A Theoretical Study on the Frequency Modes Separation of Double Tuned TEM Resonators

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INTRODUCTION: The single-tuned [1-2] and double-tuned [2-4] TEM resonators were developed to improve versatility and SNR of high field MRI. So far, the double-tuned TEM resonator was designed by disposing two sets of transmission line elements (TLEs) at the same radial position [2-4]. The double-tuning condition was achieved by adjusting the electrical parameters of each TLE's set, such that to produce two groups of resonant modes (lower and higher range), each group showing a resonant mode multiplicity that depends on the number of TLE's. However, it was noted that with this geometrical design the double-tuned TEM resonator might give a rather limited frequency separation between resonant modes. This feature could lead to a partial overlapping of the useful resonant mode (M=1) with the adjacent modes (M=0, M=2), particularly when the TEM resonator is loaded with the human head, giving potential limits due to shading artefacts and SNR loss. A solution to this problem was recently proposed [5], requiring the design of an hybrid TEM and birdcage coil.

AIMS: In this theoretical work we show that a suitable geometrical disposition of the TLEs composing double-tuned TEM resonators allows a sufficient increase of the resonant modes separation. With this novel design we expect no complications in the use of double-tuned TEM resonators due to modes overlapping.

MATERIALS AND METHODS: To study the modes separation of double-tuned TEM resonators we adopted Multiconductor Transmission Line (MTL) modelling [6]. The MTL model of single and double tuned TEM volume resonators made by N coaxial elements with equal radius and radial positioning was previously described [7-9]. Given the geometrical symmetry, the admittance $\boldsymbol{Y}$ and impedance $\boldsymbol{Z}$ of the TEM were described by circulant matrices. Here, to allow a full freedom in the selection of the geometrical parameters, the MTL model was generalized to accept any $\boldsymbol{Y}$ and $\boldsymbol{Z}$ matrices structure. This is possible by modelling the empty TEM resonator as composed by perfect conductors and using the identity $\mathbf{LC}=\mu_0\varepsilon_0\mathbf{1}_N$, where $\mathbf{C}$ is the per-unit-length capacitance matrix and $\mathbf{L}$ is the per-unit-length inductance matrix, both function of the following geometrical parameters: the resonator radius ρ_0, the coaxial radius ρ_i and the distance from the resonator centre Δ_i of each coaxial element. In this case, the product $\boldsymbol{ZY}$ is diagonal and the transformation matrix is $\mathbf{T}=\mathbf{1}_N$, where $\mathbf{1}_N$ is the identity matrix. The modes separations depends on the mutual coupling coefficients between the TLEs, calculated as $k_{ij}=L_{ij}/\sqrt{(L_{ii}L_{jj})}$. It was already noted [10] that k_{ij} depends on the RF field density between the TLE and the RF shield. Our basic idea is that by a proper positioning of the two sets of TLE's it is possible to increase the mutual coupling coefficients, thus optimising the modes frequency separation of double-tuned TEM resonators. We have modelled the double-tuned TEM resonator as composed by two sets of TLE (N/2 and N/2) with alternate values of the: element radius (ρ_i), and distance of the element from the centre (Δ_i) (Fig.1). This geometry allows studying in a systematic way the variation of the coupling coefficients k_{ij}. By a proper adjustment of the Δ_i and/or ρ_i parameters, the frequency separation (Δf) of the modes can be properly set. In this study, the terminating capacitance values c_i of the TLE's were adjusted to tune the useful modes of the double-tuned TEM resonator at the desired values.

RESULTS AND DISCUSSION: We have simulated a 4T double-tuned TEM resonator (N=24; R=18.5 cm) suitable for 31P and 1H studies. We have found that the really critical geometrical parameter for modes optimisation is the relative radial positioning of the TLE's. In Fig. 2 we show the full resonant spectrum of the TEM obtained varying the distance from the centre (Δ_H) of N/2 elements tuned at the higher frequencies (elements radius ρ_H=7.3 mm), while keeping the distance of other TLE's set at Δ_L=14 cm (elements radius ρ_L=6.1 mm). We observe that, if $\Delta_H=\Delta_L$=14 cm (standard design) the high frequency spectrum shows a relatively small separation between the higher frequency modes. In fact, for the loaded TEM resonator (assuming an average quality factor $Q_L\approx 40$ with the human head) the estimated frequency separation is only about 0.3 times the resonator bandwidth (see Table 1). On the other end, by decreasing Δ_H we observe a significant increase of the modes separation. For example, with Δ_H=12 cm the frequency separation is about 2.2 times the bandwidth, thus avoiding modes overlapping. It is also worth noting that the low frequency modes are practically not affected by the Δ_H adjustment, with a typical frequency separation of about 4.4 times the bandwidth.

