Vincenzo Miranda

Design of High-Permittivity Materials for High-Field Magnetic Resonance Imaging

Tutor: Prof. Giuseppe Ruello

Cycle: XXXVIII

Year: Third

Candidate’s information

- **MSc degree**: Biomedical Engineering, Medical Devices
- **Research Group**: Numerical Antennas Laboratory, DIETI
- **Ph.D. Start and end**: 1/11/2022 - 31/10/2025
- **Scholarship type**: PNRR - DM 351 Public Administration
- **Periods abroad**: Radiology Department, New York University
- **Periods in company**: Istituto Nazionale Tumori “Fondazione G. Pascale”

Summary of study activities

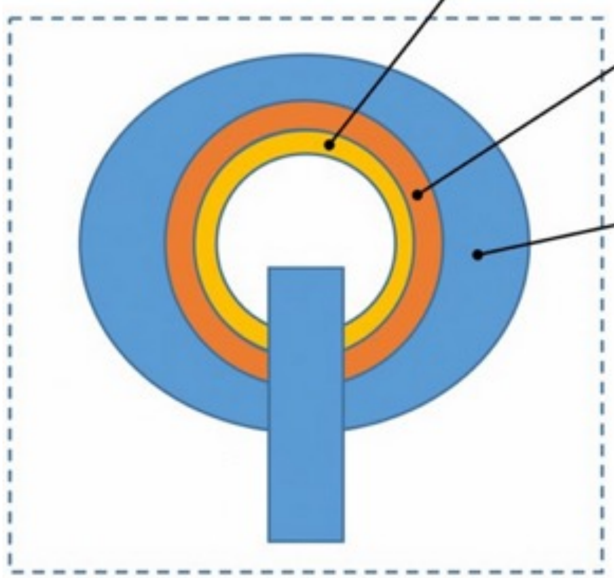
Courses	Seminars	Conference/Workshop
How to boost your Ph.D.	Electromagnetic Characterization of Coatings and Structured Surfaces for Particle Accelerators	Ricerca e formazione nella società della transizione digitale
Statistical Data Analysis for Science and Engineering Research	Dagli acceleratori di particelle alla musica digitale	CBI Science Day NYU
Electrodynamics of continuous media	Finite element software for electroporation techniques	University Federico II a New York 800 years of culture and innovation, Cornell University
Radiofrequency ablations in liver surgery: a multidisciplinary point of view	Algorithm Unrolling: Efficient, Interpretable Deep Learning for Signal and Image Processing	Bioelectromagnetic (BioEM) 2024 conference
Matrix Analysis for Signal Processing with MATLAB Examples	Insights into the Design of Transmit and Receive Coils for Ultra-High Field MRI	Ph.D. School: Surface Electromagnetics

Summary of study activities

Courses	Seminars	Conference/Workshop
Numerical methods for thermal analysis, modeling, and simulation: application to electronic devices and systems	Electric Regularized Maxwell Equations with Singularities (ERMES)	
Tecniche Elettromagnetiche in Neuroscienze	Some aspects of virtual medicine and human space science research	
Official type B tutoring activities (Fisica generale I e II)	High-Field Magnetic Resonance Imaging: Electromagnetic compatibility and optimization	
Ph.D. School Surface Electromagnetics	Myelin Mapping in the brain's white matter with multicomponent MRI signals	

Research area(s)

Electromagnetic efficiency and safety in high field magnetic resonance imaging ($\geq 3T$)



- SNR proportional to the static magnetic field

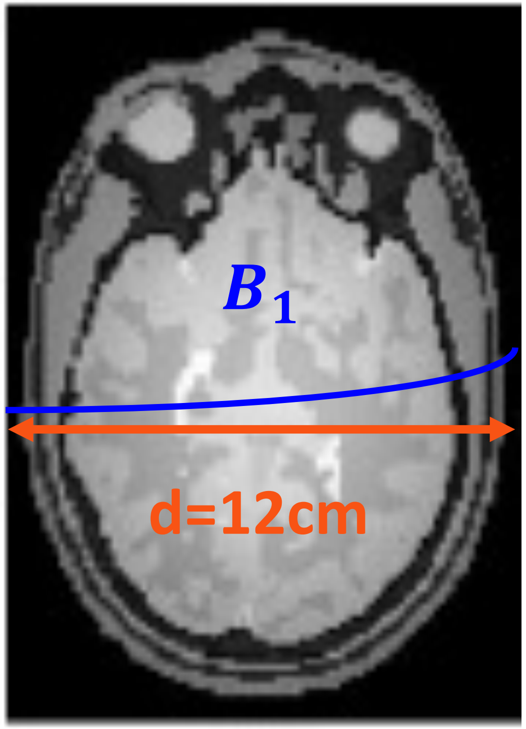
$$\text{SNR} \propto \text{B}_0$$

- Larmor Frequency for RF coils

$$f_0 = \gamma \text{B}_0$$

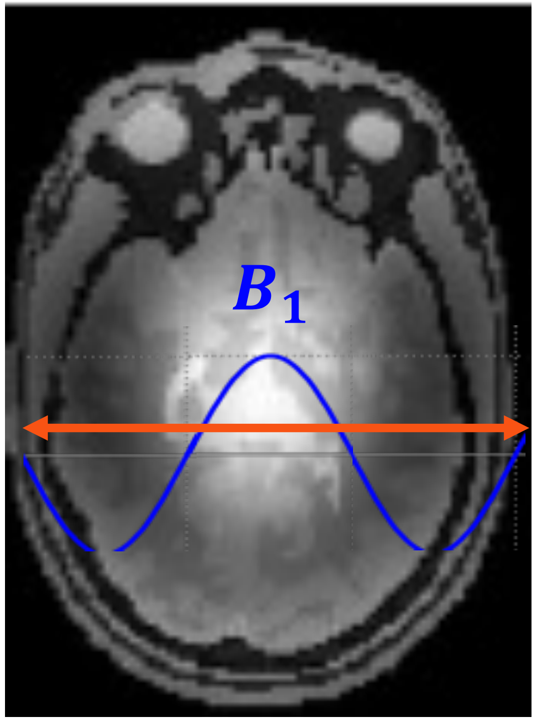
Research Problem: RF Field Control

$B_0 = 1.5T\ (64\ MHz)$



$\lambda_0 = 4.7m$

$B_0 = 7T\ (300\ MHz)$



$\lambda_0 = 1m$

– Free space Wavelength $\lambda_0\ [m]$

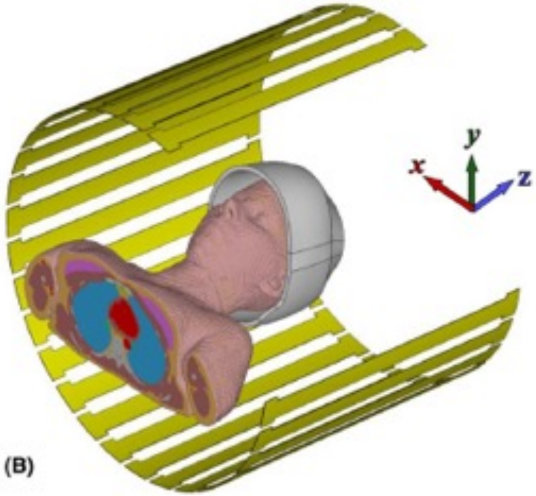
- Head Size d [m]
- RF Field $B_1\ [\mu T]$

Webb, A. G. (2011). Dielectric materials in magnetic resonance. Concepts in Magnetic Resonance Part A, 38A(4), 148–184. https://doi.org/10.1002/cmr.a.20219

Research Problem: High Permittivity Materials

What are **H**igh-**P**ermittivity **M**aterials (**HPMs**), and in what ways are they employed in **MRI**?

