Accurate and fast longitudinal RF magnetic field profiling for 7T traveling-wave MRI systems

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Introduction and Objectives: In their pioneering publication [1] Brunner et al. have proposed propagating traveling waves as a very efficient mean to provide uniform, circularly polarized, radio frequency (RF) B_1 fields along the bore of a high-field (7T) MRI scanner while relying on the bore's fundamental circular waveguide mode (TE_{11}). Most of the current traveling-wave excitation schemes rely on closed-end antenna systems, which pose a serious challenge to the patient's comfort. As a workaround to this drawback and in support of either selectivity or uniformity in the longitudinal magnetic field profile we are investigating a *fully adaptive* RF antenna system that perfectly conforms to the bore surface [2-4]. Fig. 1 depicts the *MetaBore* [5], which labels our «open» excitation architecture consisting of multiple composite right-/left-handed (CRLH) metamaterial ring antennas, each supporting a full-wave resonance (at 298 MHz) with an azimuthal current density profile that perfectly mimics the surface current distribution of the TE_{11} mode with respect to the given specific bore diameter. In our present research we are now looking for most efficient (potentially real-time) solutions to then *inverse problem*, encompassing all quadrature current amplitudes and phases of the periodically arranged ring antennas, in order to get correspondingly tailored field profiles along the bore. Besides our extensive numerical studies we have set up an experimental system for validation purposes that is designed for an easy insertion into the scanner for first proofs of concept.

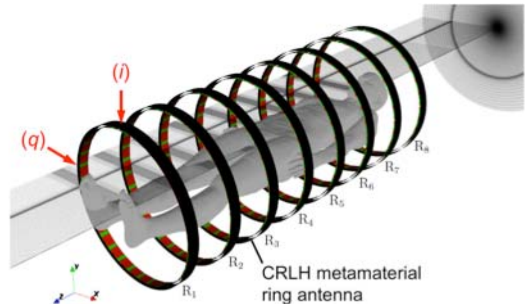

Fig 1: MetaBore: EC-FDTD model of the *N* CRLH metamaterial ring antennas and the human phantom. Quadrature current feeds (*i*) and (*q*) for circularly polarized mode excitation are exemplary for all involved ring antennas.

Materials and Methods: The solution to the *inverse problem* starts with the numerical evaluation of the electromagnetic response of the loaded bore. Each of the *N* ring antennas undergoes a unit current excitation for both feeds (*i*) and (*q*) where the resulting field is sampled and averaged within *M* periodically arranged cross-sectional planes intersecting the body (i.e. the phantom). These sampled fields are thus setting up a basis that by proper choice of the weighting (i.e. of the complex excitation current) is correspondingly superimposed to yield the desired illumination profile for the B_1^+ amplitude (while suppressing B_1^-). First designs using the iterative *Levenberg-Marquardt* algorithm as a search heuristics have proven successful for providing e.g. a uniform, 50 cm wide illumination window for the abdomen [2,3]. In order to accelerate the 3D full-wave solution to the forward *problem*, we developed the highly efficient equivalent-circuit (EC) FDTD simulation platform *openEMS* (33% speed and memory improvement compared to standard FDTD) that supports amongst others cylindrical inhomogeneous meshing, highly dispersive material models and is readily available at http://openems.de [6]. A further measure to speed-up full-wave computation is to replace the complicated CRLH ring antennas by equivalent «continuous» current strips [cf. e.g. Fig. 2(e)].

Results and Discussion: In our present investigations we are aiming at *fastest possible* profiling procedures, where first attempts have been carried out using direct least squares solutions – relying on the *Moore-Penrose* pseudo-inverse in conjunction with a singular value decomposition – to solve for the *2N* complex excitation currents given *2M* samples of the target profiles (regarding both amplitudes B_1^+ and B_1^-). As displayed in Fig. 2 an accurate 15 cm wide profile (given the wavelength of the traveling waves of 3.6 m!) for *larynx* illumination has been achieved with a suppression of the unwanted B_1^- component (compared to B_1^+) of 21 dB while showing no SAR hot spots in the shoulder-neck region [4]. Using the same ring antennas in receive mode during the retrieval of the electromagnetic response (of the loaded bore) could directly provide $2M := 2N$ rotating field amplitudes, enabling real-time profiling in the scanner prior to MRI diagnostics. We are now setting up a *MetaBore* test structure with slightly smaller ring antennas to be inserted into the 7T scanner bore for validation purposes. The antennas show the expected full-wave resonance (cf. Fig. 3) at 298 MHz even under loading conditions with an octagon prism as a body-emulating phantom. It is next to demonstrate that the *MetaBore* can act as holistic real-time scheme for «longitudinal shimming» in 7T MRI.

