Magnetic shielding investigation for a 6 MV in-line linac within the parallel configuration of a linac-MR system

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Purpose: In our current linac-magnetic resonance (MR) design, a 6 MV in-line linac is placed along the central axis of the MR’s magnet where the MR’s fringe magnetic fields are parallel to the overall electron trajectories in the linac waveguide. Our previous study of this configuration comprising a linac-MR SAD of 100 cm and a 0.5 T superconducting (open, split) MR imager. It showed the presence of longitudinal magnetic fields of 0.011 T at the electron gun, which caused a reduction in target current to 84% of nominal. In this study, passive and active magnetic shielding was investigated to recover the linac output losses caused by magnetic deflections of electron trajectories in the linac within a parallel linac-MR configuration.

Methods: Magnetic materials and complex shield structures were used in a 3D finite element method (FEM) magnetic field model, which emulated the fringe magnetic fields of the MR imagers. The effects of passive magnetic shielding was studied by surrounding the electron gun and its casing with a series of capped steel cylinders of various inner lengths (26.5–306.5 mm) and thicknesses (0.75–15 mm) in the presence of the fringe magnetic fields from a commercial MR imager. In addition, the effects of a shield of fixed length (146.5 mm) with varying thicknesses were studied against a series of larger homogeneous magnetic fields (0–0.2 T). The effects of active magnetic shielding were studied by adding current loops around the electron gun and its casing. The loop currents, separation, and location were optimized to minimize the 0.011 T longitudinal magnetic fields in the electron gun. The magnetic field solutions from the FEM model were added to a validated linac simulation, consisting of a 3D electron gun (using OPERA-3d/SCALA) and 3D waveguide (using COMSOL Multiphysics and PARMELA) simulations. PARMELA’s target current and output phase-space were analyzed to study the linac’s output performance within the magnetic shields.

Results: The FEM model above agreed within 1.5% with the manufacturer supplied fringe magnetic field isoline data. When passive magnetic shields are used, the target current is recoverable to greater than 99% of nominal for shield thicknesses greater than 0.75 mm. The optimized active shield which resulted in 100% target current recovery consists of two thin current rings 110 mm in diameter with 625 and 430 A-turns in each ring. With the length of the passive shield kept constant, the thickness of the shield had to be increased to achieve the same target current within the increased longitudinal magnetic fields.

Conclusions: A 99% original target current is recovered with passive shield thicknesses >0.75 mm. An active shield consisting of two current rings of diameter of 110 mm with 625 and 430 A-turns fully recovers the loss that would have been caused by the magnetic fields. The minimal passive or active shielding requirements to essentially fully recover the current output of the linac in our parallel-configured linac-MR system have been determined and are easily achieved for practical implementation of the system. © 2012 American Association of Physicists in Medicine. [DOI: 10.1118/1.3676692]
Key words: linac-MR, magnetic shield, longitudinal fringe magnetic fields, parallel configuration, electron gun, simulations, FEM

I. INTRODUCTION

Various groups have proposed the use of magnetic resonance (MR) imaging to accomplish real-time intrafractional IGRT and improve radiation therapy treatments for cancer patients.\(^1\)\(^-\)\(^3\) MR provides the best soft-tissue contrast and uses nonionizing radiation when imaging the patient. In addition, it can be used to track the tumor/target’s 3D motion in real-time during a patient’s treatment session. While guided by real-time MR images, a reliable radiation delivery device such as a linear accelerator (linac) or a \(^{60}\)Co teletherapy unit can be used to deliver radiation accurately to the tumor/target. Because the tumor/target location is known in real-time while the treatment beam is on, the treatment beam can be shaped to follow the tumor/target and achieve smaller CTV-to-PTV margins. The designs in which an MR system is integrated with a linac (linac-MR) or \(^{60}\)Co unit (cobalt-MR) generally fall under two categories. Category 1 makes use of a stationary solenoid MR system while the linac\(^6\) or \(^{60}\)Co\(^2\) units rotate around the MR’s solenoid magnet. The main magnetic field \(B_0\) of the MR magnets is perpendicular to the treatment beam for this design. The Utrecht group\(^4\) is integrating a 1.5 T Philips solenoid MR with a 6 MV Elekta linac. Its treatment beam passes through the MR structure (layers of aluminum and cryogens) before it reaches the patient;\(^2\) therefore, beam hardening and attenuation in their treatment beam, as well as increased scatter-dose to the patient may result. Viewray’s cobalt-MR system,\(^2\) which integrates a stationary split-field solenoid MR magnet with three \(^{60}\)Co units, also falls under this design category. In the Viewray’s cobalt-MR design, unlike the Utrecht design, the radiation beam reaches the patient without passing through the MR structures.

