Parallel Transmit RF Simulation Workflows

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PURDUE ENGINEERING

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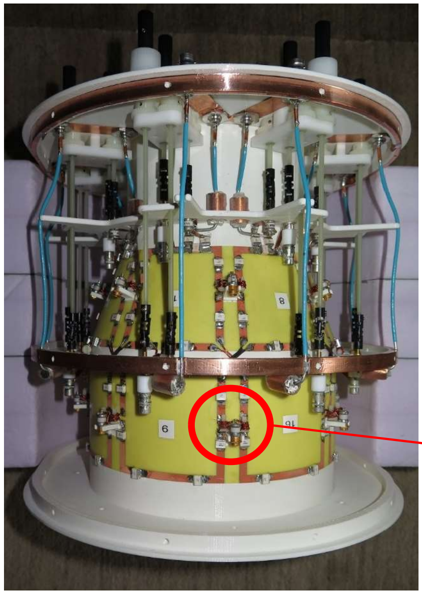
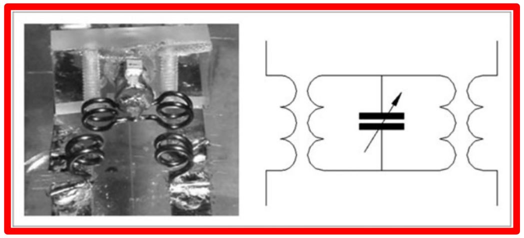
Parallel Transmit @ 7T

- Radiofrequency EM field simulations
  - 16-channel 7T transceiver array coil w/ **R**esonant **I**nductive **D**ecoupling
  - Primary motivation: E-field dosimetry safety analysis



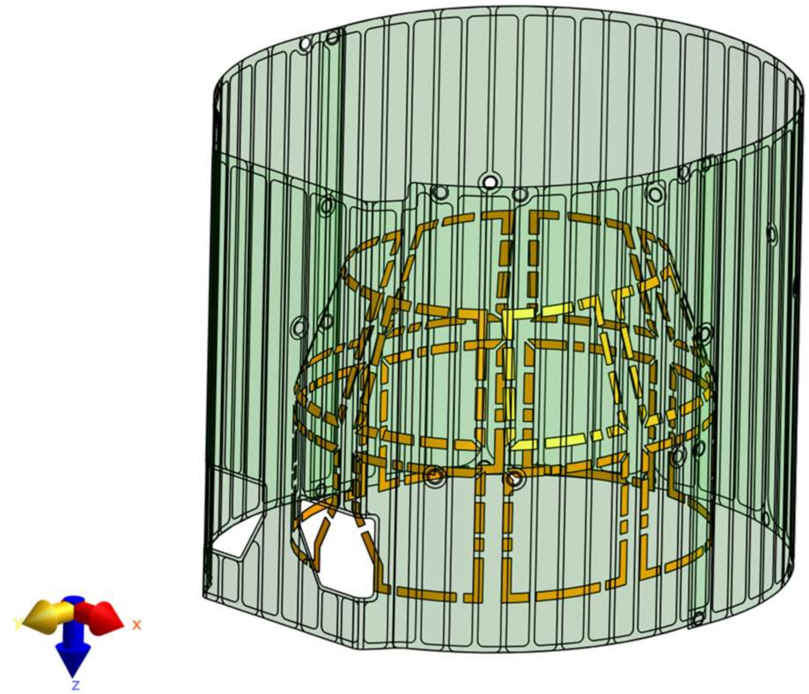
Avdievich, Pan, Hetherington, *NMR Biomed* 2013.

RID

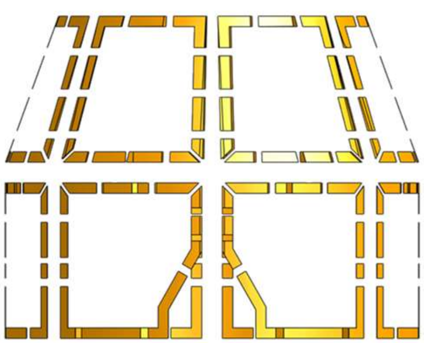


MODEL SETUP

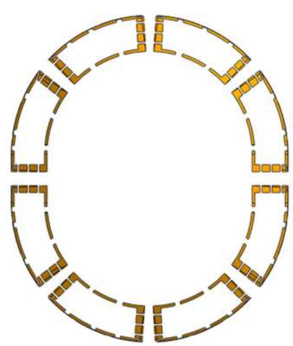
- CAD models imported into Sim4Life
    - 16 segmented coil elements, 208 total segments
    - 2-piece shield
    - Virtual Population models
- 2 mm maximum grid step
- Tissue to coil distance > 10 mm
- Free space padding: 38 cm
- Excitation: modulated Gaussian
    - center 300 MHz, bandwidth 100 MHz

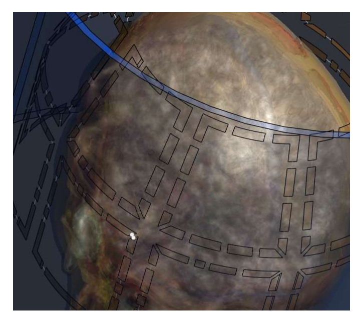


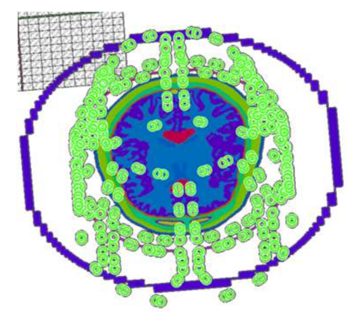
front view



top view

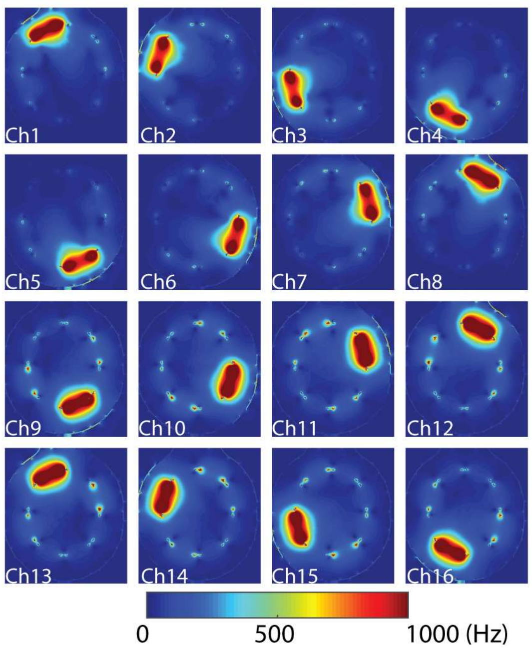






B_1^+ Maps (individual excitation)

