Title: JOULE-THOMSON MICRO-REFRIGERATOR-COOLED RADIO-FREQUENCY COILS AS DETECTORS FOR IMAGING SYSTEMS

Abstract: The present invention includes a method, system and apparatus for imaging of a sample using a cryo-cooled probe. The probe comprises a Joule-Thomson (J-T) refrigerator in thermal contact with a radio frequency (RF) coil for cooling the RF coil. A vacuum dewar is also included in the probe and surrounds the J-T refrigerator and RF coil such that a vacuum space resides between the J-T refrigerator and the walls of the vacuum dewar, insulating the sample in order to maintain the sample initial temperature.
JOULE-THOMSON MICRO-REFRIGERATOR-COOLED RADIO-FREQUENCY COILS AS DETECTORS FOR IMAGING SYSTEMS

REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to Provisional Patent Application No. 60/301,513, filed June 28, 2001, herein incorporated in its entirety.

GOVERNMENT SUPPORT

[0002] This work was supported in part by grants from the National Science Foundation, grant number BES 0071837. The government may have certain rights in this invention.

BACKGROUND

[0003] The present invention relates generally to imaging systems. More specifically, the present invention relates to magnetic resonance imaging and nuclear magnetic resonance systems.

[0004] Magnetic resonance imaging (MRI) microscopy, or μ-MRI, is fast becoming a powerful tool in biomedical research for the non-destructive characterization of tissue microstructure and composition in vitro and in vivo. 3-D images of soft tissue samples can be obtained routinely in vitro with dedicated instrumentation and exhibit exquisite contrast at linear resolutions of ~ 50 μm. MRI microscopy in vivo poses several challenges, most notably image degradation due to subject motion and the limitation of signal-to-noise ratio (SNR) by the overall scan time. The scan time needed to achieve a given SNR scales as the inverse sixth power of linear resolution, making SNR the most significant limitation to higher resolution in vivo (Callaghan, PT, Claredon Press, Oxford, 1991). Nuclear magnetic resonance (NMR) signal voltage itself is limited by the small energy separation ΔE between ground and excited nuclear spin states, being proportional to exp(-ΔE/k_B T), which is very small at sample temperatures T near room temperature (k_B is the Boltzmann constant). Since electrical noise voltages, proportional to (temperature x resistance)^1/2, arise from both coil and sample, traditional methods for improving SNR in NMR and MRI have included the use of small RF detector coils that limit electrical noise contributions from sample regions beyond the field of view, and cryogenic cooling of
both the RF coil and the sample, resulting in both decreased electrical noise and increased signal voltage and thus increased SNR.

[0005] For local regions below the sample surface, SNR improvements also have been achieved with small implanted coils, inductively coupled to a surface loop (Ford, JC et. al, Magn Reson Med 1994; 31:218-223). The latter, though, have limited application due to their invasive nature. Although imaging and spectroscopy of biological tissues usually precludes sample cooling, cryogenic cooling of the coil enhances SNR, at least as long as the RF coil and/or sample are small.

[0006] SNR improvements with a cryo-cooled RF coil room-temperature sample, have been demonstrated in NMR systems using a cold sample. (Styles et. al., J Magn Reson 1984;60:397-404). Cryogenic coil SNR gains for MRI of warm tissues have been observed with a variety of coil sizes and at various field strengths (frequencies). This SNR gain can be substantial for a cryo-cooled coil made from high-T_c superconductor (HTS) material, in which case the ac resistance is drastically reduced. For example, some current systems have reported a 7-fold gain in SNR for MR micro-imaging of an excised mouse kidney at 400 MHz, using a small superconducting Helmholtz coil pair cooled by a liquid helium cryostat (Hurlston, et. al., T. Magn Reson Med 1999;41:1032-1038).

[0007] However, the prior RF systems are difficult to handle as they require cryogenic liquids or gases as coolants. Liquid cryogens present significant risk when used in proximity to living tissues, especially for human studies. An ideal system would call for precise cooling of the RF coil while minimizing risk to the subject.