In category 2, the linac and the MR (biplanar, open, or split-field) rotate in unison around the patient.\(^1\) In this design, the linac and MR magnets are stationary with respect to each other\(^1\)\(^-\)\(^3\),\(^6\) which eliminates any eddy currents induced in the linac as the gantry rotates, and allows for an unattenuated treatment beam. There are two possible linac-MR configurations in this design which allows for the \(B_0\) field to be either perpendicular or parallel to the axis of the treatment beam. In the perpendicular configuration (as well as those in category 1), the secondary electrons liberated in the patient will experience a Lorentz force, which results in deflections in their trajectories.\(^7\) The magnetic deflection of secondary electrons in the patient can produce hotspots as high as 20% at the tissue/air interfaces such as the lungs\(^7\)\(^8\) in a 0.5 T transverse magnetic field when compared to the normal 0 T case for the same treatment plan. Although a Monte Carlo (MC) IMRT optimization\(^7\) may be used for treatment sites without tissue/air interfaces, an MC IMRT or any other optimization that successfully removed these hotspots in the lung has yet to be reported. Furthermore, the numerous beamlets that are required for the optimization need to be calculated using MC which is independent of the optimization package; this takes a considerable amount of time and can be tedious to implement. In the parallel configuration, the linac is placed such that \(B_0\) is parallel (or antiparallel) to the treatment beam and to the secondary electrons’ trajectories in the patient. In this configuration, the Lorentz force, and hence the deflections experienced by the secondary electrons in the patient, will be reduced which minimizes the occurrence of hotspots at the tissue/air interfaces\(^8\) when using the same treatment plan in the presence of 0.5 T parallel fields. In addition, the parallel \(B_0\) offers magnetic collimation of the secondary electrons in the patient, which can result in a smaller penumbra and a sharper patient’s dose distribution in regions near air cavities during treatment.\(^10\)

Because the MR system is integrated with a linac, the linac in any linac-MR system will experience large fringe magnetic fields. In the perpendicular configuration, the MR’s fringe magnetic fields traverse the linac’s waveguide perpendicular to the electron trajectories and exert Lorentz forces on the electrons inside the waveguide and electron gun. This causes deflections in the electron trajectories which reduces the current incident on the target. There is a reduction in useful radiation output as a result. The accelerating electrons within the waveguide are extremely sensitive to these perpendicular magnetic fields. In a previous publication, it was shown that a field as small as 1.4 \(\times 10^{-3}\) T can deflect all the electrons away from the target and reduce the useful radiation output to zero.\(^5\) In the parallel configuration, the MR’s fringe magnetic fields are parallel to the net electron trajectories in the linac. This results in a reduced Lorentz force on the electrons which minimizes their deflections off-axis. Therefore, the linac can produce useful radiation beams in the presence of much stronger longitudinal/parallel magnetic fields. In Ref. 6, it was shown that when a 0.011 T longitudinal magnetic field is present at the electron gun cathode, only a 16 \(\pm\) 1% target current loss\(^6\) occurs. The lost target current is caused by magnetic deflection in the nonparallel component of the electron trajectories as the electron gun focuses the electron beam to the anode.\(^6\)

This paper will focus on the recovery of the lost target current that was caused by the magnetic deflections of the electrons in the electron gun when a 6 MV in-line linac is integrated with an MR imager in the parallel configuration. The focus of this work is founded on previous work that showed the electron gun is the most sensitive part of the linac to longitudinal magnetic fields and changes in its output current has a significant effect in the linac’s target current loss.\(^6\)

The lost linac output can be minimized or recovered either by redesigning the electron gun,\(^6\)\(^11\) by moving the linac further away from the MR magnets,\(^6\) or by using magnetic shielding on the electron gun.\(^6\) When redesigning the electron gun, it can be optimized for only one electron gun-to-MR system at a time and must be redesigned for different electron gun locations and/or magnet systems. Moving the linac further away from the MR magnet would be accompanied by reduction in dose rate due to the effects of the...
II. METHODS

II.A. Electron gun’s casing

The steel casing surrounding the electron gun [illustrated in Fig. 1(b)] is roughly 1-mm-thick and is ferromagnetic. Because its presence has a nontrivial effect on the MR’s fringe magnetic fields, it was included in the magnetic field model. The magnetization curve of AISI 1020 carbon steel was used to calculate its relative permeability. There is a hole that is approximately 1 cm in diameter on the side of the gun casing which allows access for the electron gun cables [as illustrated in Fig. 1(c)]. The hole’s effects on the magnetic field inside the electron gun was investigated by comparing the magnetic fields in the electron gun with and without this hole.

