Method to extract the non-linear characteristics of high temperature superconducting (HTS) RF coils

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PURPOSE

High-temperature superconducting (HTS) resonators can strongly improve the SNR in MR microscopy (1). However the implementation of such RF coils remains difficult since power levels involved during transmission lead to a non-linear response, due to increased resistivity of the HTS material close to its critical current. This results in coil-transmitter mismatching, misadjustment of the flip angle, and shape distortion of slice-selective soft pulses (2). Those effects are interdependent since the impedance mismatching at high levels also represents a loss of transmitted power. To account for these effects with any kind of matching circuit, electrical characterization of the intrinsic HTS-coil resistance as a function of the local current is required. We describe here a new method for complete RF-coil characterization accounting for non-linear conduction. It is based on reflectometry measurements with an inductively-coupled probe, and includes a correction for strong coupling conditions between the probe and the RF coil, allowing to extend the analysis over a wide range of transmitted power.

THEORY

The measurement bench is made of an RF source that powers via a directional coupler an inductive probe coupled to an RF coil (Fig. 1.). We assume that R_P is larger than $L_P\,\omega_0$ and that R_C is smaller than $L_C\,\omega_0$ at low incident-power level.

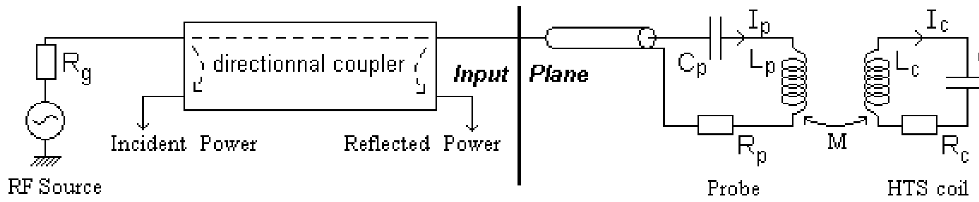

Fig. 1. Measurement scheme

The reflection coefficient ρ, defined from the incident and reflected powers at the input plane as $(P_{REFL} / P_{INC})^{1/2}$ is : $\rho = (Z_P + Z_{IN} - R_G) / (Z_P + Z_{IN} + R_G)$ where Z_P is the impedance of the probe, Z_{IN} is the equivalent impedance induced by the NMR coil in the probe, and R_G is the output impedance of the RF source. Z_{IN} can be evaluated from a dual-reflection measurement (3) involving a reference ρ_0 taken in the absence of the coil *(M = 0)*. At very low levels for which the RF-coil behavior is linear (i.e., R_C is almost constant), the intrinsic quality factor of the RF coil can be deduced from : $Q_C = (\omega_0 / BW) / [1 - (\rho(\omega_0) - \rho_0(\omega_0))]$ [1], where BW is the -3 dB bandwidth measured on the ρ -ρ_0 frequency response. The correcting factor $1\text{-}(\rho\text{-}\rho_0)$ in the denominator corresponds to the power dissipated in the probe under strong coupling conditions. Yet this approach to measure the intrinsic Q_C fails in the non-linear regime because the local current, and hence R_C, now strongly varies with the frequency offset to the RF-coil resonance.

At the RF-coil resonance, for a matched probe $(R_P = R_G)$: $R_C = M^2\omega_0{}^2[1 - (\rho - \rho_0)] / 2R_G(\rho - \rho_0)$ [2] and $R_C\,I_C{}^2 = 2(\rho - \rho_0)[1 - (\rho - \rho_0)]\,P_{INC}$ [3], where M is the mutual inductance between the probe and the RF-coil. Unlike the frequency-based analysis, the two latter equations remain valid in the non-linear regime to quantify the intrinsic dissipation effect since they only involve single-frequency measurements.

METHODS

Our method is based on the following protocol :

1. A preliminary calibration step in the linear regime (at low incident power) is done once for any new coil to be investigated, using an initial position of the inductive probe relative to the RF coil. A small pick-up loop is involved to measure the RF field B_1 produced at a given point on the RF coil axis. The current I_C is then estimated from a Biot-Savart calculation of B_1 / I_C since it closely approximates the real field distribution (2). Frequency analysis of ρ -ρ_0 gives Q_C from Eq. [1] and R_C from Eq. [3]. Finally the RF-coil inductance L_C is estimated from $Q_C = L_C\,\omega_0 / R_C$ and is assumed to remain almost constant in successive steps.
2. Any other probe/RF-coil coupling conditions can now be involved. The frequency analysis at low incident power gives the new mutual inductance M from Eq. [2], using the measured Q_C and the previous estimation of L_C to extract R_C.
3. As long as the probe/RF-coil coupling is kept constant, R_C and I_C can be extracted at high incident power levels (non-linear regime) from a ρ -ρ_0 measurement at the resonance frequency using Eq. [2] and Eq. [3], and the value of M previously estimated in the linear regime.

The probe is a single-turn copper-wire loop (∅ 12 mm) tuned to 64MHz with a 150 pF capacitor and matched to the RF source impedance using a resistance R_P of 50 Ω. Measurements have been performed with a HP4195A network analyzer.

RESULTS AND DISCUSSION

We characterized a HTS surface coil (∅ 12 mm) designed for *in vivo* skin microscopy at 1.5 T (4). Figure 2 displays the equivalent resistance of the HTS coil and the corresponding RF field at the RF-coil center as a function of the local current I_C. For very low current values R_C is constant, not actually visible on the figure. R_C increases rapidly with I_C at higher levels following a rather complex law exhibiting quite different behaviors below and above 0.05 A.

Compared to previous investigations (1, 2) this complete-characterization approach can here depict the non-linear coil behavior as a function of the actual local current in the RF coil, by clearly establishing its relation to the incident power. Our method can also be useful to investigate the non-linear regime with pulsed incident-power application. Indeed it only involves on-resonance measurements once the low-level characterization steps have been achieved. Combined with duty-cycle variations, this could help identifying potential thermal effects.

The *Rc(Ic)* characteristics is required to accurately predict the working point of the HTS coil and the corresponding flip angle as a function of the input level, or to compensate for shape distortions arising with soft RF pulses. It also provides means for the assessment of new developments, such as the design of dedicated matching circuits to minimize non-linear effects, and the elaboration of more robust RF coils based on improved materials or different coil geometries.

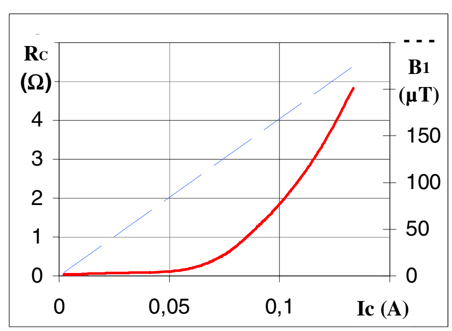

Fig.2. : Rc(Ic) characteristics of the HTS-coil, extracted from a series of 520 steps of P_{INC}

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