Counter Rotating Currents Cryogenic Surface Coils

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Introduction. Noise in MRI systems, in general, is created by conductive losses in the coil and in the body. When the coil loss is the governing source of noise ($R_{coil}>R_{body}$), it has long been recognized that cooling the coil reduces this noise contribution and therefore can significantly increase the SNR [1]. Such an SNR increase has been demonstrated by many groups with two-fold and higher SNR gains over room temperature copper coils achieved [3] by cooling, indicating that microscopic resolution of small samples [2] and high resolution imaging of small animals are possible. In this work we have developed a simple method of estimation of a potential SNR gain, which can be obtained for a given coil and body configuration [4]. Four and six bench Qs measurements were carried out for SNR gain calculation of 77 K Cu and Cu/HTS coils, respectively. The concept of coils' configurations were tested at 3 T with a planar counter-rotating-currents (CRC) [5, 6] and twin-horseshoe (HS) [7] coils using a G-10 liquid nitrogen cryostat. Cryogenic performance comparison of the CRC and HS coils were carried out using a 3.0 T GE whole-body scanner.

Method and Results. Since implementation of cryogenic coils is challenging, most reports refer to coils with inductive coupling and without detuning from the transmit coil (thus in T_x/R_x mode). In any R_x case when tuning/matching, detuning circuitry has to be used and, in addition, the coil has to be placed in a cryostat. As a result calculations of potential SNR gain from cooling have to include more components than only coil and body resistances ($1/Q_{total}=1/Q_{cryostat}+1/Q_{coil}+1/Q_{body}+1/Q_{electronics}$). Both the coil and body noise in the receiver coil system can be represented as a resistance, R, in series with an inductance L therefore Q of such circuit is defined by $Q=\omega L/(R_{coil}+R_{body})$, whereas Q of the coil can be expressed as $Q=\omega L/R_{coil}$. For an SNR comparison the ratio of square root of Q_{coil} and Q_{body} values is commonly used. However, this is only true for the SNR comparison bench test performed at the same temperature but not valid at two different temperatures. We assumed the same signal value for both the cases and that unloaded and loaded Qs at RT and 77 K for such case are: $Q_0^{295K} = \omega L / R_c^{295K}$, $Q_0^{77K} = \omega L' / R_c^{77K}$, $Q_L^{295K} = \omega L / (R_c^{295K}+R_b)$, $Q_L^{77K} = \omega L' / (R_c^{77K}+R_b)$, where L and L' are inductances at 295 K and 77 K, respectively. It leads to the following SNR gain equation for a single coil $\text{Single\_coil\_SNR}^{77K} / \text{Single\_coil\_SNR}^{295K} = \sqrt{(1+\delta+\gamma)/1+(\alpha\beta\delta+\alpha_1\gamma)}$ and for an array $\text{Array\_SNR/Single\_Coil\_SNR}^{295K} = \sqrt{(1+\delta+\gamma)/1/\mathrm{N}+(\alpha\beta\delta+\alpha_1\gamma\mathrm{N})\mathrm{N}}$ [4], where N is coil number, β is coil resistance reduction coefficient, $\gamma=R_{electronics}/R_{body}$, whereas α and α_1 are the temperature reduction coefficients for coil and electronic circuit, respectively. In such approach a figure of merit for SNR gain, $\delta=R_{coil}/R_{body}$, is equal to $\delta=(1-Q_L^{295K}/Q_L^{77K})/(Q_L^{295K}/Q_L^{77K}-Q_0^{295K}/Q_0^{77K})$. We have done SNR gain estimation and its comparison with SNR gain measured on a 3 T whole-body GE scanner.

