All polymer cryogen free cryostat for μ-MRI application at clinical field

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Abstract. To improve the detection sensitivity of Micro Magnetic Resonance Imaging (μ-MRI) in humans, small animals or biological sample, it is necessary to reach higher spatial resolution. Radio Frequency (RF) YBaCuO film coils, in superconducting state, are used for that purpose, instead of copper coils. In working condition, these miniature RF coils are located in clinical MRI scanners (few Tesla) and very close to the biological sample under investigation. A non magnetic cryostat has been designed and constructed to operate these RF coils in this particular medical environment. This cryostat is principally made of polymer materials to reduce the electromagnetic perturbations to the MRI magnet and the cryogenic scheme has been chosen to be cryogen free. In this paper, we describe the cryostat and present the experimental thermal characterizations and the first images obtained in a clinical MRI scanner.

1. Introduction

To improve the spatial resolution of Magnetic Resonance Imaging (MRI), one solution is to increase the sensitivity of the Radio-Frequency (RF) probes by diminishing their size and electrical resistivity. For that matter, miniaturized superconducting RF coils (RF probes) have been developed where the use of YBa2Cu3O7 superconductor allows also a considerable noise reduction of the probe itself [1]. The miniaturization improves the magnetic coupling between the biological tissue under investigation and the probe, increases the signal intensity and decreases the noise induced to the probe by the tissue. With such technique, high resolution images of (60 μm)³ have been obtained in human and in mouse on a 1.5 T whole-body MRI scanner [2]. But to reach even higher sensitivity for μ-MRI, the development of a specific cryostat have been imagined to test High critical Temperature Superconducting (HTS) RF probes in clinical MRI scanner [3]. This cryostat has been imagined light, transportable, and user-friendly so that it can be installed in different imaging systems available in bio-medical research centers. More over, it must bring a minimum of electromagnetic perturbations on the HTS RF probe. The cryostat has been designed under such constraints with, as much as possible, non-magnetic materials. A cryogen-free cooling concept was adopted for the simplicity of use [4]. The cryostat has been constructed and thermally characterized under cryogenic conditions before being tested in a clinical MRI scanner. This paper presents the technical details of the cryostat, the cryogenic thermal characterization under normal working conditions and the first images obtained in a clinical MRI scanner.
2. All Polymer MRI compatible cryostat

The cryostat is mostly made of polymer materials (90%) with a vacuum vessel made of PEEK and PCTFE and the rest is made of non magnetic stainless steel (316 L), aluminum and copper. The cooling source is a commercial pulse tube cryocooler which is connected to a thermal link, made of initially 6N purity aluminum slabs and Cu-OF copper support and a sapphire plate. For more details the readers is invited to consult the reference 4. It has been checked during the tests in the MRI scanner that the cryostat is not magnetically attracted to the internal side of the MRI tunnel. During preparations before MRI measurements, the cryostat stands on an aluminum profile trolley (cf. fig. 1 a)). The trolley also supports the temperature regulation system, the compressor of the cold head and the motor of the cold head. For measurements, the cryostat is inserted into the MRI tunnel in sliding from the trolley to the patient bed as the figure 1 b) shows. In that way, the testing zone of the cryostat reaches the central part of the MRI magnet. In that configuration, the compressor, the cold head motor and the temperature regulation system are left on the trolley far from the MRI. Prior to the insertion of the cryostat into the MRI system, the vacuum insulation and the cool-down is achieved. The measurements are realized under static insulating vacuum. It has been verified that the cryostat can maintain an insulating vacuum of $10^{-6}$ mbar for more than 11 hours with or without magnetic field.

![Figure 1. a) Picture of the cryostat and its ancillary systems; b) Picture of the cryostat installed in a commercial MRI system](image)

3. Thermal characterization of the cryostat

3.1. Experimental set-up

For the thermal characterization, the cryostat has been tested without magnetic field. For these tests, the sapphire plate coil holder (testing zone) has been replaced by a dummy copper plate for safety. The internal part of the vessel has been instrumented with temperature sensors. Four PT100 A grade thermometers have been installed between the cold finger of the cryocooler and the testing zone. The figure 2 shows the sensors and their locations: one sensor is located on the aluminum thermal link just below the cold finger, two sensors are located on the cylindrical copper support to verify the temperature homogeneity and one on the testing zone. The temperature sensors have been wired with the classical 4-wires method and taped to the solid parts with copper powder charged grease to ensure a good thermal contact. For temperature regulation, two commercial flexible Maganin® heaters have been glued with copper powder charged epoxy resin to the bottom part of the cylindrical support as shown in Fig. 2. The temperature measurement has been carried out by using a Lakeshore® 336 cryogenic
temperature monitor controlled by a LabView® program for data acquisition.

