The Scaling Parameterization of ITER Superconducting Nb–Ti Strands Throughout Worldwide Production

Chao Zhou, Denis Bessette, Arnaud Devred, Gennaro Romano, and Alexander Vostner

***Abstract*—The ITER superconducting magnet system will require approximately 650 tons of toroidal field and central solenoid Nb$_3$Sn strands with different designs, and more than 250 tons of Nb–Ti strands. This called for a significant scale up of the worldwide production of Nb$_3$Sn and Nb–Ti strands. Over the worldwide and mass productions, it is essential to accurately analyze and characterize the properties of ITER superconducting strands in terms of critical current (I_c) and ac loss, and thus determine the operational limits of the conductors, ultimately optimizing the operating scenarios of the Tokamak. In this paper, the proper scaling parametrization $I_c(B, T)$ and n-value as a function of I_c $(n(I_c))$ are investigated for Nb–Ti strands throughout massive production. Despite the differences in ITER Nb–Ti strand's architecture and their composition, optimized Nb–Ti strand scaling parameterizations throughout production for each supplier have been reached with the minimal deviation (<15%) for all the measured data in a wide B, T window and even <5% in the operation condition region. This is to be applied for the analysis of the Nb–Ti conductors made from these stands and to assess possible evolution over production.**

***Index Terms*—ITER, Nb–Ti, superconducting strands, scaling parameterization.**

I. INTRODUCTION

ITER, as an experimental fusion reactor, is designed to demonstrate the scientific and technological feasibility of fusion power [1], [2]. ITER superconducting magnet system will comprise Nb$_3$Sn-based conductors in the 18 TF coils and the 6 CS modules, and Nb–Ti-based conductors in the 6 Poloidal Field (PF) coils, the 18 Correction Coils (CC), as well as the feeder busbars [3]. Nine suppliers from six domestic agencies (DAs) are involved in producing approximately 650 tons of TF and CS Nb$_3$Sn strands with different designs, whereas two suppliers from two DAs are involved in producing more than 250 tons of Nb–Ti strands.

A significant scale-up of the worldwide production of Nb$_3$Sn and Nb–Ti strands is called up. Over the worldwide and mass productions, it is essential to accurately characterize and analyze the properties of ITER superconducting strands in terms of I_c, n-values and AC loss. These will provide a solid basis to analyze and predict the performance of cable-in-conduit conductors (CICC) made of those strands, and thus to determine the operational limits of the conductors.

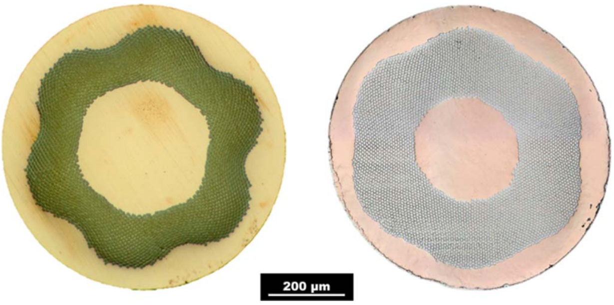

Fig. 1. Optical micrograph of the transverse cross section of the RF (right, image by Courtesy of Peter Lee) and CN Nb–Ti (left, image by Courtesy of WST) strands.

An established single pinning mechanism parametrization $I_c(B, T)$ as described by L. Bottura [4] had been adopted by the ITER. The goal of this work is to identify a single parameterization to be used to represent all strands throughout massive production, in terms of scaling parametrization $I_c(B, T)$ and $n(I_c)$. In this paper, the proper scaling parametrization $I_c(B, T)$ with the single pinning mechanism parameterization and power relationship of $n(I_c)$ are investigated and proposed forNb –Ti strands throughout massive production, which are based on the measurement results of the I_c and n in a wide range of applied magnetic field and temperature for the Nb–Ti strands from different suppliers. The scaling parameters and deviation between the measured and predicted $I_c(B, T)$ and $n(I_c)$ data are also presented and discussed.

II. SAMPLE INFORMATION AND MEASUREMENT

A. Nb–Ti Samples

There are two suppliers from two DAs for producing ITER Nb–Ti strands, Western Superconducting Technologies Co., Ltd. (WST) from China (CN) and JSC High-tech Research Institute of Inorganic Materials (VNIINM) from Russian Federation (RF). CN WST strand, as multifilament wire, has 2616 Nb–Ti filaments and a nominal diameter of 0.73 mm after Ni plating, Cu/non-Cu ratio of 2.33 and filament diameter of $7-8$ μm. Meanwhile, RF Nb–Ti strand contains 4488 Nb–Ti filaments which are embedded in a copper matrix, is with diameter of 0.732 mm, Cu/non-Cu ratio of 1.63 and filament diameter of $6-7$ μm [5]. Transverse cross-section micrographs of both strands are shown in Fig. 1.

