New Linac Designs for MR-Guided Therapy Systems

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UNIVERSITY OF ALBERTA

Alberta Health Services

(ART)^2 Advanced Real Time RadioTherapy Adaptive

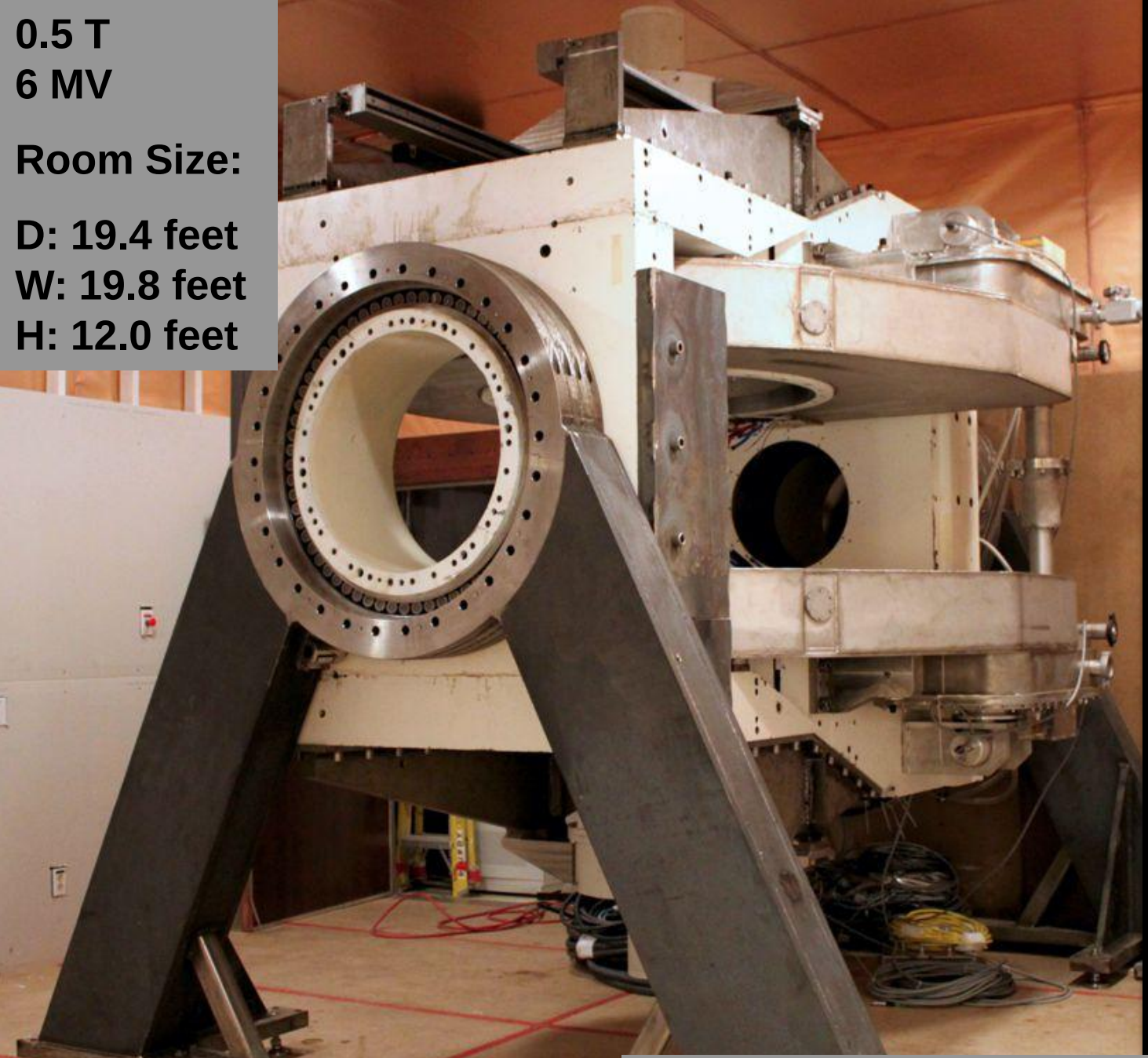
Outline

- Background
  - CCI Linac-MR (Edmonton, Alberta, Canada)
- Objective
  - X-ray Energies up to 10 MV
  - Avoiding Breakdown
- Methods
  - Simulation Techniques
- Results
  - 10 MV Accelerator
  - Varying the Energy
- Conclusions

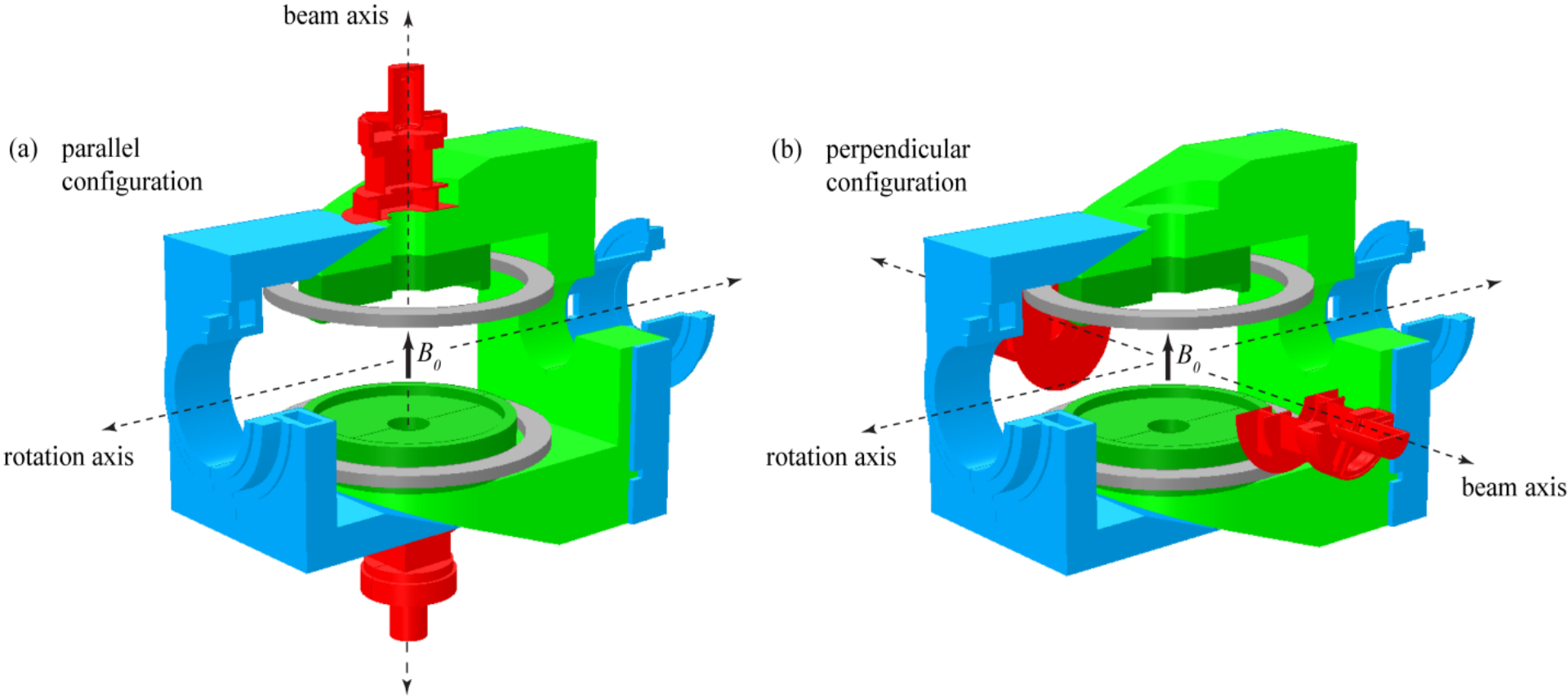
0.5 T
6 MV

Room Size:

D: 19.4 feet
W: 19.8 feet
H: 12.0 feet



Installed: 2013 Images: July 2014

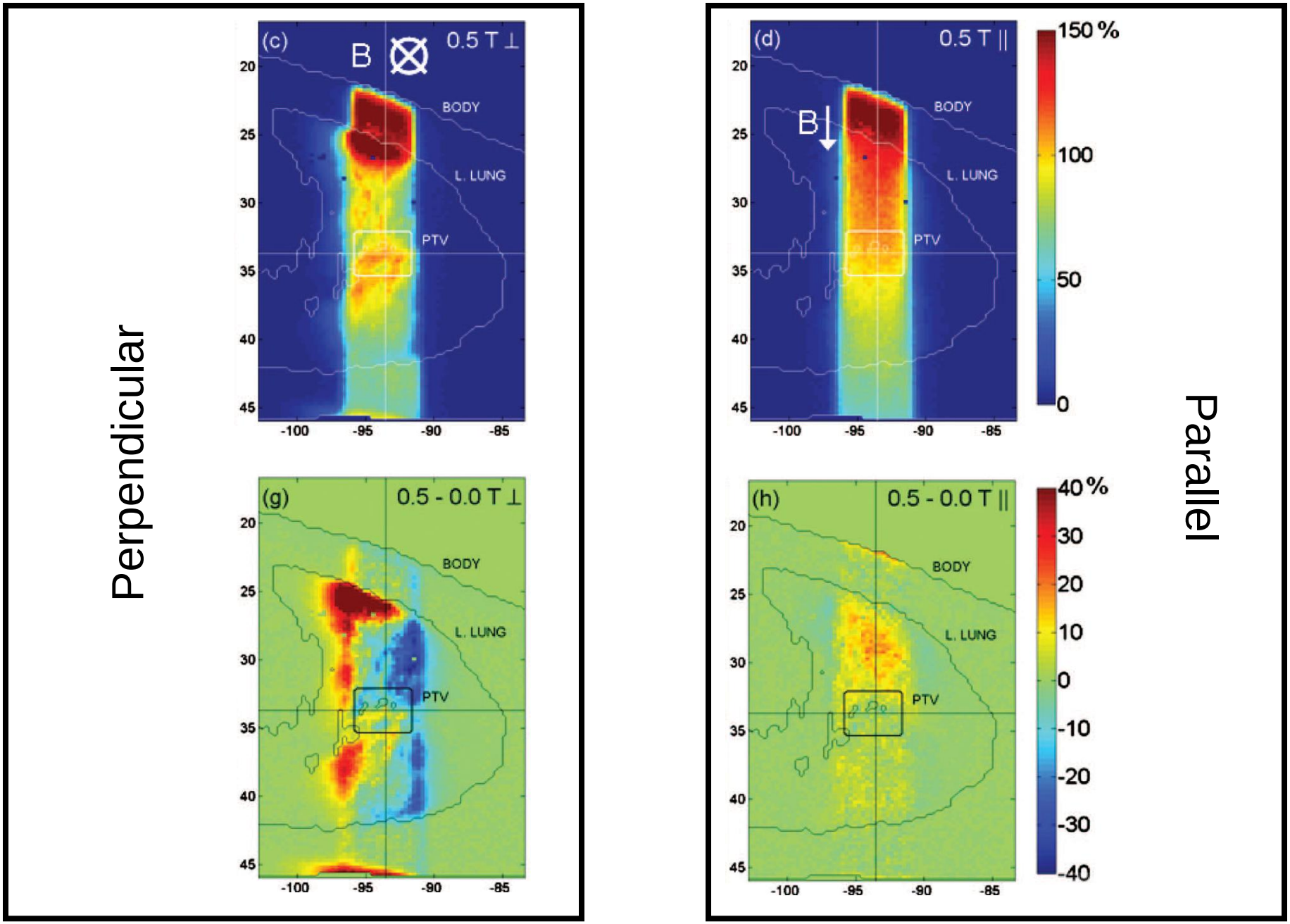


biplanar magnet assembly
superconducting coil
treatment assembly
gantry support link

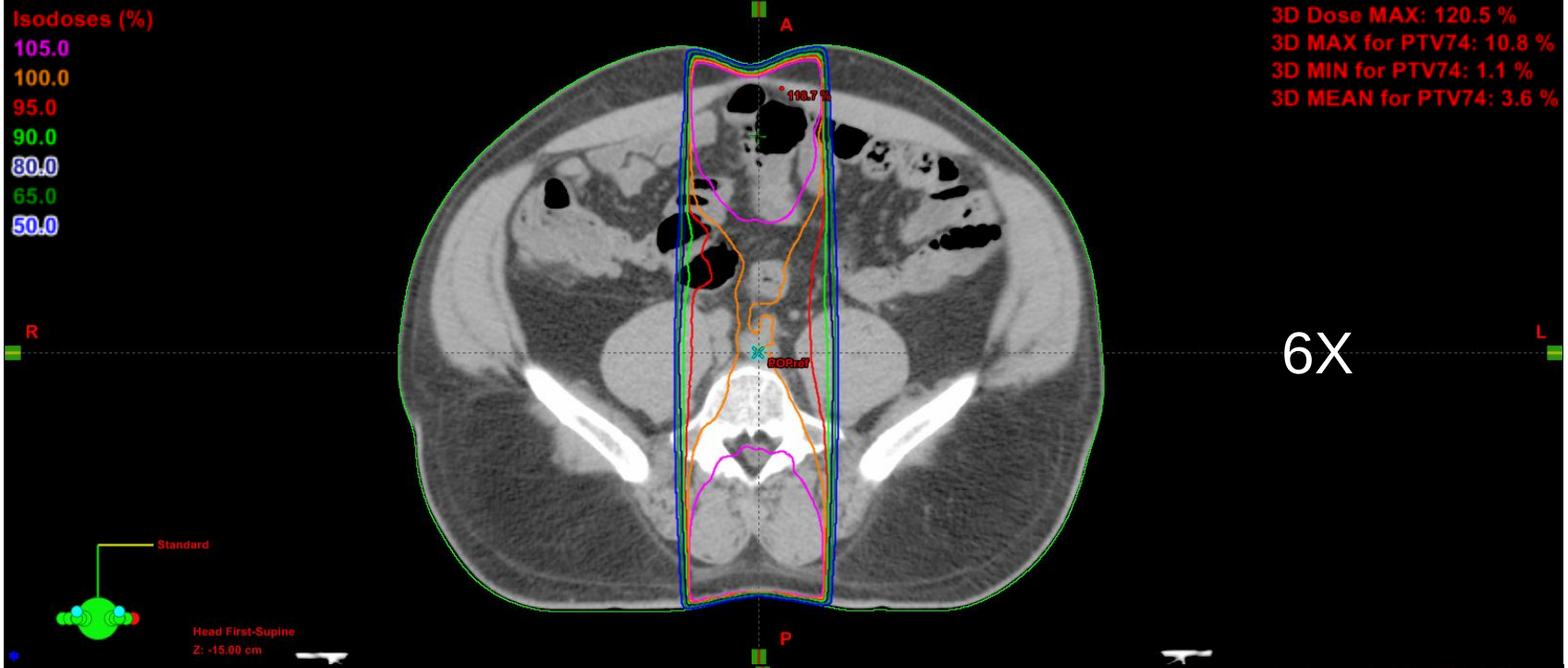
Keyvanloo, Burke, Warkentin, Tadic, Rathee, Kirkby, Santos, Fallone, Medical Physics, 39(10), 2012

St. Aubin, Steciw, Fallone, Physics in Medicine and Biology, 55, 2010

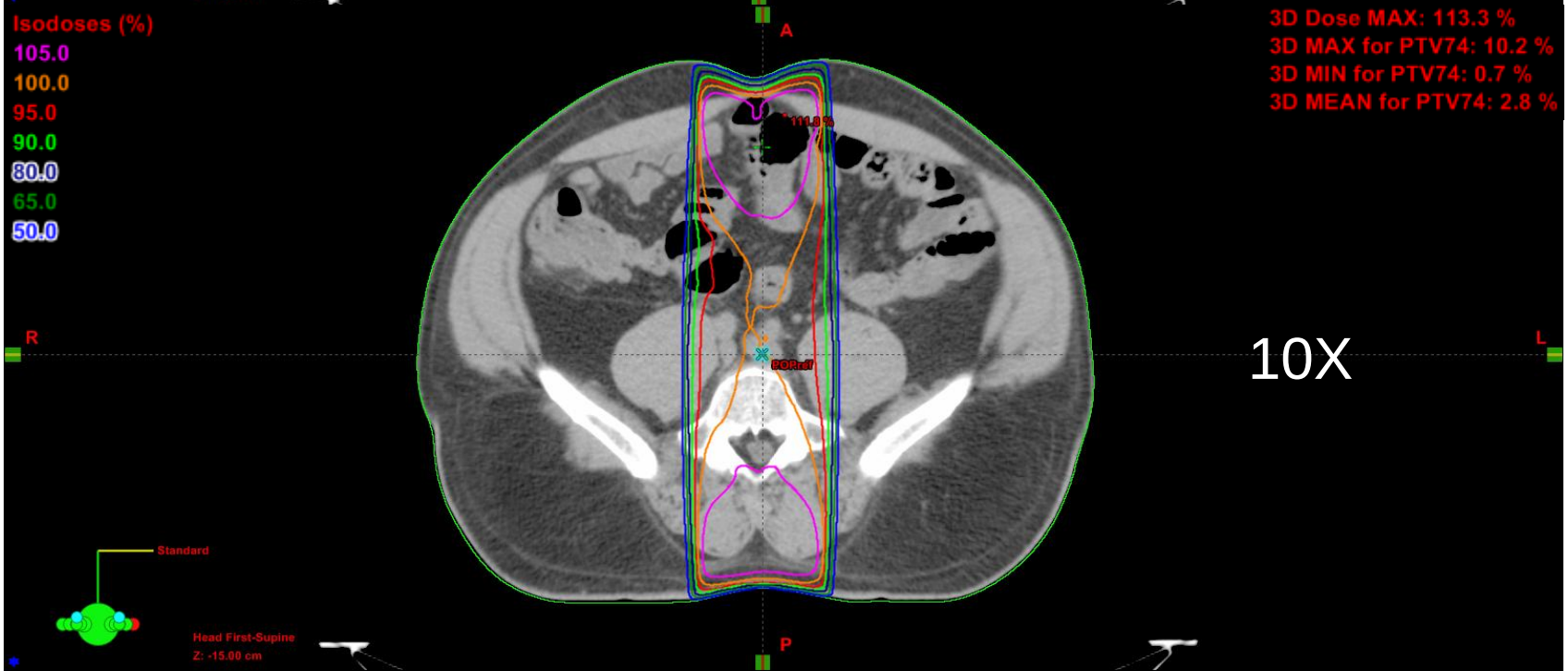
St. Aubin, Santos, Steciw, Fallone, Medical Physics, 37(9), 2010