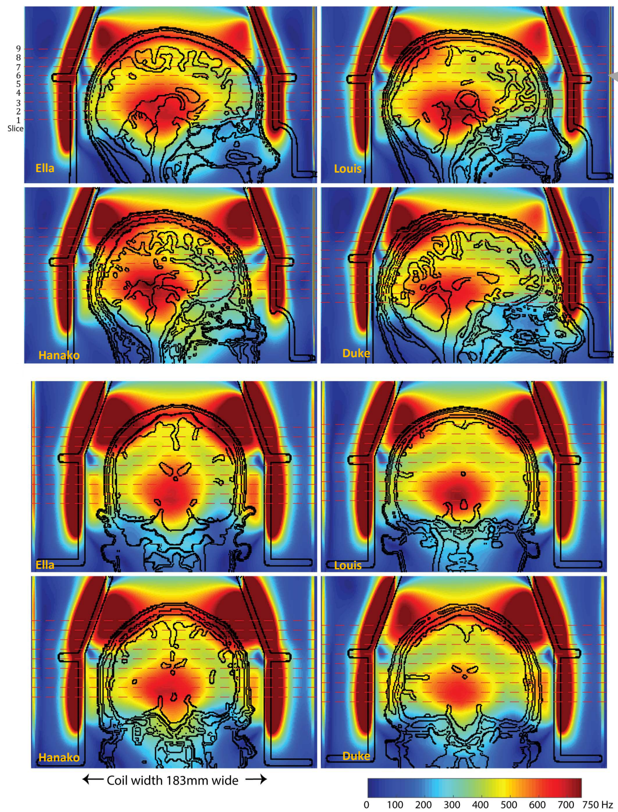
$$a_{\text{in}} = V_k e^{j(\phi_k)}$$

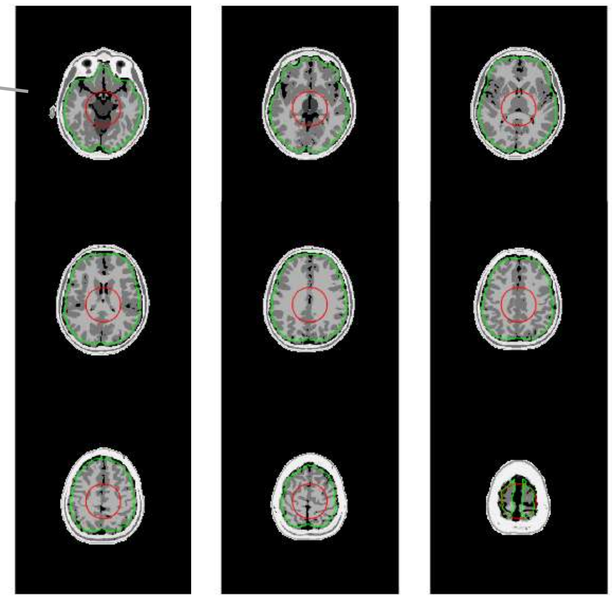


B_1^+ Maps (simultaneous excitation)