[0008] In order to open such SNR gains to the wider MRI and NMR research community, there is a need for modular, turn-key cryogenics which are safe in proximity to living tissue.

**SUMMARY**

[0009] The present invention includes a method, system and apparatus for imaging of a sample using a cyro-cooled probe. The probe comprises a Joule-Thomson (J-T) refrigerator in thermal contact with a radio frequency (RF) coil for cooling the RF coil. A vacuum dewar is also included in the probe and surrounds the J-T refrigerator and RF coil such that a vacuum space resides between the J-T refrigerator and the walls of the vacuum dewar, insulating the sample in order to maintain the sample initial temperature.
Additional objects, advantages and novel features of the invention will be set forth in part in the description, examples and figures which follow, and in part will become apparent to those skilled in the art on examination of the following, or may be learned by practice of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing summary, as well as the following detailed description of the invention, will be better understood when read in conjunction with the appended drawings. For the purpose of illustrating the invention, there are shown in the drawings, certain embodiment(s) which are presently preferred. It should be understood, however, that the invention is not limited to the precise arrangements and instrumentalities shown.

Figure 1 is a diagram of a Joule–Thomson cryo-coil assembly in accordance with a preferred embodiment of the present invention.

Figure 2 is a diagram of an exemplary assembly cryo-probe using HTS coils.

Figure 3 is a diagram of the cryo-probe assembly in accordance with a second preferred embodiment of the present invention.

Figure 4 is an exemplary diagram of a birdcage coil cryo-probe assembly using a plurality of cold stages.

Figure 5 is a diagram of a volume coil probe in accordance with a third preferred embodiment of the present invention.

Figure 6 is an illustration of a front and side view of a solenoidal coil probe in accordance with a third preferred embodiment of the present invention.

Figure 7 is diagram of a Helmholtz pair coil cryo-probe in accordance with a fourth preferred embodiment of the present invention.

Figure 8 is an illustration of a MRI or NMR system in accordance with a fifth preferred embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

The present invention relates to an apparatus, system, and method for imaging a sample using a cyro-code probe. A novel aspect of the present invention is the cooling of a radio-frequency coil comprised in the cryo-probe in order to increase the signal to noise ratio (SNR) of the image without using cryogenic liquids.
A first embodiment of the present invention is a surface coil cryo-probe, cooled by a Joule-Thomson micro-refrigerator, for use in imaging systems, such as, large-bore and whole-body MRI scanners. Figure 1 is a diagram of the surface coil cryo-probe assembly 10 in accordance with the first preferred embodiment of the present invention. The assembly 10 comprises a radio-frequency (RF) coil 11, a tuning capacitor 14, a matching capacitor 15, a Joule-Thomson (J-T) cold stage 16, and a cable 12. J-T cold stage 16 is a micro-refrigerator based on the Joule-Thomson cycle. As those skilled in the art know, these refrigerators include laminated glass plates with micro-etched channels through which a high-pressure gas can expand and cool.

Unlike closed cycle refrigerators, J-T refrigerators are silent, vibration free, require no liquid cryogens, and can operate at very low temperatures for days using only compressed, room-temperature, nitrogen gas. In the present invention, J-T cold stage 16 is used to cool RF coil 11 of probe assembly 10. J-T cold stage 16 is selectively positioned such that RF coil 11 surrounds J-T cold stage 16, wherein a single side of RF coil 11 is in thermal contact with J-T stage 16.

The glass material of the J-T stage has three benefits for cooling an RF coil for MRI: 1) it is not electrically conductive so that it does not distort the RF magnetic field generated by the surface coil; 2) it is lossless so that it does not contribute extra Johnson noise to the surface coil; and 3) it has low thermal conductivity so that a thermal gradient can be maintained at room temperature along the J-T stage from the cold tip of the stage to the base of the stage. This allows one to incorporate the J-T stage and coil assembly into a small, room-temperature module that is easily and safely positioned within the bore of a clinical MRI scanner.

