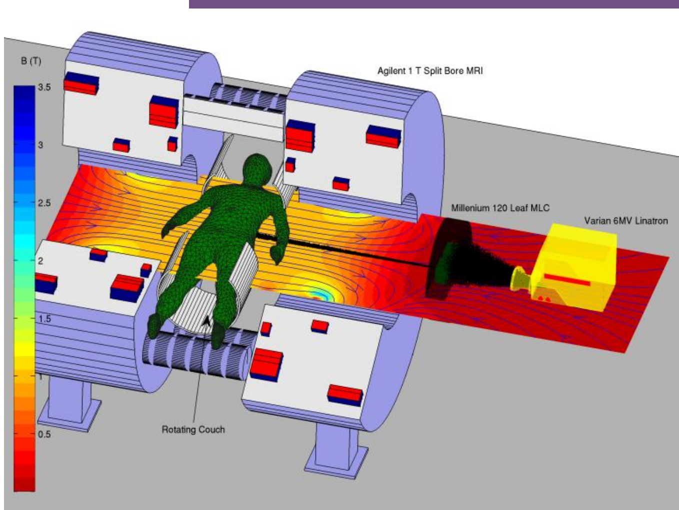
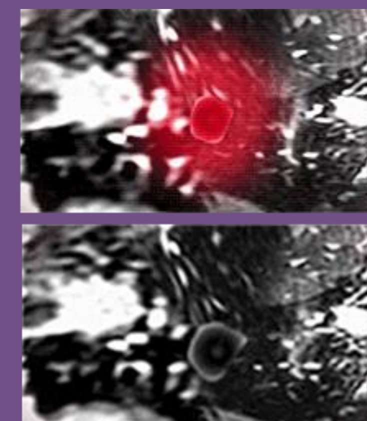
Battling Maxwell’s Equations
Physics Challenges and Solutions for Hybrid MRI Systems





PAUL KEALL, BRENDAN WHELAN and BRAD OBORN

Representing The Australian MRI-Linac Program Team

THE UNIVERSITY OF SYDNEY

Ingham Institute Applied Medical Research

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

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

http://sydney.edu.au/medicine/radiation-physics/about-us/disclosures.php

Introduction

Battling Maxwell's Equations
Physics Challenges and Solutions for Hybrid MRI Systems
AAPM 2015

THE UNIVERSITY OF SYDNEY

MAXWELL'S EQUATIONS IN FREE SPACE (in SI units)

LAW	DIFFERENTIAL FORM	INTEGRAL FORM
Gauss law for electricity	$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} = 4\pi k\rho$	$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\varepsilon_0}$
Gauss law for magnetism	$\nabla \cdot \vec{B} = 0$	$\oint \vec{B} \cdot d\vec{A} = 0$
Faraday's law of induction	$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$	$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$
Ampere's law	$\nabla \times \vec{B} = \frac{\vec{J}}{\varepsilon_0 c^2} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$	$\oint \vec{B} \cdot d\vec{s} = \mu_0 i + \frac{1}{c^2}\frac{\partial}{\partial t}\int \vec{E} \cdot d\vec{A}$

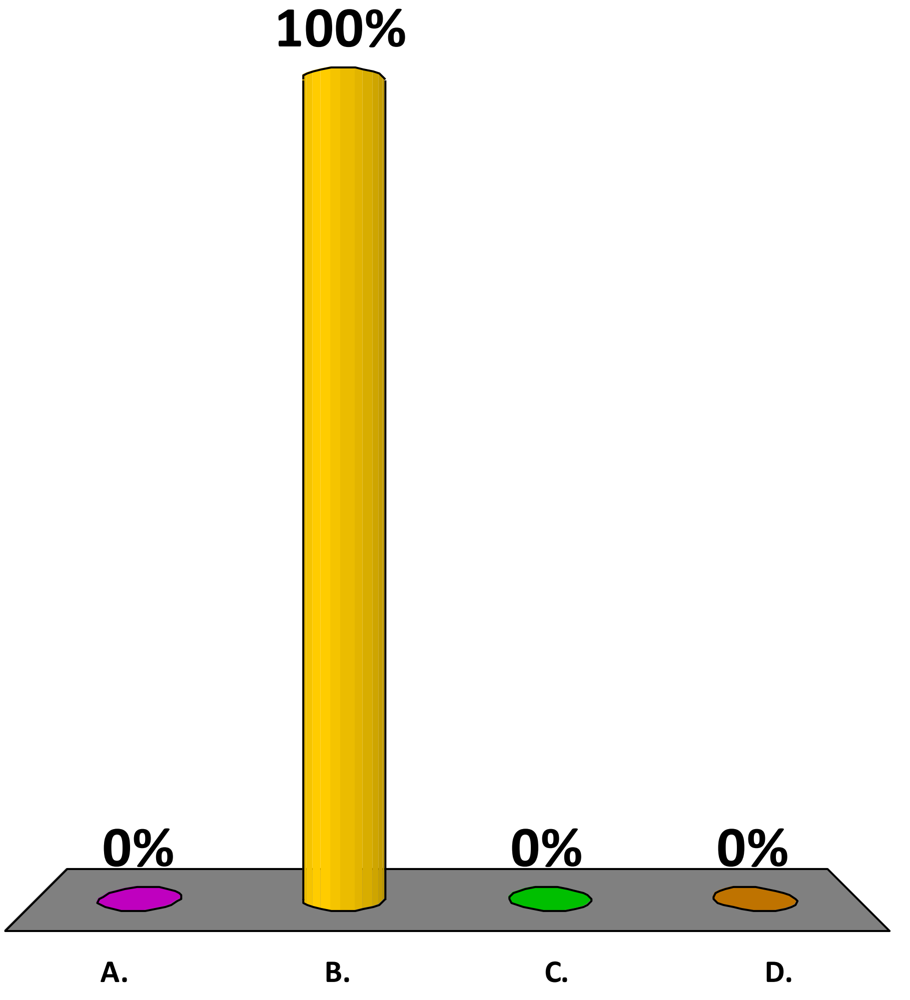
NOTES: E - electric field, ρ - charge density, $\varepsilon_0 \approx 8.85\times10^{-12}$ - electric permittivity of free space, π ≈ 3.14159, k - Boltzmann's constant, q - charge, B - magnetic induction, Φ - magnetic flux, J - current density, i - electric current,
c ≈ 299 792 458 m/s - the speed of light, $\mu_0 = 4\pi\times10^{-7}$ - magnetic permeability of free space, ∇ - del operator (if **V** is a vector function, then $\nabla \cdot$**V** is divergence of **V**, $\nabla \times$**V** is the curl of **V**).

http://www.smps.us/electrical-engineering.html

SAMS Question

Maxwell's equations describe which forces?