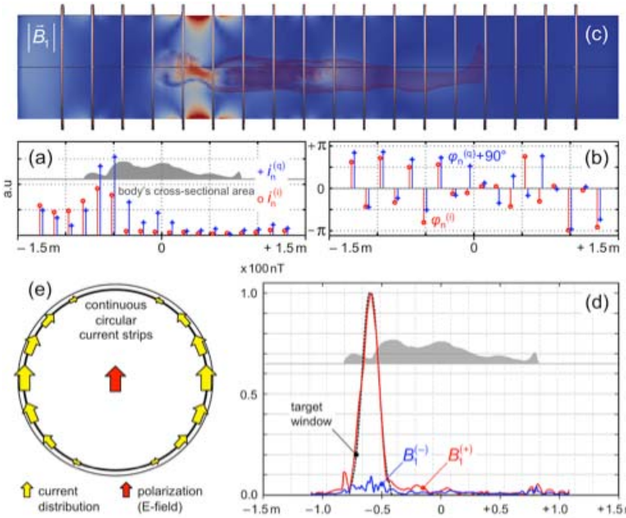

Fig. 2: Profiling scenario for *larynx* illumination (transmit): (a) amplitudes and (b) phases of the quadrature current excitations, and (c) the magnitude of the resulting transversal RF magnetic field (B_1); (d) spatial average [over the body's cross-sectional area (gray shading)] of the field amplitude B_1^+ resp. B_1^- of the right-hand/clockwise resp. left-hand/counter-clockwise circular polarized field along the bore approximating a Gaussian target profile with FWHM = 15 cm. The analysis uses $N = 18$ continuous circular current strips (e) as ring antennas (width 1 cm, pitch 15 cm, diameter 64 cm [4]) and $M = 137$ sample planes.

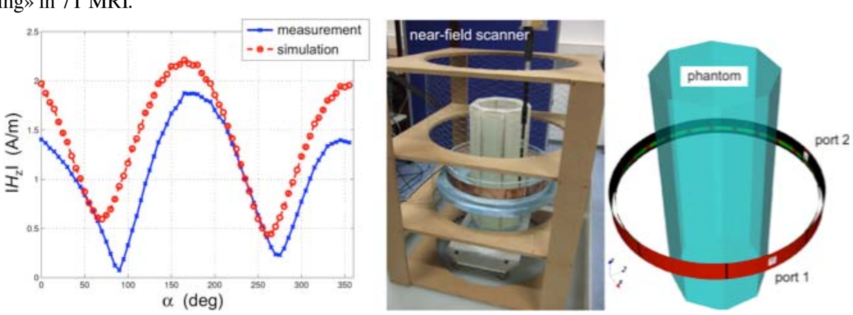

Fig. 3: CRLH metamaterial ring antennas: Each antenna (overall diameter 50 cm) of the test setup consists of 24 unit cells having a width of 1.2 cm, over a correspondingly split ground plane structure (8 cells). The magnetic field amplitudes (H_z) for a single fed ring (1 W, input at 180°) are evaluated using a *xyz*-scanning RF probe (cf. EASY4/MRI, speag), reproducing the pattern of the expected full-wave resonance. Deviations between simulation and experiment are due to additional circular wave excitation.

References: [1] D. O. Brunner, et al., *Nature*, 457, 994, Feb. 2009. [2] D. Erni, et al., *IEEE EMBS 2011*, 554, 2011. [3] T. Liebig, et al., *ESMRMB 2011*, 37, 2011. [4] H. Yang, et al., *ICEAA 2013*, 468, 2013. [5] D. Erni, et al., *German patent,* ref. no. 10 2010 010 189, 2013. [6] T. Liebig, et al., *Int. J. Numer. Model.*, 26(6), 680, 2013.