Development of REBCO magnet technology at LBNL

Xiaorong Wang\textsuperscript{a}, Stephen A. Gourlay\textsuperscript{a}, Hugh Higley\textsuperscript{a}, Mariusz Juchno\textsuperscript{a}, Soren O. Prestemon\textsuperscript{a}, Danko van der Laan\textsuperscript{b}, Jeremy D. Weiss\textsuperscript{b}

\textsuperscript{a}Lawrence Berkeley National Laboratory, Berkeley, U.S.A.
\textsuperscript{b}Advanced Conductor Technologies LLC, Boulder, U.S.A.

*Corresponding author: xrwang@lbl.gov

Lawrence Berkeley National Laboratory, together with the collaborators, is developing REBCO magnet technology for high-field fusion and accelerator magnet applications. Here we present the status of technology development, the challenges and plans to address them. The first part will focus on the recent test results of REBCO dipole magnets highlighting the implications for fusion magnet technology. The second part will present the preliminary electromagnetic and mechanical analysis of a high-current fusion cable layout made of CORC\textsuperscript{®} wires. In particular, we will discuss the impact of magnetic field and transverse compressive load on the strands in the fusion cable design.

Acknowledgment: The work is supported by the U.S. Department of Energy under contracts DE-SC0015775 and DE-SC0018125. The work at LBNL was also supported by the Director, Office of Science, Office of High Energy Physics, Office of Fusion Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.
A scalable quench analysis model for high temperature superconducting fusion magnets

Yuhu Zhai

Princeton Plasma Physics Laboratory, Princeton, New Jersey

Corresponding author: yzhai@pppl.gov

Princeton Plasma Physics Laboratory is currently performing design studies of Fusion Nuclear Science Facility (FNSF) and pilot plants based on the promising magnetic confinement configurations including the low aspect ratio Spherical Tokamaks (ST). An innovative magnet design approach is needed to close the gap between rapid advances in High Temperature Superconductor (HTS) and the fusion energy extraction from ITER-like burning plasma development. Significant performance improvement in HTS utilizing a stack of REBCO tapes provides opportunities to support design consideration of low aspect ratio spherical tokamak pilot plants. To this end, a scalable quench analysis model of pancake YBCO coils is presented for a compact central solenoid (CS) design for the HTS ST-FNSF magnet system. The model includes multi-physics solvers of EM, thermal and circuit coupled problem for HTS pancake coils. For the CS coil, a series of pancake YBCO coils with metal insulations are designed to meet the physics requirements of magnetic flux swing in facilitating initial plasma operation.
Research Work on High Field Superconductor and Magnet in ASIPP

Yuntao Song\textsuperscript{a}, Kun Lu\textsuperscript{a}, Yixiang Xing\textsuperscript{b}, Bing Zhou\textsuperscript{b}

\textsuperscript{a}Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China  
\textsuperscript{b}Hefei CAS Ion Medical and Technical Devices Co., Ltd, Hefei, China

*Corresponding author : songyt@ipp.ac.cn

ASIPP is an important base of China’s nuclear fusion research. It has established and operated four-generation tokamak experimental facilities and made a series of achievements in the physical experiments. We actively participate in ITER project, undertaking PAs successively such as conductors, correction coils, feeder system and ITER PF6 coil. In the past years, ASIPP develop some key technology of high temperature superconducting coils and conductor. Firstly, 90 kA high temperature superconducting current lead was successfully carried out and such type of HTS current leads were provided to ITER feeder, NICA project in Russia. CS coil test work in GA and so on. Besides, ASIPP cooperate with Russia and work together on the HTS SMES design work, a module coil was successfully tested in ASIPP which is made of YBCO tapes. In now stage, both sides work together on the 1 MJ HTS SMES design work. In addition, high temperature superconducting coils design work was carried out for CFETR project. In order to save the space for blanket system and get much high flux, high temperature superconducting Bi-2212 magnet with better current carrying performance under high field is supposed to be employed for CS coils of CFETR. Bi-2212 CICC conductor sample was tested at 4.2 K with critical current of 26.6 kA under its self-field. In addition, ASIPP focuses on stability study of the insert HTS coil whose conductor works under a peak magnetic field of 17T and the maximum operating current of each turn is 50kA. The simulation based on a 1-D simplified model is performed using the code THEA (Thermal Hydraulic and Electric Analysis of Superconducting cable). Finally, the effect of AC loss during current ramp-up is simplified as a perturbation with uniform power along the overall cable. ASIPP have developed the multi-scale modelling method to solve electromagnetic quantities of HTS coils. Through the validation of a double-pancake coil between the multi-scale model and the conventional model, the high accuracy and high efficiency of the multi-scale modelling method has been proved. It’s found that the differences in ac losses between multi-scale models and conventional models are only around 1%. While compared with the conventional models, the multi-scale models speed up simulations significantly by 2 orders of magnitude.
Study on HTS Conductor Application in Action Plan towards Fusion DEMO

Arata Nishimura*

*National Institute for Fusion Science, Rokkasyo, Japan

*Corresponding author: nishi-a@nifs.ac.jp

In Japan, the new structure on fusion research and development has been established in 2015 under the MEXT. The science and technology committee on fusion energy was formed to discuss and make decision of the research promotion for fusion and construction of a Roadmap towards DEMO. Under the committee, the Task Force on DEMO comprehensive strategy was organized to promote the understanding and coordination of element technologies and optimization of integrated strategy including development of an Action Plan towards DEMO. At the same time, the Joint Special Design Team was established at Rokkasyo Institute of National Institute for Quantum and Radiological Science and Technology. The team has been expected to implement the fusion DEMO design and other activities related to the fusion DEMO construction.

To summarize the items to be solved and to be performed during the fusion DEMO design, the Action Plan was composed in 2017 for each individual component, such as magnet, blanket, diverter, plasma heating device and so on, together with the plan of the fusion DEMO design. The Action Plan shows a rough schedule of the component design and there are two Check and Review points before the final decision making to move to the construction of the fusion DEMO. The first Check and Review point is expected in around 2020 and the second one is in around 2025. These points will be shifted depending on the progress of the JT-60SA and ITER constructions.

In case of the magnet, four main categories are defined, i.e. SC design, SC conductor and coil tests, High strength structural materials and radiation-proof insulation materials, Related Balance of Plant (cryogenics and coil power supplies).

As for the SC conductor, it is clear that Nb3Sn and NbTi are the candidates considering the ITER design activities. However, the HTS conductors are also considerable ones for their excellent superconducting properties especially in high magnetic field.

In this paper, the Action Plan of the magnet will be introduced together with the expected activity schedules and the possible application of the HTS conductor for the fusion DEMO will be discussed.
Status and Recent Development of HTS Strand with Quasi-isotropic Critical Current

Yinshun Wang*

the State Key Laboratory for Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China

*Corresponding author: yswang@ncepu.edu.cn

Although the Second-generation high-temperature superconducting (2G HTS) tape is attractive interesting in transmission at low magnetic field and liquid nitrogen temperature or high-field application at low temperatures due to their excellent critical current density and mechanical performance, its critical current density has strong anisotropy in particularly at liquid nitrogen temperature. On the other hand, the cable or strand consisting of multi-tapes connected in parallel is essential since the single tape has limited capacity of carrying current. In recent several years, several cables, such as Roebel cable, CORC cable, TSTC cable, TS cable, HTS-CroCo cable, were proposed. This talk outlines a type of HTS strand made from 2G HTS tapes and progress on its design and actual development in last five years. The quasi-isotropic critical current is experimentally confirmed at liquid nitrogen temperature, mechanical characteristic, AC losses, thermal stability, quench characterization are researched. Finally, the feasible process for the production of practical length of such strand is described, which is promising for applications of high fields or power transmission.
A Cable-in-conduit-conductor Made from HTS Quasi-isotropic Strands

Shaotao Dai*  

*aSchool of Electrical Engineering, Beijing Jiaotong University, Beijing, China  

*Corresponding author : stdai@bjtu.edu.cn

Due to its high magnetic field performance and mechanical characteristics, the second generation high-temperature superconducting (2G HTS) tape is promising in ultra-magnetic field magnet, large-scale magnet and transmission cable with low-inductance. However, the single tape has limited current carrying capacity, the cable consisting of parallel-connected 2G HTS tapes is necessary for high current application. In recent decade, several cables made from second-generation high temperature superconductor (HTS) REBCO tapes, such as Roebel cable, CORC, TSTC, RS, HTS CroCo and QI-S cable types were suggested and made important progress.

In this talk, we proposed a novel type of a cable-in-conduit-conductor (CICC) consisting of 8 quasi-isotropic strands by stacked HTS tape arrangement with geometrical symmetry, aiming for high engineering critical current densities and high current carrying capacity. The critical current and its anisotropic characteristics were simulated based on the dependence of critical current on magnetic field distribution in single 2G HTS tape, and thermal behaviors of the CICC were analyzed.