(A)

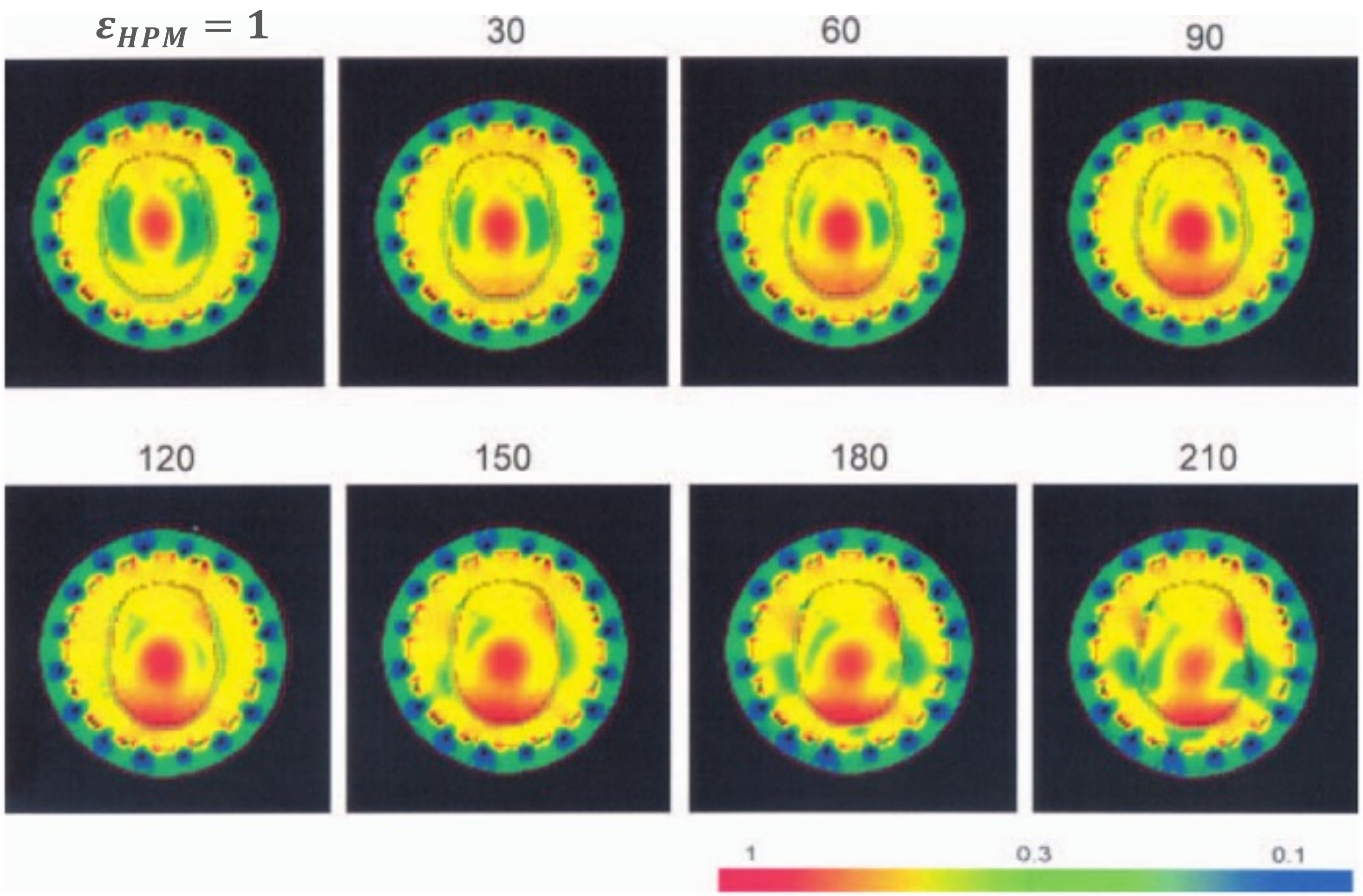


(B)

Sica, C. T., Rupprecht, S., Hou, R. J., Lanagan, M. T., Gandji, N. P., Lanagan, M. T., & Yang, Q. X. (2020). Toward whole-cortex enhancement with an ultrahigh dielectric constant helmet at 3T. Magnetic Resonance in Medicine, 83(3), 1123–1134. https://doi.org/10.1002/mrm.27962

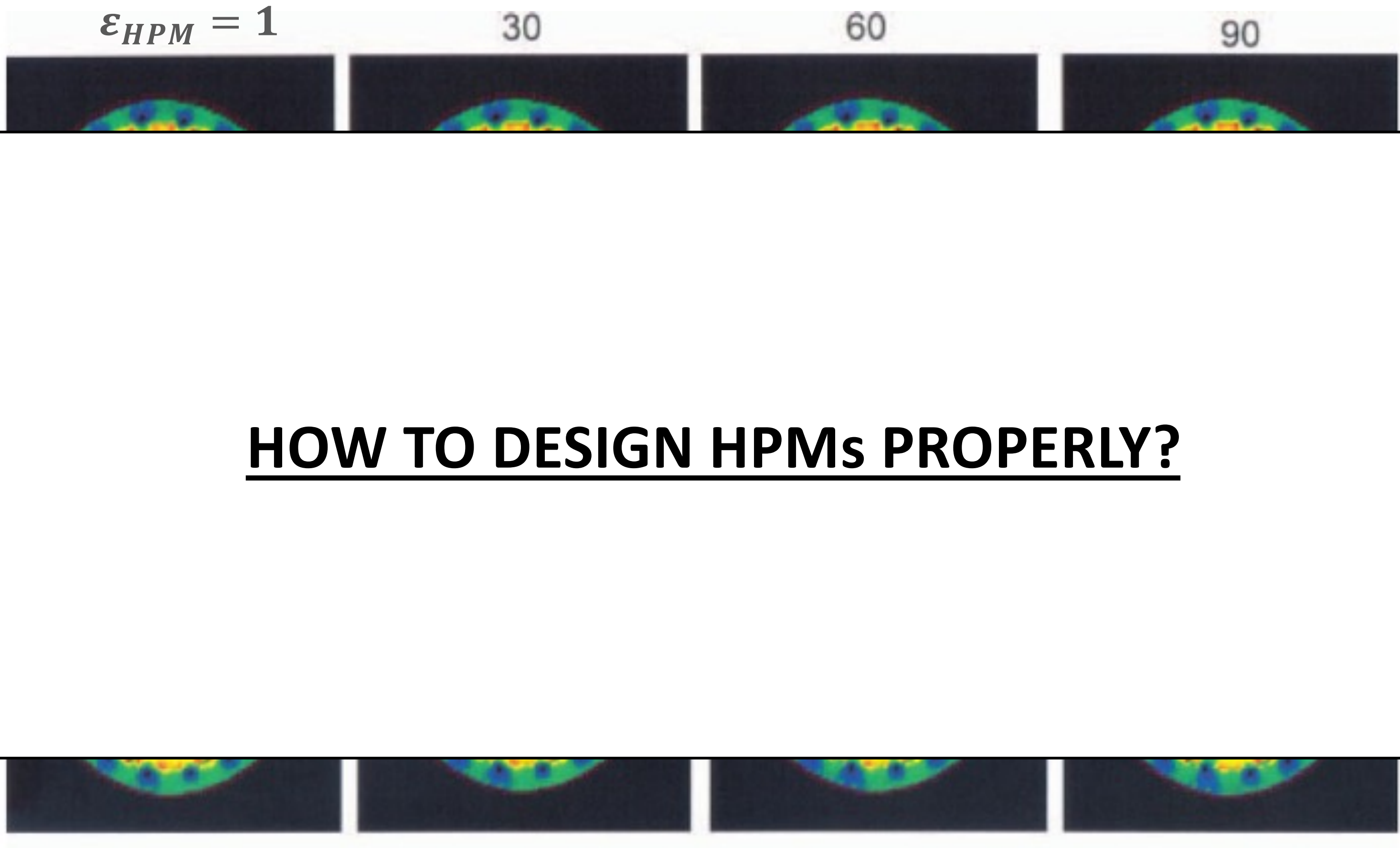
Research Problem: High Permittivity Materials

$$\frac{|B_1|}{|B_1|_{max}}$$



Teeuwisse, W. M., Brink, W. M., & Webb, A. G. (2012). *Quantitative assessment of the effects of high-permittivity pads in 7 Tesla MRI of the brain. Magnetic Resonance in Medicine, 67*(5), 1285–1293. https://doi.org/10.1002/mrm.23108

Research Problem: High Permittivity Materials (HPMs)



HOW TO DESIGN HPMs PROPERLY?

Teeuwisse, W. M., Brink, W. M., & Webb, A. G. (2012). *Quantitative assessment of the effects of high-permittivity pads in 7 Tesla MRI of the brain. Magnetic Resonance in Medicine, 67*(5), 1285–1293. https://doi.org/10.1002/mrm.23108

Research products

[P1]	V. Miranda, G. Ruello, R. Lattanzi, A theoretical framework to investigate the effect of high permittivity materials in MRI using anatomy-mimicking cylinders, Magnetic Resonance in Medicine, vol. 92 (1), pp. 416–429, 2024, DOI: 10.1002/mrm.30063
[P2]	V. Miranda, D. Riccio, G. Ruello, R. Lattanzi, A novel electromagnetic method to interpret scattering suppression from spheres, Proc. Metamaterials 2023, 2023, DOI: 10.1109/Metamaterials58257.2023.10289295.
[P3]	G. Carluccio, C. M. Collins, R. Lattanzi, V. Miranda, D. Riccio, G. Ruello, An analytical and numerical approach to investigate the role of high permittivity materials in MRI, URSI GASS 2023, DOI: 10.23919/URSIGASS56706.2023.10289315.
[P4]	G. Carluccio, C. M. Collins, R. Lattanzi, V. Miranda, D. Riccio, G. Ruello, An analytical solution to investigate the impact of an insulating layer with high permittivity materials in MRI applications, ICEAA 2023, DOI: 10.1109/ICEAA57318.2023.10297874.
[P5]	G. Carluccio, V. Miranda, C. M. Collins, D. Riccio, G. Ruello, Optimum high-permittivity materials with parallel imaging applications in MRI, Xpress Conference on Electromagnetics in Advanced Applications, 2024.

