Coupling Loss Characteristics of Nb_3Sn CIC Conductor for CFETR CS Model Coil

Yi Shi, Fang Liu, Huajun Liu, Huan Jin, Jingang Qin, Feng Long, Bo Liu, Ming Yu, and Yu Wu

***Abstract*—An Nb_3Sn cable-in-conduit (CIC) conductor with short twist pitch structure has been developed at Institute of Plasma Physics Chinese Academy of Sciences, Hefei, China, to meet the central solenoid model coil (CSMC) project of China fusion engineering test reactor (CFETR). 12 T magnetic field and 1.5 T/s field change are the most basic design target. The coupling loss characteristics of Nb_3Sn CIC conductor is the key design requirement for CSMS because the deposited energy in magnets from ac losses can decrease the safe margin in the nuclear fusion device. In order to evaluate the coupling loss performance of the Nb_3Sn CIC conductor, the ac loss measurement for Nb_3Sn CIC conductor sample was carried out at SULTAN facility. This paper presents the specific structure design of the Nb_3Sn CIC conductor and ac losses test results first. Then, the coupling losses characteristics are discussed with Multizones PArtial Shielding model and the key fit parameters are obtained from measurement results. Finally, two typical field cases are considered to evaluate the coupling loss energy of Nb_3Sn CIC conductor for safe operation of the CFETR CSMC and the optimization of the cryogenic system.**

***Index Terms*—China fusion engineering test reactor (CFETR), coupling losses, Nb_3Sn cable-in-conduit (CIC) conductor.**

I. Introduction

THE central solenoid model coil (CSMC) project of China Fusion Engineering Test Reactor (CFETR) was launched at 2014 and the purpose is to develop and verify the design and manufacture technology of the large-scale superconducting magnet [1], [2]. 12 T magnetic fields and 1.5 T/s field change are the most basic design target. Therefore, CSMC must not only satisfy the high transport performance, but also the low ac losses considering the operation requirements and safe design [3].

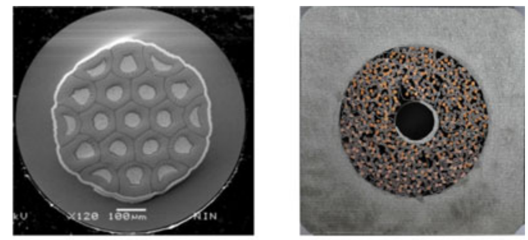
The International Thermonuclear Experimental Reactor (ITER) CS Nb_3Sn cable-in-conduit (CIC) conductor crash program led to the development of a short twist pitch (STP) cable able to withstand the transport current degradation with electromagnetic (EM) cyclic loads [4]–[7]. This design inspired the CSMC conductor developed by Institute of Plasma Physics Chinese Academy of Sciences (ASIPP), Hefei, China.

Manuscript received April 10, 2017; revised August 8, 2017; accepted August 29, 2017. Date of publication September 4, 2017; date of current version October 27, 2017. This work was supported in part by the National Natural Science Foundation of China under Grant 51507174 and Grant 51477172, and in part by the National Magnetic Confinement Fusion Science Program of China under Grant 2014GB105001 and Grant 2014GB105004. This paper was recommended by Associate Editor A. Devred. *(Corresponding author: Yi Shi.)*

The authors are with the Hefei Institute of Physical Science, Chinese Academy of Sciences, Hefei 230031, China (e-mail: shiyi@ipp.ac.cn; fangliu@ipp.ac.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2017.2749039



(a) (b)

Fig. 1. (a) Cross section of Nb_3Sn strand. (b) CIC conductor.

In order to develop the Nb_3Sn CIC conductor with STP at ASIPP, Qin *et al.* has developed the cabling technology and measured the strand deformation, as well as critical current (I_c) degradation in the cabling process [8]. Subsequently, a prototype CIC conductor manufacture and visual inspection of cable damage with deformation has been performed, which ensures the feasibility of manufacture technology for Nb_3Sn CIC conductor [9].

