EA1

National Magnetic Resonance Research Center

Application of Gradient Array Coils

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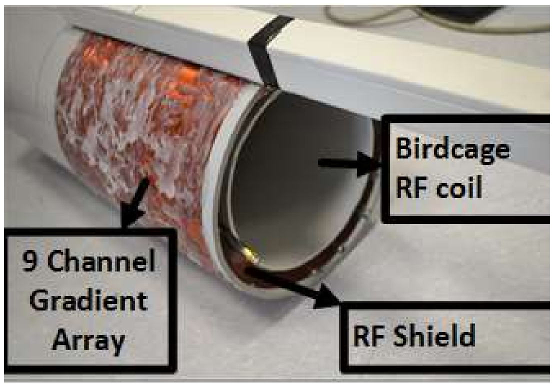
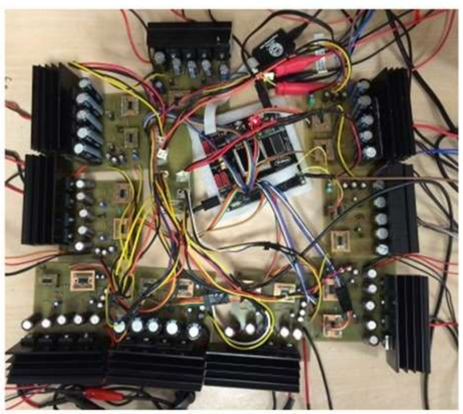
Slide 1

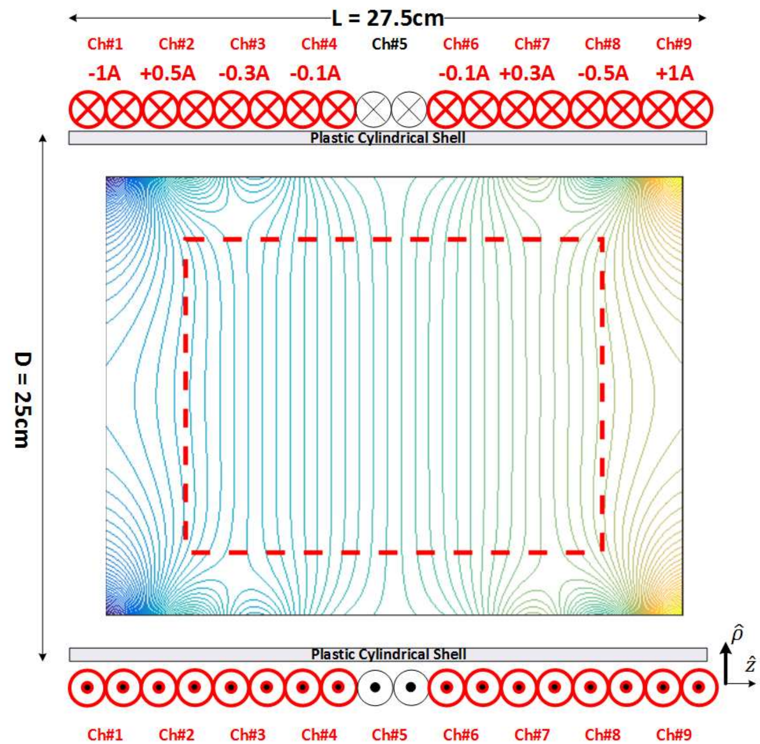
EA1 Ergin Atalar, 04/06/2023

- **Gradient Array Coils**:
  - A gradient array coil is made up of multiple elements that can be individually driven by independent gradient power amplifiers (GPAs).



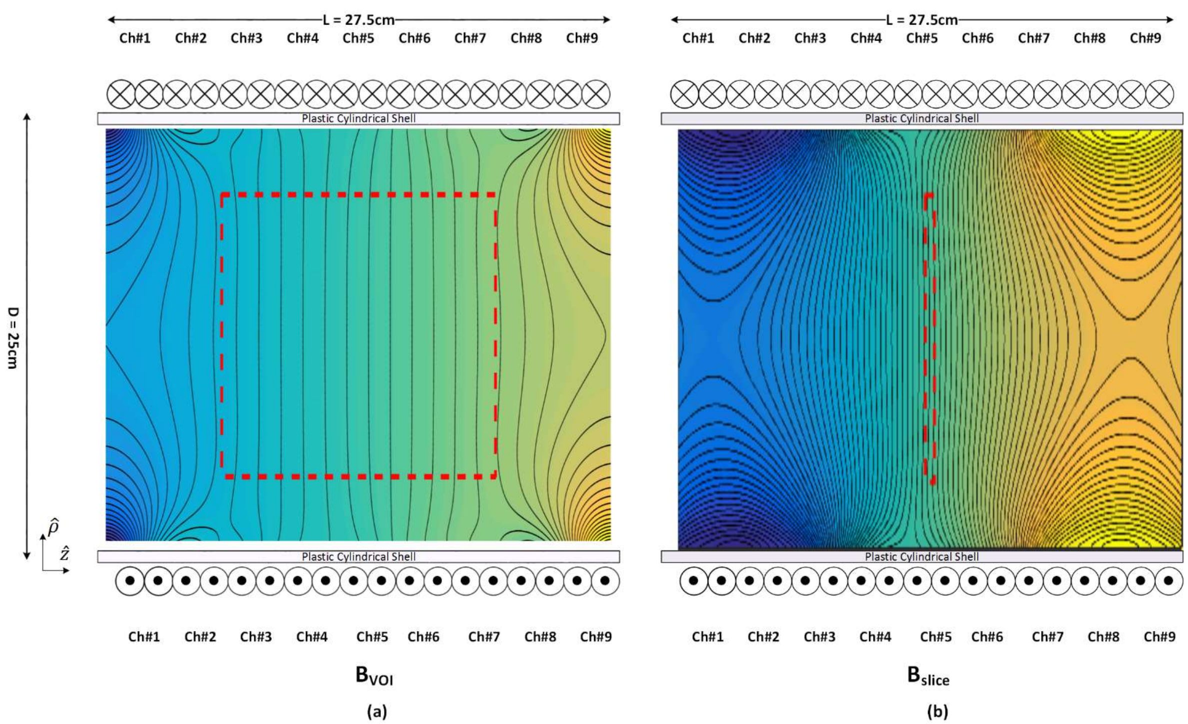
Gradient Amplifiers

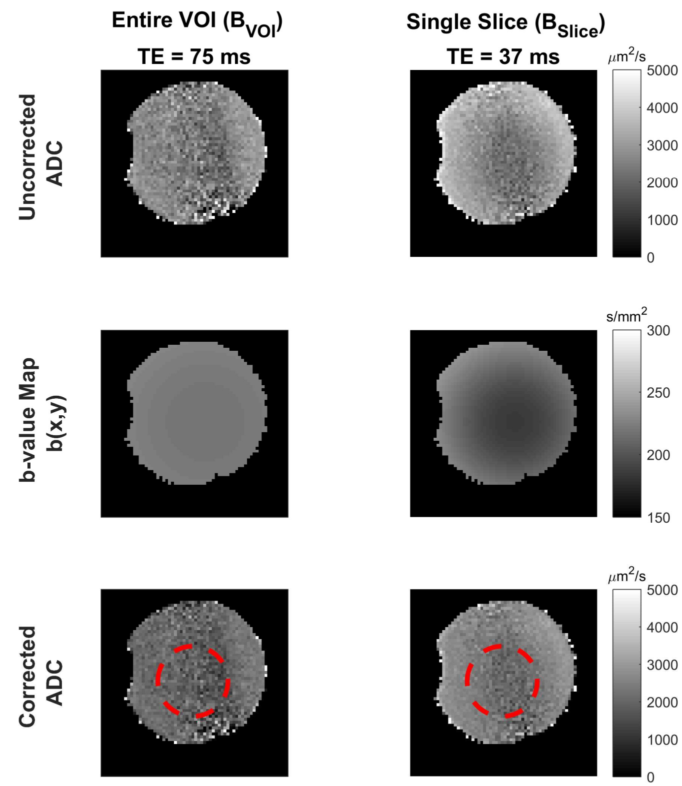




Ertan, K. and Atalar, E., Simultaneous use of linear and nonlinear gradients for B1+ inhomogeneity correction in *NMR in Biomedicine* **2017**, 30:e3742.