The results demonstrate that the CICC has approximately anisotropic critical current and high thermal stability, may have potential application for high-field magnet applications.
Overview of the Twisted Stacked-Tape Cable Conductor

M. Takayasua\textsuperscript{a}\textsuperscript{*}, L. Chiesa\textsuperscript{b}, and J.V. Minervini\textsuperscript{a}

\textsuperscript{a}MIT, PSFC, Cambridge, MA, USA
\textsuperscript{b}Tufts University, ME, Medford, MA, USA

Corresponding author: takayasu@psfc.mit.edu

One of the HTS flat-tape cabling methods, Twisted Stacked-Tape Cable (TSTC) has been developed for REBCO and BSCCO tapes. The TSTC method consists of a stack of flat tapes twisted along the axis of the stack. The cabling method has various advantages; simple cabling, compact cabling, high current density, high tape usage, good bendability, and good mechanical handling.

The HTS TSTC cabling method can provide a high field, high current cabled conductor for high field magnet applications. It is very useful, particularly for high-field fusion magnets requiring high-current cables such as Cable-in-Conduit Conductor (CICC). The conductor could be useful for other applications, such as high-field accelerator machines, and also other superconducting electric machines and power-transmission cables.

We have investigated the characteristics of a TSTC conductor consisting of twisted flat tapes. TSTC conductors of REBCO tapes have been fabricated with several different methods, including sheathing the tape stack with copper strips and embedding the stack in single and multiple helical grooves machined on a circular rod. The cables fabricated with those methods have been tested in liquid nitrogen and liquid helium. The twisted tape behavior of single tapes and TSTC conductor performance have been investigated both analytically and experimentally. Bendability of a TSTC conductor has been also evaluated. Based on the experience gathered during the fabrication process and theoretical analysis of a TSTC conductor, we will discuss the characteristics of a TSTC conductor including its fabrication and electric termination methods. Advances in TSTC conductors will also be discussed.

Acknowledgements -This work was supported by the U. S. Department of Energy, Office of Fusion Energy Science under Grants: DE-FC02-93ER54186. A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by NSF, the State of Florida and the DOE.
Properties and improvements of commercial HTS wires using an e-beam PVD process

Markus Bauer*, Veit Große, Raphaela Burzler, Eike Janocha

THEVA Dünnschichttechnik GmbH, Ismaning, Germany

*Corresponding author: bauer@theva.com

HTS wires for fusion applications can be manufactured using many different architectures and methods. One approach is to use MgO buffer layers made by inclined substrate deposition on metal substrates and vapor deposited GdBaCuO films. Recent progress in manufacturing technology at our company resulted in Ic values above 500 A/cm on several 100 m long tapes which now can be produced in a pilot production line. On short samples it was already shown that even 1000 A/cm can be reached with this type of conductor [1]. Results of normal production tapes will be shown and further possible improvements discussed.

For any real applications in fusion as well as other areas, the tapes have to be stabilized by an additional layer of copper e.g. using electroplating. This additional copper layer also serves as a chemical and mechanical protection during coil winding and soldering processes.

In addition to the critical current, several further requirements must be considered if HTS wires shall be used in an application like a fusion reactor:

One mayor demand is that the additional copper has a uniform thickness. Any so-called dog boning at the edges is to be avoided as it will decrease the packing density and lead to possible voids in coils and cables made of stacked conductors. We will show our recent progress with copper plated conductors towards a smaller thickness variation.

Also, the influence of a heat treatment e.g. during a soldering process must be considered in order to avoid any degradation during the later processing. We measured the Ic degradation during a heat treatment with typical soldering temperatures to determine the influence on the properties.

Further requirements are stress and strain tolerance or bending radius which also will be discussed for our conductors.

Status of 2G HTS Wire Production at SuperOx

Alexander Molodyk*

SuperOx, Moscow, Russia

*Corresponding author : a.molodyk@superox.ru

This talk will review the status of 2G HTS wire production at SuperOx, with an emphasis on features relevant to wire application in fusion.

In response to the increased demand on 2G HTS wire, both external and internal, the SuperOx group of companies doubled the production of wire in 2017. This was accomplished by installing new PLD HTS facility in Moscow, in addition to the existing similar facility in Japan, which remained in operation. Wire produced at both locations is of identical high quality.

Each unit of production reel-to-reel equipment at every stage of the wire fabrication route is capable of handling one- to a few kilometre-long pieces of tape. Typical lengths of continuous pieces of finished wire that come out of production are 200, 300, and 400 m.

An in-line quality management system, especially important at the early fabrication stages such as substrate preparation and buffer layer deposition, ensures high yield of finished wire and helps reduce cost by eliminating defective pieces of tape from further processing.

An industrial R&D programme is ongoing aimed at improving the wire performance in magnetic field by introducing perovskite artificial pinning centres into the HTS layer. Up to 80% improvement of $I_c$ in field has already been achieved. In Phase II of the programme, we will optimise pinning for specific temperature and field conditions and, most importantly, verify the reproducibility of the enhancements in multiple production runs.
Development of High Performance Coated Conductors for Fusion Applications

Teruo Izumi\textsuperscript{a*}, Takato Machi\textsuperscript{a}, Akira Ibi\textsuperscript{a}, Koichi Nakaoka\textsuperscript{a}, Takeharu Kato\textsuperscript{b}, Yutaka Yoshida\textsuperscript{c}, Takanobu Kiss\textsuperscript{d}, Masataka Iwakuma\textsuperscript{e}, Tatsunori Okada\textsuperscript{e}, Satoshi Awaji\textsuperscript{e}, Nagato Yanagi\textsuperscript{f}

\textsuperscript{a}Advanced Industrial Science and Technology, Tsukuba, Japan
\textsuperscript{b}Japan Fine Ceramics Center, Nagoya, Japan
\textsuperscript{c}Nagoya University, Nagoya, Japan
\textsuperscript{d}Kyushu University, Fukuoka, Japan
\textsuperscript{e}Tohoku University, Sendai, Japan
\textsuperscript{f}National Institute for Fusion Science, Toki, Japan

\*Teruo Izumi : teruo.izumi@aist.go.jp

REBCO coated conductors (CCs) has high potentials such as high in-field performance, high mechanical strength, low AC loss. Some of them are considered to be effective for fusion applications. Concerning the development of in-field performance CCs, it is known that the APC (Artificial Pinning Centers) introduction is valid to improve in-field \(J_c/I_c\) performance. The continuous progress has been taken place in PLD process. Here, the effective combination of EuBa\(_2\)Cu\(_3\)O\(_y\) (superconducting phase) and BaHfO\(_3\) (APC material) was found to be effective for high \(J_c/I_c\) even in thick film. As a typical \(I_c\) value, a 569 A/cm-w at 65 K under 3 T (\(B//c\)) was obtained in the 3.6 \(\mu\)m thick film [1]. On the other hand, the breakthrough for this field was recently made in the cost effective TFA-MOD process. In our conventional TFA-MOD process, the multi-coating & calcination process has been employed to form thick precursor films. In the new process, a thickness of once coating film (\(d_{once}\)) was made thinner comparing to the conventional condition (e.g. 170 nm), which is called as UTOC (Ultra-Thin Once Coating)-MOD. For example, the \((Y,Gd)Ba_2Cu_3O_y+BaZrO_3\) film fabricated by the \(d_{once}\) condition of 30 nm revealed double \(J_c(B)\) value at 65 K under 3 T, which is comparable to \(J_c(B)\) performance of PLD films [2]. Furthermore, the \(J_c(B)\) performance was improved by the replacement of APC from BaZrO\(_3\) to BaHfO\(_3\) and heavier doping to 12 vol\%. As a result, an extremely high \(J_c\) value of 4 MA/cm\(^2\) at 65 K under 3T (\(B//c\)) was realized. The film also showed high \(J_c(B)\) over 10 MA/cm\(^2\) at 26 K under 6T, which is applicable to the fusion applications [3].

On the technology for lowering AC loss, the filamentation structure has been known as effective. The several kinds of scribing techniques have been developed and the latest scribing method using excimer laser has several advantages such as thin slot width with high machining accuracy and high mechanical strength [4]. Then, the scribing into 10-filaments in 5 mm wide tape was successfully taken place and the 1/10 reduction of AC loss was confirmed. Additionally, the AC loss reduction even in the coil with scribed tapes was also made sure, which is only one in the world [5].

Recently, the above technologies of high in-field performance and filamentation have been combined and the other related technologies such as joint technique have been progressed. A part of this work was supported by NEDO, AMED and METI.