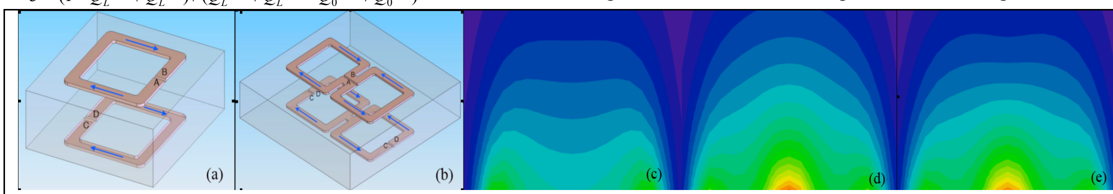

Fig. 1. A sketch of the HS (a) and CRC (b) split-rings coils. Sensitivity contour maps for the same FOV (68mm x 34mm) of a single Large-HS (c), two elements (33mm x 34mm) HS array (d) and for a single CRC (e) coils are simulated.

We followed the designs' principles for planar-pair loop-gap [5] resonators, which have been previously demonstrated as very useful in MRI. This design consists of two modified double-sided split-ring resonators connected on one end by two narrow strips (Fig. 1b). In addition, we have used a double-sided structure concept in order to introduce distributed capacitance in the coil and to minimize stray electric fields that otherwise would lead to additional dielectric loss in the body. *Rf* currents directions at a given moment for MRI useful modes are marked in Fig. 1a and 1b. The split-squares have a 34-mm outer and 27-mm inner dimensions, respectively. Such a design can be treated as two directly connected HS resonators. The gaps on two sides of the substrate in each ring are rotated 180° from one another. For easy cryo-packaging, a capacitive connection to the matching and tuning/detuning circuitry is made to either AB or CD points.

TABLE 1	Q_0(295K)	Q_0(77K)	Q_L(295K)	Q_L(77K)
$HS^{inductively}$	350	880	215	450
$LHS^{inductevely}$	410	920	170	260
$CRC^{inductevely}$	400	920	290	560
$HS^{electronics}$	290	760	160	360
$CRC^{electronics}$	290	720	210	470

Discussion and Conclusions. The HS and CRC coils were positively tested for coil tuning/matching and detuning both at room and liquid nitrogen temperatures. Qs values were measured using Ginzton/Kajfez [8] one port method, with and without phantom and/or electronics/cryostat, and results are shown in Table 1. Surprisingly, very similar SNR gain was obtained for 68 mm by 34 mm CRC coil as for 33 mm x 34 mm HS coil (8 mm distance coil-body was kept). The CRC coil showed much smaller reduction of Q after loading with the body compared to the HS of a similar size (LHS in Table 1). To cover the same FOV an array of two elements HS coils had to be used. The potential advantage of the CRC design, in addition to good isolation from the transmitting coil, is also the relatively smaller eddy current losses. Tests on a whole-body GE 3 Tesla scanner in a small plastic cryostat demonstrated ~100% SNR gain for 33 mm x 34 mm Cu HS and 68 mm x 34 mm CRC coils.

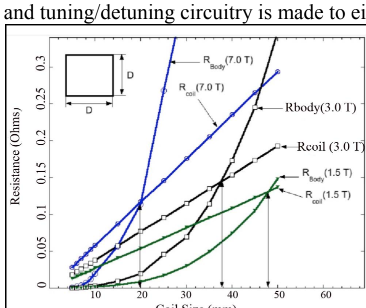

Fig. 2. Calculated using quasi-static method for 1.5 T, 3.0 T and 7.0 T comparisons between body and coil resistances as a function of square coil size D. 8 mm distance body-coil was assumed. Cross point of two plots indicate the coil size at which body and coil noise are equal. From this graph the maximum size of HS coil was selected to be 33-34 mm.

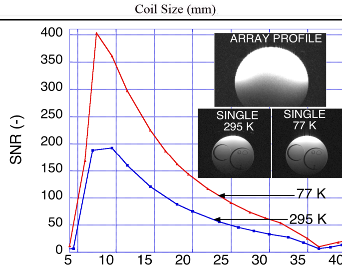

Fig. 3. Comparison of SNR profiles of the CRC coil measured at room and liquid nitrogen temperatures. Both single coil and two element arrays cases were tested on a 3.0 T GE whole-body scanner. Phantom conductivity was 0.7 S/m.

Acknowledgements
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