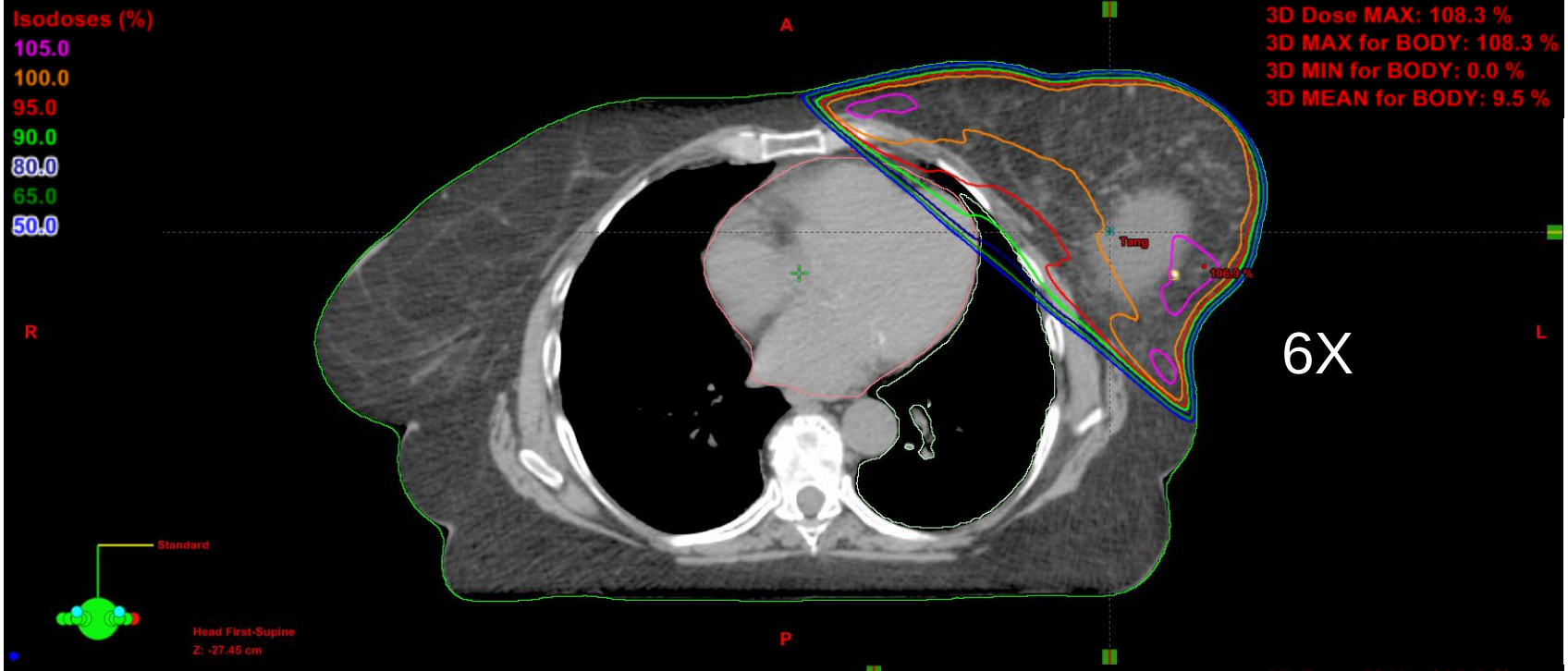
Kirkby, Murray, Rathee, Fallone, Medical Physics, 37(9), 2010

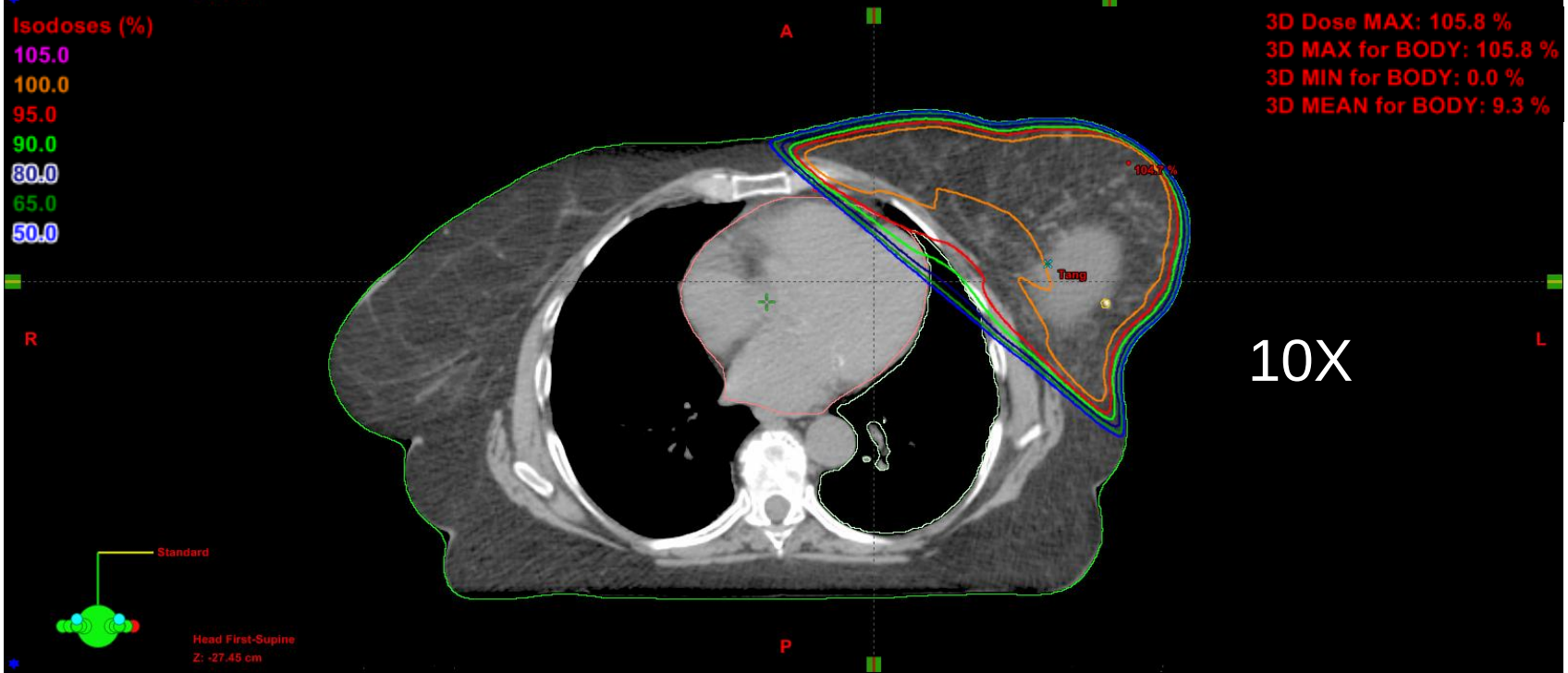

Isodoses (%)
105.0
100.0
95.0
90.0
80.0
65.0
50.0
3D Dose MAX: 120.5 %
3D MAX for PTV74: 10.8 %
3D MIN for PTV74: 1.1 %
3D MEAN for PTV74: 3.6 %
A
R
L
P
Standard
Head First-Supine
Z: -15.00 cm

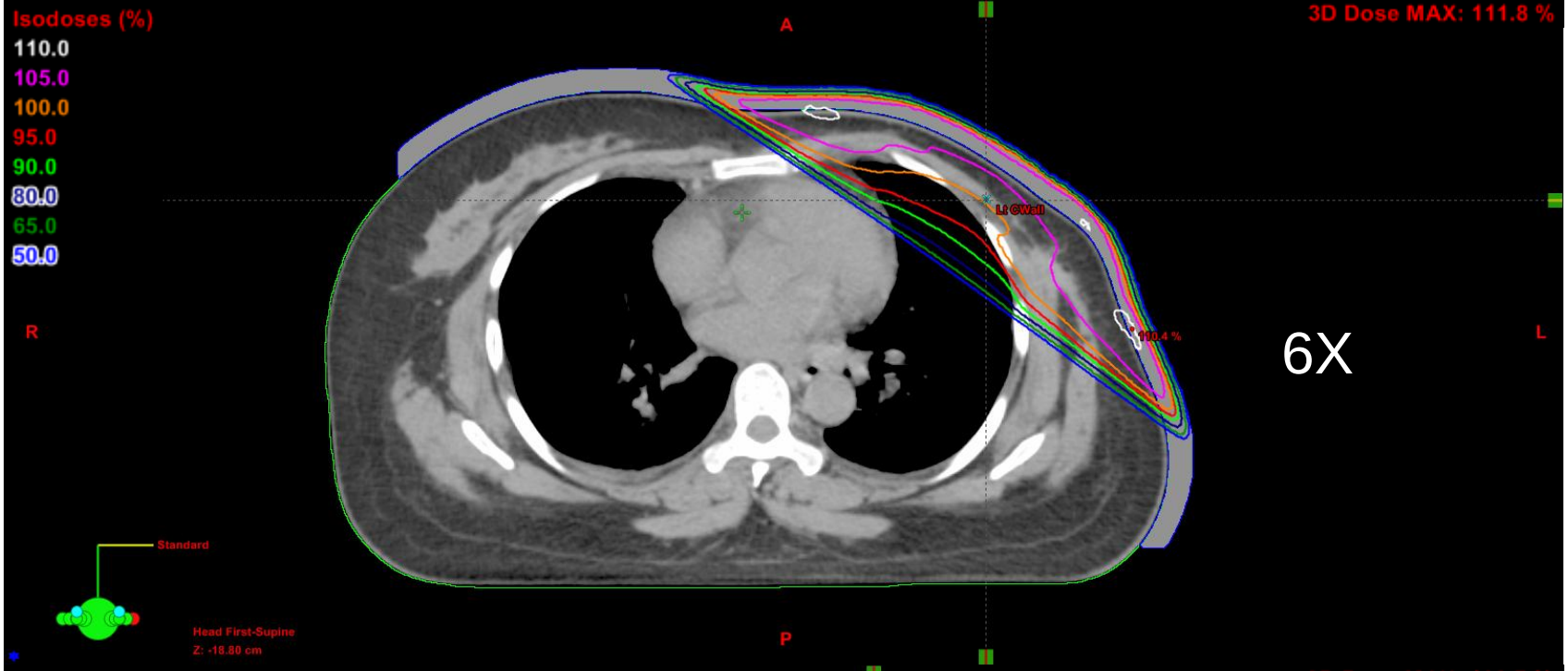
6X


Isodoses (%)
105.0
100.0
95.0
90.0
80.0
65.0
50.0
3D Dose MAX: 113.3 %
3D MAX for PTV74: 10.2 %
3D MIN for PTV74: 0.7 %
3D MEAN for PTV74: 2.8 %
A
R
L
P
Standard
Head First-Supine
Z: -15.00 cm

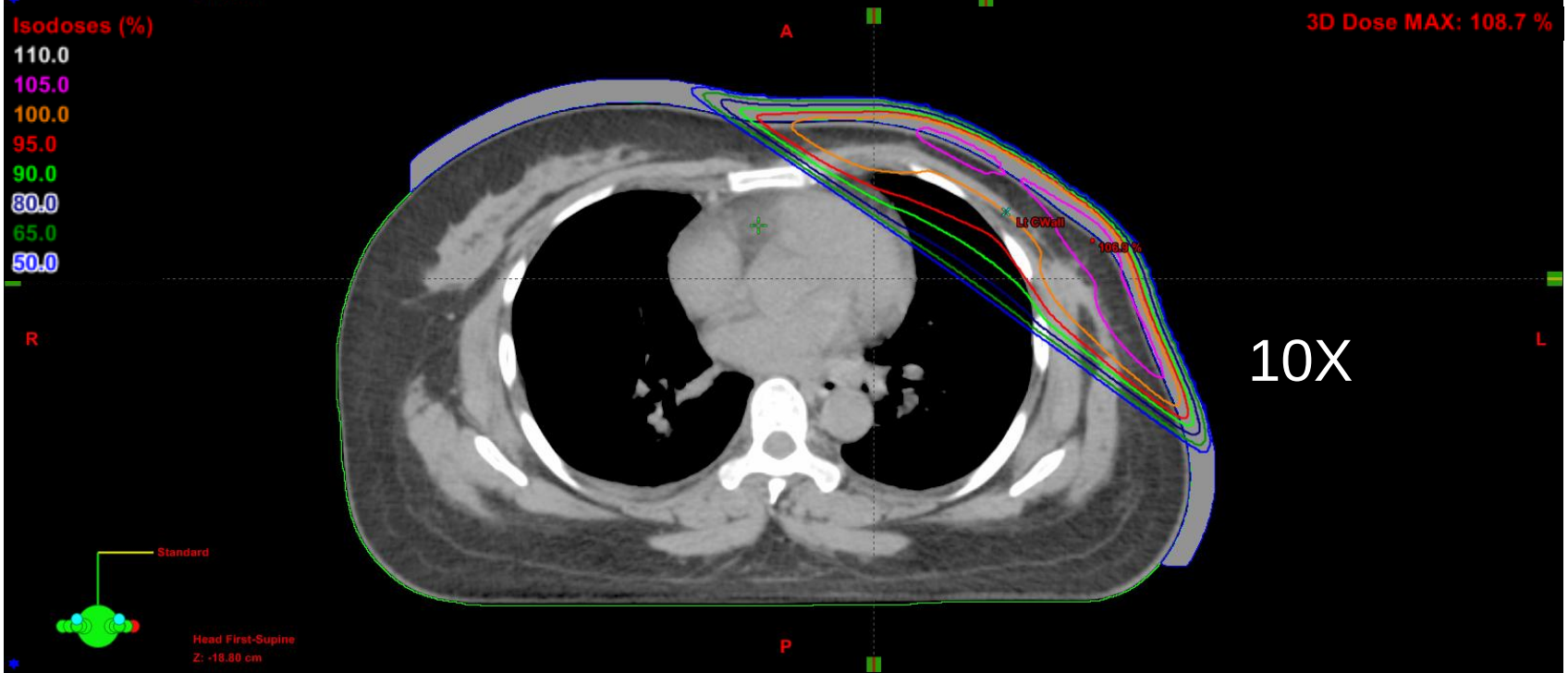
10X


Isodoses (%)
105.0
100.0
95.0
90.0
80.0
65.0
50.0
A
R
L
P
3D Dose MAX: 108.3 %
3D MAX for BODY: 108.3 %
3D MIN for BODY: 0.0 %
3D MEAN for BODY: 9.5 %
Tang
Standard
Head First-Supine
Z: -27.45 cm
6X


Isodoses (%)
105.0
100.0
95.0
90.0
80.0
65.0
50.0
A
R
L
P
3D Dose MAX: 105.8 %
3D MAX for BODY: 105.8 %
3D MIN for BODY: 0.0 %
3D MEAN for BODY: 9.3 %
Tang
Standard
Head First-Supine
Z: -27.45 cm
10X


Isodoses (%)
110.0
105.0
100.0
95.0
90.0
80.0
65.0
50.0
3D Dose MAX: 111.8 %
A
R
L
P
Lt CWall
110.4 %
Standard
Head First-Supine
Z: -18.80 cm

6X


Isodoses (%)
110.0
105.0
100.0
95.0
90.0
80.0
65.0
50.0
3D Dose MAX: 108.7 %
A
R
L
P
Lt CWall
108.6 %
Standard
Head First-Supine
Z: -18.80 cm