RF coil 11, thermally anchored to J-T stage 16, is cooled to the steady-state temperature of J-T stage 16. RF coil 11 is tuned and capacitively matched for metal coils, such as copper aluminum, silver, gold and other non-ferromagnetic metals with low resistivity by tuning capacitor 14 and matching capacitor 15, respectively. Although copper and aluminum have been disclosed as metal coils, a metal coil used in the present invention is not limited thereto. Any appropriate metal may be used instead.

It may be operated either in receive-only mode, with spin excitation provided by an external transmit coil, or in transmit/receive mode. The external transmit coil may be decoupled from the cold receive coil by active de-tuning via crossed diodes and/or a high-impedance trap. A second way of decoupling the transmit and receive
coils is by orthogonal placement of the transmit coil relative to the receive coil. A third means is accomplished by physically locating the transmit coil at a distance away from the receive coil.

Cryo-coil assembly 10 is enclosed in small vacuum dewar 18 capable of providing thermal insulation and optimized for MR imaging of superficial tissue microstructure in vivo or ex vivo. Selection of materials for a cryogenic system for use in MRI or NMR is constrained by the maximum tolerable total convective, conductive and radiative rates of heat transfer between the cold stage and its environment. Convective heat transfer, often the largest of these, is most effectively reduced by a vacuum space around the cold stage, ideally at a vacuum level within the molecular flow regime. In order to provide sufficient insulation, an exemplary gap size between J-T cold stage 16 and dewar wall 18 is ~ 2 mm, and a primary vacuum level of about 5 μm Hg.

The above-stated gap size and vacuum are used for exemplary purposes and are not intended to limit the present invention.

The gas permeability of materials used to construct dewar walls 18 should be as small as possible.

Thermal conductivity of dewar walls 18 is low to reduce conductive heat transfer at points in contact with the base of the cold stage. Radiative heat transfer can be reduced by lowering the emissivity of the walls 18. Metals have relatively low emissivity as compared to plastic, but may contribute RF losses to RF coil 11. Plastic materials, however, may be used. Covering plastic surfaces with sectioned, aluminized Mylar™ film helps to reduce their emissivity, which is particularly beneficial for cold surfaces, as the radiative heat transfer is proportional to (emissivity)x(temperature)^4 (Stefan-Boltzmann law), and is the principle behind “superinsulation” and radiation shields.

Additional considerations for appropriate dewar materials include: room temperature rigidity; low-temperature tolerance to internal stresses; ease of use (machinability, availability and cost); electrical conductivity (RF coil loading, eddy currents induced by imaging gradients); and magnetic susceptibility (non-ferrous for MRI compatibility, minimal susceptibility mismatch at interfaces). It is preferable that the vacuum vessel walls 18 be constructed from poly vinyl chloride (PVC) or G10 plastic, both of which offer strength, good thermal resiliency, low thermal conductivity, low electrical loss and low gas permeability. Glass is also a possible material. RF coil
11 is, preferably, to be positioned 1 – 2 mm from a 1 mm thick ceramic window (not shown) in vacuum dewar wall 18.

Alternatively, probe assembly 10 may use planar high-Tc superconductor (HTS) material instead of the metal coils disclosed hereinabove. Figure 2 is a diagram of an exemplary cryo-probe assembly 20 using HTS coils. Probe assembly 20, similar to the assembly 10 illustrated in Figure 1, comprises an HTS RF coil 21, a tuning capacitor 24, a matching capacitor 25, a Joule-Thomson (J-T) cold stage 26, a sapphire disk 27 and a cable 22. The components of probe assembly 20 operate in the same manner as the embodiment disclosed hereinabove. The difference, though, is in the positioning of HTS RF coil 21. HTS coil 21 is thermally anchored to surface of the sapphire disk 27, which is coupled to the end of J-T stage 26. HTS coil 21 is inductively tuned and matched via a resonant sniffer. The use of HTS coil 21 reduces the fluctuations in temperature, supporting precise temperature control in the cryo-probe assembly 20.

