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Olivier Girard, Jean-Christophe Ginefri, Marie Poirier-Quinot, Luc Darrasse. Method for nonlinear characterization of radio frequency coils made of high temperature superconducting material in view of magnetic resonance imaging applications. *Review of Scientific Instruments*, 2007, 78 (12), pp.124703. 10.1063/1.2825241 . hal-02269965

HAL Id: hal-02269965

<https://hal.science/hal-02269965>

Submitted on 23 Aug 2019

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Method for nonlinear characterization of radio frequency coils made of high temperature superconducting material in view of magnetic resonance imaging applications

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(Received 1 August 2007; accepted 24 November 2007; published online 28 December 2007)

A contactless method based on reflectometry to accurately characterize an inductive radio frequency (rf) resonator even in the occurrence of a strong electrical nonlinearity is presented. Nonlinear extraction of the unloaded quality factor and resonance frequency is possible by combining an initial low-level swept-frequency calibration with high-level single-frequency measurements. The extraction protocol relies on a simple intrinsic R , L , C model and does not involve a fitting procedure according to a particular nonlinearity model. It includes a correction for strong coupling conditions between the probe and the rf coil, which allows extending the analysis over a wide range of transmitted power. Electrical modeling based on the extracted intrinsic data allows predicting the coil behavior when loaded by any kind of matching network. The method will have implications in different domains such as Magnetic Resonance (MR) applications with superconducting probe heads or analysis of rf properties in nonlinear materials. The method is demonstrated here by characterizing a high temperature superconducting (HTS) coil dedicated to MR imaging at 64 MHz. The coil consists in a multiturn spiral design that is self-resonant close to the MR frequency of interest. The Q factor and the resonance frequency are determined as a function of the actual power dissipated in the HTS coil accounting for losses occurring in the measurement system. Further characteristics of the HTS coil are considered in the present paper. The relation between the transmitted power and the magnetic field generated by the coil, which is the most relevant characteristics for MR applications, is directly accessible. The equivalent impedance of the coil under test is also expressed as a function of the total current flowing in the windings. The method could be extended to assess the fundamental properties of the nonlinear material (e.g., the London penetration depth or the critical current density) by including any pertinent model.

© 2007 American Institute of Physics. [DOI: [10.1063/1.2825241](https://doi.org/10.1063/1.2825241)]

INTRODUCTION

High temperature superconducting (HTS) coils dedicated to magnetic resonance (MR) applications have been shown to significantly enhance the signal to noise ratio, which allows reducing either the size of the elementary detected volume (voxel) or the total scan duration in biomedical MR imaging.¹ HTS coils have also been applied early in high-resolution MR spectroscopy with typical sensitivity improvements by a factor of 4.² Indeed HTS materials strongly lower the noise contribution coming from the radio frequency (rf) coil since they offer surface resistivities lower than conventional copper by a few orders of magnitude. However, it is well known that HTS devices exhibit nonlinear electrical properties as a function of the applied current density.³ This is still an issue since a unified model has not been established yet to predict the nonlinear behavior over extended temperature and current ranges.⁴ Nonlinearities have been reported in MR imaging applications^{5,6} and can reduce the experimental performance since they are not accounted for in practical implementations. A major consequence is that rf transmission and reception steps can no longer be considered reciprocal as in classical MR (Ref. 6) since the corresponding power levels are different. During transmission of

nonrectangular rf pulses, nonlinearity may modify the pulse shape and alter the selective frequency or space excitation profiles. It may also affect the flip angle and the power deposited in the sample, respectively, leading to a misadjusted image contrast and a misevaluated heating hazard. Thus, the determination of the nonlinear characteristics of a given HTS coil is required to preserve the reliability of the diagnosis and the safety of the examination.