Effect of artificial pinning centers on the fluence dependence of critical currents in neutron irradiated coated conductor tapes

David X Fischer*, Rainer Prokopec, Michael Eisterer

Atominsitut, TU Wien, Vienna, Austria

*Corresponding author: david.fischer@tuwien.ac.at

In view of the ongoing climate change, it is an extremely worthwhile yet highly ambitious endeavor to use nuclear fusion as energy source in a power plant. Advances in technology however bring it within reach. In a fusion reactor, the high magnetic fields required to confine the fusion plasma have to be generated by superconducting magnets which are subjected to neutron radiation. Because even though the neutrons, released in the deuterium-tritium process, scatter at the blanket and mostly are stopped there, a small but relevant fraction reaches the magnet coils. There they alter the microstructure of the superconductor and change its properties. It is necessarily to know about these effects in advance, therefore irradiation studies were performed at the research fission reactor at Atominstitut.

While current plans for fusion reactors envisage conventional superconductors for the magnet coils, high temperature superconductors might be the material of choice in the future. Coated conductors are the most obvious candidates at the moment because of their favorable physical properties and their relative maturity. One main focus in their development is the optimization of flux pinning by including nanoparticles as artificial pinning centers (APCs).

Tapes of several commercial manufacturers were irradiated to fast neutron fluences of up to 3.9x10^{23} m^{-2} and characterized in this study. It was found that the presence of APCs influences the radiation resistance of the coated conductors. Tapes with APCs degrade at lower neutron fluences than tapes without them. This can be explained by the higher overall defect density which exceeds the optimal value earlier.
Furthermore, differences in the normalized pinning force curves of tapes with and without APCs vanish after irradiation suggesting that the radiation induced defects become the dominant pinning mechanism.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

We want to thank the manufacturers AMSC, SuNAM and SuperPower for providing us with samples of their coated conductor tapes.
Electric Field vs. Current Density Characteristics in REBCO Coated Conductor over Wide Range of Electric Fields Including Flux Creep and Flux Flow Regimes

Yuta Onodera\textsuperscript{a*}, Kazutaka Imamura\textsuperscript{a}, Takumi Suzuki\textsuperscript{a}, Kohei Higashikawa\textsuperscript{a}, Masayoshi Inoue\textsuperscript{a}, Akira Ibi\textsuperscript{b}, Takato Machi\textsuperscript{b}, Teruo Izumi\textsuperscript{b}, Takanobu Kiss\textsuperscript{a}

\textsuperscript{a}Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan.
\textsuperscript{b}AIST, 1-3-1 Kasumigaseki, Chiyoda-ku, Tokyo 100-8921 Japan

*Corresponding author : y.onodera@super.ees.kyushu-u.ac.jp

To design a superconductor based device, in-field critical current density ($J_c$) is one of the most important material properties. $J_c$ is usually characterized by four-probe transport measurement or magnetization measurement. These transport- and magnetization-$J_c$, however, show significant discrepancy in HTS tapes especially under in-field conditions whereas reasonable agreement was obtained in LTS. This mainly comes from the difference of electric field criterion in these two methods and the influence of rounded electric field vs. current density ($E$-$J$) characteristics in HTS. In the LTS, the transition from the zero resistance state (flux pinning state) to the flux flow state is very steep, and its $E$-$J$ characteristic shows a steep rise from $J_c$. This indicates that the $J_c$ is almost constant regardless the electric field. On the other hand, in the HTS, it is strongly influenced by local disorder and thermal fluctuation because of short coherence length. As a result, the transition to the flux flow state becomes broad. Namely, the $E$-$J$ characteristic shows rounded shape. Electric field criterion ($E_c$) of the four probe transport method is typically $10^{-4}$ V/m while $E_c$ in the DC magnetization measurement is several orders smaller. It is also important to understand the nonlinear characteristic in the low electric field region from practical point of view since superconducting devices such as magnet is usually operated with an operation current density smaller than $J_c$.

In this study, we have succeeded in measuring $E$-$J$ characteristic in REBCO coated conductor by using four probe transport method and magnetization relaxation method to cover wide range of electric fields over 8 decades from $10^{-2}$ down to $10^{-10}$ V/m. Experimental results were also analyzed within the framework of percolation transition model taking into account local $J_c$ distribution and flux creep [1]. We found the experimental results can be expressed well by the theoretical analysis.


Acknowledgements: This work was supported by “JSPS KAKENHI (JP16H02334)” and “NEDO".
Influence of critical current fluctuations on the test results of short sample, cable and coil from HTS CC tape

Fedor Gömöry*, Miroslav Adámek

Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 84104 Bratislava, Slovakia

*Corresponding author: elekgomo@savba.sk

Critical current fluctuating along the length of conductor is a common feature of commercially available HTS coated conductor tapes prepared by an industrial process. In spite of the effort dedicated to suppress this unwanted phenomenon it remains the reality that should be in a plausible way incorporated in the tape characterization and in the design of devices.

Aim of the submitted presentation is to start the debate about an efficient approach of handling this issue. Results of statistical analyses will be presented showing the influence of fluctuations – in particular the standard deviation of a Gaussian distribution of critical currents – on the value of critical current determined on samples of various lengths. Repercussions of the statistical distribution parameters on the critical current of a hypothetical superconducting cable where all the tapes are fully transposed and on a superconducting coil with rather different exposition of the tapes placed in various parts of the winding will be discussed as well.
Study on YBCO stack-in-channel Conductor

Huajun Liu\textsuperscript{a*}, Yi Shi\textsuperscript{a*}, Fang Liu\textsuperscript{a}, Xintao Zhang, Jinggang Qin, Zhuyong Li\textsuperscript{b}

\textsuperscript{a}Institute of Plasma Physics, Chinese Academy of Sciences., Hefei, China
\textsuperscript{b}Shanghai Jiao Tong University, Shanghai, China

\textsuperscript{*Corresponding author : liuhj@ipp.ac.cn, shiyi@ipp.ac.cn}

One of the advantages of YBCO tape conductor is that a high Jc value can be obtained in high magnetic field. Various techniques have been developed to assemble the coated conductor tapes into high current conductor. A method has been developed in ASIPP. The small size YBCO tapes were stacked into rectangular structure (1mm×1mm and 2mm×2mm). The stacked YBCO tapes was inserted into a cooper channel and soldered together. The advantages of this structure conductor include: the copper content can be increased; it is easy to be cabled to CIC conductor or Rutherford cable for the round section. The critical current properties of YBCO stack-in-channel conductor were tested in LN2 and LHe temperature under magnetic field.
Electromagnetic loss characterization of sock-woven HTS cable

Guy Dubuis\textsuperscript{a,b}, Zhenan Jiang\textsuperscript{a}, and Nicholas J Long\textsuperscript{a*}

\textsuperscript{a}Robinson Research Institute, Victoria University of Wellington, Lower Hutt, New Zealand
\textsuperscript{b}The MacDiarmid Institute for Advanced Materials and Nanotechnology, Wellington, New Zealand

*Corresponding author: Nick.Long@vuw.ac.nz

We present a new way of sock-weaving an HTS cable out of HTS coated conductor tapes in a manner that all strands are fully electromagnetically transposed. The cable assembly differs from existing HTS cables such as Roebel or Corc\textsuperscript{TM} in a few key aspects. In particular, this construction does not need any complex cutout or punching, and thus the strands are not mechanically weakened. This also means that there is no wastage of material. The cable can also be designed so as to minimize the magnetic field at its core. This cable assembly also offers a few advantages in terms of flexibility and is self-supporting. Possible applications would be flexible AC cryogenic current leads and low AC-loss superconducting electromagnets. It is an adaptation of a braiding concept developed for Nb\textsubscript{3}Sn wire to coated conductors.[1] This concept of cable assembly is not dependent on the type of coated conductor used.

Here we present measurements of transport loss characteristics of a set of samples with different weaving patterns. In particular, we are interested by the superior performance in AC-loss and magnetization loss of this cable. On top of these loss characteristics, our experiments show a good performance under mechanical stress. This suggest that a sock-woven cable has a niche role to play for future industrial applications of HTS technologies.