Research products

[P6]	G. Carluccio, C. M. Collins, D. Riccio, V. Miranda, G. Ruello, Numerical optimization of a 3D multilayer dielectric geometry for MRI applications, USNC-URSI NRSM 2025, ISBN: 978-1-946815-20-0.
[P7]	V. Miranda, R. Lattanzi, D. Riccio, G. Ruello, Analytical model for RF propagation in layered spheres: use of high permittivity materials in ultra-high field magnetic resonance of the brain, Proc. BioEM Conference, 2024.
[P8]	V. Miranda, G. Carluccio, R. Lattanzi, D. Riccio, G. Ruello, Magnetic Resonance Imaging of the Brain: Impact of Heterogeneous Head Model on the Analytical Design of High Permittivity Materials, Proc. BioEM Conference, 2025.
[P9]	V. Miranda, D. Riccio, G. Ruello, R. Lattanzi, A physical framework to investigate scattering suppression from coated spheres, FERMAT, 2022.

PhD thesis overview

Problem statement

- A solid physical explanation of the improvements is lacking.
- Time-consuming numerical simulations.

Objective

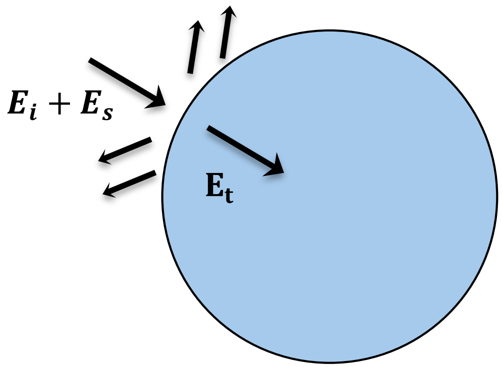
- Investigate the mechanism behind MRI improvements
- Provide a design tool to guide numerical simulations.

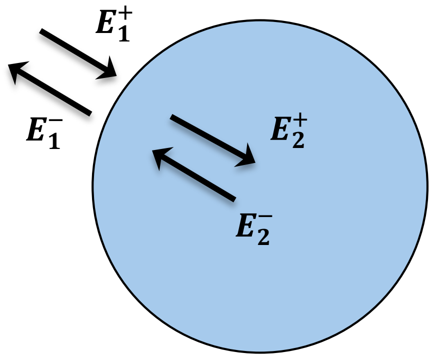
Methodology:

- New analytical scattering framework to mimic MRI experiments and study HPMs design.

Methodology

Mie Classical Theory | **New Framework**

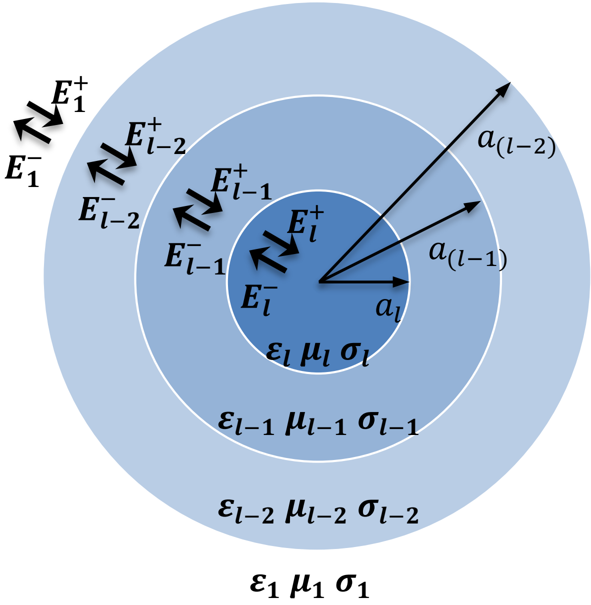


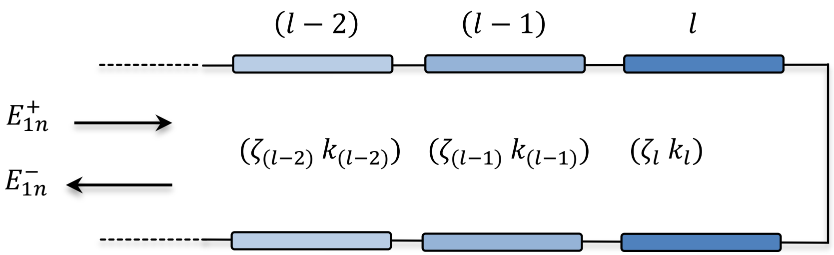


$$\boldsymbol{E}_l(r) = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} E_{lnm}^{+} \boldsymbol{M}_{nm}^{(3)} + E_{lnm}^{-} \boldsymbol{M}_{nm}^{(4)}$$

$$\boldsymbol{H}_l(r) = \frac{k_l}{i\omega\mu_l} \sum_{n=1}^{\infty} \sum_{m=-n}^{n} E_{lnm}^{+} \boldsymbol{N}_{nm}^{(3)} + E_{lnm}^{-} \boldsymbol{N}_{nm}^{(4)}$$

Methodology





Mie Scattering Coefficients

$$c_{mn} = -a_{mn}\frac{j_n'(k_1a)j_n(k_2a) - \chi j_n(k_1a)j_n'(k_2a)}{h_n^{(1)\prime}(k_1a)j_n(k_2a) - \chi h_n^{(1)}(k_1a)j_n'(k_2a)}$$

$$d_{mn} = -b_{mn}\frac{j_n(k_1a)j_n'(k_2a) - \chi j_n'(k_1a)j_n(k_2a)}{h_n^{(1)}(k_1a)j_n'(k_2a) - \chi h_n^{(1)\prime}(k_1a)j_n(k_2a)}$$

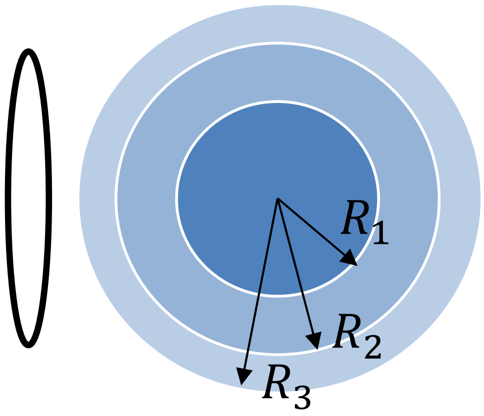
New Framework Coefficients

$$E_{1nm}^{-\text{TE}} = E_{1nm}^{+\text{TE}}\ \Gamma_{1n}^{\text{TE}}(k_1a)\frac{h_n^{(1)\prime}(k_1a)}{h_n^{(2)\prime}(k_1a)}$$

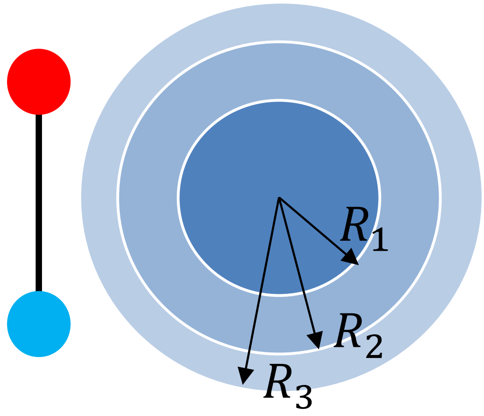
$$E_{1nm}^{-\text{TM}} = E_{1nm}^{+\text{TM}}\ \Gamma_{1n}^{\text{TM}}(k_1a)\frac{h_n^{(1)}(k_1a)}{h_n^{(2)}(k_1a)}$$