Sagittal view

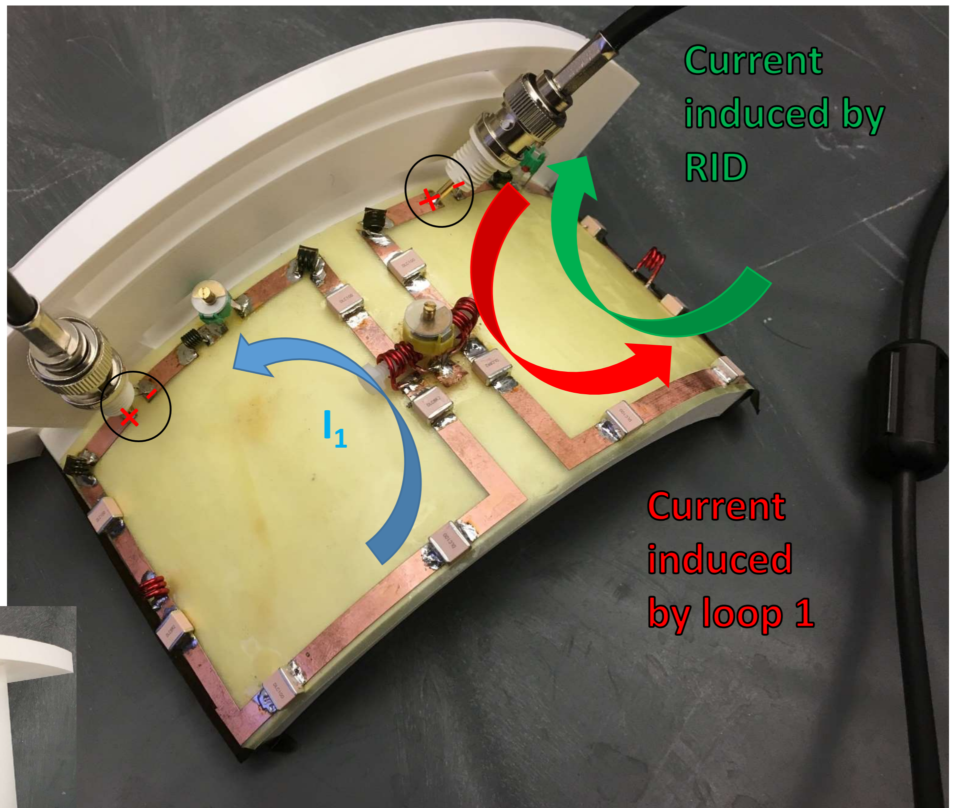
Coronal view

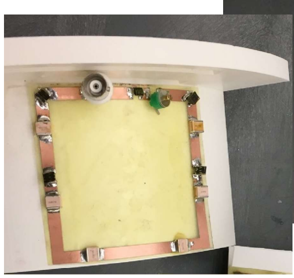




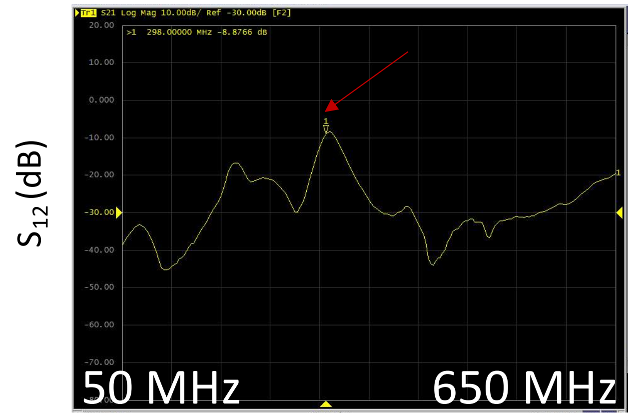
$$a_{\text{in}} = V_k e^{j(\phi_k)} = V_0 e^{j(\phi_{\text{CP}} + \Delta_{\text{inter-row}})}$$

Bench Validation of Decoupling

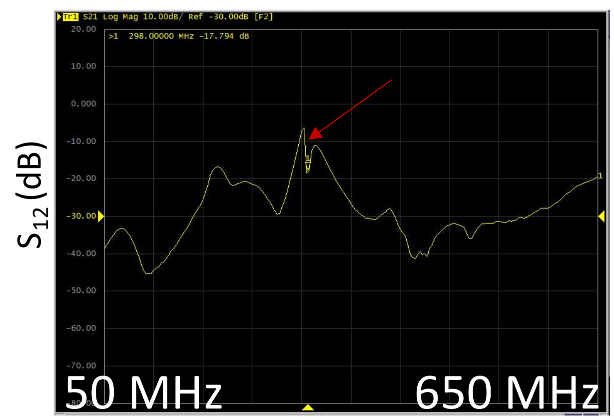




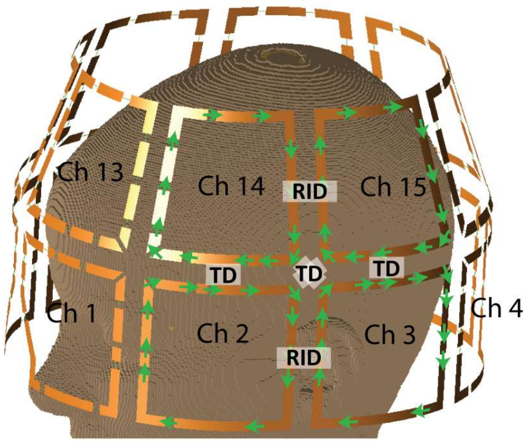
Without RID

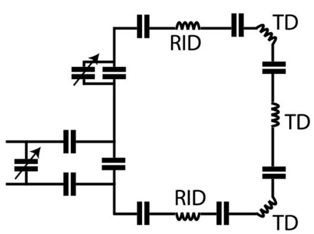


With RID

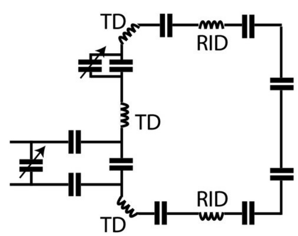


Co-simulation



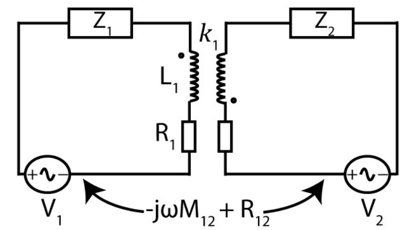


Top Row (Ch 9 -18)



Bottom Row (Ch 1 - 8)

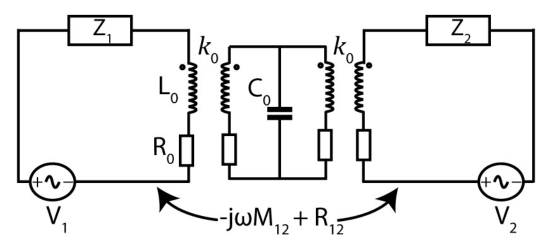
TD
(transformer decoupling)



$$\boldsymbol{Z}_{\mathrm{TD}} = \begin{bmatrix} j\omega L_1 + R_1 & j\omega k_1 L_1 \\ j\omega k_1 L_1 & j\omega L_1 + R_1 \end{bmatrix}$$

$$\boldsymbol{S}_{\mathrm{TD}} = (\boldsymbol{Z}_{\mathrm{TD}} - 50\,\boldsymbol{I})(\boldsymbol{Z}_{\mathrm{TD}} + 50\,\boldsymbol{I})^{-1}$$

