Modeling Peripheral Nerve Stimulations (PNS) in Magnetic Resonance Imaging (MRI)

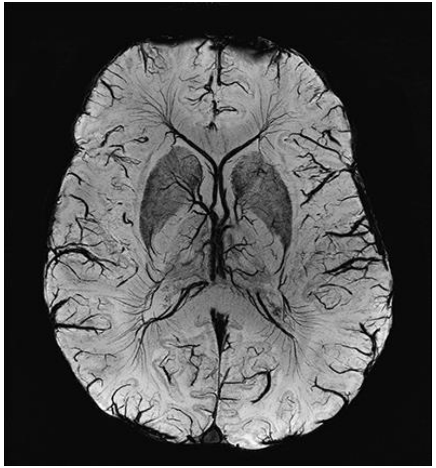
Mathias Davids

Instructor in Radiology, Harvard Medical School
Athinoula A. Martinos Center for Biomedical Imaging

Correspondence to **mathias.davids@mgh.harvard.edu**

Magnetic Resonance Imaging

- Medical imaging modality employing non-ionizing EM radiation
- MRI based on excitation of particle‘s spins and measuring spin signals for image formation
- Signal localization using so-called ***gradient coils***

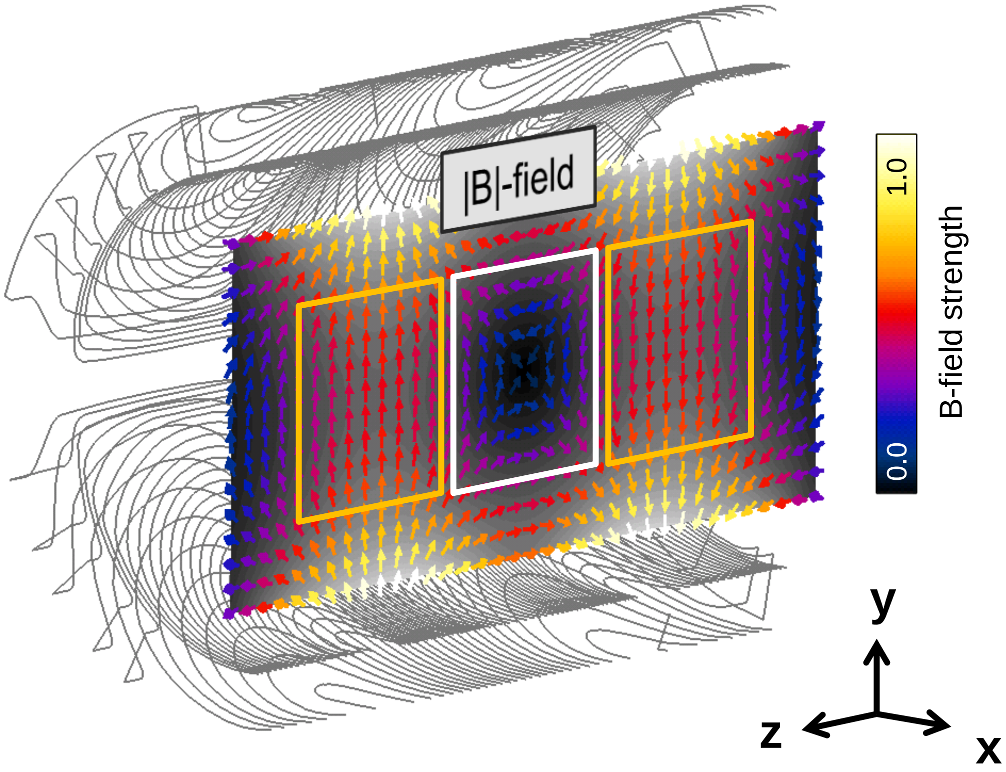


MRI gradient coils

- Create linear variation of $\mathbf{B}_z$ component
- ► **Localization of spin signal**

- **X**-gradient linear along **x**
- **Y**-gradient linear along **y**
- **Z**-gradient linear along **z**

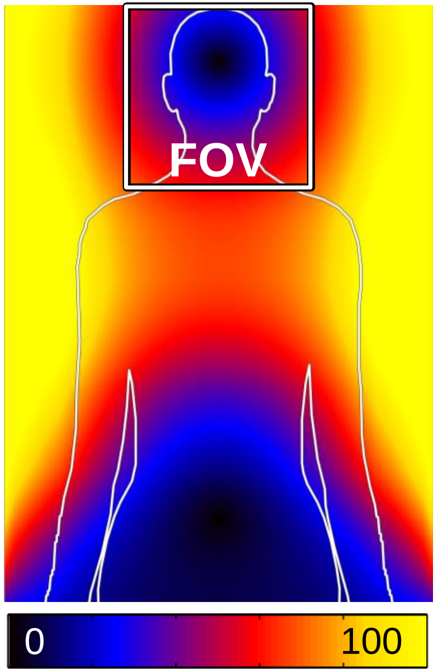
- Linearity requires large **B**-fields outside of the FOV



Magnetically induced PNS in MRI

- Rapid switching of gradient‘s B-fields induces E-fields strong enough to stimulate nerves

B-field magnitude

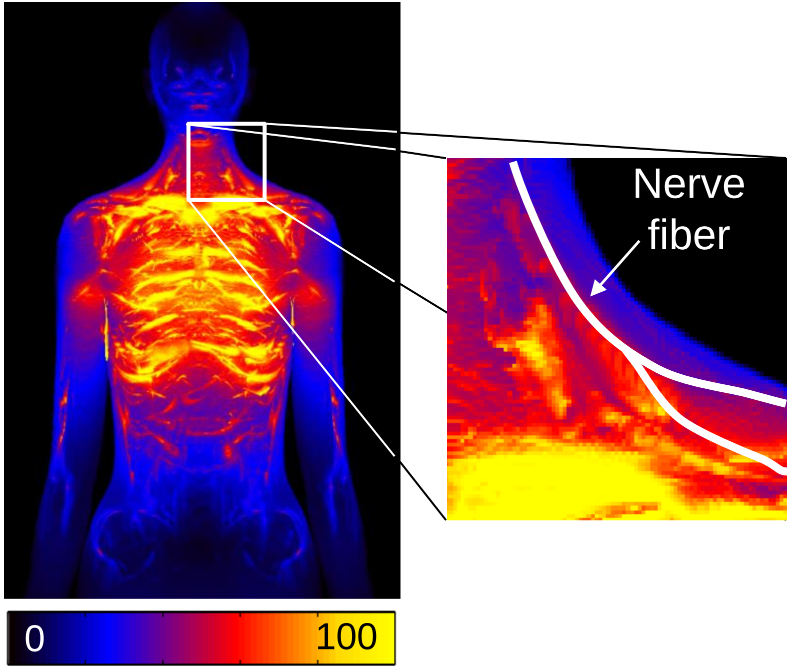


B-field magnitude [a.U.]

Faraday induction:

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

E-field magnitude



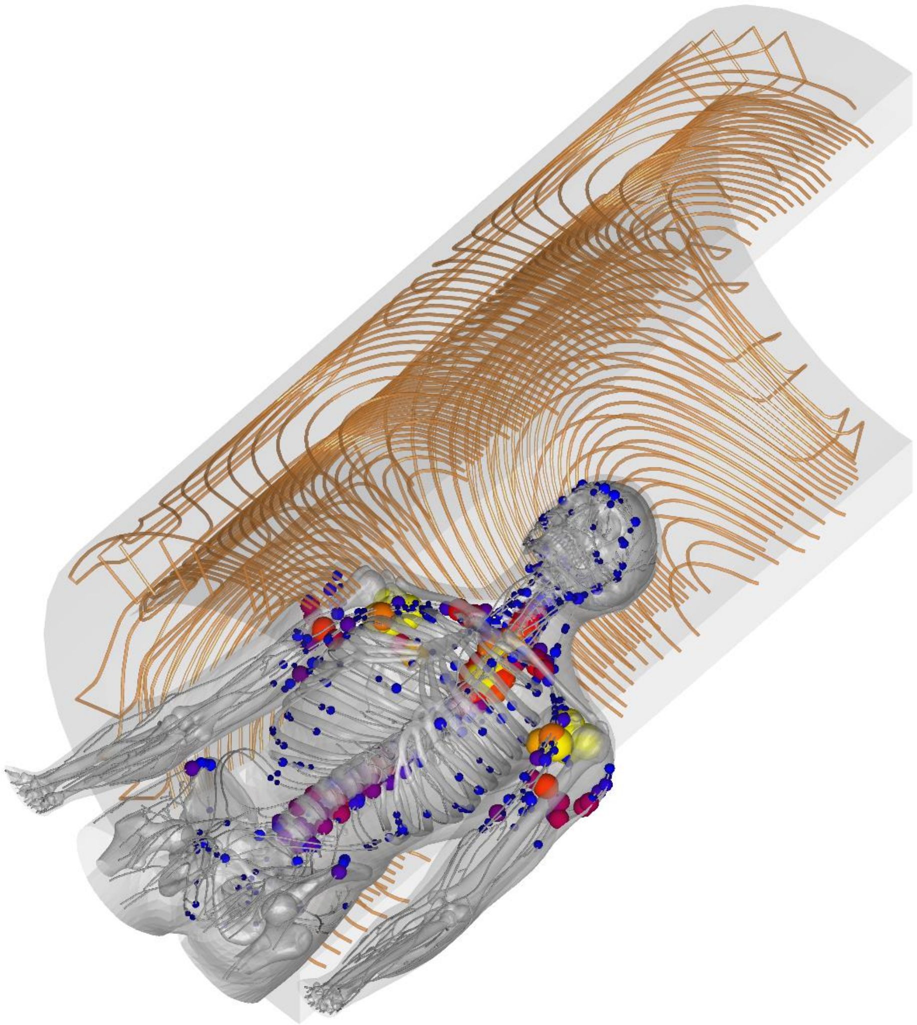
E-field magnitude [a.U.]

Peripheral Nerve Stimulation in MRI

- PNS has become a fundamental limitation in MRI
- PNS can render large portion of performance space unusable
- PNS is not directly addressed during the coil design phase

PNS modeling

- *Understand PNS: where, why, when?*
- *Predict thresholds and locations*
- *Compare different coil windings*
- *PNS constrained coil design*
- *Assess other mitigation techniques*



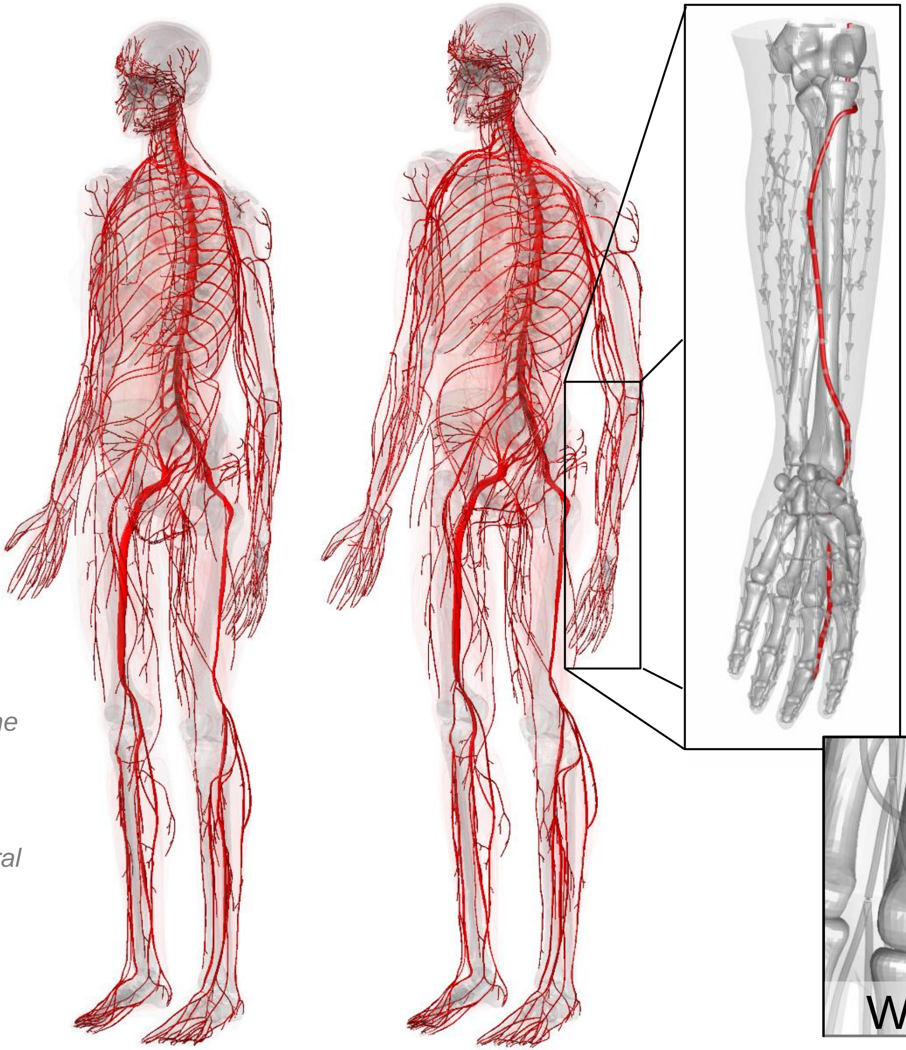
EM-neurodynamic simulations

Models of conductive tissues

- Very high spatial resolution (1 mm^3)
- Tissues labeled by dielectric properties (conductivity)