The final performance evaluation of Nb_3Sn CIC conductor needs to be performed and verified by a series of experiments. This paper mainly focuses the coupling losses characteristic of Nb_3Sn CIC conductor combined with measurement results in SULTAN facility (Villigen, CH). Finally, a preliminary coupling losses energy evaluation for Nb_3Sn CIC conductor is made in two typical test cases for safe operation of the CFETR CSMC and the optimization of the cryogenic system.

II. Nb_3Sn CIC Conductor Design and Manufacture

The internal tin process Nb_3Sn wires provided by Western Superconducting Technologies Co., Ltd., were employed for CFETR CSMC. The diameter is 0.82 mm and thickness of internal Nb filament size is 6 μm. Ta barrier is introduced out of the Nb_3Sn superconducting filaments. 19 Hexagon subelements are characterized by approximate 130-μm diameter shown in the Fig. 1(a). The high treatment temperature is 650 °C holding on 100 h in vacuum or Ar atmosphere.

Critical current density (J_c) of Nb_3Sn strand is described by the deviatoric strain model developed by University of Twente, Enschede, The Netherlands [10], [11]. I_c of single wire is about 250 A at 12 T and 4.2 K with 0.1 μV/cm electric field criterion. The scaling parameters are listed in Table I. The hysteresis loss per cycle at $\pm$3.0 T is less than 500 MJ/cm^3.

TABLE I
SCALING PARAMETERS OF J_c FOR CFETR CSMC Nb_3Sn STRAND

Parameter	Unit	Value
C_{a1}		55.22
C_{a2}		11.2
$\varepsilon_{0,a}$	%	0.293%
ε_m	%	–0.058%
$\mu_o H_{c2m}(0)$	T	31.66
$T_{cm}(0)$	K	16.13
C_1	AT	19948.5
P		0.57
Q		2.0

TABLE II
DETAIL CHARACTERISTICS OF Nb_3Sn CIC CONDUCTOR

Property	Unit	Value
Cabling layout		(2SC+1Cu) × 3 × 4 × 4 × 6
Final outer diameter	mm	32.6
Void fraction		32.7%
Twist pitch sequence	mm	24/49/89/160/450
Petal stainless steel wrap		70% overlap
Cable stainless steel wrap		overlapped
# of SC strand		576
# of copper wires		288
Heat treatment schedule °C/h		210/50+340/25+450/25+575/100+650/100
Operating current	kA	47.65
Peak field in the coil	T	12

The design of high performance Nb_3Sn CIC conductors for superconducting magnet in fusion device requires comprehensive consideration in the balance between the dc and ac performance. Contact resistance (R_c) between the inter-strands in the cable is known to be one of the important parameters which dominantly determine the current redistribution and coupling current loops generation at various disturbances. The application of Cr coating with 2 μm thickness on the surface of Nb_3Sn strands and wrap out of the subcable (70% open surface) are the useful way to control the appropriate R_c between the strands.

In addition, the void fraction and twist pitches in different stage cables are also important parameters, which affect the conductor performance under the strong EM load and cycles. 32.7% void fraction and STP design are used for the Nb_3Sn CIC conductor of CFETR CSMC that originates from design inspiration of ITER CS conductor development and feasibility of cabling technology at ASIPP. This design can effectively enhance the cable stiffness and prevent the transport current degradation under the strong EM load and cycles which is verified by measurement results of ITER Nb_3Sn CIC conductor [12]–[14]. The detail structure parameters of Nb_3Sn CIC conductor were also shown in Table II. Fig. 1(b) presents the cross section of the Nb_3Sn strand and CIC conductor.

III. COUPLING LOSSES

A. Measurement Procedure and Results

The ac losses measurement of Nb_3Sn CIC conductor sample for CFETR CSMC was performed in SULTAN facility at spring of 2016. The amplitude of the sinusoidal ac applied field was 0.2 T where the homogeneity of ac field is 10% in the 390 mm sample length. The frequency of ac applied field was from 0.1 to 7 Hz to obtain the ac losses in the wide frequency range. A biased dc field of 2 and 9 T was applied to avoid the interference from diffusion barrier out of the Nb_3Sn filaments and acquire the coupling loss characteristic in different background field.

