COMPACT CRYOGEN-FREE 3T MRI SYSTEM WITH FPGA BASED DIGITAL SPECTROMETER

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Abstract – *We have developed a complete preclinical 3T Magnetic Resonance Imaging (MRI) system with compact High-Temperature Superconductor (HTS) cryogen-free technology. The magnet, made from bismuth strontium calcium copper oxide (BSCCO) has a 3T magnetic field, 160 mm bore and 10 ppm homogeneity over a 60mm diametric spherical volume (DSV). The digital spectrometer, also developed in this project, uses modern Field Programmable Gate Array (FPGA) technology. The software has a comprehensive and user-friendly interface for pulse sequences programming, which gives freedom to users who want to create their customized pulse sequences.*

Key-words: *MRI, HTS, cryogen-free, spectrometer, pulse sequence.*

Introduction

MRI is the gold standard soft tissue imaging modality. However, uptake of MRI research tools is limited to large centers due to the substantial infrastructural investment and ongoing running costs of a superconducting MRI system. Most clinical, and indeed preclinical, MRI systems have at their heart a high field superconducting magnet that provides the highly stable and uniform magnetic field for performing MRI. The magnet typically uses liquid helium refrigerant to maintain its superconducting coils in a superconducting state. Liquid helium is an expensive consumable maintenance item that requires care in its use, often necessitating dedicated ducting systems to prevent asphyxiation in case of accidental release.

Fine Instrument Technology has developed, along with their partners at Victoria University of Wellington (New Zealand), a highly compact 3 T superconducting MRI system suitable for preclinical imaging that completely eliminates cryogens such as liquid helium, replacing them instead with a cryocooler that cools the superconducting coils in the magnet by conduction. The system simply requires a chilled water supply and can operate from a single electrical phase, presenting on average a constant 3 kW electrical load.

Here we present key features of the system, demonstrating that the magnetic field produced by the system is sufficiently homogeneous and stable to be used for MRI.

The digital spectrometer, SpecFIT Ultra, [1] uses FPGA technology to achieve high performance, easiness of update and low obsolescence. It is the central device that controls the functions of the whole system and communicates with the software on the computer.

CompSeq is a software designed for NMR, with a comprehensive and user-friendly graphical user interface, which gives users the freedom to change pulse sequence's parameters, allowing the researchers to adapt and develop sequences to their specific needs.

The system was validated acquiring some images presented here. We expect this system will change the accessibility of MRI to researchers.

Methods and materials

Magnet Design: The magnet was designed to produce a 3T magnetic field with < 10 ppm variation in magnetic field over the 60 mm imaging volume. It is passively shielded to give the smallest possible fringe field and overall dimensions. The magnet has a 160 mm warm bore. Full details of magnet design are described in [2].

HTS allows the magnet to maintain superconductivity at relatively high temperatures compared to liquid helium cooled magnets (approximately 20 K compared with 4.2 K). The BSCCO conductor is supplied by AMSC (Devens, USA), measures 4.2 x 0.3 mm and has a 77 K, self-field performance of > 145 A. [3]

Due to its tape-like form, the conductor is wound into double pancake coils, which are coils comprising two pancake-like coils of tape stacked on top of each other. [4] The superconducting coils are located inside a steel yoke to act as a return path for the magnetic flux created by the coils. The yoke also acts as the magnet cryostat.

The sizes and positions of the coils inside the yoke were determined by optimisation to produce the desired magnetic field using the finite element software Opera (Cobham Systems, Dorset, UK), with the magnet operating at 200 A corresponding to a current density of 145 A/mm^2.

The coil assembly is held in position inside the steel yoke using a suspension system. The combined thermal radiation load on the coil pack and conduction heat load along the suspension system to the coil pack was modelled by Opera FEM (Cobham systems, Dorset, UK) to be 4 W. Our FEM modelling indicated the magnet temperature should not exceed 24 K to keep the coils below 75 % of their critical current, the point at which they lose superconductivity. The Coolstar 6/30 provides 4 W cooling at 14 K and requires at most 3 kW AC power to achieve this; the magnet is therefore modeled to operate significantly below its maximum operating temperature with minimal electrical power draw.