II.B. Magnetic field models

A 3D analytic magnetic field model, which consisted of two pairs of current loops and emulated the fringe magnetic fields of a PARAmed 0.5 T MROpen™ system, was optimized previously through the superposition of analytic current loops calculated using the Biot-Savart law. This magnetic field model was generated in order to determine the vector components of the fringe magnetic field (required for the particle simulations) which was not provided in the isoline data the manufacturer supplied. This method was chosen instead of interpolating between the magnetic isoline because the current loop guarantees that the Maxwell’s equations for magnetostatics are satisfied. Due to the axisymmetric nature of the MROpen™’s fringe magnetic fields about the longitudinal axis (z-axis) at the proposed location of the linac (Ref. 6), a current loop model can accurately define its fields. This fringe magnetic model was based on the manufacturer supplied data which consisted of the 0.0005, 0.001, 0.002, 0.005, 0.01, and 0.02 T isolines in the z-x plane.

The commercially available MROpen™ may need modification when it is integrated into the parallel linac-MR configuration. Therefore, these emulated magnetic field lines may vary slightly from the modified MROpen™ system. However, it is currently unknown how these modifications would affect the MROpen™’s fringe magnetic fields, so the current fringe magnetic fields are used in this study to illustrate the feasibility of shielding the linac from an MR system.

Due to the nonlinear partial differential equations (PDEs) which are required to be solved to determine the change in the fringe magnetic field caused by the presence of ferromagnetic shielding structures, the analytic magnetic fringe field model described earlier could not be used when calculating magnetic field changes in the presence of the ferromagnetic shielding structures. In order to overcome this limitation, the analytic current loop model was recalculated using the 3D finite element method (FEM) package COMSOL Multiphysics (Burlington, MA), which is capable of accurately solving the required nonlinear PDEs. It should be noted that the support structures seen in Fig. 1(a) are made from nonmagnetic material and thus will not alter the MR’s fringe magnetic fields. Therefore, this investigation holds for any orientation with respect to the support structures.

The numerical (FEM) magnetic field model used the optimized current loop parameters (the loop currents, the loop radii, the separation distance of each current loop pair, and the number of current loop pairs) from the analytic magnetic field model described earlier. This and all subsequent FEM simulations used quadratic vector basis functions for the tetrahedral finite elements which were optimized using Delaunay triangulation. For each simulation, the average mesh density was between 0.219 elements/mm³ and 3.3 tetrahedral elements/mm³. In order to incorporate the open boundary conditions in the FEM magnetic field model, natural Neumann boundary conditions were specified at the external...
mesh boundaries. Each simulation used an iterative solver [FGMRES (Ref. 14)] with a Geometric Multigrid preconditioner\textsuperscript{15} to calculate the magnetic fields in the region of interest (the electron gun, waveguide, gun casing, and magnetic shielding).

In order to validate the accuracy of the above FEM fringe magnetic field model, the fringe magnetic field magnitudes were compared to the manufacturer supplied isoline data. Only one plane (xz-plane) was used for the validation since the manufacturer supplied fringe field isolines show that the fringe field isolines are axisymmetric in the region where the linac will be placed. The numerical magnetic field model was used to generate magnetic fields at any arbitrary points in 3D space as needed by the linac simulation.

Passive magnetic shielding techniques were studied by surrounding the electron gun’s casing and waveguide with a steel cylinder with a metal cap at one end [Fig. 1(b)]. The magnetization curve\textsuperscript{12} of AISI 1020 carbon steel was used to calculate the relative permeability of the passive magnetic shield. Passive shield thicknesses from 0.75 to 15 mm and inner lengths from 26.5 to 306.5 mm were simulated in the numerical magnetic field model. Because the 24.5-mm-long electron gun is the most sensitive component to parallel magnetic fields,\textsuperscript{6} it is always shielded. The electron gun with its gun casing is 26.5 mm long. The combined length of the electron gun and waveguide is 306.5 mm. This shield length was chosen as the maximum shield length because the linac needs to be mounted onto the linac-MR system. Having a longer passive shield would cause problems when installing the linac and passive shield onto the linac-MR. The 3D FEM magnetic field solution incorporating the passive shielding and gun casing were solved in COMSOL and serves as an input to both the electron gun simulation and waveguide simulation which are described later.