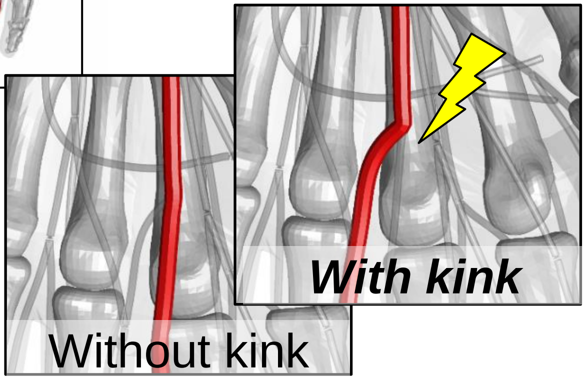
Davids et al. *“Predicting Magnetostimulation Thresholds in the Peripheral Nervous System using Realistic Body Models”*, Scientific Reports, 2017

Davids et al. *“Prediction of peripheral nerve stimulation thresholds of MRI gradient coils using coupled electromagnetic and neurodynamic simulations”*, MRM 2019

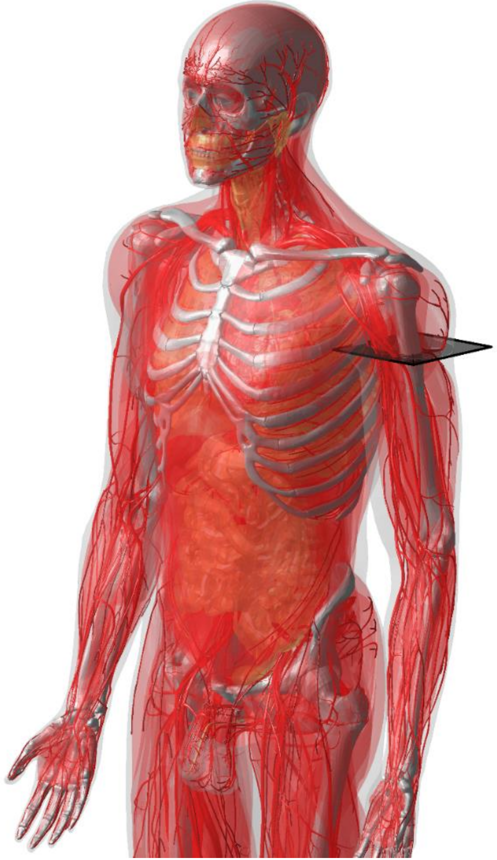


Nerve atlas for PNS modeling

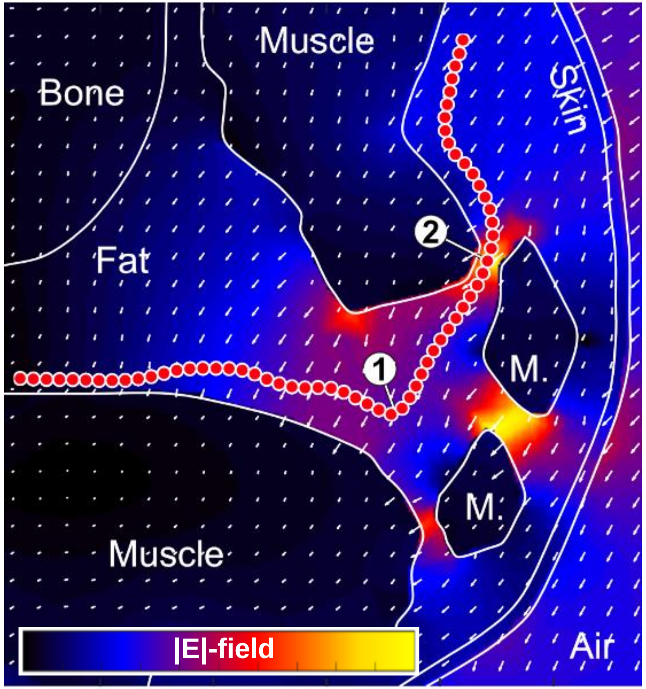
- ~2000 nerve segments labeled by local axon diameter
- Nerves embedded in correct tissue classes
- Correct definition of direction and branching points

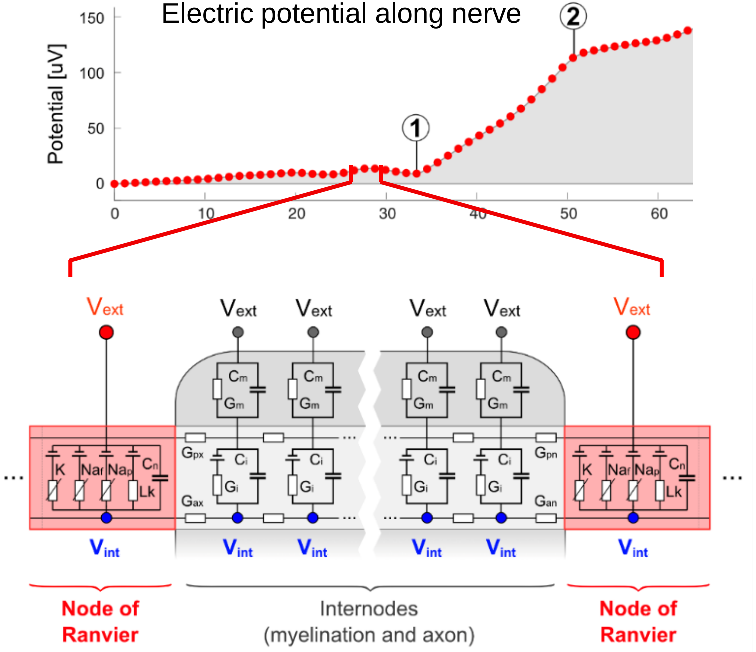


PNS modeling workflow



Electric field in male arm

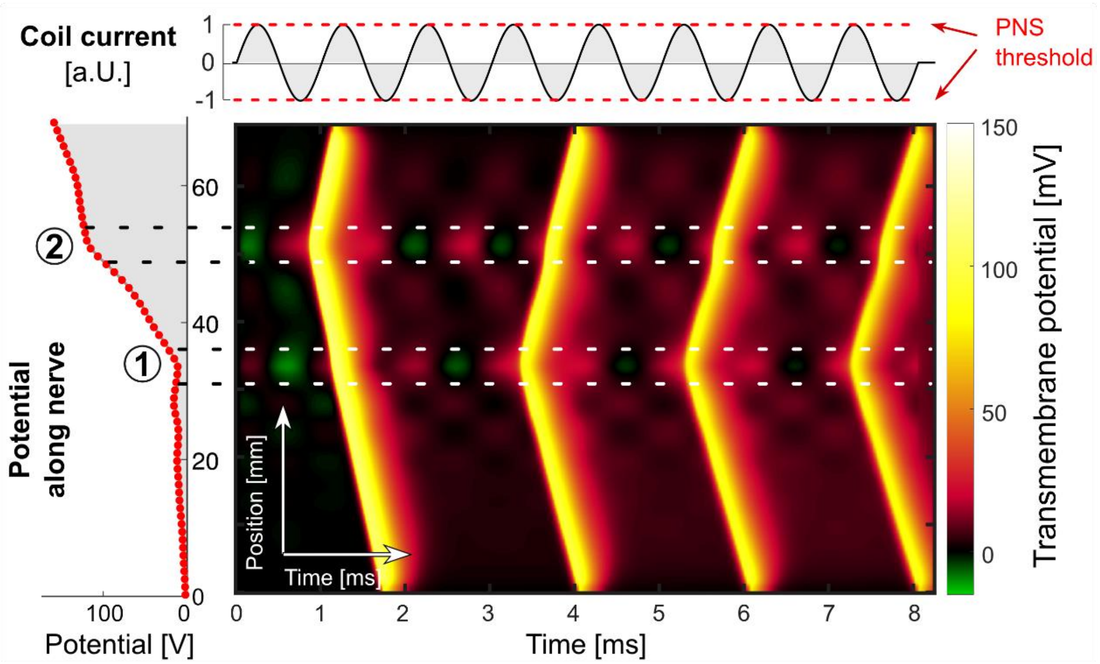




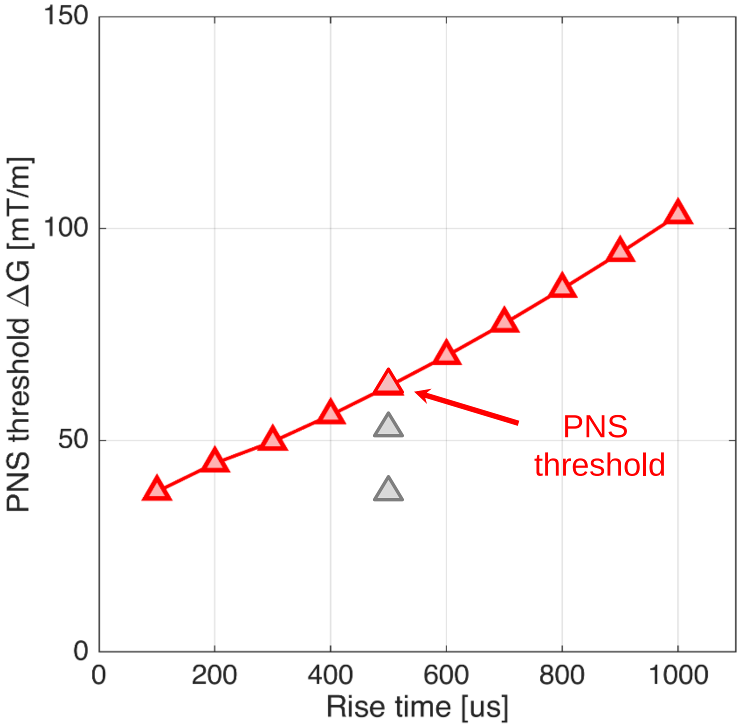
1. Electromagnetic modeling

2. Neurodynamic modeling

Threshold determination #1: Non-Linear Circuit Model

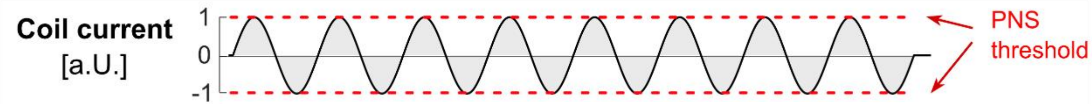


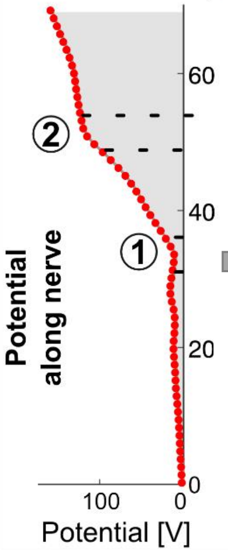
PNS threshold curve



- Modulate potentials by coil waveform
- Increase amplitude until action potentials are observed