The J-T refrigerator is ideally suited for cooling a surface coil due to its geometry and its capability for precision, localized cooling. Surface coils can be made having flat surfaces, which allow for optimum thermal contact between the J-T stage and the surface coil, and therefore, optimum cooling efficiency and capacity. In addition, thin-film HTS coils are usually flat, and therefore, best cooled by a flat cold stage. Furthermore, the precise cooling provided by the J-T refrigerator allows the surface coil safely to be placed very close to the sample, and thus, the surface coil can be made very small, thereby obtaining higher SNR. This is especially important when the surface coil is used in an MRI system for imaging living tissue.

A second preferred embodiment of the present invention is a volume coil cryo-probe assembly 30. Figure 3 is a diagram of cryo-probe assembly 30 in accordance with the second preferred embodiment. Volume coil cryo-probe assembly 30 comprises a vacuum dewar 37, a RF coil 33, a sample tube 34, and a J-T cooling stage 35 wherein the base of the J-T stage may be outside of and below vacuum dewar 37 with input and output gas lines attached. Similar to the first preferred embodiment of the present invention, vacuum dewar 37 encloses RF coil 33 and J-T stage 35 creating vacuum space 32 for insulating a sample in sample tube 34.

Volume coil 33 of the second embodiment is designed as a birdcage coil. An exemplary birdcage coil 33 may be a 12-rung, low-pass design which is thermally anchored to J-T cooling stage 35. Birdcage coil 33 is inductively driven and impedance
matched via a cooled coupling loop passing through the electrical feedthrough of J-T stage 35 base (not shown). Additionally, a cooled tuning rod may extend through the base of vacuum dewar 37 for fine tuning HTS coils when used (not shown).

[0035] As disclosed above, J-T stage 35 is in thermal contact with the birdcage coil 33. J-T stage 35, similar to J-T stage 16 disclosed in the first preferred embodiment, maintains the cryogenic system at a desired temperature, for example 35 Kelvin. Although one J-T stage 35 is displayed in Figure 3, it should be noted that a plurality of J-T stages may be utilized. An example of a birdcage coil cryo-probe assembly 30 using two (2) J-T stages 35₁, 35₂ is illustrated in Figure 4. As shown in Figure 4, each of J-T stages 35₁, 35₂ is in thermal contact with birdcage coil 33.

[0036] A third embodiment of the present invention is a volume coil probe assembly 50, including a solenoidal RF coil 53 as the volume coil, which is illustrated in Figure 5. Referring to Figure 5, J-T stage 55 of the third embodiment is in thermal contact with solenoidal coil 53 in a similar manner as birdcage coil 33 of the second preferred embodiment. Unlike the birdcage coil of the second embodiment, though. Solenoidal coil probe assembly 50 further includes tuning and matching capacitors 56 and a cable 59 similar to those disclosed in the surface coil probe assembly 10 of the first preferred embodiment. Since the J-T refrigerator provides precise, localized cooling only to the solenoidal coil, risk of cooling the sample within the capillary inserted into the solenoidal coil is minimized.

[0037] Illustrated in Figure 6 is a front and side view of the solenoidal coil probe 50 which includes an insert hole for insertion of a capillary tube 61 containing a sample tissue, the capillary tube 61 being inserted within solenoidal coil 53. A rubber grommet is also included in solenoidal coil probe 50 to seal the insert hole, maintaining the insulation resulting from vacuum space 52. Other means to seal the coil probe 50 may be used as well.

