Waveguide detuning caused by transverse magnetic fields on a simulated in-line 6 MV linac

J. St. Aubin
Department of Physics, University of Alberta, 11322-89 Avenue, Edmonton, Alberta T6G 2G7, Canada
and Department of Oncology, Medical Physics Division, University of Alberta, 11560 University Avenue, Edmonton, Alberta T6G 1Z2, Canada

S. Steciw
Department of Medical Physics, Cross Cancer Institute, 11560 University Avenue, Edmonton, Alberta T6G 1Z2, Canada and Department of Oncology, Medical Physics Division, University of Alberta, 11560 University Avenue, Edmonton, Alberta T6G 1Z2, Canada

B. G. Fallone
Department of Physics, University of Alberta, 11322-89 Avenue, Edmonton, Alberta T6G 2G7, Canada; Department of Medical Physics, Cross Cancer Institute, 11560 University Avenue, Edmonton, Alberta T6G 1Z2, Canada; and Department of Oncology, Medical Physics Division, University of Alberta, 11560 University Avenue, Edmonton, Alberta T6G 1Z2, Canada

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Purpose: Due to the close proximity of the linear accelerator (linac) to the magnetic resonance (MR) imager in linac-MR systems, it will be subjected to magnet fringe fields larger than the Earth’s magnetic field of $5 \times 10^{-5}$ T. Even with passive or active shielding designed to reduce these fields, some magnitude of the magnetic field is still expected to intersect the linac, causing electron deflection and beam loss. This beam loss, resulting from magnetic fields that cannot be eliminated with shielding, can cause a detuning of the waveguide due to excessive heating. The detuning, if significant, could lead to an even further decrease in output above what would be expected strictly from electron deflections caused by an external magnetic field. Thus an investigation of detuning was performed through various simulations.

Methods: According to the Lorentz force, the electrons will be deflected away from their straight course to the target, depositing energy as they impact the linac copper waveguide. The deposited energy would lead to a heating and deformation of the copper structure resulting in resonant frequency changes. PARMELA was used to determine the mean energy and fraction of total beam lost in each linac cavity. The energy deposited into the copper waveguide from the beam losses caused by transverse magnetic fields was calculated using the Monte Carlo program DOSRZnrc. From the total energy deposited, the rise in temperature and ultimately the deformation of the structure was estimated. The deformed structure was modeled using the finite element method program COMSOL MULTIPHYSICS to determine the change in cavity resonant frequency.

Results: The largest changes in resonant frequency were found in the first two accelerating cavities for each field strength investigated. This was caused by a high electron fluence impacting the waveguide inner structures coupled with their low kinetic energies. At each field strength investigated, the total change in accelerator frequency was less than a manufacturing tolerance of 10 kHz and is thus not expected to have a noticeable effect on accelerator performance.

Conclusions: The amount of beam loss caused by magnetic fringe fields for a linac in a linac-MR system depends on the effectiveness of its magnetic shielding. Despite the best efforts to shield the linac from the magnetic fringe fields, some persistent magnetic field is expected which would result in electron beam loss. This investigation showed that the detuning of the waveguide caused by additional electron beam loss in persistent magnetic fields is not a concern. © 2010 American Association of Physicists in Medicine. [DOI: 10.1118/1.3480481]

Key words: linac-MR, linear accelerator, Monte Carlo simulation

I. INTRODUCTION

In order to achieve true real-time image guided radiotherapy, linear accelerator (linac) magnetic resonance (MR) systems have been proposed. Our system developed at the Cross Cancer Institute in Edmonton, Alberta, Canada consists of a low field biplanar MR imager coupled to an in-line 6 MV linear accelerator (linac). Another system developed at the University Medical Center in Utrecht, Netherlands consists of a 1.5 T superconducting solenoid MR imager with a 6 MV linac. Both of these configurations have magnetic fringe fields whose direction intersects the linac transverse to its length. The effect of transverse magnetic fields on the accelerating electron beam within the linac and the resulting ef-
fects on the dose distributions have been investigated previously. Passive or active shielding designed to minimize the magnetic field strength intersecting the linac may not be 100% effective, with some magnitude of magnetic field strength persisting within the region the linac occupies. According to a work presented previously, even small transverse magnetic fields on the order of 0.0006 T can cause significant beam losses of 45 ± 1.4.

