**Presentation Title**

Effects of time-varying magnetic fields from the MRI’s gradient coils on a proton beam

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**Abstract**

**Purpose:** To investigate the effects of time-varying magnetic fields generated by the MRI’s gradient coils on the proton beam.

**Materials & Methods:** Two variants of the balanced Steady-State Free Precession (bSSFP) imaging sequence, with maximum coil strengths of 20mT/m and 40mT/m, were applied to proton beam simulations. Each sequence was sub-divided into 27 temporal segments (Fig.1), where the gradient coils’ magnetic fields (gradient fields) were assumed to be constant. For each segment, the 3D gradient fields were modelled and added to the 3D magnetic vector fields from an open-bore superconducting MRI magnet, and were applied to 150MeV monoenergetic proton beams (the source being 130cm away from isocentre (z=0cm)). A set of simulations used analytic magnetic force equations to rapidly calculate the beam’s trajectory but these were limited to propagating the beam in vacuum. Monte Carlo simulations used the GEANT4 toolkit to calculate both the trajectory and the surface dose profile on a water phantom at z=0cm for each beam. Various initial beam directions, controlled through the angles $\theta$ (from 0° to 6.8°) and $\phi$ (from 0° and 90°), were investigated. $\theta$ is the angle between the source direction and the positive z-direction, and $\phi$ is the angle between source direction and the positive x-direction. The beam’s positions and surface dose profiles were extracted and used to quantify the effects of the time-varying gradient fields on the proton beam.

**Results:** The analytic results agreed with as well as served as an independent check for the Monte Carlo results. At z=0cm, the beam’s positions from the analytic and Monte Carlo results differ by less than 0.02mm for each of the 27 unique gradient fields distributions applied to the beam. Both analytic and Monte Carlo results show that the beam’s cumulative point spread function (PSF) results in the same pattern as shown in Fig.2. When the beam is near the outer edge of the MRI’s field of view ($\theta=6.8^\circ$), the maximum extent of this pattern is 1.1mm for the 40mT/m bSSFP sequence and 0.6mm for the 20mT/m bSSFP sequence.

**Conclusions:** This investigation shows that the application of the MRI’s gradient fields on the proton...
beam changes its cumulative PSF (Fig. 2) during both the analytic and Monte Carlo simulations. This work suggests that the gradient fields can have a non-trivial impact on the proton beam’s PSF, but was limited for this magnet and source configuration to the order of 1mm.

Figure 1. The two variant bSSFP sequences applied to the proton beam. Left is the 20mT/m maximum gradient strength and right is the 40mT/m maximum strength. The light and dark shades of gray show the sub-division for each sequence. Segments A and G were repeated for each of the five phase encodes.

Figure 2. Representative beam deflections caused by the gradient fields resulted in the pattern shown (at z=0cm) in the figure after the 40mT/m bSSFP sequence was applied to the proton beam. The analytic results are shown as the circles overlaid on top of the normalized Monte Carlo dose map.