The quality factor of the rf coil is a highly relevant parameter in MR applications as it is related to the efficiency for transmission and to the sensitivity of the experiment during reception.^{7,8} Actually it represents the ratio of the stored magnetic energy by the rf coil over the dissipated energy per cycle. The classical method to measure the quality factor on the rf coil tuned at the MR frequency is by using a swept-frequency analysis of the resonant circuit. As recently pointed out^{9,10} the method is inappropriate to characterize a nonlinear resonant circuit. Indeed the intrinsic electrical parameters vary as the carrier frequency approaches the resonance since the cancellation of the reactance increases the power transmitted to the coil circuit. The change in electrical parameters appears at high power levels as a drop of the quality factor and as a weak change of the resonant fre-

FIG. 1. Swept-frequency analysis of a nonlinear HTS coil performed with the measurement bench of Fig. 2. At low incident power (-30 dBm), a classical Lorentzian shape is observed (dotted line) corresponding to a linear behavior of the HTS coil. At high incident power ($+15$ dBm) huge distortions due to the nonlinear behavior are evidenced: the solid and dashed lines correspond, respectively, to down-up and up-down frequency sweeps; the gray and black lines have been acquired with respective integration filter bandwidths of 300 and 3 Hz and emphasize complex out-equilibrium effects possibly including long-term thermal drifts.

quency, related to respective increases of the resistivity and of the dynamic inductance of the HTS material.^{10,11} The actual changes cannot be reliably evaluated since the Lorentzian shape classically observed with linear materials is affected by major distortions such as displayed on Fig. 1. It clearly appears that the maximum of the gain response can no more be attributed to the resonance frequency in a nonlinear regime.

Previous attempts to characterize the nonlinear behavior of inductive resonators made of HTS material have been reported, but with inappropriate bandwidth measurement^{5,12} or incomplete assessment of the actual transmitted power.^{5,6,12,13} Such approaches fail to extract the intrinsic nonlinear features. The method described in this paper is an extension of the inductively coupled dual- and single-loop techniques initially proposed for contactless evaluation of linear rf coils.^{14,15} Based on reflectometry at a single frequency, it can be easily implemented and provides a complete rf characterization valid in both linear and nonlinear regimes. The extraction protocol relies on a simple R, L, C model and does not involve a fitting procedure according to a particular nonlinearity model. It includes a correction for strong coupling conditions between the probe and the rf coil, which allows extending the analysis over a wide range of transmitted power.

THEORY

Consider a measurement bench made of a rf source that powers an inductive probe magnetically coupled to the HTS coil via a bidirectional coupler (Fig. 2) as suggested in the literature.¹⁵ Here the HTS coil is represented by the equivalent series R, L, C circuit tuned to the pulsation ω_0 and having the quality factor Q defined as $L\omega/R$ at the current angular frequency ω . The probe is represented by the equivalent series R_p, L_p, C_p circuit and is intrinsically matched to the impedance R_0 of the rf source at ω_0 (i.e., $R_p=R_0$ and

FIG. 2. Modeling of the measurement bench. The nonlinear HTS coil properties are inductively probed by reflectometry using a linear measurement bench.

$L_p C_p \omega_0^2 = 1$). All components are assumed to be ideal ones and the total reactance of the probe circuit to be negligible compared to R_0 at observed frequencies.

The effect of the magnetic coupling of the rf coil into the probe circuit is equivalent to introducing the additional series impedance $Z_{in} = M^2 \omega^2 / Z$, where Z is the complex impedance of the HTS coil circuit and M the mutual inductance between the two circuits. The reflection coefficient ρ is defined at the input plane from the incident and reflected powers, respectively, P_{inc} and P_{refl} , as $(P_{refl}/P_{inc})^{1/2}$,

$$\rho(\omega) = \frac{Z_p + Z_{in} - R_0}{Z_p + Z_{in} + R_0}, \quad (1)$$

where Z_p is the total impedance of the probe circuit.

The dual-reflection measurement¹⁵ involves a reference data set $\rho_0(\omega)$ taken in the absence of the coil ($M=0$) and defines the compensated reflection coefficient as $\rho_{comp}(\omega) = \rho(\omega) - \rho_0(\omega)$.

