Battling Maxwell’s Equations
Physics Challenges and Solutions for Hybrid MRI Systems

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Representing The Australian MRI-Linac Program Team
Disclosures

› **Patents:** Awarded and pending

› **Licenses:** Nano-X, Respiratory Innovations, Standard Imaging, Varian

› **Grants:** Philips (Co-Investigator), Varian (Co-I)

› **Ownership:** Cancer Research Innovations, Nano-X, Respiratory Innovations

Introduction

Battling Maxwell’s Equations
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AAPM 2015
<table>
<thead>
<tr>
<th>LAW</th>
<th>DIFFERENTIAL FORM</th>
<th>INTEGRAL FORM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauss law for electricity</td>
<td>$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} = 4\pi k \rho$</td>
<td>$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\varepsilon_0}$</td>
</tr>
<tr>
<td>Gauss law for magnetism</td>
<td>$\nabla \cdot \vec{B} = 0$</td>
<td>$\oint \vec{B} \cdot d\vec{A} = 0$</td>
</tr>
<tr>
<td>Faraday's law of induction</td>
<td>$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$</td>
<td>$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$</td>
</tr>
<tr>
<td>Ampere's law</td>
<td>$\nabla \times \vec{B} = \frac{\vec{J}}{\varepsilon_0 c^2} + \frac{1}{c^2} \frac{\partial \vec{E}}{\partial t}$</td>
<td>$\oint \vec{B} \cdot d\vec{s} = \mu_0 i + \frac{1}{c^2} \frac{\partial}{\partial t} \oint \vec{E} \cdot d\vec{A}$</td>
</tr>
</tbody>
</table>

**NOTES:** E - electric field, $\rho$ - charge density, $\varepsilon_0 \approx 8.85 \times 10^{-12}$ - electric permittivity of free space, $\tau \approx 3.14159$, $k$ - Boltzmann's constant, $q$ - charge, $B$ - magnetic induction, $\Phi$ - magnetic flux, $J$ - current density, $i$ - electric current, $c \approx 299792458$ m/s - the speed of light, $\mu_0 = 4\pi \times 10^{-7}$ - magnetic permeability of free space, $\nabla$ - del operator (if $\mathbf{V}$ is a vector function, then $\nabla \cdot \mathbf{V}$ is divergence of $\mathbf{V}$, $\nabla \times \mathbf{V}$ is the curl of $\mathbf{V}$).
Maxwell’s equations describe which forces?

A. Electric and gravitational
B. Electric and magnetic
C. Gravitational and magnetic
D. Nuclear strong and weak
Maxwell’s equations describe which forces?

A. Electric and gravitational
B. Electric and magnetic
C. Gravitational and magnetic
D. Nuclear strong and weak

$B_0$ field from superposition of current loops (Biot-Savart law)
Gradient fields (Ampere’s law)
RF transmit/receive (wave equation)
Changing magnetic fields (Eddy currents)
Electrostatic field in electron gun (Gauss’s law, Lorentz force effects)
RF in accelerating cavity (wave equation [no particles])
$B_0$ effect on treatment head and patient transport (Lorentz force)
Ferromagnetic material impact on MRI (Ampere’s law)
Magnetic field effects on the linac electron gun

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MRI field for a 1T split bore design

2/Jul/2012 10:44:56

Map contours: BMOD
2.000000E+004
1.900000E+004
1.600000E+004
1.400000E+004
1.200000E+004
1.000000E+004
8.000000E+003
6.000000E+003
4.000000E+003
2.000000E+003
6.000000E+002
Integral = 6.019034E+009

Courtesy Agilent
Electron Gun

- Thermionic cathode
- Focusing Electrode
- Anode
- Electron Beam
- 1st Accelerating Cavity

Courtesy Brendan Whelan
Impact of B fields on unshielded guns

0 T

0.016 T =

0.002 T ⊥

0.028 T =

0.004 T ⊥

Constantin Med Phys 2011
Inline \( B_0 \parallel \) electron beam) and perpendicular \( B_0 \perp \) electron beam) magnetic fields affect linac electron guns by:

