Radio Frequency Noise From the Modulator of a Linac

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Abstract—A novel approach to image-guided radiotherapy being undertaken by a few groups involves the integration of a linac with a magnetic resonance imager (MRI). In order to successfully combine a linac with a MRI, it is important to understand the characteristics and major sources of radio frequency (RF) noise from the pulse power modulator of a linac since these may interfere with the operation of the MRI. The RF noise power spectral density from the modulator of a linac, loaded separately with a magnetron and a resistive load, is measured. The RF fields emitted by the pulse-forming network (PFN) were determined by simulation and compared with measurements. Saturable reactors were introduced in the trigger circuits of the thyratron to reduce the injected voltage spikes into the trigger circuit to assess the impact of these spikes on the RF noise measurements. The results illustrate that the major source of RF noise from the modulator of a linac is the operation of a magnetron. It also eliminates thePFN coil and the grid voltage spikes of thyratron as possible major sources of RF noise. For linac-MRI systems the modulator of a linac should be housed in a separate RF cage from the MRI.

Index Terms—Linac, magnetic resonance imager (MRI), magnetron, medical physics, modulator, pulse-forming network (PFN), RF noise, thyratron.

I. INTRODUCTION

IDEALLY, during radiotherapy treatment we would like to treat cancerous tissue with a tailored dose of radiation while sparing any healthy tissue. To achieve this goal, there has been a large movement toward image-guided radiotherapy in the past decade [1]–[4]. To account for tumor changes in location, shape, and size, in between and during the treatment fractions, a geometric margin is applied around the tumor in order to ensure adequate coverage of the radiation dose. A better visualization of the tumor during the course of radiotherapy has the potential of reducing these geometric margins. Several groups have advocated improved image guidance in radiation therapy by proposing and implementing the integration of a magnetic resonance imager (MRI) with a megavoltage teletherapy unit for treatment [5]–[7]. Our group has successfully integrated a prototype system consisting of an MRI scanner with a linear accelerator (linac) [5]. The MRI will provide real-time images with exquisite soft tissue contrast during the beam-on time. These real-time images will aid in tumor visualization during treatment and allow for the reduction of the irradiated volume of normal tissue around the cancerous volume. Furthermore, in cases of cyclic motion, such as motion due to breathing, where a tumor may change its position with respect to an organ at risk, the real-time imaging will aid in tumor tracking to further reduce irradiation of healthy tissue.

ONE of the possible complications associated with the integration of an MRI with a linac is the interference from RF noise. The linac is a source of RF noise [8]; an MRI works by sending and receiving RF signals in a particular frequency band. The RF noise from a linac could be picked up by the MRI coils and fed into the image acquisition chain producing deleterious image artifacts.

Our initial work, [8], reported on the levels of RF noise within clinical vaults housing medical linear accelerators. Related studies then focused on the shielding required to obtain undegraded MR images while operating a linac [9]. The work in [9] illustrated the feasibility of an integrated linac-MR system, after the work in [5] had demonstrated that incomplete RF shielding results in MR image degradation. Studies related to the operation of a multileaf collimator were performed in [10]. The multileaf collimator is a device used to produce irregular shaped photon beams; this is accomplished by using several moving leaf collimators operated by dc motors. The work in [10] illustrated that the RF noise produced by the dc motors could be shielded such that no degradation of MRIs is observed while the multileaf collimator is operated at the same time.

However, these previous reports did not discuss the sources of the RF noise related to the linac. The purpose of this study is to investigate the sources of RF noise from the pulse power modulator of a linac. We present results from measurements and simulations, which attempt to identify the major sources of RF noise or to exclude possible mechanisms as sources of RF noise. The results from this study are useful for linac-MRI systems in...
which the generation of RF noise from a linac is important. The work specifically reports on the modulator of a linac whose microwave power is produced by a magnetron.

II. THEORY

The RF noise from the modulator of a linac was measured using commercially available electric \((E)\) and magnetic field strength \((H)\) field probes. The measurements from these probes were used to express the measured data as an RF power spectral density. A total of \(N\) time-domain waveforms, \(e_i(t)\) and \(h_i(t)\), respectively, from the \(E\) and \(H\) field probes were first obtained, where \(i\) refers to the \(i\)th waveform and \(t\) the time. One thousand waveforms were used in this study to get an estimate of the measurement. In this notation, we refer to the magnitude of the fields, since the \(E\) probe used in this study measures the magnitude of the \(E\) field and while offline we added the measured \(H\) field components in quadrature. The measured spectral density of the \(E\) and \(H\) fields \(M_E(f)\) and \(M_H(f)\) were obtained as the root-mean-squared magnitude of the discrete Fourier transform (DFT) of the \(e_i(t)\) and \(h_i(t)\) waveforms, respectively, as follows:

\[
E_i(f) = \text{DFT}\{e_i(t)\}
\]

\[
M_E(f) = \sqrt{\frac{\sum_{i=1}^{N} |E_i(f)|^2}{N}}
\]

where \(f\) is the frequency. Equation (1) can be written for the magnetic field by replacing \(e_i(t)\) with \(h_i(t)\), \(E_i\) with \(H_i\), and \(M_E\) with \(M_H\).