CONCLUSION: In this theoretical study we have shown that, by a proper adjustment of the radial position of the TLE's elements, the high frequency modes separation of double-tuned TEM resonators can be significantly increased. This should be important to prevent higher modes overlapping, thus avoiding RF sensitivity and homogeneity losses when the TEM resonator is loaded with lossy samples at 4T. One drawback of the proposed design is that, for a fixed TEM radius, the high frequency TLE's (1H) are disposed at a smaller radial value with respect to the lower frequency TLE's (31P), giving a somehow reduced sensitivity for the less sensitive nuclei. However, as shown in Table 1, a shift in the radial position from 14 to 12 cm increases the relative frequency separation to about 2.2. Assuming a linear dependence of SNR from the TLE's radial position, this should translate into a SNR reduction of less than 15 %.

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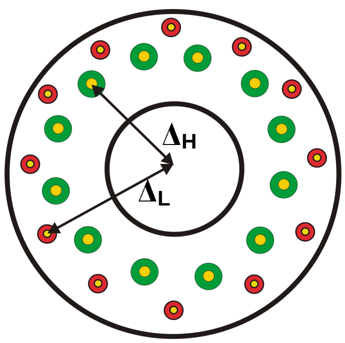

Fig 1: A schematic section of the double tuned TEM resonator model. Red elements (minor radius), positioned at Δ_L are tuned at lower frequencies; green elements (greater radius), positioned at Δ_H are tuned at higher frequencies.

Δ_H (cm)	$\Delta f_{L1}/BW_L$	$\Delta f_{L2}/BW_L$	$\Delta f_{H1}/BW_H$	$\Delta f_{H2}/BW_H$
14.0	4.2	3.9	0.4	0.2
13.5	4.3	4.1	0.6	0.5
13.0	4.4	4.0	1.2	1.0
12.5	4.6	4.2	1.7	1.5
12.0	4.6	4.1	2.3	2.1

Table1: The ratio between frequency separation **Δf** of the low and high modes with respect to the TEM bandwidth **BW** (f_{0L}=68.9MHz, BW_L=1.7MHz; f_{0H}=170.3MHz, BW_H=4.2MHz . Δf_{L1} is the frequency split between the **0L** and **1L** modes, Δf_{L2} between **1L** and **2L** modes, Δf_{H1} between **0H** and **1H** modes, and Δf_{H2} between **1H** and **2H** modes.

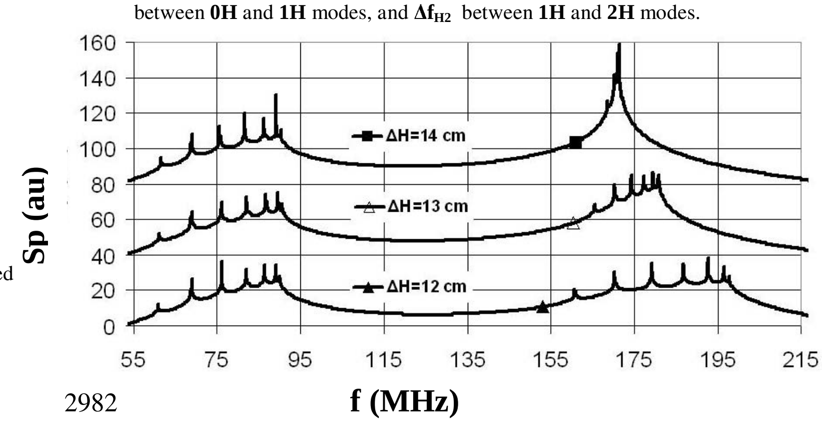

Fig 2: Simulated spectra of Double Tuned TEM Resonator obtained with: (top) $\Delta_H=\Delta_L$=14 cm; (middle) Δ_L=14 cm and Δ_H= 13 cm; (bottom) Δ_L=14 cm and Δ_H= 12 cm.