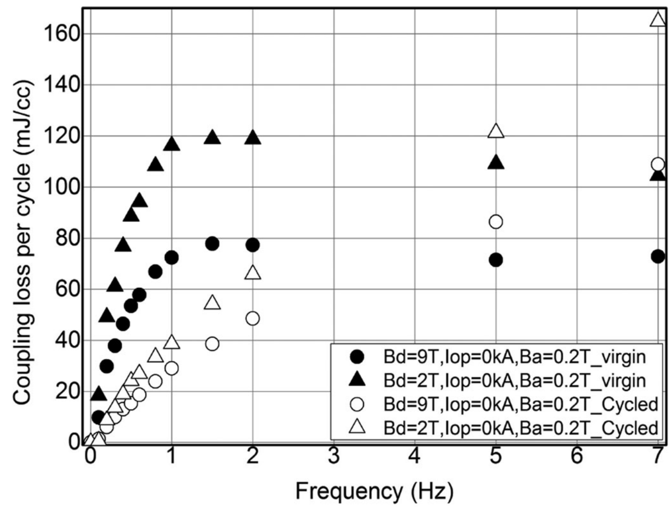


Fig. 2. Coupling losses measurement results versus frequency of Nb_3Sn CIC conductor.

8000 cycles have been applied with transport current of 48.8 kA under 10.85 T to meet the Lorentz force in the CFETR CS model coil including the two times thermal cycles between 4.2 K and room temperature. The total ac losses energy per cycle including hysteresis and coupling losses were obtained by calorimetric method. If it is assume that the hysteresis losses per cycle at full penetration of the applied field is independent of the frequency, the coupling losses can be represented by the energy losses per cycle versus frequency, described as follows:

$$Q_c = \frac{\pi \cdot B_a^2 \omega \cdot n\tau}{\mu_0} \ (\mathrm{J/m^3 \cdot cycle}) \qquad (1)$$

where the applied field is $B_a \sin(2\pi f t)$ and *n* is the shape factor, τ is coupling time constant. According to the results shown in Fig. 2, the coupling losses show a wide plateau extending to higher frequency in virgin state. The maximum coupling loss energy is 120 MJ/cm^3 per cycle at 2.0 Hz with 2 T biased dc field which is 50% higher than at 9 T biased dc field.

After cycles, the trends are not the same at all, it is found that the saturation does not appear with frequency increasing. The maximum coupling loss energy increases to 165 MJ/cm^3 per cycle at 7.0 Hz in 2 T biased dc field.

B. Multizones PArtial Shielding Model (MPAS)

AC losses measurement results of Nb_3Sn CIC conductor reveal that the shielding effect between the different coupling loops is key factor for coupling loss characteristics especially to higher frequency. The classical unique apparent time constant model is not sufficient to characterize the coupling loss for

Nb_3Sn CIC conductor in wider frequency range accurately if existence of shielding affect from different coupling loops.

Several models have already been developed considering the shielding effect to explain the experimental shape reasonably. Nijhuis *et al.* proposed an expression for the coupling losses accounting for the partial shielding [15]. Subsequently, Turck and Zani proposed a macroscopic model named MPAS to describe the partial shielding behavior with different zones in the cable that was applied in the design of JT-60SA TF conductor and ITER central solenoid conductor successfully [16]–[18]. Here the MPAS model is used because the results could be convenient to compare with other conductors.

With MPAS model, ac losses in superconducting strands are caused by transverse currents between filaments while the induced currents circulate in the peripheral shell of filaments. Those currents react to the applied external field (B_e) by creating a reacting field of value $\tau\,(dB_i/dt)$ (τ being the decay time of the induced currents). As the reacting field is exactly dipolar the internal field (B_i) inducing the circulating currents is equal to

$$B_i = B_e - \tau \frac{dB_i}{dt}. \quad (2)$$

Total coupling losses power in the cable is given by the summation of the contributions of all different domains or zones with τ_j and respective effective volume fraction k_j considering the partial shielding model such as

$$P = \frac{1}{\mu_0} \sum_{1}^{N} k_j \cdot \tau_j \left(\frac{dB_i}{dt}\right)^2 \quad \left(\mathrm{W/m^3}\right). \quad (3)$$