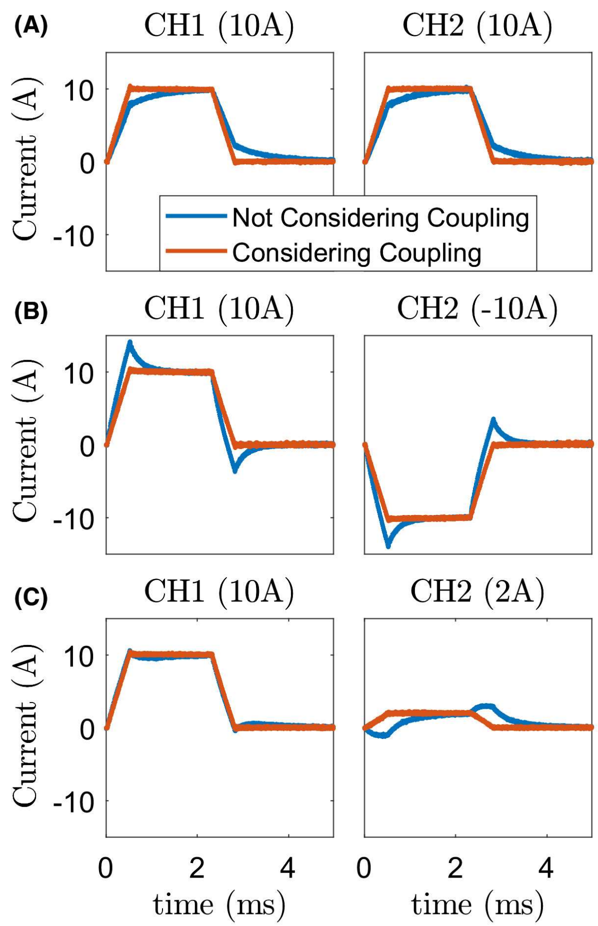
- **Gradient Array Coils**:
  - Dynamically generate optimized linear gradients for specific aims only inside the target VOI.
    - ✓ An application to Diffusion Weighted Imaging (DWI).

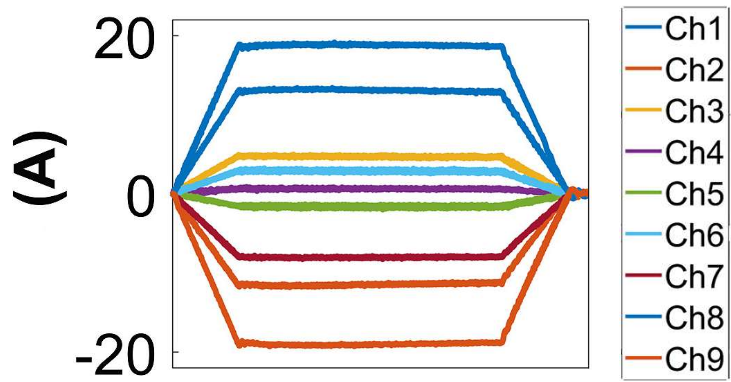


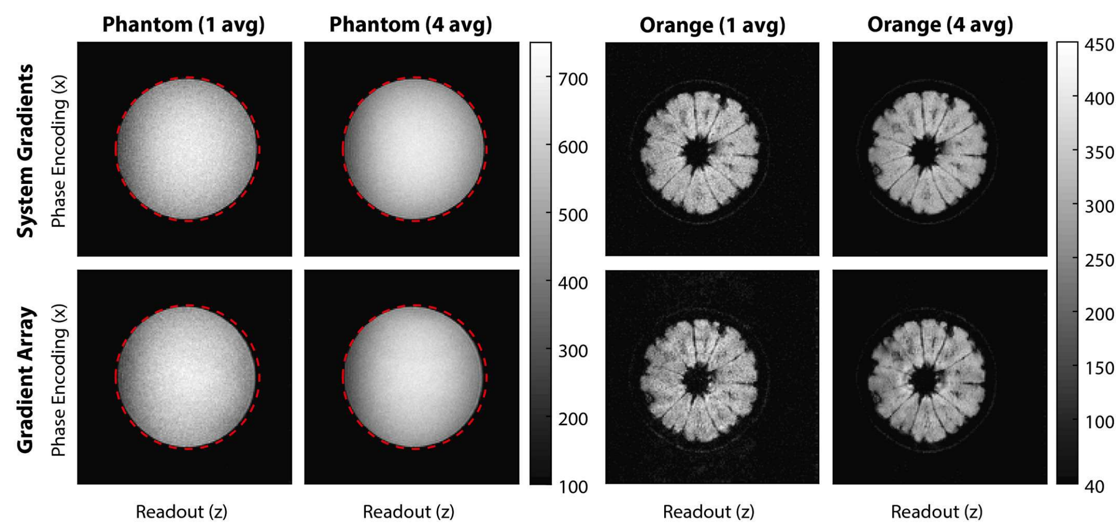


Ertan, K., Taraghinia, S., Saritas, E.U., Atalar, E., Local Optimization of Diffusion Encoding Gradients Using a Z-Gradient Array for Echo Time Reduction in DWI, ISMRM, Paris, 2018

➢ Driving mutually coupled gradient array coils:







Ertan K, et al. Driving mutually coupled gradient array coils in magnetic resonance imaging. MRM. 2019.

- **Gradient Array Coils**:
  - Generate nonlinear gradients to be used in novel applications:
    - ✓ Multi-slice excitation with a single band RF pulse.