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

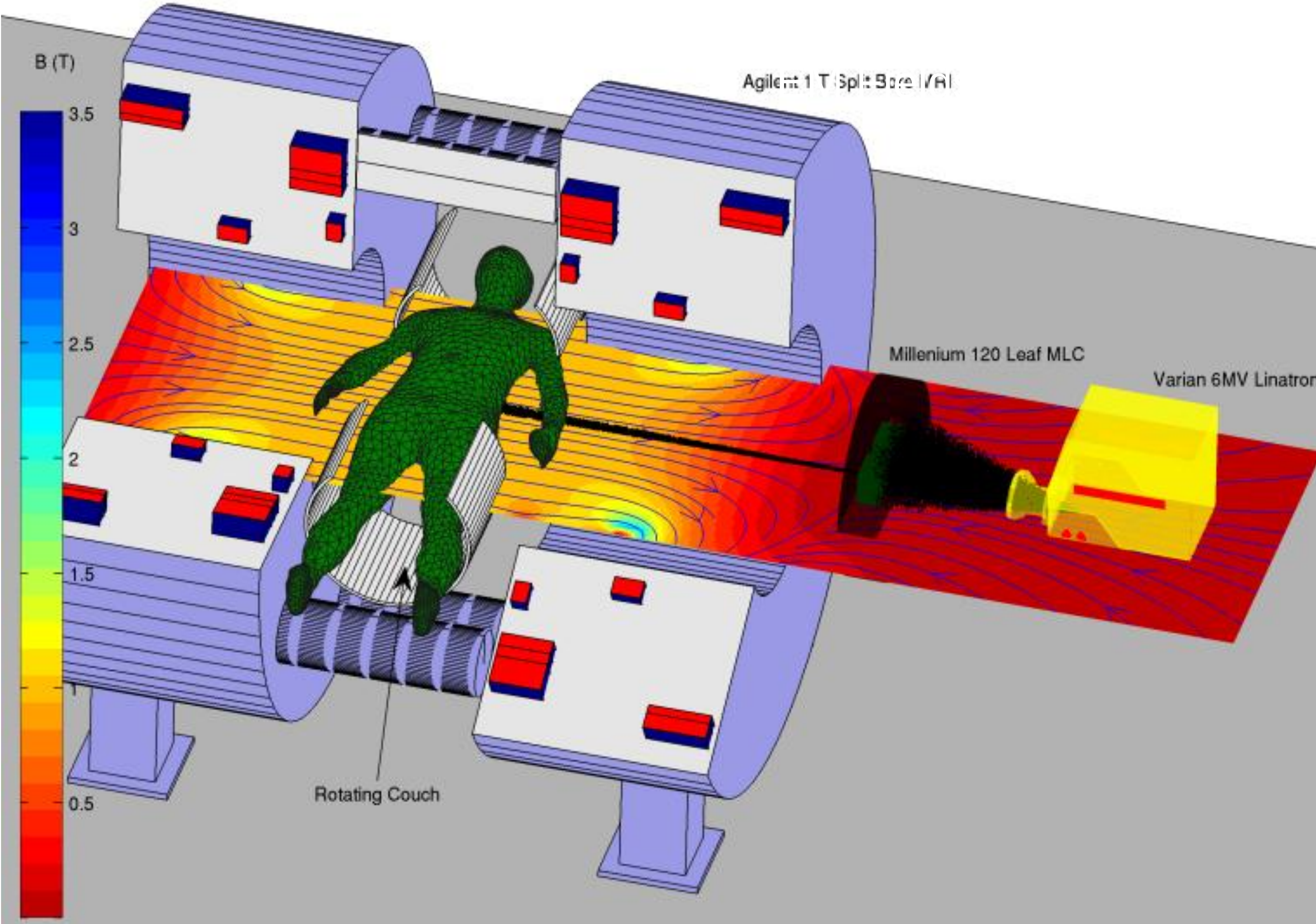


SAMS Question

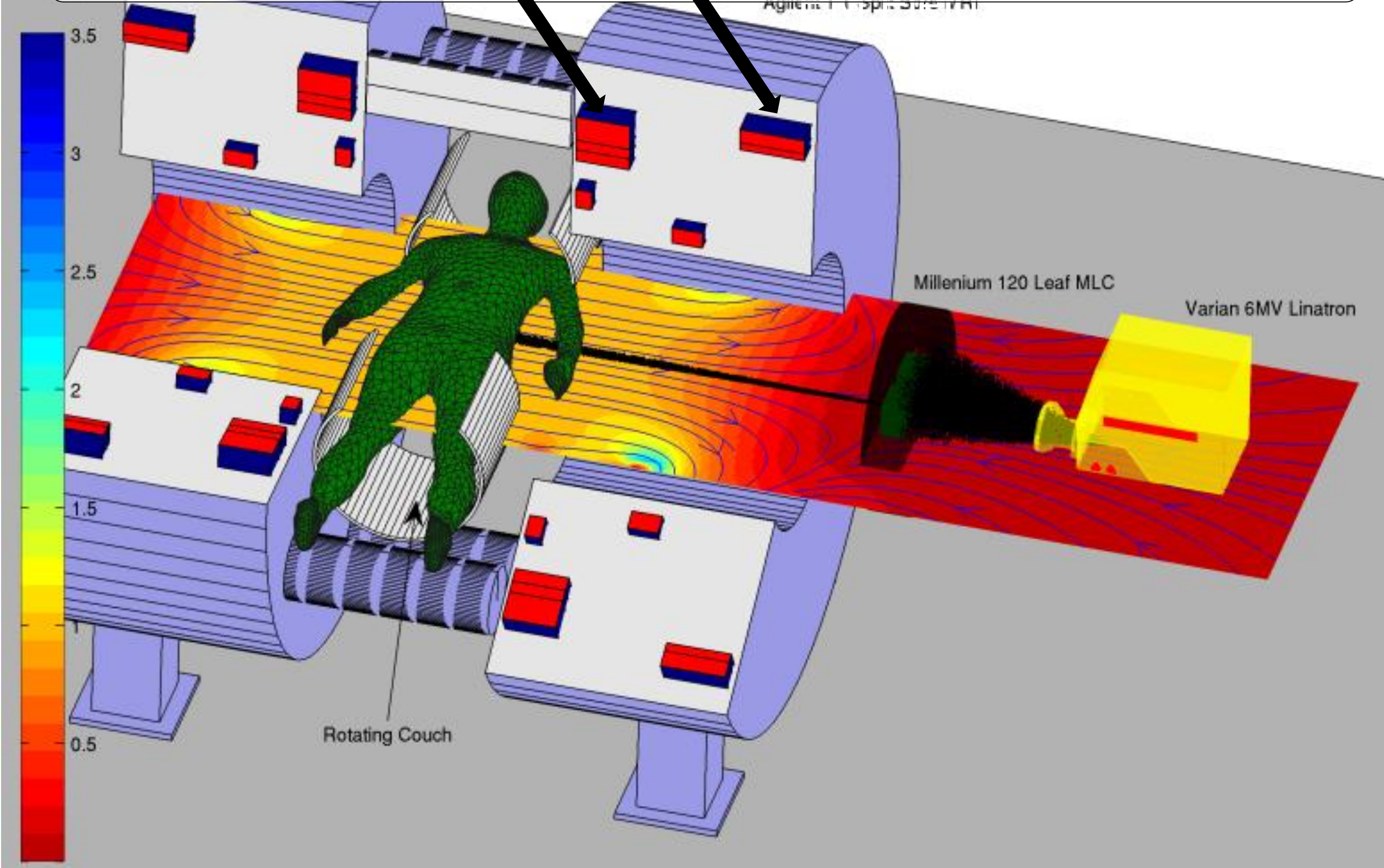
Maxwell's equations describe which forces?

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

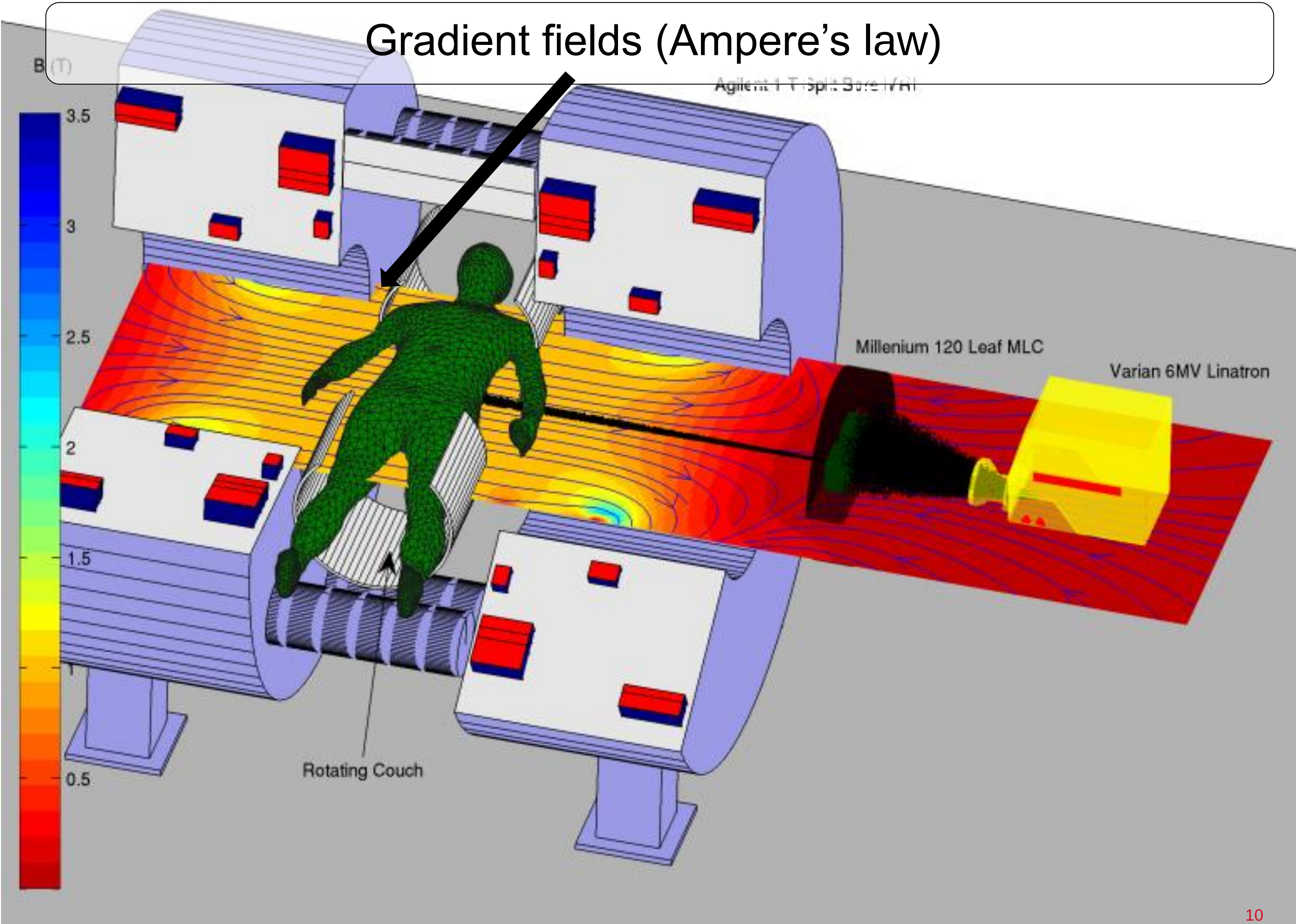
Ref: Classical Electrodynamics. Jackson (3rd edition). Free download!


B (T)
3.5
3
2.5
2
1.5
1
0.5
Agilent 1 T Split Bore MRI
Millenium 120 Leaf MLC
Varian 6MV Linatron
Rotating Couch

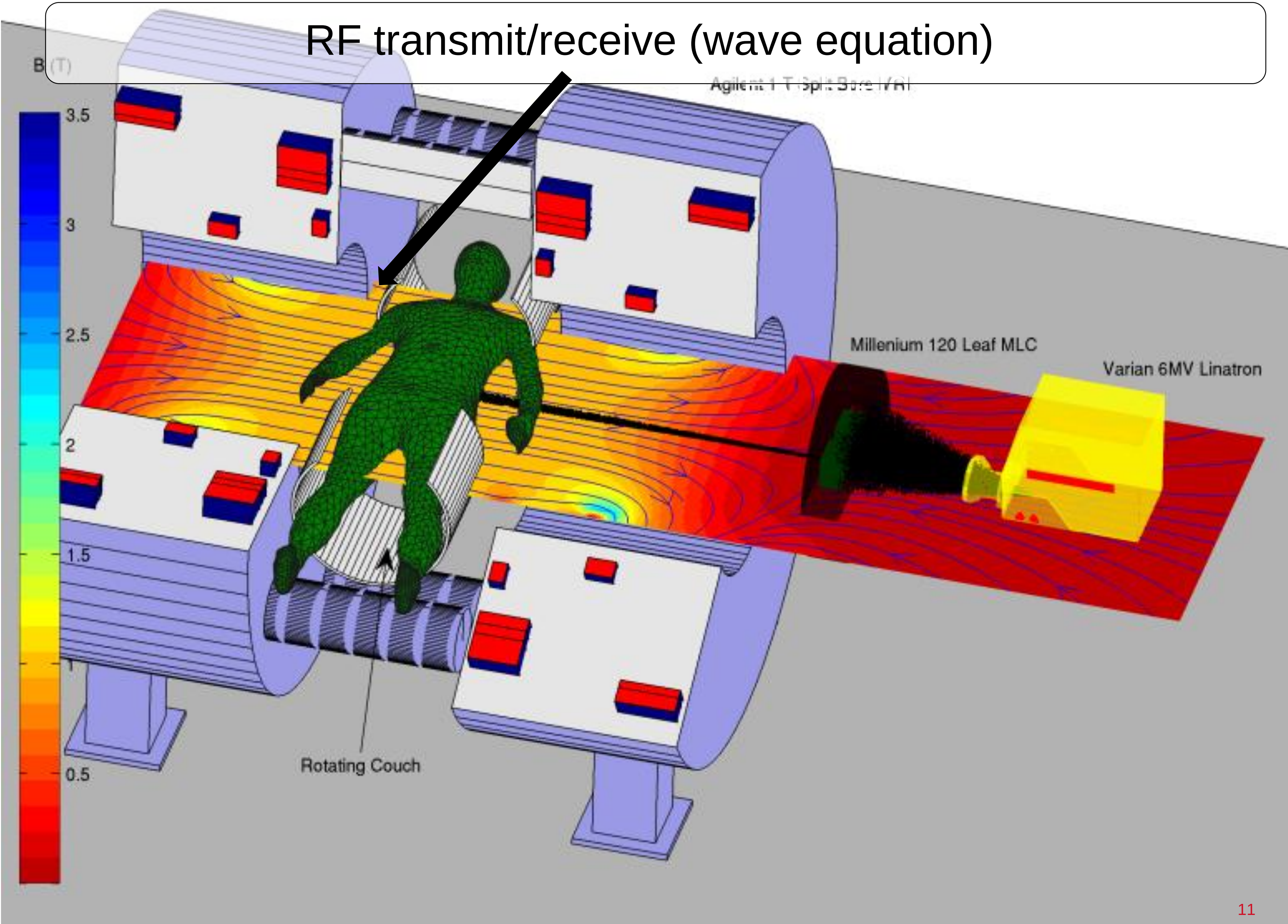
B_0 field from superposition of current loops (Biot-Savart law)