Active magnetic shielding techniques were studied by adding active shield coils, which consist of current loops, around the electron gun’s casing since the electron gun is the most sensitive part of the linac to longitudinal magnetic fields.\textsuperscript{6} The electron gun’s casing was also included in this study. The fields from these coils were optimized to cancel out the MR’s fringe magnetic fields inside the electron gun. Therefore, the net MR fringe fields inside the electron gun $B_{\text{net}}$ was added in quadrature [Eq. (1)] where $i$ is the mesh node number and $N$ is the total number of mesh nodes in the electron gun. The objective function $f$ was minimized.

$$f = \sum_{i=1}^{N} (B_{\text{net}}^i)^2$$

The total currents for each active shield coils, their separation distance, and their location relative to the electron gun cathode were optimized to minimize the magnetic field strength in the electron gun. Because of the limited space available for magnetic shielding around the electron gun in the linac-MR, the radius for each active shield coils was fixed to 55 mm. The total current in each shield coils must be in the same direction to avoid solutions that would make the each coil work against each other. The separation distance must be in between 0 and 30 mm because of the expected limited space available for shielding around the electron gun. A MATLAB built-in function (fmincon), which uses sequential quadratic programming,\textsuperscript{16-19} was used to optimize the active shield instead of the MC optimization from Ref. 6 because of its more rapid convergence. The FEM magnetic field solutions in the electron gun and waveguide serve as inputs to the electron gun simulation and waveguide simulation, respectively. Figure 2 shows the general process for both active and passive magnetic shielding techniques.

Calculations estimating the homogeneity in the MR field-of-view were performed on the 3D numerical magnetic field model to assess the effect of the magnetic shield’s presence on the MR’s imaging volume. Although the manufacturer provided data contained a map of only the MROpen\textsuperscript{TM’s fringe magnetic field isolines, the MROpen\textsuperscript{TM} discussed earlier is a 0.5 T MR imager. Therefore, the magnetic field in the imaging volume is assumed to be 0.5 T, as reflected in Eqs. (2) and (3). The resulting magnetic field offset $\Delta B_0$ (in ppm) at the isocenter of the magnet and the maximum change in the magnetic field $\Delta B_{\text{DSV}}$ (in ppm) at the 30 and 50-cm diametrical spherical volume (DSV) were calculated from Eqs. (2) and (3).

$$\Delta B_0 = \left( \frac{|B_c - B_{\text{shielded}}|}{0.5T} \right) \times 10^6$$

$$\Delta B_{\text{DSV}} = \left( \frac{\max(|B_{\text{DSV}} - B_{\text{shielded}}|)}{0.5T} \right) \times 10^6$$

In Eqs. (2) and (3), $B_c$ and $B_{\text{shielded}}$ are the magnetic fields at the isocenter of the magnet without and with the linac’s magnetic shield, respectively. Similarly, $B_{\text{DSV}}$ and $B_{\text{shielded}}$ are the magnetic fields at the DSV surface from the magnet.
without and with the linac’s magnetic shield, respectively. Since $\Delta B_0$ would cause only a change in $B_0$, the inhomogeneity in ppm for 30 and 50-cm DSV was calculated by subtracting $\Delta B_0$ from $B_{DSV}$ for each spherical volume.

To study the passively shielded linac performance in the presence of other MR magnets with larger fringe magnetic fields than the MROpen™ imager mentioned earlier, homogeneous fringe magnetic fields (from 0 to 0.2 T) were used. This simplification is justified because the magnetic fields over the length of the electron gun vary slowly,\(^6\) a change of $3.6 \times 10^{-4}$ T occurs over this length. A previous publication has shown that the lost linac output that occurs in the presence of the longitudinal magnetic fields was solely due to the changes in the electron gun’s output.\(^6\) Thus, using homogeneous fringe fields is a reasonable approximation in the study of the effects of magnetic shielding when larger fringe magnetic field strengths are present. This portion of the study used homogeneous magnetic fields that were parallel to the net electron trajectories in the waveguide and were equal in strength everywhere. The electron gun’s casing was included in this set of simulations as well. Passive magnetic shields with thicknesses from 0 to 10 mm were simulated, while the length of the passive shield remained fixed for simplicity. The 3D FEM magnetic field solutions in the electron gun and waveguide were calculated in COMSOL and served as an input both the electron gun simulation and waveguide simulation, respectively.