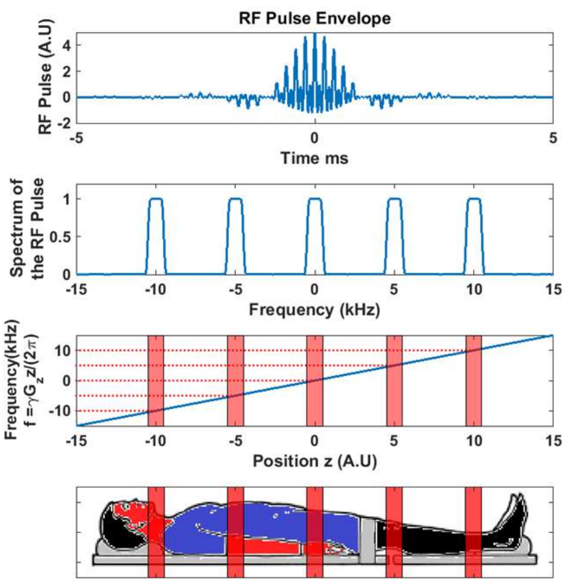
Conventional RF Pulse Design

<u>Slice Number : N=5</u>

Relative Peak RF Voltage = 5

Relative Average Energy (SAR) = 5

Relative Peak Power = 25



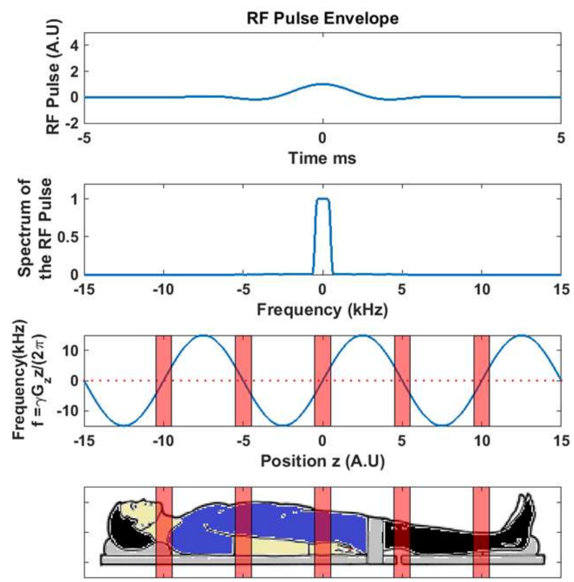
Proposed Method

<u>Slice Number : N=5</u>

Relative Peak RF Voltage = 1

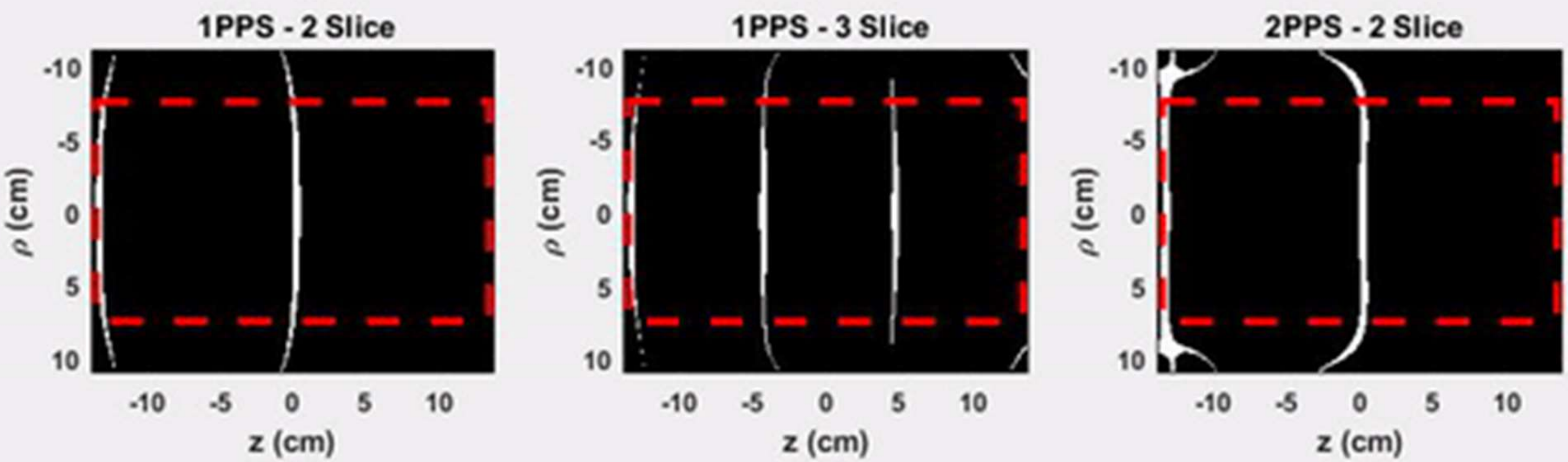
Relative Average Energy (SAR) = 1

Relative Peak Power = 1



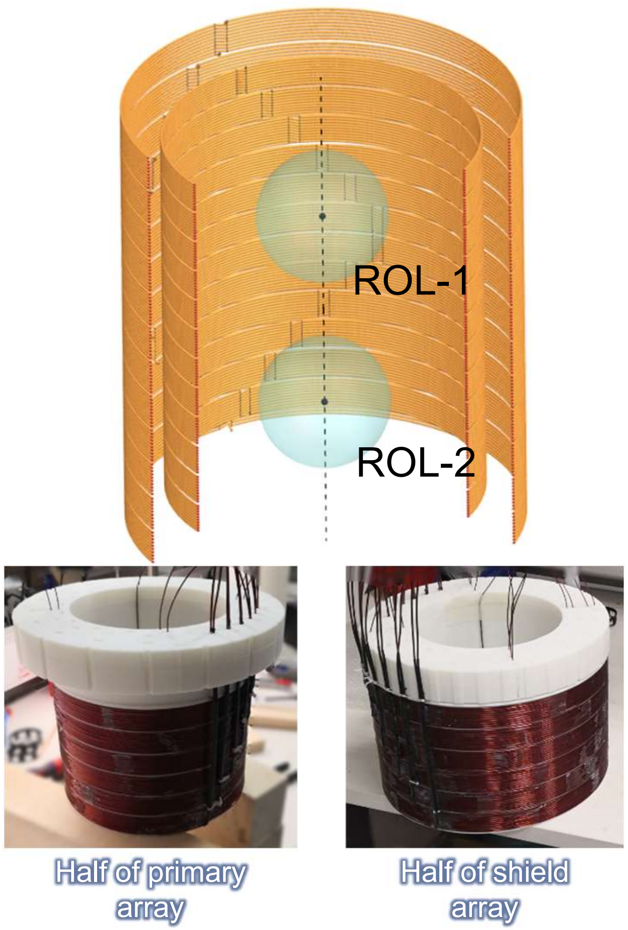
Ertan K, et al. A z-gradient array for simultaneous multi-slice excitation with a single-band RF pulse. MRM. 2018.

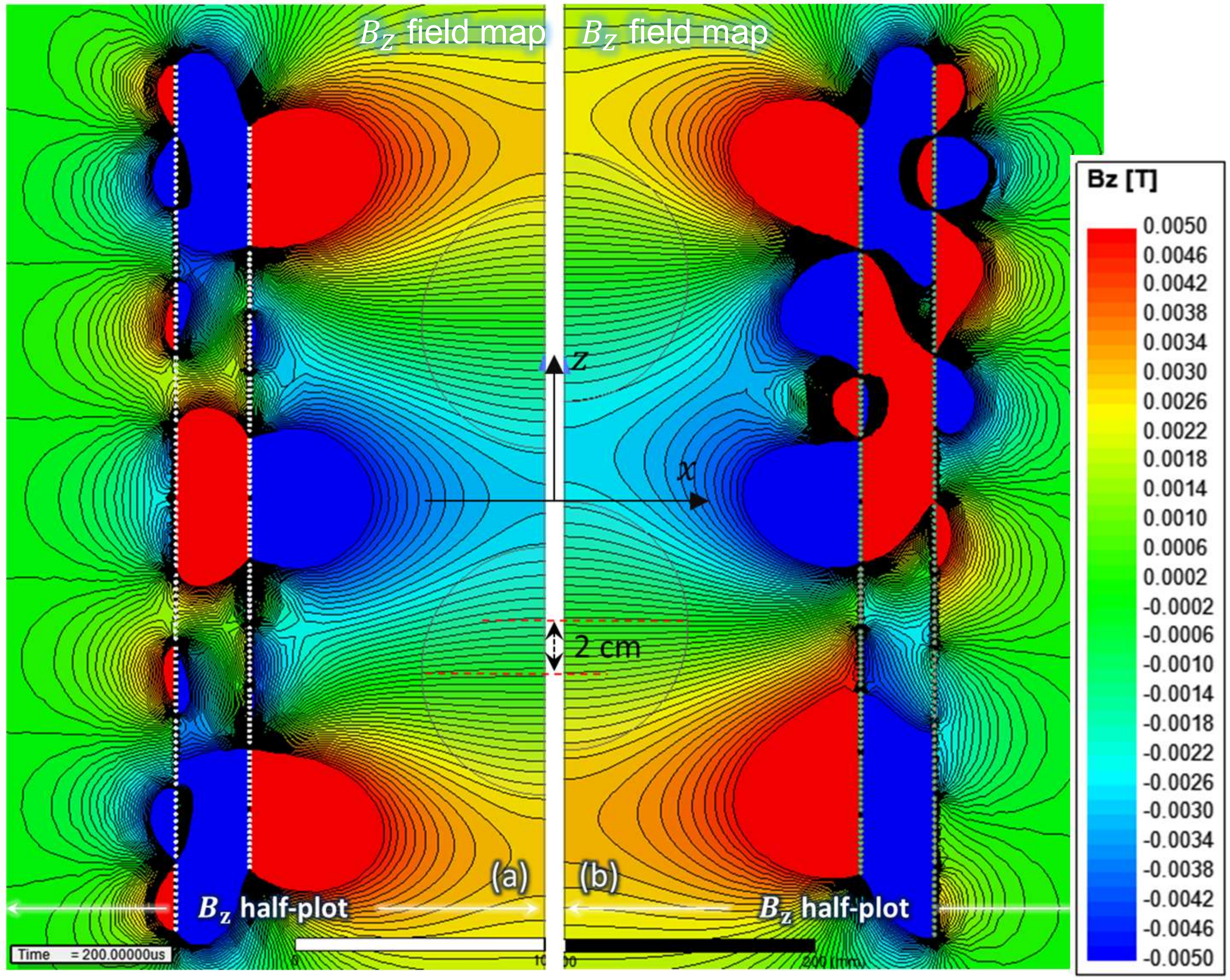
- **Gradient Array Coils**:
  - Generate nonlinear gradients to be used in novel applications:
    - ✓ Multi-slice excitation with a single band RF pulse.



Ertan K, et al. A z-gradient array for simultaneous multi-slice excitation with a single-band RF pulse. MRM. 2018.

- **Gradient Array Coils**:
  - Double & Shifted Double ROL





Takrimi M, Atalar E. Z-Gradient Array Coil Equipped With a Tunable Shield Array for Creating Multiple-Imaging Volumes. ISMRM, 2022.

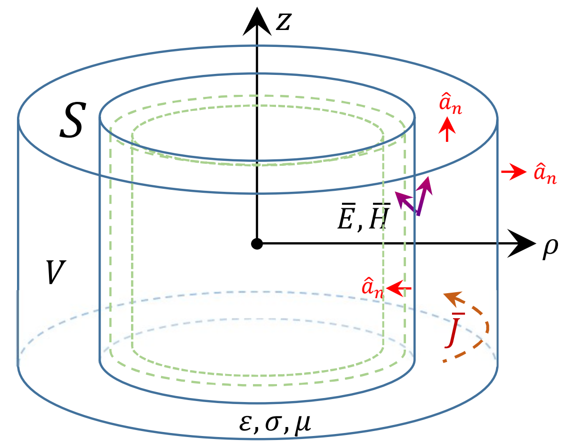
Poynting Theorem ⇒ Quadratic Calculation

Abstract #4573

Consider the warm shield's metallic body as a simple medium ($\varepsilon, \mu, \sigma \in \mathbb{R}$) of volume V enclosed by surface S. The integral form of the Poynting theorem reads:

$$-\oint_S \tfrac{1}{2}(\bar{E} \times \bar{H}^*) \cdot \hat{a}_n ds = \int_V \tfrac{1}{2\sigma}|\bar{J}|^2 dv + j4\pi f \left[\int_V \tfrac{\mu}{4}|\bar{H}|^2 dv - \int_V \tfrac{\varepsilon}{4}|\bar{E}|^2 dv\right]$$

where $\bar{J}$ is the volume induced eddy current density.



