Comprehensive numerical study of 7T transmit-only, receive-only array coils

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Purpose: The Nova 7 T RF coil, which has single-channel transmission (TX) [1] and 24 or 32 channel reception (RX) [2,3] (Nova Medical, Wilmington, MA) is notable for its excellent signal to noise (SNR) performance. The coil designers have demonstrated that separate dedicated coils for transmission and reception (TX-only, RX-only) perform better than a combined-element transceiver coil. One disadvantage of the coil available is its single-channel transmit operation. Without comprehensive and accurate numerical simulations, design of a similar high performance multi-channel RX RF coil with separate multi-channel TX elements suitable for parallel transmit applications could be an insuperable challenge. Furthermore, the SAR associated with the required complex coil feed/tune/match/decoupling arrangements for both TX and RX coils can only be reliably estimated by full simulation, because at 7T the coupling between array elements is spatially distributed and cannot be modelled using a lumped element approximation. The decoupling between TX and RX coils, and the losses introduced by decoupling sub-circuits, depend on the relevant coil impedances in "On" and "Off" states. Our goals were to develop an approach allowing joint numerical investigation of TX-only, RX-only coils, and to analyze the influence of decoupling sub-circuit impedance on TX/RX coil decoupling and transmit power balance.

Method: We employed co-simulation of the RF circuit and 3-D EM fields [4]. Agilent ADS was used as the RF circuit tool, and HFSS was used as the 3-D EM tool. The realistic coil 3-D EM model included all construction details for the resonance elements, simulated with realistic dimensions and material electrical properties, and the scanner gradient shield was defined as a copper cylinder with diameter of 683 mm and 0.045 mm thickness. For our first investigation we used a loop-based 8 channel TX-only, 8 channel RX-only coil (Fig.1) built on a cylindrical acrylic support, with diameter 250 mm or 280 mm for TX coils, and 220 mm for RX coils. The axial length of TX and RX coils was 120 and 100 mm respectively. To decrease radiation losses, a local shield of diameter 350 or 400 mm and length 300 mm was used. This coil configuration satisfies an important requirement of our approach, that all RF sub-circuits have negligible mutual coupling, and therefore can be substituted by 3-D EM ports in the 3-D EM domain. In the RF circuit domain the sub-circuits are reinstated and connected to the corresponding port of an object described by an S parameter matrix obtained from the 3-D EM model simulation. For maximal flexibility, all distributed capacitors were also substituted by lumped ports. In each radiative loop this allowed placement of up to 8 capacitors, with complementary sub-circuits for decoupling between elements of the same coil and also between the TX and RX coils. The total number of ports is 128. In the present study we used inductive decoupling and lumped serial RLC components with variable values as equivalents of TX/RX decoupling sub-circuits [5]. Such sub-circuits, like other sophisticated decoupling approaches, can be straightforwardly included in the simulation workflow as required. The resistive impedance of the high-power pin diodes used in the TX decoupling circuits was taken to be 1 Ohm (close to actuality). A Siemens 7 liter water-based phantom was used as a load. For each of the TX and RX arrays, the values of distributed capacitors and inductive decoupling were then obtained by RF circuit optimization, guided by "S_{11}" and "S_{12}" (values of coupling between next neighbouring elements) minimization, while keeping the other array in a de-tuned condition. For all coils investigated "S_{11}" and "S_{12}" were lower than -30dB and -20dB correspondently. The effective resistive impedances of radiation losses ($R_{radiated}$), of the coil internal structure including decoupling sub-circuits (R_{inter}), and of the coil load (R_{load}), were calculated by summing each element's feed current and corresponding power. For comparative purposes, the TX and RX coils were also separately simulated.

