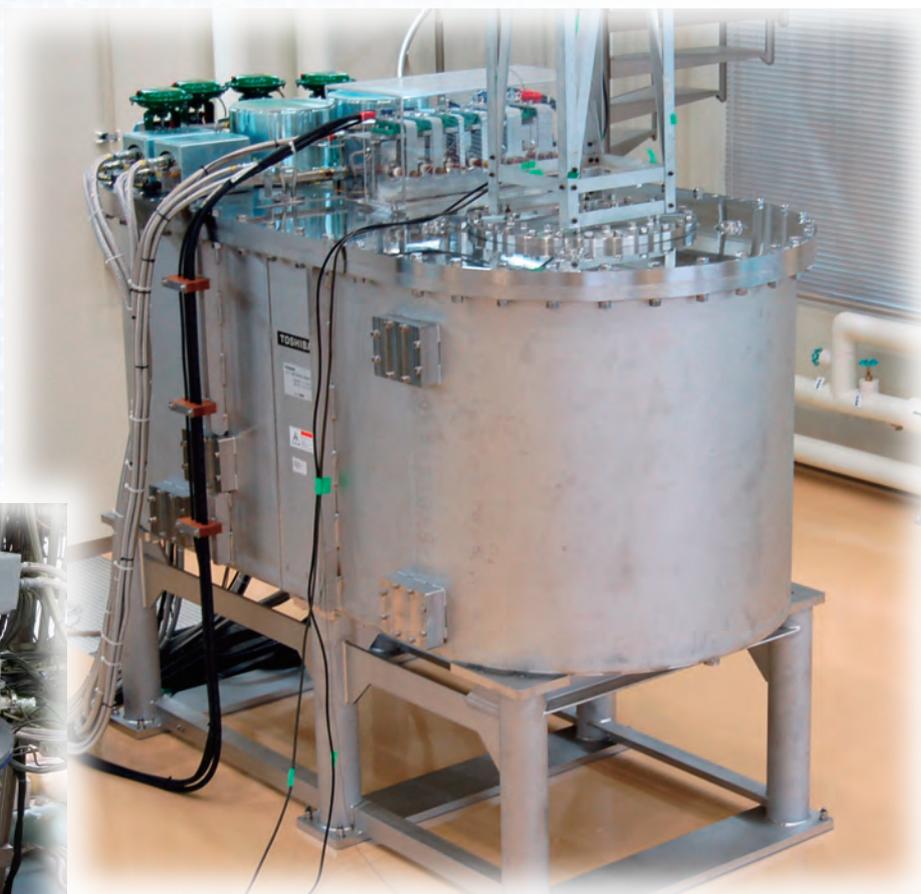


# Selected Topics in 2020 Research Highlight at HFLSM



28T-CHM



25T-CSM



High Field Laboratory for Superconducting Materials,  
Institute for Materials Research, Tohoku University

**< FRONT COVER EXPOSITION >**

**Cryogen-Free 28 T Hybrid Magnet and  
25 T Cryogen-Free Superconducting Magnet**

The world's first 28 T cryogen-free hybrid magnet developed by the HFLSM. The inner double Bitter type water-cooled resistive magnet generates 19.0 T in a room temperature experimental bore of 32 mm with the electric power of 7.2 MW. The outer cryogen-free superconducting magnet generates 9.0 T in a 360 mm room temperature bore. The cryogen-free superconducting magnet generates 24.6 T in 52 mm room temperature bore by the combination of metallic and high- $T_c$  superconductors.

## ◆◆◆ Preface ◆◆◆

This booklet reports the highlights of researches and the new improvements during FY2020 performed in HFLSM: High Field Laboratory for Superconducting Materials at Sendai. HFLSM has been developed numbers of new magnets technologies including cryogen-free hybrid magnet and cryogen-free superconducting magnets generating magnetic fields above 20 T. At HFLSM, the unique 25 T cryogen-free superconducting magnet has been operational for user program and has attracted many users. Such cryogen-free superconducting magnets surely offer long-term stable and high-quality steady fields. HFLSM offers varieties of magnets for researches in materials science, physics, applied superconductivity, chemistry and other pure and inter-disciplinary sciences performed in steady magnetic fields. It should be noted that HFLSM is now preparing for 30 T class superconducting magnet based on our original technologies. This project is one of the main objectives in the Japan High Magnetic Field Collaboratory started operation in April 2020. It has been also accepted in the load map 2020 plan for large scale facilities form MRXT. Under difficulties in Covid-19 pandemic, HFLSM is in operational with strict anti-infection majors by the strong supports and collaborations of users.

Form 2019, IMR has recognized as the new international user program named Global Institute for Materials Science Tohoku (GIMRT). In this program, a collaboration among multiple institutions including IMR can be conducted in the “Bridge type” scheme. It will enhance the diverse and strong collaboration in a global framework. Besides international collaborations with remote technologies under the pandemic, we are starting to accept users from abroad in 2021 for onsite experiments. Our new program-combination with guest professorship will enhance the exchange under the limited entry to Japan. We hope that the booklet helps you to see the overview of our activities and stimulate future research collaborations with domestic and oversea users in HFLSM and in the High Magnetic Field Co-laboratory of Japan.

1 November 2021

Hiroyuki Nojiri

Director of HFLSM



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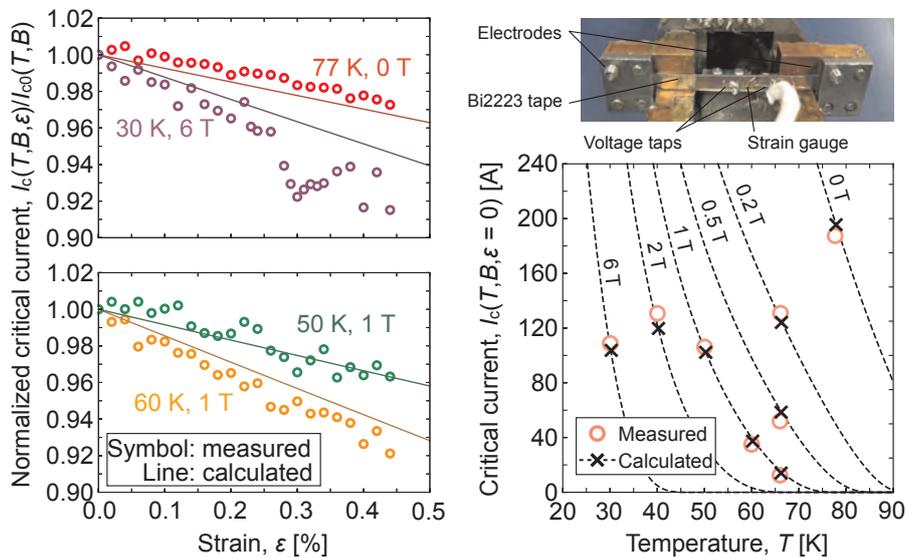
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# Mechanical and Critical Current Properties of Commercial Bi2223 Tapes under Uniaxial Tensile Strain