Methodology

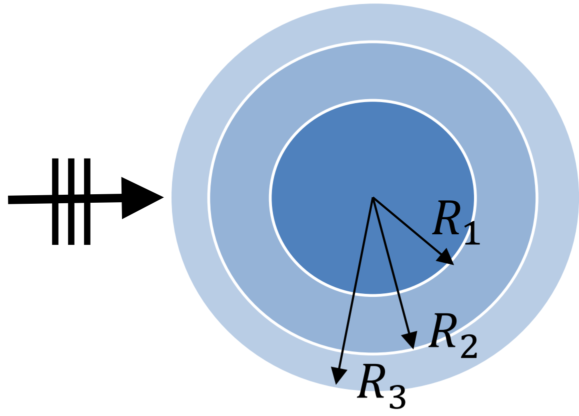
Loop Coil



Electric Dipole



Plane Wave

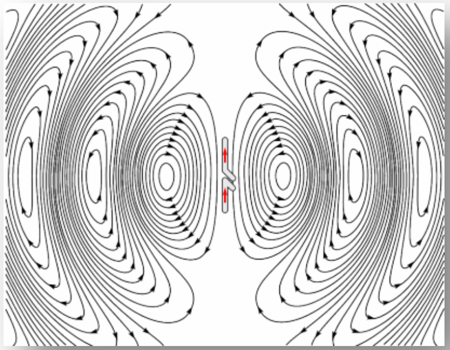


Keltner, J. R., Carlson, J. W., Roos, M. S., Wong, S. T. S., Wong, T. L., & Budinger, T. F. (1991). *Electromagnetic fields of surface coil in vivo NMR at high frequencies. Magnetic Resonance in Medicine, 22*(3), 467–480. https://doi.org/10.1002/mrm.1910220303

Ruppin, R. (1982). Decay of an excited molecule near a small metal sphere. The Journal of Chemical Physics, 76(4), 1681–1684. https://doi.org/10.1063/1.443196

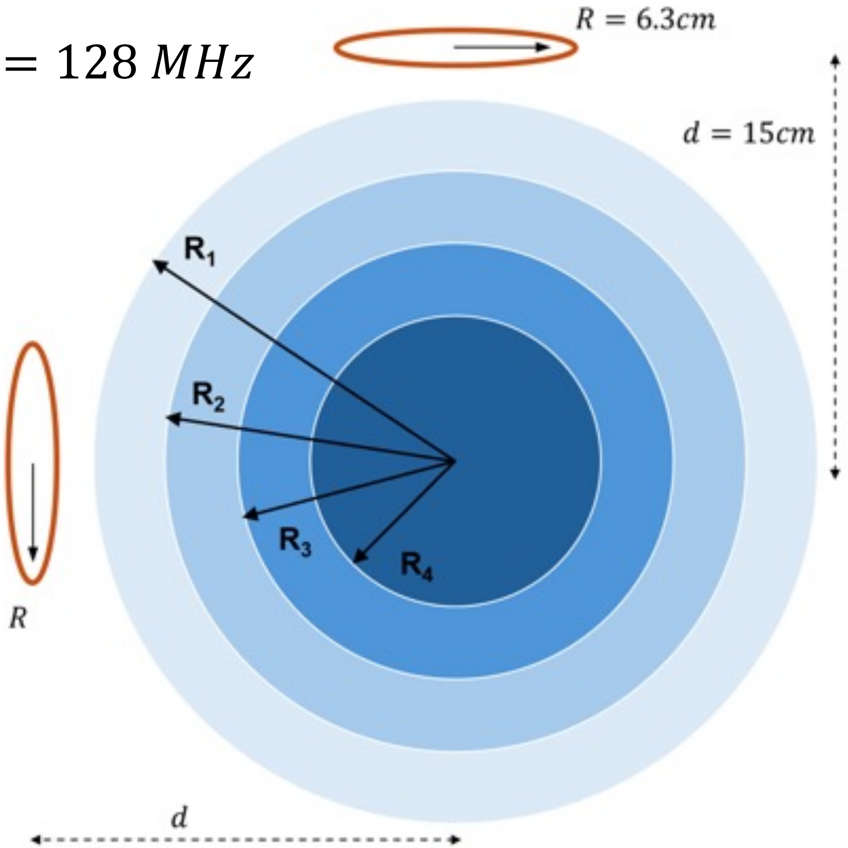
Summary of Results

1. **Numerical Validation of the Proposed Framework**
2. Application of the Model to Investigate HPMs in MRI
3. Numerical-Analytical Design of a HPM Helmet
4. Experimental Result in a 7T Scanner



Numerical Validation

$f_0 = 128\ MHz$



Region #1

R1 =12 cm
Epsilon R = 30
Sigma = 0.3 (S/m)

Region #2

R2 =10 cm
Epsilon R = 40
Sigma = 0.35 (S/m)

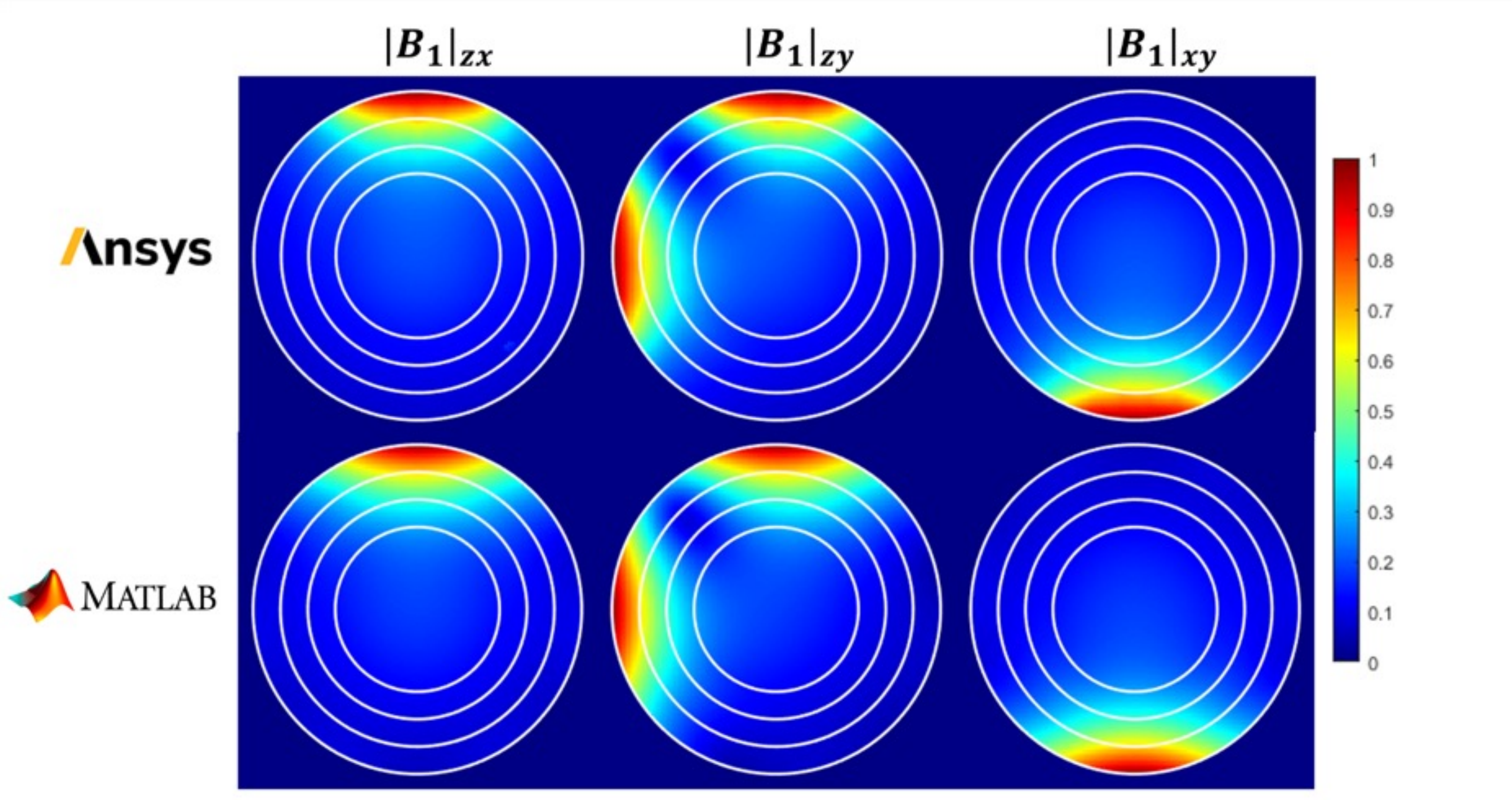
Region #3

R3 = 8 cm
Epsilon R = 20
Sigma = 0.25 (S/m)

Region #4

R4 = 6 cm
Epsilon R = 60
Sigma = 0.45 (S/m)