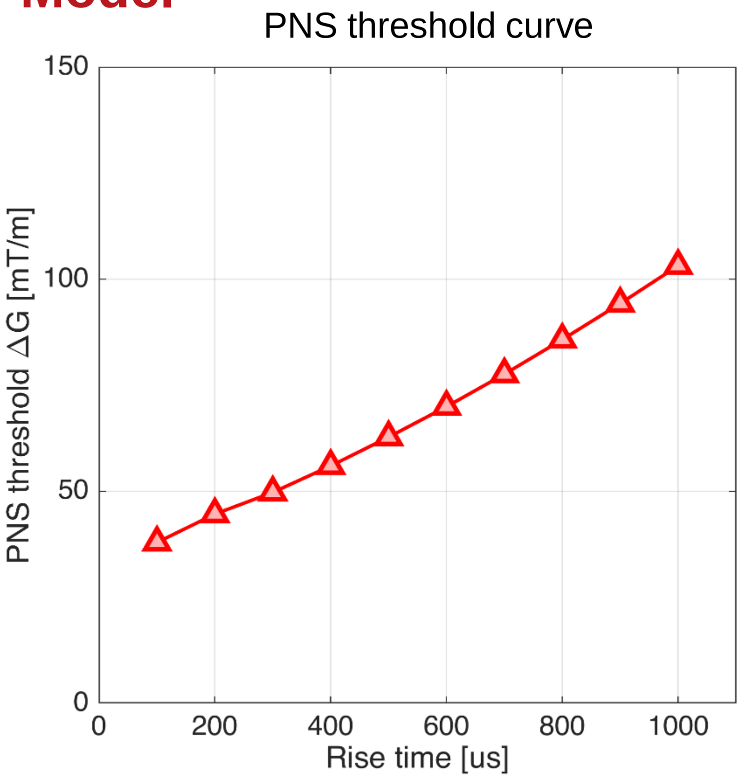
Threshold determination #2: Calibrated Linear Model





$$\textbf{PNSO}\,(r, D) = \frac{K(D)}{m(D)} * \frac{V(r-L) - 2V(r) + V(r+L)}{L(D)^2}$$

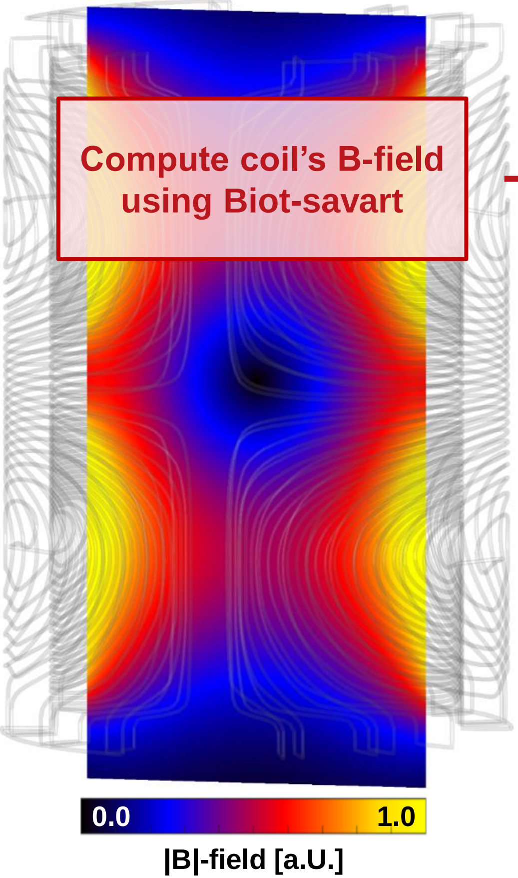
Calibrated parameters
(waveform specific)

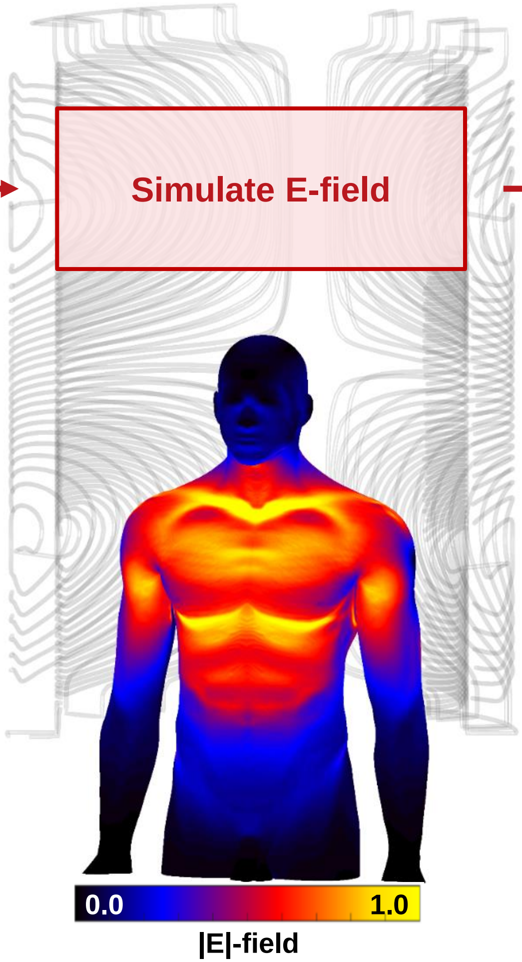


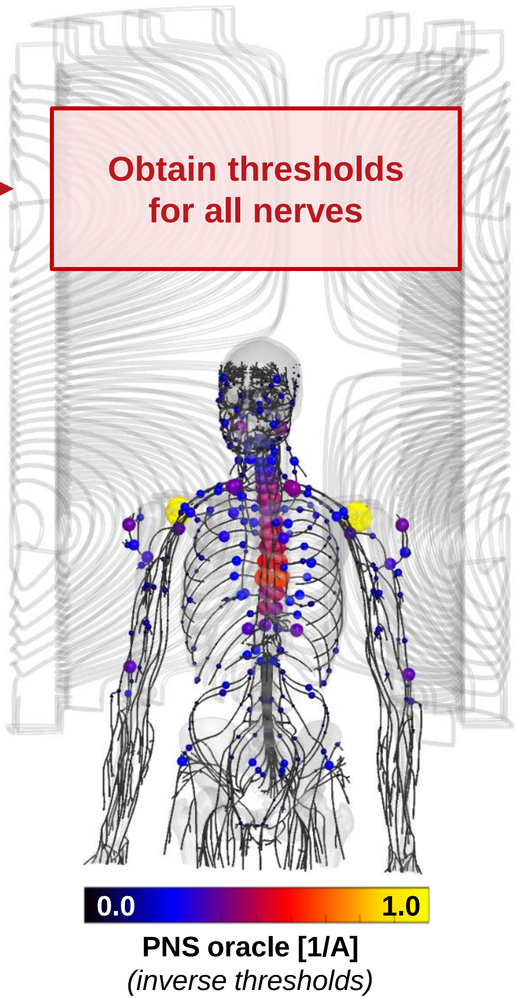
PNS oracle *(reciprocal PNS threshold)*

- Analyze spatial characteristics of potentials along nerves
- Parameters calibrated for given coil waveform (sinusoidal, trapezoidal, etc.)
- PNS oracle is linear in the electric potential (and thus in the E-field and coil current)

Traditional PNS model







MFEM-based Electromagnetic Solver

- Body model with 1mm³ hexahedral mesh elements, total of ~80M mesh elements, up to ~50 tissue classes
- EM field solver based on open MFEM library
- Solve magneto quasi-static approximation:

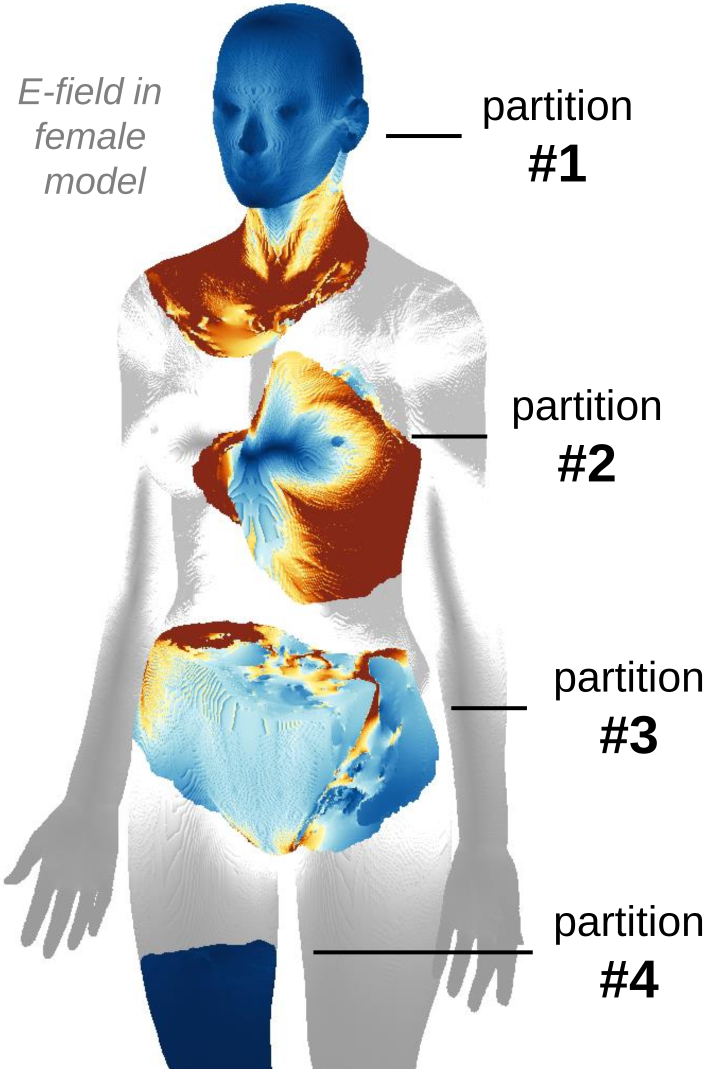
$$\boldsymbol{A}(\boldsymbol{r}) = \frac{\mu_0}{4\pi}\int_{\Omega}\frac{\boldsymbol{I}(\tilde{\boldsymbol{r}})}{\|\boldsymbol{r}-\tilde{\boldsymbol{r}}\|}\mathrm{d}^3\boldsymbol{r} \quad \rightarrow \quad \nabla\cdot\sigma\nabla\varphi = -\mathrm{i}\omega\nabla\cdot\sigma\boldsymbol{A}$$

(magnetic vector potential) (electric scalar potential φ)

- Partitioning and large-scale parallelization using **algebraic multigrid solver** (Hyper-AMG)

⇨ **~35 min.** (LHS, i.e., initialization of FE system)
plus 2-3 min. (compute RHS and solve)

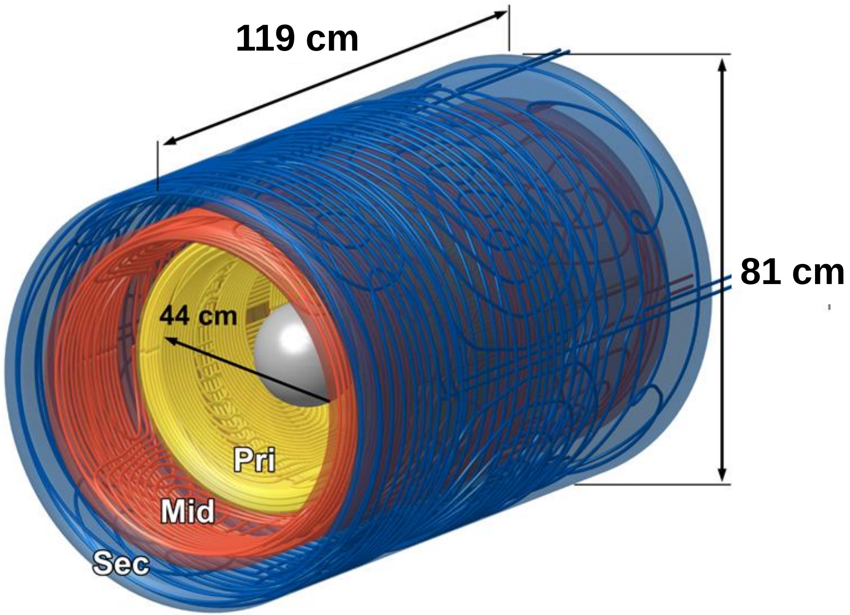
20 processes, ~400 GB memory consumption