## 一軸引張歪み下における市販 Bi2223 テープ線材の機械・臨界電流特性



Uniaxial strain characteristics of commercial DI-BSCCO Type HT-NX tape, which is a candidate for high-field magnet applications because of its high mechanical strength and high critical current, were investigated under a wide range of temperature, magnetic field, and strain-stress conditions. We found that the irreversible strain was independent of temperature, while the irreversible stress increased at low  $T$  due to an enhancement of Young's modulus. We also found that critical current decreases  $I_c$  linearly with applied strain. Based on experimental data, we constructed a model that reproduces  $I_c$  under a wide temperature, magnetic field, and uniaxial strain conditions. This model is applicable for designing a magnet.

T. Okada, K. Sakai, S. Awaji  
IMR, Tohoku Univ.

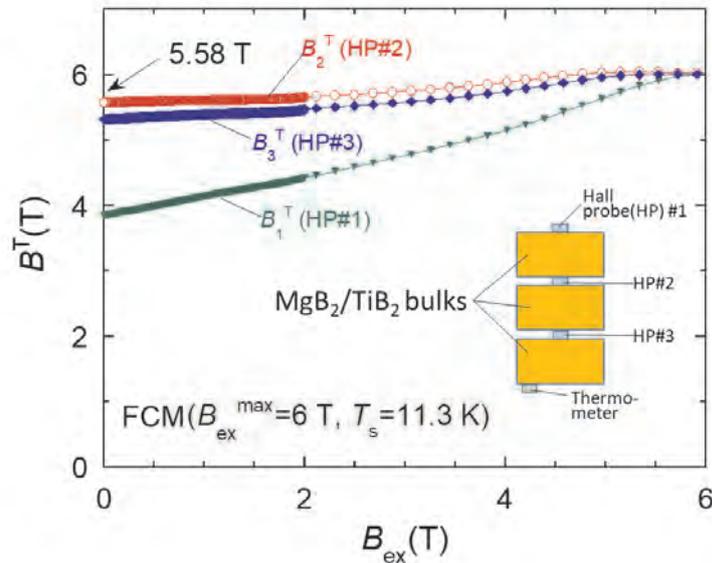
Reference: T. Okada *et al.*, "Mechanical and critical current characteristics of high-strength (Bi, Pb)<sub>2</sub>Sr<sub>2</sub>Ca<sub>2</sub>Cu<sub>3</sub>O<sub>10+ $\delta$</sub>  tapes under uniaxial strain", *Supercond. Sci. Technol.* **34** (2020) 025017.

補強合金による高い機械強度と臨界電流を有し、強磁場マグネット応用の有力候補である市販 Bi2223 線材 (DI-BSCCO Type HT-NX) の一軸引張特性を、広範な温度・磁場・応力-ひずみ下で評価した。臨界ひずみが温度に依らない一定値 (約 0.47%) を示すのに対し、臨界応力はヤング率の向上に伴って低温で増大 (30 K で約 550 MPa) した。また、臨界電流は印加した引張ひずみに凡そ線形に減少した。測定データを基に、幅広い温度・磁場・ひずみ下での臨界電流値を再現できるモデルを構築した。このモデルは、Bi2223 コイル設計時の指標の1つとして利用できる。

岡田 達典, 酒井 康平, 淡路 智  
東北大金研

# A Record-High Trapped Field of 5.6 T in the Stacking MgB<sub>2</sub>/TiB<sub>2</sub> Superconductor Bulks

MgB<sub>2</sub>/TiB<sub>2</sub> 超伝導バルク積層体による捕捉磁場 5.6 T の達成: 世界記録更新



The triple-stacked MgB<sub>2</sub>/TiB<sub>2</sub> superconducting bulks fabricated by an *in-situ* hot isostatic pressing method were magnetized at various temperatures by the field cooled magnetization (FCM) under magnetic fields of up to 8 T using the 18T superconducting magnet (18T-SM). This MgB<sub>2</sub>/TiB<sub>2</sub> stacking successfully achieved a record-high trapped field,  $B^T$ , of 5.58 T between the top and middle bulks (HP#2) by FCM from the maximum applied field,  $B_{ex}$ , of 6 T at 11.3 K, which was 0.18 T higher than the previously reported trapped field of 5.4 T among MgB<sub>2</sub> bulk magnets.

T. Naito<sup>1</sup>, Y. Takahashi<sup>1</sup>, S. Awaji<sup>2</sup>

<sup>1</sup> Fac. of Sci. Eng., Iwate Univ., <sup>2</sup> IMR, Tohoku Univ.

Reference: T. Naito *et al.*, “A record-high trapped field of 5.6 T in the stacking of MgB<sub>2</sub>/TiB<sub>2</sub> composite bulks prepared by an *in-situ* hot isostatic pressing method”, *Supercond. Sci. Technol.* **33** (2020) 125004.