Results and Discussion: TX performance data for one simulated coil are presented in Table 1. Corresponding B1+ profiles are shown in Fig.2. To avoid any TX performance penalty caused by TX de-tune circuits that increase R_{inter}, the increment of R_{inter} has to be much smaller than R_{load}. For the geometry investigated this can be achieved using a smaller diameter TX coil and a larger distance to the coil shield (which slightly decreases the coupling of both TX and RX coil elements). The tuning condition for both coils depends on the decoupling circuit impedance, but both coils can be easily re-tuned to the resonance frequency while maintaining acceptable (better than -40 dB) levels of TX/RX coil decoupling, provided that the impedance of the decoupling sub-circuit is reproducibly stable and larger than 0.5 kOhm in the "On" state. Having more decoupling sub-circuits in each coil element gives better coil isolation. However, only two sub-circuits per element already enables efficient design of TX-only, RX-only coils for the given coil geometry with a relatively small distance (15 mm) between the coils. In cash a case, if the sub-circuit impedance is greater than 1 kOhm then isolation is better than -40 dB. If decoupling between TX and RX coils fails, no dangerous power loss density hot spots appear in the load, as shown in Fig. 3 which is scaled to the maximum value for the TX-only, RX-only coil. On the contrary, the power absorbed by the load is then much lower than in the decoupled case.

Conclusion: RF circuit and 3-D EM co-simulation offers a reliable and fast workflow for investigating TX-only, RX-only coils. The flexibility of the workflow allows inclusion of almost all the RF and DC components used for feed/tune/de-tune/match/decoupling. Wide band TX/RX decoupling sub-circuits with reproducible stable impedance are preferable, because their relatively low insertion impedance is sufficient for a high level of TX/RX decoupling.

[1] Ledden, et al, Proc ISMRM 2005, p. 322. [2] Ledden, et al, Proc ISMRM 2006, p. 422.[3] Ledden, et al, Proc. ISMRM 2007, p. 242 [4] M.Kozlov, R. Turner, Journal of Magnetic Resonance 200 (2009) 147–152.
[5] N. I. Avdievich, et al, Proc. ISMRM 2007, p. 238

	"S_{11}", [dB]	"S_{21}", [dB]	"S_{TX_RX}", [dB]	I, [A]	B_1+ max, [μT]	B_1+ aver, [μT]	Power absorbed, [W]	Power in load, [W]	Radiated power, [W]	R_{load}, [Ohm]
1	<-40	-23.65	-	0.70	2.86	1.13	7.62	6.15	0.17	0.41
2	<-40	-23.25	-38.2	0.69	2.85	1.12	7.64	6.12	0.16	0.41
3	<-40	-27.57	-40.1	0.57	2.36	0.93	7.91	4.22	0.11	0.41
4	-8.3	-27.8	-9.4	0.60	2.03	0.74	3.91	2.70	0.06	0.23

Table 1. TX only coil (1), TX-only, RX-only with ideal pin diode (2), actual pin diode (3), without decoupling (4).

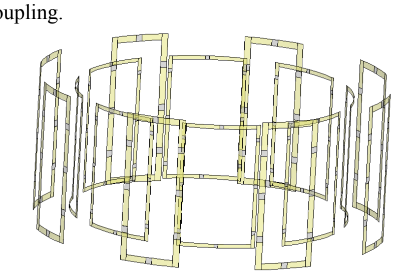

Fig.1. Coil structure

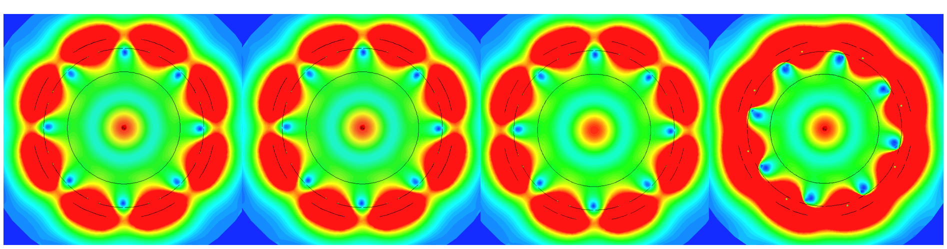

Fig.2. B1+ profiles rescaled to individual maximum. From left to right corresponding to rows of Table 1.

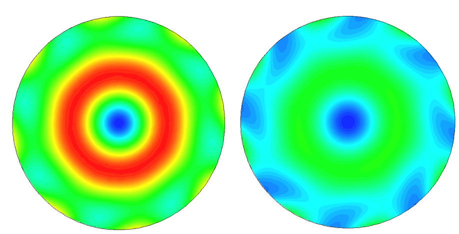

Fig.3 Power loss density profiles for (2) and (4).