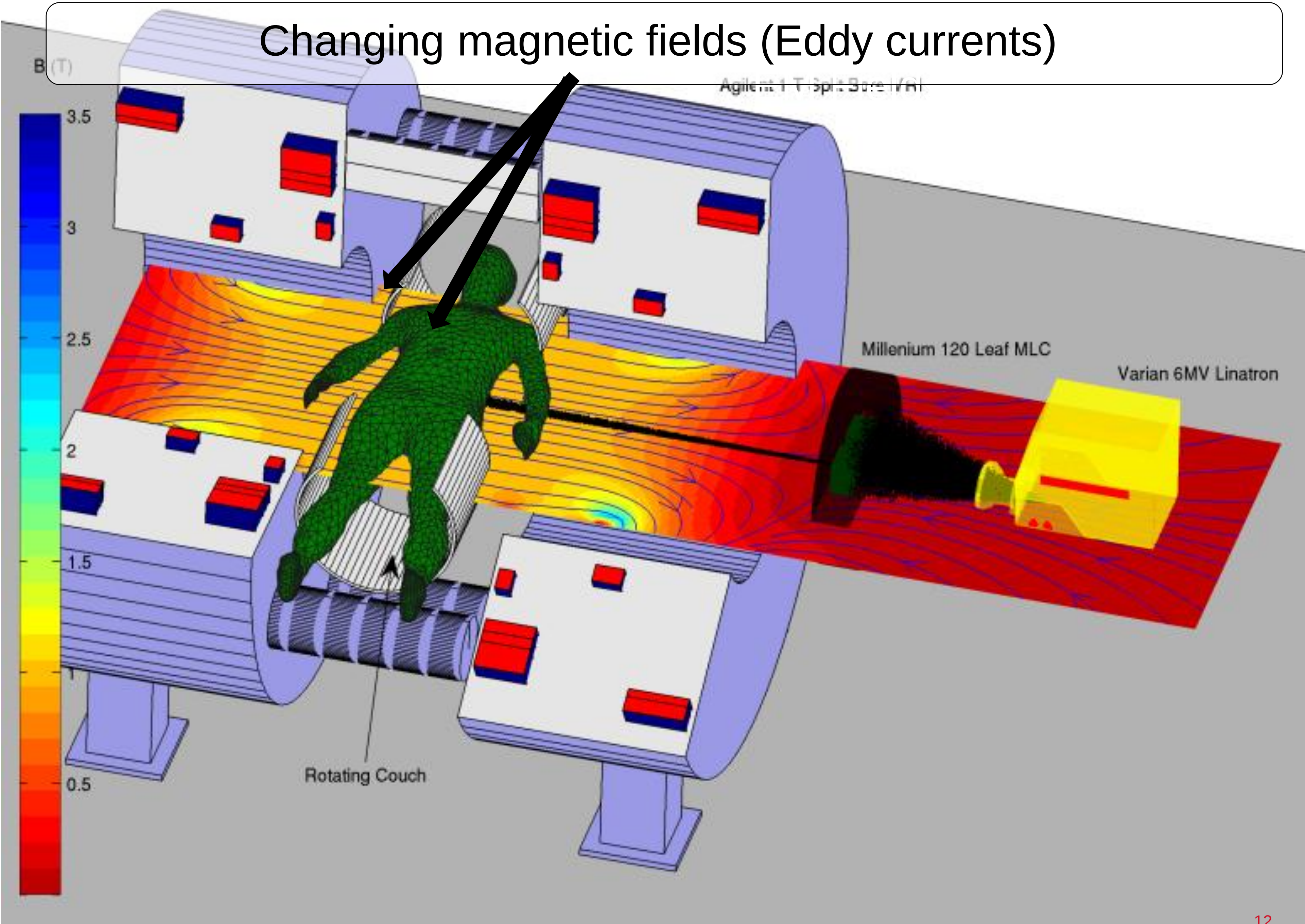
Gradient fields (Ampere's law)



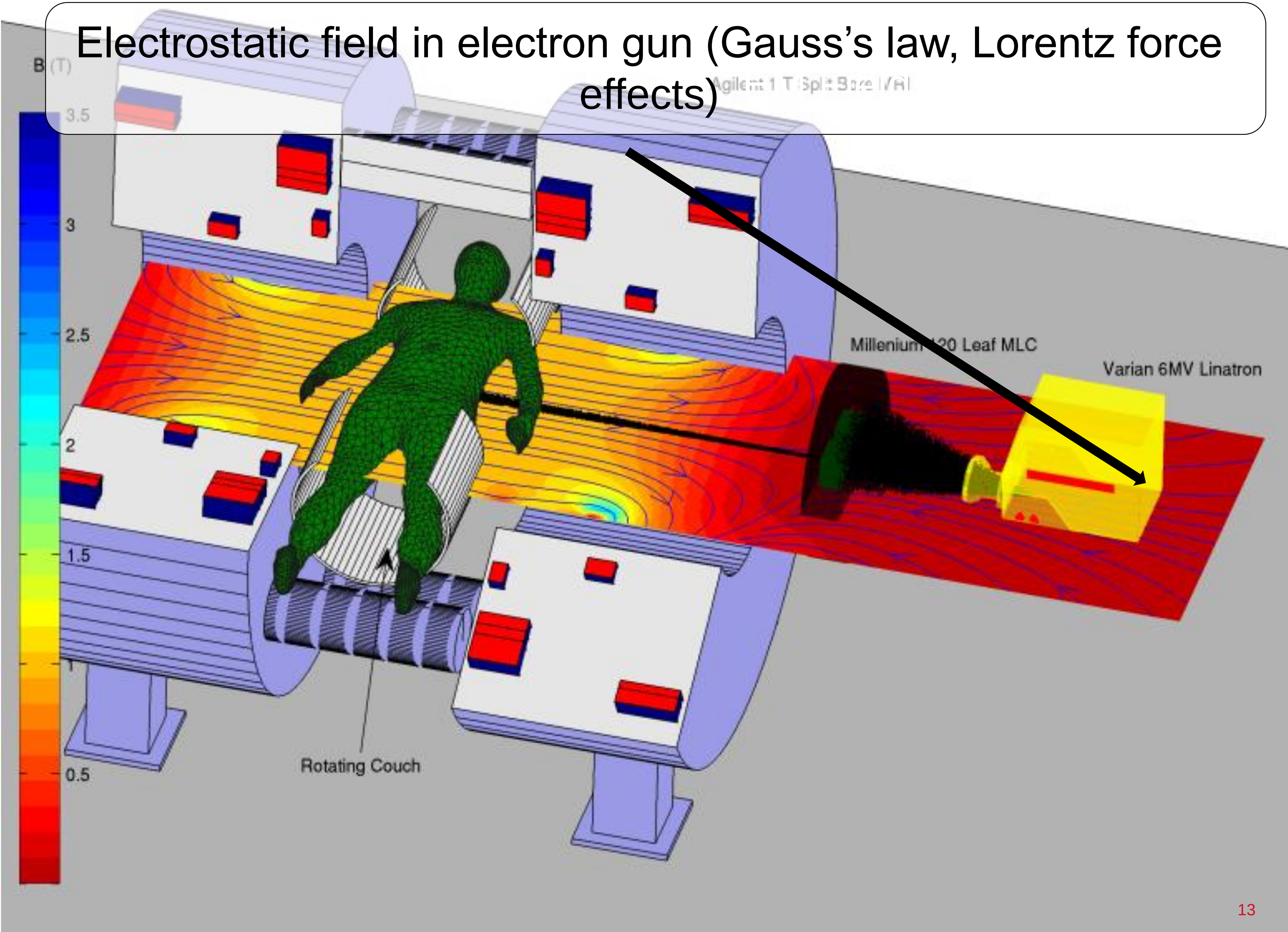
RF transmit/receive (wave equation)



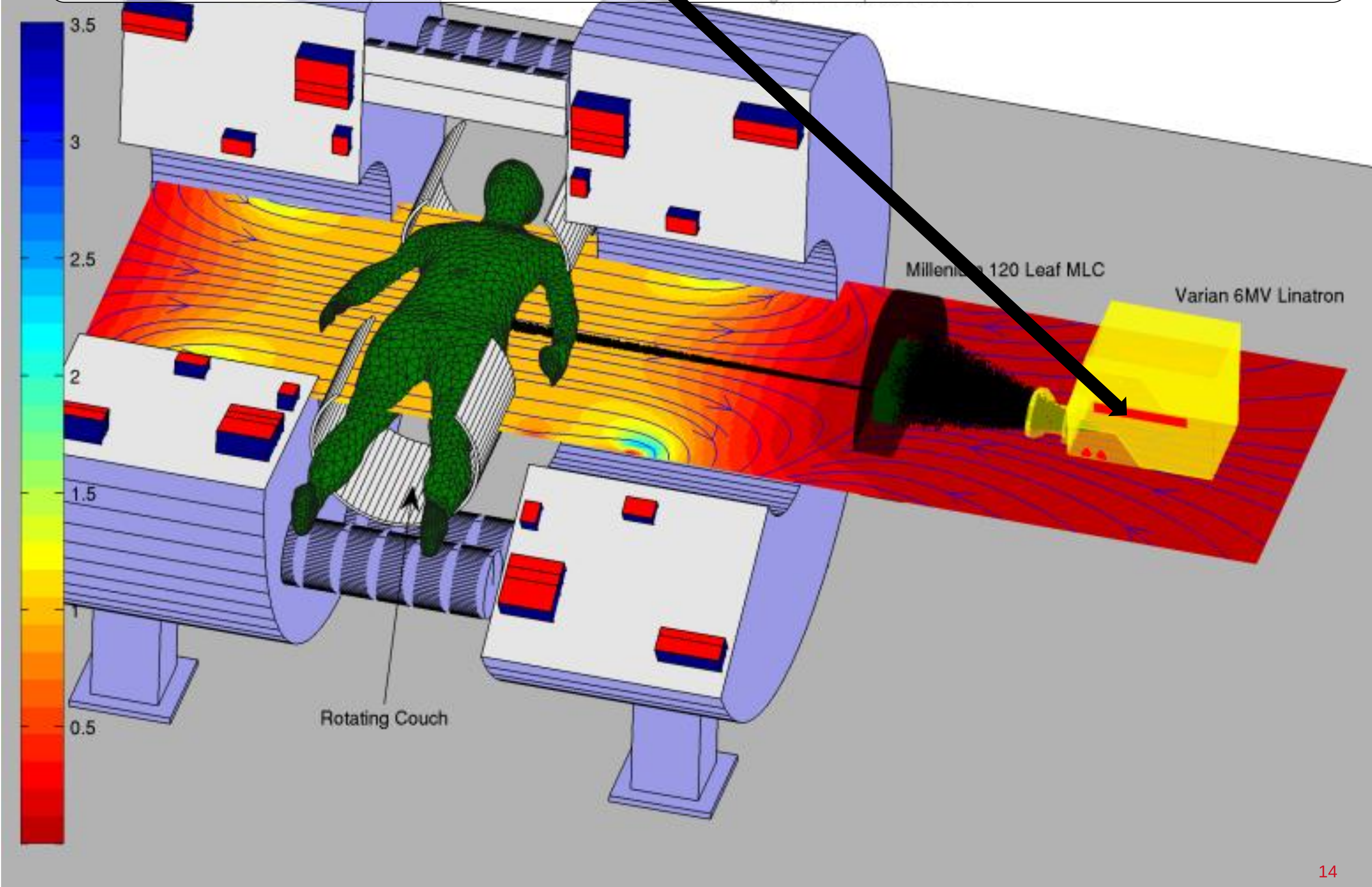
Changing magnetic fields (Eddy currents)