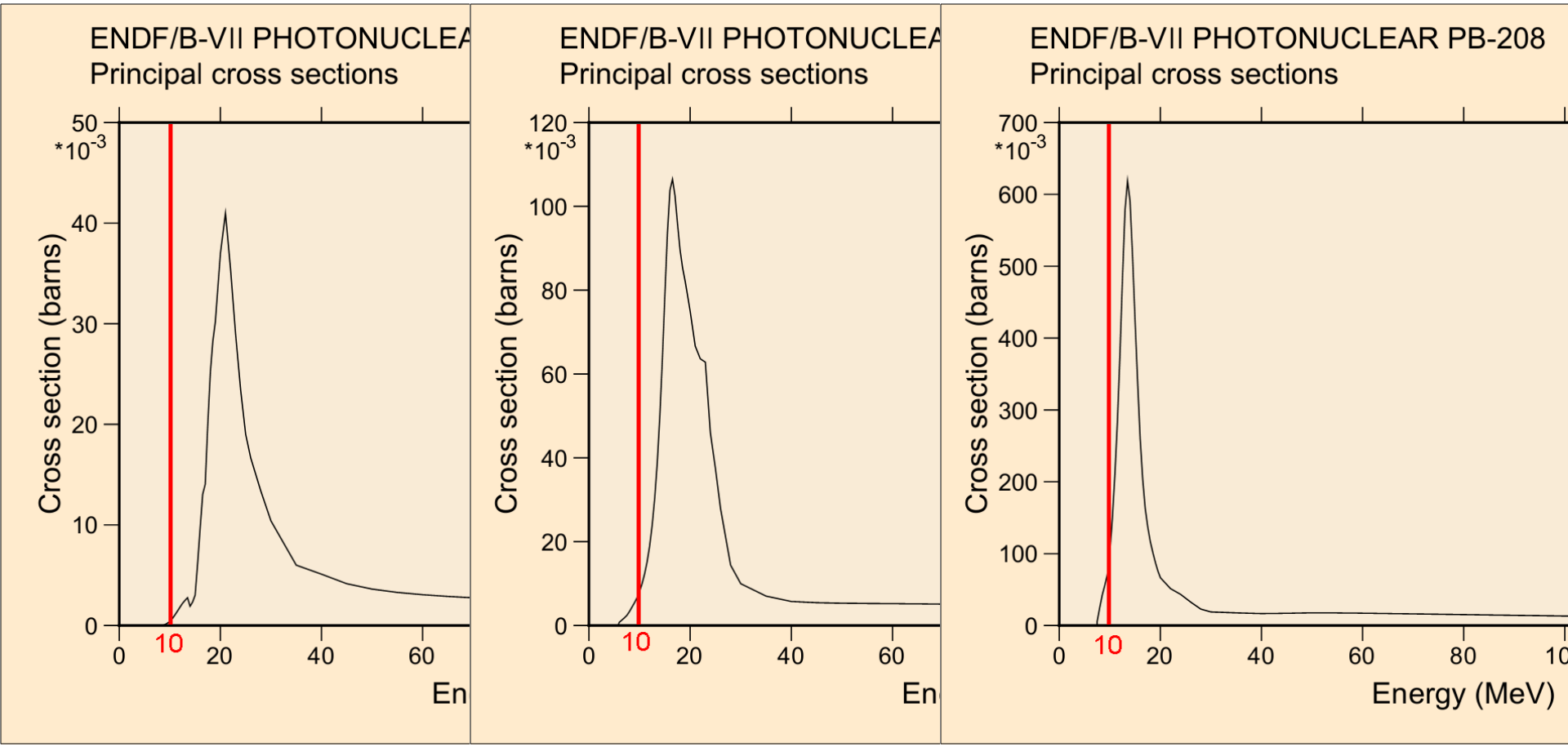
10X

Higher Energy

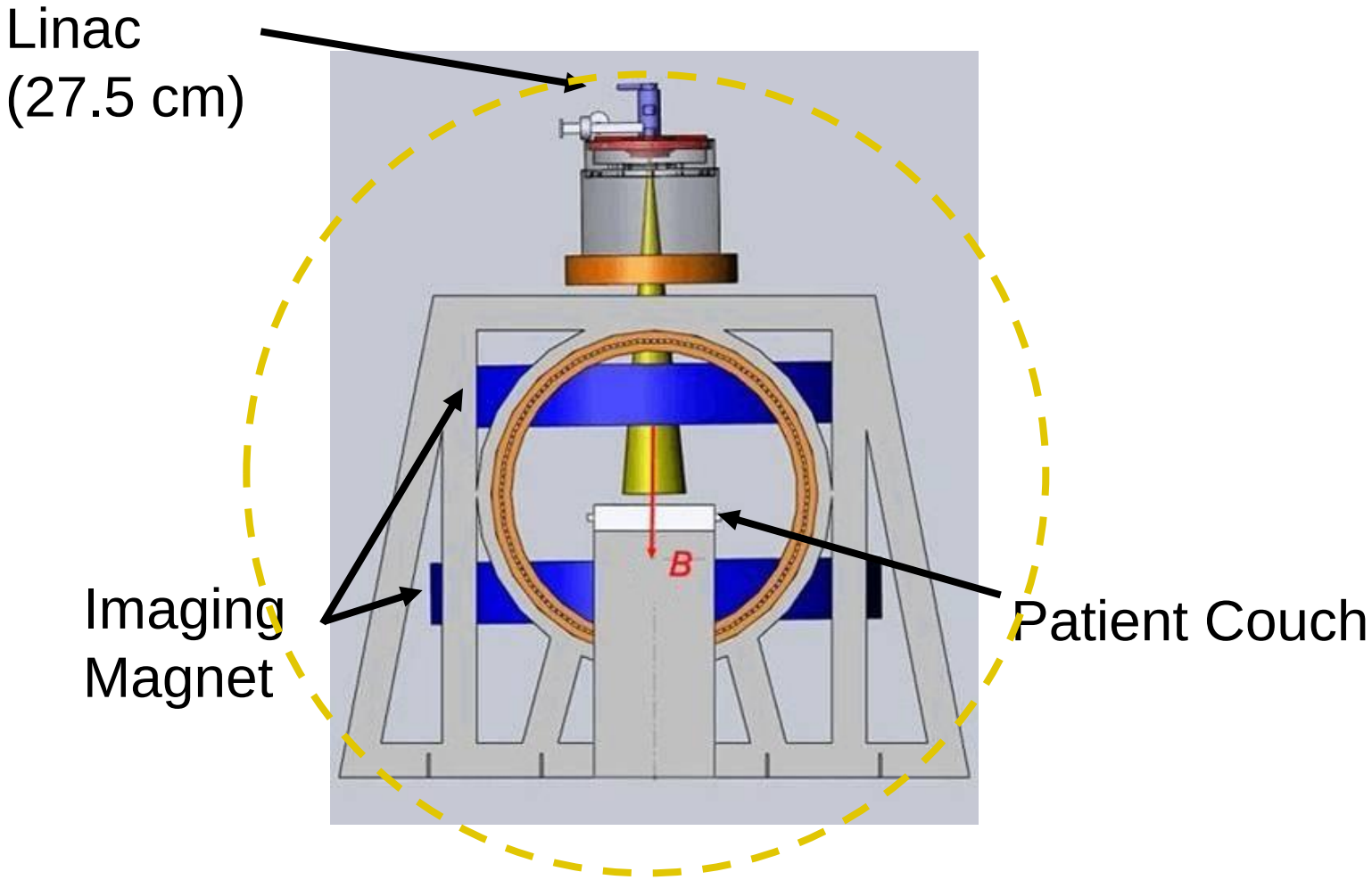
- 6 MV is most common for Modulated therapies
- 10 MV provides equivalent tumor coverage and OAR sparing to 6 MV for VMAT treatments
- Reduced dose to other healthy tissues ($V_{10\%}$ is reduced by up to 7%, D_{Mean} is reduced by ~0.5 Gy)

Pasler, Wirtz, Lutterbach, Strahlentherapie und Onkologie, 187(12) 2011

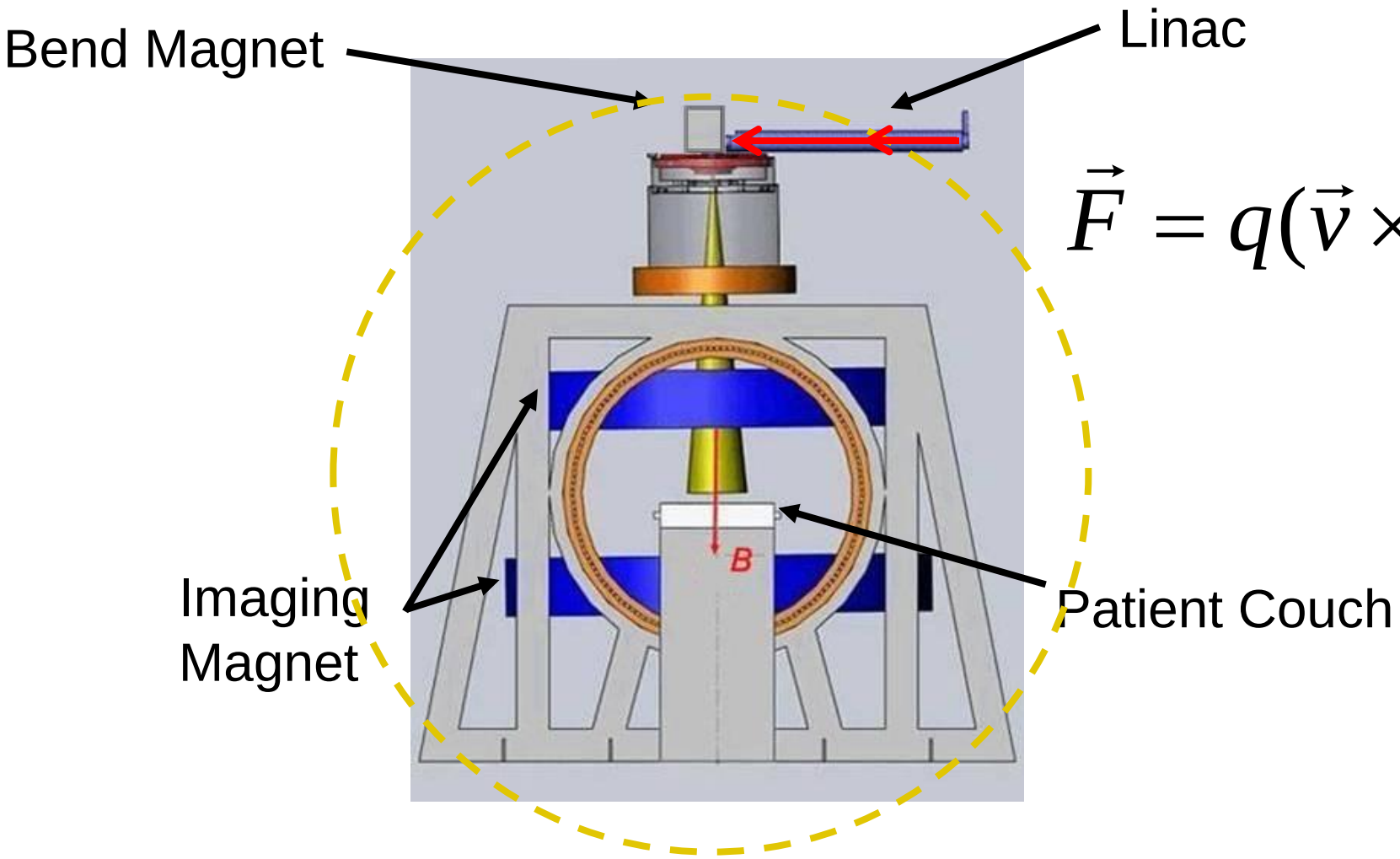
Even Higher?


ENDF/B-VII PHOTONUCLEA
Principal cross sections
Cross section (barns)
*10-3
50
40
30
20
10
0
0
10
20
40
60
En
ENDF/B-VII PHOTONUCLEA
Principal cross sections
Cross section (barns)
*10-3
120
100
80
60
40
20
0
0
10
20
40
60
En
ENDF/B-VII PHOTONUCLEAR PB-208
Principal cross sections
Cross section (barns)
*10-3
700
600
500
400
300
200
100
0
0
10
20
40
60
80
Energy (MeV)

Current System



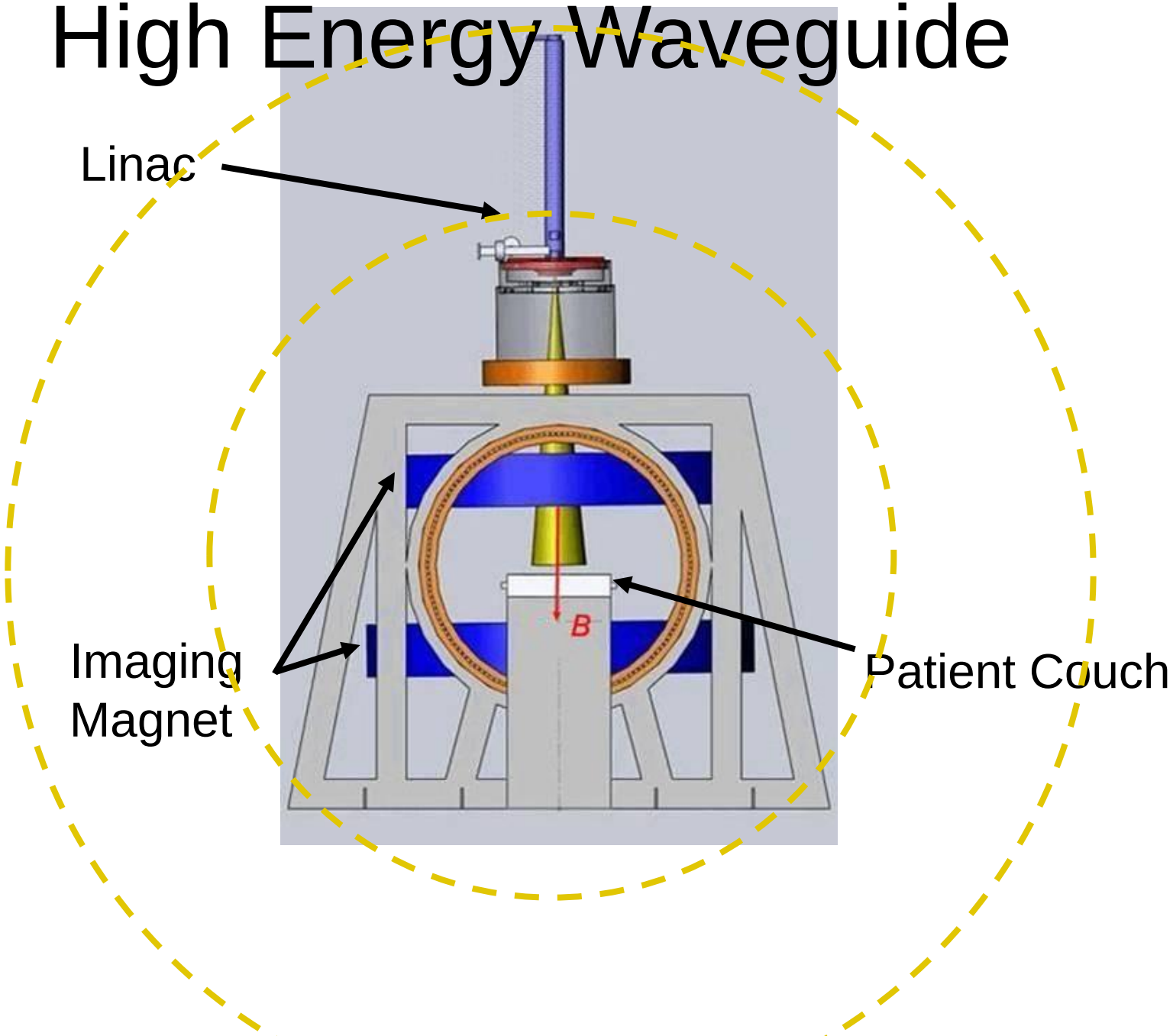
High Energy Waveguide



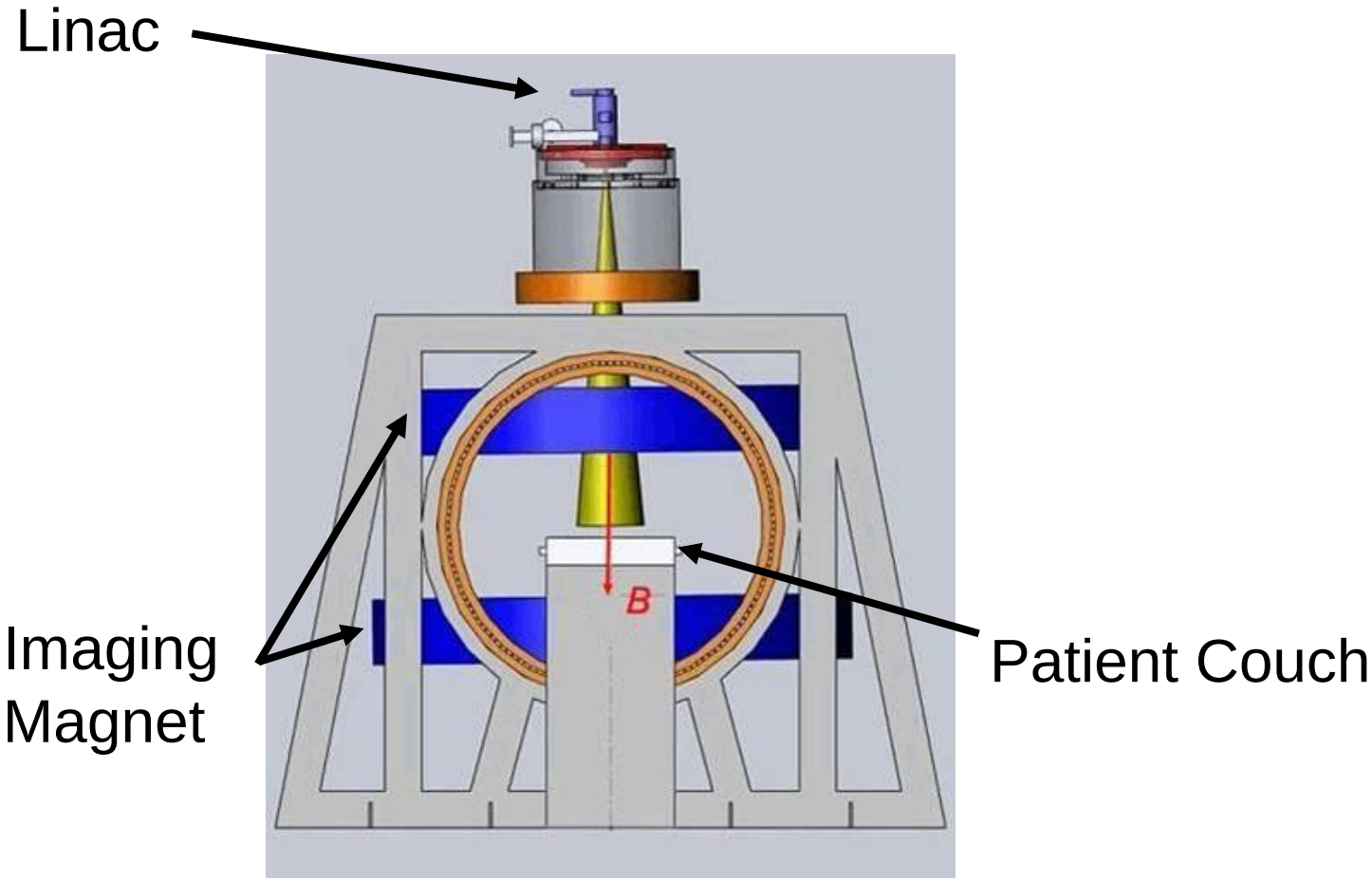
$$\vec{F} = q(\vec{v} \times \vec{B})$$

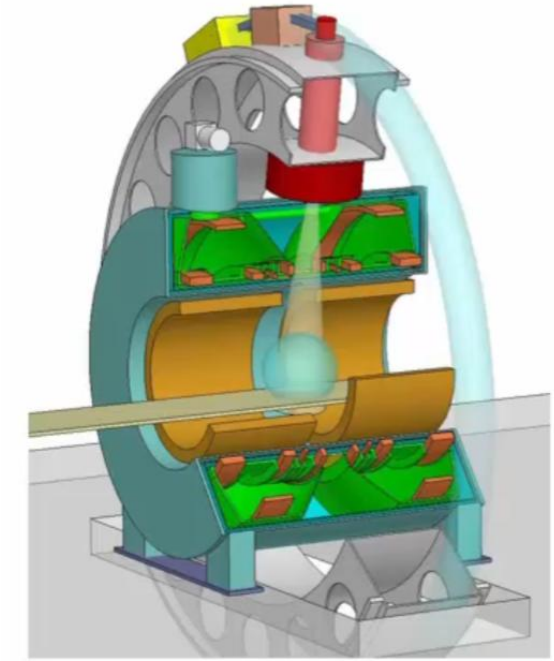
St. Aubin, Steciw, Fallone, Physics in Medicine and Biology, 55, 2010

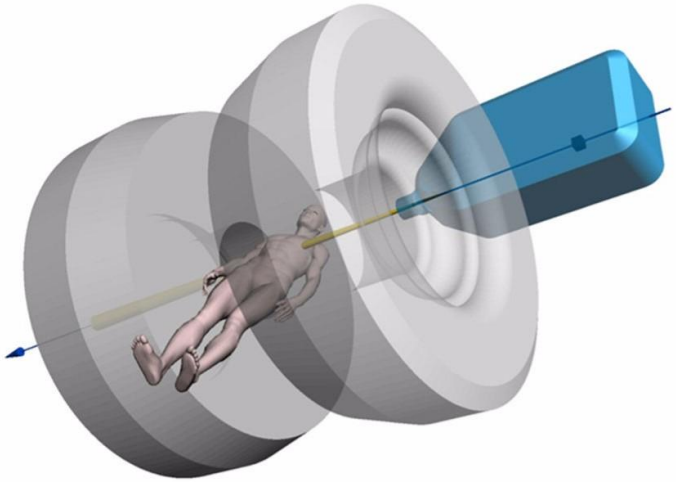
High Energy Waveguide

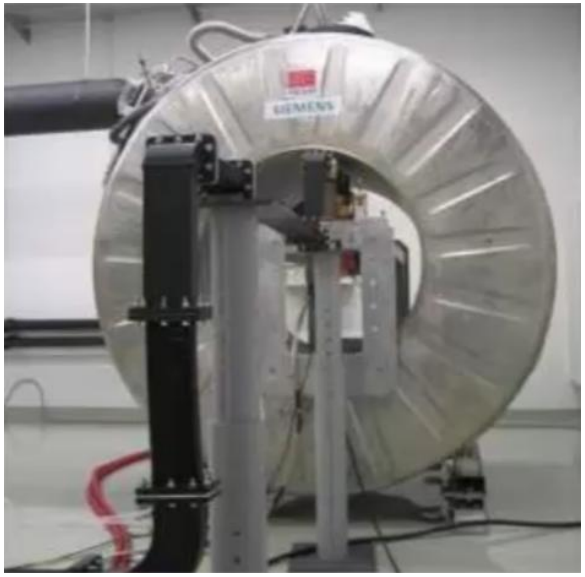


High Energy Short Waveguide








SIEMENS


VARIAN

Breakdown

- Electric Fields too high
- Arcing Within Waveguide
- Absorb RF Power
- Accelerator doesn’t function

Objective

- Design a waveguide capable of producing a 10 MV photon beam, with the length of a current 6 MV waveguide.

