiO_3$ substrates by pulsed laser deposition. To examine local structural change of MnO_3 octahedral, X-ray absorption spectroscopy (XAS) and extended X-ray absorption fine structure (EXAFS) analyses were systematically conducted. It is found that the structural and transport properties of LSMO change drastically with Sr doping content, however, the changes are not monotonic to x. The origin of these changes is discussed in terms of different oxygen states of Mn ion.

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Education (2021R1I1A3044518).

Status of MgB_2 superconducting wires and applications at Sam Dong

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Magnesium diboride (MgB_2) is known to have the remarkable potential to be applied in a magnetic resonance imaging (MRI) magnet, transmission cable, superconducting magnetic energy storage (SMES), etc. Since it has a low-cost precursor, simple crystalline structure, easy fabrication, and a relatively high transition temperature of 40 K, it enables cryogen-free operation between 10-20 K for various applications. Over the past few years, Sam Dong has successfully supplied high-performance MgB_2 superconducting wires with a kilometer-scale length by in-situ powder-in tube (PIT). For various application fields, MgB_2 wires need to be manufactured with rational design. In particular, a number of filament and selection of sheaths are crucial components. In this talk, we will report multifilamentary MgB_2 wires with variously designed architectures that Sam Dong has developed. Moreover, we will introduce key technologies for various magnet applications.

This work was supported by the National Research Foundation Grant (NRF-2020M2D8A2047959) funded from Ministry of Science and ICT (MSIT) of Republic of Korea.

Performance evaluation of differently structured REBCO tapes under uniaxial tension at 77 K

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The mechanical properties of REBCO coated conductor (CC) tapes under uniaxial tension are mainly determined by the thick layer components like the substrate and the stabilizer or even the reinforcement layers. Depending on the applications of the CC tapes, it is necessary to externally reinforce thin metallic foils to one side or both sides of the CC tapes. In this study, the effect of additional lamination or stabilizer on the strain/stress tolerance of the critical current, I_c, in REBCO coated conductor (CC) tapes were investigated. The strain dependence of I_c in differently processed 12 mm REBCO CC tapes under uniaxial tension at self-field and 77 K has been evaluated. Depending on whether the I_c of CC tapes were measured by monotonic loading by the loading-unloading scheme, reversible and irreversible strain and stress limits could be determined, respectively. As a result, similar electromechanical properties have been observed on the CC tape reinforced by stainless steel lamination and Sn-stabilized CC tape. The significant increase in mechanical properties of stainless steel laminated CC tape was mainly due to its volume (thickness) reinforcement. As indicated by the intrinsic strain sensitivity, the I_c degradation behavior is independent of whether the CC tape has a reinforcement or just has only stabilizing layers.

This research was supported by a grant from the National Research Foundation of Korea (NRF-2020-R1I1A-3058389) funded by the Ministry of Education (MOE), Republic of Korea.

Microstructure of E-beam irradiated MgB_2 superconductors

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초전도체의 임계전류밀도(Critical current density, J_c)는 재료의 미세조직(재료 내부의 비초전도 결함의 타입과 농도)에 따라 달라진다. 고온 초전도체의 경우 초전도 결정내부에 나노 크기의 결함들이 존재하면 초전도 내부의 볼텍스(Vortex)들의 이동을 효과적으로 억제한다. 재료에 미세결함을 만드는 방법으로는 비초전도 화학물질을 첨가하는 화학적 방법과 초전도체에 물리적인 힘을 가해 내부에서 결함이 만들어지게 하는 물리적 방법이 있다. 물리적 방법에는 이온빔, 전자빔, 중성자(열 또는 고속 중성자), 감마선 등이 사용된다. 본 연구에서는 한국원자력연구원의 전자빔 시설을 이용하여 입자(전자빔) 조사에 따른 MgB_2 초전도체의 초전도 특성과 미세조직을 조사하였다. 전자빔 조사량을 달리하여 조사한 결과 일정 조사 조건에서 J_c가 향상되는 결과를 얻었다. 전자빔 조사된 시료의 표면에 대해 X-ray 회절검사를 한 결과, 조사량이 증가하면 회절선의 강도가 비례적으로 감소했다. 회절선 강도감소는 반치각(FWHM, Full width half maximum)의 증가로 표시할 수 있다. 이 결과는 전자빔 조사에 의해 MgB_2의 결정성이 저하되고 있음을 의미하며(Lattice distortion), 이러한 결함으로 인해 자기장에서의 MgB_2의 J_c가 증가한 것으로 판단된다. 전자빔 조사에 따른 TEM 미세조직(Lattice image) 관찰도 유사한 결과를 보였다.