Development of 100 kA high-temperature superconducting Cable in Conduit Conductors from CORC® cables and wires

D.C. van der Laan\textsuperscript{1}, J.D. Weiss\textsuperscript{1}, D. McRae\textsuperscript{2}, X. Wang\textsuperscript{3}, H. Higley\textsuperscript{3}, S. O. Prestemon\textsuperscript{3}, L. Bromberg\textsuperscript{4}, P. Michael\textsuperscript{4}, T. Mulder\textsuperscript{5} and H.H.J. ten Kate\textsuperscript{5}

\textsuperscript{1} Advanced Conductor Technologies LLC, Boulder, CO 80301, U.S.A and the Department of Physics, University of Colorado, Boulder, CO 80309, U.S.A
\textsuperscript{2} Department of Physics, University of Colorado, Boulder, CO 80309, U.S.A
\textsuperscript{3} Lawrence Berkeley National Laboratory, Berkeley, CA 94720, U.S.A.
\textsuperscript{4} Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA, U.S.A.
\textsuperscript{5} CERN, Geneva, Switzerland and the University of Twente, Enschede, the Netherlands

Compact fusion machines require magnets that operate at high currents in fields as high as 20 T and potentially at elevated temperatures. These magnets require high-temperature superconducting cables that operate at currents as high as 100 kA in fields of 12-20 T. Advanced Conductor Technologies is developing Conductor on Round Core (CORC\textsuperscript{®}) cables and wires wound from REBCO coated conductors for use in high-field accelerator and fusion magnets. These conductors can be configured into Cable in Conduit Conductor (CICC) configurations that have the potential of reaching 100 kA at 20 T, while allowing the CICC to have a high level of strand transposition and flexibility.

An overview of the current status of CORC\textsuperscript{®} cables and wires will be presented, including their in-field performance measured at 4.2 K up to 12 T. Different CORC\textsuperscript{®}-CICC layouts, such as a 6-around-1 configuration based on CORC\textsuperscript{®} cables, or a bundle of as many as 20 CORC\textsuperscript{®} wires, will be outlined. Their performance at fields as high as 20 T will be estimated based on the individual CORC\textsuperscript{®} cable or wire performance. Design considerations that take into account the high transverse stresses on the conductors in the CORC\textsuperscript{®}-CICC, and to achieve a relatively high level of cable bending flexibility will be discussed. Finally, an overview of the current status of CORC\textsuperscript{®}-CICC development, including the recent test of a 80 kA CORC\textsuperscript{®}-CICC in SULTAN will be presented.

Acknowledgement
This work was in part supported by the US Department of Energy under agreement numbers DE-SC0007891, DE-SC0007660, DE-SC0009545, DE-SC0014009, DE-SC0015775 and DE-SC0018125.
Mechanical stability of HTS CroCos and structure material boundaries

Klaus-Peter Weiss*, Nadezda Bagrets, Walter H. Fietz, Reinhard Heller, Jan Sas, Thomas Vogel, and Michael J. Wolf

Karlsruhe Institute of Technology, PO Box 3640, 76021 Karlsruhe, Germany

*Corresponding author: klaus.weiss@kit.edu

During the past years all engineering fields developing fusion technology to allow building a device like ITER or W7-X were pushed to the limits. Now as the production of components for ITER is on-going, solutions for the next generation of fusion reactors are in the focus. Especially the cryogenic components of the superconducting magnets are crucial, as they are exerted to the Lorentz forces at the operating magnetic field up to about 12T.

The superconducting cable is a key component that has to be examined under such conditions to ensure a safe operation of the magnets. Beside of using established low temperature Nb3Sn or NbTi superconducting wires to design high current cables, the high temperature superconductor (HTS) REBaCuO coated conductor is a possible candidate to build such cables.

In this work the performance of a so-called HTS Cross-Conductor (Cro-Co) assembled as a soldered stack of coated conductors [1] is investigated under mechanical loading in axial and transversal direction at cryogenic temperatures. The possible scaling from single coated conductor mechanical behavior up to the stacked Cro-Co is considered.

The Lorentz forces that are produced within the superconducting cables of a winding pack need to be balanced by the structural material within a coil. Therefore, the overall mechanical parameters of the jacket, insulation and casing material imply a boundary to the magnet design in addition to the performance of the superconducting cable and are highlighted in this work.

Electromechanical Behaviour of High Temperature Superconducting Tapes and High-Current Cables for Fusion Applications

Federica Pierro\textsuperscript{a*}, Zijia Zhao\textsuperscript{a}, Luisa Chiesa\textsuperscript{a}, Makoto Takayasu\textsuperscript{b}, Xiaorong Wang\textsuperscript{c} and Soren Prestemon\textsuperscript{c}

\textsuperscript{a}Tufts University, Medford, USA  
\textsuperscript{b}MIT, Cambridge, USA  
\textsuperscript{c}Lawrence Berkeley National Laboratory, Berkeley, USA  

*Corresponding author: federica.pierro@tufts.edu

Rare-Earth-Barium-Copper-Oxide (REBCO) has high current and high field capabilities which makes them promising conductors for high-current cables to be used in future high-field fusion machines. The current-carrying capability of the superconducting tapes under mechanical loads is an important aspect to consider during cable design as the conductor must withstand large electromagnetic loads during the operations of high-field magnets in a fusion reactor.

Experiments on single REBCO tapes with 30 μm substrate developed by SuperPower were performed to characterize their electrical behaviour under both tension and compression in conditions relevant to fusion applications: high fields (10 T to 15 T) and different temperatures (4.2 K to 35 K). In addition, a model of the Twisted Stacked-Tape Cable (TSTC) was developed using structural finite element analysis to investigate the effect of Lorentz loads generated during high-current and high-field operations. The strain results obtained from the simulation were combined with the experimental findings on a single tape to evaluate the electromechanical performance of a Twisted Stacked-Tape Cable and provided useful insights for cable design options.
Properties of HTS Cable-In-Conduit Conductor with Al-Slotted Core under bending stress

Giuseppe Celentano\textsuperscript{a,*}, Gianluca De Marzi\textsuperscript{a}, Marcello Marchetti\textsuperscript{a}, Angelo Vannozzi\textsuperscript{a}, Giordano Tomassetti\textsuperscript{a}, Luigi Muzzi\textsuperscript{a,b}, and Antonio della Corte\textsuperscript{a}

\textsuperscript{a}ENEA Frascati Research Center – FSN Department, Frascati, Italy
\textsuperscript{b}ICAS, Frascati, Italy

*Corresponding author: giuseppe.celentano@enea.it

Aluminum based conductor has been proposed for the development of 2G High Temperature Superconductor (HTS) tapes high current cable for fusion applications. In the proposed layout HTS tapes are stacked and inserted into helical ducts formed in an extruded Aluminum cylindrical core mostly studied in the 5-slots configuration (5 \times 20 tapes – or 5 \times 30, depending on tape thickness). The cable layout, designed aiming at the industrial feasibility of the manufacturing process, has shown promising electrical, thermo-hydraulic and mechanical properties assessed in several experimental studies of cable samples [1, 2, 3, 4]. As far as bending behavior is concerned, it has been observed that the cable exhibited a rather good tolerance to bending strain ascribed to the slippage occurring among tapes within the stack. However, this feature, particularly relevant for applications, needed more studies.

In the present contribution, we report on the experimental results on bending tests on Al-slotted cable sample, which was equipped with a fully superconducting stack of tapes. The sample was 1 m long and the stack consists of 20 coated conductor tapes having a twist pitch of 0.5 m. The remaining 4 slots have been equipped with stainless-steel dummy tapes. The bending experiment was carried out through a series of measurements of single tape critical current $I_c$ obtained at fixed bending radius $R_b$, the smallest radius reached being 0.15 m. By the analysis of the $I_c$ dependence as a function of $R_b$ for each tape the effect of bending strain as a function of the tape position inside the stack was investigated. The results confirmed the good bending strain tolerance of the cable. Interestingly, the most external tapes of the stack (either innermost or outermost with respect to the core central axis) exhibited the higher $I_c$ degradation starting at $R_b \approx 0.250 - 0.275$ m. On the other hand, the tapes in the central section of the stack showed a slight but measurable increase of $I_c$ with bending strain with respect to the straight condition. The whole cable behavior upon bending is explained considering a simple analytical model from which it resulted that the current sharing mechanisms occurring among the tapes within the stack play a relevant role.

The CORC cable is composed of several layers of helically wound HTS tapes on a round core with the winding direction reversed in each successive layer. The cable is flexible but the flexibility is limited by the critical strain value when causing breakage of the HTS layer. The cables for magnets in fusion reactors experience large mechanical and electromagnetic loads arising from cabled conductor and coil manufacturing to cooling and operation of the magnet. In order to optimize the manufacture and operating conditions, the mechanical behavior of CORC cable must be understood for different relevant manufacturing and loading conditions. The complex configuration with many contact interactions between tapes and the non-linear behavior of the materials during the production and operation conditions requires the use of finite element (FE) modeling. The FE modeling will allow an accurate calculation of the stress-strain state of the cable components under various loads and importantly; avoiding large-scale and expensive experimental optimization studies.

This work presents the results of experimental tests and detailed FE modeling of the 3D stress-strain state in a CORC cable under bending load, taking the temperature dependence and the elastic-plastic properties of the individual tape materials into account, starting from the initial tape processing conditions during its manufacture up to magnet operating conditions [1]. Furthermore a comparison of the simulations with experiments is presented with special attention for the critical force, the threshold where the individual tape performance becomes irreversibly degraded.