[0038] Figure 7 is diagram of a Helmholtz pair coil cryo-probe 70 in accordance with a fourth preferred embodiment of the present invention. Helmholtz pair coil probe 70 is a volume coil probe similar to birdcage coil probe 33 of the second preferred embodiment and to solenoidal probe 50 of the third preferred embodiment. The Helmholtz coil is in thermal contact with J-T stage 75 and is surrounded by a vacuum dewar 77, which creates vacuum space 72 for insulating the sample. Coil 73 is inductively driven and impedance matched via a cooled coupling loop passing through
the electrical feedthrough of the J-T stage 35 base (not shown), similar to birdcage coil 33 of the second preferred embodiment. A sample tube 79 is inserted into the Helmholtz coil pair, for example, from the top of the vacuum dewar 77. Since the Helmholtz pair coil has a flat, planar geometry that is parallel to the surface of the J-T stage, optimum thermal contact and cooling capacity is achieved.

[0039] A fifth embodiment of the present invention incorporates the probe assemblies as disclosed hereinabove into a MRI or NMR micro-imaging system. Figure 8 is an illustration of MRI or NMR system 80 in accordance with this embodiment. System 80 comprises sources of high pressure gases 821, 822, filters/dryers 831, 832, J-T micro-refrigerator(s) 85, gas flow meters 871, 872, and an optional vacuum pump 84 and temperature controller 86. Temperature controller 86 works via feedback with a resistive heater element and ceramic RTD temperature sensor mounted on the cold stage (not shown). Connections to a probe assembly 85 consist of one or more high-pressure, non-magnetic stainless steel gas line(s) 821, 822 for gas input at, for example, 1800 psi, one or more low-pressure gas line(s) for output at atmospheric pressure, one or more cable(s) (not shown) for the RF coil, and four direct-current leads for the temperature sensor and heater (not shown). It should be noted that the probe assembly 85 could be any of the probe assemblies disclosed in the first, second, third and fourth preferred embodiments of the present invention.

[0040] Both vacuum pump 84 (for vacuum assist on the J-T output) and temperature controller 86 are optional in the sense that probe assembly 85 will operate efficiently in their absence, although they permit lower and more stable temperatures. Temperature stability is critical, however, for HTS coils. Dry nitrogen and neon gases (99.998% purity) are required to prevent clogging of probe assembly 85 due to water vapor freezing inside the micro-etched channels. For this purpose a filter/dryer 831, 832 may be placed in line prior to the refrigerator.

[0041] J-T stage cooled cryo-coils will be especially relevant for imaging at high-resolution many animal models, warm tissue samples, such as, but not limited to, osteoporosis and cataractogenesis in rabbits, diffusion imaging of spinal cord nerve regeneration in sea lamprey and rats, and gene knock-out studies of the mouse brain. It should be noted that warm tissue samples are tissue samples whose temperature are at least room temperature. High-resolution in vivo imaging in humans of superficial tissue structures having short T2 and/or short T2* relaxation times (thus SNR-poor), such as
skin, cartilage and bone, will be improved by J-T stage cooled cryo-coils. Of particular medical significance is the prediction of bone fracture risk from MR images of trabecular structure, and the investigation of steroid-induced osteopenia in rabbit models.

[0042] Furthermore, since noise voltage from the sample scales with the Larmor frequency of the nuclei, \(^1\text{H}\) imaging in low-field "open" MRI systems and imaging and spectroscopy of low-gamma nuclei (e.g., \(^{31}\text{P}\) and \(^{13}\text{C}\)) in high-field systems are two applications worthy of exploration where cryogenic cooling of the RF coil will likely produce significant gains in SNR. Similarly, targeted applications for J-T cryo-coils include low read-out field MRI with samples having non-equilibrium nuclear polarization generated by any of various methods such as a pulsed magnetic field ("pre-polarized" MRI), optically-pumped hyper-polarized noble gases (e.g., \(^{3}\text{He}\) and \(^{129}\text{Xe}\)), chemically-induced dynamic nuclear polarization (CIDNP), and para-hydrogen-induced polarization (e.g., "PASADENA").