정부(과학기술정보통신부)의 재원으로 한국연구재단의 지원을 받아 수행된 연구임 (NRF-2020M2D8A2047959).

Local Structure Analyses on MgB_2 films with Various Thickness of ZnO Buffer layer: Angle-Dependent XANES Study

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It has been known that the local structure of superconducting material plays a significant role in the superconducting mechanism. An epitaxial growth and an insertion of an appropriate buffer layer have been proved to be effective solutions that can be applied to the MgB_2 superconductor for power application. Here we report the use of X-ray absorption spectra (XAS) as a powerful method to investigate the effect of local structure distortion of MgB_2 with ZnO buffer layer on its superconducting properties. Magnesium K-edge X-ray absorption near-edge spectra (XANES) in three different angles (0, 45, and 90 degrees from the ab-plane), which are known to carry the footprint of the crystal structure, were analyzed. Projected density of states (P-DOS) generated by using the quantum espresso (QE) software on the simulated crystal structure obtained from extended X-ray fine structure spectra (EXAFS) were compared to the orbital characteristics of p orbital extracted from XANES data. Evolution of the pre-edge peak from 0 to 90-degree was observed. This change of pre-edge peak is believed to have a close relation to the anisotropic nature of MgB_2 and/or substantial change in the crystal geometry which affects the electron transfer near the Fermi surface and the superconducting behaviors.

Performance comparison of single and dual rotor Axial Flux machines with HTS Field Windings

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Axial flux motors are effective in applications where axial space constraints exist because it is more advantageous in designing them in pancake forms compared to radial flux motors. Moreover, disk shaped rotors and stators can be axially stacked to form multi-rotor/stator axial flux machines. Common advantages of multi-rotor/stator axial flux machine are mainly caused by the characteristics of the multi airgaps and stator winding forms. In order to effectively show the advantages of multi-rotor/stator configuration, dual rotor and toroidal wound stator geometry is selected and designed in this paper. This paper presents a design study and comparisons of single and dual rotor axial flux machines with high temperature superconductor(HTS) field windings. Design of 2-D equivalent model is preceded in order to reduce computational time of 3-D finite element analysis (FEA) of axial flux motors. Compared to conventional single rotor axial flux machines with HTS field windings, the characteristics of dual rotor axial flux machines with HTS field windings are shown in terms of machine volume, torque density, and efficiency.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2018R1A2B3009249).

Design methodology of REBCO magnet for magnetic levitation using local mixing of REBCO wires

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In general, the electromagnetic performance of the REBCO magnet at a specific operating temperature is determined according to the Ic(B, theta) characteristics of the REBCO wire. Accordingly, the design is performed in consideration of the magnitude and incident angle of the magnetic field across the entire magnet winding area, and the locally lowest critical current is determined as the critical current of the magnet. REBCO wire has different properties depending on the manufacturing process. There are a REBCO wire with good characteristic at low field and vice versa. However, due to the characteristics of the manufacturing process, relatively high cost is required for REBCO wire materials for high field. Here, if a wire for a relatively low field is applied to an area with a locally high critical current of the REBCO magnet, it will be possible to reduce the magnet fabrication cost. As part of the high-speed maglev study, the Korea Railroad Research Institute has continuously conducted research on REBCO magnets with an operating temperature of 40 K. In general, MMF (magneto-motive force) of magnets is used as a performance index in maglev, and currently designing superconducting electromagnets with MMF of 320 kAT is being carried out. In this paper, considering a method of mixing REBCO wires with different performances, a method of reducing design costs for REBCO magnets satisfying a target MMF is described.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2019R1A5A8083201).

A Design Study on Dual Airgap Radial Flux HTS Synchronous Motor

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With regard to conventional permanent magnet motors, studies are being actively conducted to improve the torque of the motor by changing rotor and stator configuration. By changing the rotor and stator configuration, the torque density can be improved by increasing the air gap area where electromagnetic torque is generated. Since there are few such studies in high temperature superconducting (HTS) motor, this paper presents a novel design topology of radial flux HTS motor with the dual airgap. The dual airgap topology can be divided into the following two types: (1) single-rotor, double-stator; (2) double-rotor, single-stator. Through characteristics comparison of those two types of dual airgap motors, we selected a topology that is more suitable for HTS motors. The finite element method (FEM) was used to obtain an optimal design of the HTS motor. To implement an electromagnetic design, design variables are set to characterize the geometry of the dual airgap topology. For a detailed performance comparison with conventional single airgap HTS motor, the following key motor characteristics are calculated through FEM simulation: (1) total HTS consumption; (2) airgap flux density; and (3) torque density.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2018R1A2B3009249).