The FE model appears to describe the bending test of the CORC cable adequately and thus can be used to study other types of loads, parametric research of dependent variables and optimization of the CORC cable design.

Sample preparation for electro-mechanical measurements of mechanical lap joint of 10-kA-class prototype HTS STARS conductors

Satoshi Ito\textsuperscript{a}, Tatsuki Nishio\textsuperscript{a}, Ryoichiro Hayasaka\textsuperscript{a}, Luis E. Aparicio\textsuperscript{a}, Nagato Yanagi\textsuperscript{b}, Yoshiro Terazaki\textsuperscript{b}, Nadezda Bagrets\textsuperscript{c}, Michael J. Wolf\textsuperscript{c}, Hitoshi Tamura\textsuperscript{b}, Klaus-Peter Weiss\textsuperscript{c}, Hidetoshi Hashziume\textsuperscript{a}, Akio Sagara\textsuperscript{b}, Reinhard Heller\textsuperscript{c}, Walter H. Fietz\textsuperscript{c}

\textsuperscript{a}Dept. Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, Sendai, Japan
\textsuperscript{b}National Institute for Fusion Science, Toki, Japan
\textsuperscript{c}Institute for Technical Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany

*Corresponding author: satoshi.ito@qse.tohoku.ac.jp

The LHD-type helical fusion reactor, FFHR, designed by National Institute for Fusion Science, adopts the segment-fabrication for its helical coils as the challenging option [1]. The fabrication method is called "joint-winding", in which the HTS helical coils are wound by connecting Stacked Tapes Assembled in Rigid Structure (STARS) conductors with an appropriate length [2]. The STARS conductor consists of simply stacked rare-earth barium copper oxide (REBCO) tapes embedded in copper and stainless steel jackets with internal insulation. At the joint section, REBCO tapes are connected by bridge-type mechanical lap joint, developed by Tohoku University [2,3], in which indium foils are inserted between joint surfaces, then the copper jacket and insulator are set, and the stainless steel jackets are welded. Our previous study [3] successfully achieved a joint resistance of 1.8 nΩ using a 100-kA-class prototype STARS conductor joint at 4.2 K, and showed that the joint has sufficiently large tensile strength using mechanical lap joints at 77 K, self field. Our next target is to achieve sufficiently large tensile strength for STARS conductor joint at lower temperature and higher magnetic field.

Based on the aforementioned background, we plan to perform electro-mechanical measurements of the joint by means of the FBI (F: force, B: magnetic field, I: current) measurement facility [4] at a temperature of 4.2 K, a DC current up to 10 kA, a magnetic field of up to 12 T and a tensile force up to 100 kN. The prepared joint was a mechanical lap joint of a 10-kA-class STARS conductor with a cross-sectional diameter of 20 mm was fabricated. The conductor had five layers of 12-mm-wide copper stabilized REBCO tapes and each layer is connected by the mechanical lap joint with an indium foil with a joint length of 15 mm. The stacks were embedded in a copper jacket, glass-fiber-reinforced plastics layer, and a stainless steel pipe. Design, fabrication, critical current measurement at 77 K, and tensile test up to 10 kN at room temperature of the joint were performed at Tohoku University as pre-evaluations before the joint is transported to Karlsruhe Institute of Technology. The details of the results will be presented at the workshop.

High-temperature superconductors (HTS) are promising candidates for use in the high-field magnets needed in thermal nuclear fusion reactors. Their high critical temperatures allow them to operate at temperatures far above 4 K and ease requirements on nuclear heat generation and heating during ramping of the magnetic field. Other benefits compared to low-temperature superconductors include higher mechanical strength and the possibility to operate at high magnetic fields, exceeding 16 T. Advanced Conductor Technologies is developing HTS Conductor on Round Core (CORC®) cables and wires wound from ReBa2Cu3O7-x (ReBCO) coated tapes, for use in high-field magnet applications. HTS cables can enable demountable fusion magnets that would allow easier access to the fusion experiment for maintenance and parts replacement. CORC® cables are also developed for fusion magnets operating at currents in excess of 80 kA, requiring them to be bundled into a cable-in-conduit conductor (CICC) configuration. Major technical challenges to the use of ReBCO coated conductors in fusion magnets include the need for high-current capacity magnet cables and practical, low-resistance cable joints, capable of injecting current uniformly into the many tape layers that make up the cables. Optimization steps on CORC® cables have resulted in high-current terminations that have a significantly improved contact resistance with even current injection at high ramp rates exceeding 6 kA/s. Several individual joints were constructed and tested in liquid nitrogen and liquid helium to currents up to 9,000 A with contact resistances as low as 96 nΩ at 76 K and 6 nΩ at 4 K. Schemes for bundling multiple cables together into CICC conductors are being explored to enable stable 100 kA-class joints with contact resistances of less than 1 nΩ.
Characteristics of Various Types of Ultrasonic Weld REBCO CC Joints

Hyung-Seop Shin\textsuperscript{a*}, Chan-Hoon Jung\textsuperscript{a} and Jae Hun Lee\textsuperscript{b}

\textsuperscript{a}Andong National University, Andong, 36729 Korea
\textsuperscript{b} SuNAM Co. Ltd., Anseong, Gyeonggi-do 17554, Korea

*Corresponding author: hsshin@anu.ac.kr

Recent improvements in the current density of HTS 2G coated conductors (CC) and their superior mechanical properties have driven it to high field HTS magnets and brightened the prospects of higher field fusion machines. The availability in long length CC tapes remains one of the concerns that should be considered in large-scale applications such as magnets and coils for fusion. For these applications, high performance and reliable CC joints should be established for the safe and effective operation of the superconducting devices. Having an acceptable low contact joint resistance without degradation of critical current, $I_c$ and a good adhesion will be the important characteristics of a joint method. Since various types of CC joints like lap-, butt- and bridge-structures can be considered in the fusion application, understanding the characteristics of various CC joints including mechanical controlled soldering is necessary. As a means to produce long-length high temperature superconducting wires, a practical joining technique of 2G coated conductor (CC) tapes based on an ultrasonic welding (UW) was recently developed by ANU [1, 2]. The UW CC joining technique showed a good adhesion without any damage to the superconducting film layer and with an acceptable low joint resistance, making it reliable and reproducible. We attempted to achieve a low joint resistivity through the optimization of joining parameters for UW including horn tip patterns, and the pre-Sn plating to CC tape which is equivalent to the hybrid welding (HW) which incorporates soldering to the UW. In particular, the UW technique is very effective for practical applications of CC joints because of its shorter welding time of $\sim$ 1 sec and in an easier way. The UW can be satisfactorily applicable to various joint structures of lap- and butt-, bridge-joint for Cu-stabilized CC tapes, and bridge joint for CC coils. In this study, in order to characterize the joint properties of the UW CC joints fabricated with various types of joint structures, the joint resistivity and the electromechanical properties were examined at 77 K, respectively. The electromechanical testing was performed under both loading conditions of uniaxial tension and double bending at 77 K and self-field, respectively. The irreversible tension load limit and the minimum bending diameter against the retained $I_c$ and joint resistance $R_j$ degradation for various CC joints were determined, respectively.

* This work was supported by a grant from National Research Foundation of Korea (NRF-2017-001109), funded by the Ministry of Science, ICT and Future Planning (MSIP), Republic of Korea.

References


Current transfer in superconducting tapes and devices

Nadezda Bagrets*, Rainer Nast, Klaus-Peter Weiss, Reinhard Heller

*Karlsruhe Institute of Technology, Eggenstein-Leopoldshafen, Germany

*Corresponding author: nadezda.bagrets@kit.edu

Current transfer length (CTL) and interface resistance between metallic and superconducting layers ($R_i$) are important parameters in superconducting applications. They play a crucial role in the design of current connections like joints, current leads, and current terminals.

CTL and $R_i$ are different for superconducting tapes produced by different tape manufacturers. CTL depends also on the specific layout of the superconducting tape, or, in case of superconducting device, on the layout of that device.

Moreover, CTL and $R_i$ can depend on temperature. Therefore, it is interesting to investigate the influence of temperature on these parameters, and their constancy within one batch of the superconducting tape as well.