[0043] Each and every patent, patent application and publication that is cited in the foregoing specification is herein incorporated by reference in its entirety.

[0044] The above description and the views and material depicted by the figures are for purposes of illustration only and are not intended to be, and should not be construed as, limitations on the invention. Moreover, certain modifications or alternatives may suggest themselves to those skilled in the art upon reading of this specification, all of which are intended to be within the spirit and scope of the present invention as defined in the attached claims.
CLAIMS

WE claim:

1. A cryo-cooled probe for imaging and spectroscopy of a sample comprising:
   a radio-frequency (RF) coil for receiving a radio-frequency signal from the sample;
   a Joule-Thomson (J-T) refrigerator in thermal contact with the RF coil, for cooling said RF coil; and
   a vacuum dewar surrounding said J-T refrigerator and said RF coil, such that a vacuum space resides between said J-T refrigerator and the walls of said vacuum dewar;
   said vacuum space insulating said sample from said J-T refrigerator.

2. The probe of claim 1, wherein said RF coil is a surface coil.

3. The probe of claim 2, wherein said surface coil is made from a copper or aluminum material.

4. The probe of claim 2, wherein said surface coil is made from a non-ferromagnetic metal.

5. The probe of claim 2, wherein said surface coil is made from a high-$T_c$ superconductor material.

6. The probe of claim 1, wherein said RF coil is a volume coil.

7. The probe of claim 6, wherein said volume coil is designed as a birdcage coil, said probe further including a second J-T refrigerator such that said J-T refrigerator and said second J-T refrigerator are both in thermal contact with said birdcage coil.

8. The probe of claim 7, wherein said birdcage coil is made from a copper or aluminum material.
9. The probe of claim 7, wherein said birdcage coil is made from a non-ferromagnetic metal.

10. The probe of claim 7, wherein said birdcage coil is made from a high-\(T_c\) superconductor material.

11. The probe of claim 6, wherein said volume coil is designed as a solenoidal coil, sample being inserted into said solenoidal coil using a capillary tube.

12. The probe of claim 11, wherein said solenoidal coil is made from a copper or aluminum material.

13. The probe of claim 11, wherein said solenoidal coil is made from a non-ferromagnetic metal.

14. The probe of claim 11, wherein said solenoidal coil is made from a high-\(T_c\) superconductor material.

15. The probe of claim 6, wherein said volume coil is a Helmholz pair coil.

16. The probe of claim 15, wherein said Helmholz pair coil is made from a copper or aluminum material.

17. The probe of claim 15, wherein said Helmholz pair coil is made from a non-ferromagnetic metal.

18. The probe of claim 15, wherein said Helmholz pair coil is made from a high-\(T_c\) superconductor material.

19. An imaging system including:

a cryo-cooled probe for imaging and spectroscopy of a sample comprising:

a radio-frequency (RF) coil for receiving a radio-frequency signal from the sample;
a Joule-Thomson (J-T) refrigerator in thermal contact with the RF coil, for
cooling said RF coil; and

a vacuum dewar, surrounding said J-T refrigerator and said RF coil such
that a vacuum space is left between said J-T refrigerator, and the walls of said
vacuum dewar;
said vacuum space insulating said sample from said J-T refrigerator said RF coil.

20. The system of claim 19 wherein said system is a magnetic resonance imaging
system.

21. A method of cooling a radio-frequency (RF) coil comprised in a cyro-cooled
probe for imaging and spectroscopy of a sample having an initial temperature comprising
the steps of:
thermally contacting the RF coil to a Joule-Thomson (J-T) refrigerator, and
surrounding the J-T refrigerator and RF coil with a vacuum dewar such that a
vacuum space resides between said J-T refrigerator and RF coil, whereby the sample
maintains the initial temperature.

22. The method of claim 21 wherein the sample is a warm tissue sample.