Design optimization of new head gradient

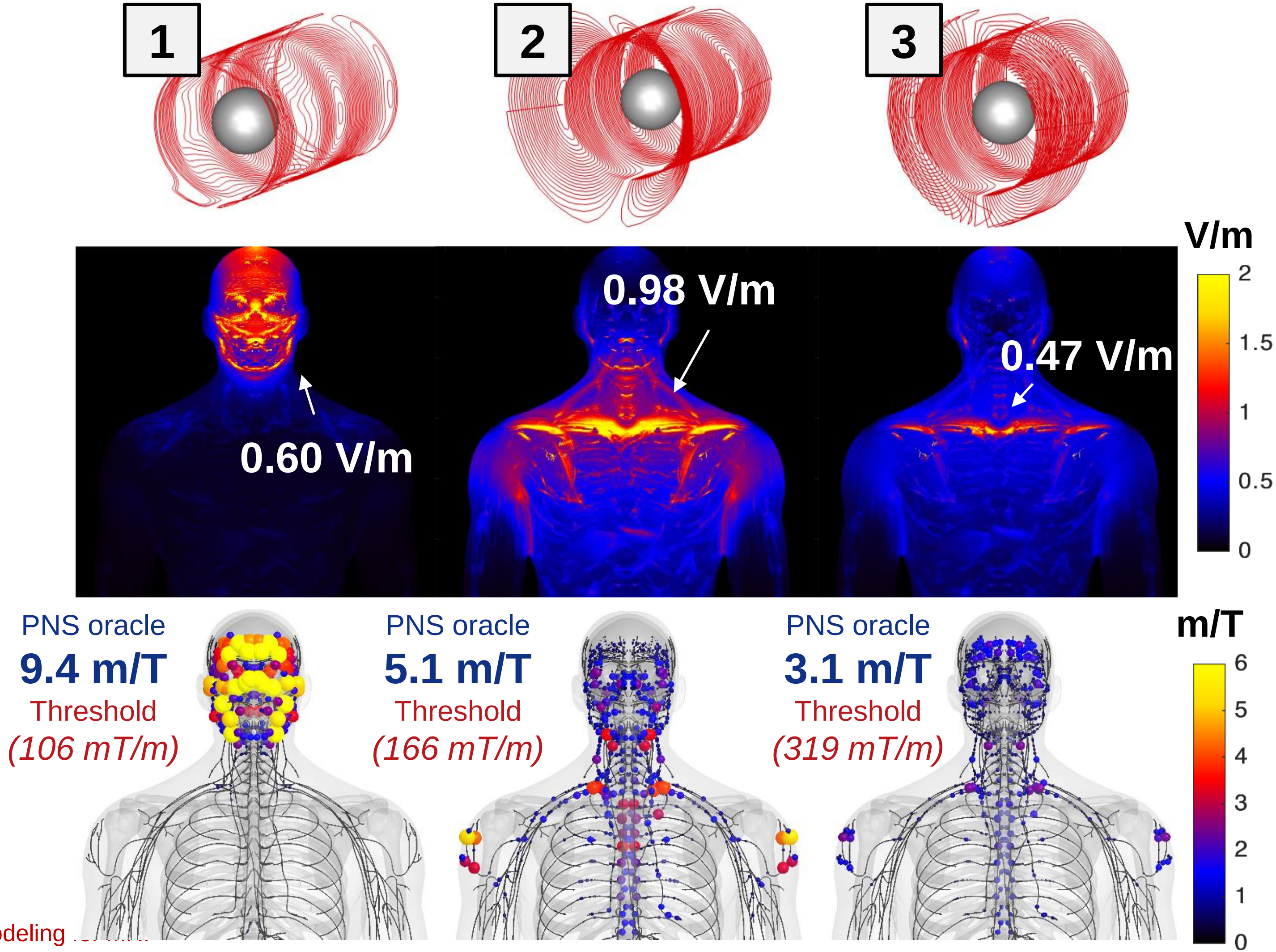
New head gradient for high-resolution fMRI

1. High-performance: **Gmax = 200 mT/m, Smax = 900 T/m/s**
2. Relatively larger inner diameter: **44 cm**
3. Comparably high field linearity: **~6% in 20 cm DSV**



Analyzing large number of coils w.r.t. PNS

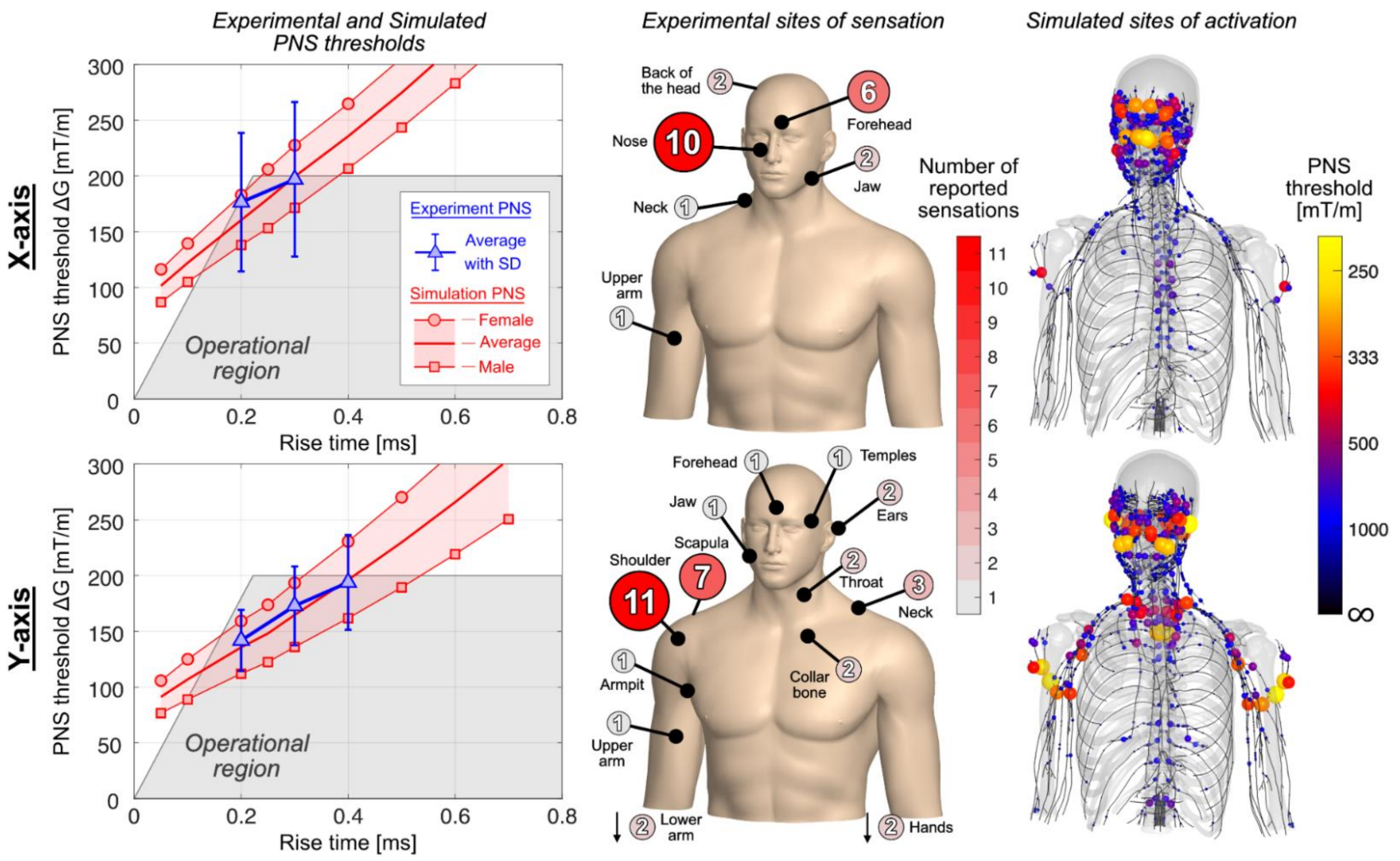
- Study different coil design strategies and impact on PNS
- Maximize worst case PNS thresholds
- Equivalent to minimizing worst case PNS oracle



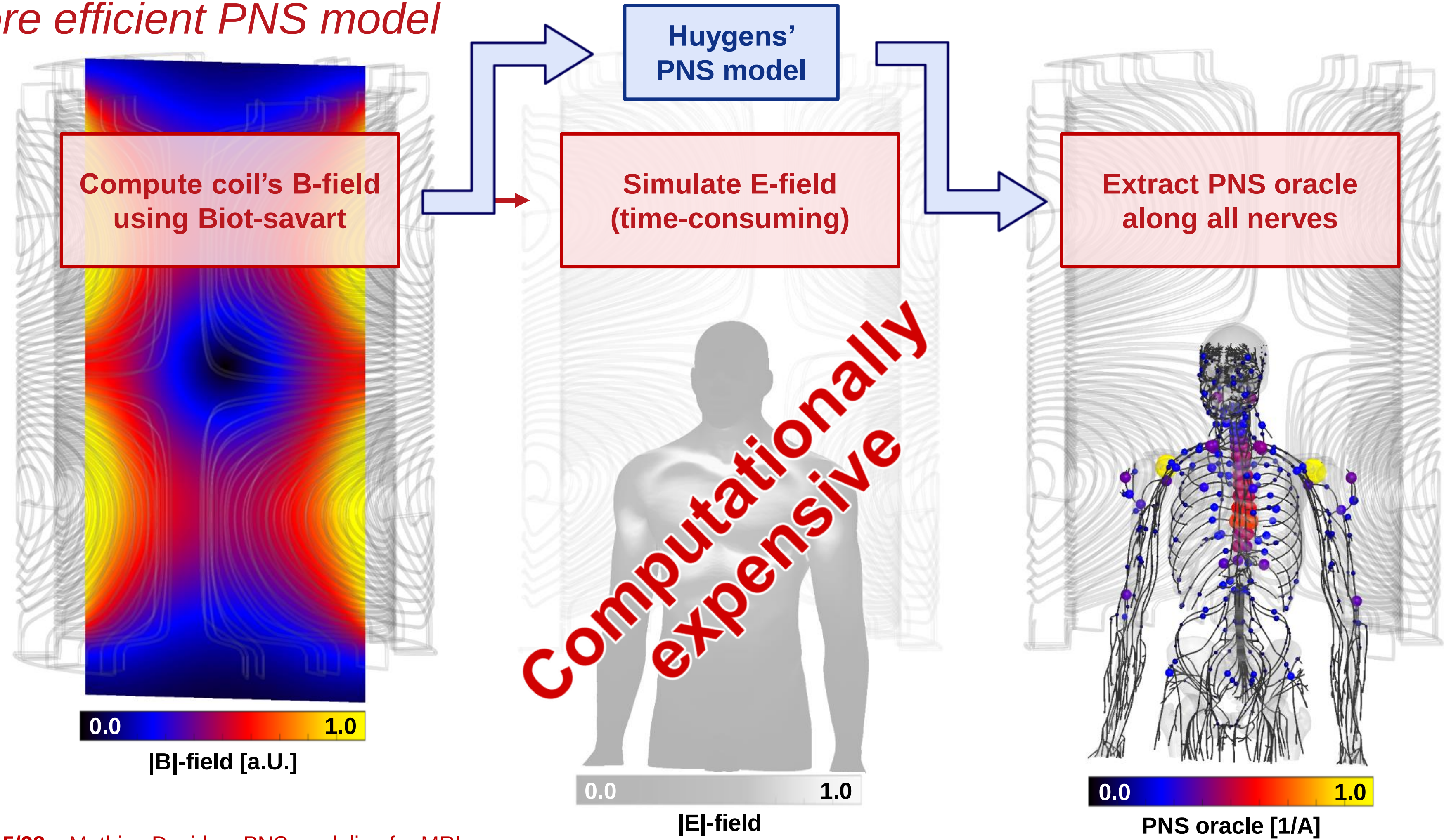
Experimental vs. Predicted PNS thresholds

- Good agreement between experim. and simulated thresholds:
  5% (single axis)
  ~15% (multi-axes)
- Good agreement with reported sites of activation

Most powerful head system in existence!