Design options for ultra-high magnetic field all-REBCO superconducting magnet

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Benefited from high engineering current density, mechanical robustness, and self-protection feature of the no-insulation (NI) winding techniques, NI techniques have been playing a key role to achieve a high magnetic field. In this study, we present design options for ultra-high field all-$REBa_2Cu_3O_{7-d}$ (REBCO, RE: rare earth elements) superconducting magnet with no-insulation (NI) multi-width (MW) winding techniques incorporated. The design target is a center field of > 40 T under bath-cooled liquid helium and a winding bore radius of > 25 mm. The critical current of the magnet is evaluated by using the in-field critical current data which is fitted to the experimental data measured at short sample. Detailed analysis results of the design will be provided including: (1) mechanical stress analysis; (2) NI charging characteristics; and (3) post quench analysis.

Keywords: No-insulation, REBCO, Superconducting magnet

This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 1711138068, KMDF_PR_20200901_0063).

Simulation and Comparison Between Simple Lumped Circuit Model and Distributed Circuit Model in Regards of Resistive Losses in NI HTS Coils

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The resistive loss is a performance limiting factor in no-insulation (NI) high temperature superconducting (HTS) coils. Accurate simulations of resistive losses are crucial for design and operation of NI HTS coils. While the distributed circuit model might provide more detailed and accurate estimations of resistive losses, it is more complicated and time consuming compared to a simple lumped circuit model. A simple circuit model could provide convenient simulation results, which might simplify the designs and operations NI HTS coils. In this study, we investigate the difference of resistive losses between a simple lumped circuit model and distributed circuit model.

This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 1711138068, KMDF_PR_20200901_0063).

Effects of epoxy composites containing various fillers as an insulator on thermal and electrical properties of GdBCO magnets

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일반적으로 고자기장 마그넷 또는 초전도 모터 및 발전기의 계자코일은 운전 시 발생하는 진동, 자기장으로 인해 발생하는 magnetic pressure 등으로 인해 야기되는 기계적인 취약점으로부터 코일을 보호하기 위해 에폭시를 함침하는 것이 일반적이다. 최근 몇 년간 이러한 특성을 보완할 수 있는 최적의 에폭시 함침 방법을 찾기 위해 많은 연구기관에서 다양한 연구가 진행되어왔으며, 수많은 함침 방법 중 vacuum pressure impregnation (VPI) 방법으로 함침된 코일의 열/전기적 특성이 우수하다고 밝혀진 바 있다. 그러나 에폭시 재료 자체의 저조한 열적 특성으로 인해 에폭시 함침 코일의 열적 안정성은 함침 전보다 저하될 수밖에 없다. 이러한 문제점을 해결하기 위해 에폭시에 다양한 filler를 첨가하여 에폭시의 낮은 열전도도를 보완하고자 하는 연구가 활발히 진행되고 있다. 본 연구에서는 열적 특성이 우수한 다양한 filler (Silver, CNT, Boron nitride)를 첨가하여 제작된 epoxy composites를 사용하여 VPI 방법으로 GdBCO 코일을 제작한 후 cool-down test, charge-discharge test 및 quench test를 진행하여 코일의 열/전기적 특성을 평가하였다. 또한, VPI 함침법이 GdBCO 코일의 turn-to-turn layer 간에 미치는 영향에 대해 논의한다.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1A2C2093122) and in part by the the Technology development Program(S3102900) funded by the Ministry of SMEs and Startups(MSS, Korea).