The measured spectral densities \(M_E(f)\) and \(M_H(f)\) are related to the \(E\) and \(H\) field strengths through the performance factors \(PF_E(f)\) and \(PF_H(f)\), respectively. For example, the \(E\) field is related to the measurement as follows:

\[
E = M_E(f)PF_E(f).
\]

Substitute \(H\) for \(E\) in (2) for the \(H\) field. As illustrated in (2), the performance factors relate the measured spectral densities in volts from the field probes directly to the corresponding field strengths. For the probes used in this study the performance factors were batch calibrated by the manufacturer. The performance factors themselves are provided in a graphical fashion as a function of frequency. Equation (2) is used with our measured spectral densities along with the graphically provided performance factors to determine the field strengths as a function of frequency. A thorough analysis of the performance factors for the near-field probes can be found in [8]. The time-averaged power density \((S_{av})\) is determined using:

\[
S_{av} = \text{Re}\left(\frac{\vec{E} \times \vec{H}}{2}\right).
\]

Where “Re” refers to the real part of the cross product of the electric field vector and complex conjugate of the magnetic field vector. In our case, the \(E\) field probe only measures the magnitude of the electric field vector. Although the \(H\) field probe can measure the direction and magnitude, the quantity

![Fig. 1. Schematic representation of the major elements in the modulator of a linac.](image-url)

“\(H\)” in (2) [i.e., \(H\) substituted for \(E\) in ([2])] is the magnitude of the magnetic field strength obtained by adding the three orthogonal measurements in quadrature. Therefore, in this study, the approximate power spectral density \((P)\) of the RF noise is calculated using the following formula:

\[
P_{\text{upper}}(f) = \frac{E(f)H(f)}{2}.
\]

Equation (4) provides an upper limit, i.e., to that of (3), of the estimation of the measured power spectral density of RF noise.

III. MATERIALS AND METHODS

A refurbished modulator of a 6-MV linac was used to study the sources of RF noise. A schematic of the modulator is shown in Fig. 1. The main components of the modulator consisted of a three phase power supply (represented by a dc supply in Fig. 1), a large choke inductor and de’Q circuit, a pulse-forming network (PFN) with a Hipotronics (Hipotronics, Inc., Brewster New York, MASF-1357-A314) capacitor bank of 10 nF capacitors, an E2 V (E2 V technologies, Chelmsford, England) CX 1140 L thyatron, and an E2 V MG5193 magnetron (denoted as the load in Fig. 1). The microwave power produced by the magnetron was fed into an electromagnetic designed water load (EM Design, Medford Oregon, model R284B-3). The water load was used to dissipate the microwave energy from the magnetron. The resistive load did not require the use of the water load.

The \(E\) and \(H\) fields produced by the modulator were measured using a near-field HZ-11 probe set (Rohde and Schwarz, Munich, Germany). The \(E\) probe measures the total \(E\) field strength, while the \(H\) probe was used to measure the three individual orthogonal components of the \(H\) field strength; these three components were added in quadrature to obtain the total \(H\) field strength (more detail regarding the field probes used is given in [8]). The measured data from the \(E\) and \(H\) probes was transferred from the oscilloscope to a PC, using a Keithley KUSB 488 GPIB interface (Keithley Instruments, Inc., Cleveland, OH). An in-house stand constructed from wood and Delrin was used for stable positioning of the probes during measurement. These materials were tested to ensure that there was no alteration of the measured fields [11]. The software program DADiSP (DSP Development Corporation, Newton, MA) was then used for offline data analysis. DADiSP was used to calculate the DFT of the measured waveforms. The resulting DFTs had bin widths of 50 kHz in the frequency domain. The final frequency spectra of the \(E\) and \(H\) fields were separately calculated as in (1). The signal strength density was estimated from 1000
time-domain measurements. The approximate power spectral density of the RF noise was then calculated using (4).