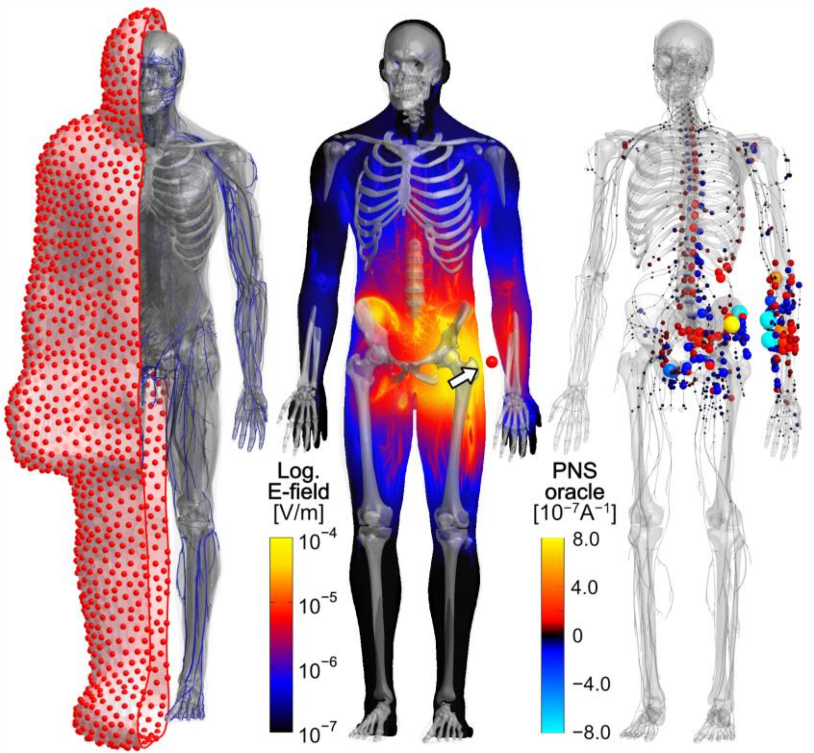
More efficient PNS model



Traditional PNS model

1. Enclose body with Huygens' surface, add basis functions

2. Precompute E-fields and PNS responses for each basis



Thousands of basis functions per model

Initialization (~35 minutes)

$$\underbrace{\nabla \cdot \sigma \nabla \varphi}_{} = \underbrace{-\mathrm{i}\omega \nabla \cdot \sigma \boldsymbol{A}}_{}$$

Matrix assemble

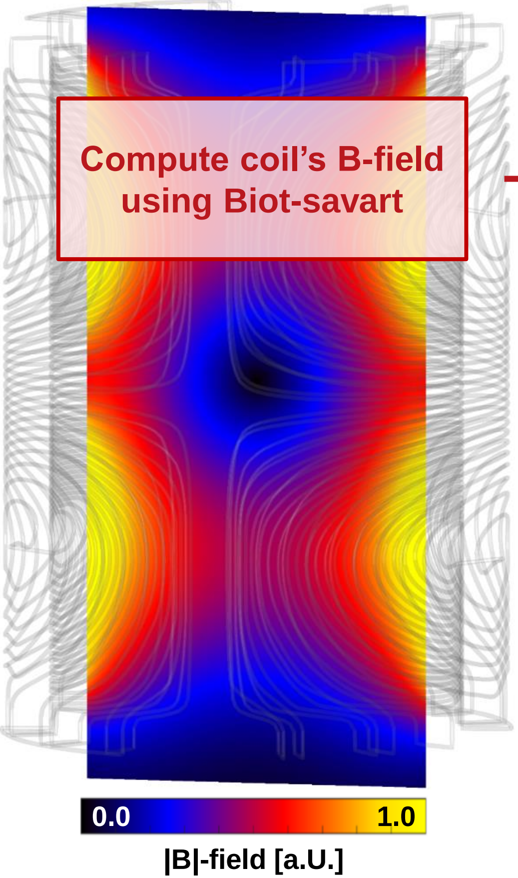
Solve per basis function
(~2 minutes)

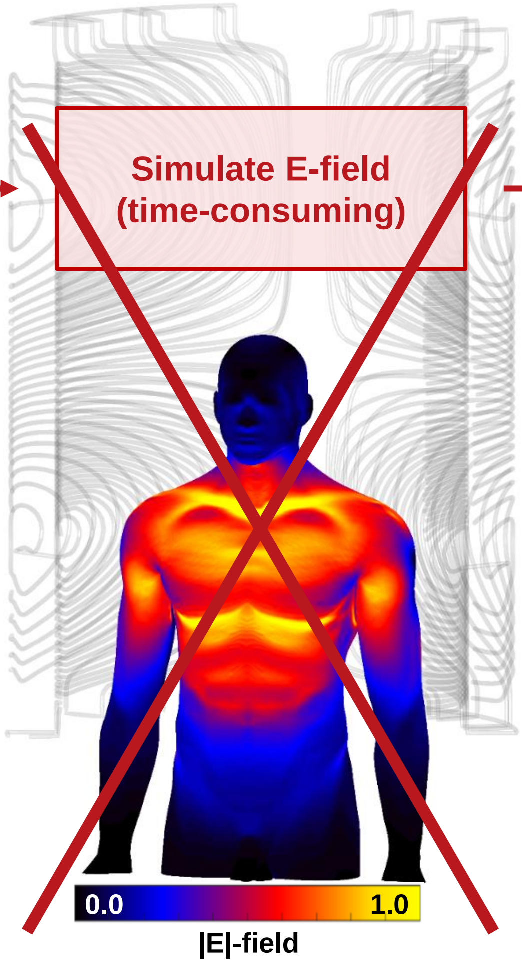
- Compute magn. vector potential $\boldsymbol{A}$
- Matrix multiply to get RHS
- Solve for electric scalar potential φ

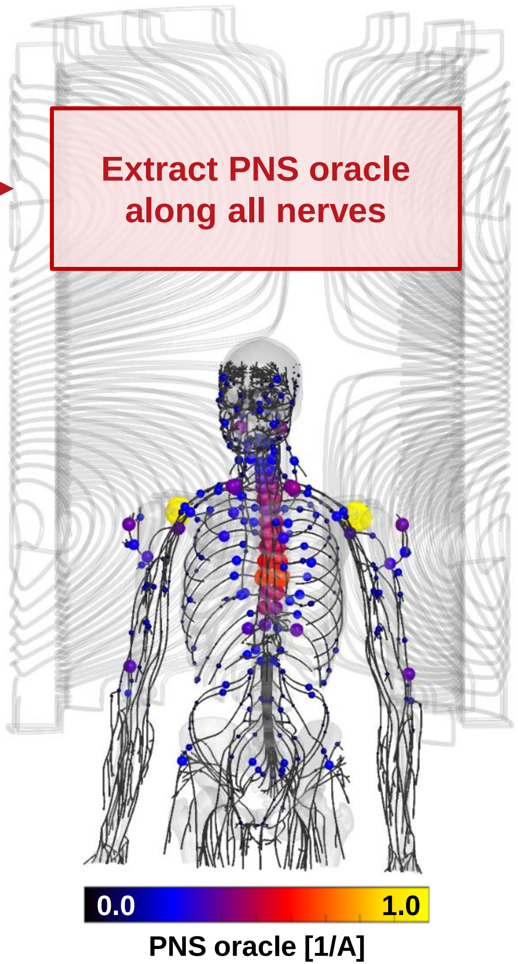
|E|-field

PNS oracle [1/A]

Huygens' PNS model

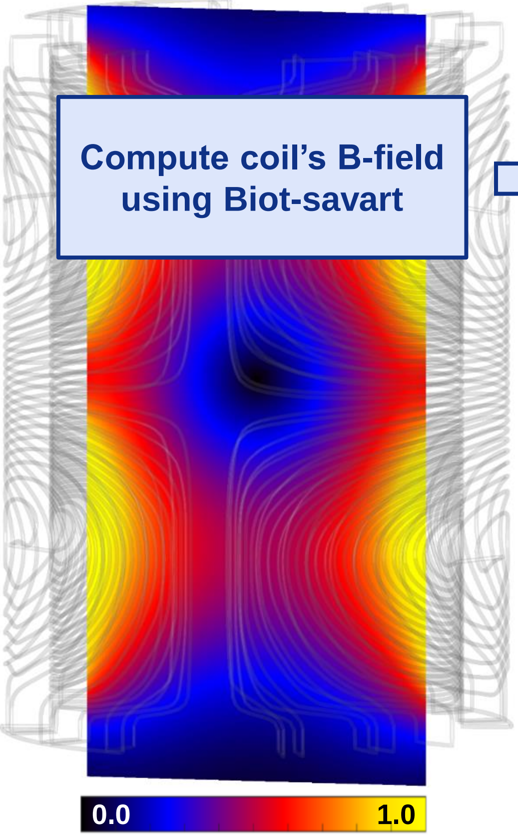






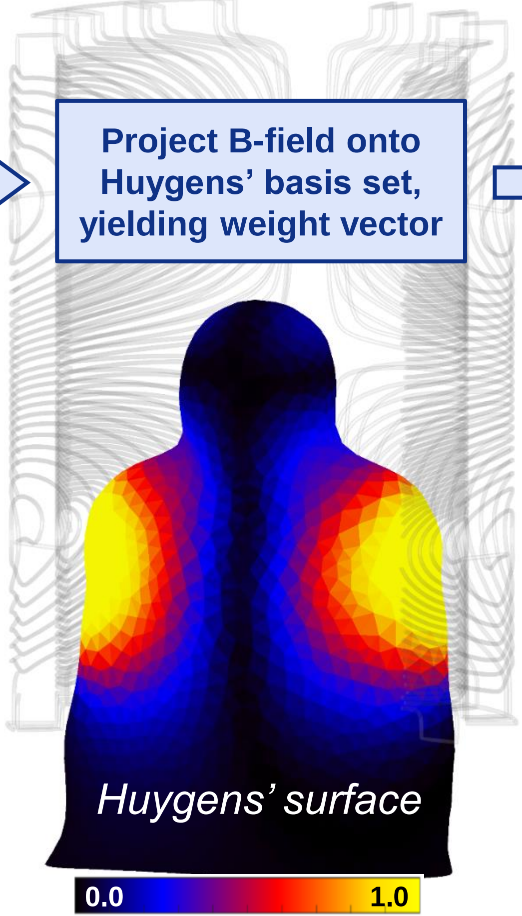
Huygens' PNS model

Compute coil's B-field using Biot-savart



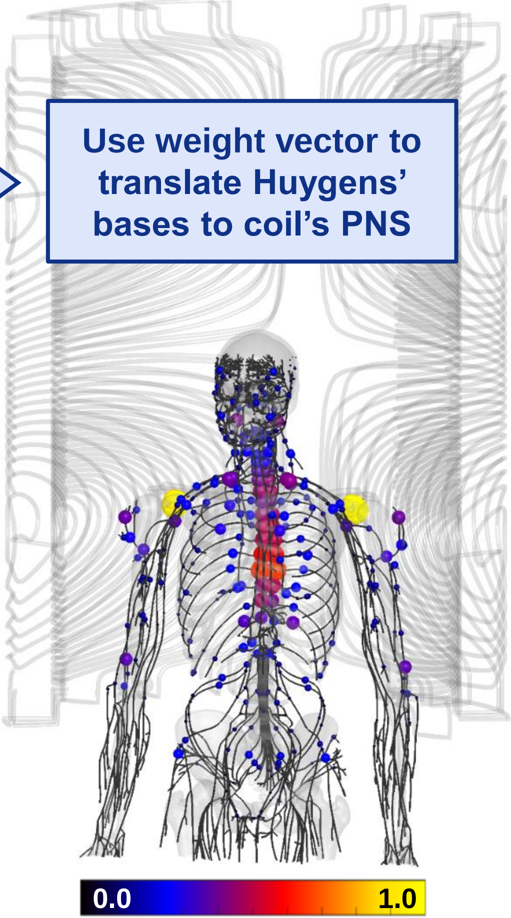
|B|-field [a.U.]