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B. *$I_c(B,T)$ and n-Values Measurements*

$I_c(B,T)$ and n-values were determined by an electric field criterion of 0.1 μVcm^{-1} and n values $0.1-1$ μVcm^{-1} averaged from three voltage taps with standard ITER I_c test barrel [6]. The data sets contain a large number of well-spread data points covering a wide field range at several temperature intervals.

The measurements for CN WST Nb–Ti strands from 60% and 90% of the production [7], [8] have been performed by the National Institute of Standards and Technology (NIST) in USA, and for RF Nb–Ti strand measurements were performed by Atominstitut (ATI), Vienna University of Technology for 30%, 60% and 90% of the production [9]–[11].

Regarding experimental error among the different measurements and strand billets from different production stages, typically it is in the range of 6–14 A, whereas the maximum can be above 20 A for high I_c (>500 A) [12]. This measurement uncertainty is comparable to that in the ITER benchmarking exercise, where the ΔI_c is about 8 A for a single laboratory and 17 A across all participants [13]. Some excellent control and good reproducibility in$I_c(B,T)$ measurement for ITER Nb–Ti strand have been achieved.

III. SCALING PARAMETERIZATION $I_C(B,T)$

A. *Determination of the Scaling Parameters*

The Bottura formula (equation (1)) with an assumption of a single pinning mechanism [4], [12], [14], [15] is adopted:

$$I_c(B,T)=\frac{C_0}{B}\left[1-\left(\frac{T}{T_{c0}}\right)^n\right]^\gamma\left[\frac{B}{B_{c2}(T)}\right]^\alpha\left[1-\frac{B}{B_{c2}(T)}\right]^\beta \tag{1}$$

where

$$B_{c2}(T)=B_{c20}\left[1-\left(\frac{T}{T_{c0}}\right)^n\right]. \tag{2}$$

C_0 is a scaling constant, B_{c20} is the upper critical field at zero temperature, T_{c0} is the critical temperature at zero field, α is the low field exponent of the pinning force, β is the high field exponent of the pinning force, γ is the exponent of the scaling constant temperature-dependent component, and n is typically 1.7 for Nb–Ti strands.

A self-field correction according to the ITER barrel configuration (equation (3)) has recently been formulated [14]:

$$B_{\mathrm{ITER}}=B_{\mathrm{app}}+\left(\frac{2}{R}-0.9\right)I_c\times10^{-4}\,\mathrm{T}\,A^{-1}. \tag{3}$$

where B_{app} is the applied magnetic field in T, R is the distance between the outermost superconducting filament and the center of the strand in mm and I_c is the critical current measured at that field. The distance between the outermost superconducting filament and the center of the strand is estimated by image analysis to be 341 μm [12].

The determination of the scaling parameters is subject to the curve fitting methods and criteria [12]. Here, the method based mainly on the procedure described by Bordini [15] using a step-by-step approach instead of ‘globally’ solving all parameters simultaneously is applied. Data with pinning force values smaller than 10% of the maximum F_p at 4.2 K are excluded [12].

TABLE I
PARAMETRIZATION FOR ITER NBTI STRANDS

Nb-Ti strand	*C₀ (A*T/mm²)*	*B_{c20} (T)*	*T_{c0} (K)*	*α*	*β*	*γ*	*n*
RF	19618	14.198	8.747	0.961	1.144	1.842	1.7
CN WST	16189	14.011	8.836	0.990	1.192	1.889	1.7

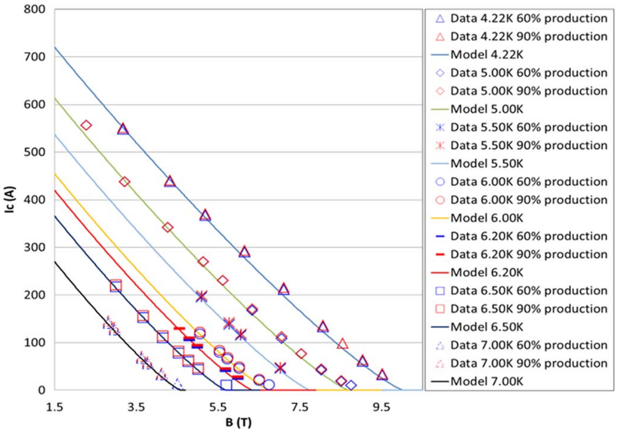

Fig. 2. Measured $I_c(B,T)$ data for CN WST strand over production and its prediction by scaling parameterization.