In order to isolate the broad-band RF noise generated by magnetron loading from other possible RF sources (such as the thyatron), a high-power resistive load replaced the magnetron and microwave water load in one set of measurements. The high-power resistive load consisted of a total of 32 50 Ω resistors, the resistors were wired such that there were two parallel banks of 16 resistors connected in series giving an equivalent 400 Ω load. An in-house constructed RF cage was placed around the resistive load to minimize any direct RF emissions from the load. The in-house constructed RF cage consisted of 0.25-inch plexi-glass sheets placed around the resistive load to prevent arcing and an aluminum enclosure built around the plexi-glass for an RF shield. In order to obtain an estimate of the RF noise produced by magnetron loading in the modulator, the RF noise was first measured with the magnetron as a load. Then the magnetron was replaced with the high-power 400 Ω load and the RF noise was once again measured with everything else being held constant. To investigate any loading effects (that is the possibility of different reflections occurring from the resistor load as compared to that of the magnetron load or any filtering effects due to capacitive differences) a pulse shaper was placed in parallel with the 400 Ω load. The pulse shaper consisted of a 0.5-mF capacitance in series with 30-kΩ resistance. The difference in the measured RF noise power between the magnetron and the resistive load can then be attributed to magnetron loading. One side panel of the RF cage, closest to the magnetron, of the modulator was removed during these measurements. The E and H field probes were mounted on the aforementioned stand such that the magnetron and probes were at approximately the same height. The probes had a direct line of sight to the magnetron when placed at a distance of 2 m from the modulator.

When unwound, the PFN coil itself is approximately 20 m in total length, it was thought that at this length it could act as a good radiator in the tens of megahertz range. A separate investigation was made to determine the RF field produced by the PFN coil during PFN discharge. The MultiSIM (National Instruments, Austin, TX) software package was used to simulate the complete circuit of the modulator, as shown in Fig. 1, and to calculate the voltages and currents at specific points in the circuit of the modulator. Specifically, the simulation included: a three-phase power supply; a large choke inductor and De’Q circuit; the PFN coil modeled as discrete inductors with mutual coupling; the thyatron modeled as a diode, a switch and a small resistance; the magnetron modeled as a biased diode of 400-Ω resistance with a small capacitance in parallel. The simulation also included the despiking network, a voltage divider circuit to measure the PFN voltage, a circuit to measure the high-voltage power supply current, a transformer between the thyatron and the magnetron, and a simple current probe was used to measure the current through the magnetron. The modulator simulation was validated by comparing the measured voltages or currents at the same locations in the modulator as those calculated by the simulation. The simulated currents through the PFN coil were used as inputs into a second software program, COMSOL Multiphysics (COMSOL Inc., Los Angeles, California), which was used to determine the E and H field strengths from the PFN coil as a function of time during the discharge of the PFN. The simulation of the fields produced around the PFN coil during discharge was done using a 2-D geometry. The coil consisted of quarter-circumference rings of the dimensions and spacing of the PFN coil itself (this could be done due to the axial symmetry of the problem). The boundary settings were set as axial symmetry at zero radius (along the axis of the coil), and all other boundaries were set to magnetic insulation ($A_\phi = 0$, where $A$ is the vector potential and cylindrical coordinates are used). The currents on the rings were set by defining functions, which contained the coil currents as a function of time. For the measurements, the E and H field strengths produced by the modulator were measured using both the near-field HZ-11 probe set and the low-frequency magnetic field from the modulator was measured using a Senis (Senis GmbH, Zurich, Switzerland) 3M12-2-2-0.2 T Hall probe together with a 3-axis type C-H3 A-E3D-1%-0.2 T magnetic field transducer (the field probes are only calibrated down to 100 kHz, a Hall probe was needed to capture the lower frequency response in both the time and frequency domains). The Hall probe was placed 0.8 m away from and at the same height as the PFN coil.

At the time of thyatron trigger, large spikes appear on the grids. We investigated the possibility of these spikes entering the grid trigger circuit and being radiated as RF noise. Two similar saturable reactors (SRs) were constructed as described by [12]. Our SR consisted of six Magnetec M-074 Nanoperm Cores (Magnetec GmbH, Lagenselbold, Germany). The SR was wound with two by five turns of Belden (Belden, Inc., Richmond, IN) 8869 high-voltage cable. A single turn from standard bench-top wire was used for the control winding. The setup used to operate the SRs is shown in Fig. 2. Two 1-A power supplies were used to bias the reactors to the desired operating point. Resistors R1 and R2 were used to set the current through the SRs and the inductors L1 and L2 operated as bias hold off chokes.