The linac waveguide is precisely designed to achieve a specified effective shunt impedance and energy gain for the electrons, and any perturbation to the designed waveguide cavity geometry results in changes in the resonant frequency of that cavity. It is known that heating caused by radio-frequency (RF) power dissipation in the copper waveguide changes the resonant frequency of the linac and requires cooling. Thus all medical linacs have cooling systems to eliminate thermal expansion of the waveguide due to heating. In transverse magnetic fields, electron deflections away from the beam axis cause the electrons to impact the copper waveguide, creating another possible heating concern. If the temperature rises too much, the deformation in the copper structure could lead to a large enough change in the accelerator’s resonant frequency to cause the input RF field to be off resonance with the entire waveguide. This in turn could increase the electron beam loss above the expected value caused by a transverse magnetic field due to higher mode mixing and further RF power losses. Thus an investigation of waveguide detuning caused by these beam losses is necessary to obtain a better estimate of linac performance in transverse magnetic fields.

II. METHODS AND MATERIALS

The calculation of waveguide detuning was derived from the beam loss per cavity calculated using our 6 MV waveguide and electron gun simulation. However, the particle-in-cell program PARMELA (Los Alamos National Laboratory, NM) does not track electrons that are lost outside the beam tube, so the trajectories and exact locations where the lost electrons impact the waveguide are unknown. This limitation of the PARMELA software caused the need for three major assumptions. The first was that the electrons were assumed to impact the copper waveguide at the same time. This assumption stems from the high degree of longitudinal bunching in the linac. The second assumption was that all the lost electrons impact the waveguide nose cones which define the beam tube (Fig. 1). Due to the high electric field concentration at the nose cones, they create a large fraction of the total capacitance of the cavity and small changes in their dimensions lead to large changes in the cavity resonant frequency. Since trajectory information was unavailable, the third assumption was that the electrons impacted the nose cones perpendicular to their surface. These assumptions represent a worst case scenario regarding cavity resonant frequency changes resulting from waveguide heating.

The energy deposited on the nose cones by the additional electron losses was investigated as follows. The number and mean energy of the electrons lost in each cavity was calculated using PARMELA. From the mean electron energy fluence incident on the nose cones, DOSRZnrc was used to calculate the total energy deposited in each cavity at each magnetic field strength investigated. In DOSRZnrc, a monoenergetic beam of electrons at the calculated mean energy was set to impact an annular ring of copper. The central region with a radius of 2.5 mm was modeled as vacuum representing the beam tube and the nose cone was approximated by two annular copper rings of widths 1 and 2.5 mm. The geometry and the radial bin widths were kept identical for all cavities and beam energies studied, but the voxel depths were adjusted depending on energy. The voxel depths varied from 0.001 mm for the lowest energy to 0.1 mm for the highest energy to obtain sufficient resolution of the energy deposition. The electron transport cutoff (ECUT) and photon transport cutoff energies were set to 0.521 and 0.001 MeV, respectively, with no range rejection being used. The value of ECUT was chosen to explicitly simulate electrons with kinetic energies down to 10 keV in order to obtain sufficient resolution in energy deposition results despite the small electron ranges in copper (e.g., 0.14 mm at 0.3 MeV).

The copper deformations and the resulting change in accelerating frequency caused by the increased energy deposited (as calculated in DOSRZnrc) were determined next. The DOSRZnrc simulations resulted in the dose per voxel normalized to the planar electron fluence. Thus the total dose was calculated from all voxels and scaled to the known fluence calculated from PARMELA under the assumption that the deflected electrons will predominantly impact one half of the nose cone (or annular ring) as seen in Fig. 1. Thus from the known mass of copper in which the dose was deposited, the total energy deposited was calculated leading to a determination of the rise in temperature using the specific heat capacity of copper. The copper deformation was calculated using the thermal expansion coefficient and modeled with the finite element method (FEM) program COMSOL MULTIPHYSICS (Burlington, MA). The FEM simulation was performed on an accelerating cavity (AC) designed previously in 2D using axisymmetry with the nose cones deformed according to the previous calculations. The change in the accelerating...
frequency $\delta \omega_p$ of mode $p$ resulting from a change in the resonant frequency of accelerating cavity $n$ ($\delta \omega_m$) was investigated using first order perturbation theory of $N+1$ resonantly coupled cavities\textsuperscript{11}

$$\delta \omega_p^2 = \omega_p^2 \cdot \sum_{n=0}^{N} W(n) \cdot \left[ \frac{\delta \omega_m}{\omega_n} \right]^2 \cdot \cos^2(\pi q n / N).$$ \hspace{1cm} (1)$$

In Eq. (1), $\omega_p$ represents the nominal accelerating frequency of 2998.5 MHz, $\omega_n$ is the cavity resonant frequency (also 2.9985 MHz), and $W(n) = \frac{1}{2}$ when $n=0$ and $W(n)=1$ otherwise. The simulated linac contains 11 cavities in total (five coupling cavities and six accelerating cavities) and operates in a $\pi/2$ mode making $p=5$. The first accelerating cavity ($n=0$) is a half cavity.