### II.C. Linac Simulation

The linac simulation, which was validated for 0 T\(^{20}\) and used previously for the longitudinal magnetic field studies,\(^5\) was divided into two parts: the electron gun simulation\(^20\) and the waveguide simulation.\(^24\) The electron gun simulation was accomplished through OPERA-3d/SCALA from Cobham Technical Services (Kidlington, UK), which will be referred to as SCALA in this document. SCALA uses FEM to solve for the electrostatic fields within the gun and uses these fields to calculate particle space-charge forces and particle trajectories in 3D based on the Child’s law thermionic emission model.\(^25\) The COMSOL generated magnetic fields from the magnetic shielding studies were added to the electron gun simulation as an external magnetic field map. The output phase-space from the electron gun simulations included the $x$, $y$, and $z$ position and $v_x$, $v_y$, and $v_z$ velocity components for the simulated particles and served as an input in the waveguide simulation.

The waveguide simulation consisted of a 3D waveguide model and a waveguide particle simulation. The time-varying radiofrequency (RF) field solutions\(^24\) in the waveguide was calculated in COMSOL previously from a user defined 3D waveguide model.\(^20,24\) These RF field solutions and the MR fringe magnetic fields inside the waveguide were added as external field maps into PARMELA (Ref. 26) (Phase and Radial Motion in Electron Linear Accelerators from Los Alamos National Laboratory, NM), which was used for particle tracking in the waveguide. PARMELA used the output phase-space from the electron gun simulation as the initial phase-space of the injected electron beam in the waveguide. It then used the RF fields and the MR fringe magnetic fields to calculate the electron trajectories inside the waveguide, based on the injected electron beam phase-space\(^5,6,20,24\) by first calculating the total impulse on each of the simulated particles using a particle-in-cell algorithm.\(^26,27\) These impulses are calculated based on the static and time-varying fields present in the waveguide. The calculated impulses are then used to update the particle positions and velocities in a leap-frog fashion\(^26\) until it is incident on the target.\(^26\) The PARMELA output consists of a phase-space for the electrons beam incident on the linac target. The beam current and electron spatial and energy distributions were extracted from both the SCALA and PARMELA output phase-spaces and were used to evaluate the performances of a magnetically shielded linac in the parallel linac-MR configuration.

In the complete linac simulation, various software packages were used in different parts of the simulation. Although SCALA cannot solve for magnetic fields, it allows for the input of externally calculated magnetic field maps. Therefore, COMSOL was used to calculate magnetic fields for both the electron gun simulation and the waveguide simulation. In the electron gun simulation, SCALA was used to track electrons in static fields because PARMELA does not have a cathode emission model based on a thermionic emission law. In the waveguide simulation, since SCALA cannot solve for nor track particles in time-varying fields, COMSOL was used to calculate RF fields and PARMELA was used to track electrons in the waveguide.

MC simulations for modeling the dose distributions were not performed for this work since it was shown previously\(^6\) that longitudinal magnetic fields do not affect the linac x-ray beam’s profile symmetry or depth dose characteristics. It was shown that greater than 96% of all points met a 1%/1 mm gamma index criterion in parallel magnetic fields up to 0.011 T.\(^5\) It was also clearly shown that the target current (and thus dose rate) dropped as a result of electron losses within the electron gun.\(^6\) Therefore, the target current was chosen as an end point for this work since target current losses in the presence of parallel magnetic fields is an indirect measure of how much dose rate would be lost. In a clinical setting, a moderate reduction in the dose rate, such as the previously observed 16% lost\(^6\) in the presence of a 0.011 T MR’s fringe magnetic fields, can be accounted for by an increase in patient treatment time. The focus of this work, however, is to investigate the use of magnetic shielding to recover the lost target current, and therefore, restoring the linac to its original 0 T state and keeping the treatment times unchanged.