Simulations

Cavity Design
COMSOL

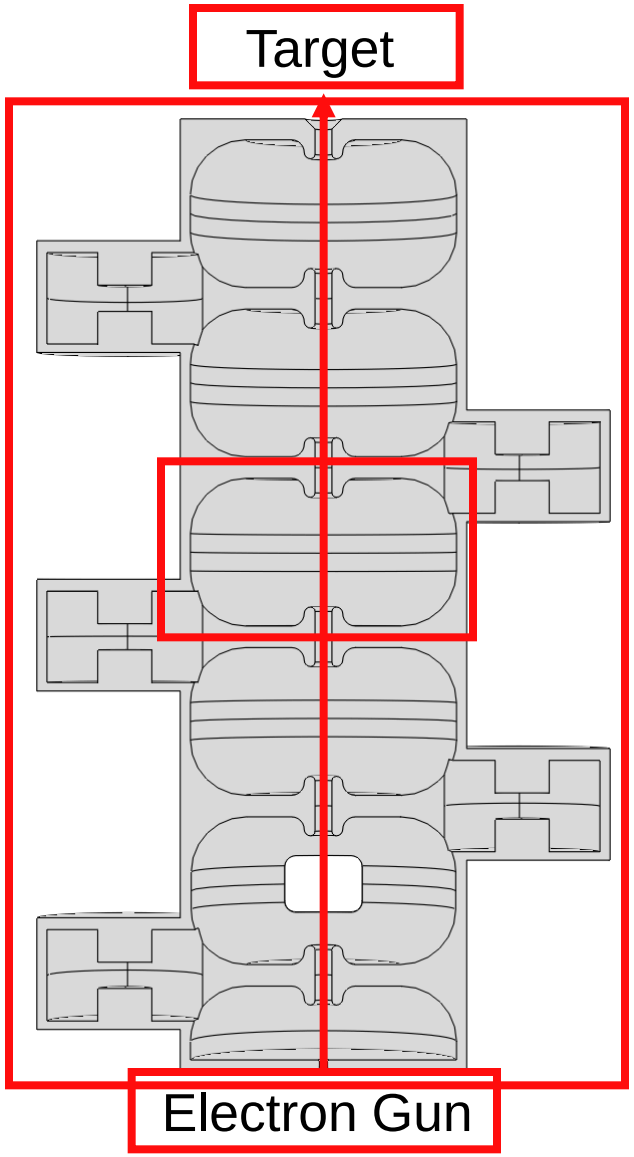
Waveguide Tuning
COMSOL Multiphysics

Electron Gun
Opera3D/SCALA

RF Fields
COMSOL Multiphysics

Electron Dynamics
PARMELA

Photon Production
EGSnrc



St. Aubin, Steciw, Fallone, Medical Physics, 37(2), 2010

St. Aubin, Steciw, Kirkby, Fallone, Medical Physics, 37(5), 2010

Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 40(4), 2013

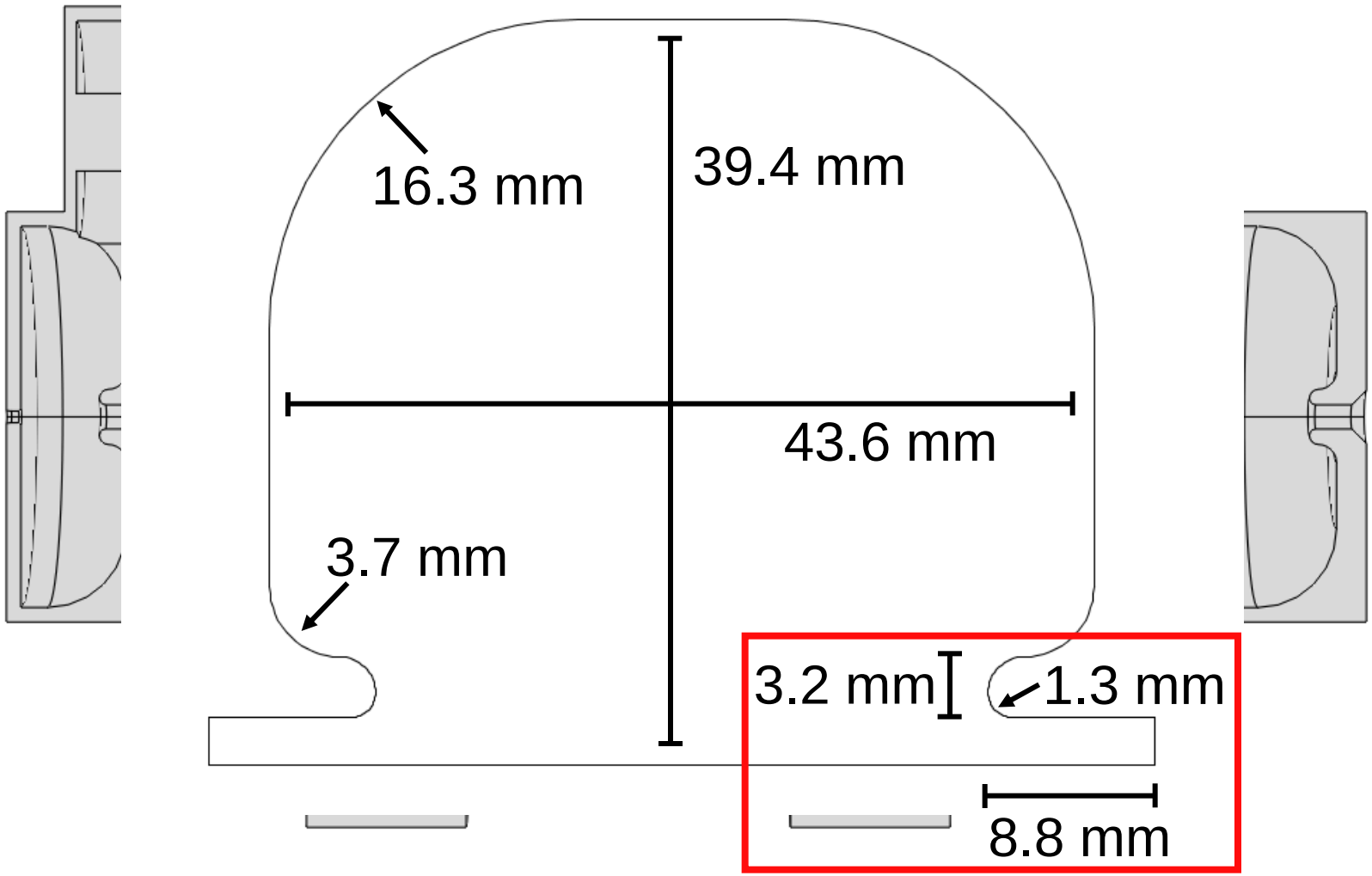
Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015

Experimental Threshold

Property	Description	Value
ZT^2/L (MΩ/m)	Efficiency of power transfer to beam	104.0
Q_{th}	Efficiency of energy storage	18520
E_P/E_0	Ratio of peak to average fields	3.61
E_{th} (MV/m)	Breakdown threshold	239.4

Tanabe, IEEE Transactions on Nuclear Science, 30(4), 1983

Cavity Geometry



Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015

Simulations

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COMSOL

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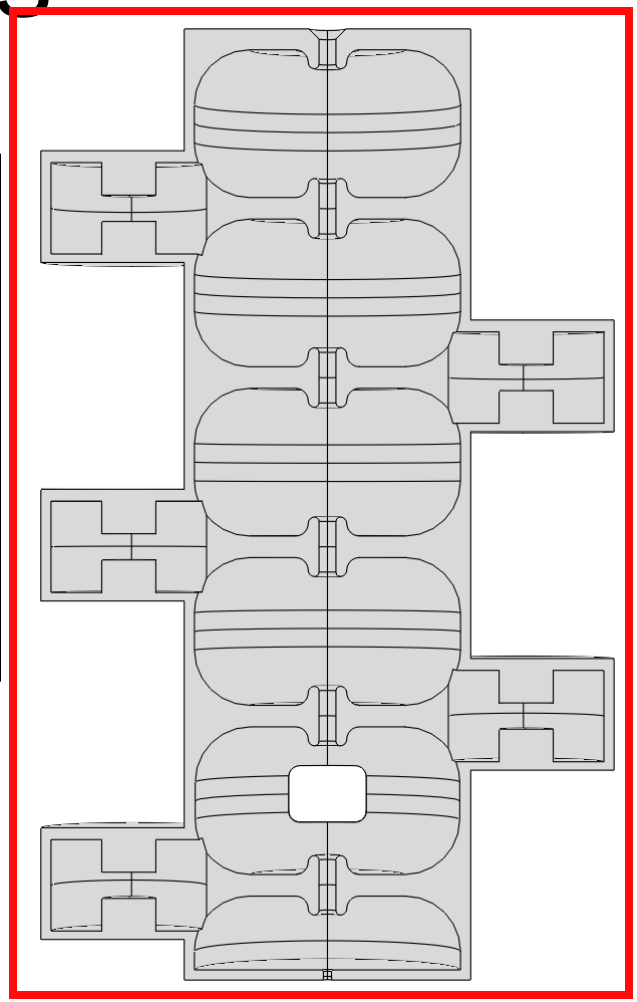
PARMELA

Photon Production
BEAMnrc + EGSnrc

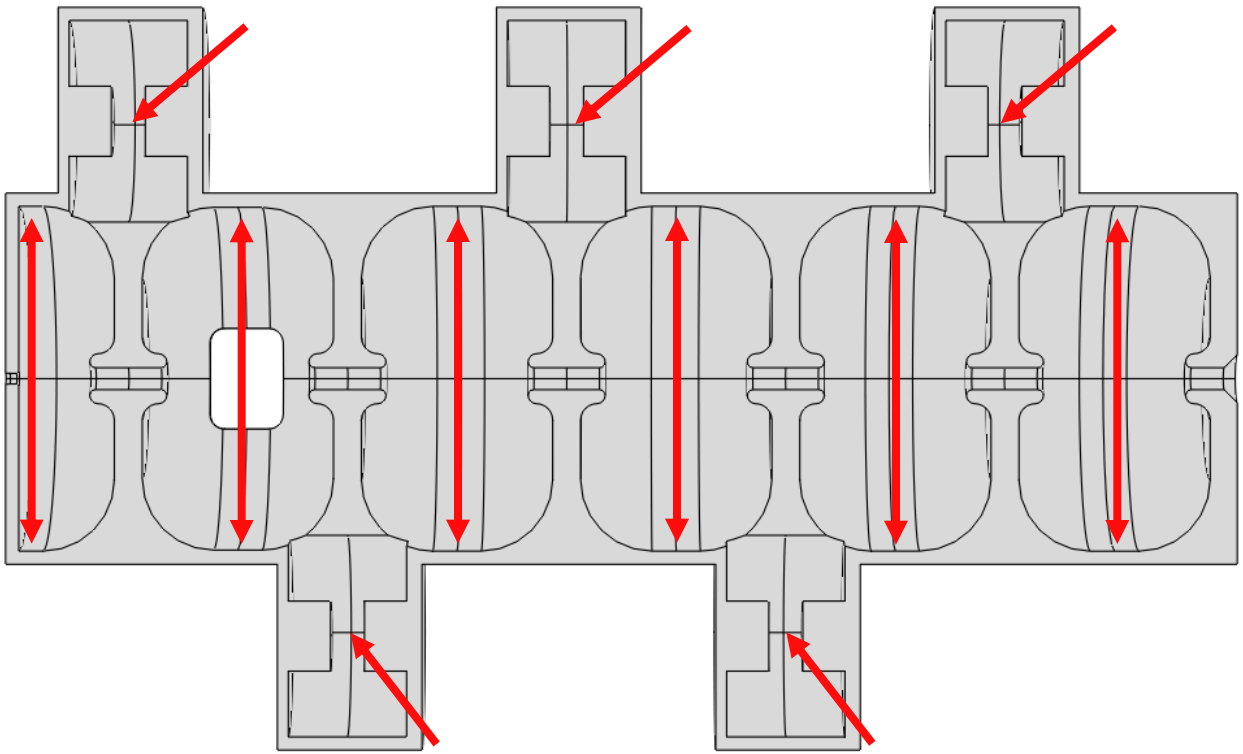
Target



Electron Gun

Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015

Full Waveguide Tuning



Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015

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COMSOL

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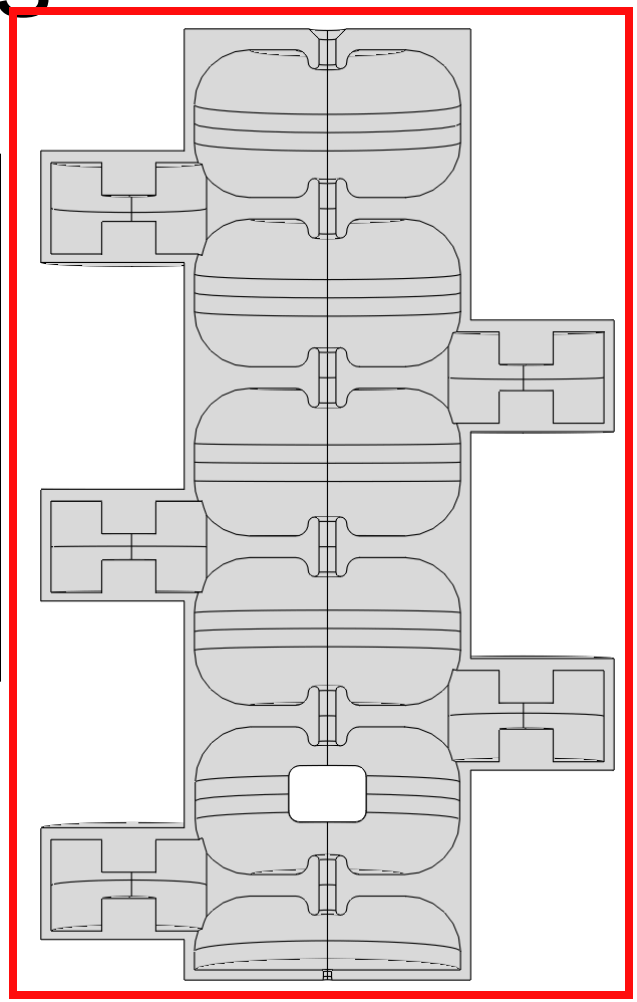
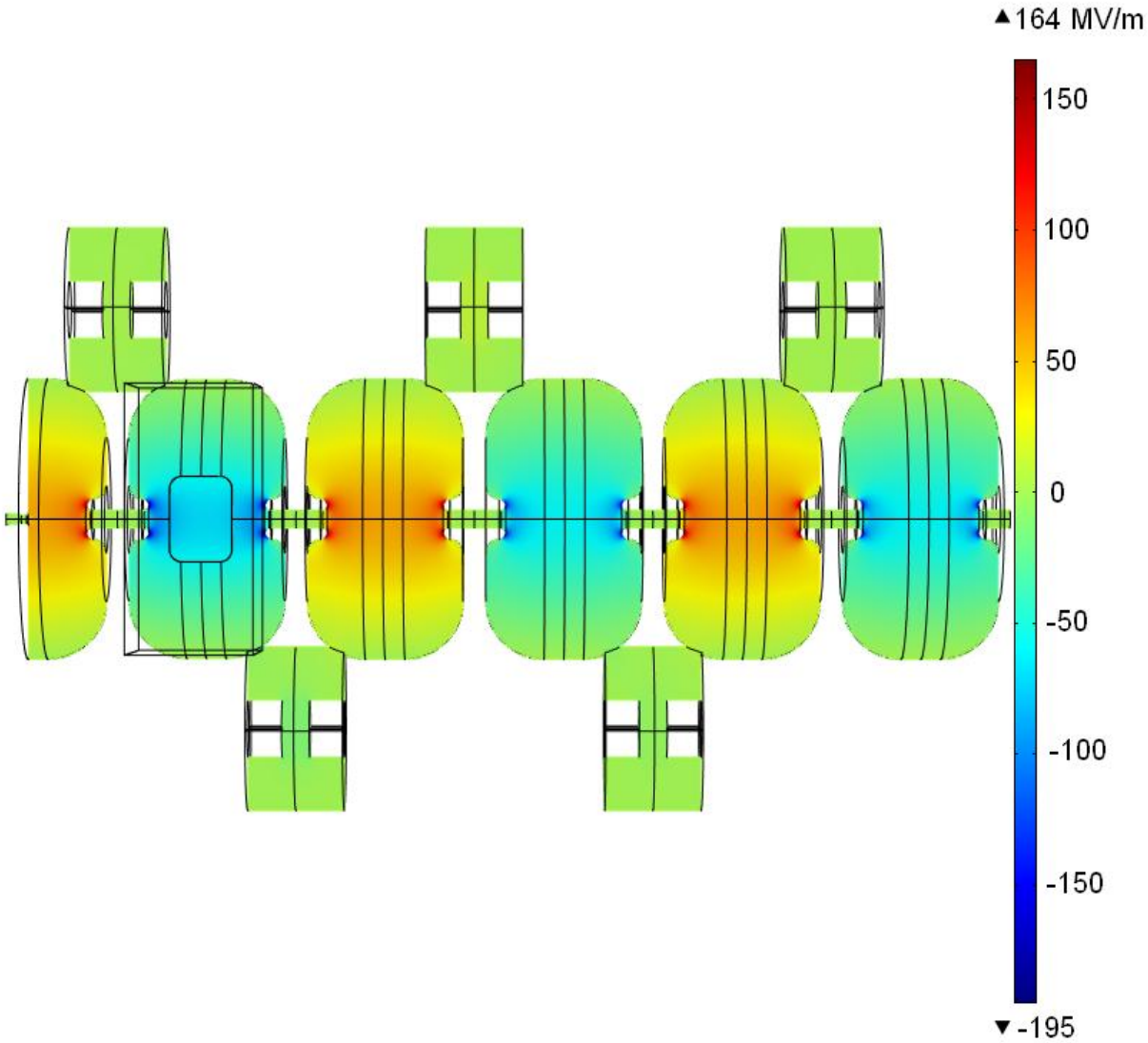
Target



