MR Physics for Physicists:
RF Field Generation, Coupling, Traveling Wave Transmission

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Target audience: Physicists, engineers, hardware and methodology interested or generally curious people.

Objective: Understanding the principle and requirements of devices that nutate spins.
Know the basic principle of most common approaches of coil constructions from a basic point of view.

Outcomes:

For inducing nutation of nuclear magnetization circularly polarized magnetic field at precession frequency of the spins has to be produced in the sample.

High power is required in order to produce the needed RF magnetic field strength.

The generated RF field couples also to the human tissue and other dielectric and conductive structures.

The concomitant losses in the sample and the device have to be kept as low as possible to provide high efficiency but also safe operation.

Typically applied devices for this purpose are basically inductors exposing the sample to the oscillating magnetic field.

To couple high power into an inductor and to achieve high field strength an electrical resonance is established.

Higher main field strengths require higher frequencies of operation at which the RF field generation becomes more intriguing because the electric and the magnetic field cannot be considered that separated from each other anymore.

Overview:

The basic requirements for a device inducing nuclear spin nutation in a sample are discussed in the context of the involved electromagnetism. This includes the alternating magnetic field components actually inducing spin nutation but also the loss mechanisms of the electromagnetic fields especially as they occur in the sample. Characterizing these losses is of special interest since they deposit RF power in the sample which then causes the tissue to heat up. The local temperature rise can be so high that the tissue is locally burned but even the total power delivered to the live organism can have adverse effects such as systemic overheating if not carefully controlled. As a consequence the local specific adsorption rate (SAR) as well as the globally adsorbed power are considered being the most relevant safety factors. In most cases they are also limiting the achievable excitation with current MRI systems. The found requirements and constraints yield directly figures of merits for the design and evaluation of such devices.

At field strengths of clinical routine systems (<3T) the frequency of operation is small enough such that the RF wavelength is bigger or in the order of the size of the sample. In this regime, the magnetic field is closely bound to the current carrying elements and the situation can be considered in a quasi-stationary limit. An electrical structure that mostly produces an alternating magnetic near-field presents an inductance at its terminals and hence to the power delivering driving source. The simplest structure that does exactly this is a loop or a solenoid coil, probably the reason why all RF field generating devices are dubbed “coil” in NMR although many current implementations have topologically hardly anything in common with a coiled wire.

Coupling RF power directly into an inductor is typically very inefficient because the electrical wave emitted by the source with purely resistive inner impedance is just mostly reflected and does not enter the coil. In order to make this power transfer efficient, the coil has to be matched to the source’s impedance. Adding effective capacitance to the coil and bringing the system to resonance is the simplest way of achieving this. The resulting resonance stores electrical energy which is then oscillating between the magnetic field of the coil and the electric field in the capacitors and hence the wave stands in the resonant circuit transferring the electromagnetic energy from the electric to the magnetic field back and forth.

Also the most frequently used bench test parameters such as the filling factor, quality factor (Q) and its drop when loading the coil are closely related to the fact that MRI coils are basically considered as inductors, however it has to be kept in mind that these measures are based on the validity of the quasi-stationary approximation, which is clearly violated in human ultra-high field (>4T) systems. At these high frequencies the electric and the magnetic field components start to interact and wave propagation phenomena emerge which lead to the possibility of remote excitation via traveling waves.

All these requirements make particular implementations of MR coils for transmission highly dedicated to the target application and many topologies are known and further adapted to date optimizing efficiency, uniformity and power handling [2].

References: [1] D. I. Hoult, Conc Magn Reson, 2000 [2] J. Mispelter, NMR Probeheads for Biophysical and Biomedical Applications, Imperial College Press, 2006.