If B_e is a sinusoidal variation which is the same as the measurement condition

$$B_e = B_a \sin \omega t. \quad (4)$$

The total coupling loss energy per cycle can be described with the respective zones as a function of the frequency ($\omega = 2\pi f$):

$$W = \frac{{B_a}^2}{\mu_0} \sum_{1}^{N} \frac{k_i \cdot \tau_i \cdot (\pi \cdot \omega)}{1 + {\tau_i}^2 \cdot \omega^2} \quad \left(\mathrm{J/m^3}\right). \quad (5)$$

C. Results Discussions With MPAS Model

In order to simplify the fit procedure and regroup the parameters of different zones, the effective transverse resistivity is considered equal for respective zones in the compacted cable [19]. Although all the combinations of zones and time constants in MPAS model are found among all the 2^N possible products (including the one equal to zero), the number of zone (presenting the number of the time constant) can simplify to *N*–1 based on the regrouping method of MPAS model, which has obtained good agreement between the fit and measurement result for JT-60SA TFJS1 and ITER CS conductors [16]–[18].

Fig. 3 shows the fitting curve together with the each zone contribution for virgin conductor in 2 T applied field using the MPAS model, as well as measurement results. The visible and limited shielding effects can be seen obviously. The fit result is in good agreement with experimental range. So the five zones model and fitted parameters can be sufficient to characterize the Nb_3Sn CIC conductor for CFETR CSMC.

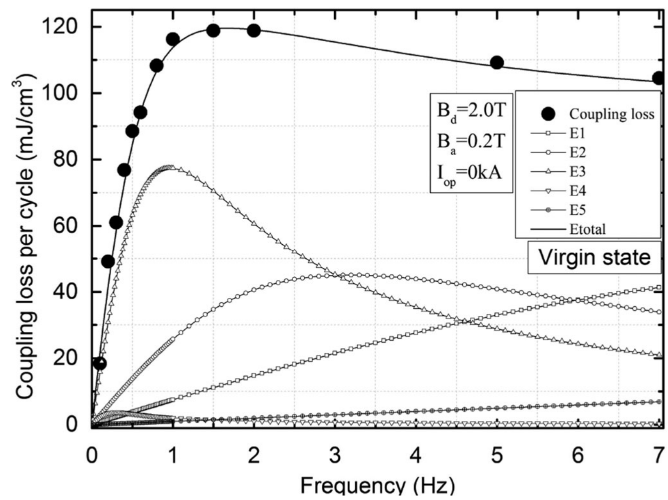


Fig. 3. Experimental data and MPAS fitting curve. The respective contributions for each time constant are also shown.

TABLE III
PARAMETERS OF THE MPAS MODEL FOR COUPLING LOSS (MS)

Domains	2T k	2T τ(ms)	9T k	9T τ(ms)	2T k	2T τ(ms)	9T k	9T τ(ms)
	Virgin state				Cycled state			
1	1.0	12	0.78	10	3.0	10	1.55	2.5
2	0.9	50	0.485	42	0.38	55	1.90	10
3	1.4	165	1.035	138	0.15	41	0.25	34
4	0.1	528	0.098	440	0.15	120	0.20	110
5	0.4	4.0	0.40	3	0.4	4.0	0.40	3.0
$\Sigma\, k_i \tau_i$	352		214		73.2		54.5	

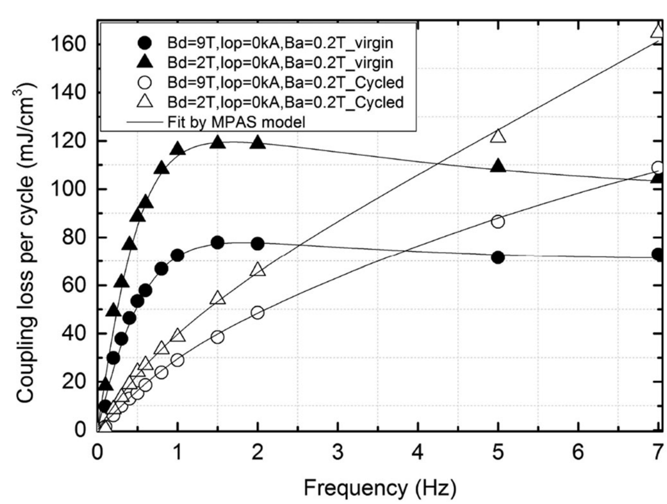


Fig. 4. Experimental data and MPAS fitting curve with different state.