It is observed that:

- $\text{Re}\{-\oint_S \tfrac{1}{2}(\bar{E} \times \bar{H}^*) \cdot \hat{a}_n ds\}$ represents the time-average ohmic power loss caused by induced eddy currents within V.
- $\text{Im}\{-\oint_S \tfrac{1}{2}(\bar{E} \times \bar{H}^*) \cdot \hat{a}_n ds\}$ represents the time-average stored magnetic energy within the V.

$$\oint_S \tfrac{1}{2}(\bar{E} \times \bar{H}^*) \cdot \hat{a}_n ds = \bar{A}\,\bar{\bar{Q}}_{\rho\varphi z}(f)\bar{A}'$$

Quadratic form of the time-average complex power delivered into the cryostat defined by a closed surface S.

- $\bar{\bar{Q}}_{\rho\varphi z}(f)$ is a $N \times N$ complex matrix to be calculated once.
- $\bar{A}$ is a vector representing the array driving currents.

For a given driving waveform $s(t)$

$$P_{s(t)}^{\text{Loss}}(\bar{A}) \cong \sum_{m=1}^{M} |2c_m|^2 \;\text{Re}\{\bar{A}\,\bar{\bar{Q}}_{\rho\varphi z}(mf_0)\bar{A}'\}$$

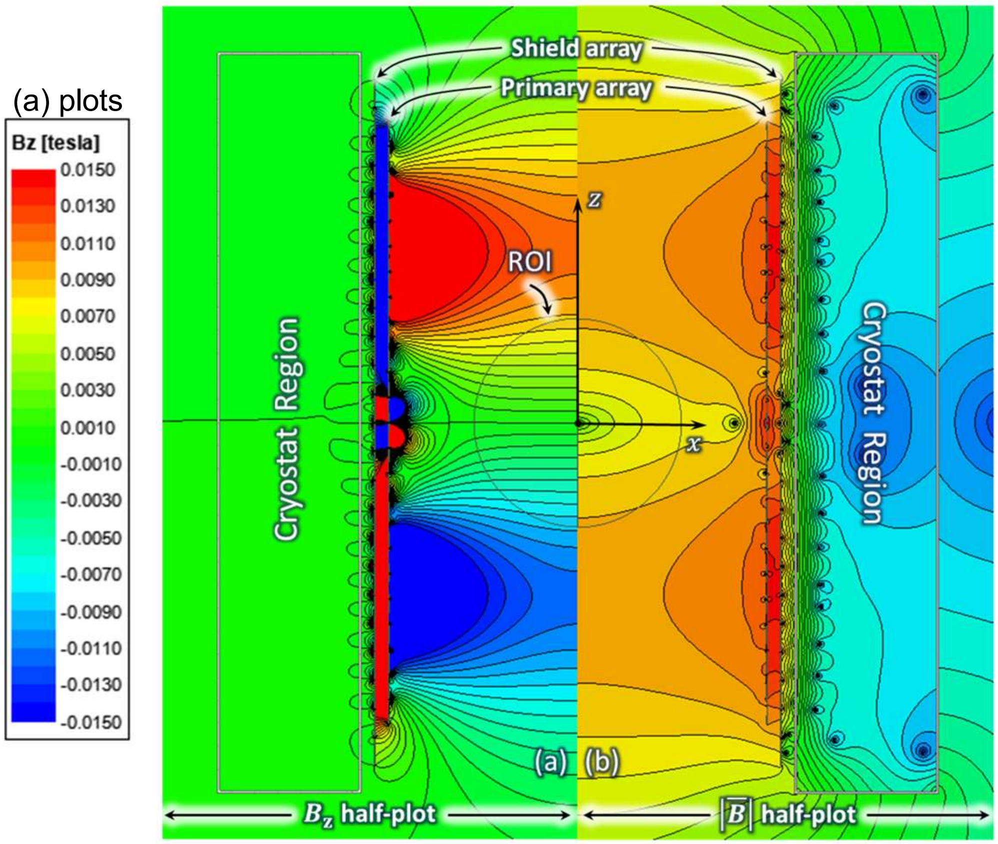
- M is the harmonic truncation number.
- c_m is the complex Fourier series of $s(t)$.

Results (I): B_z & $|\bar{B}|$ fields -Sinusoidal Excitation

Abstract #4573

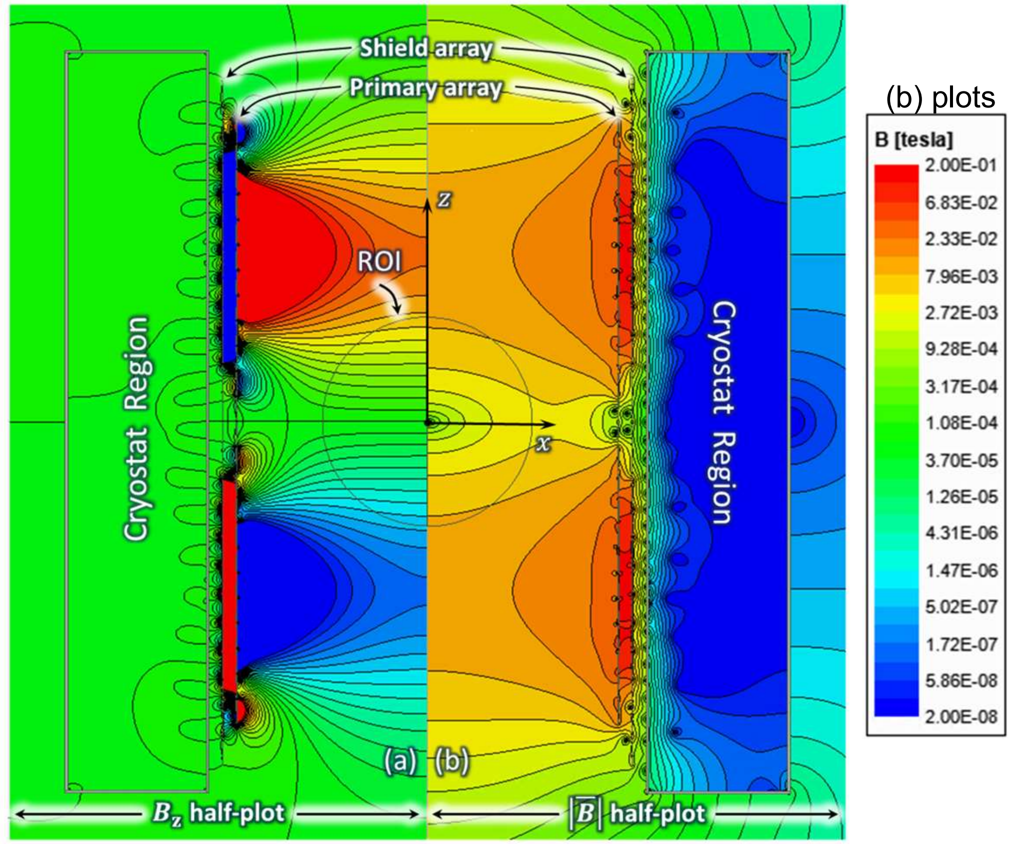
Method: *Stray field minimization* on the cryostat's surface ($N = 48$):

FOV=45cm, Err=5%, G=40mT/m, RMS=186A, Ansys=31.82W (23.61W, 0.043W, 8.16W), Proposed=31.36W, Time=44s.



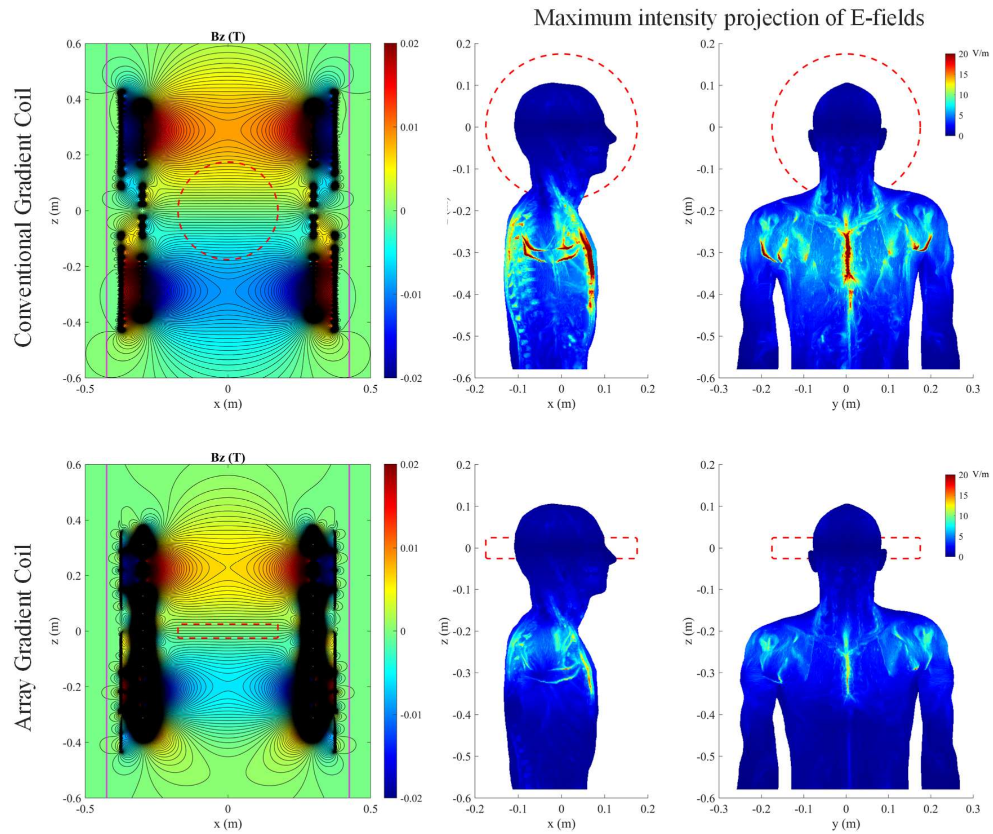
Method: The proposed *quadratic minimization* using $\bar{A}\bar{\bar{Q}}\bar{A}'$ ($N = 48$):

