

Editorial

Synopsis of Special Issue on Superconductors and Magnetic Materials

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Abstract

This editorial consists of a synopsis of the research in the Special Issue on “Superconductors and Magnetic Materials”, specifying the studies and highlighting main results and conclusions. This collection of research (1) demonstrates the possibility of notably decreasing AC losses by replacing the copper encapsulation of rare Earth barium copper oxide tapes with strong magnetic encapsulation; (2) predicts typical gains expected from soft-magnet and superconductor flux concentrators for low magnetic field sensing; (3) reveals that the n -value surfaces of high- T_c tapes can be estimated with a high accuracy using feed-forward deep neural network learning; (4) predicts the detection of a monopole plasma phase in high- T_c iron-based superconductors with a T_c above 70 K; and (5) proposes an analytical model to accurately predict the gap-to- T_c ratio for yttrium hydrides at high pressures.

Keywords: magnetic tape encapsulation; soft magnetic flux concentrator; superconducting flux concentrator; n -value surfaces; feed forward machine learning; two-condensate charged systems; deconfinement phase transition; gap-to- T_c ratio; yttrium hydrides



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1. Introduction

This editorial provides a synopsis of a Special Issue on Superconductors and Magnetic Materials, presenting a general overview of the studies, main results, and contributions of the five research papers included. Section 2 refers to a study on alternating current (AC) losses of rare Earth barium copper oxide (REBCO) tapes encapsulated with magnetic materials. Section 3 refers to research on soft magnetic and superconducting magnetic flux concentrators through theoretical simulations and experiments. Section 4 relates to a feed-forward deep neural network (FFDNN) technique that enhances the predictive modeling of n -value surfaces of representative High-Temperature Superconductor (HTS) tapes. Section 5 presents the results and conclusions from a numerical analysis on monopole production and deconfinement transition in two-condensate charged systems, which is verified in the case of high- T_c iron-based superconductors with a critical temperature above 70 K. Using previous experimental data, Section 6 proposes and validates an analytical model to predict the critical temperature T_c and gap-to- T_c ratio characteristics of yttrium hydride (Y-H) superconductors.

2. Study on AC Losses of REBCO Tapes Encapsulated with Magnetic Materials

When REBCO tapes operate with alternating currents or alternating external fields, AC losses occur [1]. Excessive AC losses may cause the tapes to quench, affecting the critical current density and critical magnetic field [2]. Previous studies proposed the introduction of magnetic materials around commercial REBCO tapes to reduce AC losses [3].

This paper studies the AC losses of representative REBCO tapes by replacing the traditional copper encapsulation layer with a magnetic encapsulation layer [4]. Tapes encapsulated with copper, consistent with Superpower SCS4050's 4 mm width, were considered as a reference. These tapes have Hastelloy, silver, and REBCO layers, respectively, with 50 μm , 2 μm , and 1 μm thicknesses. The copper encapsulation layer has a 20 μm thickness. A frequency of 50 Hz was considered by default. Results from a finite element analysis (FEA) using the H-formulation have shown that when the ratio between the maximum applied current and the critical current I_p/I_c is lower than about 0.5 the transport losses with copper encapsulation are lower than with magnetic encapsulations. For ratios higher than 0.5, the transport losses with magnetic encapsulations are the same as those with the copper. The characteristic dependence of the superconducting-layer-specific transport losses to the applied current I_p , which was calculated via a numerical simulation, approximately aligns with the that predicted using the Norris analytical model [5]. The current penetration along the tape width at the instant when the applied current magnetic flux is at its maximum is partial, with an applied external magnetic flux density B_{ext} equal to 0.01 T and total with B_{ext} equal to 0.1 T. This agrees with the results obtained for the magnetization of REBCO bulks [6].

For applied external magnetic flux densities with a B_{ext} lower than 0.1 T, the tape magnetization losses tend to be lower with strong magnetic encapsulations. For a maximum magnetic flux density of 0.01 T, the specific magnetization loss with strong magnetic encapsulation is about 10^{-5} J/m/cycle, whereas with weak magnetic and copper encapsulations the loss is, respectively, about 2×10^{-4} J/m/cycle and 6×10^{-4} J/m/cycle. For frequencies between 50 Hz and 1000 Hz, the specific magnetization losses with a B_{ext} equal to 0.05 T are about 6.5×10^{-3} J/m/cycle with strong encapsulation, while copper encapsulation assumes values higher than 1.6×10^{-2} J/m/cycle. The characteristics obtained for the specific magnetization losses of the superconducting layer with the B_{ext} approximately follow those that were predicted analytically using the Brandt model [7].

In conclusion, at low transport currents, copper-encapsulated tapes have the lowest transport losses. Under high transport currents, the transport losses with magnetic and copper encapsulation are almost the same. With respect to magnetization losses, the tapes with strong magnetic encapsulation present significantly lower losses than those with copper encapsulation.