Superconducting Joint Characteristics of the Reacted Multifilament MgB_2 Wires Using Powder Processing Method

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영구전류모드에서 높은 해상도의 자기장을 가지는 magnetic resonance imaging (MRI) 시스템을 작동시키기 위해서는 초전도 접합기법에 대한 광범위한 연구가 필요하다. 그 중 MgB_2는 39 K의 높은 임계 온도 덕분에 액체 헬륨을 사용하지 않고도 초전도 자석을 작동시킬 수 있어서 MRI 자석 개발의 유망한 후보로 부상하고 있다. 본 연구기관에서는 지난 몇 년간 MgB_2 선재를 이용한 MgB_2 초전도 접합기법을 개발하여 영구전류모드 운전이 가능한 MgB_2 MRI 자석 개발의 가능성을 보여주었다. 최근에는 reacted monofilament MgB_2 선재를 부분 가열하여 재접합을 실시, 초전도 특성을 재현할 수 있다는 것을 확인하였다. 이러한 결과는 reacted MgB_2 조인트의 접합부 또는 선재에서 quench가 발생으로 인해 손상한 부위를 다시 재접합을 함으로서 손쉽게 초전도 자석의 영구모드 운전이 가능하도록 하는 것을 의미한다. 본 연구에서는 reacted multifilament MgB_2 선재를 특수 제작한 home-made furnace를 사용하여 조인트의 부분 가열을 가능하도록 하였으며 분말야금식 접합 방식을 이용하여 초전도접합이 구현될 수 있도록 하였다. 초전도 접합 특성은 열처리 온도와 시간을 변수로 두어 vapor cooling 방식을 이용하여 측정하였으며, scanning electron microscope (SEM) 및 energy dispersive x-ray spectroscopy (EDS)를 통해 접합부위의 미세구조를 분석, 평가하였다.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1A2C2093122) and in part by the Korea Basic Science Institute under Grant D210200.

Study on the Superconducting Joint Technique using Litz MgB_2 Wires for MRI Magnet Development

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높은 해상도의 자기장을 가지는 magnetic resonance imaging (MRI) 시스템을 영구 전류 모드로 작동시키기 위해 초전도 접합이 요구된다. 최근에 본 연구진은 MgB_2 MRI 자석에 적용할 수 있는 unreacted multifilament MgB_2 선재의 초전도 접합기술 개발에 성공하였으며, reacted MgB_2 선재의 초전도 접합에 대한 연구 결과도 이미 소개된 바있다. 일반적으로 MgB_2 선재의 제조에 사용되는 powder-in-tube (PIT) 공정은 선재를 재조립하고 인발하는 공정이 수반된다. 선재를 제작하는 공정과정이 많아질수록 공정과정에서 선재에 미치는 영향이 증가할 수 있다. 따라서 선재의 균일한 초전도 특성을 얻기 위해서는 이러한 PIT 공정에서 선재의 초전도 특성이 저하될 수 있는 공정을 개선할 필요성이 있다. 그러므로 재조립 및 인발공정을 최소화하기 위해 공정과정이 최소화된 Litz MgB_2 선재를 사용할 것을 제안하였다. 본 발표에서는 Kiswire Advanced Technology Co., Ltd.에서 제조한 pitch 간격 10 mm로 꼬아진 MgB_2 연선 선재를 사용하여 초전도 접합기술에 대한 연구에 대한 최근 실험 결과를 소개한다. MgB_2 Litz 선재로 제작된 초전도 접합부의 초전도특성은 V-I 특성을 기반으로 평가하였다. 또한, 접합 샘플의 형태와 구조는 scanning electron microscopy (SEM)을 이용하여 분석하였고, 최종적으로 기개발된 접합법을 사용하여 closed loop를 제작하여 filed decay test를 통해 접합저항을 측정하였다.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1A2C2093122) and in part by the Korea Basic Science Institute under Grant D210200.

Investigation of Stress-strain and Frictional Characteristics of GdBCO Coils co-wound with Intentionally Scratched Metallic Insulation

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고자장 마그넷에서 발생되는 Lorentz force는 큰 기계적 스트레스를 야기할 수 있어 마그넷 설계 시 필수적으로 고려되어야 한다. 그러나 일반적인 stress-strain 계산에서는 코일의 턴간 마찰력은 고려되지 않고 있다. 이와 관련한 최근 연구결과를 보면 GdBCO coated conductor (CC) tape의 스크래칭을 통해 턴간 마찰력이 코일의 손상을 유발할 수 있는 strain에 영향을 미칠 수 있다는 연구결과가 소개된 바 있다. 또한, GdBCO CC tape의 직접적인 스크래치는 선재 자체의 손상을 유발시킬 수 있다는 것이 지배적인 논점이다. 따라서, 본 연구에서는 GdBCO CC tape의 직접적인 손상을 방지하고 코일의 턴간 마찰력의 변화에 따라 영향을 미치는 strain을 확인하기 위해 의도적으로 Stainless steel tape에 스크래치를 가한 후 GdBCO CC tape과 co-wound하여 코일을 제작하고, Lorentz force와 유사한 힘을 가했을 때의 strain 변화를 확인하였다. 또한, sudden-discharge test, 힘을 가하기 전 후의 V-I 특성 비교를 통해 quench 시 열 전기적 특성 및 충/방전 특성을 확인하였다.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1A2C2093122) and in part by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 1711138067, KMDF_PR_20200901_0063-01).