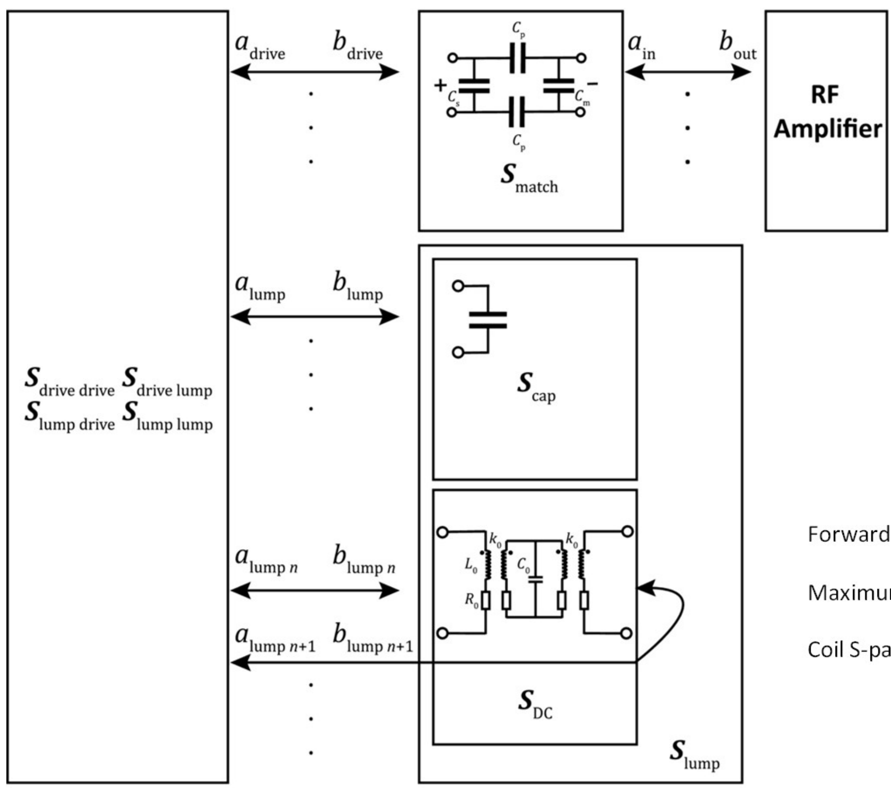
RID
(resonant inductive decoupling)



$$\boldsymbol{Z}_{\mathrm{RID}} = \begin{bmatrix} j\omega L_0 + R_0 - \dfrac{\omega^2 {k_0}^2 {L_0}^2 \left(j\omega L_0 - \dfrac{j}{\omega C_0} + R_0\right)}{\left(j\omega L_0 - \dfrac{j}{\omega C_0} + R_0\right)^2 - \left(\dfrac{j}{\omega C_0}\right)^2} & \dfrac{-\omega^2 {k_0}^2 {L_0}^2 \left(\dfrac{j}{\omega C_0}\right)}{\left(j\omega L_0 - \dfrac{j}{\omega C_0} + R_0\right)^2 - \left(\dfrac{j}{\omega C_0}\right)^2} \\ \dfrac{-\omega^2 {k_0}^2 {L_0}^2 \left(\dfrac{j}{\omega C_0}\right)}{\left(j\omega L_0 - \dfrac{j}{\omega C_0} + R_0\right)^2 - \left(\dfrac{j}{\omega C_0}\right)^2} & j\omega L_0 + R_0 - \dfrac{\omega^2 {k_0}^2 {L_0}^2 \left(j\omega L_0 - \dfrac{j}{\omega C_0} + R_0\right)}{\left(j\omega L - \dfrac{j}{\omega C_0} + R_0\right)^2 - \left(\dfrac{j}{\omega C_0}\right)^2} \end{bmatrix}$$

CIRCUIT DOMAIN VS. SPATIAL DOMAIN

Circuit Domain



Forward voltage: $a_{\text{in}} = V_k e^{j(\phi_k)}$

Maximum forward voltage: 65.5 V

Coil S-parameters: $\boldsymbol{S} = \frac{\mathbf{b}_{out}}{\boldsymbol{a}_{in}}$

Spatial Domain

$$\mathbf{B}_1^+ = \sum_{n=1}^{208} a_n \cdot \frac{\mathbf{B}^+_{1\ \text{voltage source}\ n}}{a_{\ \text{voltage source}\ n}}$$

$$\mathbf{E} = \sum_{n=1}^{208} a_n \cdot \frac{\mathbf{E}_{\ \text{voltage source}\ n}}{a_{\ \text{voltage source}\ n}}$$

Cost Function

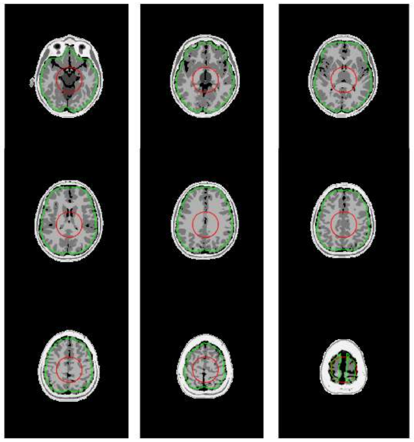
Cost function without considering B_1 inhomogeneity:

$$f(\boldsymbol{x}) = \left\| |\mathrm{diag}(S(\boldsymbol{x}))| - S_{ii} \right\| + \left\| |S_r(\boldsymbol{x})| - S_{ij} \right\|$$

Cost function considering B_1 inhomogeneity :

$$f(\boldsymbol{x}) = \left\| |\mathrm{diag}(S(\boldsymbol{x}))| - S_{ii} \right\| + W_1 \left\| |S_r(\boldsymbol{x})| - S_{ij} \right\| + W_2 \left\| \frac{\mathrm{SD}(B_1(\boldsymbol{x}))}{\mathrm{mean}(B_1(\boldsymbol{x}))} - target \right\|$$

ROI



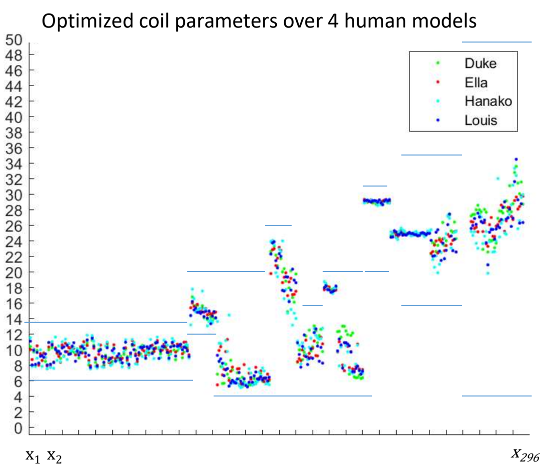
The minimum is given by the constrained optimization:

$$\hat{x} = \arg\min_{x} \{\ f(x)\ \}$$

subject to

$$x \in \{\Omega : x_{n\ \mathrm{lower}} < x_n < x_{n\ \mathrm{upper}}, n = 1,2,\ldots,296\}$$