Numerical Validation



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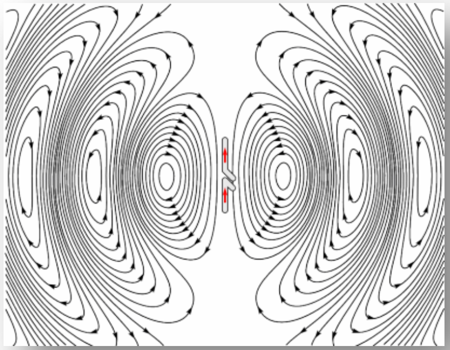
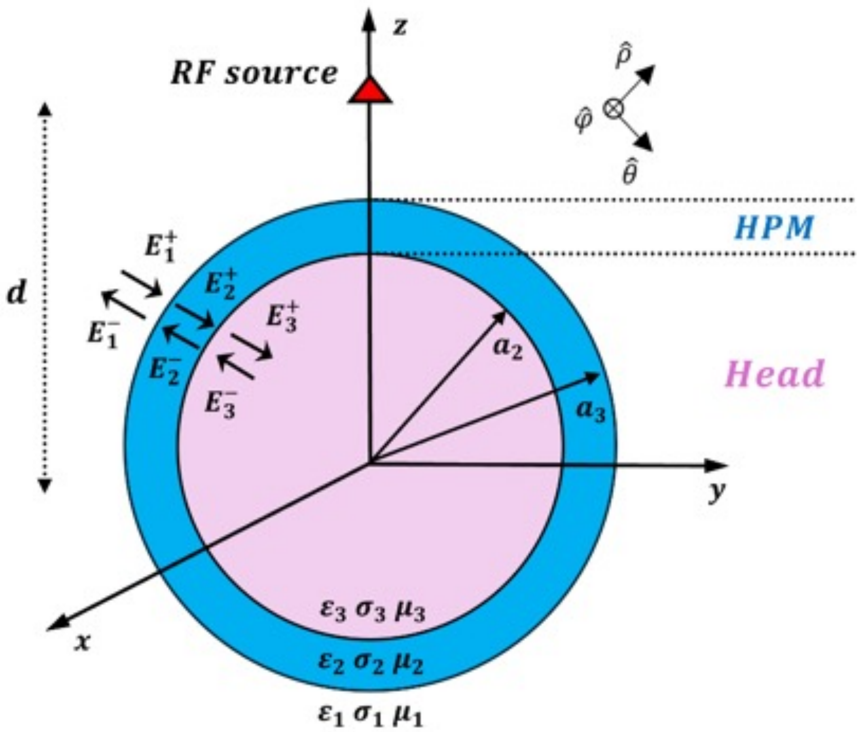


Simulation Steup

- *Foundamental Mode Analysis (n=1)*
- *Observation point placed at the sphere center ($\rho = 0\ cm$)*
- *Larmor Frequency $f_0 = 297.2\ MHz\ \ (7T\ Scanner)$*



Region #1 (HPM)

R1 =1 cm

Epsilon HPM = ???

Sigma = 0.01 (S/m)

Region #2 (HEAD)

R2 = 9 cm

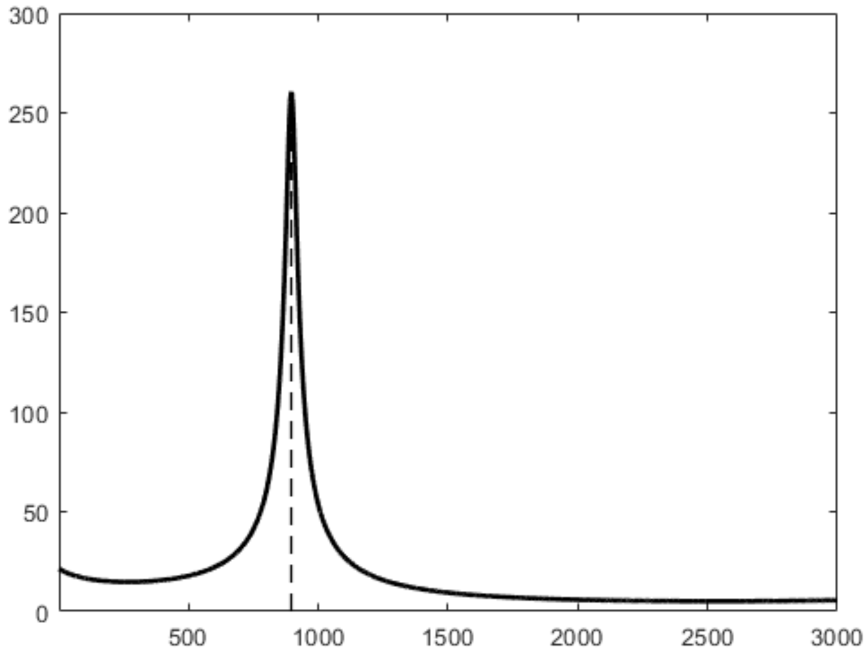
Epsilon = 50

Sigma = 0.5 (S/m)

itee PhD information technology electrical engineering

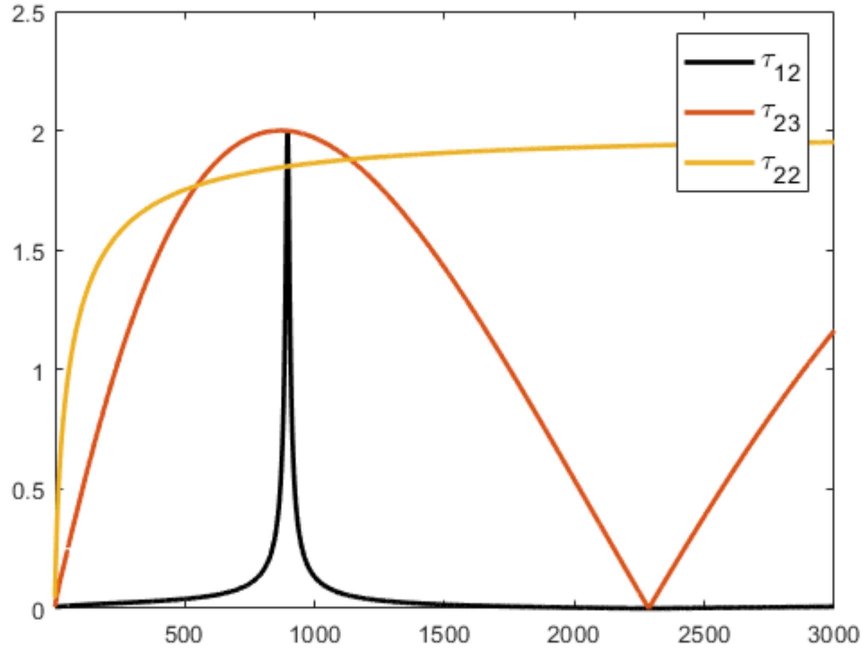
PhD thesis: Results 1

$|B_1|\ [\mu T]$



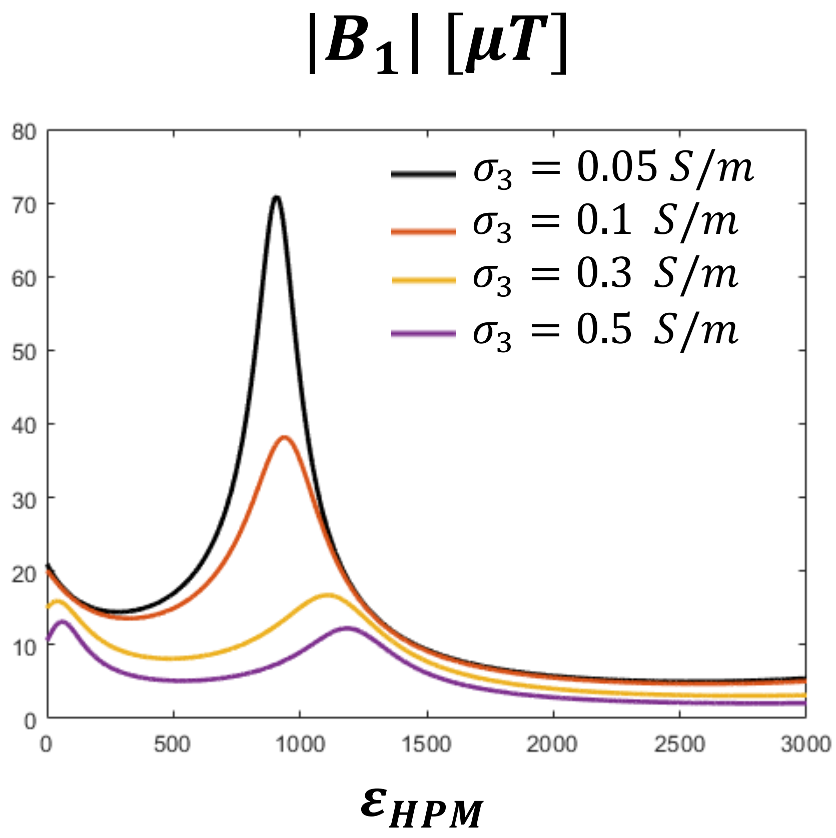
ε_{HPM}

$Reflection\ Coefficients$



ε_{HPM}

PhD thesis: Results 2



Optimal Permittivity Value ε_r^{opt}

TE Mode	$\varepsilon_{r,\,128\,\mathrm{MHz}}^{\mathrm{opt}}$	$\varepsilon_{r,\,297\,\mathrm{MHz}}^{\mathrm{opt}}$	$\varepsilon_{r,\,447\,\mathrm{MHz}}^{\mathrm{opt}}$
1	245	65/1190	31/538/2042
2	494	71/1236	52/561/2053
3	756	123/1338	55/567/2060