In this presentation investigations on the temperature dependence of CTL and $R_i$ are presented. In order to demonstrate the practical importance of CTL and $R_i$, their evaluation and applicability for the design of superconducting current leads based on commercial REBCO tapes are shown.
HTS Technology for Compact Spherical Tokamaks

Robert Slade\textsuperscript{a*}, Bas van Nugteren\textsuperscript{a}

*Corresponding author: robert.slade@tokamakenergy.co.uk

Tokamak Energy are pioneering the compact spherical tokamak (ST) route to fusion power. We are developing the use of HTS to create the plasma confinement magnetic field of several Tesla needed for a fusion demonstration ST with major radius 1-2 m. We will discuss the technical challenges faced in developing HTS for a high field ST, such as cable design, joints, quench protection, cooling, and neutron irradiation. We outline potential solutions to these problems which we plan to demonstrate using a series of test magnets over the next five years.
Status of the Conceptual HTS DEMO TF-Coil Design and Progress on HTS CrossConductor Fabrication

Michael J. Wolf *, Nadezda Bagrets, Walter H. Fietz, Reinhard Heller, Thomas Vogel, and Klaus-Peter Weiss

Karlsruhe Institute of Technology, PO Box 3640, 76021 Karlsruhe, Germany

*Corresponding author: michael.wolf@kit.edu

The ongoing increase in performance of High Temperature Superconductor (HTS) Rare Earth Barium Copper Oxide (REBCO) tapes [1] makes these materials promising candidates for the magnet system of future fusion power plants, as these materials can be operated at higher magnetic fields or higher temperatures or with an increased temperature margin compared to currently used low temperature superconductors.

Over the last years, KIT established a conceptual HTS coil design of a DEMO Toroidal Field (TF) coil winding pack [2]. In this presentation, the design approach of a DEMO TF-coil layout based on HTS REBCO tapes will be introduced. This approach includes electrical and electromechanical calculations of the conductor and winding pack, thermal-hydraulic analysis, quench assessment of the winding pack and finite-element structural mechanical calculations of the coil cross-section. Our results indicate that a DEMO HTS TF coil design is feasible with today’s HTS material.

The HTS CrossConductor [3] was designed to be used as superconducting strand of this HTS conductor. Recently, critical current densities of 480 A/mm² were demonstrated at $T = 4.2$ K, $B = 12$ T. New approaches in the fabrication of longer lengths of HTS CrossConductors in the required geometries for the HTS TF coil design will be presented.

References:
The preliminary conceptual design of the D-shaped HTS coil

Li Pengyuan*, Zuo Jiaxin, Sun Linyu

Southwestern Institute of Physics, Chengdu, China

*Corresponding author: lipy@swip.ac.cn

The second generation of high temperature superconducting (2G HTS) material has a relatively high critical transition temperature (\( > 77\text{K} \)) and critical current density (\( 10^7\text{A/mm}^2, 4.2\text{K and self-field} \)), generating a powerful magnetic field which can meet the demand for the experimental fusion device. In order to explore the magnet fabrication technique for experimental fusion device, the preliminary conceptual design of D-shaped high temperature superconducting coil is introduced.

To make sure HTS coil can be applied into the fusion reactor in the future, a large size prototype coil whose width is 1.52m and height 2.11m is designed. REBCO conductor is used for the coil to get an as high current as possible. To improve its performance, the HTS conductor is wound by stack-twist method. The coil is to be cooled by cold helium gas, and the operating temperature will be 20K. The engineering current density is 34.3A/mm\(^2\), and the maximum magnetic field is about 6T. In addition, the stress distribution is analyzed by the FEA method, the maximum hoop stress focuses on the places which locate in both inside ends of straight line section of coil and the value is about 82.5MPa which is much lower than the yield force of structural component, so the coil can work safely.

To make the maintenance of the coils and inner vacuum components in the fusion device convenient, the coil adopts a demountable structure and is divided into the symmetrically upper and lower parts to allow all the upper parts of the coils can be removed as a whole in the vertical direction. The two parts of the coil are connected by a multi-stepped and demountable joint. It is analyzed that the joint resistance is less than 200 n \( \Omega /\text{cm}^2 \), the thermal power is close to 451.2W, and the heat from the joint can be taken away totally by the coolant.


Progress of the HTS magnet design for the helical fusion reactor and the next generation helical devices with the STARS conductor

Nagato Yanagi\textsuperscript{a}, Yoshiro Terazaki\textsuperscript{a}, Toshiyuki Mito\textsuperscript{a}, Satoshi Ito\textsuperscript{b}, Hitoshi Tamura\textsuperscript{a}, Shinji Hamaguchi\textsuperscript{a}, Junichi Miyazawa\textsuperscript{a}, Takuya Goto\textsuperscript{a}, Hit hitoshi Hashziume\textsuperscript{a}, Akio Sagara\textsuperscript{a}

\textsuperscript{a}National Institute for Fusion Science, Toki, Japan
\textsuperscript{b}Dept. Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, Sendai, Japan

*Corresponding author: yanagi@nifs.ac.jp

Conceptual design studies of the helical fusion reactor are progressing at National Institute for Fusion Science (NIFS) with the aim to realize steady-state fusion energy production. The design of FFHR-d1 incorporates continuously wound helical coils having the major radius of 15.6 m, four times as large as that of the Large Helical Device (LHD). The High Temperature Superconductor (HTS) is a plausible candidate, as a “challenging option”, that facilitates the winding process of the helical coils [1]. A 100-kA-class STARS (Stacked Tapes Assembled in Rigid Structure) HTS conductor is being developed using simple stacking of ReBCO tapes [2]. A bridge-type mechanical lap joint [3] is being developed to realize the “joint-winding” that connects segmented conductors of one helical-pitch unit length. A prototype STARS conductor of 3-m length has successfully reached a current of 100 kA. In this sample, a 5.3-T magnetic field and 20-K temperature control were applied over a 0.3-m-long test section [4]. The joint resistance was measured to be 1.8 nano-ohms while conducting a 100 kA current. High stability of the STARS conductor was confirmed under the condition that the current density in the copper stabilizer was lower than 85 A/mm\textsuperscript{2}. A numerical calculation for the hot-spot temperature has been carried out in regards to the quench protection analysis of the FFHR helical coils [5].

In the next step of the conductor development, a coiled sample of a 50-kA class conductor with a 6-m length is being fabricated to further examine the stability characteristics of the STARS conductor. The sample will be installed in a uniform 13-T magnetic field and 4-50 K temperature environment provided by the new facility at NIFS [6]. The test will be carried out roughly halfway 2018.

At NIFS, the post-LHD project is now being discussed. One of the candidates is to construct a new helical machine having an optimized heliotron magnetic configuration and a higher magnetic field by employing the HTS option. Intensive discussion and suggestions by the world community of HTS4Fusion are highly welcome.

Design of High Magnetic Field Superconducting Conductor of CFETR

Jinxing Zheng*, Yuntao Song, Kun Lu, Xufeng Liu, Jiangang Li, Jingang Qin

*aInstitute of Plasma Physics, Chinese Academy of Sciences, Hefei, China

*Corresponding author : jxzheng@ipp.ac.cn

CFETR (China Fusion Engineering Test Reactor) concept design work was started in 2012. It is developed in two stage. CFETR-Phase I is designed with major radius R=5.7m, minor radius a=1.6m and magnetic field at plasma region BT=4-5T. 16 toroidal field coils and 6 central solenoid coils were designed by Nb$_3$Sn CICC with maximum operation current of 64 kA and 50 kA, respectively. Three types of plasma equilibrium shape was designed as ITER-like single null, super-X and snowflake. The maximum flux provided by central solenoid is designed as 180 volt second. However, in order to get much high operation parameters such as steady-state operation, particle and heat exhaust, disruption mitigation and avoidance, ELM control, and material damage by high heat flux and neutron, the superconducting magnet system of CFETR-phase II has been updated based on the larger machine with R = 7.0 m, a=2.0m, BT= 6.5-7T. With this new design, over 1GW fusion power can be achieved and advanced plasma performance can be obtained. In consideration of the maximum magnetic field of TF coils of CFETR-phase II, high performance of Nb$_3$Sn CICC magnet was designed which can withstand 14-15 T.

Besides, in order to save the space for blanket system and get much high flux, high temperature superconducting Bi-2212 magnet with better current carrying performance under high field is supposed to be employed for CS coils of CFETR-phase II. Bi-2212 CICC conductor sample was tested at 4.2 K with critical current of 26.6 kA under its self-field. In addition, this paper also mainly focuses on stability study of the insert HTS coil whose conductor works under a peak magnetic field of 17T and the maximum operating current of each turn is 50kA. The simulation based on a 1-D simplified model is performed using the code THEA (Thermal Hydraulic and Electric Analysis of Superconducting cable). The effect of AC loss during current ramp-up is simplified as a perturbation with uniform power along the overall cable. Simulation shows for ramp rate of 0.5T/s, 1.0T/s and 1.5T/s, the cable will operate steadily while for a higher rate of 2.0T/s it will quench. The variation tendency of which shows divergence for perturbation with different length as duration increases which is believed to be caused by the different effect of heat conduction in different situation.
AC Losses evaluation of 10 kA Bi-2212 Cable-In-Conduit Conductor used in CFETR

Jian Rong\textsuperscript{a}, Xiongyi Huang\textsuperscript{a}, Chunlong Zou\textsuperscript{a}, Yuntao Song\textsuperscript{a}, Kun Lu\textsuperscript{a*}

\textsuperscript{a}Institute of Plasma Physics Chinese Academy of Science, Hefei, China

\textsuperscript{*}Corresponding author : lukun@ipp.ac.cn

Chinese Fusion Engineering Test Reactor(CFETR) is a new TOKAMAK device, which is under the design of China National Integration Design Group\[1\]. The mission and goal of the device are fusion power 50~200 MW, steady-state operation (duty time 30%~50%), plasma current 10 MA and tritium self-sufficient. The major radius is 5.7 m, and minor 1.6 m\[2\]. The toroidal field(TF) magnet is made of 16 toroidal coils, and the toroidal magnetic field strength at R0 is 5.0 T, simultaneously the maximum field in toroidal coils reaches to 15 T\[3\].

