New Linac Designs for MR-Guided Therapy Systems

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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
(a) parallel configuration

(b) perpendicular configuration

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
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 %

3D Dose MAX: 120.5 %
3D MAX for PTV74: 10.8 %
3D MIN for PTV74: 1.1 %
3D MEAN for PTV74: 3.6 %
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%, $D_{\text{Mean}}$ is reduced by $\sim 0.5$ Gy)
Even Higher?
Current System

Linac (27.5 cm)

Imaging Magnet

Patient Couch
High Energy Waveguide

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

Bend Magnet
Linac
Imaging Magnet
Patient Couch

St. Aubin, Steciw, Fallone, Physics in Medicine and Biology, 55, 2010
High Energy Short Waveguide

Linac

Imaging Magnet

Patient Couch
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

Electron Gun
Opera3D/SCALA

Electron Dynamics
PARMELA

Photon Production
EGSnrc

Waveguide Tuning
COMSOL Multiphysics

RF Fields
COMSOL Multiphysics

Target

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

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>$\frac{ZT^2}{L} (\text{M}\Omega/m)$</td>
<td>Efficiency of power transfer to beam</td>
<td>104.0</td>
</tr>
<tr>
<td>$Q_{th}$</td>
<td>Efficiency of energy storage</td>
<td>18520</td>
</tr>
<tr>
<td>$\frac{E_p}{E_0}$</td>
<td>Ratio of peak to average fields</td>
<td>3.61</td>
</tr>
<tr>
<td>$E_{th} (\text{MV/m})$</td>
<td>Breakdown threshold</td>
<td>239.4</td>
</tr>
</tbody>
</table>

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

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COMSOL

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Electron Dynamics
PARMELA

Waveguide Tuning
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RF Fields
COMSOL Multiphysics

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
Simulations

- Cavity Design
  - COMSOL

- Electron Gun
  - Opera3D/SCALA

- Electron Dynamics
  - PARMELA

- Waveguide Tuning
  - COMSOL Multiphysics

- RF Fields
  - COMSOL Multiphysics

- Photon Production
  - BEAMnrc + EGSnrc

Target

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

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BEAMnrc + EGSnrc

Target
Electron Gun
Electron Energy Spectrum at Target

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

Cavity Design
  COMSOL

Electron Gun
  Opera3D/SCALA

Electron Dynamics
  PARMELA

Photon Production
  BEAMnrc + EGSnrc

Waveguide Tuning
  COMSOL Multiphysics

RF Fields
  COMSOL Multiphysics

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
Beam Current Incident on X-ray Target

Target Current (mA)

Coupling Cavity Shift (mm)

New Linac
Varian 10 MV

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

![Graph showing electron beam energy vs coupling cavity shift. The graph compares New Linac to Varian 10 MV.]
Electron Energy Spectrum With 1.45 mm Shift

Relative Intensity

Energy (MeV)

New Linac
Varian 10 MV

Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015
Sheikh-Bagheri, Rogers, Medical Physics, 29(3), 2002
Peak Surface Fields

12% Difference

Baillie, St. Aubin, Fallone, Steciw, Medical Physics, 42(4), 2015
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Target
Electron Gun
Depth Dose Profile

<table>
<thead>
<tr>
<th></th>
<th>New</th>
<th>Varian</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{\text{max}}$</td>
<td>2.34</td>
<td>2.37</td>
<td>1.2%</td>
</tr>
<tr>
<td>$\frac{D_{10}}{D_{20}}$</td>
<td>1.595</td>
<td>1.589</td>
<td>0.28%</td>
</tr>
</tbody>
</table>

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

New: 5.0 mm
Varian: 5.6 mm
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?

1. Patient Comfort
2. More compact machine
3. Faster treatments
4. Better magnet homogeneity
5. No hotspots in low-density regions inside/outside of the patient
What is the benefit of treating with higher energies for VMAT treatments?

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

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