Magnetization loss analysis of various types of the HTS coils with the HTS CORC

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초전도체를 교류 전력기기에 응용할 경우 필연적으로 교류손실이 발생하기 때문에, 기기에서 발생하는 교류 손실을 정확하게 예측하고, 감소시킬 수 있는 방법이 필요하다. 대부분의 전력 기기는 코일의 형태를 가지기 때문에, 본 연구진은 고온초전도체로 구성된 코일에서 발생하는 교류 손실을 샘플 시험결과를 토대로 빠르게 예측하는 방법을 제안하였다. 본 논문에서 제안하는 교류 손실 예측 방법의 적용 사례로 대전류 용 고온초전도 도체 중 하나인 CORC (Conductors on Round Core)를 사용하여 코일을 제작할 경우에 얻을 수 있는 손실감소 효과를 확인하였다. CORC 코일의 손실의 분석은 CORC 샘플 도체의 손실 측정 결과를 적용하여 진행하였다. 고온초전도 선재를 팬케이크 (pancake) 형태로 권선한 경우와 CORC 형태로 권선한 경우, 두 가지를 모두 사용한 하이브리드 (hybrid) 형태로 권선한 경우로 나누어 손실 해석을 진행하였으며 이를 통해 고온초전도 코일의 형상에 따른 손실의 차이를 확인하였고, 전력 기기의 손실을 최소화 시킬 수 있는 코일의 형상을 선정하였다.

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2019R1I1A3A01063158).
This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (2021R1F1A1063208).

A bifilar type persistent current switch for a joint-less HTS magnet

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초전도 전원장치의 중요한 구성품 중 하나인 영구전류스위치는 초전도 선재로 구성된 폐회로 일부분에 저항을 조정하여 초전도 마그넷의 전류를 충전하는 방식으로 작동한다. 이러한 방식은 온도상승을 적절히 조절하여 충분한 저항을 발생시키면서 동시에 마그넷의 온도가 상승되지 않도록 열적 설계가 필요하다. 그러나 고온초전도 마그넷의 경우 초전도 접합기술이 완성되지 않아서 영구전류운전이 어려울 뿐만 아니라 특히 전도냉각 방식으로 20 K 근방에서 동작하는 고온초전도 마그넷의 경우 초전도-상전도 상변이에 필요한 온도의 범위가 크고 냉각효율이 낮기 때문에 전도냉각 방식에서 고온초전도 시스템에 적용된 영구전류스위치의 개발은 크게 진행되지 못한 실정이다. 본 논문에서는 전도냉각 시스템을 이용하여 초전도접합이 필요 없는 무접합 마그넷의 영구전류모드 운전을 위한 고온초전도 영구전류스위치에 대한 연구를 진행하였다. 기존 연구에서 진행되었던 동심배치 형태의 무접합 마그넷 권선을 응용하여, 턴수가 같은 두 코일을 권선 후 남는 선재를 이용하여 바이필라 형태의 영구전류스위치를 권선하는 방법을 제안하였다. 또한 열해석 및 다중 물리해석을 통해 전도냉각 시스템에서 구현 가능한 영구전류스위치를 설계 및 제작하였다.

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (2019R1F1A1063397).
This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Science and ICT (2021R1F1A1063208).

Thermohydraulic performance analysis of airfoil heat sinks attached to a cryocooler

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The heat sink, attached to the cryocooler, is used to cool the cryogenic fluids. The performance of the heat sink depends on the pressure drop, heat transfer area, and overall size; In general, the lower the pressure drop, the larger the heat transfer area, and the smaller the overall size, the better the performance. To improve performance, increasing the heat transfer area increases the overall size, and increasing the heat transfer area at the same size increases the pressure drop. To solve this problem, an airfoil fin can be applied to the heat sink to reduce the pressure drop and increase the heat transfer area. The airfoil has a streamlined cross-sectional area, which can reduce the effect of an eddy that occurs when the fluid passes through the fin of the heat sink. And the flow of the fluid can have a constant flow similar to free flow while passing through the repeating airfoil fin structure. In this study, a unit model analysis was performed to investigate the thermohydraulic characteristics according to the arrangement of the airfoil fins and to predict the performance of the heat sink according to the design variable. Heat transfer performance and pressure drop were compared according to the airfoil fin arrangement, and the performance of the unit model was compared with a goodness factor. Based on the results of this study, an airfoil heat sink with excellent thermohydraulic performance will be fabricated using a metal 3D printing method.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2019R1A5A8083201).