In the linear regime, R has a constant value and $\rho_{comp}(\omega)$ is independent of the incident power level. A classical swept-frequency analysis of $|\rho_{comp}(\omega)|$ allows to extract Q ,

$$Q = \frac{\omega_0 / \text{BW}_{-3 \text{ dB}}}{1 - \rho_{comp}(\omega_0)} \quad (2)$$

linear regime

where $\text{BW}_{-3 \text{ dB}}$ is the 3 dB attenuation bandwidth measured on the $|\rho_{comp}(\omega)|$ frequency response. As compared to the quality factor usually estimated by $\omega_0 / \text{BW}_{-3 \text{ dB}}$, the denominator in Eq. (2) represents a correction factor accounting for the power dissipated in the probing system. Without correction the extra dissipated power would lead to an underestimated apparent quality factor. Using any arbitrarily strong coupling condition, the correction is equivalent to measuring Q under the weak coupling condition [$\rho_{comp}(\omega_0) \approx 0$].

When the HTS coil is driven at high incident power levels and enters the nonlinear regime, R is no more constant along a frequency sweep since the power transmitted to the coil varies across the resonance. In addition, the HTS coil inductance may slightly vary due to a change of the London penetration depth.¹¹ A new derivation of Q , no more based on the previous swept-frequency analysis and accounting for simultaneous changes of resistance and reactance, is then needed.

The following expression: $Z_{in} = M^2 \omega^2 / Z = 2R_0 \rho_{comp}(\omega) / [1 - \rho_{comp}(\omega)]$, gives the real and imaginary parts of the HTS coil impedance Z as a function of the modulus and the phase $[\angle \rho_{comp}(\omega)]$ of $\rho_{comp}(\omega)$, respectively,

$$R(\omega) = M^2 \omega^2 \frac{\cos[\angle \rho_{comp}(\omega)] - |\rho_{comp}(\omega)|}{2R_0 |\rho_{comp}(\omega)|}, \quad (3)$$

$$X(\omega) = -M^2 \omega^2 \frac{\sin[\angle \rho_{\text{comp}}(\omega)]}{2R_0 |\rho_{\text{comp}}(\omega)|}. \quad (4)$$

Both L and M may be assumed to be almost constant since the redistribution of the supercurrent occurs at a small scale compared to the HTS coil and probe dimensions. A variation of the HTS coil reactance resulting from a slight change of L can be probed using Eq. (4). Moreover, the change ΔX in reactance can be used to monitor the resonance frequency shift due to the change of inductance ΔL ,

$$\Delta \omega_0 \approx -\frac{1}{2} \frac{\Delta X}{L} = -\frac{1}{2} \frac{\Delta L}{L} \omega_0. \quad (5)$$

The three above equations indicate that single-frequency measurements of Q and $\Delta \omega_0$ are possible once L/M^2 is known. The latter value is easily estimated from a single low-level swept-frequency measurement since both above derivations of Q are applicable in the linear regime. As long as the probe is maintained at a fixed position relatively to the HTS coil, the low-level calibration can be used as the preliminary step of a nonlinear characterization of the HTS coil using single-frequency measurements at higher levels.

The power dissipated in the HTS coil $P_{\text{coil}} = R|I|^2$ is evaluated as

$$P_{\text{coil}}(\omega) = \text{Re}(Z_{\text{in}})|I_P|^2 = 2P_{\text{inc}}|\rho_{\text{comp}}(\omega)|\{\cos[\angle \rho_{\text{comp}}(\omega)] - |\rho_{\text{comp}}(\omega)|\}. \quad (6)$$

By combining Eqs. (3)–(6), the nonlinearity of the HTS coil can then be expressed either directly in the form of a (Q, P_{coil}) and $(\omega_0, P_{\text{coil}})$ characteristics, or alternatively as a $(R, |I|)$ and $(X, |I|)$ characteristics when the value of L is known.