3. Magnetic Flux Concentration Technologies Based on Soft Magnets and Superconductors

This paper studies soft magnetic and superconducting flux concentration technologies through FEA simulations and experiments, analyzing the impact of different structural parameters on the magnetic field amplification performance [8]. A study demonstrated that with a magnetic flux concentration between the side permanent magnet (PM) rings of a rotor and external PM rings, it is possible to enhance the guidance of a passive magnetic bearing by about 100 times with high-temperature superconducting (HTS) bulks magnetized by zero-field cooling (ZFC) [9].

Flux concentrators (FCs) for high-sensitivity magnetic sensors, which are able to detect weak magnetic fields, are necessary for applications in geological and marine exploration [10], geomagnetic navigation [11], non-destructive testing [12], and bio-magnetic signal detection [13]. The aim is to detect weak magnetic fields at the pico-Tesla (pT) and femto-Tesla (fT) levels, typical of magnetocardiography and magnetoencephalography, with the use of superconductors and soft magnetic materials with high magnetic permeability.

For a T-shaped magnetic FC composed of a high-permeability material, the dependence of the magnetic flux concentration gains G_m on its dimensions and magnetic relative permeability was predicted via an FEA. Concentration gains G_m of about 11 times are achieved for magnetic relative permeabilities higher than 5000, typical of iron–boron and iron–cobalt soft magnetic alloys.

The dependence of the concentration gains G_s of a superconducting FC on its dimensions was also predicted via an FEA. Such devices consist of a superconducting loop containing a constriction section. Currents are induced in the superconducting loop under the measurement of a varying weak magnetic field. There is a current concentration in the constriction section, where a much higher current density is identified. The obtained results have revealed that concentration gains G_s of about 75 times are possible to attain with loop internal perimeters of 40 mm and constriction widths $w_s = 0.1$ mm.

To experimentally validate the concentration gains predicted by the FEA, highly sensitive tunnel magneto-resistances (TMRs), with a sensitivity of 7.1 mV/Oe at 77 K, were used as magnetic-sensitive elements to transduce the obtained concentration fluxes into voltages [14]. In practice, the TMR will be part of a soft magnetic FC and a superconducting FC to enable the transduction of the measured concentration magnetic fluxes into voltage-readable values [15]. Measuring slopes of 140 mV/Oe were experimentally validated for composed devices, including the soft magnetic FC or superconducting field FC and TMR transducers.

4. Predictive Modeling of n -Value Surfaces in High- T_c Superconductors Using a Feed-Forward Deep Neural Network Technique

The n -value from the power-law formula describes the sharpness of the transition from the superconducting state to the normal resistive state as the current density approaches the critical current density. Its pattern varies under different operating temperatures T , applied magnetic flux densities B , and magnetic field angles θ [16]. Generally, high n -values indicate a sharp transition, which is desirable in order to maintain stability in superconducting applications, especially for high-precision applications like magnetic resonance imaging (MRI) machines and particle accelerators [16,17].

The n -value surfaces refer to the graphical representation of n -values over a range of operating conditions, such as temperature and magnetic field strength [18,19]. These highly non-linear surfaces provide a comprehensive understanding of the material's performance and stability across different working conditions. Traditionally, the estimation of n -values has relied on the use of look-up tables and empirical methods limited by their dependency on pre-existing data. Look-up tables rely on linear regression between two available data points, which will increase the error of estimation.

Simpler machine learning (ML) techniques have improved the estimation process by identifying n -value patterns, providing more accurate predictions in significantly less time than even look-up tables [20,21]. Deep learning (DL) enables the capture of intricate patterns from vast and complex datasets [21]. The use of the feed-forward deep neural network (FFDNN) learning technique is motivated by the need for higher accuracy and adaptability [22].

This paper investigates the use of the FFDNN learning technique for the predictive modeling of n -value surfaces, utilizing a comprehensive dataset that includes experimental data on material properties and operational conditions affecting superconductors' behavior [23]. The study uses the training data of six HTS tapes from different manufacturers, collected from an open access website by the Robinson Research Institute at the Victoria University of Wellington in New Zealand [24]. The data with more than 120,000 points was treated and preprocessed to cover the n -value of different HTS tapes for a range of operating temperatures T between 15 K and 90 K, magnetic flux densities B between 0.01 T and 8 T, and magnetic field angles θ between 2° and 240° .

The FFDNN architecture had six hidden layers, each with sixty-four neurons and four inputs—one for the type of HTS tape and the other three for the operating temperature, magnetic flux density, and magnetic field angle. One output was defined for the computed n -value. Each neuron in a layer receives input from all neurons in the previous layer, processing it through a weighted sum followed by a non-linear activation function, such as the hyperbolic tangent (tanh) or the Rectified Linear Unit (ReLU), and then passes the output to the neurons of the next layer.

N -value surfaces that were dependent on the magnetic flux density B and magnetic field angle θ were predicted for the six HTS tapes from different manufacturers, under operating temperatures of 30 K, 60 K, and 75 K. Additionally, the n -value is dependent on the operating temperature T and magnetic field angle θ when a magnetic flux density B of 0.01 T is applied. Results have shown that the developed FFDNN model can predict the n -value with an R-squared accuracy higher than 99.5%.