Design of process piping system in coldbox for 0.5 TPD hydrogen liquefaction

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수소기체를 액체로 변환하는 수소액화 공정은 수소기체를 예냉하는 과정, 기체를 액체로 변환하는 과정, Ortho/Para 변환열을 제거하는 과정으로 구성되며, 통상 중소규모의 수소액화플랜트의 경우 헬륨 냉동사이클을 통해 수소를 냉각, 액화하는 방식이 많이 사용되어 지고 있으며, 이를 위한 콜드박스는 열교환기, 극저온밸브, 팽창터빈/쥴톰슨밸브 등의 팽창장치로 구성된다. 콜드박스 내부의 열교환기 등의 구성품은 배관을 통해 연결되며, 배관은 충분한 내압성능과 압력손실, 강온에 따른 열변형을 고려하여 설계되어야 하며, 설계된 배관시스템은 열교환기, 터빈 등의 노즐에 가해지는 힘과 모멘트가 허용범위 미만의 값을 유지할 수 있게 설계되어야 한다. 본 연구에서는 0.5 TPD급 수소액화용 콜드박스의 설계를 위해, 공정설계를 통해 확정된 P&ID, 열교환기 및 팽창터빈의 상세설계를 바탕으로 콜드박스 내부 각 구성품을 연결하는 고압 및 저압 헬륨가스배관, 액체질소 및 기체질소 배관, 수소가스 배관의 3차원 layout을 설계하고, ASME 31.3 공정배관 규격에 따른 구조건전성을 배관전용 해석프로그램인 CAEPIPE 프로그램을 통해 확인하였다.

This research was supported by a grant (19IHTP-B151601-01-000000) from a development program of core technologies for commercial hydrogen liquefaction plant funded by Ministry of Land, Infrastructure and Transport of Korean government.

Process simulation for BOG re-liquefaction system of Lqiuid Hydrogen Carrier

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최근 탄소중립과 수소경제의 구현을 위한 다양한 기술개발이 진행되고 있으며, 수소경제 구현을 위해서는 대량의 그린수소를 생산, 운송하는 인프라기술의 개발이 필수적이다. 친환경적인 대량의 그린수소를 국내로 도입하기 위해서는 선박운송이 유일한 방법으로, 이를 위해 수소를 안전하게 경제적으로 운송할 수 있는 액체수소운송기술의 개발이 요구된다. 미국, 일본을 중심으로 액체수소의 운송을 위한 액체수소 운송선 개발이 진행되고 있으며, 실증을 위한 선박을 건조한 바 있고, 국내에서도 이를 위한 연구개발이 진행되고 있다. 액체수소의 운송과정에서는 열침입으로 인한 액체수소의 증발이 필연적으로 발생하며, 20 K (20,000 m^3)급 액체수소 운송선의 경우 BOG (Boil-Off Gas)는 수 톤/일에 달하는 막대한 양으로 평가되며, 수송선에서 발생하는 BOG를 처리하기 위해 재액화, 연료활용 등 다양한 방법이 제안되고 있다. 본 연구에서는 열침입으로 인해 기화되어 탱크 외부로 방출되는 BOG의 양을 줄여, 기 개발된 중소형 액화플랜트의 적용이 가능하게 하기 위해, BOG의 냉열을 이용한 재액화 공정에 대해 공정해석을 수행하였다. 공정해석은 액체수소 저장탱크 압력, 압축기 토출압력 등의 공정변수의 변화에 대해 Aspen HYSYS를 사용하여 수행하였으며, 공정해석결과 방출되는 BOG의 약 80 %를 재액화하여, 외부로 방출되는 수소가스의 양을 20 % 수준으로 감소시킬수 있음을 확인하였다.