To implement MR experiments, the dependence of the rf magnetic field B_1 generated by the HTS coil as a function of the applied power is required. In opposition to the characterization steps above, the amplitude and phase of B_1 can be derived from ρ_{comp} measurements without a low-level calibration, according to

$$B_1^{S_P}(\omega) = \frac{MI_C}{S_P} = \frac{2\rho_{\text{comp}}(\omega)}{\omega S_P} \sqrt{2R_0 P_{\text{inc}}}, \quad (7)$$

where $B_1^{S_P}$ is the average rf magnetic field through S_P , the equivalent area of the probe. Assuming a negligible deformation of the B_1 field, it is possible to derive the local nonlinear characteristics (B_1, P_{coil}) from the spatially averaged $(B_1^{S_P}, P_{\text{coil}})$ characteristics,

$$B_1 = \frac{B_{1 \text{ ref}}}{B_{1 \text{ ref}}^{S_P}} B_1^{S_P}, \quad (8)$$

where $B_{1 \text{ ref}}$ and $B_{1 \text{ ref}}^{S_P}$ are single data points measured at the same power $P_{\text{coil ref}}$ level. $B_{1 \text{ ref}}$ and $P_{\text{coil ref}}$ may be extracted *in situ* by MR using a standard rf-pulse calibration.⁷ In the actual MR experimental setup with a particular coil-transmitter matching network, the power transmitted to the HTS coil has to be monitored in order to account for the variable power reflection. Alternatively, on-the-bench local measurement of B_1 is achievable by using a small probe

FIG. 3. Experimental setup. The HTS coil (a) is a multiturn transmission line resonator (Ref. 16). The pickup coil is used to probe local B_1 (b). The high-power setup (c) involves a dedicated probe made of a single-turn copper-wire loop and a high-power 50Ω load connected using a coaxial cable. The probe is connected to the rf amplifier and the multireceiver MR console through the dual-directional coupler.

making negligible the variation of B_1 across S_P . Such a small probe allows fully characterizing the HTS coil by bench measurement. However, a larger probe may be preferred to investigate high levels of P_{coil} , since it can provide a stronger coupling coefficient and thus a larger power transfer to the HTS coil.

EXPERIMENT

The experimental setup and the HTS coil are displayed on Fig. 3. The HTS coil characterized here is a 12 mm diameter multiturn transmission line resonator¹⁶ made of YBaCuO deposited on a sapphire r-cut dielectric substrate (THEVA, Ismaning, Germany) and incorporated in a cryogenic setup suitable for proton micro-MRI at 1.5 T (64 MHz). The HTS coil is maintained at an actual temperature of about 80 K. A single-turn rf coil of same diameter as the HTS coil, but made of copper instead of YBaCuO and tuned by a 250 pF chip capacitor, was investigated in order to check the validity of the single-frequency characterization.

The probe used for the nonlinear extraction at high-power level is a single-turn copper-wire loop ($\varnothing$ 12 mm, same diameter as the HTS coil) tuned to 64 MHz with a 150 pF capacitor and matched to the rf source impedance using an R_P value of 50Ω . The actual R_P is implemented using a $\lambda/2$ coaxial cable terminated by a high-power 50Ω load. The attenuation and phase delay introduced by the transmission line of the probe have been measured and are corrected in the ρ measurements.

The low-power swept-frequency analysis is performed using a network analyzer (Agilent E5061A, USA) based on its own integrated dual-directional coupler.

The high-power measurements are done in a pulsed mode with a multireceiver MR console (Tecmag Apollo,

Houston, TX, USA), a 2 kW rf amplifier (ENI MRI 2000, Rochester, NY, USA) and a -40 dB dual-directional coupler (RFPA RFC 001400-40-600, Artigues Pres Bordeaux, France). The complete setup including the MR console and the directional coupler is calibrated at the input plane following a classical short/open/load procedure according to a one-port error model.¹⁷ The rf pulses have a rectangular shape with 2 ms duration and are periodically applied with a repetition time T_R . The value of T_R must be kept sufficiently long to avoid thermal drifts. The actual duty cycle corresponding to nonobservable drifts does not exceed 1% at the highest power levels. The incident and reflected waves are digitally sampled at a dwell time of $3 \mu\text{s}$ and averaged over a series of hundred rf pulses during the postprocessing step. A hundred samples at the center of each averaged pulse are considered in order to give the mean and standard deviation of the measured ρ . Error bars on the results are estimated with the error propagation model developed in Appendix, taking the mean and standard deviation of measured P_{inc} , $|\rho_{\text{comp}}|$, and $\angle\rho_{\text{comp}}$, plus a 0.05 dB uncertainty affecting the correction for attenuation in the transmission line of the probe.

