Cryogenic Receive-only 7 Tesla Coil for MRI of Hyperpolarized 13C

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Introduction

Dissolution dynamic nuclear polarization has been shown to generate an increase in the excess spin population of more than 10,000x for substrates such as [1-^{13}C]pyruvate [1]. Besides general benefits from SNR enhancement, such strong signal enables imaging of key biochemical processes in vivo with unprecedented sensitivity and resolution. Pyruvate is the most widely used of hyperpolarized (HP) substrates to date, due to strong polarization, favorable kinetics, and the central role of pyruvate in metabolism. Because spin polarization is preserved through chemical reaction, it is possible to visualize the distribution of the substrate as well as subsequent metabolites. Measurements are challenging because the signal is non-renewable, decays with T_1 relaxation, and depleted during excitation. Acquisition strategies must balance spatial and spectral sampling with the need to preserve magnetization for interaction with biological targets. Any methods that improve the intrinsic signal-to-noise ratio (SNR) of the measurement can ultimately be leveraged for higher sensitivity and/or spatiotemporal resolution. In principle, cryogenic and especially superconducting receive coils can provide very significant SNR gain for ^{13}C detection at 7 T, due to lower than for protons Larmor frequency of ^{13}C nuclei and resulting lower body loss compared to ^{1}H. It has been well recognized that, in the case of a sufficiently small coil, the thermal noise of the system is coil noise dominated and that cooling of receiver coils, made of either Cu or HTS materials, can provide very significant SNR improvement [3-4]. Our objective is to explore the practical limit of SNR gain due to reduction of thermal noise for the high-field (7T) MRI ^{13}C (75 MHz) receiver probe with tuning/matching and decoupling circuitry.

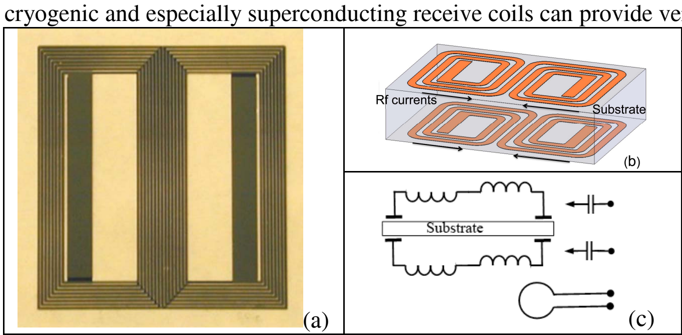

Figure 1. A prototype of a superconducting butterfly double-sided coil (a). A sketch showing layout of the coil (substrate thickness is not in scale)(b). Equivalent schematic of the coil with two options of coupling (capacitive and inductive) is shown (c).

Method and Results.

The coils were designed to fit into a cryogenic setup for small animals compatible with standard Bruker scanner transmit coils and includes a low-loss matching/tuning/decoupling electronic circuit for both cold copper and superconducting coils. Double-sided copper high frequency laminate with a dielectric constant ε=2.2 and thickness of 0.381 mm was used for the Cu coil fabrication. The coil and electronic circuit layout was patterned using LPKF PhotoMat C100. For YBCO prototype, films on both sides of a 0.33 mm thick Al_2O_3 (ε=10.4) wafer were patterned using optical lithography and wet etching into a flat Hemholtz (butterfly) coil shape (Fig. 1a). The matching/ tuning and detuning circuit was integrated with the coil inside the cryostat. Calculations of potential SNR gain from cooling have to consider cryostat and electronic losses, in addition to coil and body resistances ($1/Q_{total}=1/Q_{cryostat}+1/Q_{coil}+1/Q_{body}+1/Q_{electronics}$). The following SNR gain equation for estimation of the SNR gain of cryogenic over 295 K coils was used: $SNR\_gain=\sqrt{(1+\delta+\gamma)/1+(\alpha\beta\delta+\alpha_1\gamma)}$, where α and α_1 are the ratio of coil to body and electronics to body temperatures ($\alpha=T_{Coil}/T_{Body}$ and $\alpha_1=T_{Electronics}/T_{Body}$). β is coil resistance reduction coefficient, and $\gamma=R_{electronics}/R_{body}$. In such approach a figure of merit for SNR gain, $\delta=R_{coil}/R_{body}$, is equal to $\delta=(1-Q_L^{295K}/Q_L^{77K})/(Q_L^{295K}/Q_L^{77K}-Q_0^{295K}/Q_0^{77K})$ [5-6]. Measured Q's values with and without phantom, and with and without cooling allowed to estimate that ^{1}H 18-20 mm in diameter coil should provide 100 % gain for 77 K Cu and 150% for 77 K HTS coils for rat brain load, whereas for ^{13}C coil the same SNR gain was achieved for a much larger coil (24x34 mm). In Table I Q values are listed. Sizes of both ^{1}H and ^{13}C coils were selected to provide ~100% SNR gain after cooling.