Electron Gun

Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015



Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015

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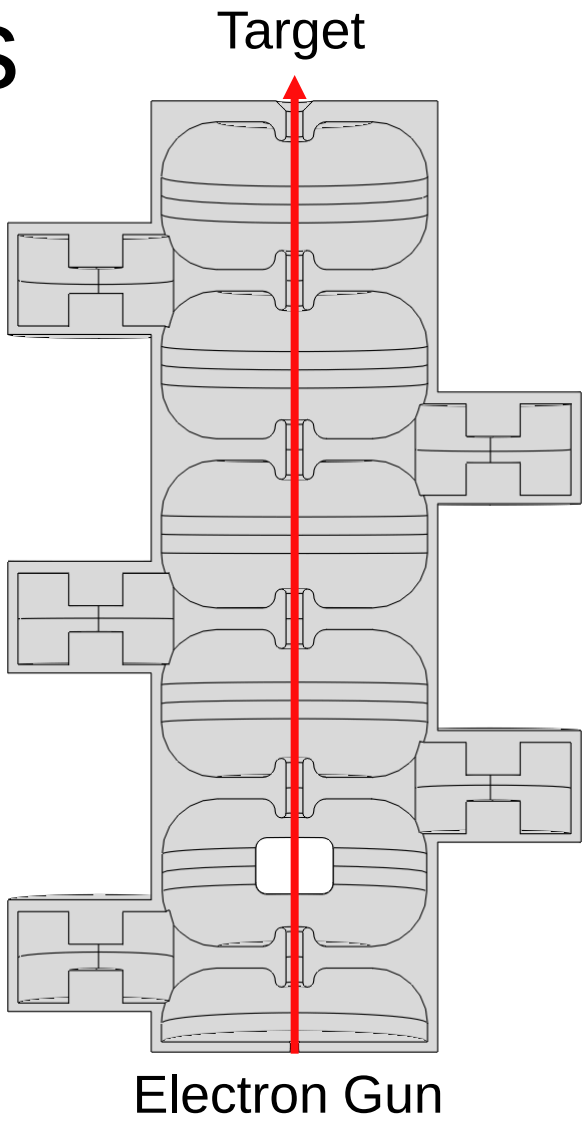

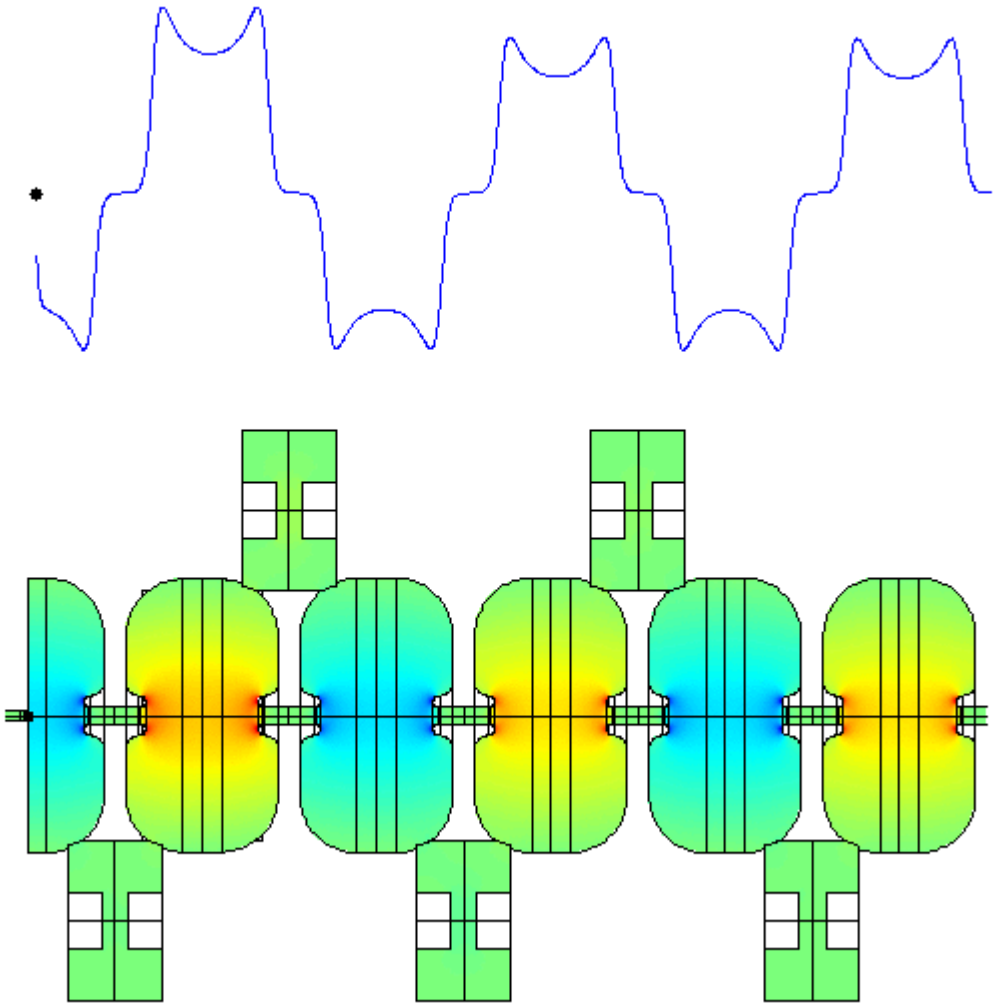

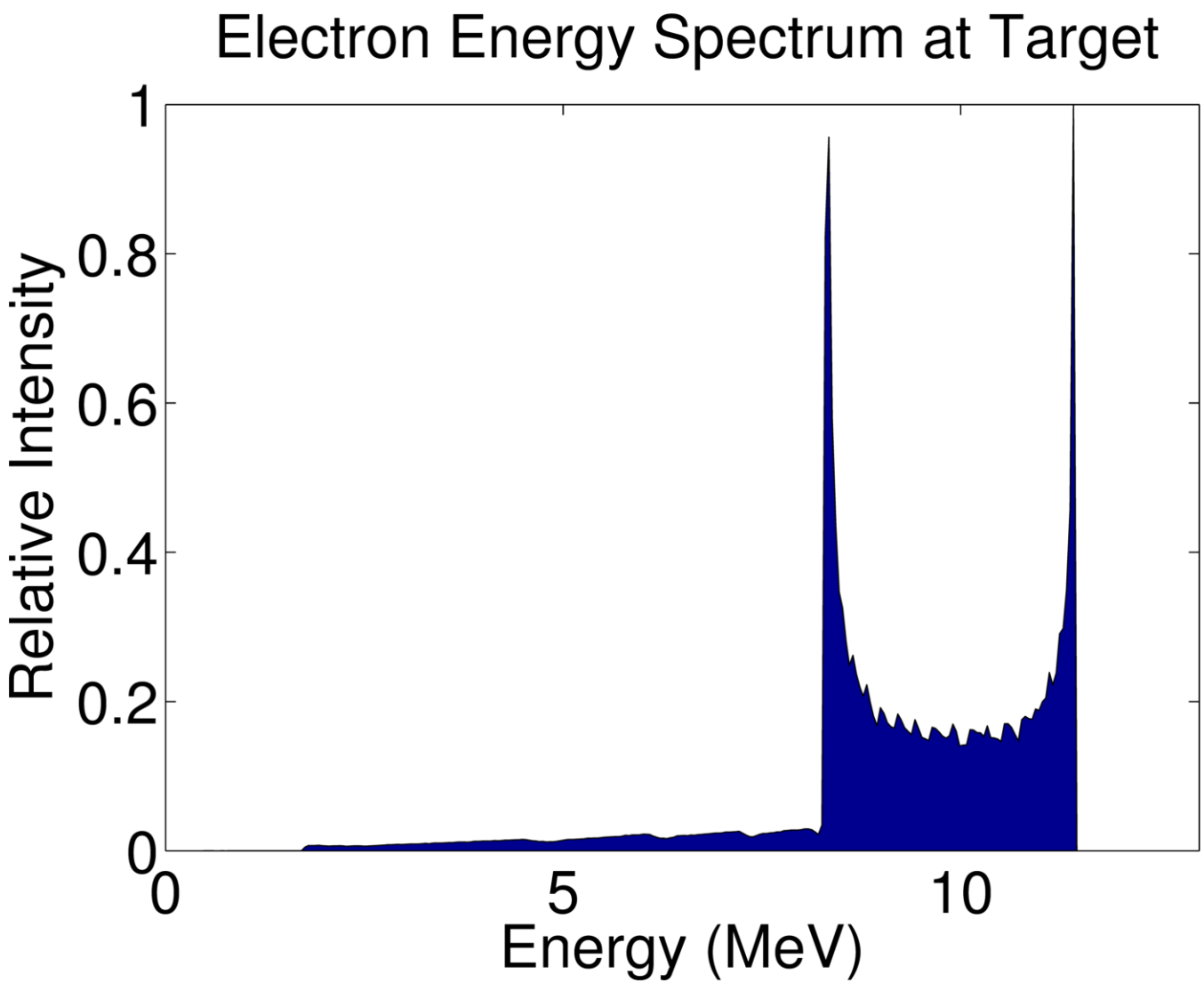

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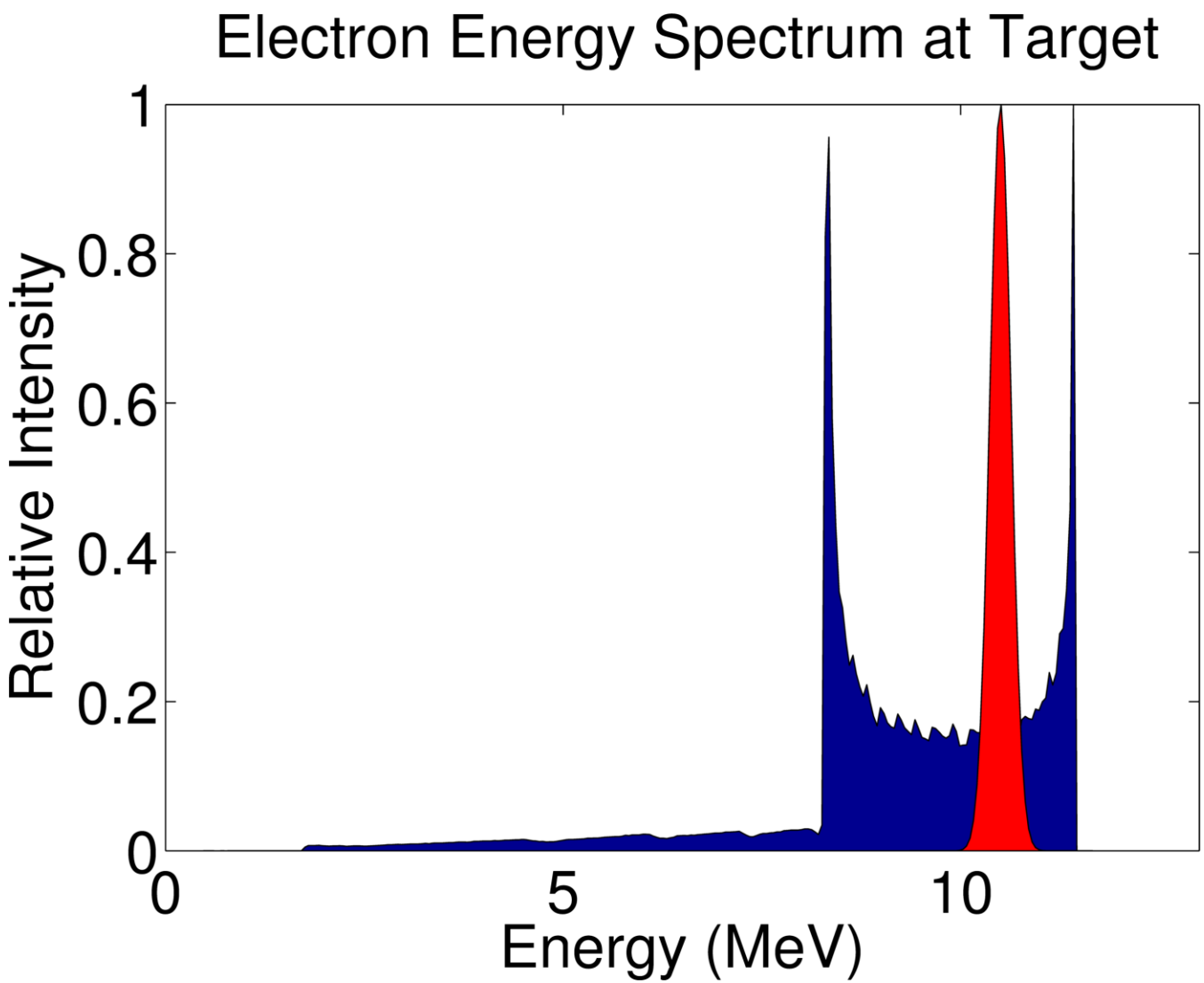

Sheikh-Bagheri, Rogers, Medical Physics, 29(3) 2002

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COMSOL

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RF Fields
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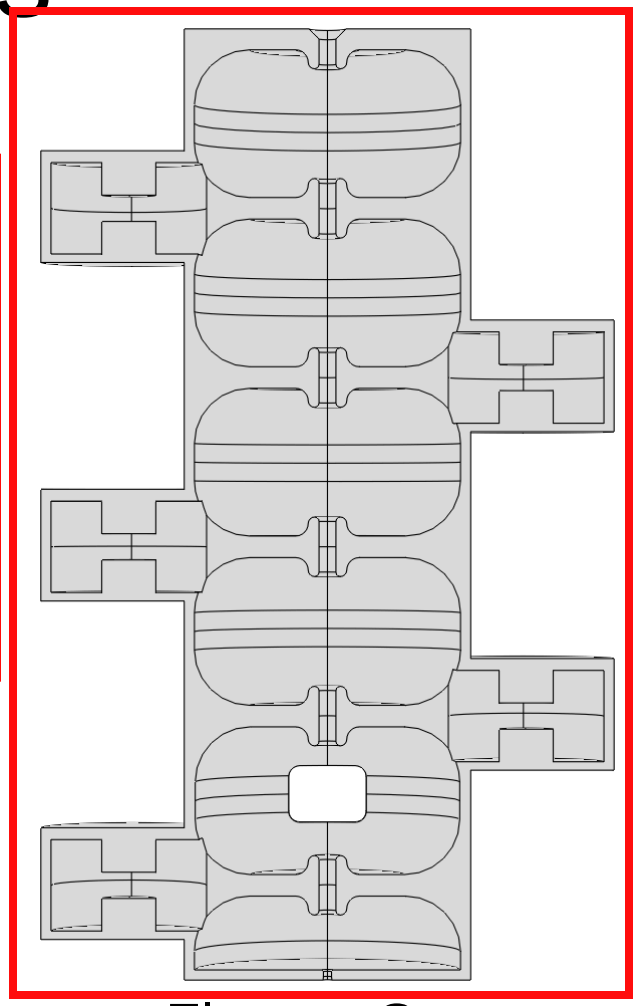
Electron Dynamics
PARMELA