### III. RESULTS AND DISCUSSION

#### III.A. Numerical magnetic field model

A simulation with no gun casing or linac magnetic shield was used to validate the numerical magnetic field model against the manufacturer supplied fringe magnetic field isoline data in a similar fashion as in Ref. 6. Since the manufacturer isolate data contained only the magnitude of the
magnetic isolines, the magnitude of the magnetic fields from the numerical magnetic field model was calculated. A comparison of the magnetic fields between the calculated magnetic field strengths and the manufacturer isoline data were made to validate the numerical magnetic field model. It shows that the magnetic field strengths from the numerical magnetic field model are within 1.5% of the manufacturer’s isoline data.

Magnetic field perturbations that are caused by the presence of a 1 cm hole on the side of the gun casing and passive magnetic shield were insignificant in the electron beam region. The plots in Fig. 3 show the magnetic field differences between two simulations (the one with and without the hole present) for the x-, y-, and z- magnetic field components [Figs. 3(a)–3(c), respectively] along the central axis of the electron gun and along 3 mm off-axis furthest from and nearest to the gun casing’s hole. The ±3 mm off-axis lines in Fig. 3 represent the maximum radius where the electron beam is present during the electron gun is operations. In the region where the electron beam is present, a maximum difference of 5.13 × 10⁻⁵ T occurs in the z-component of the MR’s fringe magnetic fields. This field strength is comparable to the Earth’s magnetic field. Since the linac operates normally in this field strength, the hole on the electron gun casing has an insignificant effect on its output current and emittance $e_{rms}$ [Eq. (4)] which is a quantitative measure of the electron beam’s laminar property.

$$e_{rms} = \sqrt{\langle r^2 \rangle \langle r'^2 \rangle - \langle rr' \rangle^2}$$

In Eq. (4), $r$ and $r'$ are the radial location and angular deflection of each electron in an electron beam, respectively.

Results from the two simulation conditions (gun casing with and without the 1 cm hole) show that the presence of the 1 cm hole on the gun casing [as illustrated in Fig. 1(c)] has an insignificant effect on the electron gun’s output beam parameters. The resulting electron gun output current from both conditions is 362.75 mA, which shows that the output current is unaffected by the presence of the 1 cm hole. The $e_{rms}$ of the output beam are 3.560π and 3.553 π mm-mrad for the gun casing with and without the 1 cm hole, respectively. The difference between these $e_{rms}$ values is less than 1%.

### III.B. Passive magnetic shield studies

With a linac-MR SAD of 100 cm, the expected MR’s fringe magnetic field strength in the electron gun is expected to be 0.011 T. Figure 4 shows the target current recovery when passive shields are incorporated in the simulations. A target current recovery that is greater than 99% of nominal is achievable for all passive shield thicknesses studied. The target current recovery for thinner shielding (≤1-mm-thick) does not increase monotonically as the passive shield length is increased (Fig. 4). At a passive shield length of 146.5 mm, a peak target current recovery of 100.3% is reached for thinner shields before the target current recovery begins to drop. This current recovery behavior occurs because passive magnetic shields become partially magnetically saturated as its thickness is decreased and its length is increased. Because of the shield’s magnetic saturation, it becomes less effective at shielding the linac from the MR’s fringe magnetic fields (Fig. 5). For passive shields that are thicker than 1 mm, the target current recovery does not exhibit this behavior and increases monotonically with increasing shield length. This behavior is reflected in Fig. 5 by the monotonic decrease in the mean magnetic field strength in the electron gun for these passive shields.

The presence of magnetic shielding can influence field homogeneity of an MR imager. Previous publications have already reported on the results of field inhomogeneity studies with large passive magnetic shields (2 × 2 × 0.05 m, with a volume of 0.2 m³). Refs. 1, 21, and 22 and have showed that the resulting field inhomogeneities are manageable by standard shimming.

The passive magnetic shields used in this...
present study are the same distance away from the MR but are much smaller in volume (\( \leq 0.0028 \text{ m}^3 \)) than the ones used in Refs. 21 and 22. Therefore, the magnetic shielding is not expected to create large field inhomogeneities in the MR’s imaging volumes. However, in order to estimate the field inhomogeneities caused by the passive shields, the numerical magnetic field model was used to calculate a worst-case scenario which is represented by the largest passive shield presented in this study (15-mm-thick and 306.5-mm-long with a volume of 0.0028 \text{ m}^3). This passive shield caused a \( \Delta B_0 \) of 124 ppm and a maximum field inhomogeneity of 66 and 136 ppm for a 30 and 50-cm DSV, respectively. These inhomogeneities can be managed by shimming.23 The passive shield used in this study will not affect the MR’s imaging volume.