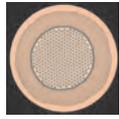
等方圧加圧焼結法 (*in-situ* プロセス) で作製した MgB<sub>2</sub>/TiB<sub>2</sub> 超伝導バルクを 3 個積層させて、様々な温度で最大 8 T の印加磁場 (18T 超伝導マグネット (18T-SM) を使用) から磁場中冷却着磁法で磁石化した。この MgB<sub>2</sub>/TiB<sub>2</sub> バルク積層体を温度 11.3 K において印加磁場 6 T から着磁したところ、上部および中間バルクの中心で 5.58 T を捕捉し、MgB<sub>2</sub> バルク磁石のこれまでの世界記録 5.4 T を 0.18 T 更新した。

内藤智之<sup>1</sup>, 高橋裕平<sup>1</sup>, 淡路 智<sup>2</sup>

<sup>1</sup> 岩手大理工, <sup>2</sup> 東北大金研

# Improvement of Mechanical Characteristics on Various Cu-Nb/Nb<sub>3</sub>Sn Wires

## Cu-Nb/Nb<sub>3</sub>Sn線材における機械的特性の向上

PARAMETERS OF CU-NB/NB <sub>3</sub> SN ROUND WIRE		
Wire-ID	LK224	
Cross-section		
Wire size	(mm)	Dia. 0.80
Cu / Cu-Nb / non-Cu	(%)	20 / 45 / 35
Nb vol% in Cu-Nb	(%)	30
Tin diffusion barrier		Ta/Nb
Bronze	-	Cu-15.7wt% Sn-0.3wt%Ti
Filament dia.	(μm)	3.2
Twist pitch	(mm)	24
Twist direction	-	Left hand helix

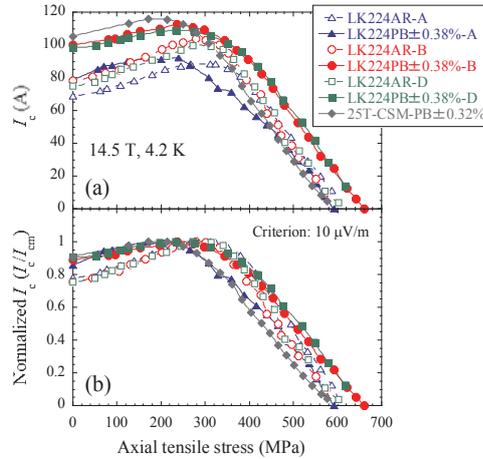


Fig. (a)  $I_c$  values of Cu-Nb/Nb<sub>3</sub>Sn wires at 14.5 T and 4.2 K, as a function of axial tensile stress. (b)  $I_c$  values normalized by each  $I_{c0}$ .

The bronze processed Nb<sub>3</sub>Sn wires composed of the Nb-rod-method Cu-Nb stabilizing reinforcer have excellent mechanical strength and a large compressive residual strain at both low and room temperatures, after Nb<sub>3</sub>Sn reaction heat treatment. Therefore, the Cu-Nb/Nb<sub>3</sub>Sn wires can be applied to the practical high field superconducting magnets manufacturing by the React-and-Wind (R&W) techniques. In this study, a Cu-Nb/Nb<sub>3</sub>Sn round wire (dia. 0.8 mm) with Cu-15.7wt%Sn-0.3wt%Ti and Cu-30vol%Nb reinforcer was developed to improve  $I_c$  characteristics under tensile stress over 300 MPa. Both the heat-treatments and the pre-bending treatments were optimized for applying to the high-strength Rutherford cables. Moreover, a Cu-Nb/Nb<sub>3</sub>Sn rectangular wire (2.1<sup>w</sup>×1.3<sup>t</sup>-0.3<sup>R</sup> mm) was developed to refine performances of ultra-high field NMR coils on both W&R and R&W process.

M. Sugimoto<sup>1</sup>, H. Ii<sup>1</sup>, D. Asami<sup>1</sup>, H. Fukushima<sup>1</sup>, T. Kato<sup>1</sup>, H. Tsubouchi<sup>1</sup>, S. Awaji<sup>2</sup>, H. Oguro<sup>3</sup>

<sup>1</sup> Furukawa Electric Co., Ltd., <sup>2</sup> IMR, Tohoku University, <sup>3</sup> Faculty of Eng., Tokai University

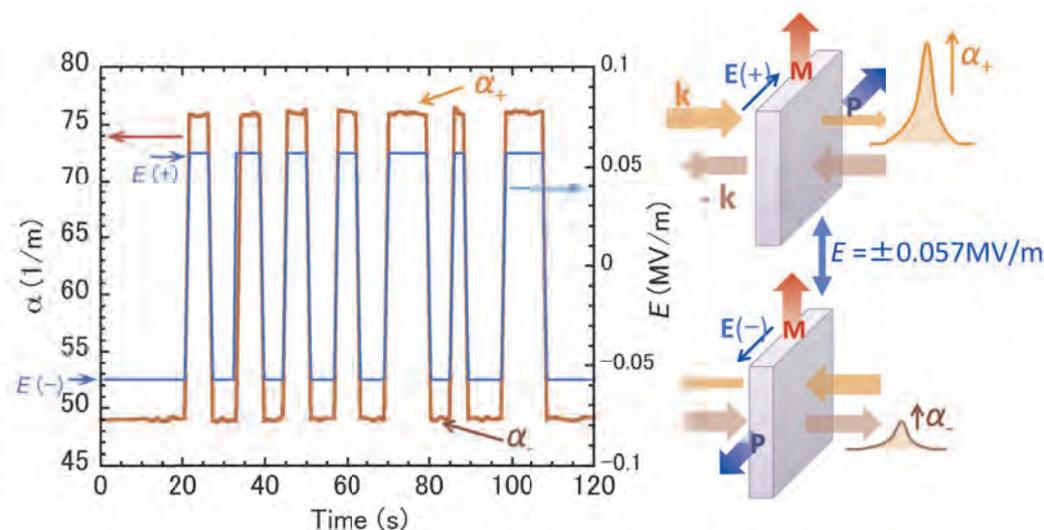
Reference: M. Sugimoto *et al.*, “Development of high-performance Cu-Nb/Nb<sub>3</sub>Sn wires for various high field magnets”, IEEE Trans. Appl. Supercond. **31** (2021) 6000605.