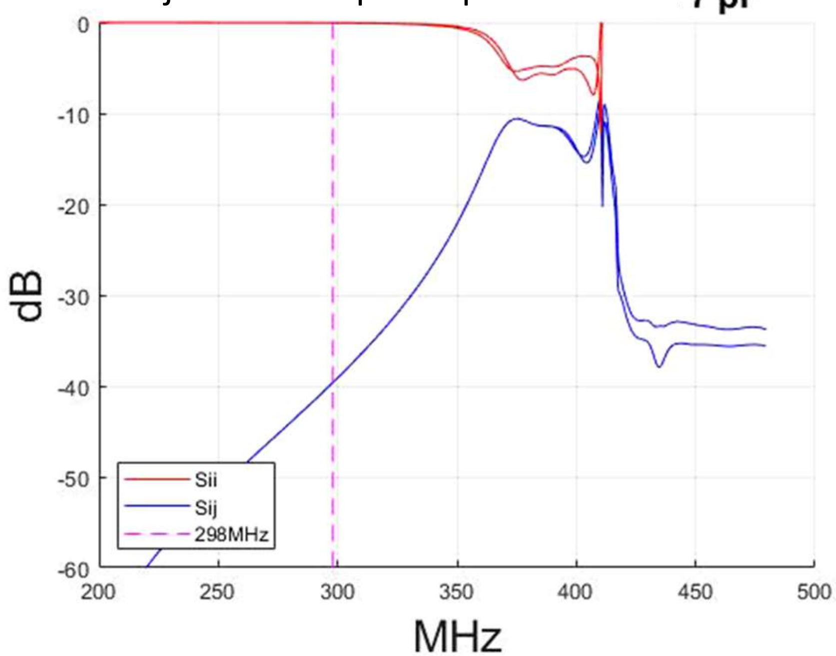
Optimize Coil Parameters



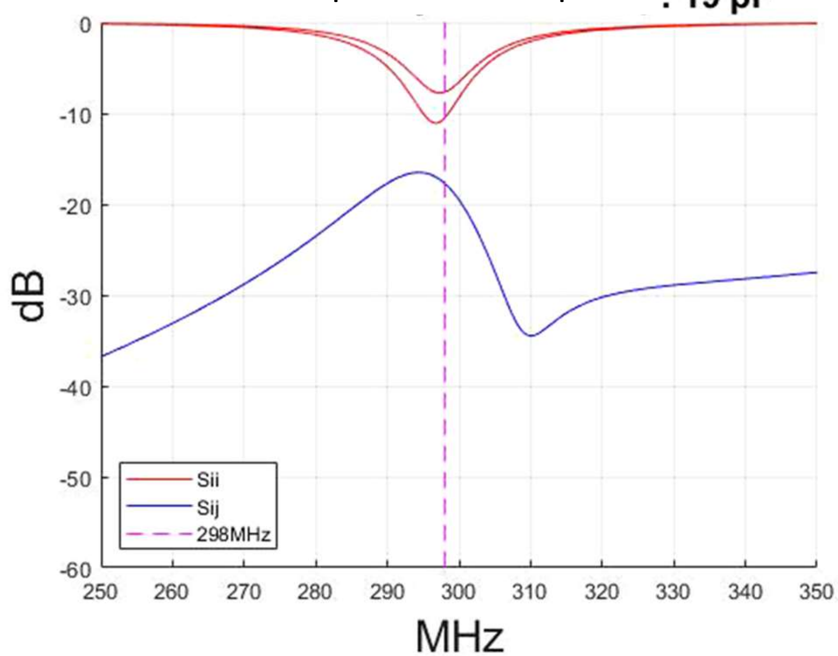
Components	Hanako	Hanako (exclude B_1^+ inhomogeneity)	Ella	Duke	Louis
x_1 - x_{96} Fixed lumped caps ("10 pF" or "8.2 pF") Optimization subject to $x_{1-96} \in [7, 13$ pF]	9.66±1.24	9.52±0.87	9.66±0.91	9.53±0.85	9.69±0.87
x_{105} - x_{112} Tuning cap, top coils [10, 20 pF]	14.19±0.85	13.75±0.50	14.80±0.24	14.19±0.40	14.37±0.56
x_{97} - x_{104} Tuning cap, bottom coils [10, 20 pF]	15.70±1.53	15.11±0.45	15.43±0.39	15.52±0.71	15.03±0.55
x_{121} - x_{128} Trimmer cap, matching, top coils [5, 20 pF]	5.56±0.30	7.28±0.70	6.58±1.01	6.61±1.05	6.02±0.46
x_{113} - x_{120} Trimmer cap, matching, bottom coils [5, 20 pF]	10.84±2.33	7.82±0.51	8.39±2.21	6.97±1.08	7.72±1.29
x_{129} - x_{144} Shunt matching cap [5, 20 pF]	6.22±0.82	6.53±0.56	6.38±0.79	5.92±0.43	6.18±0.47
x_{145} - x_{160} Parallel matching cap [5, 25 pF]	18.93±4.08	19.55±0.58	19.93±2.24	20.16±2.69	20.14±2.34
x_{161} - x_{168} RID inductor, top coils [5, 15 nH]	9.91±1.05	9.34 ±1.42	9.37±0.90	10.00±1.46	9.55±1.42
x_{169} - x_{176} RID inductor, bottom coils [5, 15 nH]	11.50±1.20	9.49±1.49	10.31±1.06	11.35±1.30	10.18±1.63
x_{201} - x_{216} RID isolated frequency [200, 298 MHz]	290.27±2.02	292.64±0.87	291.48±1.02	290.44±1.64	291.46±1.72
x_{241} - x_{256} RID Q factors [150, 350]	235.46±22.06	216.98±15.90	238.24±9.23	245.25±16.26	236.94±17.22
x_{281} - x_{296} RID k coefficients [0.06, 0.5]	0.282±0.029	0.257±0.019	0.279±0.014	0.295±0.021	0.280±0.024
x_{177} - x_{184} TD vertical inductors [5, 20 nH]	17.93±0.49	18.47±0.33	17.81±0.26	17.93±0.29	17.79±0.32
x_{185} - x_{200} TD diagonal inductors [5, 20 nH]	8.29±1.38	9.98±0.78	8.77±1.53	9.77±2.99	8.97±1.72
x_{217} - x_{240} TD Q factors [150, 350]	249.95±3.32	247.76±1.59	249.02±1.88	250.02±1.42	248.92±1.97
x_{257} - x_{264} TD vertical k coefficients [0.06, 0.5]	0.424±0.017	0.441±0.014	0.435±0.012	0.416±0.016	0.433±0.014
x_{265} - x_{280} TD diagonal k coefficients [0.06, 0.5]	0.243±0.018	0.255±0.013	0.256±0.011	0.259±0.023	0.255±0.016