The corresponding fit parameters and curves of four different conductor states are presented in Table III and Fig. 4. The corresponding value of $n\tau_{ap}$ is $\Sigma\, k_i \tau_i$ also shown. The all $n\tau_{ap}$ after cycle are about 21%–25% of the virgin state. The minimum

$n\tau_{ap}$ is only 54.5 ms after cycle at 9.0 T biased field. This can be explained by the contact resistance change between the inter-strands due to the slide friction and the pressure release after EM cycles which is the same the other Nb_3Sn CIC conductor sample.

The applied dc field shows an important factor that affects the coupling losses according to the results. This influence may be caused by the magneto-resistance effect of copper wires and matrix of the Nb_3Sn strands, which can increase the electric resistivity of copper and suppress the coupling loss energy under the higher magnetic field.

In general, coupling losses could be decreased with STP structure according to the classical coupling losses theory [19]. But the measurements results of conductor for STP option here are more than two times higher than the original ITER CS Nb_3Sn CIC conductor [18]. The feasibility explanations for this effect are as follows [14]: STP structure limits the wires potential move by increases the crossing angle of the strands, which increases the imprint or pinching between the strands in the cabling procedure. Another explanation could be possible removals of Cr plating on the strands due to the higher stiffness of the cable which results in the lower inter-strands contact resistance. These speculations need to be demonstrated in future.

D. Model Applied to Two Typical CSMC Field Cases

Once the parameters of MPAS model (time constants and volume fraction) for any given CIC conductor are obtained, the total coupling losses power can be evaluated for any type of variation for applied field. The first use of MPAS model to fit ac losses measurements is JT-60SA successfully and considers the impact of a plasma disruption on the magnetic field variations and heat deposition [17].

For CFETR CSMC, two typical cases representing the performance test are considered to evaluate the coupling loss energy of Nb_3Sn CIC conductor. One is the exponential decay field with the 8 s time constant, another is the triangular wave field with 0.4 T/s change rate and 12 T peak to peak fields. Two typical field cases can verify the different running ability respectively. Case 1 is used to validate the fast discharging ability where the maximum field changing can reach to 1.5 T/s; Case 2 is used to verify the 12 T field design requirement which is also similar as the ITER CSMC.

The simulation result of coupling losses power versus time with four different conductor states in case 1 is shown in Fig. 5. The peak values of coupling loss power appear at the range of less than 1 s for four conductor states. The maximum loss power is 0.485 MW/m^3 in the 2 T applied field and virgin state. The maximum coupling loss energy per unit volume of superconductor is 2.41 MJ/m^3 in one complete cycle presented in Table IV.

Fig. 6 presents evaluated results of coupling losses power in case 2. The coupling losses power shows the saturation state after a short time. The maximum coupling losses power is 0.043 MW/m^3 also in the 2 T applied field and virgin state after 0.4 s. The maximum coupling losses energy per unit volume of superconductor is 2.6 MJ/m^3 in one complete cycle. The detail energy deposition parameters are presented in Table V.

Those simulation results of coupling losses in two typical cases can provide the heat deposition as important input parameters to evaluate the performance of Nb_3Sn CIC conductor such as temperature rise and stability. It can also give the useful guidance for the safe operation of the CFETR CSMC and the optimization of the cryogenic system.