### III.C. Active magnetic shield studies

The active magnetic shield was optimized through a built-in MATLAB function (fmincon). The optimization of the active shield produced a pair of coils with an ideal separation distance of 29.5 mm. The total current \( nI \), where \( n \) and \( I \) are the number of windings in the active shield coils and the current for a single loop in the coils, respectively, for the active shield coil closest to the waveguide was 625 A-turns while the coil that was furthest from the magnet has a total current of 430 A-turns. By having many windings in each of the coil, this active shield can be built with conventional power and cooling. Its power and cooling requirements are much less than that required for the active shield coils in the perpendicular linac-MR configuration.29 Incorporating this optimized active shield into the FEM simulation led to a reduction of the mean magnetic field strength in the electron gun from 0.011 to 1.1 \times 10^{-4} \text{ T}. A target current recovery to 100.2\% of nominal is observed when this optimized active shield was used. This small gain in target current shows the competition between the effects of longitudinal magnetic fields on the waveguide and on the electron gun. Because this active shield uses current loops, its magnetic field strength decreases quickly as one gets further away from the shield’s center. Therefore, the active shield leaves a large portion of the waveguide unshielded while it shields the electron gun. The presence of longitudinal magnetic fields in the electron gun causes a lost in the current input into the waveguide, which results in lost target current.6 However, its presence in the waveguide can result in current gain since some of the electrons that would be lost in the waveguide under normal operation are confined by the longitudinal magnetic fields. Therefore, the target current is increased.

The magnetic fields from the active shield coils caused a \( \Delta B_0 \) of 2.35 ppm and a maximum field inhomogeneity of 1.05 and 2.13 ppm for a 30 and 50-cm DSV, respectively. These inhomogeneities can be easily managed by shimming.24

### III.D. Electron gun output

Longitudinal magnetic fields have a significant adverse effect on the electron gun output. They cause the electron trajectories at the electron gun’s output to become nonlaminar and divergent. The electron gun’s output beam is the waveguide’s injection beam. Therefore, the decrease in the injection current will ultimately lead to a reduction in linac’s target current, which in turn results in a reduced linac dose rate.6 The electron gun’s output phase-space diagram under normal operations (0 T) is shown in Fig. 6(a). The effect of a 0.011 T MR’s fringe magnetic fields on a magnetically unshielded electron gun’s output phase-space is shown in Fig. 6(b). Figure 6(c) shows the electron gun’s output phase-space when a passive magnetic shield, which has a uniform thickness of 5 mm and is 146.5 mm long, was used. The electron gun’s output phase-space when an optimized active magnetic shield was used is shown in Fig. 6(d). In all of the phase-space diagrams in Fig. 6, \( r \) is the electron’s radial distance (with respect to gun’s central axis) at the electron gun output, and \( r' \) is the magnitude of the net angular deflection of the electron from the \( z \)- (longitudinal) direction. Both output phase-spaces in Figs. 6(c) and 6(d) show that both type of magnet shield (passive and active) can return the electron gun to its normal state since the resulting phase-space resembles the phase-space presented in Fig. 6(a). The calculated \( \varepsilon_{\text{rms}} \) [Eq. (4)] for 0 T, unshielded linac, passively shielded linac, and actively shielded linac are 0.457 \( \pi \), 3.242 \( \pi \), 0.671 \( \pi \), and 0.470 \( \pi \) mm-mrad, respectively. An order of magnitude change in the \( \varepsilon_{\text{rms}} \) resulted in the electron beam phase-space in Fig. 6(b) and a target current reduction to 84\% of nominal. In Ref. 6, it was shown that the electron gun output \( \varepsilon_{\text{rms}} \) can grow up to 4 times larger than its nominal value but result in only a current reduction to 98\% of nominal. The \( \varepsilon_{\text{rms}} \) from the passively shielded linac [Fig. 6(c)] and the actively shielded linac [Fig. 6(d)] are less than 1.5 time than its nominal value [Fig. 6(a)] and resulted in a current recovery to 99.9\% and 100.2\% of the nominal, respectively.