Project B-field onto Huygens' basis set, yielding weight vector



Abs. Huygens' weights

Use weight vector to translate Huygens' bases to coil's PNS

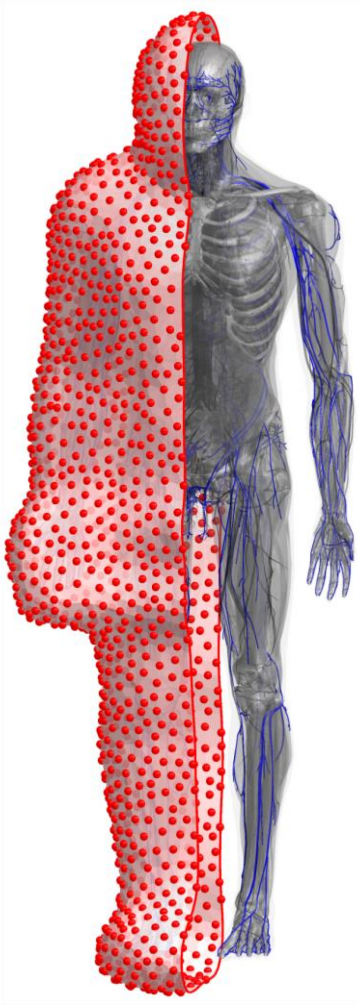


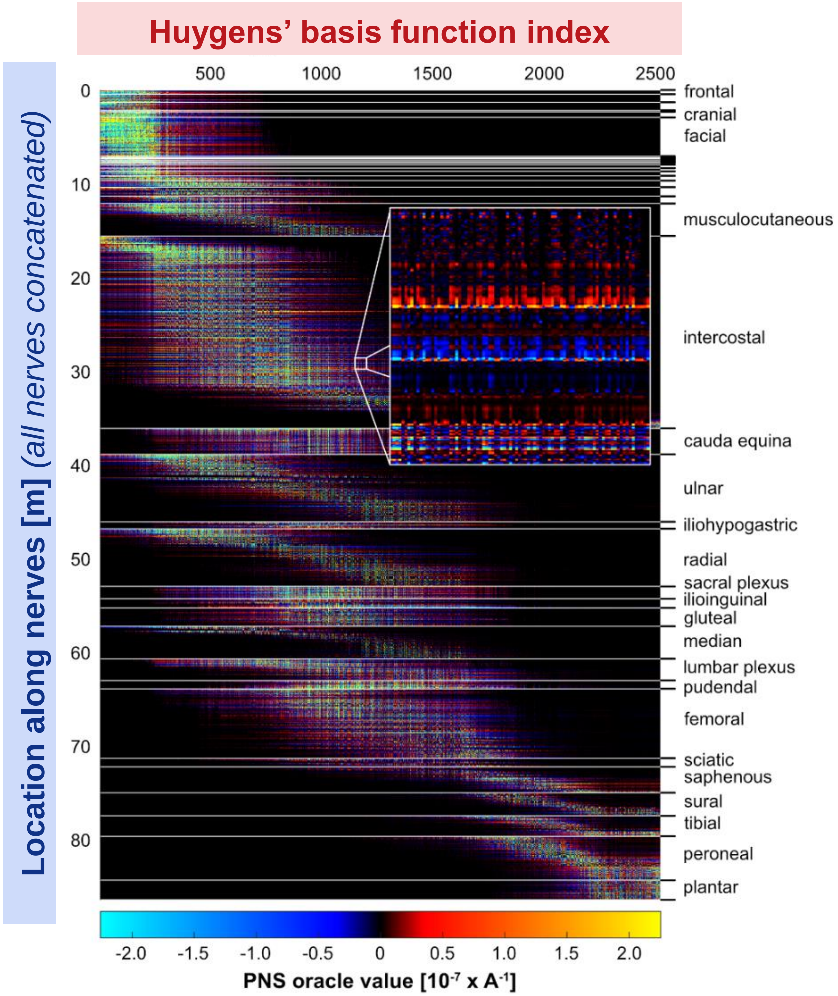
PNS oracle [1/A]

Huygens PNS model

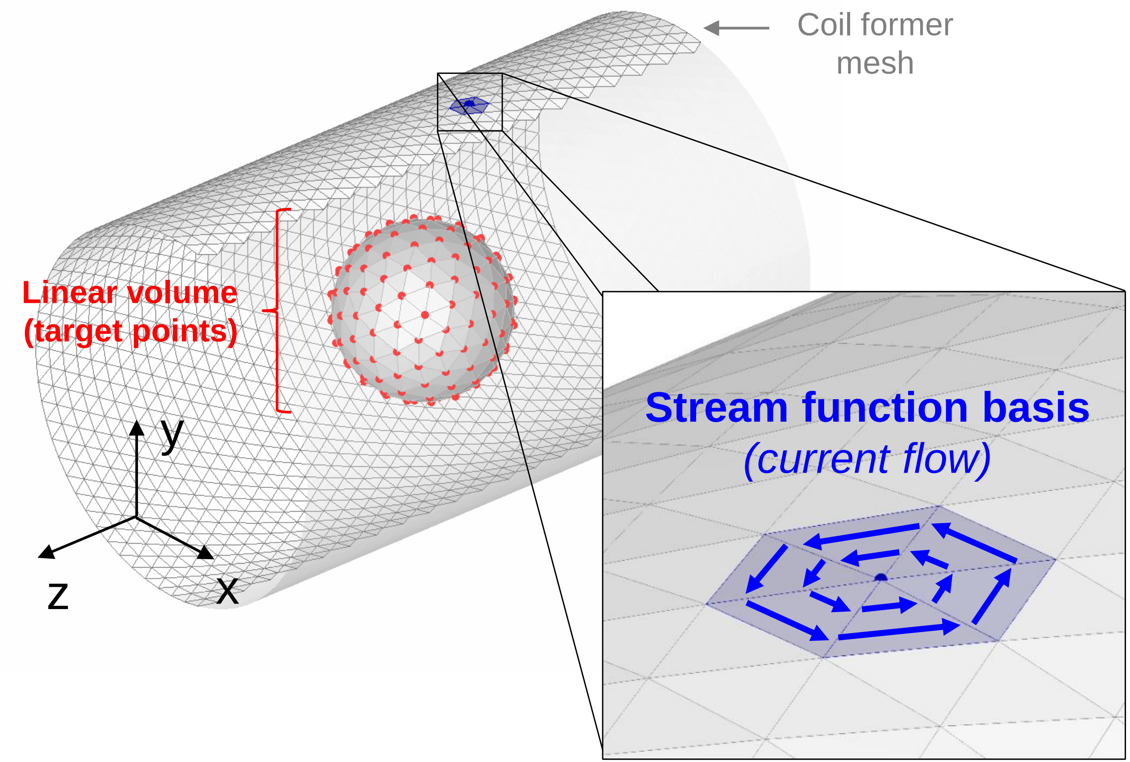
- *Huygens' PNS model represented as **P**-matrix*
- ***P***-matrix describes interaction between Huygens bases and all nerves
- ***P***-matrix is body model and waveform specific
- Easy dissemination
- PNS prediction without further EM or neurodynamic modeling (seconds)

Allows incorporation of PNS metrics in numeric coil optimization





Gradient Coil Design: *Boundary Element Method Stream Function (BEM-SF)*



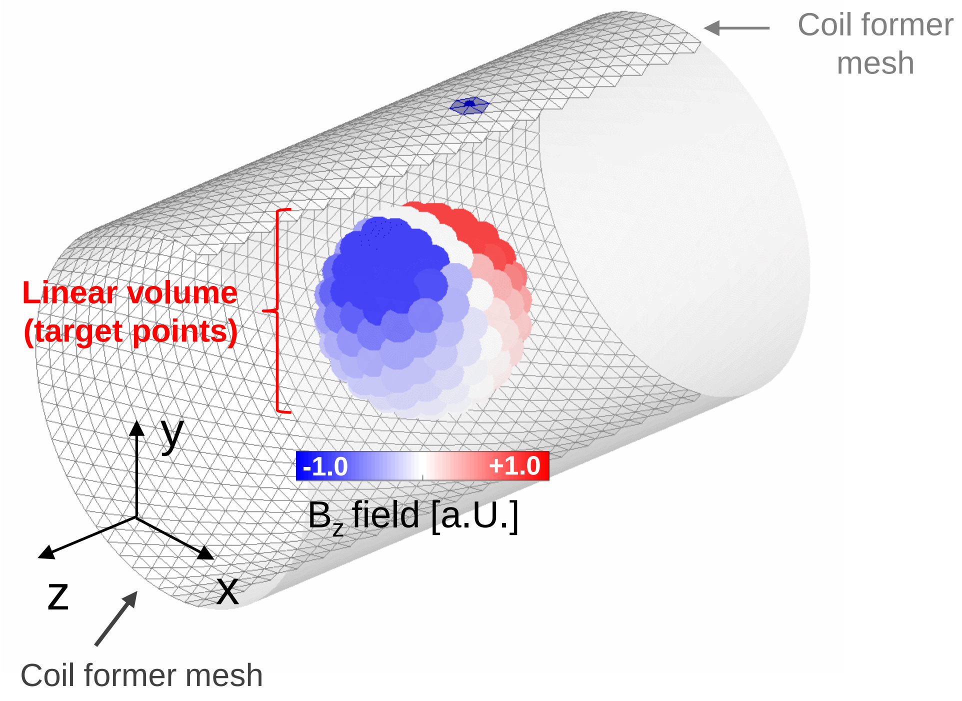
Turner et al., *"A target field approach to optimal coil design"*, J. Phys. D: Appl. Phys., 1986

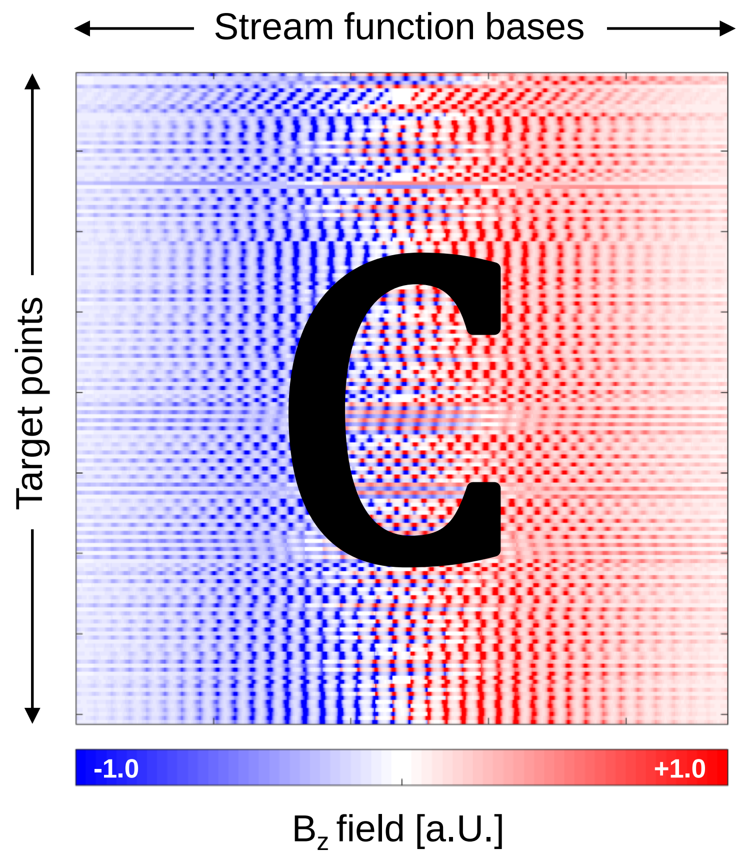
Peeren et al., *"Stream function approach for determining optimal surface currents"*. Journal of Computational Physics, 2003

Lemdiasov et al., *"A stream function method for gradient coil design"*, Concepts Magn. Reson., 2005

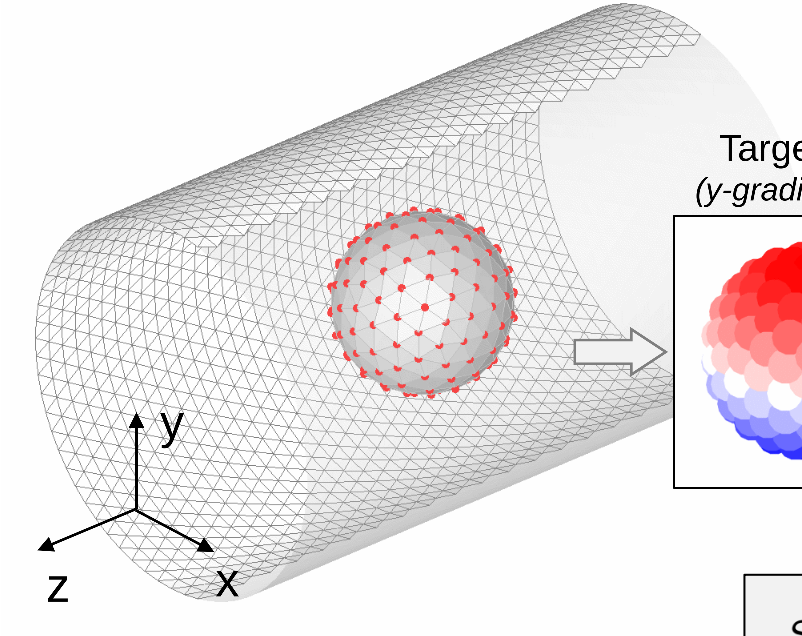
Poole et al., *"Convex optimisation of gradient and shim coil winding patterns"*. Journal of Magnetic Resonance, 2014.

