Design of an MR compatible Rotating Anode X-ray Tube

Innovation/Impact: Using hybrid X-ray/MR (XMR) systems for image guidance during interventional procedures can enhance the diagnosis and treatment of neurologic, oncologic, cardiovascular, and other disorders. We propose a ‘close proximity’ hybrid system design where a C-arm X-ray fluoroscopy unit is positioned only ~1.2 meters from the imaging field of view of a 1.5 T closed bore MR system [1]. Placing the X-ray system as close as physically possible to the MR bore allows switching between modalities with minimum disturbance to critically placed catheters and other devices used in image-guided interventional procedures.

The ‘close proximity’ XMR system geometry requires an X-ray tube capable of operating in a relatively strong MR fringe field environment. Existing rotating anode X-ray tube designs fail in such environments because the magnetic fields alter the electron trajectories in the tube and act as a brake on the induction motor, reducing the rotation speed of the anode. To solve these challenges we have designed a rotating anode X-ray tube that can correct the electron trajectories, and that employs a novel motor design that eliminates the reduced rotation speed of the anode. The various components of the complete X-ray tube design are shown in fig. 1. Correction of the electron trajectories is done using a combination of optimized resistive shielding coils along with an electron gun that utilizes a split focusing cup design with biasing electrodes on either side of the filament. The revised motor design is analogous to a modified three-pole brushed DC motor, with the radial component of the MR fringe field replacing the permanent magnet stator field used in conventional brushed DC motors.

Electron Trajectory Correction: In the ‘close proximity’ XMR design the dominant component of the MR fringe field at the X-ray tube focal spot is perpendicular to the electric field generated between the anode and cathode. Electrons traveling in this crossed field environment will experience a ‘drift’ velocity causing deflection of the focal spot position on the anode [2]. If the magnitude of the radial magnetic field is strong enough the electrons can miss the target area on the anode entirely. This problem can be corrected by using a combination of magnetostatic and electrostatic techniques. Using an L1-norm minimization method [3] it is possible to derive the different geometries of two resistive shield coils that can be placed outside of the vacuum insert. The solution coils from the optimization method minimize the power consumption of the shielding coils while satisfying magnetic field homogeneity constraints. However, for very high magnetic field magnitudes the coils can only be operated for short periods of time (i.e. minutes), due to heating constraints. To complement the shielding coils, voltages are placed on the bias electrodes in the split focusing cup to create an electric field parallel to the direction that the electrons are deflected. The electron trajectories are initially deflected toward the positive bias electrode since the dominant Lorentz force arises from the electric field. As the electrons gain velocity and travel towards the anode the magnetic field component of the Lorentz force becomes larger, while the electric field component becomes smaller. As a result the trajectories curve back towards the center of the anode. To validate the correction mechanisms finite
Fig. 2. Electron trajectory simulations for (a) no external magnetic field, (b) a 50 mT external field with no correction, (c) an 88 mT external field with -88 mT coil correction, (d) a 65 mT external field with 35 kV potential difference, (e) a 90 mT external field with -57.5 mT coil correction and 17.5 kV potential difference, and (f) a 152 mT external field with -88 mT coil correction and 35 kV potential difference.

element space charge simulations (Opera-3d, Cobham) of the electron trajectories under various field conditions are shown in fig. 2a-f.

**Motor Prototype:** A prototype of the motor design depicted in fig. 1 was machined, assembled, and tested in various magnetic field environments. All components chosen to be used in the prototype were vacuum compatible and capable of surviving the bake out procedure that is necessary for outgassing the entire X-ray tube assembly during vacuum processing. Detailed views of the inside and outside of the motor assembly are shown in fig. 3. The rotor body is machined out of ceramic to prevent the creation of eddy currents that could lead to a reduction in motor speed. There are four steel bearings used in the prototype, with three of the bearings serving as electrical slip rings to the coil windings that are slotted into the wiring grooves. Wave springs are placed in between each inner spacer and bearing to create a slight displacement of the inner races relative to the outer races. The displacement leads to a better contact between the balls and races of the bearing, which improves the conduction of current through the bearing. The phase windings are electrically commutated using a position feedback sensor. The prototype is able to accelerate to 3000 rpm within 10 seconds in a 60 mT external field and can achieve maximum speeds greater than 5000 rpm.

References: