(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
27 July 2006 (27.07.2006)

PCT

(10) International Publication Number
WO 2006/078415 A2

(51) International Patent Classification:
G01R 33/36 (2006.01)

(21) International Application Number:
PCT/US2005/046786

(22) International Filing Date:
21 December 2005 (21.12.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
11/037,627 18 January 2005 (18.01.2005) US

(71) **Applicant** *(for all designated States except US)*: **VARIAN, INC.** [US/US]; 3120 Hansen Way, D-102, Palo Alto, California 94304 (US).

(72) **Inventors; and**
(75) **Inventors/Applicants** *(for US only)*: **HUDSON, Alexander, M., J.** [GB/US]; 203 Vicksburg Street, San Francisco, California 94114 (US). **MEHR, Knut, G.** [DE/US]; 2169 Folsom Street, #304, San Francisco, California 94110 (US).

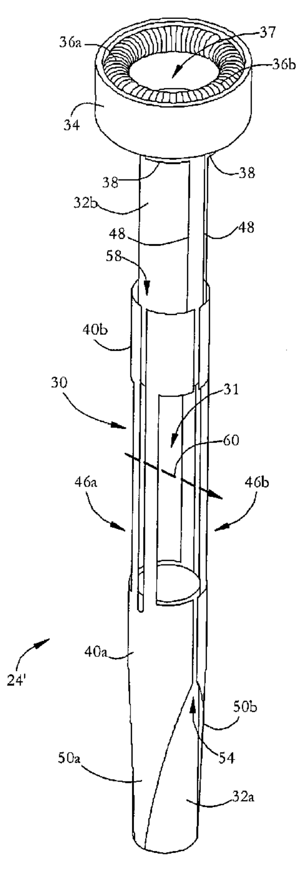
(74) **Agents: FISHMAN, Bella** et al.; Varian, Inc., Legal Department, 3120 Hansen Way, D-102, Palo Alto, California 94304 (US).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT,

[Continued on next page]

(54) Title: NMR RF COILS WITH IMPROVED LOW-FREQUENCY EFFICIENCY



(57) Abstract: According to one aspect, the low-frequency (e.g. lock channel) performance of a nuclear magnetic resonance (NMR) saddle-shaped, distributed-capacitance radio-frequency (RF) coil is improved by connecting a pair of auxiliary inductors across a plurality of leads extending upward from the coil upper ring. The upward-extending leads can be formed from the same foil as a main coil structure. The auxiliary inductors are separated from the coil window, so that magnetic susceptibility discontinuities introduced by the auxiliary inductors can be compensated for. In one embodiment, two half-toroid auxiliary inductors are positioned to form a full toroid shape. Some lost high-frequency performance can be recovered by using a split capacitance band positioned over the lower coil ring. The split capacitance band allows capacitance tuning while maintaining an RF current path close to the coil window.

WO 2006/078415 A2

RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

NMR RF COILS WITH IMPROVED LOW-FREQUENCY EFFICIENCY

RELATED APPLICATION DATA

This application is related to the U.S. Patent Application No. 11/037,605 entitled "NMR RF Coils with Movable Split Capacitance Bands," by inventor Alexander M. J. Hudson, which was filed on January 18, 2005 and is assigned to the assignee of the present application.

FIELD OF THE INVENTION

The invention in general relates to nuclear magnetic resonance (NMR) spectroscopy, and in particular to systems and methods for improving the lock signal performance of NMR radio-frequency (RF) coils.

BACKGROUND OF THE INVENTION

Nuclear magnetic resonance (NMR) spectrometers typically include a superconducting magnet for generating a static magnetic field B_0, and an NMR probe including one or more special-purpose radio-frequency (RF) coils for generating a time-varying magnetic field B_1 perpendicular to the field B_0, and for detecting the response of a sample to the applied magnetic fields. Each RF coil and associated circuitry can resonate at the Larmor frequency of a nucleus of interest present in the sample. Nuclei of interest analyzed in common NMR applications include ^1H (proton), ^{13}C (carbon), and ^{15}N (nitrogen). The RF coils are typically provided as part of an NMR probe, and are used to analyze samples situated in sample tubes or flow cells. The direction of the static magnetic field B_0 is commonly denoted as the z-axis or longitudinal direction, while the plane perpendicular to the z-axis is commonly termed the x-y or transverse direction.

Several types of RF coils have been used in NMR systems. In particular, many NMR systems include transverse-field RF coils, which generate an RF magnetic field oriented along the x-y plane. Transverse-field coils include saddle-shaped coils and birdcage coils. Birdcage coils typically include two transverse rings, and a relatively large number of vertical rungs connecting the rings. Birdcage coils are multiply-resonant structures in which specified phase-relationships are established for current flowing along multiple vertical rungs. Saddle-shaped coils normally have the current path defined by a conductor pattern around the coil windows. A particular type of saddle-shaped coil design is the Alderman-Grant coil design. An original Alderman-Grant coil design having two vertical rungs and chip capacitors was described by Alderman and Grant in their paper entitled "An Efficient Decoupler Coil Design which Reduces Heating in Conductive Samples in Superconducting Spectrometers," *J. Magnetic Resonance* 36:447-451 (1979). Other Alderman-Grant coil designs can have vertical slots defined in the vertical rungs, and can employ distributed capacitance structures rather than discrete chip capacitors.

An NMR frequency of interest is determined by the nucleus of interest and the strength of the applied static magnetic field B_0. In order to maximize the accuracy of NMR measurements, the resonant frequency of the excitation/detection circuitry is set to be equal to the frequency of interest. The resonant frequency of the excitation/detection circuitry varies as

$$\nu = 1/2\pi\sqrt{LC} \qquad [1]$$

where L and C are the effective inductance and capacitance, respectively, of the excitation/detection circuitry.

Generating high-resolution NMR spectra is facilitated by employing a temporally and spatially-homogeneous static magnetic field. The strength of the static magnetic field can vary over time due to temperature fluctuations or movement of neighboring metallic objects, among others. Spatial variations in the static magnetic field can be created by variations in sample tube or sample properties, the presence of neighboring materials, or by the magnet's design. Minor spatial inhomogeneities in the static magnetic field are ordinarily corrected using a set of shim coils, which generate a small magnetic field which opposes and cancels inhomogeneities in the applied static magnetic field. Temporal variations in the static magnetic field are commonly corrected using a field lock. Field lock circuitry monitors the resonance frequency of a reference (e.g. deuterium) signal, and adjusts the static magnetic field strength to keep the reference signal frequency constant. Deuterium is commonly added to sample solvents to provide the field lock reference signal.

In general, the field lock reference signal and the NMR measurement signal have different resonance frequencies. Consequently, if the same RF coil is used to acquire both the field lock and sample NMR signals, a conventional RF coil optimized for the sample resonance of interest may not be ideally suited for the field lock reference signals. In some NMR systems, a single coil may also be used to perform NMR measurements for multiple nuclei of interest. In such systems, the coil may not be ideally suited for all resonance frequencies of interest. Improving the performance of NMR systems over relatively broad tuning ranges would be useful for enhancing field lock accuracy, as well as improving single-coil, multi-nucleus NMR measurements.

SUMMARY OF THE INVENTION

According to one aspect, the present invention provides a nuclear magnetic resonance radio-frequency coil comprising a saddle-shaped conductive coil structure, a set of auxiliary inductors, and a plurality of inductor-connector longitudinal conductive leads electrically coupling the auxiliary inductors to the saddle-shaped coil structure. The central coil structure comprises a pair of longitudinally-spaced conductive rings, including a drive-side ring and a non-drive-side ring; and a plurality of longitudinal segments, each electrically coupling the drive-side ring to the non-drive-side ring; and a plurality of inductor-connector longitudinal conductive leads extending from the non-drive-side ring opposite the plurality of longitudinal segments. The auxiliary inductors are connected across the inductor-connector longitudinal conductive leads. The RF coil is driven across the drive-side ring. The auxiliary inductors provide a preferential path for low-frequency current such as lock current, while high-frequency (e.g. proton) current travels preferentially through the central coil structure, around a coil window perimeter.

According to another aspect, the present invention provides a patterned conductive foil forming at least part of a nuclear magnetic resonance radio-frequency coil when rolled about a longitudinal axis. The conductive foil comprises a first generally transverse longitudinally-slotted band forming a first coil ring when rolled about the longitudinal axis; a second generally transverse longitudinally-slotted band forming a second coil ring when rolled about the longitudinal axis; a plurality of longitudinal segments connecting the first band to the second band; a plurality of longitudinal drive leads extending outwardly from the second band, opposite the plurality of longitudinal segments, for providing an external connection to the coil; and a plurality of longitudinal component-connector leads extending outwardly from the first band, opposite the set of longitudinal segments, for providing a connection to at least one additional coil component opposite the external connection.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects and advantages of the present invention will become better understood upon reading the following detailed description and upon reference to the drawings where:

Fig. **1** is a schematic diagram of an exemplary NMR spectrometer according to some embodiments of the present invention.

Fig. **2-A** shows an isometric view of a part of a radio-frequency (RF) NMR coil assembly according to some embodiments of the present invention.

Fig. **2-B** shows a longitudinal side view of the coil assembly part of Fig. **2-A**.

Fig. **3** shows an isometric view of a coil support for the coil assembly part of Fig. **2-A**, and conductive capacitive bands (sleeves) mounted on the support, according to some embodiments of the present invention.

Fig. **4** shows a transverse sectional view of the a coil assembly including the coil assembly part of Fig. **2-A** and the coil support and capacitive bands of Fig. **3**, according to some embodiments of the present invention.

Fig. **5-A** is a schematic diagram of an RF coil circuit according to some embodiments of the present invention.

Fig. **5-B** is a simplified schematic diagram of the circuit of Fig. **6-A** according to some embodiments of the present invention.

Fig. **6** shows a side view of an auxiliary-inductor support according to some embodiments of the present invention.

Fig. **7** shows a side view of a coil structure having a ring that is physically distinct, and coupled capacitively, to longitudinal conductors of the coil structure, according to some embodiments of the present invention.

Fig. **8** shows an Alderman-Grant coil shape according to some embodiments of the present invention.

Fig. **9** shows a set of B_1 shift data illustrating an exemplary RF field homogeneity for an auxiliary-inductor coil according to an embodiment of the present invention.

Fig. **10** shows measured z-axis (longitudinal) RF field homogeneity data for an auxiliary-inductor coil according to an embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

In the following description, a set of elements includes one or more elements. Any reference to an element is understood to encompass one or more elements. Each recited element or structure can be formed by or be part of a monolithic structure, or be formed from multiple distinct structures. A longitudinally-monolithic foil is a foil that is not formed by connecting multiple longitudinally-separated parts; a longitudinally-monolithic foil may include multiple layers stacked along a non-longitudinal direction. The statement that a coil is used to perform a nuclear magnetic measurement on a sample is understood to mean that the coil is used as transmitter, receiver, or both. Unless otherwise stated, any recited electrical or mechanical connections can be direct connections or indirect connections through intermediary circuit elements or structures. A conductive ring is a structure that provides a ring-shaped current path to RF current; such a structure can include two or three concentric, capacitively-coupled physical rings, some or all of which may include longitudinal slots; such physical rings can be formed, for example, by part of a central foil, a capacitive shield, and a capacitance band. A conductive ring can also include a single, monolithic physical ring providing a ring-shaped path to DC current. The statement that a longitudinal conductor electrically couples two conductive rings is understood to mean that the longitudinal conductor provides a current path for RF current flowing between the two rings. Such a longitudinal conductor can be physically (resistively) connected to one or both of the rings (providing both DC and RF current paths), or capacitively coupled to one or both of the rings.

The following description illustrates embodiments of the invention by way of example and not necessarily by way of limitation.

Fig. **1** is a schematic diagram illustrating an exemplary nuclear magnetic resonance (NMR) spectrometer **12** according to some embodiments of the present invention. Spectrometer **12** comprises a magnet **16**, an NMR probe **20** inserted in a cylindrical bore of magnet **16**, and a control/acquisition system **18** electrically connected to magnet **16** and probe **20**. Probe **20** includes one or more radio-frequency (RF) coils **24** and associated electrical circuit components. For simplicity, the following discussion will focus on a single coil **24**, although it is understood that a system may include multiple nested RF coils. A sample container **22** is positioned within probe **20**, for holding an NMR sample of interest within coil **24** while measurements are performed on the sample. Sample container **22** can be a sample tube or a flow cell. Coil **24** is disposed above a lower insulator **26**, which includes a number of longitudinal apertures for passing various electrical connection therethrough. A number of electrical circuit components such as capacitors, inductors, and other components are disposed below lower insulator **26** and are electrically connected to coil **24**. Coil **24** and the various components connected to coil **24** form one or more NMR measurement circuits, as well as a field lock circuit. Probe **20** includes additional conventional components, such as shim coils used to correct spatial inhomogeneities in the static magnetic field B_0.

To perform a measurement, a sample is inserted into a measurement space defined within coil **24**. Magnet **16** applies a static magnetic field B_0 to the sample held within sample container **22**. Control/acquisition system **18** comprises electronic components configured to apply desired radio-frequency pulses to probe **20**, and to acquire data indicative of the nuclear magnetic resonance properties of the samples within probe **20**. Coil **24** is used to apply radio-frequency magnetic fields B_1 to the sample, and/or to measure the response of the sample to the applied magnetic fields. The RF magnetic fields are perpendicular to the static magnetic field. The same coil may be used for both applying an RF magnetic field and for measuring the sample response to the applied magnetic field. Alternatively, one coil may be used for applying an RF magnetic field, and another coil for measuring the response of the sample to the applied magnetic field.

Coil **24** is used for signals at multiple resonance frequencies. The multiple resonance frequencies can include a field lock signal frequency and/or one or more sample signal frequencies. In some embodiments, tuning the resonant frequency of a NMR measurement circuit that includes the coil can be achieved by adjusting the values of various variable capacitors included in the circuit, or by switching circuit components such as capacitors having different values into the circuit. In an exemplary implementation, coil **24** is used to perform proton NMR measurements and to maintain a lock on a deuterium signal. In other implementations, coil **24** can be used to perform NMR measurements at other or additional frequencies of interest. The discussion below will focus primarily on a system using a high-frequency proton signal and a lower-frequency deuterium lock signal. In an exemplary NMR system, proton and deuterium lock signals correspond to resonance frequencies of 800 MHz and 121.8 MHz, respectively.

Figs. **2-A** and **2-B** show isometric and longitudinal side views, respectively, of a radio-frequency (RF) coil assembly **24'** according to some embodiments of the present invention. Fig. **3** shows an isometric view of a support assembly **24"** comprising a pair of support tubes for mounting coil assembly **24'** thereon, and a set of exterior capacitive bands. RF coil **24** is formed by assemblies **24', 24"**, as illustrated in a transverse sectional view in Fig. **4**.

As shown in Figs. **2-A-B**, RF coil assembly **24'** comprises a central coil structure **30**, a pair of cylindrical floating shields **32a-b** disposed on opposite longitudinal sides of central coil structure **30**, an insulative auxiliary inductor support **34** mounted above central coil structure **30**, a pair of auxiliary inductors **36a-b** mounted on support **34**, and a set of conductive leads **38** connecting central coil structure **30** and auxiliary inductors **36a-b** as described below. In some embodiments, a single wire forms a pair of conductive leads **38** and a corresponding auxiliary inductor **36a-b**. Central coil structure **30**, shields **32a-b**, conductive leads **38**, auxiliary inductors **36a-b**, and a set of capacitance bands **90, 92a-b** (shown in Fig. **3**) form conductive structure of RF coil **24**.

A measurement volume **31** and a corresponding coil window are defined in the center of central structure **30**, between shields **32a-b**. The central axis of each shield **32a-b** is aligned with the longitudinal central axis of central coil structure **30**. The measurement volume **31** sequentially accommodates NMR samples of interest held in cylindrical sample tubes or flow cells. A longitudinal aperture **37** is defined through the center of auxiliary inductor support **34**, to allow the passage of NMR sample tubes or flow cells. Shields **32a-b** are capacitively coupled to central structure **30** along at least part of the surfaces of shields **34a-b** adjacent to measurement volume **31**. Shields **32a-b** serve to reduce the parasitic excitation of the NMR samples due to RF pickup from coil leads or other conductive structures, and to shield the NMR samples from undesired external electric fields. Shields **32a-b** also provide additional distributed capacitance to coil assembly **24'**.

Central coil structure **30** has a generally saddle-shaped, modified Alderman-Grant coil form. Central coil structure **30** comprises a pair of generally-transverse, longitudinally-spaced lower and upper conductive rings **40a-b**, respectively, a set of four longitudinal conductive segments (rungs, strips) **46a-b** extending between and interconnecting ring **40a** and ring **40b**, a set of four longitudinal inductor-interconnect leads **48** extending upward from the upper ring **40b**, and a pair of external-connection leads **50a-b** extending downward from lower ring **40a**.

External connection leads **50a-b** extend downward, longitudinally away from measurement volume **31**, toward the distal end of shield **32a**. Leads **50a-b** provide an electrical connection to external drive/detection circuitry. Rings **40a-b** are disposed on opposite sides of measurement volume **31**, and are disposed around the proximal ends of shields **32a-b**. Ring **40a** has a pair of longitudinal slots (gaps) **54** defined therethrough. Slots **54** are situated on axially opposite sides of ring **40a**, and extend along the entire longitudinal extent of ring **40a**, so as to divide ring **40a** into separate arcuate ring sections. Slots **54** prevent the direct flow of current through ring **40a** around a complete circle. Ring **40b** has a set of four longitudinal slots (gaps) **58** defined therethrough. Slots **58** are situated at 90^0 azimuthal positions along ring **40b**, with two opposite slots **58** aligned with slots **54**, and two opposite slots **58** along a perpendicular azimuthal direction. Slots **58** extend along the entire longitudinal extent of ring **40b**, so as to divide ring **58** into separate arcuate ring sections. Slots **58** prevent the direct flow of current through ring **40b** around a complete circle.

Each longitudinal segment **46a-b** extends along measurement volume **31**, between rings **40a-b**. Rings **40a-b** and segments **46a-b** form a set of loops facing each other along a transverse (x- or y-) direction, for generating an RF magnetic field along that direction. An exemplary magnetic field general direction is schematically illustrated at **60** in Fig. **2-A**. Current flows through the loops in the same direction (clockwise or counterclockwise), such that the RF magnetic fields generated by the two loops reinforce each other. A general direction of current flow corresponding to the magnetic field direction **60** is illustrated at **62** in Fig. **2-B**.

Each inductor interconnect lead **48** extends longitudinally upward from upper ring **40b**, away from measurement volume **31**. In some embodiments, interconnect leads **48** are arranged in two pairs situated along opposite transverse sides of ring **40b**. The leads of each pair are adjacent to and situated on opposite sides of a corresponding slot **58**, which faces the coil window defining the magnetic field direction **60**. In other embodiments, interconnect leads **48** can be positioned at other azimuthal positions. Each lead **48** is formed by a strip of metal which is preferably made as thin as mechanically feasible. Using thin leads, which have relatively low capacitance and high inductance, maximizes the impedance seen by high-frequency proton current as described in detail below.

Each inductor interconnect lead **48** is connected to a proximal end of a corresponding conductive lead **38**. In some embodiments, conductive leads **38** are formed by susceptibility compensated wire, and leads **48** and **38** are soldered together. The attachment of leads **48, 38** preferably does not generate substantial resistive losses to proton current. The four leads **38** extend azimuthally along the top side of shield **32b** for an angular extent of about 90^0, then extend vertically through corresponding longitudinal apertures defined through inductor support **34**, and are connected to corresponding terminals of inductors **36a-b**. Each of the two pairs of leads **38** can be monolithically formed together with their corresponding inductor **36a-b** from a single conductive wire. Each inductor **36a-b** is shaped as a semi-circle or half-toroid, with the inductor coil wire spun around a circumferential axis lying in a transverse plane. Inductors **36a-b** together form an approximate full toroid shape, which facilitates optimal inductive coupling between inductors **36a-b**.

Fig. **3** shows an isometric view of coil support assembly **24"**, which is used to support and provide additional capacitance to coil assembly **24'** in some embodiments of the present invention. Fig. **4** shows a transverse view of coil **24** including coil assembly **24'** and coil support assembly **24"**. As illustrated in Fig. **3**, coil support assembly **24"** includes two outer and inner supports **82, 86**, respectively. Supports **82, 86** are formed by hollow cylindrical generally-longitudinal shells, and are formed from non-conductive, dielectric material(s). An inner longitudinal bore defined within inner support **86** accommodates the sample tubes or flow cells of interest. Central coil structure **30** (shown in Figs. **2-A-B**) is disposed in a thin cylindrical space **88** defined between supports **82, 86**. Shields **32a-b** (Figs. **2-A-B**) are disposed along the inner surface of inner support **86**.

A set of capacitance bands **90, 92a-b** (shown in Fig. **3**) are disposed along the outer surface of outer support **82**. An upper capacitance band **90** is situated opposite measurement volume **31** relative to two lower capacitance bands **92a-b**. Upper capacitance band **90** is situated along upper ring **40b** and/or upper shield **32b**. Lower capacitance bands **92a-b** are positioned along lower ring **40a** and/or lower shield **32a**. Upper capacitance band **90** and lower capacitance band **92b** are fixed, while lower capacitance band **92a** is longitudinally-slidable along outer support **82**. In some embodiments, lower capacitance band **92a** is secured to a rigid, generally-longitudinal coupling rod **93**, which can be formed by a susceptibility-compensated wire.

Coupling rod **93** is used to slide capacitance band **92a** longitudinally, in order to vary the amount of additional capacitance provided by capacitance band **92a**. Coupling rod **93** is secured to a mechanical actuator situated below lower insulator **26** (Fig. **1**). The actuator is schematically represented in Fig. **3** by an actuator node **97**. A chip capacitor **95** is connected between actuator node **97** and coupling rod **93**, in order to enhance the RF isolation of capacitance band **92a**.

In some embodiments, central coil structure **30** is formed from a single susceptibility-compensated thin conductive foil. The foil can include one or multiple layers of material, and is monolithic along its main surface plane. In some embodiments, central coil structure **30** and shields **32a-b** are made of susceptibility-compensated palladium-plated copper. In general, other materials such as rhodium, platinum, copper and stacks of such materials are suitable for central coil structure **30** and shields **32a-b**. For example, a Rh-Cu susceptibility-compensated sandwich can be used. Other materials having susceptibilities of opposite signs can be used to yield a magnetic susceptibility equal to the magnetic susceptibility of air or vacuum. In some embodiments, the overall transverse size of rings **40a-b** and shields **32a-b** is on the order of 1 cm. For typical NMR applications, transverse coil sizes for coil **30** can range from a few millimeters to a few centimeters. The longitudinal extents of longitudinal conductors **46a-b** and rings **40a-b** can be on order of a few cm. In some embodiments, coil supports **82, 86** are preferably made of a dielectric material that does not interfere with NMR measurements, such as glass, while inductor support **34** is made of a plastic or ceramic material.

In an exemplary embodiment, leads **48** have a longitudinal extent (length) of about 0.61", while the rest of coil structure **30** has a length of about 1.63". Leads **48** are preferably made as thin as mechanically feasible, in order to maximize their inductance and minimize their capacitance. In an exemplary embodiment, leads **48** are 0.02" wide and 0.002" thick.

Fig. **5-A** shows a schematic diagram of a coil circuit **200** defined by coil assembly **24'** and associated external probe circuitry **290,** according to some embodiments of the present invention. The numbers used for various circuit elements in Fig. **5-A** correspond to like numbers used to denote the structures shown in Fig. **2-A**. Two auxiliary inductors **236a-b** are connected through a set of longitudinal leads represented by inductors **248a-d** to a core circuit **230** formed generally by at least parts of central coil structure **30**, shields **32a-b** and capacitance bands **90, 92a-b** (shown in Figs. **2-A** and **3**). Core circuit **230** is connected to external circuitry across nodes **202, 204**. A pair of lower capacitors **240a, 240a'** are connected across nodes **202, 204**; the capacitance of capacitors **240a, 240a'** is provided generally by the overlapping parts of lower ring **40a**, shield **32a** (Figs. **2-A-B**) and capacitance bands **92a-b** (Fig. **3**).

Two inductors **246a-b** and an upper capacitor **240b** are connected in series between nodes **202, 204**. The inductance of inductors **246a-b** is provided generally by the longitudinal segments **46a-b** shown in Figs. **2-A-B**, while the capacitance of capacitor **240b** is provided generally by an overlapping part of upper ring **40b**, shield **32b** (Figs. **2-A-B**) and capacitance band **90** (Fig. **3**). The series circuit formed by inductors **236a, 248a-b** is connected across upper capacitor **240b**. Similarly, two inductors **246a'-b'** and an upper capacitor **240b'** are connected in series between nodes **202, 204**. The inductance of inductors **246a'-b'** is provided generally by the longitudinal segments **46a-b** shown in Figs. **2-A-B**, while the capacitance of capacitor **240b'** is provided generally by an overlapping part of upper ring **40b**, shield **32b** (Figs. **2-A-B**) and capacitance band **90** (Fig. **3**). The series circuit formed by inductors **236b, 248c-d** is connected across upper capacitor **240b'**. Two lower lock (low-frequency) inductors **292a-b** are connected between nodes **202, 204**, respectively, and external circuitry. A shunt inductor **293** is connected between nodes **202, 204**. Lower lock inductors **292a-b** and shunt inductor **293** are physically located away from coil assembly **24'**, in a probe circuit region underneath the lower insulator **26** (Fig. **1**).

Fig. **5-B** shows a simplified diagram of a coil circuit **250** defined by a coil assembly according to some embodiments of the present invention. Coil circuit **250** includes an auxiliary inductor **36** and a core circuit **230'**. Auxiliary inductor **36** can represent a single physical inductor or the equivalent inductance of multiple inductors such as inductors **36a-b** (Fig. **6-A**). Core circuit **230'** is connected to external circuitry across external leads **202, 204**. Inductors **246a-b** and an upper capacitor **240b** are connected in series between leads **202, 204**.

Inductor **36** provides an auxiliary low-frequency current path **254** through coil circuit **250**, running through inductors **246a-b** and inductor **36**. A coil circuit without auxiliary inductor **36** would only employ a central coil current path **252**, running through inductors **246a-b** and capacitor **240b**. In the coil circuit **250**, which includes auxiliary inductor **36**, the auxiliary current path **254** is used preferentially by lower-frequency current, such as current corresponding to a locking signal, while central coil current path **252** is used preferentially by higher-frequency current.

The preferred systems and methods described above allow improving the low-frequency efficiency of a distributed-capacitance Alderman-Grant coil optimized for high-frequency use, with minimal degradation in performance for the high-frequency resonance. In some embodiments, the high frequency corresponds to a proton signal, while the low frequency corresponds to a lock (e.g. deuterium) or other NMR (e.g. nitrogen or carbon) signal. In one application, improved lock NMR signal efficiency is achieved when the distributed capacitance coil is dual-tuned to both proton and deuterium lock frequencies. In another application, the upper or lower frequency resonance of the coil is broadband-tuned.

Splitting a lower capacitance band into a fixed part and a slidable part (parts **92b** and **92a**, respectively, in Fig. **3**) allows tuning the high-frequency coil resonance while maintaining a RF current path close to the coil window/sample measurement volume (shown at **31** in Fig. **2**). A split capacitance band can be used with or without the top auxiliary inductors and associated components described above, but is of particular use in a system employing auxiliary inductors since it allows recovering some high-frequency performance lost because of the addition of the auxiliary inductors. Maintaining a RF current path close to the coil window allows retaining the coil's high-frequency performance (e.g. proton sensitivity) through an extended tuning range. A split capacitance band can be of particular use in systems in which the proton resonant frequency is tuned by altering the capacitance(s) of one or more variable capacitors connected between the coil and ground. In such a system, the circuit proton Q and filling factors may fall as the coil is tuned lower in frequency. Using a split capacitance band in such a system allows maintaining desired Q factors and RF magnetic field shifts across a required tuning range. It may also be desirable to minimize the proton tuning range in such systems. Minimizing the proton tuning range achieved by adjusting variable capacitors allows minimizing the proton current that flows along a path away from the coil window, which in turn allows maximizing the proton filling factor.

In some embodiments, systems and methods using auxiliary inductors as described above allowed improving the lock sensitivity by over 300%, as compared to a similar coil without the upper auxiliary inductors. The improved lock efficiency allows using shorter NMR signal pulse durations, and higher pulse powers. Increased lock sensitivity also allows an improvement in the shimming operation of the NMR system, by making the lock channel less noisy: if the NMR instrument is shimmed using the lock signal, the shimming process is easier and faster at higher lock signal signal-to-noise ratios, particularly for samples having low spin densities of locking (e.g. deuterium) nuclei. An automated shimming algorithm may require lower number of transients to achieve a desired signal-to-noise ratio. In addition, using a split capacitance band as described above was observed to improve high-frequency (e.g. proton) sensitivity.

In some embodiments, central coil structure **30** is formed from a single susceptibility-compensated thin conductive foil. Susceptibility compensation reduces magnetic field inhomogeneities and associated lineshape distortions. A susceptibility-compensated foil can include multiple materials (e.g. layers) having different magnetic susceptibilities. For example, a layer having a positive susceptibility and a layer having a negative susceptibility can be stacked to generate a two-layer foil having a net susceptibility close to that of air. The net susceptibility of coil structure **30** is preferably close to the susceptibility of the environment of coil **30**. In other embodiments, central coil structure **30** is formed from a wire, which can also be susceptibility-compensated.

Leads **48** are preferably straight, generally-longitudinal strips. The thin, straight geometry of leads **48** is chosen to maximize the impedance to high-frequency proton current, so that the circuit extension defined by leads **48** and inductors **36a-b** (Fig. **2-A**) has a minimal impact on the coil proton filling factor. The thickness and width of leads **48** can be limited by the foil cutting technique or mechanical stability requirements for the assembled coil, which can place lower bounds on the width of leads **48**. Preferably, the width of leads **48** is less than or equal to about 1 mm. In some embodiments, leads **48** can have a meandering or other non-straight shape exhibiting a higher inductance than a linear shape. Such geometries also add to the capacitance between leads **48** and shield **32b** (Fig. **2-A**), which reduces the impedance presented to proton current. For example, a meandering shape for leads **48** was calculated to lead to lower proton filling factors than a straight shape, for the chosen geometry and dielectric properties of support **86** (Fig. **3-A**). Leads **48** and **38** are soldered together at the top end of leads **48**, as far away from the coil window as practicable. Preferably, coil assembly **24'** does not include materials that can contribute to a proton background signal or dielectrically lossy materials.

Auxiliary inductors **36a-b** are separated from upper ring **40b** by a susceptibility-isolation distance. The susceptibility isolation distance is chosen to be sufficiently large that magnetic susceptibility inhomogeneities do not substantially affect linewidth. Linewidth is not affected if shimming can adequately compensate for higher-order perturbations to the static magnetic field due to magnetic susceptibility variations introduced by the auxiliary inductors. In general, the isolation distance is determined by the degree of susceptibility perturbation introduced by auxiliary inductors **36a-b**. In some embodiments, a susceptibility isolation distance larger than or equal to about 1 cm (about 0.5 in) was observed to be sufficiently large to provide adequate isolation of the RF measurement space from susceptibility variations introduced by the auxiliary inductors. In some systems, such an isolation distance is roughly equal to the coil diameter. In some embodiments, distances larger than or equal to 0.5 cm or 2 cm can provide a desired level of isolation. In embodiments using coil supports such as the cylindrical dielectric supports **82, 86** (Fig. **3**), the minimum length of leads **48** (Fig. **2-A**) can be limited by the length that supports **82, 86** extend above upper ring **48**.

In an exemplary implementation, each auxiliary inductor **36a-b** has an inductance value of about 150 nH. In other embodiments, exemplary inductance values include 90 nH and 200 nH. The inductance of inductors **36a-b** (Fig. **2-A**) is preferably chosen to be sufficiently high that proton performance is not excessively attenuated. Inductors **36a-b** are preferably self-resonant above the proton frequency. For example, in an embodiment in which the proton resonant frequency is about 800 MHz, inductors **36a-b** are chosen such that their self-resonant frequency is 850-900 MHz or higher. At the same time, if the inductance of inductors **36a-b** is too high, lock performance starts to degrade. The lock circuit becomes harder to tune, because the combined inductance of the lock circuit (given primarily by inductors **36a-b** and by two inductors situated at drive points below the coil) makes the lock signal resonate below the desired lock nucleus frequency. If auxiliary inductors **36a-b** with a relatively high inductance are used, a lock shunt inductor (inductor **293** in Fig. **5-A**) can be added across the proton leads at the bottom of coil assembly **24'**, to increase the self-resonance frequency of the lock circuit without significantly degrading proton sensitivity. In an exemplary implementation, each lower lock inductor **292a-b** has an inductance value of about 100 nH. Generally, lower lock inductors **292a-b** are preferably chosen to have a minimum inductance that allows a desired (e.g. -20 dB) level of isolation between the proton and lock ports at the proton frequency.

Inductors **36a-b** preferably have identical inductance values and are inductively coupled to each other, in order to preserve the RF field homogeneity of coil assembly **24'** by allowing similar currents to flow on both sides of the coil. If the two inductors are not identical and are not mutually coupled, a split-mode solution can result in RF field inhomogeneities. Inductors **36a-b** carry both lock current and some proton current, and are preferably shielded from any lossy materials or sample present outside of the sample measurement volume, which is the homogeneous region of the static magnetic field. Furthermore, inductors **36a-b** are preferably not exposed to any materials that generate a proton background signal. A susceptibility-compensated metal shield can also be used to surround any sample present above upper shield **32b**. In some embodiments, a high-pass circuit, series capacitance or other circuit can be inserted in the center of one or both lock inductors **36a-b**, in order to attenuate low-frequency currents such as currents caused by gradient switching.

Fig. **6** shows a side view of an auxiliary-inductor support **334** according to some embodiments of the present invention. Support **334** includes two longitudinally-spaced, parallel transverse disks **334a-b**, connected by an inner cylindrical trunk **335**. A longitudinal aperture **337** is defined through support **334**, for allowing the passage of sample tubes or flow cells through support **334**. An auxiliary inductor **336** is positioned in a space defined between disks **334a-b**. Auxiliary inductor **336** is connected to the rest of the RF coil through connector leads **338**, which extend through corresponding longitudinal apertures defined through the lower part of support **334**.

Fig. **7** shows a side view of a saddle-shaped coil structure **430** having two longitudinally-spaced cylindrical rings **440a-b** that are physically distinct from (not resistively coupled to) a set of longitudinal conductors **446**, according to some embodiments of the present invention. Rings **440a-b** are capacitively coupled to conductors **446** along overlap regions **445a-b**, respectively. Rings **440a-b** can be formed by at least part of an RF coil shield or capacitance band, for example. Fig. **8** shows an Alderman-Grant coil structure **530** according to some embodiments of the present invention. The coil thickness is exaggerated in Fig. **8** for clarity of display. Coil structure **530** includes an upper ring **540a** and a lower ring **540b** each having two oppositely-positioned longitudinal slots. Rings **540a-b** are interconnected by two continuous (un-slotted) longitudinal conductors **546a-b**.

The following examples are intended to illustrate aspects of some embodiments of the present invention, and should not be construed to limit the invention.

A coil assembly as described above with reference to Figs. **2-A** through **5-B** was evaluated in a room temperature triple-nucleus (HCN) 800 MHz probe. In back-to-back testing with the HCN probe, a coil assembly including auxiliary inductors as described above was observed to yield a 345% improvement in lock signal-to-noise, with a ~12% reduction in proton efficiency, as compared to a corresponding coil assembly without auxiliary lock inductors connected at the top of the coil. The coil assembly including auxiliary inductors also displayed improved ^{2}H (deuterium) power handling: a 32 µs ^{2}H pw90 was observed for the coil assembly including auxiliary inductors.

Table 1 shows recorded data for the auxiliary-inductor probe tuned to proton and deuterium frequencies, and a comparable probe with a proton coil without auxiliary inductors tuned to proton and deuterium frequencies. The signal-to-noise ratio for the lock signal was measured using a 9° nutation. As Table 1 shows, using a larger auxiliary inductor leads to shorter proton (^{1}H) pw90 and slightly lower lock (^{2}H) signal-to-noise (SN). For larger inductor values, it may be desirable to use a different inductor geometry than the one illustrated in Fig. **2-A**, if the illustrated inductor geometry leads to self-resonance problems close to or below the desired frequency of operation, inductors having smaller geometries or wider turn-to-turn spacings may be desirable.

Table 1

	Aux. ind.: 155nH	Aux. ind: 100nH	No. aux. ind.
Proton pw90 with 21W RF power	7.14 µs	7.65 µs	6.19 µs
Proton RF homogeneity (450/90, 810/90)	81.4 %, 67.8%	82.4%, 68.5 %	82.4%, 69.2 %
Lock pw90 with 53W RF power	77.6 µs	72 µs	220 µs
Lock SN (2000) 9° pw	17108	18708	5831

Another series of experiments was performed on an exemplary auxiliary-inductor coil, which included two 4-turn auxiliary inductors wound using 32 thousands-of-an-inch Pd/Cu wire on a 0.25”-diameter mandrel. The auxiliary inductors were cylindrical (rather than half-toroidal as illustrated in Fig. **2-A**), with the cylinder axis axes pointing along parallel transverse directions. The tested auxiliary inductors were mechanically held by their connector leads, rather than by an inductor support such as the support **34** shown in Fig. **2-A**.

The B_1 homogeneity of an exemplary auxiliary-inductor coil was evaluated in another series of experiments. A 2.5 mm-diameter 10 mm-long foil cylinder was placed off-center in a 5 mm NMR tube. The tube was both rotated and translated through the coil-sensitive volume. The resulting spatially-localized proton B_1 shift measurements map out the homogeneity of the B_1 shift. The tube was rotated in 8 steps at 10 different height increments separated by 2 mm. Fig. **9** shows a plot of recorded B_1 shift data.

To test whether the foil cylinder was masking large inhomogeneities by averaging over too large a volume, two probes were compared using smaller B_1 shifters: an auxiliary-inductor probe, and a comparable probe without auxiliary inductors. The z-homogeneity of two probes was measured using a 2 mm-long, 3 mm-diameter shifter. Fig. **10** shows plots of the resulting shift data. As Fig. **10** shows, the z-axis RF homogeneity of the auxiliary-inductor probe is comparable to that of the probe without auxiliary inductors, at a lower B_1 shift value.