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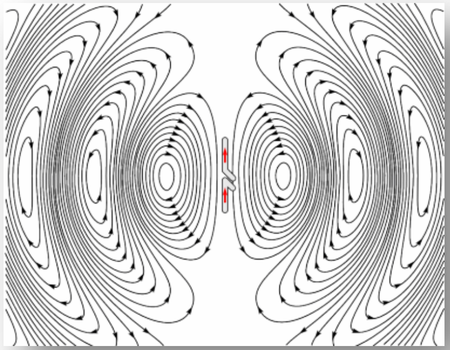
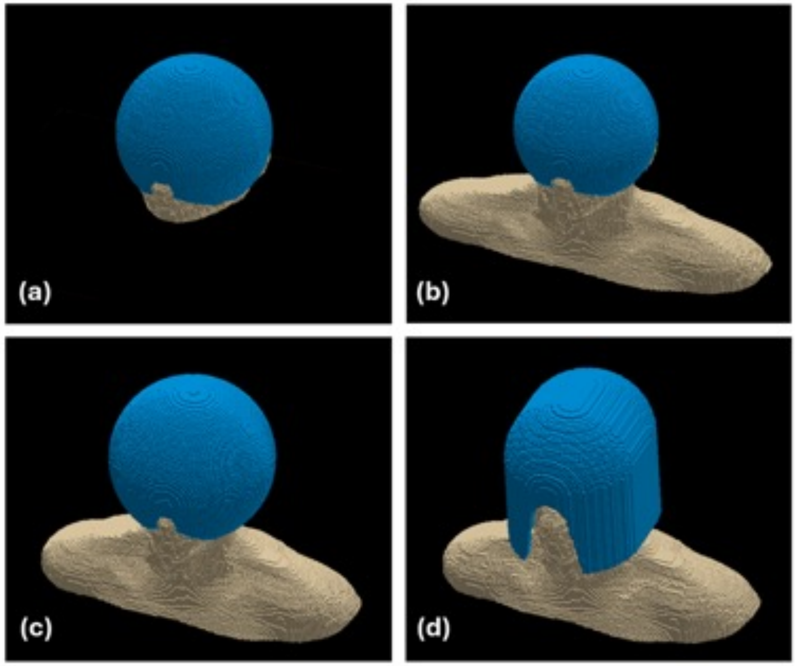
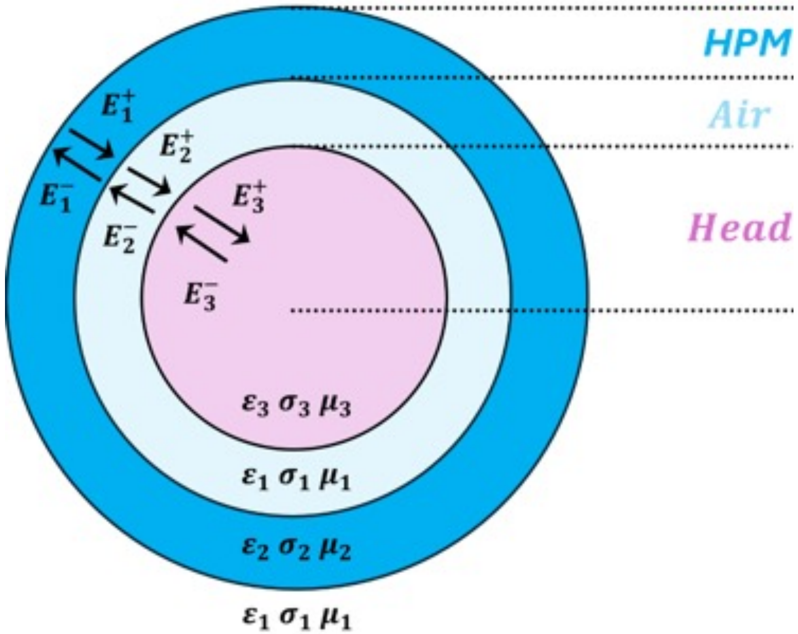


Numerical-Analytical Design of a HPM Helmet

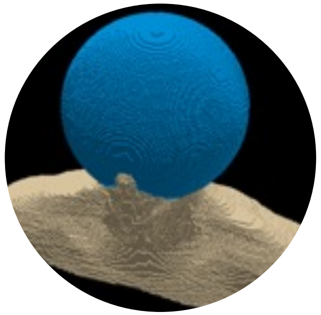
Numerical Setup



Theoretical Setup

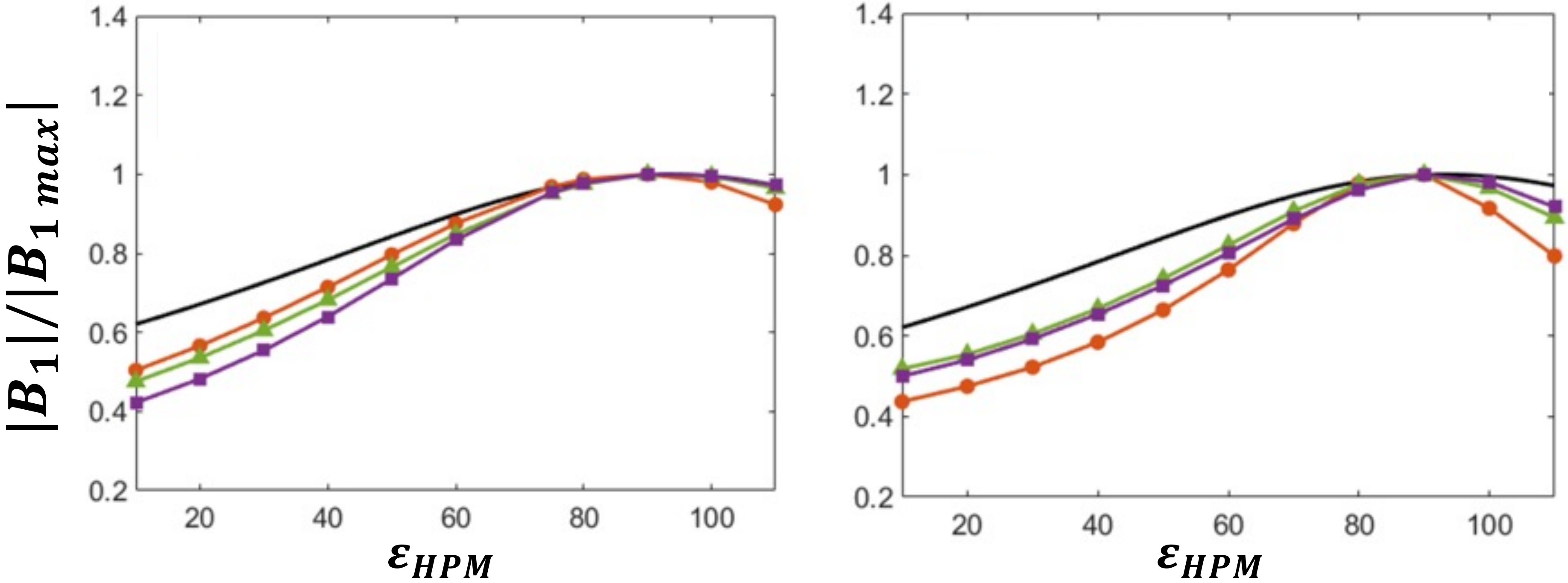


Numerical-Analytical Design of a HPM Helmet



Theoretical Model (10.5cm Head + 1cm Air)
Spherical Helmet
Spherical Helmet stretched Head
Spherical Helmet stretched Head Truncated