Figure 2. Location of the PT100 thermometers on the aluminum thermal link for the thermal characterization

3.2. Experimental results and thermal budget

Two different cool-down sequences from ambient temperature were performed to evaluate the time to reach the working and lowest temperatures with magnetic field. The figure presents the results of a cool-down without temperature regulation of the testing zone. It shows the evolution of the four temperature sensors with respect to time. The evolution of the two temperatures located on the copper cylindrical support are almost identical to the one of the dummy copper plate and cannot be distinguished in the figure. The lowest temperature of the testing zone reached 46.6 K in roughly 7h30 and 60 K (the required working temperature of the HTS RF probes) in 6h15. After the steady-state regime is attained, the temperature difference along the aluminum thermal link is 3.16 K. Regarding the temperature homogeneity around the testing zone, the temperature difference between both sides of the copper support is 0.02 K, the external side being always warmer than the internal side as expected. Finally the temperature gradient between the copper support and the testing zone is 0.15 K.

A thermal budget has been evaluated for this cool-down scenario. It corresponds to the evaluation of the total power reaching the cold head. For this test, the cold head is able to extract 18.2 W at 43 K according to the manufacturer. The power dissipated on the testing zone by conduction has been evaluated to 4.47 W mainly coming from the access flange which separated the ambient environment to the testing zone within few mm. The thermal radiation is the highest contribution in the thermal budget with 14.74 W. The testing zone receives 8.45 W from the access flange and the cryostat vessel itself, the thermal link receives 3.37 W, the copper support receives 2.33 W and the cold head 0.59 W. The overall power estimation is 19.21 W which is 5% higher than the cold head capability.

Another cool-down sequence, presented in the figure was accomplished with a temperature regulation of the testing zone set to 60 K. The temperature of the testing zone is regulated within few mK in approximation 6h45. The temperature difference along the thermal link is 9.1 K and the temperature difference on the copper support is 0.7 K. The power dissipated by the heater needed to control the temperature of the testing zone is 6.77 W. These overall results are within the expected working condition specifications.

4. Measurements in the MRI system at clinical field

Several verification tests have been performed in a 1.5 T commercial MRI scanner before the validation test. Among other tests, it has been checked that the material composition of the overall cryostat working conditions do not bring any measurable perturbation to the
Figure 3. Temperature evolution of PT sensors for a cool-down scenario without temperature regulation. Cold head plate (blue line), cylindrical copper support 1 (green), cylindrical copper support 2 (orange) and dummy copper plate (red line).

Figure 4. Temperature evolution of PT sensors for a cool-down scenario with temperature regulation set to 60 K. Cold head plate (blue line), cylindrical copper support 1 (green), cylindrical copper support 2 (orange) and dummy copper plate (red line).

measurements. As designed, acquired RM images of the part of the cryostat inserted in the MRI system shows non perturbation within a diameter of 150 mm centered on the testing zone as requested. It has been checked previously that the cryostat has the same cryogenic thermal performances when inserted in the MRI scanner.

Finally a test with a HTS RF probe has been realized on a dummy sample presented in the figure 5 a). This dummy sample is a plastic 3D printed square container representing the logo
of the project SupraSense (two S’s) and filed with water. In the present experiment, the HTS probe is a 12 mm diameter multi-turn coil made of YBaCuO 60 μm thick circular bands with six concentric loops of equal width and deposited on a sapphire support [7]. To achieve the measurement, the HTS coil has been tuned to its optimal frequency (63.897 MHz at 77.97 K) by adjusting the temperature of the sapphire support with the cryostat temperature regulation. The MR image of the water in the dummy container obtained has a resolution of 500 μm³ as shown in the figure 5 b). The bright grey part in this picture is the water surrounding the two S’s. The last picture (fig. 5 c)) shows that a 3D rebuilt image is possible with the current set-up. It is considered that the cryostat is validated for clinical MRI measurements with HTS probes.

Figure 5. a) Picture of the dummy container filled with water for the MRI test. b) MR image obtained for the dummy sample. c) 3D rebuilt image of the dummy sample obtained from the MR image.

5. Conclusions
The all polymer cryogen free cryostat has been constructed and tested successfully under real clinical conditions in a commercial MRI scanner. The design has proven that the cryostat can be used by non cryogenist expert. The next development steps concern essentially the improvement of the resolution of the image by reducing the working temperature and tuning the frequency of the coil probe by adding adaptive loops. But reducing the weight of the cryostat (40 kg) would facilitate the installation of the system MRI scanner patient bed. One way to go would be to replace the aluminum thermal link (5 kg) by pulsating heat pipes [8] thermal link that would be several times lighter.

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