The above embodiments may be altered in many ways without departing from the scope of the invention. For example, various auxiliary inductor geometries/configurations may be used, depending among others on the space constraints of the particular RF coil and probe. Auxiliary inductors may be used in conjunction with RF coil geometries other than the particular ones illustrated above, including for example non-Alderman-Grant saddle-shaped geometries. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

WHAT IS CLAIMED IS:

1. A nuclear magnetic resonance radio-frequency coil comprising:
   a conductive saddle-shaped coil structure comprising
      a pair of longitudinally-spaced conductive rings, the pair of rings including a drive-side ring and a non-drive-side ring, and
      a plurality of longitudinal segments, each electrically coupling the drive-side ring to the non-drive-side ring;
   a plurality of inductor-connector longitudinal conductive leads extending from the non-drive-side ring opposite the plurality of longitudinal segments, and electrically coupled to the non-drive side ring; and
   a set of auxiliary inductors connected across the inductor-connector longitudinal conductive leads.

2. The coil of claim 1, wherein the set of auxiliary inductors comprises a pair of mutually inductively coupled auxiliary inductors.

3. The coil of claim 2, wherein each of the pair of auxiliary inductors is shaped as a half-toroid, and the pair of auxiliary inductors are arranged to form a generally-toroidal shape.

4. The coil of claim 1, wherein the saddle-shaped coil structure comprises at least part of a patterned foil forming a distributed capacitance coil part.

5. The coil of claim 4, further comprising a dielectric cylindrical support, the patterned foil being mounted on the cylindrical support.

6. The coil of claim 4, wherein the patterned foil comprises the plurality of inductor-connector leads.

7. The coil of claim 1, wherein the saddle-shaped coil structure is formed from a single, longitudinally-monolithic patterned foil.

8. The coil of claim 1, wherein the saddle-shaped coil structure comprises a longitudinal cylindrical radio-frequency shield extending along at least part of the inductor-connector longitudinal conductive leads, the inductor-connector leads extending along an outer surface of the radio-frequency shield.

9. The coil of claim 8, wherein at least part of the radio-frequency shield forms at least part of one of the pair of longitudinally-spaced rings.

10. The coil of claim 1, wherein each of the inductor-connector leads has a longitudinal extent larger than or equal to 1 cm.

11. The coil of claim 10, wherein said each of the inductor-connector longitudinal conductive leads has a width less than or equal to 0.05 cm.

12. The coil of claim 1, wherein the saddle-shaped coil structure is susceptibility-compensated.

13. The coil of claim 1, wherein each of the auxiliary inductors has an inductance larger than or equal to 100 nH.

14. The coil of claim 1, wherein each of the inductor-connector longitudinal conductive leads has a linear shape.

15. The coil of claim 1, further comprising a non-conductive auxiliary inductor support mounted on the saddle-shaped coil structure, the set of auxiliary inductors being mounted on the auxiliary-inductor support.

16. The coil of claim 1, further comprising a shunt inductor connected across two opposite nodes of the drive-side ring.

17. The coil of claim 1, wherein the saddle-shaped coil structure further comprises:

a first ring-shaped capacitance tuning band disposed over the drive-side ring and proximal to a coil window defined between the drive-side ring and non-drive-side ring; and

a second ring-shaped capacitance tuning band disposed over the drive-side ring and longitudinally-slidable between a first position longitudinally-proximal to the first capacitance-tuning band and a second position situated further away from the coil window than the first position.

18. A nuclear magnetic resonance apparatus comprising:
a saddle-shaped radio-frequency coil having a drive-side and a non-drive side situated longitudinally opposite the drive-side;
a plurality of inductor-connector longitudinal conductive leads extending away from the coil from the non-drive side; and
a set of auxiliary inductors connected across the inductor-connector longitudinal conductive leads.

19. A nuclear magnetic resonance method comprising:
driving a nuclear magnetic resonance radio-frequency coil at a high frequency, the coil comprising
a conductive saddle-shaped coil structure comprising
a pair of longitudinally-spaced conductive rings, the pair of rings including a drive-side ring and a non-drive-side ring, and
a plurality of longitudinal segments, each electrically coupling the drive-side ring to the non-drive-side ring;
a plurality of inductor-connector longitudinal conductive leads extending from the non-drive-side ring opposite the plurality of longitudinal segments, and electrically coupled to the non-drive side ring; and
a set of auxiliary inductors connected across the inductor-connector longitudinal conductive leads; and
driving the coil at a low frequency;
wherein the non-drive side ring provides a preferential path for high-frequency current, and the set of auxiliary inductors provides a preferential path for low-frequency current.