Loop-Loop Comparison ***Loop-Birdcage Comparison***



Numerical-Analytical Design of a HPM Helmet

Numerical

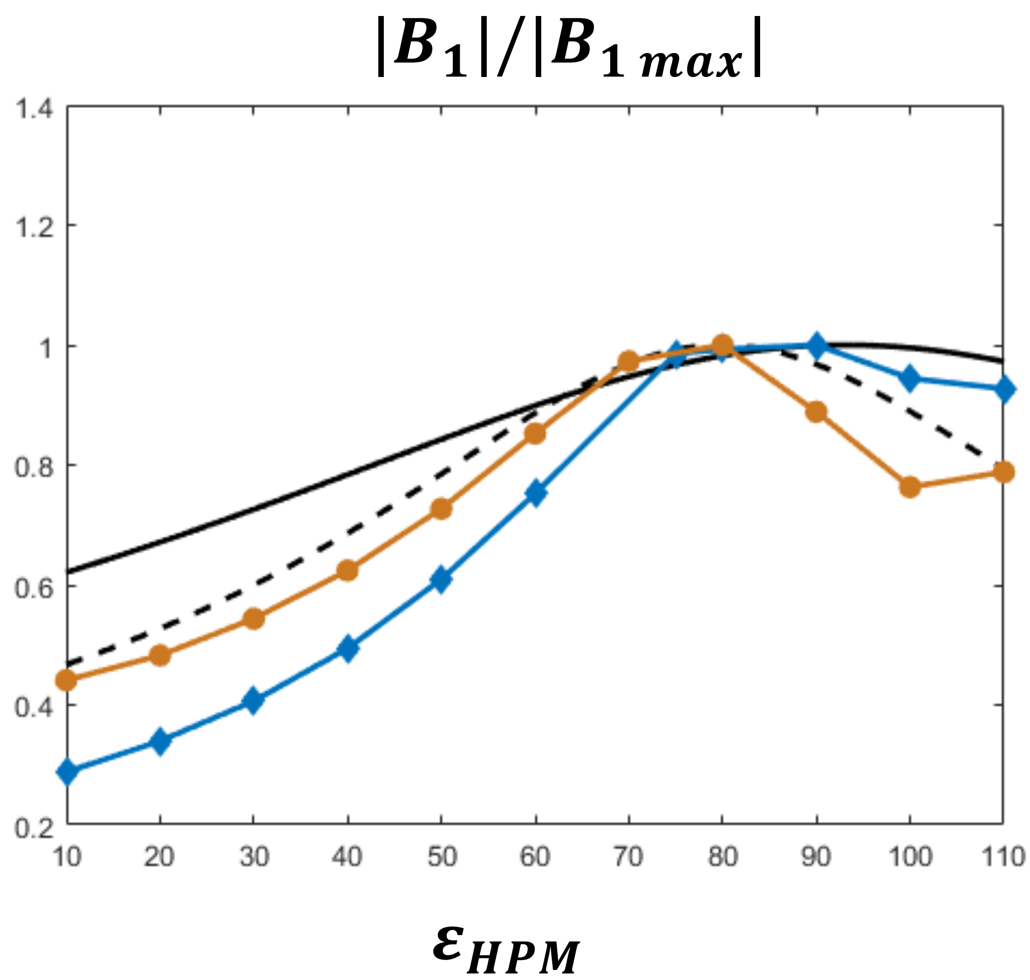
Loop Coil Real Helmet

Birdcage Real Helmet

Theoretical (Loop Only)

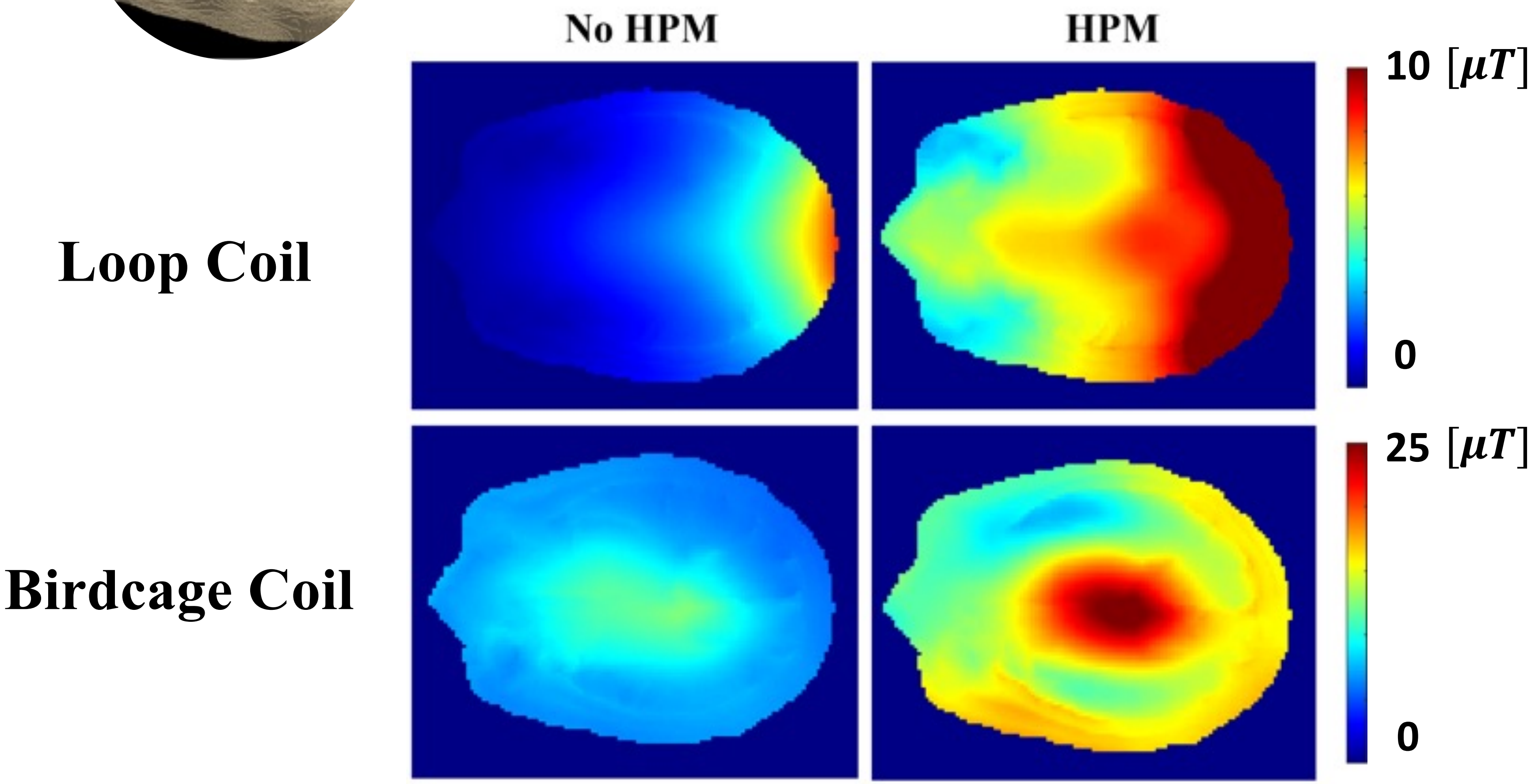
Head 10.5cm +1cm Air

Head 8.75cm +2.75cm Air



Numerical-Analytical Design of a HPM Helmet

$|B_1|$ $[\mu T]$



Comparison with prior Research

Study (year)	f [MHz]	Model/Test	Results	Present Work
Teewuisse et al., 2012	297.2	Duke (simulation) + in vivo	Pads horseshoe; ε_r^{opt} = 120–150	ε_r^{opt} = 130
Sica et al., 2020	128	Ella (simulation) + in vivo	UHDC helmet; ε_r^{opt} = 500–600 (supposed)	ε_r^{opt} = 450
Lakshmanan et al., 2021	297.2	Duke (simulation) + in vivo	Ceramic helmet; ε_r^{opt} = 107	ε_r^{opt} = 113
Gandji et al., 2021	447	Ella (simulation) + Phantom	Water-based HDC; ε_r^{opt} = 78	ε_r^{opt} = 70
Soon et al., 2024/25	297.2	Ella (simulation) + in vivo	Slurry helmet; ε_r^{opt} = 170	ε_r^{opt} = 160

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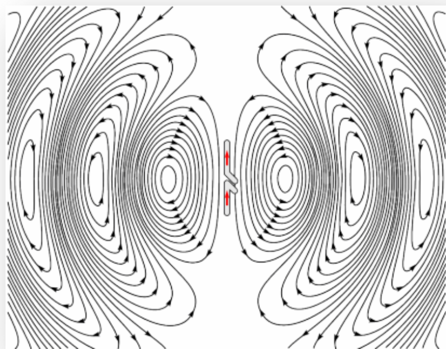


7T MRI Experiment: Phantom Exposure

Solid Head Phantom: 85% PVP 12mM + 15% NaCl 1.5M (R=3cm)

$\varepsilon_{r(297.2\ MHz)} = 48.9 \pm 0.8$ $\sigma_{(297.2\ MHz)} = 0.54 \pm 0.03\ \mathrm{S/m}$

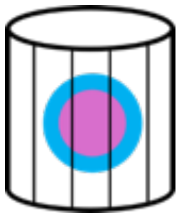
Solid HPM Shell: PVP 2mM (R=6cm)