Co-simulation with RID

Adjust the lumped caps



Tune the RID caps until decoupled



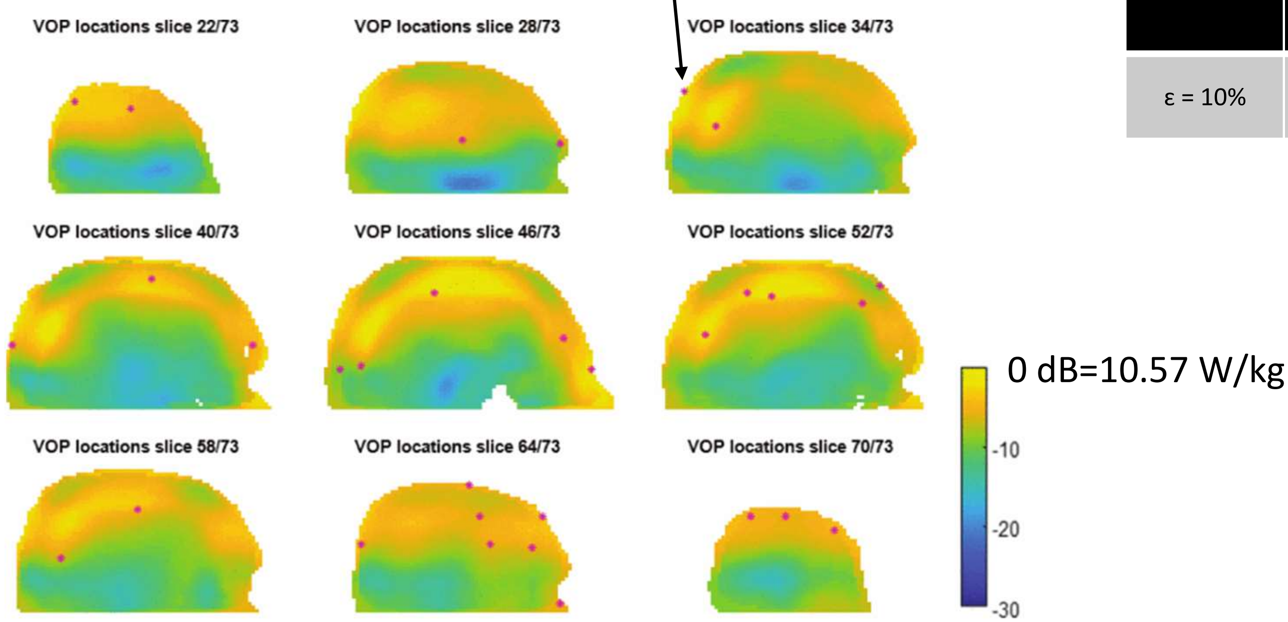
- The capacitor values of the coil affect tuning to the resonance frequency
- The capacitor values of matching circuit affect matching S_{11}
- The capacitor values of RID affect decoupling S_{12}

WORST-CASE SAR MAPS

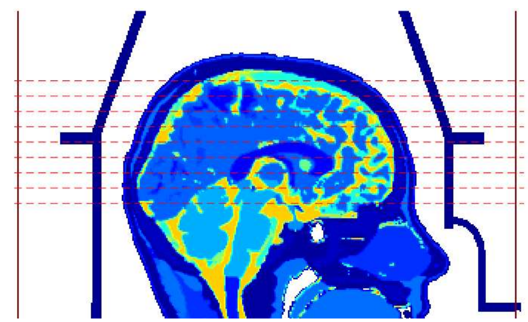
VOP locations superimposed on 10-g averaged SAR maps from the spectroscopy excitation mode.

$$\mathbf{U}^H\mathbf{Q}\mathbf{U} \leq \underbrace{|\mathbf{Q}|_2}_{\triangleq \text{ worst-case SAR}}\mathbf{U}^H\mathbf{U}$$