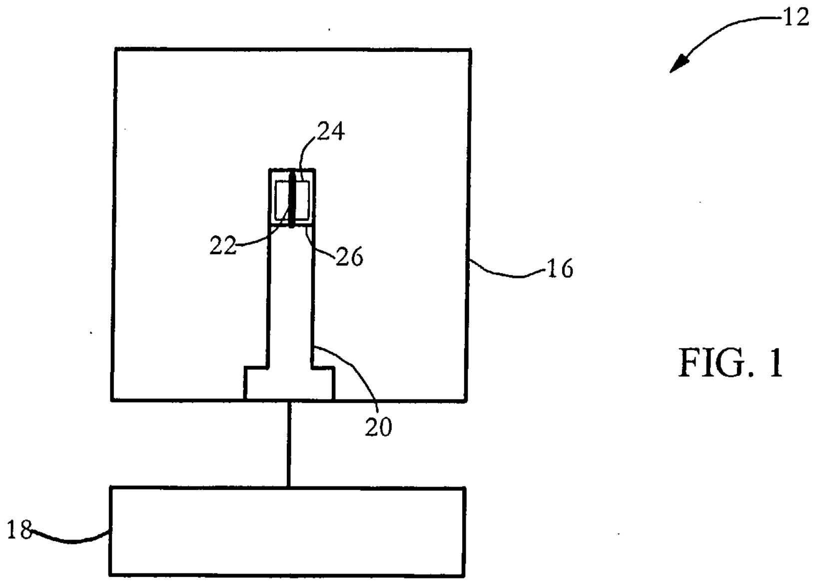


FIG. 1

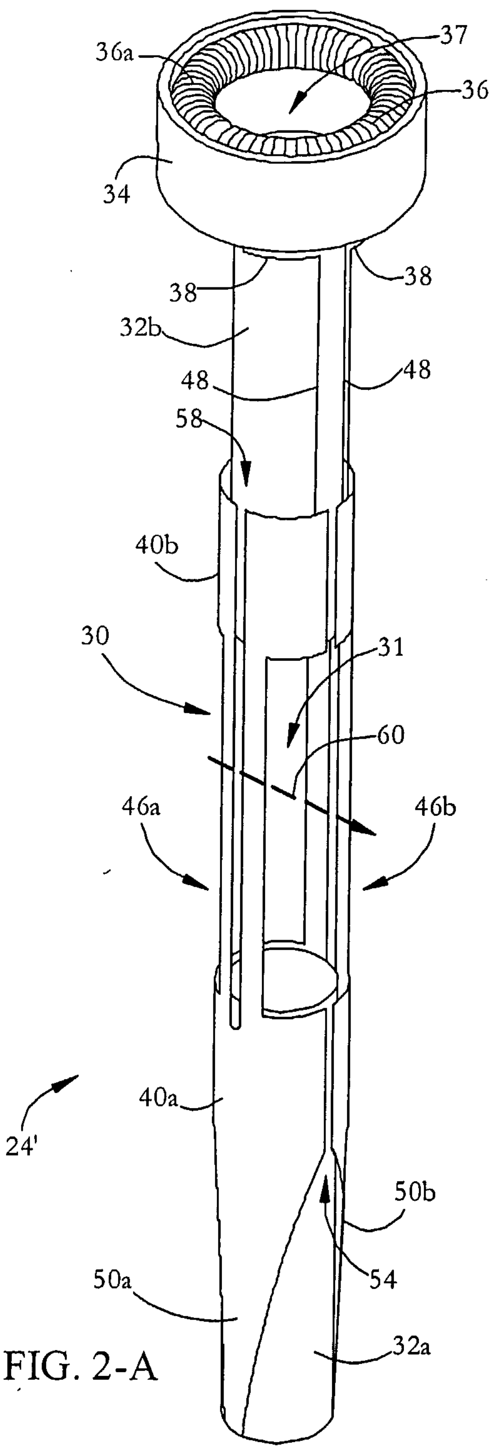

36a
37
36b
34
38
38
32b
48
48
58
40b
30
31
60
46a
46b
40a
24'
50b
54
50a
32a

FIG. 2-A

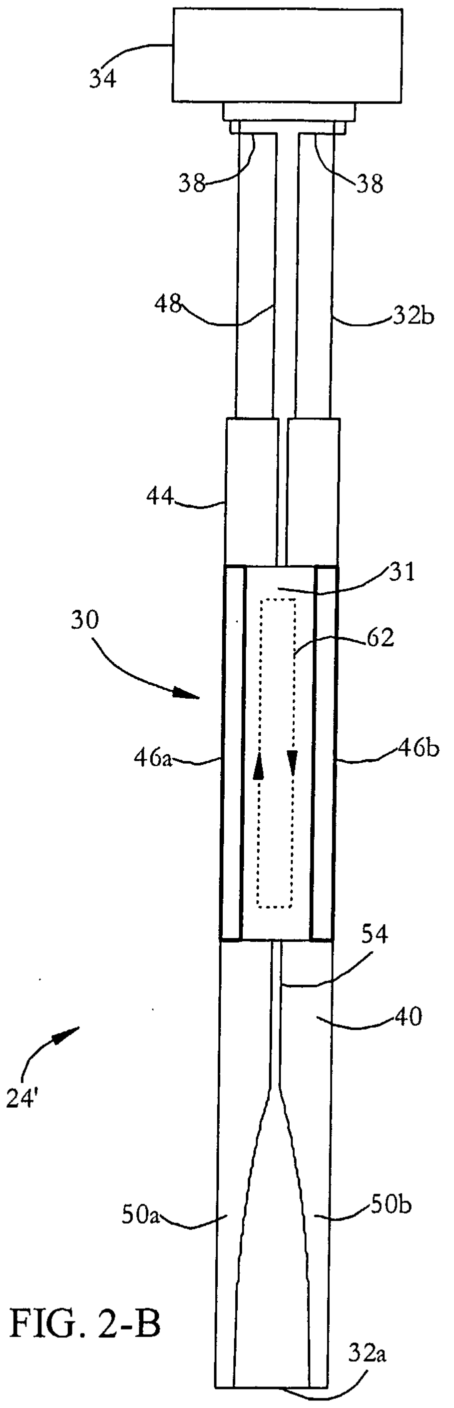

34
38
38
48
32b
44
31
30
62
46a
46b
54
40
24'
50a
50b
32a

FIG. 2-B

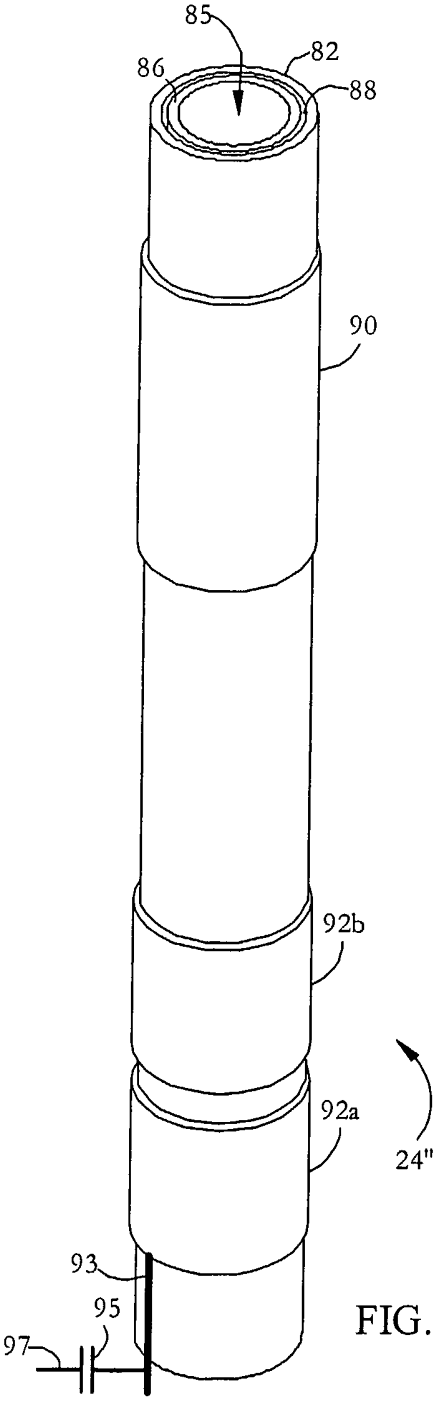


FIG. 3

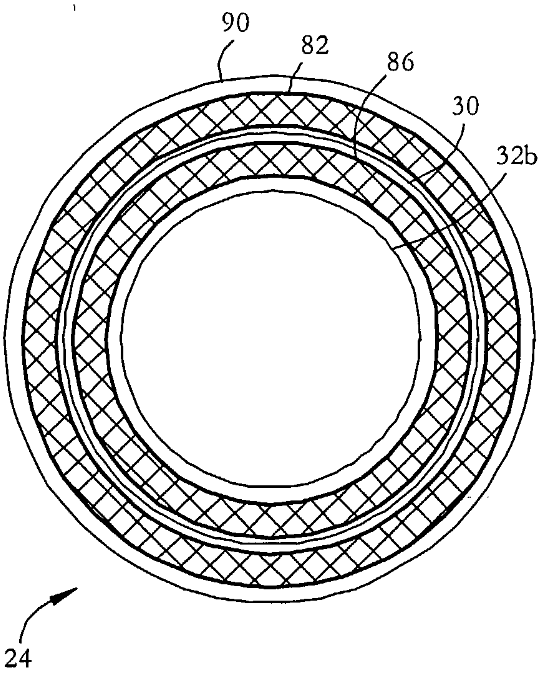


FIG. 4

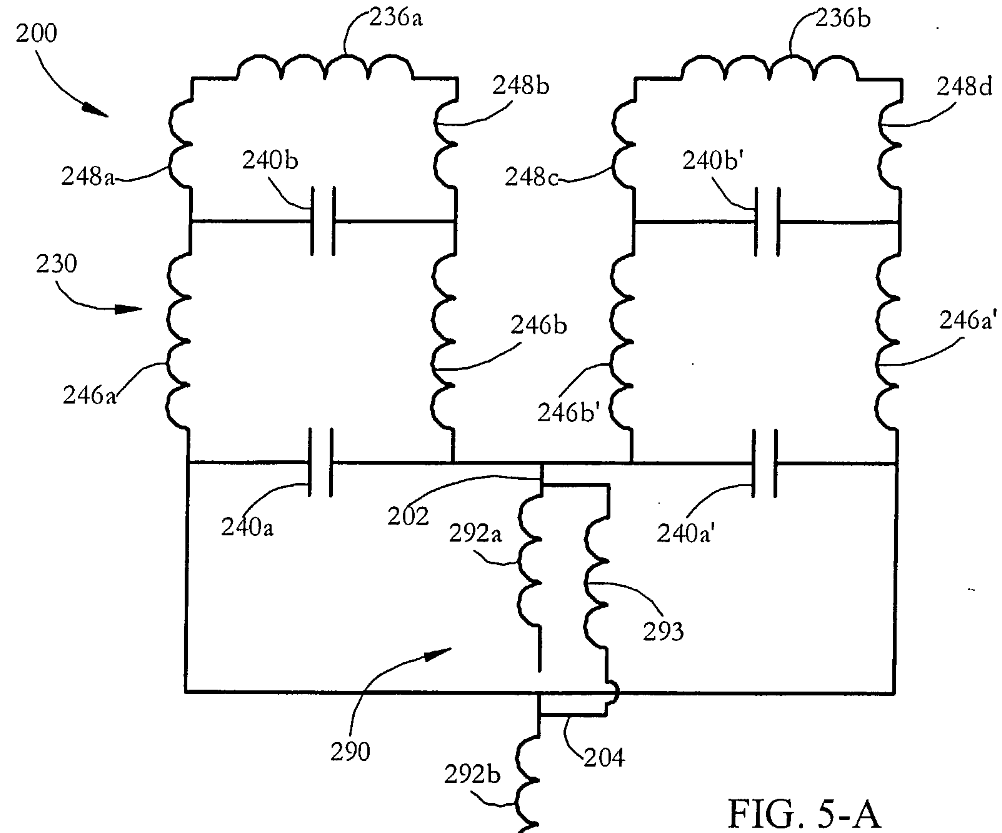

200
236a
236b
248b
248d
248a
248c
240b
240b'
230
246b
246a'
246a
246b'
202
240a
240a'
292a
293
290
204
292b

