High-temperature superconducting radiofrequency probe for MRI applications operated below ambient pressure in a simple liquid-nitrogen cryostat

Simon Auguste Lambert[1], Marie Poirier-Quinot[1], Jean-christophe Ginefri[1], and Luc Darrasse[1]
[1]*CRB3- INSERM U773, Univ Paris Diderot, Sorbonne Paris Cité, Clichy, France*

Introduction

Small high-temperature superconducting (HTS) coils operated at liquid nitrogen (LN_2) temperature have been shown to greatly improve the signal-to-noise ratio (SNR) [1] and have been successfully involved in micro-MRI applications [2]. One issue with HTS coils is the large degradation of electrical properties in the presence of the static magnetic field B_0, due to the formation of vortices with normal carriers. This effect depends both on the superconducting plane orientation relative to B_0 [3] and on the cooling temperature (T_{HTS}) [4]. In this work the coupled effects of temperature and field on the resonance frequency (f_0) and quality factor (Q) of a HTS surface coil, based on a multiturn-transmission-line-resonator (MTLR) design [5], is investigated in the 69-83 K and 0-4.7 T range.

Materials and Methods

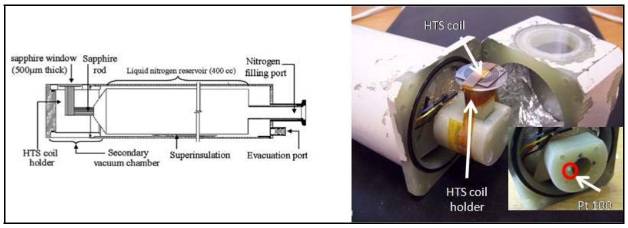

Fig. 1 : *Dedicated LN2 cryostat schematic (left), and a detailed view of the HTS coil mounted onto a sapphire cold finger into the secondary vacuum chamber of the cryostat (right). Inner parts of the cryostat body are covered with a superinsulation layer except close to the HTS coil.*

A 12 mm YBaCuO MTLR with a critical temperature of 92 K was cooled with a dedicated LN_2 cryostat equipped with a sapphire cold finger (Fig; 1). A cooling temperature control with an accuracy of about 0.5 K and a stability better than 0.1 K was ensured by pumping on the LN_2 reservoir with digital pressure regulation (Bronkhorst High-Tech B.V., EL-PRESS P-702CV Pressure Controller).

Initially, a Pt 100 probe was used to measure the temperature onto the sapphire cold finger, a few centimeters away from the HTS coil to limit B_1 distortion. In practice, the probe indication appeared poorly reliable due to rather large temperature gradients occurring both along the sapphire finger assembly and across the contact between the probe and the sapphire rod.

An alternative approach was thus involved here, based on the pressure measurement delivered by the regulation set-up with an accuracy better than 1 mbar. The LN_2 temperature was derived from the vapor pressure using the liquid-vapor steady-state equation [6]. The temperature offset between the LN_2 bath and the HTS coil was assumed to stay constant within 1% over the measurement range, since the thermal flux through the cold finger is imposed by the thermal radiation at the HTS-coil end and follows Stephan's law. The actual temperature offset (about 6 K) was evaluated from the critical-temperature transition in the earth field as done previously [7]. The B_0 amplitude was varied by positioning the HTS coil in the fringe field of 1.5 T and 4.7 T MRI magnets, with local field strength measured by a Hall-effect probe.

The parameters f_0 and Q were measured using the single-loop method [8] with alignment of the YBaCuO superconducting layers (HTS coil ab-plane) either along or orthogonal to B_0. The SNR gain expected with the HTS coil and unloading sample, as compared to a room-temperature copper-coil reference with identical geometry and a Q of 110, was extrapolated from the Q measurements according to the basic thermal noise equation [2].

Results

Rather large effects of T_{HTS} and B_0 were observed on f_0 and Q. As shown on Fig. 2A, the lowering of f_0 could be almost entirely compensated by the decrease T_{HTS} when the ab-plane of the HTS coil was aligned tangentially to B_0. The lowering of f_0 was much larger for the orthogonal orientation, and the initial f_0 value in earth field could no more be recovered by decreasing T_{HTS}. A similar trend but with more dramatic effects was observed on Q, which decreases from 37,000 in earth field down to respectively 2100 and 3700 in orthogonal 1.5 T and tangential 4.7 T fields for a T_{HTS} of 83 K. Lowering T_{HTS} appeared of limited efficiency to recover high Q values in tangential fields, with a maximum improvement by factor of 2 from 83 K to 69 K. The improvement was much larger for the orthogonal field orientations, a maximum Q of 12,000 being reached for a THTS of 69 K at 1.5 T. Finally, Fig.2B shows the expected SNR gains for HTS vs. room-temperature copper coils as a function of temperature and field, with a significantly different behavior between tangential and orthogonal orientations.

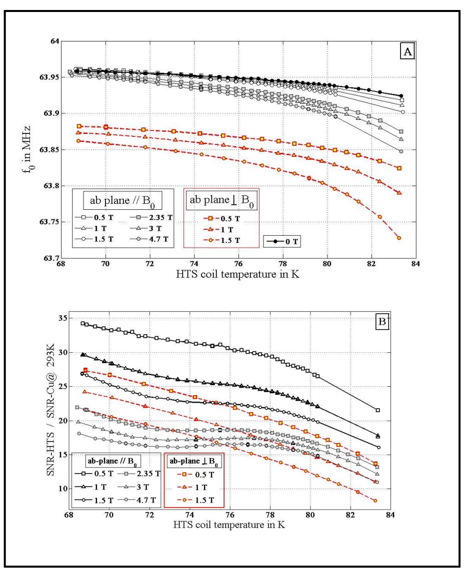

Fig. 2 : *effects of cooling temperature and field on resonance frequency(A) and on SNR gain for both along and orthogonal orientation with B_0(B)*

Conclusions, Discussions and Perspectives

This study has demonstrated significant improvements of miniature HTS coil performances by decreasing temperature. The extra SNR provided with unloading sample will also be partially available with small animals or weakly conducting biological specimen, e.g. an expected gain of more than 30 % on the mouse brain at 1.5 T according to the study [2].

The temperature control was easily implemented with a LN2 cryostat and a simple temperature monitoring set-up avoiding the use of conventional probes and related artifacts. Up-to-now some care had to be taken to position the HTS-coil plane along the magnetic field lines because of the dramatic effect of B0 on the quality factor. Decreasing the temperature allows an addition degree of freedom in the coil orientation since it has been shown particularly effective to improve the quality factor in the orthogonal position.

Finally temperature control has appeared to be an easy way to accurately retune the HTS coil to the NMR frequency inside the imaging system, offering an alternative to the previous approach by inductively coupling a closed copper loop that may degrade the overall electrical quality [2].

Additional gain in Q might be obtained by decreasing T_{HTS} even more. This way would be particularly beneficial for imaging small specimen with little loading effect at higher fields but it would require a more complex cryogenic system.

References: [1] Darrasse L, 2003, Biochimie,85,915-937. [2] Poirier-Quinot M, 2008, MRM, 60, 917-927. [3] Ginefri J, 2001, MRM, 45, 376-382. [4] Black R, 1995, JMR, Series A, 113, 74-80. [5] Serfaty S, 1997, MRM, 38, 687-689. [6] Edejer M, 1967,J. Chem. Eng. Data, 12, 206-209 [7] Ginefri J.-C., 1999, Trans Appl Supercond, 9, 4695–4701 [8] Girard O, 2007, RSI, 78, 124703-7. **Acknowledgement:** We thank Bruker Biospin for granting a PhD application related to this work.