$\mathbf{Q}_{\mathbf{core}}$

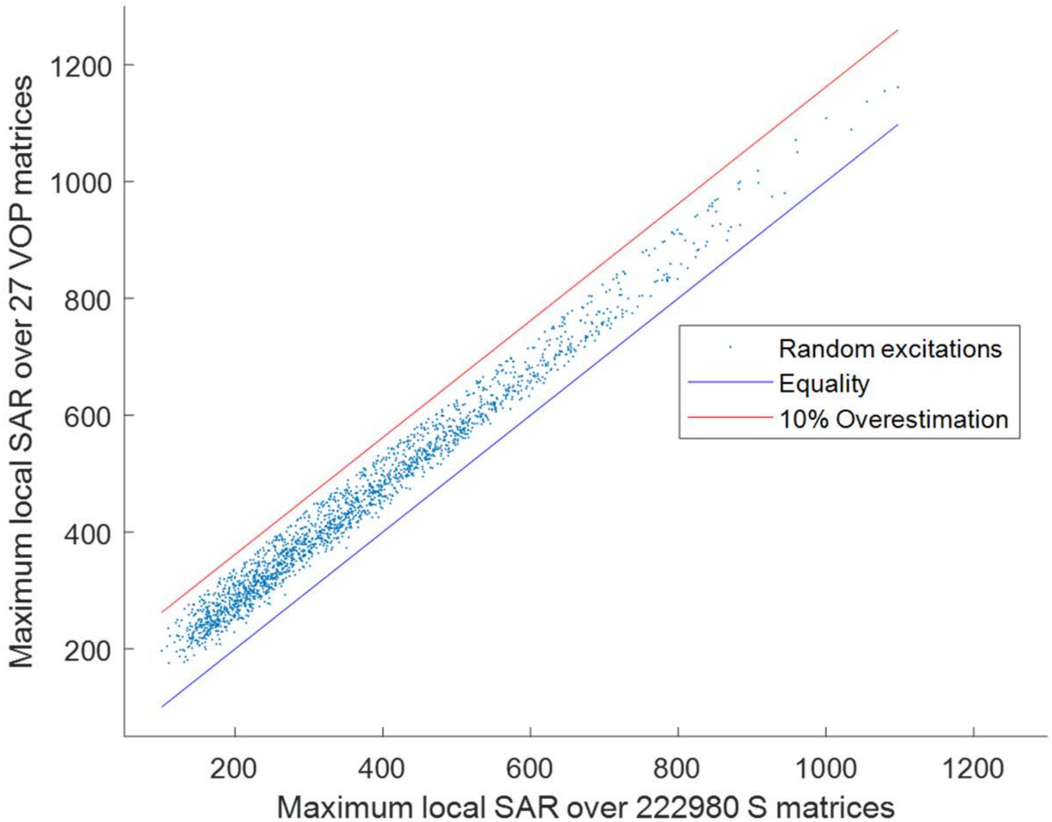


	Number of Q matrices	Number of VOPs	Compression factor
ε = 10%	194,376	272	715

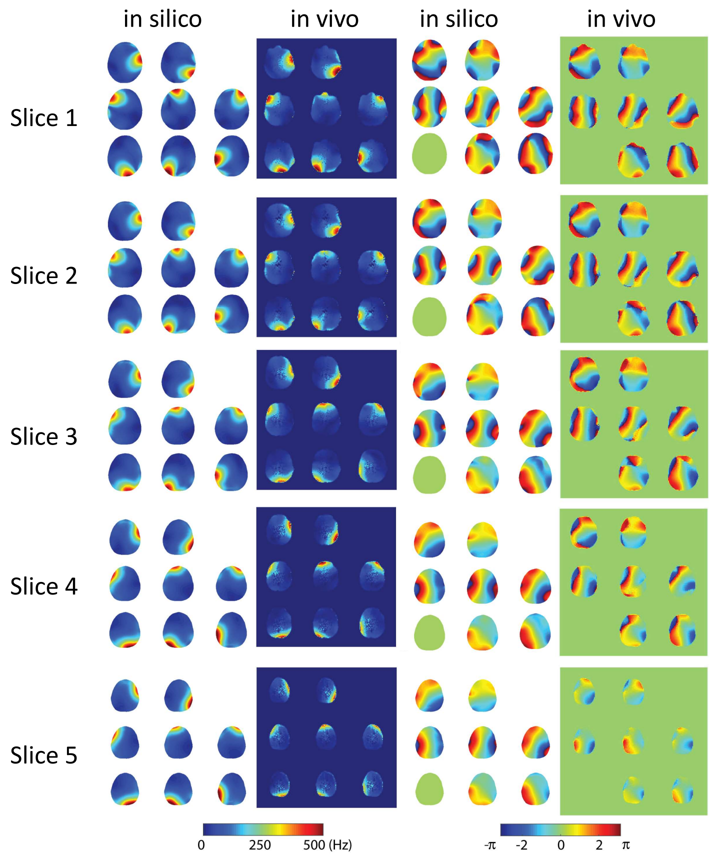


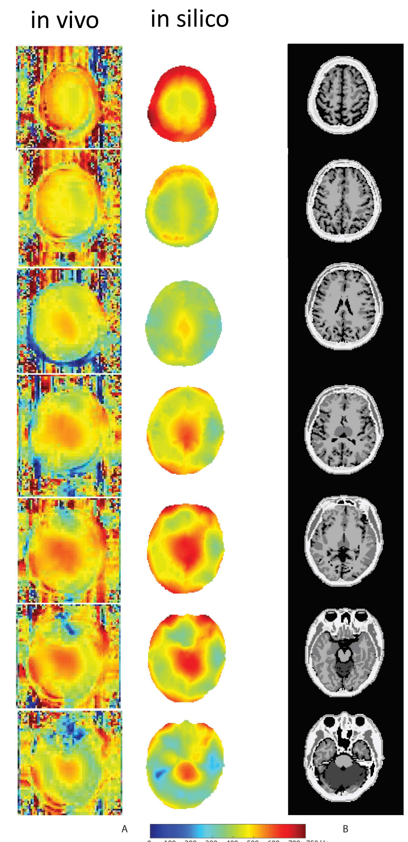
2000 RANDOM RF EXCITATIONS

$\text{SAR} = \mathbf{U}^H \mathbf{Q} \mathbf{U}$

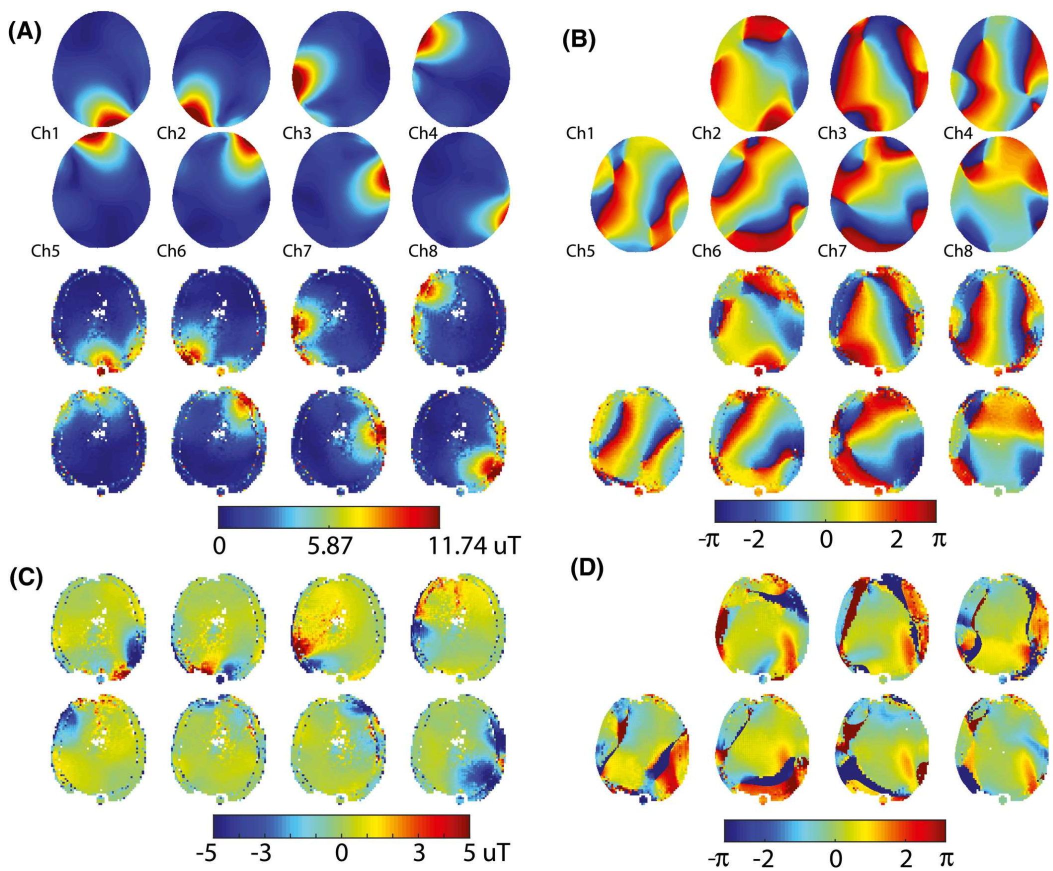


In silico vs. in vivo





IN SILICO VS. IN VIVO



A, The magnitude profiles of eight channels on one axial slice of the Louis model (first and second rows) and in vivo experiment (third and fourth rows).

B, phase profiles relative to the first channel.

C, the absolute magnitude and, **D**, phase difference between the Louis model and in vivo.

In both simulation and experiment, each coil element fed with peak 65.5 V forward voltage.

IN SILICO VS. IN VIVO

	B_1^+ Mean (Hz)	B_1^+ Std (Hz)	B_1^+ Std/Mean %	Peak Forward Power (W)	RF efficiency (Hz/$\sqrt{W}$)
A: With B_1^+ inhomogeneity in cost function					
Hanako (3.14 L)	487.5	69.2	14.2	1920.84	11.12
Ella (3.20 L)	488.3	66.6	13.6	1922.79	11.14
Duke (3.75 L)	473.8	64.2	13.6	1936.00	10.77
Louis (3.28 L)	490.9	64.2	13.1	1781.28	11.63
Mean simulated	485.1±7.7	66.0±2.4	13.6±0.4	1890.2±72.9	11.16±0.35
in vivo (n = 8)	472.7±4.3	49.37±7.34	10.5±1.5	1723±104	11.39