Gradient Design: We designed and built a set of water-cooled, actively shielded gradient coils which incorporated the provision for passive shimming and a B_0 shim and Z^2 active shim coils. The gradient coils have an inner diameter of 100 mm. Each of the gradient channels has < 5 % deviation from linearity over the 60 mm imaging volume, and have an efficiency of 1.78, 1.89 and 1.42 mT/m/A for the *x*, *y* and *z* channels respectively, with a maximum current of 175 A.

Spectrometer Design: The simplified diagram of SpecFIT Ultra is shown in Figure 1. The spectrometer is the device that controls the whole system by receiving commands from the software. The FPGA used is an Arria V GX 5AGXFB3H4F35C4N from Altera, it contains the project of the spectrometer and is responsible to do all sorts of signal processing, digital filtering, modulation and demodulation, generation of signals for gradients, RF, control signals of peripherals, etc. It communicates with software via Gigabit Ethernet and UDP protocol. The Timing PCB is used to generate the global reference clock with 5 ppb of frequency stability using OCXO since MRI applications need high clock stability, especially for long pulse sequences. The reference clock goes through FPGA and is distributed using PLLs to the whole system. This board also generates a pure sine wave with low phase noise used as the local oscillator of the mixer located in the RF Front End.

The RF Converter PCB is responsible for both digital to analog and analog to digital conversions of the RF signals. On the transmitter (Tx) chain, it receives the digital signal already modulated (Tx data) from the FPGA at an Intermediary Frequency (IF) and converts it to an analog signal (Tx IF) using the DAC AD9763 from Analog Devices. This signal is then filtered, upconverted to RF Larmor Frequency and amplified on the RF Front End PCB, resulting in the output signal (Tx RF) that goes to the RF amplifier outside the spectrometer. On the Receiver (Rx) chain, the signal goes through the opposite way, after the RMN signal is amplified by external Low Noise Amplifier (LNA), it enters on the RX input of the RF Front End, then is filtered, down-converted to IF frequency and amplified, and finally it is digitized by the ADC AD9248 from Analog Devices.

MRI applications need high Spurious Free Dynamic Range (SFDR) on the receiver, so we use a 14 bits ADC working at 50 MSPS, with this system we have an SFDR of approximately 70 dB.

Different NMR applications need different bandwidths and different power gain on both Tx and Rx. For this reason, we have variable attenuators on the RF Front End on both Tx and Rx, for fine gain adjustment selectable in the software with a range of 32 dB.

The Gradients DACS PCB has high performance 16 bits DAC's (AD8812 from Analog Devices) working at 1 MSPS for generating the four differentials signal of X, Y, Z and B0 gradients.

The AUX (auxiliary) PCB receives a signal from the FPGA and generates the RF enable signal, which controls the RF high power amplifier enable and RF coil decoupling.

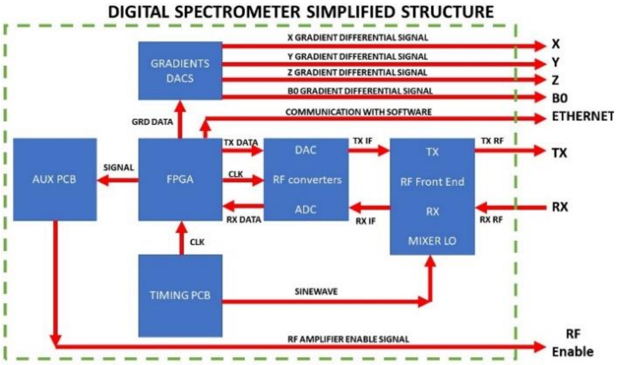

Figure 1. Simplified diagram showing the digital spectrometer structure.