$\varepsilon_{r(297.2\ MHz)} = 71.2 \pm 0.3$ $\sigma_{(297.2\ MHz)} = 0.08 \pm 0.02\ \mathrm{S/m}$

7T MRI Experiment: Phantom Exposure

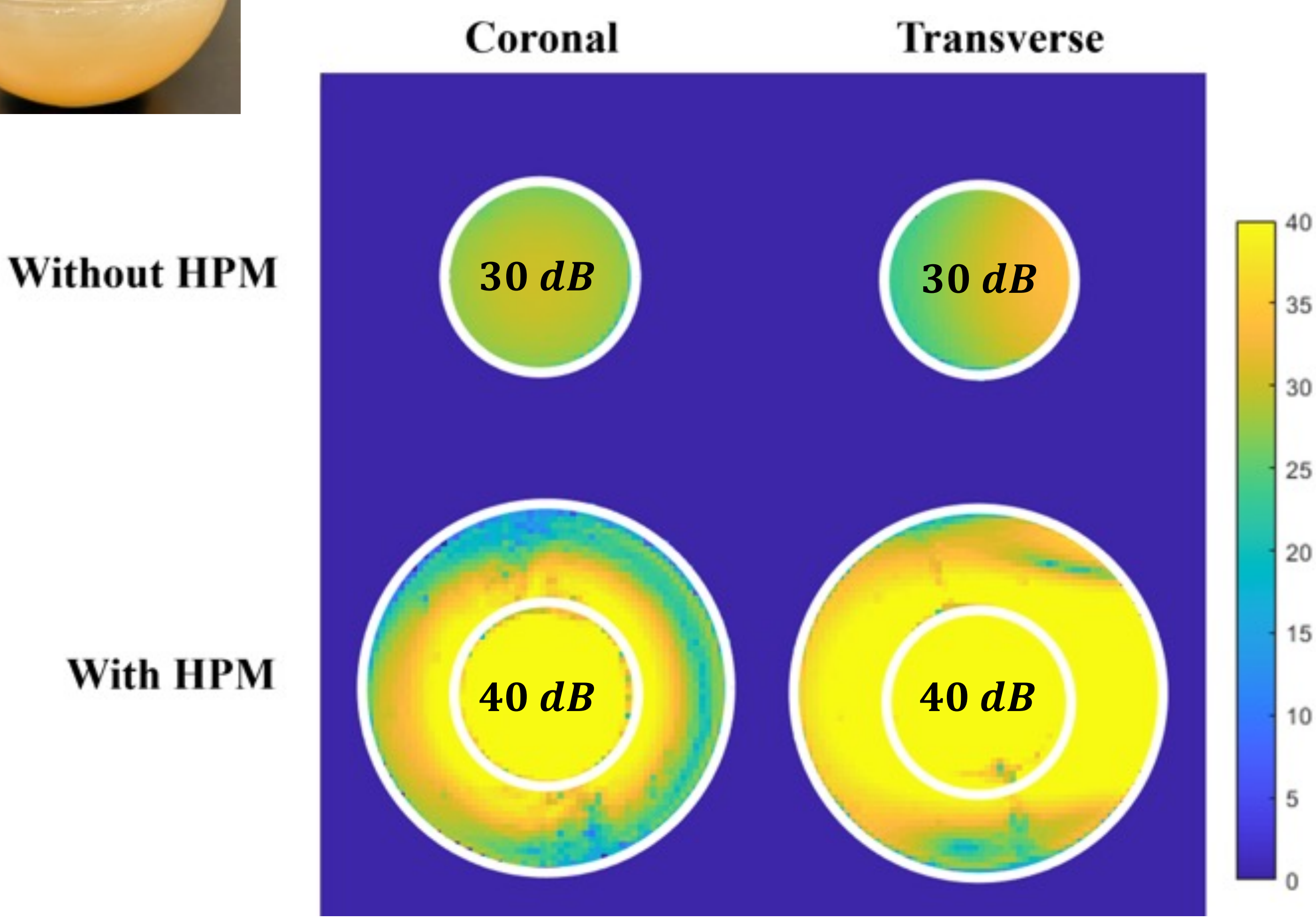
- *Scanning Sequence*: *Gradient Echo*
- *Acquisition type*: *2D*
- *Slice Thickness 2mm*
- $Repetition\ Time\ T_R = 1000\ ms$
- $Echo\ Time\ T_E = 2.47\ ms$
- $Voltage = [110\ V\ phantom;\ 300\ V\ HPM]$
- $RF\ pulse\ duration\ \tau = 10^{-3}\ s$

Birdcage Coil

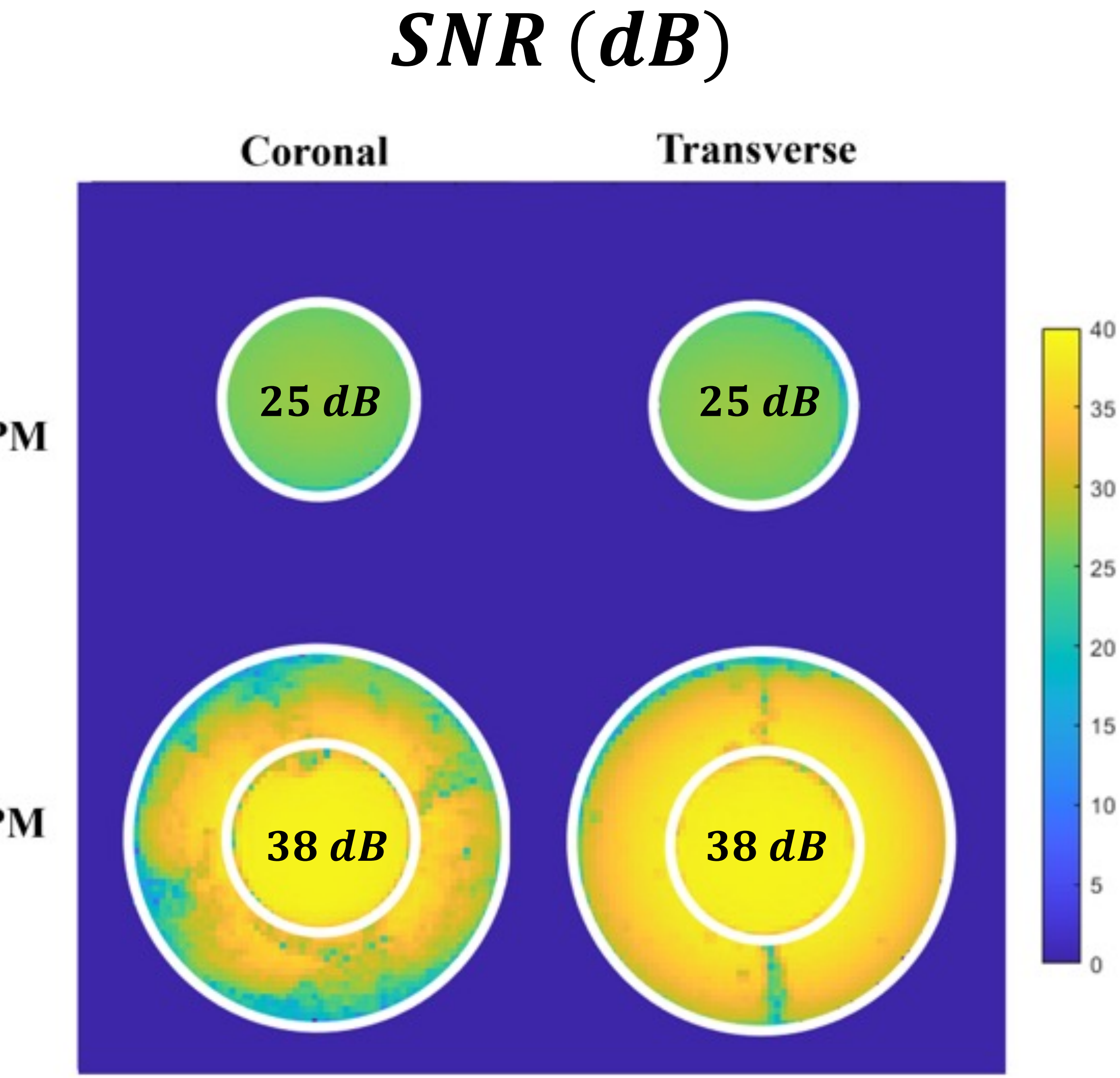


Loop Coil

7T MRI Experiment: Loop Coil Results



7T MRI Experiment: Birdcage Results



Conclusions

- Prediction of the optimal permittivity value for the design of spherical HPMs.
- The analytical tool can complement numerical simulations even in real MRI scenarios.

Future Perspectives

- Mitigate the low durability of HPMs over time.
- Verify the safety aspects for CE/FDA approval.
- Find a modal expansion for the birdcage coil.

Thank you for your attention!