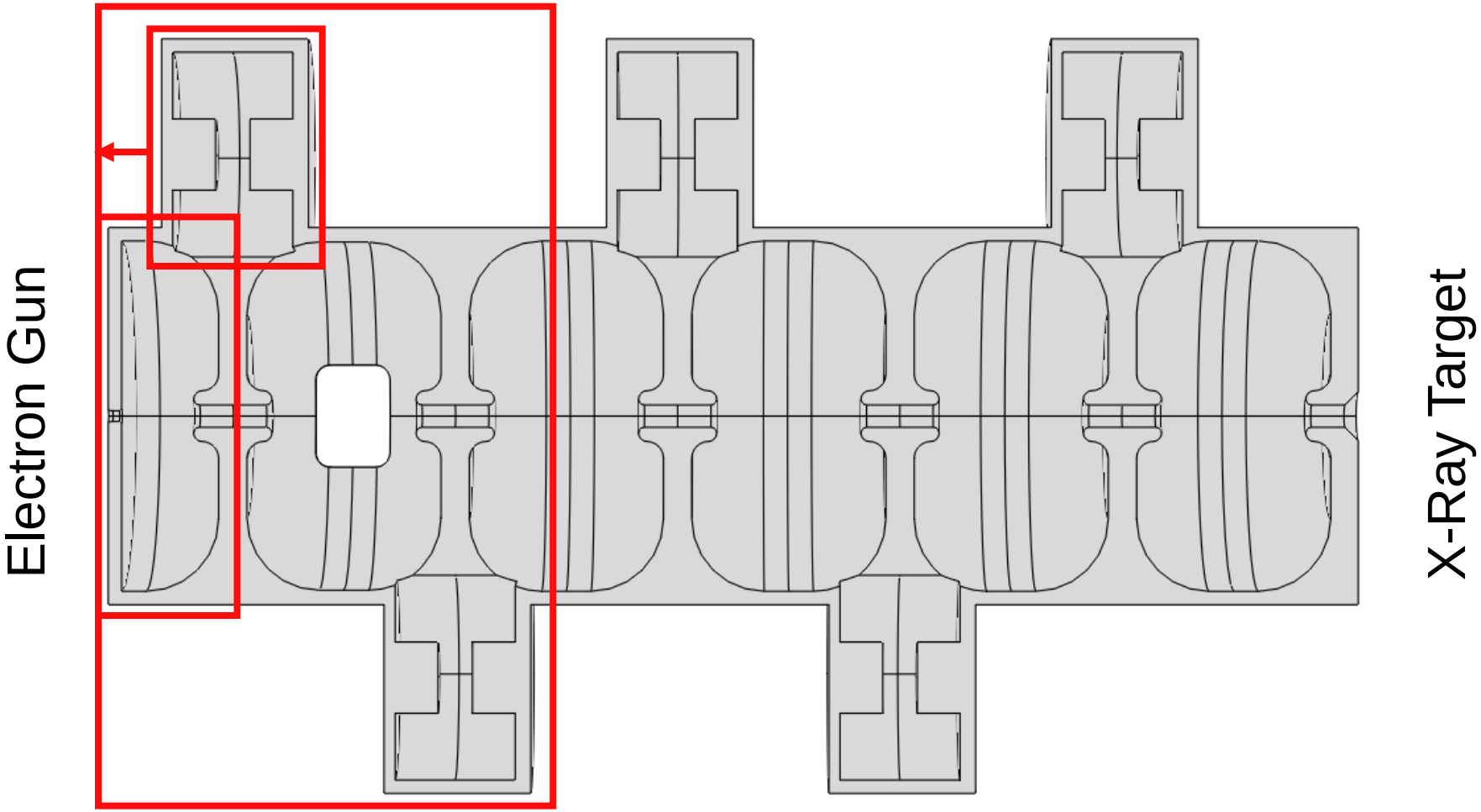
Photon Production
BEAMnrc + EGSnrc

Target



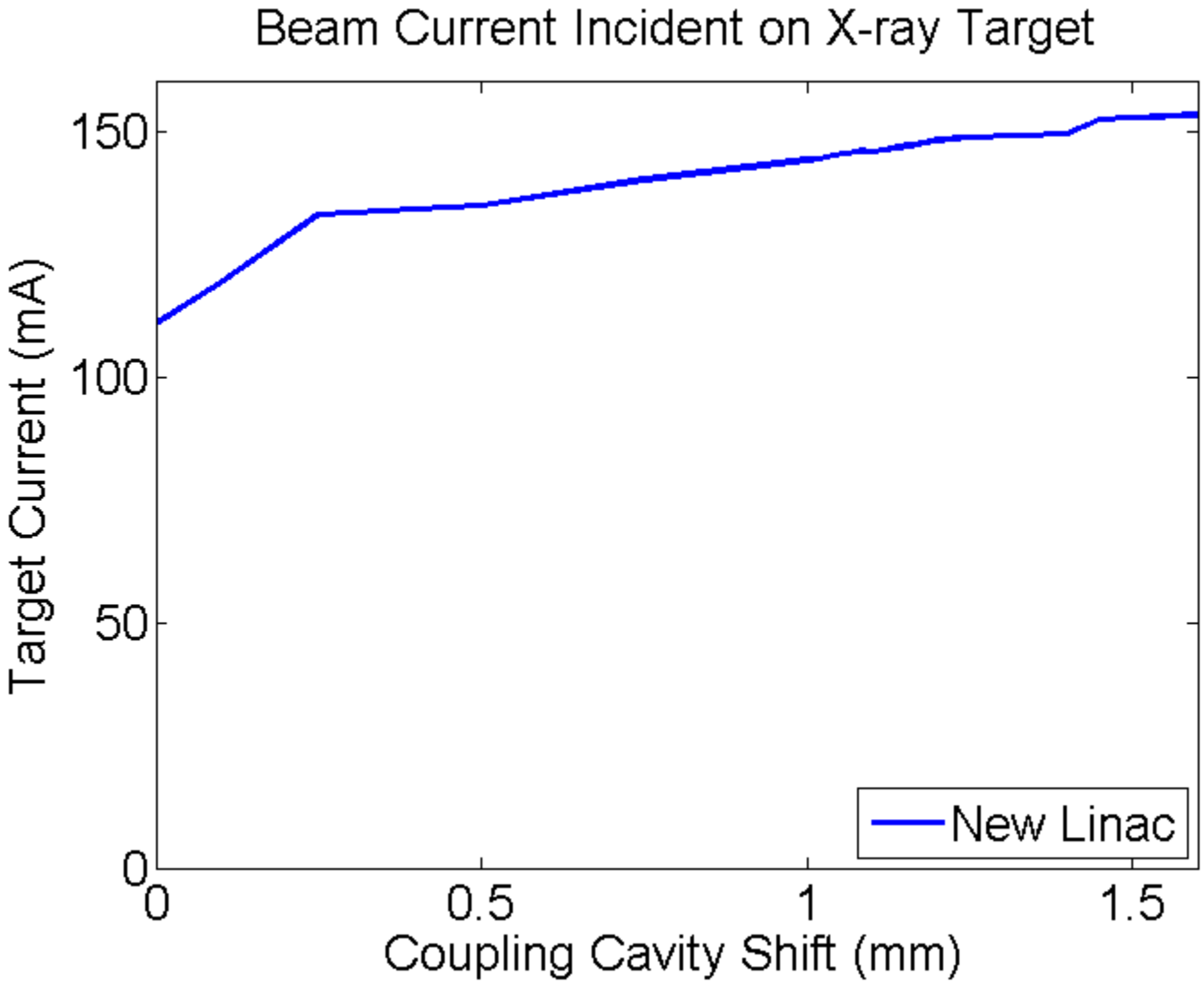
Electron Gun

Reducing the Spectrum Width



Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015

St. Aubin, Steciw, Fallone, Medical Physics, 37(2), 2010



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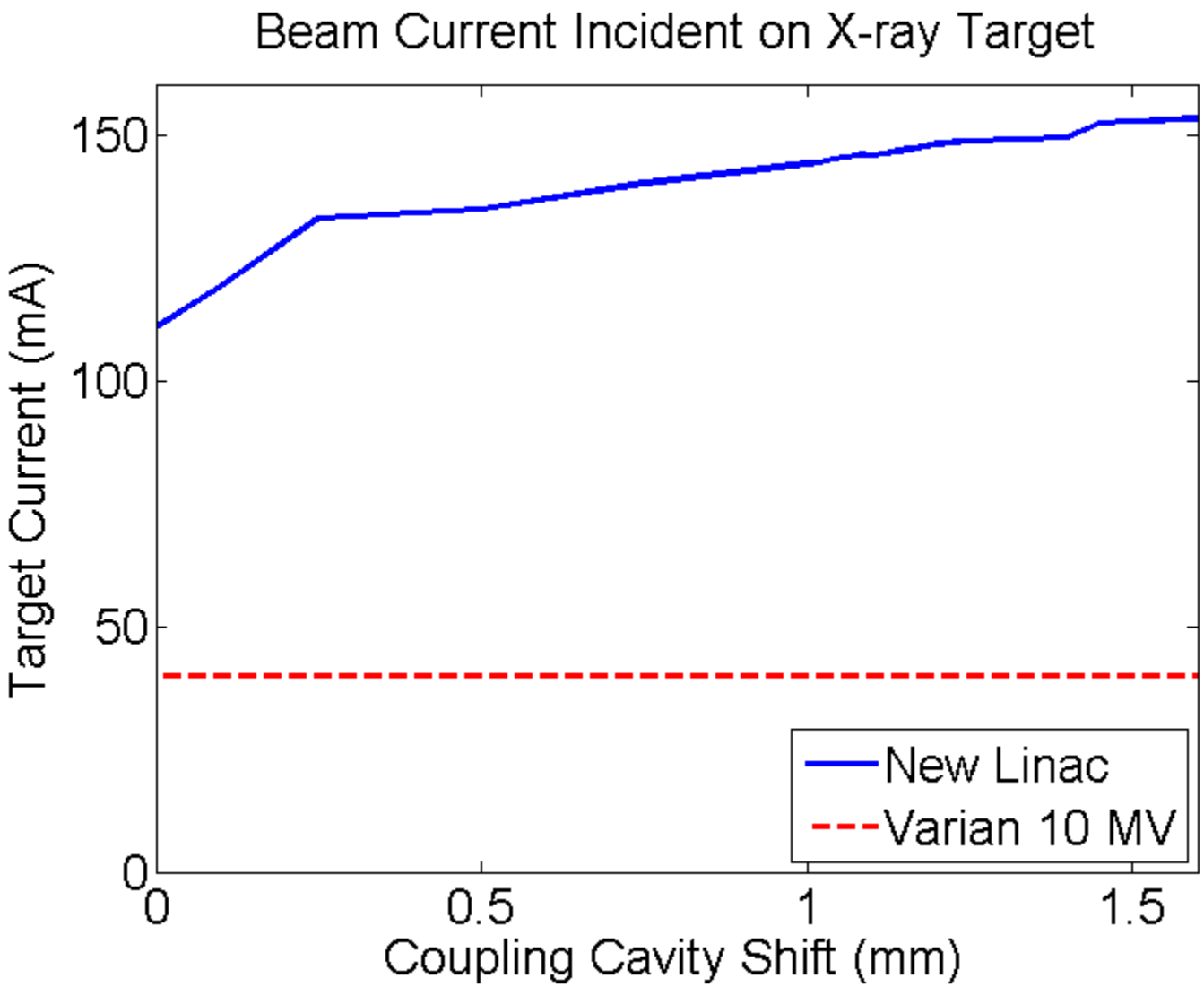

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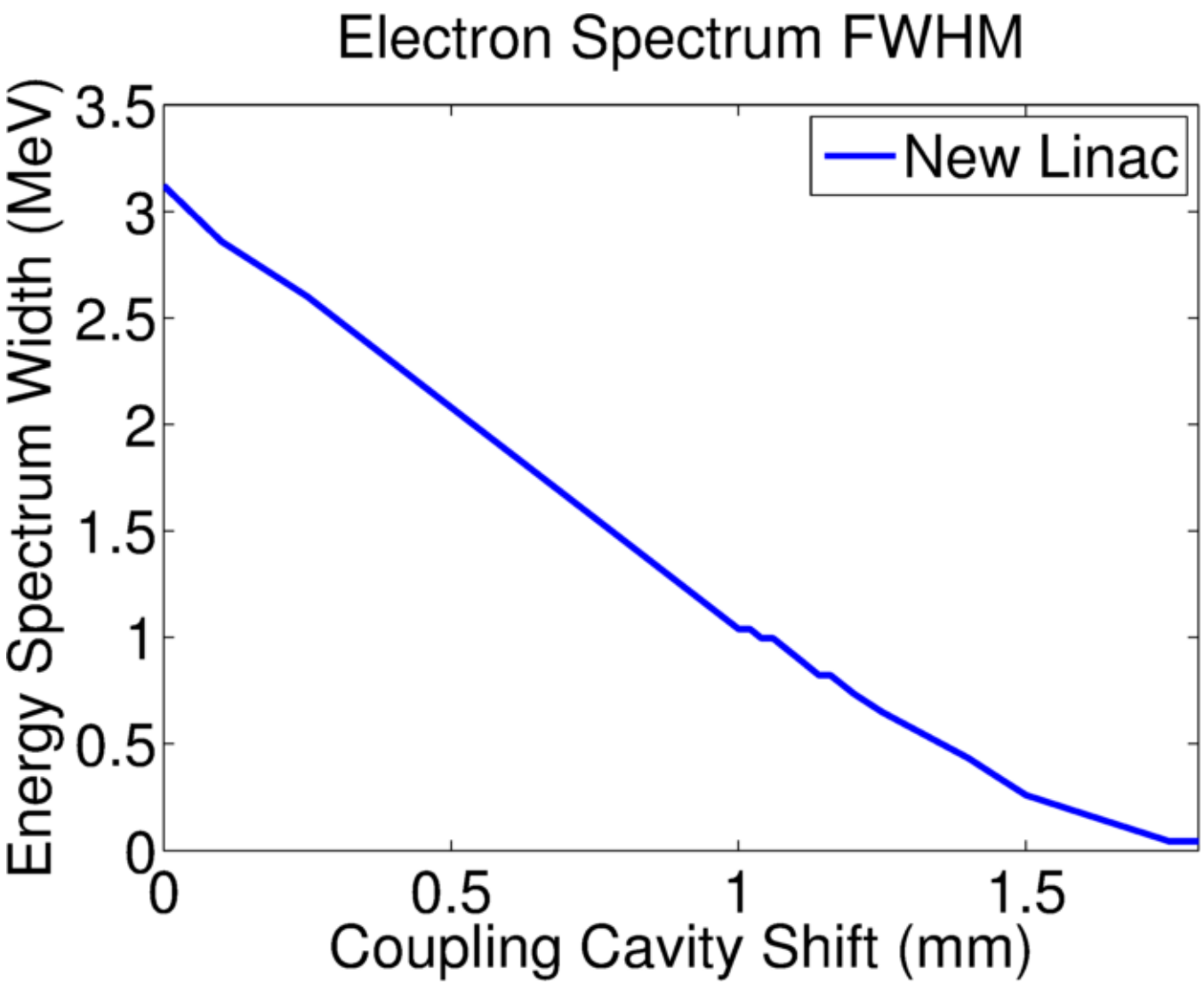

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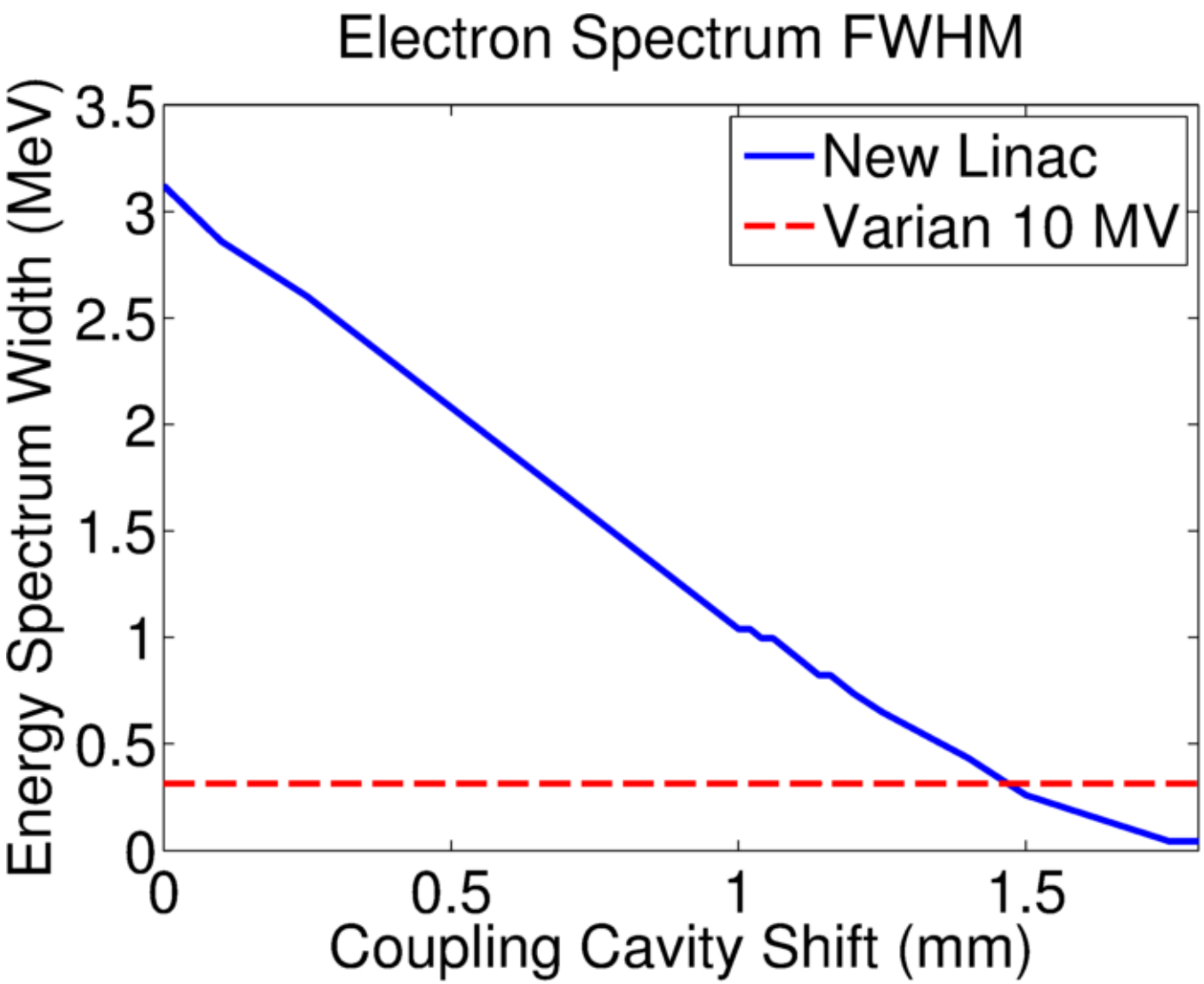

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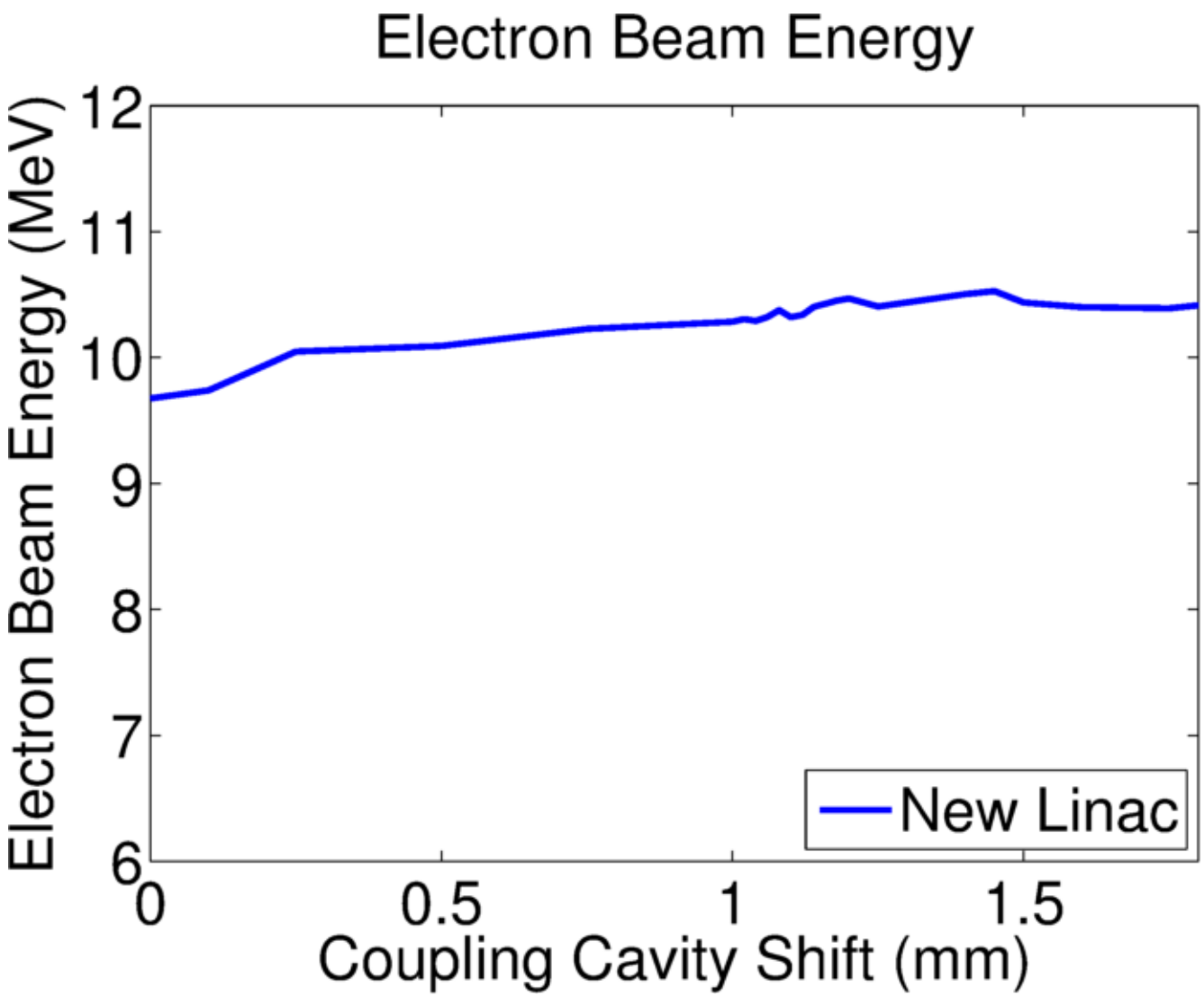