The RF noise from the spikes on the thyatron grids was investigated by measuring the RF noise during normal operation and then measuring the RF noise after installing the two SRs described earlier. As shown in Fig. 2, the SR’s were connected directly to the thyatron grid contacts such that the trigger pulses had to pass through the SR. The E and H field probe set was used to get an estimate of the power spectral density. These E and H field probes were placed at the same height as the thyatron but approximately 2 m from the thyatron. The side panel of the

![Fig. 2. Setup used to suppress the voltage spikes seen on the thyatron grids at the instant of firing.](image)
RF cage, adjacent to the thyratron, was removed for these sets of measurements. The same hardware and software techniques as previously described were followed. A direct comparison between the RF noise with and without the use of the SRs was used to deduce the RF noise generated by the spikes entering the trigger circuit.

IV. RESULTS

The measured RF power spectral density with the magnetron and resistive loads is shown in Fig. 3. The data are shown in the frequency range 0–400 MHz. Three curves of the measured RF power spectral power densities are shown in each plot; the magnetron load, the resistive load, and the resistive load with pulse shaper (modified resistive load).

Fig. 4 shows the measured and simulated (using the Multi-SIM software package) magnetron currents in both the time and frequency domains. Fig. 5 shows the resulting individual PFN capacitor voltages as a function of time during the discharge (the voltages are shown here since they provide a clearer illustration of the discharge of the PFN). The individual currents were used as inputs into COMSOL to determine the fields around the coil during discharge.

The simulated and measured magnetic field at 0.8 m from the center and perpendicular to the axis of the PFN coil is shown in Fig. 6. Fig. 7 shows the power spectral density of the simulated data illustrating that the majority of the power is contained at lower frequencies.

Fig. 8 shows the measured spike from the thyratron into the heater/trigger circuit, with and without the use of an SR. The magnitude of the spikes is smaller than expected, see [10], due to the derating curve of the probe. It can be seen in Fig. 8 that the SR greatly reduced the size of the voltage spike. Fig. 9 is the Fourier transform of the data presented in Fig. 8. It can be seen that the use of the SR greatly reduces the frequency components composed within the spike. No derating curve was applied to the data in Figs. 8 or 9; the relative reduction of RF noise due to the use of an SR was the quantity of interest.

Fig. 10 shows the measured RF power spectral densities during normal operation and when our SRs were used to block the grid spikes from directly entering the trigger circuit, data are shown in the frequency range 5–70 MHz. This range is shown since the Larmor frequencies for 0.2–1.5 T MRI systems are contained therein.

V. DISCUSSION

A linac produces radiation in the form of pulses; it is during the formation of these pulses that a modulator produces RF noise [8]. Our previous work has discussed the importance of the study of RF noise from a linac. With incomplete RF shielding, the images reported in [5] were deteriorated. The images presented
in [10] illustrate that the RF noise from a linac manifests itself as lines in k-space of MR data acquisition. The results presented in [11] illustrate degradation of the SNR with the incomplete shielding of RF noise of dc motors. For linac-MRI systems, it is desirable to understand the process and production of RF noise from the modulator of a linac. The importance of this study lies in the determination of the sources of RF noise. The information obtained in the present investigation may be useful in practical considerations in the layout of linac-MRI systems. For example, the MR signal or power cables that pass near sources of high-power RF should be rerouted.

The RF noise produced by the modulator of a linac can be picked up by the coils used in MRI; this RF noise could then produce deleterious effects on the resulting image quality. An understanding of the sources of RF noise will aid in the design of linac-MRI systems.

A magnetron is known to be a source of RF noise [13]–[17]. However, it is important to determine the contribution to the overall RF noise due to magnetron operation. For this purpose, the generated RF noise from the modulator of a linac was measured when loaded with a magnetron and then with a purely resistive load. From Fig. 3, we can see that above 35 MHz the majority of the noise produced by the modulator can be attributed to the presence of the magnetron as opposed to a matched load that is purely resistive. Below 35 MHz, other processes also contribute to the production of RF noise. Loading effects (that is different reflections on the PFN side of the transformer or filtering can occur at non-dc frequencies with a load which does not exactly represent a magnetron load) were investigated by using a pulse shaper on the resistive load. When the pulse shaper was added to the resistive load its effects were prevalent in the frequency ranges 20–55 MHz and below 4 MHz (as seen in Fig. 3). This suggests that in these frequency ranges other mechanisms of RF production may exist beyond those that can be attributed to the magnetron.