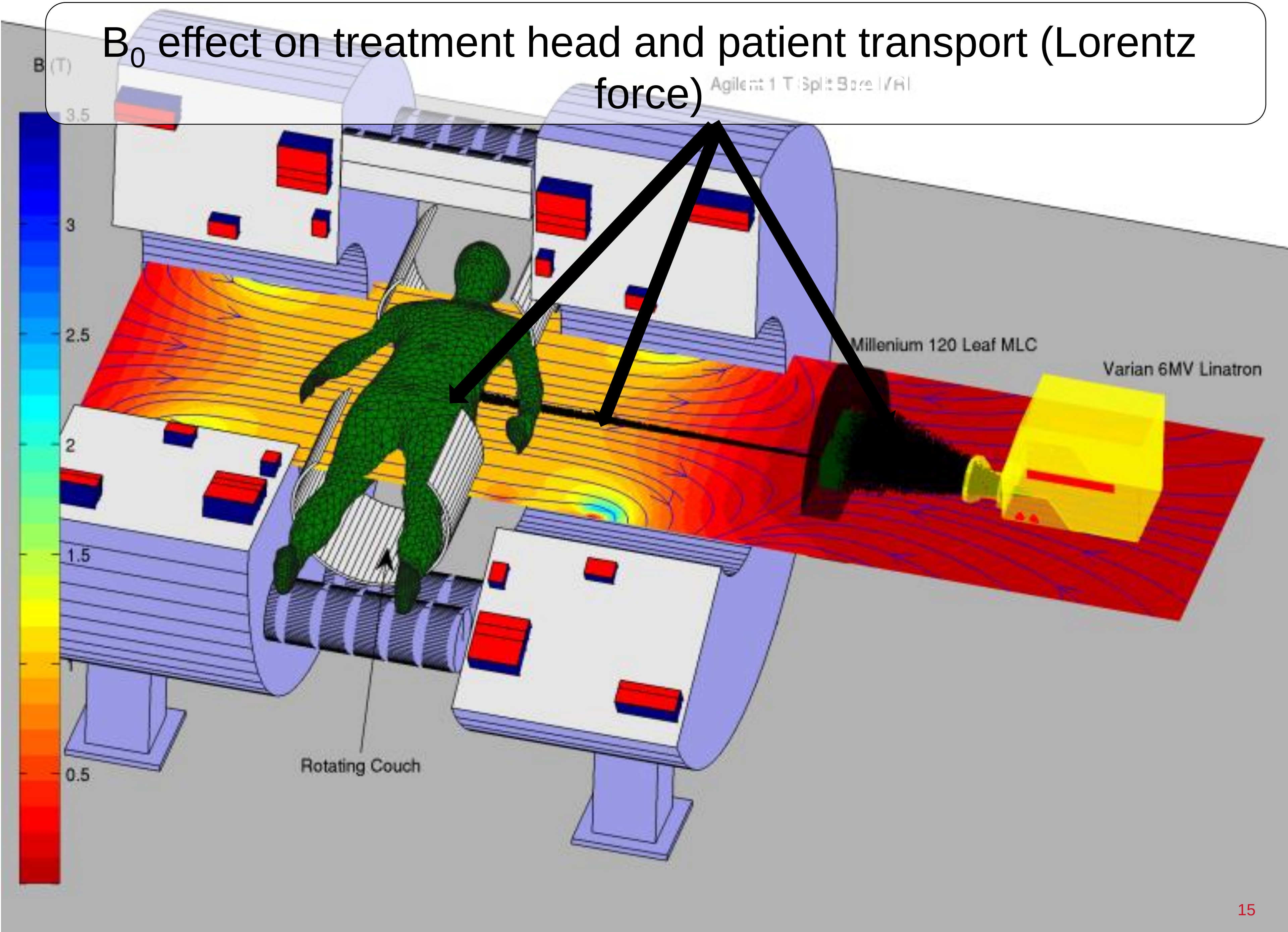
Electrostatic field in electron gun (Gauss's law, Lorentz force effects)



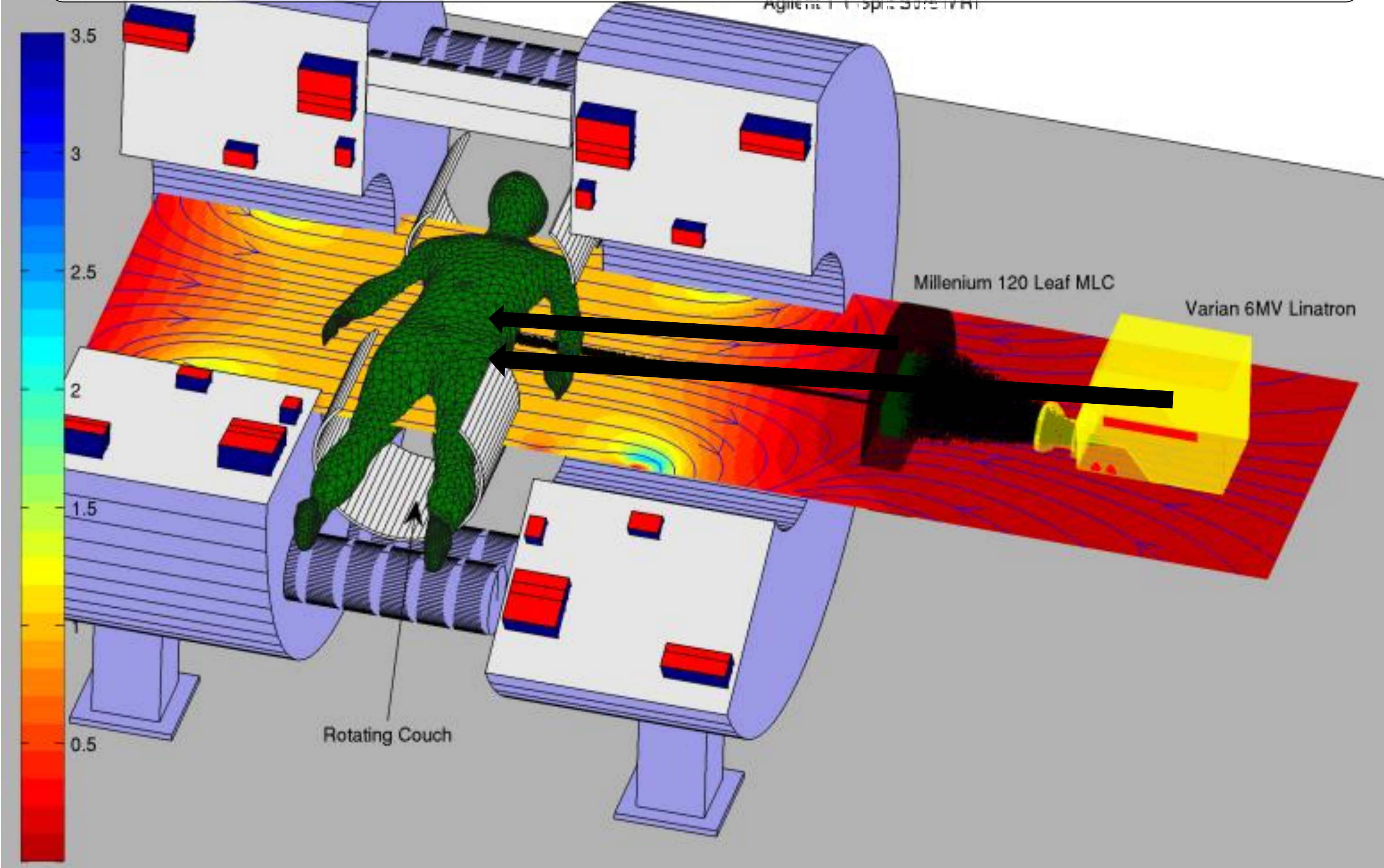
RF in accelerating cavity (wave equation [no particles])



B_0 effect on treatment head and patient transport (Lorentz force)



Ferromagnetic material impact on MRI (Ampere's law)

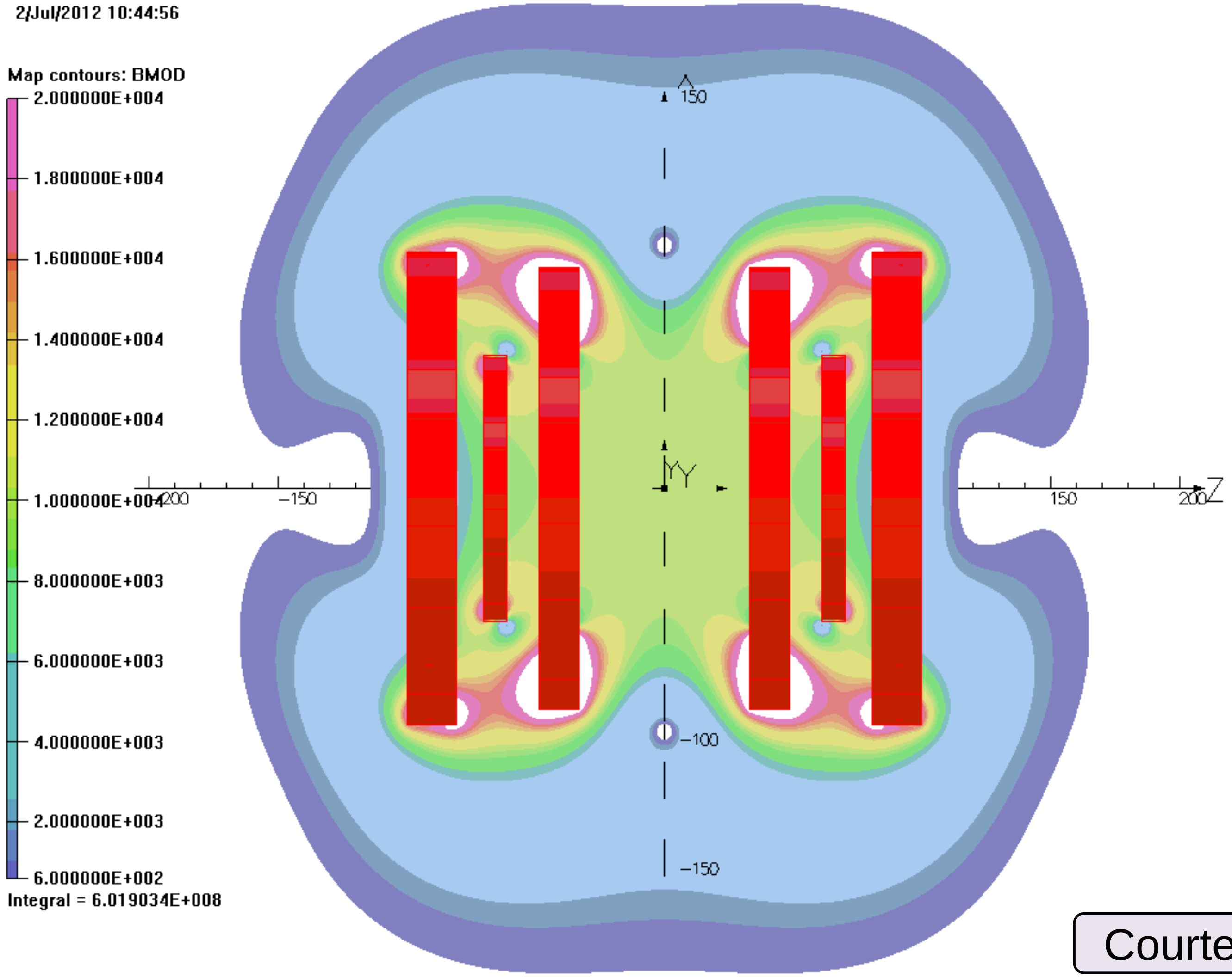


Magnetic field effects on the linac electron gun

Battling Maxwell's Equations
Physics Challenges and Solutions for Hybrid MRI Systems
AAPM 2015