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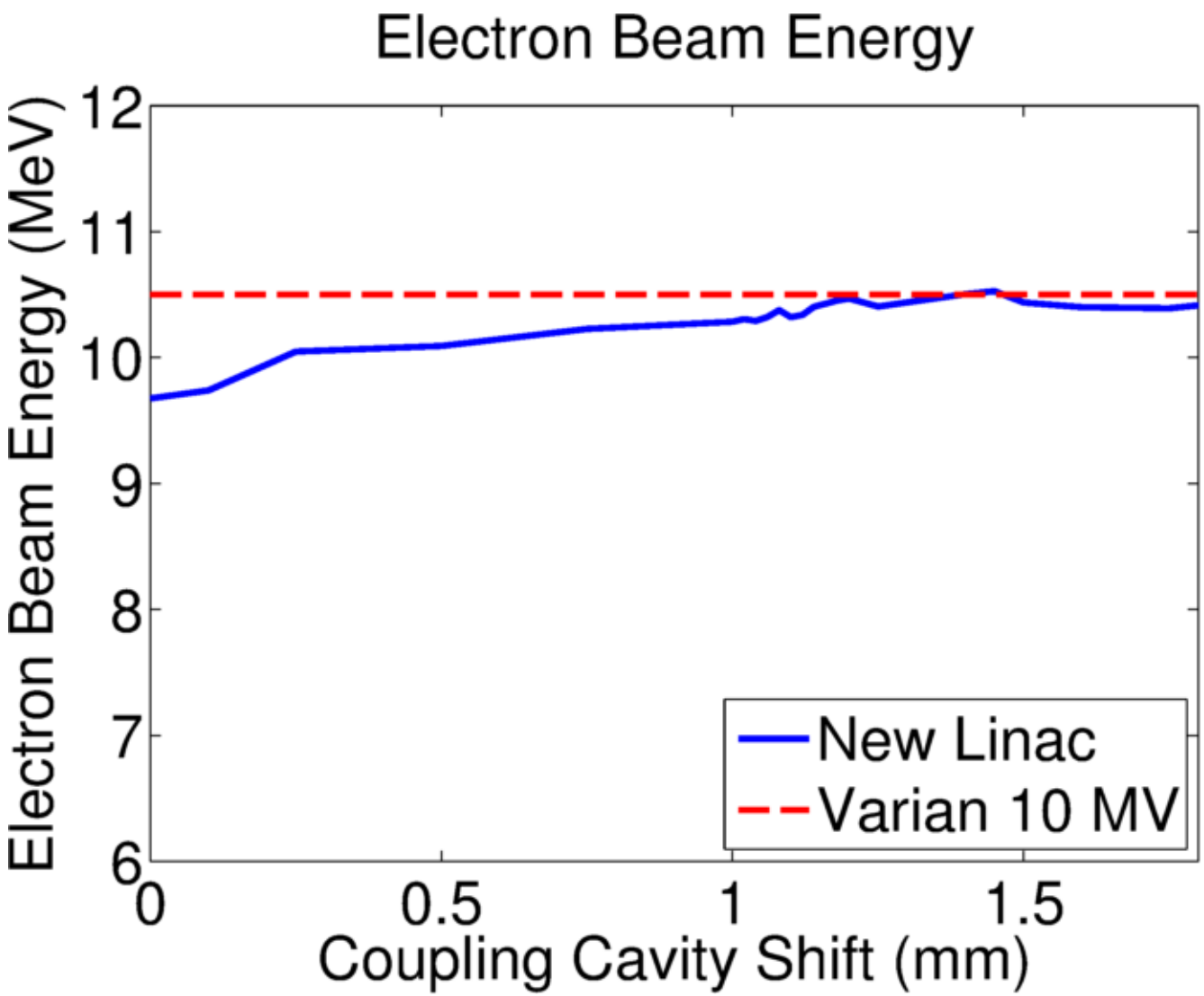

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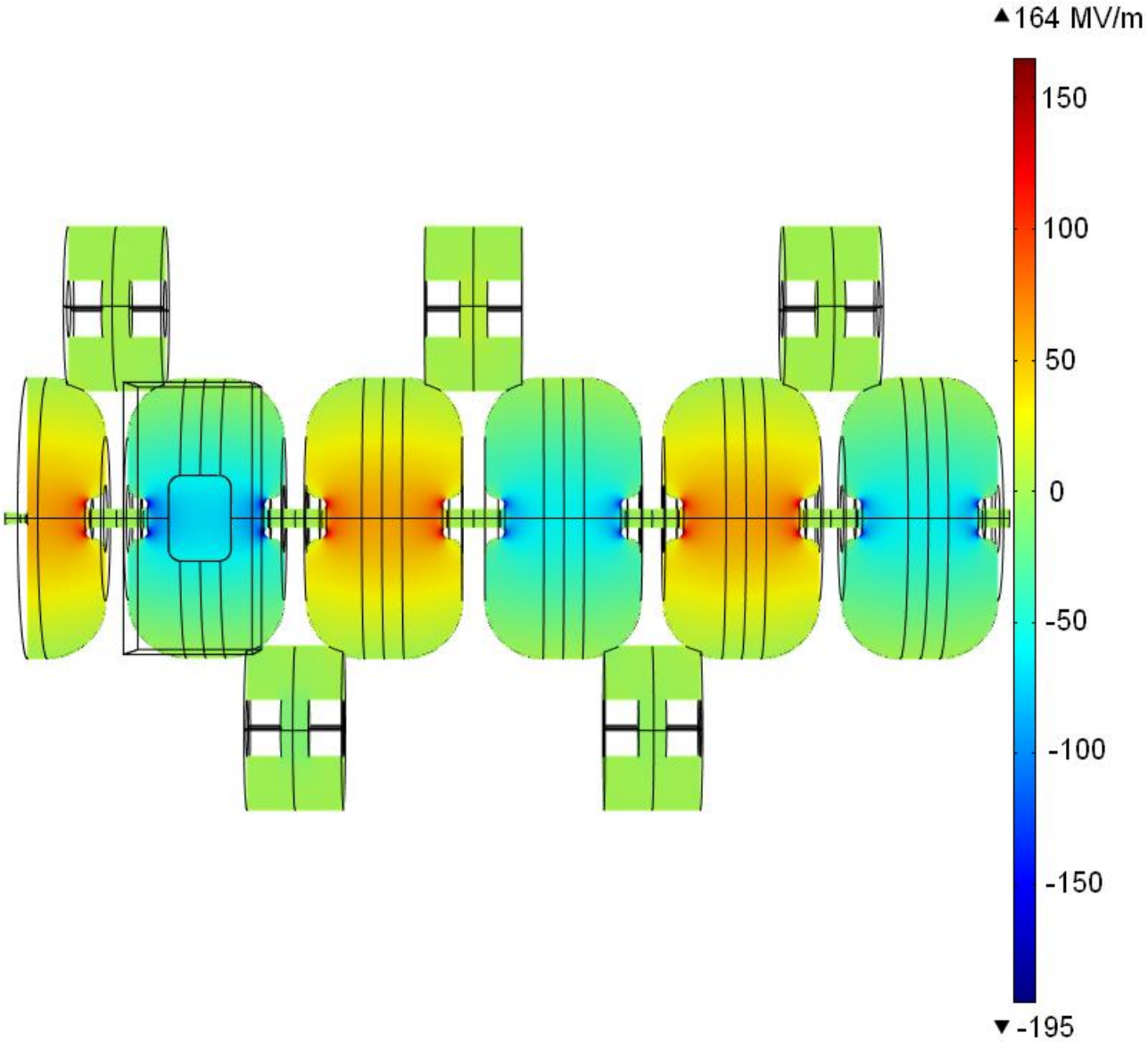
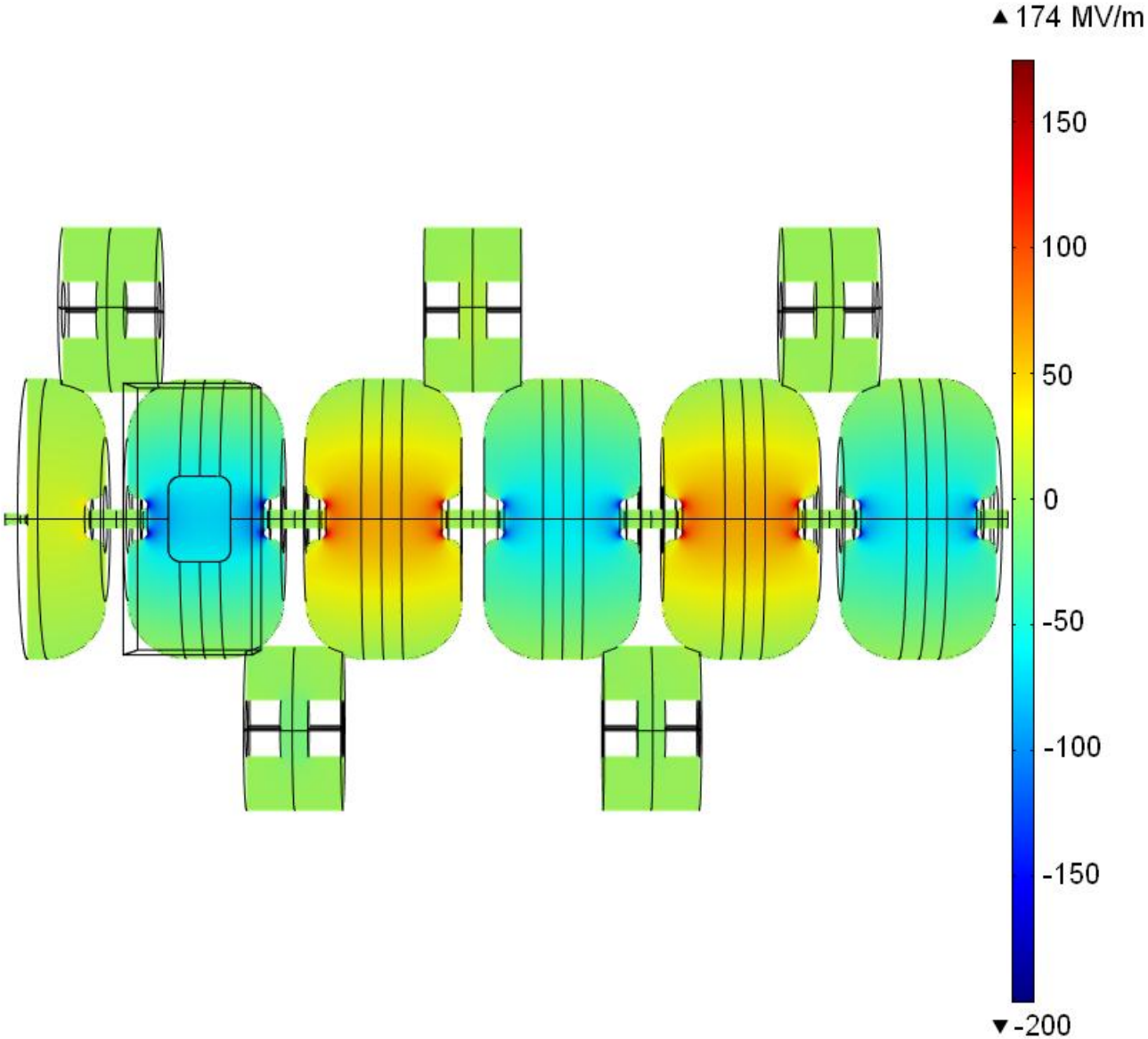
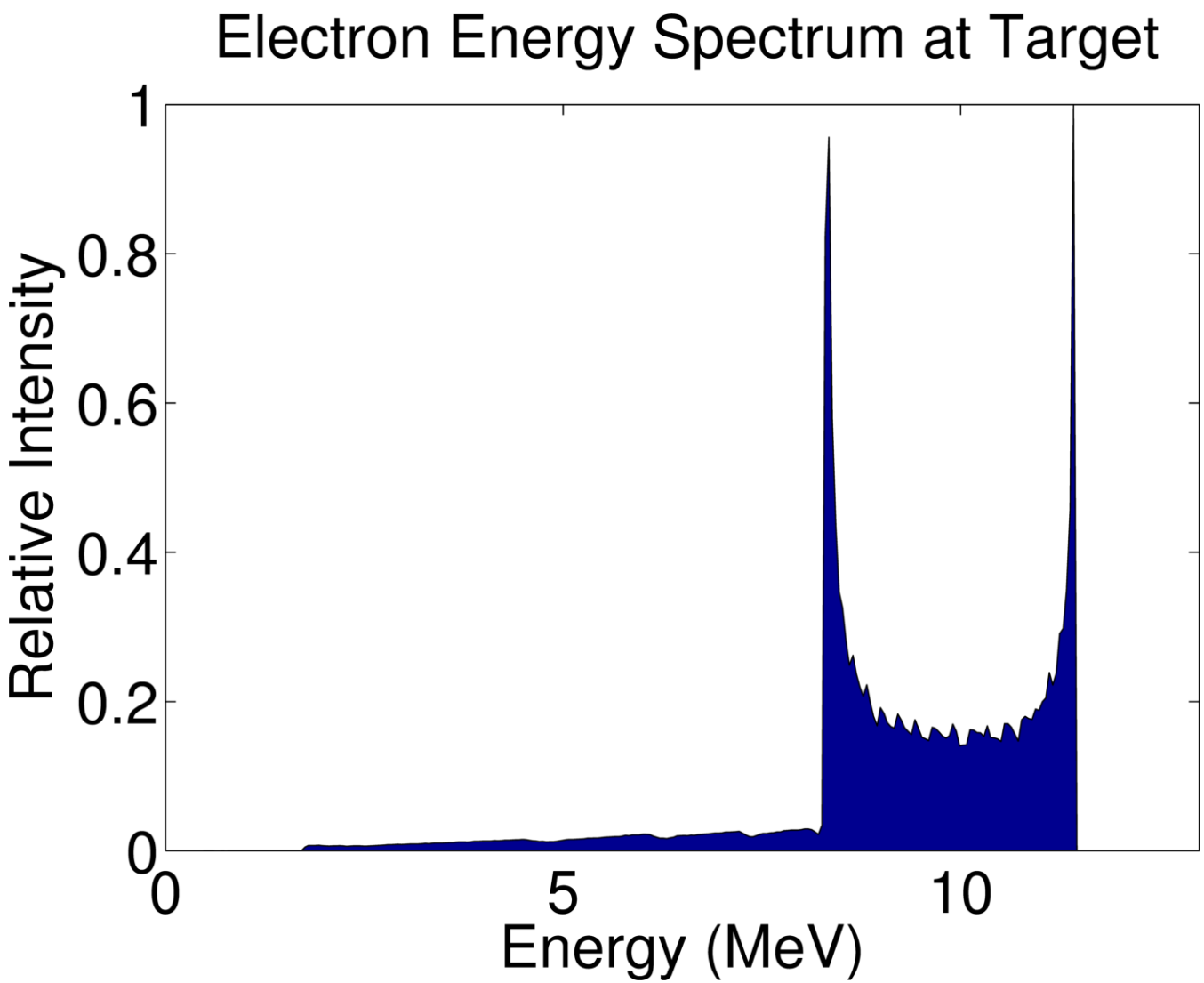

▲164 MV/m
150
100
50
0
-50
-100
-150
▼-195


▲ 174 MV/m
150
100
50
0
-50
-100
-150
▼ -200



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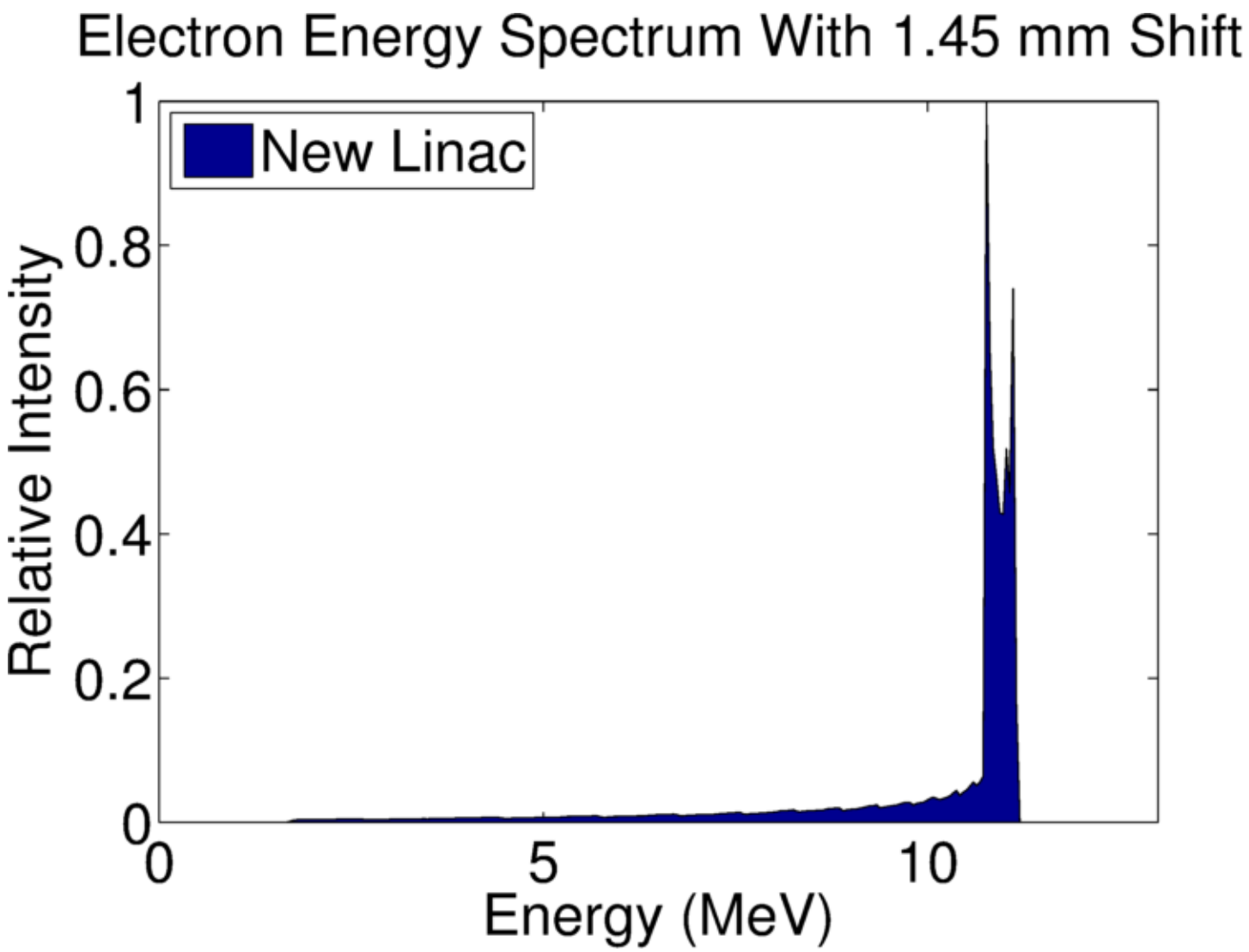