본 연구는 산업통상자원부 재원으로 한국에너지기술평가원(KETEP)의 지원을 받아 수행되었습니다. (과제번호: 20213030040460)

Mechanical properties of unidirectional and fabric laminate CFRP composites at cryogenic temperature environment

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The uses of fiber-reinforced plastics in extreme environments that require structures to operate at cryogenic temperatures are increasing in many industries. These include applications to aircraft and aerospace, such as in spacecraft and launch vehicle structures, liquid propellant tanks, and satellites. The design structures for these extreme applications are expected to perform consistently while ambient temperature changes dramatically. Fortunately, composite materials, like carbon fiber reinforced plastics (CFRPs) are now being utilized in various applications that demand materials with low density and high specific strength capabilities and can withstand a change in material properties while being exposed at extreme temperatures. To ensure the performance reliability of such composites, this study investigates the mechanical properties of CFRPs from elevated temperature of 80 °C to cryogenic temperature of -196 °C. The factors underlying the effects of temperatures on the mechanical properties of unidirectional (UD) (0° and 90°) and fabric laminate CFRPs with a thermoset resin were investigated. Modulus of elasticity and ultimate strength and strain for both tensile and compressive properties were experimentally obtained using devices made purposely to perform at various temperature environments. Both the ultimate tensile and compressive strengths of 0° UD-CFRPs are ~2.5 times greater than those of the fabric laminate CFRPs regardless of temperature environments. Marginal changes in modulus and strength were observed when tested at room and cryogenic temperatures. Information on the failure characteristics of CFRPs at various temperatures were summarized based on standard tests descriptions. These include failure modes of explosive at various areas along the gage length and lateral separation along the width direction as dominant failure features for the tensile test while brooming of fracture surfaces for the compressive test.

This research was supported by a grant from the National Research Foundation of Korea (NRF-2020-R1I1A-3058389), funded by the Ministry of Education (MOE), Republic of Korea.

Preliminary Design of Two-stage Brayton Refrigeration Cycles for High Field HTS Magnets at 20 K

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A thermodynamic study is performed as preliminary design of Brayton refrigeration cycles for application to high field HTS magnets under development in near future. As a strong magnetic field over 20 T is required in a variety of areas for breakthrough technology, it is expected that the operating temperature should be as low as 20 K, and Brayton refrigeration cycle is a feasible option in cryogenic cooling systems. A standard Brayton cycle to execute a thermal load of 3 kW at 20 K is designed with helium as refrigerant, and then two modified cycles are examined for better thermodynamic performance. In order to significantly reduce the thermal load at 20 K, the heat intercept at an intermediate temperature is proposed for current leads, mechanical supports, and radiation shields. Two-stage refrigeration cycles are devised and analyzed to provide the refrigeration at two distinct temperature levels. It is rigorously shown that the intermediate temperature has an optimum to minimize the compressor power consumption. The details of optimized two-stage cycles are presented and discussed towards the practical process design and integration with different HTS magnets as next step.

Keywords : thermodynamics, Brayton refrigeration cycle, high magnetic field, HTS magnet, heat intercept

Pressure Control of Sub-cooled Liquid Nitrogen Cryostat in SFCL Pilot System

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A pressure control scheme is designed and applied to the liquid nitrogen (LN2) cryostat in three-phase 23 kV - 2 kA superconducting fault current limiter (SFCL) pilot system under development as an Open R&D Program of the KEPCO. The goal of cryogenic cooling is to maintain the HTS modules in sub-cooled liquid nitrogen stably at 77 K and 300 kPa, while the electrical current varies over a wide range in practice. The sub-cooling of LN2 is crucial for electrical insulation, spatially uniform temperature, and fast recovery. Although the nominal pressure is 300 kPa, the actual pressure is maintained within a certain range, for example, between 290 kPa and 310 kPa. In order to avoid an excessive pressure over the upper limit, a relief valve is installed at the top and the exhaust gauge pressure is set at 209 kPa. When the internal pressure drops below the lower limit, the vapor is pressurized by high-pressure neon as non-condensable gas. The role of non-condensable gas is to effectively maintain the sub-cooled state without condensation of nitrogen vapor, even when the refrigeration exceeds the thermal load. A small neon gas tank equipped with a two-stage pressure regulator is also connected to the top of cryostat, and the exit gauge pressure of regulator is set at 189 kPa. The details of experimental apparatus in the pilot system are presented, and the effect of allowed pressure range is discussed from the operational point of view.

Keywords : pressure control, sub-cooling, relief valve, non-condensable gas, pressure range, SFCL