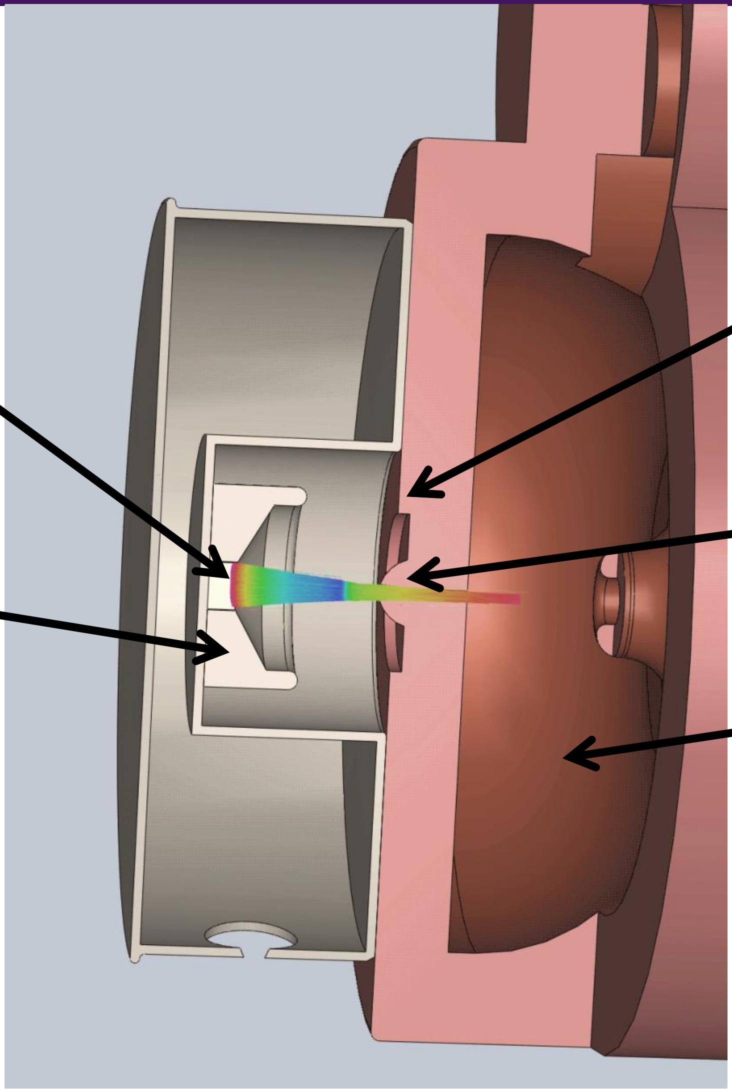
THE UNIVERSITY OF SYDNEY

MRI field for a 1T split bore design



Courtesy Agilent

Electron Gun

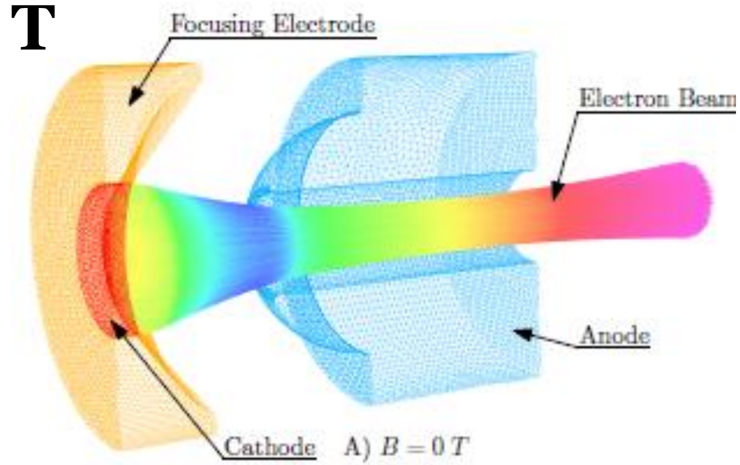


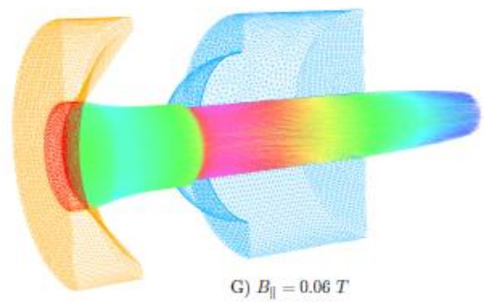
Courtesy Brendan Whelan

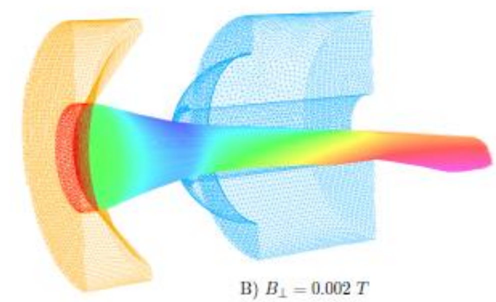
Impact of B fields on unshielded guns

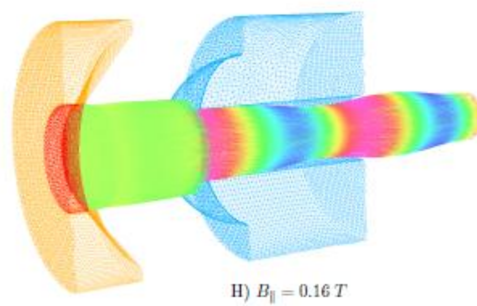
0 .016 T= **0.002 T⊥**

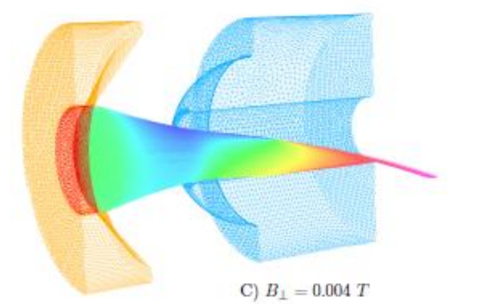
0 T











0 .028 T= **0.004T⊥**

Constantin Med Phys 2011

SAMS Question

Inline (B_0 || electron beam) and perpendicular (B_0 $\perp$ electron beam) magnetic fields affect linac electron guns by:

67% A. Inline fields affect the beam focus; perpendicular fields deflect the electrons away from the anode

21% B. Inline fields deflect the electrons away from the anode; perpendicular fields affect the beam focus

7% C. Inline fields and perpendicular fields affect the beam focus

5% D. Inline fields and perpendicular fields deflect the electrons away from the anode

Note: || = parallel; $\perp$ = perpendicular, orthogonal

SAMS Question

Inline (B_0 || 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

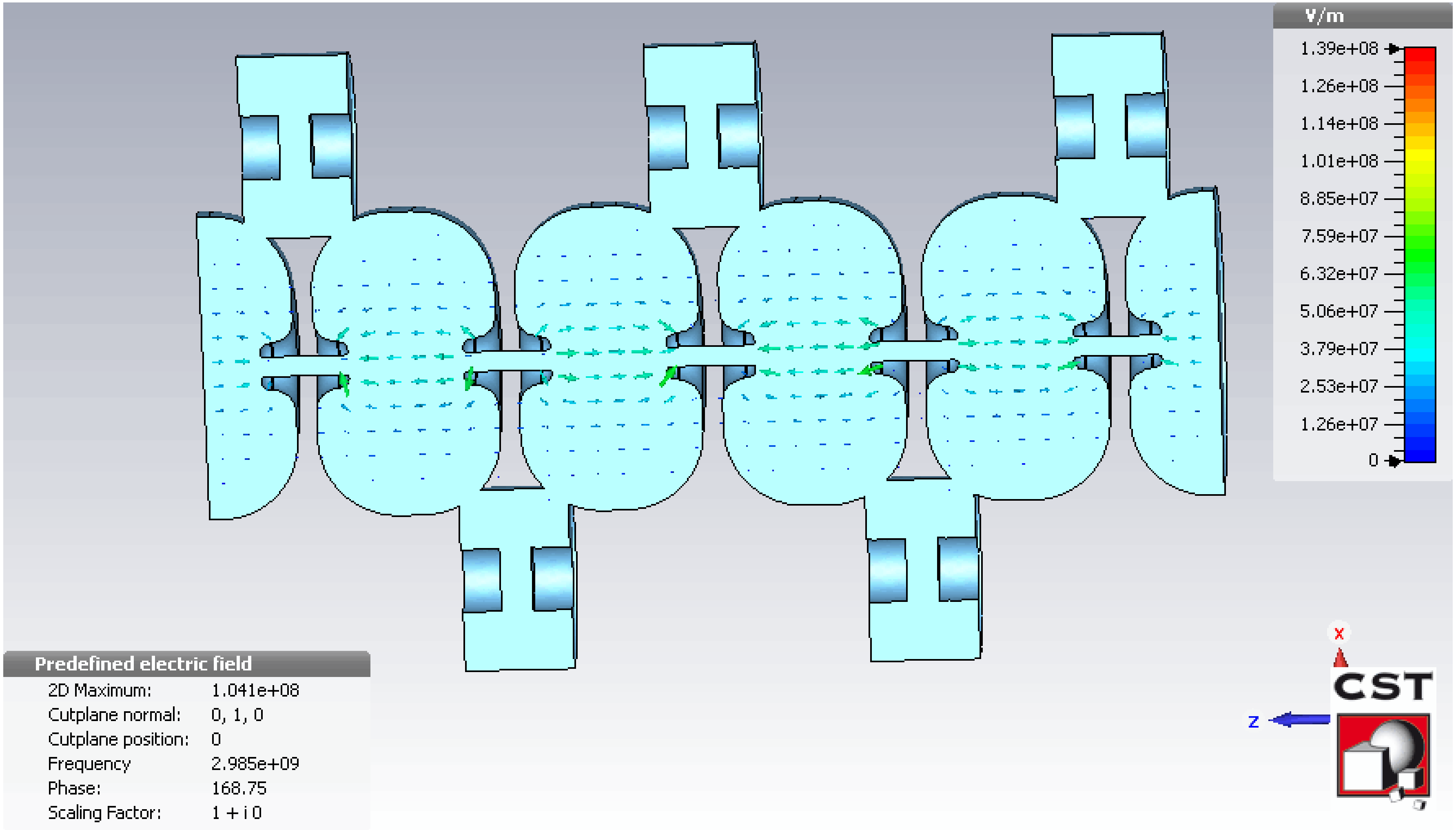
Ref: Constantin, D. E., Fahrig, R., & Keall, P. J. (2011). A study of the effect of in-line and perpendicular magnetic fields on beam characteristics of electron guns in medical linear accelerators. Med Phys, 38(7), 4174-4185.