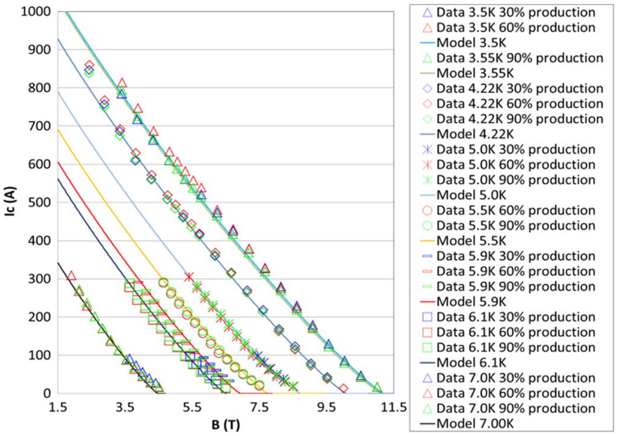

Fig. 3. Measured $I_c(B,T)$ data for RF strand over production and its prediction by scaling parameterization.

B. *$I_c(B,T)$ Scaling Parameterization for ITER Nb–Ti Strand*

Following the approach described in previous section, the single scaling parametrizations $I_c(B,T)$ are optimized for both CN and RF stands, taking into account all the measured $I_c(B,T)$ data together throughout the production for each supplier’s strand. $I_c(B,T)$ scaling parameters for both strands are listed in Table I.

Figs. 2 and 3 indicate measured $I_c(B,T)$ data over production and its prediction by the scaling parameterization for CN WST and RF strand, respectively. For CN WST strand, measured $I_c(B,T)$ at different production stages but the same B-T condition are similar with differences mainly below 5%, and worst case around 20%, whereas for RF strand, those are 5% and around 15%, correspondingly. This is partly due to their slightly varying Cu:non-Cu ratios (like 2.26–2.39 for CN WST strand) and strand diameters (0.727–0.730 mm).

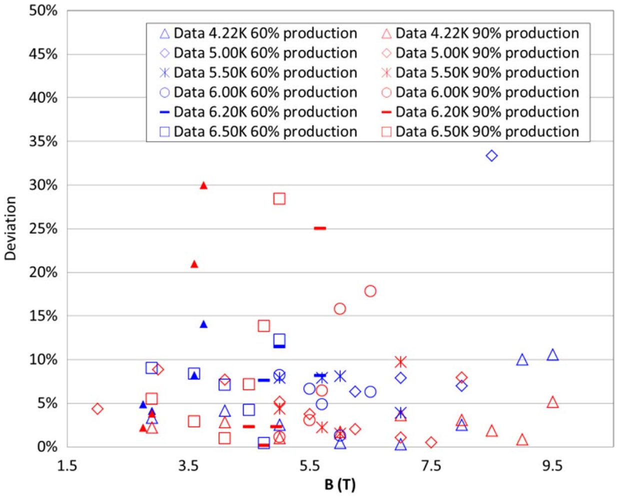

Fig. 4. Deviation between measured and predicted $I_c(B,T)$ data for CN WST strand over production.

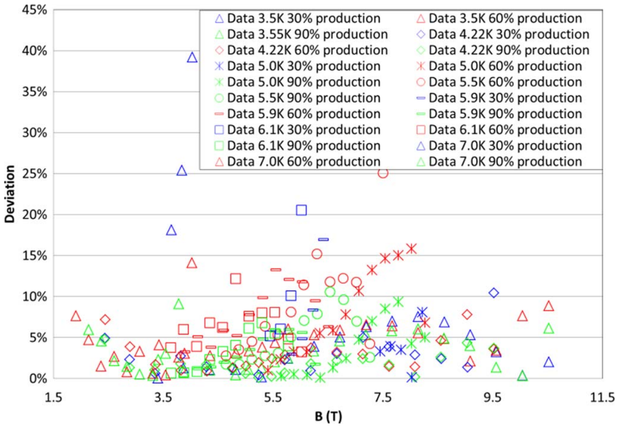

Fig. 5. Deviation between measured and predicted $I_c(B,T)$ data for RF strand throughout production.