For the bench measurement of local B_1 , the pickup coil consists in a single-turn copper-wire loop wrapped around a 3 mm diameter nylon mandrel, tuned to the MR frequency with an 80 pF capacitor and matched to the receiver by inserting a 47Ω series resistance. $B_{1 \text{ ref}}$ is measured along the coil axis at 2 mm from the coil plane which is the minimum distance needed for the cryostat insulation. Some inaccuracy may be due to the inexact knowledge of the loop area and of the actual position of the HTS coil in the cryogenic setup. Such systematic errors are not reported in the results since they do not affect the shape of the nonlinearities and could be eliminated by using further calibration procedures.

The direct measurement of L at the HTS coil ends is not accessible with the present experimental setup. Instead, the bench measurement of $B_{1 \text{ ref}}$ is combined with a Biot-Savard computation of the B_1/I ratio, assuming the multiturn HTS coil geometry with an infinitesimally thin wire and negligible propagation effects. Estimated values of I , R , and L are then deduced from simultaneous measurements of $B_{1 \text{ ref}}$, P_{coil} , and Q .

RESULTS

Confidence test with the copper rf coil

The copper rf coil exhibits a Q of 91 by swept-frequency analysis using a low coupling condition [$\rho_{\text{comp}}(\omega_0)$ of -31 dB], a narrow integration filter (100 Hz bandwidth), and a RF source level of $+10$ dBm. From this reference value of Q , a confidence interval of $[-2.5\%, +1\%]$ is observed with the pulsed single-frequency measurement over a domain of coupling conditions [$\rho_{\text{comp}}(\omega_0)$ of -30 to -5 dB] and of incident power levels (-25 to $+50$ dBm).

The extracted value of L is 26 nH from the local B_1 measured over a range of 2–15 mm distances along the copper rf-coil axis. This is in agreement within less than 3% error compared to the value obtained from a combined

FIG. 4. Experimental quality-factor drop (a) and resonance-frequency shift (b) expressed as a function of the power dissipated in the HTS coil. The low-level resonance frequency setting the shift reference is 63 910 MHz. The lowest-power data point is obtained in the linear regime using swept-frequency analysis under weak coupling condition, whereas higher-power data points are extracted from single-frequency measurements under strong coupling conditions.

measurement of the resonance frequency and the tuning capacitor.

Nonlinear characterization of the HTS coil

The pulsed characterization using a frequency of 63.910 MHz and an incident power range of -20 – 50 dBm leads to the (Q, P_{coil}) and $(\Delta\omega_0, P_{\text{coil}})$ characteristics of the HTS coil displayed on Fig. 4. This frequency corresponds within ± 0.1 kHz to the low-level resonance observed by swept-frequency calibration under strong coupling conditions [$P_{\text{inc}} = -45$ dBm, $\rho_{\text{comp}}(\omega_0) = -0.13 \pm 0.01$ dB and $\omega_0/\text{BW}_{-3 \text{ dB}} = 1270 \pm 10$]. The lowest-power Q data point of $107\,000 \pm 3\%$ is observed using the swept-frequency analysis performed in the low coupling condition [$\rho_{\text{comp}}(\omega_0)$ of -36 dB], with a narrow integration filter (10 Hz bandwidth) and a RF source level of -30 dBm. Up to this power level, not actually shown in the figure, neither the quality factor nor the resonance frequency exhibits significant variations indicating that the HTS coil behaves linearly. A strongly nonlinear behavior is evidenced on the (Q, P_{coil}) characteristics above 10^{-4} W. Up to this level, the resonance frequency stays at $63.910 \text{ MHz} \pm 1 \text{ kHz}$. Above 10^{-4} W it decreases progressively until reaching about -230 kHz at the highest power of 7 W.