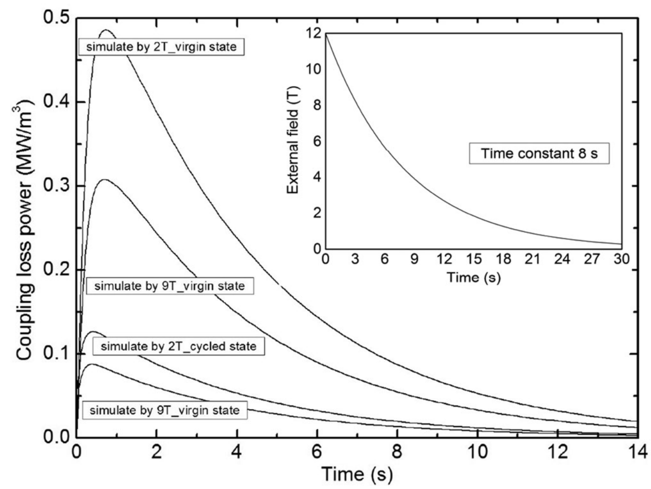


Fig. 5. Coupling loss power deposited in Nb3Sn CIC conductor for 8 s time constant of the applied field.

TABLE IV
ENERGY LOSS WITH EXPONENTIAL DECAY APPLIED FIELD (8 S)

State	2T_virgin	9T_virgin	2T_cycled	9T_cycled
P_{max} (MW/m^3)	0.485	0.30	0.126	0.087
Time for P_{max} (s)	0.72	0.70	0.40	0.37
E_{max} (MJ/m^3)	2.41	1.51	0.57	0.39

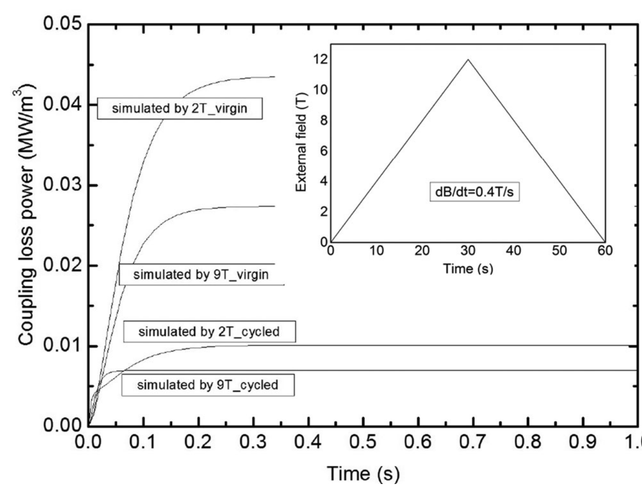


Fig. 6. Coupling loss power deposited in Nb_3Sn CIC conductor for triangular wave of the applied field.

TABLE V
ENERGY LOSS WITH TRIANGULAR WAVE APPLIED FIELD PER CYCLE (0.4 T/S)

State	2T_virgin	9T_virgin	2T_cycled	9T_cycled
P_{max} (MW/m^3)	0.043	0.027	0.01	0.007
Time for P_{max} (s)	>0.4	>0.36	>0.3	>0.06
E_{max} (MJ/m^3)	2.6	1.64	0.6	0.416

IV. Conclusion

An STP structure Nb_3Sn CIC conductor has been developed at ASIPP for CFETR CSMC project. This paper presents the structure design and coupling losses measurement results of the Nb_3Sn CIC conductor in SULTAN facility. The coupling losses is characterized by MPAS model and the key parameters were obtained. Finally, two typical field cases are considered to evaluate the coupling losses energy of Nb_3Sn CIC conductor for safe operation of the CFETR CSMC and the optimization of the cryogenic system.

Acknowledgment

The authors would like to thank P. Bruzzone at in CRPP for ac losses measurement of Nb_3Sn CIC conductor and the key discussions with A. Nijhuis at the University of Twente, Enschede, The Netherlands for ac losses analysis.

References

[1] Y. Wan, "Mission of CFETR," in *Proc. ITER Train. Forum 2nd Workshop MFE Develop. Strategy*, Hefei, China, 2012.

[2] Y. Wan *et al.*, "Design goal of the first option of CFETR," *CFETR Design Document of Integral Group*, Hefei, China, 2014.