The percentage deviation δ between measured I_{c_meas} and predicted I_{c_pred} data is defined as:

$$\delta = \frac{2\left|(I_{c\_\mathrm{pred}} - I_{c\_\mathrm{meas}})\right|}{(I_{c\_\mathrm{pred}} + I_{c\_\mathrm{meas}})}. \tag{4}$$

The results are shown in Figs. 4 and 5 for CN WST and RF strands throughout production, respectively. Those are mainly below 15% in the wide range of magnetic field and temperature, and even mostly below 5% in the PF coil operation condition region.

C. Discussion

As indicated in the previous section, a good agreement between measured and predicted $I_c(B,T)$ is achieved in the field range of 1.5 T to 11 T, and temperatures from 3.5 K to 7.0 K. The deviations are mainly below 15%, resulting in the conductor's current sharing temperature (T_{cs}) error < 0.14 K [12]. If the deviation on T_{cs} is achieved of the order of 0.1 K, which should be acceptable, since the error on T_{cs} due to various types of measurement uncertainties (I_c measurement, Cu: Cu:non-Cu ratios, strand diameter, etc.) is in the same order. Consequently, the single $I_c(B,T)$ scaling parameterization for each supplier's strand over production can be used to analyze the performance of Nb–Ti conductors made from these stands.

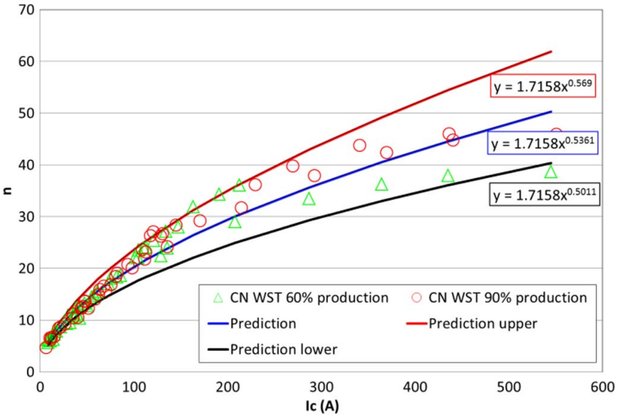

Fig. 6. Measured $n(I_c)$ data of CN WST strands over production and proposed $n(I_c)$ relationship.

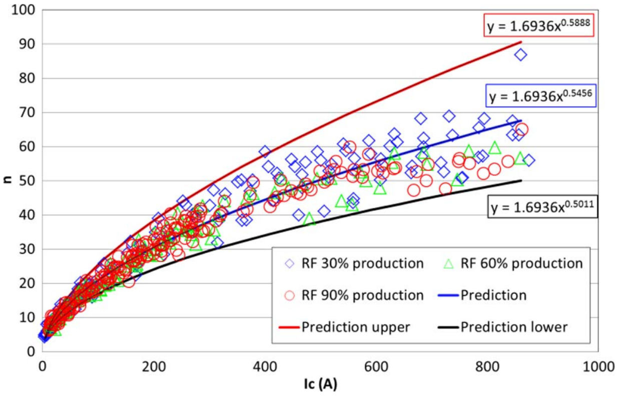

Fig. 7. Measured $n(I_c)$ data of RF strands over production and proposed $n(I_c)$ relationship.

But note that the $I_c(B,T)$ scaling parameterization underestimates I_c at high field/temperature (i.e. low current) and low field/temperature (i.e. high current) regions in the two ends (see Figs. 2 and 3). $I_c(B,T)$ scaling fitting parameters should be adjusted with narrowing down the condition window (B, T) for specific applications to achieve much higher accuracy, applied for example in low-field/high-I_c region (1.5–2 T and I_c up to 500 A within 5–6 K) for hysteresis loss analysis of PF and CC coils, as well as all busbars.

IV. POWER RELATIONSHIP OF $n(I_C)$

According to the same $I_c(B,T)$ data sets, a power relationship of $n(I_c)$ is proposed by fitting the data in Fig. 6 for CN WST Nb–Ti strand, which is

$$n = 1.7158 \times I_c^{0.5361} \tag{5}$$

and similarly for RF strand (see Fig. 7), $n(I_c)$ is

$$n = 1.6936 \times I_c^{0.5456}. \tag{6}$$

Moreover, upper and lower limiting cases are also indicated with the index range from 0.5011 to 0.5690 for CN WST strand and from 0.5011 to 0.5888 for RF strand.