FIG. 5-A

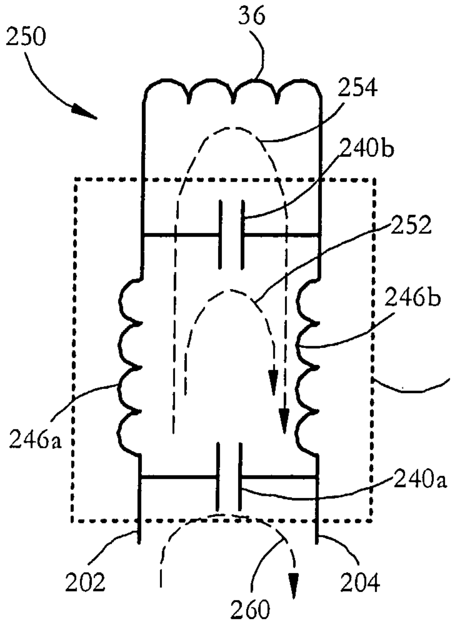

250
36
254
240b
252
246b
230
246a
240a
202
204
260

FIG. 5-B

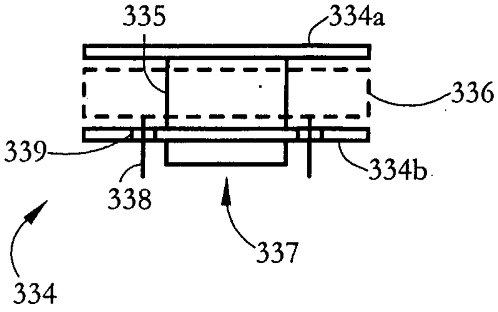


FIG. 6

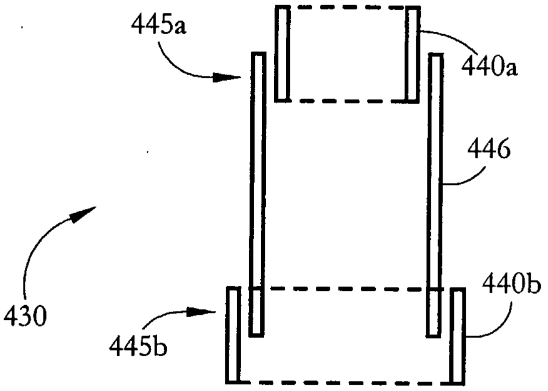


FIG. 7

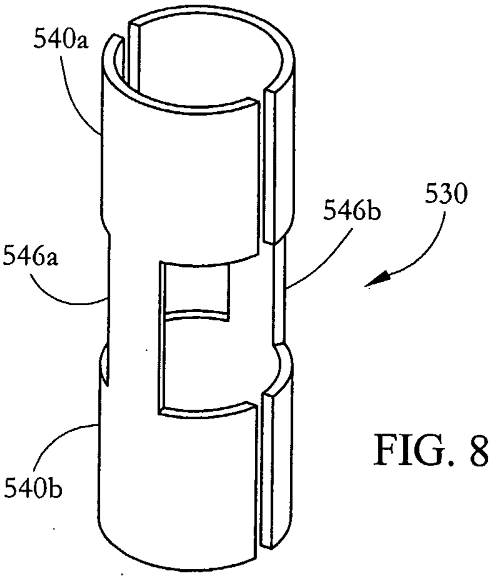


FIG. 8

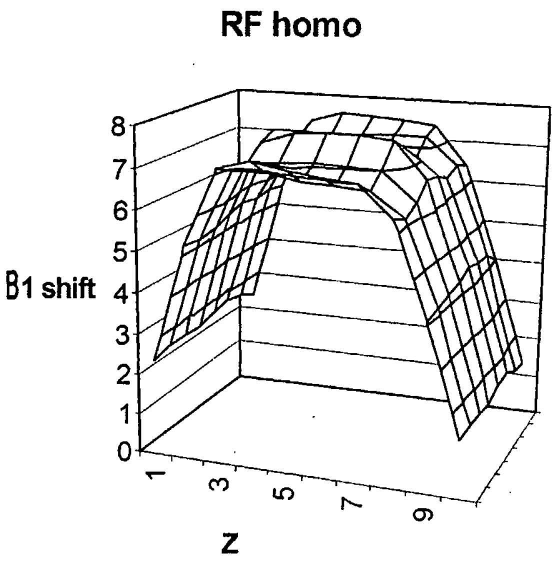

RF homo
8
7
6
5
4
3
2
1
0
B1 shift
1
3
5
7
9
Z

FIG. 9

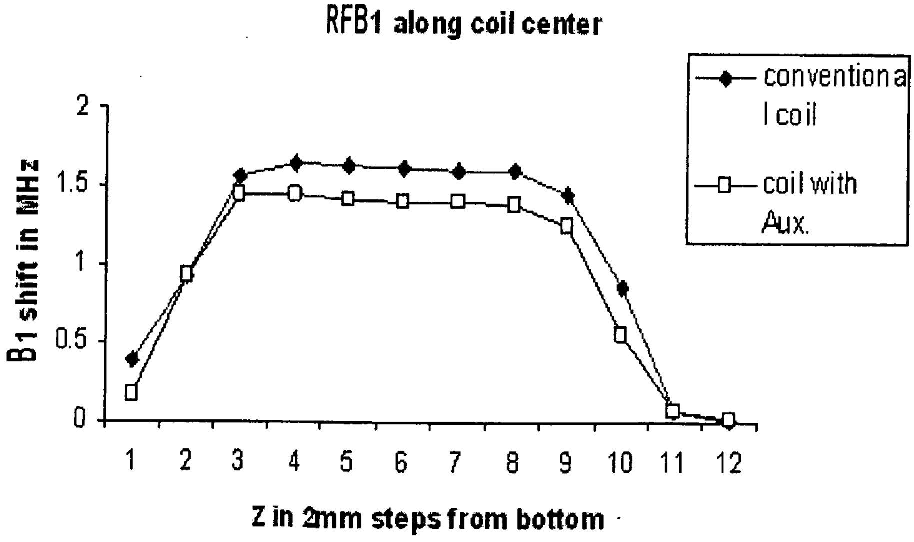

RFB1 along coil center
conventional coil
coil with Aux.
2
1.5
1
0.5
0
B1 shift in MHz
1
2
3
4
5
6
7
8
9
10
11
12
Z in 2mm steps from bottom

FIG. 10