Magnetic field effects on the linac waveguide

Battling Maxwell's Equations
Physics Challenges and Solutions for Hybrid MRI Systems
AAPM 2015

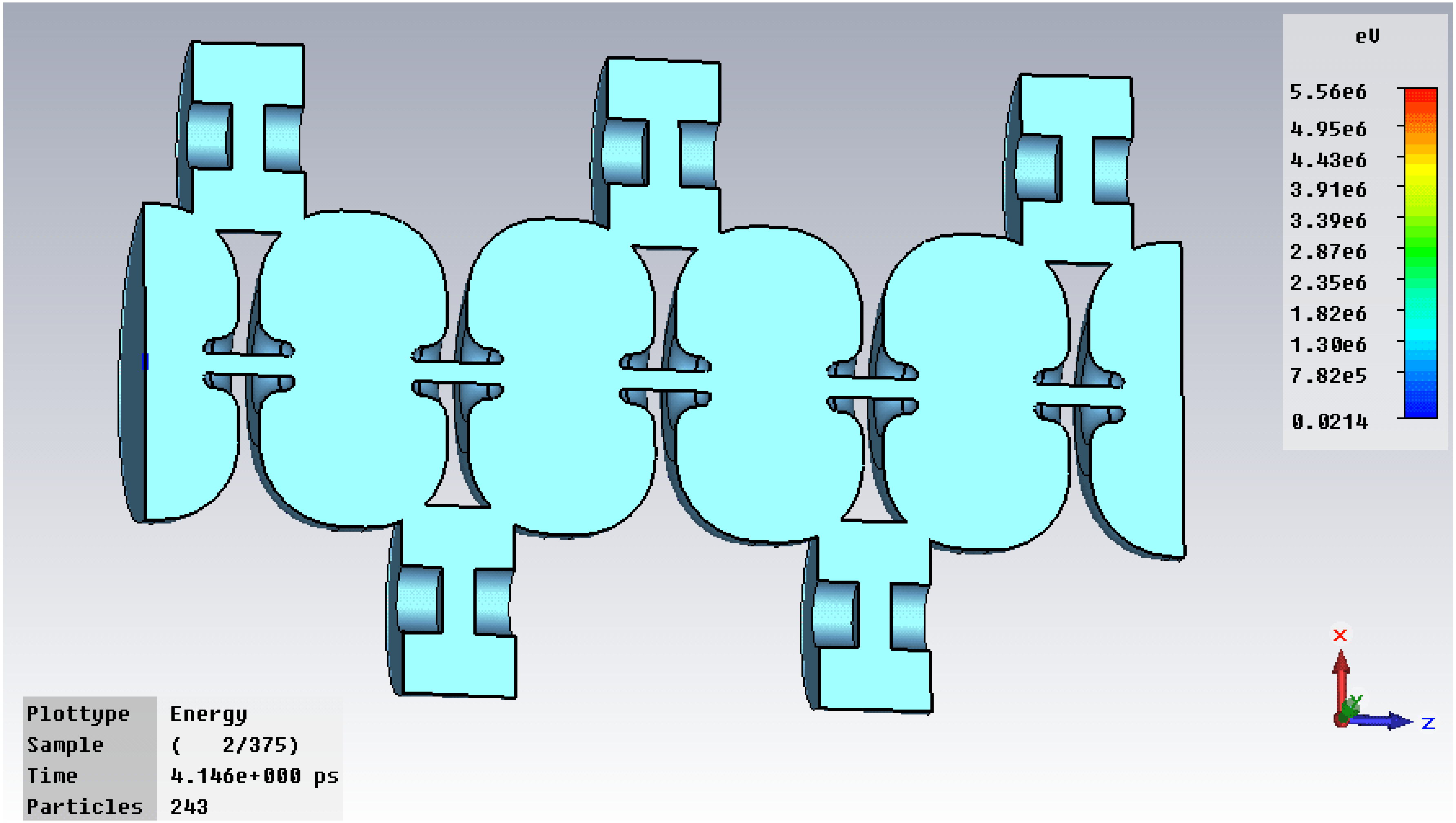
THE UNIVERSITY OF SYDNEY

An example accelerator

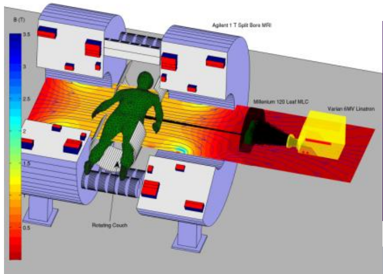


Courtesy Brendan Whelan

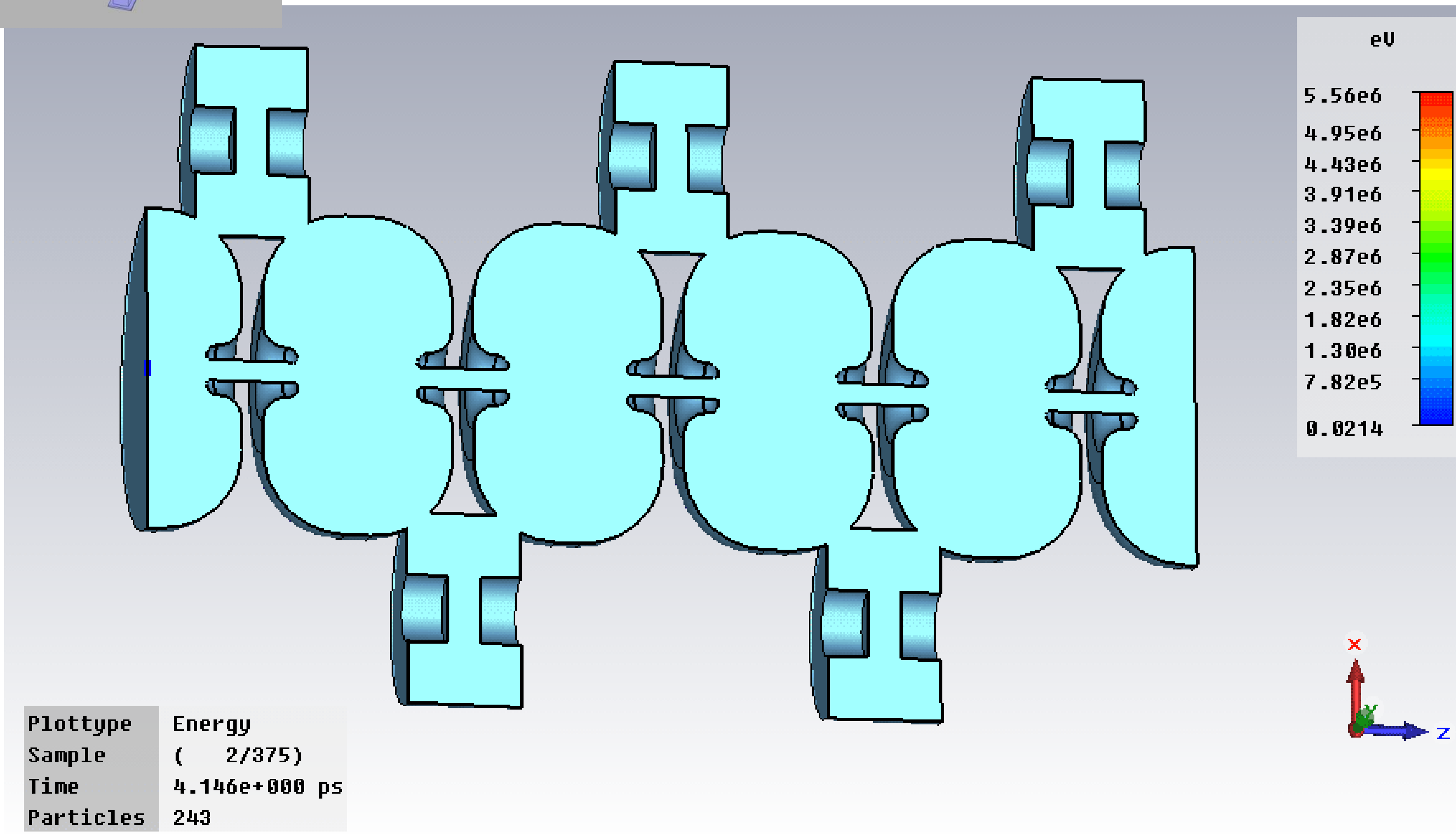
Electron transport in a linac



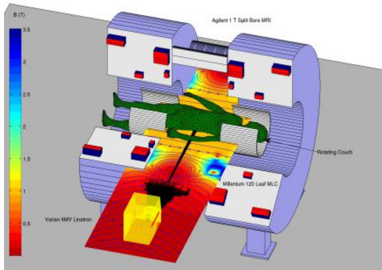
Courtesy Brendan Whelan



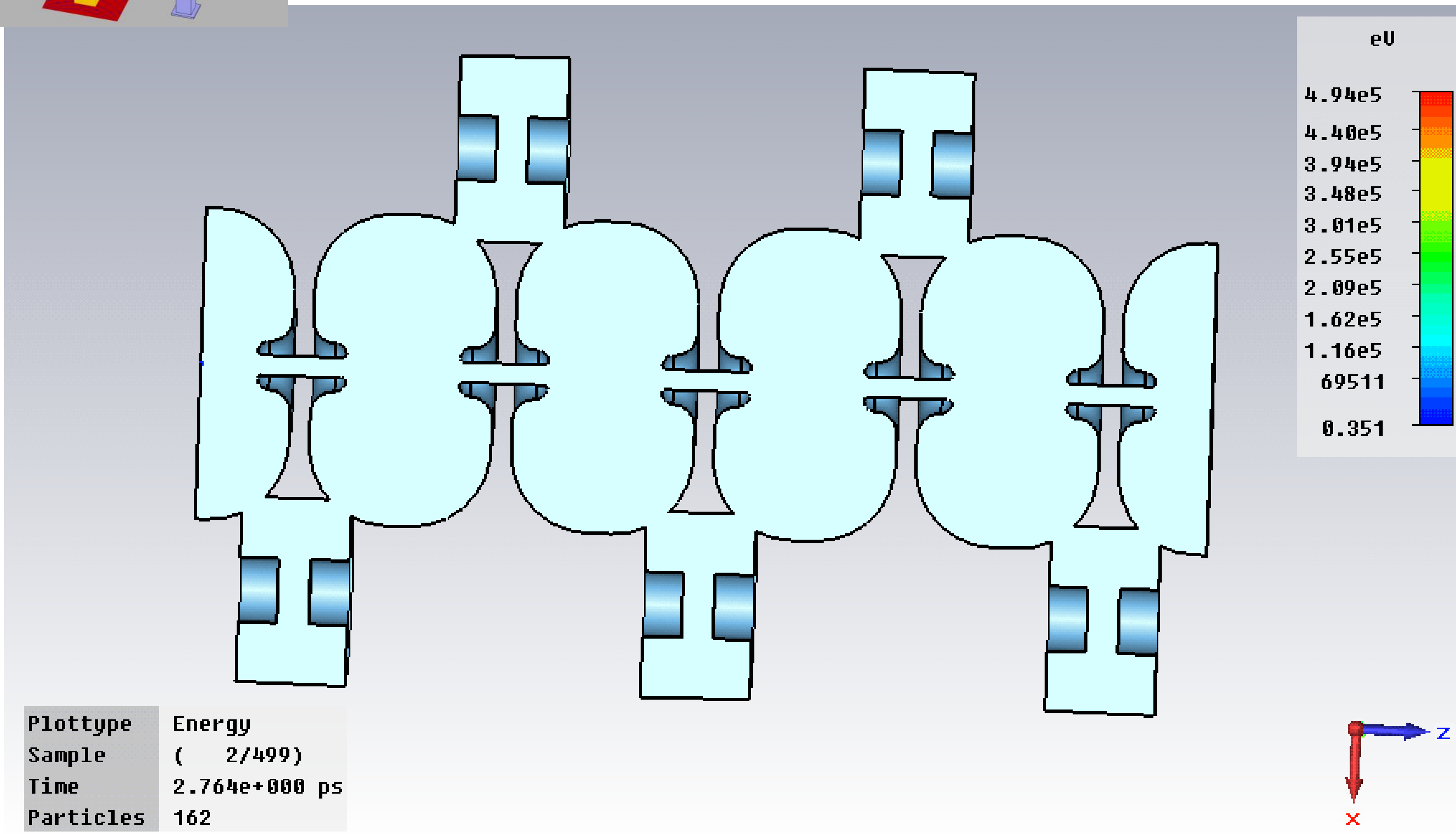
Electrons in a linac: B = 0.1T inline



Courtesy Brendan Whelan



Electrons in a linac: B = 0.05T perp.