Nb ロッド法 Cu-Nb 安定化強化材を複合化したブロンズ法 Nb<sub>3</sub>Sn 線材は、Nb<sub>3</sub>Sn 生成熱処理後に低温と室温の両方で優れた機械的特性と大きい圧縮残留歪を有しているため、R&W 法で製作される実用的な高磁場マグネットに適用できる。本研究では、Cu-15.7wt% Sn-0.3wt% Ti ブロンズと Cu-30vo%Nb 強化材を適用した Cu-Nb/Nb<sub>3</sub>Sn 丸線(直径 0.8 mm)を開発し、300 MPaを超える引張応力下での臨界電流特性を向上させた。Nb<sub>3</sub>Sn 生成熱処理条件と事前曲げ処理条件は、高強度ラザフォードケーブル用に最適化された。さらに、超高磁場用 NMR 用コイルの性能を W&R 法と R&W 法の両方で向上させるため、Cu-Nb/Nb<sub>3</sub>Sn 平角線(2.1<sup>w</sup>×1.3<sup>t</sup>-0.3<sup>R</sup> mm)が開発された。

杉本昌弘<sup>1</sup>, 浅見大亮<sup>1</sup>, 福島弘之<sup>1</sup>, 加藤智也<sup>1</sup>, 坪内宏和<sup>1</sup>, 淡路 智<sup>2</sup>, 小黒英俊<sup>3</sup>

<sup>1</sup> 古河電工, <sup>2</sup> 東北大・金研, <sup>3</sup> 東海大・工

# Nonreciprocal Directional Microwave Response in the Interacting Spin Dimer System $\text{TiCuCl}_3$ 結合ダイマー系 $\text{TiCuCl}_3$ の非相反マイクロ波応答



An electrical switching of the nonreciprocal microwave response has been achieved in the triplon Bose-Einstein phase of the interacting spin  $S = 1/2$  dimer system  $\text{TiCuCl}_3$ . We demonstrated that by applying electrical voltage the directional response of microwave absorption due to the excitation of Nambu-Goldstone magnon can be immediately reversed, thereby achieving fast interchange between transparent and absorbing direction of microwave propagation. Therefore, the triplon Bose-Einstein condensate works as an electrically controlled directional microwave switch.

S. Kimura<sup>1</sup>, M. Matsumoto<sup>2</sup>, H. Tanaka<sup>3</sup>

<sup>1</sup> IMR, Tohoku Univ., <sup>2</sup> Dept. of Sci., Shizuoka Univ., <sup>3</sup> Dept. of Sci., Tokyo Institute of Technology

Reference: S. Kimura *et al.*, “Electrical Switching of the Nonreciprocal Directional Microwave Response in a Triplon Bose-Einstein Condensate”, *Phys. Rev. Lett.* **124** (2020) 217401.

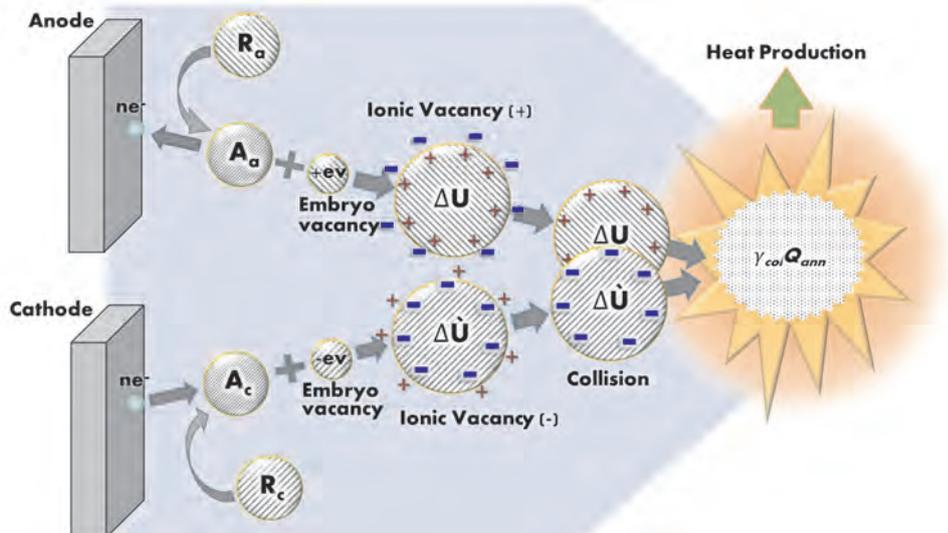
磁気秩序と強誘電が共存する結合スピンドイマー系  $\text{TiCuCl}_3$  のマグノンボース凝縮(BEC)相において、マイクロ波非相反応答の電界によるスイッチングを観測した。  $\text{TiCuCl}_3$  のマグノン BEC 相では時間・空間反転対称性の破れのため、光吸収が電磁波の伝搬方向の反転によって変化するが、  $\text{TiCuCl}_3$  の強誘電の極めてソフトな性質を利用することによって、マイクロ波が透過しやすい伝搬方向を電界による電気分極の反転によって瞬時に切り替えられる。従って、  $\text{TiCuCl}_3$  は電界によって整流方向を切り替え可能な電磁波のダイオードとして働く。

木村 尚次郎<sup>1</sup>, 松本 正茂<sup>2</sup>, 田中 秀数<sup>3</sup>

<sup>1</sup> 東北大金研, <sup>2</sup> 静大理, <sup>3</sup> 東工大理

## Collision Process of $\pm 1$ Unit-Charge Ionic Vacancies and Its Heat Production

### 正負1価のイオン空孔衝突反応による熱発生



In order to establish the universality of the excess heat production in electrochemical reaction, under a high magnetic field, as one of the most fundamental electrochemical reactions, the case of ferricyanide-ferrocyanide redox reaction was examined, where ionic vacancies with  $\pm 1$  unit-charge were collided by means of magnetohydrodynamic (MHD) flow. As a result, from the pair annihilation of the vacancies with opposite signs, beyond 7 T, excess heat production up to  $25 \text{ kJ} \cdot \text{mol}^{-1}$  in average at 15 T was observed, which was one digit smaller than the case of  $\pm 2$  unit-charges  $410 \text{ kJ} \cdot \text{mol}^{-1}$  in copper redox reaction.