FOV=45cm, Err=5%, G=40mT/m, RMS=186A, Ansys=8.34W (7.24W, 0.005W, 1.10W), Proposed=8.32W, (x3.8 less), Time=3.9s.



- **Gradient Array Coils**:
  - Increasing PNS thresholds:
    - ✓ Induced E-field minimization using field profiling.

Spherical ROL →



Disk-shaped ROL →

$|E|_{max}$ = 56.7 V/m

Reduced 60%

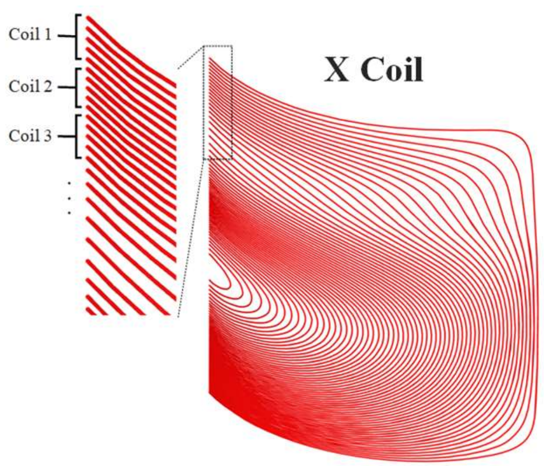
$|E|_{max}$ = 22.6 V/m

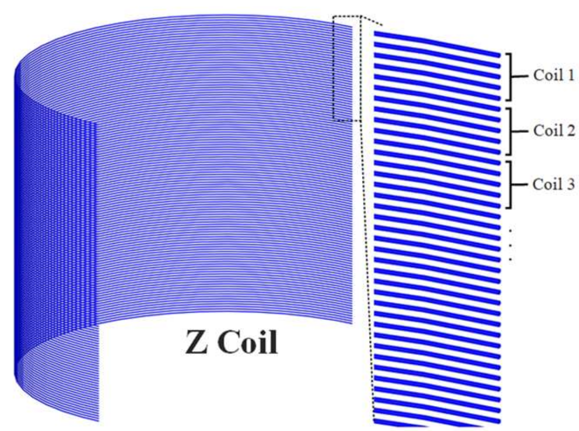
Babaloo R, Takrimi M, Atalar E. Increasing Peripheral Nerve Stimulation Thresholds Using Gradient Array Coils. ISMRM, 2022.

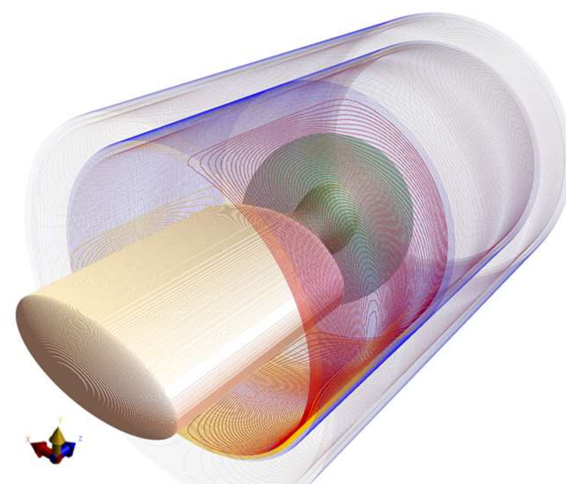
Abstract #0599

Sim4Life: MRI gradient design

- **Coils geometry:**
  - ✓ X, Y, and Z gradients (including shield)
  - ✓ X and Y coils: break down a conventional coil winding into multiple channels.
  - ✓ Z coil: the entire surface of the coil former is covered with circular loops uniformly spaced along the z axis.
  - ✓ Primary coil diameters: X: 690mm, Y: 710mm, Z: 730mm.
  - ✓ We use a simplified body model with uniform interior electrical properties.







Roemer PB et al.. Electric field calculation and peripheral nerve stimulation prediction for head and body gradient coils. MRM, 2021.

- **Field calculations:**
  - Each channel is treated as a basis element.
  - B-fields and E-fields of each channel are computed (unit current).
  - We use low-frequency magneto quasi-static solvers available in Sim4Life[1].
  - Total B-field and E-field can be expressed as a linear combination of basis elements.

  - **B-fields:**

Unit: T/A

Unit: T ←

$$b_z(x,y,z) = \underbrace{\begin{bmatrix} b_{z,1}(x,y,z) & \cdots & b_{z,m}(x,y,z) \end{bmatrix}}_{B_z(x,y,z)} \underbrace{\begin{bmatrix} i_1 \\ \vdots \\ i_m \end{bmatrix}}_{I}$$

  - **E-fields:**

$$E_{Total} = \begin{bmatrix} E_x(x,y,z) \\ E_y(x,y,z) \\ E_z(x,y,z) \end{bmatrix} = \begin{bmatrix} e_{x,1}(x,y,z) & \cdots & e_{x,m}(x,y,z) \\ e_{y,1}(x,y,z) & \cdots & e_{y,m}(x,y,z) \\ e_{z,1}(x,y,z) & \cdots & e_{z,m}(x,y,z) \end{bmatrix} \begin{bmatrix} i_1 \\ \vdots \\ i_m \end{bmatrix}$$

1. Sim4Life by Zurich Med Tech

- **Optimization problem:**

$$I = \begin{bmatrix} i_1 \\ \vdots \\ i_m \end{bmatrix}, \text{ Unknown currents}$$

$$\min_{I} \max_{(x,y,z)} \left(\left| E_{Total} \right| \right)$$

$$s.t. \quad \frac{\max_{(x,y,z)} \left(\left| B_z(x,y,z) I - b_{\text{target}}(x,y,z) \right| \right)}{\max_{(x,y,z)} \left(\left| b_{\text{target}}(x,y,z) \right| \right)} \le \alpha$$

B-field linearity error

$$\left| B_{\text{cryostat}}(x,y,z) I \right| \le B_{\text{c}}(x,y,z)$$

Maximum tolerable magnetic field at the cryostat

$$\left| i_k \right| \le i_{\max} \quad \forall k = 1,\ldots,m$$

Maximum current supported by amplifier

$$\mathbf{T} I = 0$$

Torque matrix

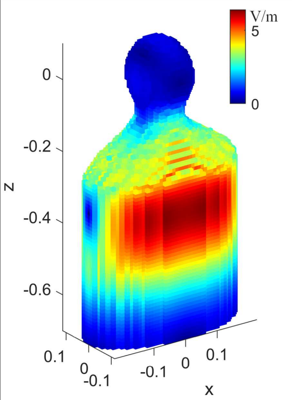
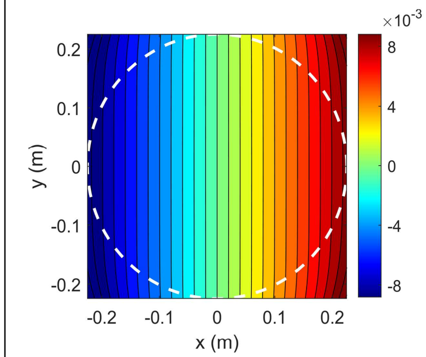
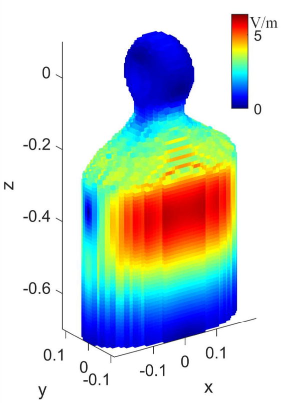
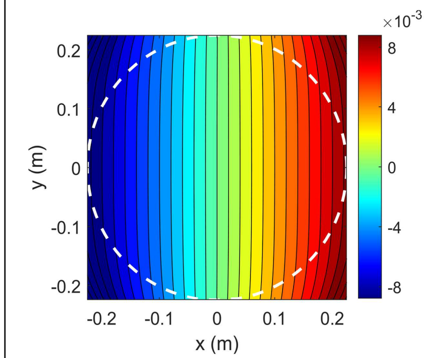
- **PNS thresholds:**
  - ✓ Linear magneto-stimulation formula: $\Delta G_{stim} = \Delta G_{min} + \Delta \text{t}\, SR_{min}$
  - ✓ The PNS parameters:

$$\Delta G_{min} = \frac{\text{rb}}{E_{max} / SR} \text{ch} \qquad SR_{min} = \frac{\text{rb}}{E_{max} / SR}$$