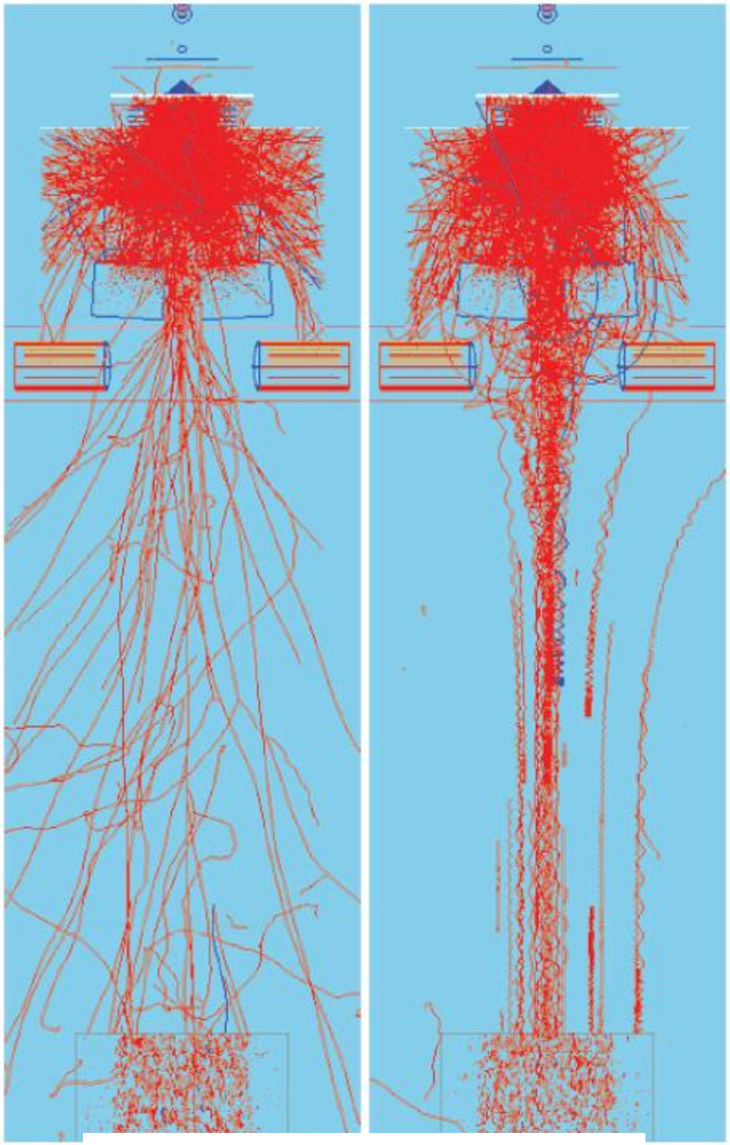
Courtesy Brendan Whelan

Magnetic field effects on treatment head/patient radiation transport

Battling Maxwell's Equations
Physics Challenges and Solutions for Hybrid MRI Systems
AAPM 2015

THE UNIVERSITY OF SYDNEY

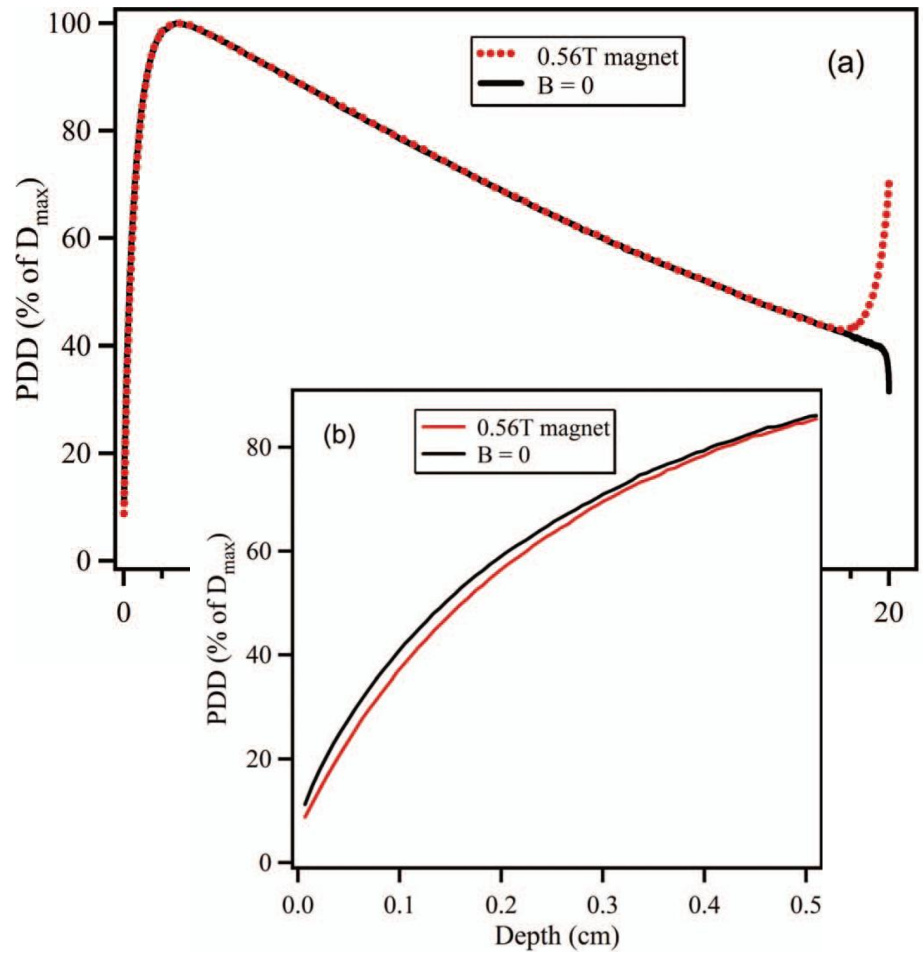
Skin dose in magnetic fields



B = 0T B = 1T MRI

Inline

Oborn Med Phys 2014



Perpendicular

Keyvanloo Med Phys 2012

SAMS Question

Inline (B_0 || 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?

1% A. Inline and perpendicular fields both decrease the skin dose

19% B. Inline and perpendicular fields both increase the skin dose

20% C. Inline fields decrease the skin dose and perpendicular fields increase the skin dose

57% D. Inline fields increase the skin dose and perpendicular fields decrease the skin dose

3% E. The magnetic field has no effect on the skin dose

Note: || = parallel; $\perp$ = perpendicular, orthogonal

SAMS Question

Inline (B_0 || 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
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

Oborn Med Phys 2014

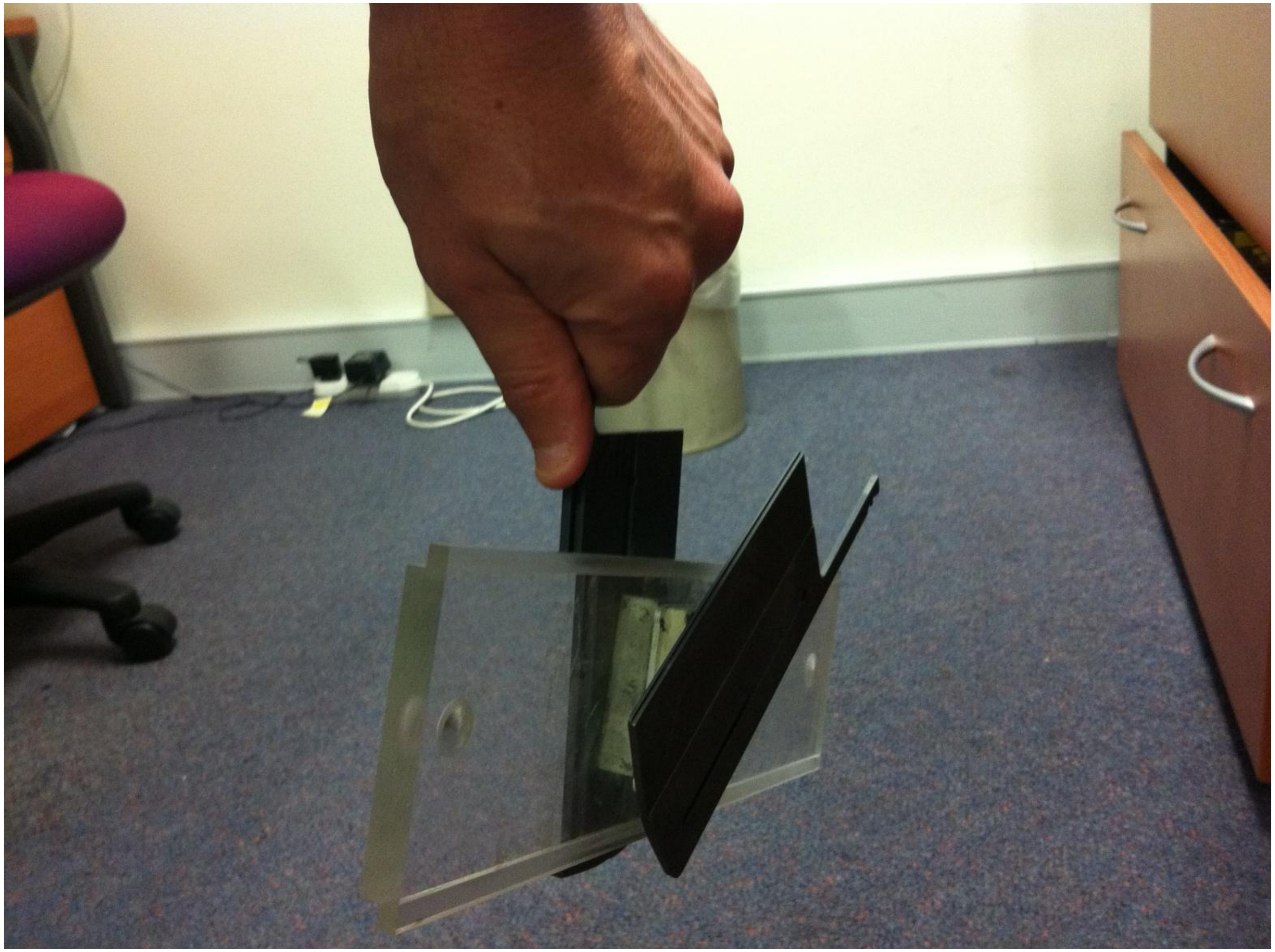
Keyvanloo Med Phys 2012

Linac effects on the magnetic field

Battling Maxwell's Equations
Physics Challenges and Solutions for Hybrid MRI Systems
AAPM 2015