[3] Y. Shi, Y. Wu, Q. W. Hao, B. Liu, and Y. Yang, "The AC loss evaluation of central solenoid model coil for CFETR," *Fusion Eng. Design*, vol. 107, pp. 100–107, 2016.

[4] A. Nijhuis, Y. llyin, W. Abbas, H. H. J. Ten Kate, M. V. Ricc, and A. della Corte, "Impact of void fraction on mechanical properties an evolution of coupling loss in ITER Nb3Sn conductors under cyclic loading," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 1633–1636, Jun. 2005.

[5] P. Bruzzone *et al.*, "Test results of two European TF conductor samples in SULTAN," *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 1088–1091, Jun. 2008.

[6] Y. Miyoshi, Y. llyin, W. Abbas, and A. Nijhuis, "AC loss, inter-strand resistance, and mechanical properties of an option-ll ITER CICC up to 30,000 cycles in the press," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1944–1947, Jun. 2011.

[7] G. Rolando, A. Devred, and A. Nijhuis, "Minimizing coupling loss by selection of twist pitch lengths in multi-stage cable-in-conduit conductors," *Supercond. Sci. Technol.*, vol. 27, 2014, Art. no. 015006.

[8] J. Qin *et al.*, "Optimization of CFETR CSMC cabling based on numerical modeling and experiments," *Supercond. Sci. Technol.*, vol. 28, 2015, Art. no. 125008.

[9] J. Qin, T. Xue, and B. Liu, "Cabling technology of Nb_3Sn conductor for CFETR central solenoid model coil," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, Apr. 2016, Art. no. 4801305.

[10] A. Godeke, B. Ten Haken, H. H. J. Ten Kate, and D. C. Larbalestier, "A general scaling relation for the critical current density in Nb_3Sn," *Supercond. Sci. Technol.*, vol. 19, 2006, Art. no. R100.

[11] Y. IIyin, A. Nijhuis, and E. Krooshoop, "Scaling law for the strain dependence of the critical current in an advanced ITER Nb_3Sn strand," *Supercond. Sci. Technol.*, vol. 20, pp. 186–191, 2006.

[12] D. Bessette, D. Ciazynski, P. Decool, J. L. Duchateau, and B. Kazimierzak, "Fabrication and test results of the 40 KA CEA conductors for NET/ITER," in *Proc. 17th Int. Conf. SOFT Fusion Technol.*, 1992, vol. 1, pp. 788–792.

[13] D. Bessete, J. L. Duchateau, P. Decool, B. Turk, and B. Baul, "Qualification of a 40 kA Nb_3Sn superconducting conductor for NET/ITER coils," *IEEE Trans. Mag.*, vol. 30, no. 4, pp. 2038–2041, Jul. 1994.

[14] Y. Nabara *et al.*, "Impact of cable twist pitch on Tcs-degradation and AC loss in Nb_3Sn conductors for ITER central solenoid," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art. no. 4200705.

[15] A. Nijhuis, H. H. J. Ten Kate, J. L. Duchateau, and P. L. Bruzzone, "Coupling time loss time constant in full size Nb_3Sn CIC model conductors for fusion magnet," *Adv. Cryogenics Eng.*, vol. 42B, pp. 1281–1288, 1996.

[16] B. Turck and L. Zani, "A macroscopic model for coupling current losses in cables made of multistage of superconducting strands and its experimental validation," *Cryogenics*, vol. 50, pp. 443–449, 2010.

[17] A. Torre, J. L. Duchateau, B. Turk, and L. Zani, "Impact of a plasma disruption on the magnetic field variations and heat deposition in the TF conductor of JT-60SA," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Dec. 2011, Art. no. 4803005.

[18] D. Bessette, "Design of a Nb_3Sn cable-in-conduit-conductor to withstand the 60000 electromagnetic cycles of the ITER central solenoid," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art. no. 4200505.

[19] T. Schild and D. Ciazynski, "A model for calculating AC losses in multistage superconducting cables," *Cryogenics*, vol. 36, pp. 1039–1049, 1996.

Authors' biographies not available at the time of publication.