The high temperature superconductor Bi-2212 has a high upper critical field(Bc2>100 T) at liquid helium temperature\[4\], and compared to Nb3Sn, Bi-2212 has a bigger temperature margin in the magnetic field 15 T. The Bi-2212 round wires are fabricated by Oxford Superconducting Technology and Western Superconducting Technology with Power-in-tube method, which makes it possible to develop a Cable-In-Conduit Conductor(CICC)\[5-7\]. The Bi-2212 CICC will be mainly used for high field magnet of CFETR.

In this paper, the design of multi-stage twisted 10 kA Bi-2212 CICC used in CFETR TF magnet is introduced, the Bi-2212 cables operate at a field 15 T and 4.5 K temperature. There are AC losses in Bi-2212 conductors because of field variation and plasma current, and it is significative for superconducting magnet stable operation to evaluate AC losses. This study focuses on the coupling current and hysteresis losses due to a variation external magnetic field in CFETR scenario. The effective filament diameter of the twisted wire was equal to the average diameter of the filament bundle. The critical current density is tested after heat treatment, during hysteresis losses evaluation. The effective twist pitch is calculated by the geometrical method, during coupling current time constants evaluation.

Using of cables instead of single conductors for winding of large superconducting magnets has advantage of inductance reduction, mechanical flexibility and higher stability.

Several HTS cable concepts have been extensively studied during last years. Basic concepts such as Roebel Assembled Coated Conductor cable (RACC), Twisted Stacked-Tape cable (TSTC) and Conductor on Round Core cable (CORC) were followed by their derivatives - Rutherford cable with Roebel cable as strand, Round Twisted Stacked Tape cable and Cross-Conductor (CroCo). Very few experiments were performed in cable-in-conduit configuration where the cable is cooled by coolant forced to flow in cooling channel, which must be for this purpose included in the cable design.

In our earlier studies we have shown that core of the CORC cable can be effectively used as a cooling channel. Following this concept we designed and manufactured CORC cable with copper tube used as a former in an industry-compatible process. The cable with total length of about 40 m exhibit no degradation of the critical current. The cable was first tested in liquid nitrogen bath, but its design allowed us to perform experiments also in forced-flow cooling configuration.

The cable was used to prepare model coil. Besides basic electro-magnetic characterization we used the coil to test thermo-hydraulic properties of several cooling media such as nitrogen gas, liquid nitrogen and helium gas. Focus of our experiments is concentrated on helium gas, which might be practical coolant for application in large magnetic systems. In this contribution we summarize our experience with forced-flow cooled CORC cable and analyze its possible use in magnetic systems.
Influence of terminal contacting areas on current distributions in a high-temperature superconductor tape

S. Matsunaga a, T. Obana a,b, Y. Terazaki b, N. Yanagi a,b

a SOKENDAI (The Graduate University for Advanced Studies), Toki, Japan
b National Institute for Fusion Science, Toki, Japan

*Corresponding author: matsunaga.shinnosuke@nifs.ac.jp

The Fusion Engineering Research Project at National Institute for Fusion Science has proposed the use of High-Temperature Superconductor (HTS) as one of the conductor options for winding the helical coils of the LHD-type helical fusion reactor FFHR [1]. The STARS (Stacked Tape Assembled in Rigid Structure) HTS conductor has been investigated as an approach to develop a practical solution to wind the HTS helical coils. In the STARS conductor, a number of ReBCO HTS tapes are simply stacked into a copper stabilizer and a stainless steel reinforcing jacket [2]. It has widely been recognized that a non-uniform current distribution occurs among HTS conductor tapes having no twisting nor transposition. This information points to a need for quantitatively evaluating the non-uniformity of a transport current and its effects on stabilities, depending on the operation conditions. Prior to the investigations on the current distribution among tapes, we started our research on the current distribution measurement in a single tape.

For this purpose, an experimental apparatus, which measures magnetic fields generated by a transport current, in a tape, has been developed in the present study. Five Hall sensors, set on the upper side of a tape sample in a row, observing parallel fields to the width direction, compose one array. Then, four arrays, were fabricated and placed along the longitudinal direction. By observing the magnetic fields at these sensors, one can estimate the current distributions.

We employed a GdBCO tape made by Fujikura Ltd. (FYSC-SC10, 10 mm width, critical current ~650 A at 77 K, self-field) as a sample immersed in liquid nitrogen. The current path length between the terminals was 800 mm. The Hall sensor arrays were placed at every 160 mm interval. Contacting areas between the power supply terminals and the sample were partially insulated by Kapton tapes. This was supposed to cause formation of non-uniform current distributions. However, in the measurements no significant variations of the current distributions were observed. This indicates that an electric contacting condition at power supply terminals hardly affects the current distributions in a HTS tape. Examination and analysis on the cryogenic stability with partial insulation are currently under way.

Electro-Mechanical Behavior of Mechanical Lap Joint Between REBCO Tapes under Cyclic Shear Stress

Luis Aparicio*a, Satoshi Ito*a, Hidetoshi Hashizume*a

*aDepartment of Quantum Science and Energy Engineering, Tohoku Univ., Sendai, Japan
*Corresponding author: lapa@karma.qse.tohoku.ac.jp

Segmented high-temperature superconducting (HTS) magnet concept using REBCO tapes has been proposed for the fabrication of the helical-type fusion reactor FFHR-d1. To realize this concept, the joint-winding of the HTS helical coil is primary option, in which the coil is wound by joining the Stacked Tapes Assembled in Rigid Structure (STARS) conductors one by one using bridge-type lap joints of the REBCO tapes contained in a single STARS conductor. Lap joints with very low joint resistance can be fabricated by mechanically pressing overlapped REBCO tapes together with indium inserted between the REBCO tapes acting as bonding material. However, lap joints inside STARS conductors will be subjected to shearing stresses due to electromagnetic forces during operation of the experimental reactor. Therefore, strength and failure mechanism characteristics of single mechanical lap joints under shear stress were evaluated in previous studies [1, 2] in order to assess their applicability for the FFHR-d1 design. From these study it was understood that, for the case of joints with cohesive failure mode, the joint resistance will not increase immediately after the joint reaches its maximum shear stress and starts deforming as lap displacement increases. However, because the helical coils of the FFHR-d1 will be subjected to repeated electromagnetic strains, it is important to understand the stability of the mechanical lap joints under such cyclic shear stress regimes.

Therefore, in this study we analyze the mechanical and electrical behavior of mechanical lap joints under repeated load cycles. In the experiment, the mechanical lap joint samples are placed in a tensile test machine, which is inserted in a liquid nitrogen bath. Constant displacement is applied using a stepper motor until a displacement limit is reached and then the motor is stopped. Next, the displacement is reverted to apply reversed shear stress to the joint after a certain amount of time has passed. This cycle is repeated several times while monitoring applied load and voltage drop across the overlapped joint area.

Results from this study will be presented during the workshop presentation.

Applicability Evaluations of a Quench Detectable Superconducting Sensor to HTS coils

Shin Hasegawa*, Satoshi Ito and Hidetoshi Hashizume

*aDepartment of Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, Sendai, Japan

*Corresponding author: shase@karma.qse.tohoku.ac.jp

Rare-earth barium copper oxide (REBCO) tapes are considered to be used for high-temperature superconducting (HTS) magnet at \( \leq 20 \text{ K} \) and \( \geq 12 \text{ T} \) in future DEMO reactors [1, 2]. However, quench detection by voltage measurement is difficult in REBCO tape because of the slow normal zone propagation velocity in it. To address this issue, we have proposed a quench detectable REBCO tape with another superconducting (SC) wire as a detector, “REBCO/SC\(_d\) tape”, where subscript of “d” means the detector. In our previous report [3], we numerically and experimentally demonstrated that quench in the REBCO tape was able to be detected by using NbTi wire with high normal conducting resistance. Another report [4] showed that quick quench detection can be achieved by applying higher load factor to low-temperature superconducting detector with taking into account the heat generation in the detectors to avoid its degradation. The applicability of Nb\(_3\)Al detector to REBCO stacked tapes assembled in rigid structure (STARS) conductor operated at 4.2 K and 12 T was also investigated for quench detection and protection of HTS helical coils of helical fusion reactor, FFHR-d1[4]. The result indicated that the maximum temperature of the STARS conductor can be reduced from over 200 K to 20 K with Nb\(_3\)Al detector. However, we have not considered the operation at 20 K, which is the first candidate for the FFHR-d1 operation.