A. Sugiyama<sup>1,2,3</sup>, M. Miura<sup>4</sup>, Y. Oshikiri<sup>5</sup>, Y. Kim<sup>3</sup>, R. Morimoto<sup>6</sup>, M. Miura<sup>7</sup>, T. Osaka<sup>2</sup>,  
I. Mogi<sup>8</sup>, Y. Yamauchi<sup>3,9</sup>, and R. Aogaki<sup>3,10</sup>

<sup>1</sup>Yoshino Denka Kogyo, Inc., <sup>2</sup>Waseda Univ. Res. Org. Nano & Life Innovation, <sup>3</sup>NIMS,  
<sup>4</sup>Hokkaido Polytechnic College, <sup>5</sup>Yamagata College of Industry and Technology, <sup>6</sup>SAITEC,  
<sup>7</sup>Polytechnic Center Kimitsu, <sup>8</sup>IMR, Tohoku Univ, <sup>9</sup>The Univ. of Queensland, <sup>10</sup>Polytechnic Univ.

Reference: A. Sugiyama *et al.*, “Excess Heat Production in Ferricyanide-Ferrocyanide Redox Reaction”, *Sci. Rep.* **10** (2020) 20072.

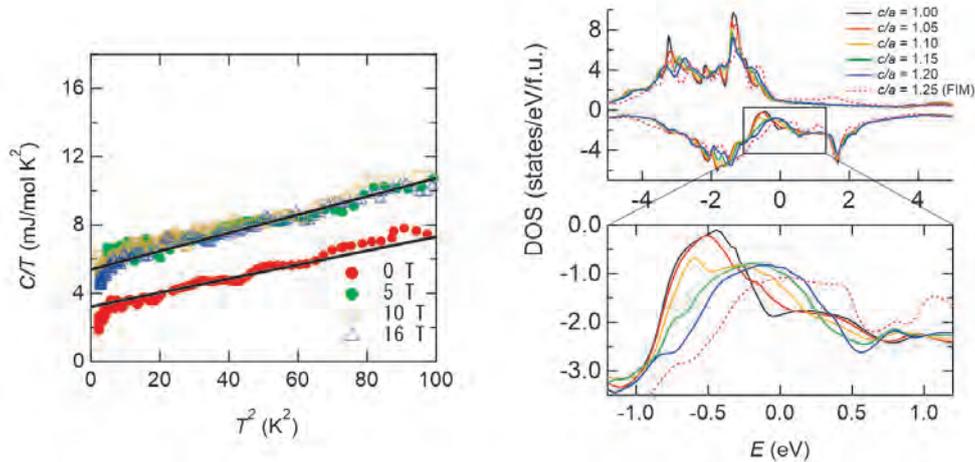
電解液の電磁流体力学(MHD)流れを用いて、カソードとアノードでそれぞれ作り出されたマイナスとプラスのイオン空孔を混合・衝突させた。フェリシアン化カリ・フェロシアン化カリの酸化還元反応における1価イオン空孔衝突による過剰熱として  $25 \text{ kJ} \cdot \text{mol}^{-1}$  の過剰熱が得られた。これはすでに測定されている銅酸化還元反応における2価空孔の過剰熱  $410 \text{ kJ} \cdot \text{mol}^{-1}$  に比べて一桁ほど小さい。

杉山敦史<sup>1,2,3</sup>、三浦 誠<sup>4</sup>、押切剛伸<sup>5</sup>、Yena Kim<sup>3</sup>、森本良一<sup>6</sup>、三浦美紀<sup>7</sup>、逢坂哲彌<sup>2</sup>、  
茂木 巖<sup>8</sup>、山内悠輔<sup>3,9</sup>、青柿良一<sup>10</sup>

<sup>1</sup>吉野電化工業、<sup>2</sup>早大ナノ・ライフ創新研究機構、<sup>3</sup>物材研、<sup>4</sup>北海道能開大、<sup>5</sup>山形産技短大、  
<sup>6</sup>埼玉県産業技術総合センター、<sup>7</sup>ポリテクセンター君津、<sup>8</sup>東北大金研、<sup>9</sup>クイーンズランド大学、<sup>10</sup>職業大

# Inverse Magnetocaloric Effect in Magnetic-Field-Induced Austenite Phase of Heusler Alloys $\text{Ni}_{50-x}\text{Co}_x\text{Mn}_{31.5}\text{Ga}_{18.5}$ ( $x = 9$ and $9.7$ )

## ホイスラー合金 $\text{Ni}_{50-x}\text{Co}_x\text{Mn}_{31.5}\text{Ga}_{18.5}$ ( $x = 9$ and $9.7$ )の磁場誘起オーステナイト相における負の磁気熱量効果



“Inverse magnetocaloric effect (IMCE)” (i.e., the rise of entropy in the system with increasing magnetic field) was observed in the magnetic-field-induced austenite phase of Heusler alloy  $\text{Ni}_{41}\text{Co}_9\text{Mn}_{31.5}\text{Ga}_{18.5}$ . To elucidate the origin of this unusual magnetocaloric property of this material, we performed specific heat measurements under the steady magnetic fields and confirmed the steep rise of the Sommerfeld coefficient through the field-induced transition. The first-principle-based calculation revealed that the density of state of this materials is sensitive to slight tetragonal distortion, implying that the IMCE in the field-induced austenite is realized by a marked change in the density of state.

T. Kihara<sup>1</sup>, T. Roy<sup>2</sup>, X. Xu<sup>3</sup>, A. Miyake<sup>4</sup>, M. Tsujikawa<sup>2</sup>, H. Mitamura<sup>4</sup>, M. Tokunaga<sup>4</sup>, Y. Adachi<sup>5</sup>, T. Eto<sup>6</sup>, and T. Kanomata<sup>7</sup>

<sup>1</sup> IMR, Tohoku Univ., <sup>2</sup> RIEC, Tohoku Univ., <sup>3</sup> Dept. of Mat. Sci., Tohoku Univ.,

<sup>4</sup> ISSP, The Univ. of Tokyo, <sup>5</sup> Yamagata Univ., <sup>6</sup> Kurume Inst. of Tech., <sup>7</sup> Tohoku Gakuin Univ.

Reference: T. Kihara *et al.*, Phys. Rev. Mater. **5** (2021) 034416.