### III.E. Homogeneous Fringe magnetic fields

We are interested in how the passively shielded linac performs over a range of magnetic field strengths. Secs. III B
and III C studied the effects of a 0.011 T fringe field strength at the electron gun, however, other fringe magnetic field strengths can be caused by a change in the $B_0$ field strength or a change in the linac-MR system’s SAD. The fringe magnetic field in the electron gun varies by only $3.6 \times 10^{-4}$ T from the cathode to the anode. By using a 0.011 T longitudinal homogeneous fringe magnetic fields, which have equal strength everywhere and are parallel to the electron trajectories in the waveguide, in place of the MR’s fringe magnetic fields, the cathode emission, injection, and target currents only change by 0.001%, 0.001%, and 1%, respectively. Therefore, homogeneous fringe fields can be used as a surrogate for our MR’s fringe magnetic fields.

To simplify this portion of the study, the passive shield length for all thicknesses simulated in this part of the study is fixed to 146.5 mm, which is the length where the current recovery in Fig. 4 reaches a maximum for thin passive shields ($\leq 1$ mm). Therefore, only the effect of the passive shield thickness on the target current recovery was investigated in this part of the study. The injection currents for each passive shield thickness (Fig. 7) show a slight increase before dropping sharply. This behavior was also observed previously. This slight increase in the injection current is caused by the increasing cathode emission current. As homogeneous fringe field strength increased, a reduction in the space-charge surrounding the electron gun cathode occurs. This leads to the increasing cathode emission. Furthermore, the radius increased with the increasing emission current. As the beam radius increased, more electrons start to impact onto the anode and are removed from the injection current causing the sharp reduction in the injection current seen in Fig. 7. This drop in injection current occurs at 0.015, 0.032, 0.08, and 0.125 T when no shield, 1-mm-thick, 5-mm-thick, and 10-mm-thick shields, respectively, are used on the linac.

Since the electron gun and waveguide need to work as a single unit in a linac, any injection current loss will result in lost target current (Fig. 8). As stated earlier, the lost target current causes a loss in the dose rate and increased in the treatment times. Although there is a slight increase in the injection currents, the target current for each passive shield thickness continue to drop as the magnetic field strength increases. Figure 8 shows the decreasing target current as the homogeneous fringe field strength increased for all the passive shield thicknesses that were studied. As the shield’s thickness increases larger field strengths are needed to create the same level of target current lost. For example, a target current that is 84% of nominal occurs at 0.0147, 0.0307,
parallel configuration still result in lost dose rate, the lost dose rate may require some cooling and additional maintenance, respectively, are used. When the MR’s fringe magnetic fields in the electron gun of a linac-MR system varies by $3.6 \times 10^{-3}$ T or less, the results shown in Figs. 7 and 8 are a valid approximation to the injection and target currents' behavior for different passive shielding scenarios. The results presented in Figs. 7 and 8 show that a passive shield designed for a MR fringe magnetic field strength such as 0.05 T can be used to shield the linac from weaker MR fringe magnetic field strengths. These two figures show how robust and flexible the passive shielding solution for different MR fringe magnetic fields. The technique of passive shielding described above can be used to optimize shielding for different cylinder lengths and different magnetic field strengths for the various linac-MR scenarios possible. Either passive or active shielding described above can be easily engineered to shield the linac and electron gun from the effects of the MR’s magnetic fields in the parallel linac-MR configuration. Active shielding may require some cooling and additional maintenance, however.

IV. CONCLUSIONS

Although the effects of magnetic fields on the linac in the parallel configuration still result in lost dose rate, the lost linac output can be recovered by using magnetic shielding. Either passive or active magnetic shielding can be used to shield the electron gun and still leave large portions of the waveguide exposed to the collimating effects of the MR’s fringe magnetic fields in the parallel linac-MR configuration. Although the electron gun casing provides some magnetic shielding, additional magnetic shielding is still required to recover the linac output that was lost due to magnetic deflections. Greater than 99% of the nominal target current can be recovered by surrounding the linac with passive shielding of thicknesses greater than 0.75 mm. An optimized active shielding that is placed around the electron gun and its casing can fully recover the lost target current. This active shield comprised of a simple pair of 110 mm diameter coils with 625 and 430 A-turns in each coil. However, the active shield may introduce additional complexity such as the need for cooling and maintenance of the coils. Although the presence of either passive or active shield causes inhomogeneities in the MR’s imaging volume, these inhomogeneities are small and can be corrected by shimming.

0.0704, and 0.0886 T when no shield, 1-mm-thick, 5-mm-thick, and 10-mm-thick shields, respectively, are used. The simulations used a fixed passive shield length (146.5 mm) for the four shield thicknesses.

![Graph showing target current for different shield thicknesses](image)