The spectrometer is currently capable of working at two RF frequency ranges, from 60 MHz to 70 MHZ to be used with 1.5T magnets, and from 120 MHz to 130 MHz, to be used with 3T magnets. The frequency working range can be selected by switching cable positions inside the RF Front End, and selecting the right frequency in the software.

We are also developing a broadband version of the RF Front End that will be able to work from 2 MHz up to 200 MHz.

System integration and imaging: the creation and edition of the pulse sequences are made with CompSeq software through the table with 128 columns labeled as events. The values of this table are encrypted in a list of numbers and store in a file with the extension ".*seq*".

In this file, all the reference parameters are stored, for example, the radio-frequency pulse (RF) duration and amplitude, gradients amplitudes and formats, field of view (FOV) in a readout and phase encode directions, k-space matrix size, echo time (TE), repetition time (TR), acquisition time (TA), etc.

In the sequence tools menu, there are shortcuts for configuring rotation matrix, to design custom digital filters, gradients and RF pulses (including adiabatic pulses).

In the script editor, the user can create an algorithm to adjust the entire sequence according to simple inputs parameters. After the user creates his sequence and click on run script, all the calculated parameters of the sequence can be seen in the codification list in the same menu, and the graphical representation is shown in the same window, as we can see in Figure 2 for a spin echo (SE) sequence.

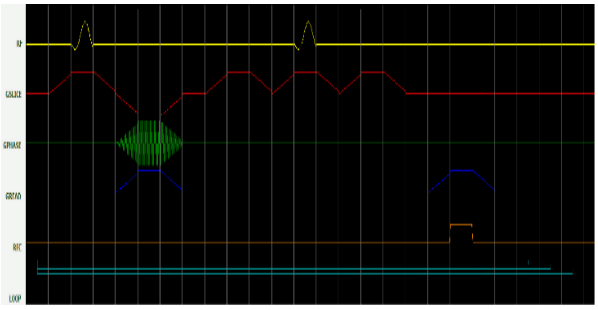

Figure 2. Graphical representation of the spin echo sequence.

The complete system with all components is shown in Figure 3.

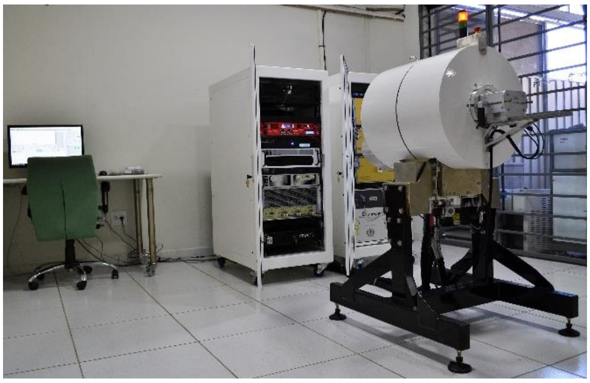

Figure 3. The complete MRI system at FIT.

Results

The magnet was successfully constructed, cooled and energized to 3 T. At 200 A, the magnet operated at 13 K, validating our thermal modeling. Upon completion of the initial testing, the magnetic field uniformity was assessed. We measured magnetic field on the surface of a 60 mm sphere on 20 axial planes and 24 radial points per plane using a small NMR probe mounted on a positioning stage. The initial homogeneity was poor, with a variation of approximately 2000 ppm. Following three passive shim iterations, [5] the homogeneity was improved to 10 ppm over the imaging volume, as can be seen in [2]. For a DSV of 45 mm, the B_0 homogeneity is only 1 ppm.

The temporal stability of the magnetic field was then assessed using an SSFP sequence, and investigating the change in phase of the NMR signal over the first few points of the FID. By calculating the rate of change of phase, instantaneous NMR frequency at every TE can be calculated. As can be seen in [2], temporal stability over the length of a typical NMR experiment is ± 5 ppb. We hence demonstrate that both the magnetic field uniformity and temporal stability are adequate to perform MRI as we show images.