Precompute field contribution for each basis

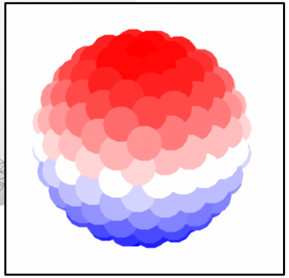




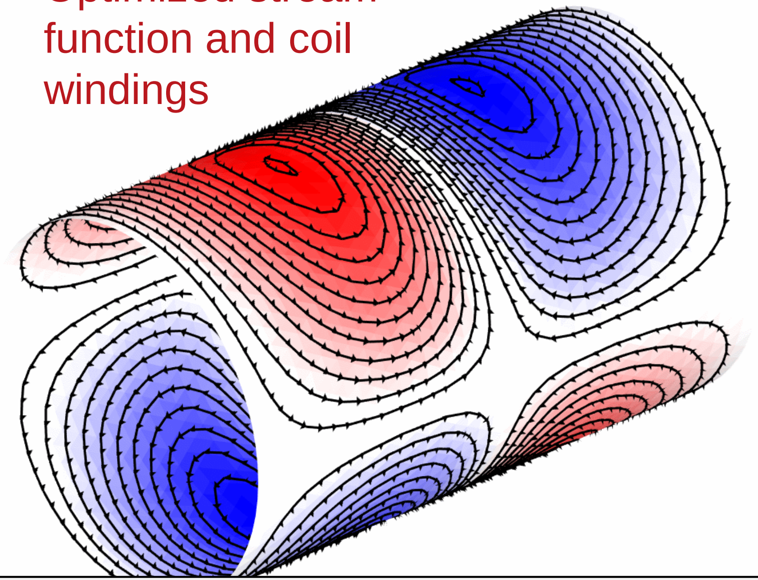
Coil design as optimization problem



Target field
(y-gradient field)



Optimized stream function and coil windings



Formulate coil design as constrained optimization problem

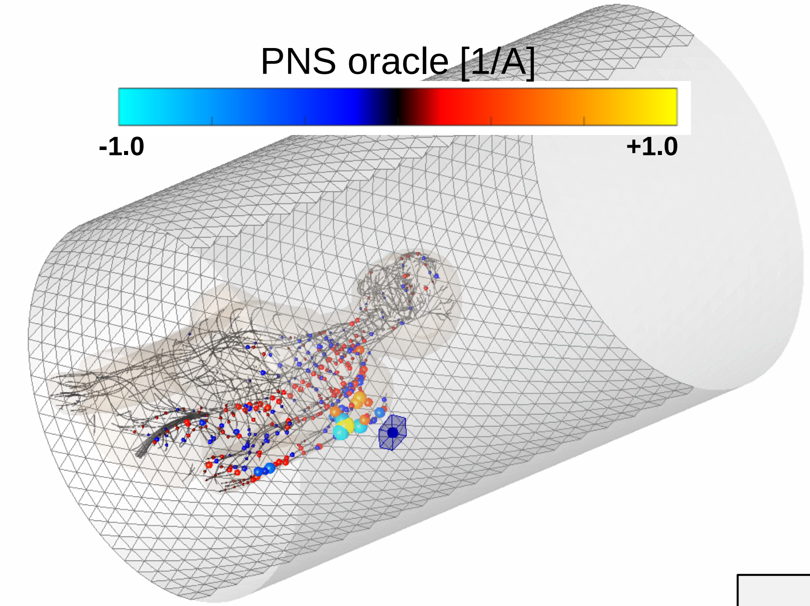
$$s_{\text{opt}} = \arg\min_{s} \left\{ s^{\mathsf{T}} \boldsymbol{L} s \right\}$$

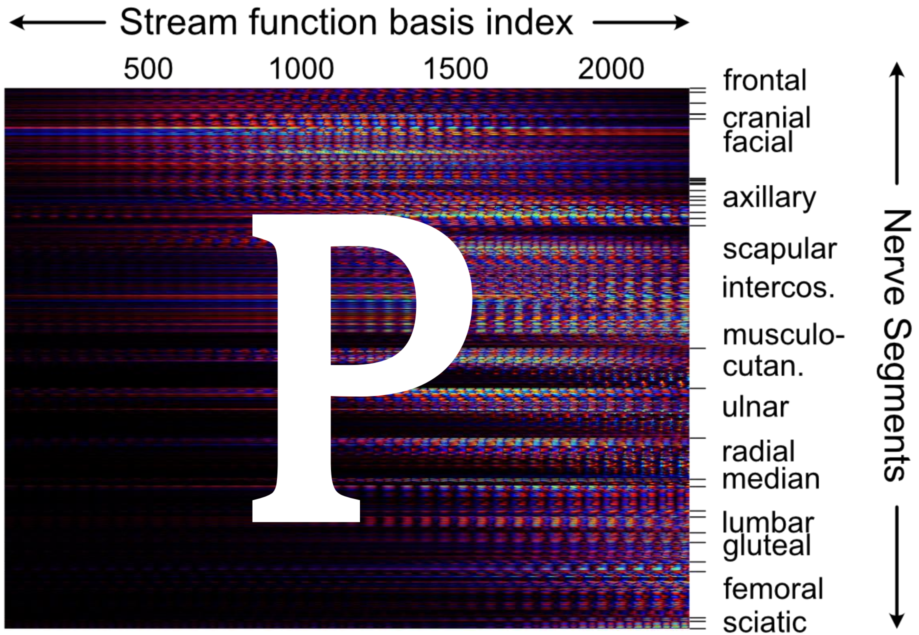
Min. inductance

$$\text{s.t.} \quad \boldsymbol{M} s \leq M_{\text{max}}$$

Includes torque, force, shielding, linearity, wire density

PNS constrained optimization





$$s_{\text{opt}} = \arg\min_{s} \left\{ s^{\mathsf{T}} \boldsymbol{L} s \right\}$$ Min. inductance

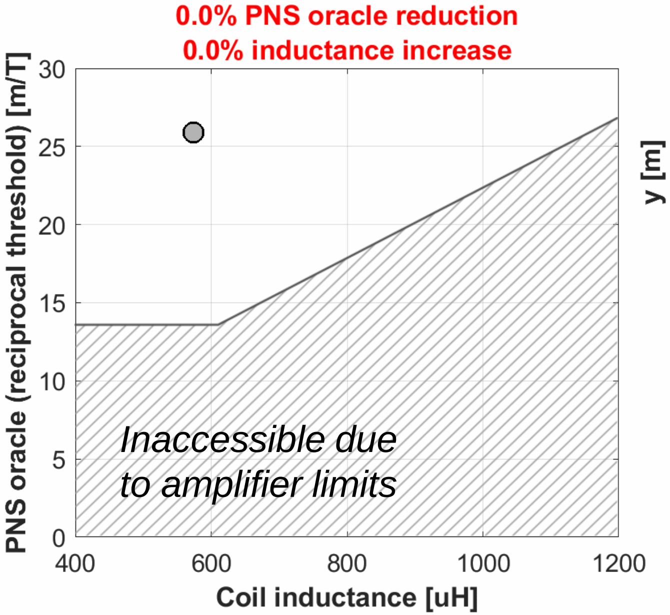
s.t. $\boldsymbol{M} s \leq M_{\max}$ — Includes torque, force, shielding, linearity, wire density

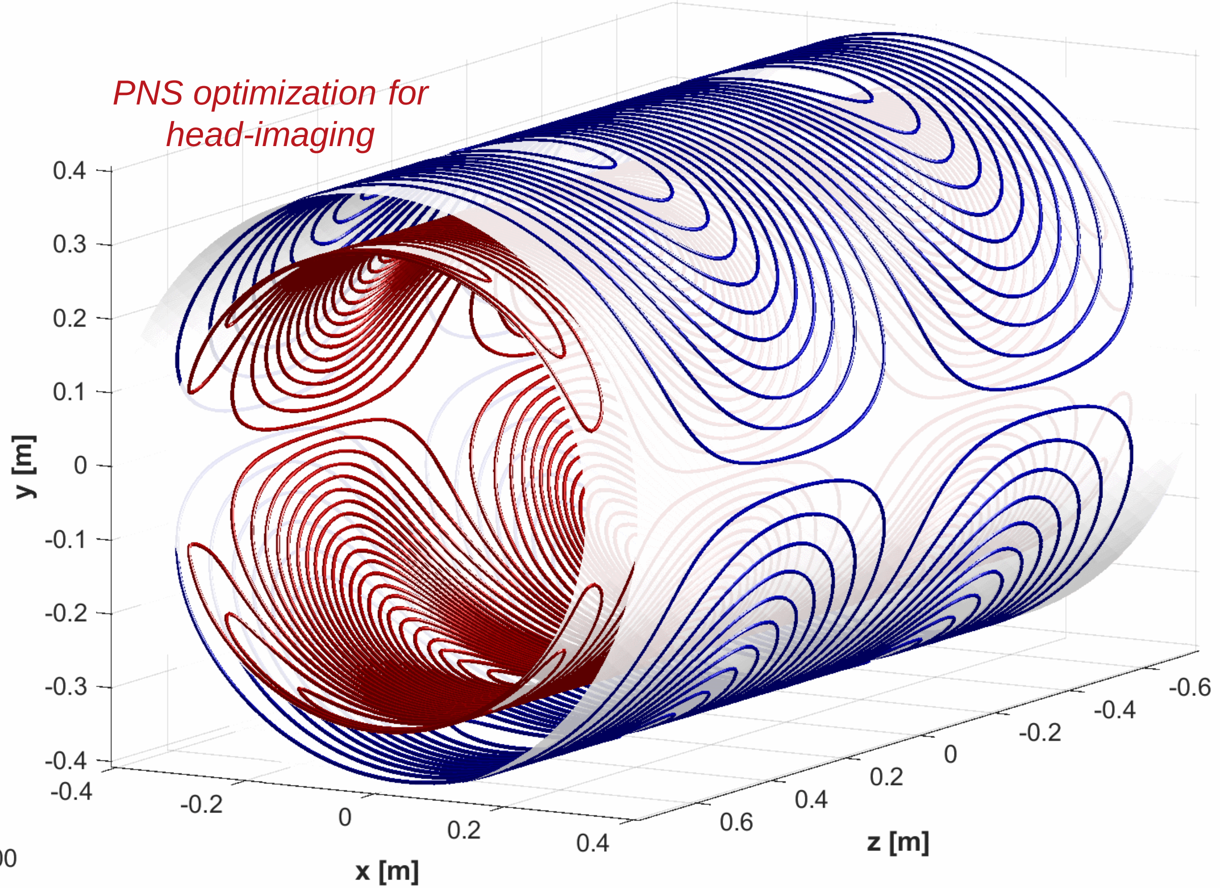
$|\boldsymbol{P} s| \leq P_{\max}$ **PNS constraint**

Davids et al., "Optimization of MRI Gradient Coils with Explicit Peripheral Nerve Stimulation Constraints", *IEEE Transactions on Medical Imaging*, **2020**, *40*, 129-142

