Optimization of 7 T YBCO Coils for in-vivo and ex-vivo MRI of Small Animals; Assessment of Achievable SNR Gain

Jarek Wosik[1,2], Kurt H. Bockhorst[3], Krzysztof Nesteruk[4], Dhivya Ketharnath[1], Tan I-Chih[5], and Ponnada A Narayana[3]

[1]*Electrical and Computer Engineering, University of Houston, Houston, Texas, United States,* [2]*Texas Center for Superconductivity, University of Houston, Houston, Texas, United States,* [3]*Health Science Center, University of Texas, Houston, Texas, United States,* [4]*Polish Academy of Sciences, Institute of Physics, Warsaw, Poland, Poland,* [5]*Center for Molecular Imaging, University of Texas, Houston, Texas, United States*

Background and purpose

In both research and clinical MRI, there is a need for high resolution and/or fast scan imaging but the SNR is the main limitation to fulfill these requirements.[1] High-temperature superconducting (HTS) materials, which have been generating a significant interest as potential materials for *rf* coils fabrication have already been used in designs of high SNR *rf* coils[2-4] and/or arrays.[5] Such materials are very attractive for making coils because they exhibit very low surface resistance R_s even at 77 K; furthermore, relatively high critical temperature of HTS materials allowed for cryostat design simplifications, which enables short range distance between the HTS coil and the body. There are two regimes for the thermal noise induced conductive losses in the MRI systems. In the first one, the overall loss is body loss dominated, so the SNR is governed by the body loss. In the second instance, loss occurs predominantly in the coil probe therefore lowering of the coil RT results in significant thermal noise reduction. We already reported the design, construction, and initial validation of Rx only cryo-probe operating at 7 T based on HTS coil. The built set-up was tested with Cu and HTS coils for SNR gain, providing values of 100% and 170%, respectively.[6] We report on further development and optimization of this design (Fig. 1) and on better understanding of practical SNR gain limitations. Our main interest in this work is the identification all losses limiting SNR, such as *rf* coil, body, cryostat and tuning/maching/decoupling circuitry losses and discussion on the probe performance optimization.

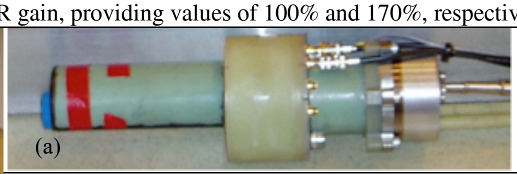

Figure 1. A picture of the close-cycle pulsed tube based G-10 cryostat stored next to 7 T Bruker scanner. A cryo-probe (a) with remotely dc voltage controlled varactors.

Method and Results.

The Cu coil and electronic circuit layout was patterned using LPKF PhotoMat C100. Double-sided Cu high frequency laminate (ε=2.2 and thickness of 0.38 mm) was used for the coil fabrication. Superconducting coils were made of epitaxially grown 0.5 mm thick YBCO films (THEVA), which were patterned using optical lithography and wet etching. Two split quasi rings with the gaps rotated 180° from each other were fabricated on both sides of a 0.33 mm thick Al_2O_3 (ε=10.4) wafer. A closed cycle pulsed tube cryogenic system (CryoMech HTP10) was used to cool the probe. Two cryo-probes were made: the first one with matching/tuning and detuning circuit with GaAs varactor diodes, and the second one with mechanically adjusted trimmers (Voltronics). Cu and HTS coil sizes were selected by using SNR gain formulas[7] with measured loaded and unloaded Q-factors at room and cryogenic temperatures. An assumption was made that 100% gain for Cu and 150% gain for HTS coil are required. From such a procedure 19-20 mm and 18-19 mm diameters for Cu and HTS cases were obtained, respectively. The following SNR gain equation was used: $SNR\_gain=\sqrt{(1+\delta+\gamma)/1+(\alpha\beta\delta+\alpha_1\gamma)}$. α and α_1 are temperature ratios: $\alpha=T_{Coil}/T_{Body}$ and $\alpha_1=T_{Electronics}/T_{Body}$. β and γ are the coil resistance reduction coefficient at T_{Coil} and 295 K and electronics to body resistance ($R_{electronics}/R_{body}$) ratio, respectively. In this approach a figure of merit δ is equal to R_{coil}/R_{body} ratio. Overall loss in the system consists of coil, body, cryostat and electronic losses ($1/Q_{total}=1/Q_{cryostat}+1/Q_{coil}+1/Q_{body}+1/Q_{electronics}$). Table I shows all these loss components in term of measured Q's factors. In addition, the influence of magnetic flux (7 T) on the HTS coil is shown in column V. YBCO thin film is in the mixed superconducting state at 7 T so it results in higher losses.[8] The electronic loss increased in 7 T from 1/1600 to ~1/900. Most likely such increase is due to magneto-resistive effects in varactors diodes.

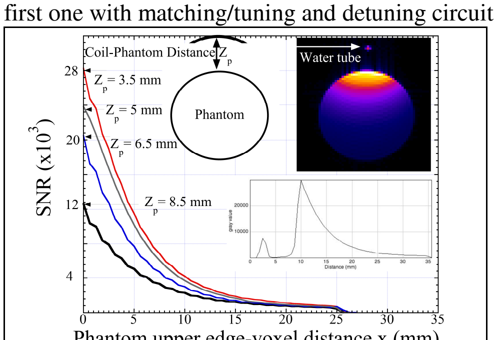

Figure 2. SNR *vs.* coil-voxel distance for different coil-phantom surface distances. Bright dot above phantom - position of the coil.

Discussion and conclusions.

From Table 1 it can be seen that the SNR gain of the system is limited by body losses, which is the case of, for example, *in-vivo* rat imaging. The gain can be adjusted by changing the coil size (change of the figure of merit δ). For small samples, such as those used for *in-vitro* microscopy imaging, electronics losses are limiting factors. Further increase of the SNR gain for microscopy will require the use of a cryogenic preamplifier. Measured by us additional varactors related loss in the presence of dc magnetic field does not have a significant influence on room temperature coils (~10%). However, for high Q HTS case, such additional loss prevents from using the varactors in the circuit. We had to replace varactors with mechanically adjusted trimmers, which makes cryostat design more challenging. One of the crucial problems with cryo-coils is how to minimize the distance between the coil and imaging object. The measurements presented in Fig. 2 show that for small coil, SNR depends very strongly on the coil-phantom distance. From the plot, it can be seen that such a distance cannot be larger than 3-4 mm, otherwise SNR gain of any HTS coil *vs.* state-of-the art commercial Cu coil will be significantly reduced.[9]

Table 1. Measured Q values related to the system loss components for Cu and HTS cases.

Q-factor	Cu-295K	Cu-60K	HTS-60K	HTS-60K-7T	HTS-60K-7T (varactors)
Coil only	360	1090	51,300	29,000	29,000
Coil+ Electronics	250 (820)	670 (1600)	1550 (1600)	1500 (1600)	830 (900)
Coil+ Electronics +cryostat	240 (820) (6000)	620 (1600) (6000)	1380 (1600) (6000)	1320 (1600) (6000)	740 (900) (6000)
Coil+ Electronics +cryostat +body	180 (820) (600) (750)	330 (1600) (6000) (750)	475 (1600) (6000) (750)	470 (1600) (6000) (750)	350 (900) (6000) (750)

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