A. Inline fields affect the beam focus; perpendicular fields deflect the electrons away from the anode

B. Inline fields deflect the electrons away from the anode; perpendicular fields affect the beam focus

C. Inline fields and perpendicular fields affect the beam focus

D. Inline fields and perpendicular fields deflect the electrons away from the anode

Note: \( \parallel \) = parallel; \( \perp \) = perpendicular, orthogonal
Inline (\(B_0 \parallel\) electron beam) and perpendicular (\(B_0 \perp\) electron beam) magnetic fields affect linac electron guns by:

A. Inline fields affect the beam focus; perpendicular fields deflect the electrons away from the anode
B. Inline fields deflect the electrons away from the anode; perpendicular fields affect the beam focus
C. Inline fields and perpendicular fields affect the beam focus
D. Inline fields and perpendicular fields deflect the electrons away from the anode

Magnetic field effects on the linac waveguide

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An example accelerator

Predefined electric field
2D Maximum: 1.041e+08
Cutplane normal: 0, 1, 0
Cutplane position: 0
Frequency: 2.985e+09
Phase: 168.75
Scaling Factor: 1 + i 0

Courtesy Brendan Whelan
Electron transport in a linac

<table>
<thead>
<tr>
<th>Plottype</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample</td>
<td>(2/375)</td>
</tr>
<tr>
<td>Time</td>
<td>4.146e+000 ps</td>
</tr>
<tr>
<td>Particles</td>
<td>243</td>
</tr>
</tbody>
</table>

Courtesy Brendan Whelan
Electrons in a linac: $B = 0.1 \text{T}$ inline
Electrons in a linac: $B = 0.05\text{T perp.}$
Magnetic field effects on treatment head/patient radiation transport

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Skin dose in magnetic fields

B = 0T          B = 1T MRI

Inline

Oborn Med Phys 2014

Perpendicular

Keyvanloo Med Phys 2012
Inline \( (B_0 \parallel \text{electron beam}) \) and perpendicular \( (B_0 \perp \text{electron beam}) \) magnetic fields affect the transport of electrons generated in the treatment head and air column. Which of the following statements is correct?

A. Inline and perpendicular fields both decrease the skin dose

B. Inline and perpendicular fields both increase the skin dose

C. Inline fields decrease the skin dose and perpendicular fields increase the skin dose

D. Inline fields increase the skin dose and perpendicular fields decrease the skin dose

E. The magnetic field has no effect on the skin dose

Note: \( || \) = parallel; \( \perp \) = perpendicular, orthogonal
Inline ($B_0 \parallel$ electron beam) and perpendicular ($B_0 \perp$ electron beam) magnetic fields affect the transport of electrons generated in the treatment head and air column. Which of the following statements is correct?

A. Inline and perpendicular fields both decrease the skin dose  
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C. Inline fields decrease the skin dose and perpendicular fields increase the skin dose  
D. Inline fields increase the skin dose and perpendicular fields decrease the skin dose  
E. The magnetic field has no effect on the skin dose
Linac effects on the magnetic field

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MLCs are magnetic
Impact of MLCs on magnetic uniformity

Setup

- Agilent split-bore MRI magnet
  - $B_0 = 1.0$ T
  - Two beam orientations

SID: Source-to-isocentre distance

Kolling Med Phys 2013
Impact of MLCs on magnetic uniformity

Increase separation

MRI imaging volume
The main effect that the ferromagnetic materials in the linac have on the MRI operation is in the:

A. Gradient system
B. Magnetic field uniformity
C. Power system
D. Cooling system
E. Radiofrequency system
SAMS Question

The main effect that the ferromagnetic materials in the linac have on the MRI operation is in the:

A. Gradient system
B. Magnetic field uniformity
C. Power system
D. Cooling system
E. Radiofrequency system
Summary

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MRI physics and engineering is challenging
Linac physics and engineering is challenging
MRI-Linac physics and engineering is challenging

Is it worth it?
- Anatomy
- Physiology
- Beyond oncology