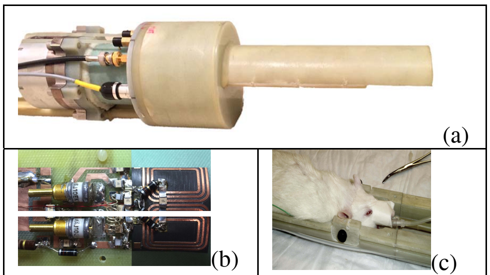

Figure 2. Pulsed tube cryogenic probe (a), butterfly Cu coil with T/M circuit (b), rat holder (c). (Compatible with the probe (a) and Bruker volume coil).

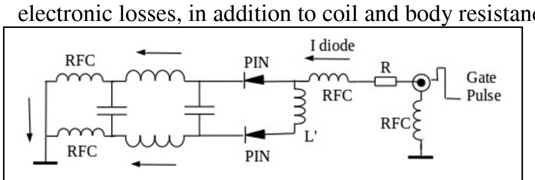

Figure 3. Equivalent circuit of the ^{13}C coil with decoupling. Rf chokes and PIN diodes are marked.

Discussion and conclusions.

SNR gains obtained at 7T for cooled Cu and HTS coils (18-20 mm in diameter) over room temperature copper, tested on rat equivalent phantoms at 300 MHz, were 80-100% (~6 dB) and 150-170% (~8 dB), respectively [7]. We have compared SNR gain performance of ^{1}H and ^{13}C Cu coils. It turned out that optimized for L/C (butterfly) designs of 75 MHz ^{13}C coil can achieve the same gain for much larger coil compared to ^{1}H (24x34mm *vs.* 18-20mm, respectively). For the ^{13}C coil of the same size as ^{1}H coil, it was found that almost 400% SNR gain (for rat brain load) can be obtained comparing with only 90-100% SNR gain achievable for ^{1}H (Table I). Further increase of the SNR gain (using smaller coils) will require use of a cryogenic preamplifier and also further reduction of the tuning/matching circuit losses. Table I includes also calculated from Q's measurements $Q_{electronics}$, $Q_{cryostat}$, and Q_{body} values (losses ~1/Q).

Table I.

Q-factor	^{1}H (19mm) Cu_295K	^{1}H (19mm) (1Cu_60K	^{13}C (24x34mm) Cu_295K	^{13}C (24x34mm) Cu_60K
Coil only	360	1090	190	490
Coil+ electronics	250 (820)	670 (1600)	140 (790)	375 (1500)
Coil+ electronics +cryostat	240 (820) (6000)	620 (1600) (6000)	135 (790) (6000)	350 (1500) (6000)
Coil+ electronics +cryostat +body	180 (820) (600) (750)	330 (1600) (6000) (750)	110 (1600) (6000) (700)	210 (1500) (6000) (700)
SNR_Gain		~100%		~100%

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