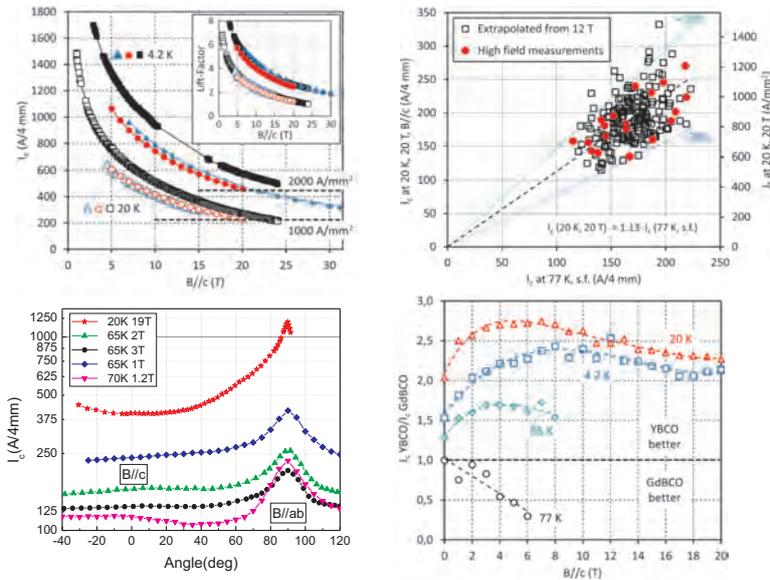
ホイスラー合金  $\text{Ni}_{41}\text{Co}_9\text{Mn}_{31.5}\text{Ga}_{18.5}$  の磁場誘起オーステナイト相において、磁場の増加に伴い系のエントロピーが上昇する「負の磁気熱量効果(IMCE)」を観測した。その起源を解明するため、定常磁場下の比熱測定を行い、磁場誘起相転移に伴う電子比熱係数の急激な上昇を確認した。更に、第一原理計算による状態密度の解析から、この系の状態密度が僅かな正方晶歪に対し非常に敏感なことが分かった。これは、この系の IMCE が状態密度の磁場応答に起因することを示唆している。

木原 工<sup>1</sup>, Tufan Roy<sup>2</sup>, 許 晶<sup>3</sup>, 三宅 厚志<sup>4</sup>, 辻川 雅人<sup>2</sup>, 三田村 裕幸<sup>4</sup>, 徳永 将史<sup>4</sup>, 安達 義也<sup>5</sup>, 江藤 徹二郎<sup>6</sup>, 鹿又 武<sup>7</sup>

<sup>1</sup> 東北大金研, <sup>2</sup> 東北大電通研, <sup>3</sup> 東北大工, <sup>4</sup> 東大物性研, <sup>5</sup> 山形大, <sup>6</sup> 久留米工大,

<sup>7</sup> 東北学院大

# Development of YBCO Based Superconducting Wires Production for Fusion



The compact fusion system SPARC, which is currently under construction by the joint team of MIT and Commonwealth Fusion Systems (CFS) relies on the availability of the HTS wires with the engineering current density  $J_e$  of at least  $700 \text{ A/mm}^2$  at  $20\text{K}$  and  $20\text{T}$ . Two years ago, even short laboratory samples with such characteristics were hardly available, while the consistent production of the thousands kilometers of such wires at reasonable cost seemed unrealistic from the viewpoint of current science, and engineering. Our team successfully developed a highly reproducible approach for the fabrication of 2G-HTS wires with the formulation based on the YBCO material with  $\text{Y}_2\text{O}_3$  nanoparticles acting as random pinning centers and specially optimized for the best performance at  $20\text{-}25\text{T}$  in the temperature range of  $4.2\text{-}20\text{K}$ . In total over  $300\text{km}$  of HTS wires with the typical piece length of  $300\text{-}600\text{m}$  were delivered for the fusion application. Such wires consistently demonstrated the expected properties, while the best performing samples exhibited  $J_e(20\text{K}, 20\text{T}) > 1000 \text{ A/mm}^2$  and  $J_e(4.2\text{K}, 20\text{T}) > 2000 \text{ A/mm}^2$

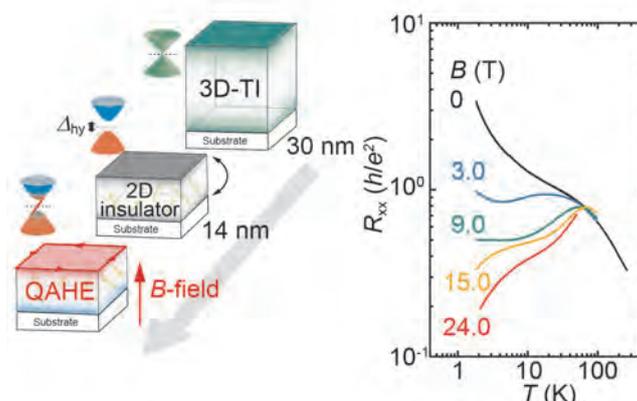
A. Molodyk<sup>1,2</sup>, S. Samoilenov<sup>1,2</sup>, A. Markelov<sup>1</sup>, P. Degtyarenko<sup>2,3</sup>, S. Lee<sup>4</sup>, V. Petykin<sup>4</sup>, M. Gaifullin<sup>4</sup>, A. Mankevich<sup>1</sup>, A. Vavilov<sup>1,2,4</sup>, B. Sorbom<sup>5</sup>, J. Cheng<sup>5</sup>, S. Garberg<sup>5</sup>, L. Kesler<sup>5</sup>, Z. Hartwig<sup>6</sup>, S. Gavrilkin<sup>7</sup>, A. Tsvetkov<sup>7</sup>, T. Okada<sup>8</sup>, S. Awaji<sup>8</sup>, D. Abramov<sup>9</sup>, A. Francis<sup>9</sup>, G. Bradford<sup>9</sup>, D. Larbalestier<sup>9</sup>, C. Senatore<sup>10</sup>, M. Bonura<sup>10</sup>, A. E. Pantoja<sup>11</sup>, S. C. Wimbush<sup>11</sup>, N. M. Strickland<sup>11</sup>, A. Vasiliev<sup>12,13,14</sup>

<sup>1</sup>S-Innovations, <sup>2</sup>SuperOx, <sup>3</sup>Joint Ins. for High Temp., <sup>4</sup>SuperOx Japan, <sup>5</sup>Commonwealth Fusion Systems, <sup>6</sup>Massachusetts Institute of Technology, <sup>7</sup>P.N. Lebedev Phys. Inst., <sup>8</sup>IMR, Tohoku Univ., <sup>9</sup>NHMFL Florida State Univ., <sup>10</sup>Univ. of Geneva., <sup>11</sup>Robinson Res. Inst. Vicotria Univ., <sup>12</sup>Kurchatov Institute, <sup>13</sup>Shubnikov Ints. of Crystallography, <sup>14</sup>Moscow Inst. of Phys. Technol.