Figure 5 displays the $(R, |I|)$ and $(X, |I|)$ characteristics based on the previous data set combined with a measured L of $4.5 \pm 0.8 \mu\text{H}$. The values of R and X at the lowest-power level are $17 \pm 0.5 \text{ m}\Omega$ and $0 \pm 10^{-4} \Omega$, respectively. The strong nonlinear regime is observed above 0.05 A with a

FIG. 5. Experimental real (R) and imaginary (X) parts of the HTS coil equivalent impedance expressed as a function of the current flowing in the windings. These characteristics are extracted with $L=4.5\ \mu\text{H}$ and the same data set as in Fig. 3.

power-law exponent progressively decreasing from 2.9 to about 1.5 at the highest current value of 0.7 A. Within an intermediate weakly nonlinear regime up to 0.05 A, also apparent on (Q, P_{coil}) characteristic, both $(R, |I|)$ and $(X, |I|)$ characteristics follow an average increase with a 0.3 power law.

Figure 6 displays the magnitude and phase of B_1 as a function of P_{coil} . The response of an ideal linear circuit, that would keep the low-level electrical properties of the HTS coil at any dissipated power level, is also plotted as a reference. As expected, the saturation of the HTS material close to its critical current tends to limit the rf magnetic field generated at high power. A B_1 -phase deviation also appears at high power in relation to the resonance frequency shift of the HTS coil.

DISCUSSION

A contactless method based on reflectometry has been demonstrated to accurately characterize an inductive rf resonator even in the occurrence of a strong nonlinearity. Non-linear extraction of the unloaded quality factor and resonance frequency is possible by combining an initial low-level swept-frequency calibration with high-level single-frequency measurements. Since the method allows investigating the

FIG. 6. Experimental amplitude (filled data points) and phase (empty data points) as a function of the power dissipated in the HTS coil. The amplitude is for 2 mm from the center along the coil axis. This characteristic is extracted from the same data set as in Fig. 3. For comparison solid (amplitude) and dashed (phase) lines represent the ideal linear case.

nonlinear regime with a pulsed power application, varying the rf-pulse duration and duty cycle can also help assessing thermal effects.

Compared to the previous investigations with nonlinear inductive rf resonators,^{5,6,12,13} the present characterization is based on complete understanding of the incident and reflected rf power as a function of frequency. The nonlinear behavior is expressed as a function of the actual power dissipated in the resonator, accounting for the absorption in the measurement probe at any coupling strength. A very large range of transmitted power is accessible by varying the coupling conditions. For accuracy purpose, the measurement probe impedance has been matched to the rf source, making the whole system nearly matched either in strong coupling conditions when the coil is highly resistive, i.e., at high-power level, or in weak coupling conditions. As compared to an unmatched probe, this results in a larger modification of the reflected power due the presence of the rf resonator over a broad range of coupling conditions.

The method will have implications in different domains such as MR applications with superconducting probe heads or analysis of rf properties in nonlinear materials.

For MR applications, the method provides a direct extraction of the intrinsic ratio $B_1/\sqrt{P_{\text{coil}}}$, which quantifies both the rf-coil efficiency for transmission and its sensitivity for reception.⁷ Once the intrinsic behavior of the HTS coil is known, it can be taken into account to design the most appropriate matching circuit for practical implementation minimizing nonlinear effects. Furthermore the accurate prediction of B_1 can be involved to correct the local flip angle errors during excitation, including phase and pulse-shape distortions. Finally, elaboration of more robust rf coils based on improved materials or different coil geometries can be considered.

Orders of magnitude for practical MR imaging experiments are a maximum transmit B_1 amplitude of about $60\ \mu\text{T}$, which corresponds to a shortest 90° pulse duration of $100\ \mu\text{s}$, and a received signal amplitude given by $E = \omega_0 \mu_0 M_0 S / 2 = RI$. The electromotive force E is estimated in the case of a receiver loop of effective area S applied onto the surface of a half-infinite sample of uniform magnetization M_0 . Taking M_0 of $0.0047\ \text{A/m}$ for a water sample at 1.5 T and S of $0.0014\ \text{m}^2$, E is about 1.6 mV. This corresponds to $I = 38\ \text{mA}$ and $P_{\text{coil}} = 6.10^{-5}\ \text{W}$ according to the $(R, |I|)$ characteristics of Fig. 5. Such data show that the HTS coil stays in the weakly nonlinear regime described above, keeping a huge quality factor for MR reception. In this regime the resonance frequency shift stays within 1 kHz, which corresponds to less than 2° of phase deviation, i.e., a nonsignificant MR signal distortion. For the B_1 -amplitude range investigated in these measurements, much larger frequency shifts of up to 230 kHz have been observed. However, according to the correspondingly lower quality factors, the maximum phase deviation does not exceed 45° and stays still lesser than 2° at the nominal level of $60\ \mu\text{T}$. Some specific MR sequences critically sensitive to the transmit or receive phase might require a phase correction based on the present method. Moreover, the nuclear spins can induce in the HTS coil a RF power level comparable to the rf-