L-curve analysis of PNS-constrained coil design

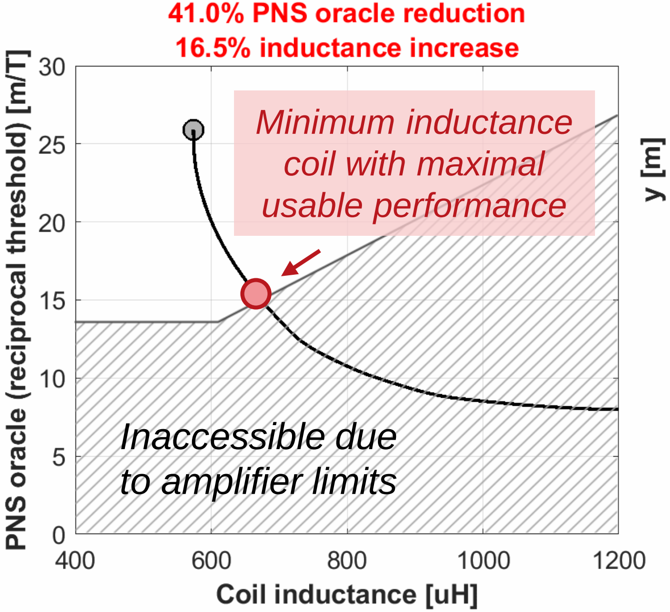
- Study tradeoff between reciprocal PNS thresholds and coil inductance

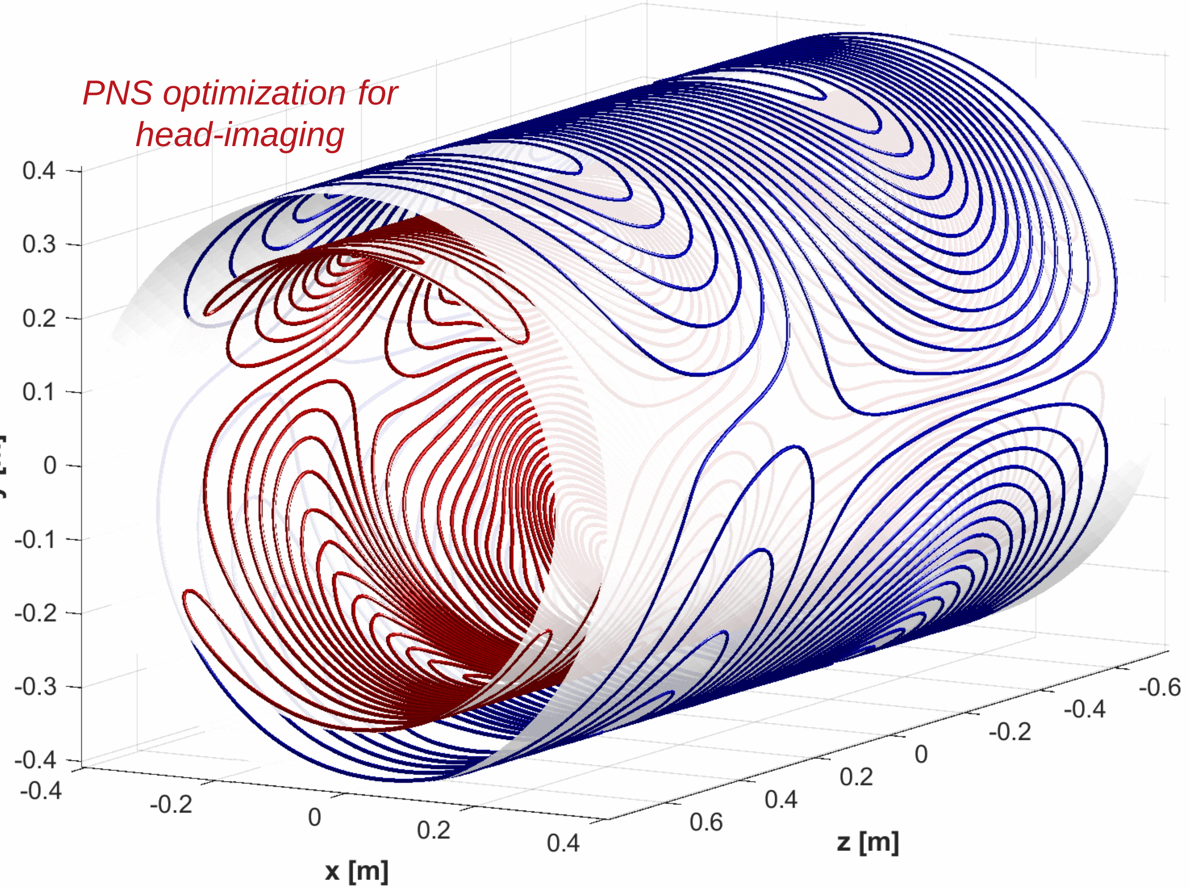




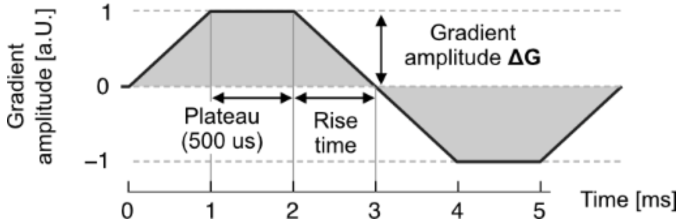
L-curve analysis of PNS-constrained coil design

- Study tradeoff between reciprocal PNS thresholds and coil inductance





Analyze full PNS curves and operational region



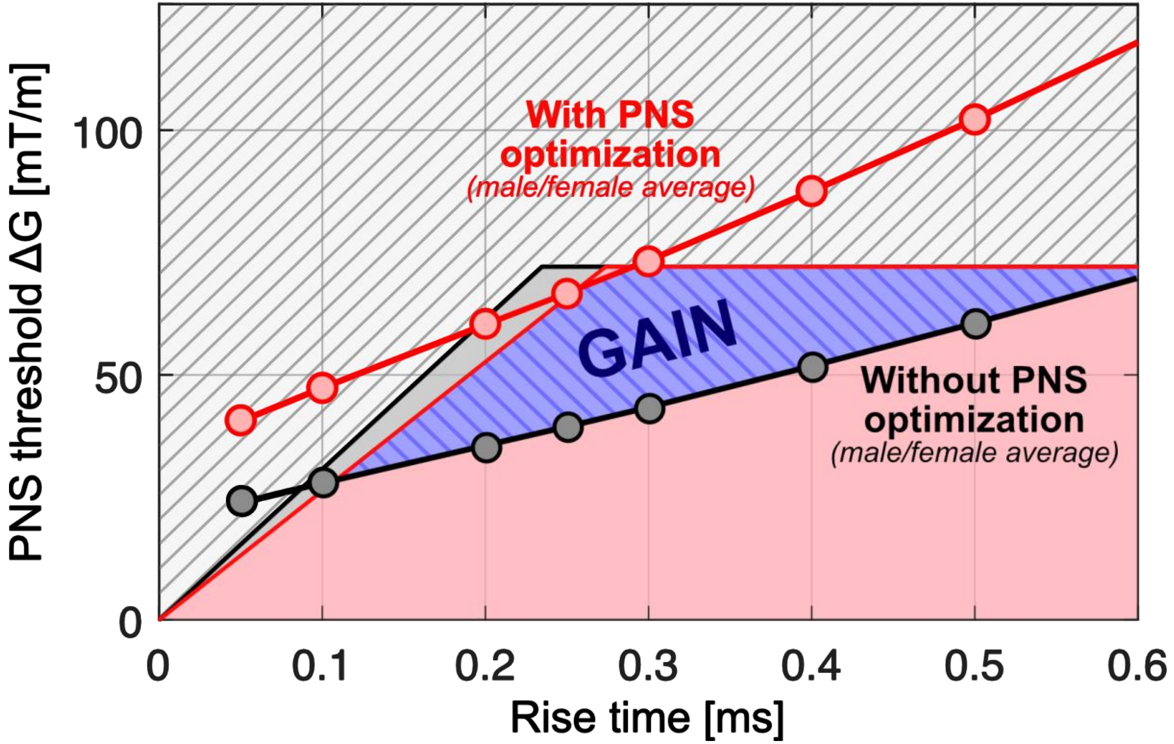
Without PNS optimization

- Low PNS thresholds
- Low inductance

With PNS optimization

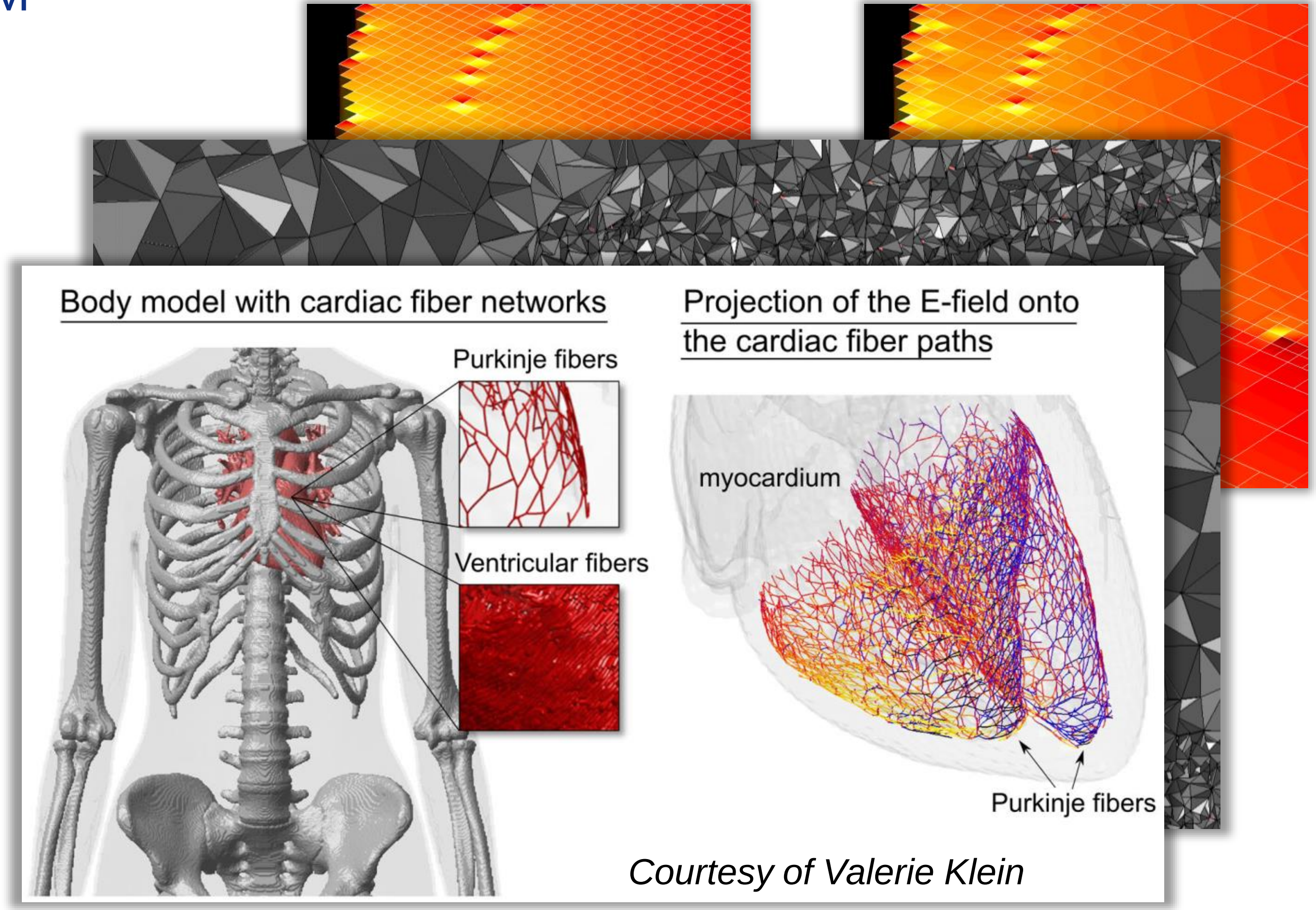
- **70%** higher PNS thresholds
- **17%** higher inductance (slightly smaller hardware operational region)

Overall ***GAIN*** *in usable performance*



Future use of MFEM

- Non-conforming meshes to increase spatial resolution
- Switch to tetrahedral meshes
- Other research activities such as cardiac and retinal stimulation



Summary

PNS modeling

- Useful tool in guiding gradient coil design phase to increase usable encoding performance
- Successfully used in design phase of new head-gradient, prototype phase of asymmetrical coils ongoing

Role of MFEM

- Enabled us to utilize Huygens’ principle to make PNS tool more accessible and easier to use
- EM solver tailored to problem at hand (reuse LHS to speed up processing)

Thanks

- *To the entire MFEM Team!*
- Special thanks to Mark Stowell, Veselin Dobrev and Tzanio Kolev