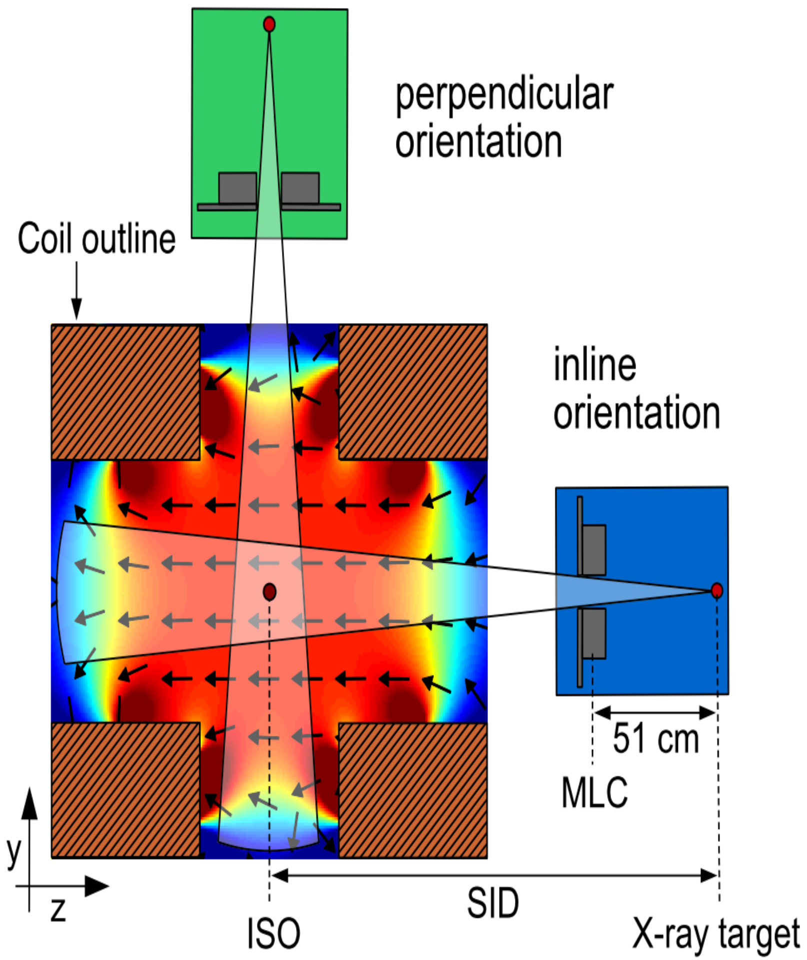
THE UNIVERSITY OF SYDNEY

MLCs are magnetic



Impact of MLCs on magnetic uniformity

Setup



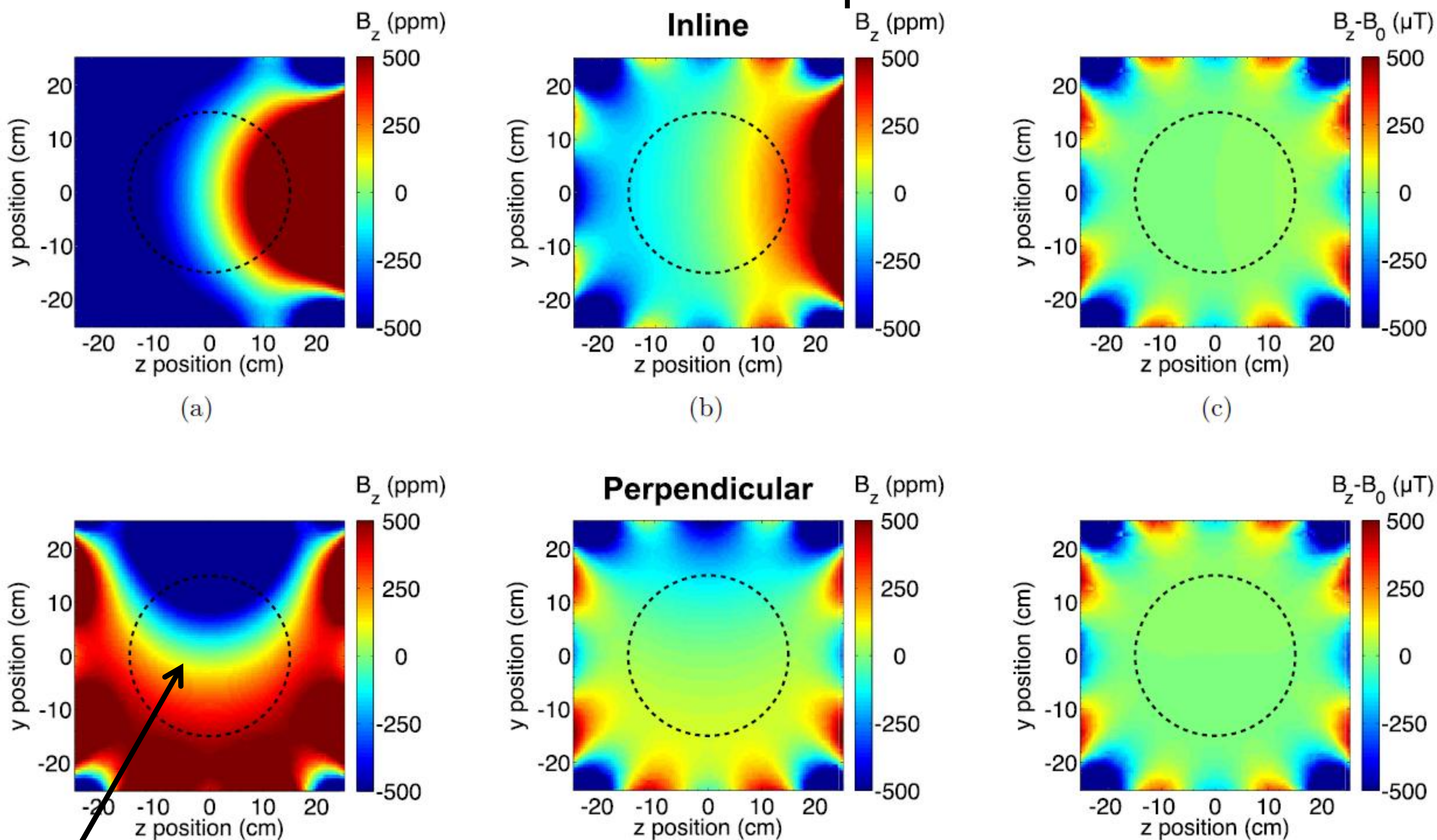
- Agilent split-bore MRI magnet
  - $B_0 = 1.0$ T
  - Two beam orientations

SID: Source-to-isocentre distance

Kolling Med Phys 2013

Impact of MLCs on magnetic uniformity

Increase separation



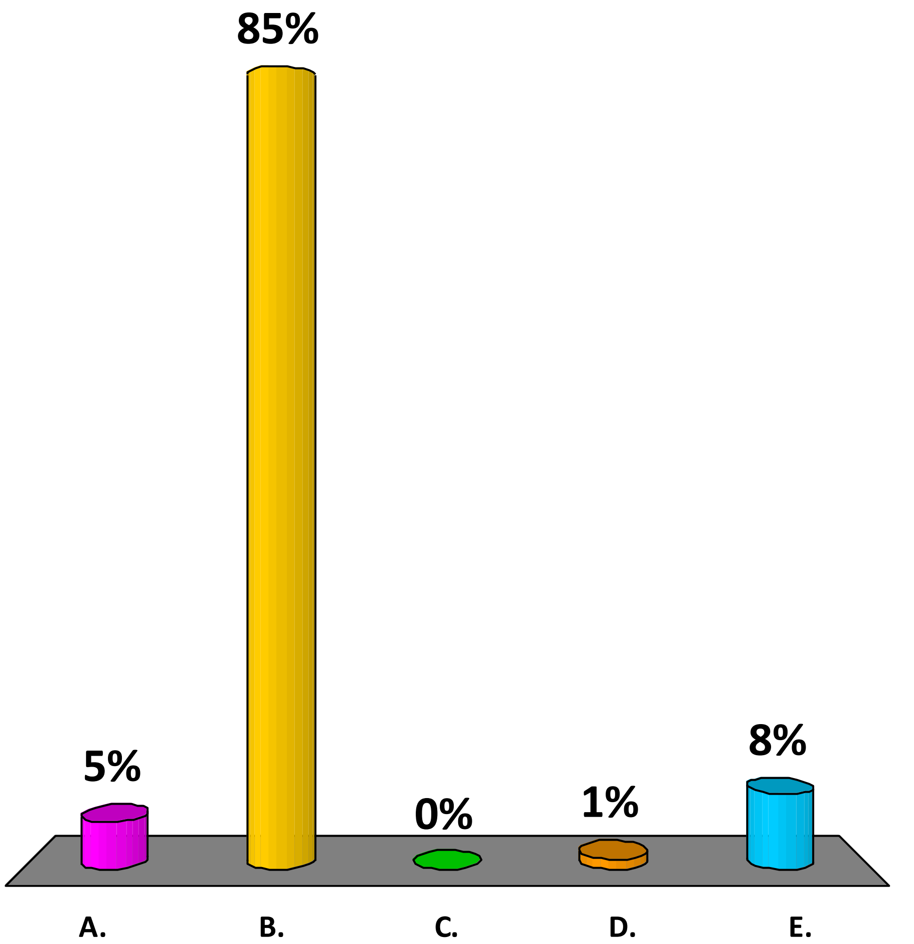
MRI imaging volume

Kolling Med Phys 2013

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



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

Battling Maxwell's Equations
Physics Challenges and Solutions for Hybrid MRI Systems
AAPM 2015

Summary

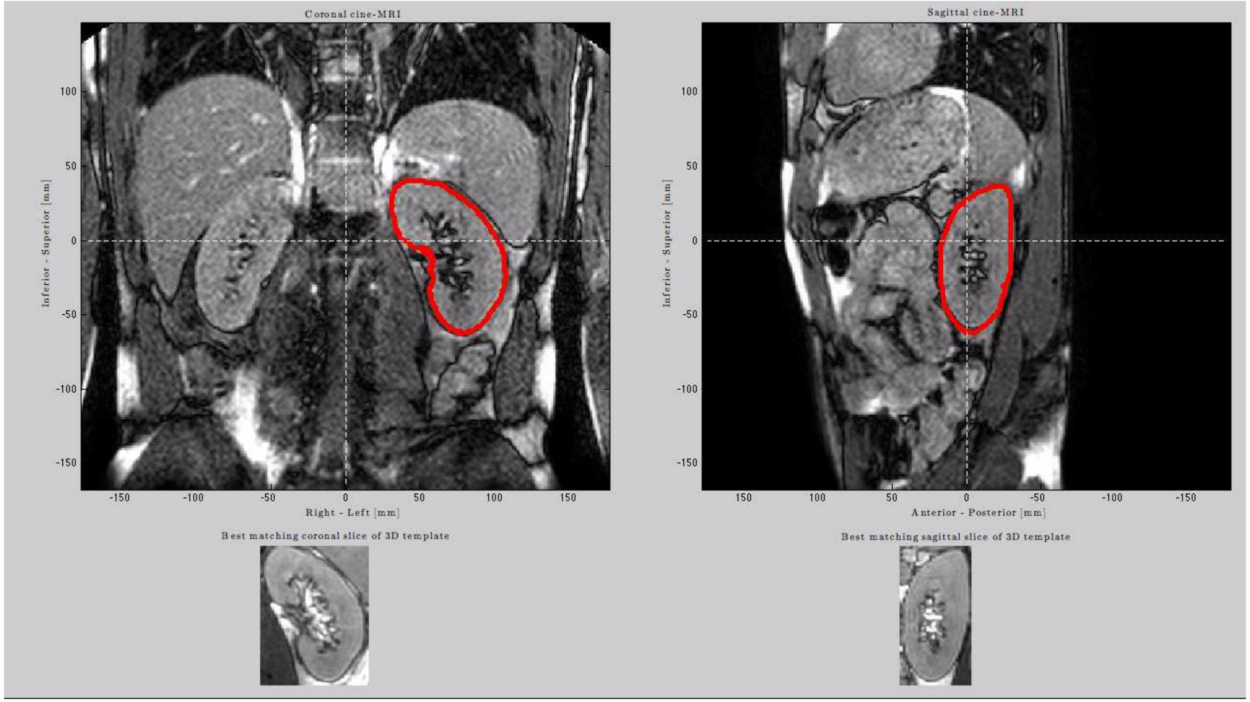
› MRI physics and engineering is challenging

› Linac physics and engineering is challenging

› MRI-Linac physics and engineering is challenging[2]

› Is it worth it?

- Anatomy
- Physiology
- Beyond oncology



Bjerre Phys Med Biol 2013