transmission one. This evidences a potential radiation-damping issue that should be solved, e.g., using dedicated electronics.¹⁸ In practice, phase deviation and radiation damping raised no problematic issues with the basic MR-microimaging implementation at 1.5 T (Ref. 16) based on an overcoupled double-tuned matching network scheme.¹⁹

In the material science domain, complex models have been developed to assess fundamental properties of HTS materials, e.g., critical current, penetration depth, and kinetics inductance, by characterizing the surface impedance of resonant HTS devices.^{10,11} The impedance Z of the resonator measured by the present method could be directly related to the actual surface impedance by applying a geometric factor accounting for the surface current distribution. The present data suggest that both weakly and strongly nonlinear regimes are explored, which remain to be closely interpreted according to pertinent nonlinearity models, outside the scope of this paper. Roughly, the current in the HTS coil appears to be asymptotically limited at about 1 A. Assuming a uniform distribution over the 200 μm width and 300 nm thickness of the HTS film, it would correspond to a current-density magnitude of the order of 2×10^6 A/cm², in fair agreement with manufacturer's specification.

Analysis of intrinsic film properties from the present inductive characterization of a RF resonator can be improved since it relies on both simple assumptions of a B_1/I distribution derived from a Biot-Savard computation and of a constant value of the equivalent capacitance C . The former assumption might introduce a scaling error on R , X , and I . The latter one ignores local saturation effects where the redistribution of the supercurrent would change C and L simultaneously. Involving a full electromagnetic computation would help to get a more accurate characterization model. Another way to discriminate for inductive and capacitive shifts could be to apply the present method using several different carrier frequencies.

ACKNOWLEDGMENTS

The authors want to thank Dr. Paul Crozat for helpful discussions. This work was granted by Guerbet Research (Roissy-Charles de Gaulle, France), by the French Ministry of Research in the frame of the RNTS Program and by the IPA Joint Program from CNRS and CEA.

APPENDIX: ERROR PROPAGATION MODEL

For clarity in this section $\rho_{\text{comp}}(\omega_0)$, with ω_0 the low-level resonance pulsation is simply noted ρ_{comp} .

Complete expression of the quasiconstant term L/M^2

L/M^2 is estimated from the linear regime on-resonance $\rho_{\text{comp}}^{\text{linear}}$ and $Q_{\text{app}} = \omega_0/BW_{-3 \text{ dB}}$ measurements as

$$\frac{L}{M^2} = \omega_0 \frac{Q_{\text{app}}}{2R_0 \rho_{\text{comp}}^{\text{linear}}}$$

Q factor and frequency-shift extraction

The quality factor of the coil is extracted from Eq. (3), $Q = L\omega/R$, and the value of L/M^2 . The complete extraction formula is given by

$$Q = \frac{Q_{\text{app}}}{\rho_{\text{comp}}^{\text{linear}}} \frac{|\rho_{\text{comp}}|}{\cos[\angle \rho_{\text{comp}}] - |\rho_{\text{comp}}|}.$$

The logarithmic derivative is used to deduce the total relative error on Q ,

$$\frac{\delta Q}{Q} = \frac{\delta Q_{\text{app}}}{Q_{\text{app}}} + \frac{\delta \rho_{\text{comp}}^{\text{linear}}}{\rho_{\text{comp}}^{\text{linear}}} + \frac{\delta |\rho_{\text{comp}}|}{|\rho_{\text{comp}}|} \frac{\cos[\angle \rho_{\text{comp}}]}{\cos[\angle \rho_{\text{comp}}] - |\rho_{\text{comp}}|} + \frac{\delta \angle \rho_{\text{comp}}}{\angle \rho_{\text{comp}}} \left| \frac{\angle \rho_{\text{comp}} \sin[\angle \rho_{\text{comp}}]}{\cos[\angle \rho_{\text{comp}}] - |\rho_{\text{comp}}|} \right|.$$