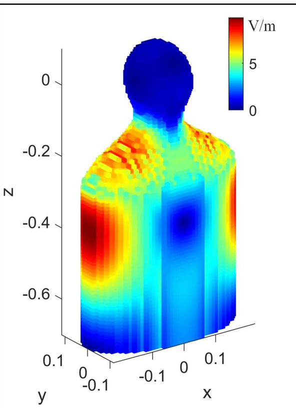
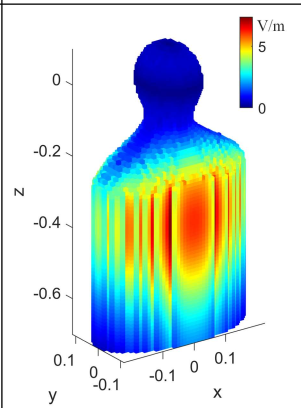
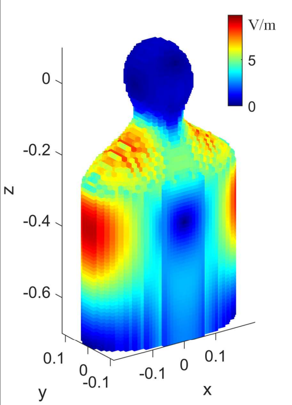
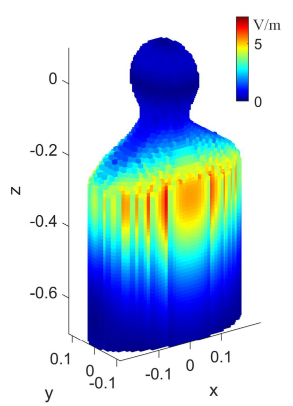
rb : Rheobase = 2.2 V/m

ch : Chronaxie =360µs

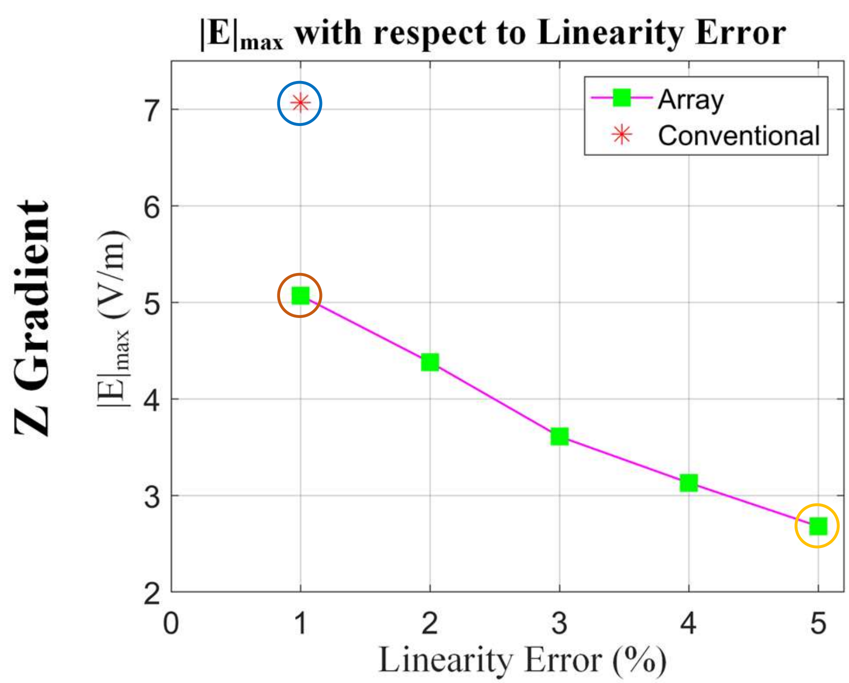
- **Spherical ROL with 225mm radius:**

<table>
<tr><td></td><td colspan="3">X gradient</td></tr>
<tr><td></td><td>Surface E-field</td><td>B-field at xy plane</td><td>Performance</td></tr>
<tr><td>Conventional</td><td></td><td></td><td>$Linearity\ Error = 3.68\%$
$RMS(I_x) = 240A$
$RMS(I_y) = 0A$
$RMS(I_z) = 0A$
$\lvert E\rvert_{max} = 6.40\ V/m$
$\Delta G_{min} = 31\ mT/m$
$SR_{min} = 86\ T/m/s$</td></tr>
<tr><td>Array</td><td></td><td></td><td>$Linearity\ Error = 3.69\%$
$RMS(I_x) = 260A$
$RMS(I_y) = 15.5A$
$RMS(I_z) = 17A$
$\lvert E\rvert_{max} = 6.05\ V/m$
$\Delta G_{min} = 33\ mT/m$
$SR_{min} = 91\ T/m/s$</td></tr>
</table>

➢ Spherical ROL with 225mm radius:

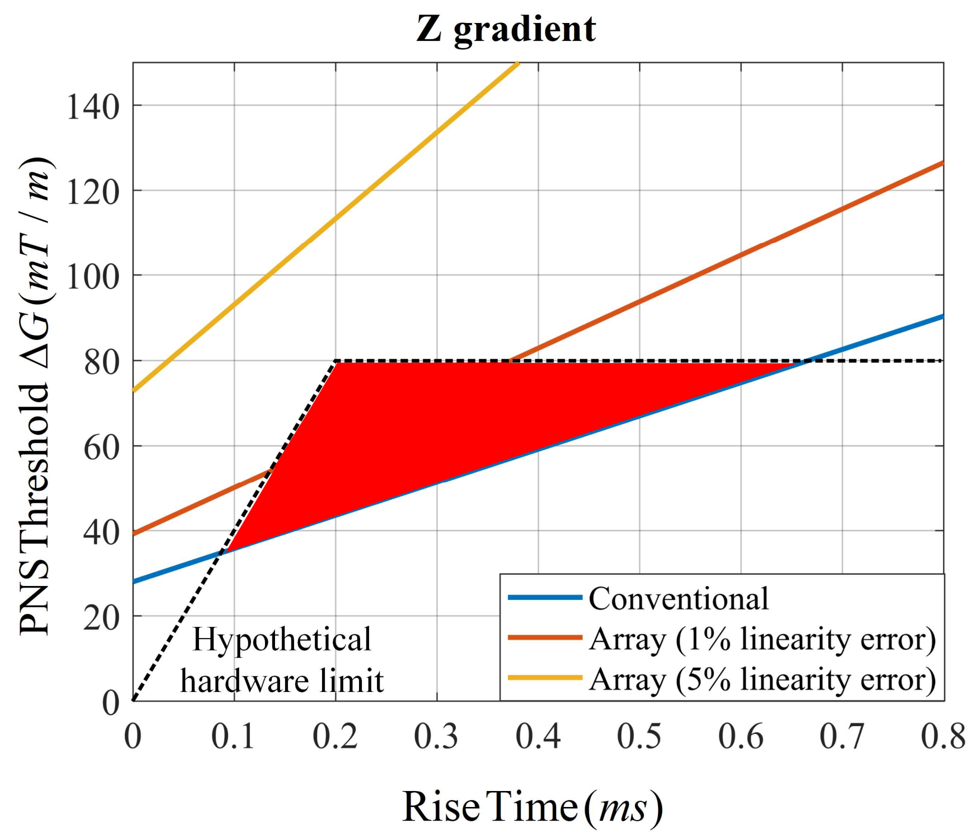
	Y gradient		Z gradient	
	Surface E-field	Performance	Surface E-field	Performance
Conventional		$Linearity\ Error = 4.18\%$ $RMS(I_x) = 0A$ $RMS(I_y) = 252.2A$ $RMS(I_z) = 0A$ $\|E\|_{max} = 9.87\ V/m$ $\Delta G_{min} = 20\ mT/m$ $SR_{min} = 55\ T/m/s$		$Linearity\ Error = 6.63\%$ $RMS(I_x) = 0A$ $RMS(I_y) = 0A$ $RMS(I_z) = 138A$ $\|E\|_{max} = 7.07\ V/m$ $\Delta G_{min} = 28\ mT/m$ $SR_{min} = 78\ T/m/s$
Array		$Linearity\ Error = 4.05\%$ $RMS(I_x) = 10A$ $RMS(I_y) = 299A$ $RMS(I_z) = 10A$ $\|E\|_{max} = 9.26\ V/m$ $\Delta G_{min} = 21.3\ mT/m$ $SR_{min} = 59\ T/m/s$		$Linearity\ Error = 6.69\%$ $RMS(I_x) = 29A$ $RMS(I_y) = 26.7A$ $RMS(I_z) = 186A$ $\|E\|_{max} = 6.42\ V/m$ $\Delta G_{min} = 31\ mT/m$ $SR_{min} = 86T/m/s$