5. Numerical Study on Monopole Production and Deconfinement Transition in Two-Condensate Charged Systems

Condensed matter Bose systems may contain effective monopole quasiparticles in their excitation spectrum [25]. Monopole or anti-monopole excitation is allowed in the two-band Ginzburg–Landau theory [26]. At low temperatures, the monopole and anti-monopole form a tightly bound state due to the string tension between these quasiparticles. With the increase in temperature, the two-condensate charged system will enter the so-called deconfinement phase, in which the thermal fluctuation will dominate the string tension, and the monopole and anti-monopole pairs at the string endpoints will become nearly free particles. A plasma phase of monopoles and anti-monopoles in the sample, above the deconfinement transition temperature, occurs for the two-band superconducting condensed matter systems with spin ice lattice structures [27].

This paper presents a numerical study on monopole production and deconfinement transition in two-condensate charged systems, predicting the probable detection of a monopole plasma phase in high- T_c iron-based superconductors with a critical temperature above 70 K [28]. The predictions are based on a numerical analysis, mapping the two-band Ginzburg–Landau theory [26] to an extended critical power model CP(1) and then performing Monte Carlo simulations [29] on the cubic lattice with periodic boundary conditions.

6. A Study on the Critical Temperature and Gap-to- T_c Ratio of Yttrium Hydride Superconductors

Previous research has demonstrated that lanthanum hydride (La-H) and yttrium hydride (Y-H) systems exhibit the presence of a stable hydrogen-rich phase for superconductivity in high-pressure conditions [30]. The superconducting properties of YH_3 , YH_4 , YH_6 , and YH_9 compounds were investigated [31]. They reported that the superconducting state of compounds YH_6 and YH_9 is verified below the critical temperatures, respectively, of 200 K and 243 K when subjected to pressures of 183 GPa and 201 GPa, respectively. These

findings are consistent with the predictions for YH_9 with T_c in the range of 253–276 K at 200 GPa [30] and for YH_6 with T_c in the range of 251–264 K at 110 GPa [32]. The critical temperature of superconductivity T_c is related to the gap energy from the valence and conduction bands with a given ratio $R = 2\Delta/T_c$, known as the gap-to- T_c . A previous report identified gap-to- T_c ratios R between 4.7 and 5.5 for yttrium hydrides [33].

This paper investigates the influence of pressure on the superconducting properties of yttrium hydride materials [34]. An analytical methodology that depends on the lattice structure of the yttrium hydrides is proposed to calculate the gap-to- T_c ratio R for several Debye cut-off temperatures Θ_D and Coulomb potentials μ^* [35]. Typical values of Debye cut-off temperatures Θ_D between 684 K and 1333 K [33] and Coulomb potentials μ^* between 0.1 and 0.13 [30] were reported for lattice structures of yttrium hydrides. From the presented analytic methodology, the characteristics of the dependence of T_c and R on the room pressure were predicted for the yttrium hydrides YH_4 , YH_6 , YH_7 , and YH_9 . The predicted value of T_c for YH_6 and YH_9 was approximately 150 K with ($\mu^* = 0.13$, $\Theta_D = 648$ K) and 240 K with ($\mu^* = 0.1$, $\Theta_D = 1333$ K) for pressures between 170 GPa and 270 GPa. The predicted gap-to- T_c ratios R were between 3.76–3.85 and 3.57–3.83 for YH_6 and YH_9 in the same range of pressures. In conclusion, the values of T_c and R predicted using the analytical models proposed in this study for YH_6 and YH_9 are close to the experimental ones stated in previous reports, confirming the validity of the proposed analytical models.

7. Conclusions

The research presented in this Special Issue has produced the following main conclusions: (i) The replacement of the copper encapsulation from REBCO tapes with strong magnetic encapsulation promotes a notable decrease in magnetic hysteresis AC losses. (ii) Flux concentration gains of about 11 and 75 times were validated for T-shaped soft magnetic FCs composed of materials with magnetic permeabilities higher than 5000 and superconducting FCs consisting of a detection loop with current constriction, respectively. (iii) With the FFDNN technique, it is possible to predict n -value surfaces for high- T_c tapes with an R-squared accuracy higher than 99.5%. (iv) The probable detection of a monopole plasma phase in high- T_c iron-based superconductors with a critical temperature above 70 K was predicted via a numerical study on monopole production and deconfinement transition in two-condensate charged systems. (v) An analytical model proposed to predict the critical temperature T_c and gap-to- T_c ratio for yttrium hydrides (Y-H) at high pressures was validated by comparing the obtained results with experimental results stated in previous reports.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
DL	Deep Learning
FEA	Finite Element Analysis
FC	Flux Concentrator
FFDNN	Feed-Forward Deep Neural Network
HTS	High-Temperature Superconductor
La-H	Lanthanum Hydride
ML	Machine Learning
MRI	Magnetic Resonance Imaging
REBCO	Rare Earth Barium Copper Oxide
TMR	Tunnel Magneto-Resistance
Y-H	Yttrium Hydride

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