When the thyratron starts to conduct, the PFN capacitors at first discharge half their energy stored sequentially starting with those closest to the thyratron and then discharging the remaining energy in the reverse order (this process is shown in Fig. 4). During this discharge, frequencies in the MHz range exist on the PFN coil. An attempt was made to quantify the production of RF noise from the PFN coil using measurements and simulations. Fig. 6 illustrates that the measurement and simulations show
similar shapes; this can be expected from the fact that this is the shape of the PFN charging voltage. However, the magnitude of the data is significantly different. The measurement taken using a Hall probe in Fig. 6 (top) was performed in order to ascertain the low frequency response, where the performance factors of the $E$ and $H$ field probes below 100 kHz were not provided by the manufacturer. During the operation of the modulator many possible sources of RF noise exist. The $E$ and $H$ field probes as well as the Hall probe respond to many of these possible sources. The simulation of the fields near the PFN coil during pulse discharge contains only the PFN coil as a source. Fig. 6 illustrates a large difference in magnitude between the simulated field from the PFN coil and the total measured field strength. It can therefore be concluded that the discharge of the PFN coil itself is not a large contributor to the total RF noise. The origin of the spike that is present at the initiation of the pulse shown in Fig. 6 is not clear. It was not observed in our modeling, which suggests that an unknown mechanism is responsible for it. The data shown in Fig. 7 illustrate that the PFN coil may produce some RF, but only at lower frequencies (below 1 MHz). When comparing Figs. 3 to 7, we can see that other mechanisms for a magnetron-loaded modulator RF noise production are significantly larger than the simulated power emanating from the PFN coil. We also note that the data, as shown in Fig. 7, are in a direction perpendicular to the PFN coil. The fields along the PFN coil axis are slightly larger but are still insignificant to those shown in Fig. 3 (these data are not shown).

A thyratron is also known to produce RF noise up to 20 MHz [18]. Large spikes are seen on the grids of the thyratron at the instant of firing just before the discharge of the PFN. These spikes can reach a substantial fraction of the anode voltage [12], which is typically 24 KV for low-energy linacs. A Fourier analysis of these spikes shows that frequencies up to 60 MHz exist; specifically frequencies in the range of 42 to 60 are present. Two SRs were constructed and placed on the grids of our thyratron, as illustrated in Fig. 2. The RF noise was measured with and without these SRs connected. The measured data, in the frequency range 5–70 MHz, are shown in Fig. 10. The RF noise is slightly reduced in the frequency range 42–60 MHz; albeit by a small amount. Further work is required to determine if the RF noise in this region can be attributed to the grid spikes. The data in Figs. 8 and 9 illustrate that the RF noise injected into the trigger and heater circuits was reduced. However, the total measured RF noise was not substantially decreased.

The authors also note that if the SR is not operated at the correct point along the BH curve, the RF noise is generally increased. The results in Fig. 10 indicate that the voltage spike directly entering the trigger circuit is not a major mechanism of RF noise production. However, other mechanisms such as capacitive or inductive coupling into other parts of the modulator could potentially lead to RF noise generation. For example, [19] suggests that the grid spikes occur as a result of inductive coupling effects.

Possible further sources of RF noise generation include an antenna effect from short bare wires, which transfers the high voltages from one element to another. For example, the PFN coil to thyratron, the thyratron to transformer, and the transformer to magnetron.

Finally, the authors would like to note that the power levels presented in this study are higher than those presented by Burke.
et al. [8]. Burke et al. reported on the RF levels relevant to a clinical setup, which included full shielding around the modulator of the linac. The work presented in this document required the removal of some of the shielding around the modulator. The lack of a complete RF cage around the modulator results in measurements of much higher RF power levels.

VI. CONCLUSION

This study has shown that the magnetron is a major contributor to the RF noise produced by the modulator of a linac. Above 60 MHz essentially all the noise produced can be attributed to the magnetron loading. Below 60 MHz other mechanisms can also contribute to the production of RF noise. The PFN coil has been shown not to be a major contributor of RF noise, especially above 1 MHz. It was also shown that blocking the large voltage spikes on the thyratron grids from entering the trigger circuit did not have a major effect on the RF noise generated in the frequency range 5–70 MHz. The RF noise generated by a magnetron-loaded modulator can only be shielded. Since the majority of RF noise produced by a modulator emanates from the magnetron loading, this study suggested that the best way to integrate a linac and MRI would be to place the modulator in an RF shield and to maximize distance to the MRI by possibly placing the modulator externally to the MRI room.

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Authors’ photographs and biographies not available at the time of publication.