- **Spherical ROL with 120mm radius:**

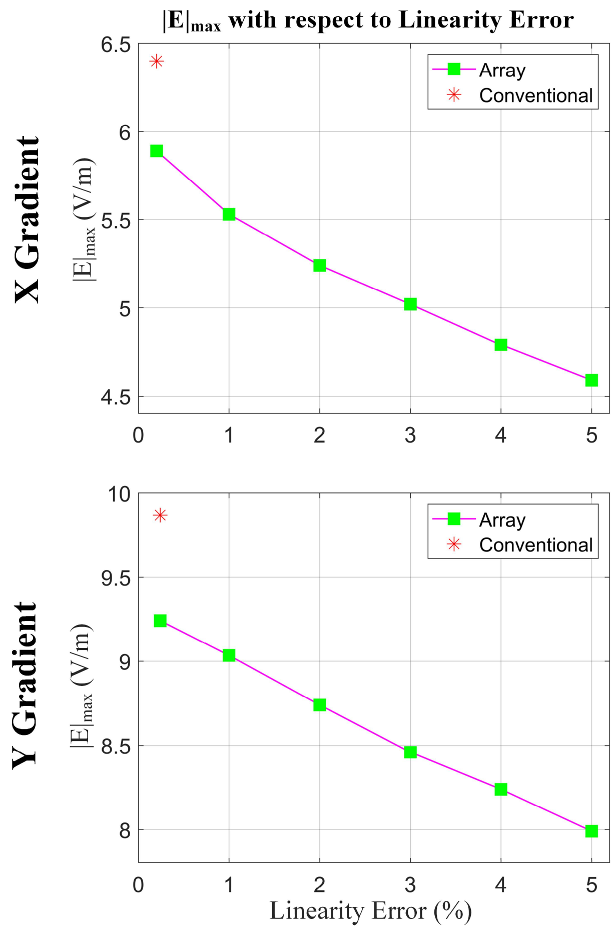


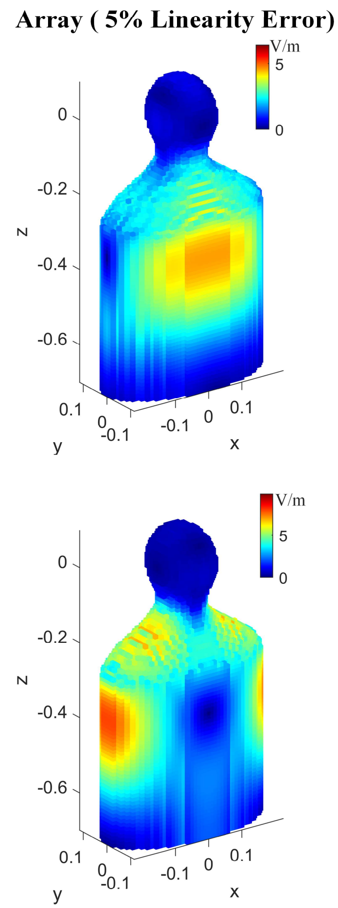
For the same linearity error: 28% reduction in $|E|_{max}$

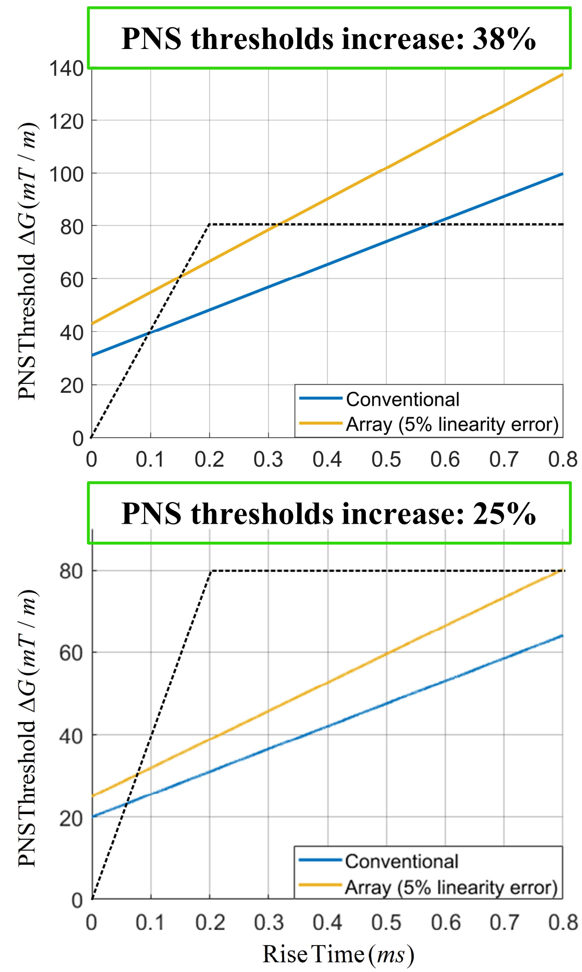
$|E|_{max}$ reduction: 62%



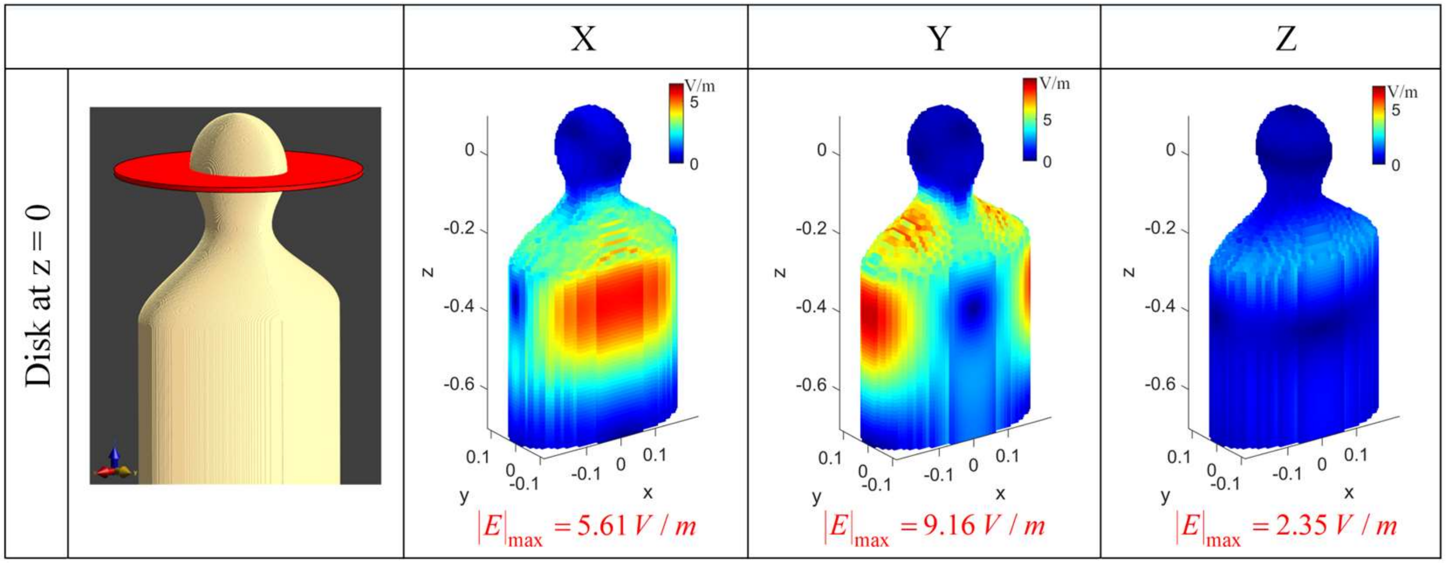
➢ Spherical ROL with 120mm radius:

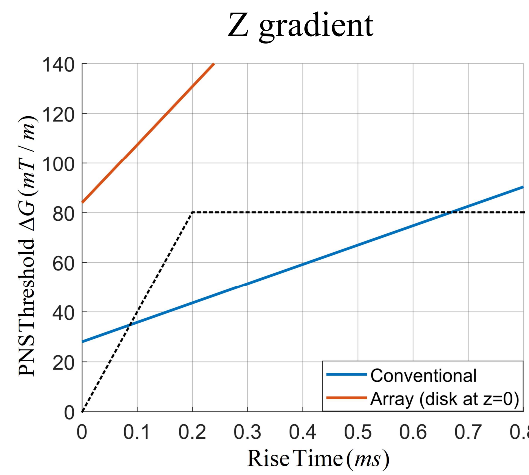






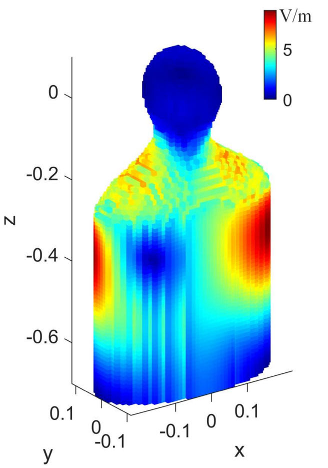
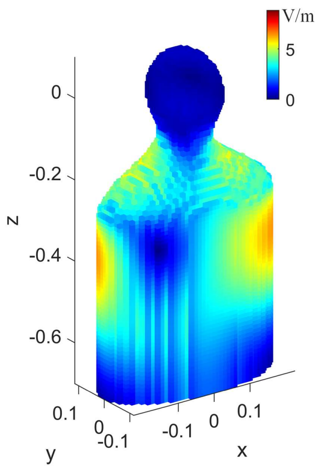
- **Disk-shaped ROL:** at z=0 (20mm thickness)

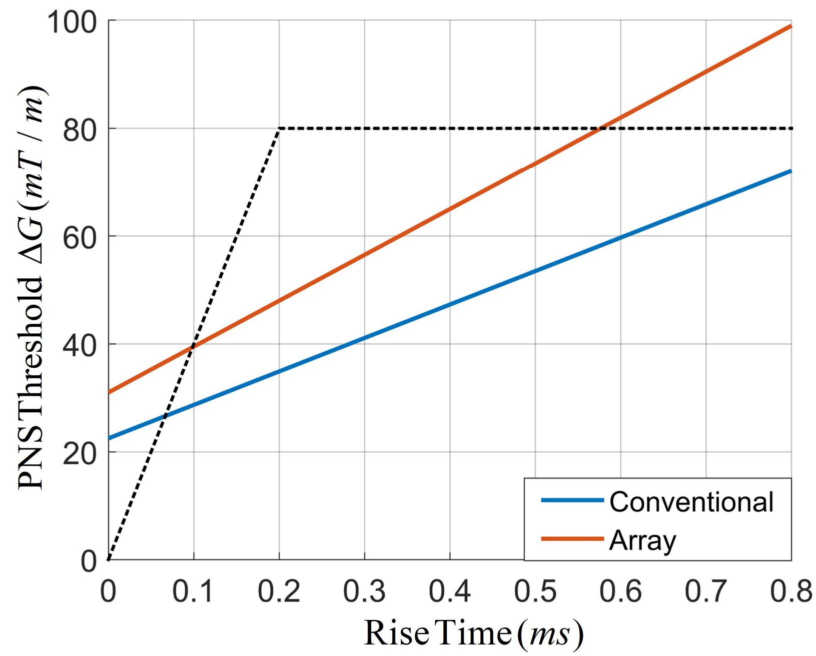




$|E|_{max}$ reduction: 67%
PNS thresholds increase: 3-fold

- **Off-center oblique slice in X+Y direction:** at 0.1m distance from the center with 40mm thickness

	Conventional	Array
X+Y axis	 $Linearity\ Error = 7.81\%$ $RMS(I_x) = 169.6A$ $RMS(I_y) = 178.3A$ $RMS(I_z) = 0A$ $\lvert E \rvert_{max} = 8.83V/m$ $\Delta G_{min} = 22.5\ mT/m$ $SR_{min} = 62\ T/m/s$	 $Linearity\ Error = 7.79\%$ $RMS(I_x) = 151A$ $RMS(I_y) = 153A$ $RMS(I_z) = 23A$ $\lvert E \rvert_{max} = 6.44\ V/m$ $\Delta G_{min} = 31\ mT/m$ $SR_{min} = 85\ T/m/s$



$\lvert E \rvert_{max}$ reduction: 27%
PNS thresholds increase: 36%

- **Alternative optimization:**

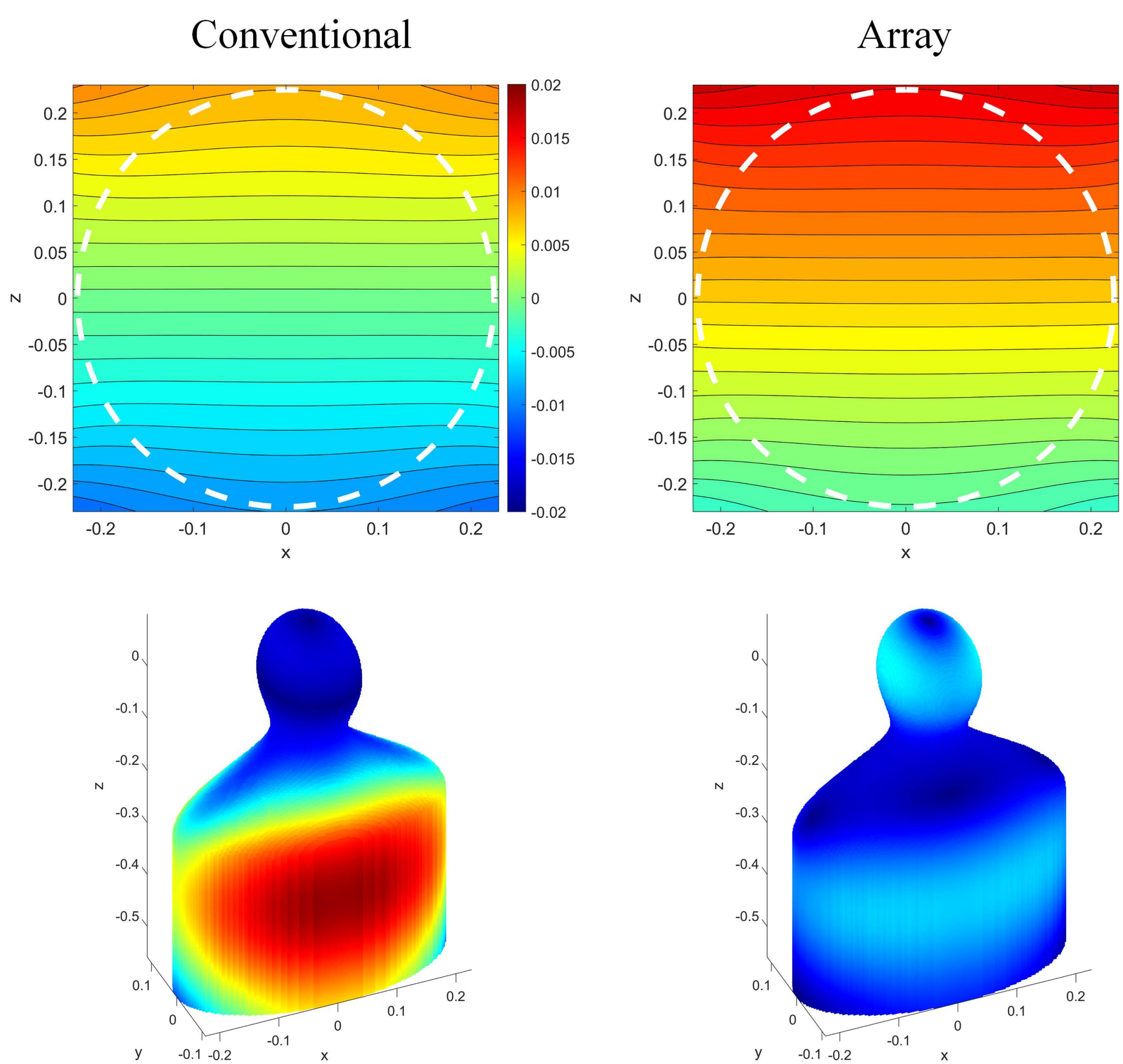
$$\min_{I} \max_{(x,y,z)} \left(\left|E_{Total}\right|\right)$$

$$s.t. \quad \frac{\max\limits_{(x,y,z)}\left(\left\|G_z(x,y,z)I - g_{\text{target}}(x,y,z)\right\|\right)}{\max\limits_{(x,y,z)}\left(\left\|g_{\text{target}}(x,y,z)\right\|\right)} \le \alpha$$

$$\left|B_{\text{cryostat}}(x,y,z)I\right| \le B_{\text{c}}(x,y,z)$$

$$\left|i_k\right| \le i_{\max} \quad \forall k = 1,\ldots,m$$

$$\mathbf{T}I = 0$$



Z gradient

- **Considering a heterogeneous body model with E-fields at the exact location of nerves:**