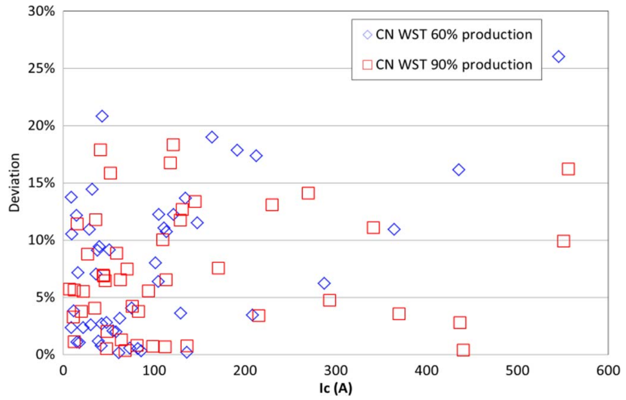

Fig. 8. Deviation between the measured and predicted $n(I_c)$ data for CN WST strand over production.

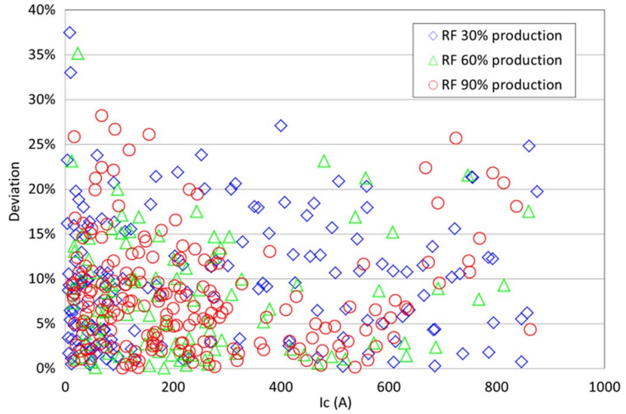

Fig. 9. Deviation between the measured and predicted $n(I_c)$ data for RF strand over production.

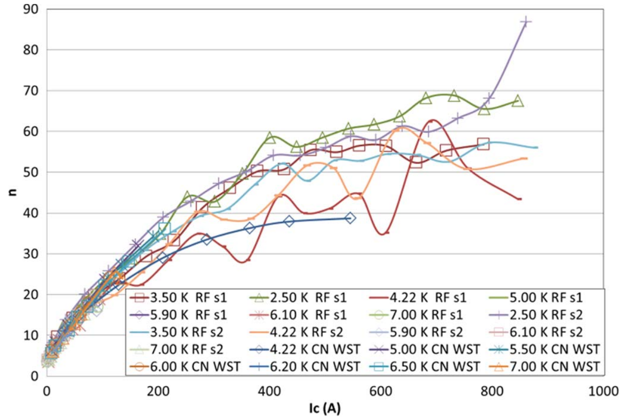

Fig. 10. Measured $n(I_c)$ data of various RF strands from 60% production and CN WST Nb–Ti strands from also 60% production at different temperatures.

The percentage deviation δ between measured n_{meas} and predicted n_{pred} data is defined as:

$$\delta = \frac{2\left|(n_{\text{pred}} - n_{\text{meas}})\right|}{(n_{\text{pred}} + n_{\text{meas}})}. \tag{7}$$

The results are shown in Figs. 8 (RF strand) and 9 (CN WST strand). For both, deviations mainly scatter below 20% for CN WST strand and 25% for RF strand. Considering the large fluctuation of the measured $n(I_c)$ under the same temperature and magnetic field (see the curves in Fig. 10), the error bar for n values in the measurement could be high (around 10–20%). The prediction of n values with a single proposed $n(I_c)$ relation for CN WST and RF Nb–Ti strand is reasonable.

V. CONCLUSION

With the aim of characterization of ITER Nb–Ti strands with single parameterization throughout massive production, the measurement results of the I_c and n in a wide range of applied magnetic field ($\sim$ 1.5 to 11 T) and temperature (3.5 to 7.0 K) for the CN WST and RF Nb–Ti strands are summarized and used. The optimized single scaling parameterization $I_c(B, T)$ and $n(I_c)$ for each CN WST and RF strand have been proposed, with reaching the minimal deviation for all the measured data over production. The deviations between measured and predicted $I_c(B, T)$ for all the measured data are mainly below < 15%, and even < 5% in the operation condition region. Although deviations for $n(I_c)$ are higher than those for $I_c(B, T)$, it is still acceptable considering the higher error in measurement for n value.

As a result, single scaling parameterization $I_c(B, T)$ and $n(I_c)$ can be simply used together for modeling the performance of ITER Nb–Ti CICCs. This is foreseen to contribute to the analysis of the Nb–Ti conductors made from these stands, and to assess possible evolution over production.

DISCLAIMER

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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