In this study, we additionally conducted quench protection analysis using the electro-thermal coupling model of the STARS conductor with a SC detector to investigate the appropriate material for the detector at 20 K and 12 T. Furthermore, we also considered the effect of the electro-magnetic forces and thermal stress on the quench detection performance of the SC detectors, then optimized the monitoring current applied to the SC detectors. The details of the protection analysis and optimization of the monitoring current will be presented at the workshop.

Development, Manufacturing and Application of Coated Conductors at SuperOx


*aSuperOx Japan, Sagamihara, Japan
bSuperOx, Moscow, Russia

*Corresponding author: sergey@superox.co.jp

The group of SuperOx companies was established with the goal of developing and commercializing a reliable and cost-effective technology for the manufacturing of second generation high temperature superconducting (2G-HTS) tapes, to deliver affordable, highly customized 2G tapes to the market and to promote new products involving superconducting materials. The core fabrication process of 2G-HTS tapes developed by our group relies on the use of Hastelloy substrate tape, ion-beam assisted deposition (IBAD) texturing process and fabrication of superconducting layer by pulsed laser deposition (PLD) process [1,2].

At present SuperOx became one of the leading producer of coated conductors delivering kilometers of highly customized superconducting tapes worldwide. In past 2 years we made a substantial progress in up-scaling of our production and installation of independent new high-throughput equipment in Japan and Russia. Our recent activities aimed to increase the production throughput and yield, improve the performance of 2G HTS wires and to provide a wider range of customization of our product tapes. Based on our production experience and recent cost analysis model we considering several potential pathways to reduce the final price of our wires, which based on the magnetron-IBAD-PLD production scheme and analyzing the main obstacles and possible competitiveness of this approach in comparison with other manufacturing techniques. Now we considering further upscaling of PLD from the viewpoint of recent progress in excimer laser technologies and latest results in 2G wire production and designing of PLD equipment made by SuperOx.

Currently SuperOx involved in several joint R&D and commercial projects including development and installation of 220kV and 3kV superconducting fault current limiters (SFCL), advanced cables and motors. The company business strategy emphasized gradual shift from the manufacturing of the plain superconducting tapes towards the integration of the 2G wires into the superconducting devices. In conclusion we will present our prospective projects aimed on the development of new materials, wire architectures, construction of pilot scale devices and electrical equipment where our 2G HTS wires will be utilized.

The Fabrication of a Small YBCO Solenoid Magnet

Sun Linyu*, Li Pengyuan, Wei Haihong

Southwestern Institute of Physics, Chengdu, China

*Corresponding author: sunly@swip.ac.cn

With the high critical temperature and critical current, the high temperature superconductor (HTS) can produce a powerful magnetic field to maintain the plasma in a steady state for a long time, meeting the requirements for fusion reactor magnet. Thus, HTS magnet has become a vital research aspect for the magnet technology in fusion device [1-2]. In order to explore the fabrication process of HTS magnet, a small YBCO solenoid magnet is wound. The YBCO coils are made in the shape of double pancake to reduce the number of welded joints. In addition, two types of coils are wound separately to obtain the maximum magnetic field. Type A has an inner diameter of 60mm, outer diameter 104mm and height 10mm; type B has an inner diameter of 60mm, outer diameter 132mm and height 10mm.

The lead tapes of all double pancake coils are connected successively by the overlapping welding process. The tin-lead solder of low melting point (about 180°C) is adopted to avoid damaging the tape. The joints which are of about 10cm overlapping length is to reduce the resistance. The minimum resistance value of joints can reach $10^{-8}\Omega$. The G10 epoxy sheets are inserted into every two coils to maintain a good insulation between each other. All coils are installed by interlocking the nested bump on the skeleton, and clamped firmly through end plates and bolts at both end of magnet.

The HTS magnet is cooled and tested by being immersed entirely in liquid nitrogen (77K). After cooling down completely, the magnet starts to load current at a speed of 0.5A/s. Given the total length of strips is 600m, in $1\mu\text{V/cm}$ of quench criteria the critical, current value of the magnet is 27A when the voltage value reaches $60\mu\text{V}$. Considering the safe operating, the running current is set at 22A, and the maximum magnetic field tested is 0.53T.

Quench Protection for the HTS Magnet in the Helical Fusion Reactor

Yoshiro Terazaki\textsuperscript{a}, Nagato Yanagi\textsuperscript{a}, Hitoshi Tamura\textsuperscript{a}, Toshiyuki Mito\textsuperscript{a}, Satoshi Ito\textsuperscript{c}, Hidetoshi Hashizume\textsuperscript{c} and Akio Sagara\textsuperscript{a}

\textsuperscript{a}National Institute for Fusion Science, Gifu, Japan
\textsuperscript{b}Tohoku University, Sendai, Japan

Design activities of the LHD-type helical fusion reactor FFHR-d1 and -c1 are progressing at NIFS. The high-temperature superconductor (HTS) is a promising option for the helical coil conductors. In addition to high cryogenic stability and low refrigeration power at elevated temperature operations at >20 K, it is proposed that the helical coils of large-diameter and complex-shape be constructed by connecting conductor segments using the advantage of HTS. A proto-type large-current capacity HTS conductor sample was fabricated and it achieved 100 kA at 20 K, 5.3 T.

In our previous studies, the hot-spot temperature, defined as the maximum temperature reached during a normal-transition and a subsequent emergency current discharge, has been calculated by a one-dimensional finite element method (FEM). The thermal diffusion along the longitudinal direction of the conductor is the governing equation, while the percolation model is used to describe the voltage generation over the critical current of the REBCO HTS tapes. The obtained hot-spot temperatures are 205 K and 456 K at the current density of the helical coils of 25 and 40 A/mm\textsuperscript{2}, corresponding to the FFHR-d1 and c1 designs, respectively. In the case of FFHR-c1, the hot-spot temperature significantly exceeds the allowable limit. To meet the requirement of such a high current density for FFHR-c1, the feasibility of applying the non-insulation coil concept is examined by numerical calculations, as another quench protection method.
Nonlinear Structural Analysis of a Superconducting Coil and Support Structure for the Helical Fusion Reactor with Multiscale Element

Hitoshi Tamura\textsuperscript{a*}, Takuya Goto\textsuperscript{a}, Nagato Yanagi\textsuperscript{a}, Junichi Miyazawa\textsuperscript{a}, Teruya Tanaka\textsuperscript{a}, Akio Sagara\textsuperscript{a}, Satoshi Ito\textsuperscript{b}, and Hidetoshi Hashizume\textsuperscript{b}

\textsuperscript{a}National Institute for Fusion Science, Toki, Japan
\textsuperscript{b}Department of Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, Sendai, Japan

*Corresponding author: tamura@nifs.ac.jp

There is a demand for a magnetic field enhancement and downsizing of a magnet system in a fusion reactor to improve plasma-confinement and reduce the difficulties in construction. Since an electromagnetic force induced by a magnet system is proportional to the square of the magnetic field intensity ratio, the stress on the magnet system become extremely severer by increasing the magnetic field. For instance, FFHR, a helical fusion reactor, several design options are being studied [1]. FFHR-d1A is a self-ignition demonstration reactor that operates at a magnetic field intensity of 4.7 T, a pair of helical coil’s major and minor radii in this type of reactor are 15.6 and 3.744 m, respectively. On the other hand, FFHR-c1 is a compact-type sub-ignition reactor that aims to realize steady electrical self-sufficiency [2]. It has a magnetic field intensity of 7.3 T and 0.7-times reduced major and minor radii as compared with those of FFHR-d1A. According to the latest structural analysis of the magnet system of FFHR-d1A, the maximum von Mises stress in the coil support structure was 764 MPa [3]. The coil support structure of the reduced-size FFHR-c1, including its thickness, needs modification, otherwise the stress level will exceed a permissible level. Coil components such as the superconductor, sheath, and insulation also need a detailed structural-soundness evaluation. A nonlinear multiscale finite element method analysis was performed to facilitate a detailed investigation of the superconducting coils and their support structure. Moreover, considering a contact and a slide between the coil winding and coil case, mechanical behaviors of the structure was evaluated. Consequently, a robust structure was introduced by referring the result of analysis and modifying the design of support structure. Detail stress and displacement distributions are shown.