For imaging tests, we used spin echo (SE) sequence (figure 2) and two different samples: a spherical phantom with 3 cm diameter filled with tap water and a Kiwi fruit.

Figure 4 shows the results of the spherical phantom acquired with SE and following parameters: TE = 2 ms, TR = 2 s, FOV = 5 cm isotropic, 256x256 matrix and no average, producing a pixel resolution of 195 μm^2 and 3 mm slice thickness.

The reconstruction of the images was performed using MATLAB *software.*

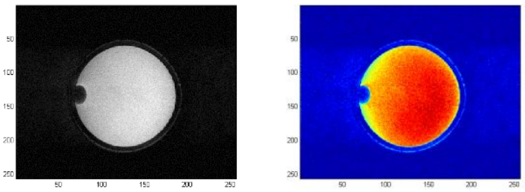

Figure 4. Images of the spherical phantom obtained with a spin echo sequence in a grayscale map (left) and RGB scale map (right), there is a small bubble of air in this phantom.

Figure 5 shows a Kiwi fruit, acquired with a spin echo sequence with a matrix size of 256x256 and an acquisition time of approximately 9 minutes and no averaging yet.

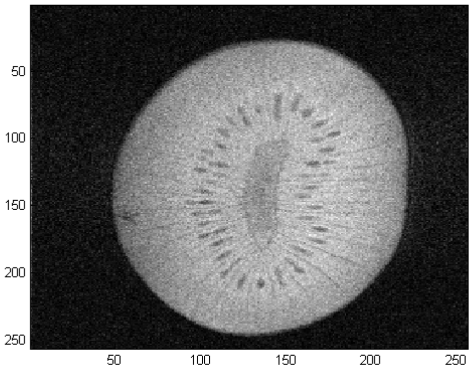

Figure 5. Image of the Kiwi Fruit with SE sequence.

Discussion and Conclusion

The homogeneity measured is considered very satisfactory for pre-clinical MRI applications and correspond to the computational modeling and the temporal stability of B_0 field, 5 ppb, is more than enough for the intended applications.

The images acquired with spectrometer, software and pulse sequence developed in this project shows the object clearly, and without any artifact. Figure 4 shows a good profile of excitation performed by RF pulsed and Figure 5 shows good quality Kiwi fruit imaging, including structural details like little seeds, intern deformation in the left side and good contrast between tissues.

Future pulse sequence developments include improvement in signal-to-noise ratio (SNR), averaging, velocity, increased slice numbers and implementing steady state mode.

The next steps include pre-emphasis filters in gradients pulses to eliminate eddy-currents effects, better adjustment of receiver gain and new sequences.

Besides the system is still in development, the results already show a good pre-clinical system with satisfactory quality images.

The partnership between a Brazilian company, a Brazilian university and a New Zealander university is resulting in the development of an innovative system combining a very compact cryogen-free HTS magnet, a modern FPGA digital spectrometer, a software that gives freedom for researchers and user-friendly pulse sequence programming language, an auto-shielded structure that avoids the need of external Faraday Cage, and the versatility of a driven-mode magnet, meaning easy and low-cost installation.

Acknowledgements

The magnet design and construction work in this article were funded by Kiwinet grant CI001007, and system completion via New Zealand Ministry of Business, Innovation and Employment grant RTVU1304. The authors would like to thank HTS-110 for peer review and design detailing of the magnet, as well as performing its manufacture. The authors also would like to thank Dr. Alberto Tannus, Dr. Mateus Martins, Dr. Edson Vidoto and Dr. Fernando Paiva for assistance with imaging and FPGA.

Finally, the author would like to thank Desenvolve SP for funding the project via Inovacred loan.

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