Reference: A. Molodyk *et al.*, “Development and large volume production of extremely high current density  $\text{YBa}_2\text{Cu}_3\text{O}_7$  superconducting wires for fusion”, Scientific Reports **11** (2021) 2084.

# Insulator-to-Metal Transition Induced by High Magnetic Field in Fe-Doped (Bi,Sb)<sub>2</sub>Se<sub>3</sub> Topological Insulator Thin Films

Feドーブ(Bi,Sb)<sub>2</sub>Se<sub>3</sub>トポロジカル絶縁体薄膜における磁場誘起絶縁体金属転移



Various exotic quantum transport phenomena emerge in a quantum anomalous Hall (QAH) state induced by the exchange interaction between Dirac surface states and a spontaneous magnetization in ferromagnetic three dimensional topological insulators (3D-TIs). Here, we report on high-field electrical transport properties of paramagnetic Fe-doped (Bi,Sb)<sub>2</sub>Se<sub>3</sub> 3D-TI thin films. Starting from a 3D TI, a two-dimensional (2D) insulator appears by thickness reduction. By applying the magnetic field up to 24 T, the 2D-insulator turns into a metallic QAH state. The international collaborative research has revealed that the observed QAH state can be ascribed to the band inversion owing to a giant Zeeman splitting. A field-driven topological phase transition observed in this study demonstrates the effectiveness of the high magnetic field on observation of quantum transport phenomena and further exploration of exotic quantum phases by external stimulus in 3D-TI thin films.

J. Shiogai, Y. Satake, S. Kimura, S. Awaji, A. Tsukazaki  
IMR, Tohoku University

Reference: Y. Satake *et al.*, “Magnetic-field-induced topological phase transition in Fe-doped (Bi,Sb)<sub>2</sub>Se<sub>3</sub> heterostructures”, Phys. Rev. Mater. **4** (2020) 044202.

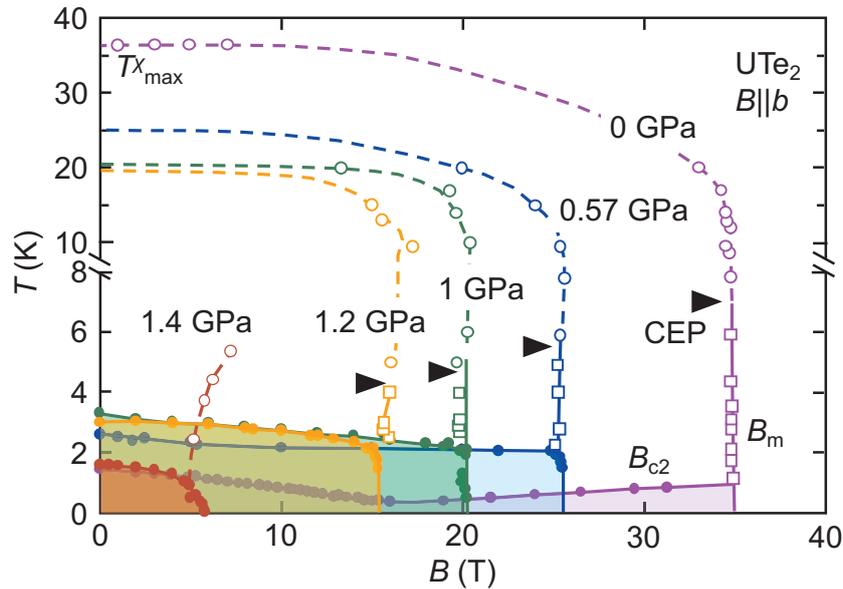
強磁性トポロジカル絶縁体における自発磁化と表面状態の交換相互作用によって現れる量子化異常ホール(QAH)相では、金属的なカイラルエッジ状態がもたらすユニークな量子輸送現象が現れる。本研究では、常磁性トポロジカル絶縁体であるFeドーブ(Bi,Sb)<sub>2</sub>Se<sub>3</sub>薄膜に強磁場を印加して伝導特性評価を行った。その結果、膜厚を薄くして絶縁体化した薄膜試料に24 Tの磁場を印加することで、QAH相の出現を示唆する金属伝導の観測に成功した。観測されたQAH相の起源がゼーマン効果によるバンド反転であることを国際共同研究で明らかにした。本研究における磁場誘起トポロジカル相転移は、量子輸送現象観測における強磁場実験の有効性を示すとともに、本物質が外場印加による量子相探索の新たなプラットフォームになることを明示した結果となる。

塩貝 純一, 佐竹 遥介, 木村 尚次郎, 淡路 智, 塚崎 敦  
東北大金研

# High-Field Phase Diagram of Spin-Triplet Superconductor

## UTe<sub>2</sub> under Pressure

### スピン三重項超伝導体 UTe<sub>2</sub> における高圧下の強磁場相図



In this work, we have investigated high-field superconducting phase diagram of spin-triplet superconductor UTe<sub>2</sub> under pressure. We have systematically observed pressure evolution of superconducting phase (colored shadow area) and metamagnetic transition ( $B_m$ ) for  $B||b$ -axis as shown in the Figure. The suppression of  $B_m$  with pressure follows the decrease of temperature  $T^{\chi}_{max}$ , where the susceptibility for  $B||b$  shows maximum as connected by dashed lines. At ambient pressure, the superconductivity is once suppressed by applying magnetic field, but the transition temperature ( $T_{SC}$ ) increases again for higher field than 16 T indicating the field re-entrant superconducting behavior. This field reinforced superconducting behavior is rapidly suppressed by applying pressure due to the increase of  $T_{SC}$  and decrease of  $B_m$ .