### III. RESULTS AND DISCUSSION

The total beam loss, calculated as additional beam loss over nominal operation, is presented in Fig. 2 for the waveguide and electron gun design presented previously.\textsuperscript{4,5,8} At 0.0014 T homogeneous field strength, no electrons are incident on the target and all are lost within the waveguide.

The results of the waveguide heating calculations are given in Fig. 3 for 0, 0.0006, 0.001, and 0.0014 T field strengths. The highest temperature increases were observed to be within the first or second AC. This is due to a combination of the electron fluence impacting the nose cones as well as their mean energy. Significant beam losses are always seen in the first and second accelerating cavity, but at lower fields (up to 0.0006 T), large losses are also calculated near the end of the waveguide. This can be explained since electrons near the central axis are deflected by a small amount in fields up to 0.0006 T, causing them to be lost near the end of the waveguide. As the field strength increases up to 0.0014 T, their deflection becomes greater causing more beam loss at the beginning of the waveguide and less near the end.

The copper waveguide is maintained at a temperature of 40 °C via water flowing through copper pipes attached to the exterior of the waveguide to dissipate RF heating and maintain a stable operating frequency. FEM simulations were conducted to investigate long term heating effects in the waveguide; however, the heat sink together with the high thermal conductivity of copper easily dissipates the instantaneous heating seen in Fig. 3, resulting in no cumulative heating effects over time.

The resonant frequency changes for each cavity were calculated with COMSOL and Eq. (1) was used to determine their effects on the $\pi/2$ accelerating frequency. Table I summarizes the results for the cavity which experienced the greatest change in frequency together with the results of the perturbation analysis at each magnetic field strength investigated. For each beam loss scenario, the change in waveguide frequency is below a typical manufacturing tolerance of 10 kHz on the design frequency.\textsuperscript{12}

Beam losses elsewhere in the linac are not expected to have a great effect on the accelerating frequency of RF field magnitude. The beam loss within the electron gun could cause additional wear on the cathode, but has no effect on the RF operating frequency. In addition, the RF accelerating frequency (2998.5 MHz) is below the cutoff frequency of the

**Table I.** The electron beam loss over nominal, maximum cavity resonant frequency change ($\delta \omega_m$), and maximum change in the $\pi/2$ accelerating frequency ($\delta \omega_\pi$) is summarized for each transverse magnetic field strength investigated.

<table>
<thead>
<tr>
<th>Field Strength (T)</th>
<th>0.0002</th>
<th>0.0004</th>
<th>0.0006</th>
<th>0.0008</th>
<th>0.0010</th>
<th>0.0012</th>
<th>0.0014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam loss (%)</td>
<td>6.1</td>
<td>19.4</td>
<td>45.4</td>
<td>75.0</td>
<td>90.0</td>
<td>97.3</td>
<td>100.0</td>
</tr>
<tr>
<td>Max. $\delta \omega_m$ (kHz)</td>
<td>2.33</td>
<td>2.49</td>
<td>2.29</td>
<td>2.46</td>
<td>2.66</td>
<td>2.93</td>
<td>3.60</td>
</tr>
<tr>
<td>(AC1)</td>
<td>(AC1)</td>
<td>(AC2)</td>
<td>(AC2)</td>
<td>(AC2)</td>
<td>(AC2)</td>
<td>(AC2)</td>
<td>(AC2)</td>
</tr>
<tr>
<td>$\delta \omega_\pi$ (kHz)</td>
<td>2.71</td>
<td>2.83</td>
<td>2.70</td>
<td>2.89</td>
<td>3.15</td>
<td>3.48</td>
<td>4.17</td>
</tr>
</tbody>
</table>
beam tube (46 GHz) and so does not propagate inside. Thus, beam loss within the beam tube is expected to have little effect on the resonance frequency of the cavity. Even with the results given in Table I representing a worst case scenario, the additional beam loss caused by transverse magnetic fields have been shown to have no serious effect on the linac accelerating frequency.

IV. CONCLUSIONS

Detuning of an in-line 6 MV linac waveguide in a transverse magnetic field caused by a larger number of electrons impacting the waveguide nose cones has been investigated. Beam losses were calculated in homogeneous magnetic fields of increasing strength up to 0.0014 T where no electrons were incident on the target and all were lost in the waveguide. The resulting resonant frequency change in each cavity due to heating of the nose cones was determined to be below a manufacturing tolerance of 10 kHz and thus is expected to have no impact on accelerator efficiency. Thus, any persistent magnetic field that is not eliminated due to passive or active shielding is not expected to affect the frequency of the waveguide operating mode.

1Electronic mail: ginofall@cancerboard.ab.ca