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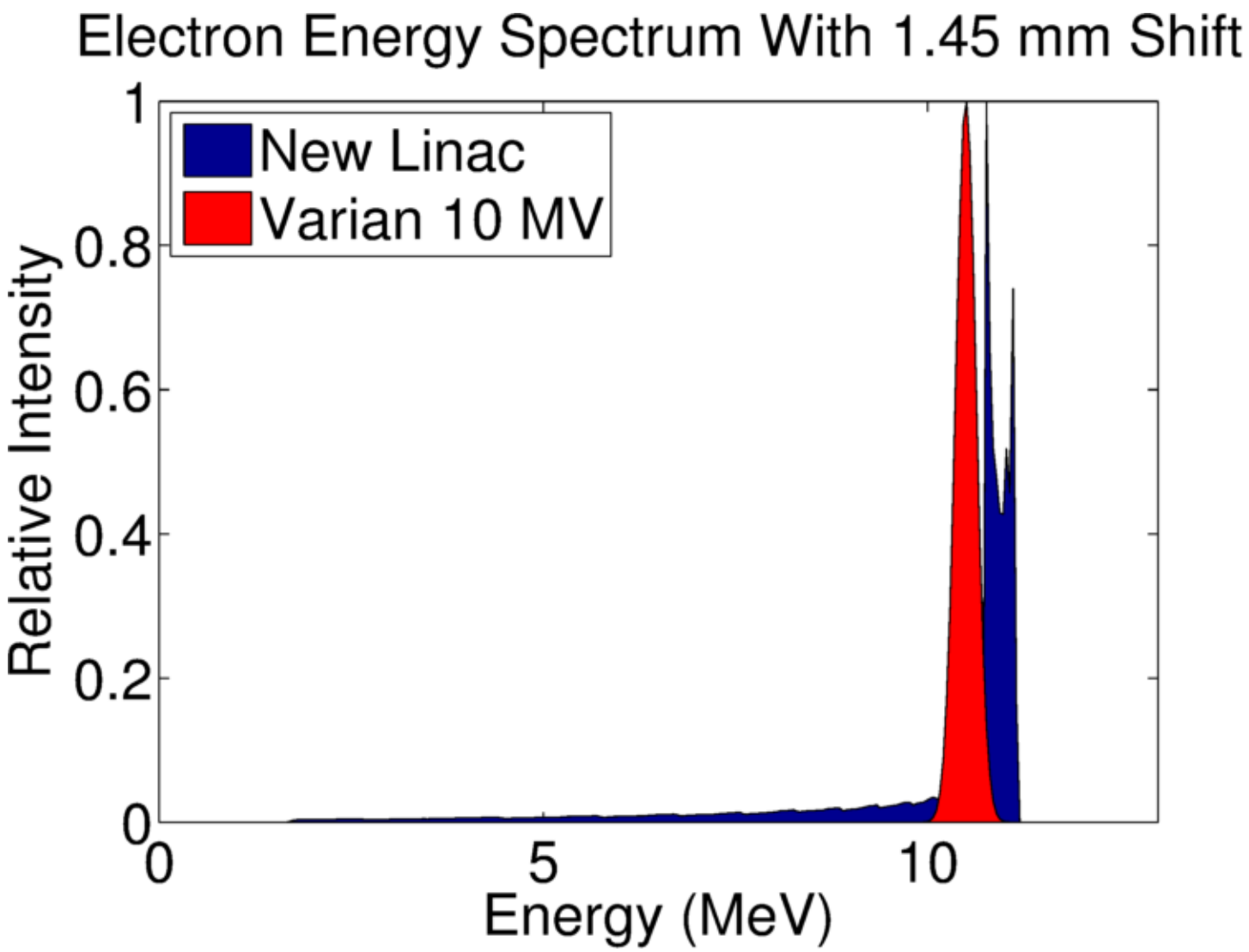

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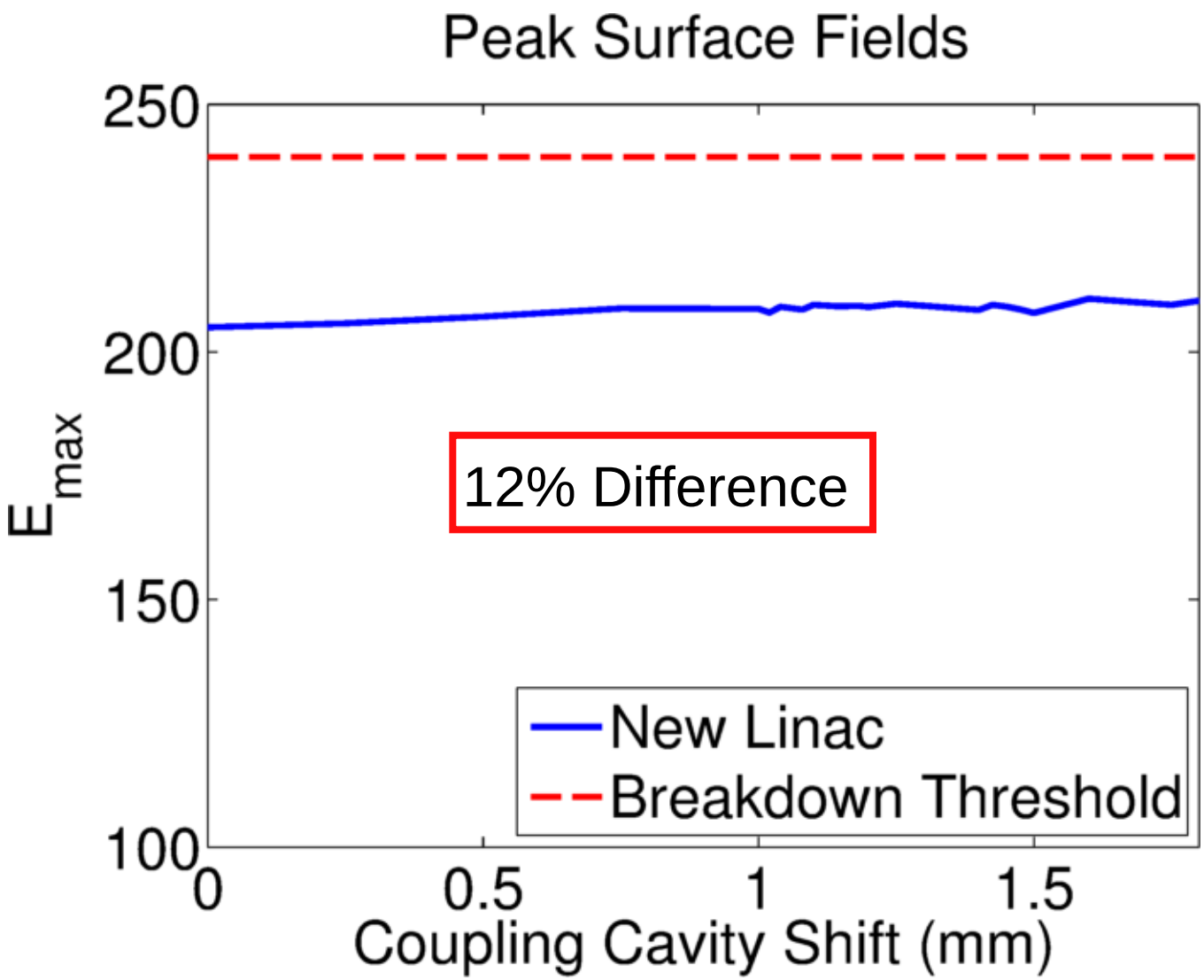
Sheikh-Bagheri, Rogers, Medical Physics, 29(3), 2002



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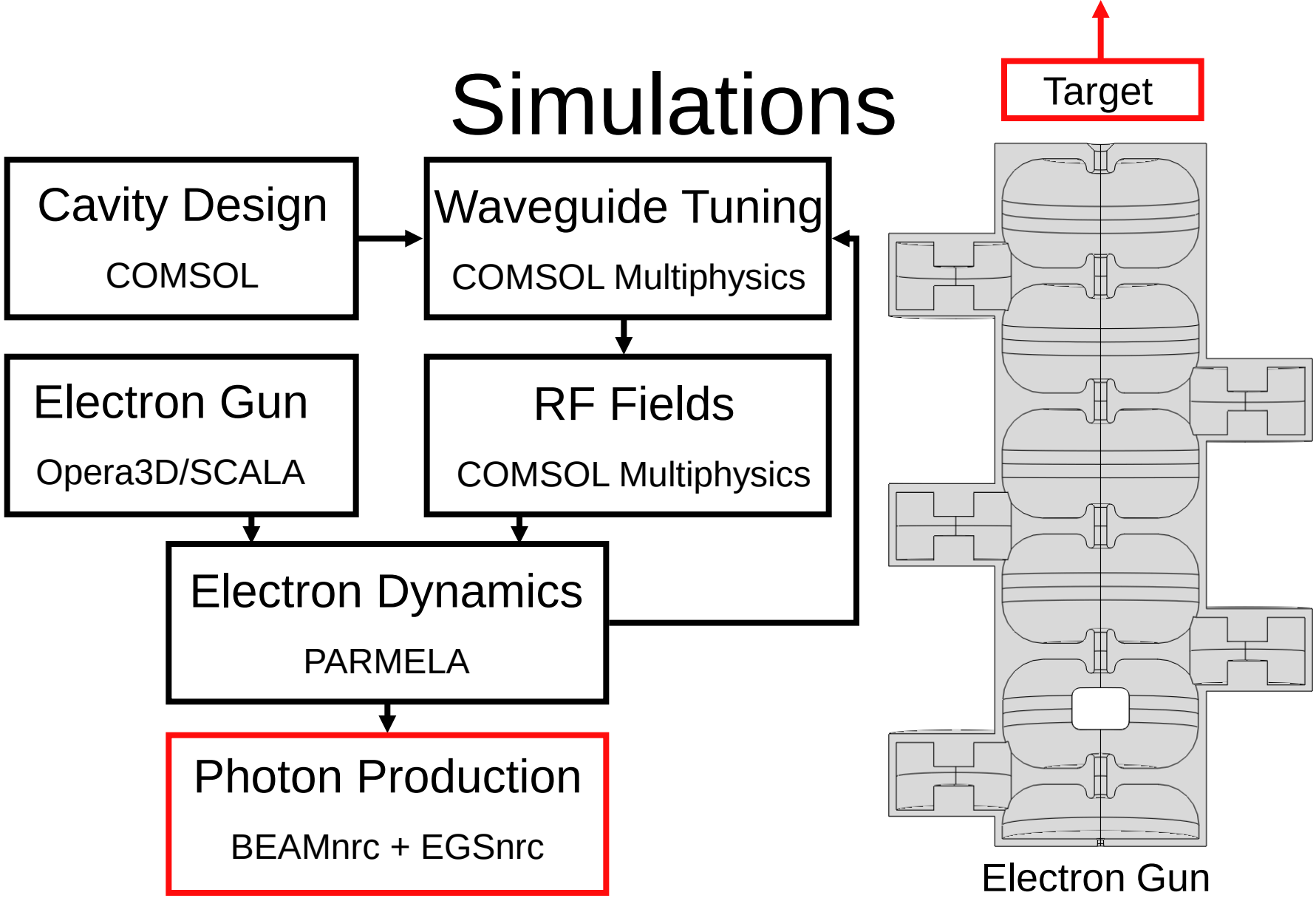
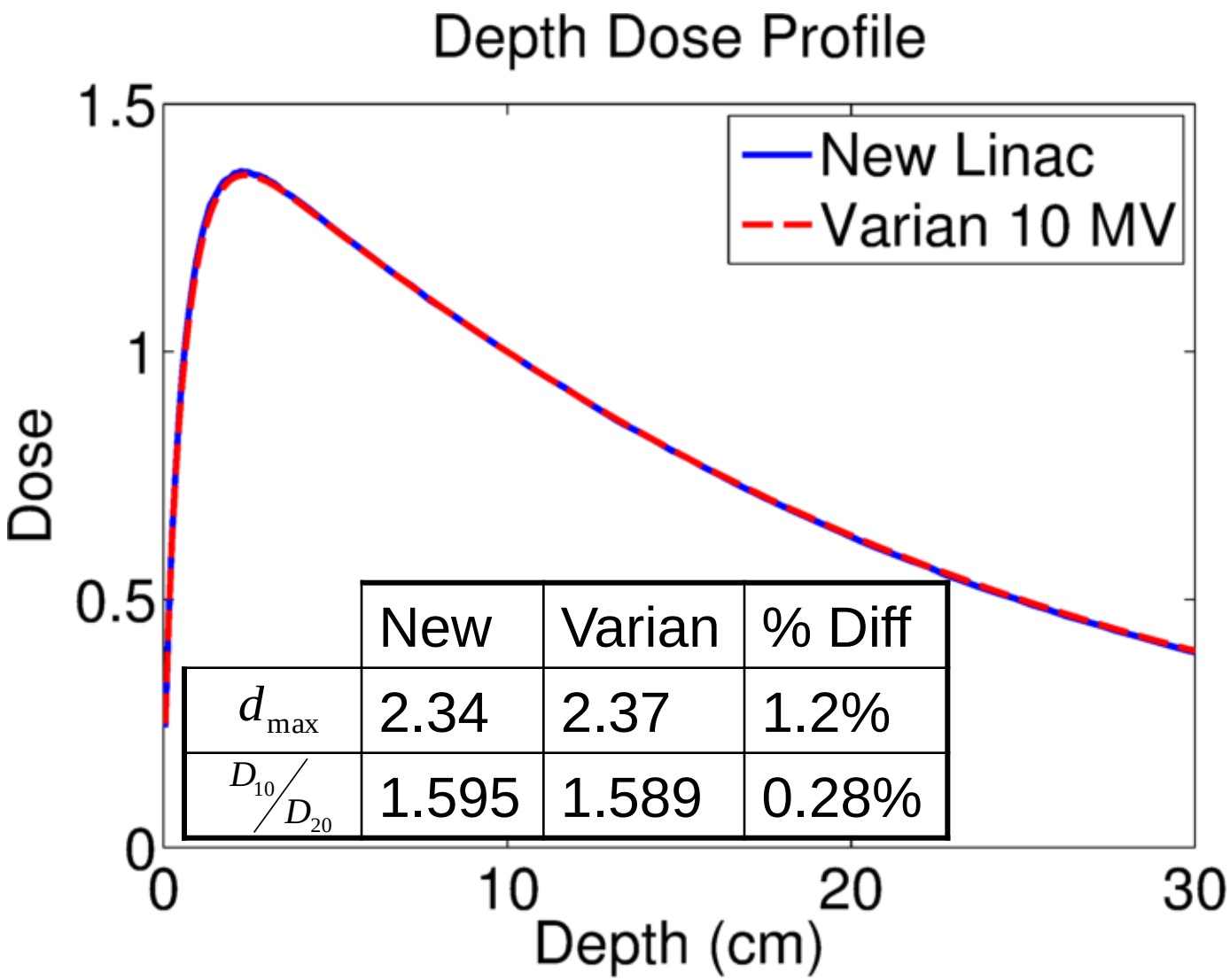
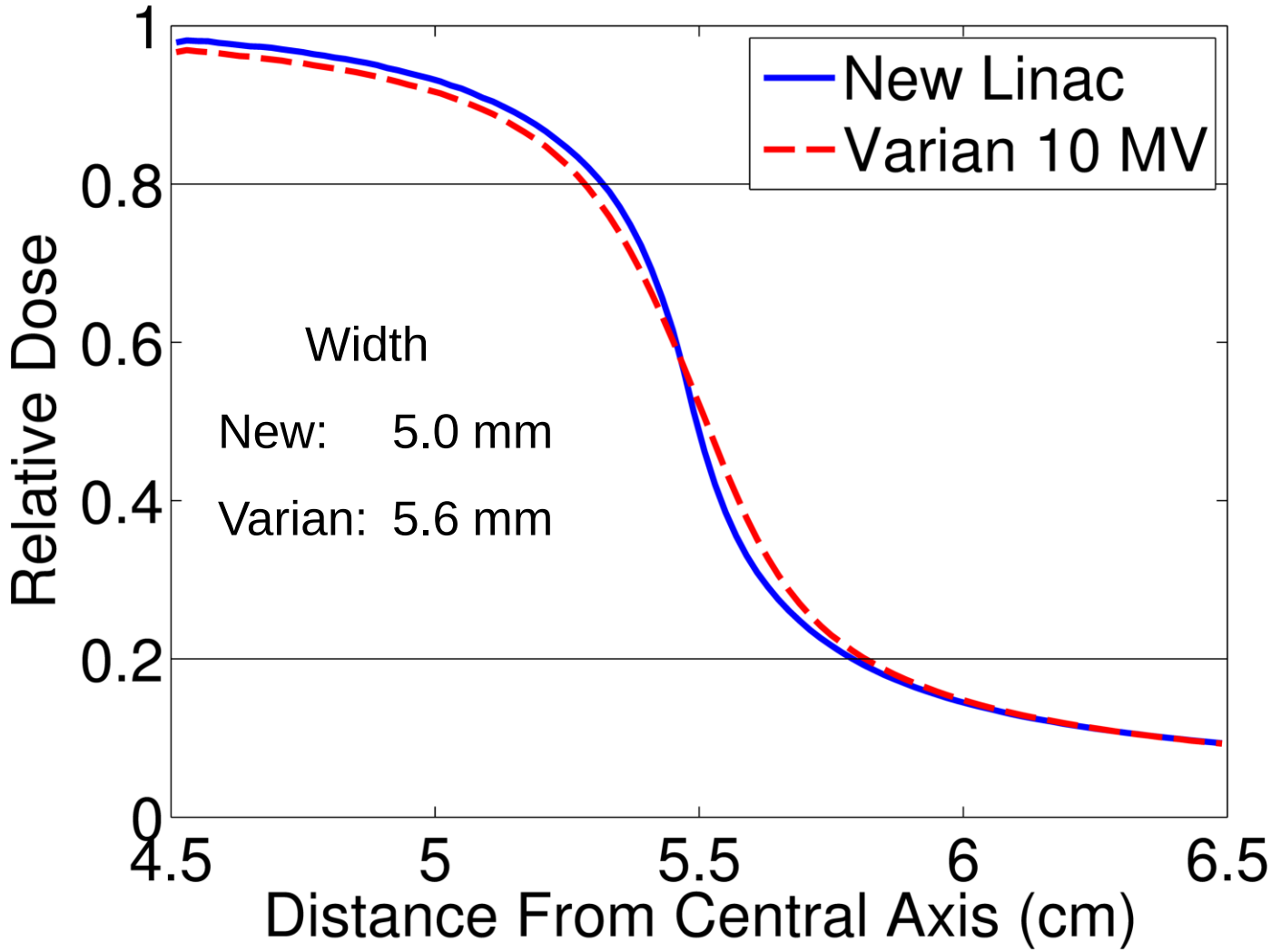
Simulations





	New	Varian	% Diff
d_{max}	2.34	2.37	1.2%
D_{10}/D_{20}	1.595	1.589	0.28%

Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015



Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015

Conclusions

- 27.5 cm accelerator waveguide
- Producing 10 MV photon beam
  - Equivalent depth dose curve
  - Sharper penumbra
- Operating within breakdown threshold

Future Work

- Heating
  - Linac
  - Target
- Tolerances
  - Manufacturing
  - Thermal/Mechanical
- Target design
- Magnetic Field tolerance
  - Parallel
  - Perpendicular
- Magnetic Shielding
  - Parallel
  - Perpendicular

What is a benefit of using a parallel beam-field linac-MR configuration versus a perpendicular one?

4%	1. Patient Comfort
32%	2. More compact machine
3%	3. Faster treatments
30%	4. Better magnet homogeneity
30%	5. No hotspots in low-density regions inside/outside of the patient

What is the benefit of treating with higher energies for VMAT treatments?

16%	1. Better OAR sparing
39%	2. Lower dose near the patient surface
2%	3. More energy efficient
3%	4. Narrower Bragg peak
39%	5. More uniform dose distributions in the tumor

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