G. Knebel<sup>1</sup>, M. Kimata<sup>2</sup>, M. Vališka<sup>1</sup>, F. Honda<sup>2</sup>, D.X. Li<sup>2</sup>, D. Braithwaite<sup>1</sup>, G. Lapertot<sup>1</sup>, W. Knafo<sup>3</sup>, A. Pourret<sup>1</sup>, Y.J. Sato<sup>2</sup>, Y. Shimizu<sup>2</sup>, T. Kihara<sup>2</sup>, J-P. Brison<sup>1</sup>, J. Flouquet<sup>1</sup>, and D. Aoki<sup>1,2</sup>

<sup>1</sup>Univ. Grenoble Alpes, France, <sup>2</sup>IMR, Tohoku Univ., <sup>3</sup>LNCMI, Toulouse, France

Reference: G. Knebel, M. Kimata *et al.*, “Anisotropy of the Upper Critical Field in the Heavy-Fermion Superconductor UTe<sub>2</sub> under Pressure”, *J. Phys. Soc. Jpn.* **89**, 053707 (2020).

本研究ではスピン三重項超伝導体 UTe<sub>2</sub> の強磁場相図を高圧下で調べた。色付きの影が超伝導相、白抜き四角がメタ磁性転移磁場( $B_m$ )である。圧力印加による  $B_m$  の減少は、図中の破線で結んだように、帯磁率が極大となる温度  $T^{\chi}_{max}$  の減少と対応している。常圧下では超伝導相は磁場の印加によって一旦減少し、16 T 以上で再び TSC が増加する。この磁場再突入型超伝導の振る舞いは圧力印加による TSC の上昇と  $B_m$  の減少により、抑制されることが明らかとなった。

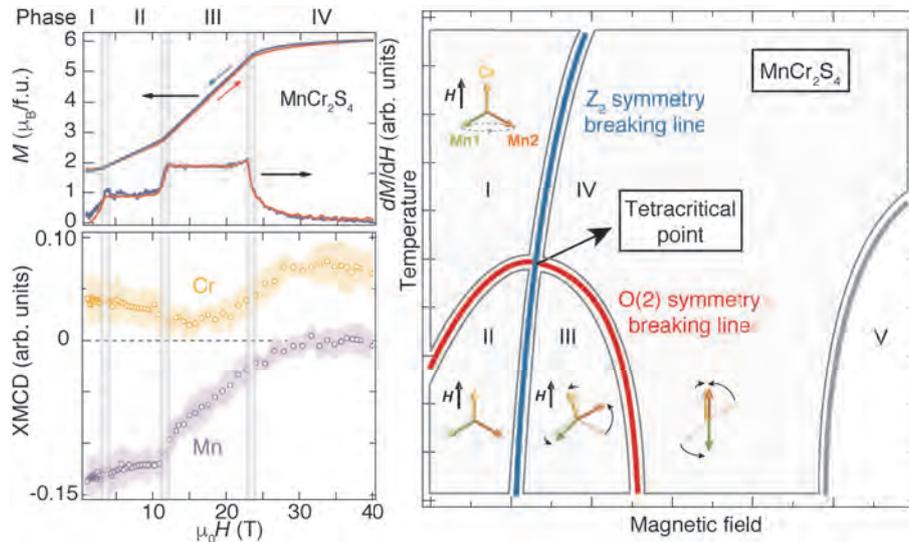
G. Knebel<sup>1</sup>, 木俣 基<sup>2</sup>, 青木 大<sup>2</sup> 他

<sup>1</sup>グルノーブルアルプ大学, <sup>2</sup>東北大金研

## Element-Selective Magnetization Process and

## Tetracritical Point in the Ferrimagnetic Spinel $\text{MnCr}_2\text{S}_4$

### スピネル型フェリ磁性体 $\text{MnCr}_2\text{S}_4$ の元素選択的磁化過程と四重臨界点



The ferrimagnetic spinel  $\text{MnCr}_2\text{S}_4$  exhibits a complex magnetic-field-temperature ( $H$ - $T$ ) phase diagram and novel magnetostructural phases due to the correlation between bond frustration and strong spin-lattice coupling. Here, we revealed the magnetic field-induced spin reorientation in the Mn and Cr sublattices element selectively by soft x-ray magnetic circular dichroism spectroscopy. Furthermore, we found a tetracritical point at the intersection of the O(2) and  $Z_2$  symmetry-breaking lines in the  $H$ - $T$  phase diagram. The tetracritical point is not predicted according to renormalization-group theory, in general, for isotropic Heisenberg magnets like  $\text{MnCr}_2\text{S}_4$ . However, our results suggest that the strong spin-lattice coupling plays a key role in  $\text{MnCr}_2\text{S}_4$ , leading to the unique biconical-fixed point.

Sh. Yamamoto<sup>1</sup>, H. Suwa<sup>2</sup>, T. Kihara<sup>3</sup>, T. Nomura<sup>1</sup>, Y. Kotani<sup>4</sup>, T. Nakamura<sup>3</sup>, Y. Skourski<sup>1</sup>,  
S. Zherlitsyn<sup>1</sup>, H. Nojiri<sup>3</sup>, J. Wosnitza<sup>1</sup> *et al.*,

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Reference: Sh. Yamamoto *et al.*, “Element-specific field-induced spin reorientation and tetracritical point in  $\text{MnCr}_2\text{S}_4$ ”, Phys. Rev. B **103** (2021) L020408.

スピネル型フェリ磁性体の  $\text{MnCr}_2\text{S}_4$  は、ボンド型の磁気フラストレーションと、強いスピン格子結合の相関により、磁場中で磁気プラトー、マルチフェロといった多彩な磁気相が現れる。本研究では、パルス強磁場下の軟 X 線磁気円二色性分光により、磁場で誘起される Mn, Cr 副格子それぞれのスピン再配列を元素選択的に明らかにした。さらに、軟 X 線分光と、比熱を含めた熱力学的測定から、温度-磁場相図において、O(2)、 $Z_2$  対称性が破れる境界線の交点で四重臨界点を見出した。等方的なハイゼンベルク磁性体において、繰り込み群の理論では四重臨界点は予測されない。 $\text{MnCr}_2\text{S}_4$  では、強いスピン格子結合により、この特異な臨界点が生じていることが示唆された。

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