A similar approach leads to

$$\frac{\delta \Delta \omega_0}{\Delta \omega_0} = \frac{\delta(\Delta X/L)}{\Delta X/L} = \frac{\delta \omega_0}{\omega_0} + \frac{\delta Q_{\text{app}}}{Q_{\text{app}}} + \frac{\delta \rho_{\text{comp}}^{\text{linear}}}{\rho_{\text{comp}}^{\text{linear}}} + \frac{\delta |\rho_{\text{comp}}|}{|\rho_{\text{comp}}|} + \frac{\delta \angle \rho_{\text{comp}}}{\angle \rho_{\text{comp}}} \frac{\angle \rho_{\text{comp}}}{\tan[\angle \rho_{\text{comp}}]}.$$

Power extraction

The logarithmic derivative of Eq. (6) directly gives the error on P_{coil} ,

$$\frac{\delta P_{\text{coil}}}{P_{\text{coil}}} = \frac{\delta P_{\text{inc}}}{P_{\text{inc}}} + \frac{\delta |\rho_{\text{comp}}|}{|\rho_{\text{comp}}|} \left| \frac{\cos[\angle \rho_{\text{comp}}] - 2|\rho_{\text{comp}}|}{\cos[\angle \rho_{\text{comp}}] - |\rho_{\text{comp}}|} \right| + \frac{\delta \angle \rho_{\text{comp}}}{\angle \rho_{\text{comp}}} \left| \frac{\angle \rho_{\text{comp}} \sin[\angle \rho_{\text{comp}}]}{\cos[\angle \rho_{\text{comp}}] - |\rho_{\text{comp}}|} \right|.$$

Magnetic field extraction

Starting from Eq. (7) the following expression is derived:

$$\frac{\delta |B_1|}{|B_1|} = \frac{1}{2} \left[\frac{\delta P_{\text{inc}}}{P_{\text{inc}}} + \frac{\delta R_0}{R_0} \right] + \frac{\delta S_P}{S_P} + \frac{\delta |\rho_{\text{comp}}|}{|\rho_{\text{comp}}|} + \frac{\delta \omega_0}{\omega_0}$$

and

$$\frac{\delta \angle B_1}{\angle B_1} = \frac{\delta \angle \rho_{\text{comp}}}{\angle \rho_{\text{comp}}}.$$

Further extraction using the inductance of the HTS coil

The relative errors affecting R and $|I|$ are given below,

$$\frac{\delta R}{R} = \frac{\delta Q}{Q} + \frac{\delta L}{L} + \frac{\delta \omega_0}{\omega_0},$$

$$\frac{\delta |I|}{|I|} = \frac{1}{2} \left[\frac{\delta P_{\text{inc}}}{P_{\text{inc}}} + \frac{\delta Q_{\text{app}}}{Q_{\text{app}}} + \frac{\delta \rho_{\text{comp}}^{\text{linear}}}{\rho_{\text{comp}}^{\text{linear}}} + \frac{\delta L}{L} + \frac{\delta \omega_0}{\omega_0} \right] + \frac{\delta |\rho_{\text{comp}}|}{|\rho_{\text{comp}}|}.$$

Looking at the expressions concerning Q , P_{coil} , and R it is clear that the measurement relative error $\delta |\rho_{\text{comp}}|/|\rho_{\text{comp}}|$

will be amplified for $|\rho_{\text{comp}}| \approx 1$ when $\angle \rho_{\text{comp}} \approx 0$ due to the $\cos[\angle \rho_{\text{comp}}] - |\rho_{\text{comp}}|$ term, which is the case for strong coupling at low power level on resonance. This explains the relatively high error bars represented on Figs. 3 and 5. On the other side the method is particularly accurate for high power level extraction. Indeed it corresponds to $|\rho_{\text{comp}}| \approx 0$ for which no relative error amplification occurs.

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