B: Excluding B_1^+ inhomogeneity in cost function					
Hanako	475.1	94.0	19.8	1705.6	11.50
Ella	475.5	80.7	17.0	1782.8	11.26
Duke	472.9	81.5	17.2	1824.4	11.07
Louis	482.7	78.0	16.1	1716.4	11.65
Mean simulated	476.6±4.3	83.6±7.1	17.5±1.6	1757.3±56.3	11.36±0.26
C: Optimizing the user-tunable 32 tuning and matching capacitors on the "fixed" transceiver T_0					
Hanako	487.2	73.3	15.1	1846.11	11.34
Ella	486.2	65.3	13.4	1931.0	11.06
Duke	484.9	66.9	13.8	1915.7	11.08
Louis	490.9	64.3	13.1	1748.2	11.74
Mean simulated	487.3±2.6	67.4±4.0	13.9±0.9	1860.3±83.3	11.31±0.32

DISCUSSION

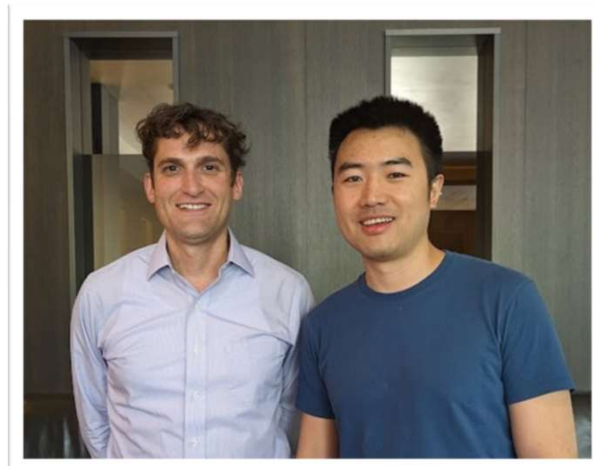
- B_1 agreement is a convenient figure of merit for the accuracy of the EM simulation, since B_1 is empirically measurable

- The optimization must consider the capacitor, inductor, and coupling coefficient values of:
  - Coil segmentation capacitors
  - Coil matching circuits
  - Decoupling circuits (inductive and resonant)

ACKNOWLEDGMENTS

<u>Colleagues</u>

- **Xin (Jack) Li**
- Nikolai Avdievich
- Jullie Pan
- Hoby Hetherington



<u>Funding</u>

- NIH R01EB024408

<u>Publications</u>

- Li, Pan, Avdievich, Hetherington, Rispoli. *MRM* 2021. doi: 10.1002/mrm.28672
- Li, Gong, Pan, Hetherington, Rispoli. *Proc. 2019 IEEE ICEAA*. doi: 10.1109/iceaa.2019.8879006